EUV resists towards 11 nm half-pitch

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ABSTRACT

As extreme ultraviolet lithography (EUVL) prepares for its insertion into the high-volume manufacturing phase, many challenges still remain to be addressed. Among several issues, development of EUV resists with tight specifications of sensitivity (dose), resolution (HP) and line-edge roughness (LER) is required. Chemically-amplified resists (CARs) have been the major paradigm in the development of EUV resists, although several alternatives, such as molecular resists and inorganic resists, are also under development. Here we present a comparative study of the performance of CARs using the PSI's EUV interference lithography tool, which can achieve patterning down to 7 nm HP. Also the current status of EUV resist availability towards 11 nm HP technology nodes is discussed. We show resolution down to 12 nm HP with CARs. Nevertheless, for patterning below 18 nm HP, the resolution is achieved at the expense of sensitivity and LER. The global trend of decreasing sensitivity with increasing LER is valid across the different resists. This trade-off between resolution, LER, and sensitivity (i.e. RLS trade-off) is mainly dominated by the acid diffusion blur and remains a challenge. In addition, pattern collapse becomes a significant problem with increasing resolution. This can be partly overcome by the reducing the resist thickness, which leads to an increase in LER. Therefore, a new trade-off between pattern-collapse limited resolution and LER emerges. These two trade-offs make the progress in EUV resist development increasingly difficult.

Keywords: EUVL, Extreme Ultraviolet Lithography, interference lithography, photoresist, chemically-amplified resist, CAR, inorganic resist, RLS, LWR, pattern collapse, LER, 16 nm HP, 11 nm HP

1. INTRODUCTION

In high-volume manufacturing (HVM) of integrated circuit technology, the state-of-the-art has been DUV immersion lithography. The current feature sizes are well beyond the resolution limit of ArF scanners, which have been possible thanks to the several strategies, such as multiple patterning. Along with this progress, the increasing costs, complexity, and restrictions will make further progress impossible, and therefore EUV lithography (EUVL) is considered as the leading lithography option for future technology nodes. EUVL has made tremendous progress in the last decade, given the facts that many components of its ecosystem did not exist and their development faced many technical challenges. As EUVL prepares for HVM, many challenges still remain, such as source power and mask defectivity [1].

The performance of EUV resists is also one of the key factors for the introduction of EUV lithography HVM. Since EUV lithography aims for high-resolution patterning with limited source power, the sensitivity of the resists is a crucial issue and will probably remain a challenge as the resolution targets increase. The performance of the resist is defined by the parameters of resolution (half-pitch (HP)), sensitivity (dose), and line-edge roughness (LER). The major goal in the resist development is optimization of these parameters where these parameters exhibit a relationship in which they are in trade-off.

This problem is coined as RLS (resolution, LER, sensitivity) trade-off and has been the subject of several studies [2-7]. This trade-off emerges from the fundamental processes involved in the chemistry and patterning of the photoresists, such as photon shot noise, photoacid diffusion, etc. Various approaches have been developed in order to account for the RLS

trade-off. Although more accurate and rigorous formulations of the interdependence of RLS parameters is possible, a simplified approach that has been formulated [4] proposed the so-called Z-factor where

$$Z = (\text{Sensitivity}) \times (\text{LER})^2 \times (\text{HP})^3. \quad (1)$$

Here the sensitivity is defined as dose-to-size. HP is introduced as a substitution to the blur [4], which was the basic parameter in the original work by Gallatin [2]. The power of the Z-factor lies in the facts that it defines a figure-of-merit capturing the overall performance of the resist and it is defined by the parameters that can be easily obtained rather than sophisticated parameters such as effective acid diffusion length, exposure latitude, areal image profile, etc.

The global effort in EUV resist development is mainly focused on chemically-amplified resists (CARs). In this paradigm, the sensitivity is achieved through chemical amplification while acid diffusion leads to blur which limits the resolution and LER. Thanks to the global efforts, significant progress has been achieved in terms of resolution [1, 4, 8-10]. Patterning capabilities of different resist platforms have been demonstrated down 14 nm HP and beyond [1, 10], whereas further optimization is needed, particularly, in LER. In order to ensure timely success of EUV resists with specifications (resolution, dose, LER) close to the targeted values [11], development of high-performance resists should now address the material solutions also for 16 nm and 11 nm HP.

In this paper, we present the status of CARs. An overview on the performance of different resists using the PSI's EUV-IL tool is presented. Main challenges in further improvement of CAR platform is discussed. The current status of EUV resist availability towards 11 nm HP is discussed. We show that the global trend of decreasing sensitivity with increasing resolution is valid and dominated by RLS trade-off. In addition, pattern collapse becomes a significant challenge. This can be partly overcome by reducing the resist thickness, which leads to an increase in LER. Therefore, a new trade-off between pattern-collapse limited resolution and LER emerges. It seems that these two aforementioned trade-offs make the progress in EUV resist development increasingly difficult. We review the status of the EUV-CARs and show that 12 nm HP resolution is already achieved. However, below 18 nm HP, the resolution is achieved at the expense of sensitivity and LER.

2. EXPERIMENTAL DETAILS

This paper presents the results with EUV-IL. We briefly describe the EUV-IL tool at PSI installed at the Swiss Light Source (SLS). PSI's tool is an effective tool for patterning of periodic nanostructures with a resolution beyond the capabilities of other tools. In the past decade it has been successfully used for EUV resist screening and has become a part of the necessary web of supporting technology for EUV lithography. As a result of our continuous effort to improve this method and its relative simplicity, it can pattern down to 7 nm HP, marking the record in photolithography [10, 12-15].

In interference lithography a periodic aerial image is generated by the interference of two or more coherent beams that are diffracted through transmission gratings. The aerial image created by interference has infinite depth of focus, i.e., the aerial image is insensitive to variations between the mask and the substrate as far as there is a sufficient area of overlapping interfering beams. The layout of the XIL-II beamline is shown in Figure 1. The EUV light is generated by the synchrotron source and focused by a toroidal mirror onto a pinhole that serves as a spatial filter. There are also several mirrors, which block the high-harmonics emerging from the undulator. Out-of-band radiation at shorter and longer wavelengths is negligible with this source and combination of mirrors. The bandwidth of the source is $\Delta\lambda/\lambda=4\%$. This is relatively broadband, since we do not need monochromatic beam for interference lithography with diffraction gratings. Another advantage of our source and optics is the tunability of the wavelength. By selecting different mirror configurations and by changing the magnetic field strength of the undulator we can select the wavelength from 2.5 nm to 18 nm. Due to this possibility and availability of broadband diffraction masks [16], we can perform optical lithography in a broad wavelength range, such as BEUV [17].

Figure 2 shows selected pictures of the XIL-II beamline with its exposure, process, and control rooms. The process room is installed in 2010 so that basic preparation and post-processing of the wafers can be done on site. It hosts photoresist developer unit, spin coater, optical microscope, optical thickness measurement tool, wet bench, and hot plates.

Figure 1. The optics layout of the XIL-II beamline at SLS, PSI. The sketch is not to scale. Electrons with 400 mA and 2.4 GeV pass through the undulator generating a synchrotron radiation. The undulator is a series of magnets with 22 pairs and 70 mm pitch. It generates EUV light with high brightness and 4% bandwidth as well as many high harmonic peaks. The light is reflected by 3 mirrors and focused onto the pinhole. Mirrors serve as a cut-off filter in order to suppress the high harmonics of the source. Mirror-1 is a toroidal mirror coated with Ni and deflects the beam by 5 degrees. Mirror-2 is a flat mirror and deflects the beam by 12 degrees. It has two different coatings, i.e. Ni and C. Mirror-3 is, in fact, a triple mirror unit and does not change the beam path. It has 3 Ru-coated surfaces with 7, 14, 7 degrees of grazing incidence angles, respectively. This mirror unit is retractable. The source is tunable by changing the magnetic field strength of the undulator. Switching the coating of the Mirror-2 and retraction of the Mirror-3 enables different cut-off wavelengths. The current setup enables operation in the energy range of about 70-500 eV ($\lambda=2.5-18$ nm). The pinhole serves as a spatial filter and it is switchable to different pinhole diameters of 10 to 100 microns. The beam expands after the pinhole and reaches the exposure chamber and is incident on diffraction gratings at a typical flux of about 35 mJ/cm². The diffracted beams interfere and create an aerial image on the wafer plane.

Figure 2. Pictures from the XIL-II beamline. (a) The endstation with exposure, process, and control rooms. (b) The exposure tool. (c) The developer unit. (d) Spin-coater and the microscope equipped with an optical thickness measurement tool. (e) Chemistry bench. (f) A typical mask, i.e. gratings patterned a Si₃N₄ membrane with a Si frame mounted on a holder. Two hot plates in the process room are not visible on these pictures. The exposure and process rooms are in cleanroom environment with particle and amine filters.

Figure 3. The design of a typical EUV-IL mask (in this case M570) at XIL-II beamline. There are 5 grating pairs (shown in different colors) for every half-pitch of 16 nm, 14 nm, 12 nm and 11 nm. The arrangement of the gratings enable the maximum overlap of the interference patterns at the same gap (mask-to-wafer) for different half-pitches and avoids overlapping of unwanted diffraction orders with the patterning areas.

The flux is measured before the mask with a retractable diode. Depending on the chosen pinhole size and other apertures it is typically about 35 mW/cm^2 . In an experiment, the flux is measured before the start of the exposure and after. A standard experimental run consists of a serial of exposures with different dose values. The dose at each field is controlled via a fast shutter (not shown in the figure) where shutter time is calculated according to the desired dose and measured flux. Since the depth of focus is irrelevant for interference lithography, there is no need for scanning the focus. A typical exposure takes about 1-100 seconds and an experimental run takes about 1-2 hours. The significant part of the time budget is spent for the pump down and venting between the runs, and wafer stage settling between the different dose fields.

Figure 3 shows the layout of a typical mask used for EUV-IL. The masks consist of different diffraction gratings on Si_3N_4 membranes. The gratings are fabricated using e-beam lithography and nanofabrication facilities at PSI. After the fabrication of gratings, the rest of the membrane is coated with a thick metal layer in order to avoid the exposure of patterns with non-diffracting transmitted light. The diffracted beams interfere and create an aerial image on the wafer plane. The masks generally consist of several grating pairs that generate patterns of different half-pitches at a single exposure. The typical tool factors, i.e. the ratio of dose-on-mask to dose-on-wafer, is about 3 to 15, which is determined by the transparency of the Si_3N_4 membranes and the diffraction efficiencies of the gratings. We note that for the same mask, the tool factors for different half-pitches can be different, since the diffraction efficiency of the gratings with different pitches can vary significantly.

We briefly describe our SEM settings, since it impacts the extracted LER values. SEM images are captured using a general-purpose SEM (Carl Zeiss SUPRA 55VP). The in-lens detector is used with a scanning speed of 10 seconds. An acceleration voltage of 1kV is used in order to minimize the electron beam damage. Typical e-beam current is about 13 pA with a 7.5 micron aperture size. Magnification is set to 400 000. Working distance is kept constant at $3 \pm 0.1 \text{ mm}$. Pictures are saved in 1024x768 pixels size. The focus and astigmatism are fine-tuned on the exposed fields and images are captured after moving the stage blindly a few microns to a fresh area in order to minimize the damage. We noticed that the LER decreases with longer exposure times. The analysis of the CD and LER values is performed with a commercial analysis and modeling software (SuMMIT®). LER values correspond to 3σ deviation averaged over 20 lines and on both sides of the lines. A bandpass filter is applied in order to remove the noise floor of the SEM. The cut-off frequencies are 2 and 120 lines/micron. These are the parameters that we used for the obtained results in the next section. We note that our parameters lead to relatively high LER values compared to many reports in literature. It should be kept in mind that for the similar patterning quality, the reported LER values vary significantly. Therefore a direct comparison of results from different reports is subject to considerable errors, in particular if quantitative comparison of Z-factor is aimed.

3. STATUS OF THE EUV RESISTS TOWARDS 11 NM HP

In this section we present the performance of CARs. Our main goal in this study is to present the overview of the results of screening the available EUV resists with particular attention to their performance for sub-16 nm resolution and with the aim of achieving resolution towards 11 nm HP. After presenting the examples of the record resolution achieved by CARs, we illustrate the challenges for further progress.

Figure 4 shows the SEM images of CARs for LS patterns at 14 nm and 12 nm HP, and CH patterns at 18 nm HP. Well-resolved patterns at 14 nm HP were obtained. Although here we show only SEM image of a selected CAR, there are other CAR formulations that are capable of this resolution. At 12 nm HP resolved LS pattern were observed with significant bridging and high LER. CH patterns at 18 nm HP were obtained with low roughness. Below 18 nm HP, significant pattern degradation was observed (not shown in this report). We note that these results mark a substantial progress compared to the status of the global resist development in recent years. However, a comparison to the last one or two years reveals the fact that the progress has been rather small. We would like to illustrate the reasons below.

Figure 5 shows the dose dependence of the critical dimension (CD) and LER for a CAR with two different initial resist thicknesses. In both experiments, the resist was evaluated in the resolution range of 22-12 nm HP. With the resist thickness of 30 nm, CD and LER values were obtained down to 15 nm HP. Beyond this resolution significant pattern collapse was observed. In order to reduce the pattern collapse, the resist thickness is reduced from 30 nm to 25 nm. In this case, patterns down to 14 nm HP were achieved. As seen in the figure exposure latitude decreases with decreasing HP. For the thick resist, dose-to-size values for all HPs are in the range of 35-43 mJ/cm² whereas for the thin resist these values are in the range of 33-40 mJ/cm². This slight difference in sensitivity is in accordance with the general observations and theoretical predictions that with decreasing resist thickness the sensitivity increases.

As seen in the Figure 5, for the 30-nm-thick resist the LER values at different half-pitches remain in the range of 2 nm to 2.5 nm, whereas for the 25-nm-thick resist the LER values increase to about 3-4 nm. A decrease of the resist thickness by 20% lead to an increase in the LER by almost factor 2. On the other hand, smallest resolved patterns decreased from 15 nm to 14 nm HP. This example dramatically shows the problem faced in the challenge of improving the resolution of CARs. With increasing resolution pattern collapse becomes a major limitation. Reducing the resist thickness is not an effective approach. Similar to the RLS trade-off, this challenge can be formulated as the LER-vs-pattern collapse trade-off. Surely, this problem has been recognized by many researchers and has been addressed with different approaches. Although effective methods for pattern collapse mitigation have been developed, these methods provide limited solution to this problem. Therefore, pattern collapse will remain as an increasingly major problem with the progress of the resist development towards higher resolutions.

Figure 4. SEM images of CARs with lines/spaces of 14 nm HP (left), 12 nm HP (middle), and contact holes of 18 nm HP (right) obtained using EUV-IL

Figure 5. Critical dimension (top) and LER (bottom) of a CAR as functions of dose for a thickness of 30 nm (left) and 25 nm (right).

Next, we would like to present a general overview of the resist screening results. Figure 6 shows LER values of different resists or their different processing parameters as functions of E_{size} , i.e. dose-to-size for 1:1 lines/spaces at the half-pitches of 22, 20, 18, 16, and 14 nm. The results shown in this figure were obtained during 2013 and reflect part of the experiments performed with PSI's tool. We should note the fact that all the data is obtained by using the same mask, same SEM conditions, and data analysis. This is a particular uniqueness of the data, since it makes a direct comparison of different materials and processing conditions sound. With this approach, the effects of the tool-related factors (i.e. tool stability, roughness of the mask, and dose calibration) and SEM analysis (i.e. SEM tool and its settings and data analysis software and its parameters) are the same or kept as minimum as possible for all different resists. The solid curves represent the constant Z-factors crossing the dots with minimum Z-factors where Z-factors are calculated using Equation (1) and obtained RLS values. These curves also serves for eye guiding and show the general tendency of the scattered data that with decreasing E_{size} LER increases for all HPs in accordance with the RLS trade-off formulated in Equation (1). A comparison of figures with different HPs reveals that with decreasing HP, the number of data points, i.e. the number resists that achieve the corresponding resolution, decreases. In addition, the average LER increases with decreasing HP.

Since a certain resist can be relatively sensitive, it is important to see the LER values. The Figure 6 provides straightforward overview to judge on the performance of a resist. As discussed in the Introduction, Z-factor is a well-established figure-of-merit to judge the performance of a resist. As mentioned, in Figure 6 champion resists, i.e. resists with the minimum Z-factors are denoted with the constant Z-factor curve.

Figure 6. LER vs. dose-to-size of different CARs or their different processing parameters for L/S patterns of different HPs. The dots represent the obtained LER and dose-to-size values for 1:1 LS patterns of different resists. The solid curves represent the constant Z-factors crossing the dots with minimum Z-factors at the corresponding HP.

Figure 7. Measured Z-factors of different CARs as a function of HP. The values are obtained from Figure 6 and using Equation (1).

Figure 8. Minimum Z-factor obtained for different half-pitches. The data is extracted from Figure 7.

In Figure 7, the Z-factors of individual resists are plotted as functions of HP. It shows that in the range of 22-18 nm HP the minimum Z-factor is obtained for a single resist. Below 18 nm HP this resists show pattern collapse. For 16 nm HP and 14 nm different resists show the minimum Z-factor. An interesting observation in Figure 7 is that the Z-factor decreases with decreasing HP for the majority of the resists. Ideally, a conclusive figure-of-merit should account for the resist performance independent of the HP. It seems that Z-factor overestimates the contribution of the HP in its form expressed in Equation (1).

The minimum Z-factors, $Z_{\min}$, obtained at different HPs are plotted in Figure 8. This figure is the culmination of all the data presented in Figures 6 and 7. The figure can be seen as the representation of the state-of-the-art in resist development. As seen in Figure 8, the $Z_{\min}$ values decrease with decreasing HP and reach a minimum at 18 nm HP and increase below 18 nm HP. There is a clear trend change at 18 nm HP, which requires some explanation. Firstly, we note that this data is only part of the results from the resist screening experiments performed with a single tool, i.e. PSI's tool. Therefore, the limited data does not reflect the global status of EUV CARs and cannot account for the state-of-the-art. Nevertheless, the data includes materials developed by many of the major resist suppliers. Moreover, our resist screening efforts mostly aim for obtaining highest resolution and therefore there might be other resists which show good performance at low-resolution, i.e. 22-20 nm HP, but not represented in this data. In addition, there is also the contribution to the Z-factor from the tool. Therefore, the same figure, i.e. $Z_{\min}(\text{HP})$, will look different for the data obtained with other tools. It would be also interesting to compare the data obtained with different tools. We believe that interference lithography is particularly advantageous in the studies of HP-dependent effects, since the aerial image of interference lithography is HP-independent in terms of profile and contrast.

Keeping these facts about the possible sampling bias and tool factors in mind, we can still make some general conclusions from the limited but rather representative data. The decrease in $Z_{\min}$ down to 18 nm HP can be attributed to the dependence of Z-factor on HP. In fact, $Z_{\min}$ in the range of 22-18 nm HP is represented by a single resist and for this one like the most of the resists, the Z-factor decreases with decreasing HP. Despite this fact, there is a trend change at 18 nm HP. This shows that the current status of EUV resists are relatively mature down to 18 nm HP and below this resolution substantial improvement of resist performance is needed. Moreover, the observed trend down to 18 nm HP can be seen as the manifestation of the RLS trade-off. This can be a result of the global effort where the most of the available tools have good contrast at this range. Therefore, developers optimize the resist formulations and their processing according to the available tools. Nevertheless there is another important conclusion that can be drawn from these results. As mentioned, the status of the EUV resists down to 18 nm HP can be seen as a consequence of RLS trade-off. Below this range other phenomenon that cannot be accounted for in the RLS trade-off becomes the dominating factor. Namely, LER-vs.-pattern collapse limits the performance of the resists. With increasing resolution, the resists with low Z-factors phase out due to the pattern collapse limiting the number of resists that has simultaneously low Z-factor and good mechanical stability. Alternatively, the thickness of the resists has to be reduced in order to avoid pattern collapse leading to an increase in LER and thereby in Z-factor.

4. CONCLUSIONS

In this report we presented an overview of the CARs in the resolution range of 22-12 nm HP. Resolved patterns down to 12 nm HP have been achieved. A comparative study of EUV CARs resulting from part of the resist screening activities with PSI's tool shows that the current status of the EUV resist development is highly advanced and significant progress has been achieved in the last decade in term of resolution. An analysis of the results from the point of Z-factor reveals that the performance of the resists for sub-18 nm HP range tends to decrease. This can be due to the fact that there is a new challenge for the resist development in addition to RLS trade-off. This challenge is the trade-off between pattern-collapse and LER, i.e. PC-LER trade-off. As the traditionally adopted resist thickness become difficult to sustain with increasing resolution, resist developers adopt thinner resists. Pattern collapse mitigation methods are surely important but they provide a minor solution only. This new trade-off may hinder or slow down the further progress needed.

In retrospect, Z-factor has been very successful in accounting for the performance of the resists, although it is relatively simplified formula to account for highly complex and multitude mechanisms. It is difficult to monitor the past progress of the resist development in terms of Z-factor, since the huge bulk of results reported in the literature were obtained with different tools and the reported LER values highly depend on the analysis. For example, Z-factors of 7.8×10^{-8} mJ nm³ have been reported in 2008 [4]. In 2011, Z-factors of 7.8×10^{-8} mJ nm³ have been reported at 32 nm HP [6]. In this study we report Z-factor of 0.84×10^{-8} mJ nm³ at 18 nm HP. These results show that there has been certainly a progress in resist development. However, the development has been mainly in resolution and the progress in terms of Z-factor has been relatively small compared to the optimistic roadmaps targeting Z-factors in the range of 10^{-10} mJ nm³. A better understanding of RLS trade-off and ultimate limits of achievable Z-factor may help to develop more realistic targets for the EUV resist development. Effective pattern collapse mitigation and LER reduction methods will improve the Z-factor. Alternative resist platforms such as molecular resists and inorganic resists may enable lower Z-factors and create a new momentum in EUV resist development.

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