One-dimensional Steeplechase for Electrons Realized

ARTICLE *in* NANO LETTERS · FEBRUARY 2002

Impact Factor: 13.59 · DOI: 10.1021/nl010099n

Jonas Björn Ohlsson

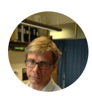
QuNano AB

Martin H Magnusson

Lund University

Knut Deppert

Lund University



Reine Wallenberg

Lund University

NANO LETTERS

2002
Vol. 2, No. 2
87−89

One-dimensional Steeplechase for Electrons Realized

M. T. Björk,[†] B. J. Ohlsson,[†] T. Sass,[†] A. I. Persson,[†] C. Thelander,[†] M. H. Magnusson,[†] K. Deppert,[†] L. R. Wallenberg,[‡] and L. Samuelson*,[†]

Solid State Physics/Nanometer Consortium, Lund University, Box 118, S-221 00 Lund, Sweden, and Materials Chemistry/Nanometer Consortium, Lund University, Box 124, S-221 00 Lund, Sweden

Received December 20, 2001

ABSTRACT

We report growth of one-dimensional semiconductor nanocrystals, nanowhiskers, in which segments of the whisker with different composition are formed, illustrated by InAs whiskers containing segments of InP. Our conditions for growth allow the formation of abrupt interfaces and heterostructure barriers of thickness from a few monolayers to 100s of nanometers, thus creating a one-dimensional landscape along which the electrons move. The crystalline perfection, the quality of the interfaces, and the variation in the lattice constant are demonstrated by high-resolution transmission electron microscopy, and the conduction band off-set of 0.6 eV is deduced from the current due to thermal excitation of electrons over an InP barrier.

The past 5 to 10 years have witnessed a revolution in the science and technology of one-dimensional (1D) systems such as carbon nanotubes[1] (CNTs) and semiconductor nanowhiskers.[2] Despite quite amazing progress, research has been frustrated by a lack of control of the conductivity-type of CNTs and an inability to form 1D heterostructures in a controlled manner. Randomly formed interfaces as kinks between metallic and semiconducting parts of CNTs have been identified and studied,[3] as have doping (pn) junctions in semiconducting CNTs[4] and nanowhiskers[5] and transitions between CNTs and semiconductor (Si and SiC) nanowhiskers.[6] However, the possibility of designing multi-heterostructures, in a way that revolutionized 3D and 2D semiconductor physics and technology during the 1960s to 1980s,[7−9] has eluded realization in 1D systems. We here report studies of structural and electronic properties of designed functional heterostructure barriers placed inside nanowhiskers.

The III−V whiskers are grown by the vapor−liquid−solid growth mode, with a gold nanoparticle catalytically inducing growth. Growth occurs in an ultrahigh vacuum chamber designed for chemical beam epitaxy (CBE). The rapid alteration of the composition is controlled by the supply of precursor atoms into the eutectic melt, supplied as molecular beams into the ultrahigh vacuum chamber. The rapid switching between different compositions (e.g., between InAs and InP) is obtained via a sequence where growth is interrupted as the indium source (TMIn) is switched off, followed by a change of the group V sources. Finally, the supersaturation conditions, as a prerequisite for reinitiation of growth, are reestablished as the indium source is again injected into the growth chamber. For details on our techniques for growth of III−V nanowhiskers, including the control of whisker diameter by the size-selected catalytic nanoparticle used, we refer the reader to a recent publication[10] and references therein.

For the abruptness of the interfaces, it has been shown[11] that analysis of high-resolution transmission electron microscope (TEM) images usually is superior to energy dispersive spectroscopic imaging (EDS) and energy filtered TEM imaging (EFTEM) for simple two-phase systems. Figure 1 shows TEM analysis of an InAs whisker containing several InP heterostructure barriers. In Figure 1a, a high-resolution image of the three topmost barriers is shown, recorded with a 400 kV HRTEM (point resolution 0.16 nm). Figure 1b shows a nonquadratic power spectrum of the HREM image, showing that the growth direction is along [001] of the cubic lattice. The reflections show a slight splitting due to the difference in lattice constants between InAs and InP. Figure 1c shows an inverse Fourier transform, using a soft-edge mask over the part of the 200 reflection arising from the InP lattice. A corresponding mask was put over the InAs part of the reflection. The two images were color-coded and superimposed in Figure 1d. Green indicates the part of the

* To whom correspondence should be addressed. E-mail: lars.samuelson@ftf.lth.se.
[†] Solid State Physics/Nanometer Consortium.
[‡] Materials Chemistry/Nanometer Consortium.

10.1021/nl010099n CCC: $22.00
Published on Web 01/19/2002

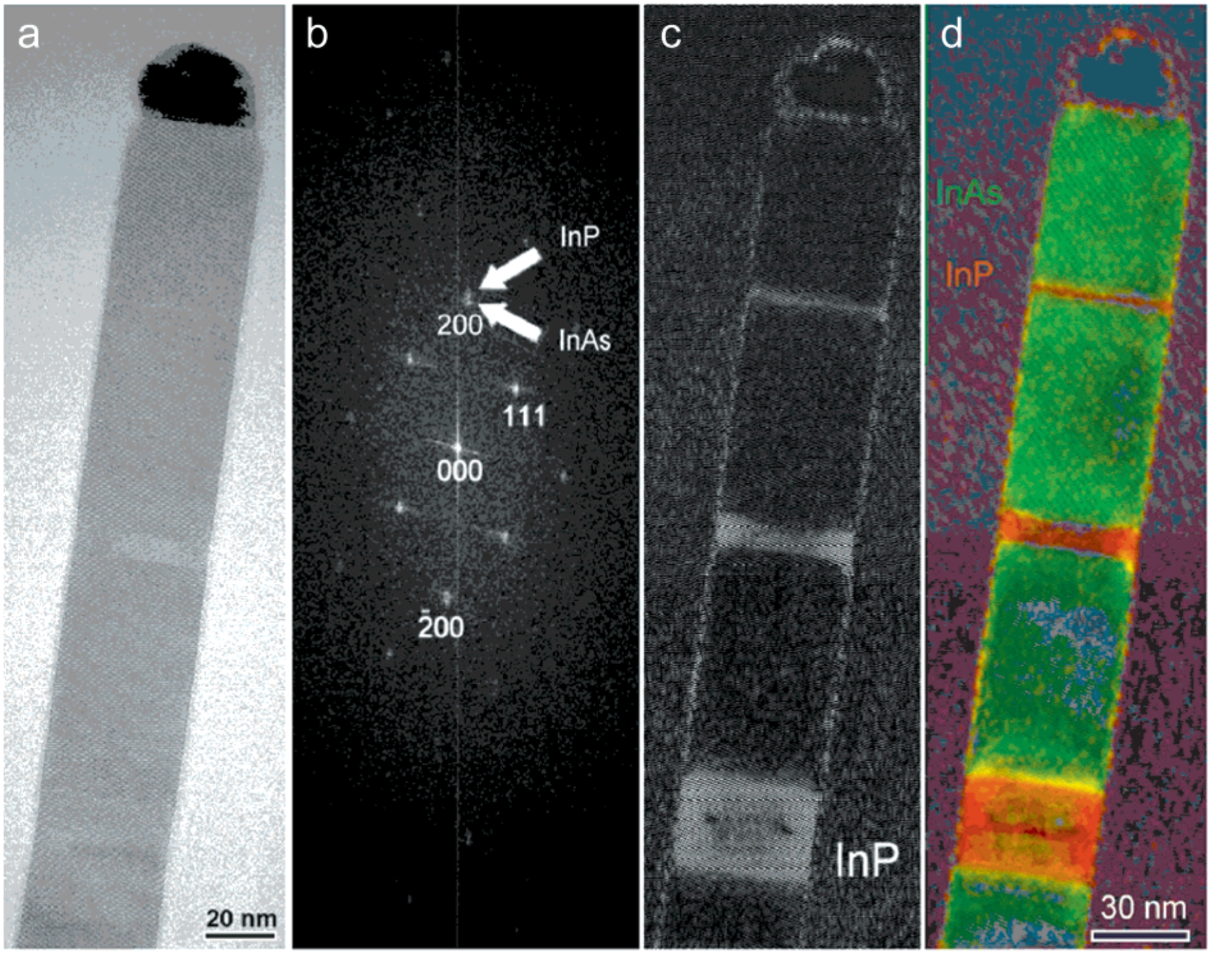


Figure 1. Composition profile of an InAs nanowhisker, containing several InP heterostructures, using reciprocal space analysis of lattice spacings. (a) High-resolution TEM image of a whisker with a diameter of 40 nm. (b) Power spectrum of the image in (a). (c) An inverse Fourier transform using the information closest to the InP part of the split 200 reflection. InP (bright) is located in three bands with approximately 25, 8 and 1.5 nm width, respectively. (d) Superimposed images, using an identical mask over the InP and InAs parts of the 200 reflection, respectively. InAs lattice spacings have been color-coded with green and InP spacings with red.

whiskers having a lattice constant corresponding to InAs and red indicates the location of parts having the lattice constant of InP.

Figure 2a shows a TEM image of an InAs/InP whisker. The magnification of the 8 nm barrier in Figure 2b shows the atomic perfection and abruptness of the heterostructure interface. Aligned with the 100 nm thick InP barrier, the result of a 1D Poisson simulation (neglecting lateral quantization, the contribution of which is only about 10 meV) of the heterostructure 1D energy landscape expected to be experienced by electrons moving along the whisker is drawn (Figure 2c). This gives an expected band offset ($q\Phi_B$) in the conduction band (where the electrons move in n-type material) of 0.6 eV. This steeplechase-like potential structure is very different from the situation encountered for electrons in a homogeneous InAs whisker, for which ohmic behavior (i.e., a linear dependence of the current (I) on voltage (V)) is expected and indeed observed (red curve in Figure 2d). This linear behavior is dramatically contrasted by the (blue) I−V curve measured for an InAs whisker containing an 80 nm thick InP barrier. Strongly nonlinear behavior is observed, with a voltage bias of more than 1 V required to induce current through the whisker. This field-induced tunnel current increases steeply with increasing bias voltage, as the effective barrier through which the electrons must tunnel narrows.

To test whether the ideal heterostructure band diagram within the 1D whisker is valid, we measured the temperature dependence of the current of electrons overcoming the InP barrier via thermionic excitation. The result is shown in Figure 2e, where the logarithm of the current (divided by T^2) is plotted as a function of the inverse of the temperature in an Arrhenius fashion, measured at a small bias voltage (V = 10 mV) to minimize band-bending effects and the tunneling processes described above. From the slope of the line fitted to the experimental data points we deduced an effective barrier height, $q\Phi_B$, of 0.57 eV, in good agreement with the simulation. This is, to the best of our knowledge, the first measurement of a designed heterostructure potential within a 1D system, and it opens the way for whole new families of 1D devices. An added benefit of this approach

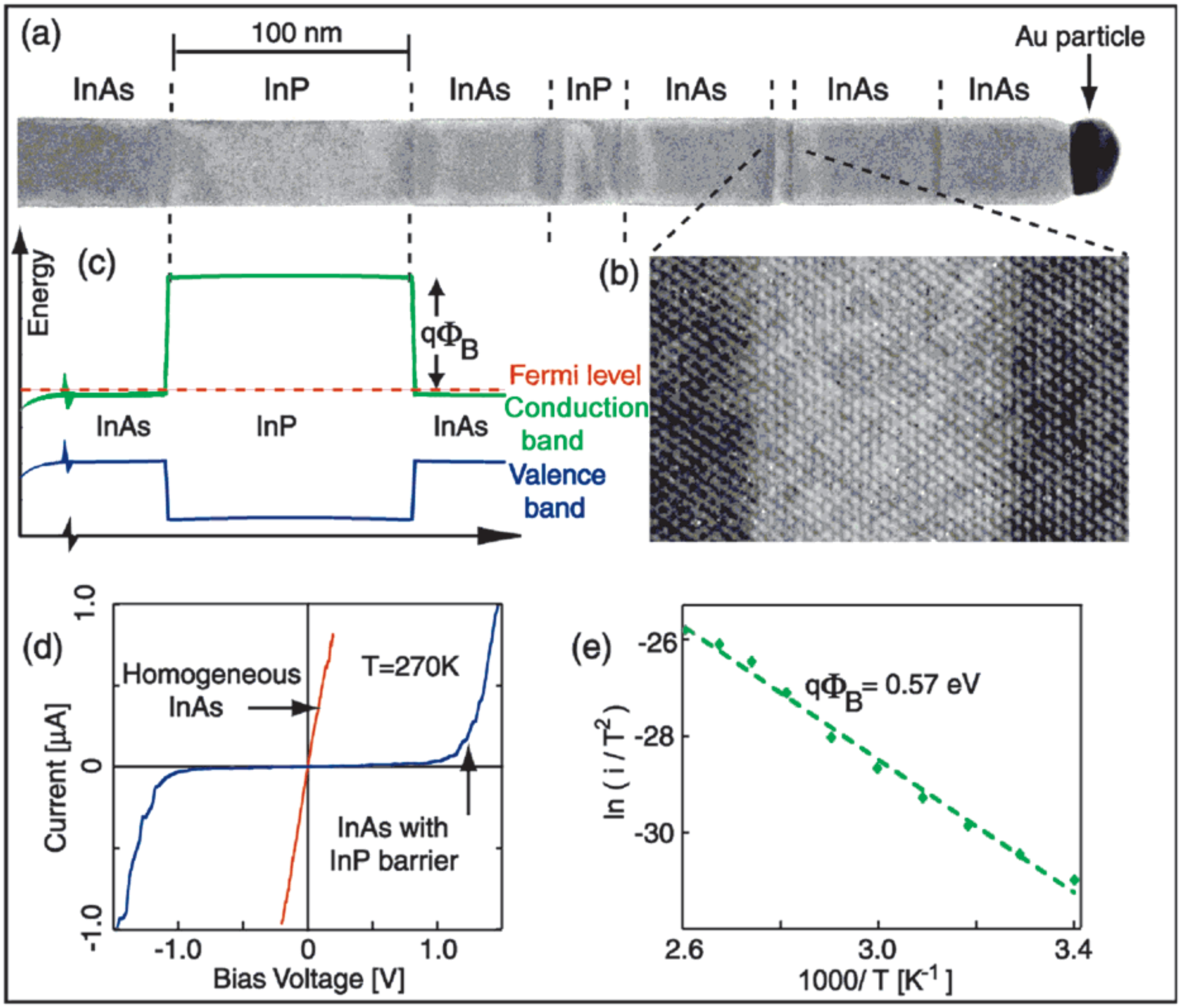


Figure 2. Analysis of InP heterostructures inside InAs nanowhiskers. (a) TEM image of InP barriers (100, 25, 8, and 1.5 nm) inside a 40 nm diameter InAs whisker. (b) Magnification of the 8 nm barrier region, showing crystalline perfection and the interface abruptness on the level of monolayers. (c) Simulated band-structure diagram of the InAs/InP heterostructures, including (left edge) ideal formation of ohmic contacts to InAs. (d) Ohmic I−V dependence for a homogeneous InAs whisker (red), contrasted by the strongly nonlinear I−V behavior seen for an InAs whisker containing an 80 nm InP barrier (blue). (e) Arrhenius plot showing measurements of thermionic excitation of electrons across the InP barrier (at a bias of 10 mV), yielding a barrier height of 0.57 eV.

to realizing heterostructures within 1D whiskers is the advantageous condition for combining highly mismatched materials, provided by the efficient strain relaxation by the proximity to the open side surface in the whisker geometry. In comparison, only a few atomic layers may be epitaxially grown in transitions between materials like InAs and InP with different lattice constants before either islanding or misfit dislocations occur, thereby preventing formation of ideal heterointerfaces. Apart from the interest of these results for materials science and nanostructure formation, there is every reason to expect that this will also lead to the realization of many different designed 1D heterostructures and devices, such as 1D superlattices of quantum dots, hitherto only dreamed of and used as physics textbook examples.

Acknowledgment. This research was supported by the Swedish Foundation for Strategic Research (SSF) and the Swedish Research Council (VR).

References

(1) Iijima, S. *Nature* **1991**, *354*, 56.
(2) Duan, X.; Huang, Y.; Cui, Y.; Wang, J.; Lieber, C. M. *Nature* **2001**, *409*, 66.
(3) Yao, Y.; Postma, Ch.; Balents, L.; Dekker, C. *Nature* **1999**, *402*, 273.
(4) Derycke, V.; Martel, R.; Appenzeller, J.; Avouris, Ph. *Nano Lett.* **2001**, *1*, 453.
(5) Haraguchi, K.; Katsuyama, T.; Hiruma, K.; Ogawa, K. *Appl. Phys. Lett.* **1992**, *60*, 745.
(6) Hu, J.; Ouyang, M.; Yang, P.; Lieber, C. M. *Nature* **1999**, *399*, 48. Zhang, Y.; Ichihashi, T.; Landree, E.; Nihey, F.; Iijima, S. *Science* **1999**, *285*, 1719.
(7) von Klitzing, K., *www.nobel.se/physics/laureates/1985/*, "For the discovery of the quantized Hall effect".
(8) Laughlin, R. B.; Stormer, H. L.; Tsui, D. C. *www.nobel.se/physics/laureates/1998/*, "For their discovery of a new form of quantum fluid with fractionally charged excitations".
(9) Alferov, Zh. I.; Kroemer, H. *www.nobel.se/physics/laureates/2000/*, "For developing semiconductor heterostructures used in high-speed- and opto-electronics".
(10) Ohlsson, B. J.; Magnusson, M. H.; Bjork, M. T.; Wallenberg, L. R.; Deppert, K.; Samuelson L. *Appl. Phys. Lett.* **2001**, *79*, 3335.
(11) Henning, P.; Wallenberg, L. R.; Järrendahl, K.; Hultman, L.; Falk, L. K. L.; Sundgren, J.-E. *Ultramicroscopy* **1996**, *66*, 221.

NL010099N