Chapter 10
EUVL System Patterning Performance

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10.1 Introduction: The Benefits of EUV Imaging

The great promise of EUVL comes from its tremendous reduction in wavelength, it being a photon-based technology and thus free of charged-particle limitations, and it being a projection-based demagnifying system, avoiding the problems of 1X and contact masks. The latter two characteristics make it clear that EUVL is simply an extension of conventional optical projection lithography, allowing us to leverage half a century of learning.

The standard lithographic resolution equation holds that

$$R = \left(\frac{k_1 \lambda}{NA}\right), \tag{10.1}$$

where λ is the imaging wavelength, NA is the numerical aperture, and k_1 is the Rayleigh constant. The Rayleigh constant is affected by several variables, including illumination conditions and mask architecture. Assuming a conservative k_1 factor of 0.5, which can be achieved readily with conventional illumination and a binary amplitude mask, the half-pitch resolution of a 0.3-NA EUV (13.5-nm wavelength) system would be 22.5 nm. Using resolution enhancement techniques such as off-axis illumination and/or phase shift masks, the ultimate resolution k_1 factor can be decreased to 0.25, corresponding to a 0.3-NA resolution limit of 11.25 nm.

Even further extendibility can be obtained by pushing the NA to 0.5 and beyond. At this NA, the resolution limits become 13.5 and 6.75 nm for $k_1 = 0.5$ and $k_1 = 0.25$, respectively. It is illustrative to view the simulated aerial images to understand the significance of the larger k_1 factor compared to that which we have grown accustomed to with 248- and 193-nm lithography. Figure 10.1 shows calculated aerial images for 0.35-NA and 0.50-NA EUVL systems with conventional disk illumination (partial coherence of 0.7) and a conventional binary mask with no optical proximity or bias correction. At 0.35 NA, strong image modulation is clearly observed even at the 16-nm half-pitch level, and increasing the NA to 0.5 readily takes us to 13-nm half-pitch.

As noted above, even better imaging performance can be achieved when we consider the use of techniques such as modified illumination and/or phase shift masks. One such technique is dipole illumination, which if applied to the 0.5-NA case, can achieve 8-nm half-pitch (Fig. 10.2). For dipole illumination, we assume a pole radius of 0.2 and a pole offset of 0.8 in the horizontal direction, providing resolution enhancement for vertical lines.

Another significant benefit of the lower NA of EUVL systems is the relatively large focus latitude it affords. The depth of focus (DOF) can be expressed in terms of the wavelength and the NA as

$$DOF = \frac{k_2 \lambda}{(NA)^2}, \tag{10.2}$$

where k_2 is a constant representative of the lithographic process conditions. A typical value for k_2 for a conventional illumination process is 0.5. For a

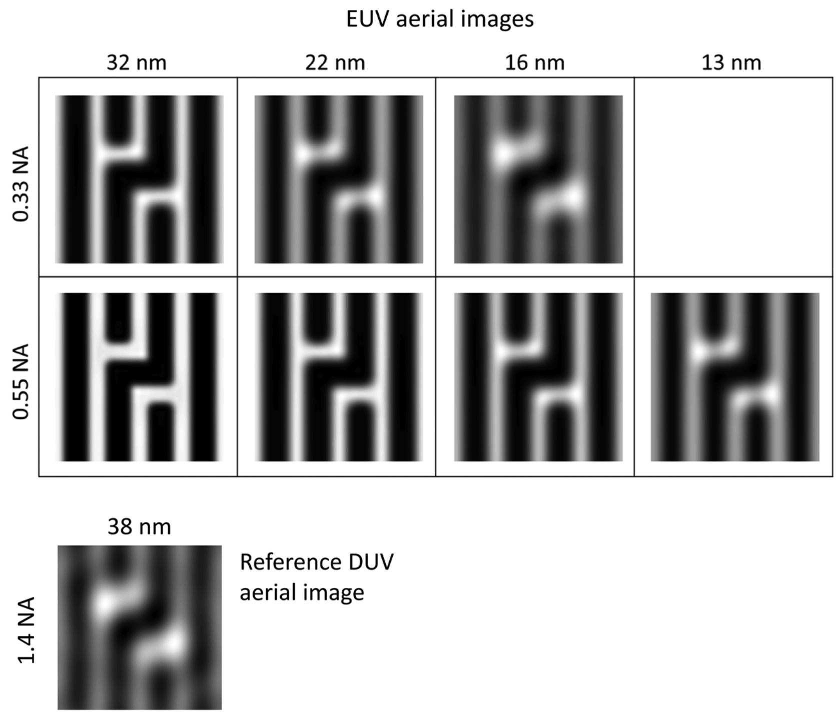

Figure 10.1 Aerial image modeling results for 0.33-NA and 0.55-NA EUV printing under general disk illumination with a partial coherence of 0.7 as compared to the reference DUV image of 38-nm half-pitch features, assuming a wavelength of 193 nm, a NA of 1.4, and optimized crosspole illumination.

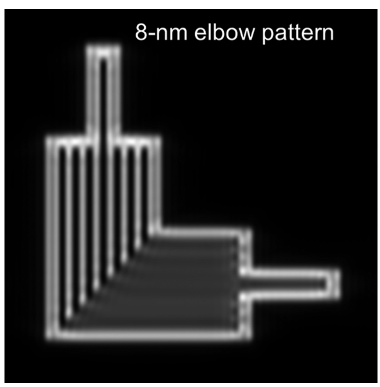

Figure 10.2 Aerial image modeling results for a 0.5-NA system with dipole illumination (pole radius = 0.2 and pole offset = 0.8) (reprinted from Ref. 49 with permission from McGraw-Hill).

0.3-NA system operating at its on-axis illumination diffraction limit (~22-nm half-pitch resolution), the DOF would be 75 nm. Using an optimized process, the DOF could be increased to 150 nm ($k_2 = 1$).

10.2 Parameters Affecting EUV Patterning Performance

10.2.1 Partial coherence

As described above, partial coherence (i.e., illumination settings) can impact the imaging performance of the system. The power of this approach is further demonstrated with the plot in Fig. 10.3, which shows the aerial image contrast $[(I_{max} - I_{min})/(I_{max} + I_{min})]$ as a function of half-pitch for a 0.32-NA EUV system under four different illumination conditions. For this example, we assume an ideal, aberration-free imaging system and an ideal binary mask.

10.2.2 Aberrations and contrast

The results presented in the previous subsection assume ideal optical systems with zero aberration. In practice, this is extremely difficult to achieve, especially in the EUV regime, where the short wavelength and reflective optics place extremely tight constraints on mirror shape errors. To quickly illustrate this effect, we consider aerial image contrast as a function of half-pitch for a 0.32-NA system with varying levels of aberration ranging from 0.25 nm to 1 nm rms (Fig. 10.4). Using the criterion of <1 nm impact on resolution, we find the aberration limit to be 0.25 nm or $\sim\lambda/50$. Assuming a 6-mirror system and the errors on each of the mirrors to be uncorrelated, this yields a wavefront error limit of 100 pm for each mirror (a surface error limit of 50 pm).

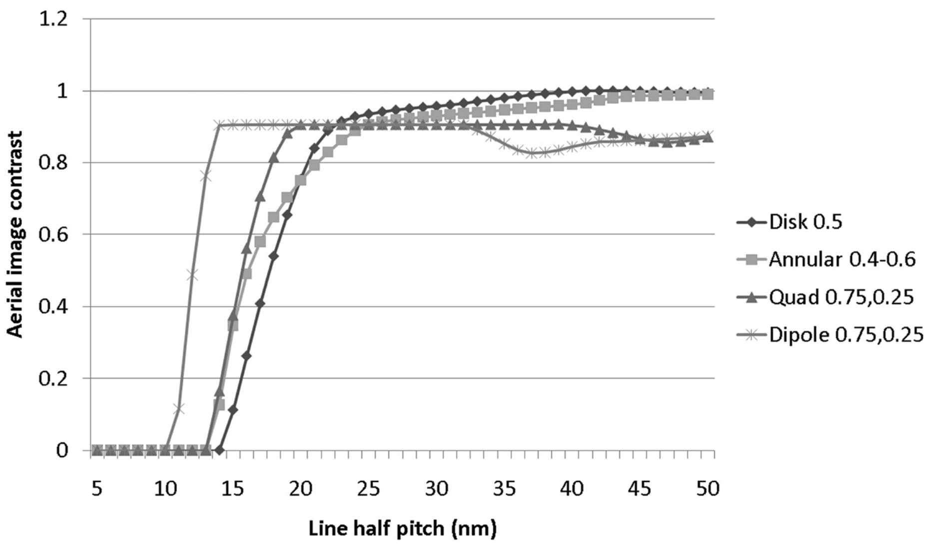

Figure 10.3 Aerial image contrast as a function of half-pitch for a 0.32-NA EUV system under four different illumination conditions (reprinted from Ref. 49 with permission from McGraw-Hill).

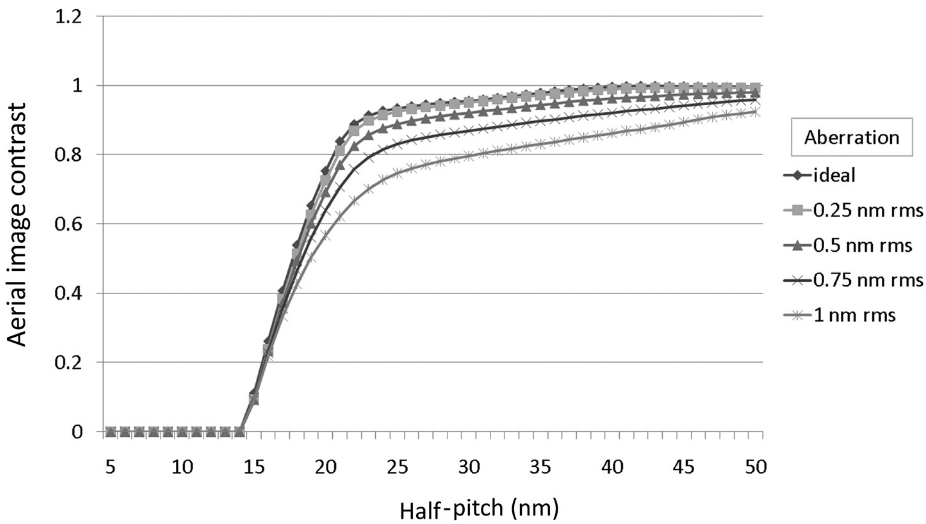

Figure 10.4 Aerial image contrast as a function of half-pitch for a 0.32-NA system with varying levels of aberration ranging from 0.25 nm to 1 nm (reprinted from Ref. 49 with permission from McGraw-Hill).

10.2.3 Flare and contrast

Mirror surface errors, which contribute to what we refer to as aberrations, are low-spatial-frequency errors. These errors are typically 10 cycles or less across the pupil and tend to affect the shape of the optical system point spread function. Finer spatial period errors on the mirrors (mid-spatial-frequency roughness), however, also play an important role in the imaging performance. Figure 10.5 shows how such errors in the pupil tend to scatter light (light purple rays) out of the point spread function (labeled 'Img' in the figure), creating a background halo of illumination into a large area surrounding the image point.

For high-quality (low roughness) optics, the total amount of light scattering into the halo, or total integrated scatter (TIS), can be expressed as

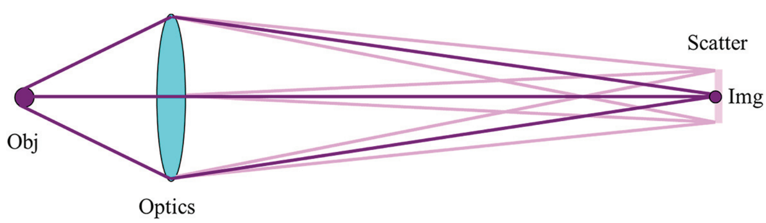

Figure 10.5 Mid-spatial-frequency roughness on the imaging optics causes light to be scattered out of the imaging cone, creating a background halo of illumination.

$$TIS \approx \left(\frac{4\pi\sigma_s}{\lambda}\right)^2, \tag{10.3}$$

where σ_s is the rms roughness of the surface, and λ is the imaging wavelength. The impact of this scattered light is to reduce the contrast through an effect called flare. Flare is defined as the amount of light seen at the center of an ideally dark feature that is significantly larger than the diffraction limit of the optic, ensuring that diffraction is not substantially contributing to the light seen at the center of the feature. This definition is depicted in Fig. 10.6. Flare will reduce the contrast of all feature sizes, and its total magnitude depends on the local feature density.

10.2.4 Chromeless phase-shift-mask printing in the EUV range

A significant benefit of EUVL is that it is simply an extension of optical lithography, which means that the toolbox of resolution enhancement techniques developed for optical lithography can also be applied to EUVL. One such example is modified illumination, as discussed Section 10.2.1. Another example is phase-shift-mask technology. Phase shift masks have played a crucial role in the extension of optical lithography and could also be used in the future to push EUVL to its ultimate limits. Another benefit of phase shift masks is their utility in print-based aberration measurement techniques.[1–3]

One method to generate a phase shift mask in the EUV range is to fabricate a relief pattern in the substrate and then overcoat with a multilayer (ML). This method is nearly identical to the method used to generate high-efficiency phase gratings in the EUV.[4–9] The method is illustrated schematically in Fig. 10.7, and a cross-section of a fabricated mask with

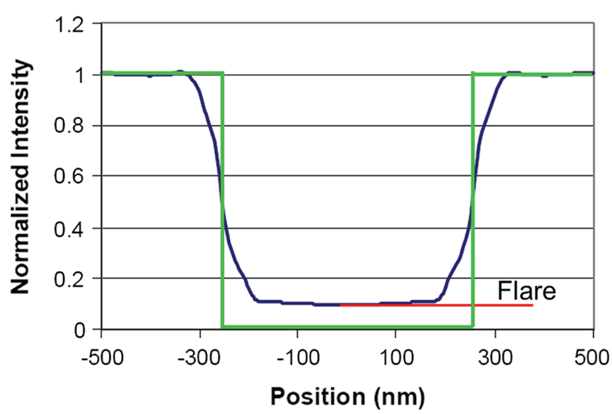

Figure 10.6 Light scattered out of the bright regions of the image and into ideally dark features is referred to as flare and reduces the contrast of the aerial image for all feature sizes.

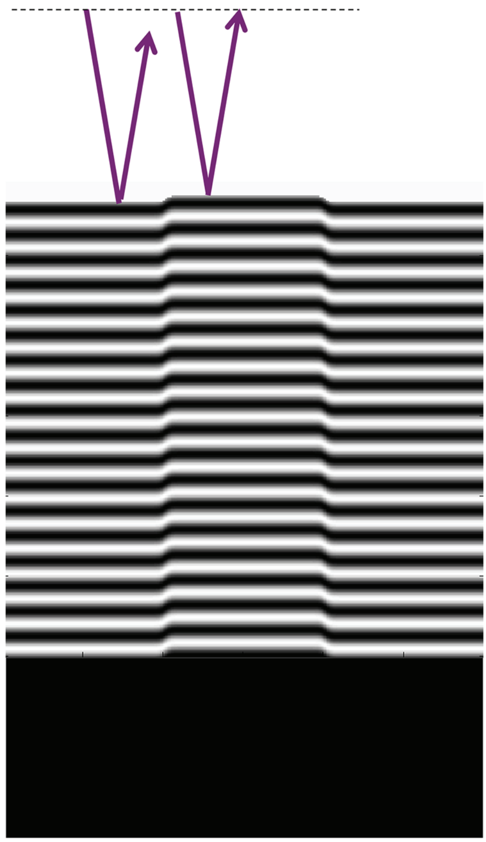

Figure 10.7 Diagram of relief-substrate phase-shift-mask method.

200-nm-pitch lines and spaces is shown in Fig. 10.8. Figure 10.9 shows through-focus printing of subresolution, isolated lines on a relief phase shift mask printed in a 0.1-NA EUV lithography tool. We define subresolution as structures on the mask with lateral dimensions smaller than the absolute diffraction limit of the optics [$0.25\lambda/(NA)$]. The printed feature size is on the order of 70 to 80 nm, near the resolution limit of the optic. Another demonstration of phase shift printing is shown in Fig. 10.10, where a large phase object is placed adjacent to an absorber feature (the mask layout is shown in Fig. 10.11). As expected from phase shift printing, only the outline of the large phase structure is printed.

The crucial problem with this method is the fact that the ML-coating process significantly limits the resolution of the phase features one can obtain on the mask. Since the time when this early work was done, a more sophisticated implementation of phase shift masks (including attenuated phase shift masks) based on ML etching has been developed and was demonstrated in a 0.3-NA exposure tool.[10] Another major benefit of using a

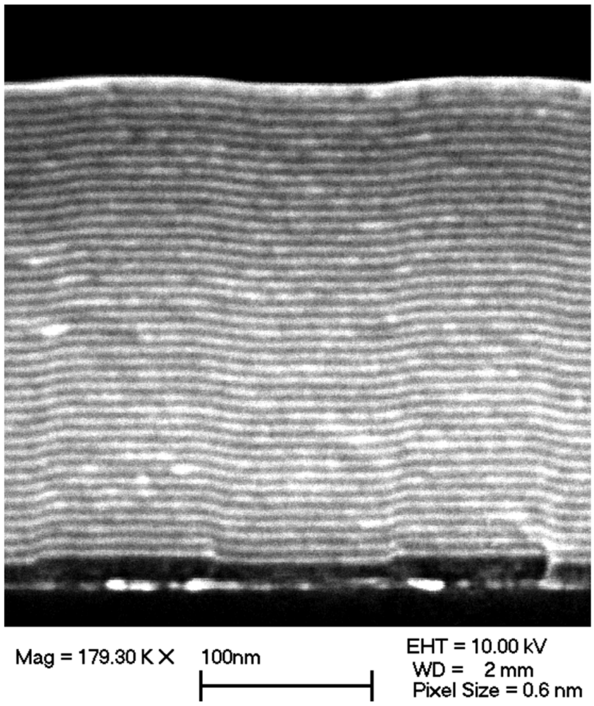

Figure 10.8 Cross-section of a fabricated mask with 200-nm pitch lines and spaces.

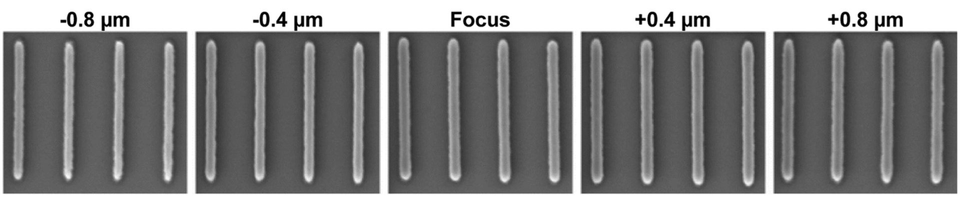

Figure 10.9 Through-focus printing of subresolution phase lines on the mask at 0.1 NA.

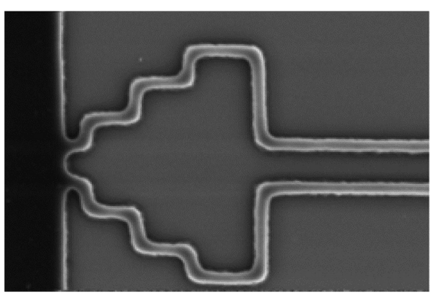

Figure 10.10 Printing of the large phase-shift structure in Fig. 10.11.

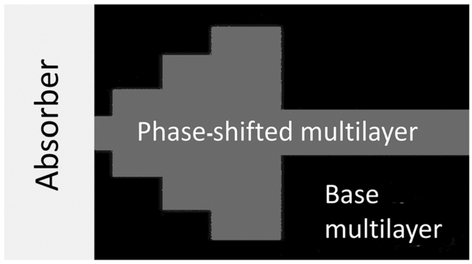

Figure 10.11 Mask layout corresponding to the printing in Fig. 10.10.

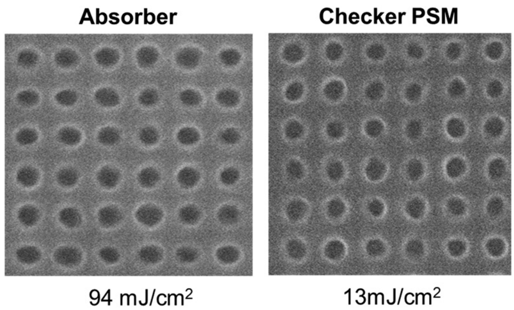

Figure 10.12 Direct lithographic patterning comparison of the conventional and the checker phase-shift mask (PSM) in the Berkeley 0.3-NA micro-exposure tool. Patterning of 25-nm contacts shows that the checker PSM provides a 7× efficiency gain relative to the conventional absorber mask (reprinted from Ref. 11).

phase shift mask is that removal of the absorber greatly improves the total optical throughput of the mask and thus the patterning tool.[11] This is especially valuable when considering contact hole features. Figure 10.12 shows patterning results for 25-nm dense contacts printed in a 0.3-NA lithography tool, directly comparing a conventional absorber mask to a chromeless phase shift mask. Note that the dose at the wafer is not actually changed, as must be the case since we are using the same resist. What is changed is the optical efficiency of the mask. This is important because if the resist were truly being patterned with 7× fewer photons at the resist, the stochastics would certainly suffer.

10.3 EUV and Aerial Image Variability

Pattern variability in the form of contact hole critical dimension uniformity (CDU) and line-edge/width roughness (LER/LWR) remains a significant challenge for EUVL. EUVL suffers from two primary EUV-specific challenges from this perspective: sub-nanometer phase roughness on the reflective mask and photon shot noise concerns arising from the high energy per photon. An additional mask source of patterning variability is mask