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In Situ Electromechanical Study of ZnO Nanowires

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One-dimensional structures such as nanowires and nanotubes are potential candidates for nanoelectronic, optoelectronic, piezoelectric devices, sensors, actuators, etc. Due to length scale effects and higher surface-to-volume ratios, nanostructures exhibit superior mechanical and electrical, as well as other length scale dependent properties [1,2]. To utilize these fundamental advantages, it is essential to investigate and understand their unique characteristics as a function of the material parameters. In spite of the great technological progress that has been made during the last decade to characterize nanostructured materials, comprehensive electromechanical characterization of a single individual nanowire is still a challenging task. In this study, a MEMS-based uniaxial nanotensile testing device E-PTP (electrical push-to-pull) with integrated four-probe electrical contacts was used for electromechanical characterization of a single ZnO nanowire, Fig. 1a and 1b.

Non-centrosymmetric wurtzite structure zinc oxide (ZnO) exhibits a strong piezoelectric tensor among tetrahedrally bonded semiconductors, and is a promising material for sensors, actuators, and energy harvesting applications [3,4]. ZnO nanowires were synthesized by a newly introduced flame transport approach at the University of Kiel [5]. Nanowires of diameter 300-400 nm and length ~20 μm were picked by a nanomanipulator and placed on E-PTP devices inside a dual-beam SEM-FIB. Pt-based GIS was used for welding and for connecting four leads to the nanowire sample as shown in Fig. 1. Strain-rate controlled tensile experiments using a PI 85, *in situ* nanomechanical testing instrument (Hysitron, Inc., Minneapolis MN), were conducted inside an FESEM. A source/measure unit was used for DC current sourcing and voltage measurements in four-point probe mode. Voltage sweeps at constant strain were performed to obtain I-V curves in order to extract electrical properties. Periodic stress or strain from the nanowires was generated by periodic variation of the applied voltage or current. One of the advantages of the *in situ* study is that instantaneous length and diameter of the nanowire can be measured from video frames and correlated with the mechanical response. True stress and true strain were determined using force-displacement data, Fig. 1c. The actual force to the nanowire was calculated by subtracting the load calculated from the spring stiffness of the flexure from the experimentally measured load. The E-PTP device stiffness of 320 N/m was measured after the fracture of the nanowire. In all the experiments, ZnO nanowires showed a steady increase in current (i.e., decrease in resistance) with a specific applied voltage during loading as shown in Fig. 2a. The non-linear stress-strain curve in the elastic tensile regime of ZnO also indicates that the mechanical response is influenced by the piezoelectric effect of the nanowire. The elastic modulus of ZnO was calculated to be ~88 GPa from a separate set of experiments where no voltage was applied. Resistivity was calculated from the linear I-V curves, Fig. 2b, as a function of tensile strain. The piezoelectric response curve in Fig. 2c shows a fluctuation in stress generated by applied voltage steps, while the nanowire is held at a constant 2.2% true strain. A finding of particular interest is that the change in stress generated by voltage fluctuation, $\Delta\sigma(V)$, depends on the amount of tensile strain (ε_T) applied to the nanowire, and $\Delta\sigma(V)$ increases with ε_T. Besides the strain-induced mobility enhancement as observed in silicon and other semiconductor materials [6], other possibility is that the piezoelectric potential across the nanowire length is influenced by tensile elongation, which in turn significantly modifies the electrical transport properties.

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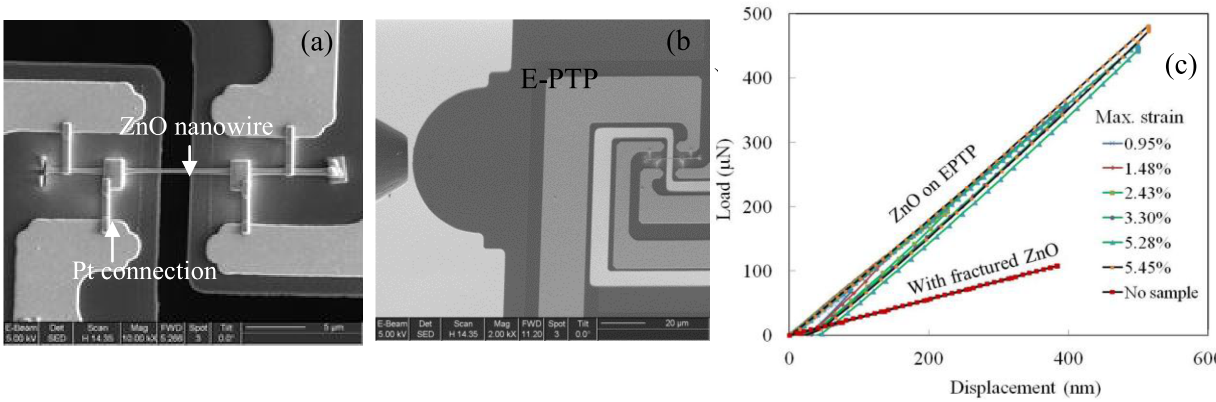

Figure 1: (a) ZnO nanowire mounted on E-PTP and connected to four leads, (b) lower magnification image displaying where indenter contacts E-PTP, and (c) load–displacement plots at different maximum strains before and after ZnO nanowire fractured.

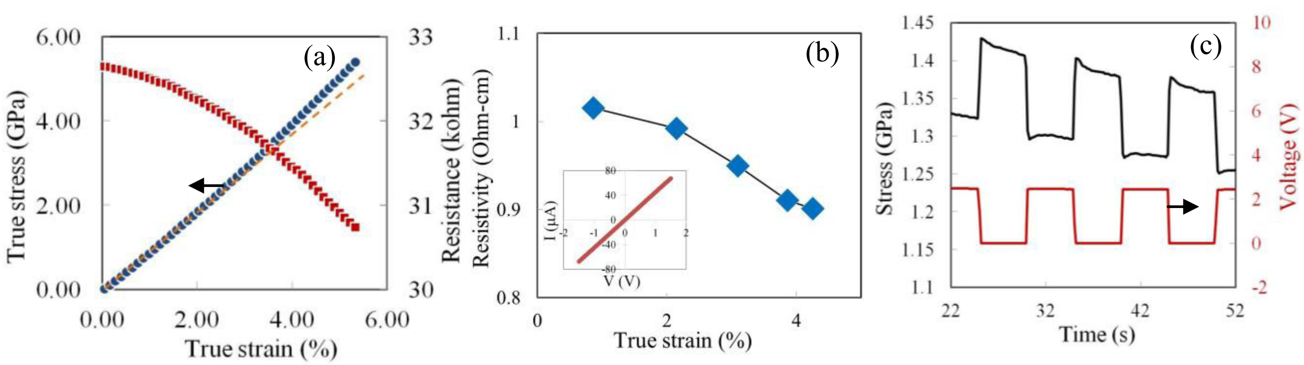

Figure 2: (a) Stress–strain and resistance–strain plot, (b) Resistivity calculated by linear I-V, inset shows typical I–V sweep, and (c) Periodic stress generated by applied square-wave voltage signal from 0 V to 2.45 V while holding nanowire at constant 2.2% strain.

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