Measurement of the electron-beam-lithography point-spread function by chromatic-aberration-corrected transmission electron microscopy and spectroscopy

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Electron-beam lithography (EBL) exposure starts with a focused electron beam that deposits energy locally in the resist. This electron beam can also excite secondary electrons (SEs), plasmons, phonons, and photons that may further deposit energy (or break bonds) in the resist. However, since the invention of EBL 50 years ago, it is not quantitatively clear all the mechanisms that lead to the final energy distribution in the resist, that is, the lithographic point-spread function (PSF). SEs are considered to be the largest contributors to the lithographic PSF[1]. The role of SEs on EBL has been extensively modeled[1-3] but it has not been directly measured to date. Furthermore, the role of plasmons on SE emission has been extensively studied,[2, 4, 5] but the plasmon effect on EBL has not been experimentally investigated. We will present a study and a disentanglement of the mechanisms of EBL exposure at the sub-10-nm scale.

In Figure 1we show the direct-beam PSF, which is the spatial energy density deposited by the direct (or forward scattered) electron beam in the resist. The direct-beam PSF was measured using chromatic-aberration-corrected energy-filtered transmission electron microscopy. We also show in Figure 2 the volume-plasmon (VP) PSF, which is the spatial energy density deposition caused by VPs in the resist. We determined the VP PSF by calculating the dielectric constant of HSQ (hydrogen silsesquioxane) at the VP energy (22.5 eV) from electron energy loss spectroscopy (EELS). Furthermore, we performed quantum simulations of EELS, and numerical[3] and Monte Carlo[1] simulations of the PSF. In Figure 3a we compared the direct-beam PSF, VP PSF, simulated SE PSF, with the lithographic PSF, determining the role of SEs and VPs in the EBL PSF. In Figure 3b we combined the VPs and SEs PSFs by weighting the energy loss of each process. The measured energy loss from VPs was 38% of the total loss. We concluded that the high probability and delocalization of VPs, combined with VPs decay into SEs[4] gives rise to significant contribution of VPs to the lithographic PSF, thus, limiting EBL resolution. **1**.Murata, K.; Kyser, D.; Ting, C. *J. App. Phys.* 1981**,** 52, 4396; **2**.Luo, S.; Joy, D. *Scann. Micros.* **1990**, 127; **3**.Wu, B.; Neureuther, A. *J. Vac. Sci. & Tech. B* 2001**,** 19, 2508; **4**.Chung, M.; Everhart, T. *Phys. Rev. B* 1977**,** 15, 4699; **5**.Kuhr, J.; Fitting, H. *J. Electr. Spec. and Rel. Phenom.* 1999**,** 105, 257.

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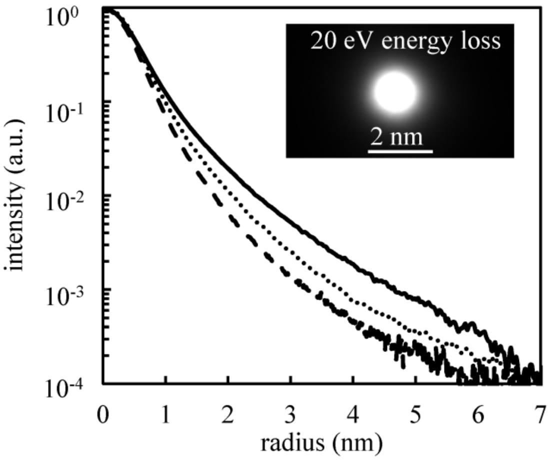

Figure 1. Measurement of the direct-beam PSF. (dotted line) Radial distribution of transmitted electrons through 20-nm-thick HSQ with no energy loss. (dashed line) Radial distribution of transmitted electrons without a sample. (full line) Radial distribution of deposited energy density in HSQ, called here as 'direct-beam PSF' - weight averaged by the intensity of transmitted electrons that lost energy from 2.5 to 122.5eV). Inset: Representative TEM micrograph of transmitted electrons that lost 20 eV used to calculate the direct-beam PSF. The incident electron energy was 200 keV.

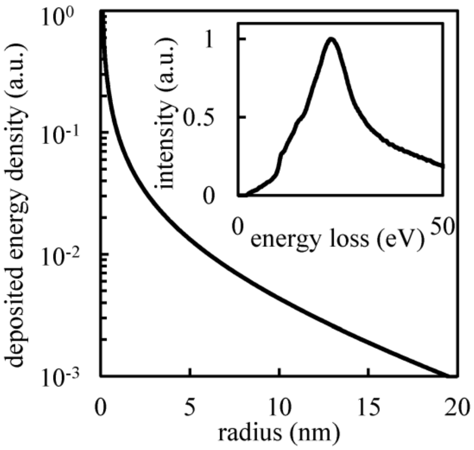

Figure 2. Volume-plasmon PSF. Volume-plasmon (VP) absorbed energy density as a function of radial distance. Inset: EELS of 40-nm-thick HSQ on top of 10-nm-thick SiN_x at 200 keV (without zero loss component). From this EELS spectrum, we calculated the dielectric constant of HSQ at the VP energy. Then, we obtained the VP propagation decay length, which leads to the VP PSF.

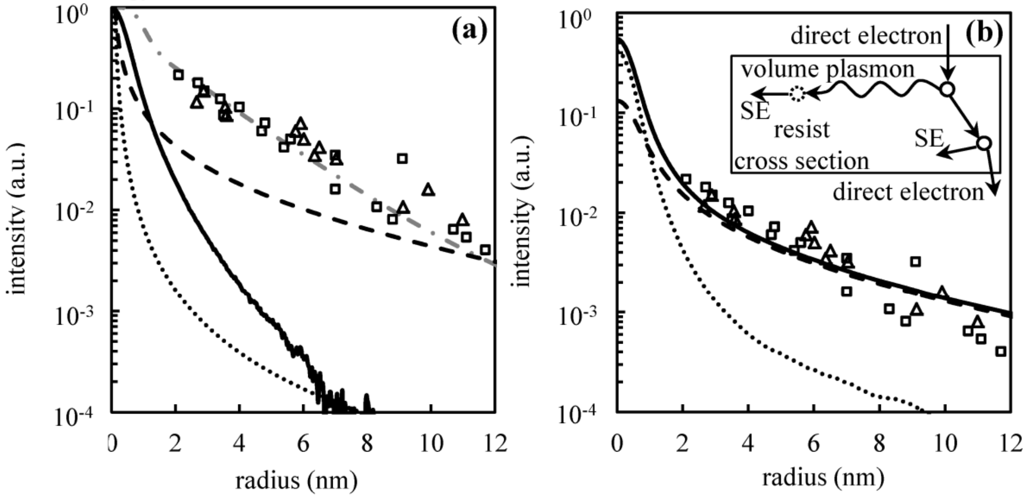

Figure 3. Components of the Lithographic PSF. (a) (full line) Direct-beam PSF, (dotted line) numerical SE PSF based on Ref. 3, (dashed line) volume-plasmon (VP) PSF, (gray line) fitted lithographic PSF, and (black squares - dataset 1 - and black triangles - dataset 2) lithographic PSF from dot-exposure method. From the direct-beam PSF to the lithographic PSF we have the total effect of delocalized energy transfer in EBL. The VP PSF was dominant at these length scales. **(b)** (dotted line) SE PSF by Monte Carlo Simulation based on Ref. 1, (dashed line) VP PSF, and (full line) SE and VP PSFs combined. The SE and VP PSFs were convolved with the direct-beam PSF (which includes the instrument spot size). This Monte-Carlo simulation includes SE generation but not VPs. We noticed that the VP PSF is a necessary component to match the lithographic PSF. The inset shows a schematics of the VP and SE generation from inelastic scattering (full circle) of the direct electron beam, and VP decay into SE (dotted circle).