Shot noise in light ion and neutral particle lithography

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A distinctive feature of helium ion or neutral beam lithography is that resists are ~100 times more sensitive than for any other particle. As a result, the ion density is sparse and subject to shot noise even in resists that are not chemically amplified.[1] This paper reports an integrated study of shot noise in helium lithographies that compares variations in the printed images of the same mask feature with the predictions of a Monte-Carlo model. The model[2] includes the following assumptions: a) threshold development of PMMA resist, b) an average exposure dose of twice the development threshold, c) the total number of particles within a printed feature is given by a Poisson distribution, d) the probability distribution of ion coordinates within a feature is governed by the aerial image, and e) the resist image is smoothed by a Gaussian internal blur function. Independent experiments were used to determine the internal and aerial image blur, 4.4 and 8.8 nm (1σ), respectively. Thus, there are no free parameters in the shot-noise model.

Neutral particle aperture array lithography[3] (figure 1) was used to print the experimental images. Briefly, the mask was illuminated by a beam of 10 keV helium atoms produced by charge transfer scattering between a 10 keV He^+ ion beam and thermal helium atoms in a differentially pumped high pressure cell. Residual ions were removed from the beam by electrostatic deflectors. The mask and wafer were clamped together with 125 µm spacers and tilted in 2-dimensions to create multiple offset exposures of individual features in the mask. A silicon template with 74.5 nm circular openings on 400 nm pitch was printed 4 times in a square pattern with 200 nm edges in Poly(methylmethacrylate) (PMMA) resist. Random shape variations were found among the four images of each mask opening, particularly within the boundary regions of partial exposure caused by penumbra. Qualitative agreement was found between amplitude and frequency content of the simulated and experimental shape fluctuations for both 74.5 nm openings and ~25 nm mask defects as shown in figure 2.

The model predicts that reducing penumbra to 0.5 nm [FWHM], which can be achieved with a 10 µm proximity gap, greatly suppresses the extent of edge roughness on 75.4 nm features (figure 3(a)). For 25 nm features, however, there are so few particles that significant shape distortion remains (figure 3(b)). This distortion is significantly reduced when using negative tone PMMA exposures which are 20 times less sensitive than positive tone. Assuming warm development conditions,[4] which further reduces resist sensitivity, reduces shape fluctuations (figure 4) to less than 0.5 nm for 10 nm dots.

We will report quantitative comparisons of the spatial power spectra of simulated and experimental printed lines at the conference. We will also discuss further experimental studies to verify the model prediction that very low noise can be achieved for 10 nm lines and vias using negative tone PMMA.

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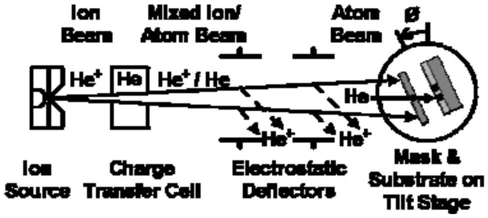

Figure 1. A schematic representation of aperture array lithography with neutral particles[3]

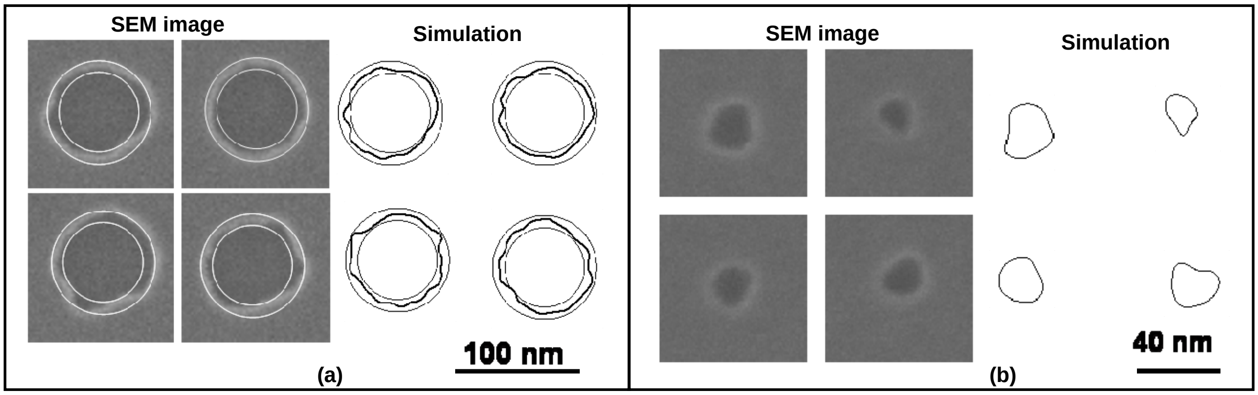

Figure 2. Images resulting from 4 exposures and 4 sequential Monte-Carlo simulations of (a) a single 74.5 nm mask opening, and (b) a ~25 nm mask defect, in PMMA resist. The superimposed circles in (a) represent the extent of 10 nm [FWHM] penumbral blur about the mean diameter in both cases. There is qualitative agreement between experimental and simulated results in the extent of edge roughness in (a) and in shape and size fluctuations observed in (b).

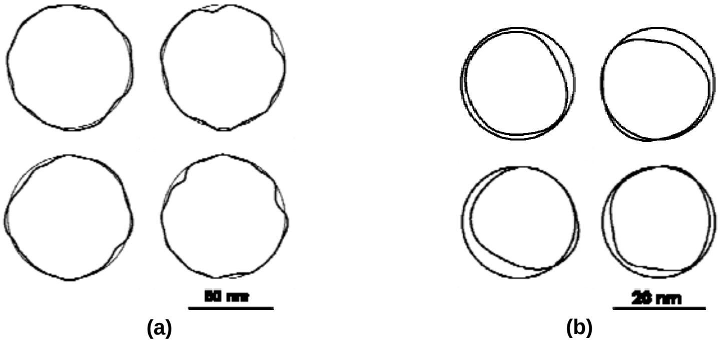

Figure 3. Images resulting from four sequential simulations of a (a) 74.5 nm diameter mask opening and (b) 25 nm diameter mask opening in PMMA resist assuming a penumbral blur of 0.5 nm [FWHM]. The superimposed circles in each case represent the shape of the mask opening. Reducing penumbral blur eliminates the dominant component of edge roughness. However, 25 nm features still exhibit shape and size distortion due to the small number of particles exposing the resist.

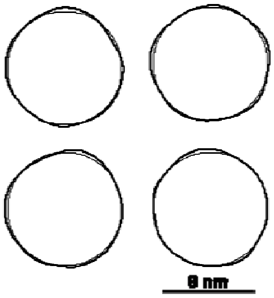

Figure 4. Images resulting from four sequential simulations of a 10 nm diameter mask opening in negative tone PMMA resist that is 20 times less sensitive than positive tone PMMA. The superimposed circles represent the shape of the mask opening. Penumbra is 0.5 nm [FWHM] and warm development is used to reduce resist sensitivity by a factor of 2 and improve resist contrast. Shape fluctuations are limited to less than 0.5 nm under these conditions.