Metrology and Analysis of Sub-10-nm-Electron-Beam Lithography

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Ultrahigh-resolution electron-beam lithography (EBL) has promising applications to bit-patterned media, high-resolution and templated self-assembly, sub-10-nm nanoelectronic devices, and mask manufacturing for integrated circuits. Much progress has been made on ultrahigh resolution EBL in recent years [1] with the help of new tools, new resists, and new resist-development process, and a lot of work has been done to explore the resolution limit and understand the fundamentals of EBL. For example, sub-5-nm-half-pitch features have been reported using salty development on hydrogen silsesquioxane (HSQ) resist [2], and reactant-diffusion-limited development is believed to occur in this system. However, there remain many fundamental questions about the resolution limit of EBL, such as how point-spread function (PSF) and development contrast determine the resolution. These fundamentals must be addressed in order to further improve the resolution of EBL. To address these issues, a series of experiments should be designed and conducted at the sub-10-nm scale. However, at such small length scales, metrology poses an extraordinary difficulty [3]. For example, qualifying a standard deviation of 10% for sub-5-nm half-pitch features implies a metrological accuracy of 0.5 nm, which poses a challenge to even the best scanning-electron microscope (SEM).

In this presentation, we adopted transmission-electron microscopy (TEM) and atomic force microscopy (AFM) to study the resolution limit of sub-10-nm-half-pitch lithography by using HSQ as the resist. We found that the feature size defined by EBL could be as small as 4 nm (as shown in figure 1, SEM and TEM micrographs of fallen-over dots; figure 2, AFM image of fallen-over lines), but dense features with half-pitch less than 8 nm were difficult to yield (as shown in figure 3, especially in figure 3d', the HSQ between the designed lines could not be removed completely) even for only 7 lines and using a high-contrast development process. To explain the results, we measured line spread function (LSF) and PSF using TEM, and found that they were not responsible for the observed resolution limit. We thus hypothesize that the resolution was limited primarily by the kinetics of development process.

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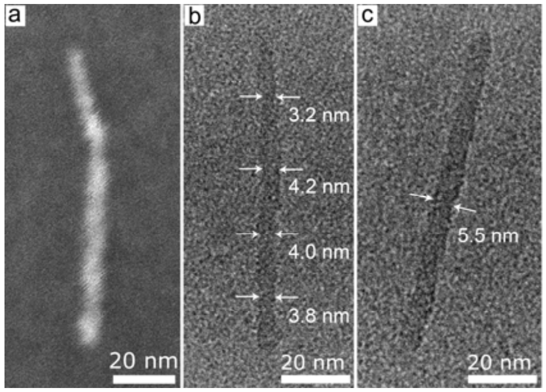

Figure 1: High aspect ratio fallen-over HSQ structures fabricated by electron-beam lithography using the Raith150 at MIT at 30 kV and salty development for 4 min. (a) SEM image at 15 fC; (b, c) TEM micrographs at 15 fC and 20 fC, respectively. The substrates for SEM and TEM metrology were silicon and 50-nm-thick silicon nitride membrane, respectively. The thickness of HSQ for SEM and TEM were about 100 nm. The beam current was about 200 pA, corresponding to a spot size about 4 nm.

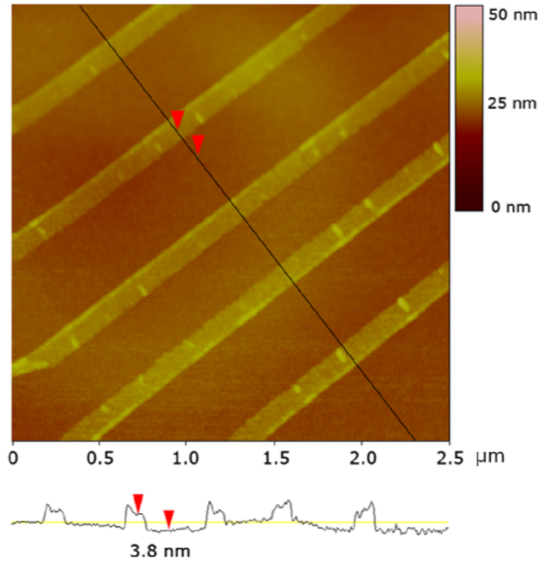

Figure 2: AFM image of fallen-over HSQ lines. The thickness of HSQ was ~100 nm, and the pitch of designed lines was 500 nm. Bottom: the section profile along the selected line. The line dose for nested Ls was ~5600 e$^-$/nm.

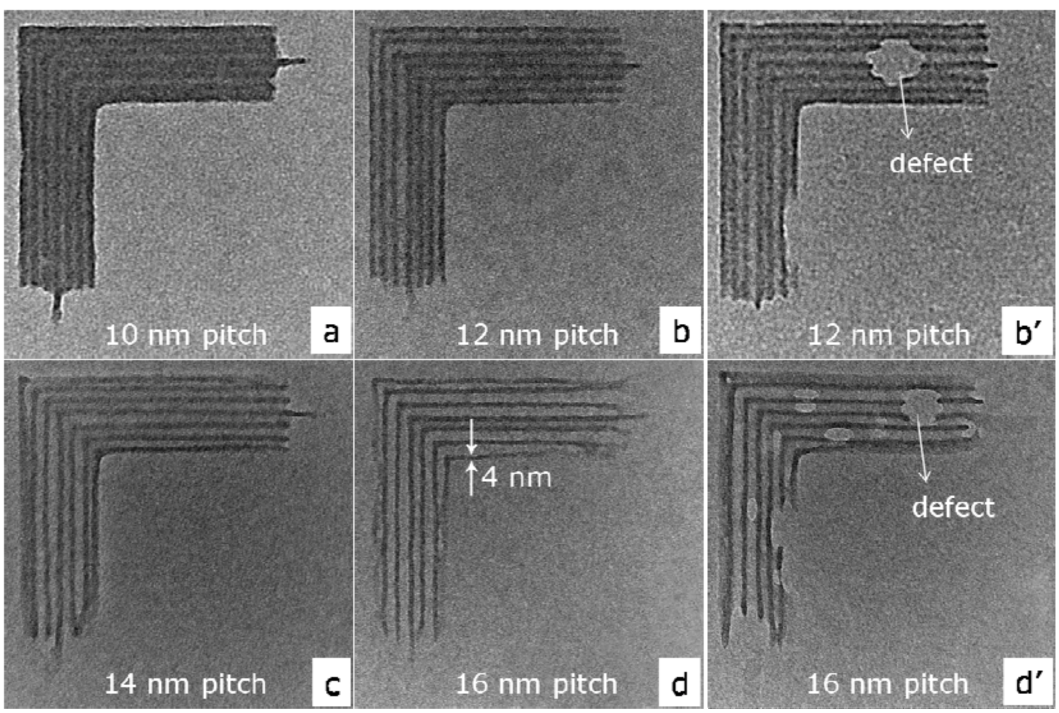

Figure 3: Bright field TEM micrographs of HSQ nested Ls with varying pitch: (a) 10 nm, (b and b') 12 nm, (c) 14 nm, and (d and d') 16 nm. The thickness of HSQ was about 18 nm. All other EBL and TEM metrology parameters were same as those in figure 1 except the exposure dose. The line dose for nested Ls was ~5000 e$^-$/nm.