Resonant Properties of High-Stress Silicon Nitride Membranes

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Abstract:
Micromechanical resonators have been studied for some time, with modern applications ranging from molecular-resolution gas sensors to micron-scale structures for the study of mesoscopic quantum physics. Of all possible resonant media, stressed silicon nitride (SiN) is among the most desirable due to anomalously large quality factors (reaching up to $10^7$), and relatively large device dimensions. We have fabricated circular SiN membranes with diameters of 20 µm - 1 mm, and thicknesses of 15-75 nm, in order to study their intrinsic energy dissipation mechanisms as functions of resonator size, vibrational mode, and environmental temperature. These efforts have lead to a more complete understanding of these systems, and ultimately higher-quality devices.

Summary of Research:
Stoichiometric SiN films (with 1.2 Gpa tensile stress) were deposited on a silicon substrate with 600 nm of thermal silicon dioxide. Millions of well defined, 100 nm diameter release holes were then patterned on the SiN films using electron beam lithography; these holes served as entry points for hydrofluoric acid during etching of the silicon dioxide, and led to suspended SiN membranes of uniform thickness. This procedure was used to make devices of varying diameters and thicknesses. Membrane thicknesses were measured by peeling of the suspended SiN and imaging with atomic force microscopy. Such an image can be seen in Figure 1.

Membrane motion was actuated physically through mounting of the samples on a vibrating piezoelectric disk. Surface motion was detected optically through the reflection of an incident laser beam (visualized in Figure 2), as in previous experiments [1-3]; in this regard, the SiN membrane and silicon backplane acted as a Fabry-Pérot interferometer. Using this setup, we measured device dissipation as a function of membrane size, thickness, and vibrational mode. Observed quality factors were strongly dependent on mode shape for thicker membranes, whereas those of thinner devices were more size-dependent (shown in Figure 3). These results indicate that vibrating membranes can reach high qualities with the appropriate choices of dimensions, stress, and mode number; this applies equally well to graphene and other stable membrane materials.

Another area we have explored is the temperature dependence of membrane dissipation. Stressed SiN deviates strongly from the “universal behavior” of other amorphous materials, resulting in devices with room temperature quality factors that are orders of magnitude larger than expected values [3]. Other glasses are known to have a sharp decrease in internal friction (meaning enhanced quality factor) below a characteristic temperature [4]. We have attempted to observe such behavior in our stressed SiN membranes using a liquid helium flow cryostat; we have not yet detected such a change in the 300 K - 10 K range. Work is currently underway to extend these measurements to ~ 20 mK in a dilution refrigerator.
References:


Figure 2: Visualization of incident detection laser beam on finished device.

Figure 3: Dissipation (inverse quality factor) for 15 nm thick devices of various diameters. Each curve displays measurements for multiple vibrational modes. For larger devices, dissipation is shown to depend heavily on mode number. There is also a strong dependence on membrane diameter.