Graphene Mechanical Resonators

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Abstract:
Because of its high tensile strength and atomic thickness, graphene is an ideal material for making extremely sensitive and tunable mechanical resonators in the MHz-GHz regime. Potential applications include mass sensing, highly tunable oscillators, and radio frequency signal processing. We have developed fabrication approaches for fully clamped graphene resonators integrated on Si substrates, including locally-gated devices suitable for direct electrical measurements at RF frequencies [5]. We are currently studying the temperature dependence of the frequency and quality factor over a broad range to identify, understand, and control the dominant sources of frequency tuning and loss in these resonators. These experiments will both increase our understanding of the fundamental physics of atomically thin membranes and allow us to improve the performance of these novel electromechanical devices.

Summary of Research:
To date, graphene resonators have been made in a variety of geometries using both exfoliated and chemical vapor deposition (CVD)-grown graphene. The first graphene resonator was made by exfoliating graphene over pre-fabricated trenches, and its motion was detected optically [1]. This resonator was a doubly clamped beam: a rectangle with two opposite sides fixed to the substrate, and the other two sides free to move. A couple of years later, similar graphene resonators were fabricated with metal contacts and detected electrically, which was a step towards making resonators that could be used on an integrated circuit [2].

After the advent of CVD graphene growth on copper foils, we fabricated large arrays of doubly clamped resonators and measured them optically [3]. The basic properties of these devices are consistent with a tensioned membrane model, where the graphene acts as an atom-thick drumhead. However, the higher order mechanical modes typically do not line up with those predicted by the tensioned membrane model, and the observed quality factors are often quite low. We also found that fully clamped resonators, which do not have free edges, have significantly higher quality factors, and the mode shapes and scaling of the frequencies with mode number and membrane size are well-described by the tensioned membrane model [4]. We then wanted to control the tension in these devices through electrostatic gating, but adding electrical contacts to the devices in Ref. [4] would be nearly impossible, considering the unusual fabrication process used to make them.

As a first step towards this goal, we started by making fully clamped graphene resonators on a silicon substrate, using a simple two step fabrication process. A typical device is shown in the SEM image in Figure 1. Trenches were etched in the silicon, and CVD graphene was patterned into strips.

Figure 1: SEM image of a keyhole resonator. The graphene is suspended over the trench; bilayer patches and wrinkles can clearly be seen on the surface.
and transferred over the trenches. In order to avoid problems associated with completely sealed chambers, we patterned long thin trenches through the devices, making a “keyhole” geometry. We actuated and detected motion on these devices optically, and Figure 2 shows a typical resonance peak for a device 14.7 µm across, with a frequency of 2.17 MHz and a quality factor of 433. These resonators perform as well as those of Ref. [4] of similar size, and significantly better than the doubly clamped resonators in Ref. [3].

We then proceeded to make electrically contacted, locally gated keyhole resonators. According to Ref. [5], local gating allows for direct electrical detection of graphene resonators, which is several times faster than the electrical detection technique that has been used with globally gated devices (i.e. utilizing the underlying silicon wafer as a global gate). An SEM of a typical device is shown in Figure 3. They were fabricated by etching trenches in silicon, depositing metal for all three electrodes in one step (source, drain, and local gate), and transferring pre-patterned graphene on top, where statistically some devices would have graphene covering them. This is mostly a self-aligned process, which makes the fabrication easy.

To make sure we could detect resonance before trying direct detection, we first used the electrical mixing technique described in Ref. [2,3]. The mixing current as a function of frequency and gate voltage is plotted in Figure 4, and the resonance peaks for two modes are easily visible above the noise floor. The frequency tuning with gate voltage indicates that the graphene is being tensioned, as in Ref. [3].

In conclusion, we have made fully clamped, locally gated resonators from CVD graphene on silicon substrates. We have measured these devices both optically and using the electrical mixing technique. We are currently using these devices in experiments to study the temperature dependence of frequency tuning and dissipation over a broad range. The results of these experiments will increase our understanding of the fundamental physics of these devices and ultimately improve their performance.

References: