Progress in EUV resists towards the deployment of high-NA lithography

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ABSTRACT

The development of EUV resists is one of the major challenges for the deployment of high-NA EUV lithography, which is on the roadmap for high-volume manufacturing of future semiconductor technology nodes. Resist performance is admittedly governed by a resolution-roughness-sensitivity (RLS) tradeoff. This study reports on the EUV resist progress achieved during the last year in the framework of the resist screening program by PSI and ASML. An extensive performance characterization of different resists was carried out using the XIL-II beamline EUV interference lithography (EUV-IL) tool at the Swiss Light Source (SLS). We present the upgraded screening metrology used in 2020 at PSI enabling increased confidence in results. We report material performance towards patterning lines/spaces features with respect to the key parameters of RLS: half-pitch (*HP*), dose-to-size (*DtS*), line-width-roughness (*LWR*), as well as *Z-factor* for overall performance consideration. General progress in EUV resist development is reviewed by considering several resist platforms available today from different vendors. Different molecular and chemically amplified resist materials are demonstrated as viable for 16 nm resolution technology nodes. One chemically-amplified resist vendor shows suitable materials for 13-nm-resolution technologies while exhibiting potential for further downscaling. We present different metal-oxide resists screening with resolutions down to 10 nm HP. We finally discuss the overall progress of materials achieved between 2019 and 2020 towards reaching high-NA.

1. Introduction

EUV lithography has become the industrial standard for chip manufacturing and deployment of high-NA scanners is planned to keep closing in on Moore's law¹. On the roadmap to delivering such systems, finding suitable resist materials is one of the most prominent challenges to allow reaching higher resolutions². Dedicated exposure tools that allow resist development are therefore valuable to assist the EUV lithography community in this challenge. The EUV-Interference Lithography (EUV-IL) exposure tool based at the XIL-II beamline in the Swiss Light Source (SLS) has been developed for this purpose. PSI has equipped its facilities with a full resist screening capacity all the way from resist processing and EUV exposures to inspection and metrology. A joint research program between ASML and PSI is dedicated to resist performance characterization and it is used to support various industrial vendors in the development of their materials. Working with a broad panel of industrial partners allows us to monitor the general progress of EUV resists over time³⁻⁵.

The potential for scalability, reduced defectivity, and throughput that are considered in the chip manufacturing process can be transcribed into the field of resist research by developing the resolution, line-width roughness, and sensitivity (RLS) tradeoff⁶. Therefore, performance metrics of interest include Critical Dimension (*CD*), dose-to-size (*DtS*) and line-width-roughness (*LWR*). We also consider the *Z-factor*⁷ to assess the overall performance of a resist by quantifying the dose-*LWR* trade-off at given feature size ($Z\text{-factor} = HP^3 \cdot LWR^2 \cdot DtS$). The *Z-factor* is limited to comparing performances at a given *HP*. Although this parameter is greatly simplified and does not provide in-depth depiction of performance through pitch, it is useful as a single metric for the first-order judgment of resist potential^{8,9}.

Here, we report resist performance results obtained in 2020 for patterning of lines/spaces (*L/S*) features. More than 200 resist films were tested by working with 7 different vendors. Different sets of materials are considered for 13 nm HP and 8 nm HP resolution, for existing NXE systems and future high-NA systems, respectively.

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In this work, we start by describing the exposure tool used for resist performance characterization and the screening protocol altogether. We then elaborate on the targets of the resist screening program before presenting the results obtained in 2020.

2. EUV interference lithography

In interference lithography, the interference pattern between two or more coherent beams is designed to obtain a aerial image, used to expose and pattern photoresists. Here, the SLS synchrotron facility is used as a coherent light source with $\lambda=13.5$ nm. As is shown in Figure 1, perpendicularly illuminated masks with adjacent transmission gratings produce diffracted beams designed to interfere on the wafer surface and provide a periodic aerial image used for resist patterning¹⁰. The intensity of the aerial image is dictated by the constructive and destructive interference of the diffracted beams and depends on the gratings' period p as¹¹:

$$I(x) = \cos^2\left(\pi \frac{x}{p}\right)$$

This interferometric tool, therefore, produces periodic features. In the present study, two-beam diffraction grating masks are used to provide L/S patterns. EUV-IL masks are obtained via e-beam patterning of the diffraction gratings with HSQ metal-oxide resist on a thin Si_3N_4 membrane, then growing a thick Ni photon stop around the gratings to isolate the diffracted beams from the incident beam. The incident plane wave is polarized along the direction of the mask gratings. Masks are typically designed with several pairs of gratings, providing different half-pitches with a single exposure.

Figure 1. Schematic representation of the EUV-IL tool. The mask with transmission gratings printed on a thin Si_3N_4 membrane is illuminated with coherent $\lambda=13.5$ nm light to generate diffracted beams that interfere at the wafer surface for resist patterning. A thick nickel photon-stop around the gratings isolates the diffracted beams from incident light.

The EUV-IL tool represents a powerful alternative to EUV scanners for resist testing^{9,11-14}. The stripped-down optical setup allows an advantage in cost-effectiveness as well as some flexibility towards testing of materials without potential outgassing and contamination issues. The method features an so-called “infinite” depth of focus, resulting in a focus-independent contrast, which allows for single-parameter dose-dependent exposure arrays. In theory, the tool produces a pitch-independent sinusoidal aerial image with a contrast of 1, which is befitting for resist screening^{14,15}. It is a high-resolution tool, as has been demonstrated¹⁶, due to the frequency multiplying principle of mask features onto the wafer.

3. Resist screening method

Resist coating and processing are conducted directly at the XIL-II beamline in a cleanroom environment. Following exposure, development, and further post-processing, patterned features are inspected on-site with a newly-commissioned SEM (Hitachi Regulus 8230). SEM parameters have been calibrated as closely as possible to IMEC's roughness protocol¹⁷. Subsequent key-parameters are shown in Table 1.

Detectors	SE+BSE
Specimen current	8 pA
Landing voltage	0.5 kV (4 kV acceleration)
Pixel size	0.83 nm
Acquisition mode	CSS

Table 1. Standard SEM parameters used for resist screening at PSI

We then use a newly available open-source pattern analysis software developed in-house at PSI to analyze subsequent images (SMILE¹⁸). The switch to this open-source software is prompted by the possibility of specifically and knowingly tailoring image analysis. Acquired SEM images are therefore pre-treated with respect to the analytical SEM image output before line edge detection, as is shown in Figure 2 (a). The average CD of an image is measured, and the unbiased-LWR (LWR_{unb}) is extracted through PSD curve fitting, as presented in Figure 2 (b).

Figure 2. PSI in-house software SEM image analysis: L/S edge detection for average CD measurement (a) and subsequent LWR unbiasing through PSD curve fitting (b).

Acquired dose-dependent CD and LWR_{unb} values are then linearly fitted to determine pitch-specific DrS and corresponding LWR_{unb} values, as is presented in Figure 3.

Figure 3. Pitch-specific DrS and LWR_{unb} extraction by linear fitting of raw data values through dose.

The XIL-II beamline flux is calibrated by material transfer. Moreover, the EUV-IL tool dose output is monitored with a reference L/S exposure carried out systematically with every shift, specifically to verify repeatability over time.

4. Resist screening program goals

The work presented here comprises two main targets. The first one aims for the optimization of resists for 0.33 NA systems by further development of materials with resolutions down to 13 nm HP. The second one targets the identification and development of suitable resist candidates with resolutions down to 8 nm HP to enable 0.55 NA systems operation.

The general guidelines shown in Table 2 are targeted in the resist screening program and the work presented here. We note that these guidelines are used as an in-house reference point for the underlying screening program and do not represent industrial targets.

Mask features	16 – 8 nm L/S
Resist type	CAR & non CAR
Throughput	$DtS \leq 60 \text{ mJ/cm}^2$
Roughness	$LWR_{unb} \leq 12\%$
General performance	$Z\text{-factor} = CD^3 \cdot LWR^2 \cdot DtS$

Table 2. ASML/PSI joint research screening program general guidelines.

5. Results

In the following section, we start by presenting results considered for 13 nm HP resolution solutions. We then show results with resist candidates for 8 nm HP resolution. In these two cases, a general overview of all the results is shown before describing the best candidates in more detail.

Materials developed by four different vendors were investigated as candidates for 13 nm resolution resists: three positive-tone chemically-amplified resists (CARs) and one negative tone molecular resist. Figure 4 (a) and (b) show LWR_{unb} values as a function of DtS of resists tested for patterning of HP 16 nm and HP 13 nm L/S, respectively. Hence, each data point represents an exposure with specific resist processing and different markers/colors represent results obtained by different resist vendors. For the sake of clarity, error bars are not shown on these figures; however, the uncertainty associated with the repeatability of the beamline reference exposure is shown in the top right of each figure. Program targets are highlighted with the red boxes, and target-equivalent performances are shown with the iso- $Z\text{-factor}$ in dashed lines (constant $Z\text{-factor}$).

This overview shows the range in which material performances from different vendors were tuned in terms of roughness and sensitivity over the year. We see that three of four vendors have materials within HP 16 nm general guideline targets or equivalent performances with regards to the iso- $Z\text{-factor}$ line. HP 13 nm plot (Figure 4 (b)) shows one vendor with results that fulfills the target specifications of the screening program.

Figure 4. LWR_{unb} as a function of DtS of resists screened for L/S patterning at HP 16 nm (a) and HP 13 nm (b). Program targets and equivalent performances are highlighted in red and with the iso- $Z\text{-factor}$ curve in dashed lines. Measurement uncertainty is shown with beamline reference repeatability errorbars in top right corners.

Figure 5 shows SEM images obtained from each vendor's best performance resist for patterning of HP 16 nm L/S. All those resists show well-resolved and defect-free lines. No stochastic defects were observed within the region of interest analyzed. The slightly different contrast of these images is due to manual adjustment of the analytical SEM parameters required for each wafer.

Figure 5. SEM images of best performance resists for HP 16 nm L/S.

Table 3 lists performance metrics associated with each selected resist in Figure 5. It also displays the targeted guidelines for HP 16 nm as well as uncertainty values. These error bars are associated with the tool's reference exposure repeatability over a year (40+ shifts). It is worth highlighting the consistency of reference DrS and LWR_{unb} values obtained in 2020.

HP 16 nm L/S	Dose to Size (mJ.cm^{-2})	Unbiased LWR (nm)	Z-factor ($\times 10^{-8}$) (mJ.nm^3)
Vendor A-Molecular	55.5	1.64	0.66
Vendor B-CAR	65.2	1.23	0.40
Vendor C-CAR	41.0	2.17	0.79
Vendor D-CAR	84.0	1.77	1.08
General guidelines	60	1.92	0.91
Beamline ref. repeatability	5.5%	7.2%	17.4%

Table 3. Performance metrics of highlighted resists for HP 16 nm L/S. Bolded values show performances within program targets.

Vendor A-Molecular resist shows both DtS and LWR_{unb} beyond program targets. Vendor B-CAR and Vendor C-CAR show the lowest roughness and the highest throughput potential, respectively, as well as equivalent performances to program targets with respect to their Z -factor. Vendor D-CAR cumulates much fewer resists tested in the past year and shows results that are slightly off target. However, considering measurement uncertainties, the general performance of this resist is also within reach of the program targets. Altogether, all four vendors show materials suitable for HP 16 nm resolution patterning.

Figure 6 shows SEM images of each vendor's best performance resist for HP 13 nm L/S. Vendor-A Molecular resist shows some rough lines with breaks and micro-bridging defects, while Vendor-B CAR shows smooth, well-resolved lines. Vendor C-CAR displays scumming and pinched lines, and Vendor D-CAR presents scumming, pinching and bridging defects.

Figure 6. SEM images of the best performance resists of different vendors for HP 13 nm L/S.

Results displayed in Table 4 show high sensitivity results for both molecular resists and CARs from Vendors A and C, respectively. These materials are close to their resolution limit but show promising performance towards reaching HP 13 nm resolution through further optimization of line roughness. Vendor D-CAR needs further development to become suitable for 13 nm resolution patterning. Vendor B-CAR sensitivity and overall performances surpass the program targets, with the lowest line roughness and, therefore, high potential for further downscaling.

HP 13 nm L/S	Dose to Size (mJ.cm ⁻²)	Unbiased LWR (nm)	Z-factor (x10 ⁻⁸) (mJ.nm ³)
Vendor A-Molecular	30.1	2.44	0.24
Vendor B-CAR	54.1	1.28	0.19
Vendor C-CAR	34.5	2.33	0.41
Vendor D-CAR	78.2	2.91	1.45
General guidelines	60	1.56	0.32
Beamline ref. repeatability	5.3%	10.9%	23.9%

Table 4. Performance metrics of highlighted resists for HP 13 nm L/S.

Altogether the work shown here has allowed to identify one suitable resist vendor's material for 13 nm HP resolution patterning. Two more vendors are closing in on targets with promising results in terms of throughput potential.

Leaning towards more aggressive resolutions, Figure 7 shows screening results obtained for HP 12 nm and HP 11 nm L/S in the past year. These results show that the CARs and molecular resists considered previously reach a bottleneck beyond HP 12 nm. It is worth noting that Vendor-B CAR shows promising results down to HP 12 nm. Subsequently, two more metal-oxide resist (MOR) vendors are considered to reach sub-10 nm resolutions. Vendor E-MOR shows performances within program targets at HP 12 nm; however, the lack of a process window at HP 11 nm has not allowed for quantitative data analysis. Vendor F-MOR shows the highest resolution achieved with process windows down to HP 11 nm.

Figure 7. LWR_{unb} as a function of DtS of resists screened for L/S patterning at HP 12 nm (a) and HP 11 nm (b). Program targets and equivalent performances are highlighted in red and with the iso- Z -factor curve in dashed lines.

Figure 8 shows high-resolution highlights obtained at PSI in 2020 within the resist screening program with SEM images of best performance resists for HP 12 nm down to HP 9 nm obtained with materials from vendors B-CAR, E-MOR and F-MOR. Vendors B-CAR and E-MOR exhibit resolution bottlenecks at HP 11 nm due to pattern collapse. This observation suggests both materials should reach HP 10 nm resolution through collapse mitigation. This can be achieved by process optimization of the resist thickness, development, underlayer, etc. Vendor F-MOR shows a bottleneck below HP 10 nm, primarily due to a high roughness component which is consistent through dose. This roughness is also observed with Vendor-E-MOR. Therefore, reaching higher resolutions with MORs ensues mitigation of line roughness.

	Vendor B-CAR	Vendor E-MOR	Vendor F-MOR
HP 12 nm
HP 11 nm
HP 10 nm
HP 9 nm	n/a	n/a

Figure 8. SEM images of the highest resolution results obtained at XIL-II in 2020.

6. EUV resist progress in 2020

The progress in resist materials in 2020 brings confidence towards reaching 8 nm resolution lithography. Figure 9 shows the evolution of *Z-factors* of the CAR and MOR best performance materials as a function of resolution HP between 2019 and 2020. The same SEM, imaging parameters and data analysis was used for all of the considered results. It is worth noting that a non-negligible part of the progress observed may also be attributed to improvements of the exposure tool, namely through optimization of masks used. Results show a clear improvement of CAR materials, as well as a higher resolution node achieved this year (Vendor B). MOR results also show some improvement (Vendor F) and, therefore, the potential to lead into sub-10 nm patterning in the future.

Figure 9: Z-factor evolution of Vendor B-CAR (a) and Vendor F-MOR (b) best performance resists screened at XIL-II between 2019 and 2020.

7. Conclusion

In this paper, we presented results of the resist screening activity carried out with the XIL-II EUV-IL tool at PSI throughout 2020, within the framework of a joint research program between ASML and PSI. More than 200 photoresist films were investigated with different processing conditions, namely resist and underlayer materials/thicknesses, baking and development conditions. This work was carried out in support of 7 vendors, including CAR, Molecular, MOR and underlayer materials, providing a broad overview of the progress in the field of EUV resists.

PSI's EUV-IL tool was presented as well as the resist screening protocol altogether. We would like to highlight the upgrade in metrology in 2020 with the commissioning of a new SEM as well as the implementation of a tailored image analysis software. Those improvements provide added confidence in the metrology outcome of the resist screening activity at PSI. Beamline monitoring has shown outstanding repeatability over the past year. Further work is underway to cross-calibrate metrology between different institutes involved in high-NA lithography research.

We presented a first set of results was presented, consisting of candidates for the optimization of the 13 nm resolution technology node. Results from one molecular as well as three CA resist were considered. Two vendors (CAR and molecular resist) show high sensitivity materials and are expected to close in on the 13 nm resolution target in the coming year(s) with interesting prospects in terms of throughput. A third vendor has put forward CARs suitable for the underlined technological node to this day. Most importantly, materials from this vendor exhibit low roughness, therefore potential for further downscaling. Achievement of 10 nm resolution with these CARs is expected in the near future through pattern collapse mitigation i.e. through investigation of thinner films.

The CAR and molecular resists considered exhibit an overall resolution bottleneck below HP 12 nm L/S. MORs provided by two more vendors were investigated to break the sub-10 nm resolution realm. By doing so, 10-nm resolution was reached in 2020. Both vendors are expected to reach an 8-nm resolution through further process optimization, focusing on roughness mitigation.

Confidence in reaching the perspectives stated here amounts from the progress observed between 2019 and 2020 for all resist platforms considered. The resist screening program will continue in 2021 with added emphasis on decoupling and understanding of the tool and resist behavior, towards achieving high-NA tool deployment.

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