A Self-Sensing Nanomechanical Resonator Built on a Single-Walled Carbon Nanotube

ARTICLE *in* NANO LETTERS · NOVEMBER 2008

Impact Factor: 13.59 · DOI: 10.1021/nl801996p · Source: PubMed

4 AUTHORS:

Adam R Hall
Wake Forest School of Medicine

M. R. Falvo
University of North Carolina at Chapel Hill

Richard Superfine
University of California, Berkeley

Sean Washburn
University of North Carolina at Chapel Hill

NANO LETTERS

XXXX
Vol. xx, No. x
-

A Self-Sensing Nanomechanical Resonator Built on a Single-Walled Carbon Nanotube

Adam R. Hall,[‡,†] Michael R. Falvo,[†,§] Richard Superfine,[†,§,||] and Sean Washburn*[,†,§,||,⊥]

Curriculum in Applied and Materials Sciences, Department of Physics and Astronomy, Department of Computer Science, and Department of Biomedical Engineering, University of North Carolina at Chapel Hill, CB 3255, Chapel Hill, North Carolina 27599-3255

Received July 8, 2008; Revised Manuscript Received October 1, 2008

ABSTRACT

We present observations of resonance behavior in a torsional nanoelectromechanical device built with an individual single-walled carbon nanotube. The effect of applied torsional strain on the transport properties of the nanotube provides an electrical signal transducer and hence a means of measuring oscillation amplitude, resonance frequency, and quality factor. The mechanical resonance is confirmed by imaging and the electromechanical signal is compared to quasi-static measurements.

Detection of resonant oscillation in carbon nanotube-based nanoelectromechanical systems has been an obstacle in device design and integration. Many solutions have been demonstrated previously such as interferometry,[1] direct imaging of resonant modes with high-resolution microscopy,[2] measurement of induced electromotive force,[3] and monitoring of field-emission patterns.[4] All of these techniques, however, meet limitations in minimum size, excessive external apparati, or both. Recent pioneering work[5] utilized the charge-conductance relationship inherent in some single-walled nanotubes (SWNT) to allow an individual, doubly clamped molecule to be used as a mixer and measure its own laterally excited vibrations. This technique has been expanded upon further to allow for high frequency mixing[6,7] and seems poised for integration into technology. Another simple system would be one that directly monitors changes in SWNT properties during resonance oscillation by exploiting their unique strain-transport relation.[8−10] Here, we present the first measurement of such transduction using a torsional paddle architecture.[11]

* Corresponding author. E-mail: sean@physics.unc.edu.
† Curriculum in Applied and Materials Sciences, University of North Carolina at Chapel Hill.
‡ Present Address: Kavli Institute of Nanoscience, Delft University of Technology, 2628 CJ Delft, The Netherlands.
§ Department of Physics and Astronomy, University of North Carolina at Chapel Hill.
|| Department of Computer Science, University of North Carolina at Chapel Hill.
⊥ Department of Biomedical Engineering, University of North Carolina at Chapel Hill.

The device fabrication has been described previously,[8,12] but briefly, a degenerately doped silicon wafer with a 1 μm thermal oxide was used as a substrate for CVD growth of SWNT. Using electron beam lithography, along the length of a selected nanotube were fabricated two large metal pads (5 μm × 5 μm) of 5−10 nm of Ti and 80 nm Au and contacted to macroscopic leads. Between these two pads and on the body of the nanotube, a smaller platform (~500 nm × ~200 nm) was fabricated consisting of a similar Ti adhesion layer and 150 nm Au. Following this, small etch windows were patterned around the platform, which allowed a controlled isotropic etch of the oxide layer in buffered hydrofluoric acid and released the paddle from the substrate. The device was then dried in supercritical CO_2, leaving the central paddle freely suspended above the substrate and supported on either side by short lengths of exposed SWNT (Figure 1a). All subsequent measurements were performed in high vacuum (1×10^{-5} Torr). Actuation was achieved by applying a bias to the underlying substrate relative to the suspended paddle. As was demonstrated previously,[8] addition of strain to the system through increased deflection of the paddle resulted in a repeatable change in measured transport across the SWNT (Figure 1b).

Following quasi-static measurements, the device was investigated as an oscillator. An AC signal of variable frequency was applied between the substrate and the paddle along with a small DC offset. This offset provided an initial deflection around which the paddle could oscillate symmetrically. A low bias (50 mV) lock-in measurement was

10.1021/nl801996p CCC: $40.75
Published on Web 10/25/2008

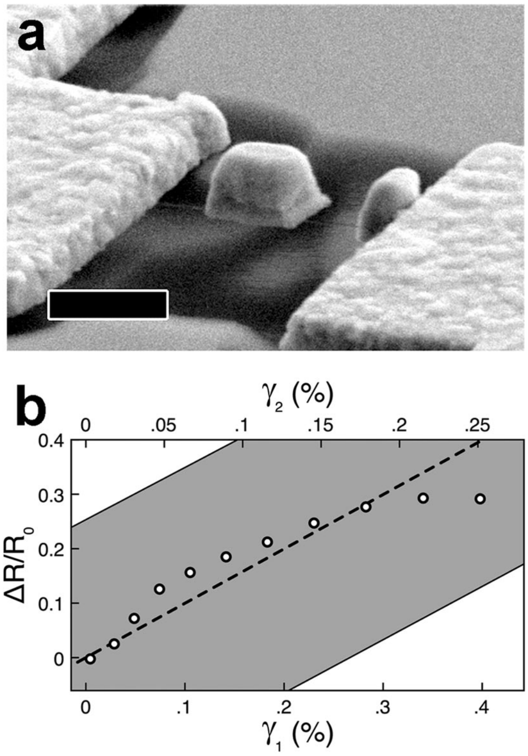

Figure 1. (a) Scanning electron micrograph of a SWNT torsional resonator (scale bar 500 nm). (b) Differential resistance across an individual nanotube during a quasi-static actuation measurement, demonstrating an increase in resistance with additional applied strain. γ_1 refers to the strain in the shorter section of exposed nanotube and γ_2 refers to that of the longer section and are measured as described in ref 12. The dashed line is a linear fit to the data and the shaded region represents experimental error.

performed between the source and drain (the support contacts). We monitored the resistance over a range of actuation frequencies, and clear peaks were observed (Figure 2a). These arise from the high average strain associated with the large amplitude of resonant motion. We note that a second, smaller peak was measured at roughly twice the frequency of the first peak, indicating a harmonic of resonant motion. We also repeated this measurement for several AC signal amplitudes. The resultant curves demonstrate a clear dependence of peak height on oscillation amplitude (Figure 2a inset). In Figure 2b, we plot the maximum differential resistance (peak height) from these curves against the square of the drive amplitude. Because the actuation is electrostatic, the latter factor is proportional to the electrostatic force and is thus a measure of the device amplitude. Interestingly, this dependence appears to be exponential. The behavior may be related to the exponential dependence of resistance on applied strain that has been observed in SWNT stretching experiments[9] and is expected to hold true for torsion as well. The higher strains present when the device is resonating at large amplitude would make the effect more pronounced than in the quasi-static measurements, where a linear approximation sufficed.[8] For this device, the measured quality factor ranged from 450 to 1150, with higher values observed at larger actuation voltages.

The location of the main peak in the frequency spectrum supports the supposition that it is a measure of resonant behavior. A relation for the expected resonant frequency of the torsional mode, ω_o, has been shown to be[13]

$$\omega_o = \frac{1}{2\pi}\sqrt{\frac{\kappa}{I}} \qquad (1)$$

where κ is the torsional spring constant of the SWNT and I is the moment of inertia of the oscillating block. We obtain a value for the former by combining direct atomic force microscopy measurements of the SWNT diameters taken previously[8,12] with theoretical values for their material properties.[14] The moment of inertia, I, in turn, can be expressed in terms of geometric quantities

$$I = \frac{\rho l w t}{12}(4t^2 + l^2) \qquad (2)$$

where ρ is the bulk density of the paddle material and l, w, and t are the length (perpendicular to the tube), width (parallel with the tube), and thickness of the paddle, respectively. We ignore the negligible inertia of the nanotube itself. All of these values were controllable fabrication parameters and were verified through direct imaging of the device. For the particular SWNT torsional oscillator measured in Figure 2, the relation yields a value of $\omega_o = 358 \pm 125$ kHz, which agrees with the experiment. The large error stems from the

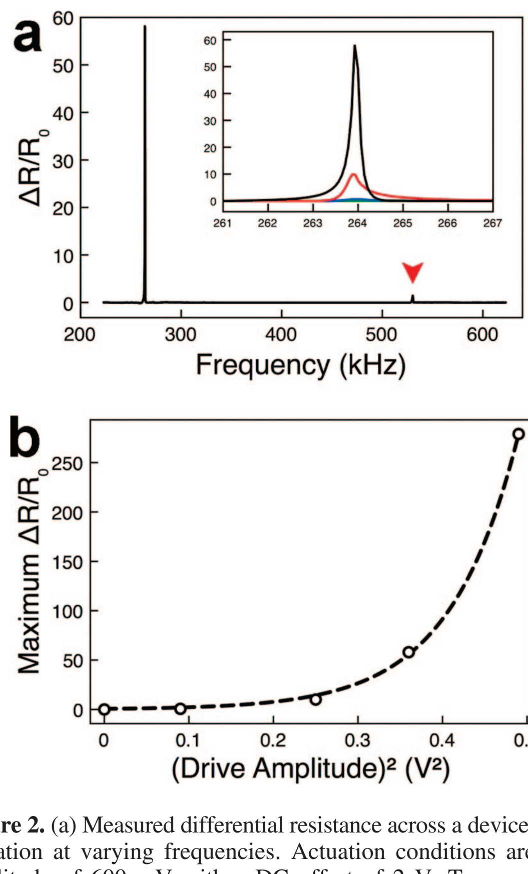

Figure 2. (a) Measured differential resistance across a device during actuation at varying frequencies. Actuation conditions are at an amplitude of 600 mV with a DC offset of 2 V. Two peaks are visible, representing the fundamental peak and the first harmonic (red arrow). Inset: Resonance peak under actuation amplitudes of 100 (green), 300 (blue), 500 (red), and 600 mV (black). Axis labels match those of the larger frame. (b) Maximum differential resistance (peak height) of the curves in the inset vs the square of the drive amplitude (device amplitude), showing exponential dependence.

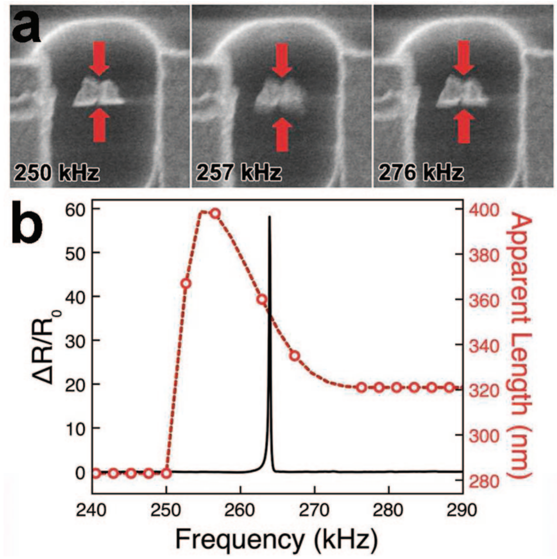

Figure 3. (a) Series of scanning electron micrographs of a device during AC actuation (frequency indicated), showing apparent blurring when resonance is met. The red arrows indicate the apparent length of the device at each frequency. (b) Plot of resonance peak measured by transport (black) and the apparent length of resonator measured directly from imaging (red).

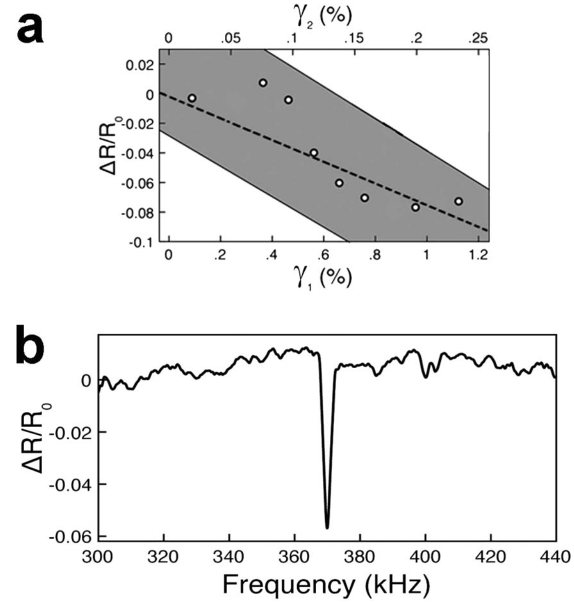

Figure 4. (a) Quasi-static measurement on a second device, demonstrating a decrease in resistance with added strain. The elements are the same as those described in Figure 1b. (b) Differential resistance vs applied actuation frequency on the same device, yielding a peak that agrees in direction with the quasi-static measurement.

value for the SWNT radius; a value for which there is uncertainty of 20%.

Mere observation of a peak in the electrical signal at a believable frequency does not necessarily validate the claim of resonance. Therefore, after completing all electrical transduction measurements, we verified that the observed affect was due to resonant behavior through direct imaging.[2,15] We again applied an actuation signal to the device and varied its frequency, but did so under direct observation with a scanning electron microscope. Under these conditions, we observed that within a highly confined frequency range, the apparent length of the paddle (perpendicular to the SWNT) increased and then decreased again at higher frequency (Figure 3a). As this quantity is an average measure of the amplitude of motion projected onto the relatively low frame rate, the effect is indicative of resonant oscillation. We plot the apparent length on the same axis as the source-drain electrical measurement in Figure 3b and the two events are shown to be nearly coincident in frequency. We attribute the slight deviation to the effect of the imaging beam on the device.

Our previous work[8] showed experimentally that the same applied torsional strain can have drastically different effects on the transport properties of different SWNT, either increasing (opening or widening the band gap) or decreasing (narrowing the band gap) their measured resistance, depending on the initial chirality of the particular tube. Therefore, we also investigated the oscillator behavior of a second device that demonstrated a decrease in resistance under quasi-static measurements (Figure 4a). We found that in such a device, the overall peak behavior was similar, but that the direction of the peak was inverted; there is a sharp dip in resistance in the frequency spectrum (Figure 4b). This supports the assertion that the strain-transport relation is in fact the basis of this device measurement technique. The particular frequency at which the peak occurs is still in agreement with expectations, considering a paddle of slightly different size from the first presented device.

In summary, we have fabricated resonant torsional oscillators using SWNT and operated them as strain transducers through the strain-transport relationship. The resonance is manifested as a peak in the source-drain resistance across the nanotube, the height of which is dependent on the amplitude of the actuation signal. We directly observed the device under operation at various frequencies and confirmed that the peak in the transport signal is indeed associated with a mechanical resonance. Finally, we showed that the direction of this peak is dependent on the reaction of the particular SWNT to the applied strain, supporting the hypothesis that transduction is the mechanism associated with the measurement. These data represent the first observation of SWNT device oscillation and measurement using this property and constitute a simpler detection mechanism than has been previously demonstrated. In addition to aiding integration of CNT oscillators into NEMS applications, the technique could be useful in nanoelectromechanical timing devices and sensors.

Acknowledgment. The authors acknowledge financial support for this work from the NASA Graduate Student Research Program and thank J. Liu for materials.

References

(1) Papadakis, S. J.; Hall, A. R.; Williams, P. A.; Vicci, L.; Falvo, M. R.; Superfine, R.; Washburn, S. *Phys. Rev. Lett.* **2004**, *93* (14), 146101.
(2) Poncharal, P.; Wang, Z. L.; Ugarte, D.; de Heer, W. A. *Science* **1999**, *283* (5407), 1513–1516.
(3) Cleland, A. N.; Roukes, M. L. *Appl. Phys. Lett.* **1996**, *69* (18), 2653–2655.
(4) Purcell, S. T.; Vincent, P.; Journet, C.; Binh, V. T. *Phys. Rev. Lett.* **2002**, *89* (27),

(5) Sazonova, V.; Yaish, Y.; Ustunel, H.; Roundy, D.; Arias, T. A.; McEuen, P. L. *Nature* **2004**, *431* (7006), 284–287.
(6) Peng, H. B.; Chang, C. W.; Aloni, S.; Yuzvinsky, T. D.; Zettl, A. *Phys. Rev. B* **2007**, *76* (3),
(7) Rosenblatt, S.; Lin, H.; Sazonova, V.; Tiwari, S.; McEuen, P. L. *Appl. Phys. Lett.* **2005**, *87* (15),
(8) Hall, A. R.; Falvo, M. R.; Superfine, R.; Washburn, S. *Nat. Nanotechnol.* **2007**, *2*, 413–416.
(9) Minot, E. D.; Yaish, Y.; Sazonova, V.; Park, J. Y.; Brink, M.; McEuen, P. L. *Phys. Rev. Lett.* **2003**, *90* (15), 156401.
(10) Tombler, T. W.; Zhou, C. W.; Alexseyev, L.; Kong, J.; Dai, H. J.; Lei, L.; Jayanthi, C. S.; Tang, M. J.; Wu, S. Y. *Nature* **2000**, *405* (6788), 769–772.
(11) Williams, P. A.; Papadakis, S. J.; Patel, A. M.; Falvo, M. R.; Washburn, S.; Superfine, R. *Appl. Phys. Lett.* **2003**, *82* (5), 805–807.
(12) Hall, A. R.; An, L.; Liu, J.; Vicci, L.; Falvo, M. R.; Superfine, R.; Washburn, S. *Phys. Rev. Lett.* **2006**, *96* (25), 256102.
(13) Evoy, S.; Carr, D. W.; Sekaric, L.; Olkhovets, A.; Parpia, J. M.; Craighead, H. G. *J. Appl. Phys.* **1999**, *86* (11), 6072–6077.
(14) Lu, J. P. *Phys. Rev. Lett.* **1997**, *79*, 1297–1300.
(15) Mihailovich, R. E.; MacDonald, N. C. *Sens. Actuators, A* **1995**, *50* (3), 199–207.

NL801996P