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Imaging properties of a patterned rough surface: effects of roughness correlation and partial coherence

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Abstract. An investigation of partially coherent speckle is performed, including the effects of a pattern structure in the object plane of an imaging system. It is demonstrated that, when forming an image of a patterned rough surface into a binary photoresist, the width variations produced in the resultant pattern (also called line edge roughness) can increase as the imaging system becomes more incoherent. This unusual behavior occurs because of an interaction between the speckle produced by a rough surface and the partially coherent imaging properties of the pattern structure. It is shown that the increase in line edge roughness for a more incoherent system requires that the surface roughness of the object structure have a correlation length that is substantially smaller than the resolution of the imaging system. [DOI: 10.1117/1.1948398]

Subject terms: imaging; coherence; roughness; microlithography.

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1 Introduction

Newly developed imaging systems, operating in the extreme ultraviolet (EUV) spectrum, are designed using entirely reflective multilayered optical elements. Due to the extremely short wavelengths these systems are designed for, surface roughness, including the roughness introduced by the multilayer deposition process, is a substantial concern.[1,2]

Because the patterned mask structure used in partially coherent EUV microlithography systems is a reflective element with a substantial amount of roughness, partially developed speckle is produced in the image plane. This effect was predicted by Beaudry and Milster[3,4] and later observed by Solak et al.[5] A substantial amount of work was done in the 1970s investigating the imaging properties of partially coherent speckle.[6–11] However, the authors believe that this initial work requires additional development to be completely applicable to the EUV microlithography systems currently under development. This publication expands the current theoretical understanding of partially coherent speckle to include the effects of a pattern structure, as well as the interaction of the correlation length of the surface roughness with the partial coherence of the illuminating optical field. Furthermore, the effects of partially coherent speckle on the pattern produced in a binary photoresist are also investigated.

Theoretical modeling and computer simulation are the primary tools used in this investigation. Modeling the statistical parameters in a computer is highly advantageous, since it allows a substantial amount of control over the statistical parameters of a rough surface. This level of control over parameters, such as correlation length and rms roughness, affords considerable understanding of the physical nature of this inherently statistical problem, and is often very difficult to achieve experimentally.

Section 2 of this article uses the theoretical framework developed by Fujii and Asakura[7] to analyze the relationship between surface roughness correlation and the coherence of the illuminating optical field, and their effects on the partially coherent speckle contrast in the image plane. Section 2.2 continues this analysis to investigate the inclusion of a pattern structure in conjunction with the rough surface in the object plane. This analysis includes the effects of the partially coherent speckle on the pattern produced in a binary photoresist. In Sec. 3, a two-dimensional Monte Carlo simulation is performed that further reinforces the theoretical predictions made in Sec. 2. Conclusions are presented in Sec. 4.

2 Theory

The effect of a slightly rough surface on the electric field reflected from a structure is modeled as

$$E(\mathbf{r}) = E_0(\mathbf{r}) \exp[i\phi(\mathbf{r})], \tag{1}$$

where the random phase function $\phi(\mathbf{r})$ is

$$\phi(\mathbf{r}) = \frac{2\pi}{\lambda} 2H(\mathbf{r}), \tag{2}$$

where $H(\mathbf{r})$ is a function representing the height variations of the rough surface. Throughout the remainder of this article it is assumed that $\phi(\mathbf{r})$ is a stationary, zero-mean Gaussian random process with a variance given by σ_ϕ^2 and a correlation function given by $R_\phi(\Delta\mathbf{r})$.

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