Electromechanical Resonators from Graphene Sheets

CNF Project # 900-00
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Abstract

Nanoelectromechanical systems were fabricated from single and multilayer graphene sheets by mechanically exfoliating thin sheets from graphite over trenches in SiO$_2$. Vibrations with fundamental resonant frequencies in the MHz range are actuated either optically or electrically and detected optically by interferometry. We extract a Young’s modulus of 1 TPa, and find that most suspended sheets are under tension. The quality factors of the suspended graphene sheets are in the range of 20-850 and show no dependence on the thickness. The thinnest resonator consists of a single suspended layer of atoms and represents the ultimate limit of two dimensional nanoelectromechanical systems.

Research Summary

The miniaturization of electromechanical devices promises to be revolutionary in the coming decades as the miniaturization of electronic devices was in the previous ones. Devices ranging from nanoscale resonators, switches, and valves have applications in tasks as diverse as information processing, molecular manipulation, and sensing. The prototypical nanoelectromechanical system (NEMS) is a nanoscale resonator, a beam of material that vibrates in response to an applied external force. The ultimate limit would be a resonator one atom thick, but this puts severe constraints on the material. It should be robust, stiff, and stable as a single layer of atoms.

Graphite consists of stacked layers of graphene sheets separated by 0.3 nm and held together by weak van der Waals forces. It has extremely high strength, stiffness, and thermal conductivity along the basal plane. In addition, graphite can be exfoliated onto an insulating substrate, producing micron-sized graphene sheets with thicknesses down to a single atomic layer. Thus far, research on these thin graphene sheets has focused primarily on their electronic properties. We demonstrate a method of suspending single and multilayer graphene sheets over trenches and show such sheets can be mechanically actuated. This work also makes a detailed study of the mechanical properties of these graphene resonators including resonance frequency, spring constant, built in tension, and quality factor.

Suspended graphene sheets are fabricated using a mechanical peeling process where the graphene sheets are exfoliated off of bulk graphite predefined trenches etched into a silicon oxide surface. Figure 1 shows that these sheets are optically visible under a microscope. The result is a micron-scale doubly clamped beam or cantilever clamped to the silicon oxide surface via van der Waals attraction (Figure 2). Some devices have pre-patterned gold electrodes between the trenches to make electrical contact [1]. Using this method, we have fabricated suspended sheets with thicknesses varying from a single atomic layer to sheets 75 nm thick.

The resonators are actuated using either electrical (Figure 3) or optical modulation. In the case of electrical modulation, a time-varying radio frequency (RF) voltage is applied to the graphene sheet resulting in an electrostatic force...
between the suspended graphene sheet and the substrate. For optical actuation, the intensity of a diode laser focused on the sheet is modulated at the resonant frequency of the graphene sheet, causing a periodic contraction/expansion of the layer that leads to motion. In both cases, the motion is detected by monitoring the reflected light intensity from a second laser using a fast photodiode. Figure 4 shows the measured amplitude versus frequency of a single atomic layer graphene resonator, with a measured resonance frequency of 70.5 MHz and \( Q = 78 \). The resonance frequencies of the fundamental modes of the fabricated sheets vary from 1 MHz to 166 MHz with quality factors, \( Q \) of 20-850.

By comparing the resonance frequency of the suspended sheets to the measured size dimensions, we can deduce a Young’s Modulus of 1 TPa using continuum beam mechanics. However, the frequencies of thinner resonators (under 7 nm) show more scatter with the majority having resonant frequencies significantly higher than predicted by bending alone. A likely explanation for this is that many of the resonators are under tension, which increases the resonance frequency. The tension likely results from the fabrication process, where the friction between the graphite and the oxide surface during mechanical exfoliation stretches the graphene sheets across the trench.

An important measure of any resonator is the normalized width of the resonance peak characterized by the quality factor \( Q = f_o/\Delta f \). A high \( Q \) is essential for most applications, as it increases the sensitivity of the resonator to external perturbation. We measure \( Q \) in the graphene sheets under vacuum of 20 to 850. This contrasts with diamond NEMS (2000-4000), silicon nitride NEMS (up to 400,000 now), and carbon nanotubes (50-100). Preliminary studies on a 20 nm thick resonator found a dramatic increase in \( Q \) with decreasing temperature (\( Q = 100 \) at 300 K to \( Q = 1800 \) at 50 K). This suggests that high \( Q \) operation of graphene resonators should be possible at low temperatures.

The high Young’s modulus, extremely low mass, and large surface area make these resonators ideally suited for use as mass, force, and charge sensors. For a 5 nm suspended sheet where we can detect the thermal vibration, we infer that we should be capable of measurements with a mass sensitivity of 7 zg, a force sensitivity of .9 fN/Hz^{1/2}, and a charge sensitivity of \( 8 \times 10^{-4} \) e/Hz^{1/2}. These values are competitive with state of the art silicon NEMS at room temperature, and could get much better at lower temperature with the onset of higher \( Q \).

However, the application of graphene NEMS extends far beyond just mechanical resonators. This robust, conducting, membrane can act as a nanoscale supporting structure or atomically thin membrane separating two disparate environments.

References