Newsletter no. 4

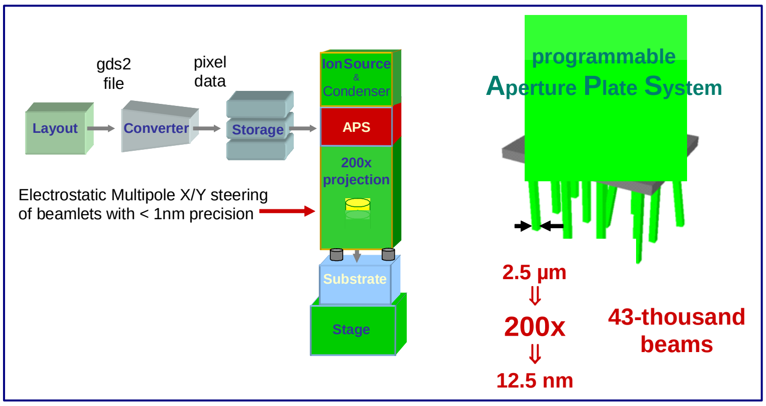
July 2009 p1

news

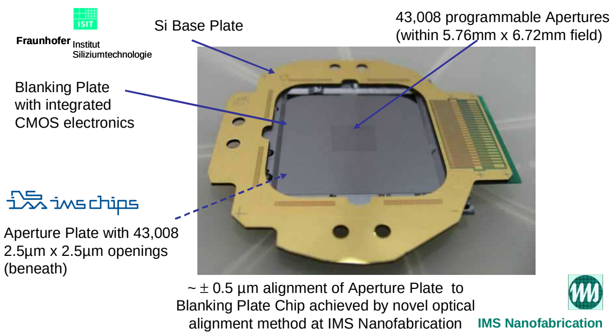
The CHARPAN (CHARged PArticle Nanotech) integrated FP6-NMP project ended March 31st 2009, after 48 project months. This newsletter gives an overview of the most important milestones reached in **tool development**, **process development, nano research** and **industrial application** and gives an **outlook on exploitation and further development.**

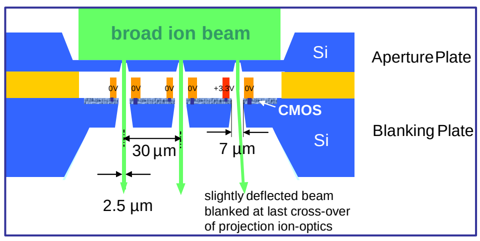
tool development

It is the project objective of CHARPAN to provide cost effective solutions for nanomanufacturing, in particular for the fabrication of three-dimensional nanosurfaces. This goal is to be accomplished by mask-less and resist-less nanopatterning using charged particle multi-beams. Charged Particle Nanopatterning, using thousands of programmable finely-focused particle beams, provides suitable throughput and flexibility for rapid nanomanufacturing in an industry environment.
In the CHARPAN Tool a **broad charged particle beam is directed to a programmable aperture plate system with about 43.000 apertures** of 2.5 µm x 2.5µm size (43k-APS). Near the apertures there are tiny deflection plates, each of which can be individually powered using integrated CMOS electronics. The slightly deflected beams are filtered out in the projection ion-optics while the undeflected beams are projected to the substrate with 200x reduction. The Figure shows the CHARPAN principle and tool.



The CHARPAN Tool was realized for ion multi-beam operation within an exposure field of about 25 µm x 25 µm. The presently used glass rule controlled stage of this tool can be operated with 150 mm Si wafers or 6" mask blanks. The 43k-APS (see figure below) consists of an aperture plate (APP) with 2.5 µm x 2.5 µm openings within an area of 5.76 mm x 6.72 mm. (192 x 224 cells of 30 µm x 30 µm). Next to the aperture plate there is a blanking plate chip with integrated 0.25 µm CMOS electronics. The openings in the blanking plate are 7 µm x 7 µm in size so that a 2.5 µm x 2.5 µm beam generated in the aperture plate can pass without touching side walls. Adjacent to each 7 µm opening there are Au electroplated ground and deflection electrodes of about 32 µm height. Powering a deflection electrode with 3.3 V led to a deflection that was sufficient to filter out the deflected beams at the last cross-over of the CHARPAN ion projection optics.





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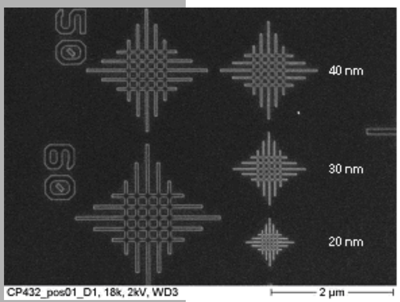
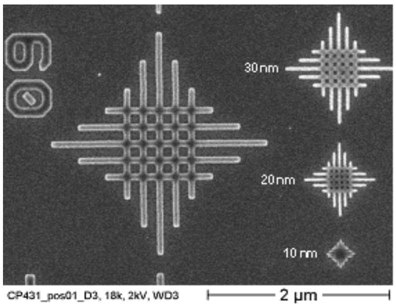
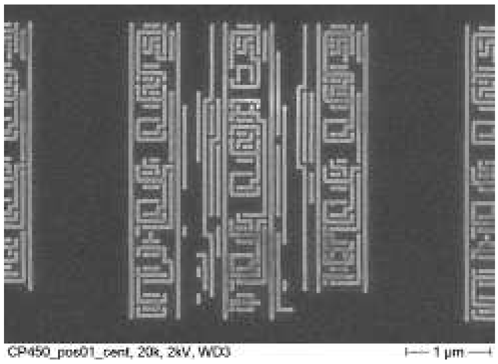
Using the CHARPAN Tool with 43k-APS a number of exposure tests were done. For this purpose **GDSII data files** were transferred into pixel data which were transferred to the 43k-APS via a flat band cable (with vacuum feed-through). For HSQ resist the exposure dose with 10 keV H_3^+ ions was 20 µC/cm^2. As the current density was set at 300 µA/cm^2 the spot exposure time was 67ms and consequently the time to expose a 20 µm x 20 µm exposure field was app. 1 min (for 50% pattern density).

A GDSII file containing **test patterns** to study the usefulness of **HSQ** / Si master stamps for SCIL™ (Substrate Conformal Imprint Lithography) was provided by Philips Research – MiPlaza.

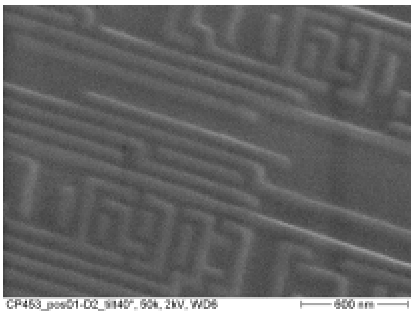




The figures show the CHARPAN 43k-APS exposure of these patterns in 20 nm HSQ (left) and in 50 nm HSQ resist (right) demonstrating 15 nm hp resolution capability. In both cases, at 20 nm and 50 nm resist thickness, the exposure dose was 20 µC/cm^2.

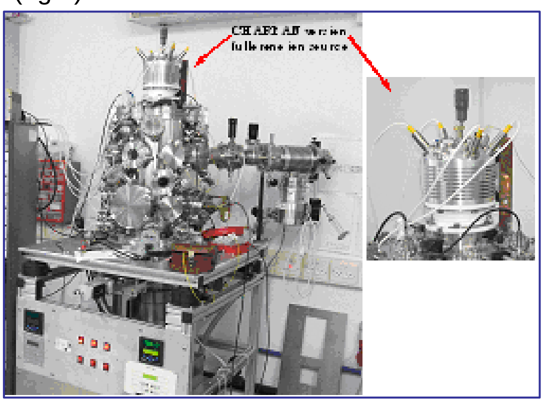


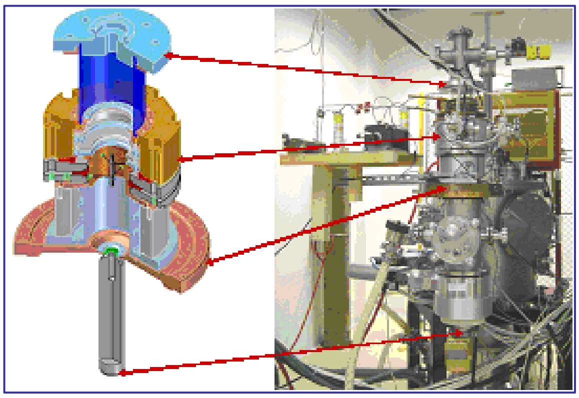
Using GDSII files from IMS-CHIPS, 40 nm hp logic test patterns were realized in 50nm HSQ resist on OMOG 6” mask blanks achieving an excellent local CD uniformity of ± 0.9 nm / 6σ for 120 nm lines. The CHARPAN Tool 43k-APS was used and exposure was with 10 keV H_3^+ ions and 20 µC/cm^2 exposure dose.



Resistless nanopatterning on Si wafer surface with 10 keV Ar+ ions was demonstrated using the CHARPAN Tool 43k-APS for sputtering a 60 nm hp logic pattern with 19.23 mC/cm2 dose to a depth of 50 nm (dark lines), and “inverse” sputtering with 38.46 mC/cm^2 dose to a depth of 100 nm (dark areas).

Within the CHARPAN project there were important developments on new ion sources: C60 **Fullerene Ion Source** by TECHNION (left) and RF driven **Multicusp Ion Source** by BIONT (right).





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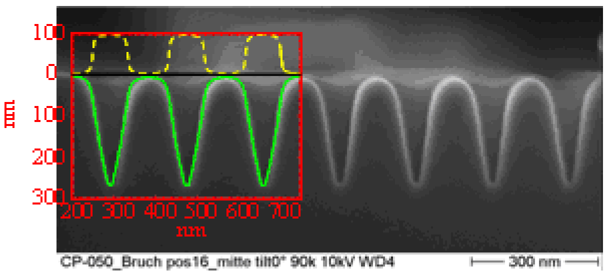
process development

The work on application specific CHARPAN process development was focused on the improvement of fundamental understanding and development of dedicated processes for ion beam nano machining with respect to basic applications and demonstration of the capabilities of the CHARPAN tool. The most important objectives which have been fulfilled very successfully during the project can be summarized as follows:

- Quantification of material processing with ion beams at nano scale and prediction of limitations,
- Development of a calibrated simulator for ion beam nano machining,
- Integration of CHARPAN processes into full process flows for nano- and microelectronics, nano mechanical devices, and nano biology,
- Development of high resolution leading-edge photomask fabrication by CHARPAN.

The patterning with ion beams is a very flexible and promising method which enables the direct fabrication of nearly arbitrary 2D and 3D structures, specifically when gas-assisted ion beam induced processing is applied. However, the interaction of the energetic ions and the material to be modified is a complex process, even for pure physical sputtering: Several secondary effects like redeposition of sputtered material, scattering of the primary ions and topography as well as material dependent sputter yields have to be properly accounted for when a targeted structure shape should be achieved.

Therefore, a very important outcome of the project is the development of the calibrated IonShaper® simulation program (IMS Nanofabrication AG), which has proven to model experimental results of complex ion beam nano processing very precisely and accurately (see figure below). It should be noted that this program is valid for both, CHARPAN and focussed ion beam (FIB) processing. Extensive work on the experimental and theoretical (by means of Monte-Carlo simulation of ion beam sputtering) determination of the material and topography specific parameters like scattered fraction of ions and sputter yield as a function of incidence angle as well as of the deposition and etching rates for gas-assisted processing accompanied the simulator activity (FhG IISB, VTU). Especially, FIB experiments performed at elevated temperatures using different target materials lead to very interesting new findings which could answer open scientific questions (VTU). Here, the determination of the real sputter yield of crystalline silicon (instead of amorphized silicon) has to be highlighted.



Overlay of IonShaper® simulation and SEM image of the 10 keV Argon ion multi-beam sputtering experiment. The dashed, yellow line on top shows the ion beam dose profile of the CHARPAN Tool as used for this experiment. The solid, green line is the simulated surface profile.

In addition, the simulator IonRevSim was developed (IMT) where the main focus was on the fast prediction of the ion dose distribution necessary for a given 3D structure, which is a very important step towards a “translation” module from 3D design to APS programming for the CHARPAN tool (here, the development of a data conversion method from 3D CAD design to ion dose distribution control data was another important step, UWC). IonRevSim takes into account the angle dependent sputter yield, only. Even with this restriction, though, very good agreement between predicted and fabricated structure shapes could be demonstrated for micron-sized structures (UWC).

Further work on an improved understanding of ion beam processing focussed on the determination of damage level and distribution which is due to the bombardment of the target material by energetic ions. Both, established high resolution characterization methods like transmission electron microscopy (TEM) as well as newly adapted electrical scanning probe microscopy (SPM) techniques like scanning spreading resistance microscopy (SSRM) have been successfully applied to monitor the created damage (FhG IISB, VTU).

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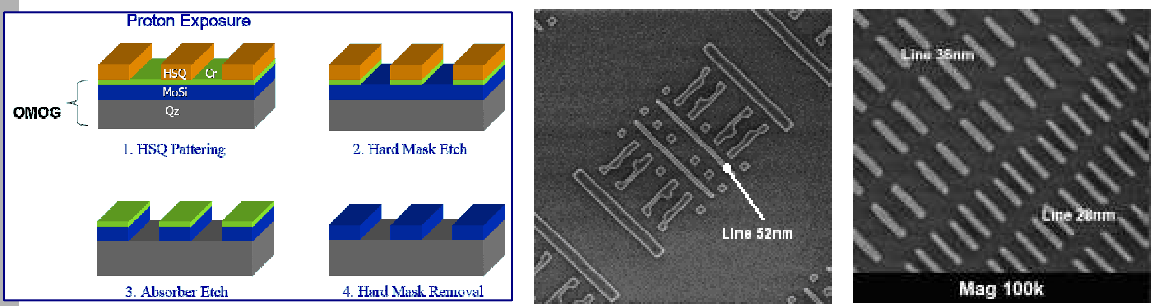
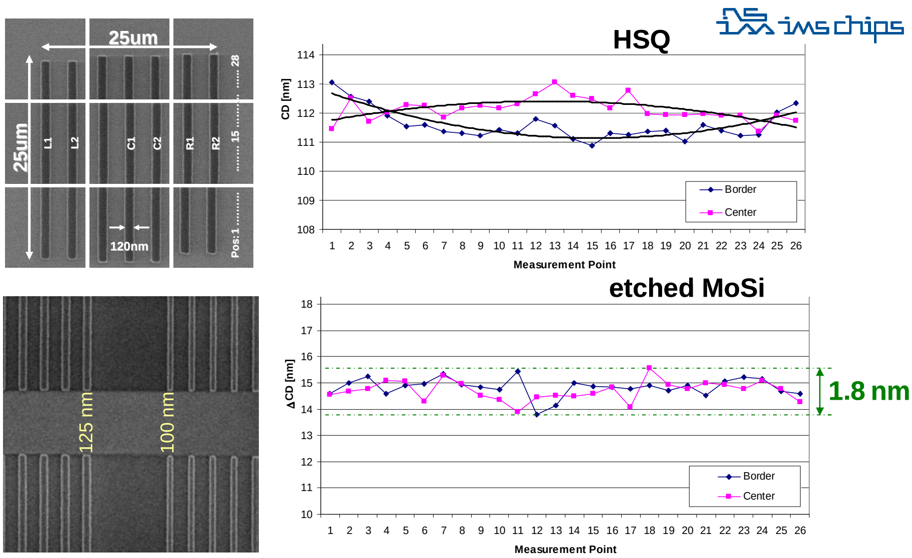
A huge variety of process flows for devices and applications in a wide range of fields, such as nano and microelectronics, nano and micro mechanics, nano photonics or nano biology, was developed where ion beam processing is the key fabrication step (CEA, CNM, UWC). For all flows, the ion beam processing step was successfully demonstrated using FIB systems resulting in innovative integrated micro-mechanical resonators and nanosensor devices (CNM), the micro-localization of cells (CEA), and patterning with complex surface structures of fused silica to fabricate and successfully use templates for Nano Imprint Lithography (NIL). Here, the development of a very flexible mix&match technology (UWC) to produce NIL templates with features from mm-scale down to nm-scale using F2 laser ablation and FIB technology has to be mentioned as a highlight.
Probably most important in this context was the impressive demonstration of the CHARPAN Tool capabilities for the fabrication of high resolution photo masks, where the CHARPAN Tool was applied for the most important HSQ patterning step which was integrated into a full process flow developed by IMS-CHIPS (see figures below).



a b c

Process flow (a) and exemplary results (b, c) for high resolution photomask fabrication using OMOG (Opaque-Molybdenum-Over-Glass) patterning by CHARPAN proton exposure



Etched MoSi lines between 100 nm and 125 nm (left) and CDSEM evaluations of local CD uniformity of 112 nm HSQ lines and etched MoSi lines

Besides, specific ion beam based fabrication process steps for nano patterning were developed using ion beam induced deposited TEOS (tetraethyl orthosilicate) as a hard mask for successive reactive ion etching (RIE) (CNM). CHARPAN sputtering processes using different ion species (e.g., H+, H3+, Ar+) were demonstrated successfully for various target materials such as resists, HSQ, Cr, GaAs, MoSi, Si, fused silica resulting in structures with feature sizes and edge angles which can definitely not be achieved when using FIB or similar approaches.

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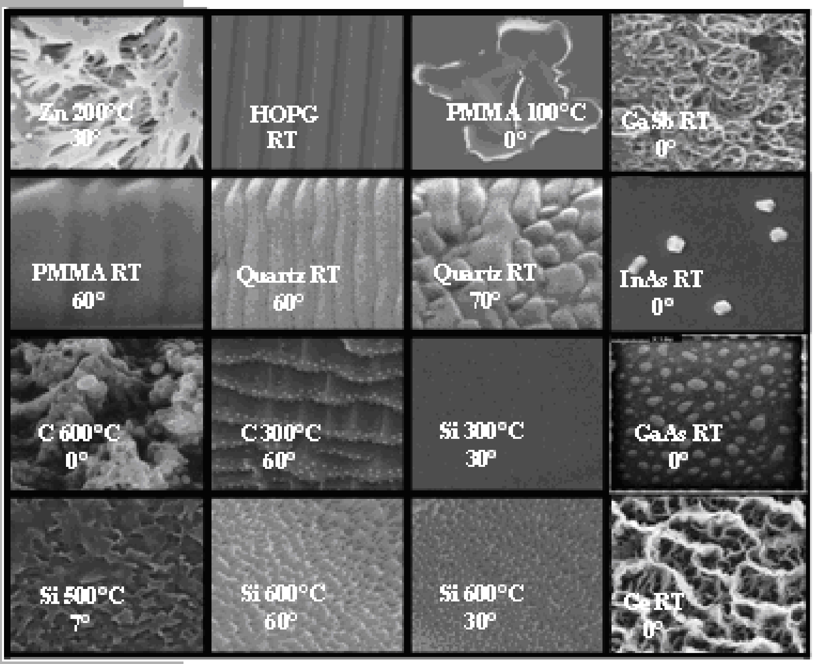
Basic and application oriented research was carried out in order to understand, control, predict and model the basic **ion beam interactions with the substrate.** Various modes of interaction of standard (atomic ion) and novel (polyatomic ion) primary projectiles with a broad range of target surfaces (semiconductors, metals, polymers, organic, etc) were studied as a pre-requisite for a successful CHARPAN implementation. On top, new types of ion sources were explored and characterized, growth and re-growth of different kinds of overlayers, self assembly processes, post processing of nanostructures, growth of nano-electronic devices and their interaction with charged beams were studied by VTU, TECHNION, CNM-CSIC, IMT.

(1) **Focused ion beam (FIB) – solid interactions** were studied for exemplary semiconductors such as Si, Ge, GaP, GaAs, InAs, metals like Au, Al, Ni and semi-metals like antimony and about more than 20 other substrates.



The morphological and chemical evolution of the surface was investigated for possible use in nano-technology applications by in-situ FIB-secondary electron microscopy combined with atomic force microscopy, high resolution transmission electron microscopy, X-ray diffraction and auger electron spectroscopy techniques. Formation of self-assembled GaAs quantum dots was observed using nano-patterened templates and sponge-like structure consisting of fibers with diameters of about 25 nm along their entire length were observed for Ge, GaSb and antimony (50 keV FIB-Ga^+). Formation of nanopatterns induced either by FIB milling under oblique angles of incidence or by simultaneous heating of the target was demonstrated.

(2) A FIB based technique for room temperature synthesis of nanowires without using any additional materials was developed along with **integration of these nanowires in CMOS compatible sensor prototypes**. A CMOS compatible self-aligning process for manufacturing a resistivity type gas sensor and a microscale pH-probe was explored.

(3) A **laser based ion source** with very narrow energy width (0.14 eV) was studied and characterized .

(4) **Sputtering and scattering interactions of fullerene ions** (C60) with a variety of surfaces were studied over a broad impact energy range (100 eV to about 15 keV). Secondary ions were probed and analyzed via time of flight secondary ion mass spectrometrey (TOF-SIMS) methods at TECHNION. Kinetic energy distributions of the emitted ions were measured and a multi-fragmentation (shattering-like) mechanism of fullerene-surface impact was studied. Growth/etching processes were investigated by mass spectrometry and time dependent SIMS.

(5) Ordered **carbon-based overlayers** were grown and characterized by FIB/HRSEM/ HRTEM methods. High quality Diamond-like-carbon (DLC) layers were prepared and then studied and characterized by micro-Raman techniques.

(6) In order to study their modification with charged beams, **methods for local functionalisation of silicon surfaces** were developed. Processes for the fabrication of large arrays of nanoelectrodes that can be adapted to CHARPAN-tool based processes were also developed.

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(7) The effect of charged beams on a single carbon nanotube field effect transistor (**CNT-FET**) was studied. Electrical characteristics were monitored simultaneously with irradiation. Electrical force microscopy was carried out. Results were applied to establish the methodology for directly contacting CNTs using electron and ion beam deposition of platinum in a single step process. Better electrical characteristics than previously reported for devices were obtained.

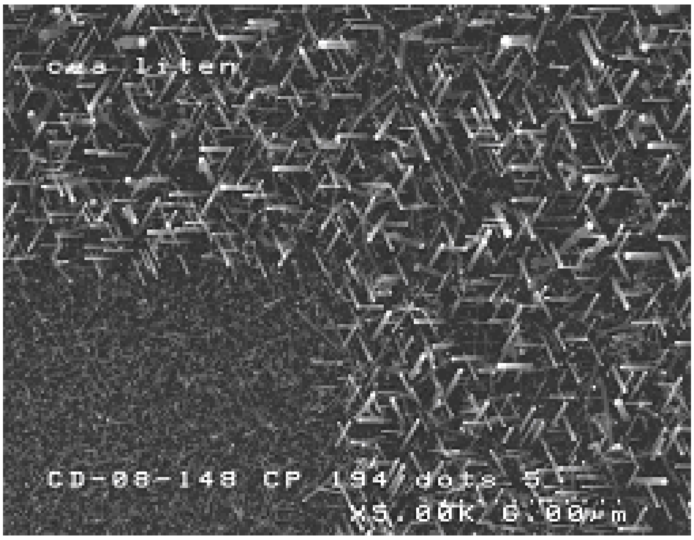
The possibility to perform **high-resolution low dose ion beam irradiation** with CHARPAN was exploited in the field of polymerics, organics, nanocomposites and inorganic materials. Supported by the choice of the applied ion species, ion irradiations allowed to change e.g. the chemical structure and composition of the topmost layers, which are responsible for essential properties such as e.g. hydrophobicity and hydrophilicity.

The research concentrated on ion irradiation experiments with polymers, silicon and metal coated samples using He+, Ar+ and Xe+ ions. In order to demonstrate the utility for low risk applications, simulations of nanostructure formation induced by ion beam irradiation were performed.

Widespread applications were investigated:

- The functionalization of silicon substrates for silicon nanowire growth by the deposition of catalyst nano particles was evaluated. Certain features are needed in order to improve the energy conversation efficiency and the power density of microfuel cells.
- The modification of mechanical properties of polymer surfaces locally modified by ion beams was determined.
- Films and nanostructures were fabricated and ion beam induced changes in hydrophobicity/ hydrophilicity properties were investigated to improve the control and monitoring of cell adhesion on nano-patterned substrates.
- Ion beam induced patterning of shape memory alloys (a lightweight, solid-state alternative to conventional actuators) was performed in order to investigate intermixing effects.
- Ion beam induced phase separation of polymer blend thin films in the sub-µm regime was investigated for application as functional elements in photonic and opto-electronic devices.
- Plasmon resonant filters comprising metallic gratings were fabricated and evaluated in order to increase the integration level of CMOS sensors.
- For the final goal of preparing ‘radioactive nano-particles for radiotherapy’, the production of nano-particles by deposition on surfaces structured by ion irradiation was performed. Reliable and reproducible technology steps for the defined growth of nano-particles and agglomerates from selected materials on pre-treated surfaces (TiO2 and Pd) were demonstrated.

The potential of CHARPAN for the utilization in emerging applications was clearly demonstrated.



Among the variety of outstanding applications only one particular example is presented. 10keV Ar+ exposures with doses ranging from 1500 to 7000 µC/cm^2 were performed on Gold coated Silicon surfaces prior to the growth of Si nano-wires. The Ar$^+$ irradiation (10 keV Ar$^+$ beam, lower left of image) led to a less dense **nano wire growth** and to smaller nano wire diameter (20nm) compared to unexposed surfaces.

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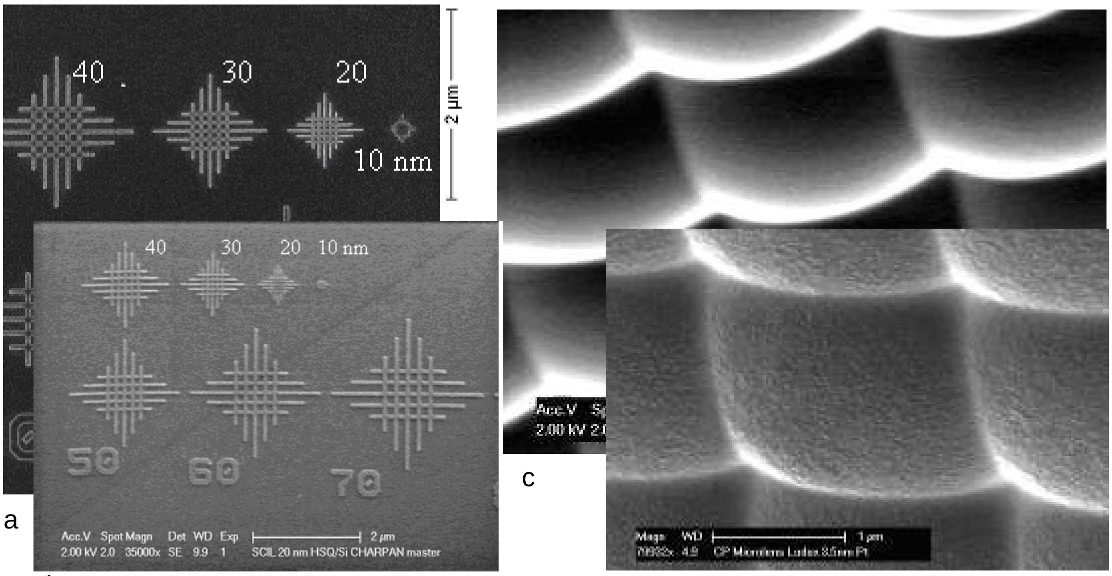
industrial applications

Clearly, there is market potential for a technology or a combination of technologies which is able to structure a wide variety of materials in 3D with nanometer resolution, provided it works reproducibly, reliably and fast. Although (chemically assisted) CHARPAN is orders of magnitude faster than single beam Electron Beam Pattern Generators and Focused Ion Beam systems, the speed needed for low cost mass production will still not be met by CHARPAN alone. Hence, for industrial applications, CHARPAN should be aiming at both the making of **masks** for mass production optical lithography and the production of **master stamps** for Nano Imprint Lithography (NIL) as e.g. Substrate Conformal Imprint Lithography (SCIL^{TM}). **Direct structuring** of a device will be mainly be used for research and testing applications, though there are also some emerging industrial applications which need localised nano-patterning.

In principle there are two CHARPAN working modes:

• **2D working mode:** thin resist layers can be exposed very fast with e.g. Hydrogen ion beams. This working mode will be suitable in particular for the fabrication of master stamps for NIL.

• **3D working mode:** the desired material can be directly sputter etched. This mode allows much more shaping freedom but is slower, especially for higher or deeper structures. The ultimate speed for (chemically amplified) 3D sputtering is still to be tested. In this mode CHARPAN can be used in the making of stamps and of coining masters for NIL / SCIL^{TM}.



2D test patterns written with CHARPAN in 20 nm thick HSQ resist (above figure a) have been used for SCIL^{TM} replication. A PDMS daughter stamp has been cast from the CHARPAN master stamp and this flexible PDMS stamp has been used to imprint in a sol-gel material. This sol-gel imprint (above figure b) features the same 20 nm resolution as the CHARPAN HSQ master.

3D structuring is shown for an array of micro-lenses in figure c. Here as well, a PDMS stamp has been cast and these deep 3D structures have been imprinted in a sol-gel material with SCIL^{TM} (figure d, surface roughness due to metal coating for gaining SEM picture).

The feasibility of (a combined) CHARPAN technology for mass production also depends on other factors:

• **Stitching and overlay:** There is the IMS Nanofabrication AG plan to realize a CHARPAN Demo Tool equipped with a laser interferometer controlled stage realized by DELONG

• **Compliance with industrially used design formats:** the 3D STL format is used which can be translated into a layered GDS-II format

The combination of CHARPAN and NIL opens up new possibilities for low cost, fast and flexible 2D and 3D manufacturing.

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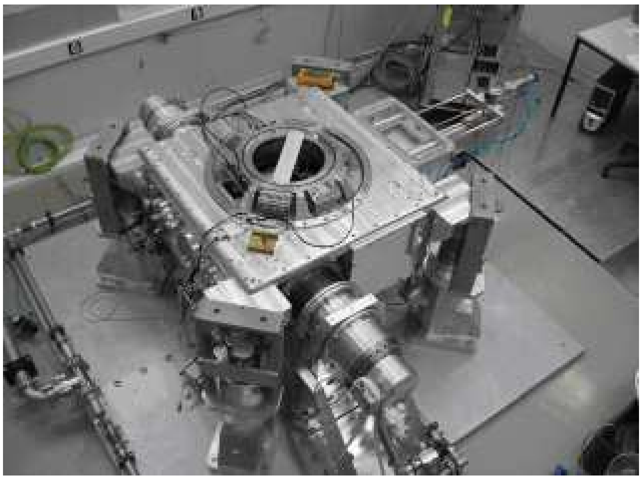
outlook

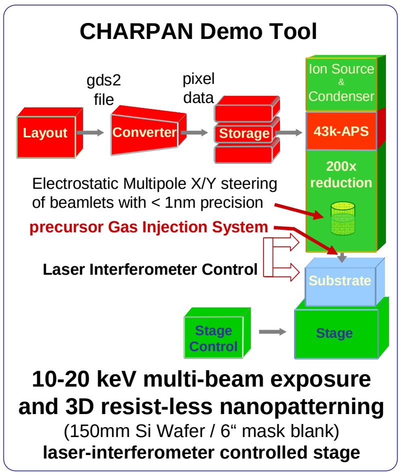
Resolution: Operating the CHARPAN Tool with a first programmable aperture plate system (APS) with integrated 0.25 µm CMOS electronics a resolution of 20 nm hp was achieved. With the present multi-cusp ion source a current density of 5.5 mA/cm2 has been realized for 10 keV Argon ions providing a total current of 0.35 nA for 43-thousand 12.5 nm beams at the substrate. The achieved resolution was in excellent agreement with ion-optical calculations. An enhancement to 1 nA is possible when integrating an improved multicusp source which has been realized and tested in the meantime. **Resolution enhancements below 10 nm are predicted** when using 20 keV ion beam energy

Commercialisation: Analyses of all feedback obtained form the industry and potential end users lead to the conclusion that tools need to be adopted to each customer groups in order to meet requirements. Therefore CHARPAN technology will best be commercialised in three product lines:

- **CHARPAN 3D Nanopatterning Engineering Tool** for R&D applications and **CHARPAN 3D Nanopatterning Production Tool**, for emerging industrial applications in Nanophotonics, NanoBiotechnology, NanoSensorics, etc.
- **CHARPAN Template Exposure Tool** for NIL application,
- **CHARPAN Mask Exposure Tool** for leading-edge complex mask fabrication.

Stitching and overlay: A laser **interferometer controlled stage** realized by DELONG has been delivered to IMS Vienna and integrated into a new platform (figure below). This platform will also house a precursor gas injection system (GIS) for 3D ion multi-beam assisted etching and deposition. Thus a CHARPAN Demo Tool will be realized (schematics are shown in the figure below) as a prototype for a commercial CHARPAN Nanopatterning Engineering Tool.





contact

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CHARPAN Coordinator
Dr. Elmar Platzgummer
phone: +43 1 21 44 894 - 19
email: elmar.platzgummer@ims.co.at

CHARPAN Administrator
Dr. Hans Loeschner
phone:+43 1 21 44 894 - 24
email: hans.loeschner@ims.co.at

IMS Nanofabrication AG, Schreygasse 3, A-1020 Vienna, Austria

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