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Determination of the Young's Modulus of Individual PZT Nanowires Using Resonance Frequencies

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The ability of piezoelectric materials to convert mechanical strain into an electrical voltage and vice versa makes them useful for a wide range of applications such as sensors, actuators, and energy-scavenging devices [1]. To incorporate piezoelectrics into these devices on the micro- and nano-scale, it is necessary to understand their material properties, which may differ from those in bulk. The goal of this study is to determine the Young's modulus of lead zirconate titanate (PZT) nanowires using a resonance frequency approach. The nanowires can be driven to oscillate in response to an applied AC voltage at certain resonance frequencies, which depend on the sample's geometry, dimensions, and material properties. For cylindrical geometries (applicable to nanowires), there exists the following relationship [2]:

$$f = \frac{\beta^2 D}{8\pi L^2}\sqrt{\frac{E}{\rho}}$$

where f is the resonance frequency, and D, L, and ρ are the wire's diameter, length, and density. β = 1.875 for the first harmonic. D, L, and f were measured, and ρ was taken to be the bulk density (~7.85 g/cm^3) [3], allowing for the calculation of the Young's modulus, E.

The samples were synthesized by electrospinning onto a ridged silicon substrate (Fig 1) and then annealing the resulting fibers. The typical diameter of the nanofibers ranged from 80 nm to 120 nm. A nanomanipulator was mounted within a Dual-Beam FIB-SEM system to conduct these experiments. Imaging was performed almost exclusively using the electron beam, with the exception of ion beam-induced vapor deposition of platinum contacts. The nanomanipulator probes were used to sever samples (7-21 μm) from the nanofiber strands. Electron beam induced deposition of carbon impurities formed a temporary adhesion between the nanowire and the probe before using the ion beam to deposit a platinum contact (Fig 3). A function generator was used to apply AC voltage through the probes to the nanowires. For each sample, the amplitude was held constant while the frequency was modulated until resonant oscillations were observed. In most cases, peak-to-peak amplitude of 1 V was applied; however, for some of the shorter wire samples, higher amplitudes (up to 2.5 V) were required to induce a more visible vibration.

The resonance frequencies of five different nanowires were plotted against D/L^2 (Fig 4). As predicted by our model, a very good linear fit is obtained, and the Young's modulus can be obtained from the slope of the linear fit. From this model, the Young's modulus of the PZT nanowires is 44 GPa. This agrees very well with the 42.99 GPa result obtained by Xu et al. using atomic force microscopy [4].

References

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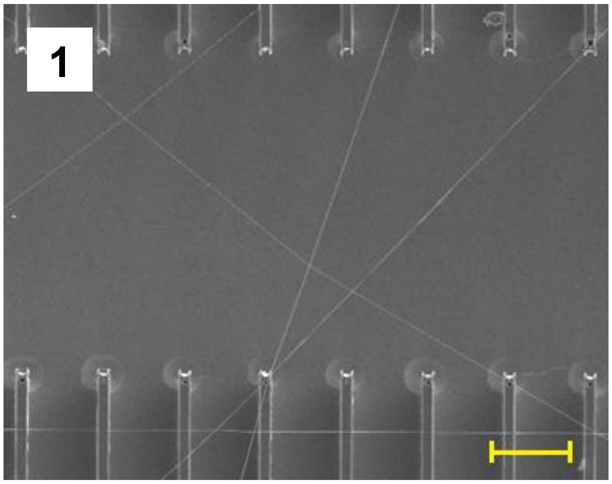

FIG. 1. PZT nanofibers lying across the silicon substrate. Ridges have a height of ~20 μm. (scale bar = 10 μm)

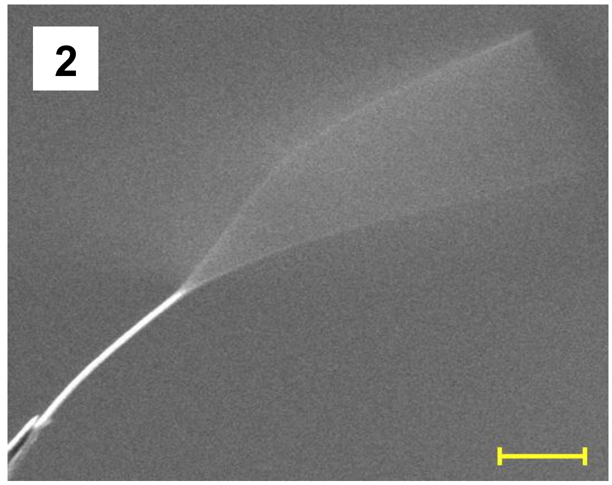

FIG. 2. Resonance induced by AC voltage. Note that the platinum-coated portion is rigid and does not vibrate. (scale bar = 2 μm)

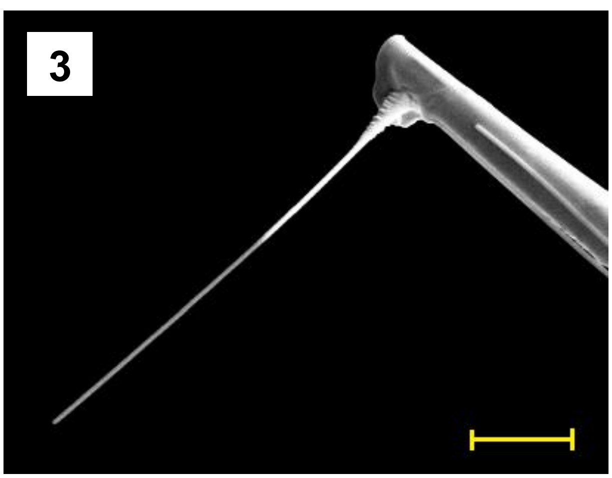

FIG. 3. Closeup of nanowire fixed to nanomanipulator probe. The base of the wire is platinum-coated. (scale bar = 2 μm)

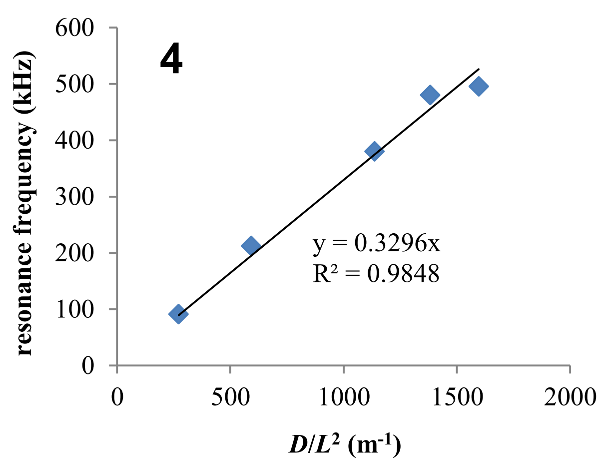

FIG.4. Resonance frequencies plotted versus D/L^2 with linear fit.

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