Quantitative measurement of the charge distribution along a tungsten nanotip using transmission electron holography

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Off-axis electron holography can be used to measure the electron-optical phase shift associated with a charge density distribution in the transmission electron microscope (TEM). The charge density can then be recovered either by integrating the Laplacian of the reconstructed phase[1] or, equivalently, by applying a loop integral[2]. Whichever approach is used, the perturbed reference wave[3] does not affect the measurement of the projected charge density inside the specimen so long as it does not itself contain any charges. Here, we study a W nanotip, in which the charge density distribution is of interest for applications in field emission and atom probe tomography. We assess artefacts and noise in the measurements.

Figure 1(a) shows an off-axis electron hologram of a W nanotip recorded at 300 kV using an FEI Titan 60-300 TEM. The interference fringe spacing is 0.318 nm, the nominal magnification is 140 000 and the voltage applied to the electrostatic biprism is 90 V. The apex of the nanotip has a diameter of approximately 5 nm and is covered with a layer of tungsten oxide. A voltage of 50 V was applied between the nanotip and a flat electrode positioned approximately 3 µm away from it. In order to remove the contribution to the phase shift from the mean inner potential, two holograms with and without a voltage applied to the nanotip were recorded. The difference between the two phase images was then evaluated after sub-pixel alignment. Figures 1(b) and (c) show the resulting unwrapped phase before and after adding phase contours of spacing 2π/3 radians. Figure 1(d) shows the charge distribution calculated by applying a Laplacian operator to a median-filtered version of the phase image. Figure 1(e) shows cumulative charge profiles along the nanotip determined both using a loop integral and by applying a Laplacian operator to either an unwrapped phase image or the original complex image wave. The integration region is marked by a green dashed rectangle in Fig. 1 (b). The measured charge profile is consistent between the three approaches. Figure 1(f) shows an evaluation of noise in the measurement obtained by performing a similar integration in a region of vacuum indicated by the red dashed rectangle in Fig. 1(b). Results such as those shown in Figs. 1(d) and (e) can be used to infer the electric field and electrostatic potential around the tip. Future work will involve comparing the present approaches with using a model-based technique for determining the charge density from a recorded phase image.

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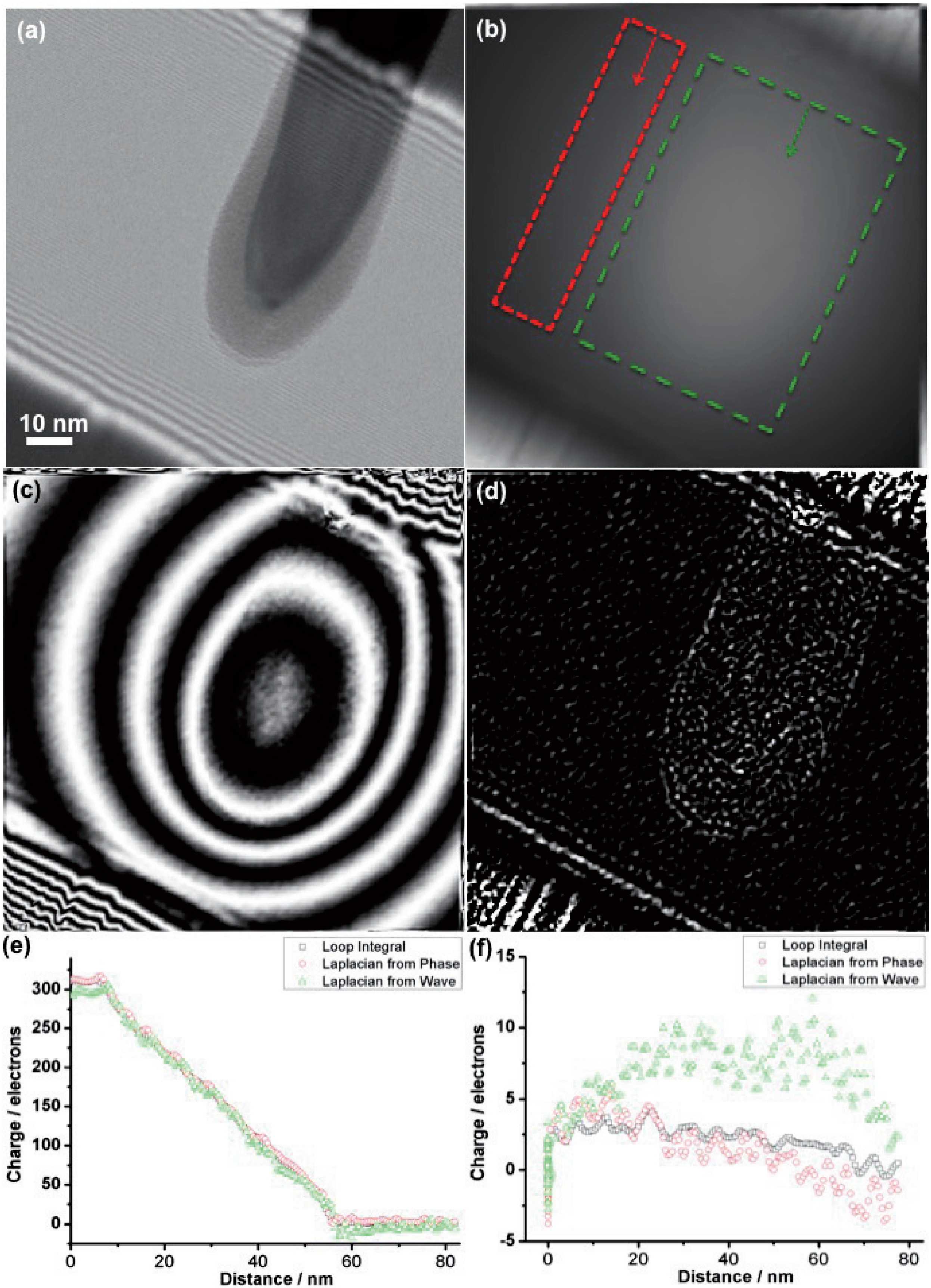

Figure 1: (a) Off-axis electron hologram of a W nanotip covered in W oxide; (b) Unwrapped phase for a 50 V bias between the tip and electrode, with mean inner potential contribution subtracted; (c) Phase contour map from (b) with a contour separation of 2π/3 radians; (d) Projected charge density calculated from Laplacian of the unwrapped phase; (e) Cumulative charge profile along the nanotip in the region marked by a green dashed rectangle in (b) using a loop integral and Laplacian of either the unwrapped phase or the original complex image wave; (f) Cumulative charge profile from vacuum alone in the region marked by a red dashed rectangle in (b).