Maskless Lithography and Nanopatterning with Electron and Ion Multi-Beam Projection

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ABSTRACT

Multi-beam writing becomes mandatory in order to stay within reasonable realization times for the fabrication of leading-edge complex masks and templates. IMS Nanofabrication has developed multi-beam projection techniques implementing a programmable aperture plate system (APS) and charged-particle projection optics with 200x reduction. Proof-of-concept of multi-beam writing was demonstrated in 2009 with 10 keV ion multi-beams and 50 keV electron multi-beams using 43-thousand and 2.5-thousand, respectively, programmable 12.5nm sized beams. In Q4 2009 the development of a 50 keV electron multi-beam Mask Exposure Tool (eMET) was started with the aim to realize 256-thousand programmable 20 nm and 10 nm sized beams. The eMET column realization will provide important synergies for the development of projection mask-less lithography (PML2) for direct write on wafers. In order to enhance throughput a Multi-Axis-PML2 scheme is put forward with potential throughput of 5 WPH for the 16 nm hp technology node and below. Clustering such maskless tools a throughput of 50-100 WPH within a scanner floor space is envisioned. Ion multi-beam techniques may be applied for 2.5D / 3D template fabrication and resistless nanopatterning.

Keywords: multi-beam, mask writing, template writing, direct write, electron beam projection optics, ion beam projection optics, programmable aperture plate system.

1. INTRODUCTION

The idea of multibeam writing is to improve the throughput of a direct write system by using a multitude of beams working in parallel on the substrate instead a conventional single beam. Only a massive parallelization of beams allows circumventing the physical limits in today's e-beam writing tools, which result from a practical limitation of the shot rate and the deflection speed in such systems. The shot rate limitation is primarily caused by the maximum possible blanking rate and maximum achievable current density, whereas the limitation in deflection speed originates from the limited bandwidth and accuracy of the DAC amplifiers involved.

The primary challenge of multi-beam writing is the requirement to simultaneously control a multitude of beams in terms of individual beam placement, size, dose, and blur. This requirement includes the ability to perform calibration of the beams in cyclic calibration procedures and sufficient beam stability in between, both essentially necessary for remaining continuous alignment and focus control with respect to the actual beam to substrate position. In addition, the system needs to allow a real-time compensation (or "beam tracking") of the mechanical motion errors of the substrate stage unavoidable during the writing process. Beam tracking needs to take into account lateral beam placement corrections and vertical focus adjustments to accommodate to substrate height variation, and it must not degrade the simultaneous control over the multitude of beams in terms of placement, etc. Obviously, it is highly desirable that these adjustments, which have to apply for all beams in the multi-beam system, can be done by one common deflector and one common focusing element.

A second challenge of multi-beam writing is the management of individual beam defects, which can range from "always on" to "always off" beams or largely displaced or blurred beams in case of local defects in the multi-beam forming element. As with increasing number of beams also the probability of defects scales up, it is of great importance that the multi-beam writing system has the handles to cope with beam defects, either by correcting for related errors of by writing at such a high redundancy level (e.g. 16x) that individual beam defects can be accepted with the lithography requirements (Figure 3).

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A third challenge of multi-beam writing is the realization of a high speed data path to control the multi-beam array of beams by on/off sequences, generating the “gray levels“ needed to allow gray-tone writing with very fine address grid. The fine address grid and suitable number of gray levels is essential to achieve a sufficiently small grid approximation error. The gray level writing strategy allows to implement process related and user defined corrections (including CD, linearity, proximity effects and process related variations) in terms of geometry (<0.1 nm) and dose corrections (< 1%). In order to minimize the complexity of the data path and data preparation the dose increment per gray level should be identical for all beams, so that the data preparation becomes independent of the stripe segmentation (independent of substrate position at which certain beam writes a pixel).

The IMS Nanofabrication multi-beam projection technology has been designed to meet the above challenges in the most effective way. A 200x reduction projection system allows to image a multitude of beams by one common electromagnetic projection system sharing deflectors and adjustment elements to control beam placement, size, dose, and blur of each beam. Individual errors in the beam defining aperture plate are de-magnified by 200x in size and pitch, the remaining errors can be statically compensated by corrections in the beam defining aperture plate (proprietary method). Essential global beam adjustments such as beam-to-beam pitch, X/Y scale, focus, center position and rotation can be performed by conventional adjustment elements that are common for all beams. Therefore the complexity of the control of the multi-beam array does not scale up with the number of beams. The low aberration electromagnetic lens system facilitates excellent control of the blur and position of each individual beam and also blur and landing angle variation across the (telecentric) beam array.

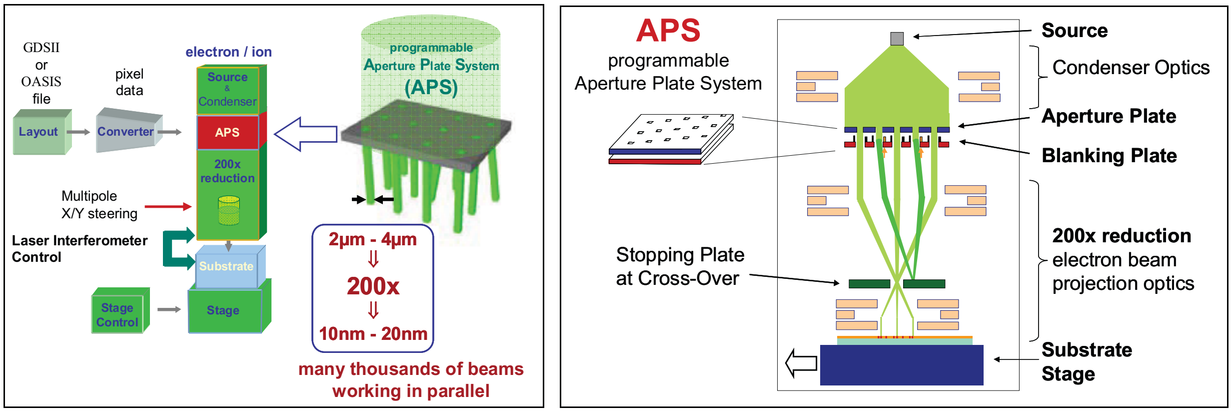
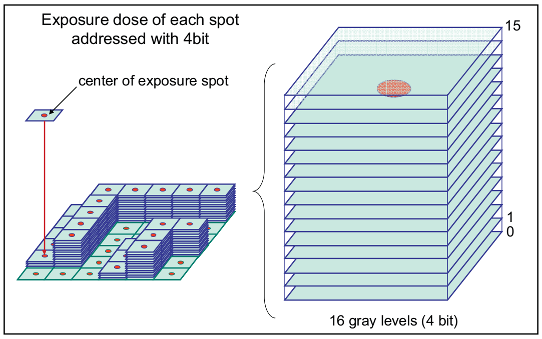


Figure 1: Principles of IMS Nanofabrication charged particle multi-beam projection techniques

A proprietary write strategy is organized in a way that many beams contribute to neighboring pixels on the substrate and directly neighboring beams in the beam forming plate do not appear next to each other on the substrate. By this method unavoidable stage vibrations (positional noise in general) but also residual distortions of the beam array are effectively reduced in their impact on the lithographic performance. Due to the fine grid and beam sequencing on the substrate the impact of defects beams can be either reduced to negligible importance or corrected by neighboring pixels.

Generally, IMS Nanofabrication has a first principles “virtual exposure tool” software ready to calculate the aerial image including all stationary and dynamic errors of either systematic or stochastic nature. The results obtained in these simulations clearly indicate the improvement factors related to the applied writing strategy and allow the establishment a detailed errors budget. The multitude of beams is used to write on a very fine physical exposure grid where the geometric beam size of neighboring pixels is 2x or 4x the physical grid size (double and quad grid, respectively, as outlined in Figure 2). The possibility to use such a fine grid causes the effect redundancy, where one single beam contributes only a small fraction of the dose at a certain substrate spot. This results in a sufficiently large reduction of the impact of individual beam errors to eventually have the possibility to tolerate defects up to a certain degree without impacting the lithographic performance.



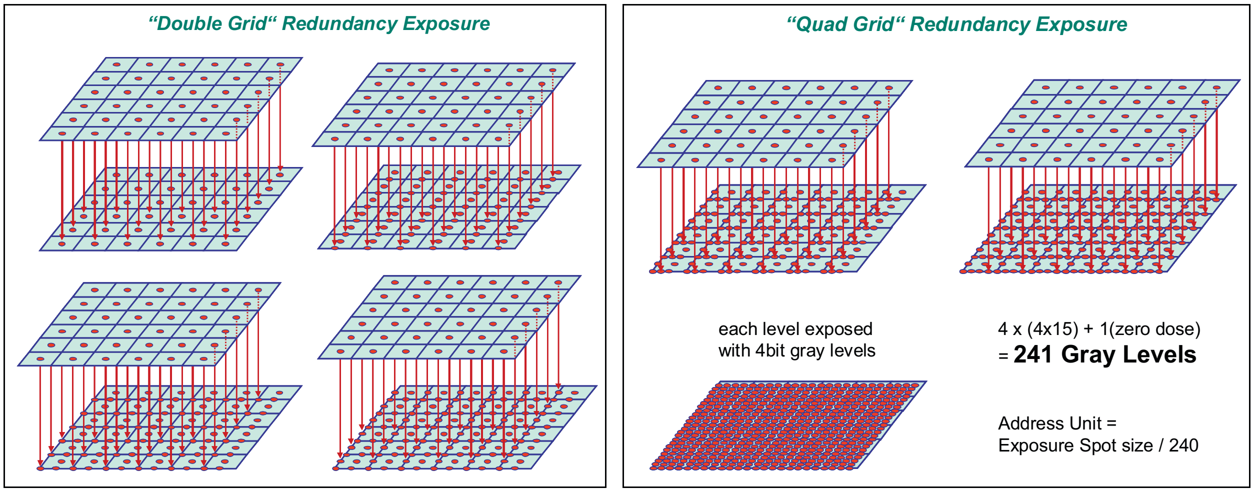


Figure 2: Principles of Double Grid and Quad Grid redundancy exposure techniques

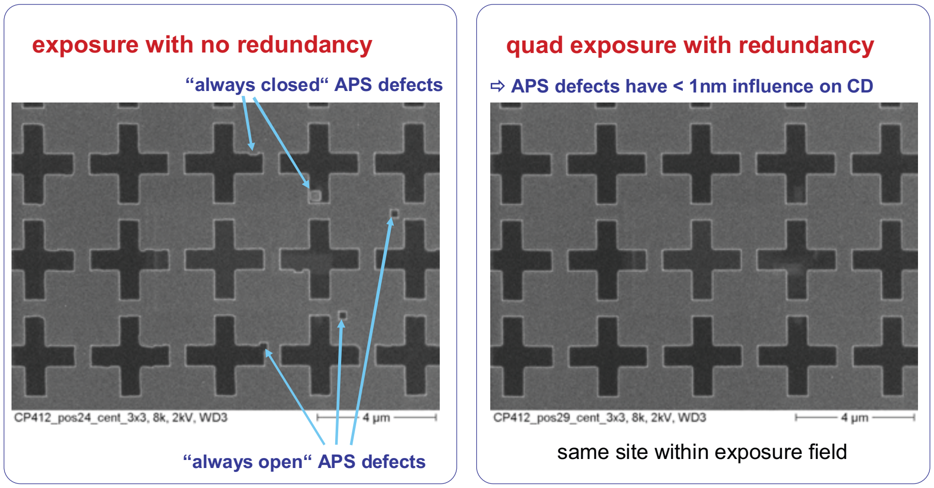


Figure 3: Demonstration of redundancy exposure techniques

Coulomb interactions are carefully taken into account in the design of the multi-beam writing tool, keeping the effects of stochastic Coulomb interaction blur and of global Coulomb space charge interactions at tolerable values for the maximum possible current variation and pattern inhomogeneity. For enhancing the throughput ultimately a patented Multi-Axis Column scheme may be adopted [3]. Consequently the required source brightness is such low that existing commercial solutions may be adopted. As a result of these measures the projection multi-beam writing promises to achieve high resolution at unprecedented mask and template writing speeds.

A high number of multi-beam techniques are focused on e-beam direct write (EBDW) applications, i.e. maskless lithography (ML2) on wafers. IMS Nanofabrication concentrates on Projection-ML2 (PML2) using the multi-beam projection principles as shown in Figure 1. The REBL (Reflective Electron Beam Lithography) principles are similar but implement a reflective blanking device. The MAPPER scheme is based on a multitude on micro-columns.

Figure 4 shows schematics of these techniques in comparison with those of the established Gaussian spot beam and VSB (variable shaped beam) techniques (a multiple variable shaped beam technique is being developed).

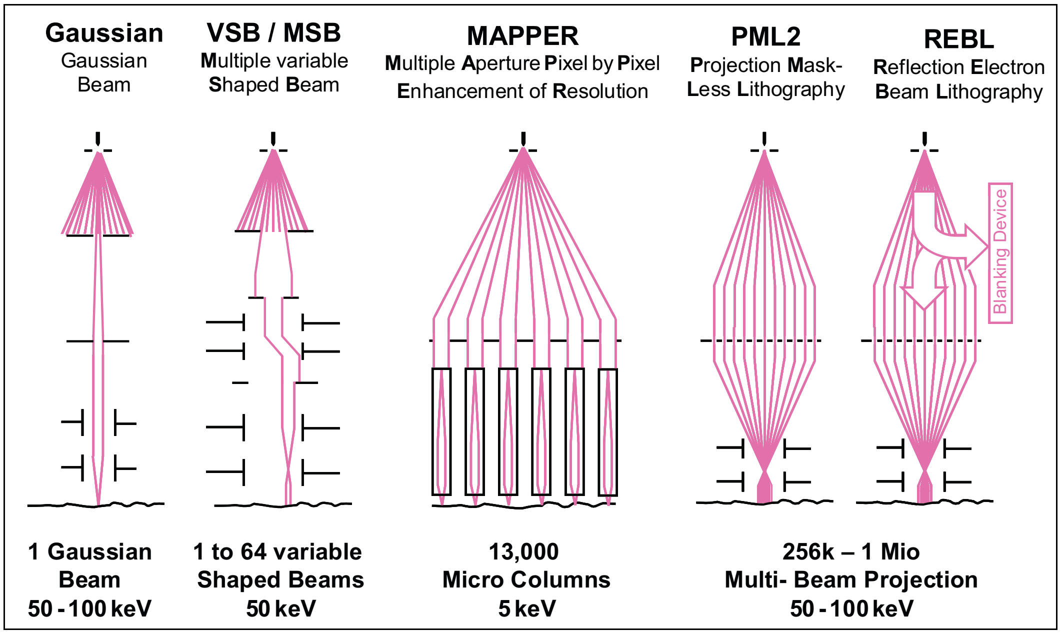
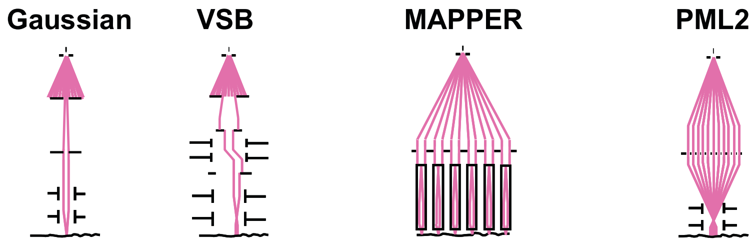


Figure 4: Principles of electron beam writing approaches

The Gaussian spot beam writers provide ultra-high resolution but the speed cannot be enhanced to the level of the PML2 technique because of source and blanking rate limitations (Figure 5). Because of these reasons VSB techniques are also facing insurmountable barriers, although the use of shapes allows a significant throughput enhancement. The MAPPER technique is comparable to PML2 with respect to throughput potential but has to provide adequate stability of the micro-column pitch and of the micro deflectors for single beam placement within each micro-column. With respect to PML2 main concerns were raised with respect to Coulomb interactions and wafer heating for direct write applications. Answers to these concerns are provided below in section 6.



Comparison when aiming for same throughput	Gaussian	VSB	MAPPER	PML2
Needed usable current from source	256,000x	~ 100x shape dependent	20x	1x (reference)
Blanking rate	256,000x	ca. 100x	20x	1x (reference)
Resolution / blur	< 1x	ca. 1x	ca. 1.5-2x	1x (reference)
Beam registration & stability limitation	DAC accuracy	DAC accuracy	Stability of micro column pitch & micro deflectors	Stability of column distortion & multipole stigmators
Beam tracking	Conventional	Conventional	Special requirements for Rz, Z	Conventional
Throughput potential	< (1/1000)x	ca. (1/50)x	ca. 1x	1x (reference)
Main concerns	State-of-the-art	State-of-the-art	Blur, Registration, Contamination, Heating	Coulomb Interactions, Substrate Heating

Figure 5: Throughput scaling and main concerns of different electron beam writing approaches

2. PROVEN MULTI-BEAM PROJECTION TECHNOLOGY

The proof-of-concept of the IMS multi-beam projection techniques has been achieved with two test systems, the RIMANA tool (Figure 6) providing 2500 programmable 12.5 nm sized 50 keV electron beams [1] and the CHARPAN tool (Figure 7) providing 43-thousand programmable 12.5 nm sized 10 keV ion beams at the substrate [2].

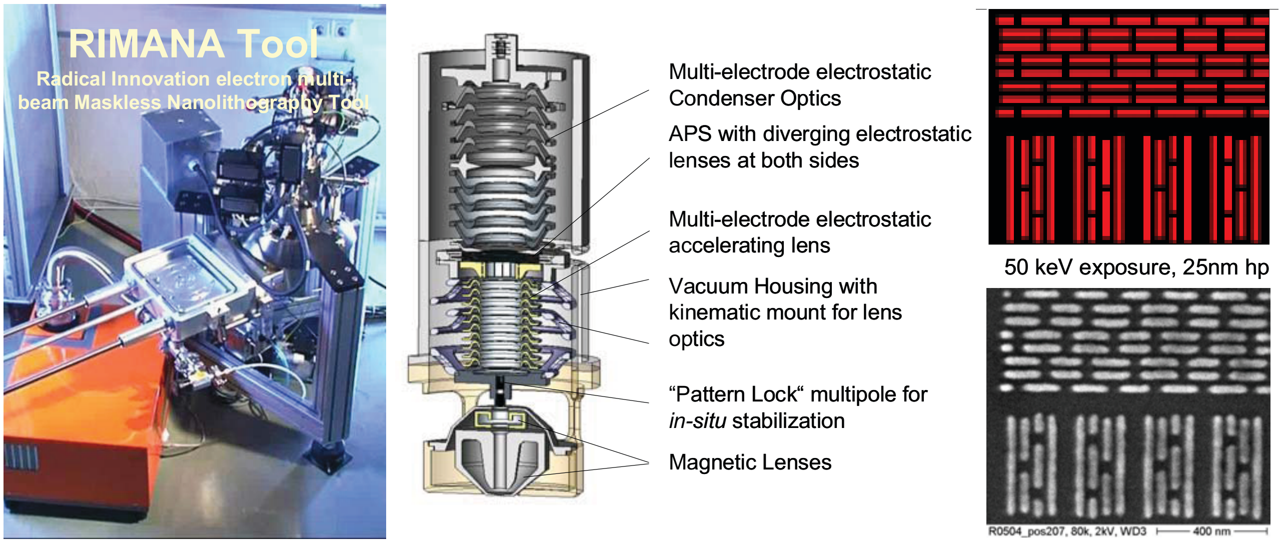


Figure 6: RIMANA Tool setup, principles and 25 nm hp exposure example in 50 nm HSQ negative resist.

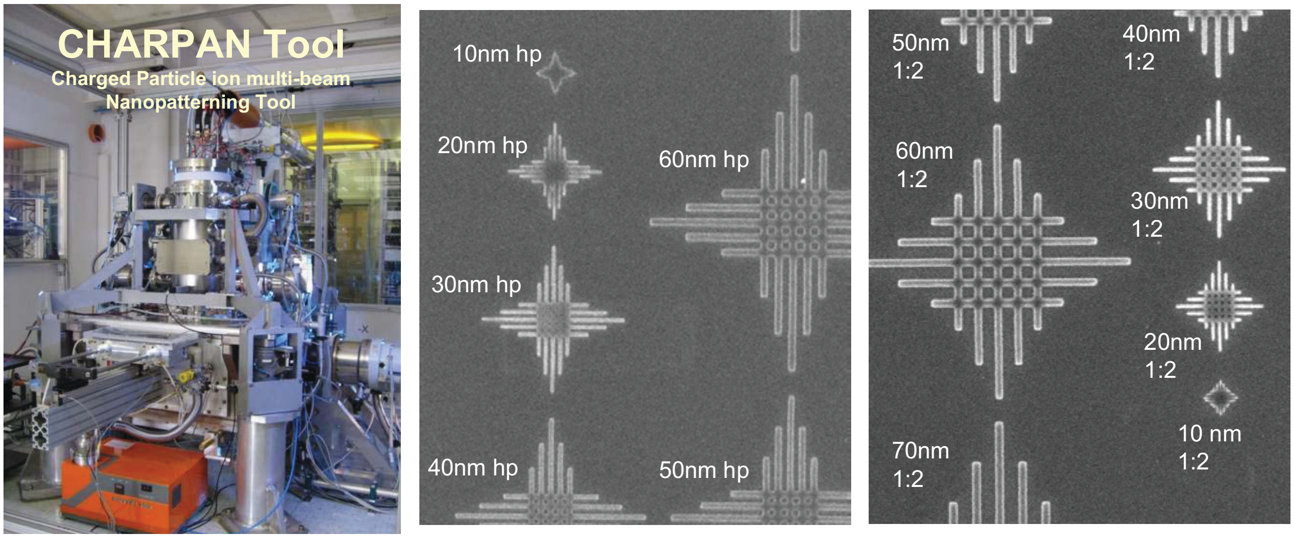


Figure 7: CHARPAN Tool setup and exposure examples in 20 nm HSQ (1:1 patterns) and 50 nm HSQ (1:2 patterns).

Using an aperture plate providing 8.3nm sized beams and overexposure there was the possibility to realize 12.5 nm hp dots and lines (Figure 8).

With the CHARPAN Tool detailed exposures were done on 6" mask blanks, exposing 40 nm HSQ resist and using the developed resist patterns for RIE pattern transfer into a 15nm Cr hardmask layer which was used for etching ca. 100 nm into the quartz surface. Finally the remaining Cr was removed and CDSEM measurements were performed (Figure 9). Excellent dose latitude and local CD uniformity was observed (Figure 10). Furthermore LMS-IPRO measurements showed low distortion and 2 nm 3 sigma distortion stability (Figure 11).

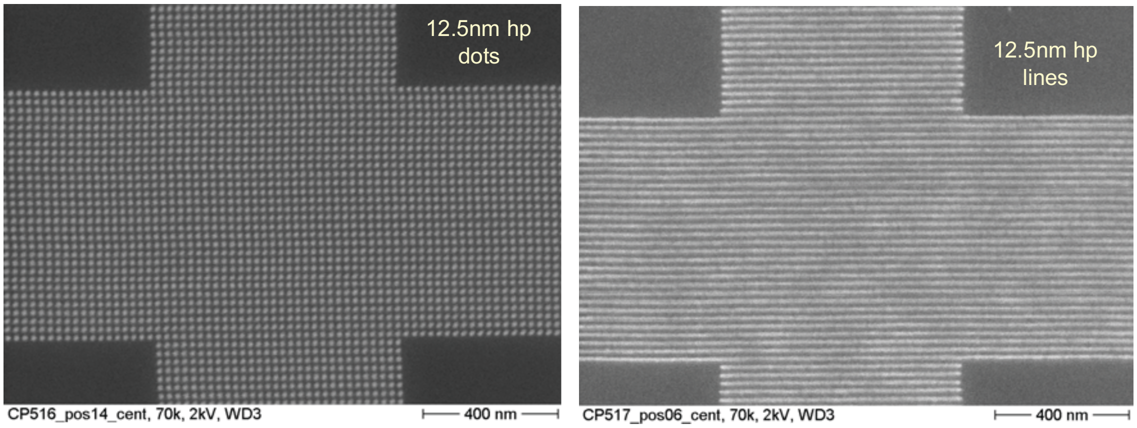


Figure 8: CHARPAN Tool exposure with 10 keV H_3^+ ions in 20 nm HSQ resist of 12.5 nm hp dots and lines.

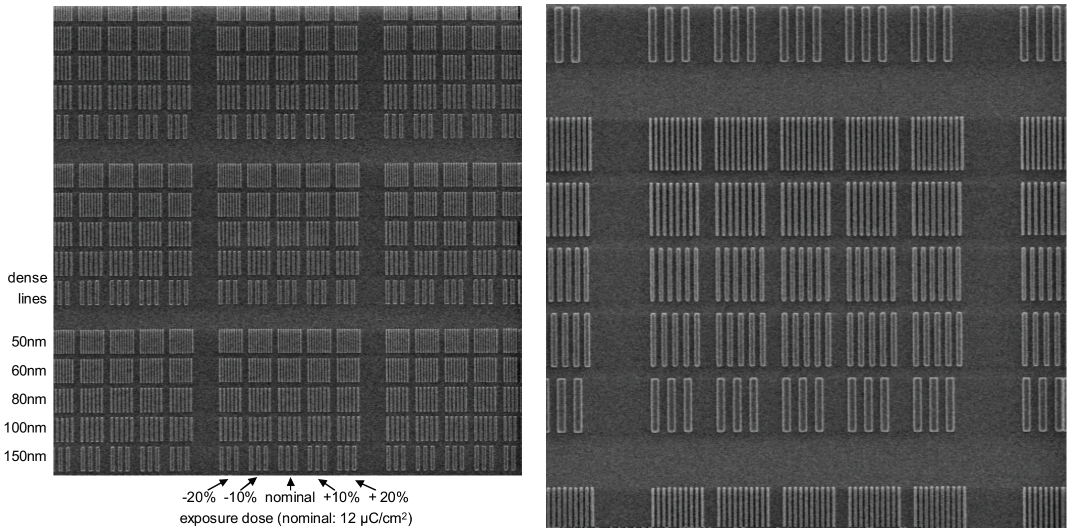


Figure 9: CHARPAN Tool exposed Bossung patterns within a 20 µm x 20 µm exposure field on 6" mask blank. CDSEM image of etched quartz pattern of 100-120 nm depth.

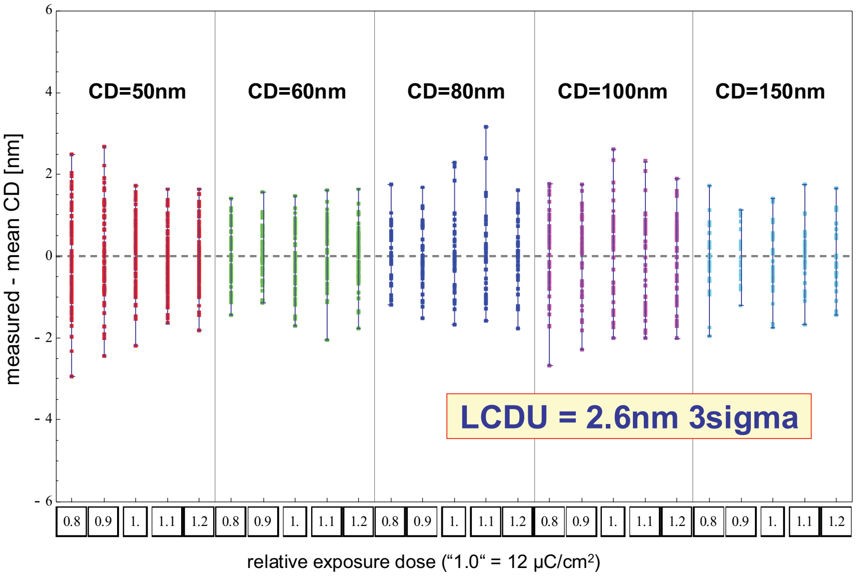
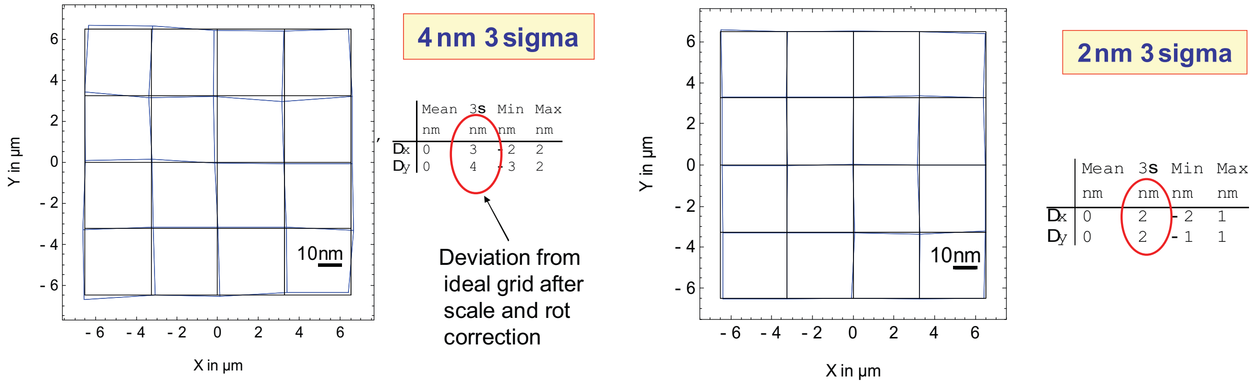


Figure 10: Bossung patterns of Exposure latitude and LCDU (local uniformity of critical dimension)



	Mean nm	3s nm	Min nm	Max nm
Dx	0	3	- 2	2
Dy	0	4	- 3	2

	Mean nm	3s nm	Min nm	Max nm
Dx	0	2	- 2	1
Dy	0	2	- 1	1

Figure 11: CHARPAN Tool distortion (left) and distortion stability (right)

3. APPLICATION FIELDS OF MULTI-BEAM PROJECTION TECHNIQUES

The application fields of charged particle multi-beam projection techniques are shown in Figure 12. There is emerging industrial interest on the CHARPAN ion multi-beam technology with respect to the fabrication of 3D master stamps for photonic applications. Furthermore there are a number of promising applications using resistless direct nanopatterning in the fields of nanosensorics, nanomagnetics and nanobiotechnology. Substantial industrial interest could be obtained for using electron multi-beam projection techniques for the fabrication of leading-edge complex masks and stamps. An industrial project was put in place in Q4 2009 to pursue this business opportunity. Projection electron multi-beam techniques are also most promising for electron beam direct write (EBDW) applications for nanodevice development and fast chip prototyping. IMS Nanofabrication has developed a patented concept for projection maskless lithography (PML2) to achieve a throughput of 1 WPH (300mm wafer per hour) for the 16 nm hp technology node and below, with extendibility to 5 WPH. Using a "Multi-Axis-PML2" column the wafer exposure is accomplished in small movement strokes allowing to shape compact systems. Thus a PML2 cluster tool could be developed with a throughput of 50-100 WPH within the floor space of an optical scanner. Presently and in coming years the semiconductor industry is focused on extending 193nm immersion lithography to the 22nm hp and possibly to the 16nm hp technology node. Further, major resources are concentrated on preparing EUV lithography to enter main stream production for the 16nm hp technology node and below. Consequently, IMS Nanofabrication is fully concentrated on the development of a 50 keV electron multi-beam Mask Exposure Tool (eMET) for the fabrication of ≤ 16 nm hp technology node leading-edge masks and templates.

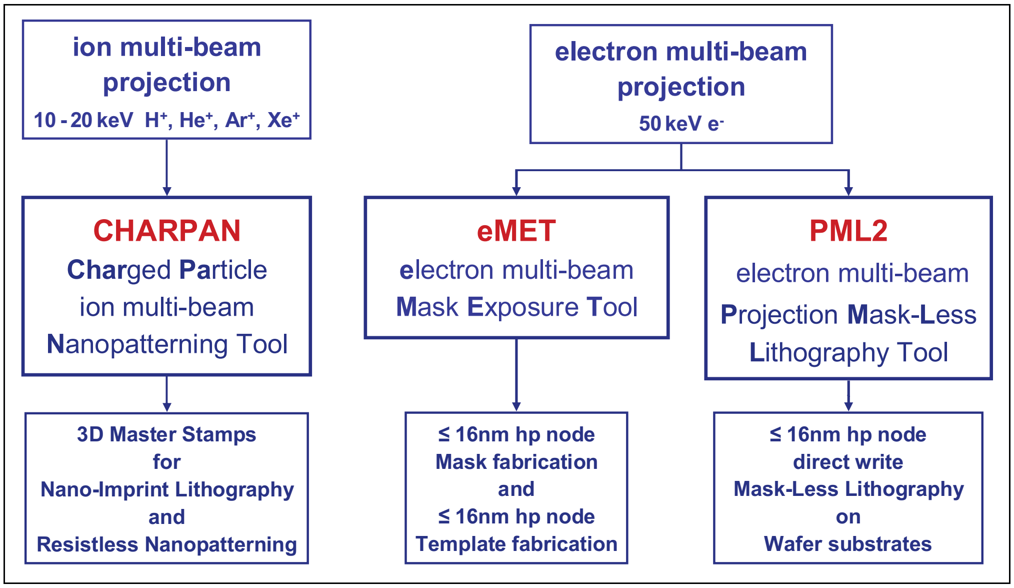
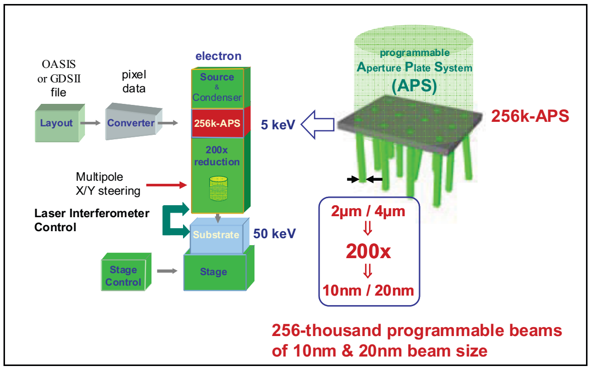


Figure 12: Application fields of ion and electron multi-beam projection techniques

4. eMET – 50 keV electron multi-beam Mask Exposure Tol

In Q4 2009 the "eMET POC" project was started with the target to realize a proof-of-concept 50 keV electron multi-beam Mask Exposure Tool for which a 256k-APS will be used providing 256-thousand programmable beams of 20 nm and 10 nm beam size (Figure 13).



eMET: 50 keV e-beam optics specifications

Electron beam energy at substrate	**50 keV**	
Exposure field of projection e-beam optics	82 µm x 82 µm	
Number of programmable beams	**256k**	
Max. current through column	**1 µA**	
Beam blur @ 1µA through column	**<12 nm FWHM** 5 nm 1sigma	
Beam size at 6" mask / stamp substrate	**20 nm**	**10 nm**
Minimum feature size	**32 nm HP** 22 nm single line	**16 nm HP** 12 nm single line

Figure 13: Application fields of ion and electron multi-beam projection techniques

The concept for the eMET column is fully established and detailed ray tracing calculations have been performed. In the following main results of the ray tracing calculations are shown. The 256k-APS has a cell size of 32 µm x 32 µm and 512 x 512 cells. Thus the active 256k-APS field is ca. 16.4 mm x 16.4 mm. With 200x reduction the eMET column exposure field is 82 µm x 82 µm.

The simulations show that the total FWHM blur within the 82 µm x 82 µm exposure field is only slightly increased from 5.1 nm to 6.2 nm with 1 µA of 50 keV electron beam current through the column. The change of distortion with 1 µA of current through the column is max. 0.64 nm. Thus, space charge causes only tolerable displacements (Figure 14).

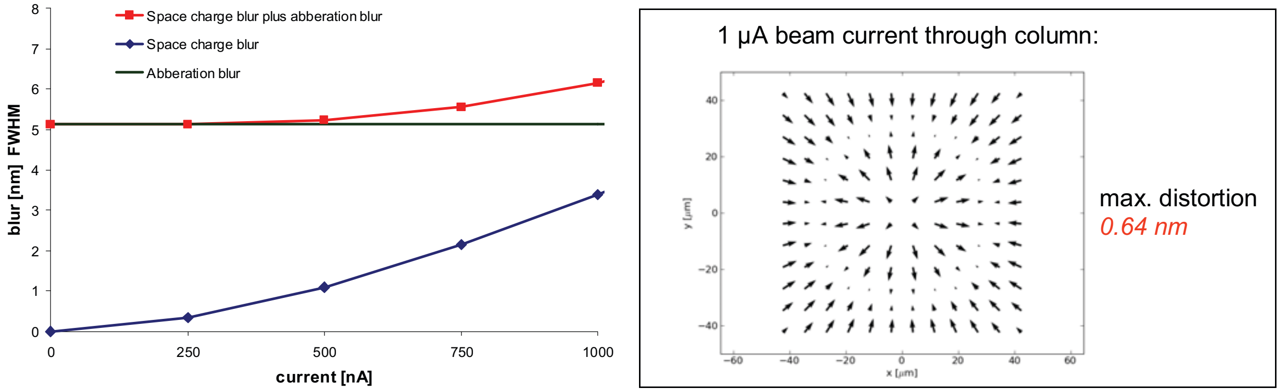
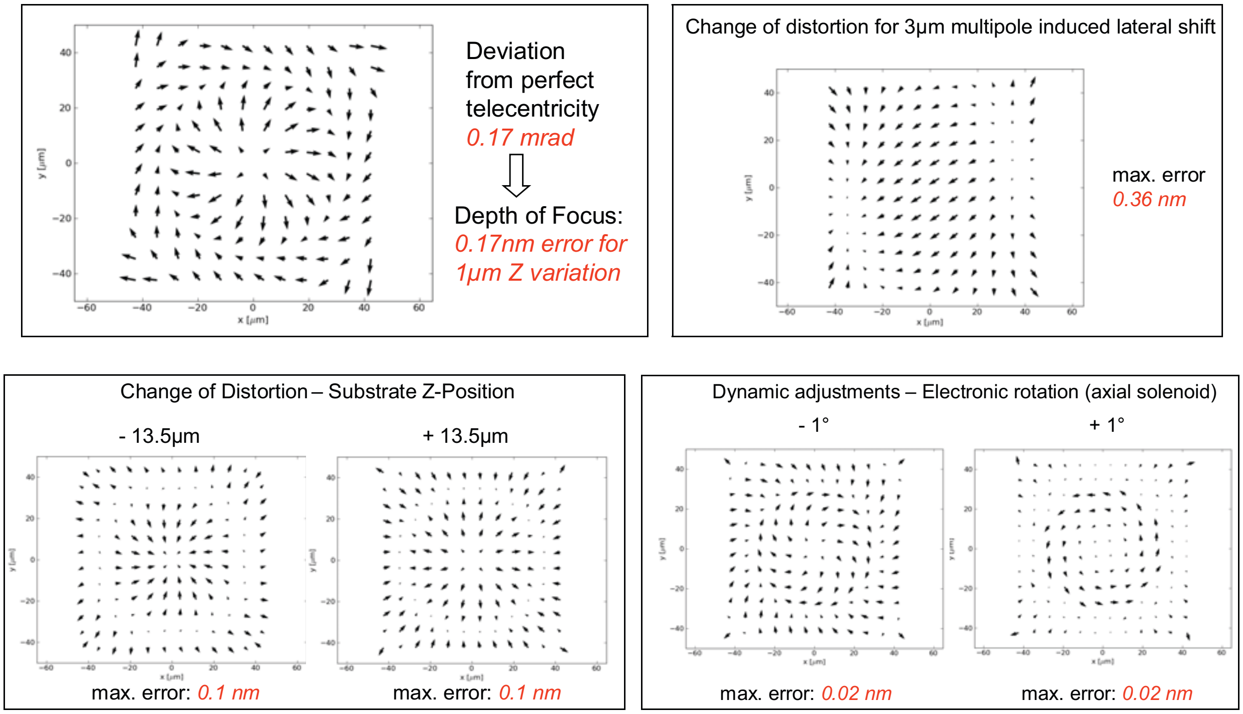


Figure 14: eMET column change of total FWHM blur and change of distortion with beam current.

The deviations from perfect telecentricty of the beam landing angle at the substrate are max. 0.17 mrad, causing 0.17 nm error for 1µm Z variation within the 82 µm x 82 µm exposure field. The change of distortion with a 3 µm lateral shift induced with in-situ multipoles is 0.36 nm. The change of distortion with 13.5 µm change of substrate Z-position is 0.1 nm. With an axial solenoid there will be the possibility of electronic fine rotation. For 1° rotation the change of distortion is 0.02 nm.

Overall the simulations show that the targets for the 50 keV eMET column can not only be fulfilled but that superior performance may be expected (Figure 15).



50 keV eMET Column	Target	Simulation
Blur within 82µm x 82µm	< 12 nm FWHM	6.2 nm FWHM
Coulomb induced distortion @ 1µA	< 1 nm	0.64 nm
Depth of focus – landing angle	> 1 µm	5 µm
Dynamic adjustment range	X/Y: 3 µm Z: ±10 µm Rz: ±1°	X/Y: 10 µm Z: ±50 µm Rz: ±5°

Figure 15: eMET column ray tracing simulation results

In order to simulate the eMET POC performance a “Virtual Exposure Tool” was established using first principles simulation:

- Mathematical model of all possible multi-beam column errors and stage/platform errors
- Top-down simulation of aerial image, applying arbitrary error configuration
- Evaluation of individual system errors by comparing aerial image of “perturbated system” with ideal image
- Relate subsystem errors to performance specs and perform system optimization

The features of the eMET Virtual Exposure Tool software are:

- Implementation of exact write strategy for aerial image simulation
- Includes all systematic & random errors of individual beams:
  - errors of optical column and APS
  - defective beams (always on or off)
  - dynamic errors of stage (beam tracking)
  - calibration accuracy
  - drift errors
  - systematic writing errors (grid approximation)

In the eMET Virtual Exposure Tool in total 75 parameters (error contributions) are considered.

Examples of Virtual Exposure Tool simulations are shown below for 20 nm beam size (Figure 16). The first example shows a part of a line of 80 nm nominal width and 82 µm length with 3nm 3sigma positional noise. The black line shows the 50% contour and adjacent the ± 10%, ± 20%, ± 30%, and ± 40% contours. From the analysis of the upper and lower edge there is conclusion that a line edge roughness (LER) of 1.6 nm 3 sigma and a local critical dimension uniformity (LCDU) of 0.8 nm 3 sigma can be expected. A further example shows the influence of positional noise of several degrees of 40 nm elbow patterns.

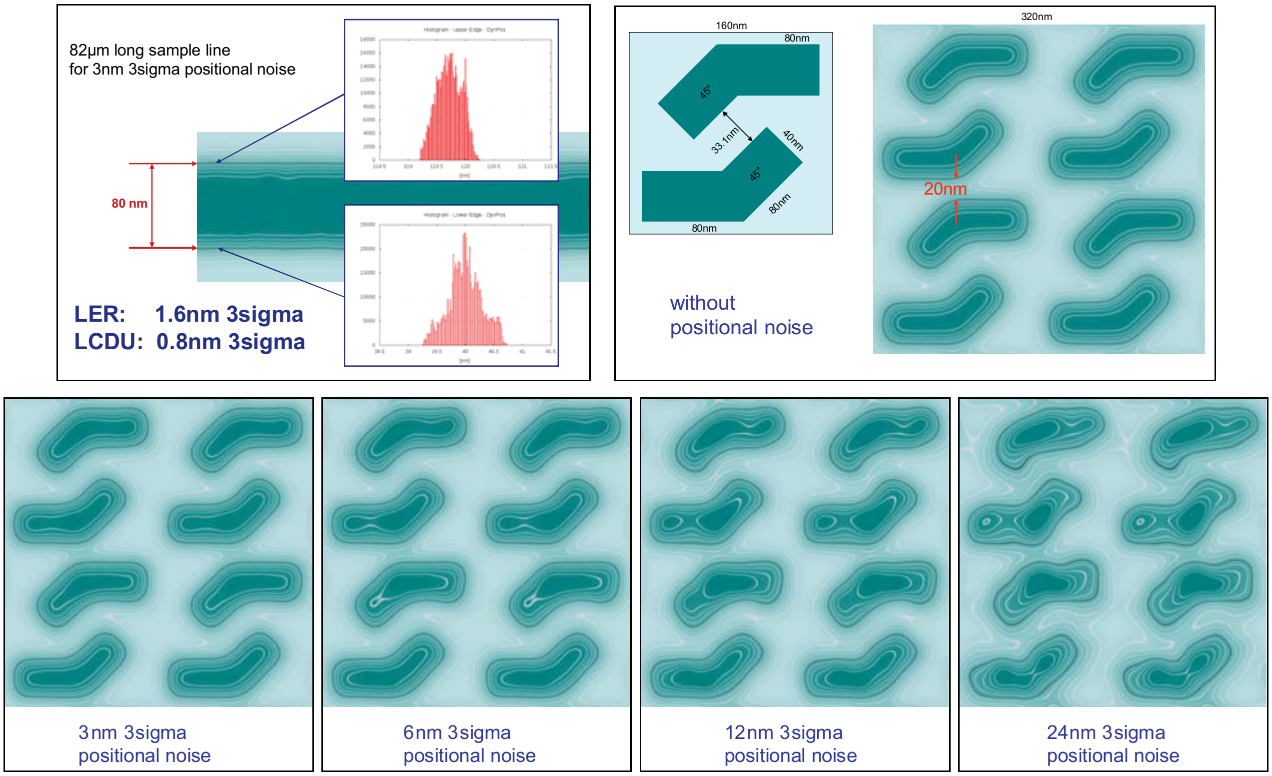


Figure 16: eMET Virtual Exposure Tool simulation of a 82 µm long line of 80 nm width and of 40 nm elbow patterns.

Isolated small patterns like 40 nm contacts are most sensitive to positional noise. When using double and quad grid exposure techniques, the positional noise has considerably less influence on anticipated eMET performance (Figure 17).

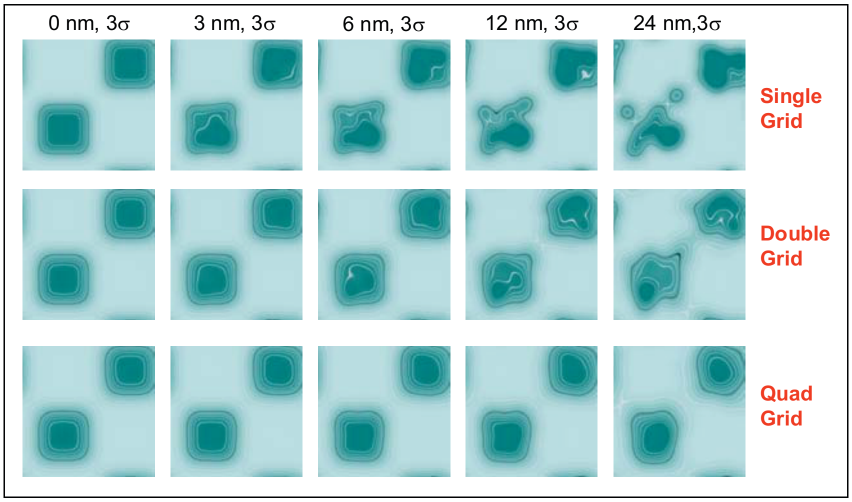


Figure 17: eMET Virtual Exposure Tool simulation of 40 nm contacts for different exposure modes and positional noise

5. POTENTIAL THROUGHPUT OF PROJECTION MASKLESS LITHOGRAPHY (PML2)

When using an eMET column on a tool platform housing a 300 mm wafer vacuum stage the potential writing speed is 20 hours for the 16 nm hp technology node. This can be improved to 5 hours when enhancing the APS from 256-thousand to 1-million beams. By adopting a multi-axis column [3] configuration ("Multi-Axis-PML2") the potential throughput is enhanced to 5 wafers per hour for the 16 nm hp technology node and below (Figure 18).

$WPH_{\text{without overheads}} = I / (D * EA) * 3600$

WPH 300mm Wafer Per Hour

I total beamlet current [µA]

D resist exposure dose [µC/cm²]

EA exposure area [cm²]

Assumptions: **D = 120µC/cm²** using 50 keV e-beam lithography for the **16nm hp** technology node

EA = 620 cm² (die field area on 300mm wafer)

Use of eMET column: I = 1µA

$WPH_{\text{without overheads}} = 0.05$ (20 hours / 300mm wafer)

Improvement of 300mm wafer throughput:

1) APS enhancement to 1 million beamlets

256k-APS fabrication is based on 0.25µm CMOS technology node.

By using 0.13µm CMOS technology:

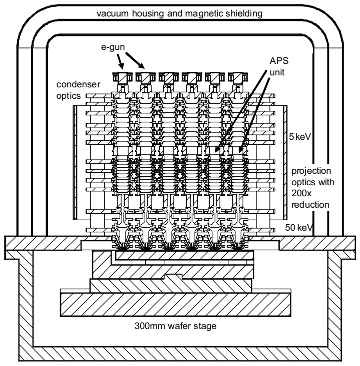
⇨ **1M-APS (1024 x 1024 beamlets)** @ same APS field size

I = 4 µA

$WPH_{\text{without overheads}} = 0.2$ (5 hours / 300mm wafer)

2) Multi-Axis-PML2 **$I_{\text{Axis}} = 4\ \mu A$**

Exposure field per axis:
2 dies of 26mm x 33mm



US patent 7,214,951

$EA_{\text{Axis}} = 17\ \text{cm}^2$

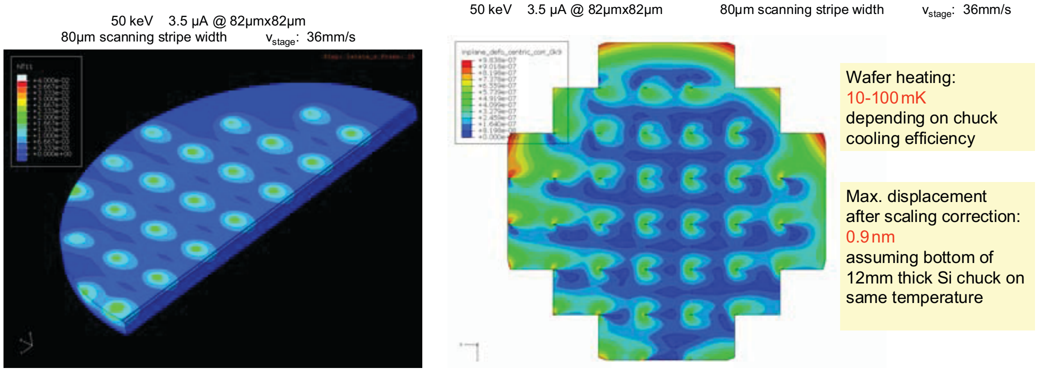
$WPH_{\text{no overheads}} = (I * 3600) / (D * EA_{\text{Axis}})$

$WPH_{\text{without overheads}} = 6$

$WPH_{\text{with overheads}} = 5$

Figure 18: Potential throughput of projection mask-less lithography (PML2) for the 16 nm hp node and below

Thus in the Multi-Axis-PML2 configuration Coulomb interactions are well governed as only a limited amount of beam current is allocated to one axis. Furthermore, finite element simulations show that there is very small wafer heating leading to less than 1nm local distortions (Figure 19) which can be predicted and thus managed.



Wafer heating:
10-100 mK
depending on chuck cooling efficiency

Max. displacement after scaling correction:
0.9 nm
assuming bottom of 12mm thick Si chuck on same temperature

Figure 19: Finite element simulation of wafer heating for the Multi-Axis-PML2 configuration.

6. SUMMARY

The status of multi-beam projection writing may be summarized as follows:

- Projection multi-beam writing demonstrated: 20 nm hp, 2.6 nm 3 sigma LCDU, complex patterns have been shown.
- The design of a 50 keV 256k-multi-beam column for the electron Mask Exposure Tool (eMET) has been completed, fulfilling needs for the 16nm hp technology node and below.
- A "Virtual Exposure Tool" software has been developed and used for quantitative analysis of multi-beam lithography errors: Detailed error analysis has been implemented for the eMET design.
- The possibility to adopt the50 keV electron projection multi-beam architecture for EBDW maskless lithography with 5 WPH throughput potential for 16nm hp and below has been outlined.

ACKNOWLEDGEMENTS

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