Project no.: 515803

CHARPAN

Charged Particle Nanotech

Instrument:	SIXTH FRAMEWORK PROGRAMME
Thematic Priority	PRIORITY 3 / NMP

WP-11 / Deliverable D-11.14

Publishable FINAL ACTIVITY REPORT

Period covered:	**2005-04-01 to 2009-03-31**	Date of preparation:	**final: 2009-06-26** **1st rev: 2009-07-21** **2nd rev: 2009-08-28**
Start date of project:	**2005-04-01**	Duration:	**48 months**
Project coordinator name:	**Elmar Platzgummer**		
Project coordinator organisation name:	**IMS**	Version:	**V-1.2**

Dissemination Level: PU

Change History

Version	Explanation	Date year-mm-dd	Author(s)	Organisation
V-0.1	draft	2009-04-20	WP-01 / Jörg Butschke /	IMS-CHIPS
		2009-04-20	WP-02 – Task 2.5 / Wolfgang Pilz	FhG ISIT
		2009-04-20	WP-02 – Task 2.8 / Eli Kolodney	TECHNION
		2009-04-20	WP-03 / Mathias Rommel	FhG IISB
		2009-04-22	WP-04 / Eli Kolodney	TECHNION
		2009-04-20	WP-05 / Wolfgang Pilz	FhG ISIT
		2009-04-21	WP-07&08 / Falco van Delft	PHILIPS
		2009-04-20	WP-09 / Jörg Butschke	IMS-CHIPS
		2009-04-15	WP-10 / Andrea Kurz	HITEC
		2009-04-21to27	WP-02, WP-11 and overall report / Hans Loeschner	IMS
V-0.2	draft	2009-05-28	Jörg Butschke / input for Final Report – E (Exploit.)	IMS-CHIPS
		2009-05-28	Andrea Kurz / input for Final Report – E (Diss / Mark.)	HITEC
		2009-06-04	Mathias Rommel / input for Final Report – B (Process)	FhG IISB
		2009-06-08	Wolfgang Pilz / input for Final Report – C (Nano-Res)	FhG ISIT
		2009-06-11	Falco van Delft / input for Final Report – D (Ind.Appl.)	PHILIPS
		2009-06-17	Hans Loeschner / input for Final Report – A (Tool Development) and F (Outlook) and overall report update	IMS
V-0.3	draft	2009-06-22	Wolfgang Pilz / critical reading of version V-2.0	FhG ISIT
		2009-06-18	Dissemination / Alois Lugstein	VTU
		2009-06-18	Dissemination / Mathias Rommel	FhG IISB
		2009-06-18	Dissemination / Jörg Butschke	IMS-CHIPS
		2009-06-19	Dissemination / Sergey Zaitsev	IMT
		2009-06-20	Disseminaiton / Wilhelm Brünger	IZET
		2009-06-23	Dissemination / Reinhard Boysen	MUAUS
		2006-06-23	Dissemination / Wolfgang Pilz	FhG ISIT
		2006-06-23	Dissemination / Dan Nicolau	UoL
		2009-06-19	WP-02 - Thruput / Falco van Delft (JEOL/CHARPAN)	PHILIPS
		2009-06-18	WP-02 – Stage performance / Michal Drsticka	DELONG
		2009-06-23	WP-02 – Stage acceptance test / Heinz Fragner	IMS
		2009-06-23	WP-02 – Stage integration / Gerald Kratzert	IMS
		2009-06-23	Eli Kolodney / input for Final Report – C (Nano-Res.)	TECHNION
		2009-06-23&24	Hans Loeschner – report update	IMS
V-1.0	final	2009-06-19	Dissemination / Francesc Perez-Murano	CSIC-CNM
		2009-06-26	Hans Loeschner – final report	IMS
V-1.1	1st revision	2009-06-30	Wilhelm Bruenger – corrections of Version V-1.0	IZET
		2009-07-21	Hans Loeschner – update and final editing	IMS
V-1.2	2nd revistion	2009-08-28	Hans Loeschner – clarification on pp. 12 and 17 that the precursor Gas Injection System (GIS) was not inserted into the CHARPAN Tool within the project period.	IMS

Main Contributor(s) List Record

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Release Approval

Date: year-mm-dd	Company	Person In Charge	Contact
2009-04-27 (V-0.1 draft report sent to EC)	IMS	Elmar Platzgummer	phone: +43 1 21 44 894 - 19 mobile: +43 664 140 4009 e-mail: elmar.platzgummer@ims.co.at
2009-06-26 (V-1.0 final)			
2009-07-21 (V-1.1 1st revision)			
2009-08-28 (V-1.2 2nd revision)			

CHARPAN publishable FINAL ACTIVITY REPORT

FP6 – NMP Integrated Project	**CHARPAN (Charged Particle Nanotech)**	
Project no.: 515803	Start: **2005-04-01**	Projection Duration: **48 Months**

Summary Description of CHARPAN Project Objectives

The general CHARPAN project objectives are to provide cost effective solutions for nanomanufacturing, in particular for the fabrication of three-dimensional nanosurfaces. This is to be accomplished by mask-less and resist-less nanopatterning using charged particles (electron / ion) multi-beams. The CHARPAN Tool development is focused on generating about 40.000 ion beamlets with sub-25nm resolution. Using stencil masks the target is to verify <20nm resolution within a 25µm x 25µm exposure field. Within the partner consortium there is the aim to explore industrial applications: (i) fabrication of leading edge complex masks, (ii) fabrication of 3D nanoimprint templates for "Above IC" nanoimprinting of microlenses for imager chips, as well as (iii) to explore direct ion multibeam nanopatterning for industry driven applications in the fields of nanophotonics, nanomagnetics, energy conversion and nanobiotechnology.

CHARPAN Contractors Involved

In order to meet its aim in various market fields, the project focuses on a **tight integration of all value chain partners** necessary for the development and commercialisation of high-value nanotechnology products. The consortium is well-balanced, representing forefront research organisations and industrial partners pushing the limits of charged particle beam technology in terms of throughput and industrial applicability. The project coordinator is an SME with a wealth of experience in advanced nanostructuring tools. **Table 1** lists the 19 CHARPAN partners (details see CHARPAN website) divided by category.

Table 1: CHARPAN partners

Industry	Research	Higher Education	Global
IMS (Austria) coordinator	FHG (Germany)	IMS-CHIPS (Germany)	IMT (Russia)
DELONG (Czech Republic)	CEA (France)	TECHNION (Israel)	UBR (Romania)
PHILIPS (Netherlands)	CSIC (Spain)	VTU (Austria)	MUAUS (Australia)
COLORCHIP (Israel)	TU/e (Netherlands)	UWC (UK)	**Support:** IZET (Germany)
BIONT (Slovak Republic)	HITEC (Austria)	UoL (UK)	

CHARPAN Coordinator and Administrator contact details

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CHARPAN Website: www.charpan.com

CHARPAN Project Partners:

Partici-pant Role[1]	Partici-pant ID No.	Participant name	Participant short name	Country	Month to enter project	Month to exit project
CO	**1**	IMS Nanofabrication AG	**IMS** *(SME)*	Austria	1	48
CR	*(2)*	*Carl Zeiss NTS GmbH*	*ZEISS*	*Germany*	*1*	*12*
CR	**3**	Fraunhofer Gesellschaft: Institut für Siliziumtechnologie (**ISIT**) and Institut für Integrierte Systeme und Bauelementetechnologie (**IISB**)	**FHG**	Germany	1	48
CR	*(4)*	*Slovak Technical University*	*STUBA*	*Slovak Republic*	*1*	*8*
CR	**5**	Manufacturing Engineering Centre, Cardiff University	**UWC**	UK	1	48
CR	**6**	Consejo Superior de Investigaciones Científicas, Centro Nacional de Microelectrónica (**CNM**)	**CSIC**	Spain	1	48
CR	**7**	Commissariat à l'Energie Atomique: **L**aboratoire d'**E**lectronique de **T**echnologie de l'**I**nformation (**LETI**), and d'**I**nnovations pour les **T**echnologies des **E**nergies nouvelles et les Nanomatériaux (**LITEN**)	**CEA**	France	1	48
CR	**8**	Vienna Technical University	**VTU**	Austria	1	48
CR	**9**	Technion – Israel Institute of Technology	**TECHNION**	Israel	1	48
CR	*(10)*	*Lambda Crossing Ltd.*	*LAMBDA* *(SME)*	*Israel*	*1*	*7*
CR	**11**	Gesellschaft für Technologie-förderung Itzehoe GmbH	**IZET** *(SME)*	Germany	1	48
CR	**12**	University of Bucharest - Romania, Intl. Centre of Biodynamics	**UBR**	Romania	1	48
CR	*(13)*	*Swinburne University*	*SUAUS*	*Australia*	*1*	*12*
CR	*(14)*	*STMicroelectronics*	*ST*	*France*	*1*	*24*
CR	**15**	Vereinigung High Tech Marketing	**HITEC**	Austria	1	48
CR	**16**	Philips Research Laboratories Eindhoven	**PHILIPS**	Netherlands	1	48
CR	**17**	Institute of Microelectronics Technology, Russian Academy of Sciences	**IMT**	Russian Federation	1	48
CR	**18**	Technische Universiteit Eindhoven	**TU/e**	Netherlands	1	48
CR	**19**	ColorChip Ltd.	**COLORCHIP** *(SME)*	Israel	8	48
CR	**20**	Biont, a.s. (Bratislava Ion Technology)	**BIONT**	Slovak Republic	9	48
CR	**21**	Institute for Microelectronics Stuttgart (ims-chips)	**IMS-CHIPS**	Germany	13	48
CR	**22**	University of Liverpool	**UoL**	UK	13	48
CR	**23**	Monash University	**MUAUS**	Australia	13	48
CR	**24**	Delong Instruments a.s.	**DELONG** *(SME)*	Czech Republic	25	48

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[1] CO = Coordinator, CR = Contractor

Description of the CHARPAN system

Flexible, cost-effective, and rapid manufacturing can best be achieved by implementing maskless techniques, requiring massively parallel working beams with resolution capability in the nanometer range. Charged Particle Nanopatterning, implementing thousands of programmable, finely-focused particle beams, provides suitable throughput and flexibility for rapid nanomanufacturing tasks under industrial production conditions.

In a CHARPAN Tool a broad charged particle beam is directed to a programmable aperture plate system with thousands of apertures of micrometric dimension (Figure 1). Near the apertures are tiny deflection plates, each of which can be individually powered (to several Volts) using integrated CMOS electronics. The slightly deflected beams are stopped near the cross-over of a charged particle beam projection optics with 200x reduction. The undeflected beams are projected to the substrate with nanometer resolution.

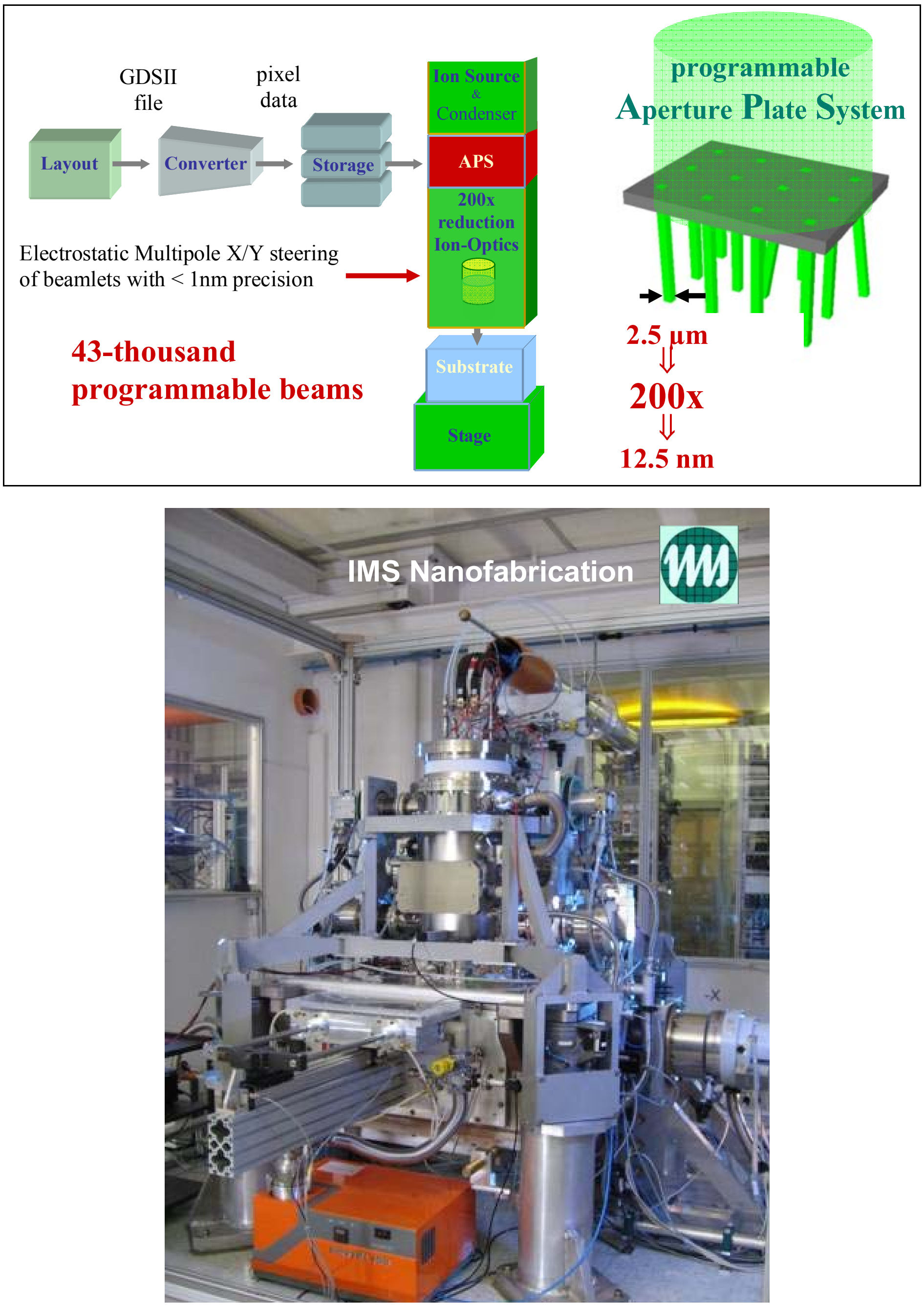


Figure 1: Principles of Charged Particle Nanopatterning and realized CHARPAN Prototype Tool

Using stencil mask templates and 10 keV Hydrogen ions a resolution of 16 nm lines and spaces could be demonstrated within the 25 µm x 25 µm exposure field of the CHARPAN ion-optical column. This result is in excellent agreement with ion-optical calculations. The calculations show that a resolution of below 10 nm lines and spaces should be possible when enhancing the ion beam energy to 20 keV (Figure 2).

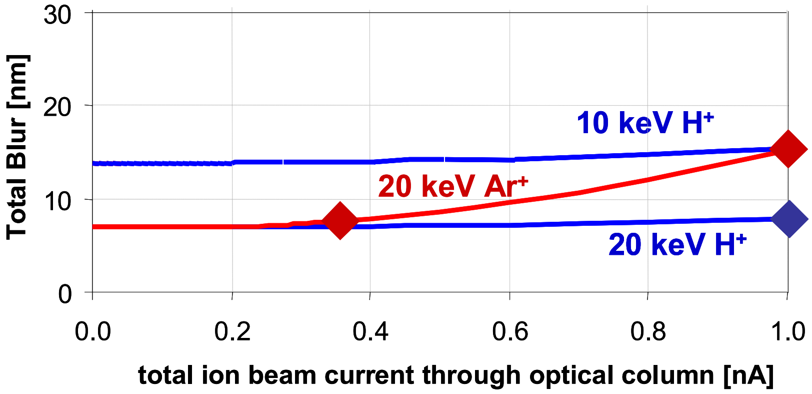


Figure 2: Calculated (ray tracing) performance of the CHARPAN ion-optical column for 10 keV Hydrogen ions and for 20 keV Hydrogen and Argon ions. The calculated resolution (equivalent to the total blur) for 10 keV H^+ ions is in excellent agreement with experimental results.

CHARPAN Work Structure

Figure 3 depicts the 11 CHARPAN work packages and their mutual dependencies.

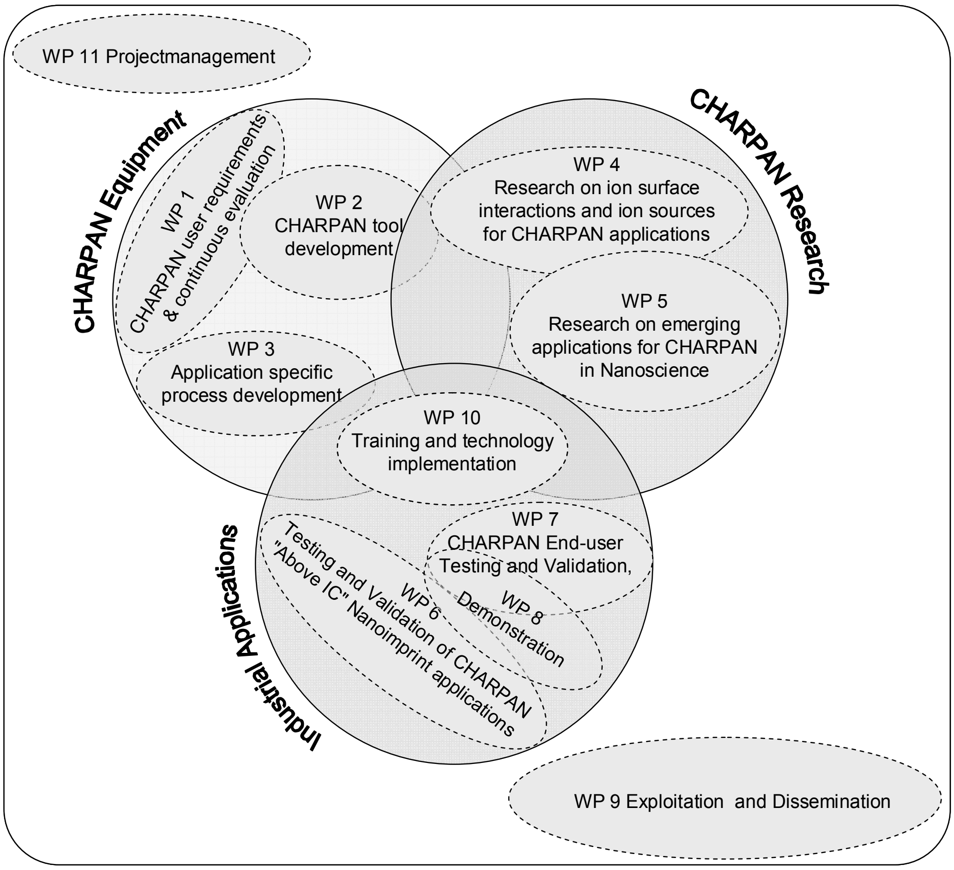


Figure 3: Structure of the CHARPAN-Project

Work Performed and Results Achieved in the Project Period April 2005 – March 2009 and Outlook Beyond

A. CHARPAN Tool Development

The CHARPAN Tool was realized for ion multi-beam operation within an exposure field of ca. 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. To meet timing and cost boundary conditions the system was designed for static exposure which means that a substrate can be exposed at different sites but is mechanically connected to the column during exposure. Fine positioning of the ensemble of beamlets which are projected to the wafer substrate is accomplished with the help of electrostatic multi-poles in X / Y direction. The status of the CHARPAN Tool is that up to 43-thousand programmable ion beams of 12.5 nm size are realized at the substrate.

A first “43k-APS” unit (Figure 4) was inserted to the CHARPAN Tool providing ca. 43 thousand programmable ion beams of 12.5 nm beam size at the substrate. This 43k-APS consisted 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). In proximity to the aperture plate is a blanking plate chip with integrated 0.25 µm CMOS electronics. The openings in the blanking plate are sized 7 µm x 7 µm 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 are Au electroplated ground and deflection electrodes of ca. 32 µm height. Powering a deflection electrode with 3.3 V delivered by the 0.25 µm CMOS electronics a deflection of ca. 950 ± 150 µrad was achieved, far exceeding the threshold of 350 µrad as needed to filter out the deflected beams at the last cross-over of the CHARPAN ion projection optics.

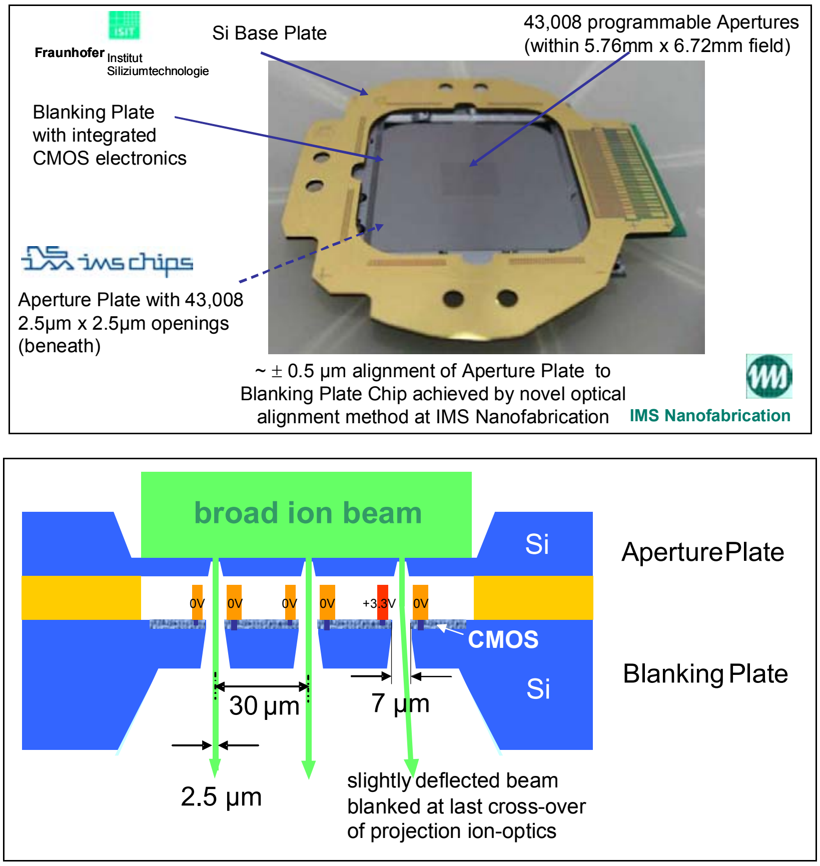
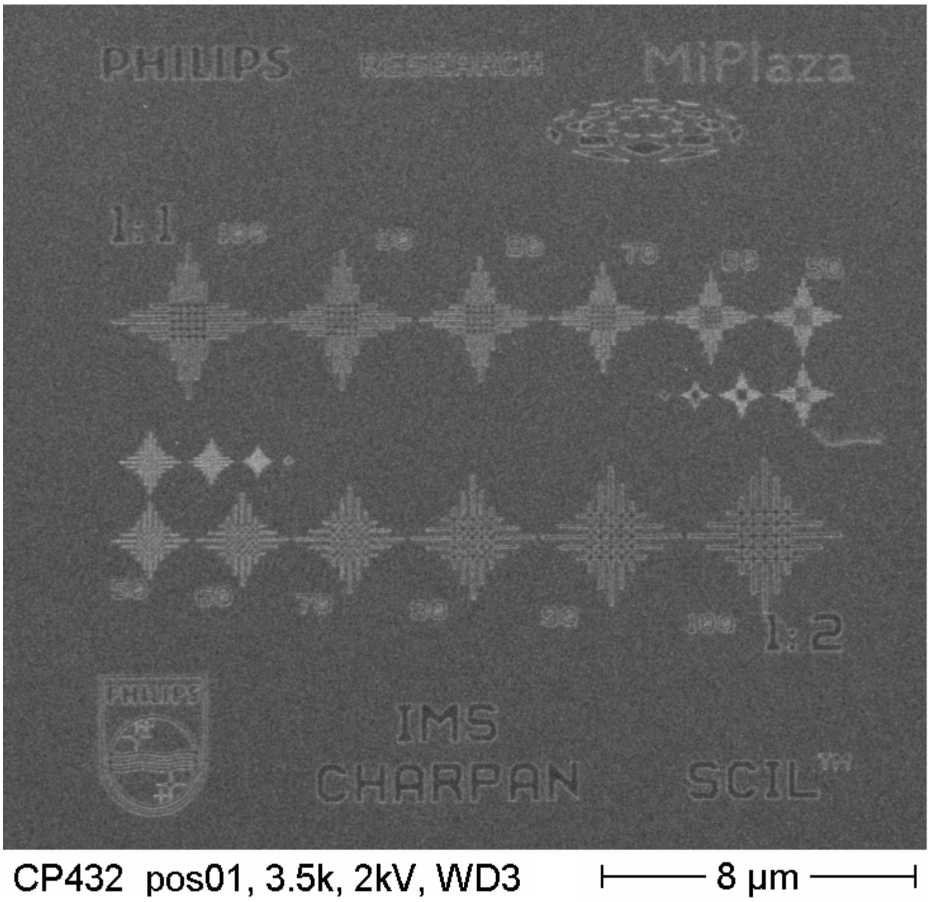


Figure 4: Realized 43k-APS unit and schematics of programmable Aperture Plate System

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). In most cases the GDSII data file had a pattern layout for an exposure field of 20 µm x 20 µm (the maximum field is 28.8 µm x 33.6 µm). The spot exposure time is defined by the exposure dose and the ion beam current density. The total exposure time is further defined by the filling factor. As there is one 2.5 µm x 2.5 µm opening within an APS cell size of 30 µm x 30 µm this filling factor is 144 in case of 100% pattern density. But in the first 43k-APS unit not yet a 3D-APP [i] but a conventional aperture plate was implemented. In order to minimize cross-talk only every second beam was used for exposure and thus for these first CHARPAN Tool 43k-APS exposures the filling factor was 576. For HSQ resist the exposure dose with 10 keV H_3^+ ions was 20 µC/cm^2. As the current density was set at 100 µA/cm^2 the spot exposure time was 0.2 s and consequently the time to expose a 20 µm x 20 µm exposure field was ca. 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 compiled by Philips Research – MiPlaza. Figure 5a shows the CHARPAN 43k-APS exposure of these patterns in 20 nm HSQ resist within a 20 µm x 20 µm exposure field; Figure 5b and Figure 5c show details of 1:1 and 1:2 patterns. Figure 5d shows 1:2 patterns in 50 nm HSQ resist demonstrating 15 nm hp resolution capability. In both cases, 20 nm and 50 nm resist thickness, the exposure dose was 20 µC/cm^2 pointing to the important advantage that with light ion beams the exposure dose is virtually independent of thickness due to the fact that the exposure is accomplished by a large number of low energy (~ 2 eV) secondary electrons generated by the Hydrogen ion beam traversing the resist. Straightforward to explain, the exposure dose was the same when using 10 keV H^+ instead of H_3^+ ions.

Operating the CHARPAN Tool with the first 43k-APS unit a resolution capability of < 20 nm was demonstrated. As this first APS unit had quite a number of “always on” and “always off” defects a proprietary single pass exposure mode with 16x redundancy was implemented greatly improving the pattern transfer quality (Figure 6).



a)

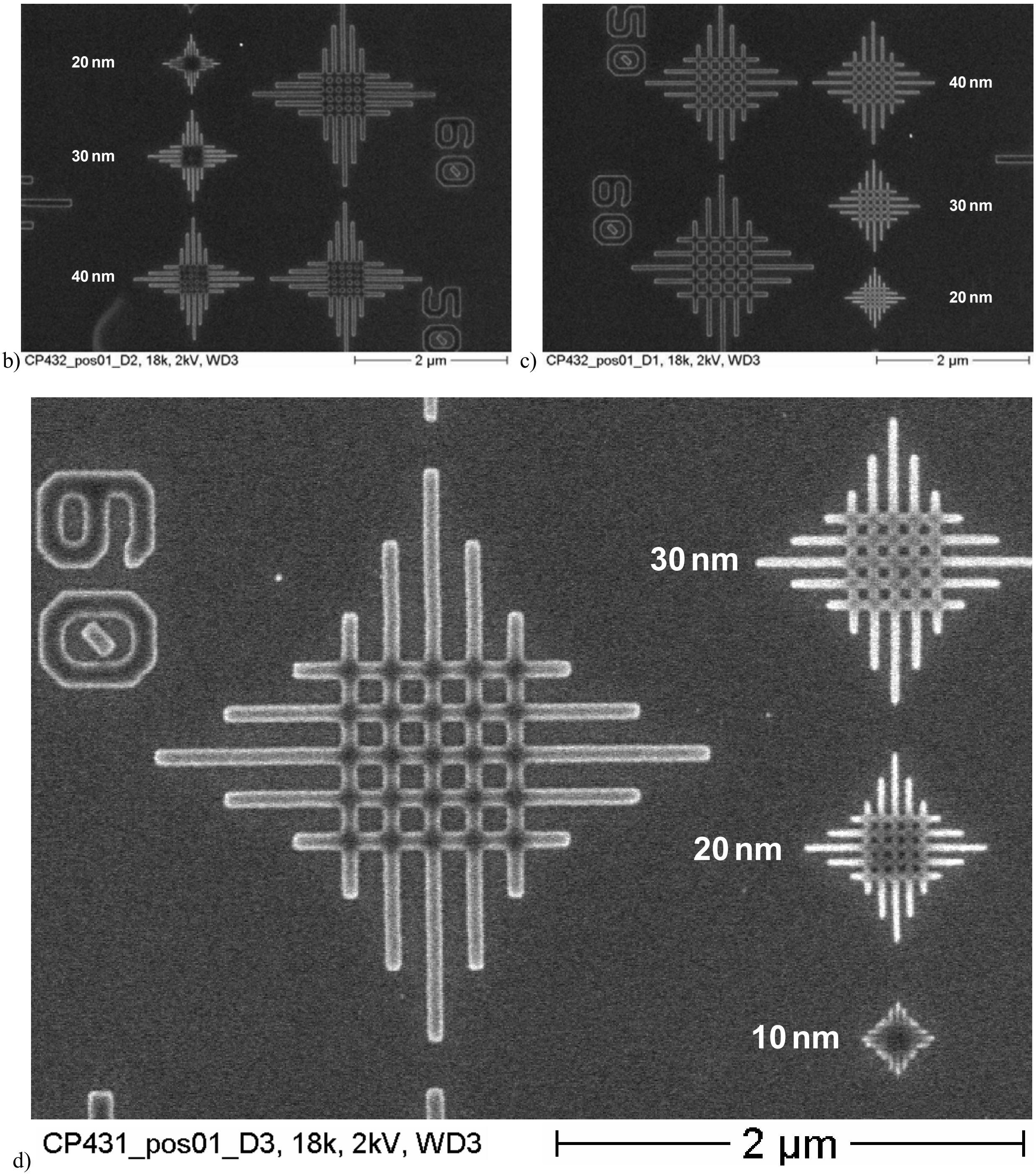


Figure 5: CHARPAN Tool 43k-APS exposure with 10 keV H_3^+ ions and 20 $\mu C/cm^2$ exposure dose in HSQ resist on Si, a) 20 µm x 20 µm exposure in 20 nm HSQ, b) detail of 1:1 patterns in 20 nm HSQ, c) detail of 1:2 patterns in 20 nm HSQ, and d) detail of 1:2 patterns in 50 nm HSQ.

Using GDSII files from the Institute for Microelectronics Stuttgart (ims chips), 40 nm hp logic test patterns were realized in HSQ resist as shown in Figure 7.

Detailed exposures were done in HSQ resist on OMOG 6” mask blanks achieving an excellent local CD uniformity of ± 0.9 nm / 6σ for 120 nm lines (see Figure 15 below).

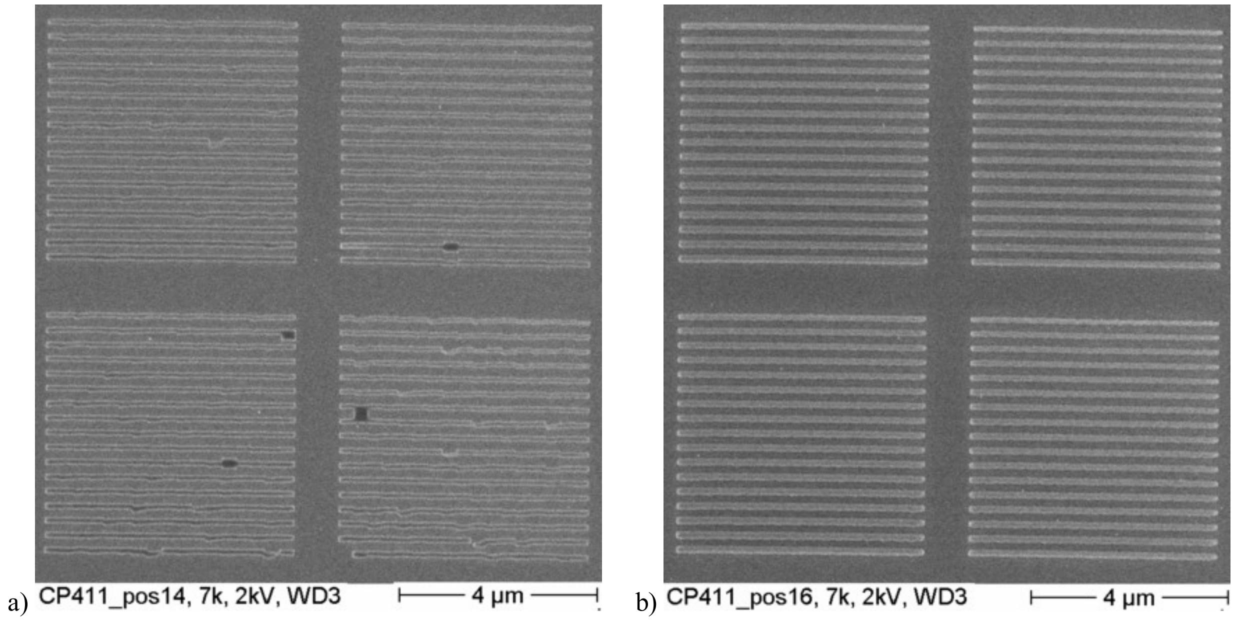


Figure 6: CHARPAN Tool 43k-APS exposure with 10 keV H^+ ions and 20 µC/cm^2 exposure dose in 50 nm HSQ resist on Si, a) exposure without redundancy showing the influence of “always on” and “always off” APS defects, b) single pass 16x redundancy exposure showing adequate definition of 125 nm lines.

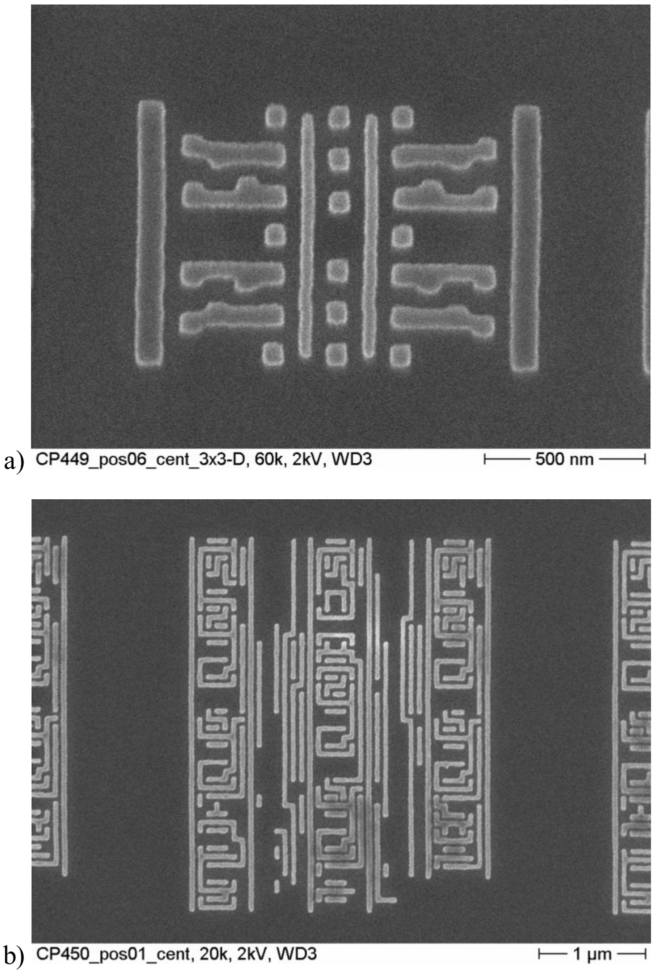


Figure 7: CHARPAN Tool 43k-APS exposure with 10 keV H_3^+ ions and 20 µC/cm^2 exposure dose in 50 nm HSQ resist on Si, a) logic pattern with 40 nm smallest feature size, b) 40 nm hp logic pattern.

There was also the possibility to realize resistless nanopatterning using 10 keV Argon ions as shown in Figure 8a. In Figure 8b and Figure 8c “inverse sputtering” was done removing all regions around 60 nm hp logic pattern features. Figure 8d visualizes both modes of sputtering in one nanopatterning example. When operating the multi-cusp plasma source with Argon a current density of 5.5 mA/cm^2 was realized at the substrate. The dose was 38.5 mC/cm^2 to achieve a sputter depth of 100 nm.

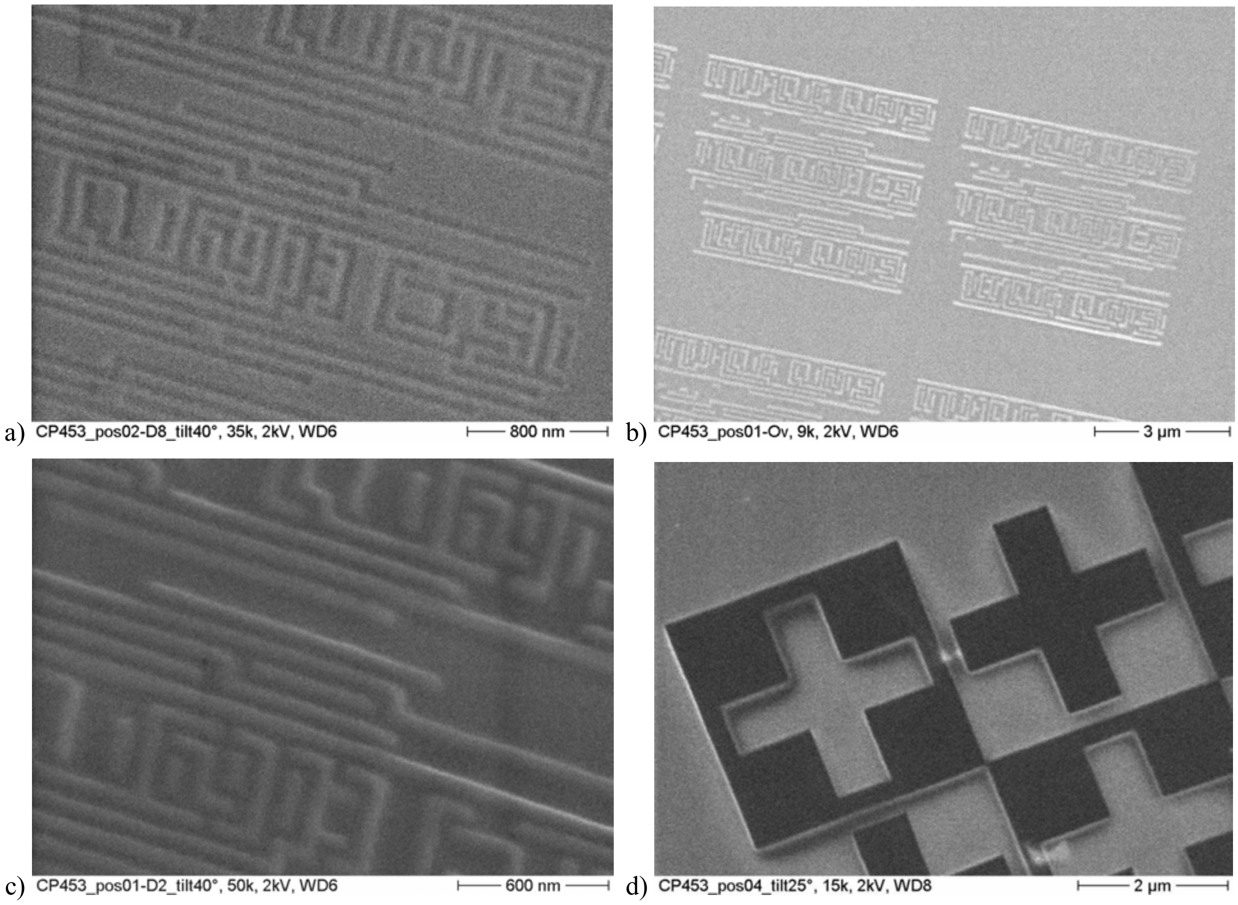


Figure 8: CHARPAN Tool 43k-APS resistless sputtering of on Si wafer surface with 10 keV Ar$^+$ ions, a) 60 nm hp logic pattern with 19.23 mC/cm^2 dose to a depth of 50 nm (dark lines), b) and c) “inverse” sputtering with 38.46 mC/cm^2 dose to a depth of 100 nm (dark areas), and d) with 40 nm smallest feature size, b) sputtering of pattern in the form of crosses; the dark areas are sputtered to 100 nm depth.

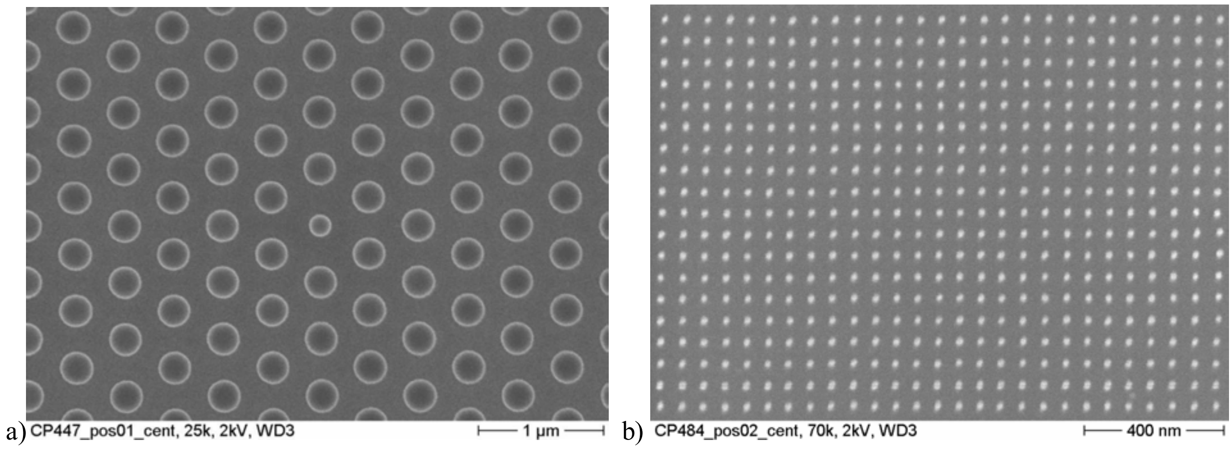


Figure 9: CHARPAN Tool 43k-APS exposure with 10 keV H_3^+ ions of a) photonic patterns in 50 nm HSQ resist on Si with 20 µC/cm^2 exposure dose, and b) < 20 nm dots with 62.5 nm pitch in 20 nm HSQ, 45 µC/cm^2 exposure dose.

For Austrian national projects (PLATON and NILaustria) photonic patterns with adequate roundness and dot patterns were realized (Figure 9). The 25 nm dots were exposed with a 2 x 2 matrix of 12.5 nm exposure shots. Here the exposure was done without redundancy leaving room for improvements. To achieve ca. 20 nm dots single 12.5 nm beam shots were used but the dose was enhanced to 45 µC/cm^2.

Within the CHARPAN project there were important developments on new ion sources: C60 Fullerene ion source by TECHNION (Figure 10a) and RF driven Multicusp Ion Source by BIONT (Figure 10b).

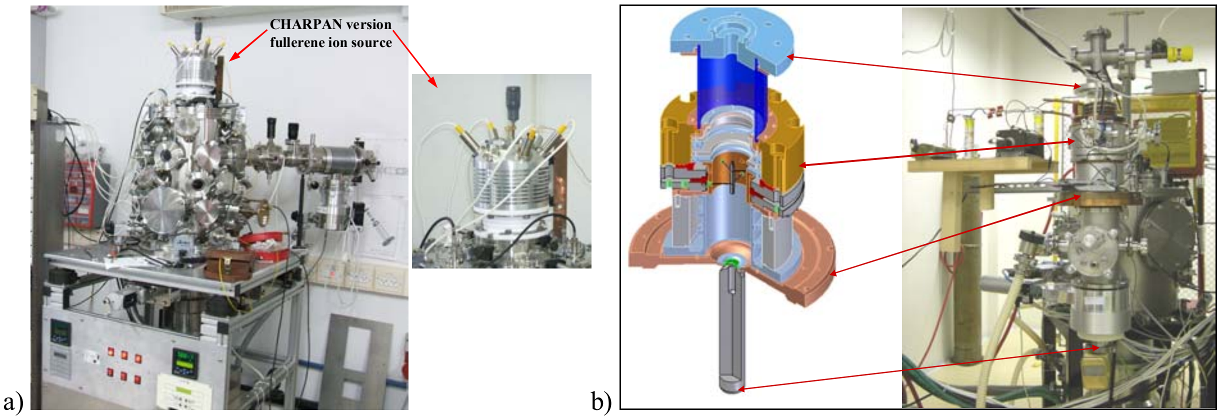


Figure 10: Ion source test benches for a) C60 Fullerene Ion Source (TECHNION) and for b) RF driven Multi-Cusp Ion Source (BIONT).

B. CHARPAN 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 within the following categories:

- 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 (Figure 11). It should be noted that this is valid for both, CHARPAN and focussed ion beam (FIB) processing. A precursor Gas Injection System (GIS) was ordered by IMS early in 2008 but unfortunately turned out to be non-functional. Thus, the CHARPAN Tool could not be equipped with a GIS as originally planned within the project period.

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.

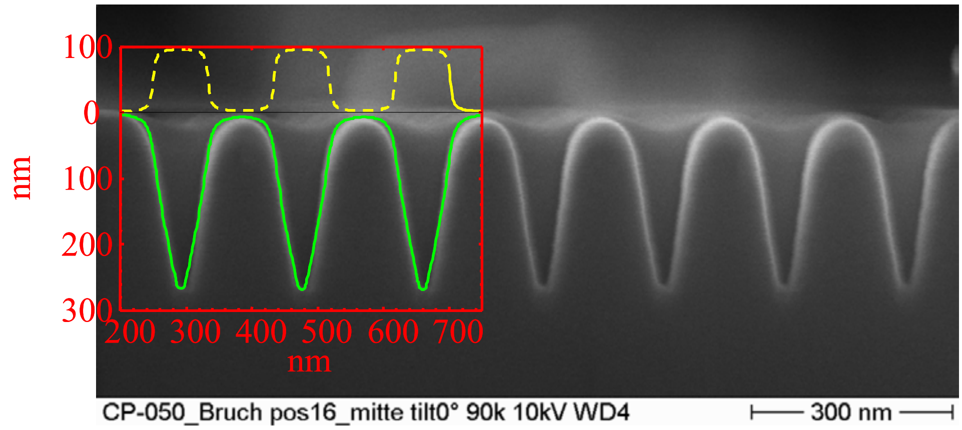


Figure 11: Overlay of IonShaper® simulation and SEM image of the experiment. The dashed, yellow line on top shows the ion beam dose profile of the CHARPAN Tool as used for this experiment. The solid, green line is the simulated surface profile.

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 highly 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).

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 NanoImprint lithography (NIL) (UWC: Figure 12). Here, the development of a very flexible mix&match technology 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 (Figure 13).

Probably most important in this context was the impressive demonstration of the CHARPAN tool capabilities for the fabrication of high resolution binary 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 (Figure 14, Figure 15).

Besides, specific ion beam based fabrication process steps for nano patterning have been 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^+, H_3^+, Ar^+)

have been 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 not be achieved by far using FIB or similar approaches.

The work on CHARPAN process development very successfully demonstrated the capabilities of the CHARPAN tool for nano engineering applications and developed process chains where the CHARPAN tool can be applied for optimized processing for a huge variety of applications with superior performance compared to today's ion beam technology.

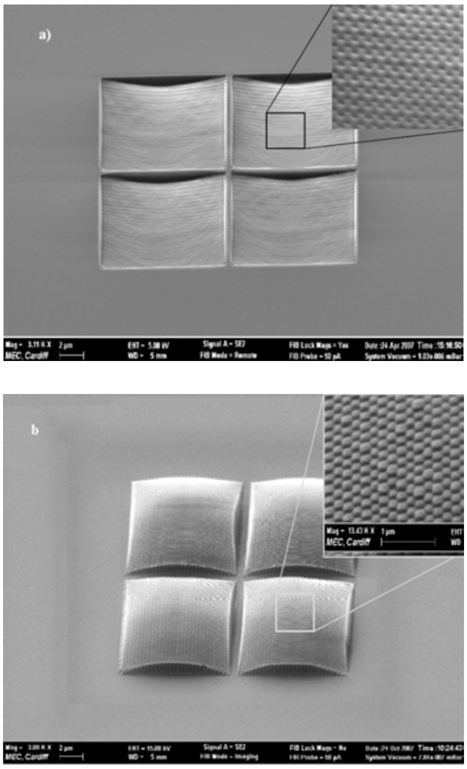
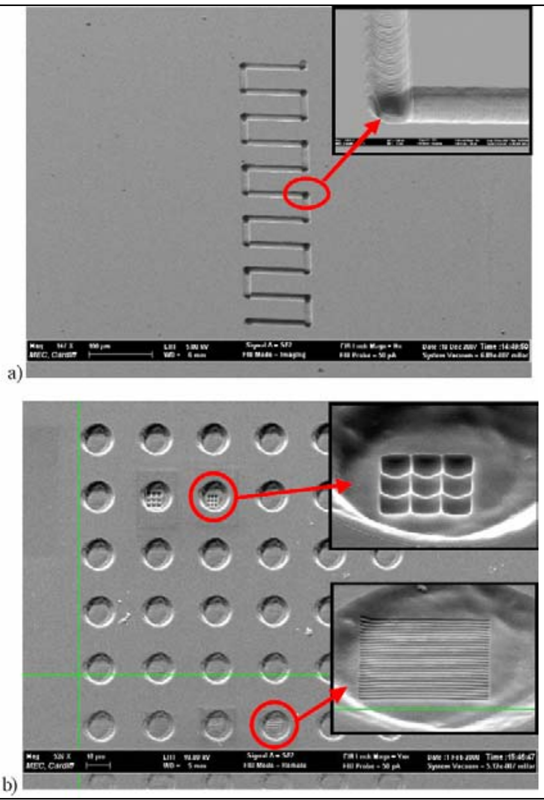
	

Figure 12: a) SEM image of FIB fabricated 2x2 array of Moth's eye lenses; insert: SEM zoom-in image; b) SEM image of NIL replicated 2x2 array of Moth's eye lenses, insert: SEM zoom-in image	Figure 13: a) SEM image of grooves with 20 µm width and total length of 1.5 mm machined by F2 laser ablation in fused silica.b) SEM image of 10x6 array of micro holes machined by F2 laser in fused silica. The top and bottom right inserts show the FIB machined concave micro lenses and 100 nm line gratings, respectively.

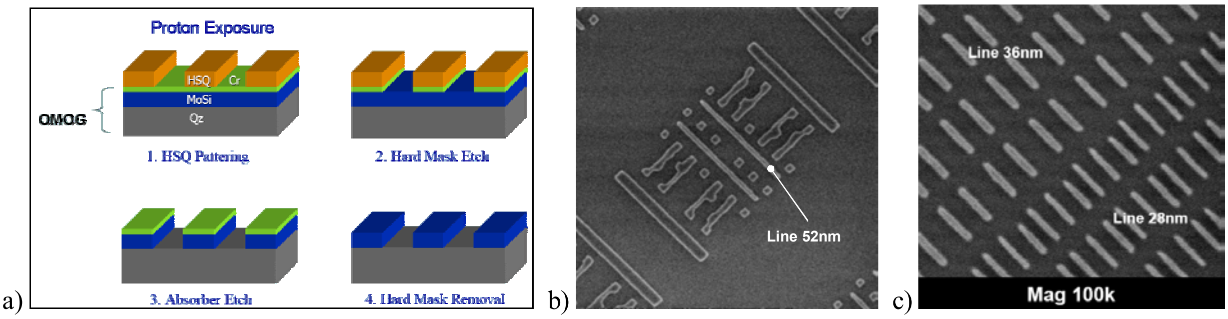


Figure 14: Process flow (a) and exemplary results (b and c) for high resolution photomask fabrication using OMOG (Opaque-Molybdenum-Over-Glass) patterning by CHARPAN proton exposure

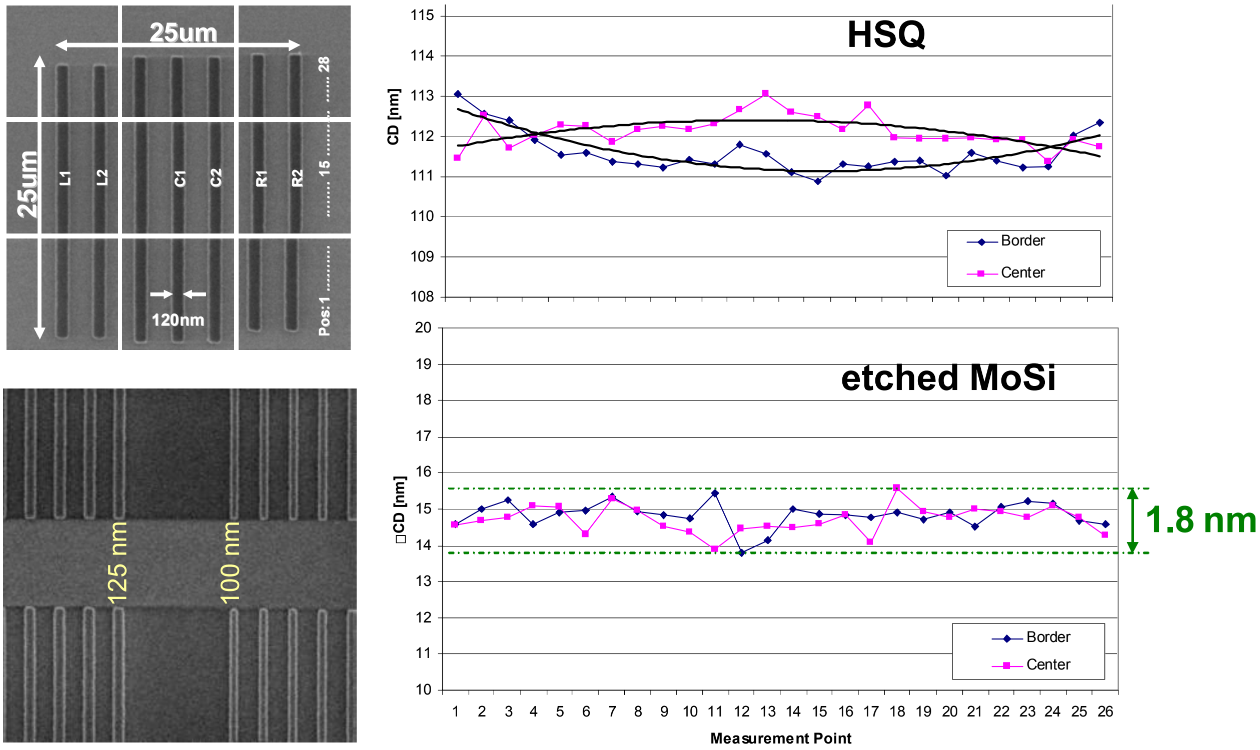


Figure 15: Etched MoSi lines between 100 nm and 125 nm (left) and CDSEM evaluations of local CD uniformity of 112 nm HSQ lines and etched MoSi lines.

C. CHARPAN Nano-Research

Within this research workpackage we have carried out basic and application oriented research in order to understand , control , predict and model the basic ion beam interactions with the substrate. We have studied various modes of interactions of standard (atomic ion) and novel (polyatomic ion) primary projectiles with a broad range of target surfaces (semiconductors, metals, polymers, organic, etc). These studies constitute a pre-requisite for a successful CHARPAN implementation. We have also explored and characterized new types of ion sources , studied 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. In the following we will briefly overview main achievements (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 is demonstrated in Figure 16.

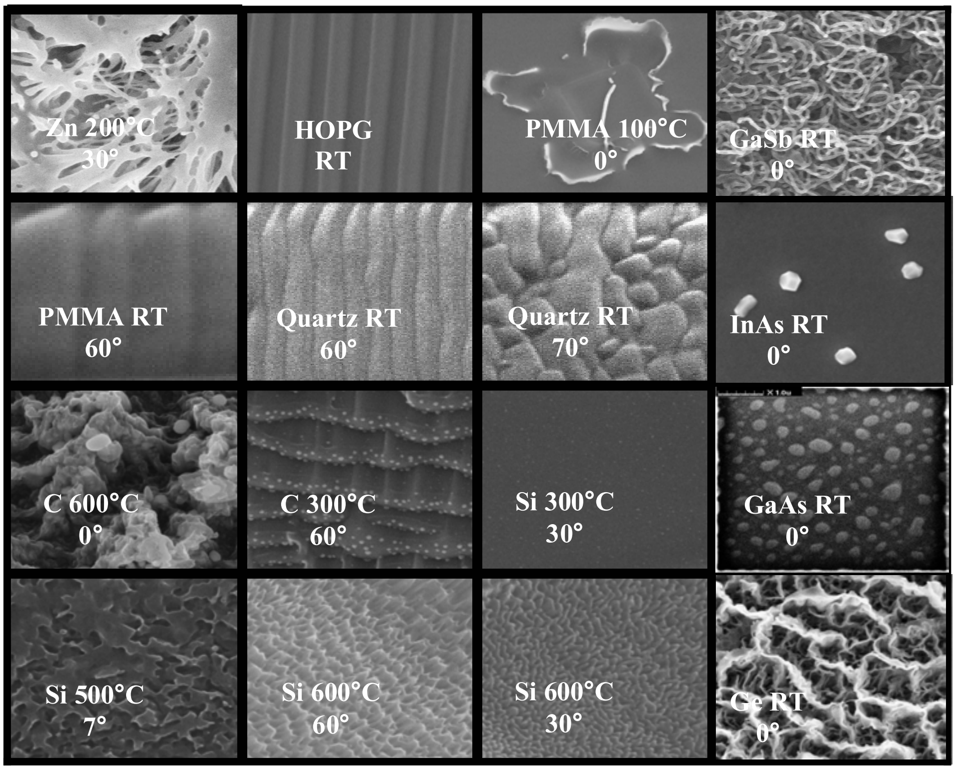


Figure 16: Nanopatterns achieved by FIB milling under oblique angles of incidence and/or target heating.

(2) A FIB based technique for room temperature synthesis of nanowires without using any additional materials source was developed along with integration of these nanowires in CMOS compatible sensor prototypes. A CMOS compatible self-aligned process of 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 developed and characterized .

(4) Sputtering and scattering interactions of fullerene ions (C_{60}) with a variety of surfaces were studied over a broad impact energy range extending from 100 eV to about 15 keV. Secondary ions were probed and analyzed via time of flight secondary ion mass spectrometrey (TOF-SIMS) methods. Kinetic energy distributions of the emitted ions were measured and a multifragmentation (shattering –like) mechanism in fullerene-surface impact was studied. Growth/etching processes were studied 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) Methods for local functionalization of silicon surfaces, in order to study their modification with charged beams, were developed. Processes for the fabrication of large arrays of nanoelectrodes that can be adapted to Charpan-tool based processes were also developed.

(7) The effect of charged beam 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 are applied to establish the methodology for directly contacting CNTs using electron and ion beam deposition of platinum (single step process). Better electrical characteristics than previously reported devices in the literature were obtained.

The possibility of CHARPAN to perform high-resolution low dose ion beam irradiation 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 of 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 have been performed.

Widespread applications have been investigated:

(i) In order to improve the energy conversation efficiency and power density of microfuel cells, the functionalization of silicon substrates by catalyst nano particle deposition for silicon nano wire growth was evaluated.

(ii) The modification of mechanical properties of locally modified polymer surfaces by ion beams was determined.

(iii) For the control and monitoring of cell adhesion on nano-patterned substrates films and nanostructures have been fabricated and ion beam induced changes in hydrophobicity/ hydrophilicity properties have been investigated.

(iv) Ion beam induced patterning of shape memory alloys (a lightweight, solid-state alternative to conventional actuators) has been performed in order to investiage intermixing effects.

(v) For the application as functional elements of photonic and opto-electronic devices ion beam induced phase separation of polymer blend thin films in the sub-µm regime has been investigated.

(vi) In order to increase the integration level of CMOS sensors plasmon resonant filters comprising metallic gratings have been fabricated and evaluated.

(vii) For the final goal of ‘preparation of 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) have been demonstrated.

The potential of CHARPAN for the utilization in emerging applications has clearly been demonstrated. Among the variety of outstanding results in different fields achieved within the CHARPAN project only one particular example is presented. 10keV Ar^+ exposures with doses ranging from 1500 to 7000 $\mu C/cm^2$ have been performed on Gold coated Silicon surfaces prior to the growth of Si nano-wires. The Ar^+ irradiation led to a less dense nano wire growth and to smaller nano wire diameter (20nm) compared to unexposed surfaces.

The most interesting CHARPAN potential with precursor gas assisted processes for 3D nanopatterning (etching and deposition) could not be demonstrated within the project period because the ordered gas injection system (GIS) turned out to be non-functional

Figure 17 shows the nano-wire formation of a partially exposed gold catalytic metal film containing nano-metric particles. In the exposed section (lower left) a less dense growth of nano-wires with a smaller diameter is visible.

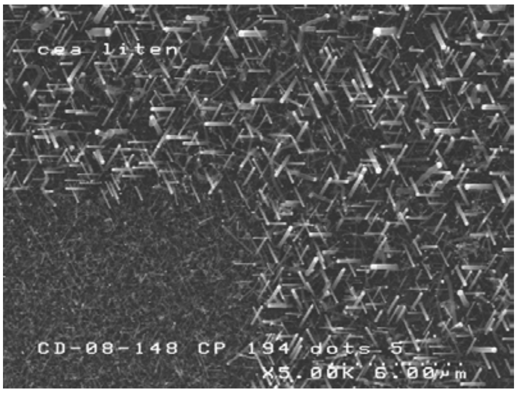


Figure 17: Silicon nano wire growth on CHARPAN Tool 10 keV Argon ion beam exposed (lower left) and unexposed surface.

D. CHARPAN Industrial Applications

In order for CHARPAN to be feasible for industrial applications, this technology should, either by itself or in combination with other technologies, be able to meet simultaneously several stringent specifications concerning resolution, speed, field stitching errors, stability, compliance to internationally accepted data formats and user friendly steering software.

Clearly, there is market potential for a technology or combination of technologies, which is able to structure all materials three-dimensionally with nanometer resolution, if 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 the making of masks (for mass production optical lithography) and stamps (for mass production imprint lithography).

Direct CHARPAN structuring of a device will be mainly used for (academic) research and testing applications though there are also some emerging industrial applications where localized nanopatterning is required and sufficient.

Two ways of working can in principle be discerned:

I) In the 2D working mode, thin resist layers can be exposed very fast with e.g. Hydrogen ion beams. Additional (Reactive Ion) Etching steps are, however, needed, allowing only a limited choice in feature shapes. This mode is to be used for (optical) mask making and thin layer stamps for e.g. micro-contact printing.

II) In the 3D working mode, the desired material itself can be directly (chemically amplified) sputter etched. This mode allows much more shaping freedom, but is slower, especially for higher / deeper structures. Here, CHARPAN is to be used in the making of stamp / coining masters for Nano Imprint Lithography (NIL) or Surface Conformal Imprint Lithography (SCIL$^{\mathrm{TM}}$).

The CHARPAN POC tool with incorporated 43k-APS system has shown to be able to meet 20 (possibly even 15) nm resolution specifications (see e.g. Figure 18a). The 2D resist exposure speed is high, but the ultimate speed for (chemically amplified) 3D sputtering is still to be tested.

The test pattern written with CHARPAN in 20 nm thick HSQ resist (as shown partly in Figure 18a) has been used in Substrate Conformal Imprint Lithography (SCIL$^{\mathrm{TM}}$). A PDMS stamp has been cast from this master, and the flexible stamp has been used to imprint in a sol-gel material; this sol-gel imprint features the same 20 nm resolution as the original CHARPAN HSQ master. Part of this SCIL$^{\mathrm{TM}}$ pattern is shown in Figure 18b.

An example of 3D structuring is shown for an array of micro-lenses in Figure 19a. Here as well, a PDMS stamp has been cast and these deep 3D structures have been imprinted in a sol-gel material with SCIL$^{\mathrm{TM}}$ (Figure 19b).

The feasibility of (a combined) CHARPAN technology for mass production purposes also depends on the possibility of dealing with field stitching and overlay errors. A limited number of applications can do without fixing the stitching issues, e.g.. optical gratings with the coherence length of light being shorter m□than the CHARPAN field size (25x25^2), but in general, field stitching issues should be tackled before CHARPAN can be applied as mask or imprint stamp master production tool.

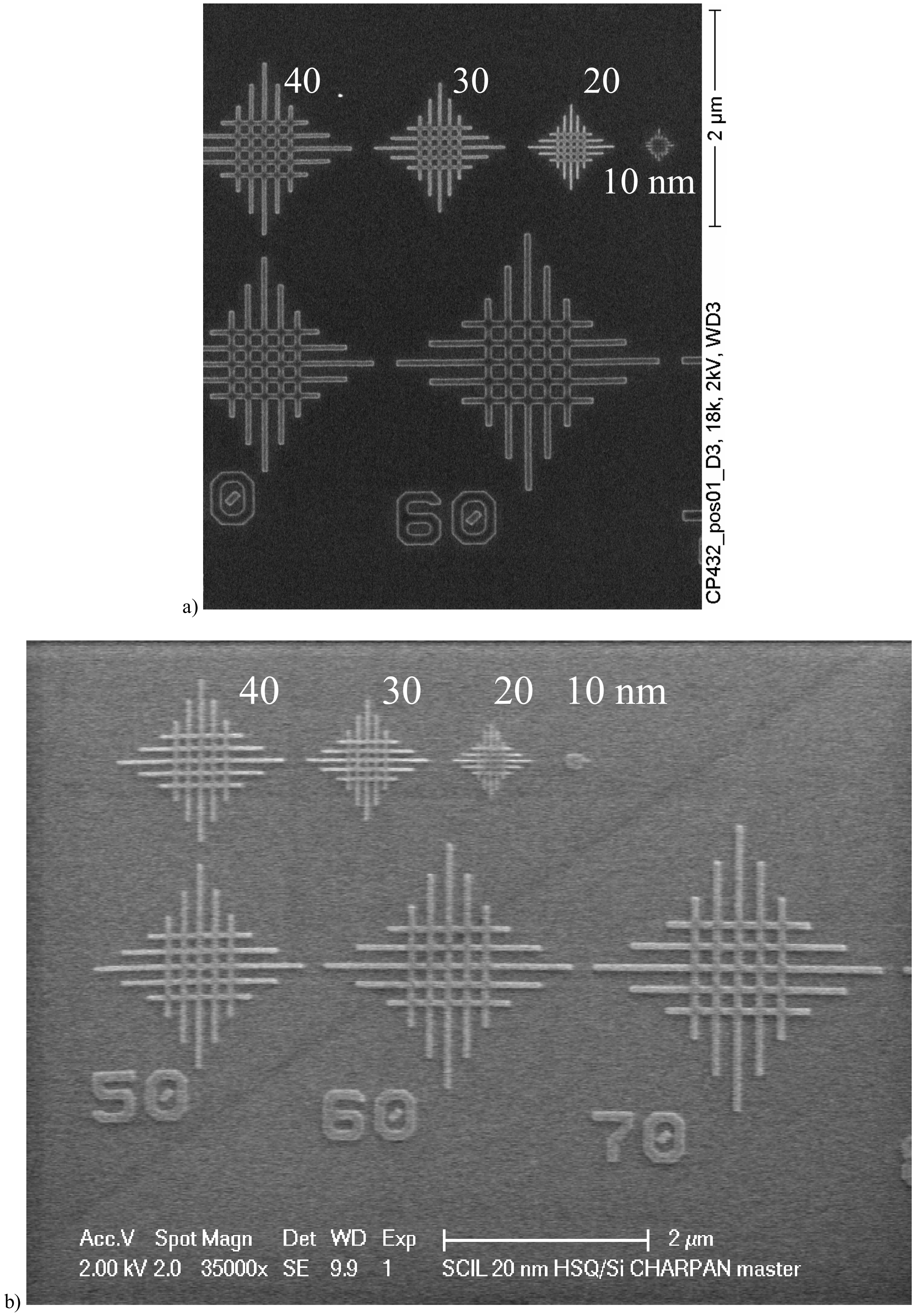


Figure 18: Test patterns of 1:2 crossing lines and spaces in respectively a CHARPAN written 20 nm thick HSQ layer (a) and the consequent SCIL^{TM} sol-gel imprint (b).

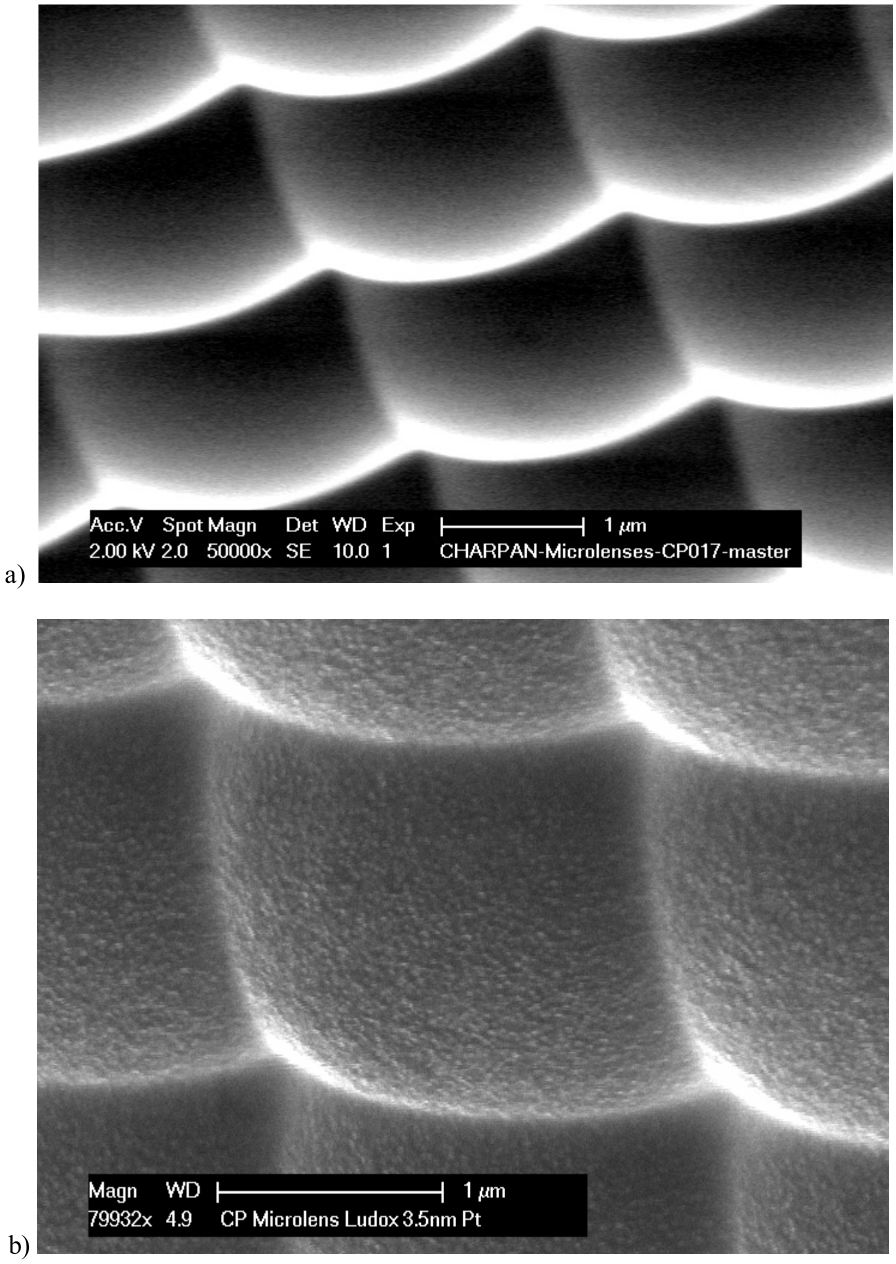


Figure 19: CHARPAN resistless 10 keV Ar^+ multi-beam sputtering made 3D master in Si with micro-lenses array (a) and the consequent SCIL^{TM} sol-gel imprint (b, roughness due to metal coating for SEM observation).

Compliance with industrially used design formats has been taken care of by usage of the 3D STL format, which can be translated into a layered GDSII format.

In micro-fluidic applications, CHARPAN in combination with SCIL will be useful because of the shaping freedom, provided that the stitching issues are taken care of. Long channels with smooth profiles and smooth bends are needed; any sharp edge, e.g. due to field stitching errors, may create a defect due to local capillary drying of - and precipitation from - attached remnant droplets, eventually blocking the fluid flow.

The combination of CHARPAN and SCIL^{TM} opens up new possibilities for low cost, fast and flexible 2D and 3D manufacturing.

E. CHARPAN Exploitation and Dissemination

In view of the radically new CHARPAN concept, methods for approaching the market were selected, that were deemed adequate to breakthrough innovations. Activities included four key elements: Dissemination, Community Building and Networking, Market Analysis and Exploitation Planning.

Dissemination:

Throughout the project, CHARPAN partners put much effort in presenting research results at major conferences and in an impressive number of reviewed publications. They met with ever growing interest and success. These activities were complemented by the CHARPAN website, and four CHARPAN newsletters distributed to the CHARPAN contact database.

In the beginning of the project the focus was on European conferences with the annual MNE (Micro and Nano Engineering) Conferences at the core of these activities. Two CHARPAN partners chaired the organising committee in 2005 (IMS) and 2006 (CNM), respectively. Conferences in the USA and Japan became more and more important towards the end of the project. At the SPIE Photomask conference BACUS, CHARPAN researchers were awarded 1st and 2nd best poster and 2nd best paper prices (IMS, IMS Chips). The number of conference contributions (talks, posters and panel discussions) made by CHARPAN partners amounted to 97 in total and were quite substantial throughout the project. The coverage was worldwide, with almost 1/3 of papers and talks given at conferences outside Europe.

On top, results of the work carried out in the CHARPAN project were extensively reported in reviewed scientific journals. In total there were 57 papers related to the CHARPAN project. They not only reflect advances in tool development but also the research into the ion projection surface structuring process, into the potential applications, into properties of material structured by ion beam, and into the simulation of ion beam structuring, which is key for process development. Further, research into the behaviour of bio-nanodevices on patterned surfaces was published.

In addition, CHARPAN dissemination was performed by means of the CHARPAN website www.charpan.com established in close cooperation of IMS and HITEC in November 2005, updated in 2007 and at the end of the project (2009). The CHARPAN website will be maintained for about 4 years after the end of the project.

Four CHARPAN Newsletters were published (May 2006, Nov 2007, Apr 2008, Jun 2009). For distribution an electronic dissemination database was established, covering about 130 contacts from 80 organisations and all user groups relevant to CHARPAN.

Community Building and Networking:

In addition to dissemination, activities like community building, agenda setting and roadmapping as well as networking with the micro-manufacturing community were carried out.

As a first step in Community Building, potential CHARPAN user groups were defined. CHARPAN partners were representing already some of them (internal experts). On top, they nominated external experts from their existing scientific and business networks.

From their ranks IMS-CHIPS, in close cooperation with the coordinator, selected the members of the User Advisory Board:
Jan-Hendrik Peters, AMTC Dresden, for Mask Manufacturing,
Laurent Pain, Leti/ST, Grenoble, for Direct Write Applications, and
Doug Resnick, Molecular Imprints, Austin, for Nanoimprint Template Fabrication.

Measures for building and maintaining the CHARPAN Community of Experts included regular information about the project's progress, involvement in requirements analysis, peer to peer exchange through invitations as speakers or chairperson at conferences, co-publication to increase visibility of a topic, mutual exchange of project ideas, to name but a few. Some contacts even resulted in visits to IMS Nanofabrication, in invitations to present the CHARPAN concept at a potential user's site or at a conference. Interesting contacts were Intel, Samsung, AMD, Quimonda, DNP, Toshiba, IBM Photronics, Toppan, Hoya, Renesas, Hitachi, Singulus Technologies, Molecular Imprints, Jeol, Nikon, Zeiss, Advantest and Mapper. Essential feedback with respect to the technical, application and market related aspects of the project were obtained.

The Network of Excellence "Multi-Material-Micro-Manufacture: Technologies and Applications (4M) is aiming the development of Micro- and Nano- Technology (MNT) for the batch-manufacture of micro-components and devices in a variety of materials into user-friendly production equipment, processes and manufacturing platforms for incorporation into the factory of the future. During more than 20 joint activities at conferences, workshops etc., CHARPAN technology and application areas were introduced to potential end-users by using the 4M and MINATEC dissemination channels.

As a consequence of these inputs the market analysis, the dissemination activities, and the exploitation plan became more focused.

Market Analysis:

Based on data and background information in journals, online publications and publicly available business data, but also based on personal interviews, an analysis of four promising markets was carried out: the generation of photomasks, the generation of NIL templates, of replication masters, and functional layers for applications in biotechnology and medicine. Since demand for the tool will always be closely related to the demand for nano-structures these underlying markets were analysed before turning to the market for tools.

The market for photomasks is mature and its volume is predictable: roughly 200 Mio. USD, 10-15 instruments per year. Investment is in high-end pattern generators capable of meeting the specifications of the semiconductor technology roadmap. For CHARPAN this segment is comparably clear in terms of structures and trends, both on the supply and the demand side. Yet the number of tools sold is quite low and partnering might become important.

The market for replication masters and NIL templates is comparatively new for applications in the nanometer range and is relatively fragmented. Both, the NIL templates, replication master and the nano optics and bionano markets are emerging, with an increasing number of players. Specialised SMEs and academic and commercial R&D labs offer know-how in mastering and tooling. There is a wide range of micro/nano-manufacturing technologies and patterning tools to choose from. It remains to be seen which centres attract enough demand to justify the investment in a CHARPAN tool.

It might be interesting to concentrate on the unique features of CHARPAN: maskless, resistless 3D structuring at nano-precision. In particular the possibility to shape the sidewalls of a 3D structure might become the core advantage of CHARPAN, since no comparable tool or process is available now. Yet, all of these 3D-applications are in emerging markets, which poses a chance to grow with them but which is also demanding, since attracting capital might be challenging. In PHILIPS' view, in order to attract future users and help with trust building, a CHARPAN tool should be placed at one of the European centres of nanotechnology.

Exploitation Plan:

Analysing all feedback obtained from the industry and potential end users as well as their demands lead to the conclusion that an all-purposes solution will not fit the customers' needs.

Therefore IMS plans to commercialise CHARPAN technology in three product lines:

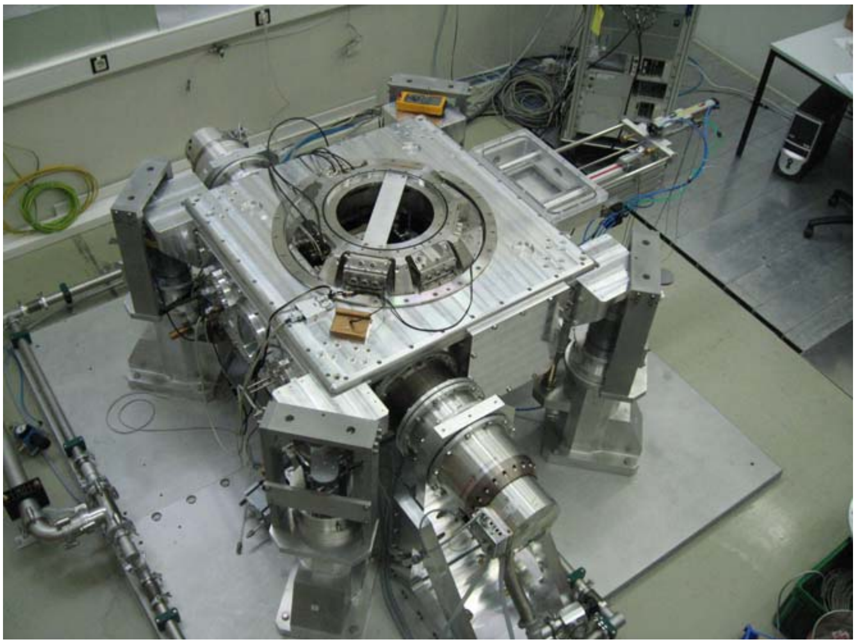
- CHARPAN 3D Nanopatterning Engineering Tool for R&D applications and CHARPAN 3D Nanopatterning Production Tool, for emerging industrial applications in Nanophotonics, NanoBiotechnology, NanoSensorics, etc.,
- CHARPAN Template Exposure Tool for the fabrication of 1:1 master templates for NIL (Nano-Imprint Lithography),
- CHARPAN Mask Exposure Tool for leading-edge complex mask fabrication.

F. Summary and Outlook

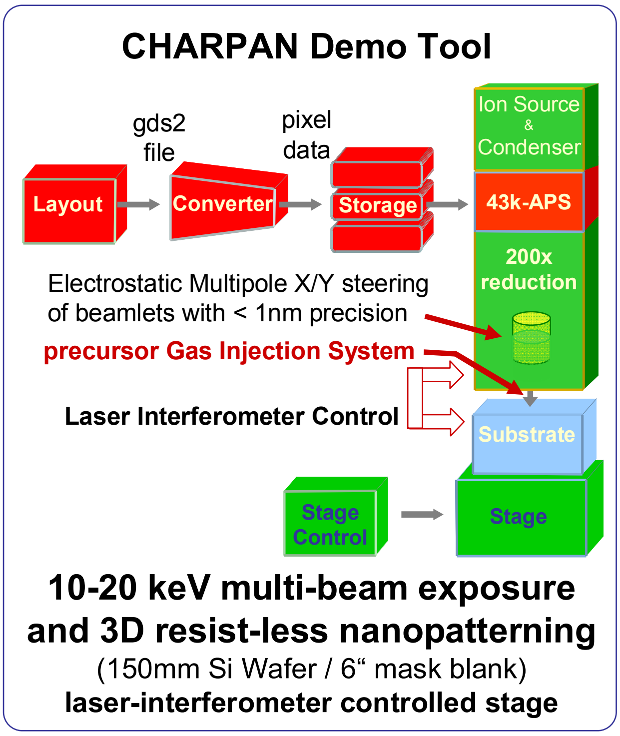
Operating the CHARPAN Tool with a first programmable aperture plate system (APS) with integrated 0.25 µm CMOS electronics 20nm hp resolution capability was demonstrated with more than ten thousand 12.5nm ion beams working in parallel. There are indications that a resolution below 20nm can be reached with further optimizations. The achieved resolution as achieved with 10 keV Hydrogen ions in exposing HSQ non-chemically amplified resist was in excellent agreement with ion-optical calculations. Resistless nanopatterning was demonstrated using 10 keV Argon ions.

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. 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 (Figure 2).

A laser interferometer controlled stage has been realized by DELONG within the project period but could not be delivered to IMS within the project period. After the project has ended this stage was delivered to IMS Vienna and integrated into a new platform (Figure 20a) which will house also a precursor gas injection system (GIS) for 3D ion multi-beam assisted etching and deposition, respectively. Thus a CHARPAN Demo Tool will be realized (Figure 20b) as prototype for a commercial CHARPAN 3D Nanopatterning Engineering Tool. Simulated IonShaper® performance of the CHARPAN Demo Tool is shown in Figure 20c.



a)



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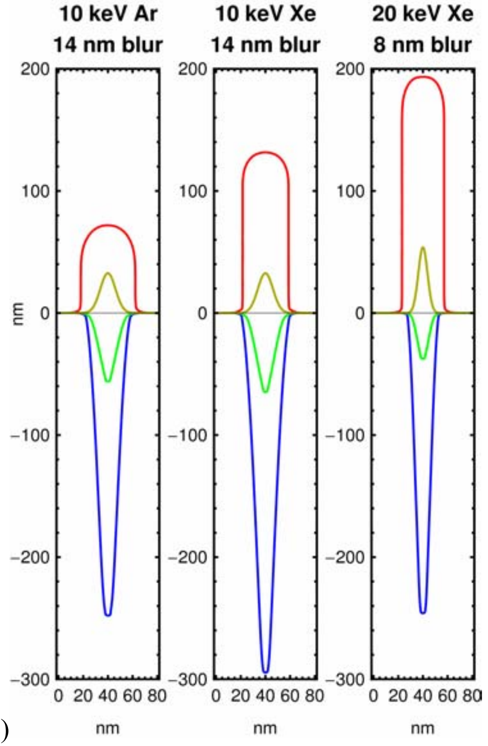

c)

Figure 20: Work at IMS in Q2/09 (after end of the project), a) Laser-interferometer controlled stage (DELONG) integrated into new IMS tool platform to be used for the realization of the CHARPAN Demo Tool, whose schematics are shown in b); c) IonShaper® simulation results using CHARPAN ion projection optics beam parameters. In each simulation the golden (smaller positive) line represents the ion beam profile of the CHARPAN Demo Tool. The green (shallower negative) line illustrates the result of a sputtering simulation. The blue and the red lines show the results of etching and deposition simulations, respectively. The ion dose was the same for all simulations.