# Point-spread function of energy deposition by an electron-beam determined by using energy-filtered TEM

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A critical step to understand and thereby improve upon electron-beam lithography (EBL) resolution is quantifying the electron-beam deposited energy in the resist at the nanometer scale, i.e. the point-spread function (PSF). Currently, the PSF is experimentally determined only indirectly by studying single-pixel exposures in resist.[1] Achieving a more direct measurement of PSF is a fundamental challenge due to multiple energy-transfer processes involving the direct electron beam and the resist, which often involve the generation of secondary electrons that further expose the resist.[2-4] But such a direct measurement of the PSF would provide a better understanding of the fundamental resolution limits of EBL. Here we measured the energy deposited in the resist and the effects of delocalized energy deposition in the resist by using energy-filtered transmission electron microscopy (EFTEM) and electron energy loss spectroscopy (EELS).

Figure 1A-1C show details of the experimental method we used to measure the energy deposited in the resist. Figure 1D shows: (1) measured electron-beam intensity with no energy loss; (2) measured electron-beam intensity with energy loss (averaged by the intensity of transmitted electrons from 2.5 to 102.5 eV), which we named "direct-beam energy loss" (DBEL); and (3) the experimental PSF at 200 keV. To compare the DBEL (green circles) to the PSF (black curve) we made two assumptions: (1) all energy lost by the direct-beam from 2.5 to 102.5 eV contributed to resist exposure (while in practice such perfect exposure efficiency is unlikely); and (2) the energy loss was approximately uniform through the resist thickness, which is a reasonable approximation because we are in the single-scattering-event regime (20 nm HSQ thickness is significantly smaller than the 272 nm inelastic mean free path measured by EELS). We observed a difference between the PSF and the DBEL, presumably due to secondary electrons. This EFTEM technique also showed that the bulk plasmon peak is a significant component of energy loss in the resist. However, further investigation is necessary to understand the role of bulk plasmons on resist exposure. We will compare our results to Monte-Carlo simulations at 200 keV.

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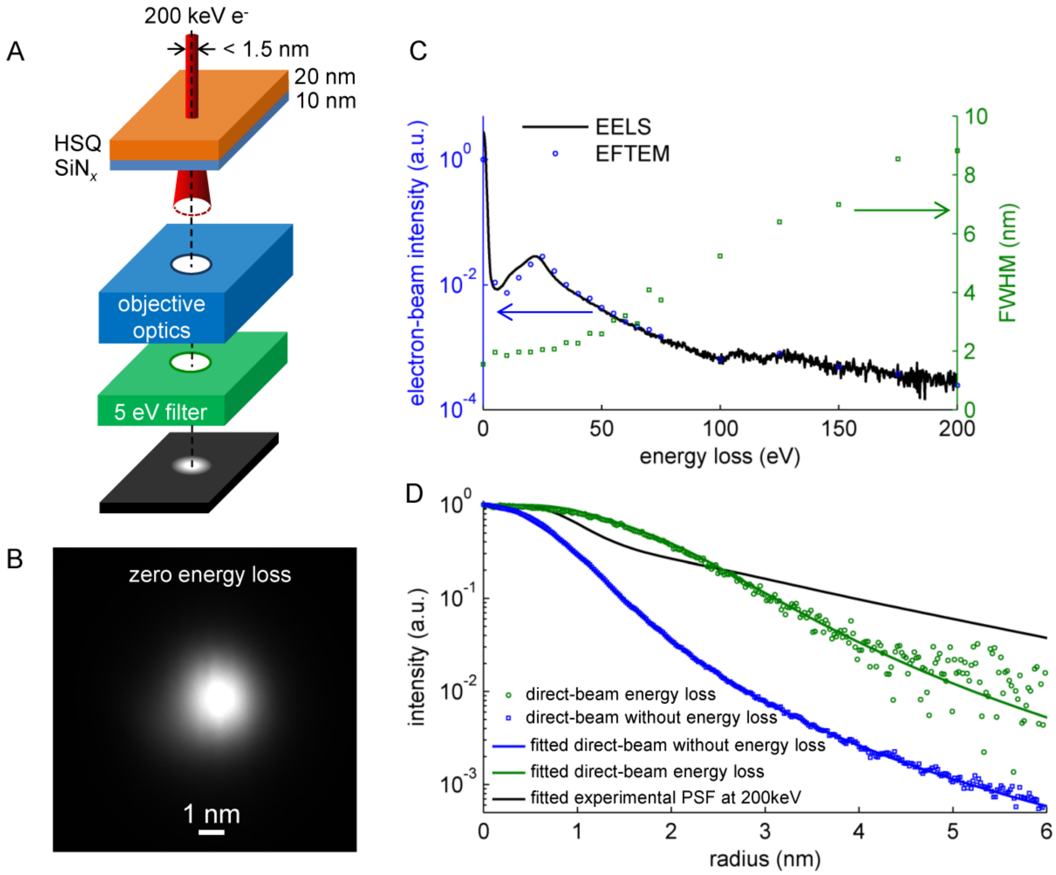


**Figure 1.** Energy-filtered TEM imaging of electron spot size coming out of the sample, i.e., electron distribution as a function of position and energy loss. (A) Schematic of the experiment. The electron beam energy was 200 keV, the landing spot size was smaller than 1.5 nm, and we used 5 eV filter slit to obtain the energy-filtered spatial distribution of the spot size. (B) A bright field TEM image of the spot size after the sample without energy loss. (C) Full-width at half maximum (FWHM) and electron-beam intensity of the spot size for energy loss Ɛ-2.5 eV to Ɛ+2.5 eV, where Ɛ goes from 0 to 200 eV. We observed the bulk plasmon peak at 22.5 eV, from a superposition of $SiN_x$ and HSQ plasmon peaks. The electron-beam intensity measured by EFTEM (blue circles) matched the EELS spectrum (black line). (D) shows: (1) spatial distribution of the measured electron-beam intensity with no energy loss (blue squares); (2) spatial distribution of the measured electron-beam intensity with energy loss (green circles), which we named "direct-beam energy loss" (DBEL); (3) and the fitted experimental PSF (black line). The experimental PSF was obtained by single-pixel exposures[1] using an aberration-corrected STEM at 200 keV as the exposure tool. The resist used was 10-nm-thick HSQ using salty development. For the PSF from 2 to 6 nm radii, we measured developed features with TEM. For sub-2-nm radius, we back-calculated the PSF using a square-grating test structure with minimum feature size of 2 nm. By comparing the DBEL to the PSF we observe deposited energy in the resist due to delocalized processes in the exposure.