Toward 10 nm half-pitch in extreme ultraviolet lithography: results on resist screening and pattern collapse mitigation techniques

Tero S. Kulmala,* Michaela Vockenhuber, Elizabeth Buitrago, Roberto Fallica, and Yasin Ekinci

Paul Scherrer Institute, Laboratory for Micro and Nanotechnology, 5232 Villigen PSI, Switzerland

Abstract. Extreme ultraviolet (EUV) lithography is considered to be the most promising option to continue with the downscaling of integrated circuits in high-volume manufacturing. One of the main challenges, however, is the development of EUV resists that fulfill the strict sensitivity, resolution, and line-edge roughness specifications of future nodes. Here, we present our EUV resist screening results of a wide range of EUV resists in their developmental phase from our collaborators from around the world. Furthermore, we have carried out extensive experiments to improve the processing parameters of the resists as well as to identify the optimal wafer pretreatment methods in order to optimize the adhesion of the resist to the substrate. We show that even though significant improvements in performance of chemically amplified resists have been achieved, pattern collapse is still the major process-limiting factor as the resolution decreases below 14 nm half-pitch. © 2015 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JMM.14.3.033507](https://doi.org/10.1117/1.JMM.14.3.033507)]

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1 Introduction

The 2013 International Technology Roadmap for Semiconductors¹ holds extreme ultraviolet lithography (EUVL) as the foremost technology candidate to continue increasing the density of semiconductor devices in high-volume manufacturing (HVM). EUVL with 13.5 nm wavelength enables patterning down to single-digit half-pitch (HP) feature sizes.²

The two major challenges hindering the industrial introduction of EUVL are the low power of EUV sources,¹ making the throughput of the lithography process insufficient for HVM, and the development of photoresist materials that match the strict performance requirements set by the industry.¹ From the resists, a combination of high resolution (HP), high sensitivity (dose, D), and low line-edge roughness (LER) are necessary. These parameters are tightly bound to the chemical working principle and, hence, the chemical formulation of the photoresist, and they depend strongly on one another. Chemically amplified resists (CARs) are the most common class of resist materials in the electronics industry today. As a CAR is exposed to EUV light, a small amount of acid is produced within the exposed areas. This acid catalyzes the fragmentation of groups attached to the polymer chain (deprotection) during a postexposure bake (PEB) step, altering the chemical properties. Finally, the deprotected portion of the resist is dissolved in a liquid developer. Even though chemical amplification significantly reduces the exposure time, the diffusion of the acid within the resist during the PEB step leads to blurring of the edges of the patterned areas, thus limiting the resolution and LER.³ The interdependency of resist resolution, LER, and sensitivity is known as RLS trade-off.⁴⁻⁶ That is, for a standard CAR

and processing, these three parameters cannot be minimized simultaneously.

While commercial EUVL scanners are being established, EUV interference lithography (EUV-IL) has been demonstrated to be a powerful platform for the development of photoresist materials beyond the resolution capabilities of EUVL scanners. In EUV-IL, the incident EUV light passes through a grating mask and diffraction occurs. In order to generate line arrays, a pair of gratings is used and the constructive interference of the diffracted light forms the aerial image in the resist material. EUV-IL offers several benefits. First, it enables high-resolution aerial images without optics. The aerial image has infinite depth-of-focus and the contrast is pitch independent. The theoretical minimum resolution achievable with the technique is ~3.5 nm, while the practical resolution is currently limited to 7 nm HP.²

In this paper, we have investigated state-of-the-art CARs from our collaborators from around the world using EUV-IL. We provide an overview of their performance and report on how optimization of different processing parameters, such as developer concentration, duration of PEB, and choice of underlayer material, can improve the performance of the resists. Finally, we demonstrate a dry-develop-rinse process (DDRP) that enables us to extend the resolution limit without having to reduce the resist thickness as commonly done in order to mitigate pattern collapse.

2 Experimental Details

For all the exposures in this paper, the EUV-IL exposure tool (XIL-II) at Paul Scherrer Institute (Villigen, Switzerland) was used. The tool utilizes EUV light at 13.5 nm wavelength from an undulator source of synchrotron facility Swiss Light

*Address all correspondence to: Tero S. Kulmala, E-mail: Tero.Kulmala@PSI.ch

Source (SLS). The undulator source provides high brightness and high spatial coherence, making the tool well suited for EUV-IL technique. PSI's EUV-IL tool has demonstrated patterning down to 7 nm HP,² which to the best of our knowledge is the current world record resolution in photolithography. Further details on the XIL beamline are given elsewhere.⁷ All of the wafer processing steps were carried out on-site in a dedicated clean room module in connection with the exposure tool.

The transmission gratings (masks) comprise hydrogen silsesquioxane gratings patterned on 100-nm-thick free-standing SiN_x membranes using electron beam lithography. The membrane outside the areas of the gratings is covered by an ~500-nm-thick layer of electroplated gold. Further details on the fabrication of the masks are given in Ref. 8. For such transmission gratings, the pitch p of the pattern on the mask is reduced in the pattern on the wafer, g , as follows:

$$p = \frac{g}{2m}, \quad (1)$$

where m is the diffraction order.² Typically, we use first-order diffracted beams for patterning and, therefore, the mask pattern resolution is halved on the wafer. This significantly simplifies the resolution requirements of the mask fabrication process. The effective numerical aperture NA for the XIL tool is given by

$$NA = \frac{\lambda}{4 \times HP}, \quad (2)$$

where λ is the wavelength used (here, 13.5 nm). The aerial image created by IL is a sinusoidal pattern and is similar to the case of dipole illumination with projection optics with NA given above.

3 Dose Calibration in Extreme Ultraviolet Interference Lithography

In exposures with EUV-IL, dose calibration is a difficult issue due to the nature of the technique. In the through-dose experiments, the flux before the mask is measured accurately with a diode prior to experiments and the dose is adjusted with a shutter. A theoretical estimation of the diffraction

efficiencies of the mask or the individual gratings is very difficult. The straightforward method to determine the dose-on-wafer is to measure the transmitted light using a charge-coupled device (CCD) and determine the diffraction efficiency of the diffraction orders contributing to the interference pattern. However, this is possible only for large gratings, and the measurements with CCD cannot be performed under the beam conditions used for the exposures because of the extreme sensitivity of the CCD.

To solve this problem, we have developed a simple method where the tool factor, i.e., the ratio of the dose on the mask and wafer levels, can be obtained unambiguously and with high accuracy under the exposure conditions.⁹ As seen in Fig. 1(a), in addition to interfering beams, there are also first-order diffraction beams that diverge from each other and are also printed on the wafer. Dose-to-clear (DtC) curves were obtained on these fields of flat exposures for each grating. In addition, DtC curve of the same resist is obtained by exposures without a mask. The ratio of the clearing dose in these two cases provides the tool factor. Figure 1(b) shows an example of a DtC curve for our reference resist obtained with PSI's EUV-IL tool. The resist thickness was measured with a profilometer. Since at the patterned area the intensity of the beam is a sum of the two diffracted beams [see Fig. 1(a)], the tool factor is given as

$$\text{Tool Factor} = \frac{1}{4} \times \frac{DtC_{\text{mask}}}{DtC_{\text{no mask}}}. \quad (3)$$

The dose on wafer is thus obtained by dividing the dose on mask by the tool factor. The factor $1/4$ in Eq. (3) is needed as the resulting intensity of two beams undergoing constructive interference is the square of the magnitude of the total electric field, i.e., four times the intensity of an individual beam. The obtained tool factors account for both the diffraction efficiency of the grating and the transmission efficiency of the supporting membrane. Due to the standard deviation of the measurements and other possible error sources, we estimate the method described here is accurate within a 5% error margin. All the doses quoted in the following sections of this article are based on tooling factors calculated as described above.

Fig. 1 (a) Schematic illustration of grating-based interference with two beams. Only zeroth- and first-order diffraction beams are shown. A sinusoidal aerial image is formed by the interference of first-order diffraction beams between the gratings. (b) An example of a dose-to-clear curve for a reference resist obtained with PSI's extreme ultraviolet interference lithography (EUV-IL) tool.

4 Data Acquisition and Analysis

The scanning electron microscope (SEM) images were acquired using a general-purpose SEM (Carl Zeiss SUPRA 55VP) and an in-lens detector. A low electron acceleration voltage of 1 kV together with an aperture size of $7.5\ \mu\text{m}$ resulting in a typical current of $\sim 13\ \text{pA}$ was used. A magnification of 400,000 and a scan speed of 10 s/image were applied. The working distance was kept at $3.0 \pm 0.1\ \text{mm}$. The images were saved in 1076×768 pixels format. The SEM images fit for further study were prescreened visually followed by analysis with commercial dedicated image processing software (SuMMIT[®]) in order to obtain the critical dimension (CD) and LER values. For the LER metrology, a linear algorithm and a relative threshold of 0.562 was used for the edge detection. The edge search range was limited to 20 pixels (1 pixel = 0.9009 nm). The LER values quoted later in the text correspond to 3σ deviation averaged over both walls of ~ 20 lines. The analysis length used was 400 nm.

We note that the SEM inspection of the samples was done by a multipurpose SEM. Therefore, the obtained CD and LER values are subject to change depending on the SEM settings and condition, although every effort was taken to try to keep the settings constant. Moreover, exposure tool stability and human factors also play a role in a research lab environment. Minor changes in the illumination optics, diode aging and its recalibration, and other tool-related factors may cause these variations.

5 Results on Extreme Ultraviolet Resist Screening

In this section, we present our latest results on EUV resist screening with a particular focus on achieving the ultimate resolution of the materials. Figure 2 shows SEM images of lines/spaces (L/S) pattern of a high-performance EUV resist with HPs from 22 nm down to 14 nm. As can be seen from the images, the lines are well resolved down to 14 nm HP below which pattern collapse is observed, yet the pattern is still resolved by the resist.

Figure 3(a) shows the CD versus exposure dose for a state-of-the-art EUV resist (same as in Fig. 2) with a thickness of

30 nm. The analysis was performed for HPs in the range of 14 to 22 nm. From Fig. 3(a), it can be seen that the exposure latitude of the resist is rapidly shrinking when moving toward lower HP values. It can also be seen that the dose-to-size (E_{size}) values for the different HPs are in the range of 33 to 35 mJ/cm². Relatively constant E_{size} for different HPs is due to the pitch-independent contrast of interference lithography. Figure 3(b) shows the filtered 3σ LER values versus the exposure dose for the same set of data as in Fig. 3(a). The LER values remain relatively constant at 2.7 to 3.0 nm for the different HPs for a wide dose range, apart from doses of $\sim 37\ \text{mJ/cm}^2$ onward, where a small increasing trend is observed. This is most likely due to onset of necking in the resist lines as the linewidth decreases.

In order to compare the overall performance of the different resists tested here, we have calculated the so-called Z-factors, as suggested in Ref. 10. The Z-factor (Z) is a resist figure-of-merit based on the RLS parameters as follows:

$$Z = (\text{Sensitivity}) \times (\text{LER})^2 \times (\text{HP})^3, \quad (4)$$

where sensitivity is defined as the E_{size} . HP is used here instead of blur, which was used in the original work of Wallow et al.¹⁰

Figure 4 shows a general overview of our CAR screening results. The LER values for different resists are displayed as a function of their E_{size} for 1:1 L/S at HPs of 22, 20, 18, 16, and 14 nm. All the data were obtained using the same mask, SEM conditions, and data analysis settings. This makes the dataset unique and allows for direct comparison of the performance of different resists as well as evaluation of the effect of changes in processing conditions for the same resist. The solid curves in Fig. 4 represent constant Z-factors crossing the dots with the minimum Z-factor values, obtained using Eq. (4). The curves serve as a guide to the eye when comparing the champion resists (i.e., the ones with the lowest Z-factor values) with the others. From Fig. 4, it is worth pointing out that for current leading resist materials, the LER values do not significantly decrease as HP decreases from 22 to 14 nm.

Fig. 2 Scanning electron micrographs of a chemically amplified resist (CAR) with line/space (L/S) patterns of (a) 22 nm, (b) 20 nm, (c) 18 nm, (d) 16 nm, (e) 14 nm, and (f) 12 nm obtained using EUV-IL. Pattern collapse for half-pitch (HP) = 12 nm structures is observed. The scale bars are 100 nm. The thickness of the resist is 30 nm. A postexposure bake (PEB) time of 60 s and developer concentration of 1.19% were used.

Fig. 3 (a) Critical dimension (CD) and (b) line-edge roughness (LER) values versus the exposure dose extracted for the exposures of Fig. 1. Resist thickness is 30 nm.

Fig. 4 LER versus dose-to-size for different CARs and/or processing parameters (black dots). The dose-to-size values are for 1:1 L/S patterns. The solid lines are the constant Z-factor values crossing the dots with the minimum values of Z. The resist with the minimum Z-factor value is the resist used in Figs. 2 and 3.

We have also studied the effect of developer concentration, PEB time, and different combinations thereof on the overall performance of selected high-resolution resists. Figure 5 shows the calculated Z-factor values for three resists (referred to here as A, B, and C) at different HPs. For two of them (resists B and C), different concentrations (0.79, 1.19, or 2.38%) of the same developer were used while the developing time was kept unchanged. Also, PEB times of either 60 or 120 s were applied to these resists. One can observe a trend that the Z-factor decreases with decreasing HP. This is due to the relatively constant values of LER and sensitivity

(here, dose-to-size). Nevertheless, differences induced by the choice of developer or duration of the PEB can be observed. First, for resist B, lowering the developer concentration from 2.38 to 1.19% decreases the Z-values for most HP values and improves the ultimate resolution. Furthermore, for resist B, increasing the PEB time from 60 to 120 s decreases the Z-values for HPs of 14, 16, and 18 nm, while they remain unchanged for 20 and 22 nm HPs. Figure 5 shows that resist C yields the lowest Z-factor values for all HPs. A small decrease in the Z-factor values compared to our best results from 2013 can be observed for 14 and 16 nm HPs.⁷ Also,

Fig. 5 Calculated Z-factor values at different HPs for different resists, developer concentrations, and PEB times. Resist C here is the same as the resist from Figs. 2 and 3.

patterning down to 14 nm HP with a 30-nm-thick resist has become possible, which has improved the measured LER values. For resist C, lowering the developer concentration from 2.38 to 1.19% is also seen to decrease the Z-factor, especially for smaller HPs. In the case of resist C, however, increasing the PEB time leads to small increases in Z-factor values and, in the case of 2.38% developer, deteriorates the ultimate resolution. The results show that the performance of high-performance resists can be further improved by fine-tuning their processing parameters.

Figure 6 provides a summary on the effects of the different developer normalities [Fig. 6(a)] and underlayers [Fig. 6(b)] on the averaged LER, averaged dose-to-size values, and the minimum HPs without collapse for all the resists used in this

study. As can be seen from Fig. 6(a), the dose-to-size values for the resists decrease as developer normality increases, while the LER reaches its minimum for 1.19% developer normality. HP of 14 nm is achieved without collapse for both 1.19 and 2.38% developer concentrations. Figure 6(b) shows that the dose-to-size values remain within experimental error for the different underlayers, while both LER and minimum HP without collapse are at minimum when underlayer E is used.

6 Pattern Collapse Mitigation

As mentioned above, pattern collapse becomes a major hurdle when patterning resists below 14 nm HP. The root cause of pattern collapse is the capillary forces acting on the resist's

Fig. 6 The effect of (a) developer normality and (b) different underlayers on averaged LER, averaged dose-to-size and on minimum HP without collapse for all the resists of Fig. 4.

Fig. 7 CD versus dose (left) and LER versus dose (right) for different underlayers at different L/S HPs. Resist C from Fig. 5 was used in the experiment (PEB time: 60 s, 1.19% developer concentration).

sidewalls as the samples are dried after the development and rinse steps.¹¹ The main parameters influencing the phenomenon are the surface tension of the liquid used for rinsing the sample (γ), the aspect ratio (height/width of structures, A), and the spacing between individual patterns (D). The maximum stress $\sigma_{\max}$ to the resist caused by capillary forces can be expressed as

$$\sigma_{\max} = \frac{6\gamma A^2}{D \cos \theta}, \quad (5)$$

where θ is the contact angle between the liquid and the resist material.¹¹ From the formula, one observes that by reducing the aspect ratio of the patterned structures (i.e., reducing the resist thickness in the case of a constant HP), one can reduce the maximum stress to the resist and, thus, the probability of pattern collapse. On the other hand, it has been shown that reducing the resist thickness increases the LER,⁷ making this approach impracticable. Also, Eq. (5) tells us that the choice of rinsing liquid (one with as low surface tension as possible) can contribute to mitigating pattern collapse. This approach to pattern collapse has been studied elsewhere.¹² Also, supercritical drying with CO₂ has been successfully demonstrated to mitigate pattern collapse.¹³

Apart from the parameters mentioned in Eq. (5), the mechanical properties of the resist as well as the quality of the interface between the resist and the substrate (adhesion) are key issues to be considered when trying to mitigate pattern collapse. The mechanical properties of the resist (e.g., Young's modulus E and fracture toughness K_{Ic}) are determined by its polymer backbone and cannot therefore be significantly altered without changes to all the other critical parameters of the resist at the same time. For instance, one route in avoiding pattern collapse is to use inorganic resist materials with mechanical properties superior to those of CARs.¹⁴ Here, we have investigated improving the adhesion of the resist to the substrate by (chemical) treatments of the wafer prior to resist spin-coating. The performance of five different underlayer materials when using our top-performing EUV photoresist was evaluated. The results are presented in Figs. 7, 8, and 9.

Figure 7 shows the CD and the LER versus the exposure dose at different HP values for the five different underlayers characterized here. The resist material and all the processing parameters (i.e., post-apply bake, PEB, and development) were identical. As seen in the figure, the dose-to-size values for the resist on the different underlayers lie between 32 and 37 mJ/cm². The small variation in the values may be due to the different thicknesses of the underlayers. Furthermore,

Fig. 8 Scanning electron microscope images of L/S patterns of resist C with HPs of 14 nm (left column), 16 nm (middle column), and 18 nm (right column) obtained using the same resist and processing conditions but different underlayer materials. The scale bars are 100 nm.

Fig. 9 Calculated Z-factor values at different HPs for the same resist (resist C) and processing conditions but different underlayers.

small changes in the exposure latitude for the different underlayers can be observed already at HP = 22 nm, and moving down toward smaller HP values, these differences become more pronounced. Only two of the five underlayers tested enabled patterning down to 14 nm HP. As can be observed from the LER data (right panel in Fig. 7), these values show a noticeable dependence on the underlayer material. While underlayer E (diamonds in Fig. 7) consistently shows the smallest LER values from 22 nm HP down to 14 nm HP, the values measured for underlayer C (up-triangles in Fig. 7), for example, show a consistent increasing trend. The LER values lie between 2.5 and 4 nm throughout the entire exposure latitude for all the underlayers tested here. Figure 8 shows SEM images of exposures with different underlayers for 14 nm (left column), 16 nm (middle column), and 18 nm (right column) HPs. As seen in the images, no distinct differences between the underlayers for 16 and 18 nm patterns are observed. However, for the 14 nm patterns, the different performances of the characterized underlayer materials become clearer. For underlayer A, distinct necking in the resist lines is observed at 14 nm HP. In the case of underlayers B and D, pattern collapse is observed at 14 nm HP suggesting insufficient adhesion between the resist and the underlayer material used. In the case of underlayers C and E, the 14 nm HP patterns are resolved without pattern collapse.

The calculated Z-factor values for data obtained for the five underlayers are presented in Fig. 9. The Z-factors for all the underlayers and different HPs lie in the range of 1 to 4×10^{-8} nm³ mJ. As in Fig. 5, a general trend of decreasing Z-factor for decreasing HP is observed here as the sensitivity, and the LER values remain largely unchanged for the different HPs. Out of the two underlayers that enable patterning of the resist down to 14 nm, underlayer E consistently shows the lowest Z-factor values for this particular resist.

Apart from the choice of an optimal wafer pretreatment, we are currently studying an approach where the capillary forces are completely removed from the postexposure processing of the wafers via the so-called DDRP.¹⁵ In this process, lithography is carried out as usual until the rinsing after development. Subsequently, the wafer is not dried but instead a layer of encapsulating material is spin-coated on it

while it is still wet from the rinsing liquid. The encapsulating material replaces the rinsing liquid and covers the resist structures. Thus, no capillary forces that might lead to pattern collapse are present. In further processing steps, the excess encapsulation material and the photoresist are removed in a dry-etching step, resulting in a negative image of the original resist pattern. We have applied DDRP to CARs patterned down to 12 nm HP, and preliminary results show remarkably reduced pattern collapse as compared to samples that were developed, rinsed, and immediately dried. However, further work is still undergoing in order to optimize the processing parameters, and we remain optimistic that DDRP will help us achieve patterning of CARs toward 10 nm HP in the near future.

7 Conclusions

In this paper, we reported on our CAR screening work toward achieving the ultimate resolution of these materials. We showed that more resist materials reaching a resolution of 14 nm HP have become available and this resolution is now reached using higher resist thicknesses, enabling significant improvement in LER and Z-factor values. We also showed how optimization of the developer concentration and PEB time has provided significant improvements on the performance, quantified as the Z-factors of the resists. Furthermore, we observed that even though the current state-of-the-art resists can resolve patterns beyond 14 nm HP, pattern collapse prevents efficient use of these resists in subsequent pattern transfer steps. In order to mitigate the issue, we have optimized the adhesion of resists to the surface by experimentally identifying the optimal wafer pretreatment method. We showed that the right choice of underlayer is critical in achieving the optimal resist performance. Finally, we introduced pattern collapse mitigation via DDRP, where capillary forces are eliminated from postexposure wafer processing, enabling us to extend the pattern collapse limited resolution without having to reduce the resist thickness.

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Tero S. Kulmala is a postdoctoral fellow at the XIL-II group in the Laboratory for Micro and Nanotechnology at the Paul Scherrer Institute, Switzerland. He holds an MSc degree in materials science and engineering from Helsinki University of Technology, Finland, and a PhD in electrical engineering from the University of Cambridge, United Kingdom. His current research focuses on extreme ultraviolet (EUV) interference lithography, EUV resist research, and nanofabrication.

Biographies for the other authors are not available.