Ultrahigh Frequency Nanotube Resonators


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We report carbon-nanotube-based electromechanical resonators with the fundamental mode frequency over 1.3 GHz, operated in air at room temperature. A new combination of drive and detection methods allows for unprecedented measurement of both oscillation amplitude and phase and elucidates the relative mobility of static charges near the nanotube. The resonator serves as an exceptionally sensitive mass detector capable of $10^{-18}$ g resolution.

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Nanoelectromechanical systems (NEMS) [1–8] are becoming ever more important for fundamental research and technical applications. Of special interest is the high-frequency NEMS resonator [2,3,6–8], which not only offers the potential for extreme mass and force sensitivity [7] but also provides a unique way to observe the imprint of quantum phenomena directly [2], including uncertainty-principle limits on position detection [6]. Various bottom-up (self-assembly) and top-down (lithographical) fabrication processes have been employed to create NEMS devices, but none has achieved the “holy grail” of ultrahigh-frequency (>1 GHz) operation at room temperature in atmospheric pressure. In the case of doubly clamped beam resonators, the highest resonance frequency, 1.029 GHz, was reported in devices made of stiff 3C-SiC beams, with motion detectable at a temperature of 4.2 K [8]. On the other hand, carbon nanotubes (CNTs) [9–12] have been considered promising candidates for NEMS resonators. Recently [13], electrical detection of mechanical resonance of doubly clamped suspended CNTs was demonstrated, although the frequencies were below 200 MHz, and no resonance was detectable at atmospheric pressure.

Here we present suspended CNT-based resonators with the fundamental mode frequency over 1.3 GHz and mechanical motion self-detectable at room temperature in air at atmospheric pressure. A new combination of drive and detection methods, along with metal nanobridges templated onto the CNT beam, are used to dramatically enhance the response sensitivity (including phase response) and to probe mobility of trapped charges of the NEMS device. Extreme mass sensitivity of the resonators is clearly demonstrated.

Figure 1(a) gives a schematic cross-sectional view of our doubly clamped CNT resonator with a local gate. The suspended CNT devices were fabricated according to a process described previously [14,15]. Two head-on source-drain electrodes (Pt 20 nm/Cr 5 nm), with a thin layer of Fe on top as a catalyst, were patterned by e-beam lithography on Si$_3$N$_4$ (50 nm)/SiO$_2$ (500 nm)/Si substrates. The gap between the source and drain electrodes was typically from 300 nm to 1 μm. After this, a second e-beam lithography step, reactive ion etching, and buffered HF etching were carried out to pattern a trench between the source and drain electrodes, with the trench depth typically between 200 and 500 nm. A successive evaporation of Pt 20 nm/Cr 5 nm and then a lift-off process finalized a local gate on the bottom of the trench [16]. Subsequently
suspended single-wall CNTs were grown by chemical vapor deposition (CVD) [14,15,17] directly across the trenches, thereby electrically bridging the source and the drain. Figure 1(b) gives a scanning electron microscope (SEM) image of a device with a suspended CNT. Such devices could be operated either with bare CNTs or with nanobridges created by coating the CNTs via a further step of thermal evaporation of metals.

Two methods were used to drive and electrically detect the mechanical oscillations of the NEMS resonators. In the first, termed the ‘‘1ω’’ method [13], an actuation rf signal is applied to the gate at frequency ω and a carrier signal is applied to the drain at a slightly different frequency ω-Δω. The drain-source current is monitored by a lock-in amplifier at the intermediate frequency Δω (≈7 KHz) again by lock-in techniques. When the oscillator is driven through resonance, a sharp change occurs in both the amplitude and the phase of the measured ac electrical current. Figure 1(c) illustrates the experimental setup for the 2ω method. The frequency doubling of the driving force results from the fact that the electrostatic force on a capacitor is proportional to the square of the voltage-induced charge [18].

Figure 2 shows the amplitude and phase response for a CNT-based NEMS resonator obtained at room temperature. This particular resonator has a metal nanobridge coating, and the detection method is 1ω. When the resonator is operated in a low pressure environment (∼10^{-6} Torr, solid triangles), a well-defined fundamental resonance is clearly observed at 1.33 GHz. When the resonator is operated in air at atmospheric pressure (hollow circles), the resonance frequency has shifted slightly downward to 1.32 GHz. The observed shift is attributable to the adsorption of air-specific molecules (such as water and oxygen) around the CNT, leading to a change of the resonator mass.

As expected, resonators with a shorter clamping CNT length generally have higher fundamental resonance frequencies. The highest resonance frequency we have observed is 1.85 GHz using a trench width of 300 nm. However, the observed resonance frequency varies even between devices with the same trench width, a consequence of different CNT diameter, CNT defect density, and effective clamping strength (which influences the effective clamping length).

We now explore details of the resonator response. Figure 3 shows the amplitude and phase for a bare CNT resonator operated at room temperature. The star symbol data are measured by the 1ω method; i.e., the rf signal applied to the gate is at the same frequency as the effective driving frequency ω. The current amplitude [Fig. 3(a)] is qualitatively similar in amplitude and phase but the resonance frequency has shifted slightly downward to 1.32 GHz. The observed shift is attributable to the adsorption of air-specific molecules (such as water and oxygen) around the CNT, leading to a change of the resonator mass.

Figure 3 shows the amplitude and phase for a bare CNT resonator obtained at room temperature. The star symbol data are measured by the 1ω method; i.e., the rf signal applied to the gate is at the same frequency as the effective driving frequency ω. The current amplitude [Fig. 3(a)]

![Figure 2. Amplitude in logarithmic scale (a) and phase (b) of the electrical current in a vacuum ∼10^{-6} Torr (triangles) and in air (circles) for a nanobridge resonator made from coating a bare suspended CNT device with 2.5 nm indium. The data were taken at V_g = 0, δV_g = 112 mV, and δV_d = 46 mV by the 1ω method.](image2)

![Figure 3. Amplitude in logarithmic scale (a) and phase (b) of the electrical current in a vacuum ∼10^{-6} Torr (triangles) and in air (circles) for a nanobridge resonator made from coating a bare suspended CNT device with 2.5 nm indium. The data were taken at V_g = 0, δV_g = 112 mV, and δV_d = 46 mV by the 1ω method.](image3)
shows a sharp decrease by more than an order of magnitude at 382 MHz with a concomitant abrupt change of the measured phase [Fig. 3(b)]. Presented also in Fig. 3 (solid circle) is the response measured using the $2\omega$ method; i.e., the rf signal at the gate electrode is set at half of the effective driving frequency. The $2\omega$ method gives a cleaner signal with a resonance frequency identical to that from the $1\omega$ method and yields a significantly stronger current amplitude than the $1\omega$ method.

The observed resonator response can be analyzed to elucidate fundamental physics of the nanotube-based NEMS resonators. Importantly, the combination of the $1\omega$ and $2\omega$ methods can be exploited to gain insight into the distribution and mobility of excess accumulated charges, which are inevitable to nanoscale systems. The relative strength of the $1\omega$ and $2\omega$ response depends on the amount and mobility of excess accumulated charges on the resonator [18]. For some samples, such as the one shown in Fig. 3, there was no significant difference in the relative strength of the resonator [18]. For some samples, such as the one shown in Fig. 3, there was no significant difference in the relative strength of the resonator [18]. For some samples, such as the one shown in Fig. 3, there was no significant difference in the relative strength of the resonator [18]. For some samples, such as the one shown in Fig. 3, there was no significant difference in the relative strength of the resonator [18].

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The overall electrical response can be ascribed to the interference of a background response and a resonance response due to the mechanical motion [3,13,19]. The background response is the signal induced by the rf gate voltage even if the resonator beam has no mechanical motion, e.g., the signal due to the field effect. The resonance response is the conductance change due to the mechanical resonant motion, which, in general, includes some strain effect and the extra field effect (e.g., resulting from a motion-induced capacitance change). Hence, we express the measured current response as

$$Ie^{i\phi} = I_b e^{i\phi_b} + I_r e^{i\phi_r},$$

where $I$, $I_b$, and $I_r$ are the amplitudes of the measured total current, the background current, and resonance-induced current, respectively, while $\phi$, $\phi_b$, and $\phi_r$ are the corresponding phases. We employ Euler-Bernoulli theory for doubly clamped beams [20], whereby the resonance-induced signal due to the fundamental mode is given by

$$I_r e^{i\phi_r} = \frac{c}{\omega_0^2 - \omega^2 - i\omega^2/Q},$$

where $\omega_0$ is the resonance frequency, $Q$ is the quality factor, and $c$ is a parameter independent of the frequency $\omega$. The background amplitude and the phase are usually treated as constants within the considered frequency range.
gigahertz resonators will pave the way for practical applications. We expect that the self-detecting variety of NEMS devices beyond the reach of current CNTs as templates may open new ways to fabricate a terahertz range. Moreover, using as-grown suspended high resonance frequencies over 10 GHz or even into the terahertz range, selecting suitable coating materials may achieve extremely high resonance frequencies over 10 GHz or even into the terahertz range. Furthermore, using as-grown suspended CNTs as templates may open new ways to fabricate a variety of NEMS devices beyond the reach of current standard lithography. We expect that the self-detecting gigahertz resonators will pave the way for practical applications, as well as provide model systems for quantum measurements [2].

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loading, the resonance frequency is 470 MHz (circles), while, after 2 nm of Fe have been deposited onto the CNT beam (measured by a quartz crystal monitor), the resonance is shifted downward to 390 MHz (triangles). Assuming that the mass loading results in a 2 nm Fe coating over a cross-sectional area 2220 nm² (the projected beam area for this resonator), we obtain a rough estimate for the added mass of \( \sim 3.5 \times 10^{-17} \) g. With the frequency shift proportional to the added mass [7], from the phase signal we have a detectable mass sensitivity of \( \sim 10^{-18} \) g with \( \delta \omega = 3 \) MHz (associated with an experimentally observed phase change of 140° near resonance for the nanobridge resonator before the mass loading). From the amplitude data, a lower-bound mass sensitivity can be estimated as \( \sim 7 \times 10^{-18} \) g by taking \( \delta \omega = 16 \) MHz, the full width of the half depth of the resonance response. We note that there is a sign change of the phase shift in the response between the unloaded and the loaded resonators. This can be well explained within the interference model by a slight change of the magnitude of the pure resonance signal from a value larger than the background signal magnitude to a value smaller than the background signal magnitude.

In summary, resonance frequencies over 1.3 GHz have been realized with CNT-based NEMS resonators. A new combination of \( 1 \omega \) and \( 2 \omega \) mixing methods allows for unprecedented measurement of both oscillation amplitude and phase and elucidates the relative mobility of static charges. Further scaling down CNT-based resonators and selecting suitable coating materials may achieve extremely high resonance frequencies over 10 GHz or even into the terahertz range. Moreover, using as-grown suspended CNTs as templates may open new ways to fabricate a variety of NEMS devices beyond the reach of current standard lithography. We expect that the self-detecting gigahertz resonators will pave the way for practical applications, as well as provide model systems for quantum measurements [2].

[8] X. M. H. Huang et al., Nature (London) 421, 496 (2003); for blade-geometry resonators, the highest fundamental frequency reported is 1.1 GHz; see V. Agache et al., Appl. Phys. Lett. 86, 213104 (2005).
[18] Details of the 2\( \omega \) method will be published elsewhere.
[19] The conductance change due to the electrostatic force on a CNT can result from field effect, strain effects along the CNT and at the contacts, and possible resonant heating. The fact that we are able to obtain similar results for semiconducting and metallic CNTs suggests that strain effects dominate the transduction process.
[21] We note that, for the best fit of Eq. (1) to the data presented in Fig. 3, \( I_1/I_2 \approx 1 \) and \( \phi_b \approx -\pi/2 \). These “coincident” fitting parameters are not universal; as expected, for some other resonators (experimentally also showing sharp current amplitude reduction and sharp phase changes near resonance), \( I_b/I_1 \) and \( \phi_b \) extracted from best fits to the interference model are different.