50 keV electron Multibeam Mask Writer for the 11nm HP node: 1st results of the Proof of Concept Tool (eMET POC)

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ABSTRACT

First results obtained with IMS Nanofabrication's 50keV proof-of-concept electron multi-beam mask exposure tool (eMET POC) are presented. The eMET POC was designed from scratch to meet the requirements of the 11nm half-pitch node and features already the same column as future high volume manufacturing (HVM) tools. All exposures shown in this paper were the result of 262,144 beams of 20nm beam size working in parallel demonstrating the capability of IMS' multi-beam technology. An Alpha Tool is scheduled for 2014, followed by a Beta Tool in 2015 and 1st generation HVM Tools in 2016.

Keywords: multi-beam, mask writer, template writer, electron beam projection optics, electron multi-beam technology.

1. INTRODUCTION

Due to the extension of 193nm immersion lithography to sub-20nm nodes and the resulting need to adopt multiple patterning techniques, the total number of required masks for critical layers is multiplied. Furthermore, the complexity of leading edge masks is currently rising exponentially from node to node due to additional RET (reticle enhancement techniques) features introduced by optical proximity effect correction (OPC), computational lithography induced inverse lithography techniques (ILT), source-mask-optimization (SMO), and others. Conventional, evolutionary improvements of currently available single-beam systems simply cannot keep up with this trend. That is why mask write times for the most critical layers are expected to exceed one day already at the 22nm node [1, 2]. In order for a mask writers to be cost effective, however, leading-edge mask write times should be less than 20h [3]. IMS' multi-beam technology addresses this issue and promises to provide a multi-generational solution for future technology nodes, starting at 11nm half-pitch.

2. eMET PRINCIPLES AND STATUS

IMS Nanofabrication's multi-beam mask writer series is called eMET, which is short for electron Mask Exposure Tool. The basic principles common to all eMET systems are shown in Figure 1 (cf. also Refs. [4, 5]). Electrons extracted at gun-level first pass through a multi-electrode stack, which acts as a condenser and generates a broad, homogeneous beam of 25mm in diameter. This electron beam then impinges perpendicularly onto a programmable Aperture Plate System (APS), where 512 x 512 (262,144) micrometer sized beams are formed (cf. 256k-APS). Additionally, each beam can be deflected individually by CMOS-controlled micro-deflectors. All beams (deflected and undeflected) then enter the projection optics of the system where they get accelerated from 5keV to 50keV beam energy in an electrostatic multi-electrode lens and 200x demagnified by a magnetic lens system located at the bottom of the optical column. Only undeflected beams make it to the substrate level. Deflected beams are filtered out at a stopping aperture plate in the projection optics. All eMET systems are designed to print 82µm wide stripes on-the-fly, i.e. the substrate is continuously moving at constant velocity underneath the column while beams at switched on and off according to the data fed into the APS via the eMET data path. In this write mode IMS' proprietary writing strategy provides an inherent redundancy of up to 16x. This high redundancy level averages out the effects of individual defective beams and thereby allows ignoring up

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to 100 (statistically distributed) defective beams. Furthermore, the operability of APS units is monitored in-situ on a weekly basis by measurements which give information on the precise position of all defective beams. This information can be used to further reduce the impact of defective beams via online correction in the eMET data path. This inherent property of the eMET writing strategy coupled with the online correction capability drastically reduce the technical risk associated with the most critical element of this new technology and speak for the suitability of IMS' multi-beam solution for high-volume manufacturing.

In 2011 a first Proof-of-Concept (POC) version – the eMET POC – was integrated and finalized based on a tight schedule [6]. The eMET POC was designed from scratch to meet all lithographic requirements of the 11nm HP node such as resolution capability (i.e. minimum feature size), pattern fidelity, critical dimension uniformity (CDU), line width roughness (LWR), registration etc. within 1cm x 1cm fields on 6 inch mask blanks. The fully integrated eMET POC at its current installation site at IMS Nanofabrication in Vienna, Austria, can be seen in the right of Figure 1.

In June 2011 integration of the eMET POC without 256k-APS and data path was successfully completed. At this stage the 256k-APS was intentionally replaced by a static stencil plate in order to allow for separation of electron-optical effects generated by the column from APS-induced effects. The optical column itself, however, was already in its final configuration which is essentially the same as for future high volume manufacturing (HVM) tools. Beam ON was achieved in July 2011, immediately showing good resolution of 80nm HP lines & spaces in 50nm HSQ negative resist. Until September 2011 the optical performance of the eMET POC system was optimized and patterning capability down to 30nm lines & spaces and 24nm single lines was demonstrated on 6 inch mask blanks (Shin Etsu Qz blank with 15nm Cr and 40nm HSQ). Here, the uniformity of all critical dimensions was found to be 3.5nm 3s or better across the 82µm x 82µm beam array field (after removal of systematic site means errors caused by proximity effect). In the time until December 2011 the eMET POC system was upgraded with a fully operational 256k-APS unit and the corresponding data path resulting in the final tool configuration.

Figure 2 (left) shows a 256k blanking chip assembly which contains a post-processed CMOS chip and connections to the eMET data path via a PCB carrier board. This is the active part of a 256k-APS which is thoroughly tested in a dedicated APS test bench prior to tool installation. In this APS test bench an 1:1 projection optics images the beams generated at the APS onto a scintillator screen allowing for live monitoring and recording of APS performance (cf. center of Figure 2). Here, properties such as number of defective beams, minimum deflection angle, charging, and cross-talk are studied. Eventually, the best available 256k-APS was selected for installation. The right side of Figure 2 shows 256k-APS#4 after insertion into the eMET POC system. This 256k-APS unit is fully functional and provides 262,077 switchable beams (67 beams are defective and cannot be switched) of 20nm size at substrate level. The image field generated by the APS is 82µm x 82µm leading to 82µm stripe width in scanning mode. The maximum net data rate supported by this APS generation is 12.8 Gbps.

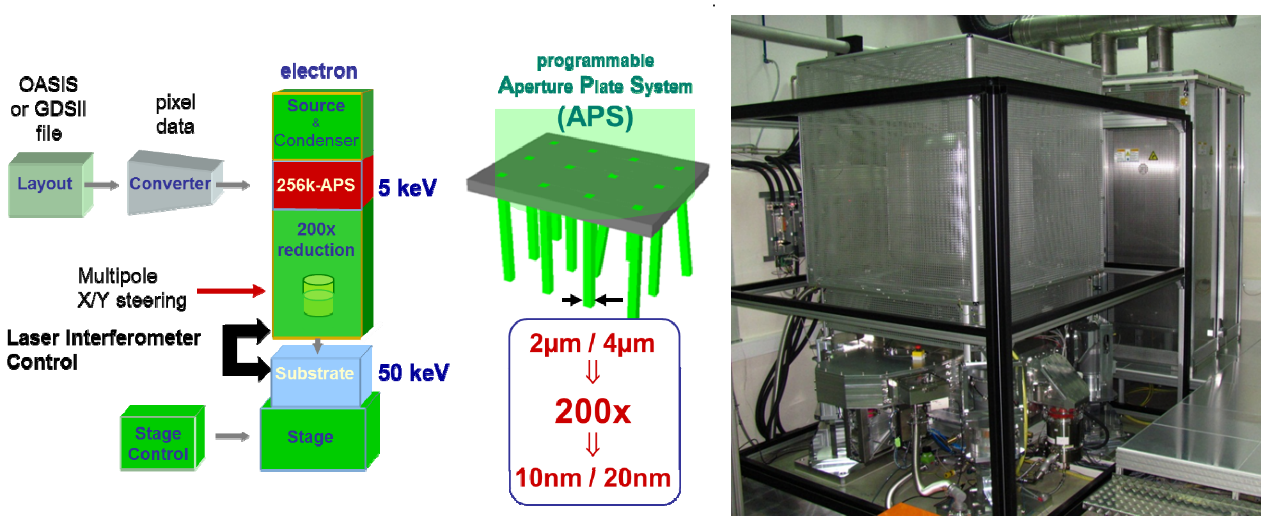


Figure 1: eMET principles (left).
Fully integrated eMET POC at its current installation site at IMS Nanofabrication in Vienna, Austria (right).

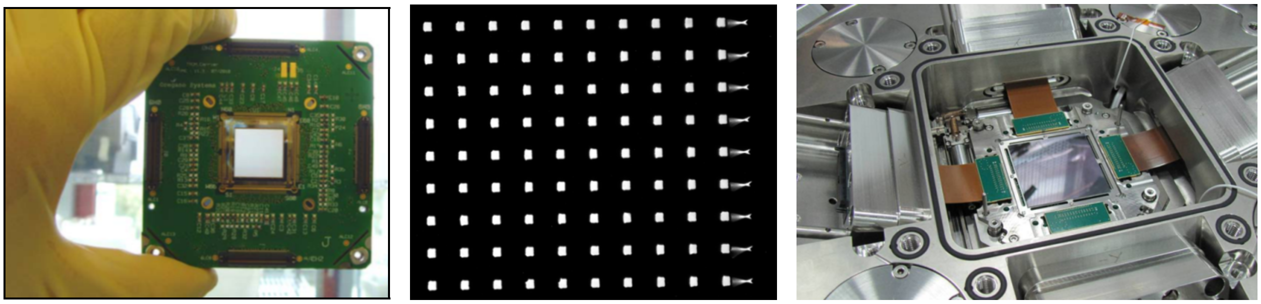


Figure 2: 256k blanking chip assembly (left). APS Testbench 1:1 projection image of beams generated at the APS allowing for live monitoring and recording of APS performance (center). 256k-APS#4 after insertion into the eMET POC column (right).

All results presented in this paper have been generated by the fully integrated eMET POC system where 262,144 beams were working in parallel to pattern an 82µm x 82µm area. The laser interferometer controlled stage was kept stationary in order to make the exposure results 1:1 comparable to results obtained in September 2011.

3. eMET POC EXPOSURE RESULTS WITH 256k-APS

Figure 3 shows SEM images of an 82µm x 82µm test pattern printed by 262,144 beams of 20nm size in 50nm HSQ on a 150mm Si wafer. This test pattern mainly contains 50nm and 100nm HP lines & spaces as well as isolated lines at various angles and doses. In the printed pattern no variation in the resolution capability can be observed across the whole image field. All regions exhibit well resolved 50nm lines and spaces as highlighted in the magnified image on the right of Figure 3. Even though 67 defective beams were present in the APS, no defects are generated in the printed structures due to the averaging effect of the redundancy inherent to IMS' proprietary writing strategy.

In order to quantify the uniformity of the printed patterns across the 82µm x 82µm image field a test pattern was designed which contains 32x32 identical cells of 2.56µm x 2.56µm. Within each cell horizontal and vertical lines and spaces of a given CD are realized.

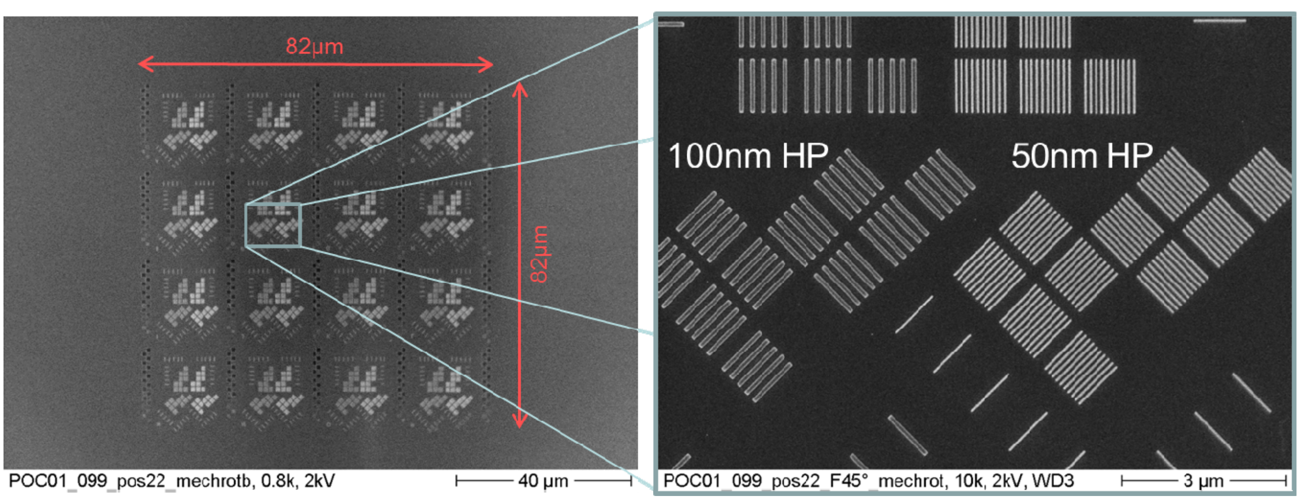


Figure 3: SEM images of an 82µm x 82µm test pattern printed by 262,144 beams of 20nm size in 50nm HSQ on a 150mm Si wafer at 1360µC/cm² exposure dose. Complete 82µm x 82µm image field showing no defects (left). Magnified image showing 100nm and 50nm HP and isolated line Bossung patterns (right).

Figure 4 shows such a test pattern as well as the location of 17 metrology areas within the 82µm x 82µm image field. The metrology areas are evenly distributed across the image field and contain one lines&spaces-cell each. Two measurement windows of 1µm x 1µm in size are placed in each metrology area and all lines within these measurement windows are measured (cf. right side of Figure 4). Here, 360 measurements are done along each line.

Figure 5 shows a SEM detail of a 50nm HP lines&spaces-cell taken at 50k magnification. Here, the area in-between adjacent beams is highlighted in order to further emphasize the fact that each SEM image shows a true multi-beam patterning result where multiple beams were working together to create the printed structure. The precise number of involved beams depends on the magnification of the SEM image. At 50k magnification typically 144 beams are working together to print the recorded area.

Lines as shown in Figure 5 were measured at 17 different locations across the full 82µm x 82µm image field following the procedure described above. Due to the fact that no proximity effect correction was applied, systematic site means errors needed to be removed before determining the 3 sigma LCDU value. The result of this analysis is shown in the right hand side of Figure 5. Horizontal lines turned out to be 2.34nm above target at a LCDU value of 3.5nm 3sigma, whereas vertical lines proved to be on target (0.29nm deviation) at 2.51nm 3sigma LCDU. Here, the difference between horizontal and vertical CD values is caused by a residual astigmatism of the optics which can be removed by improved tool calibration. It has to be stressed that the obtained LCDU value of 3.5nm 3sigma is the very first result obtained from 50nm HP patterns printed with 262,144 beams. Improved tool calibration will result in further improvement of the performance of the eMET POC system.

eMET POC exposure simulations (assuming 5nm 1sigma tool blur) show that the theoretical resolution limit at which dense lines and spaces can be printed with good contrast at every location on the 0.1nm address grid lies at approximately 1.5-times the beams size. That means that for 20nm sized beams 30nm lines and spaces are at the designated resolution limit of the tool. Therefore, 30nm HP lines were printed in order to demonstrate the patterning capability of the tool and to verify that the tool behaves as designed. SEM images of the resulting resist structures are shown in Figure 6. Here, the residual astigmatism mentioned above is clearly visible. Even at this preliminary stage of tool calibration, however, 30nm HP lines and spaces were well resolved in both, horizontal and vertical, directions.

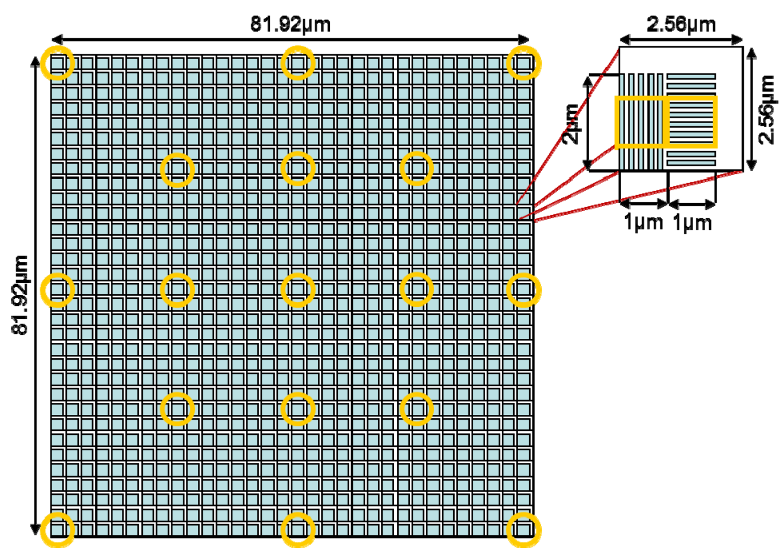
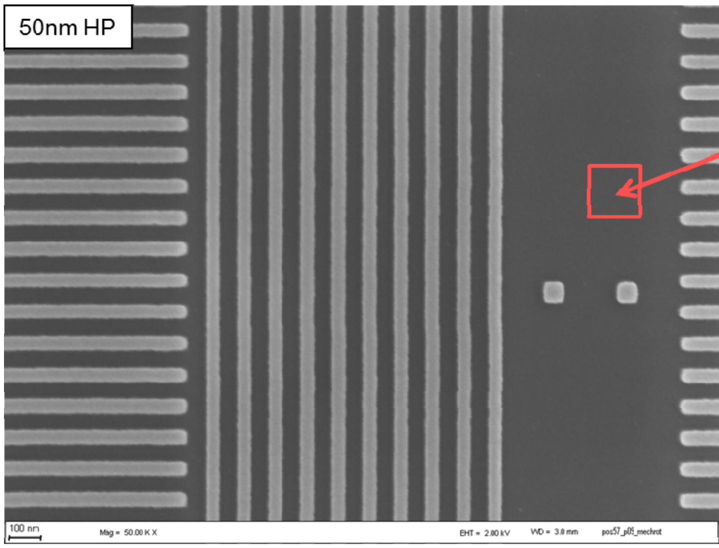


Figure 4: Test pattern for local CDU analysis. 32x32 identical 2.56µm x 2.56µm cells containing horizontal and vertical lines and spaces are printed within an 82µm x 82µm area. 17 yellow circles show designated measurement cells. Yellow squares represent 1µm x 1µm measurement windows within each measurement cell.



horizontal

Target CD	CD (center)	MTT (center)	LCDU (3s)
50nm	52.34	2.34	3.50

vertical

Target CD	CD (center)	MTT (center)	LCDU (3s)
50nm	50.29	0.29	2.51

Figure 5: Local CDU analysis of an 82µm x 82µm test pattern containing 50nm lines & spaces. The complete image field was printed by 262,144 beams of 20nm size in 50nm HSQ on a 150mm Si wafer at 900µC/cm² exposure dose. SEM image shows a magnified detail in the center of the image field and highlights the area in-between beams. LCDU for 50nm HP lines and spaces was determined to be 3.5nm 3s or better across the 82µm x 82µm image field (systematic site means errors caused by proximity effect were taken out)

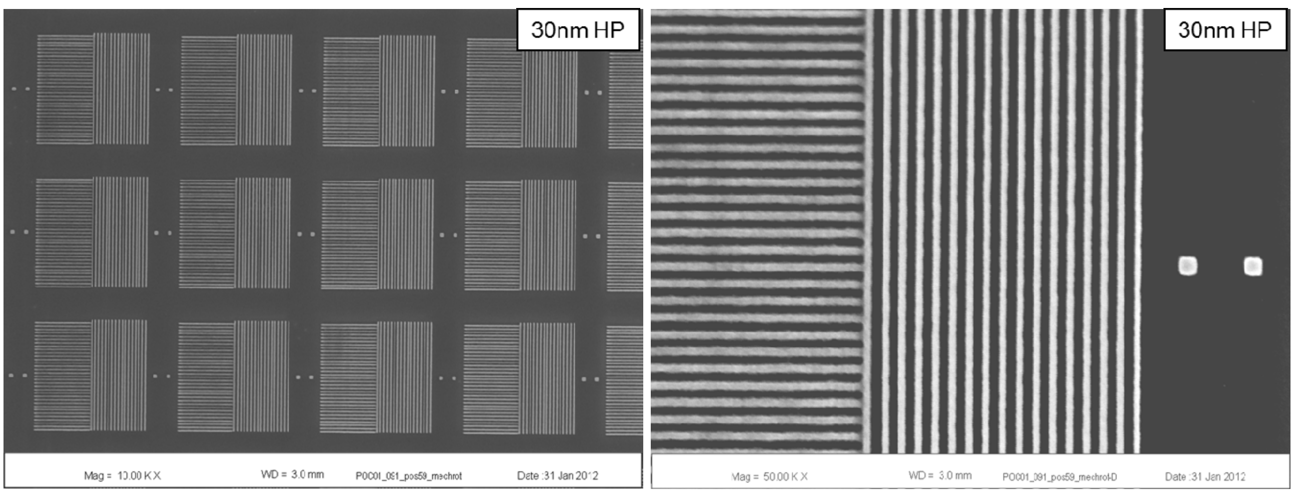


Figure 6: SEM details taken with 10k (left) and 50k (right) magnification in the center of an 82µm x 82µm test pattern containing 30nm lines & spaces. The complete image field was printed by 262,144 beams of 20nm size in 50nm HSQ on a 150mm Si wafer at 860µC/cm² exposure dose.

Furthermore, the dose was varied for 40nm HP lines and spaces test patterns in order to obtain a first estimation of the dose latitude of the eMET POC system. Figure 7 shows the resulting SEM images for 860µC/cm² (base dose, right) and 730µC/cm² (base dose -15%, left). CD measurements of these patterns resulted in 38.2nm and 34.7nm, respectively. Consequently, dose latitude was determined to be 2.3nm for 10% dose variation.

In order to test the resolution limit for single lines another test pattern was designed. Here, 1µm long single lines of 24nm – 90nm CD are placed above and below a 300nm thick line at 300nm pitch. In the complete test pattern 1024 (32 x 32) of these structures are evenly distributed across an 82µm x 82µm area, which corresponds to the size of the beam array field of the eMET POC system. The left side of Figure 8 shows a SEM detail of such a structure taken at 50k magnification in the center the image field. Here, the pattern was about 15% underexposed, resulting in CD values which are on average 3.8nm below target. Nevertheless, all single lines down to 24nm target CD are still well resolved, even though the nominal 24nm line was reduced to 20nm due to underexposure. This result further speaks for the resolution capability of the eMET POC system. It has to be stressed that all patterns were printed with 20nm beam size, so by going to 10nm beams the resolution capability of the tool can be easily extended into the 10nm range.

Deviation of the measured CD values from target (subtracted by the observed 3.8nm offset caused by underexposure) plotted versus target CD is shown in the right hand side of Figure 8. This shows the linearity of the eMET POC system for single lines in the range below 100nm. It has to be stressed that no linearity or proximity effect corrections were applied in this case; i.e. all lines were printed with the same dose of 1093µC/cm² and nominal CD. So, without any kind of corrections, the extracted linearity of the eMET POC system was found to be within ±0.5nm.

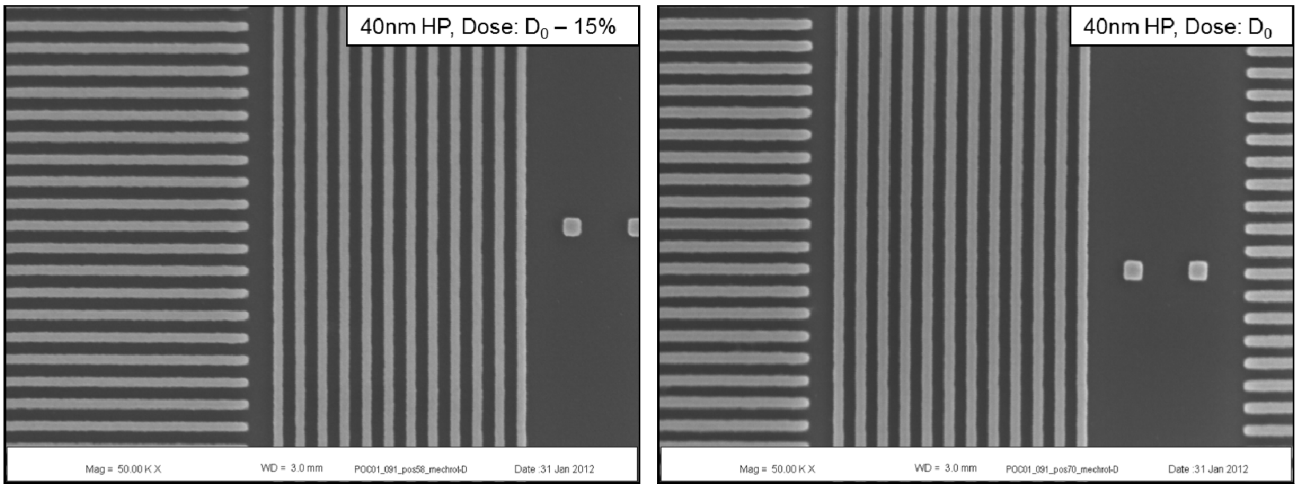


Figure 7: SEM images taken in the center of an 82µm x 82µm test pattern containing 40nm lines & spaces. The complete image field was printed by 262,144 beams of 20nm size in 50nm HSQ on a 150mm Si wafer. The dose was varied to give a first estimation of the dose latitude of the eMET POC system. Left pattern was printed at 730µC/cm², right pattern at 860µC/cm² exposure dose. The resulting dose latitude amounted to 2.3nm / 10% dose.

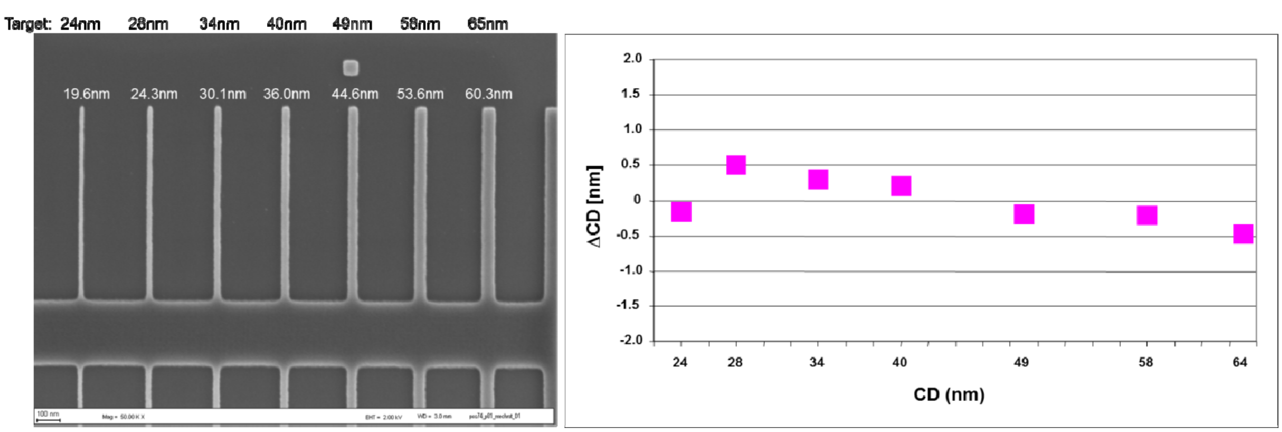


Figure 8: SEM image taken in the center of an 82µm x 82µm test pattern containing single lines of target CD values ranging from 24nm up to 90nm (left). The complete image field was printed by 262,144 beams of 20nm size in 50nm HSQ on a 150mm Si wafer at 1093µC/cm² exposure dose. The pattern was underexposed resulting in CD values ~4nm below target. On the right, the deviation of the measured CD from target (subtracted by a 3.8nm offset) is plotted versus target CD showing single line linearity within ±0.5nm.

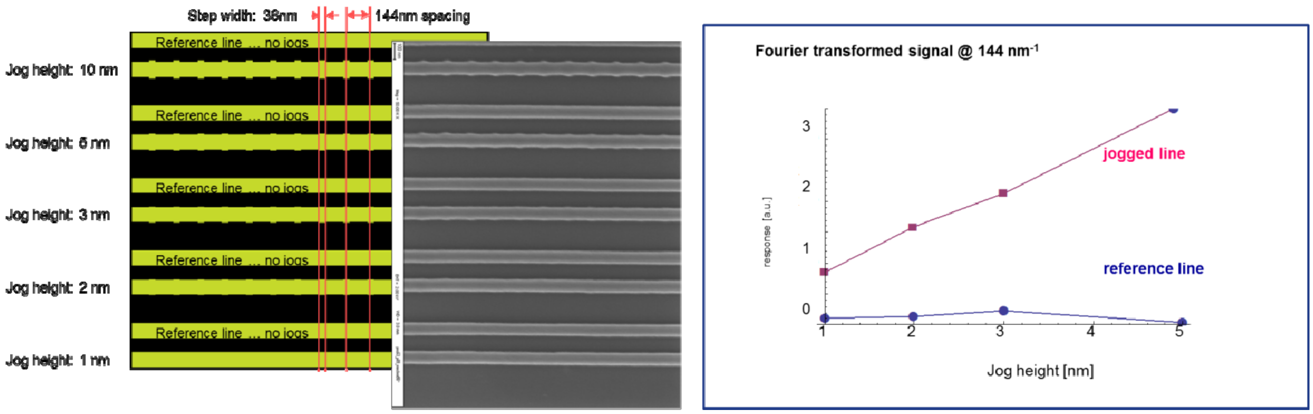


Figure 9: SEM analysis of printed 82µm x 82µm jog test pattern. Here, jogs of 36nm width and 144nm spacing are alternated with straight reference lines and the jog height is varied from 10nm down to 1nm. The SEM image was taken in the center of an 82µm x 82µm image field which was printed by 262,144 beams of 20nm size in 50nm HSQ on a 150mm Si wafer at 890µC/cm² exposure dose. In order to study the jog resolution capability of the eMET POC system the measurement data along lines with and without jogs were Fourier transformed and the signal at $144 nm^{-1}$ was plotted versus jog height showing a linear correlation and clear resolution of 1nm high jogs (right).

As a final test, OPC-like jogs of 36nm width and 144nm spacing were realized. The associated test pattern consists of alternating lines with and without jogs, where the jog height is varied from 10nm down to 1nm (see Figure 9). Here, the lines without jogs act as reference lines which can be used to calibrate the measurement. Since 1nm high jogs are not easily detectable, all measurement data was Fourier transformed and the signal at $144 nm^{-1}$ was analyzed. The right hand side of Figure 9 shows the measured signal at $144 nm^{-1}$ plotted versus jog height for lines with and without jogs. Comparison between jogged lines and reference lines shows that jogs down to 1nm height are indeed well resolved. Furthermore, a strictly linear correlation between measured Fourier signal and jog height can be observed, which additionally supports the validity of the measured results.

4. eMET ROADMAP

All results presented in this paper were obtained with the fully integrated and operational eMET POC system which was completed end of 2011. In the first quarter of 2012, on-the-fly exposures, i.e. continuous patterning on a constantly moving stage, will be tested and optimized. Final factory acceptance tests (FAT) for the eMET POC are scheduled for mid-2012. As shown in Figure 10, the eMET POC features already all essential properties of a full-blown HVM eMET system. It is designed from scratch to meet the lithographic requirements of the 11nm HP technology node; it uses the same number of programmable beams to create patterns and features the same maximum current as the final HVM tool. Essentially, the whole POC column is identical to the final column installed in future eMET production tools. Thus, early testing with eMET POC will allow for the development of all required processes and will ease the insertion of eMET HVM systems into production lines.

The main difference between eMET POC and eMET Alpha, which is scheduled for 2014, is the platform. The eMET Alpha system will feature the final HVM platform whereas eMET POC is equipped with a custom-made test platform (with reduced stability and duty cycle specifications) only. In 2013 the eMET Alpha column will be integrated with the final platform, allowing for tool optimization and FAT in 2014. The learning from eMET Alpha systems will eventually be incorporated into eMET Beta, which is physically identical to the first generation of eMET HVM tools. FAT for eMET Beta is scheduled for 2015 and first production tools are going to be available in 2016.

Throughput of all eMET systems is completely independent of the complexity of the mask layout. With an eMET Beta or 1st generation HVM tool (HVM-1), the most complex masks for critical 11nm HP layers will print in less than 10 hours. This also holds for pixelated masks. This throughput estimation is based on the assumption that an exposure base dose greater than 100µC/cm² is applied.

	POC	Alpha	Beta	HVM-1
FAT	2012	2014	2015	2016
Technology Node	Test: 11nm HP (8nm Logic)	11nm HP (8nm Logic)	11nm HP (8nm Logic)	11nm HP (8nm Logic)
# Beams (1k = 1024)	256k	256k	256k	256k
Max. Current	1µA	1µA	1µA	1µA
Throughput	<10 cm² / h	<15 h / mask	<10 h / mask	<10 h / mask

Figure 10: Overall eMET roadmap

Starting with 2016, new generations of eMET HVM tools will be released in a 2 year cycle [6] in agreement with the ITRS roadmap.

5. SUMMARY AND OUTLOOK

The development program for IMS Nanofabrication's multi-beam mask writer called eMET is on track. A 50 keV proof-of-concept electron multi-beam mask exposure tool (eMET POC) was realized in 2011 featuring all essential lithographic properties of an eMET HVM system. First multi-beam exposure results with 262,144 beams working in parallel show the targeted resolution capability of 30nm dense lines & spaces and 24nm single lines within the full 82µm x 82µm beam array field of the system. Furthermore, 1nm high OPC-like jogs of 36nm width were clearly resolved on top of 90nm thick lines.

In Q1 2012 on-the-fly exposures on a constantly moving stage will be tested and optimized, paving the ground for a FAT in mid-2012. eMET Alpha development has already been started and will be completed in 2014. The first Beta tool will be delivered in 2015 and eMET HVM tools of the first generation (HVM-1) will become available in 2016.

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