Patterning at 6.5 nm Wavelength Using Interference Lithography

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ABSTRACT

We present the results of patterning chemically-amplified and inorganic resists at 6.5 nm wavelength using interference lithography. Well-resolved patterns down to 22 nm HP are obtained. Dose-dependent line-edge roughness and critical dimensions in the resolution range of 50-22 nm half-pitch are obtained using 13.5 and 6.5 nm wavelength. The performances of the resists are compared for both cases. Increased line-edge roughness is observed for patterning 6.5 nm compared to the patterning at 13.5 nm wavelength.

Keywords: Extreme Ultraviolet Lithography, Beyond Extreme Ultraviolet Lithography, EUV, BEUV, 6.x nm lithography, HSQ, organic resist, inorganic resist, interference lithography, soft X-ray, 22 nm HP, chemically-amplified resist.

1. INTRODUCTION

Optical lithography has so far been the major patterning method in semiconductor manufacturing, which over the years has followed scaling down the feature size and has made high-throughput manufacturing possible. Further downscaling with optical lithography has been facing significant challenges, which have been overcome with immersion lithography, double patterning, etc. For future technology nodes extreme ultraviolet lithography (EUVL) at 13.5 nm is the most promising candidate. In the past years much effort has been dedicated to developing different areas of this technology ranging from photoresist to optics and light sources [1].

Since the feasible numerical aperture (NA) of reflective EUV optics will be limited to 0.5 or 0.6 NA, it can only go down to 8 or 7 nm HP with single patterning. From the optics point of view, the resolution can be further increased by reducing the wavelength. Beyond EUV (BEUV) lithography at 6.x nm has been suggested as a potential wavelength of choice for reaching future single-digit nodes [2, 3]. In addition to feasibility of light sources [2], efficient reflective optics [4, 5] can be also designed for this wavelength range. Nevertheless, the issue of appropriate photoresists for this wavelength and their patterning capabilities should be addressed for a general assessment on the feasibility of BEUVL for future technology notes [1]. In addition, lithography at wavelengths different than EUV can provide significant insight into the governing mechanisms and effects in patterning, such as shot-noise, quantum efficiency, secondary electron blur, etc.

At the XIL-II beamline of the Swiss Light Source (SLS) at Paul Scherrer Institute, Switzerland we have a platform for high-resolution EUV interference lithography (IL) [6]. Since this tool uses a synchrotron source from an undulator and grazing angle mirrors, we can change the wavelength easily in the range of 15 nm to 2.5 nm. The interference pattern is created by diffractive transmission gratings, which can operate in a broad range of wavelengths.

In this article we report first quantitative results on patterning of EUV photoresists at 6.5 nm. We demonstrate patterning of an inorganic resist and a chemically-amplified resist (CAR). We performed a comparative study with EUV and BEUV using the same mask. In both cases for both CAR and non-CAR resists we achieved well-resolved patterns down to 22 nm resolution. With BEUV lithography we observed an increase in the LER compared to EUVL.

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2. BEYOND EUV LITHOGRAPHY AT XIL

At the XIL-II beamline we perform EUV-IL for various applications. The principle of IL is shown in Fig. 1. A collimated spatially coherent beam is symmetrically diffracted by a set of gratings, fabricated on top of a Si$_3$N$_4$ membrane. At a certain distance from the mask surface the first-order diffracted beams interfere, forming a transverse standing wave. Using IL we have shown patterning of high-resolution periodic nanostructures on various photoresists [6, 7] and more recently the possibility of also fabricated quasi-periodic structures by using masks with phase-controlled grating layouts [8]. IL is optics-free with no depth of focus, which makes it an effective method for minimizing instrumental errors and consequently an efficient way of reproducible patterning for testing photoresists.

An effective photon stop is an essential part for such and interference scheme in order to eliminate non-diffracted photons to expose the photoresist at the region of interest. Since BEUV is more transparent to most of the materials and also leading to more photon damage than EUV, we had to improve our mask fabrication in order to achieve better central stop and diffraction gratings that have a high diffraction efficiency at BEUV wavelength. Therefore we could not use our EUV masks and had to fabricate dedicated masks for this purpose.

The aerial image created by diffractive gratings is a sinusoidal modulation and is pitch-independent. In addition, this aerial image is wavelength independent, i.e. achromatic. The pitch of the aerial image, $p$ is given by:

$$p = \frac{\lambda}{2\sin(\theta)} = \frac{g}{2m},$$

where $\lambda$ is the wavelength, $\theta$ is diffraction angle, $g$ is the pitch of the grating mask and $m$ is the diffraction order. In most cases, we use the interference of the first-order diffraction beams leading to two times reduction in pitch on the wafer. This formula also shows that the pitch of the aerial image is defined by the mask and is independent of the wavelength. Therefore, we can use the same mask for different wavelengths and the contrast and the pitch of the aerial image will be identical at different wavelengths. The major difference in changing the wavelength is the tool factor, i.e., the ratio of the dose on mask to dose on wafer, which is defined by the transmission of the Si$_3$N$_4$ membrane and the diffraction efficiency of the gratings.

<table>
<thead>
<tr>
<th>Table 1. Process parameters of Resist-A and HSQ.</th>
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<tr>
<td>Resist name</td>
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<tr>
<td>Resist-A</td>
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<tr>
<td>HSQ</td>
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Since we aim for the direct comparison of EUV and BEUV lithography, for both EUV and BEUV exposures we used the same mask in order to minimize any uncontrolled effect. Our masks design for this study consists of SiO$_2$ gratings of 100 nm thickness and are fabricated on 130-nm-thick Si$_3$N$_4$ membranes by patterning HSQ photoresist with electron-beam lithography. This mask configuration efficiently diffracts for both wavelengths of interest. The gratings are made with half-pitches of 100, 70, 50, and 44 nm which are estimated to have a diffraction efficiency of about 5-10%. These gratings consequently produce lines with half-pitches of 50, 35, 25, and 22 nm on the wafer. The photon stop between the gratings are made of gold and are grown by electroplating. In comparison to EUV and soft x-ray, Au is less absorbing at BEUV. Nevertheless, by electroplating of Au up to 500 nm thickness, direct photons are effectively blocked. In this study we focus on using a two-grating interference system resulting in line/space patterns on the wafer. We limited ourselves to resolution down to 22 nm in order to avoid tool-related artifacts, which should be negligible at this resolution.
3. RESULTS AND DISCUSSION

We test a positive-tone, organic chemically amplified resist (CAR) from Shin-Etsu, referred to as Resist-A and hydrogen silsequioxane, HSQ (Dow Chemicals XR-1541), a non-CAR negative-tone silicon-based inorganic resist. In this regard we evaluate the pattern quality when exposing the same resist with the same mask with EUV and BEUV, by comparing the dose-dependent average critical dimension (CD) and line-edge roughness (LER). In previous studies we have seen that both resists could be used for high-resolution EUV lithography and can provide sub-20 nm resolution. Table 1 shows process parameters for these two resists. Resist-A is specifically interesting for EUV lithography due to its high resolution and sensitivity. SEM images were taken at the same magnification, working distance, and acceleration voltage. CD and LER values were obtained using a commercial analysis and modeling software (SuMMIT ®).

The results of patterning Resist-A are shown in Fig. 2. As it can be seen in the SEM images, well-resolved lines could be patterned at both wavelengths down to 22 nm HP. The dose dependence of CD for both cases follows the similar trend as that reported in earlier studies for EUV, performed by different masks [6]. In general, for this positive-tone photoresist the CD decreases with increasing dose, and the exposure latitude are not significantly different in both cases. We point out that the dose values reported in this work refer to dose on mask and the tool factors for two different wavelengths should be significantly different and also dependent on the half-pitch. We observe that the dose values for BEUV are significantly higher than for EUV. Although the grating diffraction efficiency is slightly larger for BEUV, the Si3N4 membrane transmission is ~2.7 times smaller, resulting in the features to show up at higher doses for BEUV. In addition, relative insensitivity of the resist for BEUV, contributes to the fact that the dose to size values for BEUV are about 14 times higher than for EUV. Assuming that the diffraction efficiencies are not significantly different at large half-pitches and taking the transmission of the membrane into account, we estimate that the dose to size value for BEUV is about 5 times larger than for EUV. A theoretical estimation of the relative sensitivity at BEUV wavelength can be made by simply comparing the mass attenuation coefficient ratio at the two wavelengths [9]. For a typical organic resist such as PMMA that contains mainly O and C, the sensitivity ratio for BEUV to EUV is 4.91. As it can be seen, the above estimated relative dose-to-size, 5 is in accordance with this calculated sensitivity ratio. The exact formulation of Resist-A is unknown. The associated tool factors as well as the dose-to-clear of the resist obtained by open-frame exposures at two wavelengths involve accurate measurements that will be reported in future publications. By taking these factors into account precise estimation of the sensitivity can be made. We also note that the diffraction efficiencies at different half pitches can be different. As seen in the Fig. 2, for the half-pitch of 22 nm, the diffraction efficiencies at EUV and BEUV are different than that of other half-pitches. This leads to different dose values for 22 nm HP. Therefore, the only parameters that we can compare and draw conclusions from are the exposure latitude and the LER values. The exposure latitudes, i.e. total CD variation, in both cases are rather similar. In general, for BEUV exposures the mean LER values are clearly higher than that of the EUV case. For instance, LER at 22 nm HP for BEUV is about 40% larger that for EUV.
Figure 2. Patterning Resist-A at four different half-pitches ranging from 22 nm to 50 nm at BEUV and EUV. Average critical doses (CD) and line-edge roughness (LER) were obtained by calculating these quantities over an ensemble of SEM images of exposed patterns.
Figure 3. SEM images, CD vs. dose values, and LER vs. dose values for HSQ resists at four different half-pitches ranging from 22 nm to 50 nm for BEUV and EUV.
HSQ is a negative-tone photoresist that is suitable for high-resolution patterning with EUV lithography as well as electron beam lithography. In Fig. 3 the results of patterning with this resist at the two wavelengths are shown. The SEM images show that patterns could be made down to hp=22 nm for both wavelengths. Since HSQ is non-CAR, the dose values are significantly higher than that for a CAR at both EUV and BEUV wavelengths. The exposure latitude with HSQ is larger than that of the CAR, as expected. The average LER values at 22 nm HP are about 2 nm and below for the EUV exposures while for the BEUV exposures it is slightly larger compared to EUV.

The mass attenuation coefficient ratio of EUV to BEUV for this resist is 0.86, i.e. this resist is more absorptive at BEUV than at EUV, contrary to organic resists. To provide a theoretical estimation on the relative sensitivities, in Table 2 we have summarized the mass attenuation coefficient of HSQ and PMMA, a non-CAR organic resist.

<table>
<thead>
<tr>
<th>Resist</th>
<th>EUV attenuation length (μm)</th>
<th>BEUV attenuation length (μm)</th>
<th>EUV/BEUV mass attenuation coefficient</th>
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</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>0.191</td>
<td>0.938</td>
<td>4.91</td>
</tr>
<tr>
<td>HSQ</td>
<td>0.114</td>
<td>0.098</td>
<td>0.86</td>
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</table>

4. CONCLUSION AND OUTLOOK

We have shown first results of patterning with BEUV at 6.5 nm wavelength. Well-resolved patterns down to 22 nm half-pitch were obtained for an inorganic resist and an EUV CAR resist. We observed an increased LER for BEUV compared to EUV for both CAR and non-CAR. From the LER point of view, the CAR has a significantly better performance at EUV while HSQ provides equally high quality patterning at EUV and BEUV. This shows that this CAR has been optimized for best performance at EUV. From the theoretical mass attenuation coefficient ratio it could be predicted that a carbon-based resist requires higher dose for BEUV lithography, while for a silicon-based resist it requires slightly less due to the relatively high absorption of Si at 6.5 nm.

The increase of LER with decreasing wavelength might be a result of photon shot noise. Further studies should evaluate this effect in detail in order to reach a clear conclusion. In particular, stochastic simulations may provide further insight into such effects. Comparative experimental and theoretical studies on the LER at different wavelengths can assist better understanding of photoreactions and resist dynamics [11]. The reported results in this work provide a basis for such studies.

Most CARs are organic based which have low absorption at BEUV. Therefore, a major challenge in the realization of BEUV lithography involves developing new CARs with better performance, i.e. LER, resolution, and in particular sensitivity.
REFERENCES