In-situ visualization of local electric field at ultra sharp tungsten emitter under low voltage scanning transmission electron microscope

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It is well known that a sharp emitter tip strongly enhances the local electric field around its apex, and thus the geometrical shape of the tip has a precise affect on field emission behavior [1]. While using various theoretical approaches to analyze several experimental results of emission behavior is possible, using an in-situ visualization of the local electric field would greatly help us to understand the characteristics of emissions. We have found a simple process that can be used to fabricate an extremely sharp tungsten tip that has a radius of only a few nanometers (Fig. 1). The local electric field around the emitter chip can thus be visualized in a low voltage scanning transmission electron microscope (STEM) image [2].

We used a conventional STEM system (Hitachi S4800) equipped with a piezo actuated manipulator. An electrolytic polished tungsten probe embedded with multi-walled carbon nanotube was then mounted on the cathode actuator, as shown in Fig. 2(a). The field emission was observed when the biased voltage exceeded about 120 V. The increased emission current then heated up and melted the tip of the probe, while the Coulomb attraction force to the nanotube lengthened the tip. Finally, the force ripped the nanotube away from the probe top and created an extremely sharp tungsten apex with a radius of only a few nanometers, as shown in Fig. 2(b).

Field emission properties from such emitters, where a sharp tungsten emitter had about 130 V of the turn on voltage of the field emission, are shown in Fig. 3,. However, excessive emissions again made the apex round (Fig. 2(c)), and thus the turn on voltage for restarting the emission needed to be about 220 V. The slope of the FN-curve β can be described as a function of the local electric field F and the work function ϕ, $\beta = -0.683 \times 10^9 \phi^{3/2} / F$. The slope for the sharp tip was about three times larger than that of the rounded one just above the turn-on voltage, suggesting the tip radius was about one-third smaller than that of after the deterioration.

We also found that a locally enhanced field at the probe apex can be visualized in a STEM image with a low accelerating voltage. The primary electrons were deflected by a local field out of the STEM detector and created a dark shadow surrounding the probe apex in the image. A STEM image taken at 15 keV clearly described the differences in the local distribution (as shown Fig. 5) and corresponded to the local field intensity as a function of the gap distance. The dark surrounding region seen in (a) with a 5 μm gap at 258 V shrunk when the gap increased to 10 μm, and the dark region also shrunk when the applied voltage decreased to 230 V. Such electron deflection was analyzed as the deflection at the local charge induced at the tip apex under a Rutherford scattering scheme defined as follows: $\tan\theta = EV / b$, where the impact parameter *b* was defined as the radius of the shadow, the deflection angle θ is defined as the system geometry, and the electron accelerating voltage was V. The local electric field at the edge of the shadow shown in Fig. 4(d) was estimated to be about 2 x 10^7 V/m. These results suggested our in-situ visualizing technique can be used to precisely investigate the behavior of local field enhancement against the geometrical configuration and shape of the apex.

References

[1] R. G. Forbes, C. J. Edgcombe, and U. Valdre, Ultramicroscopy, 95,57-65 (2003).

[2] Z. L. Wang, and R. P. Gao, Appl. Phys. Lett. 80, 586-858 (2002).

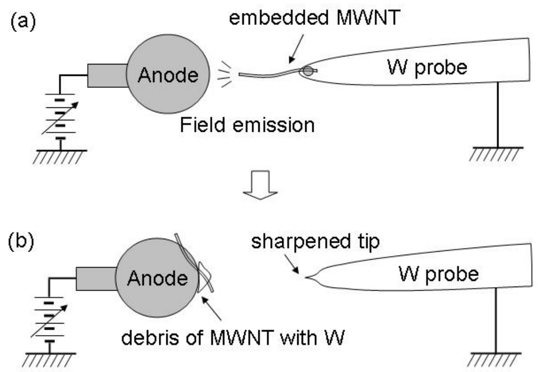

Fig. 1 Field emission measurement system

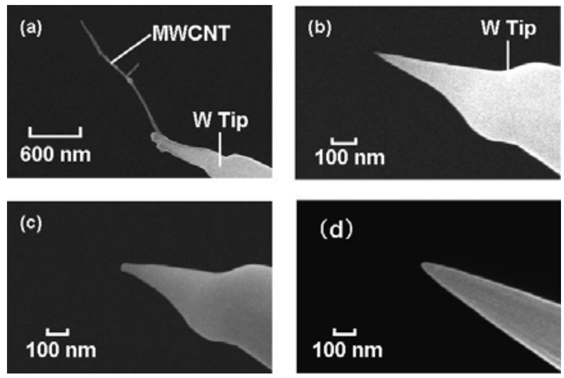

Fig. 2 HR-SEM image of emitter chips (a) MWCNT was connected on W tip (b) Sharpened W tip

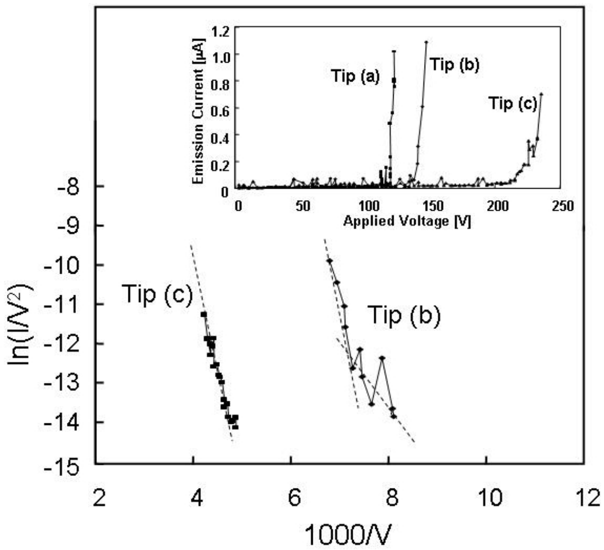

Fig. 3 Field emission behavior for tips corresponding to those shown in Fig. 2

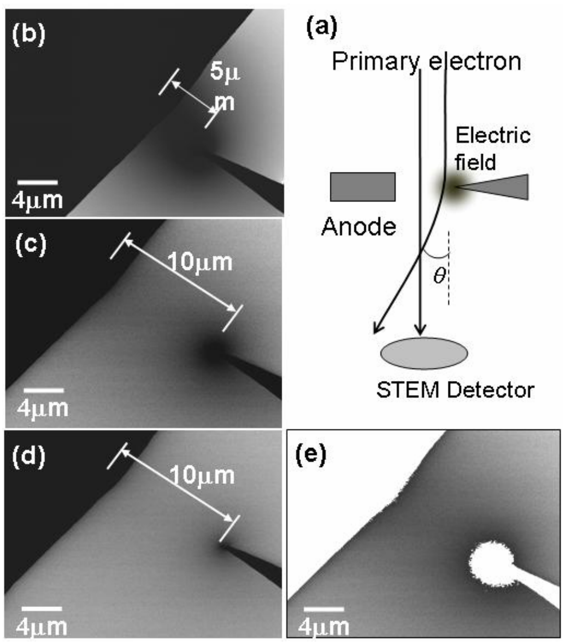

Fig. 4 FN plot for sharp (b) and round (c) tungsten tips corresponding to those shown in Fig. 2