Resolution limits of 200 keV electron-beam lithography using aberration-corrected STEM

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Electron beam lithography (EBL) readily enables the fabrication of sub-10 nm features [1]. However, the resolution limits of this technique at length scales for below 10 nm have not been thoroughly tested, and it is likely that our current understanding of electron-beam resolution will have to be modified in this regime. The known resolution limiting factors of EBL are [2]: 1) primary-electron scattering; 2) spot size; 3) development process; and 4) resist structure. We decided to minimize the influence of electron scattering and spot size to facilitate the resolution limit analysis. To minimize primary-electron scattering, we chose an exposure with 200 keV electrons. In addition, we used 20-nm-thick resist to suppress these primary-scattered electrons and Si_3N_4 membranes as the substrate to minimize backscattered electrons. To minimize the spot size, we chose an aberration-corrected scanning transmission electron microscope (STEM) as the exposure tool, featuring a 0.14 nm spot size with beam current of 150 pA [3]. STEM exposures at 200 keV have been done before [4, 5], resulting in feature sizes of ~ 6 nm and resolution (i.e., pattern period) of 30 nm. However, the resolution-limiting factors were not systematically explored in these studies. In this work, we used recently developed processing and metrology methods [1, 6] to analyze the resolution limits at sub-10 nm scale. We did STEM exposures in 20-nm-thick hydrogen silsesquioxane (HSQ) at 200 keV, and we developed it with salty development [1].

Figure 1 shows feature sizes from 3 to 7 nm and a 19 nm pitch. The feature size was controlled with nanometer precision by varying dwell times through the line-exposure of the unblanked scanning beam. We determined the required dose to print of the structure, and compared it to known dose to print at other energies. In addition, we measured the radius of dot exposures from 1 to 50,000 fC/dot and compared the results to a Monte-Carlo model. For this dose range, the maximum dot radius was only 60 nm at 200 keV, representing a relatively concentrated electron distribution or point-spread function.

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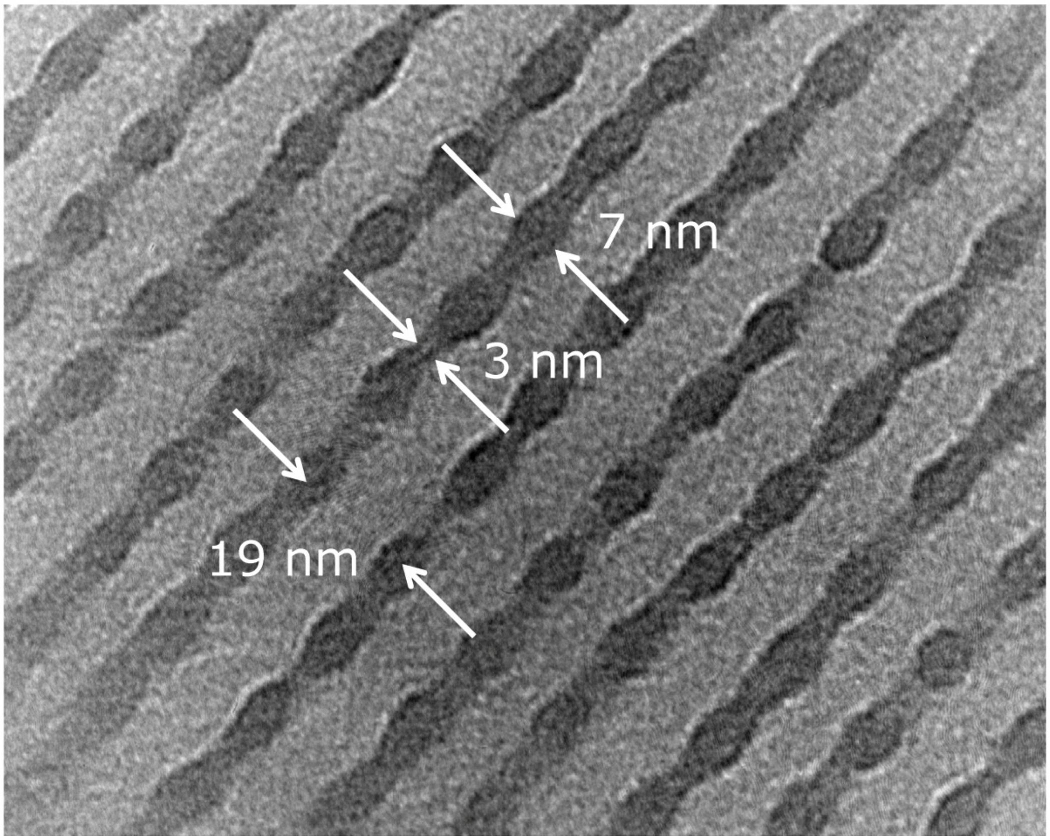

Figure 1. Bright field transmission-electron micrograph of HSQ structures exposed in imaging mode by a Hitachi STEM at 200 keV. The HSQ thickness was ~ 20 nm and it was on top of a 50-nm-thick Si_3N_4 membrane. The lines have a period (resolution) of 19 nm, with feature size variation from 3 to 7 nm. The exposure was a dot array with 19 nm step size. This feature variation is due to different dwell times (electron dose) between dot and inter-dot exposures of the unblanked scanning beam. The HSQ structure appears to be fully developed, with minimal line-edge roughness and shows the smallest feature size reported by this particular electron-beam lithography process.