Advanced Techniques and Novel Materials for Nanolithography

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Status of Ion Projection Lithography

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ABSTRACT

As part of the European MEDEA project on Ion Projection Lithography (IPL), headed by Infineon Techologies, a process development tool (PDT) has been assembled at IMS, Vienna, with the final target of 50 nm resolution in a 12.5 mm exposure field at 4x demagnification. The ion-optical system (PDT-IOS) has been integrated, including the LEICA mask changer and a sophisticated metrology stage with in-situ diagnostics. In parallel, the LEICA wafer stage and the vacuum compatible off-axis ASML wafer alignment system have been realized. At the moment (Nov00) the He^+ ion beam is aligned until the mask level. Ion beam proximity wafer exposures directly behind the mask show a performance of the illumination optics as predicted. 150 mm stencil masks with 125mm diameter, 3μm Si membranes, 50mm x 50mm design field, have been produced by IMS-Chips, Stuttgart. There is expectation to start the PDT-IOS test phase in Q1/01. Using the experimental ion projector at the Fraunhofer-Institute ISiT in Berlin recent resolution tests have demonstrated 50 nm lines and spaces without proximity effect in standard Shipley DUV resist UVIIHS at an exposure dose of 0.5 μC/cm² for 75 keV He^+ ions. This was accomplished by 8.5 x demagnification of a new generation of stencil test masks from IMS-Chips. One further promising application of IPL is the resistless structuring of thin magnetic films to produce magnetic nano dots for future ≥ 100 G bit/in² storage devices. A consortium of IBM Germany - Speichersysteme Mainz, Fraunhofer-ISiT, LEICA Jena and IMS-Chips in cooperation with IMS-Vienna has been formed to evaluate this technology.

INTRODUCTION

In 1997 the semiconductor industry started the Next Generation Lithography (NGL) development programs to secure the ongoing procedure of continuous downscaling of integrated circuits. In Europe, as part of the MEDEA program, a consortium headed by Infineon Technologies concentrates on the further development of Ion Projection Lithography (IPL) as the most promising candidate for NGL. An excellent review of IPL is given by J. Melngailis *et al.* [1]. In the first paragraph of the present paper the main arguments are collected which strongly support the use of ions as imaging particles in a future lithography tool. In the following the status of the assembly of the IPL process development tool (PDT) at IMS, Vienna, is reported (see also [2]). In parallel with the set up of the tool, resist process development and resolution tests have been conducted at the Fraunhofer-Institute ISiT in Berlin with a research type ion projector. Patterned ion beams have also the potential of surface modification without using a resist. An interesting application is the resistless nano structuring of magnetic thin films for future storage media.

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IONS AS IMAGING PARTICLES

The use of light ions (H^+, H_2^+, H_3^+, He^+) as imaging particles in a future lithography system has several advantages compared to competing technologies (x-ray, e-beam projection, EUV). In figure 1 the different scattering properties of ions and electrons are demonstrated [3,4].

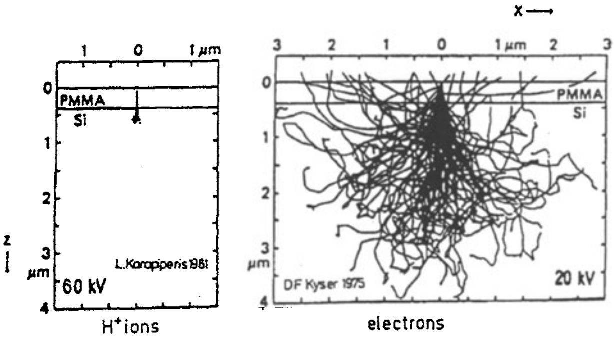


Figure 1. Scattering properties of H^+ ions and electrons.

Ions, particularly light ions, have very little forward scattering and give off energy to secondary electrons in the resist in small quantities (peak 2-5 eV). Because these secondary electrons have a range of a few nanometers [5], there is virtually no proximity effect for ion beam pattern transfer. This is a big advantage compared to 20kV – 100kV e-beam lithography (by reducing the e-beam energy to a few keV, the proximity effect gets smaller, but a pear shaped exposure profile remains and multi-layer resists have to be used which is more complicated).

As demonstrated in figure 1 light ions have much less penetration depth compared to electrons of comparable energy. The much stronger interaction with matter leads to a higher resist sensitivity, which means that the exposure dose is generally more than a factor of 10 lower than the dose required for electron exposure.

An important question is, whether ions can damage sensitive semiconductor layers like gate oxides. A comparative study has been conducted by Fraunhofer ISiT of the damage produced in MOS varactor cells by all three types of radiation (x-ray, e-beam, ions) [6]. The results for H^+ and H_2^+ irradiations are demonstrated in figure 2 together with Monte Carlo simulations made at IMS-Vienna. When the resist thickness is chosen so that H_2^+ ions do not penetrate into the gate oxide, there is no charge-to-breakdown shift at a dose of $2x10^{13}$ H_2^+/cm^2. On the other hand H^+ ions under same conditions do penetrate the gate oxide and produce a shift of the charge to breakdown value from 15.5 to 11 C/cm^2.

X-rays (1 nm) and electrons (50 keV) did not create a charge-to-breakdown shift but high frequency C-V measurements showed a flat band voltage shift of about - 380 mV at comparable lithographic doses of 1870 J/cm^2 and 350 $\mu C/cm^2$ respectively (no annealing steps have been applied). This shift was not found for ion exposure without gate oxide penetration by proper adjustment of the penetration depth. Parameters for this adjustment are the choice of ion species, the ion energy (~100 nm resist penetration per 10 keV), and the resist thickness. The penetration range straggle is small for ions ± 0.03 μm [1], so that sensitive transistor layers can be effectively protected. X-rays and electrons normally penetrate deeply into the substrate.

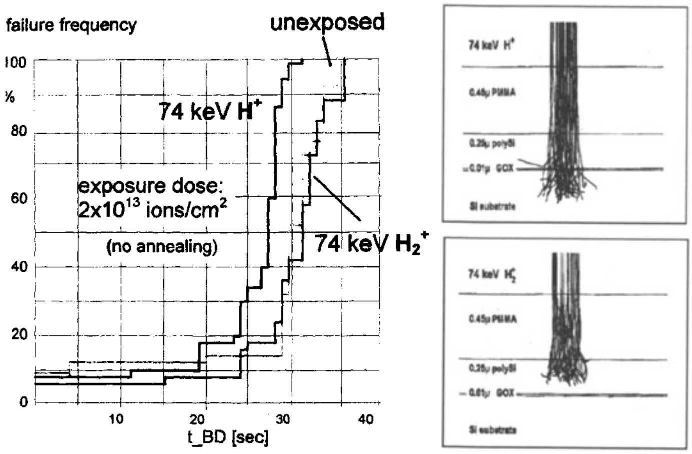


Figure 2. *Damage characterization of ion beam exposed varactor cells by charge-to-breakdown measurements, showing no damage for ions not penetrating the gate oxide.*

The properties of electrostatic ion optics are also very promising. Because of the very short particle wavelength ($5x10^{-5}$ nm for 100 keV He ions) the numerical aperture NA of ion optics can be as small as 10^{-5} before reaching <3nm diffraction limits (e-beam optics instead has to operate with NA~10^{-3}). For a given curvature of the image plane the geometric blur will stay small even for large exposure fields (see figure 3). A reduction of the curvature of the image plane is possible by implementing a diverging electrostatic lens into the system. This is accomplished by using the conductive surface of the mask as lens electrode (figure 3).

From these findings ions seem to be very adequate for pattern transfer into resist with high throughput, small proximity effect, high depth of focus, and steep resist profiles.

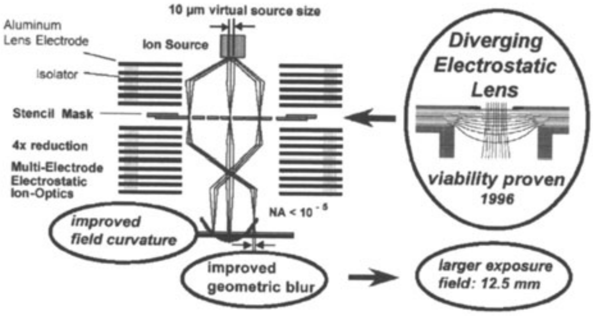
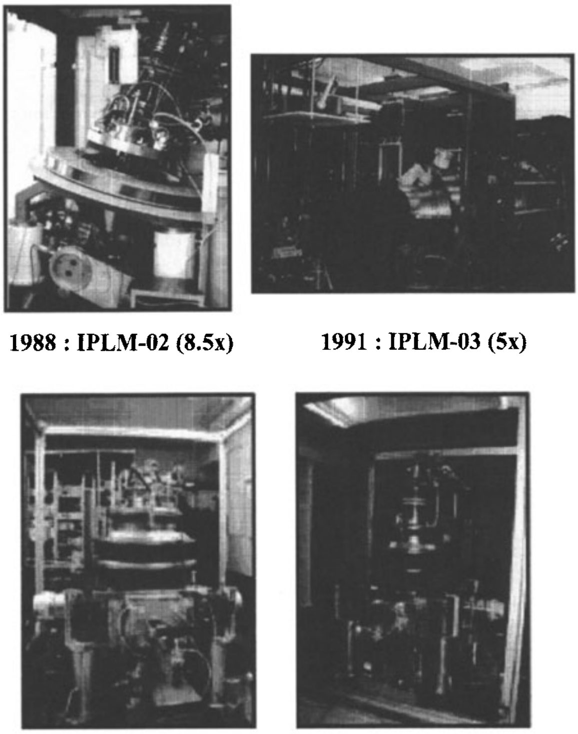


Figure 3. *Large exposure fields of ion optics resulting from small numerical aperture NA..*

ION OPTICAL SYSTEMS FROM IMS-VIENNA

The company IMS in Vienna has more than ten years of experience in designing and building ion optical systems. These activities have the aim of developing ion projection lithography as a future generation lithography (figure 4).

In 1988 the research type ion projector IPLM-02 has been delivered to the Fraunhofer-Institute ISiT in Berlin. In the following years the Fraunhofer-Institute was involved in a research project including Siemens and IMS-Vienna to develop open stencil mask fabrication and suitable resist processes for IPL. Another topic was the determination of the final resolution of this 8.5 times demagnifying electrostatic ion optical system. Latest results, after implementation of a low energy spread multicusp ion source from the Lawrence Berkeley National Laboratory, are reported in a later paragraph.



1988 : IPLM-02 (8.5x) **1991 : IPLM-03 (5x)**

1996 : MIBL (1:1) **1998 : Mini-IPL (stochastic blur experiment)**

Figure 4. *History of ion optical systems built by IMS-Vienna.*

In 1991 a new ion projector with 5 times demagnification has been built which increased the 2x2 mm^2 exposure field to 8x8 mm^2. With this instrument the pattern lock principle has been demonstrated: Ion "reference beams", generated by special openings in the circumference of the mask field are projected into slots of a scanner block whereas the "pattern beam" penetrates through a center opening. Within these slots are position detectors which measure the position of the image at any time. This information is compared with laser interferometer measurements of the wafer stage position. As a result of both pieces of information the ion image is shifted – without moving mechanical parts - into the right position on the wafer. Thus the pattern lock system can compensate in a dynamic way, also during exposure, for wafer stage vibrations or image drift of the electrostatic system. This is key to reduce stage costs and to achieve high throughput of a production tool.

In 1996 the MIBL (Masked Ion Beam Lithography) system has been constructed. In this 1:1 proximity printer the wafer is arranged directly underneath the mask leading to a large exposure area of 50 x 50 mm^2. Because of the high telecentricity of the illuminating ion beam the proximity gap can be very big (several 100 µm, which is good for MEMS applications). Even under these conditions the resolution of the MIBL system remains under 100 nm as the beam landing angle and the local beam divergence are both below 50 µrad. This has been achieved by introducing multi-electrode electrostatic ion beam optics, including the use of a diverging electrostatic lens with the stencil mask forming one lens electrode (see figure 3).

When designing particle optics for high volume sub-100nm lithography, considerations have to be focussed to achieve adequate beam currents, which are necessary for high wafer throughput. Due to stochastic particle-particle interactions, there is a corresponding contribution to image blur. The stochastic interaction takes place mainly at and near the crossover regions of the beam. Because ion optics can tolerate very low numerical apertures ($\sim 10^{-5}$) there is the possibility to work with "aberrated" crossovers and thus achieve a substantial reduction in ion beam particle density. The viability of this idea has been demonstrated in 1998 by experiments with the "Mini-IPL" system [7].

At present (Nov00) IMS -Vienna is occupied with switch-on-work of the process development tool which is described in the following.

STATUS OF IPL PROCESS DEVELOPMENT TOOL (PDT)

The main task of the European MEDEA IPL project is to develop, realize and test the performance of an IPL process development tool. The target is to achieve 50 nm resolution in a 12.5 x 12.5 mm^2 exposure field with a 4x demagnifying ion optics. Figure 5 shows a 3D view of the PDT indicating the main partners contributing different components to this tool.

At the moment all ion-optical components, which have been tested for functionality separately, have been integrated into the vacuum housing. The main subsystems are a multicusp ion source from LBNL, Berkeley, with an ion energy spread of 1.7 eV, the Leica mask changer for 150 mm stencil masks, and an IMS metrology stage including in-situ diagnostics [2]. In Jena a test bench has been realized for the Leica vertical wafer stage with magnetic bearings. A compact vacuum compatible ASML optical alignment system has been installed in front of the wafer stage and tested in air for 5 nm (3σ) repeatability.

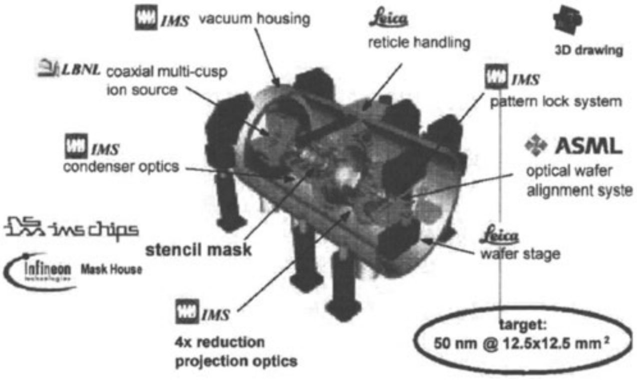


Figure 5. *Process Development Tool (PDT) and contributing MEDEA IPL project partners.*

Figure 6 shows the integration of lens electrodes into the ion optical column. They belong to the first lens behind the mask station. The electrodes are mounted to the vacuum housing through three rods in a way that with thermal drift there is only a small rotation of the electrodes but no change in axis. Each electrode has three alignment marks which are sensed by three optical beams. In this way the position of each lens can be controlled in situ and by proper positioning elements operating in X, Y, rotation, Z and tilt each lens can be brought on axis.

The roundness of the electrodes has been measured to be well within a tolerance of ± 4 μm. The remaining influence of elliptic lens contours on mask to wafer transfer is rectifiable by inducing quadrupole fields in electrostatic multipoles and/or field composable lenses (FCL). In these lenses one electrode has isolated sectors which can be set to different potentials (figure7). FCL lenses are also a powerful means to ensure machine to machine matching as well as mix-and-match with optical exposure tools.

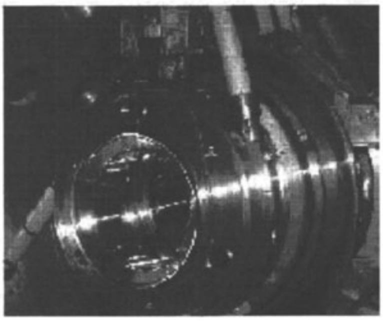


Figure 6. *First electrostatic lens behind mask of PDT-tool with 4x ion optical reduction optics.*

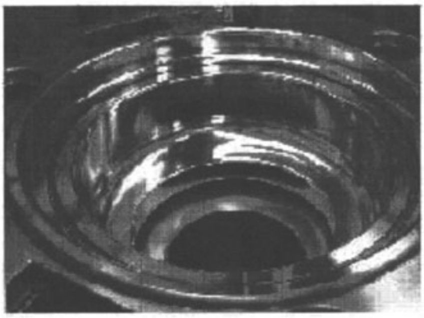


Figure 7. *Field composable lens (FCL) with isolated sectors for ion optical distortion fine tuning by multipole fields.*

End of Nov00 the ion-optical system of the (PDT-IOS) tool was complete and a He^+ ion beam has been aligned until the mask level. Ion beam proximity wafer exposures at this time have been performed at the mask stage level showing a performance of the illumination system as predicted. Exposures on the wafer level with the 4x reduction ion-optics will start Dec00.

The 12.5 x 12.5 mm² exposure field of the present PDT-tool is not large enough for future chip generations, unless for proper shrunk version. For larger chip fields e.g. 25 x 25 mm² an IPL stitcher concept has been developed as demonstrated in figure 8 [2].

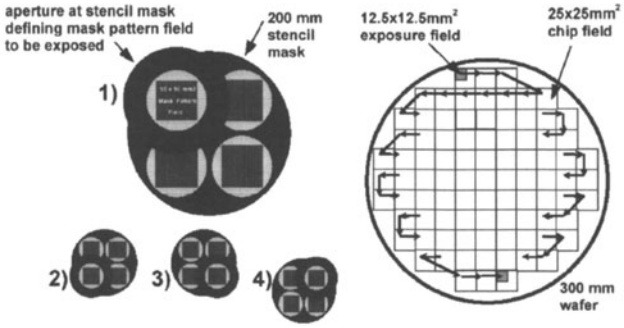


Figure 8. *IPL stitcher concept for wafer exposure of larger chip fields.*

Four 50 x 50 mm² mask fields are incorporated into one 200 mm outer diameter stencil mask. After exposing the first mask field at the right position of the 89 chip sites the same is repeated with the three other mask fields. Stitching of the partial exposure fields is facilitated by the IPL electronic image placement with on-line pattern lock control. Infineon has realized first 200 mm stencil masks, produced by an SOI wafer flow stencil mask process [8] by using the developed process of IMS-Chips on 150mm wafers as a basis.

The design of the present ion optical column was based on a maximum tolerable field strength of 4 kV/mm. In the meantime it has been confirmed that through proper measures, safe operation can be increased to >10 kV/mm. This means that in future systems the length L of the column can be shrunk from 1.9 m between mask and wafer for the PDT column to 1m (figure 9) This results in a current gain by a factor of 4.8 as the stochastic blur due to particle interactions is proportional to $I^{0,82}$ and L^2 [2, 7]. A factor of 2 is gained when using H^+ instead of He^+ [2, 7].

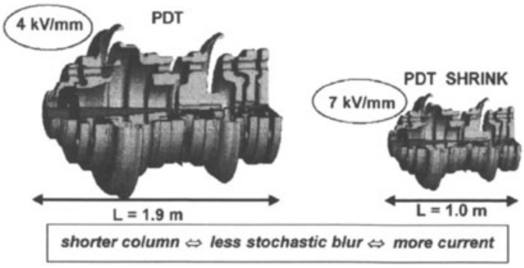


Figure 9. *Enhancement of ion beam current by shrinking the column size.*

EXPERIMENTS AT FRAUNHOFER-ISIT

In recent years the Fraunhofer Institute ISiT has supported the development of IPL by investigating critical design parameters with its experimental ion projector IPLM-02. These activities include space charge experiments [9], which gave input parameters for the calculation of maximum tolerable ion current densities before running into untolerable space charge interactions leading to image blur.

The second topic was the development of a suitable resist process for ion beam exposure. Standard DUV resists with chemical amplification proved very adequate for this purpose [10]. In figure 10 the contrast curve of Shipley UV II HS resist is shown with high sensitivity and a contrast higher than 10 for H^+ ion exposure at 74 keV.

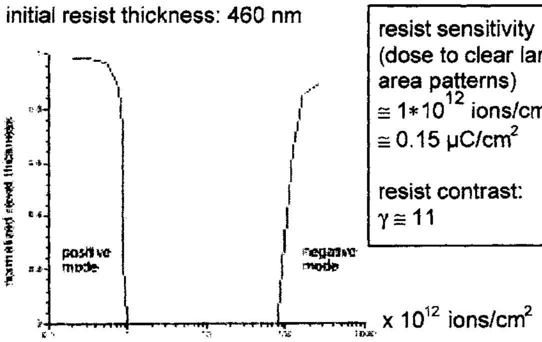


Figure 10. Contrast curve of Shipley DUV resist UVIIHS for exposure with 75 keV Hydrogen ions.

Simulations of the resist exposure and development process have been performed, assuming that particle generated acid is only produced in a narrow 2 nm wide cylinder around the straight ion path [11]. The influence of acid diffusion during post exposure bake on resolution and line edge roughness has been investigated (see figure 11).

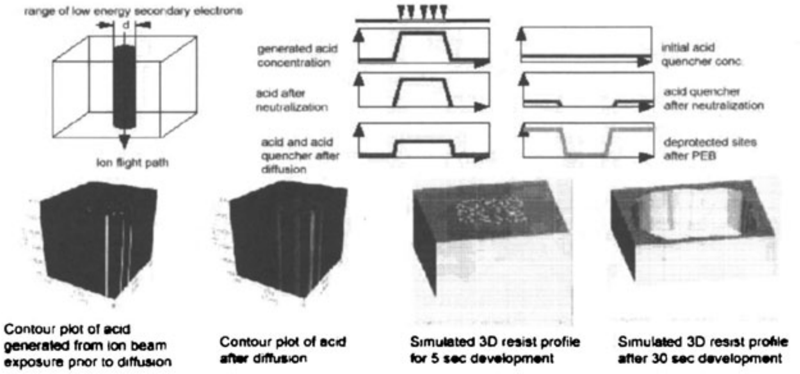


Figure 11. Simulation of development of chemically amplified resists after ion exposure.