doi:10.1017/S1431927610061994
Microsc. Microanal. 16 (Suppl 2), 2010

Charge-imbalance-induced Resonance for Functional Nanowires

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Functional ZnO nanowires offer the promise of energy scavenging and precise sensing due to their vibrational properties, but their high intrinsic resonance frequencies (in the kilohertz to megahertz range) are several orders of magnitude higher than driving frequencies involved in energy-scavenging and sensing applications. Therefore, it is crucial to find solutions to lower the frequency range in which nanowires can resonate [1].

By using *in situ* ion implantation, we have introduced a new type of resonance at ultra-low frequencies in ZnO nanowires, achieving resonance-like behavior at two orders of magnitude below the natural resonance frequency. In this paper, we describe this phenomenon and show that electric charge imbalance arising from focused ion beam exposure is responsible for the creation of this unprecedented superharmonic resonance behavior in ZnO nanowires.

We have configured ZnO nanowires as cantilevers by attaching one end to a nanoelectrode and leaving the other free in a scanning electron microscope (SEM). The nanowires were driven to vibrate by an oscillating electric field between the substrate nanoelectrode and a second nanoelectrode positioned above the nanowire. For a pristine, freshly attached nanowire, the appearance of resonances is classically dictated by the Euler equation. Figure 1 shows the primary resonance ω_0 and the second harmonic in the case of a pristine ZnO nanowire. The nanowires were then exposed to a Ga^+ ion FIB, introducing defects in their structure. After FIB exposure, the natural resonance frequency remains unaltered, but a series of superharmonic resonances below ω_0 begin to appear. These new resonances of the ZnO nanowire vary inversely with the frequency number n according to the formula $\omega_n = \frac{2\omega_0}{n}$, with an error consistently below 0.3%.

Using theory as well as Molecular Dynamics (MD) simulations, we show how ion-beam-induced electric charge imbalance can produce the observed superharmonic resonances. Using the SRIM 2008 software, we first estimated the material properties of FIB-exposed ZnO, including the depth of ion implantation and the nature and proportion of lattice defects. The simulations shows that there is a sharp cutoff between the implanted region (2 – 7% of the thickness of the nanowire) and the deeper volume where few Ga+ ions are implanted.We then modeled this implanted ZnO nanowire structure using Materials Studio GULP and Forcite,the combined effect of lattice vacancies and implanted Ga+ ions leads to a reduction of 40-50% in the elasticity modulus.

However, these mechanical changes alone cannot acount for the appearance of ultralow resonances in the FIB-exposed ZnO nanowires. FIB bombardment also increases the resistance of ZnO by as much as 7 orders of magnitude as charge carriers become 'trapped' due to the implantation effects [2]. Due to the implantation of positive Ga+ ions and the simultaneous escape of secondary electrons, FIB exposure can thus introduce an imbalance between the electric charge density of the ZnO nanowire's exposed and unexposed faces (see Figure 2). Taking into account the effect of FIB-induced charge imbalance, the response of a ZnO nanowire can be rewritten as a Mathieu equation:

$$\frac{\partial^2 u}{\partial \tau^2} = -(a - 2q\cos 2\tau)u,$$

The Mathieu equation is most commonly known for governing the response of a classical pendulum with a vertically driven support; it has been studied extensively in the field of applied mathematics [3]. This equation yields a discrete set of superharmonic solutions which follow the equation $\omega_n = \frac{2\omega_0}{n}$, where ω_0 is the natural resonance frequency, which is consistent with the behavior observed in FIB-exposed ZnO nanowires.

While the resonance behavior of regular nanowires is dictated by classical elasticity theory, we have shown that partial ion-beam exposure can lead to high-order parametric resonance due to charge imbalance. These results are promising because they suggest the application of ion implantation as a reliable technique for tuning the resonance of nanodevices. By enabling resonance to occur at frequencies two orders below the natural frequency, this method opens a new range of applications for ultra-precise sensors, energy-scavenging devices and other nanodevices [4].

References

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[5] This work is supported in part by the National Science Foundation-MRSEC (DMR-0819860).

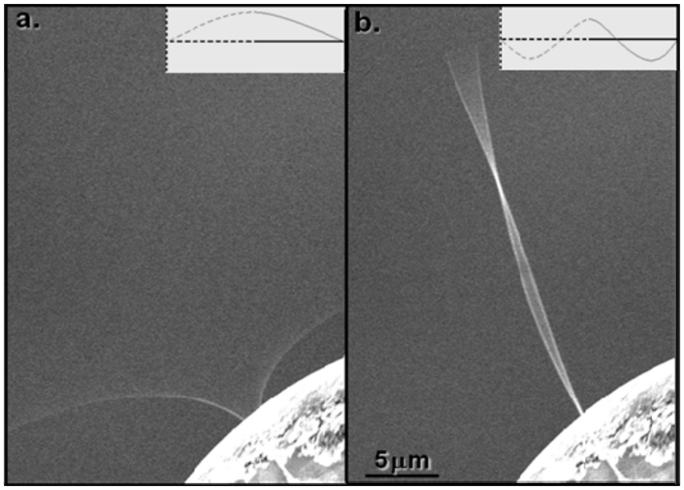

Figure 1.

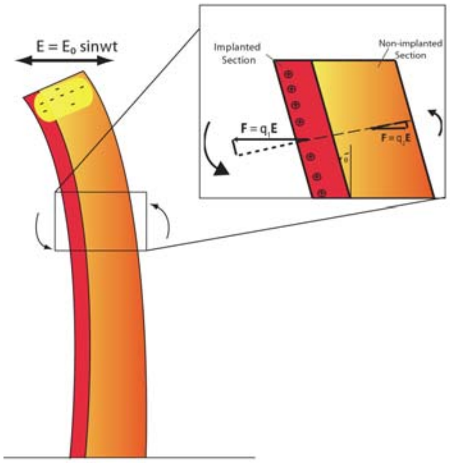

Figure 2.

FIG. 1. Scanning electron microscopy images showing the natural (a) and second harmonic (b) resonant modes of a ZnO nanowire driven by an oscillating electric field.

FIG. 2. The accumulation of positive charge on the implanted side of a FIB-exposed ZnO nanowire leads to charge imbalance, which in turns leads to a bending moment along the length of the nanowire and thus to FIB-induced superharmonic resonance.