**In situ** probing of electromechanical properties of an individual ZnO nanobelt

Anjana Asthana,1,a Kasra Momeni,1 Abhishek Prasad,2 Yoke Khin Yap,2,a and Reza Shahbazian Yassar1,a

1Department of Mechanical Engineering-Engineering Mechanics, Michigan Technological University, Houghton, Michigan 49931, USA
2Department of Physics, Michigan Technological University, Houghton, Michigan 49931, USA

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We report here, an investigation on electrical and structural-microstructural properties of an individual ZnO nanobelt via *in situ* transmission electron microscopy using an atomic force microscopy (AFM) system. The *I*-V characteristics of the ZnO nanobelt, just in contact with the AFM tip indicates the insulating behavior, however, it behaves like a semiconductor under applied stress. Analysis of the high resolution lattice images and the corresponding electron diffraction patterns shows that each ZnO nanobelt is a single crystalline, having wurtzite hexagonal structure (a=0.324 nm, c=0.520 66 nm) with a general growth direction of [1010].

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Nanogenerators, piezoelectric field effect transistors, and piezoelectric diodes were recently developed based on the unique coupling of piezoelectric and semiconducting properties of ZnO nanowires. The emergence of this nanoelectrotronic area requires further understanding on the electromechanical behavior of ZnO nanostructures. Although there are a few reports on the electromechanical behavior of ZnO nanowires, no studies are devoted on the study of ZnO nanobelts, which are structurally different. Here, we present the study on the electrical and structural properties of an individual nanobelt via *in situ* high resolution transmission electron microscopy (TEM)-atomic force microscopy (AFM) system. All the measurements were carried out on a single tilt AFM-TEM holder (Nanofactory Instruments) in a JEM 4000FX TEM system that operated at 200 kV. Our ZnO samples were synthesized by thermal chemical vapor deposition method, as reported elsewhere.

For *in situ* electrical measurement, an individual ZnO nanobelt was attached to the electromechanically etched tungsten tip by tungsten deposition using the focused ion beam (FIB) technique to ensure good electrical contact between the tip and the nanobelt. The different steps of the sample preparation are shown in Figs. 1(a)–1(c). In short, a nanobelt was picked up using the FIB probe [Figs. 1(a) and 1(b)] and attached on the tungsten tip [Fig. 1(c)] by the tungsten deposition. The tungsten tip with ZnO nanobelt was then transferred to the AFM-TEM specimen holder and approached to its opposite conducting AFM tip by the piezomanipulator. A schematic diagram of the experimental setup is shown in [Fig. 1(d)]. In order to clean the surface of the nanobelt and to achieve a good physical contact with the AFM tip, we applied a floating bias of 50 V to the nanobelt. Figures 2(a)–2(c) display the sequential images of a typical ZnO nanobelt undergoing to a stressed state by the gentle push of the piezodriven tungsten tip toward the AFM tip. It is to be noted that, for measuring the electromechanical properties in our experiments, nanobelts with shorter length of ~1–2 μm are chosen, to avoid bulking of the nanobelts. Figure 2(a) shows the bright field image of ZnO nanobelt just in contact with the AFM tip.

The current-voltage (*I*-*V*) characteristics of the ZnO nanobelt just in contact with the AFM tip [curve “a” in Fig. 2(d)] shows insulating behavior, probably due to less contact area and high contact resistance. By controlling the contacts of the nanobelt with the conducting AFM tip and also by bringing the nanobelt in a stressed state, it was possible to alter the *I*-V characteristics of the nanobelt. Figure 2(b) shows the ZnO nanobelt in a stressed state during the compression process and Fig. 2(c) shows the image at higher stressed state. A series of measured *I*-*V* curves with an increase of stress in ZnO nanobelt are respectively shown in Fig. 2(d). As we try to stress the nanobelt by delicate driving of the tungsten tip with the nanobelt against the AFM tip, a current of several nanoamps can be observed at a higher bias voltage (curve “b”). Although, the value of current obtained is not so high, however the nature of *I*-*V* curve indicates the...