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Mechanical properties characterization of Nanowire Arrays for Piezoelectric Energy Harvesting

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Abstract

Piezoelectric energy harvesting technology effectively captures mechanical vibrations and converts them into electrical energy, providing a sustainable power source for micro- and nano-scale devices without reliance on external power. The mechanical properties of nanowire arrays (NWAs) are crucial for the efficiency of this technology, making precise characterization important.

Contact resonance atomic force microscopy (CR-AFM) is employed to measure the elastic modulus of ZnO-NWAs. The Dual AC Tracking method is utilized to monitor contact resonance frequencies, while bulk ZnO is used as a reference to reduce potential errors arising from variations in the cantilever tip radius and probing force. Maintaining a consistent tip radius is vital for accurate measurements; therefore, we measure the reference material both before and after testing the NWAs to ensure tip stability. The measurement results indicate that the elastic modulus decreases as the dimensions of the nanowires decrease, consistent with existing research that shows nanoscale materials exhibit mechanical properties different from their bulk counterparts.

Researchers attribute these differences to various factors. Some propose that atomic bonding environments vary at the nanoscale, while others suggest that the Hertzian model, typically used for mechanical contact in bulk materials, may not be applicable to nanostructures. Further investigation will be conducted to clarify these discrepancies and enhance our understanding of nanoscale mechanical behavior.

Mechanical property characterization, contact resonance atomic force microscopy, Nanowire Array, Piezoelectric Energy Harvesting

1. Introduction

Energy harvesting [1,2], also known as nanogenerators (NGs), involves the use of nanostructured devices to capture various forms of energy from the surrounding environment, such as mechanical vibrations, thermal energy from heat sources, and energy from chemical or biological reactions. This energy is then converted into electrical power. This technology enables building self-powered devices, making micro- and nano-scale devices independent of external power sources. It plays a crucial role in the development of wireless sensor networks and supports the advancement of clean, renewable energy sources.

The piezoelectric effect, which links the electric field and stress field, is central to energy harvesting. Through the direct piezoelectric effect of piezoelectric materials, mechanical energy can be converted into electrical energy. As a result, the piezoelectric energy harvesting technology can harness abundant mechanical energy from environmental sources.

Zink oxide (ZnO) nanowires (NWs) are commonly used in Piezoelectric nanogenerators (PENGs). These ZnO NWs can be grown in patterns to form NW arrays (NWAs), which can be connected in series and in parallel to enhance the piezoelectric voltage and current output.

The mechanical properties of ZnO NWAs significantly impact their piezoelectric performance, demanding precise characterization. Given the small size and slender structure of NWs, typically ranging from 10 nm to 1 µm in diameters and with high aspect ratios from 1 to 300 or more, measuring the mechanical properties of these nanowires requests technologies with high resolution and low probing force, such as contact resonance atomic force microscopy (CR-AFM).

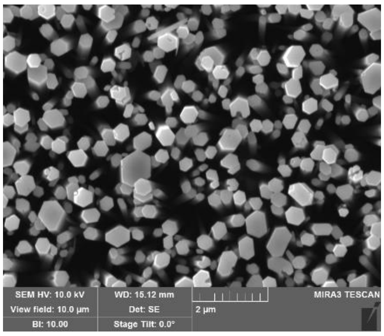
In CR-AFM [3], the cantilever tip remains in contact with the sample surface and vibrates. When the vibration amplitudes are small enough, the contact forces can be modeled as a system of linear springs and dashpots. The shift in the cantilever's contact resonance frequency, relative to its free resonance, depends on the sample's stiffness. Stiffer materials exhibit higher resonance frequencies, while softer materials show lower frequencies. This relationship allows for the quantitative assessment of the sample's material properties. Hertzian contact mechanics is used to correlate the resonance shift with the sample's mechanical properties.

In this study, three ZnO NWAs samples with different geometrical sizes are measured using CR-AFM, and their elastic moduli are characterized.

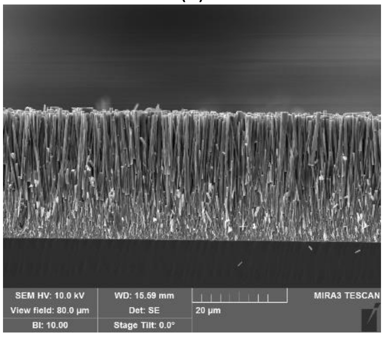
2. Characterization of the elastic modulus of ZnO NWAs

Three ZnO NWAs samples with different dimensions were measured: sample A has a diameter (D) of 200 nm and a height (H) of 1.8 µm; sample B has D = 0.65 µm and H = 26.8 µm; and sample C has D = 1.2 µm and H = 51.8 µm. The top view and cross-sectional images of sample B, obtained using scanning electron microscopy (SEM), are shown in Figure 1.

The measurement was conducted using Asylum Cypher S AFM equipped with an OPUS 240 AC-NG cantilever. The AFM operated in BlueDrive™ Dual AC Tracking (DART) mode. During the measurements, the contact force between the cantilever and the sample surface was kept constant. The cantilever was activated through BlueDrive™ photothermal actuation, and the contact resonance is detected using DuaiAC™ tracking method.



(a)



(b)

Figure 1. SEM images of ZnO NWAs with a diameter of about 0.65 µm and a height of 26.8 µm: (a) Top view; (b) Cross-sectional view.

A bulk ZnO artifact was used as a reference material to address the challenge of determining the exact values of the cantilever tip radius and the contact force. Since maintaining a constant tip radius is essential for accurate measurements, the reference material was measured before and after testing each NWA sample to confirm the stability of the tip radius. Figure 2 illustrates the contact resonant frequencies measured on the NWAs sample A and the bulk ZnO reference material.

The elastic moduli of the three NWAs were measured as 107 GPa for sample A, 118 GPa for sample B and 136 GPA for sample C. These values are all lower than the elastic modulus of the bulk ZnO reference material, which is 140 GPa. Additionally, the measured elastic modulus decreases as the dimensions of nanowires shrink, as shown in Figure 3.

Initially, it is assumed that the low axial stiffness of the slender NW contributes to the reduced measured elastic modulus. To examine this, the ratios of cross-sectional area to the length of the NWs are calculated and presented in Figure 3. Among the three NWAs samples, sample B has the smallest ratio, sample A has an intermediate value, and sample C has the largest. However, this ranking of axial stiffness does not align with the trend observed in the measured elastic modulus. Therefore, the observed decrease in the measured elastic modulus with decreasing nanowire dimensions cannot be attributed to the axial stiffness of the nanowires.

Some researchers attribute the differences in the measured elastic modulus to variations in atomic bonding environments at the nanoscale. This perspective suggests that nanoscale materials exhibit mechanical properties distinct from those of bulk materials.

Conversely, other researchers propose that the Hertzian model, commonly used to describe mechanical contact in bulk material and applied in contact resonance analysis, may not be suitable for nanostructures surface. The Hertzian model assumes that the sample surface radius is much larger than that of the probe. However, the slender nanowires do not satisfy this condition. From this perspective, the observed differences may come from the limitations of the analysis model rather than intrinsic differences between nanoscale and bulk materials.

Further research is needed to resolve these discrepancies and advance our understanding of the mechanical behavior of materials at the nanoscale.

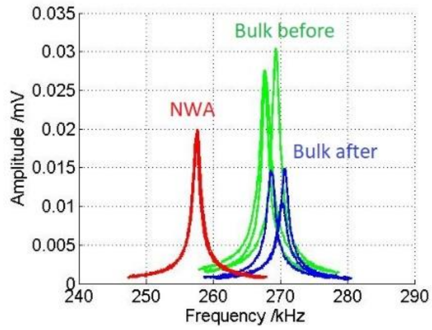


Figure 2. Contact resonant frequencies measured on the NWA and on the reference bulk material.

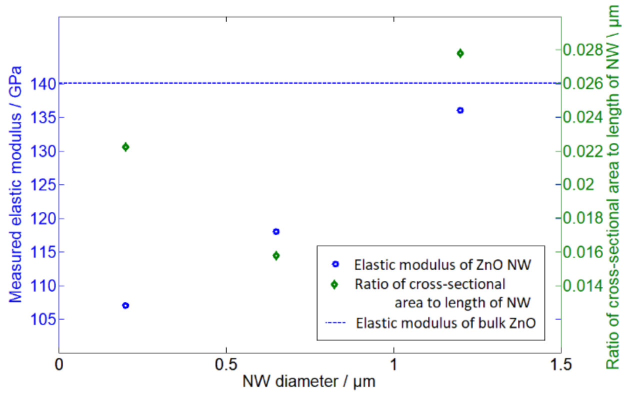


Figure 3. The measured elastic modulus decreases as the dimensions of nanowires shrink. The tendence does not correlate with the ratio of cross-sectional area to the length of the nanowires.

3. Conclusion

The elastic moduli of three ZnO nanowire arrays sample, designed for energy harvesting, were measured using CR-AFM. The results indicate that the elastic moduli of the NWAs are lower than that of the bulk material and decrease as the nanowire dimensions become smaller.

References

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