

POSTER SESSION - I



Dynamics of the Nanowire VLS Growth Unravelled by Isotope Tracing

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It has been proposed that the Vapour-Liquid-Solid (VLS) growth of nanowires (NWs) requires the involvement of both truncated facets and a main facet at the catalyst-NW interface, with the crystallization kinetics of adatoms at the former distinctly different from the latter.¹ For Au catalysed Si NW, Molecular Dynamics (MD) simulations demonstrated that the enthalpy of adding a Si atom on to a stepped truncated facet is significantly lower than the closed-packed main facet. Presented with the lower nucleation barrier adatoms undergo rapid crystallization at the truncated facets as compared to the main facet, a phenomena which affects morphology and composition of NWs.¹ In this work, we elucidate experimentally this interesting feature of VLS growth using isotope tracing. Isotopically mixed $^{28}\text{Si}_x^{30}\text{Si}_{1-x}$ NWs were grown using isotopically enriched silane precursors.² The three-dimensional atomistic imaging of as-grown NWs, performed using Atom Probe Tomography (APT), revealed that while the core of the NW is rich in the heavier isotope (^{30}Si) the periphery is rich in the lighter isotope (^{28}Si), as displayed in the radial concentration profile of the two isotopes in Figure 1. This result demonstrates that the small difference in diffusion coefficient between the two Si isotopes gets amplified as the atoms undertake a large number of diffusion steps at truncated facets. This process favours the attachment of the lighter isotope (^{28}Si) leading to an enrichment in its content about 3-5 nm near the nanowire surface (Figure 1). As consequence of this preferential attachment, the growth at the main fact involves relatively more atoms of the heavier isotope (^{30}Si) (Figure 1). The main focus of this presentation will be to describe this subtle but important mass-sensitive factor that highlights the VLS growth dynamics of Si NWs.

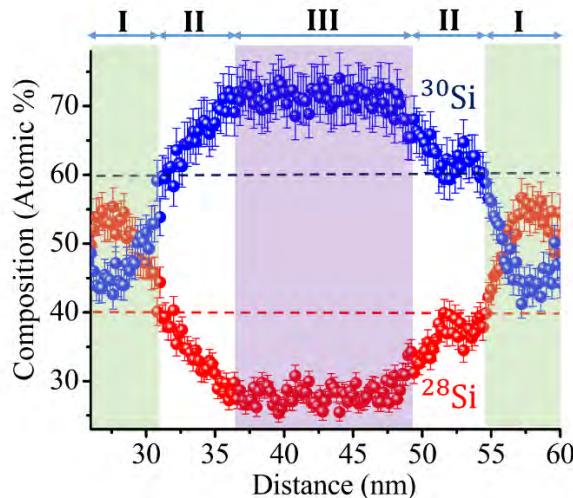


Figure 1: A radial concentration profile of the two Si isotopes, taken across the growth axis of the $^{28}\text{Si}_x^{30}\text{Si}_{1-x}$ NW. The profile clearly indicates the presence of three distinct zones of different isotopic composition within a NW – one rich in ^{28}Si (I), one rich in ^{30}Si (III), and a transition zone (II).

References:

1. Wang, H., Zepeda-Ruiz, L. A., Gilmer, G. H. & Upmanyu, M. Atomistics of vapour-liquid-solid nanowire growth. *Nat. Commun.* **4**, 1956 (2013).
2. Mukherjee, S. et al. Phonon Engineering in Isotopically Disordered Silicon Nanowires. *Nano Lett.* **15**, 3885–3893 (2015).

The Role of Hydrogen in Ge Nanowire Growth

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Preparation of semiconductor nanowires of different morphology is of key importance for their future applications. Especially the nanowire growth direction and sidewall faceting are essential, because they strongly influence the physical properties of nanowires. In our contribution, we will focus on the growth of germanium nanowires by the VLS mechanism using a conventional Au catalyst. In case of the thermal evaporation technique (PVD) the nanowire growth direction is almost exclusively $<110>$ with the $\{111\}$ sidewall facets [1,2]. This is in contrast to the nanowires grown from the vapour phase (CVD), where the $<111>$ direction is predominant [3]. We will discuss possible reasons for this dissimilarity. More importantly, we will present our latest results on the possibility to alter the growth direction of PVD grown nanowires by introducing hydrogen during the growth and the influence of hydrogen on nanowire morphology.

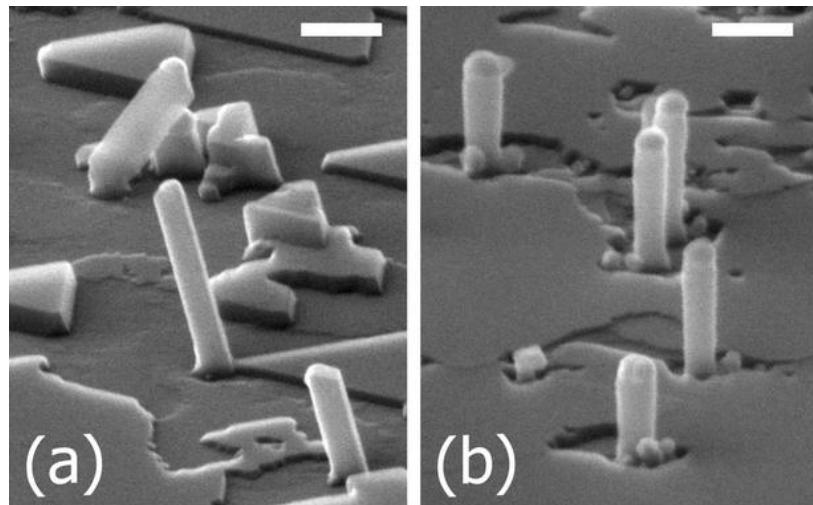


Figure 1: Ge nanowires grown using the Au catalyst on the Ge(111) substrate. (a) The nanowires exhibit the $<110>$ growth direction exclusively if evaporated under UHV conditions. Sidewall facets are of the $\{111\}$ orientation. (b) The presence of hydrogen changes the morphology of the nanowires – the growth is in the $<111>$ direction. Both images are tilted by 70° with respect to the surface normal. The scale bars are 300 nm.

References

- ¹ M. Kolíbal *et al.*, *Appl. Phys. Lett.* **99**, 143113 (2011).
- ² M. Kolíbal *et al.*, *Appl. Phys. Lett.* **100**, 203102 (2012).
- ³ H. Adhikari *et al.*, *Nano Lett.* **6**, 318–323 (2006).

Characterization of Ge nanowires under Mn implantation

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Currently, the study of semiconductor nanowires is one of the technological key issues for the development of several applications such as spintronics, where Germanium nanowires (Ge NWs) synthesized by the vapor-liquid-solid mechanism (VLS) in the bottom-up approach appear as well adapted structures for dilute magnetic semiconductors (DMS).¹ Various attempts were made to incorporate manganese (Mn) atoms in Ge NWs especially by in-situ doping during VLS growth. Unfortunately, while the VLS is a non-equilibrium process, all our attempts by UHV-CVD growth failed to incorporate Mn into nanowires.² Therefore, ex-situ doping with ion implantation was considered as an alternative.

We have performed preliminary experiments aiming at testing the radiation resistance of Ge NWs embedded in a removable silica matrix and observing the potential precipitation of Mn. Ion beam incidence was kept normal to the matrix i.e along the vertical as-grown nanowires. Implantations were carried out at room temperature (RT) and at 300°C to evaluate the influence of thermal dynamic annealing during implantation. At RT, amorphization is observed around the projected range Rp, while at 300°C a dynamic restructuration takes place during implantation and the crystallinity of NWs was preserved. Increasing the fluence resulted in a high sputtering of the NW surface and a large mixing with the matrix.

To monitor the accumulated damage in Ge nanowires, in-situ transmission electron microscopy (TEM) observations during implantation were carried-out as a function of the Mn fluence on Ge NWs lying on SiN membranes. Special interest lies on the enhanced sputtering of nanowires and on the dynamical recovery due to surface effects. It appears that the main parameter is the ion flux. The influence of electron beam was also observed during implantation. It is worth noting that no Mn clusters were observed up to the highest studied.

References

¹ J.S. Kulkarni, *et al.*, *Applied Physics A* **85**, 277 (2006).

² C.Renard, *et al.*, *Physica Status Solidi C* **11**, 315 (2014).

Induction of Twinning and Polytypes in Diameter Controlled Germanium Nanowires

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Nanowires have attracted increasing interest due to their potential application in optically active devices, as building blocks for nano-circuitry, in energy conversion devices. Control over the dimensions and crystal structure is essential for the implementation of one-dimensional nanostructures in such devices. Widely popular bottom-up nanowire growth models refer to unidirectional growth resulting from any three phase systems, for example, vapour-liquid-solid (VLS), vapour-solid-solid (VSS) growth processes. In this research, colloidal magnetite iron oxide nanoparticles were used to seed growth of Ge nanowires in a Vapour-Solid-Solid (VSS) regime, where nanowire diameters were controlled by the dimension of the catalysts. These iron oxide nanoparticles regulated the radial dimensions of the nanowires due to the minimal expansion and aggregation during the growth process (Figure 1). Control over the mean diameter was displayed even for sub-10 nm growth. Limiting techniques, such as catalyst nanoparticle concentration, were also explored to maximise diameter control. The uncommon occurrence of heterogeneously distributed multiple layer {111} twins, directed perpendicular to the nanowire growth axis, were also observed in {111}-directed Ge nanowires, especially those synthesized from patterned hemispherical Fe₃O₄ nanodot catalysts. Consecutive twin planes along {111}-oriented nanowires resulted in a local phase transformation from 3C diamond cubic to hexagonal 4H allotrope. Localized polytypic crystal phase heretostructures were formed along {111}-oriented Ge nanowire using magnetite nanodot catalysts (Figure 1).

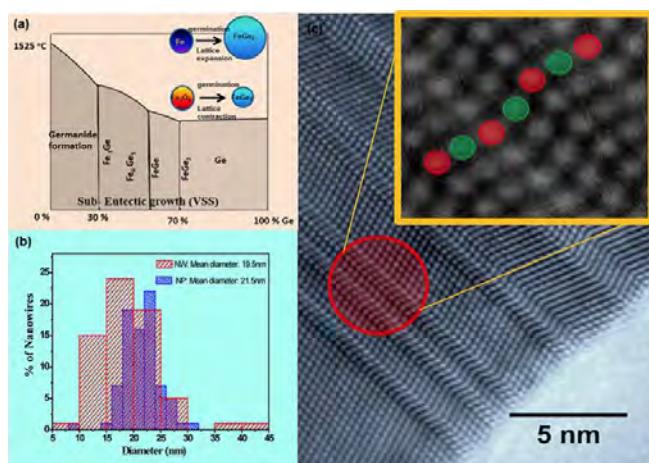


Figure 1: (a) Germanium – Iron phase diagram and the lattice expansion from Fe compared to the lattice contraction from Fe₃O₄ to FeGe₂, (b) diameter distribution of nanoparticles (red) compared with nanowires (blue) and (c) TEM image of the lateral twin boundaries.

References

- ¹ S. Biswas, et al., *Chemistry of Materials* **27**, 3408-3416 (2015).

Exploring the Growth Regimes of Platinum Catalyzed Silicon Nanowire Growth

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The use of platinum (Pt) as catalyst material for vapor-liquid-solid (VLS) synthesis of silicon nanowires (SiNW) can be traced back to the mid 60's.¹ Surprisingly, the number of publications in this research area is still rather limited. The reason might be related to the required high synthesis temperature and the related complex silicide phase diagram, although certain advantages are evident. In comparison to gold (Au) as the standard VLS-catalyst, Pt is known to form less deep traps in silicon² and to provide more control over the SiNW crystal orientation.³

Using ultra-thin Pt catalyst films, nanoparticles, and beam-deposited Pt, a non-VLS growth regime for Pt-catalyzed SiNW synthesis could be clearly identified. The SiNW synthesis was obtained at temperatures between 700 °C and 800 °C in a quartz tube furnace using SiH₄ as process gas. To elucidate the key parameters triggering the growth regimes, experiments were conducted that allowed proposing the first comprehensive growth model for Pt catalyzed SiNW growth. The model includes the simultaneous formation of Pt- and Si-rich silicon phases exhibiting different melting points. While Pt-rich silicide droplets nucleate nanowires as per the VLS method with a catalyst present at the tip of the nanowire (Fig.1A), Si-rich phases nucleate SiNWs by solid state diffusion similar to vapor-solid-solid growth but with a polycrystalline tip (Fig.1B) and the catalyst present at the interface to the substrate. The local Pt concentration was identified as a critical parameter determining the SiNW nucleation rate and growth velocity as well as the preferred growth regime (Fig.1C). A more detailed investigation of Pt-based SiNWs was obtained based on our recent results regarding beam-deposited Pt⁴ as well as experiments evaluating the influence of the substrate material, its pretreatment, and the influence of dopants, pressure, and temperature.

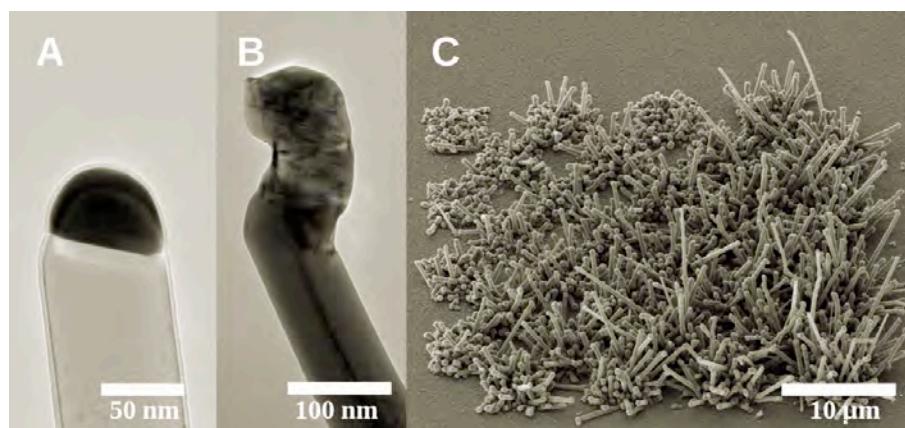


Figure 1 **A:** VLS grown SiNW with a Pt silicide catalyst at the tip. **B:** SiNW grown in a non-VLS regime by solid state diffusion exhibiting a polycrystalline tip and involving a Si-rich silicide present at the interface to the substrate (not shown). **C:** SiNWs grown from a beam-deposited Pt chessboard pattern with Pt thickness gradient demonstrating the influence of the local Pt concentration on the SiNW growth.

References

- 1 R. S. Wagner, W. C. Ellis, *Appl. Phys. Lett.* **4**, 89 (1964)
- 2 T. Baron, M. Gordon, F. Dhalluin, C. Ternon, P. Ferret, and P. Gentile, *Appl. Phys. Lett.* **89**, 233111 (2006)
- 3 R. He and P. Yang, *Nature Nanotechnology* **1**, 42 (2006)
- 4 N. Hibst, P. Knittel, C. Kranz, B. Mizaikoff, and S. Strehle, *Appl. Phys. Lett.* **105**, 153110 (2014)

Silver as a catalyst for growth of GaAs nanowires

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The research field involving growth of III-V semiconductor nanowires (NWs) is becoming more and more mature as a result of the many years of efforts devoted to understanding how these structures are formed using gold as seed/catalyst material [1]. Gold-free methods to synthesize NWs have also been explored. One example is using a so-called self-seeding strategy in which the group III material of the final NW plays the role of seed/catalyst droplets [2]. Recently, a few investigations of using other seed metals than gold have been reported for the growth of III-V NWs [1]. Compared to gold catalysed NW growth, the understanding is still very limited and there is a need for further research in order to find the actual role of the seed material itself. All methods to synthesize NWs have their “pros and cons” in terms of accessible or tuneable properties of the NW crystal quality [3], heterostructure combinations and interface abruptness [4] and growth directions [5]. Besides requirements on the generic properties of the NWs for future device applications, going from proof-of-principle devices in a laboratory environment towards integration of NW-based devices with Si electronics may also induce constraints with respect to being compatible with gold-free processes to protect the functionality of the complete semiconductor device [1][6]. Here we have explored another seed material, with many similarities to gold, to get further insights into the actual role of the seed material itself. We used silver and study the feasibility to grow GaAs NWs using both (111)B and (001) oriented substrates and Molecular Beam Epitaxy. We find that GaAs NWs can indeed be grown using silver as seed material. In addition, we observe that the NWs have a high quality crystal structure, both zincblende and wurtzite phases can be achieved, and be grown vertically on both surface orientations. Here we will present our growth experiments and discuss the role of some growth parameters, especially the growth temperature, and how going beyond gold as seed material may provide new possibilities for III-V NWs.

References

- ¹ K.A. Dick and P. Caroff, *Nanoscale*, **6**, 3006 (2014).
- ² A. Fontcuberta i Morral, *et al.*, *Appl. Phys. Lett.*, **92**, 063112 (2008).
- ³ P. Caroff, *et al.*, *IEEE J. Sel. Top. Quantum Electron.*, **17**, 829 (2011).
- ⁴ K. A. Dick, *et al.*, *Nano Lett.*, **12**, 3200 (2012).
- ⁵ S. A. Fortuna and X. Li, *Semicond. Sci. Technol.*, **25**, 024005 (2010).
- ⁶ A. J. Tavendale and S. J. Pearton, *J. Phys., C: Solid State Phys.*, **16**, 1665 (1983).

Effect of V-III ratio on low-temperature growth Sn-seeded GaAs nanowire

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Au has been mostly employed as seed particle for III/V nanowire growth. Besides the efforts on gold free nanowire growth including selective area growth, self-seeded growth, and non-gold foreign metal seeding, a special case of the later, namely alternative foreign metal seeding has attracted a lot of interest since it could potentially introduce interesting properties¹. Sn can successfully initiate GaAs nanowire growth with a self-assembled core shell p-n junction, a Sn doped-n core and a C doped-p shell as previously reported². However, only a limited temperature range (487 °C – 525 °C) is suitable for successful, straight nanowire growth. However, for growth temperatures below that window most of the nanowires are kinked.

Here we show that successful, straight GaAs nanowire growth can be achieved in low temperature range by changing the V-III ratio instead of the use of a two-temperature approach which has been usually employed for nanowire grown at low temperature. We found a close link between the nominal V/III-ratio and the GaAs nanowire kinking, by supplying more trimethylgallium (TMGa) at a growth temperature of 455°C we observe a high yield of straight nanowires as shown in figure 1.

From photoluminescence (PL) experiments, we observe that heavy Sn related n-doping shifts the Fermi level into the conduction band, which increases the average radiative recombination energy. PL did not show any noticeable changes with excitation power density apart from the intensity, which supports our interpretation. We also see indication that V/III ratio would affect dopant incorporation into the nanowire.

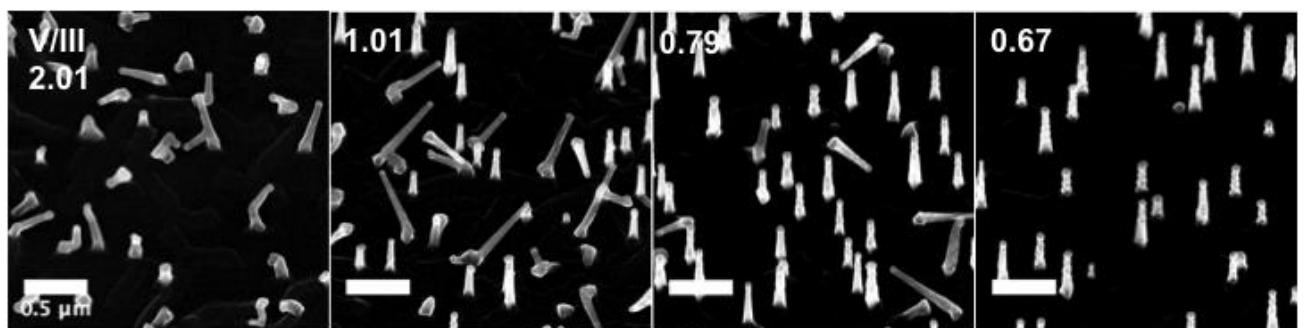


Figure 1: Sn seeded GaAs nanowire grown at 455°C with decreasing V-III ratio.

References

¹ K. A. Dick et al, *Nanoscale*, 2014, 6(6), 21

² R. Sun et al, accepted by *Nanoletters*

Ga-Catalyst GaAs Nanowires grown on Silicon by HVPE

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Hydride Vapour Phase Epitaxy (HVPE) is the only III-V semiconductor crystal growth process working close to equilibrium. Gold Catalyst-assisted GaAs nanowires (NWs) growth from HVPE shown a constant cylinder shape over unusual growth rate (170μm/h) and free of crystal defects.^{1,2} However, using of gold like catalyser harms the properties of semiconductors by causing for example the deep-level trap sites.

Our recent work reveals the formation of *in-situ* Ga-assisted catalyst-free GaAs NWs by HVPE deposited on patterned silicon wafer for the first time. Gallium liquid catalyst NWs had shown morphology curved and randomly distributed, with diameters of around 80 nm. These NWs present a surprisingly fast solidification rate as more than 1000μm/h on account of lower growth temperature (600°C). A discussion based on thermodynamics will be proposed.

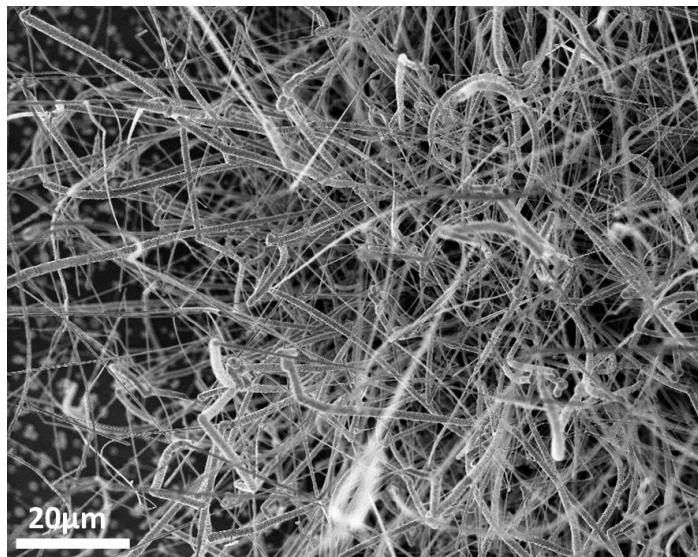


Figure 1: SEM image of Ga-assisted GaAs NWs on Silicon

References

¹E. Gil, *et al.*, *Nano Lett.*, **14**, 3938–3944, (2014).

²M. R. Ramdani, *et al.*, *Nano Lett.* **10**, 1836–1841 (2010).

Self-induced growth of GaAs nanowires on lithography-free Si/SiO_x patterns

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Self-induced growth of GaAs nanowires (NW) on Si(111) surface is typically performed by vapour-liquid-solid mechanism, either through random pinholes in silicon oxide layer that covers the substrate or by selective-area growth (SAG) on nanopatterned Si/SiO₂. A disadvantage of the self-induced method is that it does not allow control over the size and density of the pinholes which affects the uniformity of the NWs. SAG, on the other hand, provides deterministic tailoring of the oxide pattern but increases significantly the complexity of the NW fabrication process.

Here, we demonstrate self-induced growth of GaAs NWs on lithography-free Si/SiO_x patterns fabricated in situ by a method based on droplet epitaxy (DE)¹. GaAs mounds grown by DE have been successfully used as platforms on which self-induced NWs can be nucleated². In our approach³ we use DE for the growth of GaAs nanoislands on oxide-free Si(111) surface, oxidize the sample, and thermally evaporate the GaAs nanoislands. By this procedure we obtain uniform self-assembled Si/SiO_x nanopatterns with tunable hole size and density. We show that highly uniform self-catalyzed GaAs NWs can be grown on these patterns in typical NW growth conditions. For example, Fig. 1(a) shows 4.3 μm long NWs having length deviation of less than 1%.

For optical investigations the GaAs NWs were covered with an AlGaAs shell. These coaxial heterostructure NWs exhibit strong room temperature emission at 1.43 eV. Furthermore, the high optical quality of the NWs is proved by measuring a biexponential decay with photoluminescence lifetimes of 1.0 ns and 3.0 ns, as shown in Fig. 1(b).

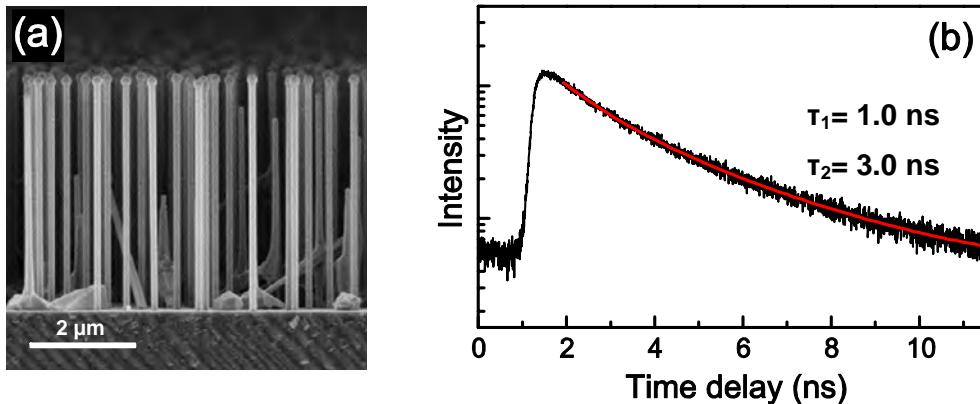


Figure 1: (a) Cross-sectional SEM picture of the GaAs NWs grown on lithography-free oxide pattern, (b) time response of the photoluminescence emission measured at 300K.

References

- ¹ N. Koguchi, S. Takahashi, T. Chikyow, J. Cryst. Growth 111, 688 (1991).
- ² C. Somaschini, S. Bietti, A. Trampert, U. Jahn, C. Hauswald, H. Riechert, S. Sanguinetti, and L. Geelhaar, Nano Lett. 13, 3607–13 (2013).
- ³ T.V. Hakkarainen, A. Schramm, J. Mäkelä, P. Laukkanen, and M. Guina, Nanotechnology 26, 275301 (2015).

Tailoring of GaAs NW for in-situ X-ray investigations using a portable MBE

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The integration of III-V nanowires on silicon allows to merge the cost-effectiveness of silicon-based technology with the excellent electrical and optical properties of III-V semiconductors¹.

With our portable molecular beam epitaxy system² for in-situ X-ray investigations at ANKA, we have studied the zincblende-wurtzite polytypism in gallium arsenide (GaAs) nanowires³. The setup allows time-resolved investigation of the crystal structure of nanowires by X-ray diffraction⁴ or RHEED during the complete growth process.

For the preparation of GaAs nanowires, we use a Ga-assisted growth mode where Ga droplets are deposited onto the native oxide layer of the silicon substrate acting as nucleation site of the NW growth. By an in-situ annealing step - prior the initial growth – one is able to tailor the density of the Ga droplets and thus the density of GaAs nanowires.

Using time-resolved RHEED measurements we investigate the evolution of the phase composition of growing NWs by two different ways of initiating the GaAs nanowire growth. The arsenic activated Ga-assisted growth mode leads to a considerable large fraction of wurtzite phase segments in the nanowires, whereas almost no wurtzite is found in nanowires grown by the gallium activated Ga-assisted growth mode. Selected RHEED pictures of these two different growth modes are shown in Figure 1.

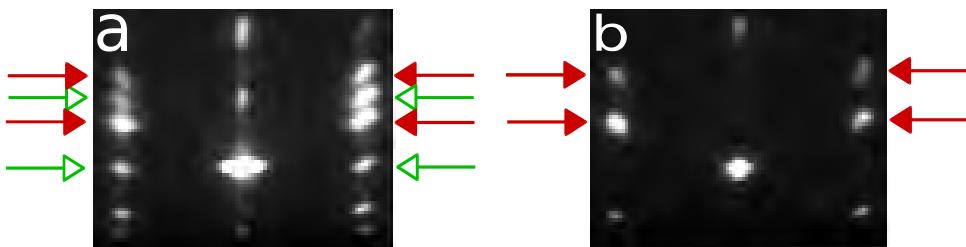


Figure 1: RHEED images after 30 minutes of growth. (a) As activated growth, with a clear wurtzite signal (green, open arrows) and (b) Ga activated growth, with only zincblende signal (red, solid arrows).

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References

- ¹ R. Chen, *et al.*, *Nature Photonics* **5**, 170-175 (2011).
- ² T. Slobodskyy, *et al.*, *Rev. Sci. Instrum.* **83**, 105112 (2012).
- ³ M. Köhl, *et al.*, *J. Synchrotron Rad.* **22**, 67-75 (2015).
- ⁴ P. Schroth, *et al.*, *Phys. Rev. Lett.* **114**, 055504 (2015).

Thermal annealing of GaAs nanowires studied by in-situ time-resolved x-ray diffraction

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GaAs nanowires (NWs) are promising candidates for optoelectronic applications. AlIBV NWs grown by MBE onto Silicon (111) substrate often show polytypic behavior with randomly distributed structural defects degrading electrical and optoelectronic performance of possible NW devices. Therefore control of structural perfection during and after NW growth is highly demanding. In this work, we report on the dynamics of polytype composition and the sublimation kinetics of GaAs NWs during post-growth annealing investigations by means of in-situ x-ray diffraction. An attempt is made to study possibilities to modify the structure and size of GaAs NWs after growth.

The experiment has been performed using a portable Molecular Beam Epitaxy (pMBE)¹ chamber at beamline P09 of PETRA III (DESY) synchrotron using a photon energy of 15 keV and a beam size of about 70x50μm illuminating about 2×10^4 individual GaAs NWs. The evolution of phase composition has been investigated monitoring the (220) and (311) zinc-blende, and (10.3) wurtzite Bragg reflections in asymmetric diffraction geometry.

Prior to the annealing experiment, the GaAs NWs were grown onto Si(111) substrates by a self-catalyzed method². After SEM inspection, the samples were reloaded back into the MBE chamber. The annealing process was performed by increasing the substrate temperature from 270°C to 670°C in steps of 50°C. At each temperature, the three Bragg reflections mentioned above were monitored repeatedly for three loops separated by 10 min. The decomposition rates for GaAs ZB, ZBT, and WZ were calculated from the evolution of the integrated intensities of the corresponding reflections. Preliminary analysis of data showed that the rate of decomposition drastically increased at $445 \pm 25^\circ\text{C}$ for a sample with NW density of $1 \mu\text{m}^{-2}$, mean NW length of $1.5 \pm 0.5 \mu\text{m}$, and mean NW diameter of $30 \pm 15 \text{ nm}$. Moreover, we detected an x-ray facet like pattern close to X-ray diffraction peaks which allows for the extraction of the evolution of some properties of the NW side facets (e.g. NW diameter) during the annealing process. Contrary to the SEM and TEM based investigation of Loitsch et al.³ at an annealing temperature of 680°C, we employ time-resolved X-ray diffraction. This way, the annealing of a given sample is studied without intermediate exposure to air. Moreover, an extended range of temperatures has been studied.

References

- ¹ T. Slobodskyy, *et al.*, *Rev. Sci. Instrum.* **83**, 105112 (2012).
- ² J. Jakob, *et al.*, "Tailoring of GaAs NW for in-situ X-ray investigations using a portable MBE", this conference.
- ³ B. Loitsch, *et al.*, *Advanced Materials* **27**, 2195 (Feb 2015).

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Modeling of GaAs nanowire formation via selective-area MOCVD

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The selective-area MOCVD nanowire growth has been studied extensively for the last decade. The growth parameter ranges have been determined to form homogeneous nanowire arrays. Nevertheless, the optimization of the growth process is still an unsolved problem in many cases, for instance, the determination of the optimal distance between nanowires (or pitch) with the given diameter to minimize the growth time.

In the present work, we propose a simple model to depict the formation of GaAs nanowires grown via selective-area MOCVD. A complete hydrodynamic model of the processes in an MOCVD reactor is rather complicated and, therefore, for the simplified analysis we use the boundary layer model that has proven to be a useful approximation for interpretation of experimental results for the MOCVD growth [1]. The key assumption of the modified boundary layer model is the introduction of two material fluxes. The first is the precursor flux to the substrate and the second is the flux produced by the precursor decomposition on the nanowire facets. The data presented in the literature [2] are used to determine material constant of the model. The stage of mask window filling and the nanowire growth stage are sequentially modeled. The model allows for explaining the decay of the nanowire length on the pitch (Fig.1) observed experimentally by Noborisaka *et al.* [2]. We find that the nanowire length dependence on the pitch has a maximum that is influenced by the initial growth stage. An increase of the nanowire length at the fixed diameter with the increase of the pitch is attributable to the increase of the first material flux while the decrease of the nanowire length at large values of the pitch is explained by the second flux decrease. The present model allows the determination of the value of the optimal pitch for particular growth conditions and minimization of the growth time of nanowires with desirable length.

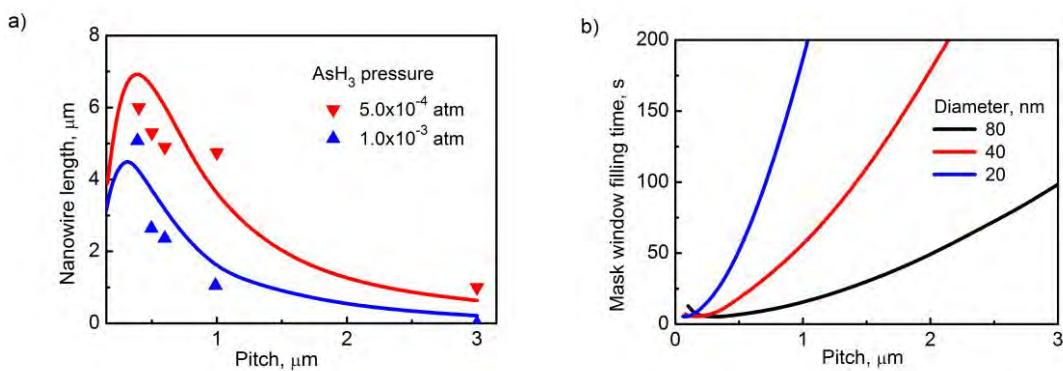


Figure 1: (a) The nanowire length dependence on the pitch. Dots are experimental data [2], lines are simulation results. Growth time equals 20 min, nanowire diameter equals 80 nm . (b) Mask window filling time versus pitch at the AsH₃ pressure of 1.0x10⁻³ atm and the mask height of 20 nm.

References

¹ G.B. Stringfellow, *Organometallic vapor-phase epitaxy: theory and practice* (Academic Press: London), p. 308 (1999)

² J. Noborisaka, J. Motohisa, and T. Fukui, *Appl. Phys. Lett.* **86**, 213102 (2005)

Modelling of the growth Au-catalysed of InGaAs nanowires: interplay of group III elements and the role of group V

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This theoretical study is dedicated to explanation of growth of a ternary In-Ga-As nanowire in a MBE process with the help of Au catalyst droplet. While modelling of the crystal structure of III-V nanowires was already theoretically studied for the case of only one type of group III element, [1,2] a comprehensive study of a system with two different atom types of III group that would also include the dynamics of group V element into the model is yet to be performed due to the difficulty of correctly grasping mutual influences of all elements.

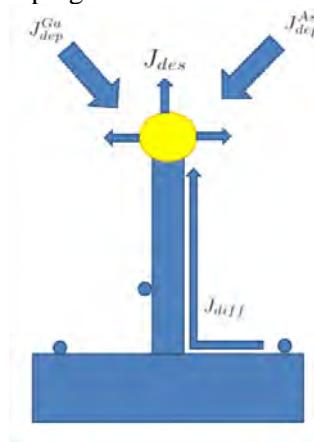


Figure 1: Transport to and from catalyst droplet, group III and V deposition rates, diffusion of group III into the golden catalyst droplet and desorption of group V

The key processes that mediate the nanowire growth are nucleation from the catalyst droplet to the top of the nanowire (this process limits the transport of the material from liquid to solid, and hence the the growth rate) and the transport of the material from vapour phase to and from the liquid droplet [3]. To quantitatively estimate both of these processes it essential to know the chemical potential inside the catalyst droplet, and since liquid on top of the nanowire is in this case a quaternary solution careful considerations were made to calculate this accurately. [4] Then it is possible to apply material balance equations for to determine concentrations of different element atoms inside the droplet. Once this is done it is possible to explain such results as crystal structure type (wurtzite/zincblend) dependencies on known experimental parameters: material influxes and temperature.

References

- ¹ E. Gil, et al, *Nanoletters* **14** (7), pp 3938–3944 (2014)
- ² V. G. Dubrovskii, *Appl. Phys. Lett.* **104**, 053110 (2014)
- ³ V. G. Dubrovskii, *Nucleation Theory and Growth of Nanostructures*, Springer (2014)
- ⁴ V. G. Dubrovskii and J. Grecenkov, *Cryst. Growth Des.*, **15**(1), (2015)

Step propagation and the shape of nanowires

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The present work is devoted to a study of radial nanowire growth in terms of formation of steps and their propagation along nanowire sidewalls. Our model considers the step nucleation only at the nanowire base and nanowire tip. The step at the nanowire base appears when the adatom concentration reaches some critical value. Step generation at the nanowire tip is determined by droplet expanding. The velocities of steps,

$$\frac{1}{S_F} \frac{dl_i}{dt} = D \frac{dn_i}{dz} \Big|_{z=l_i+0} - D \frac{dn_{i+1}}{dz} \Big|_{z=l_i-0} = \beta_+[n_i(l_i+0) - \tilde{n}_i] + \beta_-[n_{i+1}(l_i-0) - \tilde{n}_i],$$

are determined from the solution of the surface diffusion equation subject to the equations of the material balance at the steps [1]:

$$D \frac{dn_i}{dz} \Big|_{z=l_i+0} = \beta_+[n_i(l_i+0) - \tilde{n}_i] + \beta_p[n_i(l_i+0) - n_{i+1}(l_i-0)],$$

$$-D \frac{dn_{i+1}}{dz} \Big|_{z=l_i-0} = \beta_-[n_{i+1}(l_i-0) - \tilde{n}_i] + \beta_p[n_{i+1}(l_i-0) - n_i(l_i+0)].$$

Here, l_i is the coordinate of the i -th step, S_F is the area per atom on the sidewalls, n_i is the adatom concentration on the i -th terrace of the nanowire sidewall, D is the surface diffusion coefficient, \tilde{n}_i is the equilibrium adatom concentration near the i -th step, β_+ and β_- are the incorporation coefficients from upper and lower terrace, respectively, and β_p is the step permeability coefficient.

Numerical modelling of the nanowire shape in different growth conditions was done. In particular, it is shown that at certain conditions the steps could form a system of bunches on the nanowire sidewall. This allows us to explain formation of the tower of Babel shape of nanowires (Fig.1) in addition to usually observed cylindrical, conical and pencil-like shapes.

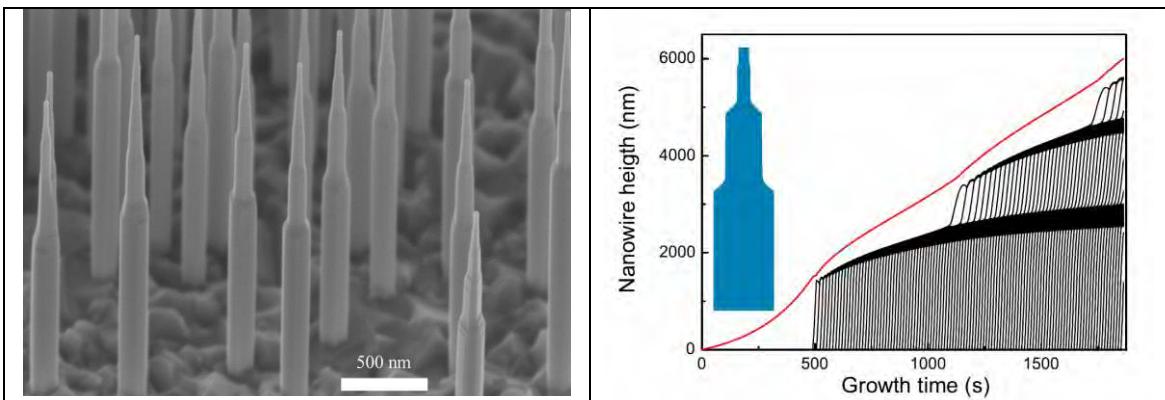


Figure 1: a) SEM image of InAs nanowires with the tower of Babel shape [2]. b) The trajectories of steps on the nanowire sidewalls (black lines) and resulting dependence of nanowire length on the growth time (red line).

References

- ¹ S. N. Filimonov and Yu. Yu. Hervieu, *e-J. Surf. Sci. Nanotech.* **12**, 68-74 (2014)
- ² M. Tchernycheva, *et al.*, *J. Appl. Phys.* **102**, 094312 (2007).

STUDYING THE PHASE STABILITY OF THE NANOSCALE IN-SB SYSTEMS

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III-V semiconductor nanowires have promising applications for future electronic and optoelectronic devices. To engineer the properties of nanowires (e.g., band gap energy), a precise control over their fabrication is required. The most common nanowire growth mechanism is the Vapor-Liquid-Solid (VLS) process in which upon the supersaturation of the liquid seed particles with the gaseous growth species at elevated temperatures, the crystalline phase (nanowire) begins to grow. To optimize the growth of nanowires of a desired materials system, numerous experimental attempts are often needed, being both cost-inefficient and time-consuming. However, using the available computational techniques, it would be possible to model the growth mechanism for each specific materials system. Such an approach would guide successful nanowire fabrication much more efficiently than experimental trial-and-error.

We have studied the phase stability of the In-Sb nano-scale systems [1], which will be helpful for modeling the growth process of InSb nanostructures. We have used the powerful CALPHAD (CALculation of PHAse Diagrams) technique [2], which is based on the minimization of the Gibbs energy. The Gibbs energy of a bulk phase is a function of temperature, pressure and composition, whereas there is an additional surface contribution to the Gibbs energy of a nano-scale phase. Therefore, the experimental or calculated data on the surface energies of the phases in a system are required to extend the CALPHAD model to include the size of a system. We calculated the surface energy of the InSb compound using Density Functional Theory. The empirical Butler equations were used to estimate the surface energy of the solution phases.

The calculated phase diagram of the In-Sb nanoparticles with radius of 80, 18 and 5 nm are shown in Figure 1. The results show that the liquidus and phase transition temperatures decrease as the size of the particle/nanowire decreases. The eutectic solubility of In in the Sb-rich side and that of Sb in the In-rich side increases with decreasing size. We believe that knowledge of the phase equilibria of this system at nano-scale would help to understand the growth properties of self-seeded In-Sb nanowires.

References

[1] Ghasemi, Zanolli, Stankovski, Johansson., *Size- and shape-dependent phase diagram of In-Sb nano-alloys*. Submitted 2015.

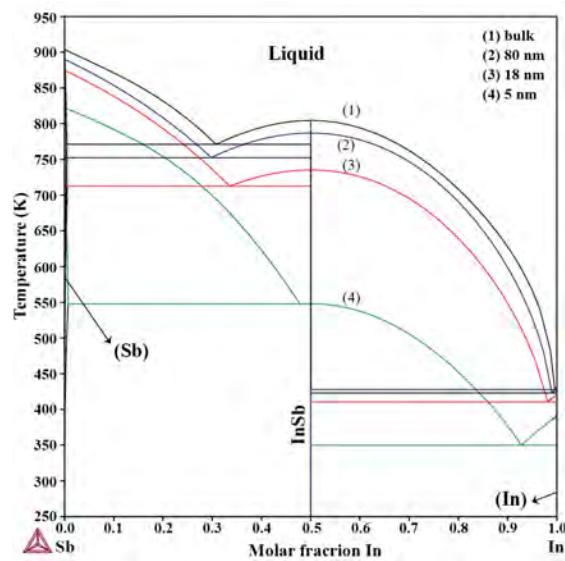


Figure 1: The phase diagram of bulk In-Sb and for In-Sb nanoparticles with radius = 80, 18 and 5 nm.

[2] Kaufman and Bernstein, Computer calculations of phase diagrams, Academic Press Inc, 1970.

Homoepitaxial growth of Sn-seeded antimonide-based nanowires by MOVPE

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The direct nucleation of Au-seeded InSb and GaSb nanowires has proven to be challenging, partly related to the surfactant properties of Sb [1]. Occurrence of such problems has led to the use of other III-V nanowires as stem materials such as InAs in InAs-InSb axial heterostructure geometry on InAs substrates. However, the use of other III-V materials can limit the growth parameter space of antimonides since for instance the InAs stem may decompose during antimonide growth. Therefore, alternative approaches are required to circumvent the challenges which occur during the direct nucleation of antimonide-based nanowires.

We report on direct nucleation of antimonide-based nanowires (both InSb and GaSb) using *in situ* formed Sn nanoparticles on similar substrates (both (111)A- and (111)B-type substrates) by metalorganic vapor phase epitaxy (MOVPE) [2]. In case of the Sn-seeded GaSb nanowires, the results of our study indicate that nanowires grow vertically on (111)B substrates (figures 1(a,b)) whereas there are two types of nanowires on (111)A substrates, vertical and inclined ones, (figure 1(c, d, e)). The yield of each type of such nanowires and their growth direction is affected by their growth condition. Scanning electron microscopy (SEM) images of the nanowires grown on (111)B (figure 1(b)) and inclined nanowires grown on (111)A substrates (figure 1(e)) indicate that such nanowires contain a high density of twin planes, also supported by transmission electron microscopy analysis.

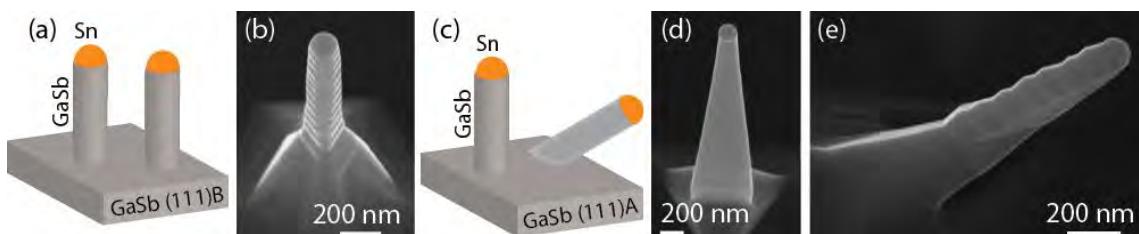


FIG. 1: Schematic illustrations of Sn-seeded GaSb nanowires (a) vertically grown on (111)B substrates and (c) kinked and vertically grown nanowires on (111)A substrates. SEM images of (b) vertical Sn-seeded GaSb nanowires on (111)B substrates, containing high density of twin planes (d) vertical and (e) kinked nanowires grown on (111)A substrates where kinked nanowires (such as (e)) contain a high density of twin planes.

1. Mattias Borg, B. and L.E. Wernersson, *Synthesis and properties of antimonide nanowires*. Nanotechnology, 2013. **24**(20): p. 202001.
2. Sun, R. et al., *Sn-Seeded GaAs Nanowires as Self-Assembled Radial p-n Junctions*. Nano Lett., 2015.

Arsenic flux - induced suppression of lateral growth in InAsSb nanowires grown on Graphite

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The advent^{1, 2} of the two-dimensional (2D) graphene, has sparked enormous research interest owing to its extraordinary electronic and optical properties including ultra-high carrier mobility³, ⁴, exceptionally high thermal conductivity, flexibility and high optical transparency^{5, 6} which offers huge potential for applications in transparent, stretchable and flexible electronics. The monolithic integration of semiconductor nanowire (NWs) on graphene/graphitic substrates (GS) has stimulated enormous research interest over the recent years as it would enable the exploitation of the exceptional qualities of the former with the intriguing properties of the latter and provide a unique platform for the development of high performance, sophisticated, flexible and cost-effective optoelectronic nanodevices. The growth of thin InAsSb NWs with high aspect ratio are essential for the investigation of important material related properties such as spin-orbit coupling and quantum confinement as well as enable applications in high performance devices^{7,8}. However, the growth of thin InAs_{1-x}Sb_x nanowires is extremely challenging due to Sb-induced suppression of axial growth and enhancement in radial growth. In this work, we demonstrate the suppression of lateral growth by high As- flux.

InAsSb NWs growth was realized on graphite by solid-source molecular beam epitaxy (MBE) using Indium (In) as catalyst. In order to investigate the influence of the GS on InAsSb NWs growth, a reference sample was also grown on Si(111) at identical conditions. The surface morphology of as-grown NWs was investigated by FEI XL30 SFEG scanning electron microscope (SEM). Although the InAsSb NWs on both substrates show an increase in lateral dimensions as a function of Sb content, it will be shown that the Sb-induced modifications in NWs geometry on graphite is dramatically less in comparison to that on Si. Significantly, the use of a highly As rich conditions enhanced the suppression of lateral growth to enable the growth of thin NWs. In addition, the GS favours the growth of high aspect ratio NWs in comparison to that on Si.

References

1. K. S. Novoselov et al, Proc. Natl. Acad. Sci. U.S.A. **102**, 10451 (2005).
2. K. S. Novoselov et al, science **306**, 666 (2004).
3. K. S. Novoselov et al, Nature **438**, 197 (2005).
4. Y. B. Zhang et al, Nature **438**, 201 (2005).
5. A. K. Geim et al, Nature materials **6**, 183 (2007).
6. Z.-S. Wu et al, ACS Nano. **3**, 411(2009).
7. A. Arlauskas et al, Nano Lett. **14**, 1508 (2014).
8. K. Jung, P. K. Mohseni and X. Li, Nanoscale **6**, 15293 (2014).

Realization of InAs/AlSb core-shell NWs grown by MBE

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The growing interest in semiconductor core-shell NWs is motivated by improving the NWs properties such as optical properties, electron mobility and tuning bandgap [1]. This development is attributed to the reduced influence of the surface states through an efficient surface passivation resulting from shell layers with different compositions. The core-shell structures are expected to improve the performance of nanowire-based devices [2]. Recently, antimonite semiconductors have widely employed in optical device applications. InAs/AlSb heterostructures have attracted a particular interest because of their unique intrinsic physical properties. For instance, InAs has a high mobility ($8 \times 10^5 \text{ cm}^2/\text{Vs}$ at 4.2 K), its combination with AlSb gives a very small lattice mismatch of 1.18% while the conduction-band offset is as large as 1.35 eV which offers an excellent confinement to the electrons, together with type-II bandgap alignment, the InAs/AlSb heterostructure is proposed to be an ideal candidate for high-speed electronic devices and high performance optoelectronics operating in infrared spectral range [3].

This work reports the realization of InAs/AlSb core-shell NWs, for the first time, grown on Si (111) substrate by molecular beam epitaxy (MBE). Scanning electron microscope (SEM) image shows that the NWs have an average diameter of $60 \pm 12 \text{ nm}$, length of $2.11 \pm 0.87 \mu\text{m}$ with a density of $5.57 \times 10^8 \text{ cm}^{-2}$. It also shows that some NWs are bended NW (81%) while others are quasi-straight NWs (19%). The bending is attributed to the uneven strain resulted from the non-uniform thickness deposition of AlSb on the core InAs. This is confirmed by transmission electron microscopy (TEM) which clearly reveals that the shell structure has distinct thickness up to 6 nm. The bended NWs have an asymmetry core-shell structure while the straight NWs are symmetry as shown in Figure 1. The successful realisation of these core-shell NWs opens a route towards advanced devices based on InAs NWs.

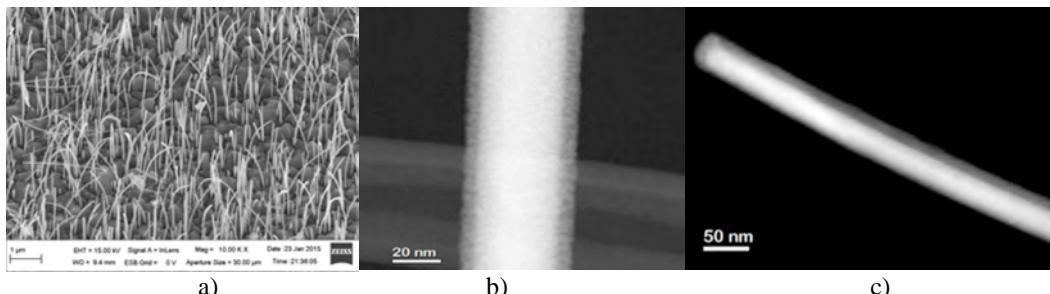


Figure 1. Tilted SEM image of InAs/AlSb core-shell NWs a), and TEM images of a single quasi-straight NW b) and a single bended NW.

References

- [1] A. Biermanns, "Axial strain in GaAs/InAs core-shell nanowires," *Appl. Phys. Lett.*, 2013.
- [2] R. Popovitz-Biro, "InAs/GaAs core-shell nanowires," *Cryst. Growth Des.*, p. 7, 2011.
- [3] G. Theodorou and G. Tsegas, "Theory of electronic and optical properties of bulk AlSb and InAs and InAs/AlSb superlattices," *Phys. Rev. B*, vol. 61, pp. 10782-10791, 2000.

Growth and characterization of twin-free InAs_{1-x}Sb_x nanowires

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InAs and InSb nanowires have recently received considerable attention for electronic transport experiments due to high spin-orbit coupling, large g-factor, and high electron mobility [1]. Ternary InAs_{1-x}Sb_x nanowires are expected to offer new opportunities based on the tunable band gap of the ternary alloy. Furthermore, incorporation of antimony is known to reduce the polytypism in self-assisted III-V nanowires. However, in InAs_{1-x}Sb_x nanowires it remains a challenge to suppress the twinning completely [2].

In this work we study the growth of InAs(Sb) nanowires without a foreign catalyst on GaAs(111)B substrates using molecular beam epitaxy (MBE). The antimony content is measured by energy dispersive x-ray spectroscopy (EDX) in a scanning transmission electron microscope, and the crystal structure of nanowires with different composition is compared using high resolution transmission electron micrographs. Our results show that incorporation of antimony dramatically improves the nanowire crystal structure, going from polytypic InAs nanowires with a high density of stacking faults to twin-free pure zinc blende InAs_{1-x}Sb_x nanowires with an antimony content above 25%. To the best of our knowledge this is the first report on twin-free self-assisted indium-based nanowires. Field-effect measurements and Raman spectroscopy show that incorporation of antimony also has a significant effect on the electrical and optical properties of InAs_{1-x}Sb_x nanowires.

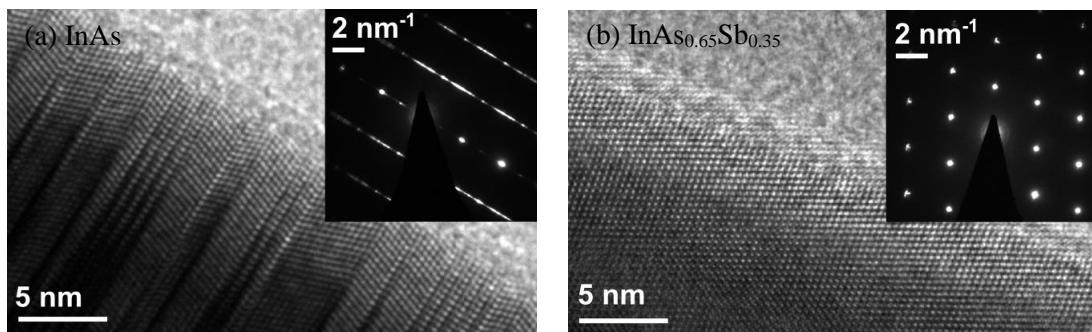


Figure 1: High resolution transmission electron micrograph and diffraction pattern of (a) an InAs nanowire with WZ and ZB segments and (b) a twin-free pure ZB InAs_{0.65}Sb_{0.35} nanowire.

References

- ¹ V. Mourik, *et al.*, *Science* **336**, 6084 (2012).
² M. Sourribes, *et al.*, *Nano Letters* **14**, 1643 (2014).

InAs_{1-x}Sb_x / Al core-shell nanowire epitaxy

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The ability to control the properties of Semiconductor/Superconductor (SE/SU) interfaces has recently shown to be a powerful method for designing materials with gate dependent and hard gap induced superconductivity in semiconductor nanowires with strong spin orbit coupling[1]. Such wires are not only interesting materials for superconducting quantum transport experiments but also promising candidates as building blocks for topological quantum computation[2]. Growth studies of InAs/Al hybrid nanowires has given detailed insight into the mechanisms of Al grain growth on InAs[3], and especially how the growth evolution depends on the morphology of the growth substrate (e.g. NW type, facets, planar substrate, ect.). This framework has made it possible to design SE/SU hybrid structures of various configurations, with epitaxial matched bicrystal interfaces by exploiting the NW faceting nature.

In this study we show that the hybrid system, InAs_{1-x}Sb_x/Al, offers new possibilities to form alternative epitaxial matched interfacial domains by changing the semiconductor lattice constant with the molar fraction of Sb. Changing the molar fraction of Sb from pure InAs to pure InSb, not only the lattice parameter can be tuned to find different commensurate bicrystal matching, but also the electronic properties of the semiconductor core can be controlled with desired electronic properties. By including Sb we also enhance the spin orbit coupling in the system, which may be very useful when designing topological superconducting materials [4]. An example of the InAs_{1-x}Sb_x/Al hybrid system is shown in figure 1 with x = 0.34.

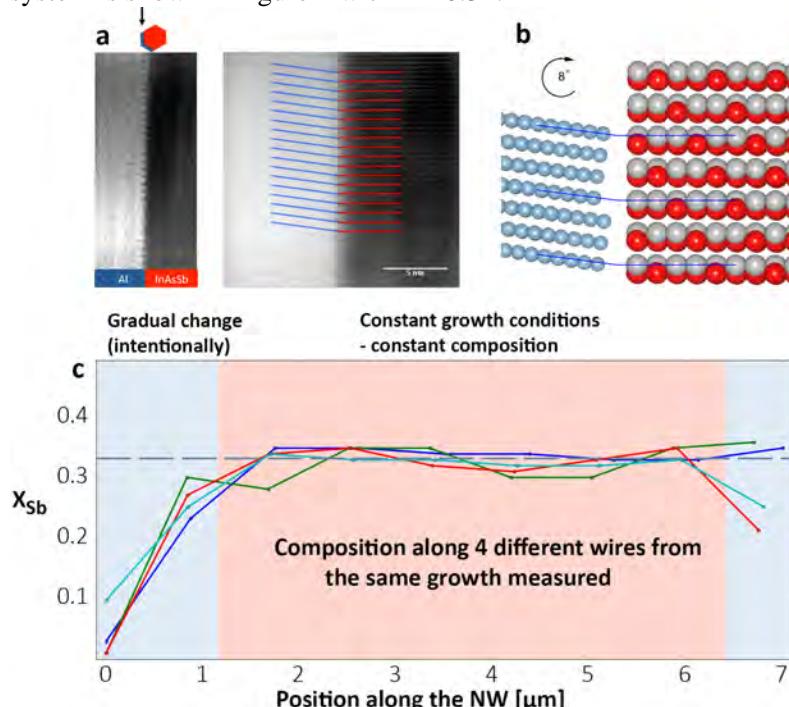


Figure 1(a) shows a HR-TEM image of the $\text{InAs}_{0.66}\text{Sb}_{0.34}/\text{Al}$ NWs where the 3:2 lattice matching is seen as clear diffraction peaks along the interface in this particular diffraction condition. (b) A simulation of the atomic plane matching as seen from the same angle as in (a). (c) Compositional analysis along four different $\text{InAs}_{1-x}\text{Sb}_x/\text{Al}$ NWs from the same growth. The Sb fraction is found to be 0.34 using a quantitative EDX method which are verified by HR-TEM following Vegard's law. The Al is measured to be 1% axial strained perfectly agreeing with a rotation of 8 degrees.

References

- [1] Chang, W., et al. "Hard gap in epitaxial semiconductor-superconductor nanowires." *Nature Nanotechnology* **10**(3): 232-236. (2015)
- [2] Alicea, J., et al. "Non-Abelian statistics and topological quantum information processing in 1D wire networks." *Nature Physics* **7**, 412–417 (2011)
- [3] Krogstrup, P., et al. "Epitaxy of semiconductor-superconductor nanowires." *Nature Materials* **14**(4): 400-406. (2015)
- [4] Van Weperen, I., et al. "Spin-orbit interaction in InSb nanowires." *Physical Review B* **91**(20). (2015)

Epitaxial Growth of Aluminum on InSb Nanowires

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InSb nanowires are known to have strong spin-orbit interaction, high carrier mobility and a large g-factor, thus fulfilling strict material requirements for the detection of Majorana fermions in semiconductor/superconductor hybrid devices. Recently, InSb nanowires have been used to demonstrate the possible existence of Majorana fermions in the solid state.^[1] There are, however, remaining challenges to meet on semiconductor/metal interfaces.

For detection of Majorana particles it is important to have a flat and clean interface between the semiconductor and superconductor. Recently, a new approach for making epitaxial and oxide-free nanowire/metal interfaces was reported for the InAs/Al system.^[2]

In this work, we investigate the growth mechanism and properties of epitaxial aluminium grown on InSb nanowires. The InSb wires are grown by metalorganic vapour phase epitaxy (MOVPE) and a partial shell of aluminum is grown on the wires by molecular beam epitaxy (MBE). The metal/semiconductor interface has been studied by high resolution and cross sectional transmission electron microscopy.

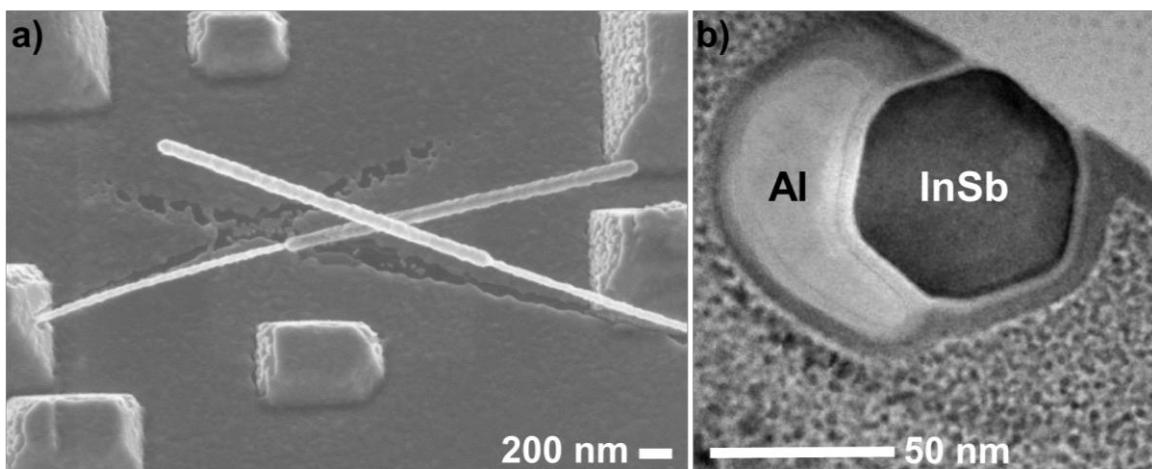


Figure 1: a) SEM of InSb nanowires with partial aluminum shell; b) cross sectional TEM of an InSb wire with a partial shell.

References

- ¹ V. Mourik, *et al.*, *Science* **336**, 1003 (2012).
² P. Krogstrup, *et al.*, *Nat. Mater.* **14**, 400 (2015).

In-situ MBE Al Coated Thin InAs Nanowires and Merged Intersections

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Ever since the observation of a zero bias conductance peak in superconductor/semiconductor hybrid devices based on either InSb [1] or InAs [2] nanowires (NWs), intensive work has been devoted to confirming its relation to a Majorana bound state. One of the key elements in such hybrid devices is having an intimate contact between the superconductor and the nanowire; yet allowing varying the electron density in the wire. Following the pioneering work by P. Krogstrup et al. [3], we pursued MBE growth of in-situ Al on titled InAs nanowires grown on (001) InAs substrate (Figure 1a). This growth method demonstrated before [4] as a way to form merged InAs nanowires allows in-situ Al side coating of Y-shape InAs intersections (Fig. 1b). The Al-coated nanowires were studied by SEM and TEM and were tested by preliminary conductance measurements. The large lattice mismatch (Al lattice constant 4.046Å, and that of WZ InAs nanowire is 7.005Å along the C axis) is mostly relieved by formation of interfacial domains [3], though semi-periodic dislocations located at the interface, embedded in the InAs NW (Fig. 1c) can sometimes be observed, relating to partial strain relaxation and associated with bending of thin (40nm) wires (Fig. 1d). Nevertheless, no bending was observed in the Y-shaped nanowire intersections of the same diameter thanks to the lack of flexibility (Fig. 1b).

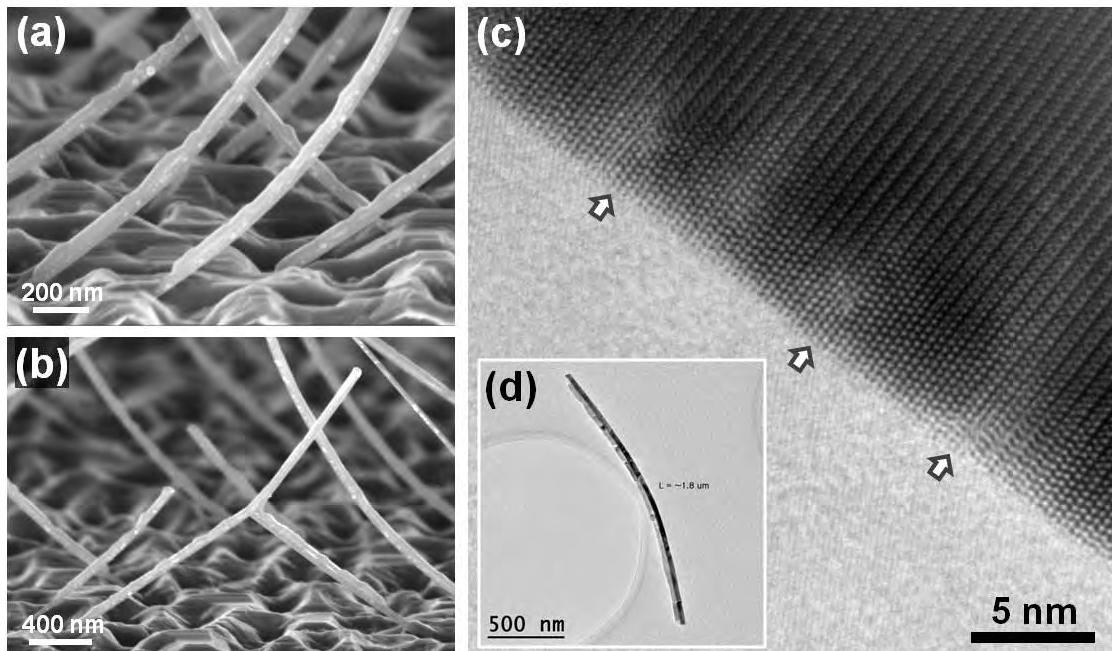


Figure 1: (a) SEM image of Al-side-coated InAs NWs grown on (001) InAs. (b) Similar image of Al-side-coated of InAs Y-intersection. (c) Low magnification TEM image of a single side-coated InAs NW. (d) High resolution TEM image of a side coated InAs nanowire showing the dislocations in the InAs.

References

- ¹ V. Mourik, et al. *Science*, **336**, 1003-1007 (2012).
- ² A. Das, et al. *Nature Physics*, **8**, 887–895 (2012).
- ³ P. Krogstrup, et al. *Nature Materials*, **14**, 400-406 (2015).
- ⁴ J. H. Kang, et al. *Nano Letters* **13**, 5190-5196 (2013).

Exploring growth of silver catalysed InAs nanowires

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Controlling the growth of nanowires by using gold as seed particles has been known for many years. While other metals have been tested, no other seed material has been as thoroughly investigated as gold [1]. Silver is in many ways similar to gold with the same crystal structure and comparable melting points [1], which makes it a suitable candidate for metal-seeded nanowire growth. Implementing silver as seed particle can increase the basic understanding on growth processes in general and give insight as to what might be possible to achieve with other catalyst materials. Recent promising results show that silver can be used as seed material for growth of various III-V-nanowires [2][3][4]. However, much work remains in order to fully understand the possibilities and limitations of silver as a catalyst, which highly motivates further work in this area. Here we explore the possibilities of using silver as a seed particle for InAs nanowires. Our experiments have been twofold: Firstly, we investigate how a thin film of silver is affected by annealing and the interaction of the silver with the 111B InAs surface. This was performed in order to increase the understanding of how silver nanoparticles may be formed directly onto the substrate using a thin film annealing strategy for particle seeded nanowire growth inside a Molecular Beam Epitaxy system (MBE). We show what impact different annealing of the substrate has on both the dimensions and the density of silver particles formed on the InAs surface. Secondly, we performed experiments focused on exploring growth of InAs nanowires for different growth temperatures and fluxes. We present successful MBE growth of silver catalysed InAs nanowires on an InAs substrate.

References

- ¹ K.A Dick and P. Caroff, *Nanoscale* **6**, 3006 (2014)
- ² A. T. Vogel *et al*, *Nanotechnology* **22**, 015605 (2011)
- ³ D. Pan *et al*, *NanoLetters* **14**, 1214 (2014)
- ⁴ K. Huang *et al*, *Nanotechnology* **26**, 255706 (2015)

Nucleation mechanisms and growth kinetics of Catalyst-free InAs nanowires grown on Si (111)

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Au-free growth of III-V semiconductor nanowires (NWs) on Si is a fundamental step for the integration of the III-V nanowires with the present Si technology which eliminates the problems due to Au-induced defects and traps in the Si.

Several experimental studies on catalyst-free InAs NW growth on Si (111) rule out a self-catalyzed Vapor-Liquid-Solid mechanism, pointing to the Volmer-Weber growth as the key nucleation mechanism. The initial InAs islands undergo several shape transitions to minimize their surface energies and either grow anisotropically into nanowires or continue to grow isotropically as islands^{1,2}. After analyzing the nucleation mechanism, we have explored the impact of various growth parameters on InAs NW grown by Chemical Beam Epitaxy (metal-organic (MO) precursor line pressures, their ratio and growth temperature), leading to a two stage growth protocol, using TBA and TMI as MO precursors for As and In, respectively. SEM micrograph in Fig. 1a shows an example of the growth of InAs NWs along with parasitic islands.

The growth appears to be strongly affected by adatom diffusion on the NW sidewalls, with the characteristic 1/D dependence of the axial growth rate (Fig 1b). In addition, the NW volume growth rate is monotonically decreasing with TBA flux, indicating a strong influence of group V flux on overall MO pyrolysis efficiency. Including both adatom diffusion and a pyrolysis efficiency term we obtain the following growth rate expression³

$$\langle L \rangle = A \left(\frac{P_{TMI}}{P_{TBA}} \right)^{\frac{3}{4}} (P_{TMI} P_{TBA})^{\frac{1}{2}} \left[t + \frac{3\sqrt{3}}{8} \frac{\lambda \tan \alpha}{v} \ln \left(\frac{\langle D \rangle}{\langle D_0 \rangle} \right) \right] + \langle H(D_0) \rangle$$

(L is the NW length, F_{MO} are the MO fluxes, λ is the diffusion length, α is the MO angle of impingement, D₀ (D) and H are the initial (final) NW diameter and length). Finding the numerical parameters through the maximization of the correlation function between model and experimental data, it has been possible to accurately model all the samples grown, in a wide range of the experimentally controllable parameter space, see Fig. 1c.

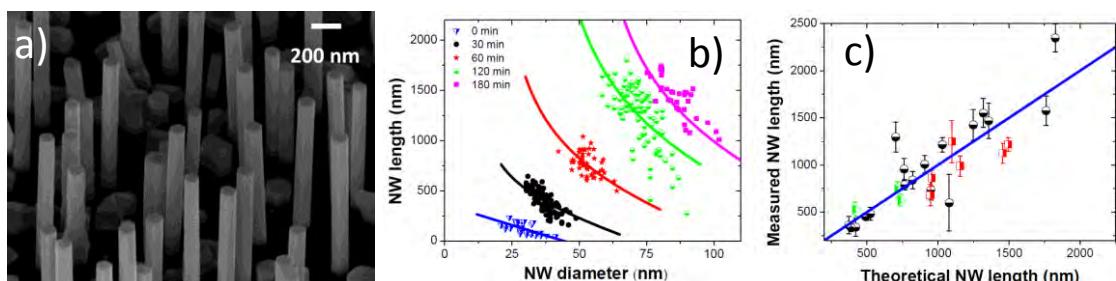


Figure 1: (a) SEM image of InAs NWs on Si (111); (b) length-diameter dependence for different growth times; (c) correlation between modelled axial growth and experimental results.

References

- ¹ S. Fernandez-Garrido, et al., *Nano Lett.* **13**, 3274 (2013).
- ² V. Consonni, et al., *Phys. Rev. B* **81**, 085310 (2010).
- ³ U. Prasad Gomes, et al., submitted to *Nanotechnology*.

Growth modes of InAs nanowires on Si(111) substrates

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InAs nanowires were grown on silicon substrates by molecular beam epitaxy. Five different growth modes were explored: (1) Au-assisted growth, (2) patterned Au-assisted growth, (3) Au-free growth, (4) positioned Au-assisted growth using a patterned oxide mask, and (5) Au-free selective-area epitaxy (SAE) using a patterned oxide mask. Effects of temperature and V/III flux ratio are shown for each growth mode with the aim of controlling nanowire morphology and improving vertical yield. The highest yield (72%) is achieved with the SAE method at a growth temperature of 440 °C and a V/III flux ratio of 4. The selective-area growth mode is further studied using a model to predict a temperature and V/III ratio dependent region in which a high yield of III-V nanowires can be achieved.

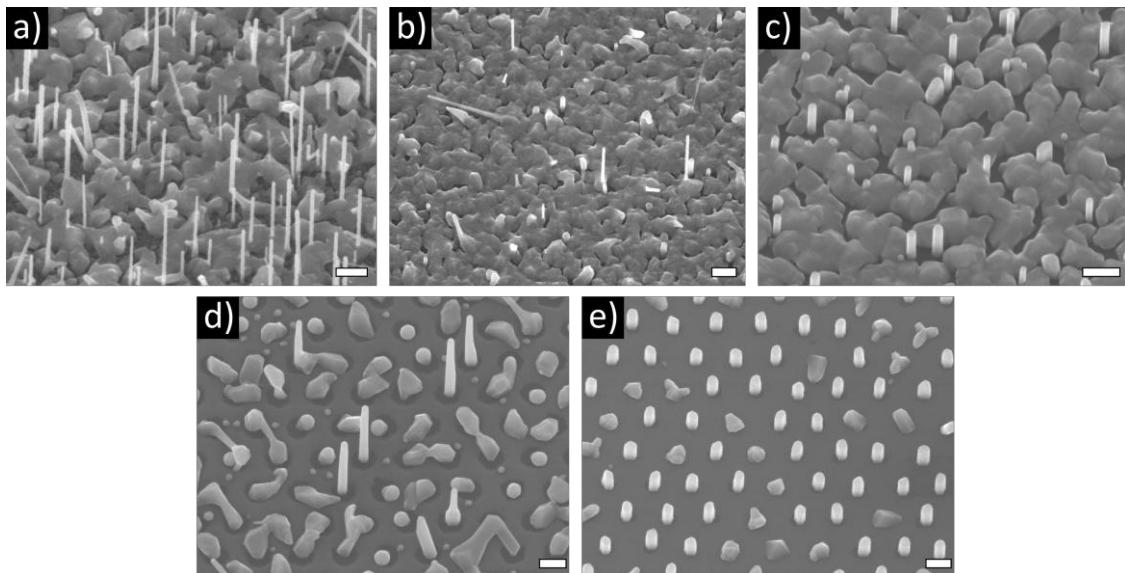


Figure 1: SEM images for the various growth modes studied. a) Au-assisted VLS growth, b) patterned Au-assisted growth (with low yield), c) bare silicon catalyst-free growth, d) positioned Au-assisted growth using a patterned oxide (with low yield), and e) selective-area epitaxy growth.

Simulation of self-catalyzed InAs and GaAs nanowire growth

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The main method of GaAs and InAs nanowire growth is self-catalyzed growth that is based on vapor-liquid-solid (VLS) mechanism. Monte Carlo (MC) realization of VLS mechanism of GaAs nanostructure growth was described in [1]. In present work modified variant of lattice MC model is suggested. In this model liquid arsenic was excluded from consideration and liquid phase was suggested only for indium (gallium). Cardinal change has been done with description of processes in the liquid drop and at drop/crystal interface. Now arsenic dissolution and diffusion through liquid drop are described by unified exchange reaction: $In(liq) + As \rightarrow As + In(liq)$. Reactant neighbourhood specify the process: As dissolution in liquid metal or exchange diffusion through the drop. Overestimation of energy parameters responsible for phase transformation was required after model modification. The diffusion activation energy in liquid In of 0.3 eV was taken according to experiment [2] and in liquid Ga of 0.7 eV according to [3]. The activation energies of In (Ga) dissolution in liquid drop and In (Ga) crystallization at drop/crystal interface in the form of InAs (GaAs) were chosen by fitting simulated and experimental solubility of InAs (GaAs) in liquid In (Ga) [4]. Results of such fitting are shown in Fig. 1a. Activation energy of In (Ga) crystallization was found to be equal to 1.5 (1.2) eV and 1.85 (1.7) eV for In (Ga) dissolution. Using specified energy parameters self-catalyzed growth of InAs nanowires was carried out (Fig. 1b).

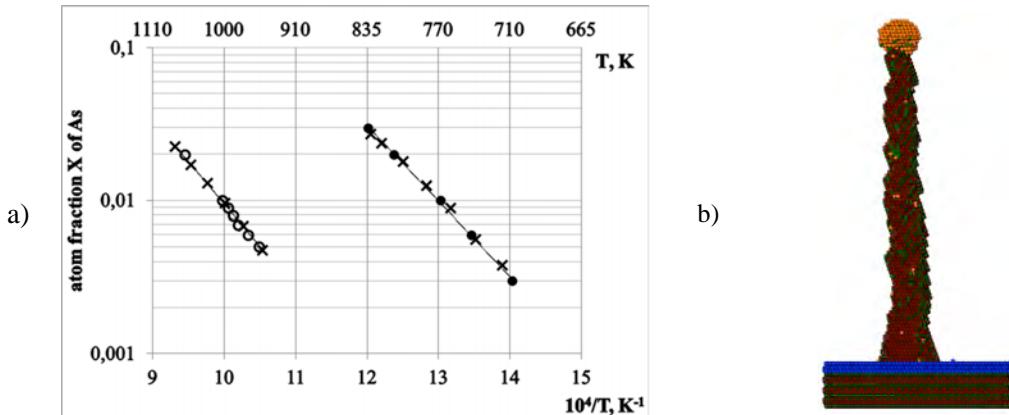


Figure 1: a) Temperature dependence of equilibrium arsenic concentration in liquid metal (In – solid circles, Ga – open circles from experimental data [4], crosses - simulation results), b) 3D view of InAs NW grown at $T = 800$ K, $F_{In} = 0.5$ ML/s, $F_{As2}/F_{In} = 1.4$ ($In_{(liquid)}$ is marked in orange, $In_{(solid)}$ in red, As in green, film-mask material – in blue colors).

Interest to heterostructure nanowires on the base of A^3B^5 semiconductors is due to their promising photovoltaic application. Analysis of misfit dislocation influence on elastic stress in InAs-GaAs core-shell nanowires with zinc-blend crystal structure was fulfilled by molecular dynamic modeling using Tersoff potential [5]. The critical core radius and critical shell thickness of coherent radial heterostructures were estimated.

Acknowledgements

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References

- ¹ M. Vasilenko, *et al.*, *Com. Mat. Sci.* **102**, 286 (2015).
- ² T. T. Dedegekaev, *et.al.*, *Cryst. Res. Technol.* **21**, No. 6, 95 (1986).
- ³ V.A. Gorokhov, *et.al.*, *Crystal Res. & Technol.* **19**, 1465 (1984).
- ⁴ R. N. Hall, *J. Electrochem. Soc.* **110**, 385 (1963).
- ⁵ T. Hammerschmidt, *et.al.*, *Phys. Rev. B*, **77**, 235303 (2008).

Mechanisms leading to broadened length distributions of nanowires

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The axial growth rate of nanowires (NW) depends on their diameter according to Gibbs-Thomson dominated or diffusion limited growth regimes which leads to characteristic length-diameter-dependencies¹⁻³. However, even at very narrow diameter distributions of the seeds, which can be achieved by the use of monodisperse particles, a broadening of the length distribution with time can be found.

In order to account for effects that may lead to a broadening of the length distribution two mechanisms are taken into account. On one hand, the growth of nanowires is supposed to proceed in a layer-by-layer fashion where the time between the nucleation of each layer follows a statistical distribution leading to an effect known as Poissonian or Sub-Poissonian broadening^{4,5}. On the other hand, the period until the first layer is nucleated, which is also known as the incubation time, can be described using non-steady state nucleation theory where the time lag until the first nucleation event is statistically distributed. We propose a model taking both contributions to the broadening into account to explain the observed spread in length even at the beginning of NW growth.

In order to study the length distribution associated with different incubation times, InAs nanowires were prepared on InAs(111)B substrates by means of metal-organic vapour phase epitaxy at a substrate temperature of 450°C and a nominal V/III-ratio of 41 of the incoming precursors. Nominally monodisperse gold particles have been used as seeds with diameters ranging from 20 – 50 nm and short growth times between 20 s and 6 min have been applied.

SEM analysis of the samples revealed an incubation in the interval between 120 s and 180 s. while the increase of the standard deviation of length does not seem to be diameter dependent (see figure 1). The observed broadening exceeds an expected Poissonian broadening during growth by almost an order of magnitude which can be explained by different incubation times of individual nanowires.

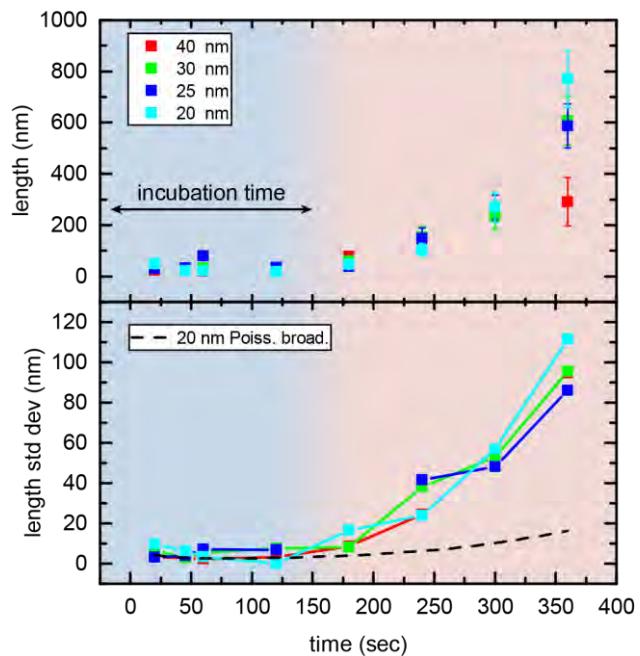


Figure 1: Length and length standard deviation of InAs NW as a function of growth time for varying diameters. Error bars correspond to standard deviation. Poissonian broadening has been calculated in accordance with ref. 5.

References

- ¹ J. Johansson, C.P.T. Svensson, et al., *J. Phys. Chem. B* **109**, 13567 (2005).
- ² V.G. Dubrovskii and N. V Sibirev, *J. Cryst. Growth* **304**, 504 (2007).
- ³ V.G. Dubrovskii, N. V Sibirev, et al., *Phys. Rev. B* **79**, 1 (2009).
- ⁴ F. Glas, J.C. Harmand, et al., *Phys. Rev. Lett.* **104**, 2 (2010).
- ⁵ V.G. Dubrovskii, *Phys. Rev. B* **87**, 195426 (2013).

Diameter distribution of InAs nanowires grown by Au-assisted methods

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III-V semiconductor nanowires have attracted intensive research interest because of their promising optical and electronic properties that can be manipulated by tailoring composition and morphology. In particular changing the NW diameter can be accompanied by a change in crystal structure [1]. In this way, it is possible to modulate energy gap, carrier confinement and carrier mobility [2]. Despite extensive research it remains challenging to precisely grow NWs with desired morphology. In fact, on the same sample grown under specific growth conditions, NWs of different diameters are obtained. Furthermore, a wide distribution of NW diameter on the same substrate prevents large scale integration and also hinders investigating the correlation between growth conditions and NW properties. For these reasons it is important to precisely control and accurate measure the NW diameter distribution.

In this work, we analyze the control of diameter distribution of Au-catalyzed InAs nanowires. Au colloidal nanoparticles dispersed on InAs (111) B substrates and nanoparticles obtained by annealing of Au films were used as catalysts for InAs nanowire growth. By varying key parameters such as Au film thickness, colloid sizes, annealing temperature and time, significant understanding has been developed to control InAs NW diameter distribution. It is found that the average NW diameter and standard deviation of InAs NWs seeded from thermally dewetted Au NPs increases by increasing Au film thickness, annealing temperature and time. The relative standard deviation (Δd) is in the range of ~20-40% (stars in Fig.1). An alternative approach to achieve diameter control by utilizing Au colloidal NPs is also investigated. We find that annealing temperature and time do not have significant influence on the NW diameter. Furthermore, multiple peaks are seen on the NW diameter distribution. A closer inspection of the distribution profile shows that the peaks are arising as a result of NWs growing from single colloidal NPs or agglomerated NPs. The relative standard deviation of NW diameter is in the range ~10-20% (dots in Fig.1). Instead the relative standard deviation is <10% if each colloid seeds the growth of one NW (squares in Fig.1). We therefore conclude that the diameter distribution can be improved by preventing their agglomeration during substrate preparation. Along with NW diameter, density is another crucial parameter that needs a careful control. We found that colloids do not facilitate uniform growth on the sample surface while high uniformity is obtained with Au film.

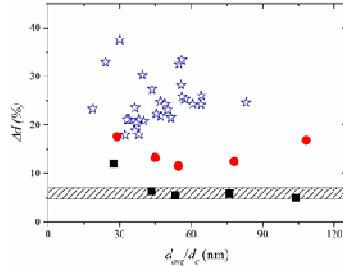


Figure 1: Comparison of Δd of InAs NWs grown from Au film (stars) and colloids (circles) as a function of d_{avg} . The squares represent Δd obtained from the main Gaussian peak and plotted as a function of d_c . The shaded region is the relative standard deviation of initial Au colloidal NPs as supplied by the manufacturer and detailed in the experimental section (5-7%).

References

- [1] K. Dick, J. Bolinsson, M E. Messing, S. Lehmann, J. Johansson, and P. Caroff, *J. Vac. Sci. Technol. B Microelectron. Nanom. Struct.* **29**, 04D103 (2011)
- [2] C L. Dos Santos and P. Piquini, *Phys. Rev. B - Condens. Matter Mater. Phys.* **81**, 1–10 (2010)

Atomically-abrupt interface by stacking fault engineering

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III-V compound semiconductor nanowires (NW) have been considered as next-generation building blocks. On one hand, engineering the carriers and photons for functionalities is realized by adding heterostructures into NWs.¹ The atomically abrupt interface, as the ideal interface of heterostructures, is very difficult to be achieved in NWs for the reservoir effect.² On the other hand, the stacking fault, very often present in NWs, is generally believed to be a defect and degrade the optical and electronic properties. Here we show the formation of the atomically abrupt interface in InAsP NWs by engineering stacking faults.

We synthesized the InAsP NWs in a metalorganic vapor phase epitaxy system. The crystalline substrate (InP or Si) is usually used and <111>-oriented InP(As) NWs are epitaxially grown on the substrate.²⁻⁴ However, if the SiO₂ amorphous substrate is used and indium particles are deposited on the surface for the subsequent NW growth via the self-catalysed vapor-liquid-solid (VLS) mode, the <112>-oriented InP(As) NW are synthesized (Fig. 1a). The <112>-oriented NW has a rectangular cross-sectional shape and is surrounded by two (110) and two (111) side facets. The inside stacking fault is parallel to the <112> growth direction and (111) side facets. Moreover, we found that the InAs_xP_{1-x} NW exhibits varied composition in the regions separated by stacking faults, as indicated by arrows in Fig. 1b.

We further clarified the structure and composition variation of the InAs_xP_{1-x} NW by using aberration-corrected STEM, which enables the analysis with atomical resolution. There are different polarities of the two regions located on each side of the stacking fault (Fig. 1c). The As composition in the upward side region (InAs_{0.8}P_{0.2}) is higher than that in the downward side region (InAs_{0.59}P_{0.41}) by quantitative compositional measurement (Fig. 1d). We identified the growth front faces of the <112>-oriented NW is alternatively-changed (111)A and (111)B. The polarity difference of (111) growth front induces the higher incorporation efficiency of As into the InAsP NW along the (111)A front face. Notably, the composition is comparatively homogeneous in each region and changes at the stacking fault with atomical abruptness (Fig. 1d). The polarity difference, induced by the stacking fault defect, causes different incorporation efficiency of V-group atoms into InAsP NWs and therefore results in atomically-abrupt interface. We further found the phenomenon is common in other NWs like InGaP, indicating the wide applicability and high-potential adoption of the technology in various materials.

In summary, we demonstrate that the atomically-abrupt interface in NWs is formed by engineering the defect of stacking faults. This work offers a new way to form the atomically-abrupt interface by defect engineering and open up new opportunities forming new novel structures and devices for new functionalities.

References

- [1] M. D. Birowosuto, *et al.* *Nature Mater.* **13** 279 (2014). [2] K. A. Dick, *et al.*, *Nano Lett.* **12** 3200 (2012). [3] G. Zhang, *et al.*, *AIP Advances* **3** 052107 (2013). [4] G. Zhang, *et al.*, *Nanotechnology* **26** 115704 (2015).

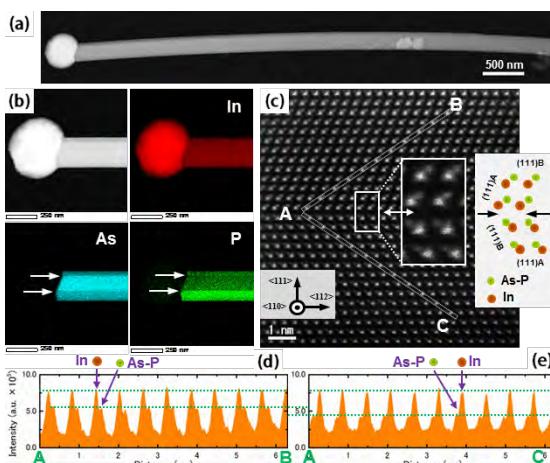


Figure 1: (a) HAADF-STEM image of a single <112>-oriented InAsP NW. (b) HAADF-STEM and elemental mapping (In, As, and P) images of the NW tip area. The regions separated by the stacking faults show different composition. The scale bar denotes 250 nm. (c) Cs-STEM image of two adjacent domains with a stacking fault interface, indicated by arrows. The inset STEM image and the atomic model diagram reveal the different polarities of the two regions. (d) and (e) The intensity profiles of atomic columns of In and As-P along the A→B and A→C lines drawn in (c). The dotted lines are guides to the eye.

Kinetics of spontaneous nucleation and PAMBE growth of GaN nanowires on amorphous Al_xO_y studied by RHEED

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Silicon is the most common substrate used for nitride nanowire growth by MBE, what is due to its low price, availability in large size wafers and easy integration of nitride devices with silicon microelectronics. However, silicon is not transparent for visible light, which seriously limits external efficiency of light emitters and complicates optical access to GaN NWs. Moreover, at high temperatures used for growth of high quality GaN NWs silicon is incorporated from the substrate to NWs modifying their properties.¹ Thus transparent and chemically inert to gallium alternative substrates are needed for high temperature growth. In our recent report we have shown that efficient catalyst-free nucleation of GaN NWs can be obtained by PAMBE if sapphire substrate is covered by amorphous Al_xO_y ($\text{a-Al}_x\text{O}_y$) buffer while under the same conditions no NWs are formed on monocrystalline parts of the substrate.² This finding paves the way to new designs of semiconductor nanostructures in which high quality crystalline NWs are deposited on cheap amorphous substrates.

In this work we report on quantitative analysis of nucleation kinetics of GaN NWs on $\text{a-Al}_x\text{O}_y$ buffers grown at low temperature by atomic layer deposition. The results are compared with those obtained on Si(111) substrates under the same growth conditions. The incubation time that precedes catalyst-free nucleation of NWs was determined by measuring time evolution of diffracted signal intensity collected from a fixed RHEED image area containing one GaN 3D spot. As shown in Fig. 1a presence of the $\text{a-Al}_x\text{O}_y$ buffer led to much shorter incubation time and significantly higher nucleation rate of GaN NWs in comparison to bare Si(111) substrate. We found that increase of the growth temperature from 720°C till 794°C with the same nominal Ga and N fluxes led to an exponential increase of the incubation time of NWs on $\text{a-Al}_x\text{O}_y$ buffer from 1.5 min to 200 min (Fig. 1b). Even longer incubation times up to ~400 min were observed for the same Ga and N fluxes and temperature of 766°C on silicon substrates. The Arrhenius plot $\ln(t_{inc})$ vs. $1/kT_{gr}$ gave value of activation energy of the NWs on $\text{a-Al}_x\text{O}_y$ buffer equal to 6 eV being remarkably smaller than 10.2 eV that we found under the same conditions on nitridized Si(111). Our findings are explained by a higher density of surface defects on $\text{a-Al}_x\text{O}_y$ where Ga adatoms may accumulate allowing easier creation of GaN critical nuclei and thus enhancing GaN nucleation rate.

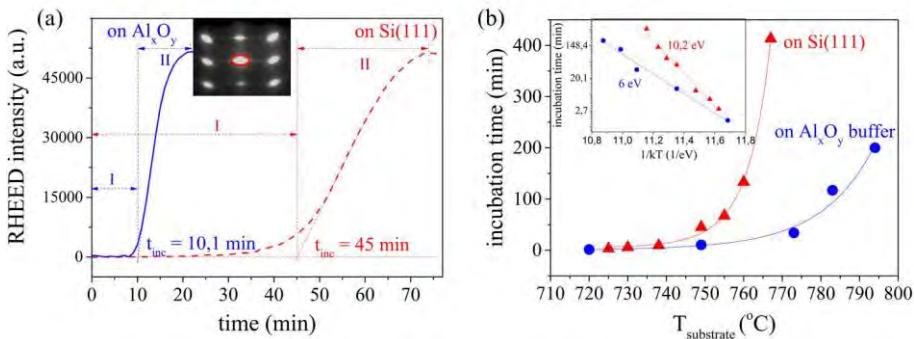


Fig. 1: (a) evolution of GaN 3D RHEED spot intensity during nucleation of GaN NWs on Si substrates (blue solid curve) and on $\text{a-Al}_x\text{O}_y$ buffer (red dashed curve) after opening of Ga shutter at $t = 0$ and for substrate temperature of 749°C. The inset shows 3D RHEED pattern during nucleation of NWs. The GaN RHEED spot where intensity was measured is marked in red; (b) dependence of the incubation time t_{inc} on temperature T_{gr} for GaN NWs grown on $\text{a-Al}_x\text{O}_y$ and on nitridized Si. The inset represents Arrhenius plots $\ln(t_{inc})$ vs. $1/kT_{gr}$ from which nucleation energies of 6 eV and 10.2 eV, respectively, are obtained.

¹ P. Corfdir, *et al.*, *Phys. Rev. B*. **90**, 195309 (2014).

² M. Sobanska, *et al.*, *J. Appl. Phys.* **115**, 043517 (2014).

New Templates for Self-induced Growth of Vertical GaN Nanowires

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In this study we show that inexpensive amorphous substrates can be used to grow high quality vertical GaN nanowires (NWs). In literature, it has been widely proven that high quality polycrystalline Si with large-size grains can be obtained using a process called aluminium-induced crystallisation of silicon (AIC-Si).¹⁻³ Layers of amorphous Si (a-Si) and Al, when heated at a temperature below their eutectic temperature, results in the formation of (111) fiber textured Si film with the interchange of the two layers.⁴ Y. Cohin et al, have already demonstrated that these substrates can be used to grow vertical GaAs NWs.⁴ In the present work, we obtain self-induced vertical GaN NWs at 800 °C using plasma-assisted molecular beam epitaxy (PAMBE) on these AIC-Si templates. The template consists of a stack of a-Si/SiO_x/Al deposited using DC magnetron sputtering, followed by thermal annealing at 250 °C for 5 h and at 500 °C for 10 min. As shown in Fig.1(a), we obtain good growth selectivity for the NWs which form only on the AIC-Si islands. The average growth direction is normal to the substrate surface, with a narrow angular distribution which reflects the non-ideal fiber texture of the AIC template. Strong deviations of orientation are observed occasionally for NWs grown at the periphery of the AIC islands.

As another possibility, we have investigated the self-induced growth of GaN NWs, directly on bulk fused silica wafers and on thermal silica obtained by oxidation of Si (001) wafers. Slightly lowering the growth temperature enables NWs to grow on silica, which acts as a mask at higher temperatures. Although the amorphous structure of these surfaces prevents any epitaxial relationship, the NWs grow with a remarkable alignment of their axis with the substrate normal. Their properties are comparable to those of GaN NWs obtained on bulk Si (111) with optimized conditions, in terms of crystalline quality, polarity and photoluminescence. TEM images show that the NW base has wurtzite structure with no stacking faults or defects. We have determined the polarity of the NWs with KOH etching method.⁵ Alignment and in-plane orientation of the NWs are studied using X-ray diffraction pole-figures. These results are very promising for the development of high-quality GaN without the need for bulk crystalline substrates.

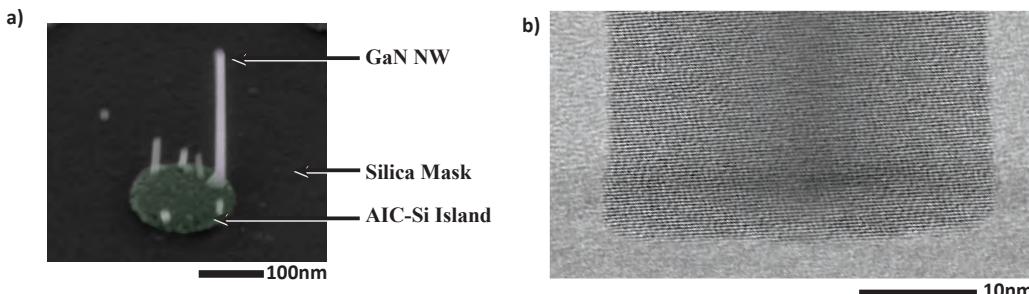


Figure 1: (a) 45° view SEM image of GaN NWs grown on patterned AIC-Si island
(b) TEM image of base of GaN NW grown directly on Fused Silica substrate

References

- [1] O.Nast, *et al.*, *Applied Physics Letter* **73**, 3214 (1998)
- [2] T. Antesberger, *et al.*, *Journal of Non-Crystalline Solids* **354**, 2324-2328 (2008)
- [3] M. Scholz, *et al.*, *Applied Physics Letter* **94**, 012108 (2009)
- [4] Y. Cohin, *et al.*, *Nano letters* **13**, 2743-2747 (2013)
- [5] L. Largeau, *et al.*, *Crystal Growth & Design* **12**, 2724-2729 (2012)

Abstract for Nanowire Growth Workshop 2015, Barcelona

MBE growth and characterization of InGaN nanowires on Si (111)

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Multi-junction solar cells have received wide attention because their energy conversion efficiency can be increased significantly compared to single-junction solar cells. Theoretical considerations show that an InGaN/Si tandem solar cell could be an optimal implementation of a double-junction solar cell, as two different wavelength regions of the broad solar spectrum can be utilized by each junction connected via a resonant tunnel junction which is expected to form at an indium content of 46 % [1].

As a first step towards such an InGaN/Si tandem solar cell, the growth of high quality InN directly on Si (111) substrates by molecular beam epitaxy (MBE) has been investigated. The growth of InN as a homogeneous thin film suffered from an insufficient quality. The obtained layer-like structures showed high surface roughnesses in atomic force microscopy and various epitaxial orientations observed by high resolution X-ray diffraction. A possible alternative to layer growth is the growth of nanowires to reduce structural defects, since the lattice mismatch induced strain can relax through the nanowire sidewalls. By varying the applied growth parameters, namely substrate temperature and III/V-ratio, the InN nanowire growth has been optimized.

HAADF STEM and EELS elemental maps of the optimized InN nanowires have shown a homogeneous distribution of In and N atoms along the nanowire as well as a hexagonal cross-section with a flat top surface. However, a pronounced oxidation of the nanowire surface has been observed, forming an approximately 5nm thick indium oxide shell.

By applying an additional Ga flux to the optimized growth parameters of InN nanowires, InGaN nanowires have been grown. With increasing Ga flux, a decrease in nanowire length and diameter, but an increase in density has been observed. In order to determine the Ga content of the InGaN nanowires, EDX measurements have been performed. An optical characterization of the InGaN nanowires has been done via Raman scattering. To understand the electrical transport properties of InGaN nanowires on Si(111) substrates, I-V measurements on single NWs have been performed by conductive atomic force microscopy. The measurements show a diode behavior for pure InN nanowires which becomes more ohmic for InGaN nanowires with increasing Ga content.

[1] L. Hsu and W. Walukiewicz, *J. Appl. Phys.* **2008**, 104, 024507.

Large scale in-plane Si nanowire arrays on Si substrate: An *insitu* hard mask block copolymer approach

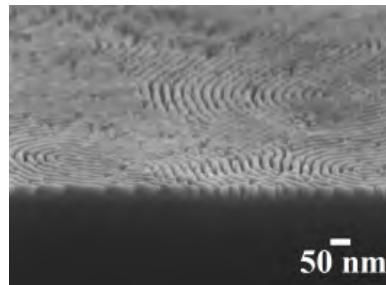
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The computer processor industry is facing a number of challenges in defining 1D (nanowire) nanostructures at substrate surfaces. These challenges are related to lithographic and etch limitations and, in particular, the need to use double or triple patterning to create 1D features for use in logic or interconnect circuitry. Advances in extreme UV lithography have been slow and costs are spiralling. Directed self-assembly (DSA) where arrays of nanowires can be created by a combination of spontaneous arrangement of materials and ‘directing’ forces which force the patterns into alignment with a surface feature/direction. The most promising technique appears to be the DSA of block copolymers (BCPs) which have been shown an extremely versatile platform to form highly regular nanostructure arrangements and also can be used as templates to achieve secondary patterns of interest. But, Si nanopatterns formed by block copolymer templating suffer from edge anisotropy, roughness and dimensional variability. In contrary, hard masks offer the ability to create high aspect ratio features by subtractive processing. We report a simple technique to fabricate horizontal, uniform Si nanowire arrays with controlled orientation and density at spatially well defined locations on substrate based on *insitu* hard mask pattern formation approach by microphase separated polystyrene-b-poly(ethylene oxide) (PS-b-PEO) BCP thin films. The methodology may be applicable to large scale production. Ordered microphase separated patterns of the BCP were defined by solvent annealing and the orientation was controlled by film thickness and annealing time. Spin coating and solvent annealing is an efficient approach where ordering can be achieved in short time periods under solvent atmospheres since the solvent swells the polymer, creating free volume and providing the necessary chain mobility to the polymer blocks to facilitate self-assembly. Films of PEO cylinders with parallel orientation (to the surface plane) were applied to create ‘frames’ for the generation of inorganic oxide nanowire arrays. These types of nanoporous templates were created by the ethanol treatment which etch/modify the cylindrical PEO domains. These PEO cylinders were subject to selective metal ion inclusion and subsequent processing was used to create iron oxide nanowire arrays. The oxide nanowires were isolated, of uniform diameter and their structure a mimic of the original self-assembled BCP nanopatterns. The phase purity, crystallinity and thermal stability of the nanowires coupled to the ease of large scale production may make them useful in technological applications. We also demonstrate that the oxide nanowire arrays could be used as a resist mask to fabricate densely packed, identical ordered, good fidelity horizontal silicon nanowire arrays on the substrate (Figure). These oxide nanowires exhibits extremely high pattern transfer fidelity into silicon with a capability to produce structures orders of magnitude thicker than the original mask thickness through ICP etch. This large area controlled periodic Si nanowire arrays with good sidewall profiles and desirable crystallographic orientation implies one vital step towards future nanoscale devices that employ silicon and may have significant application in the manufacture of transistor circuitry.



Modification of the surface properties for achieving high yield GaAs nanowire arrays on silicon

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Self-assisted growth of GaAs nanowire arrays on silicon substrates offers great perspectives in the optoelectronics and solar cell industry. Up to now, obtaining GaAs NW arrays has been shown to be challenging and difficult to reproduce. In this work, we provide some of the key elements for obtaining a high yield of GaAs nanowires on patterned Si in a reproducible way: contact angle and pinning of the Ga droplet inside the apertures achieved by the modification of the surface properties of the nanoscale areas exposed to growth [1]. Matteini et al have shown that Ga droplet should have a contact angle around 90° in order to promote vertical growth [2]. In this work we present two examples of Si surface modification that lead to a desirable contact angle and, as the consequence, to the vertical NW growth.

First example, an amorphous silicon layer between the crystalline substrate and the oxide mask resulted in a contact angle around 90°, leading to a high yield of vertical nanowires (Fig 1.). Another example for tuning the contact angle is anticipated, native oxide with controlled thickness [1, 2]. This work opens new perspectives for the rational and reproducible growth of GaAs nanowire arrays on silicon.

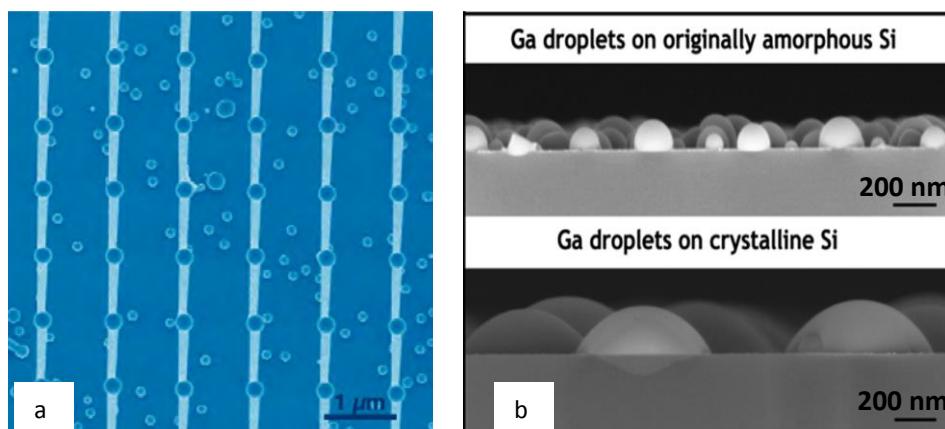


Figure 1: a) SEM image of the high yield GaAs NW array grown on Si substrate, b) Cross-sectional SEM images of Ga droplets deposited on originally amorphous silicon (top) and on crystalline silicon (bottom). The droplets have different sizes and contact angles depending on the surface [2]

References

¹ E. Russo, *et al.* Nano Lett., 15, 2869–2874, 2015.

² Matteini et al, Cryst. Growth Des. Article ASAP, 2015.

Selectivity and yield improvement in selectively grown GaAs nanowires on Si

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Controlling the size, density and position of III-V nanowires (NWs) may greatly improve their optical and device performance characteristics. Although most of the work to date on GaAs NWs grown by the Ga-assisted molecular beam epitaxy (MBE) technique has focused on random, self-assembled NWs on native-oxide covered Si substrate, there have been increasing attempts recently to grow GaAs NWs selectively on Si substrate masked with a nano-patterned SiO₂ film. Successful selective-area growth by MBE requires a high selectivity so that the adatoms are incorporated only within the Si nano-hole regions instead of the oxide mask. A high yield of Ga droplet formation in the nano holes (Figure 1a) is also necessary to initiate Ga-assisted growth of a single nanowire in each hole.

This work aims to investigate the factors leading to improved selectivity and yield in GaAs NWs grown by MBE on Si(111) substrate masked with a thin, patterned thermal SiO₂ layer. The SiO₂ mask is patterned by electron-beam lithography and wet chemical etching. In theory, growth selectivity can be achieved due to the lower sticking coefficients of Ga and As species on SiO₂ relative to Si. It is believed that Ga and As species are strongly desorbed from the oxide mask¹⁻³. However, there is evidence from our work and others that a high selectivity is not easily achieved due to the presence of Ga droplets^{3,4} or GaAs crystals on the oxide mask, with a density up to $\sim 10^{10}$ cm⁻². Furthermore, the nanowire yield is reportedly influenced by the Ga flux^{1,3} and surface properties of the Si windows⁴.

We demonstrate how selectivity can be improved by adjusting the growth parameters (substrate temperature, Ga flux, V/III growth rate ratio) and by employing appropriate pre-growth surface treatment. It is found that the formation of Ga droplets on the oxide mask in the early stage of the growth process can be suppressed by an appropriate surface chemical treatment (Figure 1b). The effects of the oxide mask quality and Si substrate properties on the nanowire growth selectivity and yield are also discussed.

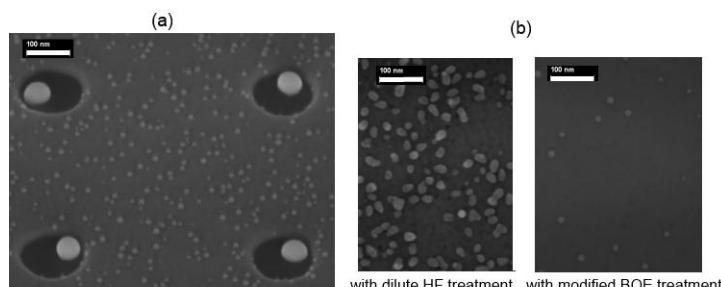


Figure 1: Scanning electron microscope images showing: (a) Ga droplet formation in the Si nano-hole regions. (b) Ga droplet formation on the oxide mask is strongly reduced with a pre-growth treatment of modified buffered oxide etchant (BOE), instead of dilute hydrofluoric acid (HF). The scale bars correspond to 100 nm.

References

- ¹ S. Plissard, *et al.*, *Nanotechnology* **22**, 275602 (2011).
- ² P. Krogstrup, *et al.*, *J. Phys. D* **46**, 313001 (2013).
- ³ A. M. Munshi, *et al.*, *Nano Lett.* **14**, 960 (2014).
- ⁴ Russo-Averchi, *et al.*, *Nano Lett.* **15**, 2869 (2015).

Focused Ion Beam Pre-Patterning of Si substrates for the growth of GaAs nanowires

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Semiconductor nanowires (NWs) have promising properties and high potential for the use as building blocks of future electronic, optical and sensing devices. A main challenge on the way of integrating NWs in conventional electronic circuits is the control of the diameter and the position of NWs in a technically and economically efficient way.

In most cases, NWs growth in Molecular Beam Epitaxy (MBE) onto Silicon (111) substrates is realized onto a thin native Silicon oxide throughout native openings providing a completely random distribution of NWs¹. Here we report on pre-patterning the Silicon substrates using the Focused Ion Beam (FIB) technique in order to define nucleation sites for further GaAs NW growth in the MBE (Figure 1). By defining 324 fields of 2D periodic arrays of holes with certain parameters onto the substrate covered by thermal oxide layer, we could optimize the ion dose to obtain up to 57% yield of vertical GaAs NWs during MBE growth. It has been realized that pre-deposited Gallium droplets accumulate in such opening holes catalysing for the growth². By means of an obtained linear relation, we can estimate the depth of the patterned holes throughout thermal oxide layer as function of the used ion dose to prevent any critical damage to the Silicon substrate by ion beam. Damage events on Silicon substrate by focused Gallium ions are investigated as ion-solid interaction.

In order to achieve selective area growth with high yield of vertical GaAs NWs, we measured the oxide layer thickness of the substrate before FIB exposure. Depending on oxide thickness and considering the linear relation between depth of holes and ion dose, the proper ion dose has been selected to obtain the most promising openings for the growth of vertical GaAs NWs.

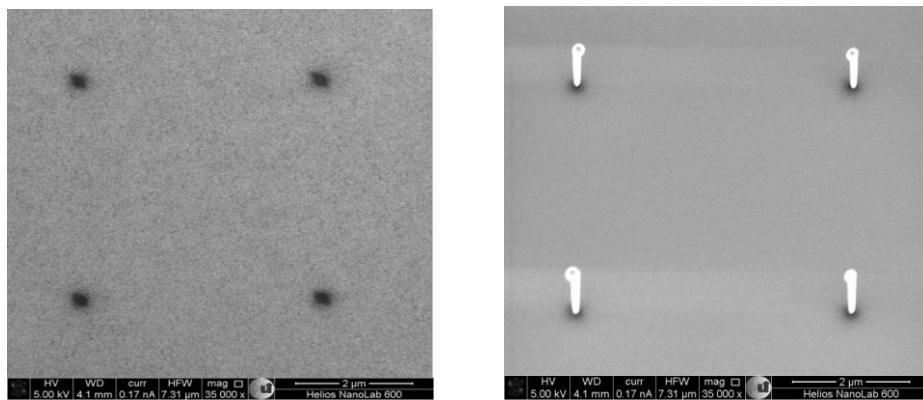


Figure 1: The vertical NWs have been grown on pre-patterned Si substrate.

References

¹ A. Fontcuberta, *et al.*, *Applied Physics Letters*, **92**, 063112, (2008).

² S. Plissard, *et al.*, *Nanotechnology*, **22(27)**, 275602, (2011).

Catalyst-free selective area MBE of semiconductors nanowires on a Si pattern substrate

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ABSTRACT

Semiconductor nanowires have attracted much attention over the past few years as a key building block for nanodevices. By controlling the growth on a nanometre scale we can achieve unique opportunities for combining materials, manipulating properties, and designing novel devices¹. In this study, we have developed a site controlled InAsSb nanowires (NWs) grown on Patterned Si (111) substrate using selective area Molecular Beam Epitaxy (MBE) growth and defined by electron beam lithography (EBL). This method is very promising to form a wire arrays without the use of Au-catalyst or metal droplet that can limit the performance of the grown devices². High quality vertically aligned NWs were obtained with highly uniform diameters along the growth direction as confirmed by Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM), X-Ray and Photoluminescence (PL) analysis. The NWs exhibited phase pure- zinc blende crystal structure. PL spectroscopy at 4K revealed a peak emission consisting of emission from the InAs section at 0.435 eV and more intense emission from the InAsSb section at 0.370 eV(see figure 1(b)). Photodetectors fabricated from doped p-i-n nanowires have shown a dark current density more than an order of magnitude lowers than state of the art InAs devices. These results show a promising route for integration of well- aligned and high quality MBE- grown InAsSb NWs with silicon technology for next generation devices³.

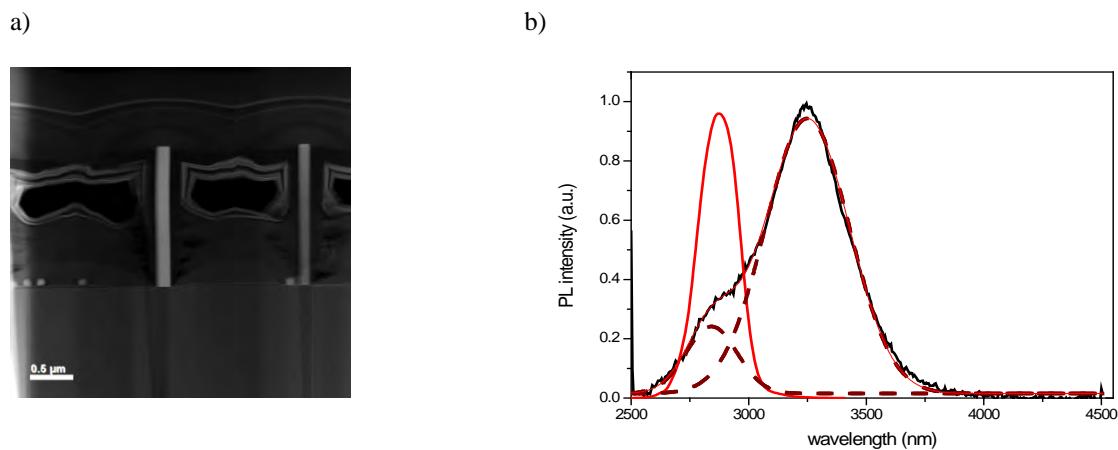


Fig 1: a) SEM images of InAsSb NWs on Patterned Si (111) substrate b) Normalized PL spectra measured at 4k for InAs bulk at 2800nm and InAsSb NWs at 3400nm.

REFERENCES

1. Bernhard Mandl et al. Nano Lett., Vol. 6, No. 8 (2006)
2. Marion J. L. Sourribes et al. Nano Lett, Vol.14, No.1643–1650 (2014)
3. S.Hertenberger, et al. Journals Of Applied Physics 108,114316-1 (2010)

Fabrication of Dual-Type Nanowire Arrays

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Dual-type nanowire (NW) array is a novel structure¹, where two types of NWs – with selective-area epitaxy (SAE) and via vapour-liquid-solid (VLS) – are grown side-by-side on a common substrate using metalorganic vapour phase epitaxy (MOVPE). Figure 1 shows a schematic illustration of the primary steps to fabricate such an array and a false-color SEM image of the resulting structure. In this work, we present the complete fabrication steps leading to a dual-type NW array and present the possibilities and properties of the structure; improved light trapping, compositional control, crystalline quality studied with high spectral resolution Raman scattering and photoluminescence measurements and methods to mitigate the parasitic growth problem arising from the two separate growth steps.

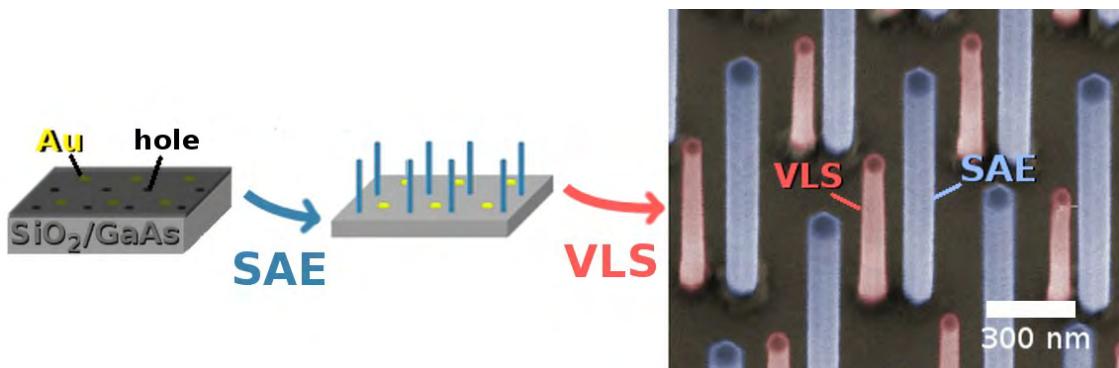


Figure 1: Schematic illustration of the primary steps for dual-type NW array fabrication and a false-color SEM image of GaAs/GaAs dual-type array.

Controlled compositional control and complex configurations can be achieved by using different precursor materials or varying growth conditions in each growth step. Complex configurations increase light trapping of the structure and compositional contrast introduces an additional band gap, which in turn could widen the absorption spectrum. These qualities are beneficial, for example, in a solar cell application.

References

- ¹ Kakko et al., Nano Letters, 15 (3), pp. 1679–1683 (2015), DOI: 10.1021/nl504308x

Heterostructures based on GaAs nanoscale membranes

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III-V nanostructures are of great interest since the last decade thanks to the advantages brought by their confined geometry. With small scales come unique electrical and optical properties, and potential for future optoelectronic devices. The understanding of the growth mechanism of such III-V nanostructures would enable us to tailor their properties for novel optoelectronic applications.

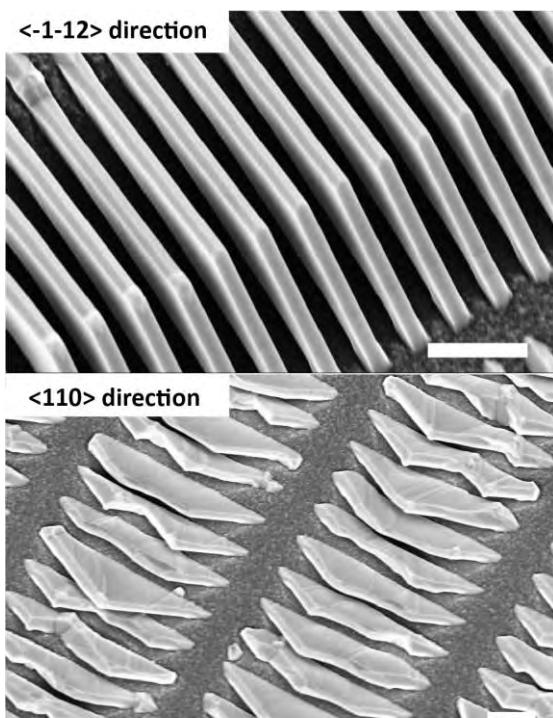


Figure 1: The comparison of GaAs Nanomembranes grown in $<110>$ and $<-1-12>$ directions under optimized growth conditions

In this work, we present our results on GaAs nanoscale membranes and related heterostructures grown by Molecular Beam Epitaxy (MBE).¹ It has been already shown for GaAs/AlGaAs core/shell NWs that the high degree of precision over the growth conditions offered by MBE and the lattice match of GaAs and AlGaAs enable us to obtain high quality heterostructures and such structures demonstrate unique optical properties.^{2,3} While our research continues on GaAs/AlGaAs core/shell nanowires we have expanded our work to other geometries; GaAs nanoscale membranes. GaAs nanoscale membranes have the potential to be defect-free when they are grown in a particular orientation, while twin defects, stacking faults and polytypism are more likely to occur in the case of NWs.⁴ Our ultimate purpose is to understand the effect of geometry and crystal structures of mentioned nanostructures on their optoelectronic properties. In this work we will also show the ongoing studies on the crystallinity and chemical distribution at the atomic scale, and latest results obtained from cathodoluminescence and photoluminescence studies to investigate the optical properties of the nanoscale membranes..

References:

- ¹ G. Tutuncuoglu et al. *Submitted*
- ² A. Fontcuberta i Morral et al. *Small* **4**, 899–903 (2008)
- ³ M. Heiss et al. *Nature Materials* **12**, 439–444 (2013)
- ⁴ C. Chi et al. *Nanoletters* **13**, 2506-2515, (2013)

Compatibility of hydride vapor phase epitaxy process with synthesis of horizontal and vertical GaN nanowires

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This paper reports the growth of high-quality GaN nanowires by vapor-liquid-solid (VLS) and selective area growth (SAG) approach by using hydride vapor phase epitaxy (HVPE) process.

The large-scale, high-precision incorporation of as-grown out-of-plane (aligned) nanowires into nanodevices remains challenging and is now slowing advances in the fabrication of electronic devices such as integrated circuits based on nanowires. First, we present the growth of horizontal GaN nanowires by using a bimetallic catalyst gold-nickel (Au-Ni), which leads to a high growth rate up to 100 $\mu\text{m}/\text{hr}$ ¹. We observed that the catalyst composition play a crucial role to control the growth direction of the GaN nanowires. By adjusting the ratio between nickel and gold in a bimetallic catalyst, the horizontal GaN nanowires have been achieved on different substrates. A gold-rich condition resulted in the growth of horizontal GaN nanowires with a short length (< 2 μm). A nickel-rich condition resulted in the growth of out-of-plane and non-oriented GaN nanowires. A compromise is found between Ni and Au composition: ultra-long, rod-like shape horizontal GaN nanowires are then obtained with 23% of Ni and 77% of Au (see figure 1a). These horizontal nanowires exhibited good optical and structural properties similarly to the vertically grown nanowires. The bright-field image from horizontal nanowires does not show any stacking fault (figure 1 b and c), in contrast to the GaN nanowires grown by VLS-MOVPE² and VLS-MBE³. The achievement of horizontal growth highlights the potential of these nanowires for the large-scale integration into devices including LEDs, lasers, photovoltaic cells, and high-power circuits.

Second, we present the growth of GaN nanowires on silicon (111) and (100) substrates by using SAG-HVPE. Prior to the growth, the thin AlN buffer layer of about 20 nm was deposited by sputtering at room temperature. For selective area growth of GaN nanowires, nanoimprint lithography has been performed (array of 190 nm and 230 nm diameter circular holes). We observed that the length growth of the GaN nanowires is insensitive to the hole diameter (about 1.5 μm for 30 min growth). The morphology of the GaN nanowires is dependent on the growth parameters: temperature, V/III ration and carrier gas. By varying the growth parameters, high densities of c-plane oriented GaN nanowires are obtained at 950 $^{\circ}\text{C}$ and low V/III ratio (see

figure 2 a-d). Finally, an InGaN/GaN core-shell also will be presented in this work using a combination of HVPE and MOVPE.

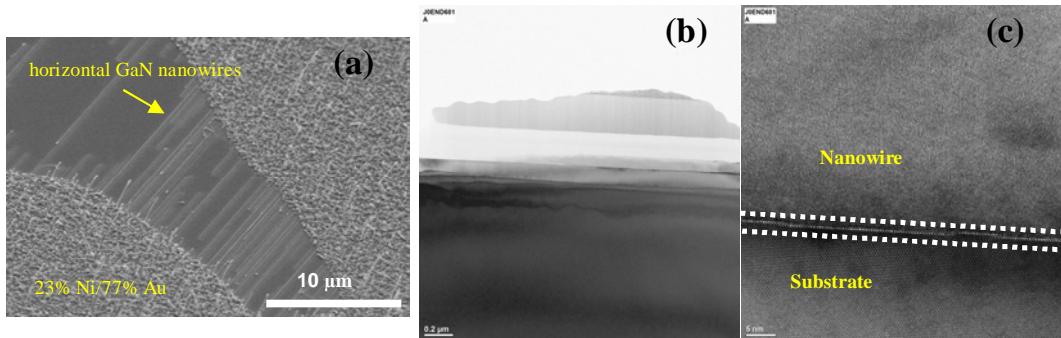


Figure 1. (a) SEM images of horizontal GaN nanowires grown on sapphire substrate, using Au/Ni bimetallic catalyst (23 %Ni/77%Au). (b) Cross-sectional TEM image of a \sim 80 nm horizontal GaN nanowire without stacking faults. (c) Cross-sectional HR-TEM image of the nanowire-substrate interface.

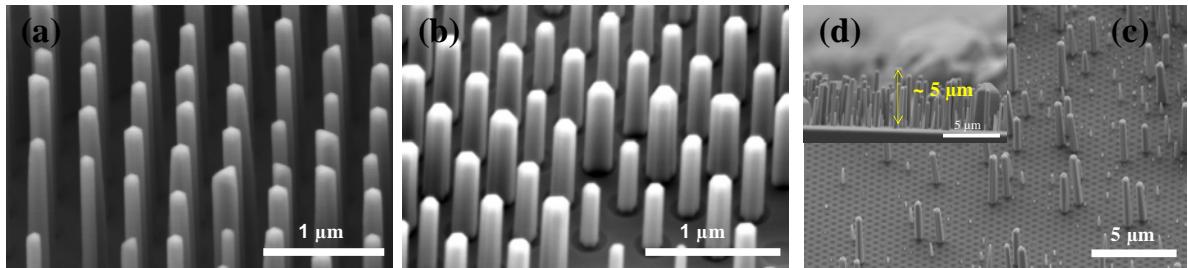


Figure 2. 45°tilted SEM image of SAG GaN nanowires array grown on mask-patterned silicon (111) substrate with hole diameter of (a) 90 nm and (b) 230 nm. (c) 45°tilted SEM image of SAG GaN nanowires array grown on mask-patterned silicon (100) substrate with hole diameter of 230 nm. (d) A cross-sectional SEM image of GaN nanowires grown on silicon (100).

References

- ¹A. Avit et al, *Nano Letters*, **14**, 559–562, 2014
- ²X. Zhou et al, *Nanotechnology*, **23**, 285603, 2012
- ³C. Cheze et al, *Nano Letters*, **10**, 3426–3431, 2010

Control of dislocations in GaN nanowires

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Wide bandgap semiconductors based on GaN, ternary and quaternary alloys of AlGaN, InGaN and AlInGaN play an influential role in electronics and optoelectronics devices. The band gap of these materials is tunable in the range of 0.7-6 eV by different material compositions and they are direct bandgap semiconductors with comparably high electron mobility, making them the strongest material contenders for fabrication of UV- LEDs, Visible LEDs and powerful RF-devices^{1, 2}. The most fundamental challenge of these devices is still material related, descending from poor lattice-match between the nitride semiconductors and the original growth substrate and the consequent formation of edge, screw and mixed dislocations. These detrimental issues limit the device applications by affecting material properties such as lifetimes, leakage current and carrier mobility, thus degrading efficiency and yield of nitride devices. Here, we present fabrication of dislocation-free nano-templates with compositions and lattice-dimensions assigned to enable truly dislocation-free fabrication of nitride electronic and optoelectronic devices.

Short nanowires, approximately 400 nm long were grown by selective area -MOVPE on a planar GaN layer which is grown on Si. A Si₃N₄ mask with an opening size of 75 nm and pitch of 1μm was used; The NWs where grown at 1042 °C. No anneal-step or nucleation-step was used, typical NW growth conditions³ were applied after 5 minutes of temperature stabilization at the growth temperature. By TEM, dislocations are seen to terminate towards the SiN mask, but when a dislocation is seen to extend through the mask opening, it deflects towards the side facet at an early stage as shown in Fig 1a. Dislocations deflecting towards the extended surface are generally seen in asymmetric NWs while no dislocation has been found in symmetrical NWs, seen in Fig. 1c. This behavior, of accelerated growth in the direction of the dislocation deflection, provides the possibility to identify NWs with dislocations by NW shape. By adjusting nucleation conditions or decreasing hole size the occurrence of asymmetrical NWs can be avoided.

REFERENCES:

- [1] J. Cho et al., *Jpn. J. Appl. Phys.* **54** (2015), 02BA04
- [2] D.S. Wuu et al., *Photonics Technology Letters, IEEE* **17** (2005), 288
- [3] Z. X. Bi et al., *Physica Status Solidi (c)* **11** (2014), 421

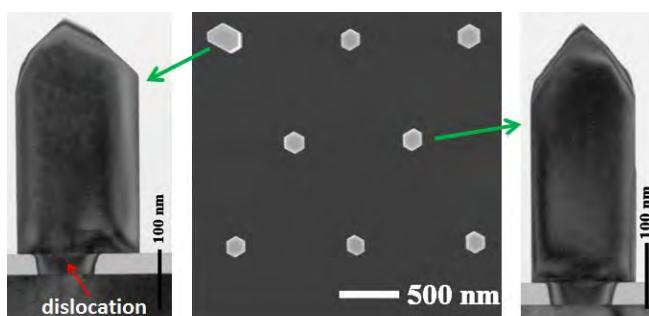


Figure 1: Identification of GaN NWs with a dislocation propagating from underlying GaN buffer layer. **a)** A TEM image showing asymmetric growth caused by deflection of a dislocation from underlying GaN buffer layer. **b)** A top view SEM of GaN NWs. **c)** A TEM image of a symmetric GaN NW which is free of dislocations. Mark a), b) and c) in the figure

Dislocation-filtering and polarity in the selective area growth of GaN nanowires by continuous-flow MOVPE

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Nanowires have emerged as an interesting alternative for the growth of defect-free heterostructures, due to enhanced lateral strain relaxation, and for their integration onto almost any substrate, including amorphous and even plastic materials. These properties are especially interesting in the case of GaN since it is well-known that the performances of III-nitrides devices are limited by a high density of structural defects, in particular dislocations.

The selective area growth of GaN NWs is the favoured method of achieving a high reproducibility and high homogeneity in terms of size and optoelectronic properties. However, this approach increases the probability of forming defects and/or inversion domain boundaries on top of the mask^{1, 2}. In this study we show that our GaN nanowires grown on GaN-on-sapphire templates with a patterned dielectric mask³ can be defect-free and purely Ga-polar.

A detailed study using Transmission Electron Microscopy (TEM) has been performed to fully characterize the structural quality of the site-controlled GaN NWs, paying special attention to the region close to the dielectric mask. Scanning electron microscope (SEM) images of such NWs grown on mask with different pitch sizes can be seen on Figure 1(a-b). By TEM we further show that the size of the aperture in the dielectric mask (from 200 nm to about 800 nm) determines the presence or absence of threading dislocations coming from the underlying template inside the NWs, which results in dislocation-free NWs for the smallest aperture diameters (Figure 1c). Besides, dislocation bending can be achieved on larger aperture diameters thanks to a 3D growth mode. Finally, CBED measurements demonstrate that the Ga-polarity of the underlying GaN-on-sapphire template is conserved in all NWs irrespective of the aperture size, even in the nanowire regions grown laterally above the mask. The pure Ga-polarity assures spatially homogeneous optical properties as evidenced by cathodoluminescence⁴. These results demonstrate that GaN NWs can present a perfect structural quality over a wide range of diameters which open new perspectives for the growth of nitrides on highly-dislocated templates.

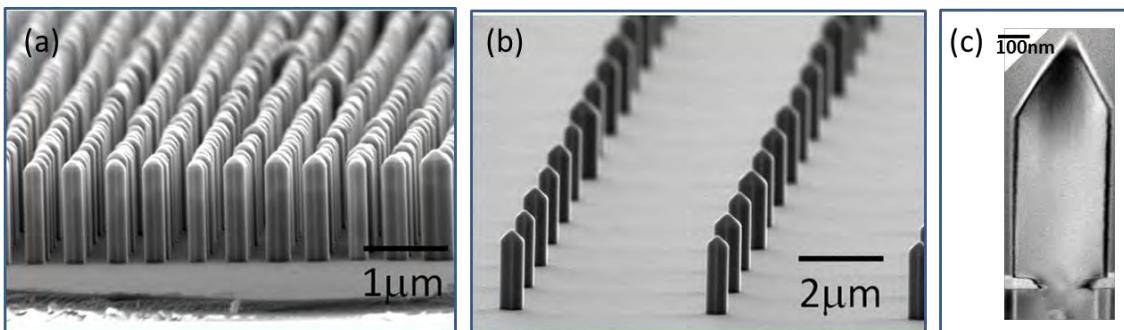


Figure 1: SEM images of GaN NWs grown on masked GaN-on-sapphire templates with a 500 nm (a) and 5000nm (b) pitch pattern. Bright field TEM image along the [10-10] zone axis with $g=000\cdot2$ of a NW grown on a 200nm mask opening (c).

References:

- ¹ W. Bergbauer, M. Strassburg, Ch. Kölper, N. Linder, C. Roder, J. Lähnemann, A. Trampert, S. Fündling, S. F. Li, H. H. Wehmann, and A. Waag, *Nanotechnology* **21**, 305201 (2010).
- ² X. J. Chen, G. Perillat-Merceroz, D. Sam-Giao, C. Durand, and J. Eymery, *Appl. Phys. Lett.* **97**, 151909 (2010).
- ³ P. M. Coulon, B. Alloing, V. Brändli, D. Lefebvre, S. Chenot, and J. Zúñiga-Pérez, *Phys. Stat. Sol. (b)*, 252, 1096 (2015).
- ⁴ P. M. Coulon, B. Alloing, V. Brändli, P. Vennéguès, M. Leroux, and J. Zúñiga-Pérez, under review.

POSTER SESSION - II



COMPOSITION AND CRYSTALLINITY CHARACTERIZATION OF TIN-CATALYZED $\text{Si}_{1-x}\text{Ge}_x$ NANOWIRES GROWN BY PLASMA-ASSISTED VAPOR-LIQUID-SOLID

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Semiconductor nanowire structures are highly desirable for new generations of electronic and photonic devices. Silicon-germanium alloys are promising materials for nanowires since their bandgap, lattice parameter and electrical properties can be tuned with Ge atomic fraction and strain. What's more, they are also good candidate for integration of III-V materials on silicon¹. Plasma-assisted vapor-liquid-solid (VLS) SiGe nanowire growth using Sn as catalyst is a promising way to synthesize $\text{Si}_{1-x}\text{Ge}_x$ nanowires with high electrical performance at low temperature (~400 °C). Moreover, atomically sharp Si/Ge heterojunction nanowire structures can be achieved due to the low solubility of Si and Ge in Sn. In this study, we have grown SiGe nanowires with plasma-assisted VLS method using Sn as catalyst and SiH_4 , GeH_4 and H_2 as gas precursor. The Ge fraction (0% to 70%) has been characterized by Raman scattering and spectroscopic ellipsometry. We have found that the Ge fraction has a linear relationship with the $\text{GeH}_4/(\text{GeH}_4+\text{SiH}_4)$ gas flow rate ratio and that the Ge fraction increases when H_2 partial pressure is increased. What's more, we have found that Ge/Si fraction ratio in nanowires is around 76 times larger than $\text{GeH}_4/\text{SiH}_4$ gas flow rate ratio. The crystallinity of nanowires has been characterized by transmission electron microscopy and Raman scattering. The changes in the crystalline structure of nanowires from i) monocrystalline, to ii) monocrystalline core/defective crystalline shell, then iii) to monocrystalline core/defective crystalline shell/amorphous shell, and finally iv) to bended and strained monocrystalline core/defective crystalline shell/amorphous shell structure with the increase of the growth duration have been studied in detail.

Key words: SiGe nanowires, characterization, VLS, PECVD, Sn

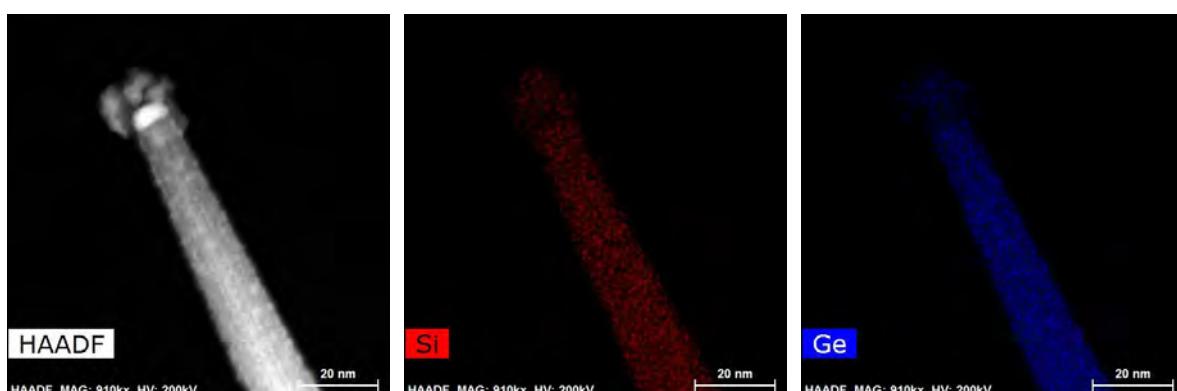


Figure 1: Scanning transmission electron microscope high-angle annular dark field image and energy dispersive X-ray (EDX) maps of Si and Ge in a SiGe nanowire

References

- ¹ R. Cariou, J. Tang, N. Ramay, R. Ruggeri, P. Roca I Cabarrocas. *Solar Energy Materials & Solar Cells* 134 (2015) 15–21

High Ensemble Uniformity and Low Disorders in Quantum Well Tube Nanowires Probed by Photoluminescence Spectroscopy

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Semiconductor nanowires have received much attention over the past decade and there are already a number of applications utilising them such as solar cells¹⁻², terahertz detectors³ and LED devices⁴. Customisation of the bandgap in particular is essential for such nanowire applications. Ternary materials are traditionally used to tailor the bandgap, although the growth of nanowires with a uniform composition remains challenging. However, an alternative method for tailoring the bandgap energy is to take advantage of quantum effects by producing a quantum well tube (QWT) along the nanowire axis by growing a thin layer of lower bandgap material within the higher bandgap shell layer.

Here, we have investigated spectroscopic distributions of 150 individual core-multishell nanowires from three growth recipes with different GaAs QWT shell layers and core and we have determined their energetic disorder. Using room temperature photoluminescence measurements (Figure 1), we have found the QWT of the 3 samples to possess an average width of 2.1, 4.0 and 2.0 nm and a standard deviation of 0.3 nm or less. A disorder parameter associated with the non-thermal broadening was extracted from the fits of the spectra and correlated to the structure of the nanowire. The core is measured to have a very low disorder of 8 ± 2 meV, while the QWT disorder was found to be 40 ± 10 meV approaching the ideal limit of $k_B T$. This suggests the suitability of these nanowires to be used in tuneable optoelectronic devices.

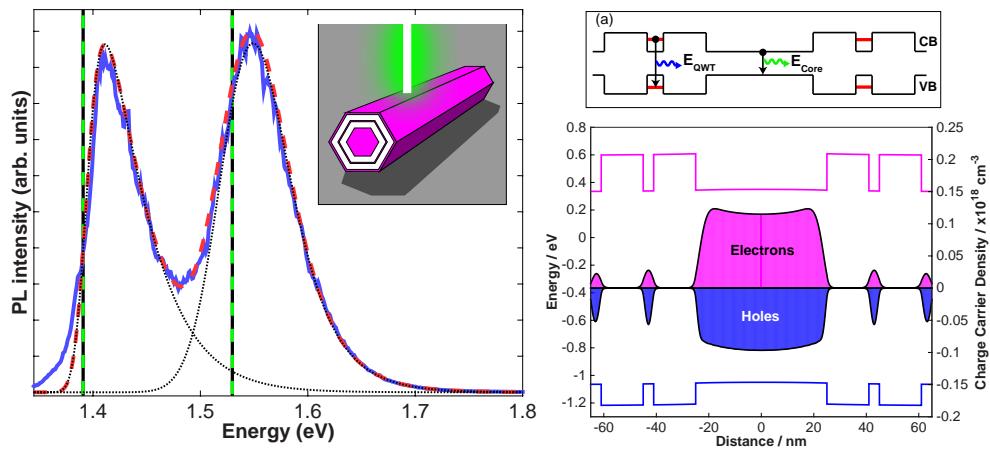


Figure 1: (left) PL spectrum of a typical nanowire shown on a linear scale. (right) Simulation of QWT nanowire showing band structure and charge carrier density.

References

- ¹ M. Yao, *et al.*, *Nano Letters* **14**, 3293-3303 (2014).
- ² Y. Qu, *et al.*, *Journal of Materials Chemistry* **22**, 16171 (2012).
- ³ K. Peng, *et al.*, *Nano Letters* **15**, 206-210 (2014).
- ⁴ C. Pan, *et al.*, *Nature Photonics* **7**, 752-758 (2013).

Shell-Thickness Controlled Semiconductor-Metal Transition in Si-SiC Core-Shell Nanowires

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Among the many applications that have been demonstrated for silicon nanowires (Si NWs), chemical sensing is certainly one of the most promising. The large surface-to-volume ratio and the possibility to tune their properties at growth time controlling the composition, crystal orientation, and diameter make Si NWs bound to outperform any other conventional alternative in a large class of sensing environments [1,2]. On the other hand, because of its excellent chemical and mechanical stability, high hardness and low density it is widespread belief that SiC is a much better biocompatible material than Si. Moreover, its ease to be grown on Si substrates makes it a perfect *bridge* material between the electronic and biological world.

The combination of Si and SiC in a nanostructure, as shown by recent experiments [3], could lead therefore to a material with the *smart* properties of Si (that can be facilely integrated into current technology) and the biocompatibility of carbon-based systems.

In this work we present Density Functional Theory (DFT) electronic structure calculations of Si-SiC core-shell nanowires [4] and argue that are ideally suited as biocompatible sensors. Our calculations highlight two major points: **(i)** first, for ultrathin Si-SiC core-shell NWs the presence of a thicker shell (more than one monolayer) has a drastic effect on the electronic structure leading to a semiconductor-metal transition (as shown in Fig. 1); **(ii)** this occurrence is fortunately not observed in the case of larger diameter wires, which remain semiconducting also for four monolayer (ML) shells assessing their potential as biocompatible nanostructures.

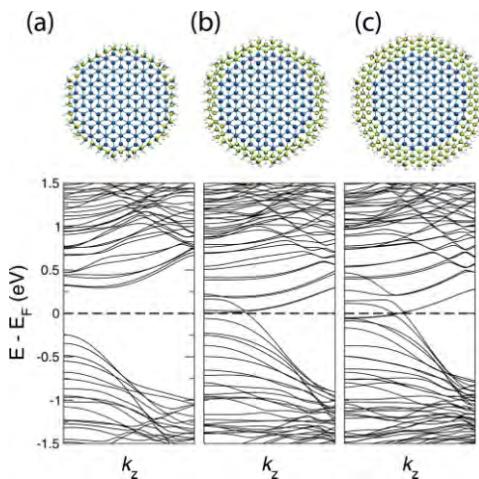


Figure 1: Cross-section view and band-structure diagram of a Si core SiC shell NW with a core of 2.5 nm and a shell of (a) 1, (b) 2, and (c) 3 MLs of SiC. Blue, yellow, and white spheres represent Si, C, and H atoms, respectively.

References

- [1] R. Rurali, Rev. Mod. Phys. **82**, 427 (2010)
- [2] M. Amato, M. Palummo, R. Rurali, and S. Ossicini, Chem. Rev. **114**, 1371 (2014)
- [3] L. Latu-Romain and M. Ollivier, J. Phys. D **47**, 203001 (2014)
- [4] M. Amato and R. Rurali, Nano Lett., DOI: 10.1021/acs.nanolett.5b00670 (2015)

STRAIN-INDUCED PHASE TRANSFORMATION IN GE NANOWIRES

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Nanowires show unique deformation behaviour resulting from the nanoscale size effect. This specific behaviour can cause unexpected structural reorganizations of atoms inducing the creation of novel functional materials as well as innovative heterostructures. We report on a stress induced martensitic phase transformation in Ge nanowires attributed to the size effect. <111>-oriented Ge nanowires with standard diamond structure (3C) undergo plastic deformation under external stress leading to a phase transformation toward the hexagonal 2H-allotrope. The obtained nanostructures exhibit Ge-2H nano-domains heterogeneously embedded along their length. This polytypism was successfully achieved from both bottom-up and top-down fabrication approaches with diameters ranging from 40 to 230 nm. Uncommon phases of Ge have been of high interest for researchers for the past two decades. Theoretical studies predict in particular a direct small gap in Ge-2H¹. Thereby, this novel heterostructure 2H/3C in Ge nanowires can pave the way to exciting applications of group-IV material for next-generation devices. For instance, the periodic formation of phase boundaries could induce a strong reduction of thermal conductivity while the electronic conductivity is conserved therefore enhanced thermoelectric properties are expected. Understanding the origin of this metastable phase formation is critical to evaluate the potential of those technological applications. The generation of the 2H allotrope was observed in both silicon and germanium upon hot indentation. The cubic to hexagonal diamond phase transformation was assigned to a martensitic phase transformation where a mechanism of local relaxation stress in the region of twin intersection was proposed^{2, 3}. Structural (HRTEM) and physical characterizations have been performed in our transformed nanowires. We have studied various key parameters such as the diameters of the nanowires and the temperature of the transformation. A strain-induced martensitic transformation could account for the transformation in nanowires with a threshold temperature of 300° C; below this temperature the stress induces plastic deformation. In the case of nanowires twin-twin interaction seems yet not to be a relevant mechanism. Raman shift evidence both a residual stress within the nanostructures and the presence of the 2H phase.

References

¹J. D. Joannopoulos, *et al.*, *Phys. Rev. B*, **7**, 2644 (1973)

²V. G. Eremenko, *et al.*, *Phys. Stat. Sol. (a)* **14**, 317 (1972)

³S-Q.Xiao, *et al.*, *J.Mater.Res.*, **7**, 1406 (1992)

Ordered Silicon Nanowires by Metal Assisted Chemical Etching

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Silicon nanowires (SiNWs) have attracted an increasing interest in recent years, due to good scalability and their peculiar physical properties, which make them relevant for possible applications in electronics, optoelectronics and thermoelectric devices^{1,2}. A promising method of obtaining SiNWs, presenting noticeable advantages in term of cost, size control (section shape, dimensions) and typology (doping level and type), is Metal-Assisted Chemical Etching³. We used MACE in presence of gold film, patterned by nanosphere lithography, to produce ordered arrays of nanowires. These arrays are good candidates for high performance nanostructured anodes for solid state batteries, for gas and bio sensing and for nanoelectronics.

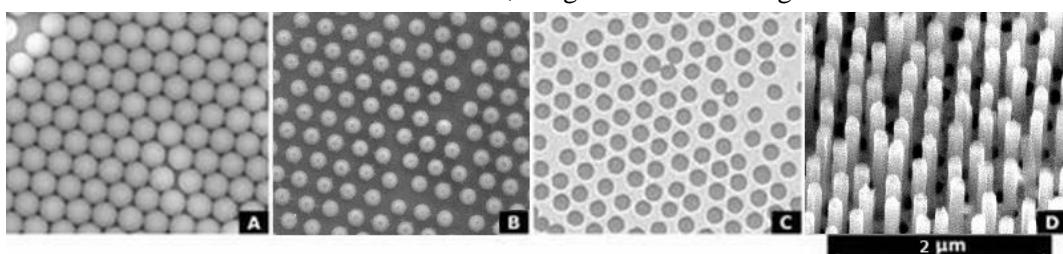


Figure 1: SEM images, Si NWs fabrication steps: A) Polystyrene nanospheres are spread on the silicon substrate by spin-coating; B) Reduced nanospheres after O₂ plasma etching; C) Metal “antidot” pattern after nanospheres ablation; D) Obtained SiNWs after 1 min etch.

Polystyrene nanospheres with diameter of 260 ± 10 nm were spread on highly p-doped Silicon 10-20 mΩ·cm <100> substrates by spin-coating, in order to obtain self-assembled monolayer arranged into hexagonal closed packed structure (Figure 1A). Oxygen plasma etching was performed, reducing their dimension down to 120 ÷ 130 nm (Figure 1B). At this stage, a 20 nm thick gold film was deposited on the sample using an e-beam evaporator. A so-called “antidot” metal pattern remained on the silicon surface after spheres removal in ultrasonic bath (Figure 1C). MACE was performed dipping the sample in the chemical solution composed of deionized water, hydrogen peroxide and hydrofluoric acid in different concentrations, obtaining an ordered array of well-defined Si nanowires (Figure 1D).

In order to electrically characterize single nanowires, we fabricated electrical nanodevices. A first level of Niobium electrical paths and probe pads was made on a 300 nm silicon oxide substrate by photolithography process and sputter deposition of Nb. After that, silicon nanowires previously obtained were scratched on it. Using a Gas Injector System (GIS) in a dual beam Scanning Electron Microscope (FEI), isolated nanowires were stuck to the substrate, depositing Platinum spots. Nanopatterned metal paths, which connect Nb micrometric paths to the nanowires, were realized using a customized Electron Beam Lithography (EBL) process and a following sputter deposition of Nb. This solution ensures robust and stable electrical contacts to the SiNW. In the Figure 2 a detail of the final structure of the device is shown.

References

- ¹ M. Hasan, *et al.*, *SpringerPlus* **2**, 151 (2013).
- ² A. I. Hochbaum *et al.*, *Nature* **451**, 163–7 (2008).
- ³ Z. Huang *et al.*, *Adv. Mater* **23**, 285 (2011).

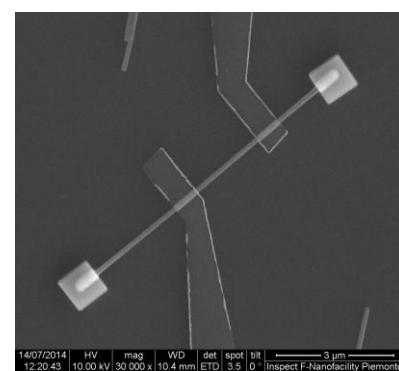


Figure 2: SEM image of a nanowire stuck to the substrate by two squared Pt spots with two nanopatterned Nb contacts.

Micro-Raman spectroscopy and imaging of epitaxial SiGe nanowires grown on Si(001)

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Silicon-Germanium (SiGe) epitaxial nanostructures are suitable materials for integration into the silicon platform. Nanowires (NWs) are one of their most interesting morphologies both from fundamental as well as practical point of view. Their development can lead to specialized functionalities for different fields of application such as nanoelectronics, thermoelectrics, photovoltaics, energy storage, information and communication technologies. Epitaxially grown SiGe NWs on Si (001)-oriented wafers are particularly interesting for device integration to preserve the compatibility with standard microfabrication technology.

We have studied the formation of SiGe epitaxial in-plane NWs by Molecular Beam Epitaxy (MBE) on Si (001) substrates by using AuSi seeds obtained by annealing Au layers deposited on clean Si surfaces. We find conditions in which an homogeneous growth of in-plane NWs not mixed with other nanostructure geometries is achieved. The NWs grow along the [110] directions and their lateral dimensions depend on the seed nanoparticle sizes, as is typical for a vapor-liquid-solid (VLS) process.

In this contribution, we show confocal Raman microspectroscopy and imaging results of these samples, where individual NWs can be studied within the spatial resolution of the system. Quantitative evaluation of the spectroscopic information reveals intriguing composition and residual strain distributions that help us to understand the growth processes. In particular, the results indicate that the $\text{Si}_{1-x}\text{Ge}_x$ composition seems to be mainly determined by the liquid-solid thermodynamic equilibrium given by the AuSiGe phase diagram. In the used conditions of flux and substrate temperature, it is possible to grow different compositions x from the Ge-rich end to a Si-rich value of $x \sim 0.3$. The NWs evolution is dominated by the surface diffusion kinetics of the Ge adatoms. The strain distributions, with both tensile and compressive residual values, are also consequence of the Ge kinetic behavior.

In addition, the Raman intensity of the substrate provides a probe to investigate the optical absorption of the NWs. We observe differences in Raman scattering intensity when the light polarization is parallel or perpendicular to the nanowire axis. These variations are correlated to the anisotropic absorption in thin nanowires.

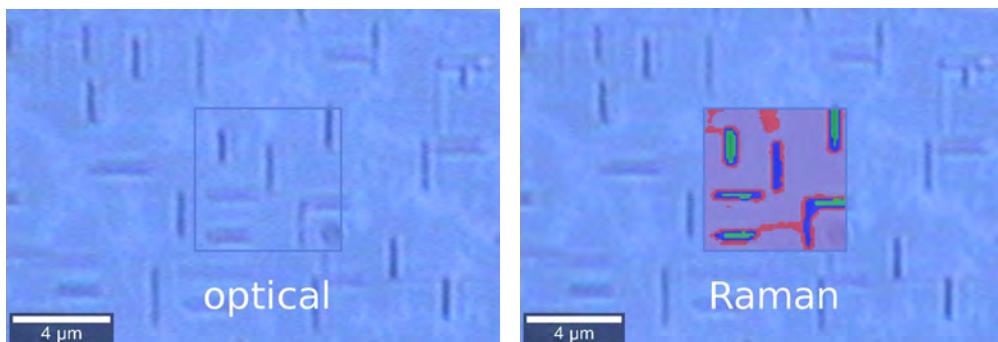


Figure 1: Comparison between optical image and Raman contour plot of the indicated area. Different colors illustrate the diverse composition regions identified on the sample.

Hexagonal GaP-Si-SiGe core-multishell nanowires studied by Atom Probe Tomography

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Crystals of group IV materials with hexagonal lattice structure are expected to have interesting optical and electronic properties. While pure hexagonal Ge is predicted to have a direct band gap, hexagonal Si is predicted to have an indirect gap^{1,2}. By making SiGe alloys with different compositions we can possibly tune the directness of the band gap and the band gap energy. Hexagonal GaP (Wurtzite) nanowires were used as a template for a hexagonal Si-SiGe shell system. As possible (local) variations in Si:Ge ratio and interdiffusion between core and shell potentially may have large influences on the optical properties it is essential to get 3D atomic scale information on the chemical composition and purity of the layers and the abruptness of the interfaces. In this contribution we report the analysis of GaP-Si-SiGe core-shell-shell nanowires by the combination of cross-sectional Transmission Electron Microscopy and Atom Probe Tomography. Compositional gradients in the SiGe shell have been studied in the radial direction as well as phase separation close to the corner facets. In addition, the diffusion pattern of the elements across the GaP-Si heterojunction has been imaged. We observed an increase in the Si content in the SiGe shell towards the outer regions, while the corner facets show a different alloy composition all together. The Ga and P profiles show a diffusion pattern with enhanced diffusion along spiky features.

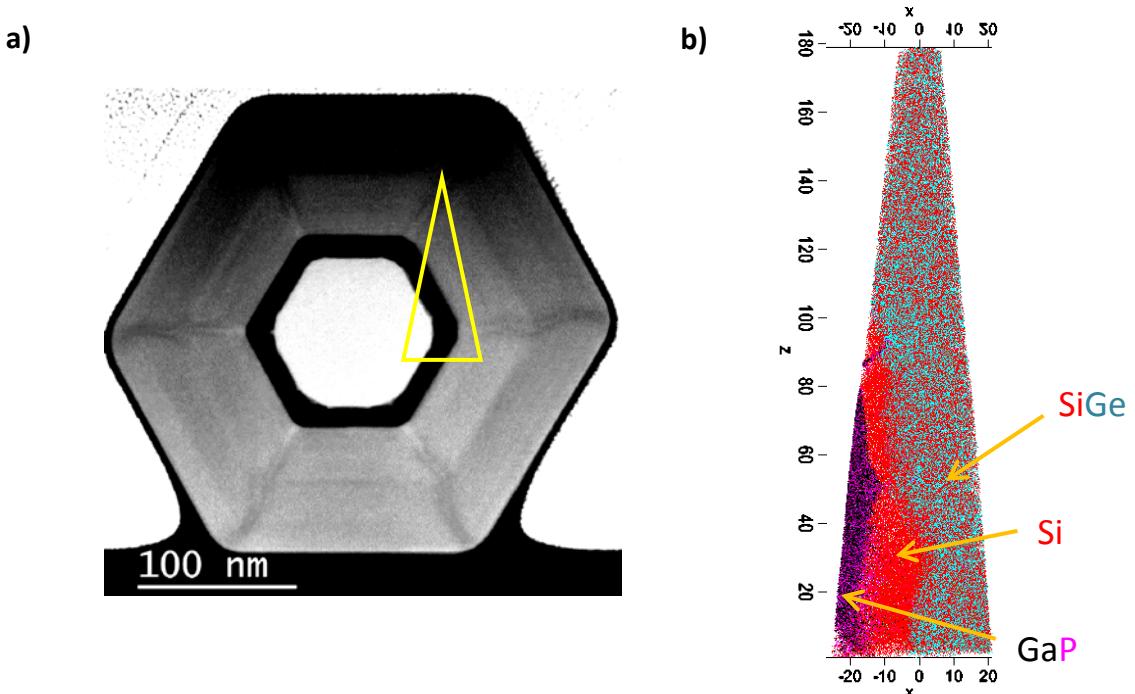


Figure 1: a) Cross-sectional Transmission Electron Microscopy image of a GaP-Si-SiGe core-shell nanowire. The change in contrast indicates the different alloy compositions. b) Atom-probe image of a region similar to the one indicated with the yellow triangle in a), showing the atomic make-up of the interface region. Each point indicates a detected atom, where the color coding indicates the chemical element.

References

¹ J.D. Joannopoulos and M.L. Cohen, *Physical Review B* **7**, 2644 (1973).

² A. De and C.E. Pryor, *Journal of Physics: Condensed Matter* **26**, 045801 (2014).

Optical properties of single wurtzite/zinc-blende ZnSe nanowires grown at low temperature

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Semiconductor nanowires (NWs) have been increasingly studied in the last few years, both for fundamental research and applications in electronics and optoelectronics [1]. Among the many attractive properties they offer, the most peculiar one is the high surface/volume ratio, which has a profound effect on the crystal growth and can result in crystal structures not observed in the bulk. This effect has been observed for IV [2], III-V [3] and II-VI [4] semiconductor NWs. Moreover, the nanometer-sized diameter offers the opportunity for quantum confinement and for the growth of various axial and radial heterostructures.

ZnSe is a direct wide-band-gap II-VI semiconductor ($E_g = 2.7$ eV at 300 K), suitable for light emission in the blue-green region of the visible spectrum. The stable crystal structure of ZnSe is zinc-blende (ZB), but it also may occur in the wurtzite (WZ) structure, metastable at room temperature and therefore difficult to obtain. Unlike the bulk case, ZnSe NWs often display WZ crystal structure, although the number of reports on ZB ZnSe NWs exceeds those of WZ ones. In this contribution we report on the optical properties of single ZnSe NWs grown at low temperature (300°C) by means of Molecular Beam Epitaxy assisted by solid Au nanoparticles [5]. Transmission Electron Microscopy (TEM) studies show that the NWs crystal structure is mainly wurtzite with thin zinc-blende insertions. These polytypic NWs have been analyzed by micro-photoluminescence and cathodoluminescence to correlate the NWs structure with their optical properties. A dominant intense near-band-edge emission is observed where the WZ free exciton line can be identified. The NW emission displays a linear polarization perpendicular to the NW axis, in contrast with the usually observed light polarization along the NW axis [6]. This effect is explained by the selection rules in the WZ structure. Crystal phase quantum dot features due to a type II band alignment between ZB and WZ ZnSe have been evidenced by time-resolved photoluminescence. From these measurements we estimate values for the conduction and valence band offsets of +50 and -98 meV respectively.

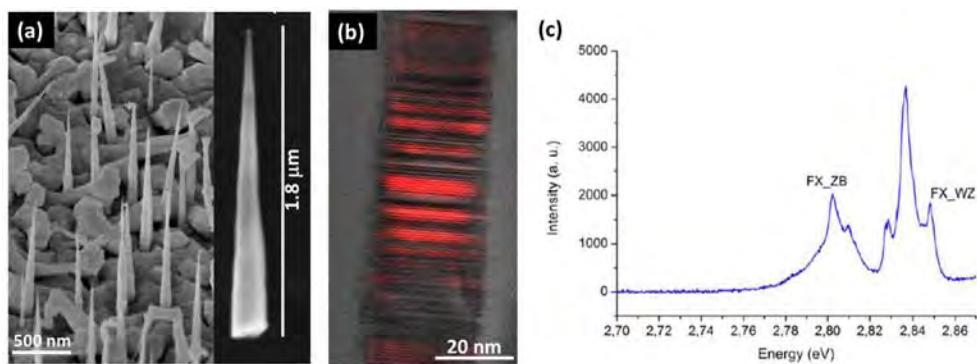


Figure 1: (a) 45°-tilted SEM image of ZnSe NWs grown at 300°C on GaAs(111)B. The inset on the right is a magnified image of a representative NW, mechanically transferred onto a Si wafer. (b) False colour HRTEM micrograph of a NW where the alternation between WZ (red) and ZB segments is highlighted. (c) Photoluminescence spectrum of a single WZ/ZB ZnSe NW acquired at 5K.

References

- [1] T.J. Kempa *et al.*, *Journal of the American Chemical Society*, **135**, 18354 (2013)
- [2] P.B. Sorokin *et al.*, *Journal of Experimental and Theoretical Physics Letters* **92**, 352 (2010)
- [3] P. Kusch *et al.*, *Physical Review B* **89**, 045310 (2014)
- [4] P. Rueda-Fonseca *et al.*, *Nano Letters* **14**, 1877 (2014)
- [5] V. Zannier *et al.*, *Physica Status Solidi (RRL) - Rapid Research Letters* **8**, 182 (2014)
- [6] J. Wang *et al.*, *Science* **293**, 1455 (2001)

Randomly distributed phase domains in single GaAs NW's

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Coherent x-ray diffraction (CXDI) is used to record 2D diffraction patterns from individual GaAs nanowires near the expected Bragg peak position. Instead of Bragg peak, however we measure a complex speckle patterns due to high number of stacking faults in single nanowire (NW) (fig.1 a,b,c). In this work we demonstrate that the complex speckle patterns measured are the result of the random arrangement of the ZB and TZB phase domains where the length of phase domains is less than 3 unit cells along the growth direction. Two spatial resolutions (low resolution (LR) and high resolution (HR)) were achieved in experiments, corresponding to the possible minimum size of a phase segment in real space, which still can be reconstructed is 3.48nm (LR) and 0.98nm (HR) corresponding to 12 and 4 bilayers, respectively. A combination of the phase retrieval algorithms and methods such as Error-Reduction (ER), Hybrid Input-Output (HIO) and Shrink Wrap (SW) [1, 2] (fig. 1 d,e). Taking into account the fact that the nanowire of finite size has constant density and is structurally homogeneous perpendicular to the growth axes, we model the NW by a number of phase domains with a relative phase change of 0 and $(\pm 2\pi)/3$ to each other. Probing about 10^4 different trial phases no unique solution for phase is found but the average number of phase changes is rather constant and. In summary, our approach allows for a quantitative defect analysis of single nanowires by use of coherent x-ray diffraction imaging accompanied by a modified phase retrieval algorithm. Considering the total height of the nanowire, a resolved mean defect density of 0.23 ± 0.01 defects/nm, 0.22 ± 0.01 defects/nm for LR case and 0.48 ± 0.01 defects/nm for HR for two single nanowires. The achievable spatial resolution makes it impossible to determine the detailed defect arrangement of the highly defective NWs. However, our approach might be successful for NWs with much lower defect density which is matter of a future experiment.

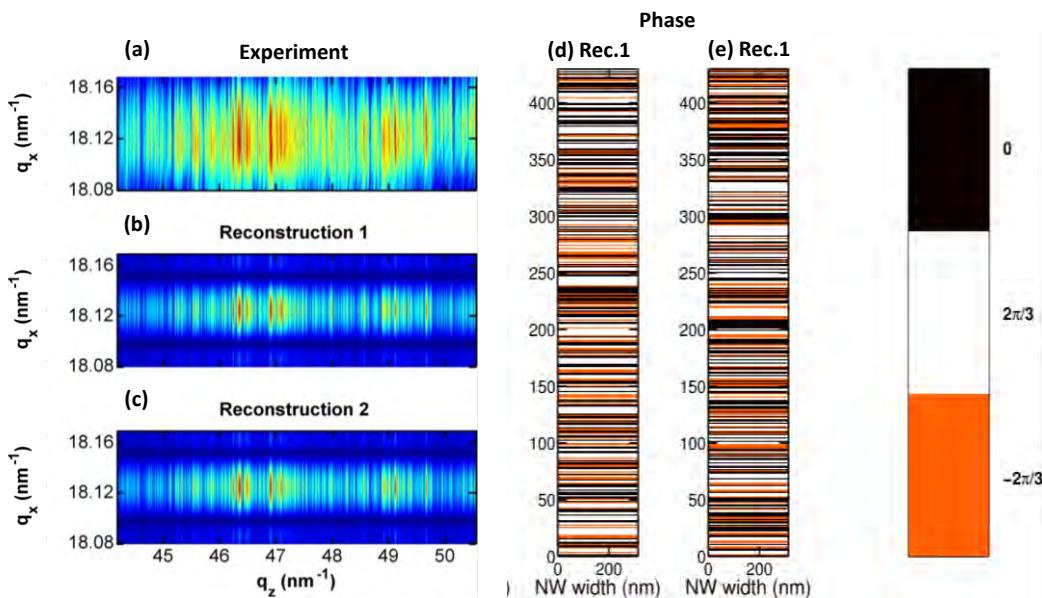


Figure 1: (a) Experimentally recorded (CDI) speckle pattern of the single GaAs NW. (b,c) Fourier transform of the reconstructed NW after the phase retrieval. (d,e) Retrieved phase of the NW for two different trial phases in phase retrieval algorithm.

References

- Marchesini, S., et al., *X-ray image reconstruction from a diffraction pattern alone*. Physical Review B, 2003. **68**(14).
- Fienup, J.R., *Phase retrieval algorithms: a personal tour*. Applied Optics, 2013. **52**(1): p. 45-56.

Influence of growth conditions on optical properties of GaN nanowires grown by PAMBE on amorphous Al_xO_y

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In our recent report we have shown that efficient catalyst-free nucleation of GaN NWs can be obtained by PAMBE if crystalline sapphire substrate is covered by amorphous Al_xO_y (a- Al_xO_y) buffer, while under the same conditions no NWs are formed on monocrystalline parts of the substrate.¹ As the result neither AlN epitaxy nor substrate nitridation are no longer needed for catalyst-free growth of GaN NWs on sapphire. The result has been explained by microstructure of the buffer surface allowing easier creation of GaN critical nuclei and thus enhancing nucleation rate on amorphous sapphire as compared to its monocrystalline phase. Since GaN NWs have a huge potential for opto-electronic applications, it is crucial to check if the buffer has any impact on optical properties of NWs. Aim of this work was to analyze influence of growth temperature on photoluminescence spectra and PL kinetics of NWs grown on amorphous Al_xO_y buffers and to compare the results with those for NWs grown under similar conditions on nitridized Si(111) substrates. The NWs studied were grown by PAMBE on Si(111) substrates covered with 15 nm thick amorphous Al_xO_y layer deposited by atomic layer deposition at 85°C. Nitrogen-rich conditions and a wide range of growth temperatures 720 – 783°C were used.

At helium temperature, two features dominated the PL spectra: a 3.471 eV peak of donor-bound excitons (DX) and the 3.45 eV band having similar energy to emission attributed to inversion domains in planar GaN structures. The peak at 3.42 eV that is commonly observed in GaN NWs, and is related to stacking faults (SF), was relatively weak. A significant increase of photoluminescence intensity and much longer PL decay times, close to those on silicon substrates, are found for samples grown at the highest temperature (Fig. 1a-b) what indicates their high optical quality. Those samples have quite narrow PL lines which allowed analysis of nature of residual donors present in NWs. Positions of the DX line in the NW grown on Al_xO_y were regularly lower ($h\nu = 3.471$ eV) than in samples grown directly on silicon ($h\nu = 3.472$ eV) suggesting that oxygen, instead of silicon, was the dominant donor (Fig. 1c). Moreover, comparison of the DX/FX PL ratio being lower in GaN NWs on a- Al_xO_y than in those grown on nitridized Si indicated lower concentration of donors in GaN NWs grown on a- Al_xO_y buffer. Finally, we show that proper UHV cleaning of the a- Al_xO_y buffer prior to growth reduces concentration of residual acceptors in NWs having no impact on total concentration of donors.

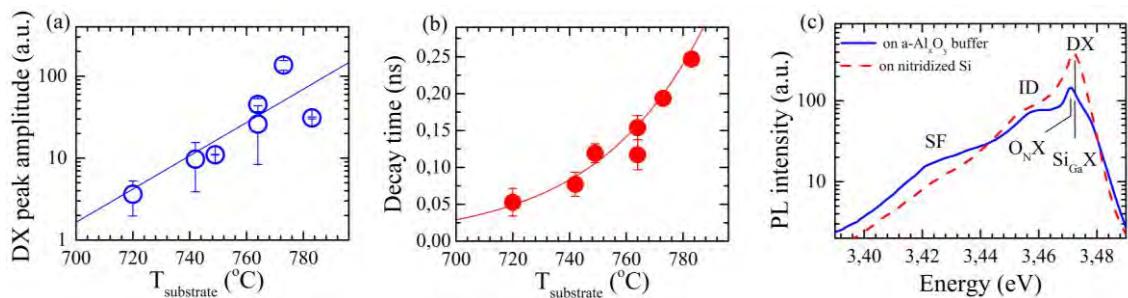


Fig.1: (a) amplitudes and (b) decay times of the DX peaks in GaN NWs grown on a- Al_xO_y at various temperatures; (c) comparison of PL spectra of two samples grown at 764°C on Si(111) and on a- Al_xO_y . The position of the DX peak is shifted by 1 meV suggesting that oxygen, instead of silicon, is the dominant donor in NWs grown on a- Al_xO_y .

¹ M. Sobanska, *et al.*, *J. Appl. Phys.* **115**, 043517 (2014).

High Si incorporation in MBE-grown GaN nanowires

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This work reports on the structural and electrical properties of Si-doped GaN nanowires (NWs) grown by molecular beam epitaxy (MBE), with a typical length of 2-3 μm and a radius of 20-200 nm. A series of Si-doped GaN NWs were grown with the same growth conditions except for Si cell temperature. There is no visible morphology change with low Si doping. Upon higher Si doping, the radius of the NW is gradually increased while the length is decreased (Figure 1(a)). In the case of the most doped NWs, the radius continues to increase until reaching a certain equilibrium value, and then the wire elongates with a 12-fold symmetry of the top facet. A small but progressive tensile strain with increasing doping has been found by Raman spectroscopy, which has fully relaxed at the most heavily doped sample. With the purpose of mapping the Si content in nanoscale, NWs from two samples with high Si doping (Si cell temperature of 938°C and 950°C) have been analyzed by EDX in a SEM and TEM (Figure 1(b-d)), separately. The measured Si concentrations from two techniques are similar. The NWs grown with the highest Si cell temperature have a core with Si concentration ranging from $2-4 \times 10^{20} \text{ at/cm}^3$ with a Si enriched outer part up to 10^{21} at/cm^3 . For high Si cell temperature (938°C), both techniques have shown a relatively constant Si concentration throughout the NW with an average value of 10^{20} at/cm^3 , as a clue of a larger solubility limit of Si in NWs compared to two-dimensional layers. Furthermore, we have performed electrical transport measurements (four probe resistivity and resistivity temperature dependence) on this series of NWs. Four probe resistivity measurements have shown a controlled doping level with resistivity from 10^2 to $10^3 \text{ }\Omega\cdot\text{cm}$, corresponding to non-intentionally doped (NID) and the highly doped samples, respectively (Figure 1(e)). Resistivity temperature dependence measurements down to 5K reveal a semiconducting behavior for the NID and lowly doped GaN NWs, a metallic behavior for more doped NWs. This implies a carrier concentration from 10^{17} to 10^{20} cm^{-3} , which is consistent with the high doping level previously achieved on microwires⁵.

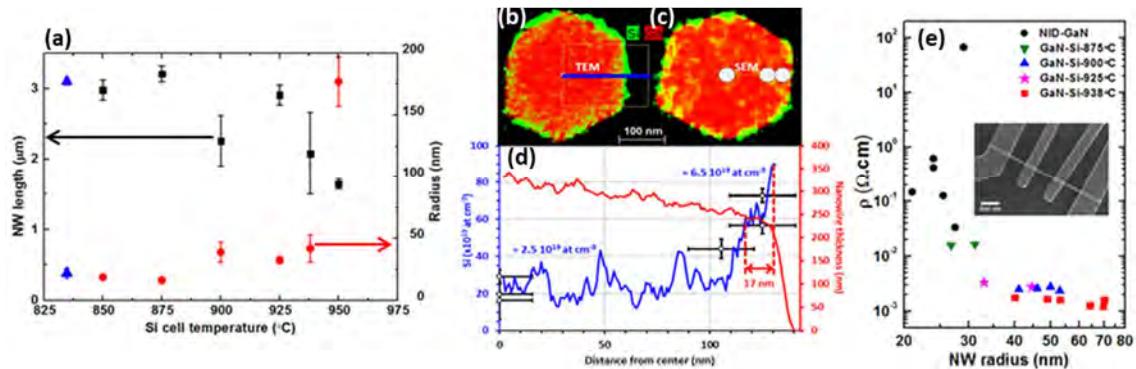


Figure 1: (a) NW length (left axis) and NW radius (right axis) of samples grown upon different Si cell temperatures, the blue data points correspond to the length and radius of the NID NWs. EDX maps of two NWs grown with highest Si cell temperature obtained: (b) at 200 kV using a FEI Osiris TEM and (c) at 4 kV using a ZEISS Ultra 55 SEM. Green and red colors correspond to Si and Ga, respectively. Si concentrations were computed for STEM EDX data (blue line profile in (d)) and for the SEM EDX data (white circles in (d)). The NW thickness of the STEM observation is shown on the red curve in (d). (e) Room temperature four-probe resistivity versus NW radius of samples ranging from NID to the highly doped ones, and a SEM image of one contacted NW is included in the inset.

References

- ¹P. Tchoulfian *et al.* *Appl. Phys. Lett.* 102, 122116 (2013); *Appl. Phys. Lett.* 103, 202101 (2013)

SELECTIVE AREA GROWTH AND SURFACE RECOMBINATION VELOCITY MEASUREMENTS IN N-POLAR GALLIUM NITRIDE NANOWIRE ARRAYS

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Ordered arrays of gallium nitride nanowires (GaN NWs) are a convenient platform for measurement of the surface recombination velocity (SRV), an important metric in high surface-to-volume nanostructures. NW arrays with controlled diameters and spacing are obtained by use of selective-area growth techniques and the SRV is extracted via diameter-dependent, time-resolved photoluminescence (TRPL) measurements. We demonstrate that long-range selectivity is realized for N-polar NWs, enabling arrays where the NW spacing far exceeds the Ga diffusion length, and permits characterization of single or ensembles of NWs in the same growth sample. Further, flux-shadowing effects are eliminated in widely spaced NW arrays, allowing synthesis and evaluation of core-sleeve passivation schemes.

N-polar NW arrays were grown by molecular beam epitaxy (MBE) on Si (111) substrates. By growing an initial AlN layer under Al-rich growth conditions, N-polarity was induced into subsequent nucleation layers and verified by polarity-dependent surface reconstructions observed in the Reflection High Energy Electron Diffraction (RHEED) patterns. NW arrays were then grown at a substrate temperature of ~ 850 °C, using a silicon nitride growth mask with hexagonal hole arrays.

The resulting arrays comprised epitaxially oriented NWs with c-plane tips and m-plane sidewalls (Fig 1a). The PL lifetime exhibited the expected linear relation to NW diameter (Fig 1b), from which the SRV was calculated as $SRV = 1/(4 \cdot \text{slope})$ [1]. Interestingly, the PL lifetime was found to increase for closely spaced NWs and is possibly related to photon-recycling effects [2]. In some samples, an AlGaN surface passivation layer was grown and found to produce a lower SRV than samples with no AlGaN layer (Fig 1c).

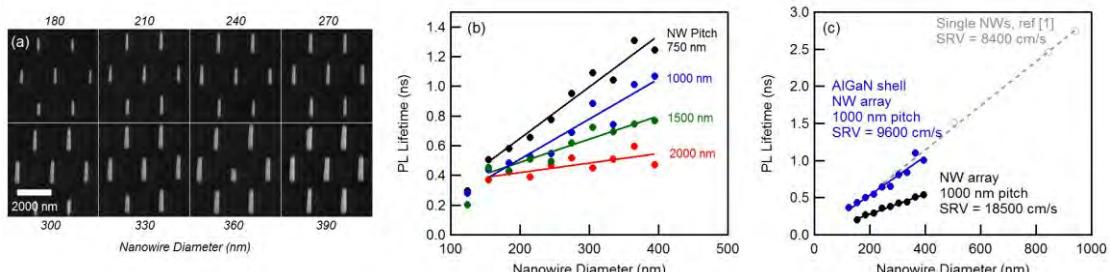


Figure 1: Selective-area, N-polar GaN nanowire arrays (a) imaged by scanning electron microscopy and (b,c) characterized by time-resolved photoluminescence (TRPL) measurements. The PL lifetime is plotted as a function of geometrical array parameters in (b) and sample structure types in (c).

References

- ¹ J. Schlager, *et al.*, *J. Appl. Phys.* **103**, 124309 (2008).
² R. K. Ahrenkiel, in *Minority Carriers in III-V Semiconductors: Physics and Applications* **39**, 39–150 (1993).

Growth and electrical transport properties of GaN nanowire/diamond heterojunctions

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$\text{Al}_x\text{Ga}_{1-x}\text{N}$ nanowire/diamond heterojunctions are promising candidates for optoelectronics since they could close the gap of available LEDs emitting in the deep UV spectral range. A major benefit of heteroepitaxial diodes compared to purely AlGaN-based devices is that material-specific drawbacks, e.g., p-type doping of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ and n-type doping of diamond can be avoided. Another envisaged application of our work is quantum information processing, where AlGaN nanowires (NWs) could be utilized as nano contacts to manipulate the charge state of individual qubits, e.g., NV centers in the vicinity of the diamond surface. In addition, the high refractive index of GaN and the waveguide geometry of NWs can serve as a nano antenna for efficient optical read-out of the NV quantum state.

Recently, we have developed the growth of doped GaN NWs on diamond with a high crystalline quality at the heterointerface. [1, 2] To verify the potential for applications of these heterostructures, the electrical transport properties of GaN NWs on p-type doped single crystalline diamonds have been investigated in a systematic way. Self-assembled GaN NWs with different doping profiles have been grown on boron-doped diamond (111) substrates by plasma-assisted molecular beam epitaxy. I-V measurements on single NWs have been performed by conductive atomic force microscopy and show a clear diode behavior of the heterojunctions. In addition, the electronic band structure alignment of the GaN NW/diamond interface has been investigated by 1D and 2D numerical simulations. We find that the effective interface dipole determined by the GaN crystal polarity plays a key role for the resulting band offsets. As a possible application, a prototype GaN NW/diamond LED has been fabricated and the electroluminescence properties of these devices will be presented. Finally, the heteroepitaxial growth of position-controlled GaN NW arrays with adjustable diameter will be demonstrated on diamond and other substrates by the use of a nano-patterned TiN mask. [3] Due to the higher uniformity in height, periodicity and diameter compared to self-assembled growth, it is expected that we will be able to improve both, the performance and reproducibility of future devices.

References:

- [1] F. Schuster, et al., Nano Lett. **12**, 2199 (2012)
- [2] F. Schuster, et al., J. Appl. Phys. **117**, 044307 (2015)
- [3] F. Schuster, et al., Nano Lett. **15**, 1773 (2015)

Growth, structural and optical characterizations of AlGaN/GaN nanowire heterostructures

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This abstract reports our recent work on AlGaN sections grown on top of GaN nanowires (NW) on Si (111) substrate by molecular beam epitaxy. Our team previously demonstrated that structural and optical properties of such sections are governed by the presence of compositional fluctuations associated with strongly localized electronic states [1,2]. We have then investigated more in detail the dependence of these properties on kinetic parameters such as AlGaN growth temperature and notably shown that fluctuations optically behave as quantum dots.

For our experiments, several series of AlGaN/GaN NW samples have been grown in slightly N-rich conditions, at different average compositions verified by XRD. For each series, the GaN base was grown in the same conditions and the metallic fluxes were fixed to the same values, whereas the AlGaN growth temperature has been varied over a much wider range than investigated in [1,2]. SEM/STEM has been performed on these series, revealing firstly that AlGaN NW population partly exhibit an irregular shape when grown at low temperatures (Fig. 1 a). Secondly, for NWs with regular shape (Fig. 1 b), the thickness of pure AlN sections, which preferentially nucleate on top of GaN stems despite unfavourable GaN/AlN lattice mismatch, drops when decreasing AlGaN growth temperature. It turns out that the AlN section features do not only depend on kinetics: for AlGaN grown on wider GaN stems, Ga incorporation is easier. However, controlling the GaN base diameter is rather tricky. In view of making lightning devices based on AlGaN/GaN NWs, this unwanted AlN section, acting as a carrier blocking layer, must be suppressed. Macro(M)- and micro(μ)- photoluminescence(PL) have been respectively carried out on as-grown samples and mechanically-dispersed wires. On M-PL spectra, luminescence intensity drops for samples exhibiting AlGaN NWs with irregular shape. As to μ -PL spectra, sharp lines linked to compositional fluctuations (Fig. 1 c) are observed and reveal similar behaviour for wide temperature range PL, whatever AlGaN sample growth temperature. These carrier localization signs are present at very small scale, as they are also observed for AlGaN NW insertions in AlN, less than 2-3nm thick. Moreover, related μ - time-resolved PL data do not show any dependence of decay times with growth temperature. Photon correlation experiments have been accomplished as well on these μ -PL sharp lines, for several samples. Antibunching has been observed (Fig. 1 d), typical of a quantum dot-like behaviour.

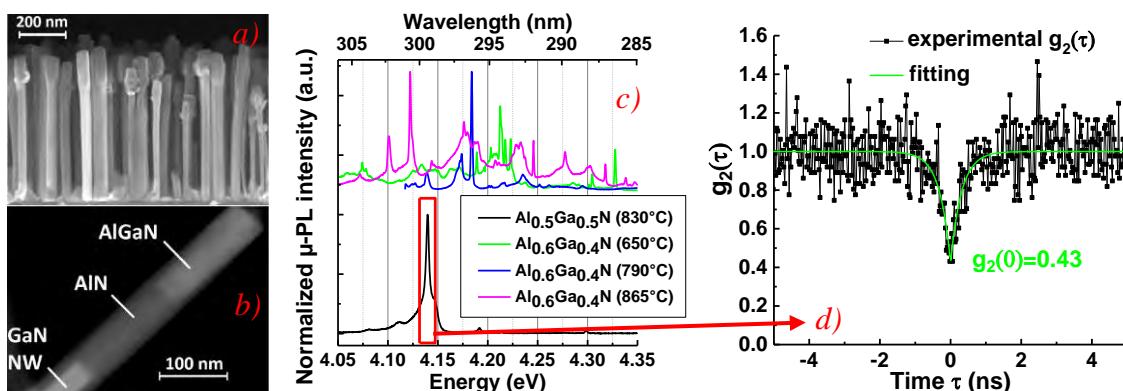


Figure 1: a) SEM image of $Al_{0.6}Ga_{0.4}N$ sections grown on top of GaN NW at low temp. (650°C), taken at wafer center, b) STEM-HAADF image of a regular $Al_{0.6}Ga_{0.4}N$ section grown at high temp. (860°C), c) μ -PL sharp lines associated with compositional fluctuations in AlGaN NWs grown at different temps, d) Experimental second-order intensity correlation related to the line framed in red, antibunching observed.

References

- [1] A.Pierret, *et al.*, *Nanotechnology* 24 115704 (2013).
- [2] A.Pierret, *et al.*, *Nanotechnology* 24 24 305703 (2013).

UV photodetector based on single GaN/AlN nanowire heterostructures

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Semiconductor nanowires (NWs) are investigated as building blocks of integrated photonic circuits. In particular, the photodetector capabilities of single NWs and NW arrays are studied for a variety of materials, and GaN is a promising choice to cover the ultraviolet (UV) range. In comparison with planar devices, almost defect-free GaN NWs grown by molecular beam epitaxy open the possibility of exploiting photoconductive gain while avoiding the deleterious effects of grain boundaries on the spectral response. The incorporation of heterostructures in the NWs might potentially increase the accessible wavelength range and improve the response at low bias as a result of the polarization-induced internal electric field.

In this work, we report the correlated investigation of the photocurrent performance and photoluminescence (PL) characteristics of a single GaN NW incorporating 20 periods of Ge-doped GaN/AlN nanodisks. The as-grown NWs are dispersed on Si substrates capped with SiN_x and single NWs are electrically contacted using electron beam lithography [inset in Fig. 1(a)]. At low-temperature (5 K), the micro-PL of the nanodisks shows a peak around 345–350 nm [lower inset in Fig. 1(a)]. At reduced excitation density, the PL peak decomposes into an ensemble of lines related to localization at monolayer thickness fluctuations of individual nanodisks. The NWs display an asymmetric current-voltage characteristic, both in the dark and under illumination [Fig. 1(b)], which is indicative of the polarization fields present in the active region of a heterostructure grown in the polar *c*-direction. With increasing UV laser (325 nm) illumination, the asymmetry is slightly reduced, as expected from the screening of the electric field. The spectral response [Fig. 1(a)] of the photocurrent presents a sharp cutoff with on/off contrast larger than three orders of magnitude, independent of the modulation frequency of the impinging optical signal. When switching off the illumination, the photocurrent decay [inset in Fig. 1(b)] consists of a fast component with the lifetime slowing down from 2 to 4 ms for decreasing excitation density, and a slow component with a lifetime of 50 ms, which is independent of the excitation conditions. Therefore, the NW does not show a significant persistence of the photocurrent, which makes these structures promising for nanoscale photodetector applications.

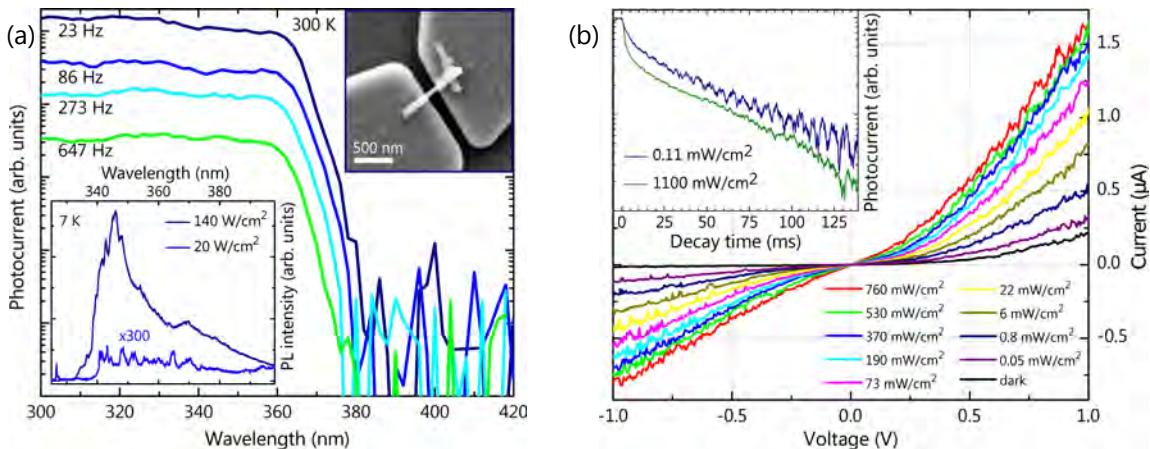


Figure 1: (a) Room-temperature spectral photocurrent response of single AlN/GaN NW heterostructure measured at different chopping frequencies. Top inset: Scanning electron micrograph of contacted NW. Bottom inset: Low-temperature micro-PL spectra of the investigated NW at two different excitation densities. (b) Current voltage characteristics of the NW in dark (black) and under increasing UV laser excitation. Inset: Photocurrent decay at two different excitation densities.

Bottom inset: Photocurrent decay at two different excitation densities.

InGaN/GaN p-i-n nanocolumns grown on SiO₂/Si (100) substrates employing AlN/graphene

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High-density, vertically aligned GaN nanocolumns were successfully grown on an amorphous SiO₂ employing AlN buffer layer and multilayer graphene (MLG). An InGaN/GaN multiple quantum well (MQW) and Mg-doped p-type GaN were grown on the top of the GaN nanocolumn to produce InGaN/GaN p-i-n nanocolumns. InGaN/GaN MQWs prepared on GaN nanocolumns emitted a single-peak photoluminescence spectrum with the peak wavelength of 535 nm, evincing the highly crystalline quality of grown InGaN/GaN nanocolumns.

Graphene is applicable to an electrode of flexible optical devices owing to preferable features (e.g., high transmittance, high conductivity, and brief transfer)¹, as well as to a nucleation layer of crystal growth². Graphene is expected to block an epitaxial relationship with underlying layers, resulting in a relaxed lattice mismatch with those. These features of graphene enable a fabrication of high-efficient device structures on a high-reflection dielectric mirror by inserting the low-resistance high-transparency graphene film between them.

In this study, we grew self-organized nanocolumns on MLG/SiO₂ by RF-plasma assisted molecular beam epitaxy (RF-MBE). Prior to the growth, a chemical vapour deposition (CVD)-grown graphene was transferred on the surface of a thermal oxidized SiO₂/Si (100) substrate. In the growth of GaN nanocolumns, firstly the migration enhanced epitaxy (MEE) of AlN buffer layer was performed to cover the MLG to prevent that reacting with the supplied excited N*. The MEE time sequence of Al/φ/N* (φ: duration of no atomic irradiation) was 4 s, 5 s, and 3 s, respectively. On the MLG covered by AlN, Si-doped n-type GaN nanocolumns were grown; the employment of a 160-periods MEE-grown AlN resulted in high-density and vertically aligned nanocolumns, as shown in Fig. 1(a); here, on the top of the GaN nanocolumn, 3 periods of InGaN/GaN QWs and a Mg-doped p-type GaN were grown. A TEM image of the top of the grown nanocolumns is shown in Fig. 1 (b), which evinced that dislocation-free InGaN/GaN p-i-n nanocolumns were prepared. A single peak PL spectrum with the peak wavelength of 535 nm was observed from InGaN/GaN MQWs on the tops of nanocolumns, as shown in Fig. 1(c).

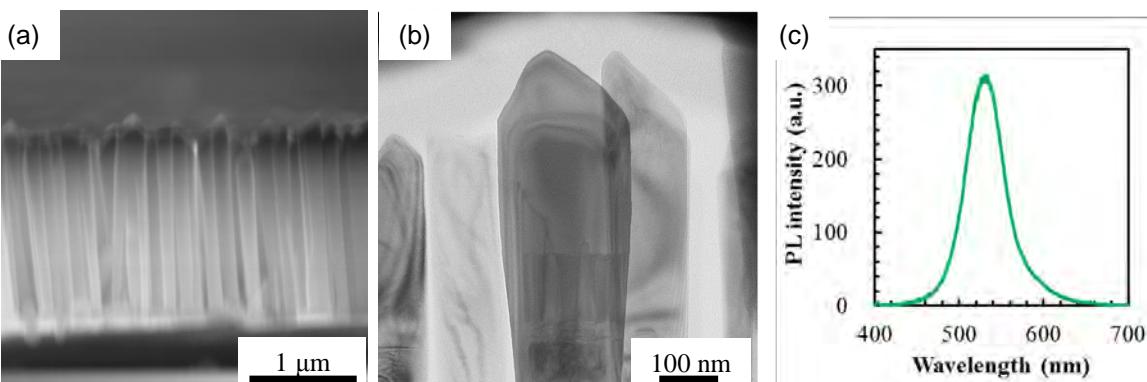


Figure 1: (a) Cross-sectional SEM image and (b) HR-TEM image of the top of InGaN/GaN p-i-n nanocolumn. (c) PL spectrum of InGaN/GaN nanocolumns on MLG.

Acknowledgements

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References

- ¹ J. M. Lee, *et al*, *Appl. Phys. Lett.* **99**, 041115 (2011).
- ² Y. J. Hong, *et al*, *Nanolett.* **12**, 1431 (2012).
- ³ A. M. Munshi, *et al*, *Nanolett.* **12**, 4570 (2012).

MOVPE grown axial n-GaN/p-GaAs nanowires

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GaN pn junctions suffer from limited conductivity of the p-layer due to the low activation of deep acceptors [1]. In this work we propose to replace the GaN hole injector by p-type GaAs. This approach shall provide a higher conductivity along with a huge valence band discontinuity. The latter effect results into a repelling of holes towards the n-GaN and significantly improves the pn-junction I-V characteristics. This concept has been previously realized by wafer fusion of epitaxial layers [2] with limited performance [3]. Using nanowires, the growth of highly mismatched and low-defect density n-GaN/p-GaAs heterojunctions may become possible paving the way towards high performance devices.

We report the MOVPE growth, the energy dispersive X-ray spectroscopy (EDS) analysis, and the I-V characteristics of axial GaN/GaAs heterojunction nanowires. N-GaN nanowires were grown by a self-assembled and catalyst-free process in an Aixtron shower head reactor using Trimethylgallium (TMGa), ammonia, and silane diluted in H₂ at 1030 °C. This process [4] was transferred to n-type doped (111)Si substrates via in-situ hydrogen bake-out for native oxide removal and a deposition of an AlN layer avoiding the Ga melt-back. On the n-type GaN nanowires templates, p-type doped GaAs:C was grown for 1 h at 650 °C in a low-pressure AIX200 RF MOVPE (Fig. 1a). TMGa, Tertiarybutylarsine and CBr₄ were used as group-III and group-V precursors [5]. On top of the GaN nanowire p-doped GaAs spheres of 2 μm diameter were grown with abrupt interface (Fig. 1b). The pn-junction nanowires were deposited on an isolating host substrate for I-V characterisation. To achieve ohmic contacts behaviour on both sides, Ti/Au metal system was used (Fig. 1c). A voltage of -1V – 10V was applied for the I-V characterisation. The DC-measurement of the axial pn-Junction shows diode behaviour (Fig. 1d).

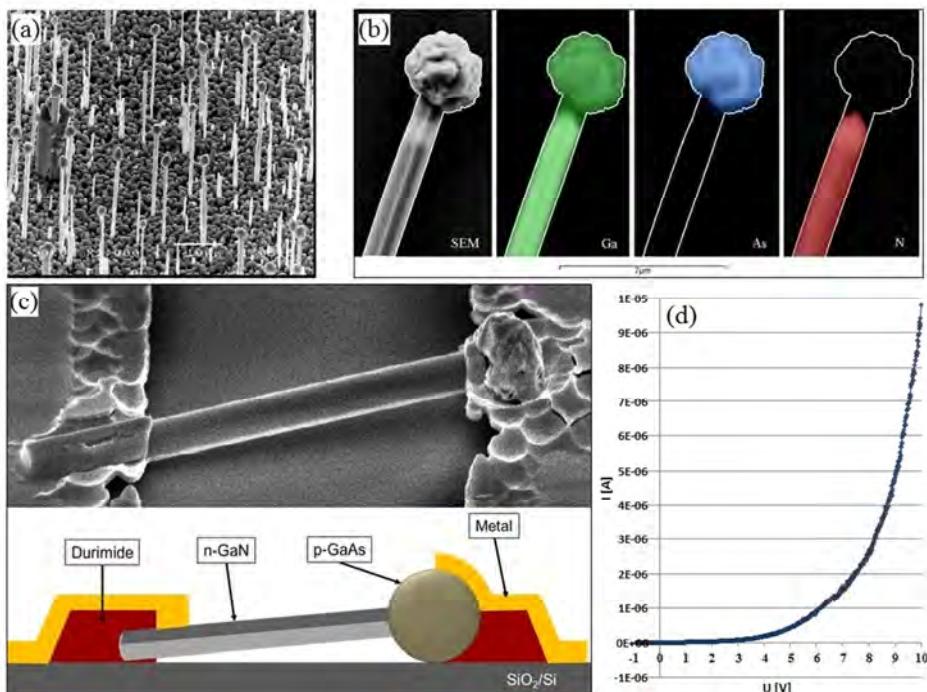


Figure 1: (a) MOVPE grown n-GaN/p-GaAs nanowires with axial pn-junction on (111) silicon substrate, (b) EDX of NW shows Ga (green), As (blue) and N (red), (c) schematically and SEM images of contacting NW, (d) Current-Voltage measurement of axial p-GaAs/n-GaN heterojunction nanowires at room temperature.

References

- ¹ H. Xing et al., *J. Appl. Phys.*, **97**, 113703 (2005). ² S. Estrada, et al., *Applied Physics Letters*, **83**, p. 560-562 (2003).
- ³ C. Lian, et al., *Applied Physics Letters*, **93**, p. 112103 (2008). ⁴ R. Koester, et al., *Nanotechnology*, **21**, p. 015602 (2010).
- ⁵ P. Velling, et al., *Progress in Crystal Growth and Characterization of Materials*, **41**, p. 85-131 (2000).

Towards axial Si/GaAs nanowire heterostructures

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III-V/Si semiconductor heterostructure nanowires are a promising strategy to integrate light emitters on Si. Indeed, the small nanowire cross-section allows to elastically release strain on the lateral walls of the nanowires, preventing the formation of misfit dislocations. For example, GaAs/Si has a lattice mismatch of 4%. Such structures can be created in axial heterostructure nanowires with diameters up to 80 nm [1], whereas such high lattice mismatch is detrimental in two dimensional GaAs epitaxy on Si [2,3]. Based on these theoretical assumptions, we fabricated GaAs/Si axial heterostructure nanowires and studied their structural properties using transmission electron microscopy.

The Si nanowires were grown on Si (111) substrates by the vapor-liquid-solid mechanism using Au colloids in a chemical vapor deposition reactor. Then, we transferred the Si nanowire samples to the molecular beam epitaxy (MBE) reactor to grow the GaAs segment. As the samples were exposed to air between the growth sequences, we treated the Si nanowires to remove the native SiO_2 just before the introduction to the MBE chamber. Different chemical solutions were tested to remove the native oxide including hydrofluoric acid and buffered oxide etch. The GaAs segment was successfully grown from the Au catalyst sitting on top of each Si nanowire. We observed that, during the temperature rise up to the GaAs growth temperature, Au diffuses on the side walls of the Si nanowires and induces the growth of lateral GaAs needles. Additional defects were observed such as GaAs shells and segment kink at the GaAs/Si interface (see Fig. 1). Surface treatments and growth parameters will be discussed.

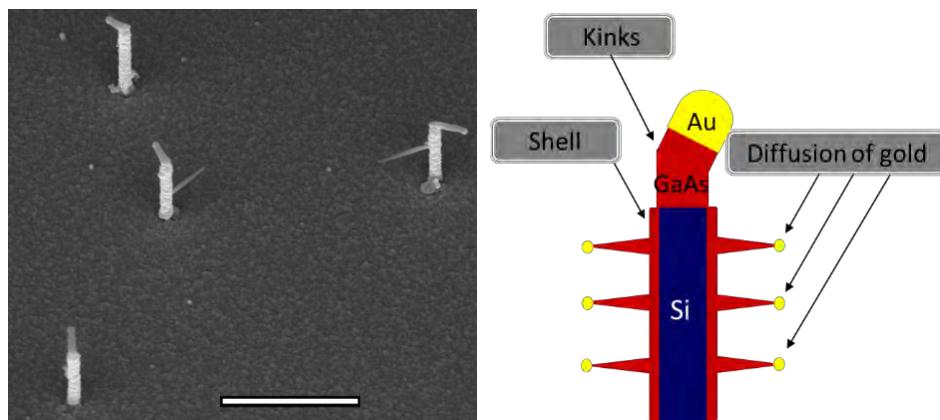


Figure 1. SEM image of GaAs/Si nanowires (scale bar 1 μm) and schematic representation of the main challenges related to GaAs/Si nanowire growth.

References:

- ¹ F. Glas, *et. al.*, *Physical Review B* **12**1302(R), (2006)
- ² H. Kroemer, *et. al.*, *Journal of Crystal Growth*, **81**, 193–204 (1987);
- ³ I. J. Luxmoore, *et al.*, *Scientific reports* **3** (2013);

ZN DOPANT INCORPORATION VIA CONTACT ANNEALING OF GAAS NANOWIRES

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Electrical conductivity in III-V nanowires (NWs) is currently under extensive research, as they show great promise for use in future optoelectronic devices¹. Due to the small dimensions of NWs and necessarily small contact surface area, the contacts themselves have a large influence on the measured electrical properties². It is therefore important to optimise the process of contacting NWs and understand how the contact metals interact with the wires.

In this study, Si-doped GaAs NWs were contacted with Au/Zn/Au (5nm/10nm/100nm) and annealed at increasing temperatures. 2- and 4-point IV measurements were taken after each annealing step. It was found that wire resistance begins to increase significantly above 360°C, as previously demonstrated for AlGaAs/GaAs radial heterostructures², yet decreases again above 450°C, as shown in Figure 1. At 510°C the wires were seen to conduct metallically, however, this led to the complete destruction of the wires during measurement.

We hypothesize that above 450°C Zn doping occurs in the wires; above 510°C, metallic conducting channels are formed, leading to current densities too high for the 60nm diameter wires to sustain. This was further investigated through the formation via contact doping of p-n junctions in undoped GaAs wires.

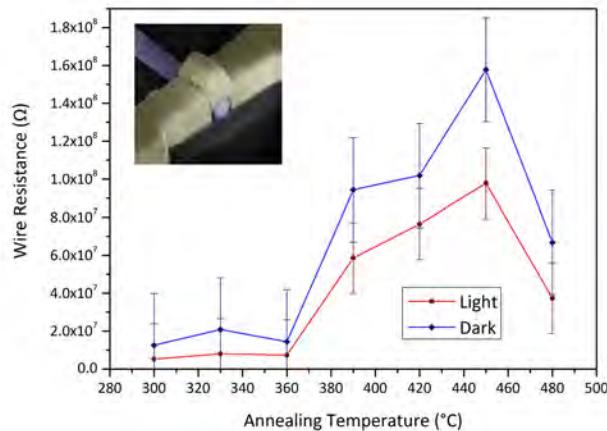


Figure 1: Average 4-point resistance of several wires as a function of annealing temperature.

Inset: FIB-milled cross-section of contact to wire.

References

- ¹ Yan, Ruoxue, Daniel Gargas, and Peidong Yang. "Nanowire photonics." *Nature Photonics* 3.10 (2009): 569-576.
- ² Lin, Yen-Fu, and Wen-Bin Jian. "The impact of nanocontact on nanowire based nanoelectronics." *Nano letters* 8.10 (2008): 3146-3150
- ² Wirths, S., et al. "Preparation of Ohmic contacts to GaAs/AlGaAs-core/shell-nanowires." *Applied physics letters* 100.4 (2012): 042103.

Quantum confinement effect in InAs/InP quantum dot nanowires (QD-NWs) grown on silicon

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We study the optical properties of InAs/InP QD-NWs grown on silicon by solid source Molecular Beam Epitaxy (ssMBE) using the Vapor-Liquid-Solid (VLS) method [1,2]. The investigation of this material system enables us to tune the emission wavelength of the NWs into the telecommunication bands. We aim at VLS growth of vertically standing wurtzite InP NWs on Si(111) for a good control of the insertion of InAs QDs and the NW shape.

We show that an *in-situ* deposition at 500°C of a gold-indium (Au-In) alloy as catalyst leads to droplets which do not react with the Si substrate and to vertical NWs, whereas an alloy is formed with the Si substrate at higher temperature leading to inclined NWs. The first minute of the NW growth is then investigated step by step by TEM measurements to follow the formation of the pyramid-shaped pedestal which was evidenced prior to the NW growth. A high degree of verticality was thus obtained ensuring a cylindrical symmetry for the QD-NWs during axial or radial growth which is necessary to reach a good waveguide behavior.

Growth conditions were then optimized to control the structural quality and shape of InAs QDs inserted into the InP NWs. The purity of the wurtzite structure for the QD-NWs was confirmed by TEM and PL measurements. Then, the VLS growth method allows us to control the InAs QD height to diameter ratio H/D with sharp interfaces as also revealed by TEM measurements (Fig.1). When the ratio is in the order of 1 with height and diameter typically in the 10-14 nm range, low temperature PL measurements performed on QD-NW populations revealed a single peak at 0.84 eV. For smaller ratios, the carriers are mainly confined by the QD height, and the PL spectra presented multiple peaks which are attributed to monolayer fluctuation in the InAs QD height (Fig.2).

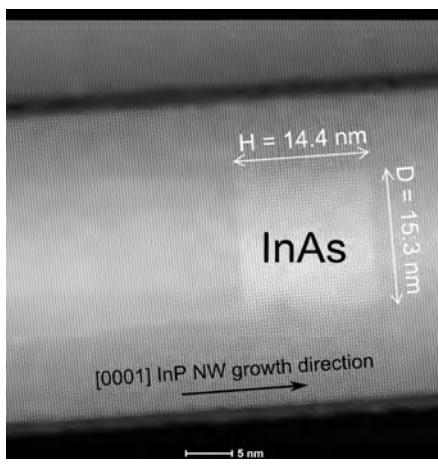


Fig. 1: Atomic resolution STEM-HAADF image of an InAs/InP QD-NW.

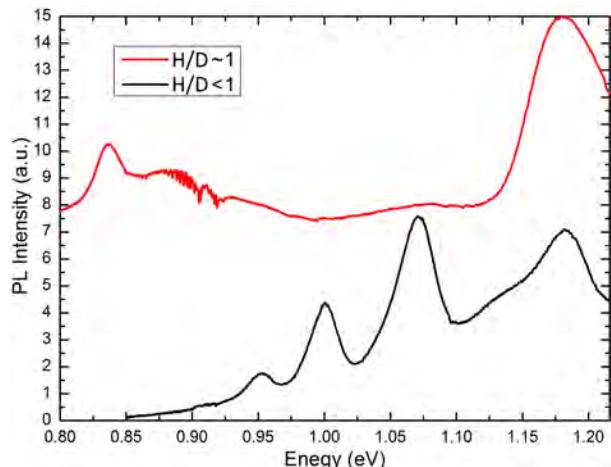


Fig. 2: PL spectrum at 14 K of two InAs/InP QD-NWs with a different H/D ratio.

References

- [1] H. Khmissi, K. Naji, M. H. Hadj Alouane, N. Chauvin, C. Bru-Chevallier, B. Ilahi, G. Patriarche, and M. Gendry, Journal of Crystal Growth 344, (2012) 45-50.
- [2] R. Anufriev, N. Chauvin, H. Khmissi, K. Naji, J. Barakat, J. Penuelas, G. Patriarche, M. Gendry, C. Bru-Chevallier, Journal of Applied Physics 113, (2013) 193101.

Correlation of microstructure and electrical transport characteristics in InAs Nanowires

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Semiconductor nanowires have gained increased attention in recent years due to their promising applications in integrated circuits and fundamental research in low dimensional systems. The superior electronic characteristics, such as the large electron mobility and small electron mass, make the integration of InAs NW devices onto silicon highly desirable. For this it is essential to know the influence of growth parameters, microstructure, aspect ratio and contact metal on the electrical properties of the NWs.

In this work we present recent results on the electrical transport of nominally undoped and Si-doped MBE grown InAs nanowires (NWs). In particular, we explore the influence of growth parameters, microstructure, aspect ratio and contact metal on the electrical properties of the NWs. Four-terminal measurements on planar, back-gated NW field effect transistor (NWFET) devices revealed room-temperature mobilities ranging from 500 to 2000 cm²/Vs and on-off ratios of $>10^3$ at 4.2K. The typical electron densities obtained are of the order of 10^{17} cm⁻³ for undoped NWs, while accordingly higher densities are realized for Si-doped NWs. Determination of these transport parameters is based on a unique measurement route that allows for hysteresis-free transconductance even at room-temperature. Furthermore, a strong effect of the diameter and the microstructure on the mobility was observed, controllable by adjusting growth parameters. The latter was correlated with HRTEM investigations, simulations and temperature-dependent measurements of carrier density and mobility in detail. Here, the impact of scattering and band discontinuities induced by stacking faults, WZ/ZB crystal phase boundaries and polarization sheet charges is evaluated.

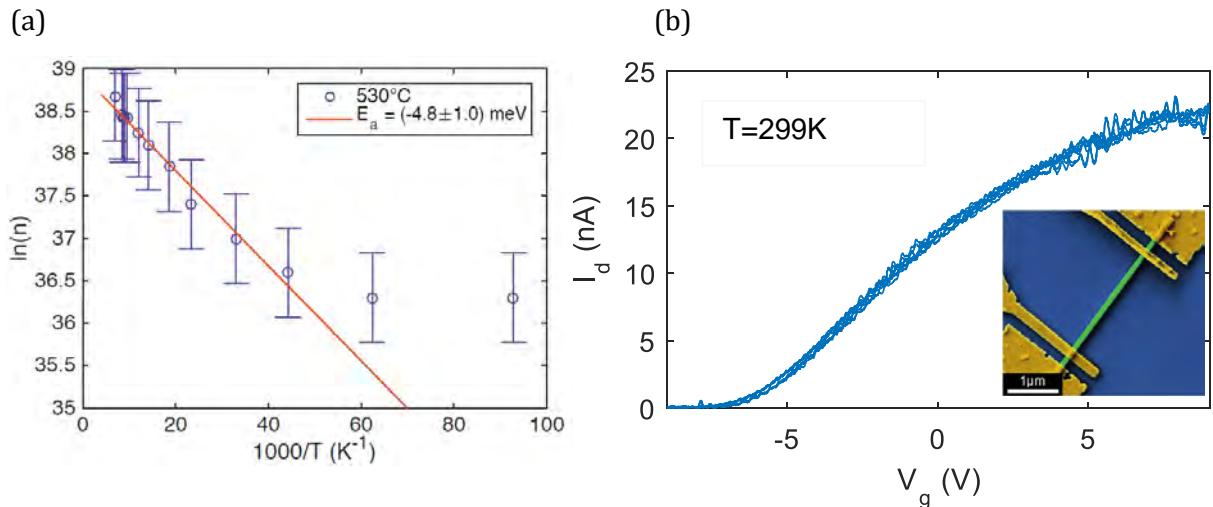


Figure 1: (a) Temperature dependent measurement of charge carrier density for an undoped InAs NW, based on (b) a hysteresis-free transfer curve of planar back-gated InAs NW-FET at room temperature. Inset: false-colour SEM micrograph of typical 4-terminal InAs NWFET device structure.

References

- ¹ S. Hertenberger et al., App. Phys. Lett. 98, 123114 (2011).
² J. Becker et. al. in preparation (2015)

Growth of Selective-Area MOVPE In(Ga)P Nanowires

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InP nanowires (NW) grown by selective-area metal-organic vapor phase epitaxy (SA-MOVPE) show enormous potential for optoelectronic applications¹. In particular, they exhibit exceptional optical quality, such as long lifetime and optically-pumped lasing at room temperature². As InP nanowire-based solar cells are currently limited by material quality, SA-MOVPE NW are expected to represent a significant step forward, towards next-generation solar cell devices. Also, a critical step en route to photovoltaic applications is the development of 2- and multi-junction solar cells. InGaP NW would be an invaluable building block for 2-junction solar cells based on InAsP-InGaP nanowires, which can theoretically reach 47% efficiency.

We fabricated solar cells based on InP NW grown via SA-MOVPE. Growth is carried out without catalyst at high temperature ($>700^{\circ}\text{C}$), resulting in exceptional material quality. Selective area InP NW exhibit pure wurtzite crystalline structure with very low density of stacking faults ($<<1 \text{ SF}/\mu\text{m}$). Solar cells and LEDs based on a p/i/n/n⁺⁺ doping profile have been devised. The first device has shown an efficiency of 4.7% with a V_{oc} of 0.7V, showing great potential for improvement. At the same time, we developed In_{1-x}Ga_xP nanowires, grown with the same technique, with a Ga fraction (x) between 0 and 24%. We show for the first time tunability of the bandgap for InGaP ternary alloy, maintaining growth uniformity and homogeneity, while showing outstanding optical properties. InGaP NW pave the way towards high-efficiency 2-junctions solar cells.

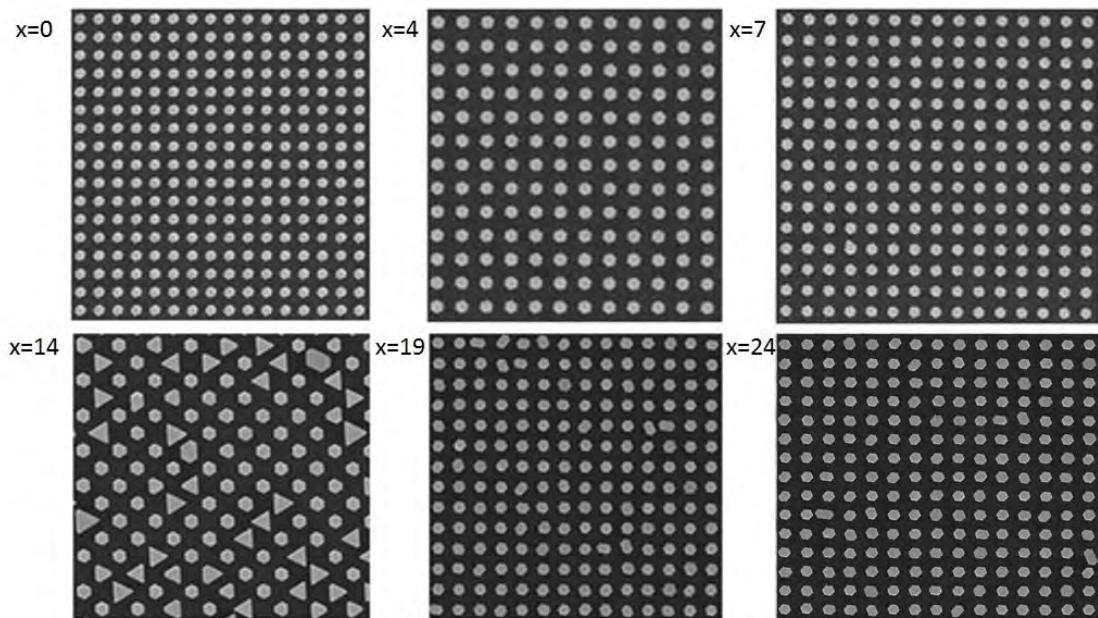


Figure 1: Top-view SEM images of In_{1-x}Ga_xP NW with 0 < x < 24%

References

¹ Mohan, *et al.*, *Nanotechnology* **16** 2903–2907 (2005)

² Gao, *et al.*, *Nano Lett.* **14**, 5206–5211 (2014)

Dead-space effect in InGaAs nanopillar avalanche photodetectors

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Avalanche photodetectors (APDs) are essential components in quantum key distribution systems and active imaging systems requiring both ultra-fast response time to measure photon time-of-flight and high gain to detect low photon flux. The internal gain of an APD can improve system signal-to-noise ratio (SNR) without increasing detector area if the excess noise is kept sufficiently low¹. Excess noise is typically kept low through the selection of material with intrinsically low excess noise for the multiplication region², using separate-absorption-multiplication (SAM) heterostructure³, or taking advantage of the dead-space effect using thin multiplication regions⁴. The dead-space effect has been observed in GaAs, AlGaAs, and InP APDs, but no report exists for InGaAs due to prohibitively high tunneling currents. In this work we demonstrate reduced excess noise in InGaAs nanopillar avalanche photodetectors with 200 nm multiplication regions with electric fields approaching 10^6 V/cm. The reduction in junction area by over two orders of magnitude results in a corresponding reduction in tunneling current, allowing the observation of the dead-space effect in InGaAs for the first time. Arrays of p-doped InGaAs nanopillars were grown on n-doped GaAs (111)B substrate by catalyst-free, selective-area epitaxy using metal-organic chemical vapor deposition (MOCVD). Figure 1a shows a scanning electron micrograph (SEM) of the fabricated device, and the inset shows the result of tilted metal deposition: a self-aligned nanohole array which functions as a 3-dimensional plasmonic grating in addition to the electrical contact to the nanopillars. The room-temperature dark current, photocurrent, and the extracted gain, M , as a function of bias measured from a typical device is shown in Figure 1b. The initiation of gain at such low bias voltage suggests a very large electric field exists at the junction. The excess noise was measured by illuminating the APD with a 1064nm laser with shot noise limited RIN and measuring the noise power spectral density with a network signal analyzer. DC bias was applied through a bias tee using a low noise power supply. The amplifier noise was measured and subtracted from the APD noise. Figure 1c shows the measured excess noise. The best fit to McIntyre's model occurs for $k = 0.14$ which significantly smaller than bulk InGaAs, for which $k = 0.2 - 0.5$ ⁵. We find good agreement with the predicted gain and excess noise using 3-dimensional dead-space multiplication theory.

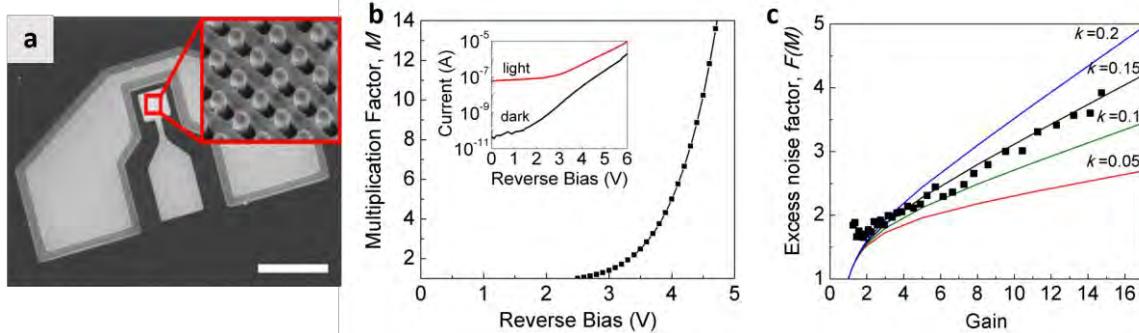


Figure 1. a) SEM of fabricated InGaAs nanopillar APD (scale bar 80 μ m). b) Gain as a function of reverse bias. Inset: IV characteristics under dark and illuminated conditions. c) Excess noise measurement (symbols) and McIntyre's model for $k = 0.05$ through 0.2.

References

- [1] Campbell, JC. "Recent advances in telecommunications avalanche photodiodes," *J Lightwave Technol* 2007, **25**(1): 109-121.
- [2] Stillman GE, Robbins VM, Tabatabaie N. "III-V compound semiconductor device - optical detectors," *IEEE Trans Electron Devices* 1984, **31**(11): 1643-1655.
- [3] Susa N, Nakagome H, Mikami O, Ando H, Kanbe H. "New InGaAs-InP avalanche photodiode structure for the 1-1.6 micron wavelength region," *IEEE J Quantum Electron* 1980, **16**(8): 864-870.
- [4] Campbell JC, Chandrasekhar S, Tsang WT, Qua GJ, Johnson BC. "Multiplication noise of wide-bandwidth InP/InGaAsP/InGaAs avalanche photodiodes," *J Lightwave Technol* 1989, **7**(3): 473-478.
- [5] Goh, YL, Ng, JS, Tan, CH, Ng, WK, and David, JPR, "Excess noise measurements in In0.53Ga0.47As", *IEEE Photon. Tech. Lett.*, , 2005, **17** (11), 2412-2414.

Improved selective-area epitaxy using flexible UV-imprint lithography

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Many nanowire (NW)-based device applications require very strict control over position, density, uniformity and scalability of the NW structure, as in e.g. NW solar cells, detectors, vertical transistors, and nano-laser device structures. In addition, monolithic integration on Si platform is of further enormous relevance, demanding growth processing schemes that are compatible with standard CMOS-technology. Nano-imprint lithography (NIL) is coined a core technology in the future Roadmap of Semiconductors¹, as it holds the potential to pre-patterning Si substrate wafers in a cost-effective manner, i.e., both at large scale and with minimum fabrication time.

Here we show that by developing a state-of-the-art UV-imprint process we can significantly enhance the flexibility of NIL using a novel home-designed table top device. By producing NIL stamps with various patterns – easily available using standard electron beam lithography and reactive ion etching – full control over the inter-NW spacing can be achieved, while maintaining the great benefit of significantly faster substrate preparation. Being able to adjust the pitch of large scale NW arrays is a crucial prerequisite to further increase the efficiency of NW-based solar cells fabricated from InGaAs-InAlAs NW heterostructures², since the pitch strongly affects the absorption characteristics. Using optimized prepatterned SiO₂/Si(111) substrates, NW growth is performed in a completely catalyst-free growth regime via molecular beam epitaxy (MBE), allowing detailed insight into morphology and luminescence/absorption properties for different interwire-spacings. Adapting both the parameter for imprint procedure and growth conditions we can tune the pitch over two orders of magnitude (from 250nm to 10μm) while maintaining a high yield despite the significant change in filling factor and growth kinetics (i.e. from material to diffusion limited regime). This allows choosing the optimum geometry for the respective application like single NW spectroscopy or vertically integrated NW channels for transport measurements.

These findings will help to increase efficiency and scalability of novel NW-based opto-electronic applications especially in the field of photovoltaics and detectors.

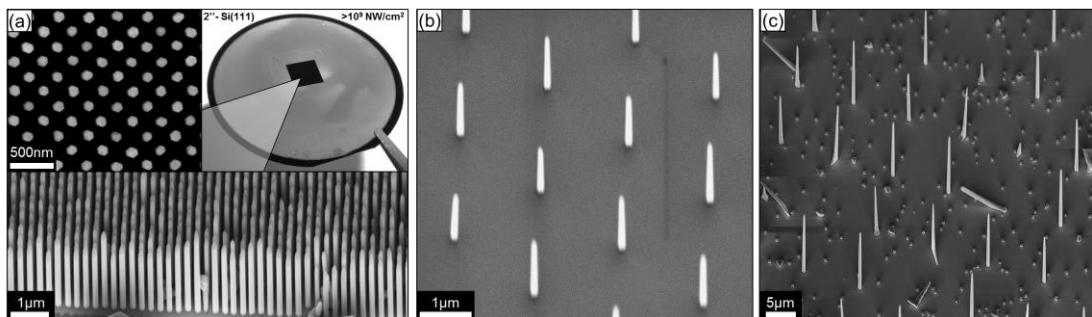


Figure 1: (a) Optimized selective area epitaxy of InAs NW on a 2'' Si(111) wafer using a pitch of 250nm. The black area of ~1cm consists of the NW shown in the SEM image in top and side view with a high yield above 90%. (b)-(c) NW grown with different interwire-spacings of 2μm and 10μm.

References

¹ International Technology Roadmap of Semiconductors (IRTS), www.itrs.net

² J. Treu, *et al.*, *Nano Lett.* 15, 3533 (2015).

Optical investigation of surface Fermi level-pinning in high-periodicity InGaAs nanowire arrays

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InGaAs nanowires (NWs) have been intensively investigated in the past few years, as they are promising candidates for future nano-electronic and -photonic devices, like tunnel-field-effect-transistors, lasers and photonic integrated circuits, as well as solar cells. However, given the large surface to volume ratio, the presence of high surface state densities can not only act as detrimental non-radiative recombination centers¹ but also lead to pronounced surface Fermi level-pinning especially in In-rich InGaAs NWs. The nature of surface states, the associated Fermi level position at the InGaAs NW surface and its effect on surface band bending have, however, remained quite elusive. Hence, to resolve these details is critical for e.g. efficient contact formation, enhancing radiative recombination and carrier dynamics across core-shell interfaces.

Here, we report optical investigations of the surface Fermi level pinning related effects in high-uniformity $\text{In}_{x-1}\text{Ga}_x\text{As}$ based NWs produced via catalyst-free selective area growth on SiO_2/Si (111) using a combined MBE-nanoimprint lithography process.² In particular, we study the micro-photoluminescence (μPL) spectral response of as-grown InGaAs NWs terminated by native surface oxides in comparison with NWs etched in hydrofluoric (HF) acid where surface states are mostly removed. Furthermore, by employing a successive digital etching procedure we can accurately tune the diameter of both oxide-terminated and surface-state depleted NWs, thereby resolving the magnitude of surface band bending as a function of NW diameter³. Remarkably, for highly In-rich InGaAs NWs ($x(\text{Ga}) < 0.2$) we find that (i) depleting the surface states results in a characteristic blue-shift of the PL peak energy, while (ii) HF-passivated NWs with decreasing NW diameter lead to a gradual red-shift. This behaviour is directly associated with the dominant PL recombination changing from a spatially indirect transition triggered by recombination via surface states to more spatially direct transitions in the absence of surface states. Concurrent electronic simulations of the surface band bending are found to agree with the shifts in PL peak energy for the given doping densities of the InGaAs NWs. In addition, we further tune the energetic position of surface states by changing the composition of our InGaAs NW, which allows us to change from n-type to mainly p-type surface accumulation layers.⁴ These studies thus contribute important insights into the critical surface electronics nature in narrow-gap semiconductor NWs.

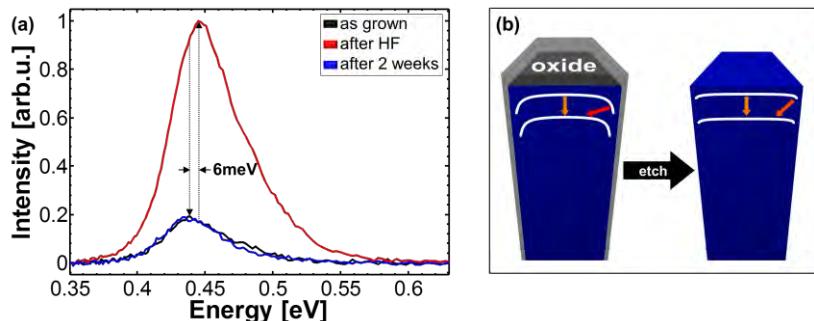


Figure 1: (a) Evolution of the PL signal of InAs NW before and after HF treatment. A significant signal enhancement and a distinct peak shift can be observed, indicative for a successful removal of surface states. The original signal is recovered after 2 weeks under ambient conditions (b) Schematic illustration of the etching procedure, leading to less surface states and in turn reduced band bending.

References

- ¹ J. Treu, *et al.*, *Nano Lett.* **13**, 6070 (2013).
- ² J. Treu, *et al.*, *Nano Lett.* **15**, 3533 (2015).
- ³ M. Speckbacher, *et al.*, in preparation (2015).
- ⁴ K. Kajiyama, *et al.*, *Appl. Phys. Lett.* **23** *458* (1973).

Growth and doping evaluation of p-type GaInP nanowires

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Intentional doping of semiconductor nanowires (NWs) is a rapidly developing field with intense discussions on the understanding and control of doping due to its importance in optoelectronic applications^[1]. Growth of quantitatively controlled p- and n-type NWs still remains a big challenge, especially for NWs where the doping leads to depletion of carriers close to the surface due to Fermi level pinning. The surface depletion results in problems in forming transparent electrical contacts to the materials, for instance, p-type InP NWs^[2].

We systematically investigated the particle assisted synthesis of GaInP NWs using Diethylzinc (DEZn) and Bis(cyclopentadienyl)magnesium (Cp_2Mg) as dopant precursors in a low pressure (100 mbar) metal organic vapor phase epitaxy (MOVPE) system. The catalytic Au particles were defined in an array by use of nano-imprint lithography, metal evaporation and lift-off. After the growth, the NWs were broken off from the growth substrate and deposited on a degenerately doped Si substrate with a thermally grown SiO_2 layer on top. After the deposition, metal contacts were defined to single NWs by electron beam lithography, metal evaporation and lift-off. Gate dependent (via the substrate and the SiO_2 layer) I-V measurements, four-probe resistivity measurements and spatially resolved Hall measurements were used to evaluate the doping. Our results show that p-doping using DEZn does not affect the growth dynamics severely. We observe carrier concentrations up to $2 \times 10^{18} cm^{-3}$ as a consequence of doping, but poor contacts prevent assessment of the carrier concentration for low doped NWs. The *in situ* use of Cp_2Mg leads to inhomogeneous growth, and the I-V characteristics do not indicate any change in the conductivity of the NWs. DEZn is thus the preferred dopant precursor both with respect to control over synthesis and doping.

References

- ¹ J. Wallentin, *et al.*, *J.Mater.Res.*, **26**, 2142 (2011).
- ² M. T. Borgström, *et al.*, *Nanotech.*, **19**, 1-6 (2008).

DESIGN AND REALIZATION OF InP/InAsP NANOWIRE-BASED AVALANCHE PHOTODETECTORS

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The controlled emission and detection of infrared radiation is crucial for applications in optical communication which require access to fast and sensitive discrete photodetectors, as well as to high-resolution 2D focal plane arrays for imaging purposes. These systems benefit a lot from avalanche photodetectors due to their increased photocurrent gain as compared to conventional photodetectors. A spatially separated multiplication region in a high bandgap material is especially useful to avoid the tunneling leakage currents in smaller bandgap materials needed for absorption at 1.3/1.55 μm wavelengths. Self-assembled III-V semiconductor nanowires (NWs) have key advantages owing to the enhanced absorption due to optical resonance effects¹ and strain relaxation facilitating monolithic integration of different III-V heterostructures on strongly mismatched substrates e.g. silicon.

Here, we present electrical and optical characteristics of vertically contacted large ensembles of InP/InAsP NWs, axially grown on p⁺ InP substrates. The NW base consists of an InP p-n junction acting as the avalanche region followed by an InP/InAsP absorption region, and ending with a top InP n⁺-segment. The 130nm diameter NW arrays are contacted in a vertical geometry using SiO_x as the insulating layer and ITO as the top contact². The optimization of the doping profile is crucial for the realization of the avalanche effect, wherefore the n-doping in the avalanche region is varied and its influence studied. Also the bandgap in the absorption region is varied from pure InP to smaller bandgap InAsP by varying the As content. Clear interband signals from different crystal phases of InP/InAsP are observed in photocurrent spectroscopy. We also compare electrical results from single NWs contacted laterally from the same as-grown samples, where a clear avalanche breakdown and a high multiplication factor is observed. These results give useful insight towards optimization of avalanche photodetector devices based on III-V NWs.

References

¹ J. Wallentin, *et al. Science* **339**, 1057-1060 (2013).

² V. Jain, *et al. Nano Res.* **7** (4), 1-9 (2014).

Pure Wurtzite GaP/InGaP core-multishell quantum well nanowires for Solid State Lighting

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Solid State Lighting (SSL) is considered to be the next generation of light sources. In Light Emitting Diode (LED) applications nanowires are of particular interest^{1,2}, as they show unique properties such as strong waveguiding and asymmetrical emission, with a promising Internal Quantum Efficiency (IQE) reaching 50%^{3,4,5}. Their advantages over planar technology are manifold: a higher junction area allows for higher efficiency per device while unlocking new crystal symmetries for the emitting material, such as direct bandgap Wurtzite (WZ) in III-Phosphides⁶, which are conventionally always grown as Zincblende (ZB) in bulk material.

Here we demonstrate the growth and optical properties of pure WZ GaP/InGaP core-multishell quantum well nanowires, obtained using a crystal structure transfer⁷ technique, emitting in the visible region around 590nm. In order to obtain homogeneous growth of the WZ shells and reduce the ZB overgrowth on the top of the nanowires, the Au droplet was etched ex-situ and an optimized flow of HCl has been used as precursor during the shell growth. Our results show strong emission at low temperature (4-100K) and appreciable emission at room temperature. This work is oriented towards demonstrating efficient nanowire III-Phosphide LEDs based on Wurtzite alloys.

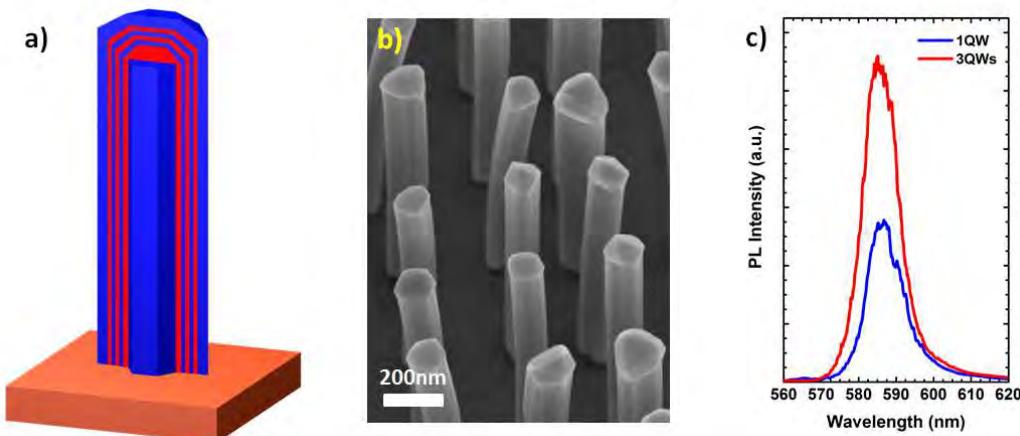


Figure 1: a) concept of WZ GaP/InGaP core-multishell nanowire. b) SEM image of the WZ GaP/InGaP nanowires. The bending observed is given by strain c) PL spectra of nanowires with respectively one and three Quantum Wells.

References

- ¹ M. Tchernycheva *et al.*, *Nano Letters* 14 (6), 3515-3520 (2014)
- ² C. Pan *et al.*, *Nature Photonics* 7, 752-758 (2013)
- ³ J. Motohisa *et al.*, *Nano Letters* 14 (6), 3653-3660 (2014)
- ⁴ H.P.T Nguyen *et al.*, *Nano Letters* 13 (11), 5437-5442 (2013)
- ⁵ H.P.T Nguyen *et al.*, *Nano Letters* 11 (5), 1919-1924 (2011)
- ⁶ S. Assali *et al.*, *Nano Letters* 13 (4), 1559-1563 (2013)
- ⁷ R. Algra *et al.*, *Nano Letters* 11 (4), 1690-1694 (2011)

Effects of uniaxial strain on the PL emission spectrum of WZ GaP nanowires

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Semiconductors exhibiting the cubic zinc-blende structure in bulk material may crystallize in the hexagonal wurtzite phase when grown as a nanowire. Theoretical works propose significantly altered electronic and optical properties of these wurtzite-type materials but up to now little experimental data is available due to the lack of phase pure material. Recent progress in synthesis, however, enabled the growth of phase pure wurtzite nanowires in various material systems. Here we report on the investigation of the band structure of gallium phosphide nanowires grown in the hexagonal crystal structure. Photoluminescence spectroscopy was employed in order to reveal their optical and electronic properties. The nanowires are integrated into a micro electro mechanical device allowing for the dynamic application of high uniaxial strain levels. Mechanical strain is correlated with shifts in the photoluminescence emission spectrum to gain further insight into the band structure of these wurtzite-type materials. Piezoelectric effects on the emission spectrum will be discussed. Deformation potentials for the different bands are given and the experimental results are compared with simulation results of the band structure under strain.

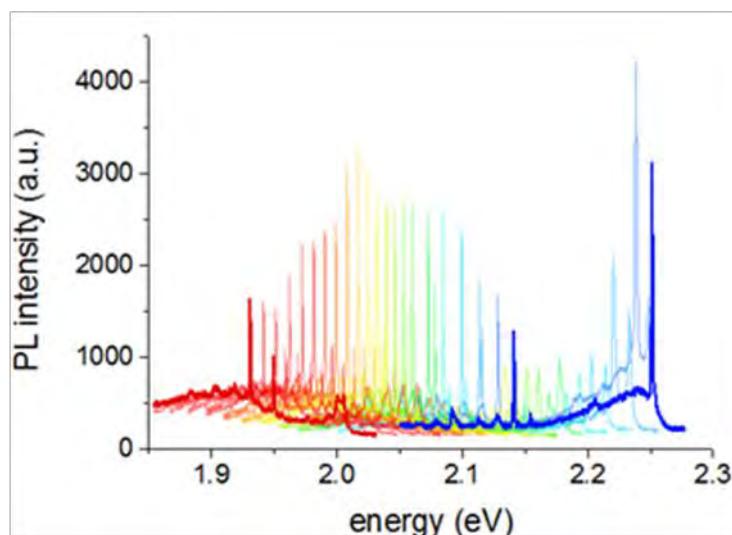


Figure 1: PL spectra of WZ GaP NW under increasing uniaxial strain from 0% (blue) to 6% (red).

Surface-dependent oxidation of branched InAs nanowires

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Oxides formed on semiconductor nanowires surfaces represent a key element in nanowire based devices. While removing native oxides at interfaces is essential for the device performance, forming high quality insulating oxides (such as HfO₂ or Al₂O₃) is equally important. Controlling the oxidation of the nanowire surface opens the possibility of controlled formation of different materials of interest. The focused laser beam of the micro-Raman set-up can be used for purposes beyond the investigation of the nanowires properties, such as chemical modification¹, morphology engineering² and metal welding³.

It has been verified by Raman spectroscopy that the local oxidation induced by laser irradiation of InAs or GaAs nanowires results into the formation of crystalline arsenic. The detailed morphology of the oxidation resulted compounds has been investigated by methods such as atomic force microscopy (AFM) and scanning electron microscopy (SEM)^{1,4}. The latter methods don't provide atomic scale imaging such as transmission electron microscopy (TEM) due to the substrate incompatibilities. Here we combine Raman spectroscopy with TEM in order to have a full comprehension of the laser induced thermal oxidation of InAs nanowires. Polarization dependent Raman measurements confirm the presence of crystalline arsenic, while TEM measurements reveal the remaining oxides compounds. The oxidation process, investigated on branched InAs nanowires, is also found to be Facet-related. The mechanism of the oxidation is discussed in terms of transition state kinetics.

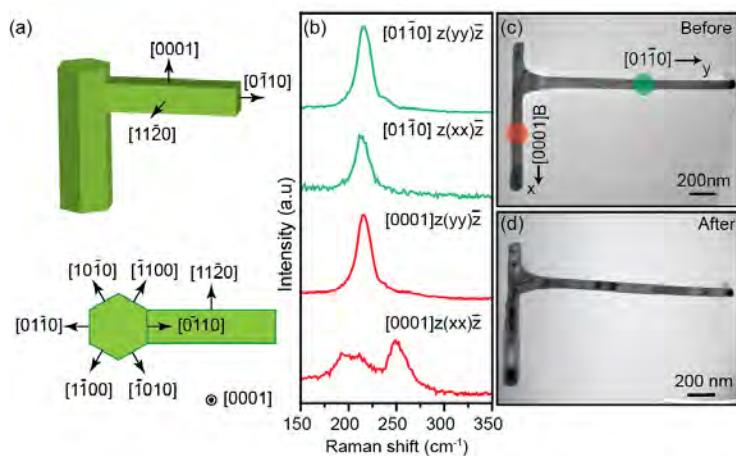


Figure 1: (a) A schematic illustrating the geometry of the branched nanowire. (b) Raman spectra at the two stems of kinked InAs nanowire with polarization indicated by Porto notations. (c) and (d) TEM images of the nanowire measured in (b) before and after measurement, respectively.

References

¹Yazji, S. et al. *Nanotechnology* **22**, 325701 (2011).

²He, J., Chen, P., Lu, W., Dai, N. & Zhu, D.-M. *J. Appl. Phys.* **111**, 094316 (2012).

³Garnett, E. C. et al. *Nat. Mater.* **11**, 241–9 (2012).

⁴Pal, S., Aggarwal, R., Kumari Gupta, V. & Ingale, A. *Appl. Phys. Lett.* **105**, 012110 (2014).

Formation and optical properties of GaAsSb nanowire networks

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The growth of branched nanowires (NW) recently gained interest due to new developments in quantum optics and mesoscopic physics [NatPhys2011Alicea]. Recent studies reported the growth of InAs and InSb NW networks [NL2006Dick; NL2013Dalacu, NatMat2013Plissard, AdvMat2014Car] that are the most promising material candidate for Majorana's braiding. These new 3D structures enable fabrication of advanced devices such as photonic crystals and multiple terminal Field Effect Transistors (FET).

Here, we investigate the growth and optical properties of T-shape GaAsSb NWs grown by molecular beam epitaxy (MBE). These Ga-seeded nanostructures are studied via High Resolution Transmission Electron Microscopy (HR-TEM) and compositions are determined via EDS measurements. Depending on the antimony concentration and the growth conditions, the crystalline structure can be tuned from zinc blende to wurtzite. A new growth mechanism is proposed in order to explain the formation of these 3D structures.

Optical methods are extremely powerful technique to investigate the electronic properties of nanowires as well as their crystal structure. Therefore, we have performed low temperature micro-photoluminescence studies to examine the quality and crystal structure of a single T-shape GaAsSb NW. Linearly polarization resolved measurements allow us to identify the zinc blende and wurzite regions of the nanowire. The emission energy for wurzite part of the nanowire is at higher energy than for zinc blende. This information brings a new light for the electronic properties of GaAsSb NWs, as to the best of our knowledge this is the first observation of a wurzite structure in this system. Additionally, the most striking effects is that the emission from this structure is very bright, which is highly unusual for a NW grown without shell. This result with further investigations and optimization of the optical performance of T-shape structures opens a new way for future applications such as for example nanowire based beamsplitters.

Photocurrent Mapping of Single GaAsSb Nanowire Diodes

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Semiconductor nanowires (NWs) provide very interesting electrical and optical properties for next-generation electronic, optoelectronic, and energy harvesting devices.¹ Among various semiconductor NWs, Sb-based III-V ternary NWs are expected to play an important role in future electronic and optoelectronic applications, such as telecommunication devices and infrared sensors due to high carrier mobility and bandgap tuning by compositional engineering. Recently, we reported that GaAsSb NWs grown by Ga-catalyzed molecular beam epitaxy (MBE) without any intentional doping show a rectifying behaviour due to a self-induced compositional variation in the NW.² It was found that the characteristics of each Schottky contact in the GaAsSb NW device depend on the self-induced compositional variation. In order to develop electronic and optoelectronic devices based on such GaAsSb NWs, it is essential to understand how the Schottky contact is affected by the self-induced compositional variation. Among various tools to study Schottky contacts, scanning photocurrent microscopy has been demonstrated to be a versatile tool for the determination of the band-structure profile and the characterization of the Schottky contacts in nanoscale devices.³

Here, we have investigated GaAsSb NWs with a self-induced compositional variation using the scanning photocurrent microscopy. The highest photocurrents are shown to originate near the contacts, resulting from the energy band bending at the Schottky contact. Figure 1(a) and (b) show clearly that the value of the photocurrent at the NW-top (near the Ga-droplet) is higher than that at the NW-base. Considering that the value of the photocurrent is affected by the Schottky contact, the difference in the photocurrent indicates that the GaAsSb NW device consists of asymmetrical Schottky contacts, which is in agreement with our previous results.² We have also investigated the passivation effects of an Al₂O₃ layer on the GaAsSb NW device. The bias dependence and laser power dependence of the scanning photocurrent in the GaAsSb NW device show a similar tendency, regardless of the passivation layer, whereas the value of

the photocurrent and the photocurrent ratio between the NW-top and the NW-base increased after the passivation. From *in-situ* confocal Raman spectroscopy, it was confirmed that the composition of the GaAsSb NW are not affected by the passivation process. These results indicate that the optoelectronic property of the GaAsSb NW device depends on the Schottky contact and the NW surface.

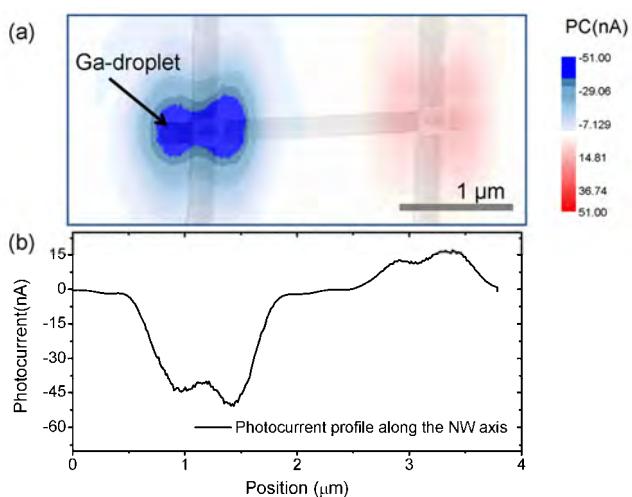


Figure 1. (a) 2-dimensional photocurrent mapping image of a GaAsSb NW device under zero bias. The mapping image is overlaid on the SEM image. (b) Photocurrent profile along the NW axis.

References

¹ Charles M. Lieber, *et al.*, *MRS Bulletin* **32**, 99 (2007).

² Junghwan Huh, *et al.*, *Nano Lett.* **15**, 3709 (2015).

³ Jonathan E. Allen, *et al.*, *Adv. Mater.* **21**, 3067 (2009).

Protective capping and surface passivation of III-V nanowires by ALD

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Although nanowires (NWs) offer far superior and unique properties than the material in bulk, however, one disadvantage associated with NWs is the presence of high density of surface states (very high surface to volume ratio). These surface states can act as recombination centres /surface charge traps, and can make additional electronic states within the band gap and Fermi level pinning can occur, as commonly seen in GaAs NWs. To use NWs in functional devices, the two important key issues are (1) surface passivation¹ and (2) long-term protection of the device from oxidation/environmental attack.

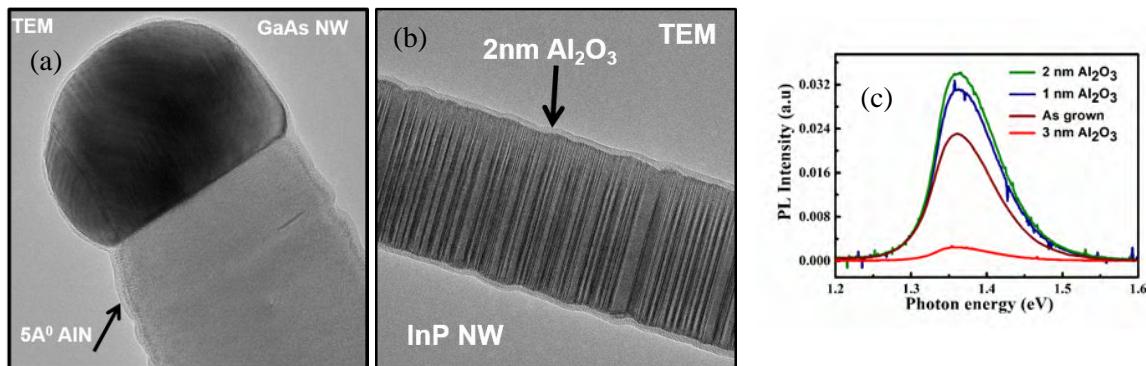


Figure 1: TEM images of (a) GaAs and (b) InP NWs capped with ALD grown AlN and Al₂O₃ films, and (c) PL spectra from InP NWs capped with 2nm thick Al₂O₃.

We have explored the suitability of wide range of atomic layer deposition (ALD) grown films for protective capping as well as the surface passivation for III-V NWs and nanopillars. Specifically, plasma-enhanced ALD grown films of AlN, TiN, Al₂O₃, GaN & TiO₂ were tested for passivation of bottom-up grown GaAs and InP NWs, and top-down fabricated InP nanopillars. For as-grown GaAs NWs, no PL emission was detected due to the surface fermi-level pinning. However, among all the ALD films tested as capping layers, only the AlN material passivated the GaAs NWs surface but only at low temperatures (15K), and the best passivation was achieved with few monolayer thick (2Å⁰) film. For InP NWs, which unlike GaAs NWs show good PL at RT, the best RT passivation (2x enhancement in PL) was achieved with a capping of 2nm thick Al₂O₃ film. All other ALD capping layers except AlN resulted in de-passivation effect and possible damage to the InP NW surface. Top-down fabricated InP nanopillars show similar passivation effects as InP nanowires. In particular, TRPL measurements reveals that a capping with 2 nm thick Al₂O₃ increased the decay time from 251ps (as-etched InP nanopillars) to about 525 ps. A decrease in PL and carrier lifetime was observed with an increase in capping layer thickness beyond the optimum. In summary, AlN and Al₂O₃ were found to be the best ALD materials for III-V NWs and nanopillars. Although the passivation was mild but these materials are ideal as protective cappings for long term stability of the devices i.e. prevention from oxidation/environmental attack. Additionally, ultra-low (<200C) growth deposition temperature of ALD films makes them compatible with most semiconductor device processing technologies.

References

- ¹ V. Dhaka, et al., *Nano Letters* **13**(8), 3581-3588 (2013).

Efficient and simple surface passivation method for GaAs nanowires

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It is commonly known that surface states hamper nanowire (NW) device performance, and that the surface passivation is essential for many III-V materials, especially GaAs. Most commonly, NW passivation is acquired via coating the NW with a relatively thick shell, such as AlGaAs for GaAs. However, this complicates the growth process, requires high deposition temperature and inevitably affects the morphology and band structure of the NW. We propose an alternative passivation method of the GaAs surface states by thin InP and GaP caps, whose thickness is in the range of monolayers¹. Such minimal thickness has little impact on any other properties of the nanowires besides the surface states. Furthermore, these layers can be deposited in similar temperatures to those used in NW growth (~200 °C lower than typically used for thick shells). This difference allows the presence of wider range of materials on the growth template during the NW growth, e.g. metals that would form unusable alloys at ~600 °C.

Another advantage of the reported method is its simplicity. Efficient passivation was acquired even by switching from As-rich atmosphere to P-rich during the cooldown. A more stable passivation on the other hand was acquired by switching from GaAs growth to InP growth for a few seconds, still keeping the temperature below 500 °C, followed by P-rich cooldown.

The passivation efficiency was observed as a several orders of magnitude increase in photoluminescence (PL) intensity compared to unpassivated NWs. This passivation performance was comparable to that obtained by AlGaAs shells. On the other hand, the unpassivated NWs showed no signal in the PL measurements even at 20K (the several orders of magnitude increase is from the smallest detectable signal, and the actual increase can be even larger). In addition, passivation was observed beneficial in electrical measurements.

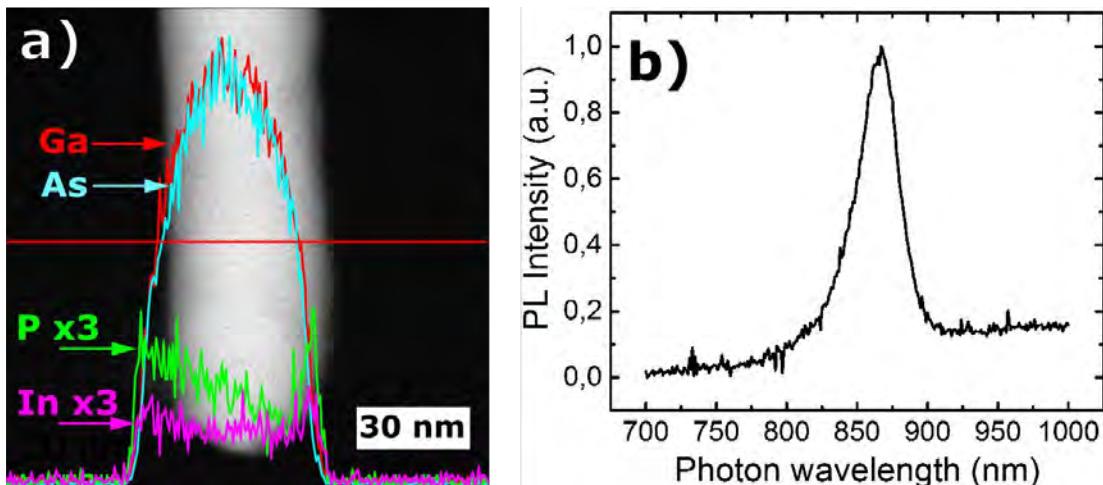


Figure 1: GaAs NW with thin InP caps imaged in TEM with high-angle annular dark-field transmission electron microscope and an energy-dispersive X-ray spectroscopy line scan (measurement line indicated with the red line) (a), and PL spectrum from InP-passivated NWs, measured at room temperature (b).

References

- ¹ T. Haggren, et al., *Applied Physics Letters* **105**, 033114 (2014).

Coaxial GaN/Ga₂O₃ heterostructure nanowires formed via ammonification process

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We report on the formation of coaxial GaN/Ga₂O₃ nanowires formed after ammonification of β -Ga₂O₃ nanowires grown on Au nanoparticles coated sapphire substrates. Coaxial GaN/Ga₂O₃ nanowires have been formed with length in the range of several hundreds of micrometer and diameter in the range of a few hundreds of nanometer. GaN shell thickness in the coaxial nanowires have been tuned by utilizing ammonification temperature. FESEM images (Fig 1(a) and 1(b)) show the morphology of as-formed coaxial GaN/Ga₂O₃ nanowires at ammonification temperature of 900°C for 1h. XRD patterns as shown in Fig 1(c) illustrate the temperature dependent formation of GaN shell from Ga₂O₃ nanowires. Higher ammonification temperatures such as 1050°C for 1h together with similar other experimental parameters, leads toward the complete conversion from Ga₂O₃ nanowires to GaN nanowires. TEM characterization (Fig 1(d)) shows contrast imaging of a particular coaxial GaN/Ga₂O₃ nanowires. Lattice resolved HRTEM images and SAED demonstrate the conversion of lattice fringe and spot pattern of β -Ga₂O₃ to lattice fringe and spot pattern of wurtzite GaN.

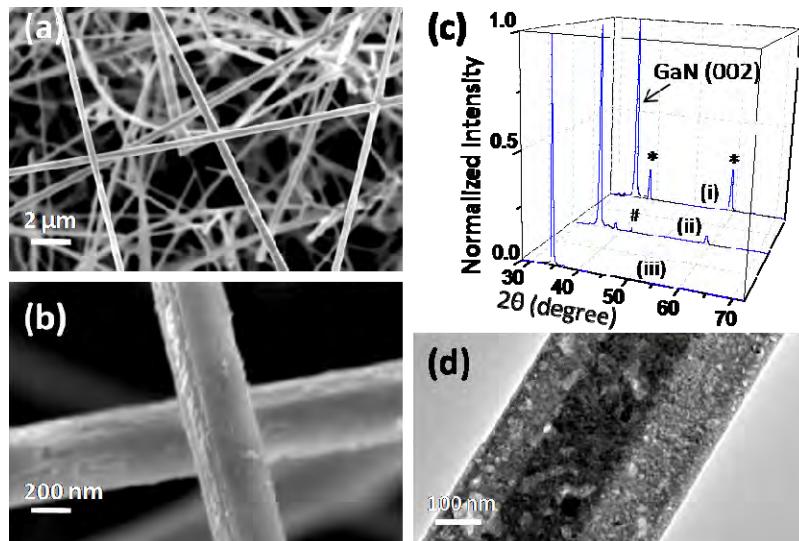


Figure 1: (a), (b) FESEM images of coaxial GaN/Ga₂O₃ nanowires formed at 900°C for 1h in NH₃ and N₂ gases. (c) (i) its XRD pattern. (c) (ii) and (c) (iii) XRD spectra for ammonification temperature at 950°C for 1 h and 1050°C for 1h, respectively. Symbols (*) relate to Ga₂O₃ XRD peaks and (#) relate to sapphire substrate. Fig 1(d) TEM image of coaxial GaN/Ga₂O₃ nanowires formed at 900°C for 90 min in NH₃, N₂ and H₂ gases.

Raman investigations show the diminishing of Raman peaks related to octahedral and tetrahedral bonds of β -Ga₂O₃ together with evolution of E_2 high and A_1 LO phonon modes of GaN as ammonification temperature is increased from 900°C to 1050°C. Similarly, Photoluminescence spectra show the shifting of weaker defect related luminescence of Ga₂O₃ nanowires toward enhance near band edge luminescence of GaN with increase of ammonification temperature. Further, kelvin probe force microscopy (KPFM) study suggest the formation of unintentional n-type GaN in the coaxial GaN/Ga₂O₃ nanowires. Electrical characterization of these nanowires using electron beam lithography fabrication processes will also be presented.

Reference

C H Hsieh et.al., *Nano Lett.* **8** 3288-3292 (2008)

Conformal growth of ultra-thin p-conductive polymer shells on n-type semiconductor nanowires by oxidative chemical vapour deposition

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Inorganic-organic hybrid systems consisting of conjugated polymers and inorganic semiconductors are promising for the development of cheap, versatile and tailored electronic and optoelectronic devices. ZnO, as the inorganic semiconductor of the hybrid system, is particularly suitable as it is transparent throughout the visible spectral region, easily n-type doped to moderate to high levels and exhibits high electron mobility. Organic p-conductive polymers adsorbed at the ZnO surface can form electronic junctions which may provide optoelectronic and sensing functionalities. By carefully controlling and adjusting layer thickness, doping level and side-chains of the polymer, the optical and electronic structure of the hybrid systems can be optimized and new functions can be generated.

Hybrid semiconductor/polymer core-shell nanowires were fabricated by oxidative chemical vapour deposition (oCVD), a solventless and dry method where the oxidising agent and the monomer are provided in the gaseous phase. The advantage of oCVD compared to conventional wet-chemical approaches, including spin-coating of conductive polymers from solutions, is the absence of liquid solvents with potentially strong acidic or basic character that can result in etching and degradation of the semiconductor surface. The desired monomer passes through the reaction chamber together with a constant flow of nitrogen carrier gas. The polymerisation reaction of the monomer molecules on the sample surface is kept up by an oxidising agent which also dopes the polymer. In our experiments, we use FeCl₃ as an oxidising agent and the p-conductive polymers polypyrrole (PPy) and poly(3,4-ethylenedioxythiophene) (PEDOT) to conformally coat n-type ZnO nanowires with ultrathin conductive polymer layers.

SEM and TEM measurements confirm the 3D conformal coating of the nanowires with the conductive polymer. The layer thickness is on the order of a few tens of nanometres and can be controlled by the total amount of the oxidising agent which is provided during the coating process. Photoluminescence spectroscopy reveals a broadening of the exciton line of the ZnO nanowires after polymer coating which is attributed to the etching process of the ZnO surface caused by the FeCl₃ during the polymerisation process.

The electronic properties of the interface formed by the n-ZnO and the p-polymer were studied in I-V measurements. By applying a one-diode equivalent circuit model, we determine the barrier height at the hybrid interface and the energy position of the HOMO in the PPy deposited on n-ZnO structures. Our results are consistent with the reported literature values for PPy and provide the basis for further optimising the electronic properties at the hybrid interface.

Towards defect-free hexagonal Si from suppression of crack defect formation

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Up to now, both experimental studies¹ and theoretical models² of defect formation in core-shell nanowires have been restricted to mismatched materials, where the appearance of defects is driven mainly by the difference in the geometry and crystalline structure of the core and shell materials. However, the formation of defects in core-shell heterostructures in nanowires can also be driven by strain relaxation, arising not only from the lattice mismatch of the core and the shell materials, but rather from the specific details of the growth process, in particular from the thermal history.

In this work, we show that defect formation in lattice-matched GaP/Si core-shell nanowires can be ubiquitous. In such systems, we report on the formation of a special type of defect, known as a crack.³ The origin of these cracks is driven by the thermal history of the growth process, which can induce a brittle to ductile transition (BDT) in the Si shell.

The understanding of the mechanism that underlines this unexpected formation of defects requires structural characterization by means of Transmission Electron Microscopy, which provides crucial information to design novel growth conditions and achieve GaP/Si defect-free core-shell nanowires. This understanding can be also important in order to refine existing theoretical models of defect formation and explore new physical properties of novel materials such hexagonal Silicon.

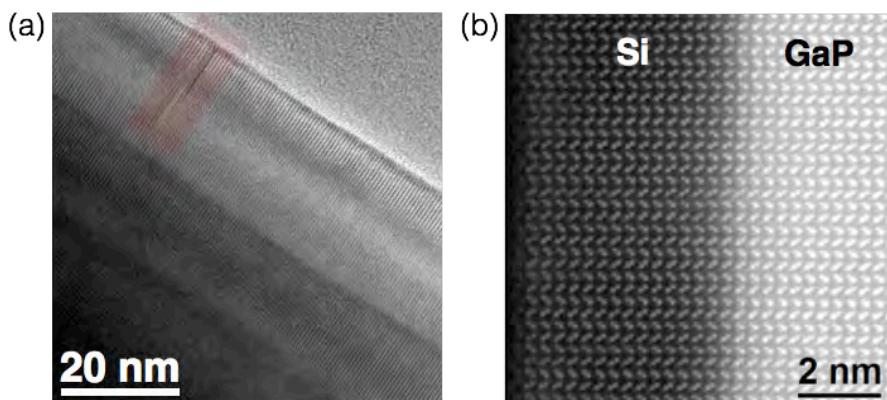


Figure 1: (a) HR-TEM image of a GaP/Si core-shell nanowire exhibiting a crack defect on the Si shell;
(b) HR-STEM image taken along the [11-20] zone axis demonstrating the quality of Si shell

References

- ¹ S.A. Dayeh, *et al.*, *Nano Letters*, **13** 1869 (2013).
- ² K. L. Kavanagh, *et al.*, *Semicond. Sci. Technol.* **25** 024006 (2010).
- ³ S. Conesa-Boj, *et al.*, *Nano Letters*, **15** 2974 (2015).

Magnetic and structural properties of MBE grown wurtzite (Ga,Mn)As shells in a radial quantum well nanowire heterostructures

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Investigation of (Ga,Mn)As ferromagnetic semiconductor in a form of quasi 1-dimensional nanostructures is important in the context of ferromagnetic nanowires which were proposed as a base for a new type of nano-magnetic memory structures [1] and magnetic logics [2] manufactured from nanowire grids [3]. Conditions required to prepare a ternary (Ga,Mn)As alloy, which are dictated by low temperature MBE growth are in contradiction to the growth procedure of metal-induced formation of NWs. Hence, the only way to produce (Ga,Mn)As in a nanowire geometry can be realised as a shell deposited on a beforehand grown semiconductor core nanowire templates. Here, in order to additionally tune the magnetic anisotropy by strain, cores made from (In,Ga)As alloy were chosen. Variation of In concentration in the core allows to achieve desired strain state in the shell. In addition, the presence of In in the cores not only determines strain, but also induces wurtzite crystalline structure, which is inherited by magnetic (Ga,Mn)As shells. However, in earlier studies we found that such core-shell NWs lack a long-range magnetic order and magnetically behave as super-paramagnets [4], despite, 5 % of Mn content, what is more than sufficient to induce ferromagnetism in planar (Ga,Mn)As. We attribute this behaviour to a lack of itinerant holes, which mediate the long-range ferromagnetic interactions. Assuming that the shell growth is optimised to obtain both smooth morphology and the lowest concentration of defects while keeping the highest amount of Mn possible, the lack of the mobile holes was attributed to their out diffusion towards the core and/or to the surface depletion. To counter act these effects, NWs with high temperature Al_{0.4}Ga_{0.6}As or low temperature grown GaAs post-growth annealed at 600 °C in order to create metallic As nanoclusters pinning the Fermi level in the middle of the GaAs band-gap [5] barriers for holes between the In_{0.2}Ga_{0.8}As core and the Ga_{0.95}Mn_{0.05}As shell were prepared. The high crystalline quality of these multi-shells of NWs has been confirmed by dedicated XRD for the ensembles of NWs and high resolution TEM studies of individual NWs in two geometries: cross-sectional and perpendicular to the side facets. For these NWs a weak spontaneous magnetisation has been observed below 24 K during a cool down from high temperatures, which is the first such observation in the MBE grown NWs with (Ga,Mn)As shells - a form different than planar epilayer. By comparing these results with our previous findings [4] we can conclude that in the re-designed NWs we literally witness the birth of the long range FM order, which is just surfacing from the still (present) overwhelming SP component.

References

- [1] Hayashi, M., Thomas, L., Moriya, R., Rettner, C., Parkin, S. S. *Science*, **320**, 209 (2008).
- [2] Omari, K. A., Hayward, T. J. *J. Phys. Rev. Appl.*, **2**, 044001 (2014).
- [3] Kang, J. H., Cohen, Y., Ronen, Y., Heiblum, M., Buczko, R., Kacman, P., Popovitz-Biro, R., Shtrikman, H. *Nano lett.*, **13**, 5190 (2013).
- [4] Šiušys, A., Sadowski, J., Sawicki, M., Kret, S., Wojciechowski, T., Dluzewski, P., Gas, K., Szuszkiewicz, W., Kaminska, A., Story, T. *Nano lett.*, **14**, 4263 (2014).
- [5] Maranowski, K. D., Ibbetson, J. P., Campman, K. L., Gossard, A. C. *Appl. Phys. Lett.*, **66**, 3459 (1995).

Elastic strain relaxation in GaAs/InGaAs/GaAs core-shell NW heterostructures grown by MBE on Si (111)

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The strain field of core-shell nanowires (NWs) grown onto silicon [111] substrates has been investigated by high-resolution X-ray diffraction (XRD).

The GaAs/In_{0.25}Ga_{0.75}As/GaAs NWs have the same core diameter (150nm) and cap layer thickness (30nm) with varying the In_{0.25}Ga_{0.75}As shell thickness (6 to 40nm). Measurements taken on NW ensembles with momentum transfer along the growth direction demonstrated pseudomorphic growth, i.e. core and shell material always share the same out-of plane lattice parameter. On the other hand lattice parameters measured perpendicular to the growth axis show well separated Bragg peaks for the core and shells. A very rough estimate shows that the peak separation to unstrained GaAs corresponds to an In content close to 25% within the InGaAs shell. While the width of the GaAs core and cap layer peaks roughly correspond to the nominal core diameter and cap layer thickness, resp., the angular width of the InGaAs peaks is much broader and reflects an average of different shell widths/In concentrations of the different NWs inspected. The data are interpreted in terms of finite element method (FEM). Preliminary data analysis predicts that for samples with thin InGaAs layers the experimental data have to be modelled using different In contents along the [1-10] side planes and along [11-2] edges. On the other, hand a homogenous indium distribution was used to model the samples with larger InGaAs thickness.

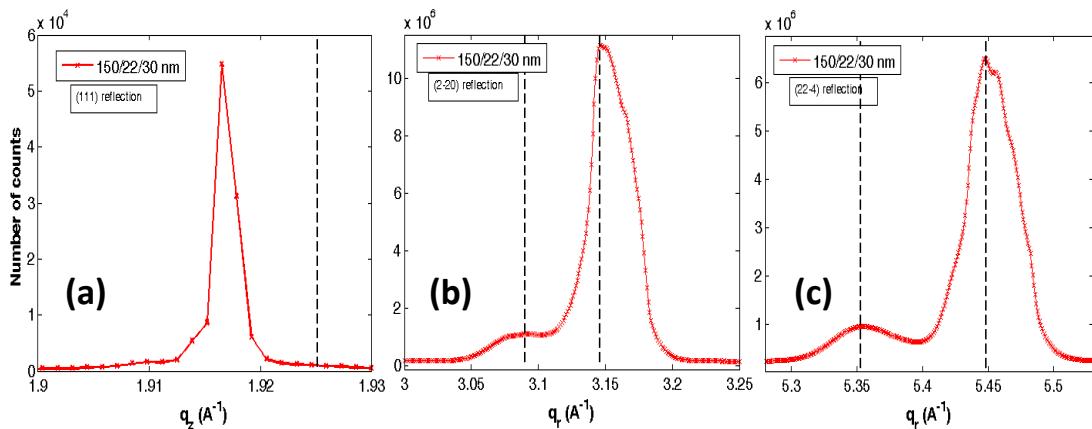


Figure 1: XRD measurements performed on a sample with 22nm InGaAs layer thickness. (a) shows XRD along [111] growth direction. (b) and (c) show XRD along [2-20] and (22-4) in-plane directions, resp. The dotted lines on the left and right sides correspond to cubic InGaAs and GaAs, resp.

High Ensemble Uniformity and Low Disorders in Quantum Well Tube Nanowires Probed by Photoluminescence Spectroscopy

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Semiconductor nanowires have received much attention over the past decade and there are already a number of applications utilising them such as solar cells¹⁻², terahertz detectors³ and LED devices⁴. Customisation of the bandgap in particular is essential for such nanowire applications. Ternary materials are traditionally used to tailor the bandgap, although the growth of nanowires with a uniform composition remains challenging. However, an alternative method for tailoring the bandgap energy is to take advantage of quantum effects by producing a quantum well tube (QWT) along the nanowire axis by growing a thin layer of lower bandgap material within the higher bandgap shell layer.

Here, we have investigated spectroscopic distributions of 150 individual core-multishell nanowires from three growth recipes with different GaAs QWT shell layers and core and we have determined their energetic disorder. Using room temperature photoluminescence measurements (Figure 1), we have found the QWT of the 3 samples to possess an average width of 2.1, 4.0 and 2.0 nm and a standard deviation of 0.3 nm or less. A disorder parameter associated with the non-thermal broadening was extracted from the fits of the spectra and correlated to the structure of the nanowire. The core is measured to have a very low disorder of 8 ± 2 meV, while the QWT disorder was found to be 40 ± 10 meV approaching the ideal limit of $k_B T$. This suggests the suitability of these nanowires to be used in tuneable optoelectronic devices.

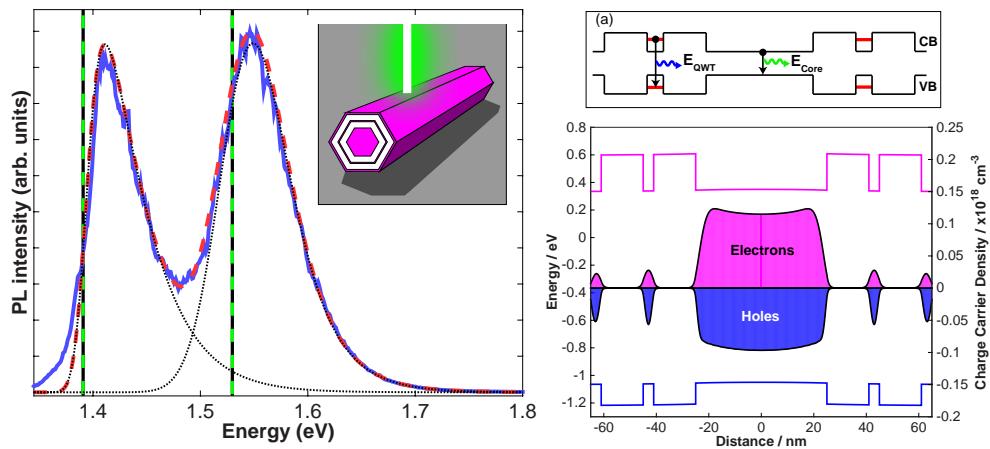


Figure 1: (left) PL spectrum of a typical nanowire shown on a linear scale. (right) Simulation of QWT nanowire showing band structure and charge carrier density.

References

- ¹ M. Yao, *et al.*, *Nano Letters* **14**, 3293-3303 (2014).
- ² Y. Qu, *et al.*, *Journal of Materials Chemistry* **22**, 16171 (2012).
- ³ K. Peng, *et al.*, *Nano Letters* **15**, 206-210 (2014).
- ⁴ C. Pan, *et al.*, *Nature Photonics* **7**, 752-758 (2013).

Process of manufacturing of a carbonaceous material for supercapacitors applications

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Both batteries and supercapacitors base their operation on the ion-exchange as well as on reduction-oxidation reactions on the surface of the electrode. A key factor to the capture of a large amount of ions in the interface between the electrode and the electrolyte consists in developing a high specific surface in the electrode. The greater the specific surface, the greater the capacity to accumulate electric charges.

Nevertheless, this area must be accessible for the ions, having the need to develop porous surfaces where ion kinetics is enhanced by the porosity. It is crucial for the design of a well-operating electric charge storage system that the combination of porosity and porous size to be adapted to the anions and cations size, which are going to be carried by the electrolytic solution.

Many carbon substances have been used to manufacture electrodes for supercapacitors and/or redox batteries according to the state of the art. Some examples are: carbon nanowires, carbon nanofibers, graphene, etc. It is also possible to use activated carbon under a various chemical attack processes.

On the other hand, electrochemical capacitors can be classified according to the mechanism used to store the electric charge. Electric Double Layer Capacitors (EDLCs) suffer from an electrostatic attraction between the ions and the surface of the electrode. Moreover, pseudo-capacitors bear charge transfer reactions (equal to batteries where the only difference is that the transferred charge is proportional to voltage). Suitable materials for pseudo-capacity, as previously mentioned, are usually metal oxides from VII and VIII groups such as MnO₂ or RuO₂.

Pseudo-capacity can also be achieved by doping the carbon with heteroatom¹ (nitrogen). The final value of the electric capacity of the super-capacitor is closely related to the nature and surface of electrodes and to the interface with the electrolyte. One of the novelties from this work relies on the material utilized and the deposition technique. By means of that it is possible to optimize the quantity of used material and also provides a system to design new ways to modify the physical structure of the electrode and the super-capacitor obtained.

The present work wants to show a new technique to obtain a material designed to manufacturing of super-capacitors. The process makes the most of the waste of fabrication of cellulose acetate fibers to make a material with desirable high properties. In addition, the method allows getting a high porous carbonaceous material suitable for supercapacitor electrode. The material has been deposited by Electrospray method. This method allows the electrode to have any shape as a difference with other techniques.

References

¹ N. Palanichamy, et al., IJRET vol 03, 09 (2014).

Spatially-resolved measurement of ZnO nanowire band structure using cathodoluminescence

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Due to their tuneable bandgap and excellent electronic properties, ZnO nanowires have many possible applications such as thermoelectrics, LEDs, gas sensing and photovoltaics. Critical to all of these applications is the quasi-1D geometry of nanowires. Because of the large surface-area to volume ratio of nanowires it is important to understand the properties of surfaces of ZnO nanowires in order to optimize them for their various applications.

Tapered ZnO nanowires have been grown by plasma assisted molecular beam epitaxy and imaged using scanning transmission electron microscopy (STEM), whilst simultaneously measuring the spatially resolved cathodoluminescence (CL) signal giving a spatial mapping of band gap in ZnO nanowires with nanoscale resolution. Within an individual nanowire we resolve surface and bulk signals. Due to the growth process, the nanowires taper slightly, and have a continuously varying diameter. We measure the dependence of the width of the surface depletion region on the nanowire radius.

A typical CL spectrum shown in figure 1(a) has a large intensity peak at the ZnO bandgap (3.35eV) with some intensity at lower energies and a well resolved defect peak. As shown in the inset of figure 1 (a) the CL intensity varies radially across the nanowire. The luminescence from transitions across the bandgap (red crosses) is confined to the bulk of the nanowire, whilst lower energy luminescence is maximised near the edges of the nanowire (blue). The spatial variation of luminescence suggests a surface depletion layer surrounds a bulk semiconducting core. By fitting a Gaussian profile to the radial CL profiles we extract the depletion layer thickness from the variance of the Gaussian and nanowire dimensions. This is done along the growth axis of a nanowire giving the dependence of depletion layer thickness on nanowire diameter. This data is shown in figure 1 (c). Understanding the size of the depletion layer and its properties is critically important for many applications. For example the optical transitions at the surface will play a crucial role in the behaviour of any nanowire photovoltaics, and the interplay between thermal and electrical properties of surface and core will determine the efficacy of nanowire thermoelectrics.

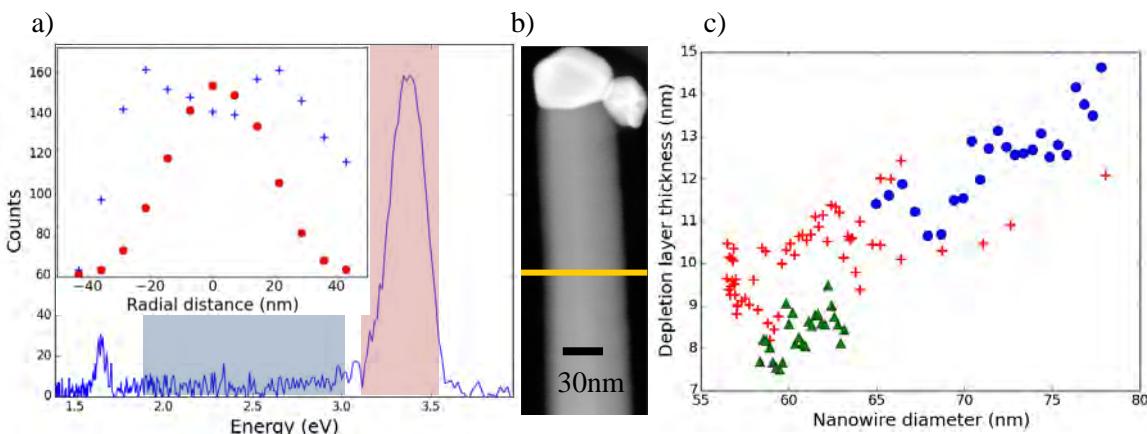


Figure 1: (a) Typical CL spectra from ZnO nanowires. Shaded areas indicate the energy range integrated in the inset whilst moving along the yellow line in (b). Red circles correspond to the large intensity peak shaded red whilst blue crosses indicate low intensity spectrum below inset shaded blue. (c) Depletion layer thickness dependence on nanowire diameter for nanowire cross sections of three nanowires. Different marker styles indicate different nanowires.

POSTER SESSION - III



Monolithically integrated core-shell GaAs-AlGaAs NW lasers on Si

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Low-dimensional nanoscale lasers like Nanowires (NWs) with their unique one-dimensional geometry and thus low loss single mode optical waveguiding have recently proven their huge potential with remarkably low threshold pump powers and lasing up to room temperature [1,2]. By using III-V semiconductor materials the on-chip implementation of coherent light sources on silicon substrates could be realized. The small footprint and enhanced lateral strain relaxation associated with the 1D geometry enables NW growth directly on silicon based photonic circuits, providing much scope for applications such as optical interconnects.

However, the low refractive index contrast between III-V NWs and the silicon growth substrate provides insufficient modal reflectivity to achieve lasing. So far, the NWs have been detached from the growth substrate and transferred onto a low-refractive index material to provide sufficient modal reflectivity at the end facets. Recently, monolithically integrated III-V nanopillar lasers have been demonstrated on silicon [3], however, their large geometrical footprints accompanied by multimode waveguiding leads to comparably low spontaneous emission factors $\beta \sim 0.01$ and, thereby, comparatively large threshold pump powers.

In this contribution we demonstrate operational NW lasers integrated directly on silicon substrates. The GaAs-AlGaAs core-shell NW lasers are grown using molecular beam epitaxy within nano-apertures defined in a ~200nm thick SiO_2 layer on silicon. To facilitate lasing operation, nano-apertures with a size below 100nm are appropriate to receive sufficient modal reflectivity at the NW- SiO_2 interface.

Exciting individual NWs optically, laser action at 10K can be observed. By detecting emission along the NW axis while exciting perpendicular to the NW axis, remarkably high spontaneous emission factors up to $\beta = 0.16$ were determined [4] (see figure). Measurements of the second order correlation function as a function of excitation level reveals bunching in the amplified spontaneous emission regime and $g^2(0)=1$ in the lasing regime. Comparing the experimental results (linewidth, modulation behavior) show an excellent agreement with the predictions of a rate equation model. Ongoing simulations, growth optimizations and further optical experiments implement InGaAs NW lasers on Si substrates. This material system has the potential to emit in the 1.3-1.55 μm gap and thus below the transparency limit of Si, enabling on-chip waveguiding.

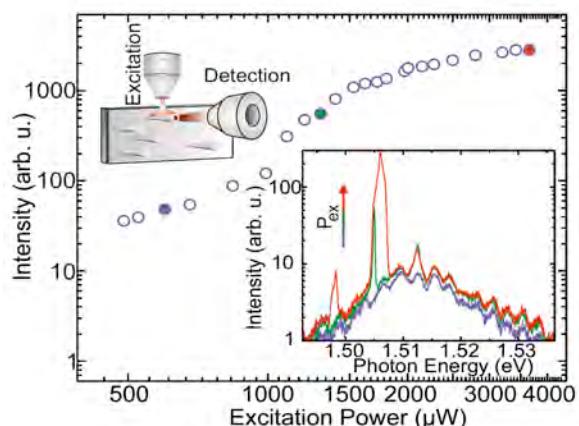


Figure - Typical input-output curve of a NW laser integrated on a silicon substrate (blue points) as obtained by in the two-axis measurement geometry. The inset shows typical spectra below (blue, $P/P_{\text{th}}=0.7$), at (green, $P/P_{\text{th}}=1.5$) and above threshold (red, $P/P_{\text{th}}=4.2$) on a log scale.

- [1] Mayer, B. et al. *Nature Comm.* **4**, (2013).
- [2] Saxena, D. et al. *Nature Photonics* **7**, 963-968 (2013).
- [3] Chen, R. et al. *Nature Photonics* **5**, 170-175 (2011).
- [4] B. Mayer, et al, submitted (2015).

Investigation of single objects in GaAs Nanowire ensemble measurements by x-ray diffraction

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X-ray diffraction is a powerful technique to study the crystal structure and even strain in nanowires (NWs) and our group has formerly performed x-ray diffraction on ensembles of NWs as well as single NWs[1]. By using a focused beam in addition to low density samples of GaAs NWs a diffraction signal associated with just a few NWs and nanoobjects was obtained. In this work we study the diffraction of single objects although we measured an ensemble of GaAs NWs.

The x-ray experiment has been performed at PETRA III synchrotron source (DESY), beamline P09, and a focused x-ray beam of $\sim 5 \times 5 \mu\text{m}$ spot size. With a photon flux of $\sim 10^{13}$ per second and a photon energy of 15keV we were able to resolve the GaAs symmetric (111) and (333) reflections as well as the asymmetric (422) zinc-blende Bragg reflection. The used GaAs NWs were grown onto Silicon (111) by a self-catalyzed method under an arsenic atmosphere by Gallium pre-deposition. A comparable high substrate temperature during growth leads to a small number density of vertically grown NWs (< 0.1 per μm).

Considering the high parallel incident beam and the fact that the grown NWs show always a small disorientation to each other the measured (422) Bragg reflection split into speckle like fractions associated with single NWs. Fig.1 shows up to 6 different spots along q_x direction of the (422) Bragg peak which can be assigned to different NWs. The study of these signals could lead to the mean zinc-blende segment lengths and structural information of the nanoobjects. Further investigation can combine this information with an insitu x-ray diffraction measurement that was done during NW growth of the same sample [P. Schroth, *et al*, at this conference].

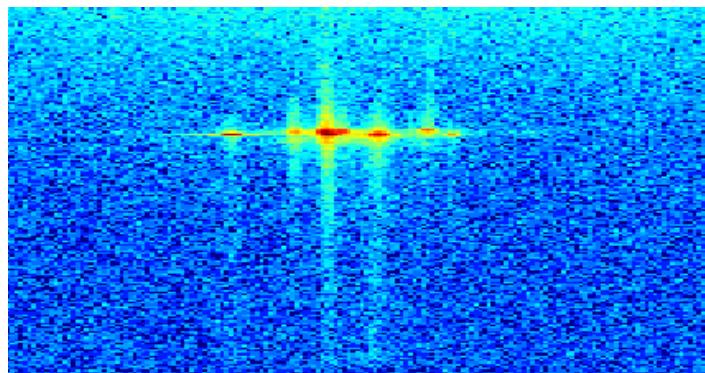


Figure 1: Diffraction signal of a small ensemble of GaAs NWs. Due to small disorientations between the single NWs the (422) Bragg peaks are shifted and single objects can be distinguished.

References

- ¹ A. Biermanns, *et al.*, *J. Appl. Cryst.* **45**, 239-244 (2012).

0D quantum emitters in ultrathin GaAs nanowires

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In this contribution, we present the optical properties of interesting quantum confinement phenomena of GaAs-AlGaAs core-shell NWs epitaxially grown on silicon with ultrathin GaAs core diameters below 10 nm.¹ The ultrathin NWs consist of mainly zincblende crystal (ZB) with occasional wurtzite (WZ) segments embedded along the NW axis. This produces a 0D quantum dot like (QD) potential, where the exciton is confined radially by thin NW diameter and axially by the band offset between WZ and ZB GaAs. Power dependent PL measurements show saturation of the PL intensity for higher excitation power and the appearance of higher charge states of the exciton. Time-resolved PL reveals that higher charge states of the exciton decay into the single exciton state. Time-correlated single photon spectroscopy exhibit a dip of the second order correlation function at zero time difference indicating that these QDs behave as a non-classical light emitter. Interestingly, we observe relatively short lifetimes below 1 ns, unlike lifetimes of several ns observed for excitons localized in WZ/ZB segments in thick GaAs NWs where electron and hole are spatially separated because of the type II band alignment between WZ and ZB. This indicates that either a transition from a type II to a type I band alignment between WZ and ZB GaAs is present because of the strong radial quantum confinement or that different mechanisms are responsible for the quantum confinement potential along the NW axis, such as monolayer thickness fluctuations. We have further investigated polarization and temperature dependent properties of these QD emitters.²

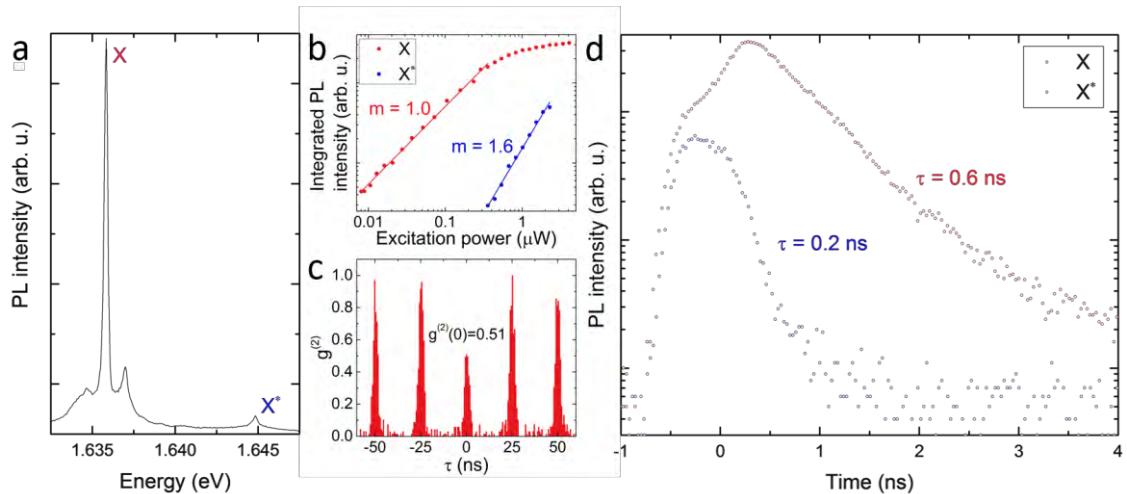


Figure 1. (a) PL spectrum of a QD emitter in the ultrathin NW core, where single and multiexciton are labelled as X and X*. (b) Extracted integrated PL intensity as a function of the excitation power for both charge states, X and X*. Solid lines are fits to the data using a power law function with exponent m. (c) Autocorrelation measurement of X under pulsed excitation. (d) Time evolution of the two charge states showing that X* decays into X.

References

¹ B. Loitsch, *et al.*, *Advanced Materials* **27**, 2195–2202 (2015)

² B. Loitsch, J. Winnerl, *et al.*, *in preparation* (2015)

Study of the Schottky barrier on single GaAs nanowires by X-ray PhotoEmission Electron Microscopy

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In order to use semiconductor nanowires (NWs) in devices, a specific characterization of the metal-semiconductor contact is fundamental. The Schottky barrier (SB) can be studied directly in devices analyzing the I-V or C-V characteristics. However, using X-ray Photoemission Spectroscopy (XPS) it is possible to investigate the early stages of the formation of the SB, obtaining complementary information that can help to understand the physics beneath the device operation. Nevertheless, due to the difficulty in performing measurements on NWs with lateral averaged and standard laboratory techniques, XPS has been scarcely employed to investigate SB formation on NWs[1].

Here, we present a study on the SB formation between single GaAs NWs and copper by the use of X-ray PhotoEmission Electron Microscopy (XPEEM). The measurements were carried out at the NanoESCA beamline of the Elettra synchrotron radiation facility (Trieste, Italy).

GaAs NWs were grown by MBE, using gold as growth seed. Tellurium or silicon was added during the growth to obtain *n*[2] or *p*[3] doping, respectively. The NWs were covered in the growth chamber by amorphous As, to keep their surface clean during the transfer process. Then, they were mechanically transferred from the growth substrate to a silicon wafer. The amorphous As was removed by an annealing at 350°C *in situ* right before the start of the measurements.

XPEEM images are obtained collecting electrons with well-defined binding energy. The image intensity is related to the lateral distribution and amount of the corresponding emitting element. By acquiring a stack of images taken at different binding energies we can extract photoemission spectra from individual NWs at increasing Cu coverage. A preliminary analysis of the data, using well-known relations[4], gives a Schottky barrier height of $q\phi_n=0.4$ eV and $q\phi_p=0.6$ eV for Te-doped and Si-doped GaAs NWs, respectively.

Being the NWs several μm long and tapered, the lateral resolution of our XPEEM (~ 70 nm) allows us to follow possible variation of the SB along the NW axis, as predicted by theoretical calculations[5]. The analysis of the axial dependence of the barrier is presently ongoing.

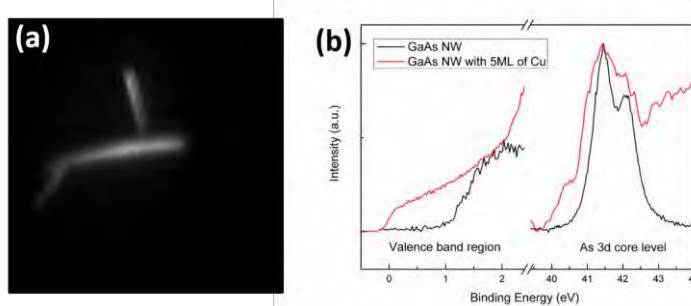


Figure 1: (a) XPEEM image at the energy of the As 3d core level that show three GaAs NWs on a Si substrate; (b) XPS spectrum of a single GaAs NW before and after the coverage with 5ML of Cu.

[1] S. N. Das *et al.*, Appl. Phys. Lett. **96**, 092111 (2010)

[2] J. Czaban *et al.*, Nano Lett. **9**, 148 (2009)

[3] M. Piccin *et al.*, Physica E **37**, 134 (2007)

[4] Y.-J. Lin, Appl. Phys. Lett. **86**, 122109 (2005)

[5] Y. Calahorra *et al.*, J. Appl. Phys. **117**, 034308 (2015)

Shell quantum dots in core-shell GaAs-AlGaAs nanowires studied by photoluminescence and cathodoluminescence

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Since a few years quantum dots (QDs) have attracted much attention as the most promising candidates for efficient and controlled single-photon sources and sensitive sensors. Their unique properties can be further enhanced when they are embedded in nanowires (NWs). For instance, the QD-in-NW configuration provides the possibility to overcome the low extraction of light emitted by QDs in planar devices⁽¹⁾ and can be exploited to obtain QD-based single-photon detectors with subwavelength spatial resolution⁽²⁾.

Here we study self-assembled QDs embedded in core-shell GaAs/Al_xGa_(1-x)As NWs^(3,4) obtained by molecular beam epitaxy (MBE). They show bright single-photon emission with narrow linewidth. Although it is clear that the QD formation is based on a segregation process happening in the shell, a complete understanding of the reason sparkling their nucleation is still lacking and needs further investigations. In addition, specific post-growth analysis is also required in order to reliably link the properties of the system with the growth conditions.

In this work, we present a study on the QD local emission properties based on low temperature micro-photoluminescence (PL) and cathodoluminescence (CL). PL provides the possibility to study several emitters in order to draw conclusions on a statistically founded dataset, while CL improves the spatial resolution of this technique. We find that a thickness threshold is necessary to observe QDs, whose occurrence increases in a non-monotonic way with increasing shell thickness. Simple engineering of the NW core-shell structure, such as the deposition of a thin AlAs layer between the core and the shell, enhances the QD presence. Emission-energy shifts are also observed and are linked with the shell thickness and QD position.

The observations with the two techniques are consistent. They are interpreted in function of the QD evolution with the shell growth. Therefore, this study can be regarded as a beneficial step towards the full comprehension of the QD formation that would eventually allow the precise control of the system in view of applications in optical devices.

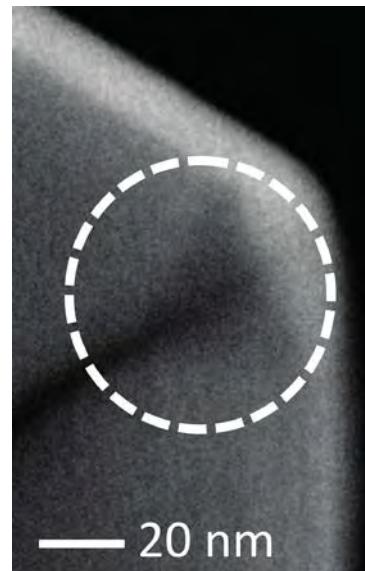


Figure 1: HAADF-STEM image of a NW cross-section zoom on the detail of a corner pyramidal QD, as shown in the dashed circle.

References

- ¹ J. Claudon, *et al.*, *Nature Photon.* **4**, 174 (2010).
- ² G. Bulgarini, *et al.*, *Nature Photon.* **6**, 455 (2012).
- ³ M. Heiss, *et al.*, *Nature Mater.* **12**, 439 (2013).
- ⁴ Y. Fontana, *et al.*, *Phys. Rev. B* **90**, 075307 (2014).

TOWARDS FLEXIBLE GAAS NANOWIRE-BASED SOLAR CELLS

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III-V nanowires (NWs) have a great potential for solar energy applications due to their exclusive optical properties enhancing absorbance of light. Core-shell radial p-i-n structures provide the orthogonal direction of light absorption to the carrier collection, therefore the minority carrier diffusion length can in all cases be shorter than the optical absorption length [1]. In this work, radial p-i-n GaAs nanowires (NW) were grown on p-doped (111) Si substrate by Molecular Beam Epitaxy (MBE) using self-catalysed method. By optimizing growth parameters and thickness of native oxide on Si substrate, self-assembled GaAs NWs were grown vertically with desired geometrical properties [2]. After growth, the NWs were embedded in Polydimethylsiloxane (PDMS), which is a transparent flexible polymer. For analysing radial p-i-n GaAs NWs as a solar cell structure, NW-PDMS composite was directly contacted from the top with transparent ITO. For developing flexible solar cells, NW-PDMS composite can be peeled from the substrate and contacted by transparent electrodes from both sides, as shown on the scheme in Fig. 1a. First attempts to develop flexible solar cells based on GaAs self-assembly nanowire array were made. A proof of concept is shown in Fig. 1b and 1c. Fig. 1d shows a cross-section SEM image of the developed pilot device structure on Si substrate. Finally, optical and electrical properties of GaAs NW based solar cell structure were analysed using different measurement techniques.

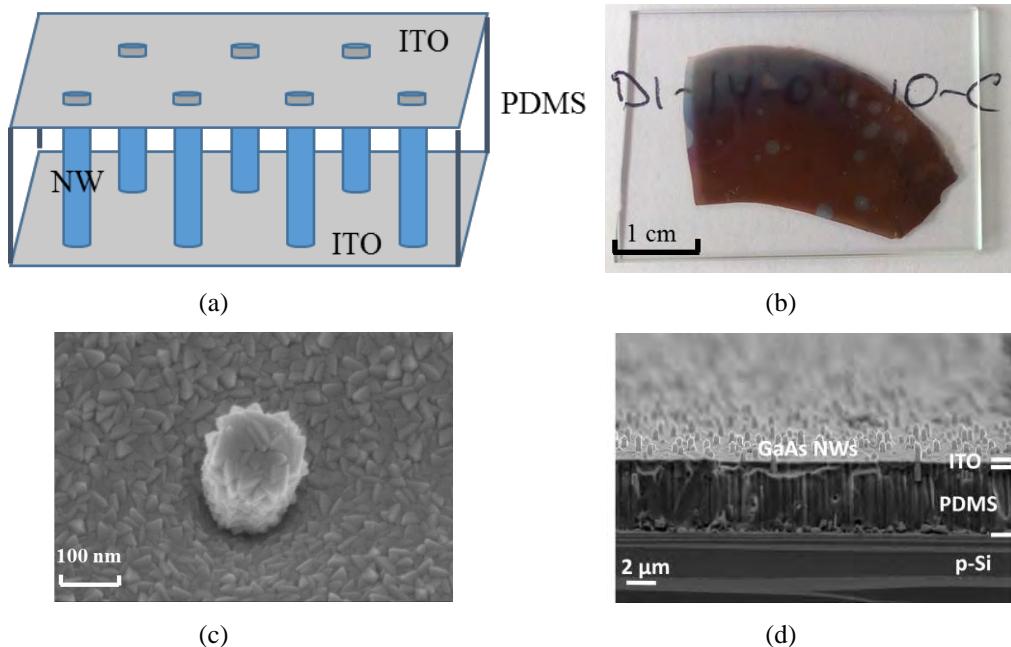


Figure 1: a) The scheme of GaAs NW based flexible solar cell; b) NW-PDMS composite; c) Top view SEM image of NW-PDMS surface covered by ITO; d) Cross-section SEM image of GaAs NWs embedded in PDMS and covered by ITO film

References

¹ P. Krogstrup et al, Nature Photonics 7 (2013) 306-310

² F. Matteini et al, Nanotechnology 26 (2015) 105603

Photocatalytic water splitting with GaAs nanowires

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The need of a clean fuel, coming from a clean production, brings the present research to focus on photocatalytic water splitting: obtaining fuel, as hydrogen, from solar energy.

Our project focuses on achieving water splitting with (Al)GaAs semiconductor nanowires grown on a silicon substrate (Fig.1). Nanowires are an ideal platform because their large surface/volume ratio enhances the overall reaction rates [1]. Furthermore, nanowires harvest light with a higher efficiency than other nano-structures and thin films thanks to their particular geometry [1]. Also, (Al)GaAs is a promising photoanode material for a water splitting device, thanks to the energy position of its band gap. For all these reasons, our project includes a physical and photo-electrochemical characterization of (Al)GaAs nanowires, as photoanodes in a water splitting devices.

Due to instability of GaAs-based compounds in aqueous environments, we present different ways to protect the (Al)GaAs nanowires from side reactions with electrolyte. We show different protective schemes that suit our application and that can be transferred to other unstable systems.

Finally we also show a new characterization technique targeting the probing of light-to-fuel conversion at the micro- and nano-scale. In order to achieve so, we have coupled a micrometer-sized probe in a Scanning Electrochemical Microscope with a light source. The probe consists on a nanometer/micrometer metal wire surrounded by an insulating shell, which is approached to the active surface in order to map its photocatalytic activity.

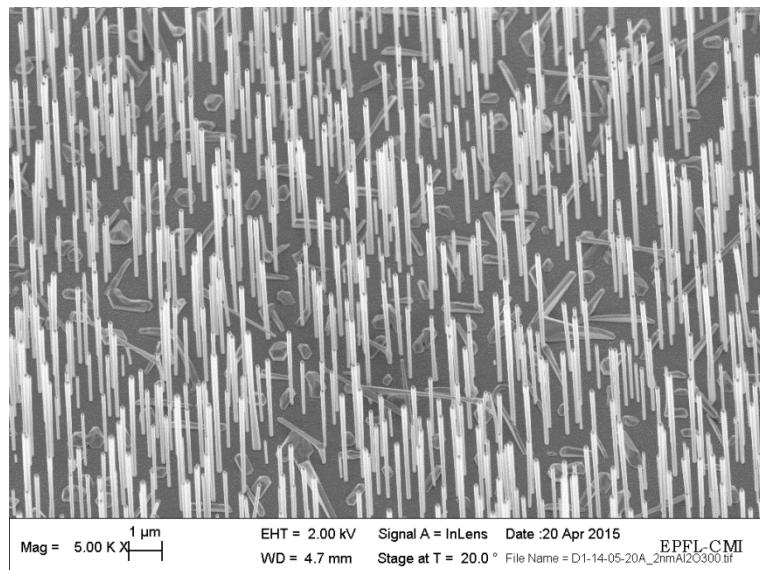


Figure 1: AlGaAs semiconductor nanowires grown on a silicon substrate.

References

- ¹ C. Liu, N.P. Dasgupta, P. Yang, *Chem of Mater*, **26**, 415-422 (2014).

Angle dependent magnetoconductance oscillations and Hall measurements in GaAs/InAs Core/Shell Nanowires

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GaAs/InAs core/shell nanowires are very interesting objects for studying magnetic flux dependent quantum transport phenomena, due to the fact that the low bandgap InAs shell forms a cylindrical tube-like conductor around the high bandgap GaAs core [1]. This allows the emergence of phase coherent transport phenomena, i.e. h/e flux periodic conductance oscillations [2].

In this contribution, we present angle dependent magnetotransport measurements of GaAs /InAs core/shell nanowires with Hall contacts at various temperatures in a magnetic field applied at different tilt angles relative to the wire axis. Thereby it is possible to measure the crossover from magnetoconductance oscillations (B_{\parallel}) to the regime of universal conductance fluctuations (B_{\perp}). A detailed analysis show indications of an anisotropic phase coherence length.

The same approach is also used to measure the Hall voltage in this nanowires for different temperatures and gate voltages to calculate the carrier concentration and mobility. We can show, that the quality of the hall signal is strongly affected by the size and the shape of the hall contacts.

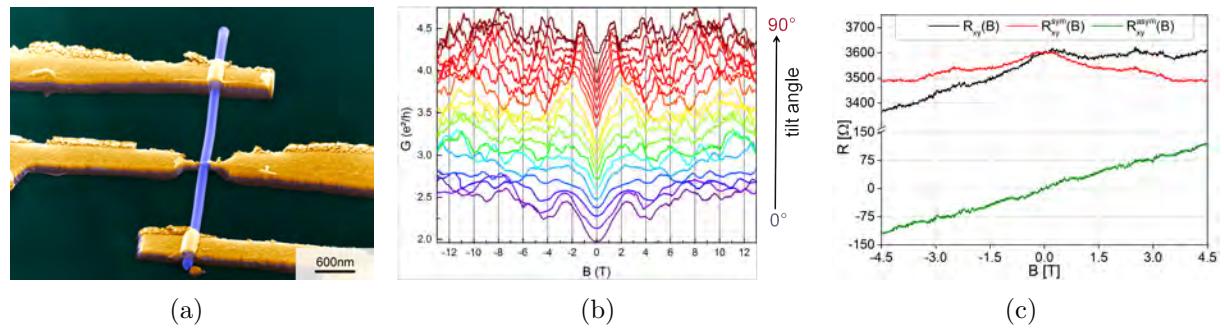


Fig. 1: (a) SEM picture of a GaAs/InAs core/shell nanowire with hall contacts. (b) Evolution of the magnetoconductance for rising tilt angles between the applied magnetic field and the wire axis. For B_{\parallel} , the classical background is superimposed by flux periodic oscillations. If $B(\alpha)$ comes closer to B_{\perp} , the periodic oscillations vanish and are replaced by universal conductance fluctuations. (c) Resistance across the two hall contacts [$R_{xy}(B)$] for $B = B_{\perp}$ and a current flow from source to drain. The splitting of the signal by performing an (anti-)symmetrization reveals a linear hall resistance [$R_{xy}^{asym}(B)$] on top of a symmetric background [$R_{xy}^{sym}(B)$].

[1] T. Rieger et al. (2012) Nano Letters **12**(11) 5559.

[2] C. Blömers et al. (2013) Nanotechnology **24** 035203.

Improved selective-area epitaxy using flexible UV-imprint lithography

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Many nanowire (NW)-based device applications require very strict control over position, density, uniformity and scalability of the NW structure, as in e.g. NW solar cells, detectors, vertical transistors, and nano-laser device structures. In addition, monolithic integration on Si platform is of further enormous relevance, demanding growth processing schemes that are compatible with standard CMOS-technology. Nano-imprint lithography (NIL) is coined a core technology in the future Roadmap of Semiconductors¹, as it holds the potential to pre-patterning Si substrate wafers in a cost-effective manner, i.e., both at large scale and with minimum fabrication time.

Here we show that by developing a state-of-the-art UV-imprint process we can significantly enhance the flexibility of NIL using a novel home-designed table top device. By producing NIL stamps with various patterns – easily available using standard electron beam lithography and reactive ion etching – full control over the inter-NW spacing can be achieved, while maintaining the great benefit of significantly faster substrate preparation. Being able to adjust the pitch of large scale NW arrays is a crucial prerequisite to further increase the efficiency of NW-based solar cells fabricated from InGaAs-InAlAs NW heterostructures², since the pitch strongly affects the absorption characteristics. Using optimized prepatterned SiO₂/Si(111) substrates, NW growth is performed in a completely catalyst-free growth regime via molecular beam epitaxy (MBE), allowing detailed insight into morphology and luminescence/absorption properties for different interwire-spacings. Adapting both the parameter for imprint procedure and growth conditions we can tune the pitch over two orders of magnitude (from 250nm to 10μm) while maintaining a high yield despite the significant change in filling factor and growth kinetics (i.e. from material to diffusion limited regime). This allows choosing the optimum geometry for the respective application like single NW spectroscopy or vertically integrated NW channels for transport measurements.

These findings will help to increase efficiency and scalability of novel NW-based opto-electronic applications especially in the field of photovoltaics and detectors.

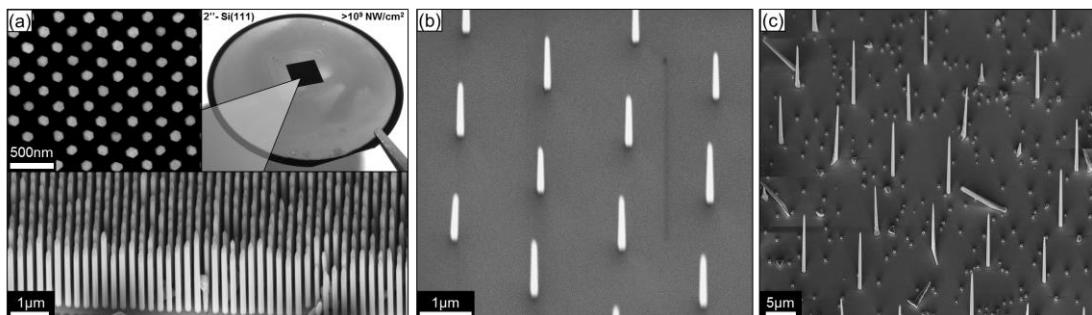


Figure 1: (a) Optimized selective area epitaxy of InAs NW on a 2'' Si(111) wafer using a pitch of 250nm. The black area of ~1cm consists of the NW shown in the SEM image in top and side view with a high yield above 90%. (b)-(c) NW grown with different interwire-spacings of 2μm and 10μm.

References

¹ International Technology Roadmap of Semiconductors (IRTS), www.itrs.net

² J. Treu, *et al.*, *Nano Lett.* 15, 3533 (2015).

NONLINEAR MECHANICAL MODE COUPLING AND QUANTUM DOTS IN GROWN GaAs NANOWIRES

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Because of their small dimensions and potentially defect-free growth, nanowire cantilevers are very promising as ultrasensitive force transducers for scanning probe microscopy. Moreover, nanowire heterostructures can host optically active quantum dots that can be coupled to the nanowire motion, making such nanowires monolithic hybrid systems. We observe nonlinear motion of nanowires and use it to demonstrate mechanical mixing as well as small signal amplification [1]. Furthermore, we find that the nonlinearity induces a coupling between motion in orthogonal modes [2]. Finally, we demonstrate that the nonlinear motion can be coupled to embedded quantum dots, opening the way to study the relatively unexplored interplay between nonlinear dynamics and quantum physics.

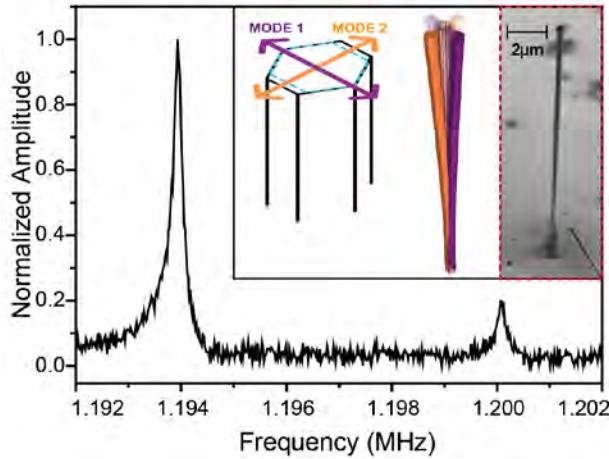


Figure 1: Frequency sweep of nanowire mechanical, at low driving amplitude. Two mode resonances can be distinguished. Inset: scheme of the direction of the two modes in a nanowire with a small asymmetry in the cross-section and a scanning electron micrograph of a GaAs nanowire with similar dimensions as the one investigated.

References

- ¹ F. R. Braakman, D. Cadeddu, G. Tütüncüoglu, D. Ruffer, F. Matteini, A. Fontcuberta i Morral, and M. Poggio, *Appl. Phys. Lett.* 105, 173111 (2014).
- ² D. Cadeddu, F. R. Braakman, G. Tütüncüoglu, D. Ruffer, F. Matteini, A. Fontcuberta i Morral, and M. Poggio, *Under Review for publication*

Electrical studies of controlled crystal polytypes in InAs nanowires for thermoelectric applications

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Through careful tuning of nanowire growth parameters, it is possible to grow III-V segments of different crystal phases within the same wire. [1] As such homostructures are composed of the same material, only with different crystal phases, relative differences in band structure and electronic properties are often smaller than in heterostructures of binary semiconductors. For InAs, theory predicts a 30-90 meV discontinuity between the conduction band energy of zinc blende and wurtzite. [2,3] In order to increase the efficiency of thermoelectric devices, insertion of interfaces or nanostructures with barrier heights of a few kT can filter low energy carriers to increase the thermopower without compromising the electrical conductivity. [4] Together with the low thermal conductivity of nanowires and high mobility of InAs, InAs nanowires containing crystal polytypes are therefore of interest for thermoelectric applications. [5]

In order to utilize III-V nanowire homostructures for thermoelectric energy filtering, it is important to experimentally verify the theoretical predictions for the properties of such homojunctions. As the wurtzite phase of InAs does not exist in bulk form, any information on conduction band energy offsets is also valuable for refining band structure models. However, due to the low expected conduction band offset, band-bending and tunnelling will strongly influence determination of barrier heights. In addition, the electronic properties of semiconductor nanowires are likely to depend on details in the native surface oxide. As a result, the few published experimental studies of InAs zinc-blende-wurtzite junctions have come to rather different conclusions. [6,7]

In this study we investigated transport in zinc blende InAs nanowires with wurtzite InAs insertion lengths varying from 10 nm to 320 nm. We performed temperature-dependent electrical characterization to study the relative roles of tunnelling and thermionic emission current across energy barriers created by the wurtzite segments. Through the application of a back gate voltage, the conduction band energy relative to the Fermi level can be modified, which affects band-bending and the relative strength of the two charge transport mechanisms. Based on electrostatic modelling of the band diagram, and extraction of barrier heights from the experimental data with a thermionic emission model, we can explain how the lengths of the wurtzite insertion affect transport for different Fermi level energies. The results are essential for understanding not only devices based on InAs homostructure nanowires, such as single-electron transistors and thermoelectric devices, but also for transport in random mixed-phase InAs nanowires.

References

- ¹ A. Dick, *et al.*, *Nano Letters* **10**, 3494 (2010).
- ² M. Murayama, *et al.*, *Physical Review B* **49**, 4710 (1994).
- ³ A. De, *et al.*, *Physical Review B* **81**, 155210 (2010).
- ⁴ J. Bahk, *et al.*, *Physical Review B* **87**, 075204 (2013).
- ⁵ P. Wu, *et al.*, *Nano Letters* **13**, 4080 (2013).
- ⁶ C. Thelander, *et al.*, *Nano Letters* **11**, 2424 (2011).
- ⁷ M. Hjort, *et al.*, *ACS Nano* **8**, 12346 (2014).

IV and III-V nanowires for efficient sunlight harvesting and conversion into fuel

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The large versatility of NWs makes them excellent candidates as building blocks for contributing to solving the energy problem in the near future.

One of the main characteristics of semiconductor NWs is their ability to act as optical antennas that exhibit absorption cross-sections larger than the geometrical ones. The light self-concentrating effect is a consequence from guided and leaky modes given in the nanostructures.

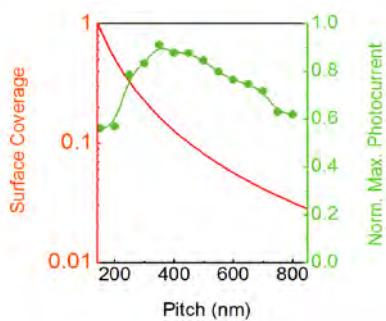


Figure 1. Maximum photocurrent obtained for GaAs NW array as a function of pitch distance and 1Sun illumination. Photocurrent is normalized to the thermodynamical maximum for GaAs. Red curve is the surface filling factor.

electrochemical reactions happen at the semiconductor surface. As a consequence, NWs enable the use of low-cost catalysts (e.g. MoS_x) even though they exhibit lower performances than noble metals (e.g. Pt). In order to assess the effects of nanostructuring photo-electrodes for solar fuel generation, we have studied photo-cathodes based on Silicon nanopillar structures. We observe that apart from antireflection properties, the fact of nanostructuring improves the onset potential, and thus the overall efficiency (see figure 2). By coating the surface with thin TiO₂ layers, the performance is further improved. We explain these findings by using an electro-kinetic model of the semiconductor-water junction. We find that the TiO₂ layers actually act as surface passivator and hole blocking layer, preventing recombination.

Optical resonances depend on NW geometry and dielectric environment. We have used finite-difference time-domain (FDTD) electromagnetic simulations to understand and design NW-based sunlight scavengers. For instance, a GaAs NW array that is only covering 3% of the surface can generate more photocurrent than a planar film, considering a 30% reflectivity (see figure 1). Also that thanks to optical resonances, an indirect-bandgap material such as Si is capable of absorbing most of the light within a 2um long NW array that only covers 7% of the device surface. In this work, we evaluate the NW array distribution effects on the overall efficiency in III-V on Silicon tandem solar cell devices.

On the other hand, solar energy can be directly converted into fuel (such as hydrogen) in a photoelectrochemical (PEC) cell. In this case, the large surface-to-volume ratio of NW forests is an important asset, especially since the

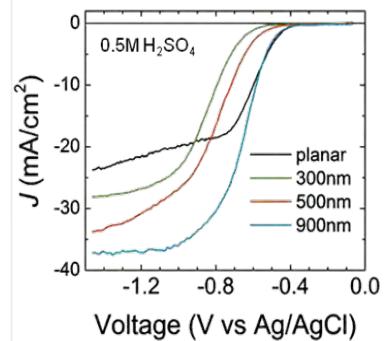


Figure 2. PEC performance of Si photo-cathodes with pillar diameter from 300 to 900nm under 1Sun illumination. Planar reference is also shown.

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Non-contact free carrier probing induced by photonic modes in suspended nanowires

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Thanks to its non-destructive and spatial resolution, micro-Raman spectroscopy is a powerful tool for the characterization of semiconductor materials. Recently this technique has also been applied to the characterization of nanowires. In particular, Raman spectroscopy can give information about crystallinity, orientation, size and chemical composition.^{1,2,3} In polar semiconductors it is also possible to detect free carriers, through the coupling with longitudinal optical modes.^{4,5} However, the LO mode is absent in zinc-blende {1-10} for back-scattering configuration, due to the selection rules. Nanowires with {1-10} facets which are horizontally lying on a substrate are therefore not expected to show the coupled mode.

In our previous work,⁶ we have shown that the Raman spectra is affected by the low dimension of the structures due to the presence of the photonic modes, in terms of local probing and selection rules. In this work, we take advantage of the presence of the photonic modes in nanowires in order to enhance the response of the longitudinal optical phonon mode.

We compare the Raman scattering response of GaAs nanowires lying on a Si substrate and suspended over a trench in back-scattering geometry. We have found the presence of LO mode for an incident polarization perpendicular to the nanowire, which is not expected from the Raman selection rules. Moreover, we have found that its intensity depends on the photonic environment, i.e. the intensity is enhanced in the suspended nanowires. Our observation can be explained by a change of the direction and polarization of the internal field with respect to the macroscopic one.

Thanks to the enhancement of the LO mode by the trench, we are able to detect free carriers in p-type and n-type nanowires in back-scattering geometry.

References

- ¹ E. Anastassakis, *et al.*, *J.Appl. Phys.* **82**, 1582 (1997).
- ² S. Hernández, *et al.*, *J.Appl. Phys.* **98**, 013511 (2005).
- ³ D. Spirkoska, *et al.*, *Nanotechnology* **19**, 435704 (2008).
- ⁴ A. Pinczuk, *et al.*, *Sol.State Comm.* **21**, 956 (1977).
- ⁵ B. Ketterer, *et al.*, *Nanoscale* **4**, 1789 (2012).
- ⁶ F. Amaduzzi, *et al.*, *J.Appl. Phys.* **116**, 184303 (2014).

Hybrid Devices – Transport measurements on GaAs/InAs core/shell nanowires with superconducting contacts

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GaAs/InAs core/shell nanowires are very interesting objects for quantum transport measurements due to their electron confinement inside the InAs shell. In recent publications we have shown, that these InAs nanotubes allow the observation of h/e flux periodic oscillations in the magnetoconductance, when a magnetic field is aligned parallel to the nanowire axis.^{1,2} Furthermore we have shown that flux periodic oscillations with $h/2e$ period can also be observed with GaAs/InAs core/shell nanowires contacted by superconductors.³

In this contribution we present transport measurements on GaAs/InAs core/shell nanowires with a new superconducting contact design shown in figure 1. This contact design allows us to measure the topological properties of the junction by choosing contact pairs of different geometrical alignment on the nanowire. We observe $h/2e$ flux periodic oscillations over all contact pairs with amplitude of the order $\sim e^2/h$, thus two orders of magnitude higher than with normal Ti/Au contacts. This strong enhancement of the oscillation amplitude can be explained by phase-coherent Andreev reflections at the interface between superconducting contacts and nanowire. At the interface electron-hole trajectories, enclosing the penetrating magnetic flux, interfere positively and as a consequence enhance the oscillation amplitude. This effect is called reflection-less tunnelling and can be understood as a standing wave in a resonator.

Beside the flux periodic oscillations we present indications of Andreev reflection at all three contact pairs, as well as their magnetic field and temperature dependencies.

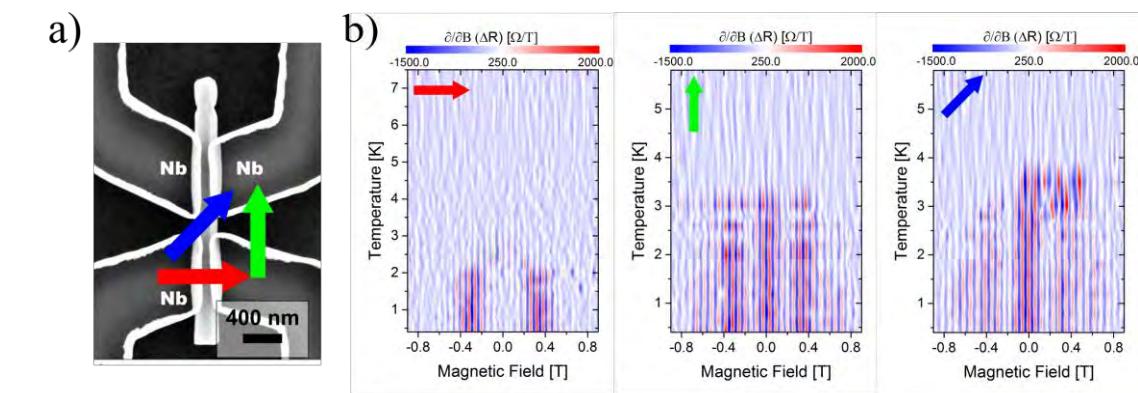


Figure 1: (a) SEM image of the measured nanowire structure. Three contacts with all different possibilities were used for the presented measurements, indicated with coloured arrows. (b) Flux periodic oscillation in the magnetoresistance for all the contact pairs.

References

- ¹ T.Wenz, *et al.*, *Applied Physics Letters* **105**, 113111 (2014)
- ² C. Blömers, *et al.*, *Nanotechnology* **24**, 035203 (2013)
- ³ Ö. Günel, *et al.*, *Nano Letters* **14**, 6269-6274 (2014)

Scattering infrared near-field optical investigations of local free charge carrier concentrations in contacted InAs nanowires

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Due to the high surface to volume ratio of nanowires (NWs), their properties are strongly dependent on their surface. Thus, surface states play a major role in their overall electrical characteristics. Standard electrical measurements unfortunately only provide an insight into the NW properties as a whole or in segments between contacts. However, scattering type scanning near-field optical microscopy (s-SNOM) is capable of locally resolving (≈ 10 nm) the dielectric function of a sample illuminated by suitable infrared light close to the plasma frequency. Using the Drude model, it is then possible to extract the free charge carrier concentration [1]. This technique can be employed as a control for the changes in conductivity affected by chemical passivation treatments or by backgate electrostatic effects.

The effect of sulfide based surface passivation on electrically contacted InAs nanowires (NWs) was investigated by an s-SNOM to determine the changes in the spatial charge carrier concentration. Highly doped InAs NWs were deposited onto a back-gated SiO_2 covered Si substrate and electrically contacted to a sample holder developed specifically for the use with an s-SNOM. The infrared experiments were supplemented by room temperature transport measurements to obtain the global specific resistance and charge carrier concentration before and after the passivation treatment. With s-SNOM imaging we observed charge carrier concentrations in the order of $n \approx 5 \times 10^{18} \text{ cm}^{-3}$ for non-passivated samples, which is consistent with the incorporated doping [2]. Slight variations in the spatial charge carrier concentrations were also observed along the NW. More systematic field-effect transistor measurements, passivation effects and spectroscopic investigations are ongoing and will be presented.

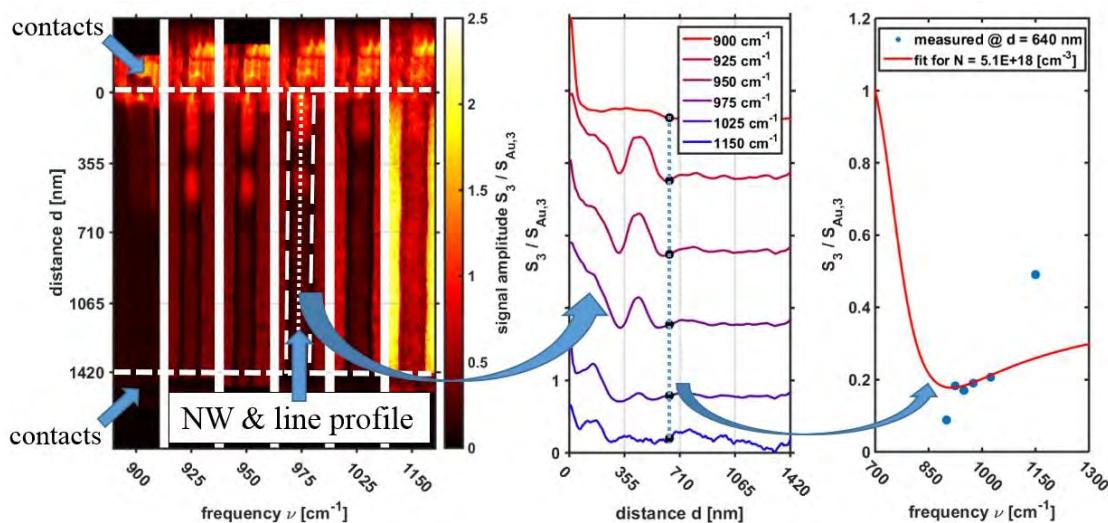


Figure 1: Spectroscopy of the normalized signal amplitude imaged by s-SNOM along a contacted InAs nanowire. Variations of the signal amplitude and phase (not shown here) along the NW are attributed to local variations in free charge carrier concentration.

References

- ¹ B. Hauer, et al., *Nano Lett.*, **15** (5), 2787-2793 (2015).
- ² S. Wirths, et al., *J. Appl. Phys.*, **100**, 053709 (2011).

Tunneling magnetoresistance in silicon nanowires

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Magnetic tunnel junctions are the basic elements in modern magnetic sensors and magnetic data storage systems. They consist of ferromagnetic electrodes separated by a thin tunnel barrier. When the magnetization of the electrodes changes from antiparallel to parallel the resistance of the junction can drop, which results in tunnelling magnetoresistance, $TMR = [I_P - I_{AP}]/I_{AP}$, where I_P (I_{AP}) corresponds to the parallel (antiparallel) value of the current through the junction.

It has been proved that the presence of spin scattering drastically decrease the magnetoresistance. Due to quantum confinement, semiconductor nanowires show reduced spin scattering and therefore are potential components for magnetic tunnel junctions. In particular, silicon nanowires are interesting due to their compatibility with the mature silicon technology and have been adapted in a variety of nanoscale devices (transistors, photodetectors, solar cells). The ability to control the diameter, composition and length makes silicon nanowires a desirable platform for spintronics. The dependence of the transport on the structure of the nanowire has been studied in Ref. [1]. Here we present a study of the tunneling magnetoresistance of small diameter H-passivated silicon nanowires between iron electrodes, using density functional theory (SIESTA package [2]). Electron transport calculations are performed using the non-equilibrium Green's function approach as implemented in the SMEAGOL package [3], which is interfaced with SIESTA.

For magnetic tunnel junctions formed by $<110>$ silicon nanowires sandwiched between iron electrodes, we find evidence of spin injection represented by a high tunneling magnetoresistance, see Figure 1. At the Fermi energy the magnitude of the magnetoresistance is about 200%. The current-voltage characteristic resembles the intrinsic behavior of semiconducting nanowires for a small-applied bias, whereas the magnetoresistance is almost completely suppressed for high bias. The effect of *n*-type and *p*-type doping is discussed as the modified carrier concentration potentially affects the spin injection. The effect of the nanowire growth direction is also analyzed.

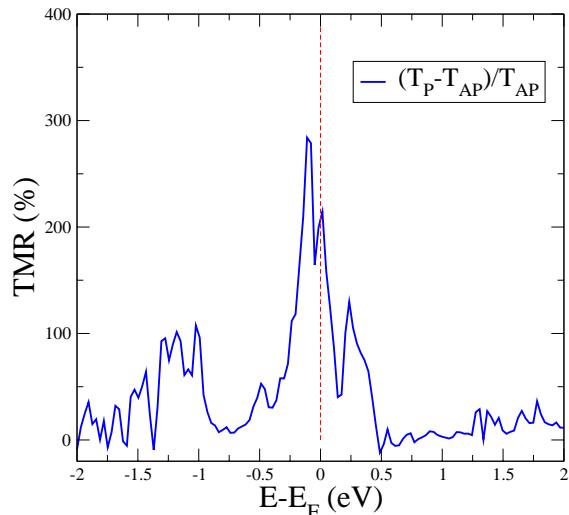


Figure 1: TMR of a magnetic tunnel junction formed by a $<110>$ silicon nanowire sandwiched between iron electrodes.

References

- ¹E. Montes, K. Gkionis, I. Rungger, S. Sanvito and U. Schwingenschlögl. *Phys. Rev. B* **88**, 235411 (2013).
- ²D. Sanchez-Portal, P. Ordejón, E. Artacho, and J. M. Soler, *Int. J. Quantum Chem.* **65**, 453 (1997).
- ³A. R. Rocha, V. M. Garcia-Suarez, S. W. Bailey, C. J. Lambert, J. Ferrer, and S. Sanvito, *Nat. Mater.* **4**, 335 (2005).

Highly sensitive 3D silicon nanowire sensors for ppb levels detection of NO₂

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The atmosphere is a complex natural gaseous system that is essential to support life. Stratospheric ozone depletion due to air pollution has been recognized as a threat to human health as well as to the ecosystems. Some of the most prominent gaseous air pollutants are SO_x, NO_x, CO, NH₃ and VOCs, all mainly produced by human activity. Moreover the ability to monitoring the air quality is essential to prevent health effects.

Regarding the NO₂, which reacts with the intern mucus membrane of lungs, and produces nitric acid, the recommended long period exposure is below the olfactory level (300ppb). Most commercial sensors, using metal oxide as sensitive layer, have two drawbacks: sensitivity in the ppm range and global power consumption. One-dimensional nanostructures, such as nanowires¹, hold a great potential for the new generation of high sensitive sensors, nevertheless very few demonstrations showed such a benefit, with sub-50 ppb sensitivity^{2,3}.

Here, we report 3D devices (Fig1.a) based on silicon nanowires (SiNW) for chemical gas sensing, working at room temperature. This sensor combines for the first time high sensibility, selectivity, reversibility, low-power consumption, reliability and low-cost large scale fabrication. Under controlled atmosphere, the sensor demonstrates high sensitivity and selectivity, by discriminating NO₂ and NH₃ without being interfered with CO and C₃H₈ (Fig1.b). A very high response (30%) is obtained at 50 ppb of NO₂. Compare to the state of the art, 25% reached for 200 ppb³, this significant response indicates that the lowest detectable NO₂ concentration by our device is greatly below 20 ppb. In addition, the recovery of the sensor is achieved naturally at room temperature, without flushing³ or specific illumination² for the NO₂ molecules desorption, with reliability over 6 months.

The SiNW are developed through a top down approach: combination of photolithography to control the number, spacing and position of each nanowire and so achieve a high reproducibility and sacrificial oxidation to tune the diameter. The device is composed by two symmetrical aluminium contacts (low access resistance) at each extremity of the NWs, including a top contact done by air bridge approach (Fig 1.c). In addition, this CMOS approach is top-down and bottom-up compatible, leaving a choice for the selection of appropriate materials in function of the target species.

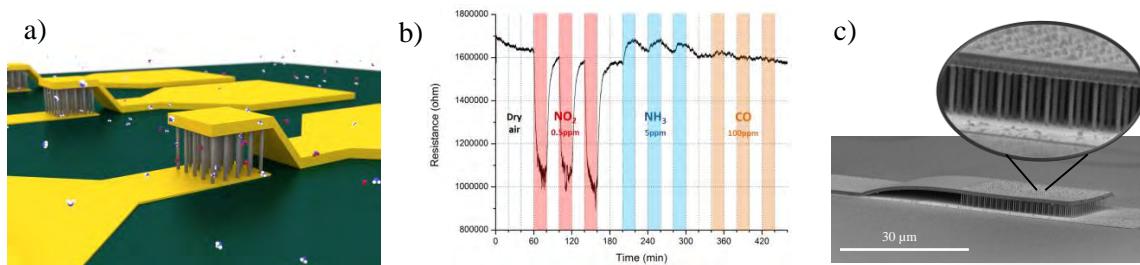


Figure 1: a) 3D model; b) Response of the device to NO₂, NH₃ and CO; c) SEM picture of the sensor.

References

- ¹ N. S. Ramgir, *et al.*, *Small*, **vol. 6**, no. 16, 1705–1722 (2010).
- ² D. Zhang, *et al.*, *Nano Lett.*, **vol. 4**, no. 10, 1919–1924, (2004).
- ³ M. C. McAlpine, *et al.*, *Nat. Mater.*, **vol. 6**, no. 5, 379–384 (2007).

Hybrid solar cells using nanocrystalline Si quantum dots and Si nanowires

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Si solar cells with radial junction nanowire (NW) arrays offer the opportunity to use lower-grade Si wafers to produce efficient solar cells, due to the decoupling of charge carrier collection and light absorption directions with enhanced light trapping, thus resolving the drawbacks of bulk Si solar cells. Recently, non-radiative energy transfer (NRET) has been proposed for hybrid nanostructures that combine absorbing components (e.g., quantum dots (QDs)) with high-mobility semiconducting channels.¹ Use of colloidal semiconductor nanocrystals in these hybrids provides the advantage of absorbing a wider range of the solar spectrum than Si layers are able to; and exploiting the NRET process can overcome the limitations of low charge transfer efficiency in charge transfer-based devices. Long-range dipole-dipole interaction in NRET hybrids can exceed both short range charge transfer and radiative energy transfer (RET). The experimental evidence has been observed in hybrid semiconductor heterostructures under optical excitation between a single semiconductor nanostructure and an adjacent layer of organic molecules or colloidal QDs. In this work, we introduce a new energy transfer -mediated 12.9%-efficient all-Si solar cell structure.

The n-type SiNW arrays were fabricated by metal-catalyzed electroless etching using n-type (100) Si substrates (Fig. 1(a)). The p-type Si shell layer was formed by CVD (Fig. 1 (b) and (c)). The nc-Si QDs capped by 1-octadecene shown in Fig. 1 (d) were then spin-coated onto the top layer of cells. Finally, hybrid solar cells were formed as shown in the inset of Fig. 1 (e).

Figure 1 (e) shows the I-V characteristic curves for the hybrid nc-Si QDs modified radial p-n junction thinner Si solar cell under 100 mW/cm² illumination by an AM 1.5G solar simulator in comparison with that of the solar cell without QDs. The J_{sc} for the hybrid cell increased from 32.67 to 38.70 mA/cm² with an overall power conversion efficiency improvement of 10.9% to 12.9%, indicating the contribution arising from the presence of nc-Si QDs. Realization of the contributions from NRET and RET from nc-Si QDs to the Si layer was demonstrated by time-resolved photoluminescence (PL) decay measurements. The PL decay curves clearly revealed the presence of an extra energy transfer channel in the hybrid structure and showed that the NRET rate is ~ 1.6 times faster than RET rate to the underlying Si layer. Hence, our data shows the possibility of NRET from nc-Si QDs to SiNW solar cells.²

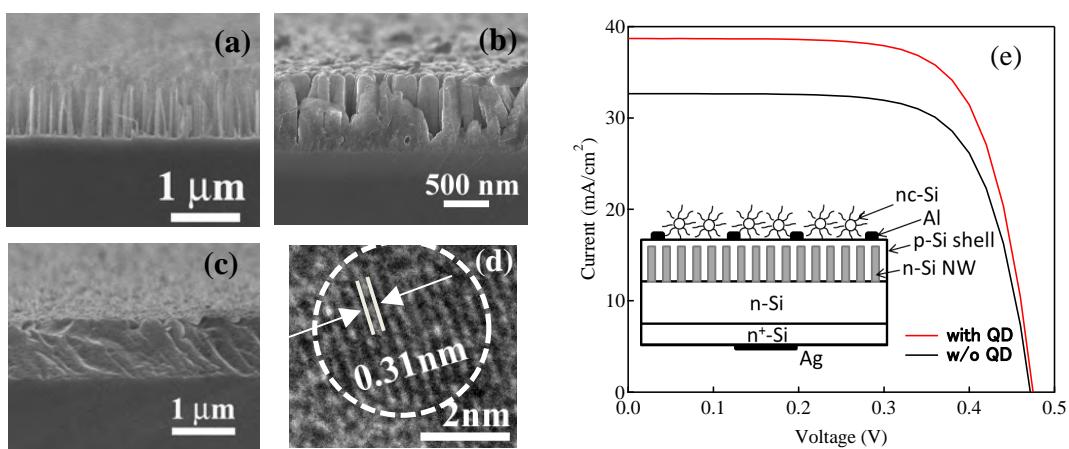


Figure 1. (a) Cross-sectional SEM image of SiNW arrays. (b) and (c) corresponding structures after 5 min and 3 min of shell growth respectively. (d) Representative HRTEM images of 1-octadecene capped nc-Si QDs. (e) Current-voltage characteristics of SiNW array solar cells with and without nc-Si QDs. Inset is a schematic diagram of the n-SiNW arrays embedded in a p-Si matrix solar cell.

References

- ¹ S. Lu et al., *Nano Lett.* **7**, 3443 (2007)., ² M. Dutta et al., submitted

Radial Stark effect in (In,Ga)N nanowires

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Spontaneously formed (In,Ga)N nanowires (NWs) offer a bandgap tunable across the visible spectral range, which, together with the large surface area, makes them an attractive candidate for the electrode material in photoelectrochemical water splitting.¹ However, the pinning of the Fermi level at the surface of NWs may strongly affect their optical and electrical properties. We study the combined role of the resulting radial electric fields and compositional fluctuations in the ternary alloy (In,Ga)N on the emission properties in unintentionally doped and Si-doped $\text{In}_x\text{Ga}_{1-x}\text{N}$ NWs with a low In content ($x < 0.2$) grown by molecular beam epitaxy.

The emission band observed at room temperature for the unintentionally doped $\text{In}_x\text{Ga}_{1-x}\text{N}$ NW ensembles is centered at about 800 meV lower energies than expected from the In content measured by x-ray diffraction and energy dispersive x-ray spectroscopy. Figure 1(a) shows the photo-luminescence (PL) spectra of an undoped NW ensemble as a function of temperature. At low temperatures, an additional peak appears at an energy close to the expected bandgap of the alloy. The evolution of the energy (E) and intensity (I) of the two emission bands is illustrated in Fig. 1(b). For the low energy band, the intensity quenches strongly between 10 K and 100 K, is almost constant up to 150 K, and decreases at higher temperatures. In contrast, the intensity of the high energy band is continuously quenched with increasing temperature and is strongly reduced at room temperature. This behavior can be explained considering the competition between spatially direct (high energy) and indirect (low energy) recombination channels, which is a result of the combination of the built-in electric fields with the compositional fluctuations inherent to (In,Ga)N alloys. The spatially indirect transitions experience a radial Stark shift up to several hundreds of meV. At cryogenic temperatures, electrons and holes are distributed uniformly across the NW diameter, enabling both direct and indirect transitions. With increasing temperature (up to 125 K), electrons are delocalized towards the core of the NW, which favors the direct transition and leads to the step in I_{low} in Fig. 1(b). At further elevated temperatures, also holes are delocalized and the indirect transition between electrons at the core and holes close to the surface of the NWs dominates. This interpretation is supported by time-resolved PL measurements and an analysis of the temperature-dependent PL spectra for samples with various Si concentrations.

We propose that the radial Stark effect contributes to the experimentally observed broadband absorption of (In,Ga)N NWs across the entire visible range,¹ which makes these nanostructures a promising platform for solar energy applications.

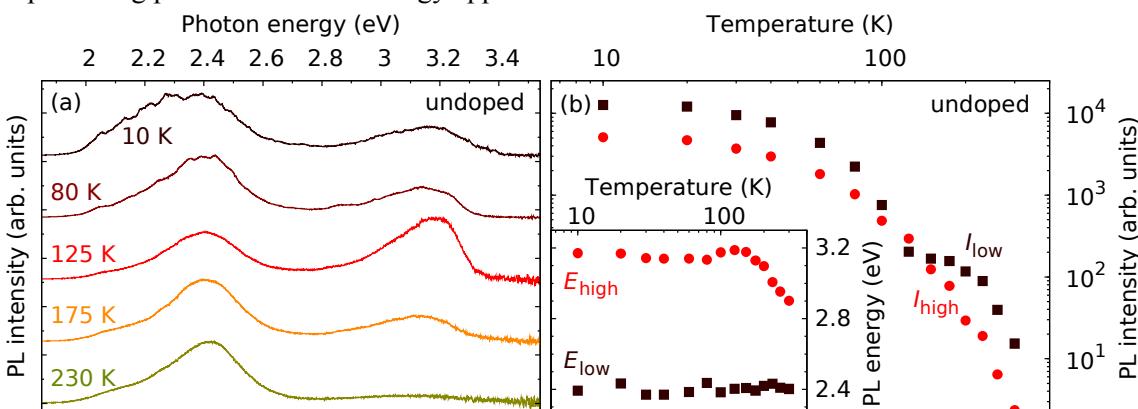


Figure 1: (a) PL spectra for temperatures between 10 and 230 K of the undoped $\text{In}_x\text{Ga}_{1-x}\text{N}$ NWs with $x = 0.06$. The two emission bands centered around 2.32 and 3.12 eV show a different quenching behavior of the intensity with temperature as highlighted in (b) by the spectrally integrated intensities I_{low} and I_{high} of the two bands. The inset in (b) shows the evolution of the PL peak energies E_{low} and E_{high} .

References

- ¹ J. Kamimura *et al.*, *J. Am. Chem Soc.* **135**, 10242 (2013).

Luminescence dynamics of core-shell InGaN/GaN micro- and nanowire LED structures

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GaN is an efficient and widely established material for optoelectronic devices and sensors, especially for light-emitting diodes (LEDs). Three-dimensional core-shell GaN-based micro- and nanowires with embedded InGaN multi-quantum-well structures (MQW) on non-polar sidewalls are promising candidates to further improve the efficiency and tailor the spectral range of LEDs and lasers in the green to ultraviolet spectral region. The large area of the active layers in the 3D structures in relation to the surface area of the substrate is a further significant advantage of the wire structures.

We study the optical properties of micro- and nanowire structures produced by two different MOVPE growth mechanisms. One sample was fabricated by continuous selective-area growth (SAG) through a SiO_x mask on GaN/sapphire. The other samples were grown by self-organisation with a nucleation layer in a vapour-liquid-solid (VLS) growth mode on sapphire. We use time-integrated photoluminescence (PL) measurements to analyse the concentration and homogeneity of the indium, and we study the temperature dependence of the luminescence dynamics of the InGaN MQWs in time-resolved experiments using a femtosecond laser system and a streak camera (time resolution < 10 ps) in order to characterise the fundamental optical relaxation and recombination processes.

All samples show a characteristic decay time of the InGaN PL between 60 and 80 ps at room temperature, while the decay time at 12 K is 170 ps up to 300 ps. The maximum of the InGaN luminescence shifts to lower energies with increasing temperature for all analysed samples. The time-resolved PL spectra show an additional red-shift of the PL maximum after excitation which points to different relaxation processes of the excited electron-hole pairs at different spectral positions. This effect is most pronounced at higher temperatures and can be attributed to thermally activated trap centres that substantially influence the relaxation and recombination processes of the charge carriers and therefore also the quantum efficiency of the LED structures at higher temperatures. We developed a phenomenological rate-equation model to simulate the PL transients under different excitation conditions.

In order to extend the available wavelength region and to achieve selectivity in sensing devices, coatings of the micro- and nanowire structures with organic perylene dyes or colloidal nanoparticles are promising approaches. We show first results of the optical characterisation of such dyes, nanoparticles and hybrid samples.

Polarity studies of GaN nanowires by scanning probe microscopy

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The development of polarization-based devices or the generation of electricity in piezotronic energy-harvesting systems based on GaN and ZnO nanowires (NWs) are two examples of emerging fields of research exploiting the pyroelectric and piezoelectric properties of these materials. Since the specific polarity strongly affects the optical and electronic properties of NWs, reliable methods for its control and characterization are needed. In this work we have investigated the polarity of GaN NWs grown by molecular beam epitaxy obtained by two different growth methods and presenting opposite polarities: self-assembled NWs grown on Si with an AlN buffer [1]; and selective area growth (SAG) NWs grown on a GaN template covered with a Mo mask [2]. We have employed three complementary scanning probe microscopy techniques: Kelvin probe Force Microscopy (KPFM), light-assisted KPFM, and Piezoresponse-Force Microscopy (PFM). KPFM allows the assessment of the polarity of individual NWs from large images in terms of the local contact potential difference (CPD), and provides statistics on the polarity of the ensemble with an accuracy hardly reachable by other methods (resolution~50 nm). In spite of their wide distribution of heights, most self-assembled NWs have homogeneous CPD values around 0.75 V which are compatible with N-polarity (Fig. 1 (a) and (b)). SAG NWs, on the other hand, present Ga-polarity as deduced from their CPD in the range 0.3-0.5 V. The pyramid edges and apex of these NWs appear at lower CPD values indicating a higher density of dangling bonds (Fig. 1 (c) and (d)). Light-assisted KPFM provides the evolution of the CPD with time under illumination by ultraviolet light and in dark. From these measurements the surface photovoltage (SPV), defined as the change in CPD induced by light, is determined. Our measurements are performed on untreated NWs and keeping the tip and the NWs under feedback. Finally, PFM has imaged self-assembled NWs with a Ga-polar core and an N-polar shell. In this technique, while the Ga-polar material vibrates almost in phase with the modulation voltage applied by the tip, the N-polar regions appear 100° out of phase. Our results are in agreement with the core-shell structures observed in similar samples by annular bright field high resolution scanning transmission microscopy images [1].

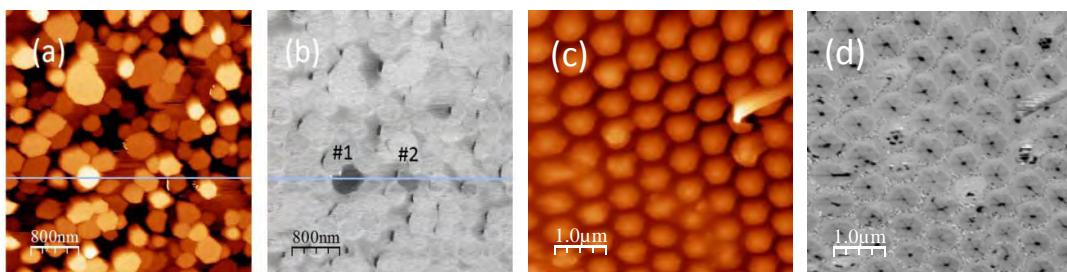


Figure 1: (a) AFM topography and (b) CPD maps of self-assembled GaN NWs. Gray scale spans from 0 to 1 V. Darker NWs (#1 and #2) present opposite polarity. (c) AFM topography and (b) CPD images of SAG GaN NWs. Gray scale from -1 to 1 V. Negative CPD is obtained for the protuberant GaN material, identified as zinc-blende material.

References

- ¹ T. Auzelle et al., J. Appl. Phys. 117, 245303 (2015)
- ² A. Urban et al., New J. Phys. 15, 053045 (2013)

GaN nanowires based piezogenerator

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Semiconductor nanowires (NWs) presenting piezoelectric properties have recently emerged as excellent candidates to fabricate novel ultra-compact and high-efficient piezoelectric generators. Thanks to their superior mechanical properties (larger elastic deformation, higher flexibility and resistance), higher sensitivity to applied force and higher piezoelectric response¹ with respect to bulk materials, the NWs possess three essential properties to fundamentally improve the mechanical-electrical energy conversion. In particular, among different piezoelectric semiconductors, GaN NWs are materials of choice to fabricate high-efficient piezo-generators due to their strong piezoelectric coefficients and their high electric generation potential.

The piezoelectric properties of PA-MBE grown GaN NWs were investigated by atomic force microscopy (AFM) equipped with an adapted home-made Resiscope module for local electrical characterization. Under external mechanical solicitation of the nanostructures, an average output voltage about -236 mV and a maximal value reaching $-443 \text{ mV} \pm 2\%$ ² were measured. This latter value is the highest reported so far for GaN NWs. Based on the measured output signal, we have estimated that the average power densities generated by one optimized layer of GaN NWs may reach tens of mW/cm^2 . This result evidences the strong potential of GaN NWs to convert a mechanical deformation into electrical energy.

These promising GaN nanostructures have been integrated into a first piezogenerator device (Fig. 1a) and tested by using a cyclic flexion strain setup to ensure the mechanical deformation (substrate plus the GaN NW array).

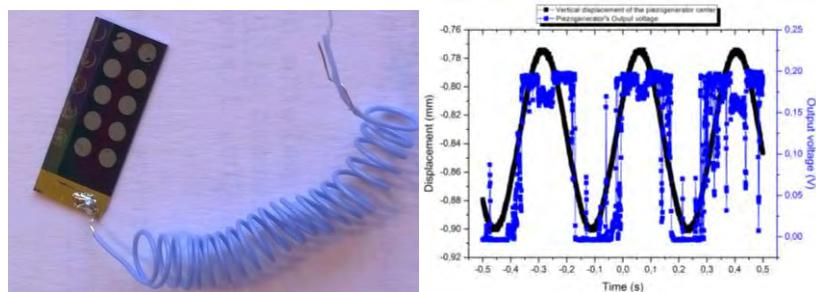


Figure 1: a) GaN NWs based piezogenerator prototype, b) Output voltage generation

Figure 1b presents the output voltage generated by the piezogenerator in response to its deformation (substrate plus the GaN NW array). A maximal output voltage of about 200 mV is measured for a deformation force of 1.5 N. The estimated power density reaches a value of the order of $1.3 \mu\text{W/cm}^2$. Although this result is lower than the above-mentioned prediction based on AFM measurements, it is at the state of the art³ for GaN NWs-based piezo-generators. It demonstrates the feasibility of ultra-compact and integrable renewable energy sources for sustainable, independent and maintenance-free operation of micro-devices. Further improvement of the piezoconversion is expected with organized nanowire arrays, which are currently under optimization.

References

¹ N. Minary-Jolandan *et al.*, *Lett.* **12**, 970 (2012)

² N. Gogneau *et al.* *Phys. Stat. Sol.* **8**, 414-419 (2014)

³ C.-Y. Chen *et al.* *ACS Nano* **6**, 5687 (2012)

In-depth physical description of the current conduction in light-emitting diodes based on (In,Ga)N/GaN nanowire ensembles

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III-N nanowires (NWs) are an attractive alternative to conventional planar layers as the basis for light-emitting diodes (LEDs), since the NW geometry enables the growth of (In,Ga)N/GaN heterostructures with high In content on cost-effective Si substrates in high crystal quality. The current-voltage (I-V) characteristics of a LED contain much useful information about the charge carrier transport dynamics and the recombination mechanisms. Nevertheless, the analysis of the I-V curves is often tricky. For LEDs based on NW ensembles this analysis becomes even more difficult because of their three-dimensional nature and the lack of appropriate characterization tools for the estimation of doping level, In content and charge carrier mobilities.

In this study we present an in-depth investigation of the electrical properties of NW-LEDs grown on Si by molecular beam epitaxy. The leakage current mechanisms were analysed by studying the temperature dependent I-V (I-V-T) curves in reverse bias, where the parasitic effects dominate the charge transport. Deep level transient spectroscopy measurements reveal the presence of different band gap states with high density ($\approx 5 \times 10^{17} \text{ cm}^{-3}$), which likely originate from nitrogen antisite point defects inside the NWs, boundary dislocations at the edge of coalescing NWs, and/or dangling bonds present on the free sidewalls. We developed a physical model that takes into account the different deep levels and describes quantitatively the peculiarities of the I-V-T characteristics of the NW-LEDs in reverse bias regime [see Fig. 1(a)]. The reverse leakage current can be described by the interaction of two competing mechanisms: variable range hopping and emission from Coulomb centres located roughly 570 meV below the conduction band edge. The latter is described as the sum of two contributions defined by phonon-assisted tunnelling and the Poole-Frenkel effect.

In addition, we propose an original interpretation of the I-V curves in forward bias regime. Specifically, we take into account that NW ensemble LEDs consist of many individual nano-devices contacted in parallel. To this end, we introduce in the Shockley equation an ideality factor that depends on the average properties of the individual nano-LEDs. Thus, I-V curves of NW-LEDs with different densities of contacted nano-devices are well fitted [see Fig. 1(b)].

Our in-depth analysis provides a better understanding of the operation principles of LEDs based on NW ensembles in general, regardless of the type of semiconductor employed.

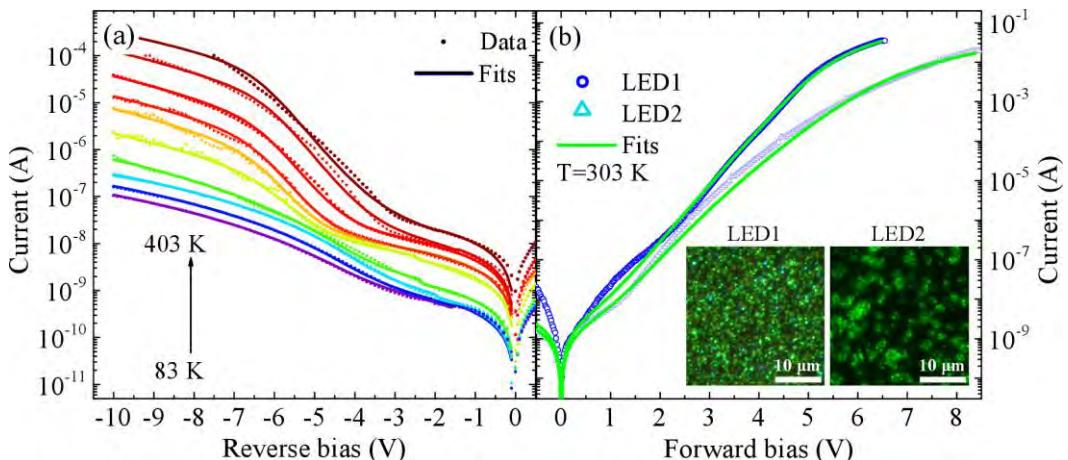


Fig. 1: (a) I-V curves in reverse bias (data points) and fits (solid lines) for temperatures increasing from 83 to 403 K (from bottom to top). (b) Room temperature I-V characteristics in forward bias (data points) and fits (solid lines) of two NW-LEDs with different density of contacted nano-LEDs. The inset shows top-view electroluminescence maps of the two devices acquired under an applied bias of +6 V.

Tunable optical absorption resonances in wurtzite and zinc blende GaP nanowire arrays

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Nanowires allow for the tuning of the performance of optical devices through the nanowire geometry and the crystal phase of the nanowire material. Here, we experimentally and theoretically study the tunability of the absorption spectra of vertical zinc blende and wurtzite GaP nanowire arrays as a function of nanowire diameter and length. We found for both polytypes an absorption peak that blue-shifts into the ultraviolet when decreasing nanowire diameter. The absorption peak in the zinc-blende GaP nanowire arrays stops blue-shifting at $\lambda \approx 330$ nm with decreasing diameter. In strong contrast, for the smallest-diameter of wurtzite GaP nanowires we succeeded in fabricating, the absorption peak still continues to blue-shift at $\lambda \approx 330$ nm. Since we compared zinc blende and wurtzite nanowires of similar dimensions, this difference in the resonant response shows that the optical response of the zinc blende GaP material must differ from that of the wurtzite GaP material. Thus, these findings show that the dielectric function of zinc blende GaP differs from that of wurtzite GaP. This crystal-phase dependent difference is so large that it can, as demonstrated, affect the ability to excite optical resonances, similar to the situation for InP polytypes¹ as well as for InAs polytypes.²

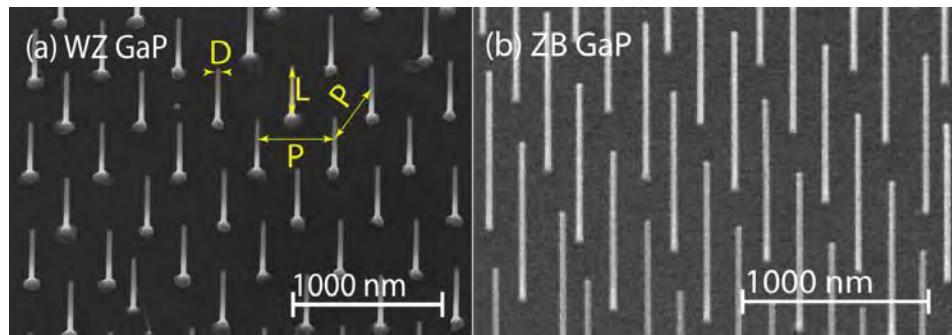


Fig. 1. 30° tilted scanning electron microscopy top view image of a periodic array of (a) wurtzite GaP nanowires of 32 ± 2 nm in diameter and 1270 ± 37 nm in length and (b) zinc-blende GaP nanowires of 34 ± 1 nm in diameter and 1700 ± 42 nm in length. Here, the uncertainty denotes the standard deviation in the determined dimensions of approximately 50 nanowires for each array.

References

¹ M. Aghaeipour, *et al.*, *Opt. Express* 22, 29204-29212 (2014).

² N. Anttu, *et al.*, *Nano Lett.* 14, 5650-5655 (2014).

Coherent Single Charge Transport in MBE-Grown InSb Nanowire

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III-V semiconductor nanowires have unique properties, such as a narrow bandgap, strong spin-orbit interaction, and a small effective mass, and therefore, have the potential applications in nanoelectronics and optoelectronics [1]. InSb nanowire-based quantum devices have been the recent focus of an extensive research effort in exploring novel topological quasiparticle state. [2-3].

Here, we report fabrication and low-temperature electrical transport studies of InSb nanowires grown by molecular beam epitaxy (MBE). Individual nanowire devices exhibit Coulomb blockade oscillations characteristic of single charge transport on length scales up to 700 nm. Detailed finite-bias transport measurements demonstrate coherent electron transport through discrete quantum levels. In the few electron regime, strong signatures of higher order inelastic cotunneling occur which can directly be assigned to excited states. With this spectroscopy we extract the main characteristics of a single InSb nanowire, namely, the Landé g factor and the the magnitude of the spin-orbit interaction. We also present experimental studies of devices composed of an aluminum superconductor in proximity to single InSb nanowire. We observed gate-tunable supercurrent flowing through the InSb nanowire and multiple Andreev reflection characteristics.

Our results exhibit that the InSb nanowires can provide a promising platform for exploring quantum transport and topological electronics in a solid state system.

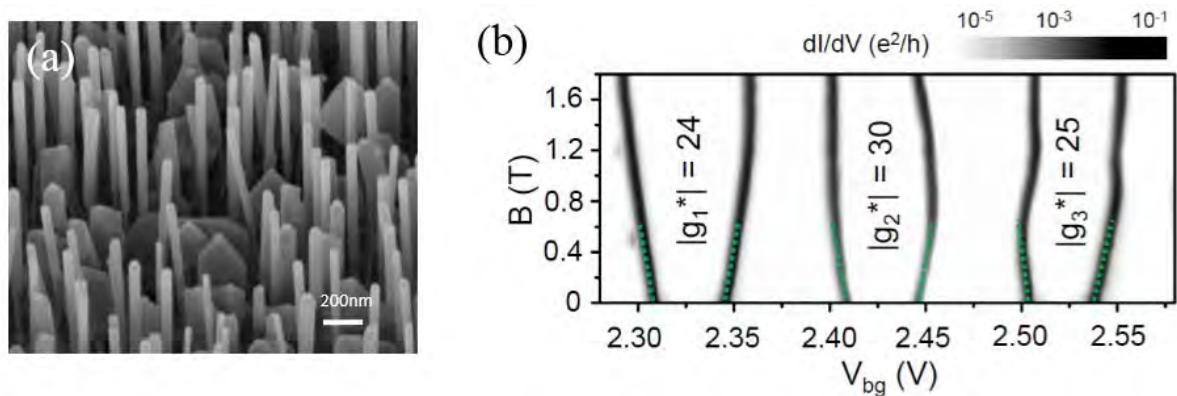


Figure1: (a) SEM image of InSb nanowires grown on a InP substrate. (b) Gray Scale plot of magnetic field evolution of the differential conductance measured in the linear response regime.

References:

- [1] L. B. Wang, J. K. Guo, N. Kang, Dong Pan, Sen Li, Dingxun Fan, Jianhua Zhao, and H. Q. Xu, Appl. Phys. Lett. 106, 173105 (2015).
- [2] V. Mourik, K. Zuo, S. M. Frolov, S. R. Plissard, E. P. A. M. Bakkers, and L. P. Kouwenhoven, Science 336, 1003 (2012).
- [3] M. T. Deng, C. L. Yu, G. Y. Huang, M. Larsson, P. Caroff, and H. Q. Xu, Sci. Rep. 4, 7261 (2014).

Polarized Light Absorption in Wurtzite InP Nanowires

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Ensembles of III-V nanowires (NWs) are a cost-effective option for light conversion-based devices. However, formation of wurtzite (WZ) phase and polytypism (WZ and zincblende, ZB, co-occurrence) is quite common in these NWs, and to achieve optimal device performance its effect on the NW electronic properties needs to be thoroughly understood.

Here, the electronic band structure of InP NWs with WZ phase has been investigated in well-aligned ensembles by polarization-resolved photoluminescence excitation (PLE) at $T=10$ K [Figure 1 (a)]. The wavelength-dependent degree of linear polarization (ρ_{abs}) mirrors the symmetry of the three highest valence bands involved in the A, B, and C transitions and discloses the subtle, yet important role played by excitons on the NW optical dispersion and absorption.¹

Moreover, quantitative analysis of the photoluminescence (PL) and PLE spectra recorded in the $T=10$ -310 K temperature range [Figure 1 (b)], reveals that the A, B, and C transitions have the same temperature dependence, which is similar to that found for the band-gap transition in ZB InP [Figure 1 (c)].² This provides insight into the lattice thermal expansion and the extent of the electron-phonon interaction. These findings could be used to improve the design of NW-based thermoelectric devices.

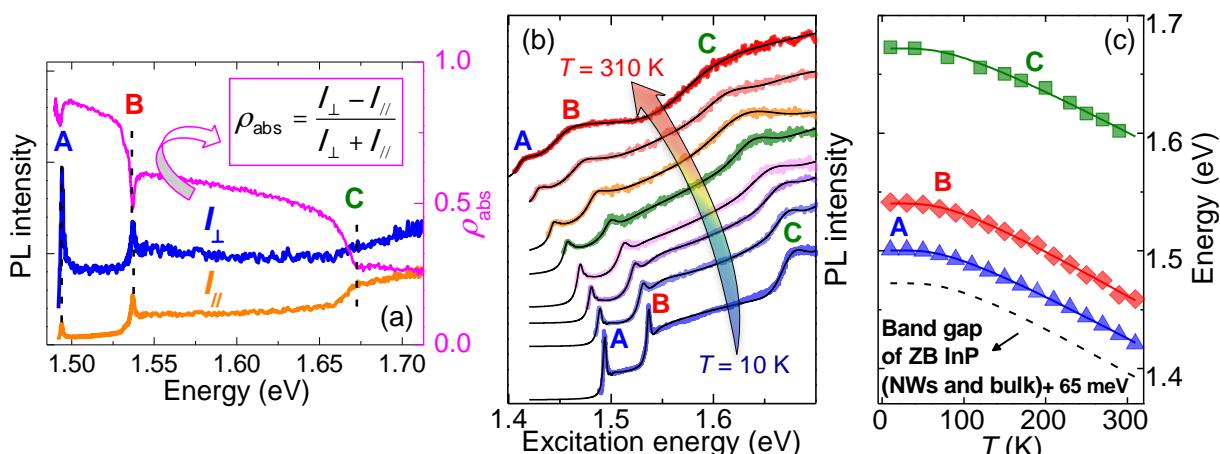


Figure 1 (a) PLE spectra recorded for exciting photons having polarization vector orthogonal (blue line) or parallel (orange line) to the NW \hat{c} axis, and resulting degree of linear polarization ρ_{abs} (pink line). A, B, and C label the three main excitonic resonances associated to transitions A, B, and C pertaining to the WZ band structure. (b) PLE spectra (thick lines) recorded from 10 to 310 K. Thin lines are fits to the data taking into account both exciton and continuum states. (c) Thermal shift of A, B, and C transitions (full symbols and lines) in WZ InP NWs and of band-gap transition (dashed line) in ZB InP (NWs and bulk) as determined by fits to temperature-dependent PL and PLE spectra.

References

¹ M. De Luca, *et al.*, *Nano Lett.* **15**, 998 (2015).

² A. Zilli, *et al.*, *ACS Nano* **9**, 4277 (2015).

Carrier Recombination Dynamics in Sulfur Doped InP Nanowires

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ABSTRACT: Studying recombination dynamics of photo-generated charge carriers in semiconductor nanowires (NW) is essential for their applications such as solar cells and photodetectors. At the same time it is essential for understanding the fundamental processes related to element composition and the role of surfaces of these new structures. We have investigated the dynamics of photo-generated charge carriers in a series of as grown InP NW with different sulfur (S) doping levels. Time resolved photo-induced luminescence (TRPL) measurements have been employed to investigate radiative and non-radiative charge recombination processes. We observe that the PL decay time as well as the time- and wavelength- integrated PL intensity decreases with increasing S-doping. We attribute these observations to trapping of photo-generated holes which is well in line with our earlier conclusions on the low quantum yield (Q) of PL in this type of NWs¹. We observe that trapped charges recombine non-radiatively on much longer time scale. The PL decay rate in the NWs with low S concentration has been also found to be dependent on the excitation pulse photon density and repetition rate. We assign this effect to saturation of long lived hole traps. This model is supported by our finding of trap saturation observed in PL pump-probe experiment. Trap saturation was found to require higher excitation power densities for higher S-doping level of the InP NWs. We correlate this observation to a much higher number of traps and a faster non-radiative recombination of photo-generated charges in those NWs. Thus, we conclude that S doping introduces additional traps to InP NWs, reducing the PL lifetime and overall intensity.

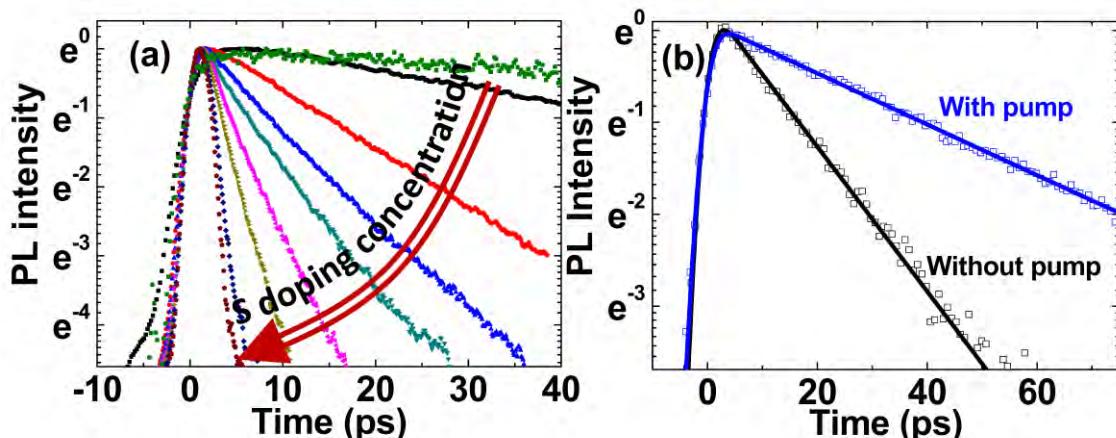


Figure 1: (a) TRPL decay of InP NWs with different sulfur contents as a function of time after photo-excitation at 400 nm (3.1 eV). (b) TRPL decay (probe) of low S doping concentration NW with (blue) and without (black) pump excitation corresponding to the black data in (a).

References

¹Iqbal, A.; Beech J. P.; Anttu, N.; Pistol, M.-E.; Samuelson, L.; Borgström, M. T.; Yartsev, A. Nanotechnology 2013, 24, 115706.

Improved Fermi-level splitting enables InP nanowire solar cell with 19% efficiency

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Solar cells based on III-V nanowires have proven to be promising, but efficiencies have so far been limited to 13.8%¹. We measure the quasi-Fermi level splitting of etched InP nanowires using PL efficiency measurements. By using etched nanowires, we can compare the quasi-Fermi level splitting in NWs with planar InP originating from the same MOVPE grown wafer. This indicates that the V_{oc} of nanowire solar cells is potentially about 75 mV higher than the V_{oc} of planar devices. The higher V_{oc} in NWs can be explained due to the concentration of light inside the nanowires. These measurements clearly prove that the large surface area of a nanowire is not detrimental for solar cell performance. We subsequently demonstrate a single junction InP nanowire solar cell with an energy conversion efficiency of 19.07%, approaching the record efficiency for bulk InP. The nanowire solar cell has been created by etching nanowires from a planar solar cell. We show that the conical geometry of the etched nanowires allows for a photocurrent close to 30 mA/cm^2 , which approaches the fundamental limit for InP of 34.5 mA/cm^2 . Our work shows that nanowire solar cells have the potential to outperform planar solar cells, both in terms of photocurrent and V_{oc} .

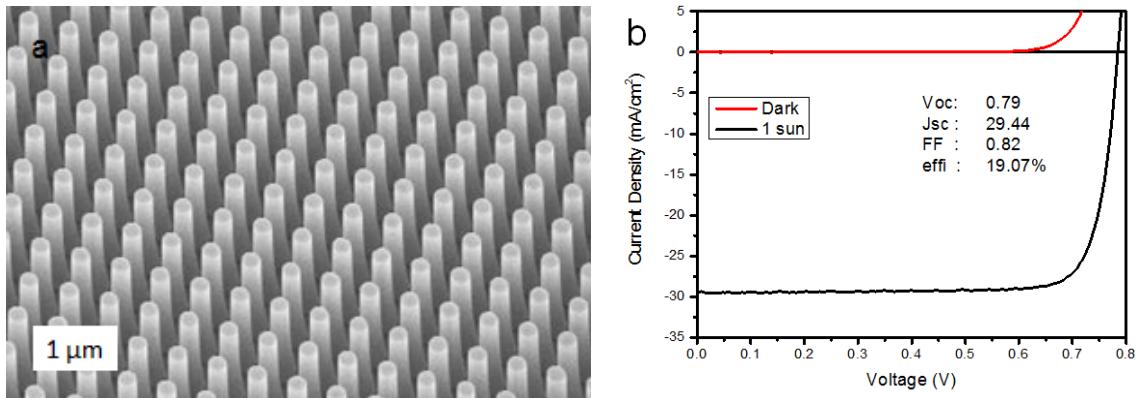


Figure 1: a) etched nanowire array. b) J-V curve of nanowire solar cell under dark and 1 sun illumination

References

- ¹ J.Wallentin *et al. Science* **339**, 1057-1060 (2013).

Hybrid Semiconductor Nanowire–Metallic Yagi-Uda Antennas

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Semiconductor nanowires are an excellent platform for optoelectronic and photonic applications because of their unique optical properties. The possibility of controlling their composition, geometry, and crystallographic morphology opens up a great freedom in designing different devices with desired properties. The photoluminescence properties of nanowires and the coupling of their emission to leaky and guided modes in being intensively studied.^{1,2} In addition, the coupling of nanowires with plasmonic nanostructures modifies their optical properties.³

In the past decade many efforts have been done to enhance the efficiency and modify the direction of the emission of quantum emitters. Yagi-Uda optical antennas are an example of a structure showing a pronounced directionality of the emission. In this system, the emission of a single quantum emitter couples to the antenna feed element, which is a metallic nanorod acting as a half-wavelength dipole nanoantenna. The permittivity of noble metals and the size of the nanorods lead to plasmonic resonances in the visible range of the electromagnetic spectrum. These resonances modify the spontaneous emission rate of the nearby emitter. Subsequently, the scattering of the feed element emission with the antenna elements and the interference of this scattered radiation in the far-field give rise to a strong directional emission. This emission can be controlled by the resonant response of the elements forming the Yagi-Uda antenna and their spacing.

In this contribution, we demonstrate a hybrid semiconductor–metal Yagi-Uda antenna.⁴ This hybrid system is realized by replacing the resonant metallic feed element of the Yagi-Uda by a non-resonant semiconductor nanowire. The non-resonant emission from the nanowire is not a limitation for the strong directional emission of the Yagi-Uda antenna. To demonstrate the strong dependence of the emission with the antenna parameters, we have fabricated two devices with different dimensions to direct the emission in opposite directions. These results can be exploited for the development of electronically driven optical Yagi-Uda antennas for directional single photon emission.

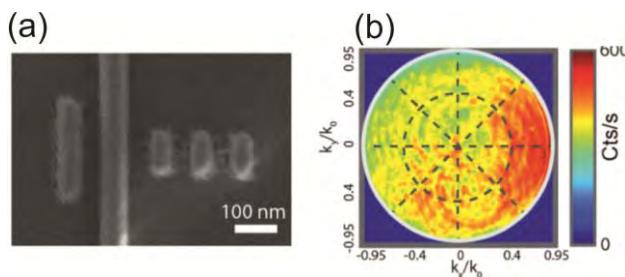


Figure 1: (a) SEM image of a hybrid GaAs nanowire-metal Yagi-Uda antenna. (b) Polar plot of the directional photoluminescence of the hybrid Yagi-Uda antenna.

References

- ¹ G. Grzela, *et al.*, *Nano Lett.* **14**, 3227 (2014).
- ² R. Paniagua-Dominguez, *et al.*, *Nanoscale* **5**, 10582 (2013).
- ³ O.L. Muskens *et al.*, *Opt. Lett.* **32**, 2097–2099 (2007).
- ⁴ M. Ramezani *et al.*, *Nano Lett.* DOI:10.1021/acs.nanolett.5b00565 (2015).

Aharonov-Bohm oscillations and electron gas transitions in hexagonal core-shell nanowires with an axial magnetic field

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The magnetoconductance properties of InAs/GaAs core-shell nanowires (NWs) under axial magnetic fields have recently received noticeable attention,^{1,2} revealing field-periodic magnetoconductance oscillations. The latter, assigned to Aharonov-Bohm (AB) periodic modulations of the electron energy spectrum due to the tubular shape of the conducting channel, have been exclusively analysed approximating the device (NW + back-gate) as a cylindrical system. Therefore, both the real NW hexagonal cross-section as well as the potential induced by the back-gate voltage were neglected.

In this contribution we go beyond simple cylindrical³ and non-interacting⁴ models and perform a spin density functional theory calculation in a hexagonal domain that preserves the discrete symmetry of the system.⁵ Our calculations explain why AB magnetoconductance oscillations are observed in experimental devices with back-gates (Fig. (b)), in spite of the asymmetric voltage potential, and predict symmetry induced vanishings of the oscillations under specific gate-all-around voltages (Fig. (a)). The electronic system is shown to undergo different direct Coulomb and localization regimes as the magnetic field is increased up to the complete depletion limit. Abrupt transitions between the different Coulomb regimes occur at discrete magnetic fields when the system gets, first, spin-polarized and, second, exclusively formed of electrons from the first Landau band. These transitions show up as kinks in the subband spectrum (Fig. (c)), total electron density and free energy; and step-like magnetoconductance drops (Fig. (d)).

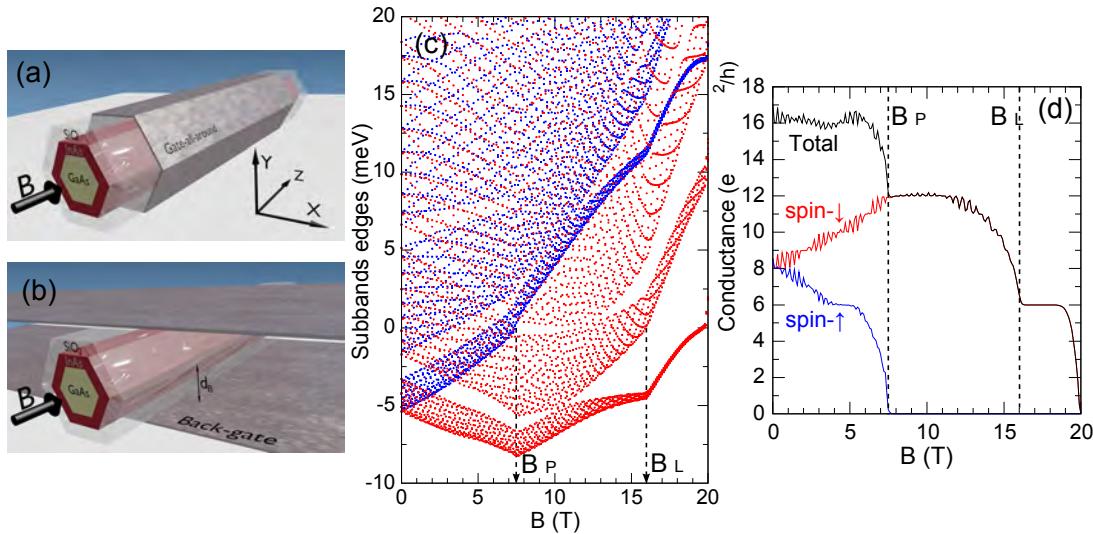


Figure 1: (a) gate-all-around and (b) back-gate core-shell NW device configurations, (c) spin-subbands edges energies as a function of the applied field, (d) total and spin-resolved magnetoconductance.

References

- ¹ Ö. Güл, et al., *Phys. Rev. B* **89**, 045417 (2014).
- ² Ö. Güл, et al., *Nano Lett.* **14**, 6269 (2014).
- ³ T.O. Rosdahl, et al., *Phys. Rev. B* **90**, 035421 (2014).
- ⁴ G. Ferrari, et al., *Nano Lett.* **9**, 1631 (2009).
- ⁵ M. Royo, et al., *Phys. Rev. B* **91**, 115440 (2015).

Nanowire Photoconductive Detectors for Terahertz Time-Domain Spectroscopy

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Terahertz time-domain spectroscopy is a powerful optical tool for investigating ultrafast phenomenon in a variety of materials. Traditionally, photoconductive antenna based on Auston-type switches¹ on bulk semiconductor have been employed for coherent detection of terahertz pulses, however, interest in near-field optics has prompted the development of new materials for this application.

Single nanowires have several properties which are advantageous for use in near-field photoconductive antenna detection. In particular, their inherently nanoscale dimensionality, high carrier mobility² and tuneable (surface recombination dominated) photocarrier lifetime² provide great promise for incorporation into time-domain spectroscopy applications. Here, we present the development of such antenna based on a number of nanowire types with different optoelectronic properties³. The antenna are fabricated on quartz substrates using either a direct laser write technique⁴, or traditional photolithography, enabling single nanowire devices to be prepared. Figure 1 shows a typical layout and microscopy image of a fabricated device.

We have investigated the performance of such single nanowire detectors relative to conventional devices³. While the device sensitivity was found to be lower, and antenna resonances play a role in the spectral response of such detectors, the devices are shown to operate well over an effective detection range. Coupled with their potential as near-field detectors, single nanowire detectors have a promising future.

We will also present recent work on optimizing the antenna geometry and nanowire properties, providing a route towards higher sensitivity and broadband terahertz performance.

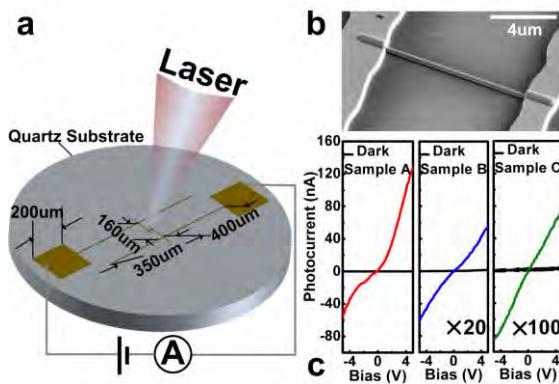


Figure 1: (a) A schematic of the detector geometry, along with (b) a typical SEM image of the centre of a fabricated single-nanowire detector. (c) Room-temperature dark and light current-voltage measurements on three investigated nanowire types.

References

- ¹ D. Auston, *Appl. Phys. Lett.*, **26**, 101 (1975)
- ² H. Joyce *et al.*, *Nanotechnology*, **24**, 214006 (2013)
- ³ K. Peng *et al.*, *Nano Letters*, **15**, 206 (2014)
- ⁴ P. Parkinson *et al.*, *Nanotechnology*, **23**, 335704 (2012)

Ultrafast dynamics of lasing semiconductor nanowires [1]

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The recent progress in understanding the fundamentals of semiconductor nanowires (NW) lasers has led to visionary concepts that might exploit coherent radiation available at dimensions below the wavelength barrier. Besides optical switching and nonlinear frequency generation using NWs, the recent development of nanophotonics and photonic circuitry requires NW lasers as nanoscale light source to circumvent the forthcoming limitations of conventional electronic circuits by optical data processing. Compound semiconductor NWs consisting of gallium nitride (GaN), zinc oxide (ZnO) or cadmium sulfide (CdS) show beneficial Fabry-Pérot resonator, efficient waveguide properties and high optical gain values in order to allow room temperature lasing, as schematically shown in figure 1(a).^[2-4] These smallest photonic laser systems operate furthermore at ultrafast timescales made accessible by a novel double-pump technique,^[5] which takes advantage of the non-linearity of the NW laser device itself. Ultrafast carrier thermalization within the optically excited semiconductors by carrier-phonon interaction leads the fastest laser onset time of ~ 1 ps in ZnO in comparison to CdS and GaN exhibiting values of ~ 2.5 ps and ~ 3.5 ps, respectively (figure 1(b)). The NW diameter independent laser onset time can be tuned by varying the pump energy relative to the semiconductor band gap. Meanwhile, the also determined laser pulse width depends on the transverse mode properties of the NW laser system. While the thinnest possible NWs exhibit the fastest ultrashort pulses, a sudden change in pulse width from ~ 5 ps to ~15 ps is obtained at a critical diameter coinciding with the transition from single to multimode waveguiding, which is indicated by a change in polarization (figure 1(c)).

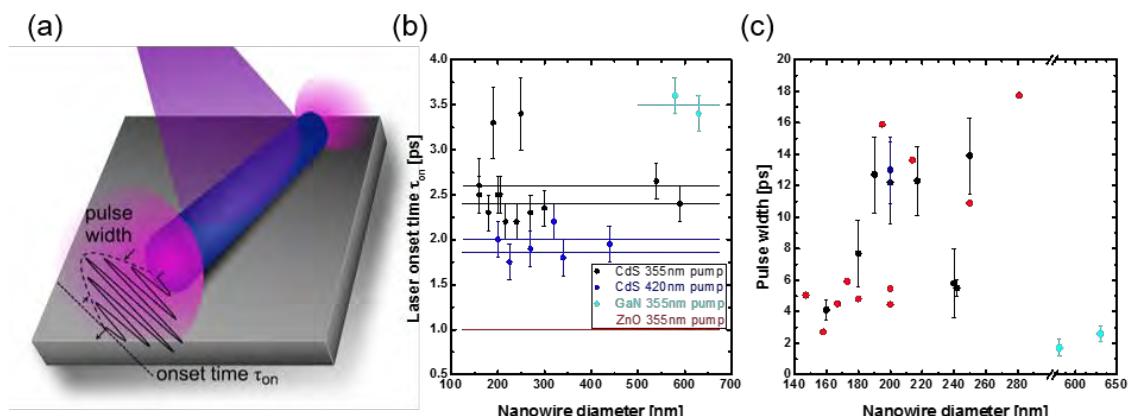


Figure 1: (a) Schematic drawing of a lasing nanowire lying on a low refractive index substrate. (b) Measured laser onset times τ_{on} versus nanowire diameter for GaN (cyan), CdS (black) and ZnO (red) pumped at 355 nm and CdS pumped at 420 nm (blue). (c) Laser output pulse width for CdS (355 nm pump, black for 355 nm pump, blue for 420 nm pump), GaN (cyan) and ZnO (red) NW lasers versus the diameter.

References

- R. Röder, et al., *Nano Letters*, (2015), DOI: 10.1021/acs.nanolett.5b01271.
- S. Geburt, et al., *Nanotechnology*, **23**, 365204 (2012).
- C. Tessarek, et al., *ACS Photonics*, **1**, 990–997 (2014).
- M. A. Zimmler, et al., *Semiconductor Science and Technology*, **25**, 024001 (2010).
- T. P. H. Sidiropoulos, et al., *Nat Phys*, **10**, 870–876 (2014).

Non-destructive mechanical and optical characterization of semiconductor nanowires

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The novel and versatile physical and chemical properties of nanowires have stimulated large fundamental and technological interests during the last decades. The appearance of novel boundary conditions, compared to bulk materials, drastically modifies the behaviour of these materials. Modified sound velocity,¹ thermal conductivity,² and optical refractive indices³ are examples of phenomena that have been observed in nanowires. It is thus important to develop novel technique that can in-situ and non-destructively characterize the optical and mechanical properties of nanowires.

Femtosecond time-resolved pump-probe spectroscopy is a unique way to generate and detect coherent acoustic phonons. An intense laser pulse is absorbed by a material and electron-hole pair are generated. These carriers yield their excess energy to the lattice, thus creating coherent acoustic phonons. A second, time delayed pulse, is sent to the sample and its reflectivity is modified by the coherent acoustic phonons.

Here, we applied this technique to various arrays of semiconductor nanowires. We show that, due to the confined geometry of nanowires, phonon and photon dispersion are greatly modified and new modes emerge. By comparing the phonon modes observed experimentally to simulations, we are able to retrieve the mechanical properties of the structure. We then investigated the light and sound coupling and demonstrate the possibility to retrieve the refractive index of the structure. Our results, in addition to the characterization capabilities, also provide an understanding of the effects of confinement on photon - phonon interaction and opens new possibilities for light control at the nanoscale.

References

- ¹ P.-A. Mante *et al.*, *Nano Lett.* **13**, 1139 (2013).
- ² D. Li *et al.*, *Appl. Phys. Lett.* **83**, 2934 (2003)
- ³ P. M. Wu *et al.*, *Nano Lett.* **12**, 1990 (2012).

Local Spectroscopy of One-Dimensional Electronic States in Semi-Conducting Nanowires

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Conductance measurements have suggested that topological superconductivity is realized when superconductivity is induced to semi-conducting nanowires with strong spin-orbit coupling subject to a Zeeman field. Zero bias peaks, suggestive of the long-sought Majorana modes, have been reported in such systems. However, little is known about the one dimensional electronic states that underlies the topological superconductivity. We perform scanning tunneling microscopy and spectroscopic mappings of these electronic states in pristine semi-conducting InAs nanowires. We visualize their spectral quantization, response to disorder and evolution with an external magnetic field that should render them approximately helical. Our findings bare implications on the realization of Majorana modes in InAs nanowires, and set the path for spectroscopic investigations of those intriguing states.

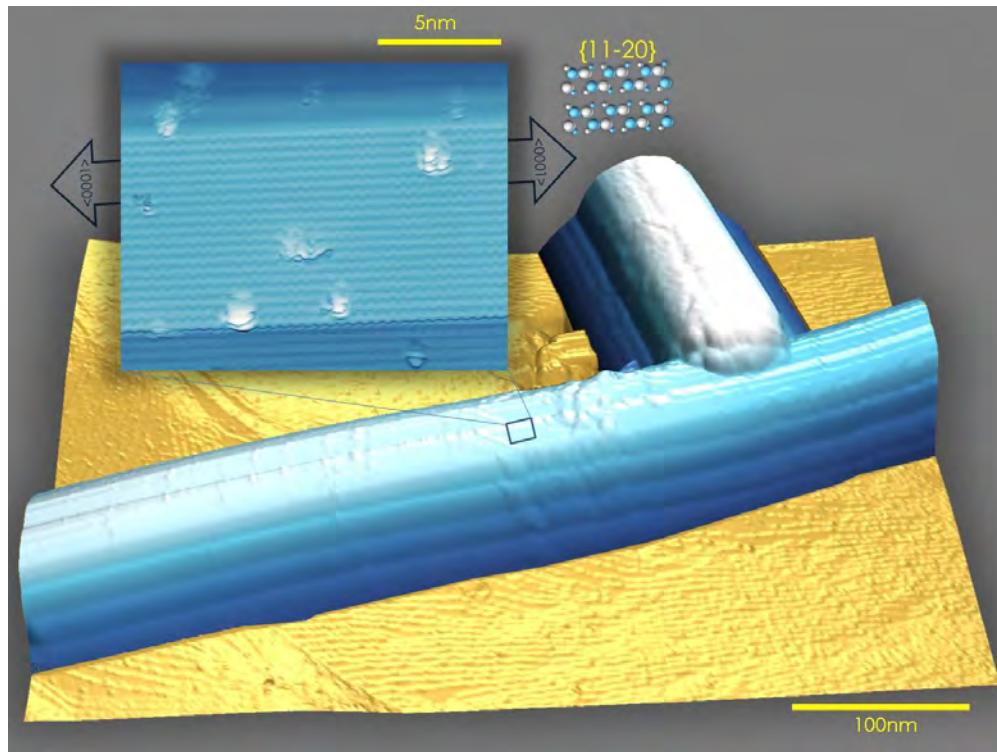


Figure: A topographic STM image of two InAs nanowires on a Au (111) substrate. The inset displays a zoomed-in topography of the {11-20} facet of the Wurtzite nanowire grown along the <0001> direction evidenced by the zigzag atomic positions resolved.

Development of nanowires based-devices for intra-cellular recording.

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Due to constant aging of the world population, neurodegenerative diseases will constitute a major issue in the near future. A roadblock in the development of new therapies is related to the poor understanding of age-related diseases at the single cell level due to limits of space / time resolution of current characterization tools. To increase our understanding of neuronal behavior, intra-cellular recordings are expected. In that scope, 1D-nanostructures offer real benefits thanks to their very small sections allowing to be less intrusive combined with their high aspect ratio (surface/volume) leading to a higher affinity between the nanowire and the cell.

Lieber's group first demonstrated extra-neuronal signal recording using horizontal nanowireFET [1] and then intra-neuronal measurements using a bio-probe composed of a kinked silicon nanowire [2]. This last work is an important step but is limited by the uniqueness of the measure and issues related to the feasibility of long-term measurements. More recently, H.Park's group demonstrated the ability to detect neuronal electrical signals using vertical nanowire arrays [3], which is adapted by long term analysis and multiple sites of measurements even if this work was limited to the demonstration of a single cell (soma).

Our work aims at developing an intracellular detection platform based on nanowires by combining vertical nanowire arrays (nano-electrodes) and horizontal NW device (nano-transistors) to record action potentials, not only in the soma but also along cell connection (axon) with the accuracy needed to investigate the reactions and the mechanisms involved in presence of a perturbation (chemical, virus ...).

Here, we will present a top-down approach using conventional lithography tools to co-integrate planar and vertical NW-based devices. This process is cost-efficient (optical lithography), and large scale CMOS compatible. A stress retarded oxidation step is used to tune the nanowire dimension. Si / Al₂O₃ core-shell type recording devices (figure 1a) is fabricated that include efficient isolations from culture media, allowing intracellular measurements. Cultures of rat cortical neurons have been performed on nano-patterned substrates (dense and organized nanowire arrays) and on chemical functionalized surfaces. A first study allowed the NW design in order to promote intracellular penetration of the probes (figure 1b). We highlighted that this kind of neuronal growth on ordered nanowire arrays lead preferential axonal growth directions, in contrary to random growth on bulk substrates. We also developed an unprecedented surface functionalization approach in order to locate single neurons and guiding the growth of their extensions at sub-micrometer scale (figure 1c). Our devices, coupling with this functionalization, will stimulate and accurately record action potentials generated by these neurons in somas but also along the axons during several weeks.

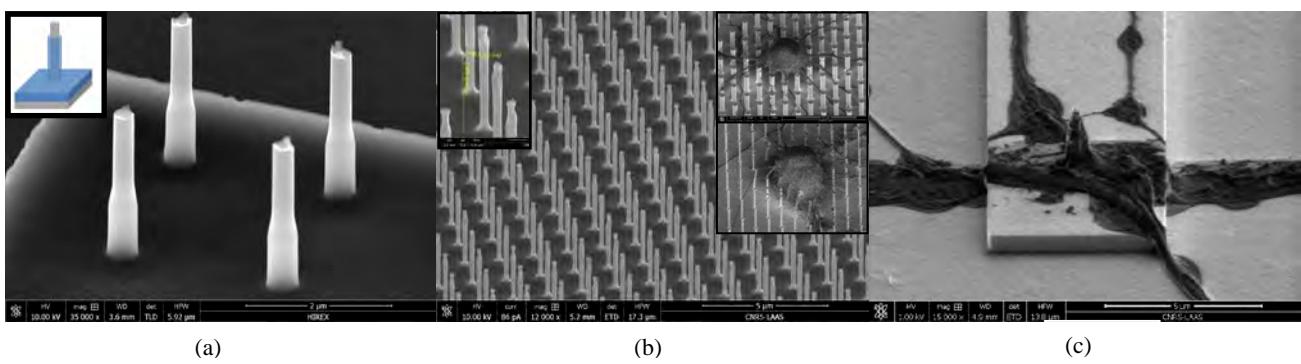


Figure 1: (a) Si / Al₂O₃ core-shell type recording device (b) top-down nanowires array d=190nm H= 2.7μm and rat cortical neurons on two different nanowire arrays d=200nm and d=600nm, (c) a dendrite perfectly located on a nanowire.

References

- [1] F. Patolsky et al., Science, 313(5790), pp. 1100 – 1104, (2006).
- [2] B. Tian et al., Science, 329 (5993), pp. 830 - 834, (2010).
- [3] Jacob T. Robinson et al, Nature Nanotechnology, 7, 180–184, (2012).

Shockley-Queisser detailed balance efficiency of a tandem nanowire array solar cell with axial junctions

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III-V semiconductor nanowire array solar cells are good candidates for next generation photovoltaics¹⁻³. Here we consider the Shockley-Queisser detailed balance efficiency^{3,4} of a tandem nanowire array solar cell by optimizing both the constituent materials and the geometry design. As shown in Figure 1(a), we consider a structure with two series connected p-i-n junctions in each nanowire. These two sub-cells consist of different materials and bandgaps and the nanowires are placed on top of an inactive substrate.

The Shockley-Queisser detailed balance efficiency analysis takes into account the balance between electron-hole recombination and generation in a solar cell⁴. There are two kinds of recombination processes: radiative and non-radiative. In this work, we assume perfect surface passivation and a defect free nanowire material to study the upper limit for the efficiency³. In this case, only the fundamental radiative recombination limits the efficiency of the solar cell.

First, the nanowire array is considered as a conventional thin film cell with total absorption of light incident from all angles. In this way, we can easily consider the Shockley-Queisser efficiency as a function of material bandgaps. From these results, we chose suitable materials for the nanowires. We allow for lattice mismatched materials for the sub-cells since a larger mismatch can be incorporated in the nanowire geometry, as compared to a thin film cell, due to strain relaxation in the radial direction⁵. Next, the absorption spectrum of the nanowire array is calculated with a scattering matrix method⁶ to derive a rigorous efficiency limit for the tandem nanowire cell.

To optimize the geometry, we have developed an efficient iteration method. With this method, we are able to solve the computationally demanding problem of maximizing the Shockley-Queisser efficiency of the tandem nanowire solar cell. In this way, we find for the tandem nanowire solar cell with a 2000 nm long top cell an efficiency of 38.7%, considerably higher than the 32.5% limit of a single-junction nanowire solar cell².

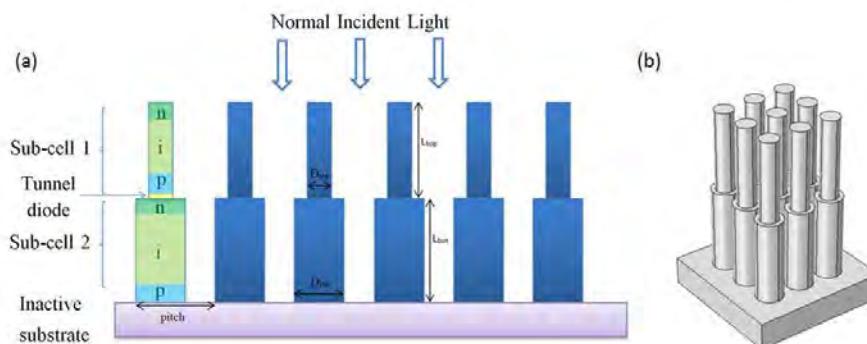


Figure 1: Schematic diagram and parameters in a dual junction nanowire array based on an inactive substrate. (a) Geometry parameters. In the left-most nanowire, we show a schematic for a possible realization for the electrical design of the cell including axial pin-junction cells with a tunnel junction to connect them. (b) 3D schematic diagram.

References

- ¹ J. Wallentin, *et al.*, *Science* **339**, 1057 (2013).
- ² N. Anttu, *ACS Photonics* **2**, 446 (2015).
- ³ S. Sandhu, *et al.*, *Nano Lett.* **14**, 1011 (2014).
- ⁴ W. Shockley, *et al.*, *J. Appl. Phys.* **32**, 510 (1961).
- ⁵ I. García, *et al.*, *Appl. Phys. Lett.* **94**, 053509 (2009).
- ⁶ N. Anttu, *et al.*, *Phys. Rev. B* **83**, 165431 (2011).

The Impact of Lead Geometry and Discrete Doping on NWFET Operation

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Due to the continuous reduction of the channel length, the resistance of access regions in Si nanowire MOSFET (NWFET) may appear as the main contributor of the global resistance. Therefore, we used a 3D real-space non-equilibrium Green's function (NEGF) approach to provide a physically consistent modeling of NWFET where both realistic lead geometry and discrete doping are taken into account. Electron-phonon scattering is included using the self-consistent Born approximation (SCBA).

We consider two lead geometries for NWFETs with $L_G=8$ nm as schematically shown in Fig. 1. We shall refer to the device with the uniform transverse section in Fig. 1.a by (UN), and by (NUN) to its non-uniform counterpart Fig. 1.b. I_D-V_{GS} curves of the UN and NUN (not shown) are very similar when a continuous dopant concentration of 10^{20} cm^{-3} is assumed in the source (S), drain (D) and access regions (AR) - represented by yellow regions in (Fig.1). The aforementioned continuous doping concentration corresponds to less than two dopants in a volume of $2 \times 2 \times 4 \text{ nm}^3$. Therefore, we replaced it by one impurity in each AR in both UN and NUN devices exactly localized on the same positions along the channel symmetry axis. I_D-V_{GS} curves show that sub-threshold behavior - mainly controlled by the channel, which remained unchanged in both devices - has not been affected by the discrete aspect of the doping in AR. However, as expected [1], the discrete dopants degrade the ON-current. Surprisingly, the degradation depends on the access region geometry since ON-current reductions are 19 and 30% respectively for the UN and NUN. The corresponding LDOS for UN transistor (Fig. 2) shows that the impurity levels (IL) are close to the Fermi level of their respective contacts. They are consequently strongly coupled to S and D and thus efficiently contribute to the injection and extraction of carriers in the device. In NUN device, the IL is no longer a quasi-localized state of the coulombic potential (Fig. 3). Indeed the larger cross-section reduces the impurity binding energy [2] leading to delocalized IL's well above the Fermi levels. Since injection and extraction are no longer improved by the ILs, the ON-current reduction due to discrete dopant is larger than in the UN counterpart.

This result shows the importance of considering both realistic lead geometry and discreteness of the dopants to provide an accurate modeling of NWFETs, where access regions will have an increasing influence.

References:

- [1] A. Asenov *et al.*, *IEEE-Trans. Elec. Dev.*, 61 (2014) 2745.
- [2] M. Diarra *et al.*, *Phys. Rev. B*, 75 (2007) 045301.

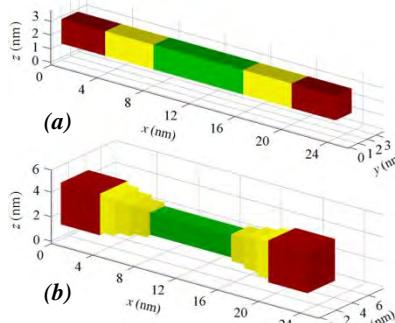


Fig. 1

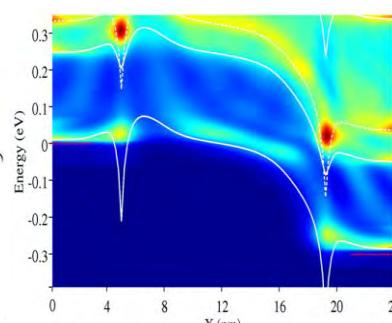


Fig. 2

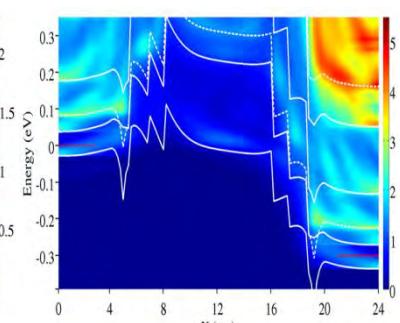


Fig. 3

Fig. 1 : Considered gate-all-around NWFETs (a) UN : with uniform cross-section of $2 \times 2 \text{ nm}^2$ and (b) NUN : non uniform cross section. Same channel length $L_{CH} = 8$ nm and cross-section of $2 \times 2 \text{ nm}^2$ (green) are assumed for both devices. Gate insulator is 1 nm thick. Source and drain are represented in red and are 4 nm long, while the access regions are represented in yellow (with a length of 4 nm). Source (drain) cross-section in NUN device is $3.6 \times 3.6 \text{ nm}^2$. For all the simulations $V_{DS} = 0.3$ V and $T = 300$ K. **Fig. 2 :** LDOS in ON-regime for the UN device with impurities placed in access regions along the channel symmetry axis at $x = 5$ nm and $x = 19$ nm. White lines correspond to the eigenvalues of transverse valleys (m_t in the transport direction) and white dashed lines correspond to the longitudinal ones. Fermi levels in source and drain are indicated in red dashed lines. **Fig. 3 :** Similar physical quantities as in Fig. 2 but for the NUN device.

DFT/NEGF study of discrete dopant in a Ultrascale Si FinFET

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FinFet nanowire transistors have been in production since 2010. The channel lengths of these transistors are around 20 nanometers. In the near future it is expected that these transistors shrink to sub 10 nm dimensions. In general, doping is assumed continuous when calculating the current voltage characteristics of devices. In addition, a simple Drift-Diffusion model is considered to describe the electron transport. Only few works assume the dopants as discrete charges and use a full quantum mechanics description of electron transport [1]. However the self-consistent calculation produces an electron density around the dopant, which does not resemble the Si lattice symmetry. In addition, the spatial shape of the electron density associated to the dopant electron extracted from Density functional theory is quite different from the obtained shape when using an effective mass approximation theory. In this paper we calculate the electron density of an electron of a substitutional phosphorus impurity embedded in a 511 supercell of Si atoms using the Siesta [2] code. The density obtained by DFT is shown in Fig. 1a. Note the tetrahedral symmetry of the impurity. We introduce this density into NEGF-Poisson formalism. This is necessary as the effective mass approximation in the NEGF formalism is not accurate enough to produce by itself the donor electron density calculated by DFT. In this paper the impurity has been located at the middle of the channel of a Si FinFET. The current calculated for the device with the DFT density produces lower current as compared with the device that the impurity is assumed concentrated in a mesh point as can be seen in Fig. 1b. However because the electron distributions differ substantially only in a radius of 0.4 nanometers the impact in the current-voltage characteristic is small. We have also simulated the current voltage characteristic including two impurities in the channel.

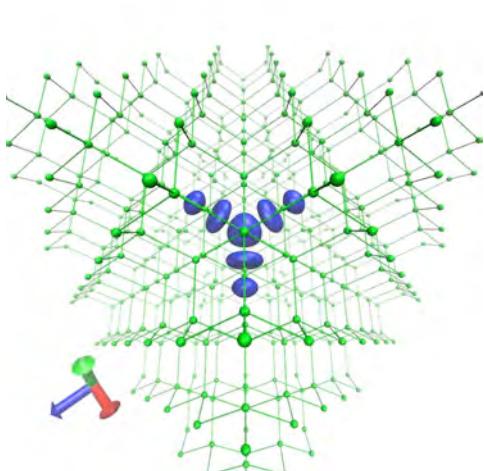


Figure 1a: 512 atoms Si supercell with a Phosphorous impurity at the centre. The electron density is shown in blue.

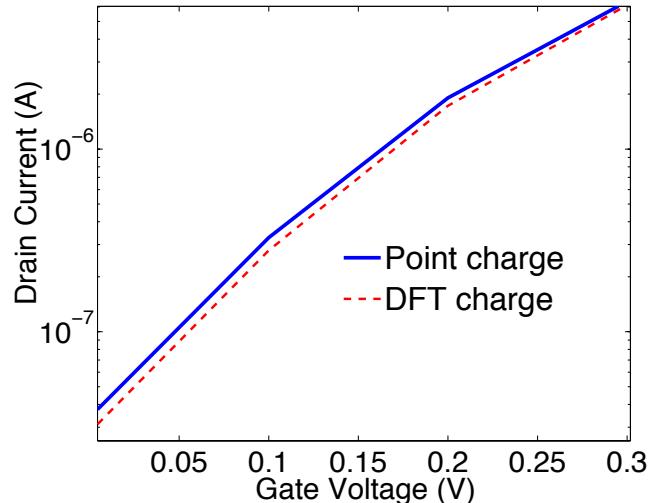


Figure 2a: The current voltage characteristic of the transistor considering a point donor and with the DFT charge distribution.

¹ A. Martinez et al, IEEE Transactions on Electron Devices, 58, pp. 2209–2217(2011).

² P. Ordejón, et al Phys. Rev. B 53, R10441 (1996)

Study of mobility in Si, GaAs and InGaAs NWFETs using the NEGF formalism.

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Nanowire field effect transistors (NWFETs) are likely to succeed FinFETs. They have good electrostatic integrity and channel lengths as small as 6 nm are possible. III-V materials such as GaAs and InGaAs are being considered as suitable nanowire cores because of their high mobility. In this work, NWFETs of cross-section $2.2 \times 2.2 \text{ nm}^2$ and $4.2 \times 4.2 \text{ nm}^2$, with 6 nm channel lengths have been simulated, and three different nanowire cores have been considered: Si, GaAs and InGaAs. For each device the phonon-limited mobility has been calculated. All relevant scattering mechanisms have been considered. For Si: X-X intervalley scattering with f-type and g-type phonons and acoustic phonons. For GaAs and InGaAs: intervalley scattering (Γ -L, L-X, Γ -X, L-L, X-X) and intravalley scattering, including acoustic, optical and polar optical phonons. The simulations use the Non-equilibrium Green's Formalism (NEGF), which has been widely used to simulate quantum devices. The effective mass approximation has been deployed and renormalised using masses extracted from tight binding simulations [1].

Figure 1 shows the phonon-limited mobility for (a) $2.2 \times 2.2 \text{ nm}^2$ and (b) $4.2 \times 4.2 \text{ nm}^2$ cross-section NWFETs with a 6 nm channel length. For the $2.2 \times 2.2 \text{ nm}^2$ cross-section NWFETs in figure 1 (a) the Si NWFET has the highest mobility. This is because in the III-V $2.2 \times 2.2 \text{ nm}^2$ cross-section NWFETs the low mass Γ -valley becomes elevated in energy such that it's higher than the heavier L and X-valleys, resulting in low current and mobility [2]. The Γ -valley has been found to lower with increasing oxide thickness, increasing the current [3]. For the $4.2 \times 4.2 \text{ nm}^2$ cross-section NWFETs, the InGaAs core NWFET has the highest mobility, with a mobility of $1887 \text{ cm}^2/\text{Vs}$ at low channel charge.

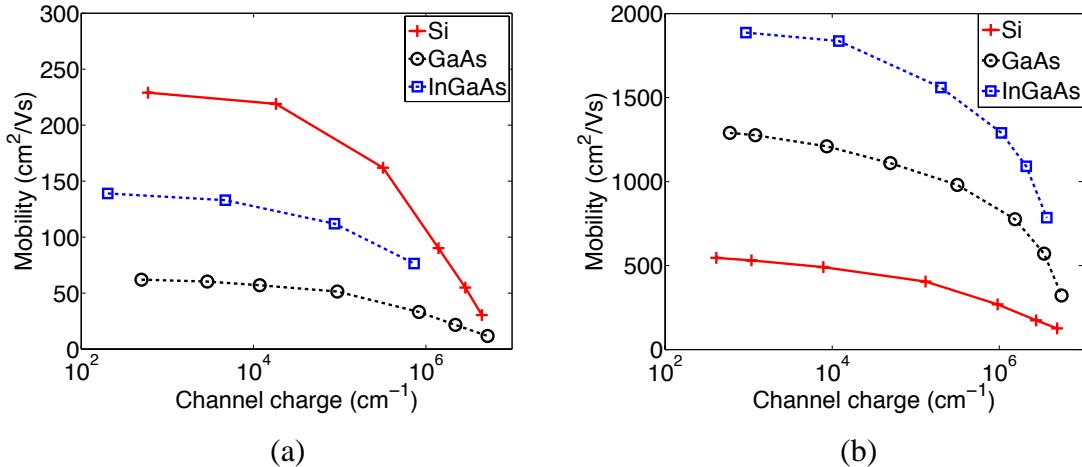


Figure 1: Phonon-limited mobility for Si, GaAs and InGaAs core NWFETs with (a) $2.2 \times 2.2 \text{ nm}^2$ and (b) $4.2 \times 4.2 \text{ nm}^2$ cross-section and a 6 nm channel length.

[1] Y. M. Niquet, A. Lherbier, N. H. Quang, M. V. Fernandez-Serra, X. Blase and C. Delerue, *Phys Rev B* **73**, 165319 (2006).

[2] A. Price and A. Martinez, *J. Appl. Phys.* **117**, 164501 (2015).

[3] A. Price and A. Martinez, *J. Phys. Conf. Ser.* **609**, 012004 (2015).

Light hole exciton emission from a single CdMnTe/ZnTe nanowire quantum dot evidenced by polarization-far field measurements

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Quantum dots (QDs) provide an ideal system for emitting single photons or manipulating the magnetization of embedded magnetic dopants. Nevertheless the full control of those processes requires to precisely understand the quantum states of the trapped carriers. In most systems, in particular flat CdTe/ZnTe QD, the valence band splitting of the hole states implies that the QD emission corresponds to heavy-hole (HH) transitions but strain and confinement potential can induce mixing of the hole states. However emission from a dominantly light-hole (LH) transition is rarely demonstrated.

In this context, the dot-in-a-nanowire configuration is particularly versatile as virtually any material combination, dot shape and built-in strain can be engineered. Here we use gold-catalysed MBE grown Cd(Mn)Te QDs in ZnTe-Zn(Mg)Te core-shell nanowires (NWs). Extensive structural and optical characterizations of those systems have already been undertaken.^{1,2} We present here a microphotoluminescence analysis of a single as-grown NW. Cathodoluminescence provides a complete knowledge about the shape of the NW as well as to where the QD is located. We study both the polarization and the far-field radiation diagram of the dot itself and of the ZnTe NW base. The combined results can only be explained if one considers that the QD hole state is dominantly a LH, contrary to the ZnTe exciton which is HH as expected from the tensile strain due to the shell. Numerical simulation of the radiated field with no other degree of freedom but the valence band mixing are in good agreement with our observations. Further magneto-PL measurements on the same NW are under way in order to complement our knowledge about the nature of the hole state in the QD by the determination of its spin properties.

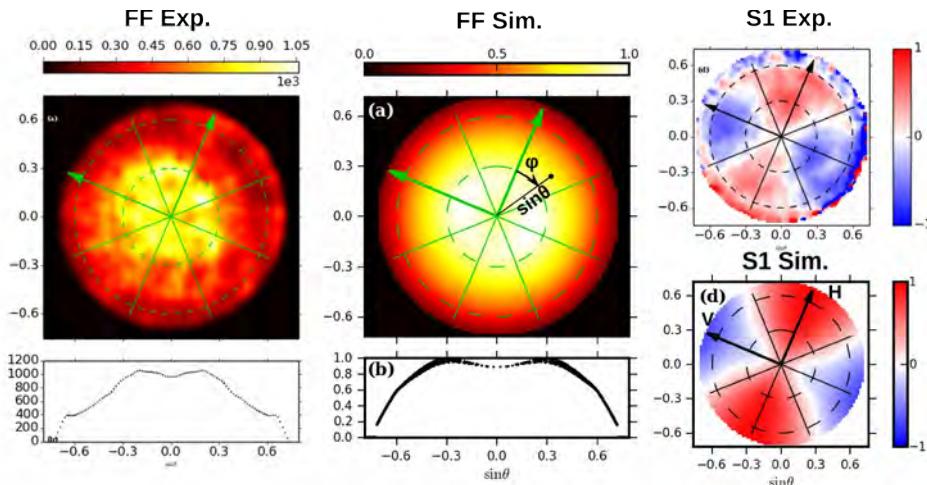


Figure 1: Far field radiation pattern (FF) and Stokes parameter S1 showing the degree of linear polarization in the (H,V) base. All data are displayed in the θ, ϕ Fourier plane with cross sections for the radiation pattern. Experimental results are compared to numerical simulations

References

¹ P. Rueda-Fonseca, *et al.*, *Nano Letters* **14**, 1877 (2014).

² A. Artioli, *et al.*, *Appl. Phys. Lett.* **103**, 222106 (2013).

Electro-optical analysis of modulation-doped GaAs-AlGaAs core-shell nanowires

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The concept of modulation doping is an attractive means to overcome limitations in charge carrier conductivity in highly downscaled nanowire (NW) geometries and to enable high-mobility channels for studies in condensed matter physics as well as practical devices, such as high-speed/high-frequency modulation-doped field effect transistors (MODFET).

Here, we demonstrate remotely, i.e., Si delta(δ)-doped radial GaAs-AlGaAs core-shell NWs that clearly exhibit distinguished confined electron gas properties with enhanced low-temperature field-effect mobilities, as well as very good state-of-the-art MODFET characteristics. Using correlated electronic band profile simulations, atom probe tomography (APT), and transport characterization our approach enables powerful control over the free two-dimensional electron gas density (2DEG) and conductivity. In particular, transfer characteristics measured at low-temperature exhibit unambiguously the anticipated enhancement in electron field-effect mobility, which is $\sim 5 \times 10^3 \text{ cm}^2/\text{Vs}$ at 4.2 K and a factor of $> 5 \times$ higher as compared to room-temperature at 2DEG densities of $\sim 10^{11} \text{ cm}^{-2}$ [1]. Detailed gate-bias dependent measurements and simulations further revealed that the pinch-off characteristics of these FETs are governed by the complex depletion of two superimposed carrier channels, i.e., 2DEG- and 1DEG-like carrier channels, respectively. Multi-gated NW-FETs allowed us to further spatially resolve channel width- and crystal-phase-dependent variations in electron gas density and mobility along single NW-FETs.

We further suggest that alloy fluctuations in the AlGaAs shell layer pose a limit to the electron mobility by perturbing the potential profile at the core-shell heterointerface. Indeed, systematic APT analysis reveals randomly distributed nanoscale Ga-rich clusters inside the entire AlGaAs shell, where we determined their compositions, size distributions, and interface characteristics. Importantly, the presence and distribution of these Ga-rich nanoclusters give also rise to a band of discrete emitters right below the band gap of AlGaAs [2].

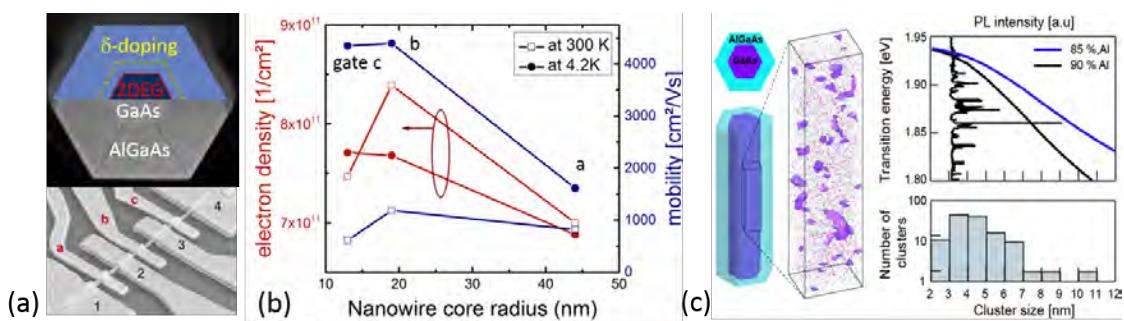


Figure 1: (a) STEM-HAADF cross-sectional image and as-fabricated NW-FET of a Si delta-doped core-shell GaAs-AlGaAs NW; (b) plot of 2DEG density and mobility for different gate positions (i.e., NW radius) and measurement temperatures; (c) correlated APT- μ PL analysis of AlGaAs shell structure exhibiting a distribution of Ga-rich nanoclusters responsible for sharp-line emission centers.

References

¹ S. Morkötter, et al., *Nano Lett.* 15, 3295 (2015).

² N Jeon, et al., submitted (2015).

Catalyst-free selective area MBE of semiconductors nanowires on a Si pattern substrate

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ABSTRACT

Semiconductor nanowires have attracted much attention over the past few years as a key building block for nanodevices. By controlling the growth on a nanometre scale we can achieve unique opportunities for combining materials, manipulating properties, and designing novel devices¹. In this study, we have developed a site controlled InAsSb nanowires (NWs) grown on Patterned Si (111) substrate using selective area Molecular Beam Epitaxy (MBE) growth and defined by electron beam lithography (EBL). This method is very promising to form a wire arrays without the use of Au-catalyst or metal droplet that can limit the performance of the grown devices². High quality vertically aligned NWs were obtained with highly uniform diameters along the growth direction as confirmed by Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM), X-Ray and Photoluminescence (PL) analysis. The NWs exhibited phase pure- zinc blende crystal structure. PL spectroscopy at 4K revealed a peak emission consisting of emission from the InAs section at 0.435 eV and more intense emission from the InAsSb section at 0.370 eV(see figure 1(b)). Photodetectors fabricated from doped p-i-n nanowires have shown a dark current density more than an order of magnitude lowers than state of the art InAs devices. These results show a promising route for integration of well- aligned and high quality MBE- grown InAsSb NWs with silicon technology for next generation devices³.

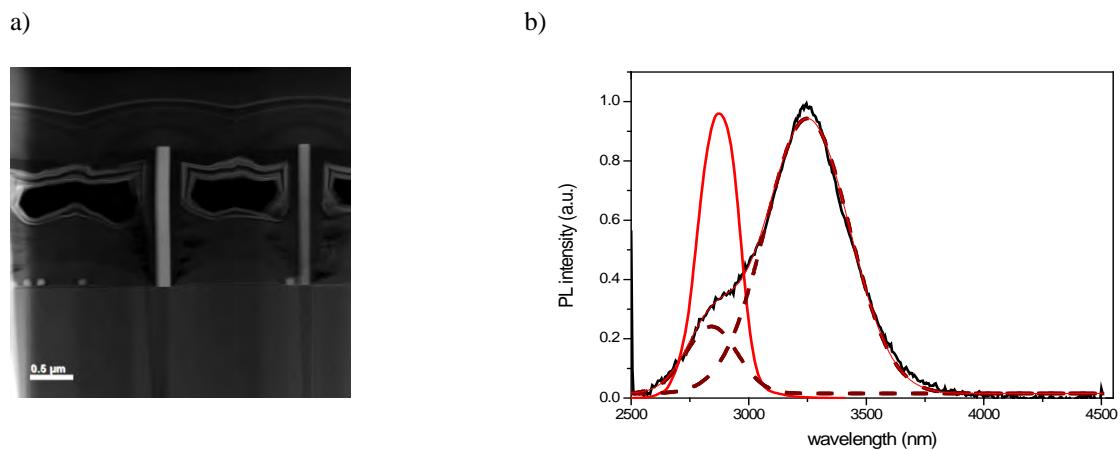


Fig 1: a) SEM images of InAsSb NWs on Patterned Si (111) substrate b) Normalized PL spectra measured at 4k for InAs bulk at 2800nm and InAsSb NWs at 3400nm.

REFERENCES

1. Bernhard Mandl et al. Nano Lett., Vol. 6, No. 8 (2006)
2. Marion J. L. Sourribes et al. Nano Lett, Vol.14, No.1643–1650 (2014)
3. S.Hertenberger, et al. Journals Of Applied Physics 108,114316-1 (2010)