

## Mechanical Dissipation in Disordered Materials: Micro-scale to Nano-scale

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**Motivation**—Small mechanical oscillators are increasingly important for new technological areas, including clocks/filters for electrical circuits, mechanical-based detectors for chemicals/biological species, and scanning probes for force detection. The performance of these systems is limited by mechanical dissipation,  $1/Q$ , where  $Q$  is the quality factor. Fundamental understanding of mechanisms that control dissipation in small oscillators is severely limited. Knowledge is especially lacking in mechanisms that control dissipation in disordered or amorphous materials. This work describes an experimental and theoretical effort aimed at understanding mechanical dissipation in oscillators of micron-scale to nanometer-scale dimensions.

**Accomplishment**—A variety of mechanical oscillators were fabricated out of one class of amorphous materials, tetrahedral amorphous carbon, ta-C [also termed “amorphous diamond,” — see Fig. 1(a-c)]. These oscillators were created with dimensions ranging from many microns [1(a)] down to 10s of nanometers [1(c)], with designs that were chosen to minimize mechanical losses to the supports. The oscillator resonance frequencies ranged from about 1 kHz to over 10 MHz, permitting a study of time-dependent relaxation processes. Concurrent with these experimental activities, molecular dynamics theoretical simulations were performed on another class of amorphous materials, amorphous silicon, which was chosen for the availability of large, multi-atom theoretical unit cells [see Fig. 2 (inset)]. Dissipation in the theoretical system was identified through observation of the decay in amplitude of the lowest frequency vibrational mode in the system.

Experimental measurements of  $Q$  in ta-C oscillators revealed a nearly dispersionless dissipation (i.e., no frequency dependence). This dissipation differs from dissipation found in crystalline materials, which is often controlled by intrinsic processes, e.g., thermoelastic dissipation, or by specific defect relaxation processes, e.g., vacancy motion. In ta-C, the dissipation is controlled by a relatively flat spectrum (uniform concentration) of defects, and measurements of dissipation vs. frequency permit determination of the defect relaxation activation energies [see Fig. 1(d)]. Defect activation energies are small, which is consistent with local (non-diffusional) relaxation processes, but the exact nature of the dissipative defects is still to be determined. Theoretical simulations provided a unique view of dissipation in a model amorphous material. Low  $Q$ s were observed in amorphous Si, whereas  $Q$ s for simulations on crystalline Si were about 2 orders of magnitude higher. The dissipation in the amorphous silicon cell did not appear to be limited by a single specific defect; rather, the low phonon mean free path appeared to play a greater role. Studies using larger cells should offer even greater insight.

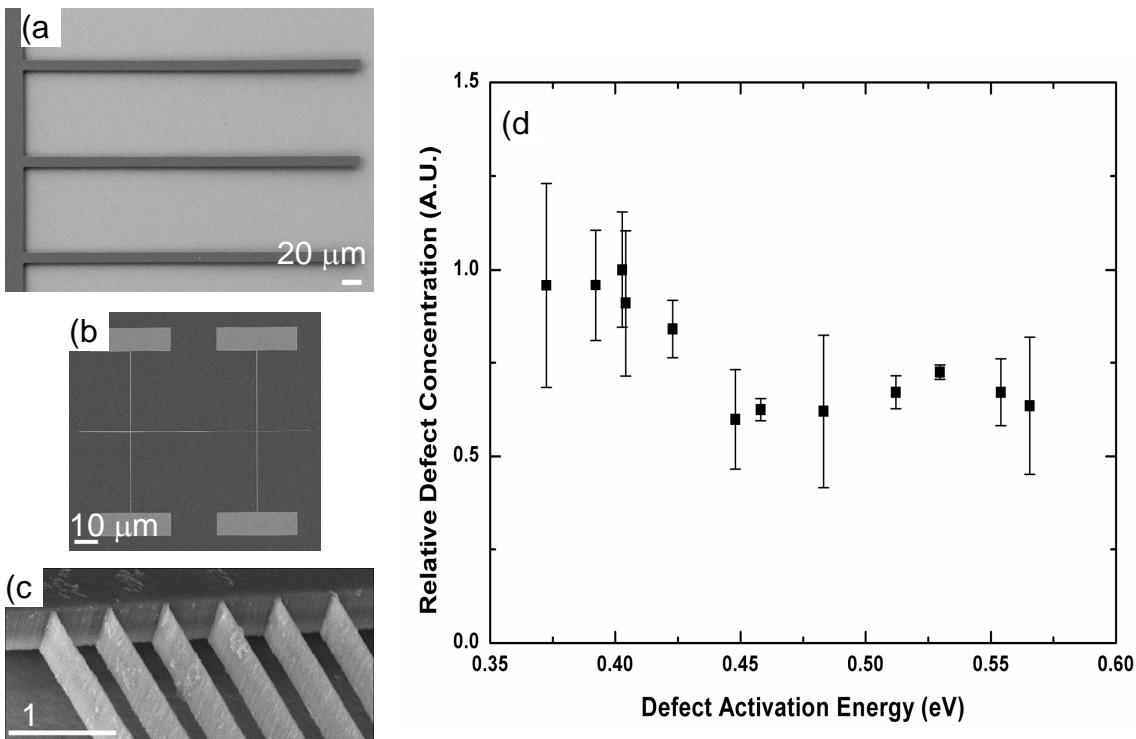
**Significance**—Studies of fundamental dissipation mechanisms in small oscillators will provide scientific understanding of the mechanical behavior of small (down to nano-scale) mechanical systems. This knowledge is critical for a number of revolutionary technologies, including single molecule/single spin detectors, systems of multiple miniature chemical or biological sensors, and high frequency oscillators for electronic signal processing.

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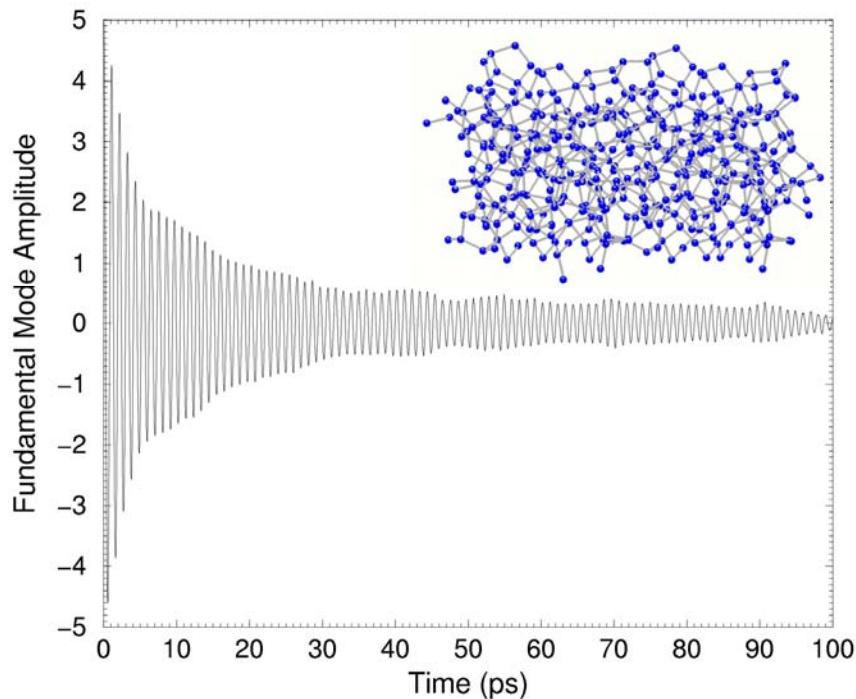
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**Figure 1.** Tetrahedral amorphous carbon oscillators with microns to sub-micron dimensions (a-c), and (d) distribution of activation energies for the mechanically dissipative defects in this material.



**Figure 2.** Computer simulation of mechanical dissipation of the lowest resonant mode of a 432 atom amorphous silicon cell (shown in inset).  $Q$  and  $f_0$  are 3.6 and 943 GHz, respectively.