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Energy dissipation in suspended micromechanical resonators at low temperatures

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Abstract

We have measured mechanical dissipation in micron-sized single-crystal gallium arsenide torsional resonators. The temperature dependence of the quality factor Q and the shift in resonance frequency can be explained by the presence of two-level systems. The dependence of Q on magnetic field is compatible with the existence of localized electronic states around material defects. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Dissipation; Internal friction; Micromechanical resonator

As micron-sized mechanical resonators begin to be applied to fundamental measurement problems in physics, it becomes necessary to understand the mechanical properties of the constituent crystalline materials at an appropriate size scale. In particular, models must be developed to fully explain the dependence of the quality factor Q on various parameters. Although high Q is the quantity most relevant to fundamental measurements, there does not currently exist any model which can predict the Q of a micron-sized single-crystal resonator. This work is an effort to delineate the microscopic mechanisms predominantly responsible for dissipation in micromechanical resonators.

The resonators used in this experiment are two-element torsional resonators fabricated from single-crystal GaAs–AlAs–GaAs heterostructures (Fig. 1). Their torsional elements have a lateral extent of ~ 25 μm and their thickness is 800 nm. Motion is excited and detected by the magnetomotive technique [1] in magnetic fields from 0.5 to 8 T, via a gold electrode deposited on the outer torsion element. Four different normal modes are detected for each device, with frequencies ranging from 600 kHz to 2.75 MHz, and quality factors ranging from 10^4 to 10^5. In one of the modes, henceforth denoted the antisymmetric torsional mode, the motion is predominantly in the metal-free inner torsion element.

The temperature dependence of the quality factor, Q, exhibits three principal features, as shown in Fig. 2. First, in all modes Q decreases slowly with increasing T below 50 K, while the rate of change varies among devices. Second, Q decreases more rapidly above 50 K. Finally, there is also a dissipation peak near 20 K in some of the lower Q modes. However, the peak temperature is not the same in all devices. The results described above are not compatible with clamping loss or the thermoelastic effect. Clamping loss, or the loss of energy in the resonator by propagation of phonons at the resonance frequency through the torsion rods into the environment, is a function of their transmission probability, which we presume to be dependent only on geometric factors. Thermoelastic damping for flexural modes in GaAs at MHz is predicted to be orders of magnitude weaker [2] than the values measured here, and is absent in torsional modes. Instead, the results suggest the importance of intrinsic relaxation mechanisms. These mechanisms are also characterized by a temperature dependence in resonance frequency similar to the results shown in Fig. 3. In our resonators, the dependence of resonance frequency on temperature is monotonic but weak below 30 K, and increases rapidly up to at least 90 K. Although we observe a dependence in Q of the antisymmetric torsional mode on the size of the inner torsion element, the qualitative behavior of both Q and the resonance

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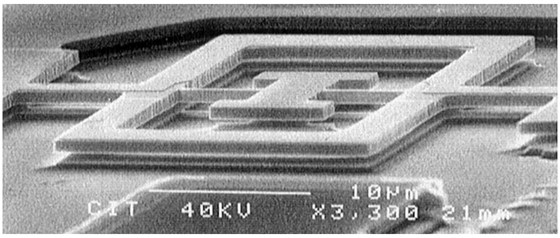

Fig. 1. SEM image of the suspended GaAs resonator.

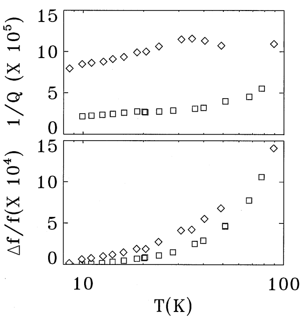

Fig. 2. Dependence of dissipation and frequency shift in torsional mode (squares) and flexural mode (diamonds).

frequency as functions of temperature is similar in all modes of the resonators studied.

The only significant qualitative difference between the dissipation in different modes is in its magnetic field dependence. For torsional modes, the magnetic field dependence is negligible. For flexural modes, dissipation $1/Q$ increases quadratically with magnetic field, roughly doubling from 0.5 to 8 T. We are currently investigating whether the quadratic magnetic field dependence is indicative of a microscopic mechanism which involves electronic scattering.

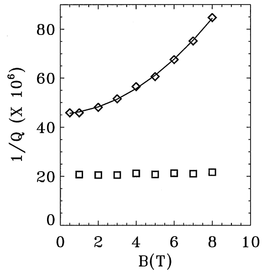

Fig. 3. Magnetic field dependence of dissipation $1/Q$ of the resonator in torsional mode (squares) and fundamental flexural mode (diamonds), along with quadratic fit.

We have observed reproducible trends in the temperature dependence of dissipation and sound velocity, as well as the magnetic field dependence of dissipation in micromechanical resonators. As seen in previous work [3], a possible mechanism for dissipation is an intrinsic defect process which involves coupling between the mechanical resonance mode and electronic defect states.

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