Limiting Factors in Sub-10-nm Scanning Electron Beam Lithography

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Achieving the highest possible resolution using scanning electron beam lithography (SEBL) has become an increasingly urgent problem in recent years, as advances in various nanotechnology applications have driven demand for feature sizes well into the sub-10-nm domain. In this work, we have theoretically and experimentally investigated the various limiting factors of SEBL and used the results to understand the fundamental limits of the technology.

Recent improvements in SEBL resolution have been made primarily by increasing the contrast of the resist-development process.[1,2] Unfortunately, as figure 1 illustrates, this approach is reaching a point of diminishing returns; even with a perfect resist, the minimum-achievable pitch in an arbitrary pattern is limited to approximately the effective width of the electron beam, which increases as the incident electrons undergo scattering and emit secondary electrons in the material.

Understanding the various contributors to the effective beam width, then, is critical. It is well-known, for example, that forward scattering has a substantial effect on beam width in thicker resist.[3,4] However, below a certain “critical resist thickness” at a given beam energy, scattering becomes negligible and the point-spread function is nearly identical to the initial width of the beam. This critical thickness is shown in figure 2 as a function of beam energy. Interestingly, our simulation results were not significantly different when secondary-electron generation was taken into account, suggesting that secondary electrons do not significantly contribute to the effective beam width.

Based on these results, it should be possible to yield features with a pitch on the order of a SEBL tool’s spot size, assuming a high-contrast and thin resist. Figure 3 shows the results of spot size measurements at various voltages on the MIT Raith-150 system;[5] at 20 keV, the beam diameter is approximately 4 nm, suggesting that features with a 4 nm pitch should be achievable in this system.

Interestingly, the minimum pitch we have yielded to date is approximately 9 nm, rather than 4 nm. Assuming that our models are accurate and our imaging resolution is sufficient, this discrepancy suggests that the contrast behavior of HSQ at sub-10-nm length scales may be dramatically different from the micro-scale measurements generally used to extract contrast data. If this is the case, the previously uninvestigated feature-size-dependence of the resist-development model significantly complicates sub-10-nm patterning, and may represent a new limit to SEBL resolution.

[1] L. E. Ocola and A. Stein, J. Vac. Sci. Technol. B **24**(6)**,** 3061-3065 (2006).
[2] J. K. W. Yang and K. K. Berggren, J. Vac. Sci. Technol. B **25**(6)**,** 2025-2029 (2007).
[3] A. N. Broers, IBM. J. Res. Develop. **32**(4)**,** 502-513 (1988).
[4] D. C. Joy, Microelectron. Eng. **1,** 103-119 (1983).
[5] ASTM International **E986-04** (2004).

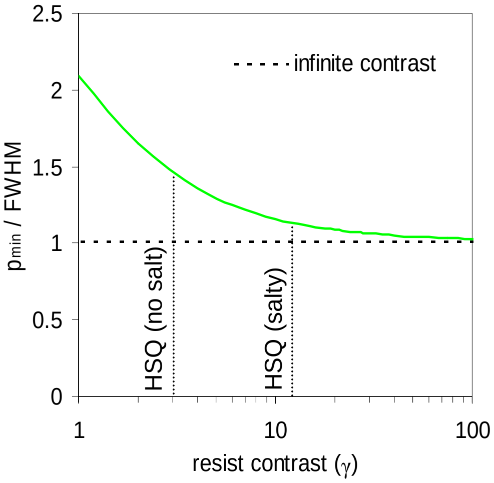

Figure 1: Calculation of minimum achievable pitch, normalized to the FWHM of the beam point-spread function (the effective beam width), as a function of resist contrast for simultaneous yield of dense and isolated features. As resist contrast increases, the minimum yieldable pitch decreases. In the case of HSQ, using "salty development[2]" significantly improves the resolution over the standard salt-free process, but further contrast enhancement yields diminishing returns; even with infinite contrast, the minimum achievable pitch is ~1.01*FWHM.

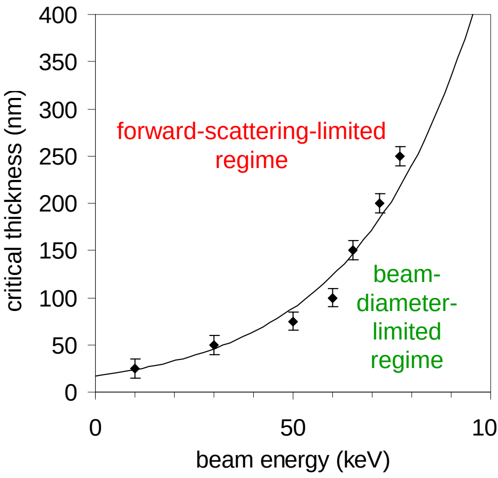

Figure 2: plot of "critical resist thickness" (the maximum resist thickness where forward scattering is negligible) as a function of beam energy for HSQ, extracted from Monte Carlo simulations and assuming an initial beam diameter of 4 nm. At thicknesses below the critical thickness, the diameter of the incident beam defines the point-spread function (PSF); above the critical thickness, the PSF is primarily influenced by forward scattering in the resist. Note that this data refers only to the deposited energy profile in the resist; in reality, aspect-ratio limitations will make yielding developed narrow features in thick resist problematic, even if scattering is negligible.

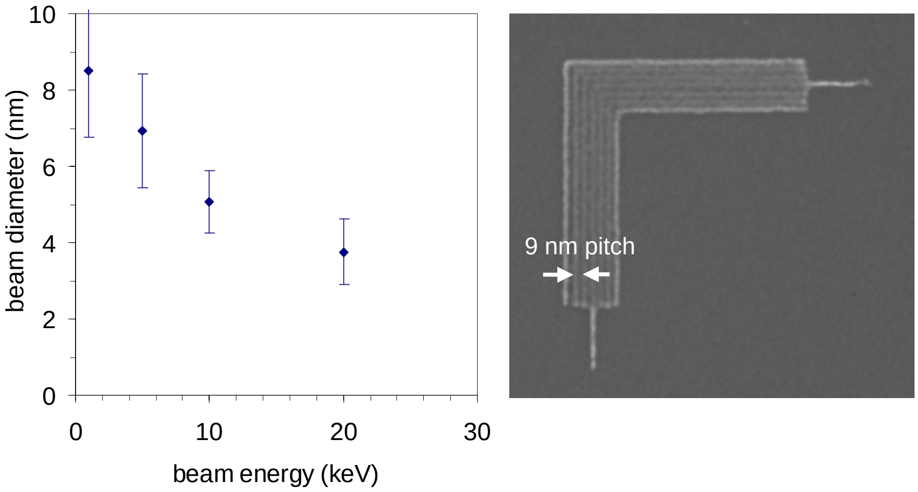

Figure 3: *Left*: electron-beam diameter as a function of accelerating voltage, measured via the ASTM[3] method on MIT's Raith-150 SEBL tool. At 10 keV the spot size is ~5 nm, suggesting (from figure 2) that 5-6 nm pitches should be yieldable at this energy. *Right*: A 9-nm-pitch "nested-L" structure fabricated in 10-nm-thick HSQ at 10 keV, the smallest pitch we have successfully yielded at any voltage. The large discrepancy between the predicted and actual yieldable pitches suggests that HSQ behaves very differently at sub-10-nm length scales, exhibiting contrast much lower than that obtained in our bulk-scale measurements.