Micro-scale and Nano-scale Tetrahedral Amorphous Carbon Mechanical Oscillators: Material Properties and Performance

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Introduction

Mechanical oscillators have found widespread use in electronics (as clocks, filters, switches, etc.), sensors (for chemicals, biological agents, pressure, acceleration, etc.), and metrology (scanning probe microscopy). Miniaturization of the mechanical oscillators leads to higher operating frequencies and the potential for increased sensitivity. It has been commonly observed, however, that miniaturization leads to increased internal dissipation, and this is usually attributed to the increased influence of surface losses (1). The fundamental loss mechanisms are poorly understood, however, especially at dimensions approaching the nano-scale and in materials that are dominated by defect-related loss mechanisms.

In this work, we report the properties of micro-scale and nano-scale mechanical oscillators fabricated out of tetrahedral amorphous carbon (ta-C). This diamond-like carbon material (about 80% sp^3) has a high Young's modulus (about 700 GPa) and an abrupt surface termination – properties that favor high resonance frequencies and low surface losses. We also report the thermal stability of these oscillators following high temperature annealing up to approximately 1300 K.

Results and Discussion

A number of mechanical oscillator designs were fabricated out of ta-C using standard microelectromechanical system (MEMS) processing (2). The oscillator structures included out-of-plane cantilevers of a few hundred to over one thousand microns in length, in-plane free-beam oscillators with dimensions approximately 100 microns by 0.5 microns, and arrays of in-plane cantilever oscillators with dimensions as small as 1 micron by 50 nm (see Figure 1). These oscillator structures were designed to probe the scaling of internal dissipation down to sub-micron dimensions and at resonance frequencies ranging from about 1 KHz to nearly 100 MHz. The structures were also designed to probe the effects of different forms of mechanical clamping losses.

Analysis of these structures revealed a remarkably dispersionless dissipation (near-constant quality factor, Q) over several orders of magnitude in frequency (see Figure 2). This indicates the existence of a dissipation process that is independent of time scale from millisecond to approximately 10 nanosecond times and that is insensitive to length scale from the millimeter to sub-micron lengths. Alternatively, this behavior would be consistent with the existence of a wide spectrum of dissipative defects that together are operative over a large distribution of time scales. Clamping losses did not seem to dominate the quality factor as similar Q's were observed for widely differing forms of mechanical support.

The thermal sensitivity of the mechanical oscillators was evaluated by annealing the as-fabricated oscillators at a range of temperatures approaching up to 1300 K for 2 hours. Measurement of the oscillator behavior was performed following cooling back to room temperature. Remarkably, the oscillator resonance frequency showed only very small changes (only about a 1% change) despite the large structural relaxations that occur in ta-C annealed at these temperatures (3). This suggests the existence of an interesting physical effect wherein softening of the Young's modulus is countered by density changes in the material. The insensitivity of the oscillator resonance frequency to high temperature treatment is a desirable property for oscillator based environmental sensors that are exposed to extreme temperature transients.

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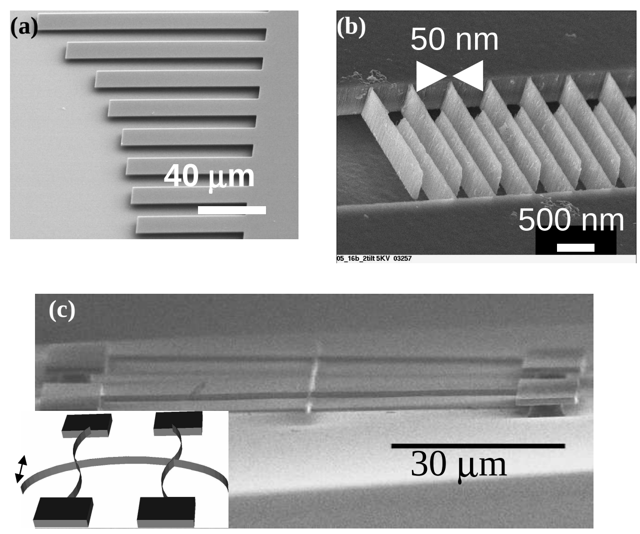
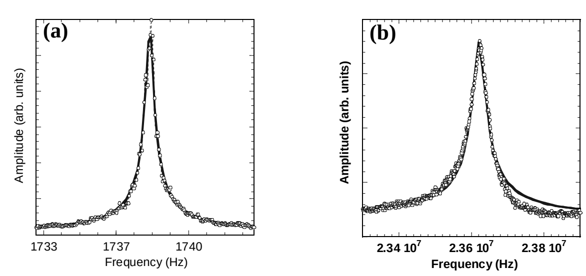


Figure 1. SEM images of a variety of mechanical oscillators fabricated out of ta-C: (a) out-of-plane cantilevers, (b) in-plane cantilevers, (c) free-beam oscillator with inset showing motion (figure rotated 90° from SEM image).



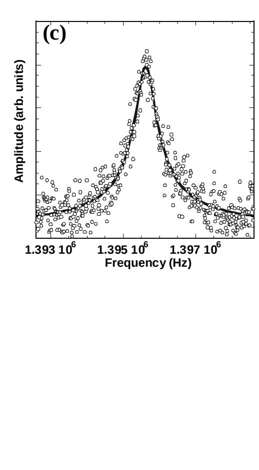


Figure 2. Measured resonance plots for the three different types of ta-C oscillators. Resonance frequencies vary over 4 orders of magnitude and Q varies from 4×10^3 to 1×10^3.