Effects of object roughness on partially coherent image formation

Neil A. Beaudry and Tom D. Milster

Optical Sciences Center, University of Arizona, Tucson, Arizona 85721

Received November 4, 1999

Phase perturbations in the object plane of a partially coherent imaging system are found to produce artifacts in the aerial image. It is demonstrated that phase perturbations of as little as $\lambda/30$ rms can produce visible deformation in the final image for modest coherence factors, such as $\sigma_c = 0.4$. A combination of simulation and experiment is used to demonstrate the effects. Application to line-edge roughness in lithography is described. © 2000 Optical Society of America

OCIS codes: 110.4980, 030.5770, 260.7200, 110.7440, 180.7460, 110.5220.

One can improve resolution in imaging systems by either increasing the numerical aperture (NA) or decreasing the wavelength (λ). Depending on the coherence of the source, the resolution is given approximately by $\lambda/(2\text{NA})$. The depth of focus, given by $\lambda/(2\text{NA}^2)$, is also an important consideration in imaging systems that use short-wavelength illumination sources. Extreme-ultraviolet (EUV) imaging systems typically have a NA of 0.1 and use an illumination wavelength of approximately $\lambda = 13$ nm.[1] With these specifications, an EUV imaging system has a resolution of 65 nm and a depth of focus of 0.65 μm. A deep-ultraviolet imaging system at $\lambda = 120$ nm with a NA of 0.8 has comparable resolution, but the depth of focus is nearly seven times smaller.

Applications for EUV imaging technology include projection lithography[2,3] and high-resolution optical microscopy.[4] In systems that use sources in the EUV region of the electro-magnetic spectrum ($\lambda < 20$ nm), phase irregularities introduced by reflection from polished surfaces or coating nonuniformities can become significant. In this Letter we show that these phase irregularities cause artifacts in the aerial image. These artifacts are not typically observed with visible and deep-ultraviolet imaging systems ($\lambda > 100$ nm) because the roughness of a well-polished surface is several hundred times smaller than the wavelength of the source.

Here we use computer simulations and a proof-of-principle experiment to demonstrate that small random phase perturbations manifest themselves as random irradiance modulation in the aerial image. This random modulation leads to low-frequency line-edge roughness when a line-space pattern is printed in photoresist.[5]

In the object plane, the phase perturbations $g(\mathbf{x}_1)$ are modeled in the following way:

$$g(\mathbf{x}_1) = \exp[i\phi(\mathbf{x}_1)], \tag{1}$$

$$g(\mathbf{x}_1) \approx \left[1 + i\phi(\mathbf{x}_1) - \frac{\phi(\mathbf{x}_1)^2}{2}\right], \tag{2}$$

where $\mathbf{x}_1$ is a vector that represents the object coordinates and $\phi(\mathbf{x}_1)$ is the random optical phase. For a simple rough surface, the optical phase $\phi(\mathbf{x}_1)$ can be written in terms of an optical path difference that is introduced by the random height variations $h(\mathbf{x}_1)$ on reflection from the mirror surface.

Whereas an exact quantitative relationship is not obvious, given the nonlinear relationship between $\phi(\mathbf{x}_1)$ and image irradiance $I(\mathbf{x}_1)$, several qualitative relationships can be implied by consideration of the limiting cases when the parameters of the system are set to extreme values. By substitution of Eq. (1) into the incoherent imaging equation presented Sec. 6.1.3 of Ref. 6, it can be shown that the image variance that is due to $\phi(\mathbf{x}_1)$ approaches zero as the illumination approaches a perfectly incoherent system. It can also be shown that, as the image contrast decreases (say, with increasing σ_c), the amount of line-edge roughness in the image that is printed in photoresist increases.[5] This relationship is demonstrated experimentally by Sanchez *et al.*[7] Finally, it can be shown theoretically that, for small amounts of phase perturbation, such that approximation (2) is valid, the amount of irradiance modulation in the aerial image increases quadratically with $\phi(\mathbf{x}_1)$.[5]

One particularly troublesome error that occurs in the final image for photolithography applications is the variation in width of line features printed in the photoresist. This defect is known as line-edge roughness. There are several possible factors that contribute to this image defect, including resist chemistry[7] and modulation owing to $\phi(\mathbf{x}_1)$. Because the variance in the image irradiance σ_I is a function of position, a straightforward relationship exists between σ_I and the variance in image feature width σ_w.[5]

To illustrate these effects, we constructed a simple 3× projection lithography system, using Köhler illumination with a Hg source that is filtered with a narrow-band 546.1-nm interference filter. The projection camera is doubly telecentric, with a NA of 0.1. A schematic of the setup is shown in Fig. 1. The projection system uses two achromatic doublets to image the mask onto the image plane. Because of the relatively low NA and the small field of view,