Multilevel visualization of the local electric field at a sharp probe apex by scanning electron microscopy

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In situ visualization of the local electric field distribution generated at a sharp probe apex is a key to better understand, and thus, improve the dynamic properties of electron-related device behavior. Such a local field distribution at a sharp, long tip can be analyzed numerically using conventional static electromagnetic mechanics, and it could also be obtained by solving Laplace's equation. However, in situ and real time visualization would be of great benefit to understand the dynamic behavior of a device, such as ballistic switching at a small gap.

We have demonstrated that a scanning transmitting electron microscope (STEM) operated with a low accelerating voltage can be used to visualize the local electric field induced at a sharp probe apex [1,2]. The primary electrons were scattered by the strong local field at the apex via Rutherford scattering, as shown in Fig. 1. We also used an orifice to restrict the deflection angle and thus define the threshold of the detection sensitivity; a smaller diameter yielded a higher sensitivity. If we define the impact parameter b as the distance from the electron trajectory to the probe apex, the impact parameter for Rutherford scattering can be written as $b = \frac{1}{4\pi\varepsilon_0}\frac{ze^2}{mv^2}\cot\frac{\theta}{2}$, where e is the electric charge, m is the electron mass, v is the electron velocity, z is the apparent charge number, θ is deflection angle, and ε_0 is the permittivity of the vacuum. As the local electric field at a distance b from the apex is given by $E_b = \frac{1}{4\pi\varepsilon_0}\frac{ze}{b^2}$, the expression for the local electric field E_b can be recast in terms of the deflection angle θ and the impact parameter b as $E_b = \frac{mv^2}{eb}\tan\frac{\theta}{2} \approx \frac{V}{b}\tan\theta$. In this detection scheme, the primary electron beam deflects out of the STEM detector and generates a dark shadow in STEM images. Thus, the local field will be projected as a monotone dark shadow located at the probe apex in the STEM bright field image, as shown in Fig. 2(a) and (c).

In contrast, here we report a breakthrough technique to realize multilevel visualization by scanning electron microscopy (SEM). We used a detection grid instead of an orifice, as shown in Fig. 1. The detection grid was fabricated with a 100-nm-thick gold film, and had 3-μm-wide lines and 10-μm pitch. The principle of multilevel visualization was simple: when the primary electron almost grazes the probe apex, the deflection angle is expected to be the maximum and thus the electron should reach the farthest grid. The contrast of the secondary electron emission between the gold grid and Si substrate was sufficiently large to generate ring-shaped contours at the probe apex, and the ring separation was defined by the Rutherford scattering formula. Fig. 3(a) shows the initial setting of the probe and detection grid. A counter anode was placed approximately 1 mm from the probe, and the grid was placed ~30 mm downstream of the probe. The primary electrons were accelerated by 5 keV. When we applied a positive bias to the counter anode, deflected electrons hit the gold grid, and the emitted secondary electrons generated ring-shaped contour lines at the probe apex. After increasing the bias voltage up to 230 V, a maximum of 6 contour lines appeared, as shown in Fig. 3(e). The innermost ring was a dark region, and thus an electron passing very near to the probe apex should reach at least 60 μm from the grids edge; a deflection that corresponds to a field of ~2×10^6 V/m at the probe apex. However, it should be noted that such a ring-shaped contour was not reflected the absolute value of the electric field, but suggested a directional cosine component of the real electric field. Fig. 4 shows simulation results using the finite element method (FEM), which we implemented in cylindrical coordinates, setting the z axis parallel to the probe. The induced electric field just above the probe surface should be parallel to the surface, and the FEM results completely agree with this physical prediction, as shown in Fig. 4(a). However, the primary electrons are deflected, according to the Rutherford scattering, toward to the counter anode. It follows that the directional cosine component of the real electric field should contribute to the scattering. The distribution map shown in Fig. 4(b), where the cosine components were extracted from the field distribution shown in (a), was in good agreement with the visualized image.

REFERENCES

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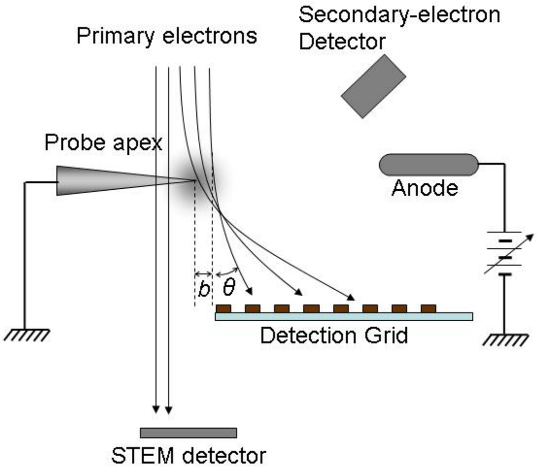

Fig. 1 Schematics of local field visualization.

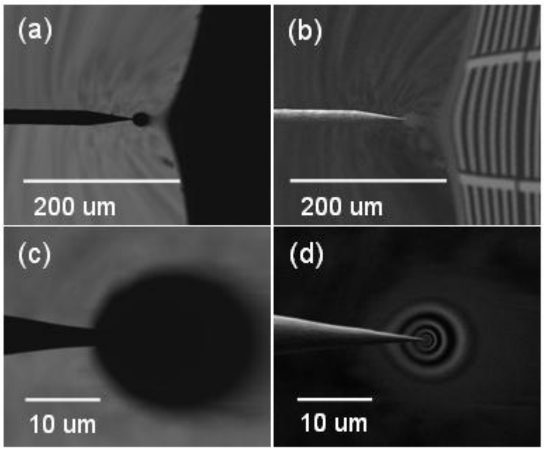

Fig. 2 Visualized field (a) and (c) under the STEM mode, and (b) and (d) under the SEM mode.

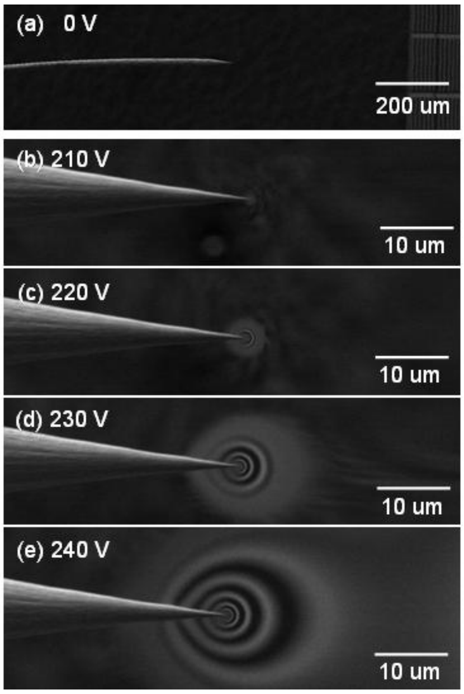

Fig. 3 Contour rings increase in number with increase in bias voltage.

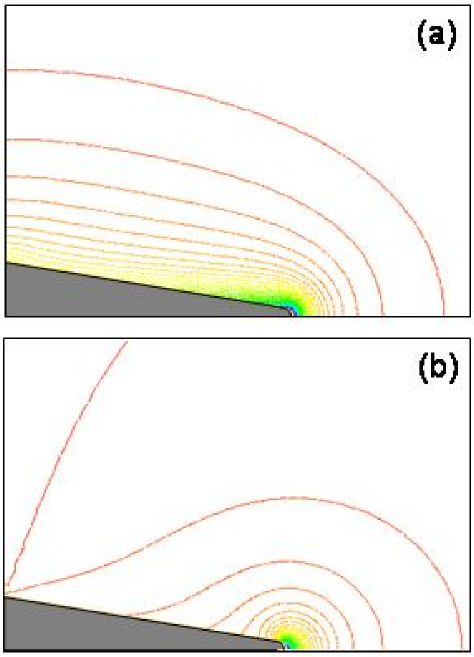

Fig. 4 Results of FEM simulation.
(a) distribution of the absolute intensity of the electric field.
(b) distribution of the cosine component extracted from (a).