# Simulated secondary-electron trajectories in helium-ion-beam lithography

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Scanning helium-ion-beam lithography (HIBL) can fabricate patterns with sub-10-nm half-pitch.[1,2] While people have argued that the ultimate surface-imaging resolution of a helium-ion beam is superior to that of an electron beam,[3,4] does superior surface-imaging resolution translate to superior resist-exposure resolution for lithography? The interaction volume of a beam with a sample is one measure of the spatial extent of energy deposition in that sample, and thus of lithographic resolution. To evaluate limits on the interaction volume of a helium-ion beam and its generated secondary electrons (SEs) inside a resist layer, we have developed a Monte Carlo simulator using the theory and software of Ziegler et al,[5] a parametric model for SE generation by helium ions,[6] and a "fast secondary" model for SE propagation.[7,8] Our simulator also models primary-electron propagation, and we have used this capability to compare helium-ion-beam interaction volumes to those of electron beams.

Figure 1 suggests that the contrast-reducing proximity effect, common in dense patterns written with ≥10-keV electron-beam lithography (EBL), is absent for 30-keV HIBL. The interaction volume of the helium-ion beam is smaller than that of the electron beam, and no helium ions backscatter to the hydrogen silsesquioxane (HSQ) resist layer. HSQ was chosen for this simulation because of its status as a high-resolution EBL resist,[9] because experiments by the authors – using HSQ – correspond with our electron model,[10] and because HSQ has been used for sub-10-nm-half-pitch HIBL.[1,2]

Figure 2 suggests that, at least for resist thicknesses larger than a few nm, 30-keV HIBL can pattern smaller features than ≤30-keV EBL. This is because the helium-ion beam does not "fan out" with depth as rapidly as the electron beams do (Figure 2(a)). However, it seems that SE generation limits the interaction "diameter" of the helium-ion beam to ~ 2 nm because the helium-ion beam generates more SEs closer to the surface than do the electron beams (Figure 2(b)).

Our simulations suggest that HIBL may ultimately prove superior to EBL in the effort to simultaneously minimize (1) the proximity effect and (2) feature size, both of which limit resolvable half-pitch in resist-based lithography.

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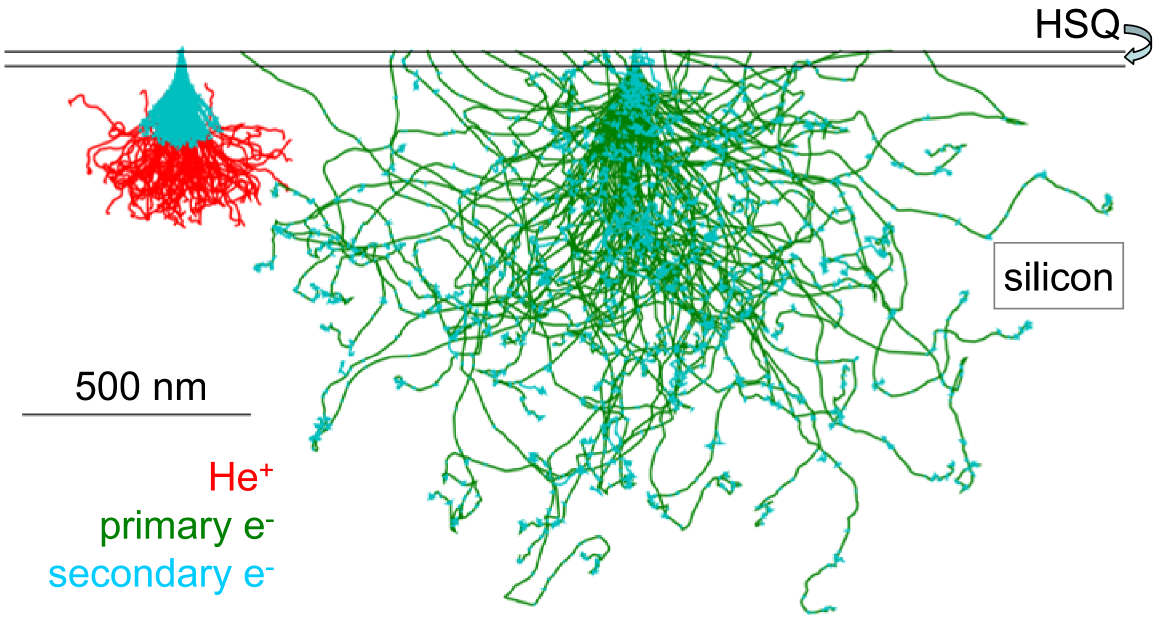


*Fig 1:* Simulated trajectories of 100 30-keV helium ions (left) and 100 10-keV electrons (right), into 30-nm-thick hydrogen silsesquioxane (HSQ) resist on silicon. 10-keV electron landing energy was chosen because this is a typical low-end value for electron-beam lithography. The trajectories of secondary electrons generated by each particle beam are also simulated and plotted (light blue).

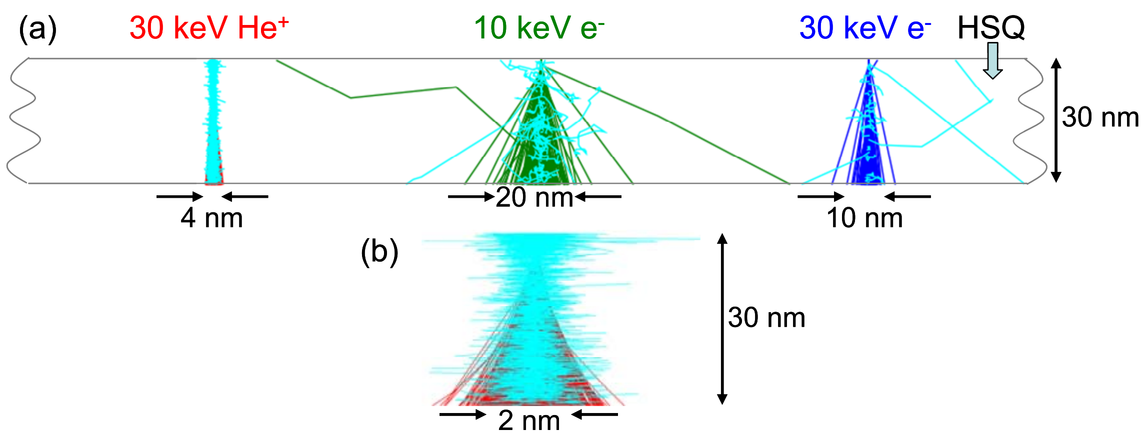


*Fig 2:* **(a)** Simulated trajectories (1000 each) of 30-keV helium ions (left), 10-keV electrons (center), and 30-keV electrons (right), and also those of the secondary electrons generated by each beam (light blue), in a 30-nm-thick "membrane" of hydrogen silsesquioxane (HSQ) resist. No trajectories are tracked below the HSQ, and thus no backscattered particles emerge from below the HSQ. Vertical and lateral scales are equal; **(b)** Magnified graphic of the 30-keV helium ions (red) and their generated secondary electrons (light blue), where the lateral scale is stretched relative to the vertical scale to emphasize the SE tracks.