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Mechanical dissipation at elevated temperatures in tetrahedral amorphous carbon oscillators

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Abstract

We have measured the temperature dependence of mechanical dissipation in tetrahedral amorphous carbon flexural and torsional resonators over the temperature range from 300 to 1023 K. The mechanical dissipation was found to be controlled by defects within the material, and the magnitude and temperature dependence of the dissipation were found to depend on whether flexural or torsional vibrational modes were excited. The defects that were active under flexural stresses have a relatively flat concentration from 0.4 to 0.7 eV with an ever increasing defect concentration up to 1.9 eV. Under shear stresses (torsion), the defect activation energies increase immediately beginning at 0.4 eV, with increasing defect concentration at higher energies.

Keywords: Diamond film; Defects; Thermal properties; Micro-electromechanical systems (MEMS)

Micro- and nano-electromechanical systems [1,2] (MEMS and NEMS) are being utilized in mass detection [3], force and acceleration sensing [4], and RF applications [5]. Some of these structures are being made from thin films of tetrahedral amorphous carbon (ta-C) [6,7]. Ta-C films are purely amorphous carbon films, with a bond composition of roughly 80% sp^3 and 20% sp^2 [8,9]. Understanding the sources of mechanical dissipation, Q^{-1}, of the MEMS or NEMS structure is tantamount in the performance of the aforementioned applications. As examples, the sensitivity of mass detection and the bandwidth of RF filters and clocks scales as $Q^{1/2}$ and Q^{-1}, respectively [5]. Recently, internal dissipation in ta-C thin films has been investigated, with the conclusion drawn that extrinsic internal dissipation mechanisms dominate dissipative effects [7]. Examples of such mechanisms are structural reconfigurations or atomic motion between equilibrium and metastable states.

In this study, we investigated the temperature dependence of mechanical dissipation in ta-C and related the dissipation to thermally activated defect relaxation processes. We achieved this by measuring the quality factor (Q) of fixed-free (cantilever) beams and singly clamped torsional oscillators at temperature ranging from 300 to 1023 K and at pressures below 10^{-4} Torr. Following from the previous work, we determined that the Q of the fixed-free beams and the torsional oscillators was not limited by thermoelastic dissipation, phonon–phonon dissipation, clamping losses or air damping [7], even at elevated temperatures. In order to determine the relative defect concentrations, we assume that the strain field, associated with the defect, couples with the external stress field, giving rise to a Debye-like relaxation. This assumption permits us to compare relative defect concentrations with different activation energies. Explicitly, we expect the defects to exhibit a Debye-like relaxation of the following form:

$$Q_{\text{defect}} = A\left[\frac{\omega\tau^*}{1+(\omega\tau^*)^2}\right]^{-1}, \tag{1}$$

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Fig. 1. Scanning electron micrographs of the oscillator structures. (a) Plan view of a fixed-free beam (cantilever). (b) Plan view of a torsional oscillator.

where A is related to the concentration of the defect and τ^* is the relaxation time for the defect motion. For any given defect, there would be a minimum in Q where $\omega\tau^*=1$. Since we expect the defect relaxation to be thermally activated, the relaxation time would follow an Arrhenius behavior, given by:

$$\frac{1}{\tau^*} = \frac{1}{\tau_0}\exp\left(\frac{-E_A}{k_B T}\right), \tag{2}$$

where $1/\tau_0$ is the characteristic atomic vibration frequency, on the order of 10^{13} Hz, E_A is the activation energy for the relaxation process, and k_B is Boltzmann's constant.

The ta-C micro-resonators were fabricated using surface micromachining methods as described in Ref. [10]. As a brief description, ta-C films were deposited using pulsed-laser deposition (248 nm laser, graphite target, ~100 J/cm^2 fluence) on bare Si. The micro-resonators were defined by electron beam lithography in conjunction with aluminum lift-off. The ta-C was etched in an oxygen plasma containing a dilute amount of CF_4. The resonators were released from the substrate by undercutting the silicon below the ta-C using a mixture of dilute HF in HNO_3. Measurements were performed on fixed-free beams (Fig. 1a) with lengths 50, 75, 100, 150, 200, and 300 μm and torsional oscillators (Fig. 1b) with paddle widths of 15, 17.5 and 20 μm.

The resonant frequencies of the fixed-free beams and torsional oscillators were measured using a laser interference technique [7]. In order to achieve elevated temperatures, the silicon chip with the surface micromachined resonators was attached to a resistive heater element. The oscillators were excited by driving a piezoelectric actuator, separated from the heater element by a porous ceramic thermal isolator. A spectrum analyzer was used to drive the piezoelectric actuator while concurrently measuring the frequency spectra of the voltage from the photodetector. From a least squares Lorentzian fit of the data, we calculated the quality factor, Q, of the devices.

A plot of the quality factor of a 200 μm long fixed-free beam at various temperatures can be seen in Fig. 2. A general trend can be seen in the data that as the temperature increases, the quality factor decreases.

Following from Eqs. (1) and (2), the activation energy of the defects can be calculated at the corresponding temperature and frequency for all cantilever lengths. Assuming that Q is proportional to the number of defects and that the nature of the defect relaxation is the same for all defects (i.e. only the activation energy for defect relaxation varies), then we can also determine the relative defect concentration for the oscillators. The defect concentration is normalized by taking the ratio of the inverse Qs at all temperatures by the largest Q (smallest number of defects) for a given oscillator length. A plot of the relative defect concentration versus activation energy for all the cantilever lengths can be seen in Fig. 3. This shows a relatively flat concentration of defects with energies less than 0.7 eV and an increase in the number of defects with increasing activation energy. From a single plot of concentration versus energy, it is not possible to determine whether the defect spectrum represents a varying distribution of configurationally similar defects having dissimilar activation energies or whether the spectrum represents a distribution of configurationally dissimilar defects. The energy range explored in our study includes the energy needed for interstitial self diffusion in crystalline diamond, 1.3 eV [10], but does not extend to energies required for vacancy self diffusion in crystalline diamond, 2.3 eV [11]. In light of the lower density of ta-C compared to crystalline diamond (about 3.05 g/cm^3 compared to 3.52 g/cm^3), it would be reasonable to expect that a process similar to interstitial self diffusion could be active in ta-C films in this activation energy range. Of course, due to the amorphous nature of ta-C, the distribution of activation energies for self-interstitial

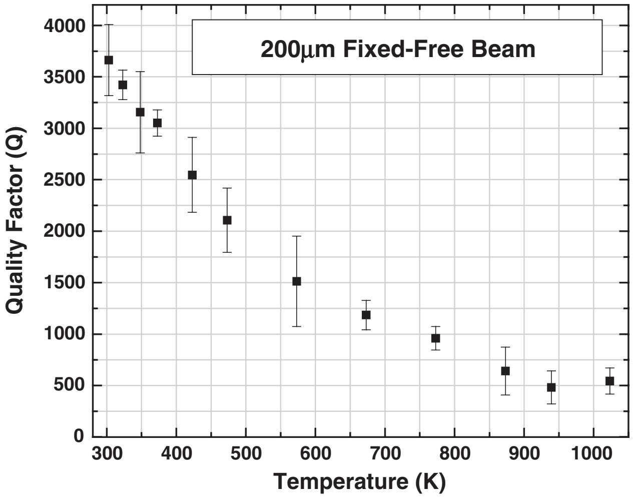

Fig. 2. A graph of the Q of a 200 μm long cantilever beam at temperatures ranging from 300 to 1023 K. The Q decreases with increasing temperature for the values measured here.