EUV Resists: Illuminating the challenges

Patrick Naulleau, Chris Anderson, and Simi George

Center for X-ray Optics
Lawrence Berkeley National Laboratory
Berkeley, CA, USA

As extreme ultraviolet (EUV) lithography enters the commercialization phase with potential introduction at the 3x nm half-pitch node in 2013, the attention of advanced EUV resist research has turned to addressing patterning at 16-nm half pitch and below. Whereas line-edge roughness is the primary concern at 2x half pitch and larger, research at the 16-nm half pitch level is uncovering broader.

Keyword: photoresist, extreme ultraviolet, shot noise, line-edge roughness

1. Introduction

Extreme ultraviolet (EUV) lithography has now entered the pilot line phase and introduction into manufacturing is possible as early as 2013 at 3x-nm half pitch. The role of advanced resist research using microfield exposure tools has thus primarily moved on to 16-nm half pitch and below. Despite current microfield exposure tools [1,2] being limited to numerical apertures of 0.3, resolution enhancement techniques can be used to address preliminary 16-nm half pitch research.

At half pitches of 2x-nm and larger, line-edge roughness (LER) remains the most significant issue facing EUV resists, here we examine a series of potential sources of this LER. Moving to 16-nm half pitch, however, resolution becomes the dominant concern. We compare the relative performance of leading commercial chemically amplified resists to an experimental inorganic resist and address the question of current tool limitations.

2. Potential sources of LER

2.1. Current status

While various chemically amplified (CA) materials achieving 22-nm resolution have been demonstrated, these materials all have LER values that are quite far from the goal of 8% of critical dimension. Table 1 shows sensitivity and LER performance from 5 champion CA resist exposed on the SEMATECH Berkeley MET [1] using dipole illumination.

Table 1. CA resist performance at 22-nm half pitch.

Resist	Sensitivity (mJ/cm^2)	LER (nm)
A	20	2.7
B	13	4.2
C	15	2.9
D	15	3.7
E	17	3.8

2.2. Mask contribution to LER

We note that the LER data in Table 1 has been corrected for mask contributions [3-6]. Despite the recently observed importance of mask contributions, the relative magnitude compared to the resist LER remains small. The primary mask contributors to LER have been shown to come from LER on the mask itself as well as surface roughness in the reflective multilayer. The contributors can be characterized and their effects on image-plane LER modeled [3,6]. Figure 1 shows the modeled image plane LER due to the mask alone assuming the imaging and mask characteristics of the SEMATECH Berkeley MET as configured to obtain the results shown in Table 1. Analysis of these lines yields an LER of 1.1 nm.

Figure 1. Modeled mask-induced image-plan LER for imaging and mask parameters matching those used in Table 1. The resulting LER is 1.1 nm.

Although the mask-induced LER seems rather large, noting that it is most certainly uncorrelated from the resist LER, its contribution to the total LER will be in quadrature to the resist LER. For example, the total experimental LER that had been measured for Resist A was 2.9 nm. Given that the mask added 1.1 nm in quadrature, the resist contribution can be found as sqrt(2.9^2-1.1^2), or 2.7 nm. Thus, the 1.1-nm mask contribution only has a 0.2 nm impact on the final LER.

2.3. Photon Noise Limit

A long standing concern for EUV has been photon noise owing to the high photon energy and dearth of source power. In this section we consider the potential role of photon noise in the data shown in Table 1. To study this problem, a variety of shot noise models have been developed [7-10]. For the results presented below, we use the numeric implementation [8] of the analytic stochastic model first described in Ref. 7.

Figure 2 shows the modeled photons noise limited LER as a function of sensitivity along with the data from Table 1. The model assumes a resist blur of 10 nm, which can be shown to correspond to the near ideal blur in terms of LER for 22-nm half pitch features. Also assumed is a resist absorptivity of 0.0042 nm^{-1}, a thickness of 50 nm, a quantum efficiency of 2, a PAG concentration of 0.1 nm^{-3}, a deprotection rate of 1.5 nm^3/sec, and an acid/base annihilation rate of 1.5 nm^3/sec. These values were chosen based on typical EUV CAR parameters. The resist sensitivity in the model was changed by varying the base loading while keeping all other parameters fixed. We note that the base-loading method for varying sensitivity is often used in experimental studies as well [11-13]. The modeling results show that resist improvement relative to the photon noise limit is still possible.

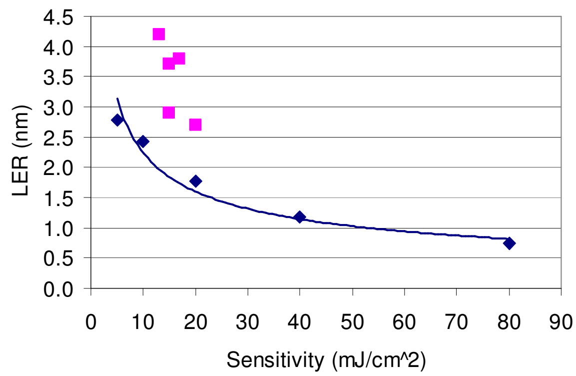

Figure 2. Modeled shot noise LER (diamonds) and power law fit (solid line) along with measured resist LERs (squares).

Table 2. Prediction of material limited LER for data from Table 1 assuming photon noise LER from Figure 2.

Resist	Sens. (mJ/cm²)	Meas. LER (nm)	Phot. LER (nm)	Mat. LER (nm)
A	20	2.7	1.65	2.1
B	13	4.2	2.05	3.7
C	15	2.9	1.91	2.2
D	15	3.7	1.91	3.2
E	17	3.8	1.79	3.4

Given the predicted photon noise limited LER, it is now possible to estimate the residual material/process limited LER, again assuming the two LER terms to be uncorrelated. Table 2 shows the results with the best case being 2.1 nm. These results suggest both that photon noise limits are a concern and need to be addressed with increased absorptivity and also that other material properties remain the dominant effect.

2.4. Interface effects

The use of underlayers to enhance the imaging properties of EUV resist is now an area of active exploration [14-16] for both minimizing pattern collapse and enhancing sensitivity. Looking at the details of the resist to substrate interface [17], has also suggested that interface properties may be playing a significant role in LER and thus that underlayers might be able to mitigate these effects. Figure 2 shows an off-axis view of features in a leading EUV resist demonstrating a significant increase in LER at the resist to substrate interface and large anisotropy in the spatial scaling characteristics of the LER.

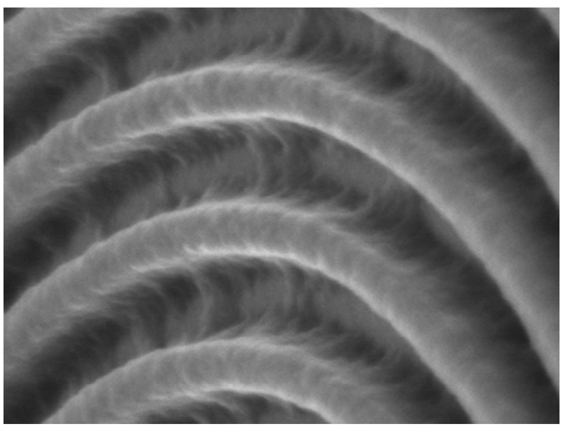

Figure 3. SEM image showing highly anisotropric nature of 3D LER.

The better quantify this effect and gain insight into the source, it is useful to characterize the LER as a function of height through the resist. Such a measurement can be approximated from a top-down SEM image by changing the analysis threshold used to detect the line edge position. The threshold setting can then be approximately related back to height along the sidewall.

Figure 4 shows such data for 100-nm lines and spaces printed in 200-nm thick resist. Near the top of the resist (180-nm in Fig. 4) we see little correlation as a function of height as evidenced by the evolution of the line edge data going from 180-nm height to heights of 160 and 140 nm. As we go below 140-nm, however, we see the roughness magnitude and correlation increase with roughness features being clearly replicated over height ranges that are larger then the correlation along the length of the line. The results suggest the potentially important role of the resist to substrate interface in the definition of the LER. Noting that current resist formulations all fall in the sub-60-nm range, the importance of this issue is evident.

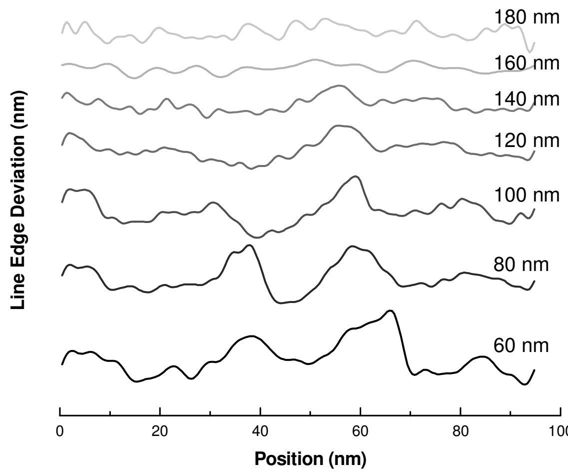

Figure 4. Line edge position data at various heights along the sidewall demonstrating increased roughness correlation as the surface resist/substrate interface is approached.

2.5. Out-of-band

Another significant area of concern for EUV resists is the impact of out-of-band (OOB) UV radiation. Source power constraints make spectral filtering a concern, putting burden on the resist to tolerate non-zero levels of UV radiation. Controlled experiments into the effect of OOB radiation can be achieved through a double exposure process. This has been implemented at the SEMATECH Berkeley Microcfield Exposure Tool which uses a spectrally pure synchrotron light source for the EUV and has capabilities to flood expose the same wafer with UV light generated by a laser-driven light source.

First order analysis of the OOB effect would predict that OOB exposure acts much like flare and simply reduces the aerial image contrast proportionally to the relative amount of OOB light and the relative sensitivity of the material to the OOB light. Assuming the LER to be inversely proportional to aerial image contrast, one would thus expect LER to increase with increased OOB exposure. Figure 5 shows preliminary results from OOB testing of a variety of materials showing that this first-order view may not be adequate. The results show four different materials printed with EUV only and with 10% relative 193-nm exposure in addition to the EUV. The results indicate that the change in LER is not well correlated to the OOB sensitivity of the material as measured by the change in dose to size.

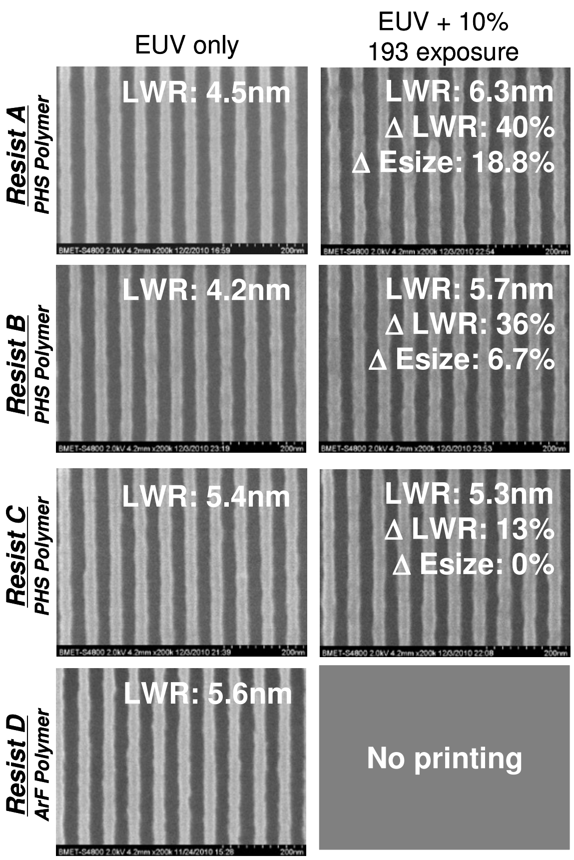

Figure 5. Effect of additional UV exposure on EUV printing.

The results show that LER can indeed be degraded by OOB radiation and that simple material sensitivity to OOB is not an adequate metric for resist imaging performance. It should be pointed out, however, that these results do not indicate that OOB could a cause of the LER limits seen in Table 2 since those tests were all performed on the SEMATECH Berkeley MET with no OOB present. We also note that the setup used in these tests led to significant delays between the EUV and OOB exposures and it is not yet clear what impact that might or might not have on the results.

3. Resolution performance

Owing to the significant challenges in developing high power EUV sources, the focus of EUV resist development has understandably been on CA resists. Despite the intrinsic diffusion limitations such material arguably suffer from, tremendous resolution progress has been made since the SEMATECH Berkeley MET was first brought online in early 2004 (Fig. 6). At that time, the best EUV resists were performing at a level of approximately 45 nm. By 2008, we had seen a reduction by more than a factor of two with moderate losses in sensitivity. As demonstrated in Fig. 6, however, progress in the ultimate resolution of CA resists stalled in 2008 with arguably no progress since that time.

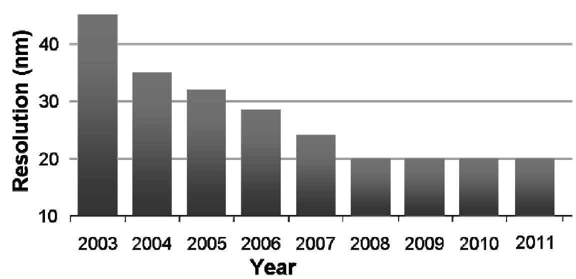

Figure 6. Ultimate resolution in EUV CA resist from 2003 through June 2011.

These results raise the question of tool limitations. Although the NA and illumination capabilities of the SEMATECH Berkeley MET should support significantly better resolution, the tool does not include aerial image monitoring capabilities that could be used to verify the expected resolution. Thus the only way to prove that the tool is not the limitation, is to find a resist that supports higher resolution than the CA materials shown in Fig. 6. To address this concern, a non-CA imageable hardmask material provided by Inpria Corporation has been employed [18].

Figure 7 shows imaging results obtained using this material under dipole illumination as well as the predicted aerial image contrast. Excellent agreement between the predicted contrast and imaging performance is found indicating that the tool is indeed operating as expected and thus validating the results in Fig. 6 as being resist limits as opposed to a tool limit.

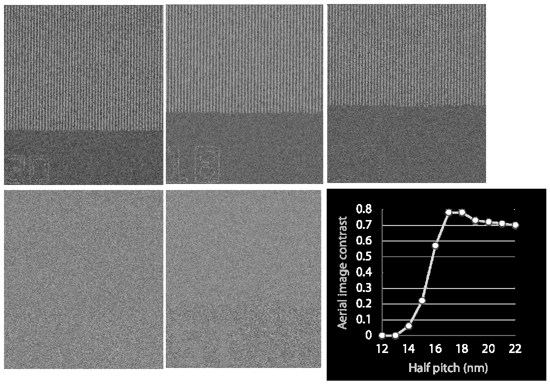

Figure 7. Printing in non-CA imageable harmask resist compared to predicted aerial image performance.

In order to test the ultimate performance of the non-CA resist in Fig. 7, an even more aggressive illumination is used compared to the 18-nm optimized dipole used in Fig. 7. To simultaneously address any mask limitations that might also be playing a role, the pseudo phase shift mask technique [1] is employed. Figure 8 shows printing performance in the Inpria material using this illumination demonstrating resolution down to 15 nm.

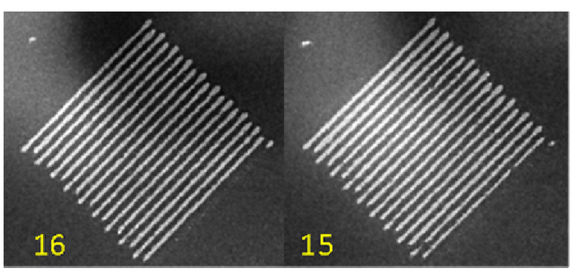

Figure 8. 16 and 15 nm half pitch lines in Inpria imageable hardmask material.

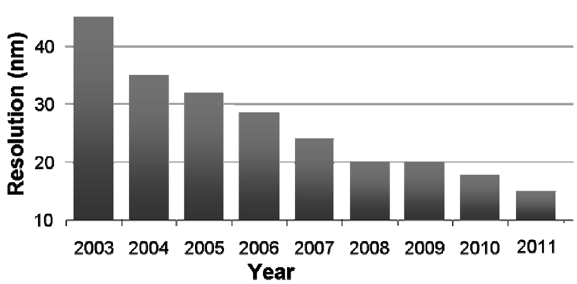

Figure 9. Ultimate resolution in EUV including non-CA resist from 2003 through June 2011.

Expanding the plot from Fig. 6 to include non-CA resists tested on the SEMATECH Berkeley MET, a less pessimistic picture of the progress arises as shown in Fig. 9. It is important to note that these resolution gains have not come without a tradeoff. The sensitivities for the highest resolution materials in 2010 and 2011 were 40 and 70 mJ/cm^2, respectively.

4. Resolution requirements

In addition to the first order effect on resolution, resist blur plays an important role in LER [19]. From the stochastic noise perspective, it can be shown that the ideal blur is approximately equal to one half the target half pitch. Resist blur, however, also affects the mask error enhancement factor (MEEF) and thus how mask LER couples to resist LER. Figure 10 shows modeled mask-induced LWR in resist as a function of blur as well as the computed MEEF. The mask-plane line-width roughness (LWR) is 3.2 nm and a magnification of 4 is assumed. The results indicate the ideal blur from this perspective to be approximately 0.25 times the half pitch, considerably smaller than the stochastic optimal of approximately 0.5 times the half pitch. Performing similar analysis for mask contact size variations yields essentially the same results.

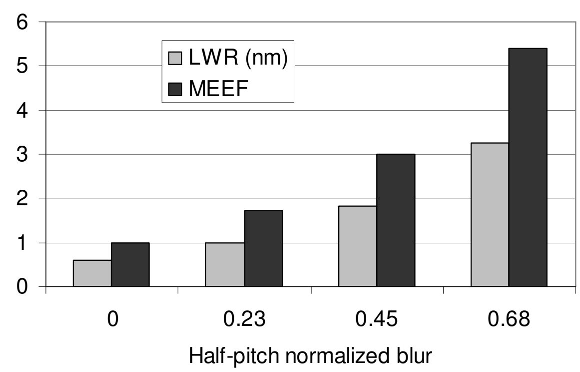

Figure 10. Modeled mask-induced LWR in resist and computed MEEF versus resist blur. Mask-plane LWR is 3.2 nm, magnification is 4x.

5. Summary

At 22-nm CD, LER remains the largest challenge. Although photon noise is an issue of concern given current resist absorptivity levels, the effect remains small compared to material effects estimated by removing model-predicted photon noise effects from the measured LER in quadrature.

In terms of resolution, champion EUV resist performance from a conventional projection lithography system has been pushed to below 16 nm. This, however, was achieved in a non-CA material requiring an exposure dose of 70mJ/cm^2.

Considering only CA materials, the ultimate resolution progress has arguably stalled at approximately 20-22-nm half pitch for the past three years.

Looking at future resist blur requirements from the perspective of minimizing mask-induced LER yields requirements on the order of 0.25 times the half pitch, which for the 16-nm half-pitch node corresponds to 4 nm.

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References

1. P. Naulleau, et al., "The SEMATECH Berkeley MET pushing EUV development beyond 22-nm half pitch," Proc. SPIE **7636**, 76361J-1 (2010).
2. Y. Tanaka, K. Matsunaga, S. Magoshi, S. Shirai, K. Tawarayama, and H. Tanaka, "Resolution capability of SFET with slit and dipole illumination," Proc. SPIE. **7969**, 79690Q (2011).
3. P. Naulleau and G. Gallatin, "The line-edge roughness transfer function and its application to determining mask effects in EUV resist characterization," Appl. Opt. **42**, 3390-3397 (2003).
4. N. Beaudry, T. Milster, "Effects of mask roughness and condenser scattering in EUVL systems," Proc. SPIE. **3676**, 653-662 (1999).
5. P. Naulleau, "The relevance of mask-roughness-induced printed line-edge roughness in recent and future EUV lithography tests," Appl. Opt. **43,** 4025-4032 (2004).
6. P. Naulleau, D. Niakoula, G. Zhang, "System-level line-edge roughness limits in extreme ultraviolet lithography," J. Vac. Sci. & Technol. B **26**, 1289-1293 (2008).
7. G. Gallatin, "Resist blur and line edge roughness," Proc. SPIE **5754**, 38-52 (2005).
8. P. Naulleau and G. Gallatin, "The effect of resist on the transfer of line-edge roughness spatial metrics from mask to wafer," J. Vac. Sci. Technol. B, *to be published* (2011).
9. S. Robertson, J. Biafore, M. Smith , M. Reilly, J. Wandell, "Predictive linewidth roughness and CDU simulation using a calibrated physical stochastic resist model," Proc. SPIE **7639**, 763934 (2010).
10. C. A. Mack, "Stochastic approach to modeling photoresist development", J. Vac. Sci. Technol. B **27**, 1122-1128 (2009).
11. R. Brainard, P. Trefonas, J. Lammers, C. Cutler, J. Mackevich, A. Trefonas, S. Robertson, "Shot noise, LER, and quantum efficiency of EUV photoresists," Proc. SPIE **5374**, 74-85 (2004)
12. C. Szamanda, et. al., "Measuring acid generation efficiency in chemically amplified resists with all three beams," J. Vac. Sci. Technol. B **17**, 3356-3361 (1999);
13. A. Pawlowkski, A. Acheta, H. Levinson, T. Michaelson, A. Jamieson, Y. Nishimura, C. Willson, "Line edge roughness and intrinsic bias for two methacrylate polymer resist systems", J. Microlith. Microfab. Microsys. **5**, 023001 (2006).
14. H. Xua, J. Blackwell, T. Younkin, K. Min, "Underlayer designs to enhance the performance of EUV resists," Proc. SPIE **7273**, 72731J (2009).
15. D. Guerrero, C. Beaman, R. Sakamoto, T. Endo, B. Ho, "Organic underlayers for EUV lithography," Journal of Photopolymer Science and Technology **21**, 541-455 (2008).
16. H. Yao, Z. Bogusz, J. Shan, J. Cho, S. Mullen, G. Lin, M. Neisser "EUV Underlayer Materials for 22nm HP and Beyond," Proc. SPIE **7972**, (2011)
17. S. George, P. Naulleau, A. Krishnamoorthy, Z. Wu, E. Rutter, J. Kennedy, S. Xie, K. Flanigan, T. Wallow, "Characterization of line-edge roughness (LER) propagation from resists: underlayer interfaces in ultrathin resist films," P roc. SPIE **7636**, 763605 (2010)
18. J. Stowers, A. Telecky, D. Keszler, A. Grenville, P. Naulleau, C. Anderson, "Directly patterned inorganic hardmask for EUV lithography," Proc. SPIE 7969, *to be published* (2011).
19. D. Van Steenwinckel, J. Lammers, T. Koehler, R. Brainard, P. Trefonas, "Resist effects at small pitches," J. Vac. Sci. Technol. B **24**, 316-320 (2006).