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Self-sensing torsional resonators based on inorganic nanotubes

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1. Abstract

Inorganic nanotubes have unique mechanical and electronic properties making them promising candidates for key components in nanoelectromechanical systems (NEMS). In this work, we fabricated torsional resonators based on individual multi-wall WS_2 nanotubes and studied the resonant mechanical properties of the nanotubes using an interferometric detection technique. Utilizing the piezoresistivity of the nanotubes, we demonstrated all-electrical detection of the mechanical resonance of inorganic nanotube resonators for the first time.

WS_2 nanotube torsional resonators are characterized by high resonant frequencies, and are readily detected electrically, allowing for self-sensing devices which could be employed in various sensors, such as gyroscopes.

Keywords: NEMS, nanomaterials, nanotubes, resonator, torsion, sensors

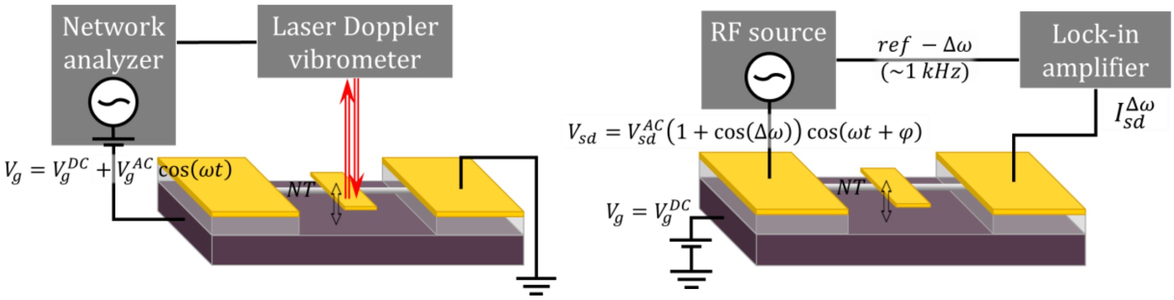

Figure 1. Schematic descriptions of nanotube torsional resonator devices, with two detection schemes: an optical detection scheme using a laser Doppler vibrometer (left); and an electrical detection scheme using a lock-in amplifier, based on signal mixing at the nanotube (right).

2. Introduction

Nanoelectromechanical systems (NEMS) are the miniaturization of microelectromechanical systems (MEMS), showing great potential for nanoscale devices due to high resonance frequencies and low power consumption. Applications include sensitive chemical sensors, accelerometers and gyroscopes.

Materials fit for nanoelectromechanical systems NEMS is an ongoing challenge – requirements call for robust, processable materials that exhibit outstanding mechanical and electronic properties. Nanotubes (NTs) - carbon as well as inorganic – are especially attractive components, as the special tube-like atomic structure lends them unique properties. Among the toughest materials known, nanotubes possess rich electronic properties as well. NEMS based on inorganic nanotubes were recently demonstrated [1], and offer several advantages compared to their carbon counterparts. The interlayer forces in multi-wall NTs are dependent on the chemical composition of the NT, and inorganic nanotubes have been shown to exhibit strong interlayer coupling, as opposed to carbon nanotubes [2]. This is a significant parameter when considering torsional stiffness of the NT and energy dissipation due to internal friction. However, the study of electromechanical properties of inorganic nanotubes in resonance toward their exploitation in NEMS is still in its infancy.

Nanotubes of tungsten disulfide (WS_2) are semiconducting with functional electronic properties [3] while boasting exotic mechanical features [4]. By twisting nanotubes the electronic band structure is altered due to the deformation of the atomic lattice. This electronic-mechanical has recently been demonstrated in WS_2 nanotubes (WS_2NTs) [5], allowing the detection of mechanical motion through a change in the electrical properties of the nanotube. Multi-wall WS_2 have also been shown to possess a high shear modulus [4], and thus assume a role as natural candidates for resonator devices with high resonant frequencies and self-sensing capabilities. Such devices have great potential for applications as well as a platform for studying properties and phenomena of nanomaterials, such as nanoscale interlayer friction.

This study demonstrates the potential of WS_2 nanotubes for NEMS and paves the way for their application in nanoelectromechanical sensors and study of inorganic nanotube properties.

3. Methods

We fabricated torsional paddle resonators based on WS_2NTs using nanofabrication techniques. WS_2NTs (NanoMaterials LTD, grown using an outside-sulfurization method) were dispersed on SiO_2/Si substrates, on top of which contacts and a paddle were patterned using e-beam lithography. Device geometry was characterized using AFM (figure 2(b)) and the electrical transport properties were obtained using a Keithley 4200-SCS.

The nanotube and paddle were suspended above the Si by etching the underlying oxide, and the devices were actuated electrostatically using a combined AC/DC signal applied to the substrate at different frequencies, and the mechanical resonance behavior was studied using a laser Doppler vibrometer system (MSA-500, Polytec GmbH), as depicted in figure 1(a). The mechanical resonance spectrum was detected by electrical signal mixing, using a lock-in amplifier (Signal Recovery DSP-7280), as depicted in figure 1(b).

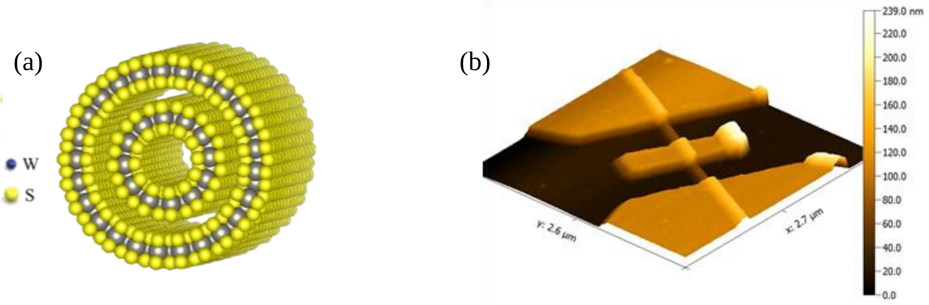

Figure 2. (a) Schematic depiction of WS_2 nanotube with two concentric walls. (b) AFM height map of a fabricated nanotube torsional resonator device.

4. Results

We observed the mechanical resonance spectrum of a WS_2NT torsional resonator using signal mixing, an all-electrical method. Resonance features were apparent in both the current and phase spectra, and they corroborated as mechanical resonance using an optically acquired resonance spectrum (see figure 3).

Using optical vibration analysis we identified different modes of vibration of the torsional paddle resonator, namely torsion and bending modes of vibration. We find that the torsion mode is consistently the lower frequency mode, as predicted by calculations. By analyzing the resonance spectra of over 15 devices, we gain insight into the resonant mechanical behavior of WS_2NTs, suggesting that the NTs twist as solid rods, incorporating all the layers (see figure 4).

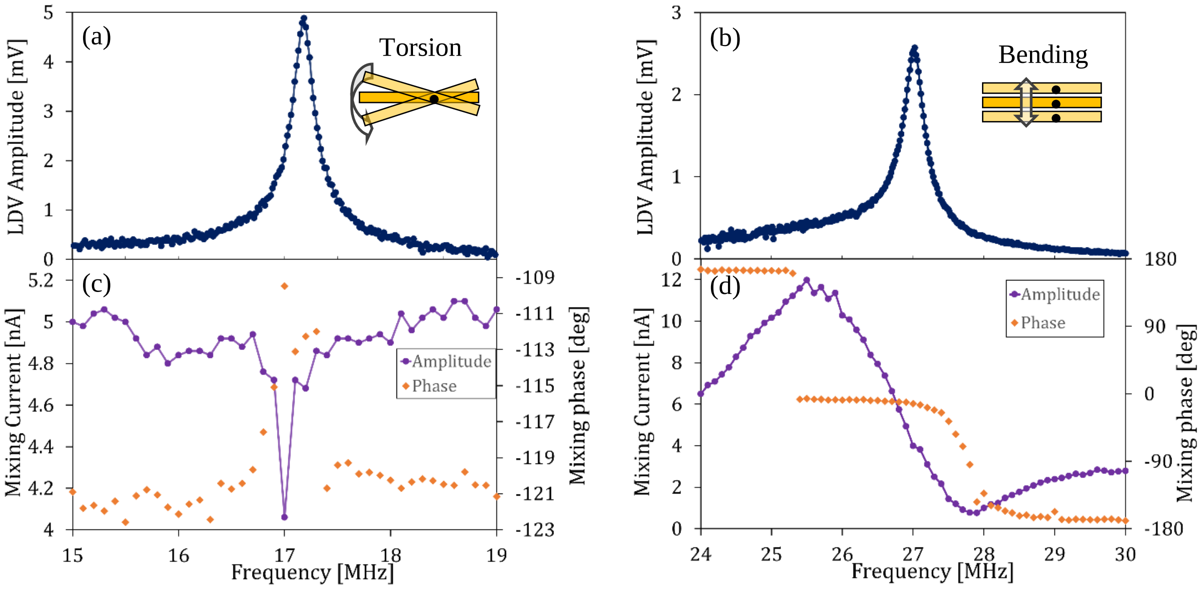

Figure 3. Comparison of resonance spectra acquired optically (a, b) and electrically (c, d) from the same device at two different frequency ranges, exhibiting two resonant peaks at 17.2 MHz (a, c) and 27 MHz (b, d), attributed to the torsion mode and out-of-plane bending mode of the resonator, respectively. Electrically obtained data include the lock-in current amplitude and phase. The resonances are apparent by a change of current as well as a feature in the phase spectrum of the current measured, although these trends differ in the two modes.

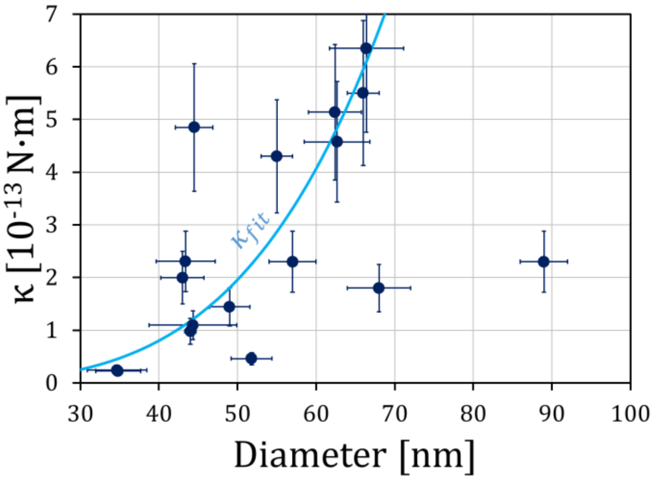

Figure 4. Torsional spring constants (κ) of different devices vs. nanotube diameter. Data is fit to a model of an elastic solid rod ($\kappa \propto Gr^4$). Value of shear modulus G obtained is consistent with previous observations.

5. Conclusions

In this study we perform for the first time an all-electrical actuation and detection of inorganic nanotube resonators using electrical signal mixing, demonstrating that the piezoresistivity of WS_2NTs can be utilized to detect resonance in these devices. These results show how WS_2NT torsional resonators can operate as self-sensing devices, allowing for the further development of functional devices based on inorganic nanotube resonators.

We also show that WS_2NTs resonantly twist as solid rods, incorporating all the layers in the motion, as opposed to carbon nanotubes. This result suggests decreased energy dissipation in WS_2NT due to the absence of interlayer friction during twisting, and thus higher quality factors.

The results of this work show the potential of WS_2NT as key components for high quality factor resonators operating at high frequencies, which can serve various application such as nanoscale accelerometers and gyroscopes.

6. References

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