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7-nm e-beam resist sensitivity characterization

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ABSTRACT

Over time mask makers have been driven to low sensitivity e-beam resist materials to meet lithographic patterning needs. For 7-nm logic node, resolution enhancement techniques continue to evolve bringing more complexity on mask and additional mask builds per layer. As demonstrated in literature, low sensitivity materials are needed for low line edge roughness (LER) but impact write tool through put.[2,3,4] In characterizing resist sensitivity for 7-nm, we explore more broadly what advantages and disadvantages moving to lower sensitivity resist materials brings, where LER, critical dimension uniformity, resolution, fogging, image placement, and write time results and trends are presented. In this paper, resist material performance are reported for sensitivities ranging from 20 to 130 μC/cm^2 at 50% proximity effect correction, where the exposure will be using a single beam platform. Materials examined include negative tone resist types with chemical amplification and positive tone without chemical amplification focusing on overall trends for 7-nm e-beam resist performance.

ITRS (nm)	Optical Mask		EUV Mask	
	10nm	7nm	10nm	7nm
	2015	2017	2015	2017
LER	-	-	2.6	2.1
CDU dense line	1.3	1	2.4	2
CDU contact	0.6	0.5	1.6	1.3
Resolution primary	80	80	62	49
Resolution SRAF	44	40	-	-
Image placement	2.9	2.4	2.9	2.4

Figure 1. ITRS roadmap mask making requirements, 2013 ed.[1]

TAKE A LOOK INSIDE:

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Editorial

Is it time for an integrated approach to inspection and metrology?

Jerry Cullins, HOYA Corporation, Mask Blanks Division

The most recent 2016 International Symposium on EUV Lithography in Hiroshima is now behind us and EUV in production is closer than ever. ASML is reporting increased orders and delivery of systems. They have directly invested in Zeiss's optics division which, with their acquisition of Hermes Microvision in 2016 and Cymer in 2013 shores up their supply chain. But in my opinion there is a critical piece of the puzzle that will not gate implementation of EUV but might gate its widespread adoption.

Mask inspection and metrology. We have seen investment in key scanner components. We have seen investment in research and enabling technology for mask blanks. What we have not seen is investment in actinic patterned mask inspection and metrology. Is our current suite of metrology and inspection tools sufficient for EUV?

Is metrology accurate enough to place patterns where they need to be for the advantage of EUV in overlay to really be seen? Will multi-patterning for EUV require new tools? When we need multi-patterning and pitch splitting, will the fact that EUV reticles will be chucked flat become an issue? Is our go to solution of a CD SEM going to be good enough to measure hot spots and take into account shading and other mask effects that are not as critical on optical reticles? And what impact will the planned high NA optics have?

On the inspection side, an actinic blank inspection tool has been developed, but, what about patterned masks? When will we see an actinic patterned mask inspection (APMI) tool? I suspect after the first generation of EUV products has been released and then only if defects that are not found with non-actinic inspection become an issue.

But what I do see is a unique opportunity to change the way we look at mask inspection, pattern registration, and CD metrology. An opportunity we can take advantage of to finally put together an integrated inspection and metrology solution. There is no reason that a high accuracy interferometer could not be integrated into an APMI tool's stage. Since the low thermal expansion materials used for EUV blanks are less sensitive to temperature changes than quartz, we might be able to get accurate repeatable measurements without the huge climate control chambers and perform registration metrology while inspecting the pattern. And it would allow us to chuck the reticle flat so it mirrored the conditions a reticle sees inside an EUV scanner. For CD metrology, why not integrate an aerial imaging microscope type metrology system into the inspection tool? Use the actinic light you are inspecting the pattern with to also make decisions about whether the pattern's critical dimensions are what you want them to be similar to how repairs are qualified currently.

But, all of this requires the investment of both years of development time and millions of dollars, a tall order with the loss of key consortia. I think the individual components will ultimately be needed, but I'm waiting to see when that investment is made and whether we have the foresight to try to make the individual components work together in an integrated solution.

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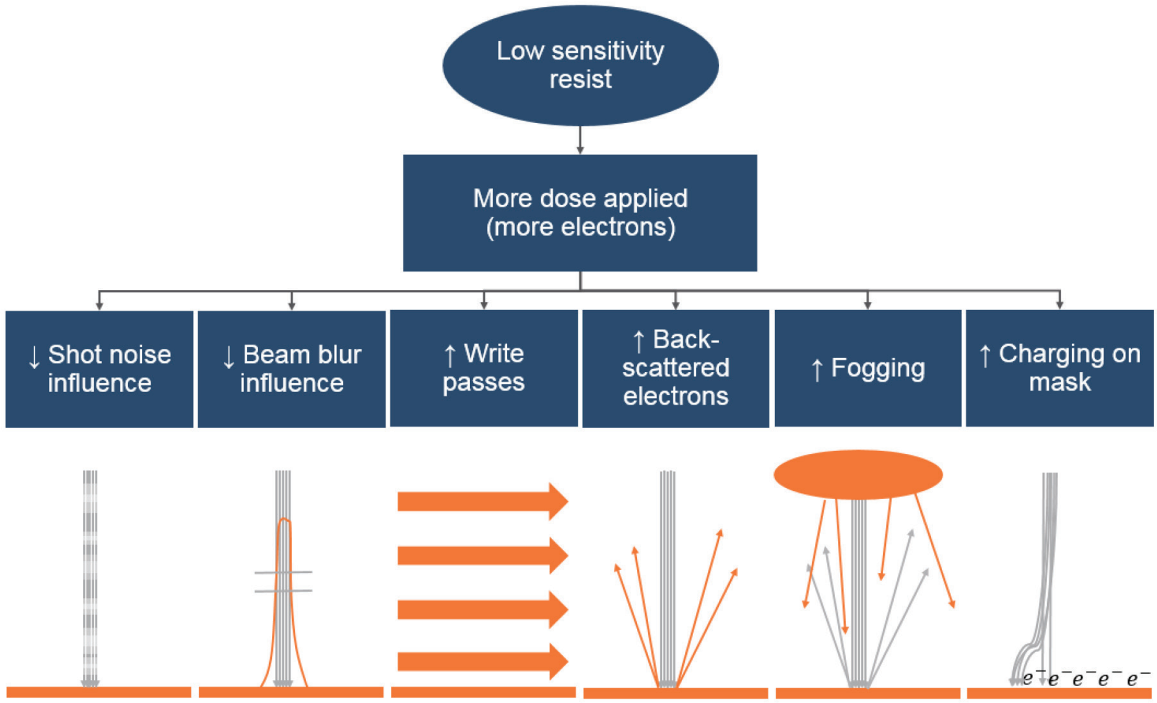

Figure 2. Factors influenced by applying a higher dose of primary electrons.

Sensitivity	1	2	3	4	5
Dose - 50% PEC ($\mu C/cm^2$)	18-20	27-30	36-40	72-80	115-130

Resist Type	A	B
Tone	N	P
Chemically amplified?	Y	N
Thickness (nm)	125	120

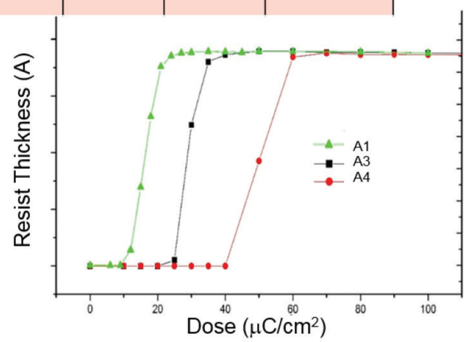

Figure 3. Resist material description by resist type and sensitivity (left) and example contrast curve of resists A1, A3, and A4 (right).

1. Introduction

As optical resolution enhancement techniques bring multi-patterning to an extreme number of masks, EUV insertion for a subset of layers becomes advantageous, where 7-nm logic node will proceed with a combined EUV and optical solutions. For both 7-nm node optical and EUV masks, critical dimension uniformity (CDU), resolution, and image placement require improvement to enable lithographic needs as described by the ITRS roadmap for masks requirements in Figure 1.[1] LER reduction is specifically needed for EUV masks as more frequencies of LER directly transfer for wafer, but also warranted for optical LER transfer and CDU improvements. Low sensitivity resist materials continue to be a piece of the solution to meet these specifications.

Inherently, the use of lower sensitivity resist materials means that a higher dose of electrons is needed to expose and provide contrast in the photoactive material. Applying a higher dose of electrons can influence many factors during print (see Figure 2). Both the shot noise and beam blur influence are reduced as more electrons are used to expose the resist, where more electrons smooth shot noise and increase the intensity for

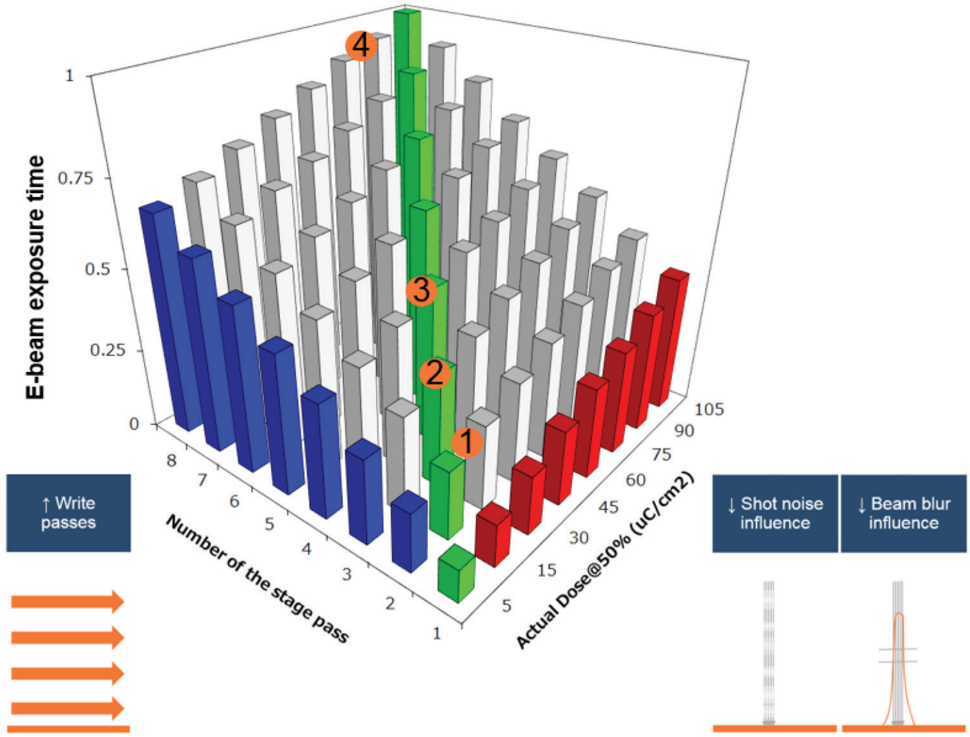

Figure 4. E-beam exposure time as a function of number of stage passes and actual dose applied.

improved contrast. More dose can also cause resist heating during print, so as increase in write passes are needed to improve write accuracy. Lastly, additional back-scattered electrons and secondary fogging electrons will increase with more charging on the mask surface. Each component has an influence on resist and final mask performance, such as line edge roughness, magnitude / complexity of e-beam corrections, resolution, write throughput, and image placement. Each parameter will be reviewed in this paper with the impact to mask performance.

2. Resist Materials

In this paper, the resist materials explored are negative tone chemically amplified (A) and positive tone non-chemically amplified (B), where the resist films are 120-125 nm thick. Resist material performance will be reported for sensitivities ranging from 20 μC/cm^2 to 130 μC/cm^2 at 50% proximity effect correction (PEC), where the exposure will be using a single beam platform. The resist materials will be referenced by resist type and sensitivity as described in Figure 3. Example contrast curves of resists A1, A3, and A4 are provided. The large sensitivity range is explored because we acknowledge that new evolving paradigms of e-beam exposure have potential to allow faster write times with low sensitivity resists, including increasing e-beam current densities, in-line write tool cleaning and multi-beam exposures.

In general for each type of e-beam exposure platform, e-beam throughput is influenced by the number of write stage passes and primary electron dose (see Figure 4). Simply increasing dose can induce localized resist heating. When

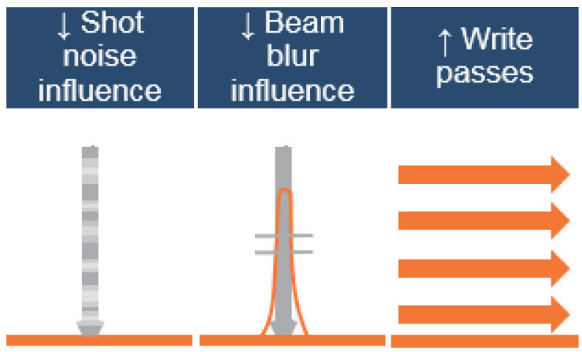

Figure 5. More electrons needed for lower sensitivity materials reduces shot noise influence, beam blur influence, and increase the number of write passes with benefit to printed feature LER.

additional write stage passes are introduced, resist heating is reduced and accuracy of write is improved at the expense of write time. As lower sensitivity materials are employed, both number of write passes and exposure dose must be increased to balance accuracy and throughput. For a single e-beam tool, the increase in print length is about 1.7 times longer when the dose and number of passes is doubled.

A similar outcome of worse write throughput with higher doses would be expected for a multi-beam mask writer and remains a factor for optimal sensitivity selection.

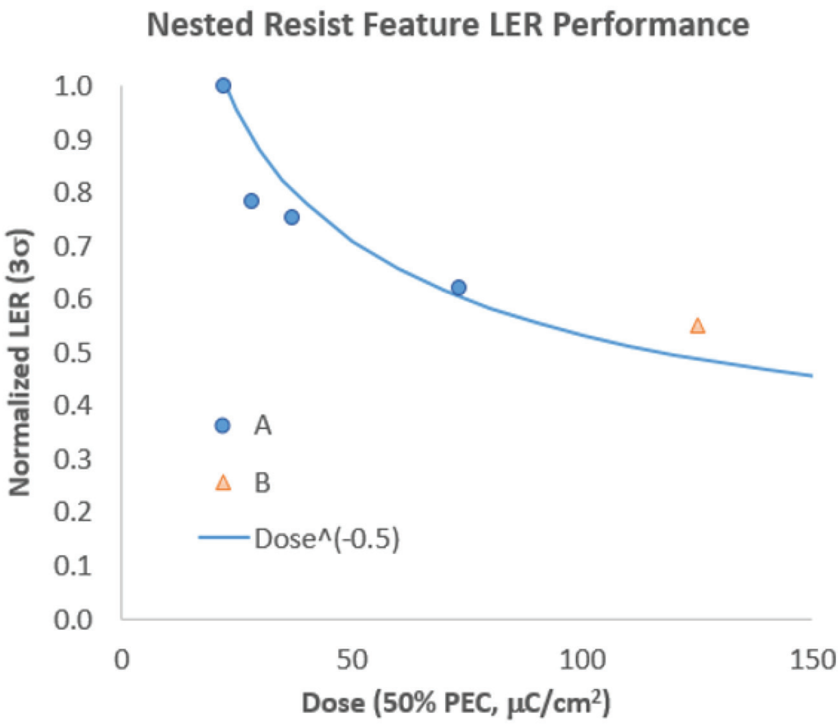

Figure 6. Line edge roughness (LER) through exposure dose of negative tone chemically activated (A) and positive tone non-chemically activated (B) resists. LER and dose values are for nested line/space structures at 50% PEC.

3. Line Edge Roughness

LER is a primary driver for using lower sensitivity resist materials. As the sensitivity of the resist film is lowered, more electrons are needed to provide contrast in the photoactive resist film. As the number of direct expose electrons increases, shot noise influence and beam blur influence are reduced which results in less low frequency roughness over a larger process window. As described in the previous section, using lower sensitivity materials also dictates the need for additional write passes. Writing the pattern in separate stage passes provides more averaging across the pattern edges, which smooths other low frequency roughness effects, such as shot stitch errors.

3.1 Line edge roughness through sensitivity

Line edge roughness was measured for resist 1:1 nested features at the 50% PEC condition (see Figure 6). Negative tone chemically amplified materials (A) followed previously reported trend with Dose^(-1/2).[2,3] The positive tone non-chemically amplified material (B) behaves at a similar LER as that predicted for chemically amplified resist A at 120 μC/cm^2. At this condition, the operating spaces of chemically amplified and non-chemically amplified begin to merge. Power spectral density (PSD) analysis also shows the lower frequency LER components from shot noise, beam blur, shot stitch, and other errors largely decreasing in power with resist sensitivity (see Figure 7). As sensitivity continues to move to higher doses, more material options become available to meet the low LER demands. Resolution, etch durability, and process control are additional factors that would have to be evaluated to assess whether chemically amplified or not is better suited for the application.

3.2 Critical dimension uniformity random component

Critical dimension uniformity (CDU) of features across the mask can be influenced by line edge roughness and thus by resist sensitivity.[5] As reported in previous work, depending on the feature type and the region of interest measured, the contribution of LER on CDU can vary.[4,6] We chose to measure 200 nm isolated line and 250 nm nested contact features across the mask to measure the CDU response through sensitivity. Because process can also influence CDU by leaving a systematic character, we evaluated the random component of CDU, where the total and random CDU are related by equation 1 and an example is provided in Figure 8. The random CDU of resist type A through sensitivity is plotted in Figure 9. Resist CDU random improves with lower sensitivity for both isolated line and contact measurements similar to the trends in LER in section 3a. Contact type measurement region of interest is smaller than line type resulting in LER contributing more to the contact CDU. For that reason, contact measurements at 250 nm feature size continue to improve in CDU out to lower sensitivity than line measurements. Depending on the desired feature type and size, sensitivity may need to be optimized to meet those needs. Line type features may not benefit from a CDU perspective as much as contact types.

$$CDU_{tot} = \sqrt{\left(CDU_{sys}{}^2 + CDU_{ran}{}^2 + CDU_{metro}{}^2\right)}$$

Equation 1. Total CDU relationship with systematic and random components.

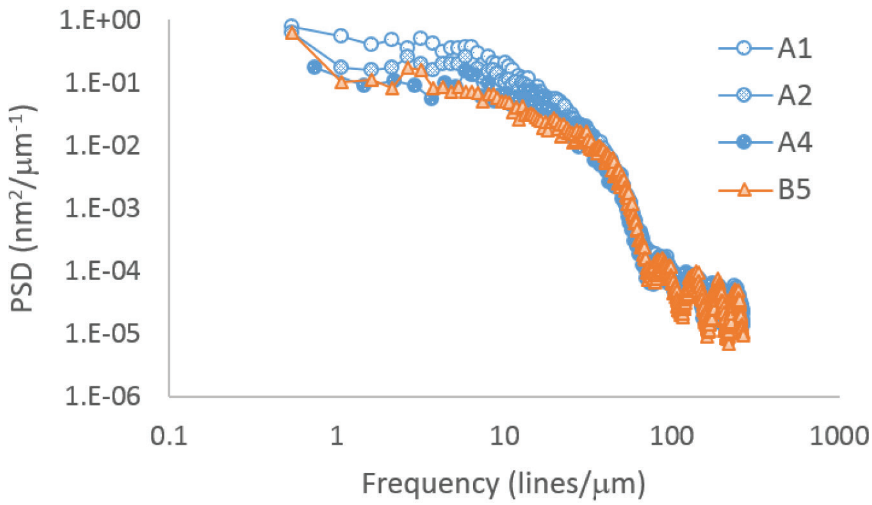

Figure 7. Power spectral density (PSD) curves of negative tone chemically activated (A) and positive tone nonchemically activated (B) resists. Features analyzed are nested line/space structures.

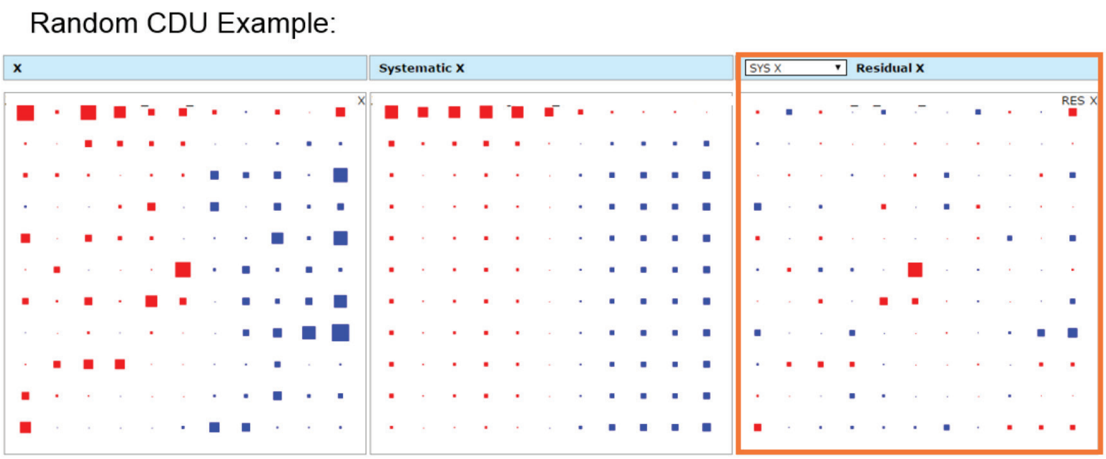

Figure 8. Example of CDU total (left), CDU systematic (middle), and CDU random (right).

4. Fogging

Direct expose electron energy and fogging electrons increase for lower sensitivity resist materials but the exposure threshold of the resist is proportionately increasing. Theoretically, the overall exposure ratio remains constant, and the applied fogging correction percent is constant through sensitivity. We compared resist A1, A3, and A4 fogging behavior in Figure 10. As shown in the left, fogging effects were measured from 0% to a higher density ranging from 10-90%. The optimal fogging correction was generated assuming a constant process threshold. The result plotted on the right chart shows an error in the optimal fogging corrections, where application of the appropriate process threshold and process optimization would result in constant fogging correction through sensitivity.

5. Resolution

Resist resolution was evaluated in terms of minimal resist feature size and manufacturable resolution on the final mask. In Figure 11, the minimal resist feature size for isolated line, nested line, and isolated space patterns is shown for resists A3 and A4. The profile performance is qualitativily similar between the two materials and the minimum size is similar. On the other hand, lower sensitivity resists have been shown previously in literature to improve manufacturable resolution with better pattern fidelity, where subresolution assist features (SRAFs) are inspected in final mask absorber pattern with 193 nm inspection (see Figure 12).[7] The top row are opaque or absorber lines and the bottom row are spaces or clear features. Features outside of the mask defect criteria would be highlighted as a defect with a 193 nm final mask inspection. For example, if the inspection criteria is 35 nm, the inspection would begin to stop sooner on resist A1 clear SRAFs because the length of

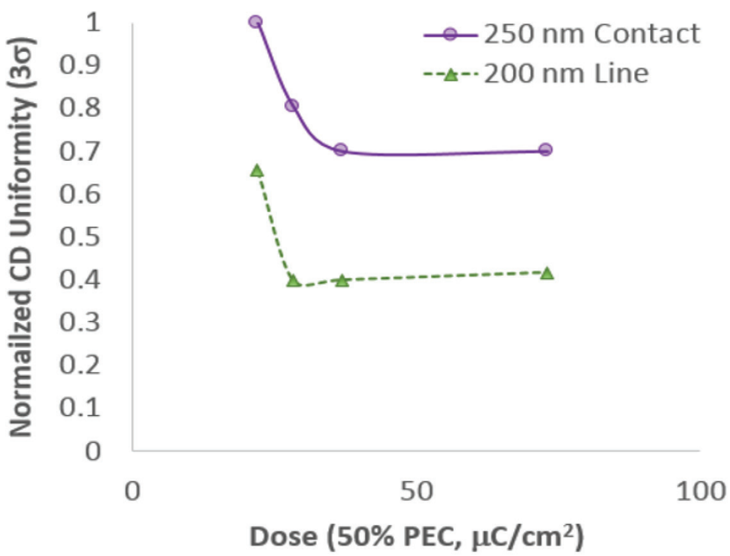

Figure 9. CDU random component for resist type A through dose for isolated line and nested contact features.

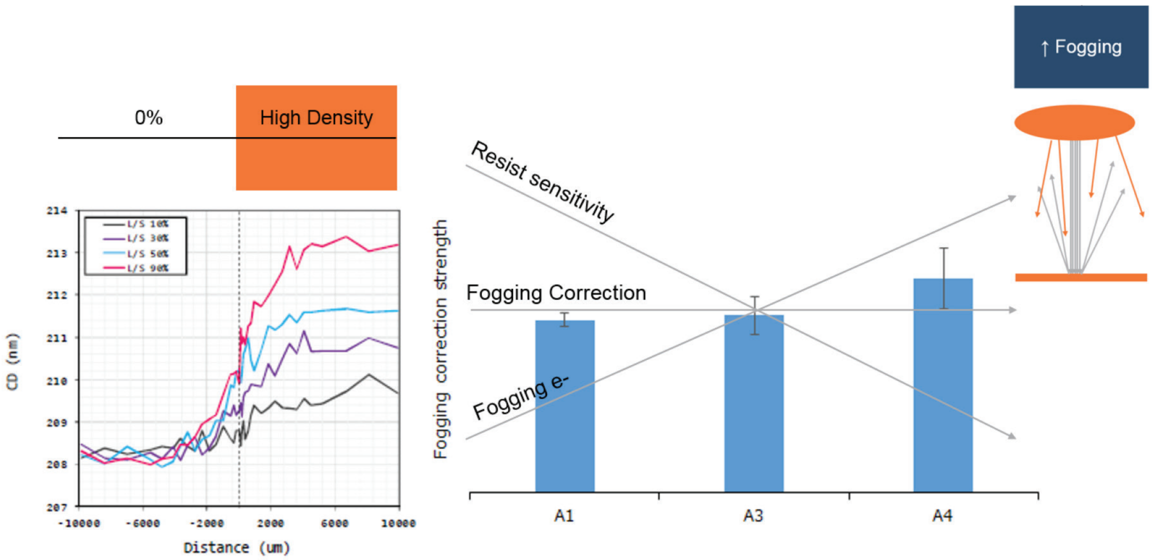

Figure 10. Example fogging behavior through density (left) and fogging correction strength through resist sensitivity (right) for resist A1, A3, and A4.

the SRAF is too short and exceeding the defect criteria. The main driver has been attributed to improvements in line end shortening and pattern fidelity. With additional electrons at exposure, the beam blur contrast is improved and shot noise reduced to enhance the line end and overall pattern fidelity.

In this paper, we measured the line width and length changes for opaque absorber SRAFs created with different sensitivity resists to explore changes in pattern fidelity and quantify the effect. In Figure 13, resists A1, A3, and A4 SRAF sizes relative to design are graphed for both feature width and length. The width of the opaque SRAFs have minimal improvement through sensitivity, while the length is significantly closer to target at lower sensitivity. The result demonstrates an example of line end shortening or pattern fidelity improvement through sensitivity.

6. Image Placement

As more direct dose is applied for lower sensitivity resist materials, charging on the mask surface will increase. Mask surface charging can worsening the image placement performance of the patterns written by ebeam as the electrons are repelled out of desired position, but is dependent on the e-beam configuration. In Figure 13, we captured image placement data through 9 pattern densities across mask written on the same single e-

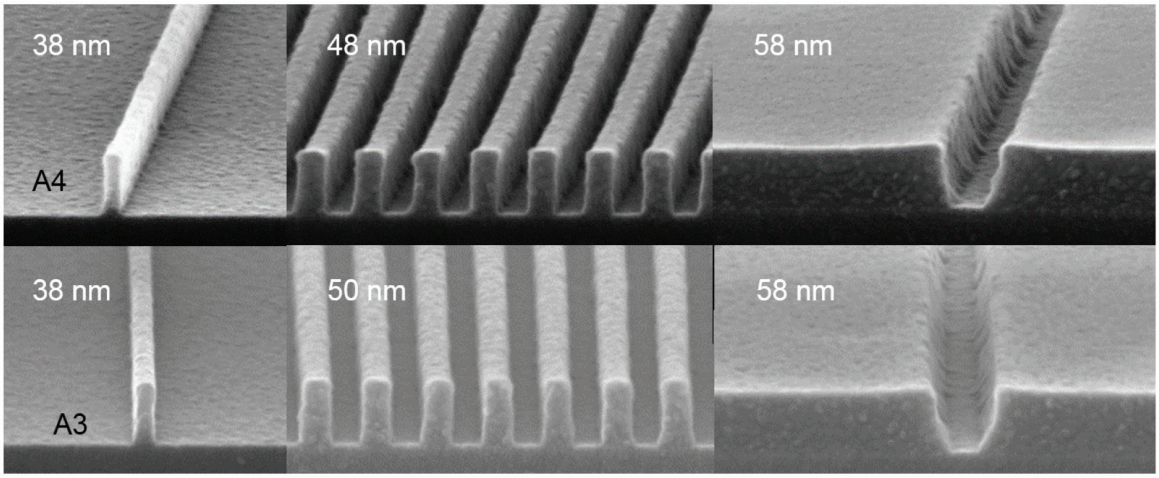

Figure 11. Resist cross-section images of resist A4 (top) and A3 (bottom).

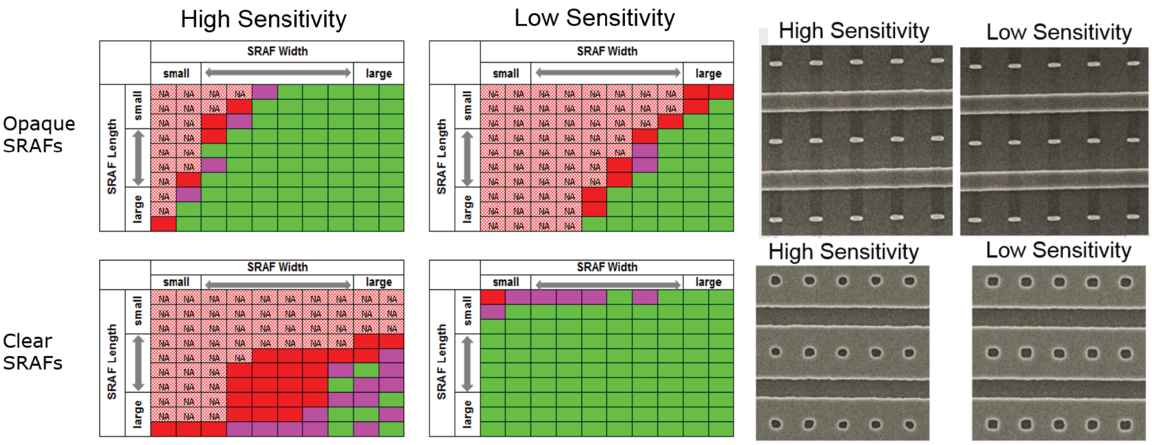

Figure 12. Resist sensitivity improves manufacturable resolution with pattern fidelity.[7]

beam mask write tool to measure the error in image placement as a function of density. Lower sensitivity resist A3 has worse image placement error than resist A1 as a result of increased charging across the mask with higher doses for exposure. The errors are e-beam mask write tool structure specific and correctable, but could result in additional correction residual error.

7. Summary and Conclusions

In summary, lower sensitivity resist materials were successfully evaluated from 20 to 130 μC/cm^2 at 50% PEC dose for 7-nm node (see Figure 15). Sensitivity continues to provide a knob for LER through 72 μC/cm^2 and CDU through 40 μC/cm^2 enabling future node development but with a cost to write throughput. Non-chemically activated resist materials and chemically amplified materials begin to converge in same LER / sensitivity space at 120 μC/cm^2, meaning more material options are available for mask makers at the convergent space. Fogging effects are theoretically balanced with resist sensitivity but process threshold and process optimization are needed to obtain manageable correction errors through density. Additional mask charging was measured driving more image placement corrections but result will be specific to e-beam structure. Lastly, line end shortening and thus manufacturable resolution improvements through sensitivity were measured on SRAF structures with lower sensitivity resist.

In conclusion, 7-nm logic node mask fabrication will continue moving to lower sensitivity to meet CDU and resolution requirements for optical and EUV applications (see Figure 16). For EUV, more frequencies of LER directly transferring to wafer from EUV masks, which provides another benefit low sensitivity materials can provide. For optical masks, throughput is concerning for layers with multi-patterning resolution enhancement techniques because more masks must be built per layer, where lower sensitivity becomes a hindrance for write throughput. For these reasons, EUV masks will move more quickly than optical to lower sensitivity. Resist sensitivity must be considered for both lithographic requirements and manufacturability, and resist sensitivity was selected for the most balanced solution.

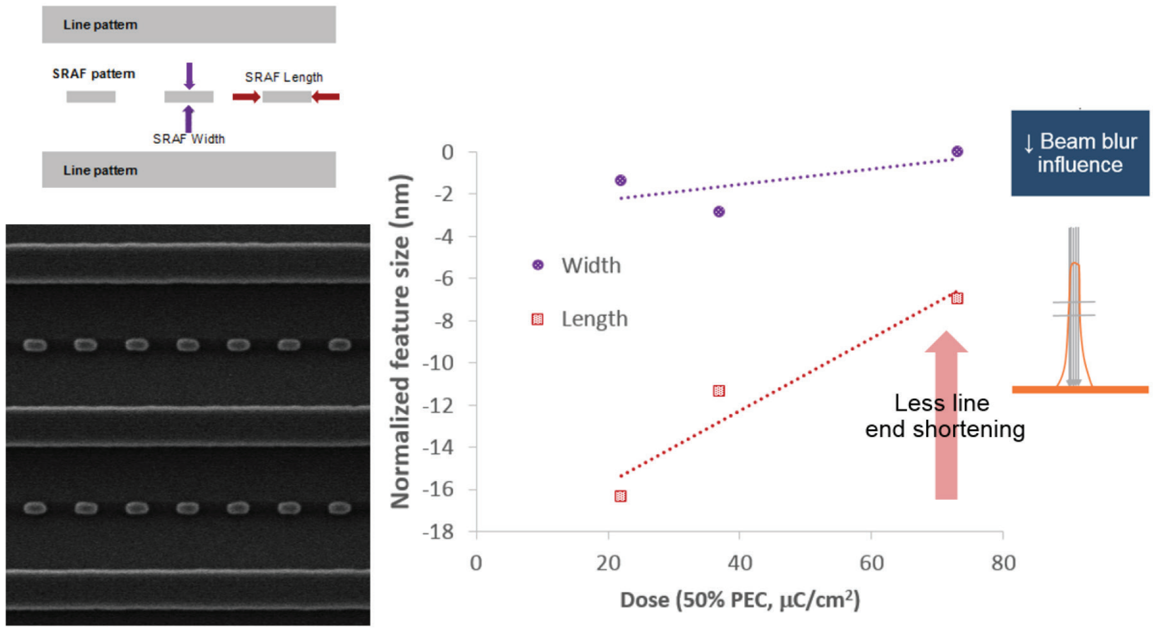

Figure 13. SRAF width and length measured on final absorber mask.

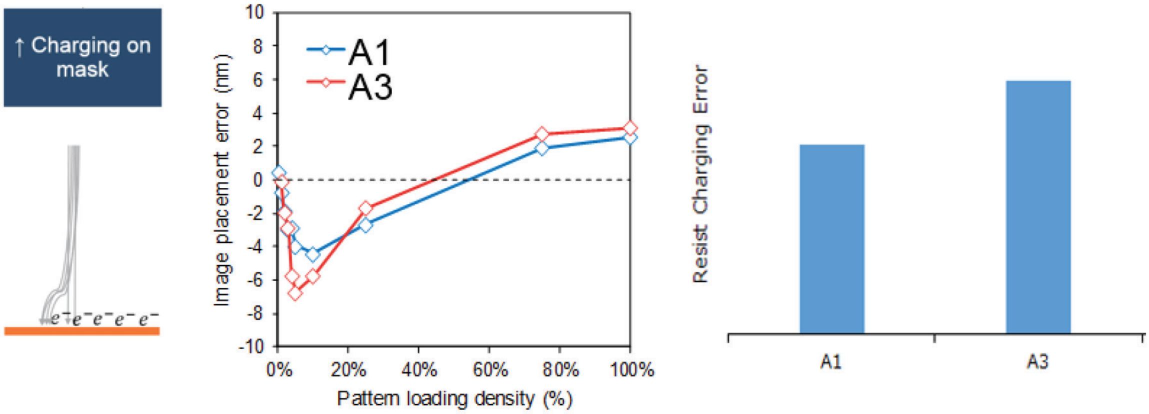

Figure 14. Image placement error through pattern density for resists A1 and A3.

8. Acknowledgements

The authors would like to acknowledge the materials, print, process, metrology, and inspection teams at Toppan and GLOBALFOUNDRIES for their efforts to explore a broad range of resist sensitivities.

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+	=> improvement
=	=> no impact
-	=> degradation

	Lower sensitivity
LER	+
CDU_{random}	+
Write throughput	-
Fogging	=
Image placement	- Tool dependent
Resolution	+

Figure 15. Summary of low sensitivity resist performance.

Low sensitivity resist solution
Low sensitivity resist hindrance

	Optical Mask	EUV Mask
LER		
CDU		
Resolution primary		
Resolution SRAF		
Image Placement	E-beam write tool dependent	
Multi-patterning		

Figure 16. Low sensitivity resist solutions and hindrances to meeting 7-nm optical and EUV mask build Targets.

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Industry Briefs

Third Quarter 2016 Worldwide Semiconductor Equipment Billings Reach $11B, Reports SEMI

Solid State Technology, December 2016

SEMI, the global industry association representing more than 2,000 companies in the electronics manufacturing supply chain, today reported that worldwide semiconductor manufacturing equipment billings reached US$11.0 billion in the third quarter of 2016. The billings figure is 5 percent higher than the second quarter of 2016 and 14 percent higher than the same quarter a year ago. The data is gathered jointly with the Semiconductor Equipment Association of Japan (SEAJ) from over 95 global equipment companies that provide data on a monthly basis.

Worldwide semiconductor equipment bookings were $11.3 billion in the third quarter of 2016. The figure is 30 percent higher than the same quarter a year ago and 5 percent lower than the bookings figure for the second quarter of 2016.

http://electroiq.com/blog/2016/12/third-quarter-2016-worldwide-semiconductor-equipment-billings-reach-11b-reports-semi/

IEDM Highlights: TSMC, IBM Detail 7-nm Work, Upbeat on EUV Lithography

Rick Merritt, *EETimes*

Like presents under a Christmas tree, separate papers on 7-nm process technology from TSMC and IBM energized a packed ballroom on the first day of the International Electron Devices Meeting (IEDM). They showed results nudging forward both Moore's law and extreme ultraviolet lithography (EUV).

TSMC reported the smallest 6T SRAM to date in a process that it aims to put into risk production by April. IBM described the smallest FinFET made to date in a research device made with EUV. Conference organizers highlighted the papers in October as late-news headliners for the event. Nevertheless, both companies surprised some attendees with more upbeat results than expected.

IBM showed FinFETs with contacted poly pitch of 44/48 nm, a metallization pitch of 36 nm, and a fin pitch of 27 nm. One device included a source-to-drain contact opening of about 10 nm and a gate length of about 15 nm. TSMC described a 256-Mbit SRAM test chip with the cell density of 0.027 mm2 with full read/write capabilities down to 0.5 V. The node should provide up to a 40% speed gain, a 65% power reduction, and a 3.3x routed gate density increase compared to TSMC's 16FF+ process now in volume production, said Michael Shien-Yang Wu, a senior director of N7 development at TSMC.

Although it was not part of his formal paper, Wu also commented on work using the 7-nm process to validate EUV. The next generation lithography provided "comparable patterning fidelity" and "comparable yield" to the conventional immersion steppers it will use in the commercial 7-nm process next year.

The EUV systems from ASML are still in a pre-production release. TSMC already announced its plans to start using EUV in its 5-nm node. But Wu declined to give details of how the 7-nm process compares to its 10-nm node or nodes from rivals such as Samsung. He also declined to give aspect ratios of his 7-nm FinFETs, details about a "novel strain technology" the node uses or figures for yields of a test chip that included a GPU and ARM Cortex A-72 core, except that they were in "double digits."

Wu did say TSMC had reached 50% yields on its 7nm SRAM. That suggests it is on a path to have volume manufacturing in the process by late 2017, Kanter said.

http://www.eetimes.com/document.asp?doc_id=1330940

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