Towards 10 nm half-pitch in EUV lithography: Results on resist screening and pattern collapse mitigation techniques

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ABSTRACT

Extreme ultraviolet lithography (EUVL) is considered to be the most promising option to continue with the aggressive scaling required in high-volume manufacturing (HVM) of integrated circuits. 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 pre-treatment 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 (HP).

Keywords: EUVL, Extreme Ultraviolet Lithography, interference lithography, photoresist, chemically amplified resist, CAR, RLS, line-edge roughness, LER, pattern collapse

1. INTRODUCTION

The 2013 International Technology Roadmap for Semiconductors (ITRS) [1] holds extreme ultraviolet (EUV) lithography as the foremost technology candidate to continue increasing the density of semiconductor devices. In EUVL, light at 13.5 nm wavelength is used, enabling patterning down to single-digit half-pitch feature sizes [2]. In EUV interference lithography (EUV-IL), the 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 image in the resist material. EUV-IL offers several benefits. First, the technique has no depth-of-focus enabling a mask-to-wafer separation of 0.2 – 1 mm. Second, the period of the interference pattern on the wafer is reduced from the pattern on the mask. The theoretical minimum resolution achievable with the technique is around 3.5 nm [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 (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 post-exposure bake (PEB) step altering its 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, line edge roughness 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.

In this paper we have investigated state of the art CARs from our collaborators from around the world. 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) at Paul Scherrer Institute (Villigen, Switzerland) was used. The tool utilizes EUV light at 13.5 nm wavelength from an undulator source of our synchrotron facility (Swiss Light Source). The undulator source offers high brightness and high spatial coherence making the tool well suited for EUV-IL process development and photoresist testing. PSI's EUV-IL tool has demonstrated patterning down to 7 nm half-pitch [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].

The transmission gratings (masks) comprise of HSQ gratings patterned on 100-nm-thick freestanding SiN_x membranes via electron beam lithography. The membrane outside the areas of the gratings is covered by a ~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 typically used for patterning, and therefore the mask pattern resolution is halved on the wafer. This simplifies significantly 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 NA is therefore comparable to the case of bipolar illumination.

All of the wafer processing steps were carried out on-site in a dedicated clean room module in connection with the exposure tool. 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 μm resulting in a typical current of about 13 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 ± 0.1 mm. The images were saved in 1076×768 pixels format. The SEM images fit for further study were pre-screened visually followed by analysis with commercial dedicated image processing software (SuMMIT®) in order to obtain the critical dimension (CD) and LER values.

Figure 1. Scanning electron micrographs of a CAR with line/space 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 HP = 12 nm structures is observed. The scale bars are 100 nm.

3. RESULTS ON EUV RESIST SCREENING

In this chapter we present our latest results on EUV resist screening with a particular focus on achieving the ultimate resolution of the materials. Figure 1 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.

Resist thickness = 30 nm

Figure 2. a) CD and b) LER values versus the exposure dose for a chemically amplified resist. The thickness of the resist was 30 nm.

Figure 2a shows the CD versus exposure dose for a state-of-the-art EUV resist (same as in Figure 1) with a thickness of 30 nm. The analysis was performed for half-pitches in the range of 14 – 22 nm. From Figure 2 it can be seen that the exposure latitude of the resist is rapidly shrinking when moving towards lower HP values. It can also be seen that the dose-to-size values for the different half-pitches are in the range of 33 – 35 mJ/cm². Figure 2b shows the filtered 3σ LER values versus the exposure dose for the same set of data as in Fig 2a. The LER values remain relatively constant at 2.7 – 3.0 nm for the different HPs for a wide dose range, apart from for doses from ~37 mJ/cm² onwards, where a small increasing trend is observed.

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. [9]. The Z-factor (Z) is a resist figure-of-merit based on the RLS parameters as follows:

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

where sensitivity is defined as the dose-to-size. HP is used here instead of blur that was used in the original work of Wallow et al. [9].

Figure 3 shows a general overview of our CAR screening results. The LER values for different resists are displayed as a function of their dose-to-size values (E_{size}) for 1:1 lines/spaces (L/S) at half-pitches of 22, 20, 18, 16 and 14 nm. All the data was 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 resist as well as evaluation of the effect of changes in processing conditions for the same resist. The solid curves in Figure 3 represent constant Z-factors crossing the dots with the minimum Z-factor values, obtained using Equation 3. 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 Figure 3, it is worth pointing out that for current leading resist materials, the LER values do not significantly decrease as HP decreases from 22 nm to 14 nm.

Figure 3. LER vs. dose-to-size for different chemically amplified resists 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.

We have also studied the effect of developer concentration, post-exposure bake time and different combinations thereof on the overall performance of selected high-resolution resists. Figure 4 shows the calculated Z-factor values for three resists (referred here to 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, post-exposure bake times of either 60 or 120 seconds 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 s to 120 s decreases the Z values for HPs of 14, 16 and 18 nm, while they remain unchanged for 20 nm and 22 nm HPs. Figure 4 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 nm and 16 nm HPs [7]. Also, patterning down to 14 nm HP with 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 4. Calculated Z-factor values at different half-pitches for different resists, developer concentrations and post-exposure bake times.

4. 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 sidewalls as the samples are dried after the development and rinse steps [10]. 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 σ_{max} to the resist caused by capillary forces can be expressed as

$$\sigma_{max} = \frac{6\gamma A^2}{D \cos \theta} \quad (4)$$

where θ is the contact angle between the liquid and the resist material [10]. 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) or by enlarging the line spacing 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, Equation 4 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 [11]. Also supercritical drying with CO₂ has been successfully demonstrated to mitigate pattern collapse [12].

Apart from the parameters mentioned in Equation 4, 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. However, one route in avoiding pattern collapse is to use inorganic resist material with mechanical properties superior to those of CARs [13]. 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 5 different underlayer materials when using our top-performing EUV photoresist was evaluated. The results are presented below in Figures 5, 6 and 7.

Figure 5 shows the critical dimension (left panel) and the filtered 3σ LER (right panel) versus the exposure dose at different HP values for the 5 different underlayers characterized here. The resist material and all the processing parameters (post-application bake, post-exposure bake and developing) were identical. As seen in the left panel of 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, small changes in the exposure latitude for the different underlayers can be observed already at HP = 22 nm and moving down towards smaller HP values, these differences become bigger. Only two of the 5 underlayers tested enabled patterning down to 14 nm HP. As can be observed from the LER data (right panel in Figure 5), also these values show a noticeable dependence on the underlayer material. While underlayer E (diamonds in Fig. 5) 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. 3), for example, show a consistent increasing trend. The LER values lie in between 2.5 nm and 4 nm throughout the entire exposure latitude for all the underlayers tested here.

Figure 6 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 nm and 18 nm patterns are observed by naked eye. 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 Figure 7. The Z-factors for all the underlayers and different half-pitches lie in the range of $1 - 4 \times 10^{-8} \text{ nm}^3 \text{ mJ}$. As in Figure 4 above, 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. Therefore, underlayer E is found to be the most promising wafer pretreatment material when aiming at further increasing the resolution of EUV lithography with CARs.

Figure 5. CD vs dose (left) and LER vs dose (right) for different underlayers at different L/S HPs.

Figure 6. SEM images of line/space patterns with half-pitches 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.

Apart from the choice of an optimal wafer pre-treatment, we are currently studying an approach where the capillary forces are completely removed from the post-exposure processing of the wafers via the so called dry

developing and rinse process (DDRP) [14]. In the process, lithography is carried out as usual until the rinsing after development. After that, however, 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 the DDRP process 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 towards 10 nm HP in the near future.

Figure 7. Calculated Z-factor values at different half-pitches for the same resist and processing conditions but different underlayers.

5. CONCLUSIONS

In this paper we reported on our CAR screening work towards achieving the ultimate resolution of these materials. We showed that more resist materials reaching a resolution of 14 nm HP have become available in the last year 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 different developer concentrations and post-exposure bake times have 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 allowing the optimal resist performance. Finally, we introduced pattern collapse mitigation via DDRP process where capillary forces are eliminated from post-exposure wafer processing, enabling us to extend the pattern collapse limited resolution without having to reduce the resist thickness.

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