Underlayer Designs to Enhance EUV Resist Performance

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Extreme ultraviolet (EUV) lithography has gained momentum as the method of choice for <32-nm half-pitch device fabrication. In this paper, we describe our initial efforts to increase the EUV resist’s performance via introduction of a thermally crosslinkable underlayer. We have demonstrated the benefits of adding an EUV underlayer into the regular EUV litho stack and investigated the effect of underlayer film thickness, post-coat bake temperature, and adding other additives such as PAG and sensitizer on the overall litho performance of EUV resists.

Keywords: EUV, underlayer, photoacid generator, sensitizer, PAG

1. Introduction

EUV lithography (EUVL) is expected to offer a single-exposure solution for use in manufacturing at 22-nm half pitch, and possibly for some applications at 32-nm half pitch. However, in order to successfully implement EUVL in time, several technical hurdles must be overcome, including mask fabrication with low defects, reliable EUV sources with high output power and sufficient lifetime, contamination control of all mirrors, high throughput, photoresists with sufficiently low line width roughness (LWR), and low exposure dose. For resist requirements, the International Technology Roadmap for Semiconductors (ITRS) set targets for 3σ LWR at <3 nm and for sensitivity at <10 mJ/cm², which, to date, has not been achieved simultaneously in an EUV resist. Earlier research has actually found that most efforts simply result in a compromise between LWR, resolution, and sensitivity, e.g., good sensitivity but rough lines, or improved LWR but poor resolution. Although the design of new EUV photoresists and an improved understanding of the patterning mechanism has allowed significant progress for simultaneously achieving improved EUV resolution, LWR, and sensitivity (RLS), the trade-off is clearly a natural limitation for chemically amplified resists.7,8,9

In previous studies and publications, we have demonstrated the benefits of introducing an EUV underlayer (UL) beneath the resist. The UL is a crosslinkable polymeric system that can be coated onto a substrate through a regular spin-on process and then thermally cured so that the photoresist can be applied thereafter. Most ULs have exhibited less outgassing than positive tone photoresists during EUV exposure.10 We also provided initial data on the relationship between film density, absorption, and EUV litho performance.11 Additional benefits of using an EUV UL include, but are not limited to, planarization of a substrate with topography, protection of underlying layers from possible damage caused by high-energy EUV photons, improved adhesion for high-aspect-ratio resist profiles, and improved etch selectivity for better pattern transfer. Our goal in this paper is to take one of the first-generation EUV ULs—BSLX07333—and investigate various process conditions and functional additives.
To more quantitatively analyze the data to examine the RLS trade-off, the concept of Z factor was used to evaluate the balance of resolution, LER/LWR, and photospeed. Z factor, as described elsewhere, is defined in Equation 1 as:

\[
Z = \text{Resolution}\times(\min\text{ LER})\times E_{\text{size}} \quad (\text{Eq. 1})
\]

The current target for 32-nm half-pitch line/space patterning is 2.0-nm 3\( \sigma \) LWR (or 1.4-nm LER) and 10-nm/cm\(^2\) dose to size, or Z-factor (32-nm target) = 6.6E-09, which is defined as the target. A normalized value can then be defined as nZ (32 nm): nZ\(_{32} = Z \text{ factor}/ Z \text{ factor (32-nm target)}

2. Method

2.1 Materials and process conditions

All the ULs studied in this paper are based on a crosslinkable linear polymer system. As shown in Figure 1 below, the basic formulation includes a methacrylate polymer, a crosslinker, and small-molecule additives.

![Chemical structures of underlayer used in this study](image)

**Figure 1.** Chemical structures of underlayer used in this study.

Polymer, crosslinker, and additives were dissolved completely in typical semiconductor-grade solvents (such as PGME, PGMEA, and combinations of the two) and filtered through a 0.1-\( \mu \)m filter before use. Each of the final formulations (% solids = 1.5% ~ 2.5%) was spin-coated at 1500-3000 rpm onto a silicon substrate and then baked at 130\(^{\circ}\)-205\(^{\circ}\)C for 60 seconds. The coated film thicknesses ranged from 20 to 80 nm, depending on the specific requirement of the lithography stack. The film was rinsed with ethyl lactate (EL) to test the film’s resistance to the solvent and was also immersed in photoresist developer (TMAH base solution) without light exposure to evaluate the dark loss. All the formulations used here were under 5% EL stripping and dark loss without specification.

2.2 EUV exposure and CD-SEM measurements

Most EUV exposures were performed on a microexposure tool (MET) at the Advanced Light Source (ALS) in Berkeley. The ALS-MET utilizes a 5X-reduction, 0.3-NA optic, providing a 200-600 \( \mu \)m exposure field at the wafer plane. All processing was performed using Berkeley BKMs as previously reported. The CD and LWR measurements were made using a CD Scanning Electron Microscope (CD-SEM). The methodology used to measure LWR has been detailed previously. All of the LWR values reported in this article are an average of at least five to seven lines repeated at five different locations in the array.

2.3 Cross-section SEM

The wafers were then sent to Cerium Labs in Austin, TX, for cross-sectioning and imaging. The cross-section images shown in Figure 6 are after metal sputtering in the focused ion beam (FIB) and imaging using a Hitachi S4800 high-resolution SEM/STEM.

3. Results and Discussion

3.1 Underlayer effect on EUV lithography

It has been slowly recognized that a properly selected UL between the substrate and the EUV resist could contribute to enhancing the overall EUV resist’s performance. BSI.X07333 is one of the first-generation ULs used here as a baseline for studies described in this paper. As clearly shown in Figure 2, under the same tool setting, exposure condition, and photoresist, there is an obvious difference between coating resist directly on HMDS primed Si wafers and onto BSI.X07333. An 80-nm thick resist was used here to challenge the resolution around and below 32-nm HP due to the high aspect ratio. The roughness of 40- and 32-nm HP lines is significantly improved with an EUV UL present, while the ultimate resolution can also be pushed further down. The explanation for this improvement is not clear at this point, but we believe it is possibly among the following reasons: improved adhesion by introducing a hydrocarbon based interlayer between inorganic substrate and organic resist, formulation compatibility with the
resist, and sensitizing ability from the anthracene chromophore.

The UL used is based on a thermally crosslinking system via acid catalysis, in which various baking temperatures will result in different crosslinking densities and level of acidic catalyst residues. To test if these changes in the composition and structure of the UL will have a positive or negative effect on the performance of an EUV resist, four different post-application bake (PAB) temperatures were used for BSL.X07333 before applying Resist C. The results from the 30-nm HP images (Figure 4) show that there was little change in photosensitivity, but LWR was greatly improved by lowering baking temperature, up to 15% less at 135°C bake. However, the DOF was degraded slightly, and more important, the SEM images at 26-nm HP clearly show that lower bake temperature hastened pattern collapse. The reason might be due to a higher level of acidic catalyst residues at lower temperature. Extra acid from the UL can help to smooth the patterned resist lines. On the other hand, it can cause line collapse due to isotropic diffusion during post-exposure bake (PEB). For the following studies, a 200°C bake was used.

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3.2 Effect of underlayer thickness on lithography

For traditional BARCs, film thickness plays an important role in determining the reflectivity and light distribution inside the resist. To find if there is any clear relationship between the thickness of an EUV UL and the performance of a resist, we tested Resist C on BSL.X07333 with various thicknesses ranging from 23 to 86 nm. The data are summarized in Figure 3. The results show very similar, if not identical, CD and dose to size across all the film thicknesses tested. Clearly, there is no obvious swing curve behavior as observed in traditional 193- and 248-nm lithography. LWR, the calculated Z-factor, and exposure latitude are also very similar. For the following studies, unless otherwise indicated, a 60-nm UL thickness was used.

3.3 Effect of underlayer bake temperature on lithography

Figure 2. The comparison of top-down SEM images, at 40- and 32-nm L/S between HMDS-primed and BSL.X07333-coated wafers with 80-nm TOK-P1123.

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Figure 3. Comparison of CD, LWR, dose to size, calculated Z-factor, and exposure latitude on EUV patterned Resist C at 30-nm half pitch (HP), with BSL.X07333 UL at various thicknesses.

3.4 Effect of adding photoacid generator and sensitizer to underlayer performance

Figure 4. The comparison of dose to size, LWR, DOF, calculated Z-factor, and ultimate resolution (UR) of Resist C at 30-, 28-, and 26-nm HP, with BSL.X07333 as the UL, after PAB at various temperatures.
A major challenge for resist and UL design is to increase the photospeed to compensate for the low EUV power sources available to date. We have investigated various additives to the baseline formulation for BSLX0733. In order to increase resist photospeed, the key is to harvest as much energy as possible and then feed it back to the resist in different forms, e.g., photons, secondary electrons, or photo-generated acids. Adding EUV sensitizers (phenol types) have shown great effect in enhancing photospeed when added directly into photoresist. Therefore, our first study was carried out by adding TPS-triflate as the PAG and 2,5-dimethyl phenol as energy sensitizer into the UL design in an effort to enhance the photoresist performance, i.e., increased photospeed without compromising LWR and/or ultimate resolution. Figure 5 shows the structures of the additives used.

**Figure 5.** Chemical structures and PAG and EUV sensitizer.

LWR and ultimate resolution were used to check the effect of the additives on the photosensitivity of the resist. Wafers were patterned using the ALS-MET at Berkeley with TOK-P1123 EUV photoresist. A 5X9 FEM was used, with 100-nm focus step and 7% of central dose as dose step. Figure 6 shows a side-by-side comparison of 32- to 60-nm HP top CD SEMs from BSLX0733 UL, UL with TPS-OTf, and UL with both TPS-OTf and 2,5-dimethyl phenol. There is a clear decrease in E_{size} with added PAG, a further decrease with sensitizing phenols, 7.6%-24% varied at different pitches compared to the original formulation. However, the imaging quality deteriorated with the addition of PAG and/or phenol. Especially at smaller pitches, the line roughness increased rapidly (7%-26%), and lines started to fall off at 32- and 34-nm HP. Clearly, the LWR and resolution were more compromised than the modest improvement in photospeed. CD-SEM images in Figure 6 show that the nZ2 calculated for each UL at the ultimate resolution are 14.1 for the original BSLX0733 UL (34-nm HP); 22.3 for UL with PAG (36-nm HP); and 17.4 for UL with PAG and sensitizer (36-nm HP). Clearly there is no significant RLS improvement observed, although using a PAG in combination with a sensitizer showed slightly better performance than a PAG-only UL.

**Figure 6.** CD-SEM images of TOK P1123 on BSLX0733 and derivatives by adding triflate PAG and/or phenol-type sensitizer. Cross-section SEM images for 60- and 40-nm HP were also included. Ultimate resolution is indicated in black boxes.

Cross-section SEM images were taken at the best dose and focus for 40- and 60-nm HP to evaluate the pattern profile and line shape. As shown in Figure 6, footing was observed with original X07333 and became more severe as CD size decreased from 60 nm to 40 nm. Adding PAG and/or phenols not only decreases the required dose to size, which is in agreement with CD-SEM observations, but also helps to keep the resist profile straight by reducing footing and scumming. Therefore, the photoacids generated and then diffused from the UL can balance acid deficiency at the bottom of resist layer and keep the resist profile straighter. However, uncontrolled PAG/photoacid diffusion from the UL can also cause line collapse, especially in semi isolated lines, which explains why the ultimate resolution was not as good as the baseline, where no PAG was added.
In an effort to control PAG diffusion in the UL and still maintain the benefit of decreased $E_{\text{acc}}$ without sacrificing LWR and resolution, a PAG utilizing a bulkier anion was employed. TPS-triflate has been known to have a long diffusion length that can lead to unwanted line collapse and lifting. PAG C1 with a branched multi-fluorocarbon functionalized anion, was used in the following study in comparison with TPS-triflate to see if the selection of PAG would lead to a difference in patterning quality. Wafers were patterned with Resist C. An 11X21 FEM was used, with 40-nm focus step and 0.75-mJ/cm² dose step.

![Figure 7](Image)

Figure 7. Comparison of Resist C performance on BSI.X07333 UL, UL with the triflate, and UL with bulky PAG.

The results are shown in Figure 7, comparing the $E_{\text{acc}}$, LWR, Z-factor, and DOF for UL, UL with triflate, and UL with PAG C1. The results in this test vary slightly from those observed in Figure 4 due to the difference in process conditions used. However, there is still no convincing increase in Z factor from the addition of TPS-triflate to the UL. Focusing on the difference between triflate and PAG C1, it is easy to notice that the UL with PAG C1 did generate an obvious advantage over the UL with triflate PAG. Smoother lines, smaller Z-factor, and bigger DOF for the same $E_{\text{acc}}$. This actually confirmed our initial assumption that by using an equal amount of PAG C1 instead of triflate, the same photospeed increase could be achieved while not greatly impacting LWR and resolution due to a more controllable diffusion length of a bulky anion.

4. Conclusions

In summary, the use of an appropriate UL can clearly impose some benefits on the overall EUVL performance (e.g., slightly decreased LWR), independent of the resist used. There is no direct relationship between film thickness and litho performance. UL bake temperature, on the other hand, can have a significant effect on LWR, ultimate resolution, and DOF. The addition of PAG into an EUV UL reproducibly showed the ability to increase the photospeed of the resists, i.e., 7%-25% in $E_{\text{acc}}$. ULs with PAG (or together with sensitizer) can also reduce footing and scumming between patterned lines, keeping the resist shape more square and straight. However, uncontrolled photoacid diffusion still causes this improvement to be subject to the RLS trade-off by compromising LER and resolution.

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References


