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Field Emission from Zinc Oxide Nanowires

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ZnO nanostructures (nanowire/ nanobelt/ nanotube etc.) have been studied as an effective FE source [1-3]. ZnO nanowires/nanobelts are of interest for field emission applications particularly in flat panel displays as they can be synthesized in a well aligned and densely packed arrays. Until now, most of the studies on the field emission of ZnO nanowire/nanobelt have been carried out in a simple vacuum chamber consisting of cathode and anode and a field emission detection system [4]. From the extensive FE studies on the CNT's, it has been observed that field enhancement properties depend on the inter-electrode distance, radius, geometry and shape of the nanotube and the emission process is highly sensitive to the exact tip structure (open/ closed end of the nanowire/nanotube). However, it is difficult to estimate the distance precisely inside a vacuum testing chamber without microscopy attachments. In order to perform an accurate investigation, it will be highly desirable to do the in-situ FE experiment inside an electron microscope. In view of this, we report here, the FE property measurement on the individual ZnO nanowires using scanning tunneling microscopy (STM) and *in situ* high resolution transmission electron microscopy (TEM). All the measurements were carried out on a single tilt STM-TEM holder in a JEM 4000FX TEM system that operated at 200kV. Our ZnO samples were synthesized by thermal CVD method. The electrochemically etched gold wire with ZnO nanowires was attached to the piezo-driven movable part of the holder facing the fixed and sharp tungsten STM tip as its counter electrode, and oriented perpendicular to the electron beam in the TEM. Field emission measurement was conducted by applying different bias voltages to the gold electrode with the nanowire sample at its tip, while the tungsten STM tip was grounded. Several nanowires with different shapes and dimensions were investigated for field emission properties. Figs. 1(a-d) show the bright field images of ZnO nanowires with different tip geometries aligned between the two counter electrodes during the field emission process. Fig. 2(a) depicts typical field emission current (I) obtained from various nanowires shown in Figs. 1(a-c). For I-V curves in the low voltage region, the emitted current is very low and seems to be independent of the applied field. It is observed that both threshold voltage and the field emission current depend on the shape and tip diameter of the nanowires. The threshold voltage for the emission current was low (~ 6.50 V and 8.05 V, Fig. 2a) for the nanowire having sharp agavelike tip structure (Figs. 1a &1b, width, w = 10 *nm* and 18 *nm*) as compared to the nanowire having a round tip (w = 22nm, Fig. 1c, Fig. 2a). The I-V curves for the broader-tip nanowire (w = 40 *nm*, 80 *nm* and 200 *nm*) were also measured. There is a sharp increase of field emission current with the voltage, once the threshold voltage is reached to start the electron emission. Once the emission is fully operating, I-V follows the Fowler-Nordheim emission. The highest emission current of ~ 502.5 μA is obtained for the sharp agavelike-like tip nanowire (Fig. 2a, w = 10*nm*) with low turn-on voltage of 6.75 V. This is followed by emission current of ~ 425.6 μA for nanowire also having sharp agavelike tip structure, w = 18 *nm* at turn-on voltage of ~ 8.75 V. For the round-shaped tip nanowire, the field emission current was ~ 190.54 μA, with turn-on voltage of ~ 15.04V. As is evident (Fig. 3b), with the increase in the width and decrease in the sharpness of the tip, the threshold voltage increases and field emission current decreases. The emission current-voltage characteristics were analyzed by using the Fowler- Nordheim (F-N) theory [5]. According to the F-N theory the field emission current density is

$$J = a(\beta^2 V^2/\varphi\phi d^2) \exp [-bd\varphi\phi^{3/2}/\beta V] \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where J is current density, a and b are universal constants given by $a = 1.5414 \times 10^{-6}\ AeVV^{-2}$ and $b = 6.830888 \times 10^{9}\ eV^{-3/2}Vm^{-1}$, and ϕ is the work function of the ZnO. To determine the field enhancement

factor β, it is easy to trace the F- N plot through $\ln(I/V^2)$ versus $1/V$, which follows a linear relationship with the slope dependence of ϕ and β. The enhancement factor, β can thus be determined by fitting the slope value and taking a reasonable ϕ value. In conclusion, it can be said that the field emission measurement of the individual ZnO nanowire have been carried out in-situ inside a high resolution TEM. It was observed that both threshold voltage and the field emission current depend on the shape and tip diameter of the nanowire. There is a decrease in the threshold voltage to start the field emission and increase in the value of the field enhancement factor, β as the diameter of the ZnO nanowire decreases. The nanowire having agave like tip structure and smaller diameter (10 *nm*) tip was found to be the best field emitter under the present investigations. The highest field emission current of ~ 502.5 μA and largest value of field enhancement factor, β (= 4562) are obtained for the above nanowire.

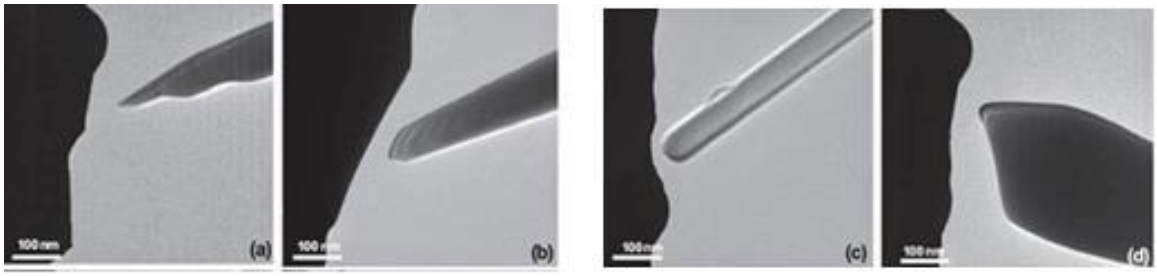

Figure 1. The bright field images of the ZnO nanowires with different tip shape and width, w ranging from 10–200 nm

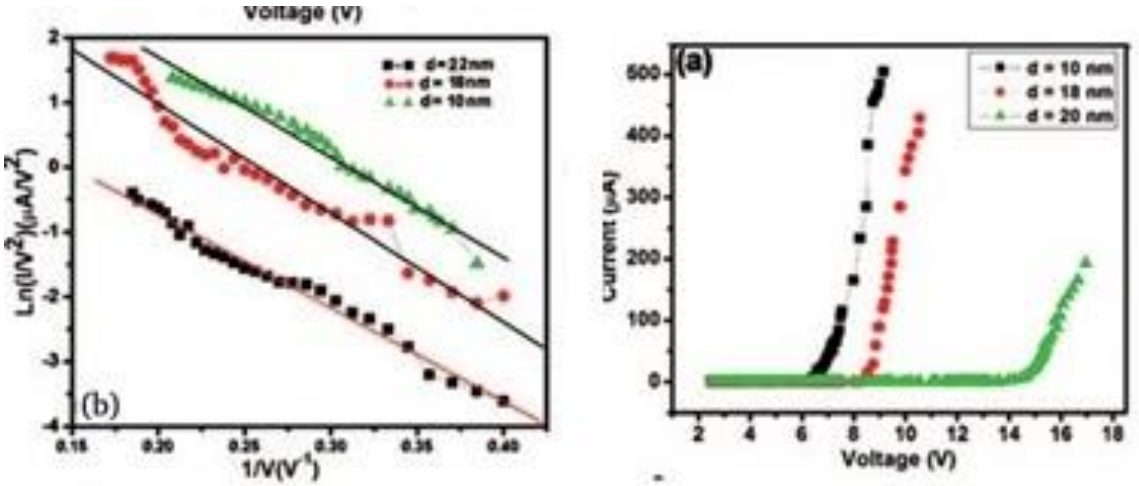

Figure 2. The I-V curves of the nanowires having width, w - 10, 18 and 22 nm and the F –N plots of the nanowires having w - 10, 18 and 22 nm

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