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Mask roughness impact on extreme UV and 193 nm immersion lithography

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ABSTRACT

The contribution of mask absorber line edge roughness on printed resist lines is studied for extreme UV and 193 nm immersion lithography. Programmed roughness modules were designed for roughness transfer function evaluation on 88 nm pitch line space patterns. The tested modules were designed applying variations of roughness amplitude and spatial frequency. Power spectral density analysis was performed on top-down SEM images. The effect of frequency roughness filtering by the lithographic optical system was studied with different illumination settings. It was found that, except for the degradation of the aerial image due to the filtering effect, less performing illuminations show an increased deterioration of the aerial image quality and thus contribute further to line edge roughness. A comparison with previous work was completed on different mask architectures and photoresist platforms. Resist performance can attenuate the roughness transfer from mask but at the cost of worse chemical gradient at the edges of the exposed regions.

1. Introduction

Roughness of printed features is a main issue that needs to be overcome by the semiconductor industry for the coming technological nodes. Depending on the lithographic platform, roughness originates from different causes, including aerial image quality, resist performance and mask quality. This study focuses on roughness transmission through the lithographic optical system.

Following previous work [1], a reticle with programmed roughness was designed for roughness transfer function evaluation [2], for both ArF and Extreme UV (EUV) lithography. Both correlated and anti-correlated roughness on 88 nm pitch structures were considered (Fig. 1). The tested modules were designed with varying roughness amplitude and spatial frequency. Power Spectral Density (PSD) analysis [3] was performed on top-down SEM images with the LERDEMO [4] software developed by NCSR Demokritos.

This paper is divided in two parts. The first deals with 193 nm immersion lithography, where the influence of illumination shape and symmetry on the transfer of mask features on resist is examined. The second part focuses on EUV lithography. Two resist platforms and two EUV reticles with programmed absorber roughness were exposed and compared in terms of spatial frequency analysis of the patterned features.

2. Experimental details

Vertical 88 nm half pitch Lines and Spaces (L/S) with different roughness amplitudes and frequencies were considered for this work. The chosen roughness amplitudes and frequencies are reported in Table 1. Line Width and Edge Roughness (LWR, LER) measurement were performed on top-down SEM images of 2 μm long lines, using rectangular Field of View (FoV), to capture LF resist roughness [5]. For ArF exposures, 105 nm thick resist on 37 nm organic Bottom Anti Reflecting Coating (BARC) was exposed on ASML XT:1900i scanner with the illuminations reported in Table 1. EUV exposures were done on the ASML Alpha Demo Tool (ADT) installed at IMEC, with a film stack consisting of 60 nm resist on 20 nm BARC, exposed with conventional illumination of $\sigma = 0.5$ at 0.25 Numerical Aperture (NA).

Pattern transfer fidelity strongly depends on the resolution of the optical system. The physical limits of any optical system are fundamentally connected to diffraction phenomena. The optical system can act as a “filter” depending on the pitch of the features on mask [1,2]. For the simple case of a L/S array, one can define a set of frequency limitations outside of which the imaging of periodic mask features is no longer possible. These limits, for the case of XY symmetrical illumination (e.g. c–Quad) are described by the following equations:

$$f_{max} = \frac{NA * (1 + \sigma_{out})}{\lambda} \quad (1)$$

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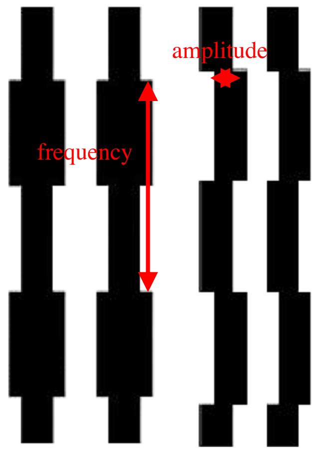

Fig. 1. Design of the programmed roughness features for the anticorrelated (left) and the correlated (right) cases.

$$f_{min} = \frac{NA * (1 - \sigma_{out})}{\lambda} \tag{2}$$

where NA is the numerical aperture, σ [8] is the partial coherence (or fill factor) of the illuminator and λ is the wavelength of the illumination. f_{min} is the lowest frequency limit at which the 1st diffraction order is not anymore fully collected by the pupil (aerial image distortion) and f_{max} is the highest frequency limit, above which the 1st diffraction order is completely outside the pupil (flat aerial image). This is graphically represented in Table 1. The values of the cut off frequencies are shown in Table 1.

3. Results and discussion

The spatial frequency analysis was done with LERDEMO, averaging 30 SEM images for each case. From the outputs of the edge detection analysis the PSD graphs were plotted and thus mask LER (LER_M) contribution with respect to the optical system cut off was examined. According to Parseval's theorem, the area enclosed by the PSD curve and the frequency axis is proportional to the square of the LER value.

Depending on the chosen amplitude and frequency pattern, μ-bridging and extensive pattern collapse were observed for the extreme LER_M modulations. This was particularly present for the anticorrelated (Fig. 1, left) roughness modulation and at large amplitudes. Along the L/S direction, space Critical Dimension (CD) is strongly modulated, and the resolution is compromised. Those images were not considered in our PSD analysis. Due to the above, for the rest of this study only correlated roughness modules were considered (Fig. 1, right).

When LER_M structures with a defined pitch were imaged into the photoresist, clear peaks in the PSD analysis were noticed for those LER_M pitches which correspond to $f < f_{max}$. Since the PSD chart represents a spatial frequency view of the printed features, any perturbation on the edges (i.e. programmed roughness) is registered as an additional frequency component of the mask structure. An imaged roughness pitch corresponds to the entry of at least one diffraction order, besides the 0th, in the pupil. When more relaxed roughness pitches (i.e. lower frequencies on the PSD chart) were considered, multiple peaks due to the collection of higher diffraction orders were noticed in the PSD curves.

3.1. 193 nm Immersion exposures

A detrimental effect of the aerial image is connected with the optical system imaging ability along the edges of mask lines: mask absorber LER is imaged by the optical system and transferred on wafer as resist LER. The same resolution limits that govern the imaging of L/S patterns also apply on roughness, since it can be considered as deviations from the desired CD along the line edges. The Normalized Image Log Slope (NILS) [6] is an useful parameter to evaluate the quality of aerial image. LER is greatly affected by the resolution of the line edges as they are the physical boundaries between soluble and insoluble resist areas [7]. This effect is evident for roughness frequencies higher than the cut off, for any type of illumination (Fig. 2).

The resolution of the illumination along the direction of the roughness plays an important role when considering the transfer of native mask roughness to wafer LER. In the case of XY symmetric illuminations (e.g. conventional, c–Quad20) there is no resolution reduction when roughness is concerned, but for asymmetric illuminations (e.g. Dipole90X) the imaging ability is low. This effect,

Table 1
Diffraction order positioning on the imaging pupil plane, depending on roughness frequency. Only the + 1 diffraction orders are shown for simplicity. The orientation is on the Y axis since the features of interest are the roughness modules, which are perpendicular to the direction of the line (Fig. 1). The SEM images for the frequencies examined are also shown. The programmed roughness amplitude in these images is 11 nm for the ArF exposures and 9 nm for the EUV exposures.

Freq.	193 nm immersion		EUV
	Dipole $\sigma_{in} = 0.55$ $\sigma_{out} = 0.75$	C Quad σ_{in}=0.82 σ_{out}=0.97	Conventional $\sigma = 0.5$
f_{min}	2.11 μm^{-1}	0.21 μm^{-1}	9.26 μm^{-1}
f_{max}	9.66 μm^{-1}	13.78 μm^{-1}	27.78 μm^{-1}