Internal Friction of Amorphous Silicon in a Magnetic Field

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The internal friction of e-beam amorphous silicon was measured in a magnetic field between 0 and 6 T, from 1.5–20 K, and was found to be independent of the field to better than 5%. It is concluded that the low energy excitations observed in this experiment are predominantly atomic in nature.

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It is well known that amorphous solids have a broad spectrum of low-energy excitations. At low temperatures, characteristic signatures of these excitations can be seen in a variety of thermal (e.g. specific heat, thermal conductivity) and elastic (e.g. internal friction, ultrasonic attenuation, sound velocity) measurements. They are commonly described with the two-level tunneling model in which it is assumed that the disordered structure of the material permits atoms or groups of atoms to tunnel between two spatial positions in close proximity and with energy splittings spanning a wide temperature range. The microscopic nature of these tunneling states, however, is still unknown.

It has been suggested that tetrahedrally bonded amorphous solids (a-Ge and a-Si) are structurally overconstrained and will therefore have a lower density of tunneling states, or perhaps none at all. Experimental searches for evidence of tunneling states (or lack thereof) in such materials has been difficult, as these materials can only be grown as thin films on substrates. In practice, most experimental techniques employed must compare measurements of the bare substrate (e.g. its heat capacity in the case of specific heat) to those of the substrate plus the thin film. The value for the film itself is then extracted by measuring the film-substrate geometry. Since the addition of the film to the substrate will often produce only a small change in the raw measurements, the sensitivity of these measurements is necessarily limited. Indeed, experiments trying to determine the existence of such states have given inconsistent results: some experiments showed evidence for such states, and some did not, as recently reviewed.

Of particular relevance to the present work were low-temperature specific heat measurements with e-beam a-Ge by van den Berg and v. Löhneysen. Specific heat is a direct measure of the excitations that exist within a solid—the two level tunneling model predicts a contribution linear in temperature which at sufficiently low temperatures will dominate the $T^3$ phonon contribution. However, the presence of specific heat in excess of the phonon contribution is not necessarily the result of tunneling states. One early example was the specific heat of several silica-based glasses, which showed excitations in addition to two-level tunneling states. These additional excitations vanished in the presence of a moderate magnetic field, and were attributed to spins from iron impurities. Although a-Ge was indeed shown to have an excess specific heat below 1 K, it almost completely vanished in the presence of a 6 T magnetic field. Hence the extra excitations were concluded to be electronic—not atomic—in nature, and were attributed to exchange coupled clusters of dangling bonds, which experienced Zeeman splitting in a magnetic field. However, for the reasons mentioned above, these experiments were not sensitive enough to completely rule out a separate magnetic-field-insensitive linear contribution underlying the electronic contribution to the specific heat, but could only be used to determine an upper bound to its magnitude.

Liu and Pohl of whose work this paper is an extension, probed the existence of low energy excitations in a-Si and a-Ge films through measurements of internal friction at low temperatures using silicon double-paddle oscillators as substrates. A bare double-paddle oscillator itself has an extremely small internal friction background, typically $Q^{-1} = 2 \times 10^{-8}$ at liquid helium temperatures. The internal friction of a thin film will then dominate—and not be a small perturbation to—the total damping of a film-carrying paddle. Generally, amorphous solids have a temperature-independent internal friction “plateau,” whose width extends from approximately 100 mK to 10K, depending on the measuring frequency. The prototypical amorphous solid, a-SiO$_2$, has an internal friction $Q^{-1} = 4 \times 10^{-4}$ in this plateau, and almost all amorphous solids have internal frictions within a factor of 3 of this value (referred to as the “glassy range”). For e-beam a-Ge films, $Q^{-1} = 0.7 \times 10^{-4}$, close to the glassy range. Based on this value and using the tunneling model, the specific heat was calculated to be close to the upper limit determined experimentally in large magnetic fields. However, since the internal friction had been measured in zero B-field, one has to ask whether the states seen were truly atomic in nature and not electronic.

To this end, we measured the internal friction of paddle oscillators with e-beam a-Si films in a $^4$He cryostat above 1.4 K and in magnetic fields as large as 6 T. In a magnetic field $B$, an electronic excitation will have a Zeeman splitting $g\mu_B B$ raising its excitation temperature by $g\mu_B B/k_B$. Using $g = 2$ and $B = 6$ T, this temperature is approximately 8 K. Therefore, any damping resulting
FIG. 1. Enhancement of background internal friction due to magnetic field in three paddles without a-Si films. Solid diamonds: full electrode coverage, 2.4 K; solid circles: full electrode coverage, 6.8 K; open squares: ‘T’ electrodes, 4.9 K. Zero field background internal friction is $2 \times 10^{-8}$ for full electrode paddles and $1 \times 10^{-8}$ for the ‘T’ electrode paddle is (see text for details). The inset, a drawing of the paddle, shows full electrode coverage (shaded areas) and ‘T’ electrode coverage (darker shaded areas). Arrows on head and wings describe the antisymmetric mode studied in this work. B-field direction is parallel to the neck.

from the relaxation of electronic excitations—most likely to occur by one-phonon emission—should be drastically reduced at sufficiently low temperatures.

Details of sample preparation and measurement are the same as described previously. The following changes were made to the apparatus for work in a magnetic field, which was applied parallel to the paddle’s axis of rotation. First, we replaced the ferromagnetic Invar block to which the paddle is usually attached with one made of silicon in order to avoid disturbance of the field. Second, we found that the usual metal layer deposited on the back of the paddle and which acts as an electrode—30 Å Cr followed by 500 Å Au covering an area indicated in gray shading in the inset to Fig. 1—caused an unacceptably large background damping in a magnetic field. According to Ref. 8, the presence of a 0.7 μm a-Si film is estimated to increase the zero-field internal friction to $Q_{\text{paddle}}^{-1} \approx 4 \times 10^{-7}$. At a field of only 1 T, however, the bare paddle background internal friction was $Q_{\text{paddle}}^{-1} = 5 \times 10^{-8}$, over an order of magnitude larger than that of the film-carrying paddle in zero field. The magnetic field dependence of this background internal friction is shown in Fig. 1 for two different paddles at constant temperatures. No attempts were made to quantitatively account for the large magnitude of this damping, which is likely due to eddy currents. However, by making the metal film electrode in the shape of a thin ‘T,’ shown in dark gray shading in the inset to Fig. 1, the large field effect was reduced by three orders of magnitude, with $Q_{\text{sub}}^{-1}$ rising only by a factor of 4 in a field of 6 T. Furthermore, this background internal friction was temperature-independent between 1 and 20 K, as is shown in Fig. 2, and could be described simply as the following function of magnetic field:

$$Q^{-1} = 1.106 \times 10^{-8} + 1.503 \times 10^{-9} B^{1.60},$$

(1)

where the magnetic field $B$ is measured in Tesla. Note that even for zero magnetic field, the background internal friction is decreased by a factor of 2 below that observed with the large metal electrode. Since metal films are known to have large internal frictions, the reduction in the size of the metal film electrode can explain the observed reduction of the damping.

Since the paddle oscillators themselves are very fragile, the preparation must follow a certain order: the a-Si film must be deposited before epoxying the oscillator to the silicon block, and the metal electrodes deposited thereafter. Once affixed to the block, a paddle cannot be removed without a large risk of breaking it. Hence we had to use two different oscillators for the measurements with and without films. Considering the strong dependence of the background damping on details of electrode shape and the irreproducibility in depositing the ‘T’ electrodes, the background damping of the two oscillators used might differ. After comparing two different bare oscillators with ‘T’ electrodes, we concluded that such differences are no larger than 25% over the entire range.
of magnetic field and thus should not significantly affect the analysis.

We extract the internal friction of the film itself using

\[ Q_{\text{film}}^{-1} = \frac{G_{\text{sub}}t_{\text{sub}}}{3G_{\text{film}}t_{\text{film}}} (Q_{\text{paddle}}^{-1} - Q_{\text{sub}}^{-1}) \]  

(2)

The thickness of the paddle oscillator substrate is \( t_{\text{sub}} = 300 \mu\text{m} \), the shear modulus of crystalline silicon in the direction of the neck, \((110)\), is taken as \( G_{\text{Si}} = 6.2 \times 10^{11} \text{dynes/cm}^2 \), and that of the film \( G_{\text{film}} = 3.63 \times 10^{11} \text{dynes/cm}^2 \) (Ref. 3). Film thickness was \( t_{\text{film}} = 708 \text{ nm} \) in this measurement.

The internal friction of the film-carrying paddle for \( B = 0, 2, \) and \( 6 \text{T} \) is plotted in Fig. 3a, together with temperature independent background computed from eq. (2). In zero field, \( Q_{\text{film}}^{-1} = 8.5 \times 10^{-5} \) at \( 1.5 \text{K} \), increasing with increasing temperature to \( Q_{\text{film}}^{-1} = 1.1 \times 10^{-4} \) at \( 18 \text{K} \), as shown in Fig. 3b. These values vary by at least 97%. Similarly, Stephens \( 4 \) found in zero field a suppression by at least 97%. Whether this hysteresis and the apparent field effect are real or artifacts of the background measurement or other experimental details cannot presently be decided.

The very small changes observed in our experiments are to be compared with the specific heat measurements. Writing their linear specific heat term as \( C = aT \), van den Berg and v. Löhneysen \( 2 \) measured \( a = 4.5 \times 10^{-6} \text{J/g K} \), while in 6 T, \( a \leq 1 \times 10^{-7} \text{J/g K} \), i.e. a suppression by at least 97%. Similarly, Stephens \( 4 \) observed a complete removal of the specific heat anomaly caused by 12 ppm of iron in a borosilicate glass below 2K in a magnetic field of \( B = 3.3 \text{T} \). Biggar and Parpia \( 5 \) studied the magnetic field dependence of the internal friction of boron-doped crystalline silicon \( 6 \) in which phonon

FIG. 3. (a) Internal friction of film-carrying paddle as a function of temperature in 0, 2, and 6 T, together with temperature-independent background computed from eq. (2). (b) Temperature dependence of film internal friction, with background subtracted via eq. (2).

![Graph](image)

FIG. 4. Magnetic field dependence of the internal friction of the a-Si film at 4.3 K and 1.45 K. Time history of the 4.3 K data is traced.

For a quantitative estimate of the upper limit of the effect of electrons, the internal friction of the film itself is computed using eq. (2). In zero field, \( Q_{\text{film}}^{-1} = 8.5 \times 10^{-5} \) at 1.5 K, increasing with increasing temperature to \( Q_{\text{film}}^{-1} = 1.1 \times 10^{-4} \) at 18K, as shown in Fig. 3b. These values are 30% smaller than those reported in Ref. 5, but this can be explained considering the large sensitivity of the internal friction to moderate heat treatment noted previously in these films. Although the film-carrying paddle shows virtually no variation with magnetic field, the fact that \( Q_{\text{sub}}^{-1} \) increases with magnetic field implies a small decrease of \( Q_{\text{film}}^{-1} \) with increasing magnetic field. The variation of \( Q_{\text{film}}^{-1} \) with increasing \( B \), however, is not simple; it is shown in more detail for two temperatures in Fig. 4. In both cases, \( Q_{\text{film}}^{-1} \) has a maximum near 2 T, followed by a decrease with larger fields. The data were taken over the course of several days, and for 4.3 K, the time history of the data is traced. Some hysteresis is observed; the initial zero-field data have lower damping than the final zero-field data by approximately 4%. Whether this hysteresis and the apparent field effect are real or artifacts of the background measurement or other experimental details cannot presently be decided. The very small changes observed in our experiments are to be compared with the specific heat measurements.
scattering from holes bound to acceptor (boron) atoms causes a large internal friction in the absence of a magnetic field. This excess damping was observed in paddle oscillators fabricated from such crystals, and was reduced by 98% in a 6 T magnetic field. Compared with these experiments, the suppression observed in our experiments is insignificant. It is therefore concluded that electrons play only a negligible role in our experiments and that the relaxation observed is caused by atomic motion as predicted by the tunneling model.

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