Sequential Infiltration Synthesis for Line Edge Roughness Mitigation of EUV Resist

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It is well known that high line-edge roughness (LER) and line-width roughness (LWR) are one of the key problems hindering utilization of extreme ultraviolet lithography (EUVL) in fabrication of semiconductor devices at advanced technology nodes where pattern with sub-20 nm half pitch lines and spaces is required. Sequential infiltration synthesis (SIS) has never been used before in lithography for line-edge roughness mitigation, but this concept has proved its value for 14 nm half pitch block copolymer lines formed by directed self-assembly. During this process an inorganic scaffold is being deposited inside the resist material after performing several sequential infiltration cycles with metal-organic precursor and its oxidizing agent. Etching in oxygen atmosphere after is required to transform former resist pattern into metal oxide one and improve (up to 40%) the pattern roughness. In this paper, for the first time we demonstrate feasibility of sequential infiltration synthesis (SIS) for smoothing of EUV resist lines.

Keywords: SIS, EUV photoresist, Line-edge roughness

1. Introduction

Among the challenges impeding introduction of extreme ultraviolet lithography (EUVL) to manufacturing processes at advanced technology nodes, high line-edge roughness (LER) and line-width roughness (LWR) are the most crucial ones from a materials standpoint. Line-edge/width roughness has high impact on the electrical properties of the device [1] and as feature sizes are getting smaller in EUV lithography, LER and LWR need to meet much tighter specifications. The current state-of-the-art in EUVL for 3σ LWR and 3σ LER for 16 nm resist lines is 4.5 nm and 3.0 nm respectively. Meanwhile, LWR below 10% of line’s width after pattern transfer are required for implementation in chip fabrication process.

A number of approaches have been developed to address high line-edge roughness problem. Part of them is aimed at optimization of EUV resist composition and processing conditions during the lithography step. In this group of methods such factors as molecular size, protection ratio, PAG diffusion length and concentration are considered for optimization of the photoresist performance [2-5]. Other techniques for line-edge roughness mitigation rely on the smoothening effect of plasma treatment and ion bombardment [6-9]. Though great progress has been achieved in both directions, these methods cannot provide sufficiently low LER and LWR values for sub-20 nm half pitch features. In this paper, we introduce a method utilizing deposition approach – the sequential infiltration synthesis (SIS) - as new smoothening technique for EUV photoresist.

The idea of SIS has been adopted from atomic layer deposition (ALD) – a surface technique allowing growth of the inorganic layers with atomic-level precision through alternating exposures to the precursors vapors [10]. The key distinction between the ALD and SIS techniques is
that the latter one can provide the bulk synthesis of the inorganic material when employed on polymers (or any other porous structures) [11-13]. For that the precursors exposure times are extended in SIS compared to ALD to facilitate diffusion into the volume of the organic film. Polar functional groups of the polymer layer help to the precursor molecules to attach inside the layer through chemical reaction or physisorption mechanism [14,15].

Though SIS has never been used before in lithography for line-edge roughness mitigation, this concept has proved its value as an effective technique for the photoresist hardening [16,17]. An increase in etch resistivity can be attained, for example, through functionalization of the organic material with silicon through soaking in hexamethyldisilizane (HMDS). This method called silylation was first introduced by Roland et al in 1985 in DESIRE [18] process and later utilized in it derivatives - PRIME, SUPER, SAHR and other processes [19-21]. When SIS is followed by ashing step it can be used to form 3D structures using different resist pattern as a template. Recently Dandley et al showed that patterned with e-beam lithography poly(methyl methacrylate) layer can be converted into aluminum oxide that precisely mimics the original features [22].

For the line-edge roughness improvement effectivity of SIS has been first demonstrated for 14 nm lines formed by directed self-assembly of poly(methyl methacrylate)-b-polystyrene block copolymer [23]. The results of our preliminary study with EUV resist also showed considerable decrease of the LER/LWR values for 22 nm lines, but to develop the proposed approach into efficient and reliable technique, SIS needs to be understood at fundamental level and qualified for implementation into EUV lithographic processes. Here we report the first results in this direction.

2. Experimental

Exposures have been performed on the ASML NXE:3300 scanner, interfaced with TEL LITHIUS PRO Z track for resist coating and development. For line-space patterning free form illumination at NA=0.33 was used. All the samples were coated with imec POR resist on bare silicon wafer. The thickness of the resist was 45 nm.

SIS has been carried out in ASM deposition tool with the use of aluminum precursor and oxidizing agent. To remove the resist material after the SIS ashing in O2/Ar plasma was performed in TEL’s etch chamber.

The lines width (CD), 3σLER, and 3σLWR before and after SIS have been measured using Hitachi’s CG-5000 scanning electron microscope (CD SEM) using square and rectangular FOV respectively. Frequency analysis was performed on CD-SEM top-down images with LERDEMO software, developed by Demokritos National Center for Scientific Research.

3. Results and discussion

The SIS process we study in this work is schematically shown in Fig. 1 in parallel with the results of X-SEM inspection. During the SIS process the resist pattern is subjected to several sequential infiltration cycles during which the material first is fully soaked with trimethylaluminum (TMA) (1st half-cycle) and then exposed to its oxidizing agent – water (2nd half-cycle). Between the half-cycles the reaction chamber is purged with nitrogen to remove unreacted precursor and products of the chemical reactions. The results of the SEM inspection at this stage show that after the infiltration with TMA vapor, increase of the lines width and height occurred due to swelling of the photoresist but no line-edge roughness improvement is observed at this stage.

As a result of the TMA and water diffusion into the bulk of the polymer followed by chemical reaction between them, aluminum oxide is deposited within the resist pattern forming an inorganic scaffold – a network of AlOx distributed through the resist lines. Ashing step in O2/Ar plasma is applied afterwards to selectively etch the organic part and to convert EUV resist pattern into the metal oxide one. During that step, considerable line shrinkage is observed due to the densification of alumina framework. From X-SEM inspection (Fig. 1) it is evident that lines reduce their size in vertical and lateral direction. The shrinkage is accompanied by line smoothing with a decrease of LER/LWR values.

To have better control over the SIS process in regards to smoothening, we investigated the influence of a number of infiltration and ashing parameters on the line-edge roughness of the EUV resist lines. For convenience, we will refer to them as process A, B and C. Process A corresponds to “long SIS” and “short ashing” afterwards, process B – to “short SIS” and “short ashing”, and process C – to “long SIS” and “long ashing”. The results of this study show that effectivity of SIS can be increased by adjusting the processing conditions.
Figure 1. Schematic representation and corresponding XSEM images of the process for SIS of alumina in EUV resist.

Figure 2 indicates that process C allowed the best conditions for smoothening. However, it caused considerable line shrinkage, which reached 60% for 26 nm lines.

To further illustrate the impact of SIS on line-edge roughness the power spectrum density (PSD) analysis has been performed which allows to determine if the dominant input to LER/LWR values is due to changes in high, mid- or low-frequency range of spatial wavelengths. Results plotted in Fig. 3 were obtained for line-space pattern with original CD of 26.3 nm and pitch of 44 nm after process B, corresponding to “short SIS” and “short ashing” conditions. These results show that SIS improves roughness in mid-, but also in a challenging low frequency range.
Fig. 3. PSD plot for the LER and LWR before and after SIS. Solid line is for original resist pattern with 44 nm pitch; dashed lines are for alumina pattern obtained after SIS.

4. Conclusion

The first results of utilization of SIS process for smoothening of EUV lines demonstrate its effectiveness for line space pattern with 44 nm pitch. The technique allows up to 40% LER/LWR improvement mainly in low- and mid-frequency range. Line-edge roughness improvement relies on the shrinkage of the inorganic network which also leads to considerable CD decrease. The smoothening performance depends on infiltration and ashing conditions. Considering complexity of the infiltration and shrinkage processes, more understanding of the influence of processing parameters and resist structure is required to explore possibilities of smoothening with minimization of CD reduction.

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