Low Temperature Acoustic Properties of Amorphous Silica and the Tunneling Model

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Internal friction and speed of sound were measured on a-SiO$_2$ above 6 mK using a torsional oscillator at 90 kHz, controlling for thermal decoupling, vibrational heating, background losses, and nonlinear effects. Strain amplitudes $\epsilon_A = 10^{-8}$ mark the transition between the linear and nonlinear regimes. In the former, agreement with the tunneling model was observed for both internal friction and speed of sound above 25 mK. The observed deviations in the speed of sound below 25 mK can be described with a cutoff energy of $\Delta_{0,\min}/k_B = 6 \pm 0.5$ mK. In the nonlinear regime, above 10 mK the behavior was typical for nonlinear harmonic oscillators, while below 10 mK different behavior was found.

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The low temperature acoustic, thermal, and dielectric properties of amorphous solids have long been successfully described by the phenomenological tunneling model (TM). In this model, the low energy localized vibrational excitations, a common feature of amorphous solids, are described by noninteracting two-level defects which are thought to be caused by tunneling of atoms or groups of atoms between nearly degenerate potential minima. The excitation energy between the two lowest states of the double well potential, $E = \sqrt{\Delta^2 + \Delta_0^2}$, is determined by the asymmetry, Δ, and the tunneling splitting, Δ_0 [1]. Low temperature internal friction and speed of sound measurements on a-SiO$_2$ using the torsional oscillator technique between 66 and 160 kHz above 50 mK have shown excellent agreement with the TM [2,3]. However, other acoustic and dielectric experiments have indicated deviations from this model below 100 mK [4–8] and have been interpreted as evidence for tunneling defect interactions [9,10]. We extended the torsional oscillator measurements to 6 mK in order to investigate this defect interaction.

It is well known that in low temperature acoustic measurements the sources of uncertainty are thermal decoupling caused by spurious heat input and vibrational heating, lack of knowledge of the influence of mounting, and nonlinear effects resulting from moderate strain amplitudes [2,5,6,8,10]. Taking particular care to control these problems, we have found excellent agreement with the predictions of the standard, noninteracting TM to at least 25 mK, and at lower temperatures we have observed the first evidence of a low energy cutoff in the tunneling spectrum in elastic measurements. Below 10 mK, we find novel nonlinear behavior which is not understood. Our results also emphasize the extreme care with which low temperature acoustic work must be carried out.

The amorphous silica sample, Suprasil-W ($<$5 ppm OH$^-$ impurities, 4 mm diam, 22.33 mm long) was mounted in a torsional composite oscillator resonating at $\sim$90 kHz [11] in a dilution refrigerator (0.07–2 K) and in a vibrationally isolated dilution refrigerator with a demagnetization stage (0.006–0.100 K) [12]. In the latter, the sample was surrounded by a Nb tube (5.4 mm i.d., 60 mm long) in order to shield it from residual magnetic fields except for the Earth's field ($<$0.5 G).

Before presenting our results on the acoustic properties, we describe the thermal and strain studies that are crucial for avoiding experimental errors. We begin by considering *thermal decoupling* of the undriven sample. The temperature of the sample was measured directly by epoxying a 1 kΩ RuO$_2$ Dale resistor onto the free end of the a-SiO$_2$ sample, with the leads (76 μm diameter Evanohm) thermally anchored along its length (see Fig. 1 inset). A twin Dale resistor was attached to the base. RuO$_2$ resistors have been successfully used as thermometers from 0.015 to 80 K in magnetic fields up to 20 T [15]. The resistances for the two resistors, read with a self-balancing resistance bridge (Linear Research, LR700) using a power $= 10^{-15}$ W and calibrated against a He^3 melting curve thermometer, were found to have identical temperature dependencies above 10 mK with very little scatter; see Fig. 1a. Below 10 mK, however, irreproducible resistances for both resistors were observed (error bars). They are caused by spurious rf radiation [16]. Because of this irreproducibility, thermal decoupling of the undriven sample can be definitely ruled out only above 10 mK. Heating of the oscillator through vibrational noise in this cryostat below 10 mK is nonetheless considered to be unlikely. The lowest frequency mode of the sample, $f \approx 3$ kHz, is that in which the stiff oscillator bends the thin Be:Cu torsion rod (1 mm diameter, 3 mm long). Because of its relatively large metallic thermal conductivity, this heat should readily be removed to the base. Also, a torsional oscillator in the same refrigerator connected by a hollow Be:Cu torsion rod previously showed no signs of decoupling to 1 mK [17].

Vibrational heating occurs when the oscillator is driven. The strain amplitude, ϵ_A, is defined as one-half of the maximum angular displacement between the two ends of the silica sample. The electrical measurement of ϵ_A was calibrated by reflecting a laser beam off the sample and measuring its deflection with a photodiode [18]. The power dissipated is $Q^{-1} f_0 \frac{1}{2} G V \epsilon_A^2$, where Q^{-1} is the internal friction, f_0 is the resonant frequency, G is the shear

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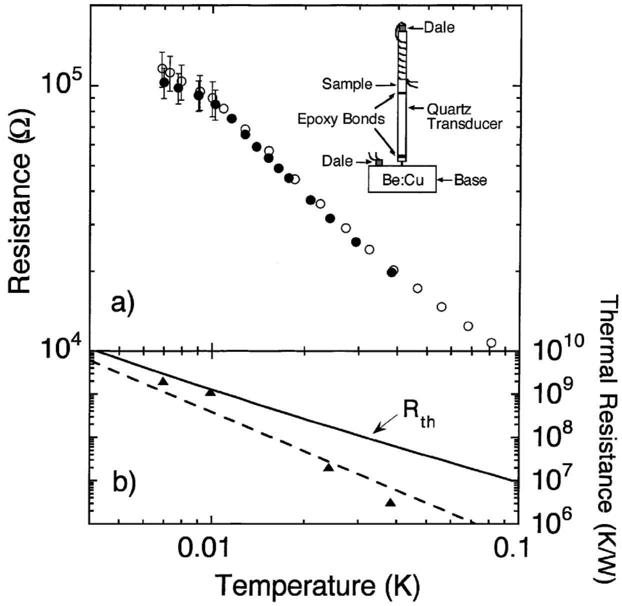

FIG. 1. (a) Resistance versus temperature for 1 kΩ RuO_2 Dale thick film resistors mounted on the sample (solid circles) and the base (open circles). The inset shows the experimental setup for this experiment. (b) Measured (triangles) and calculated thermal resistances of the torsional oscillator. The solid line is the calculated thermal resistance, $R_{th} = \frac{87\,500}{T^2}(K^3/W) + \frac{181}{T^3}(K^4/W) + \frac{204}{T^3}(K^4/W)$, using the method outlined in Ref. [13] and the data table of Ref. [14], where the terms are the thermal resistances of a-SiO_2, Casimir, and boundary, respectively. The dashed line is the calculated thermal resistance without a-SiO_2. (The thermal resistance of the wires connecting the sample to the cryostat was much larger than that of the mounted oscillator.)

modulus, and V is the volume of the sample. The thermal resistance of the oscillator was measured by heating the sample thermometer (Fig. 1 inset) with a controlled power input from the LR700. The data are close to the dashed line which was calculated ignoring the thermal resistance of the glass sample (see Fig. 1 caption). The explanation may be that heat enters the glass over its entire surface by way of the resistor leads. R_{th} was calculated by adding the thermal resistance of the glass (known only above 20 mK [19]) to that shown as a dashed line and was used to determine the upper limit of the temperature rise of the driven oscillator for a measured mechanical power loss. For example, our oscillator with $Q^{-1} = 10^{-6}$ driven with $\epsilon_A = 10^{-8}$ at 10.6 mK is calculated to heat by the negligible $\Delta T = 40\ \mu$K. A tenfold increase of ϵ_A, however, would lead to a substantial increase (≈4 mK).

The elastic properties of our torsional oscillator without tunneling defects, i.e., the acoustic *background,* were studied by replacing the amorphous sample with a crystal quartz sample of equal size. The frequency traces of the background oscillator (quartz on quartz) at different strain amplitudes showed a Lorentzian line shape at all amplitudes and temperatures. Figure 2a shows two traces taken at nominally 2 mK (i.e., ignoring the ΔT due to self-heating). They show that neither the epoxy nor the Be:Cu metal base lead to nonlinear behavior even when the strain amplitude was varied by a factor of 100. The background internal friction was found to be slightly temperature dependent while the speed of sound was independent of temperature to within ~0.1 ppm, as shown in Fig. 3 with the dashed lines.

Elastic measurements are sensitive to *nonlinear effects* as can be seen in frequency traces of a driven a-SiO_2 at increasing driving voltages (peak power dissipation). These traces are plotted in Figs. 2b–2d at 27 mK, 10.6 mK, and 7 mK, respectively, for different strain amplitudes. The dashed curves always are the normalized response of the oscillator carrying a crystal quartz sample. At 27 mK, the Lorentzian line shape for a-SiO_2 is clearly resolved from that of the quartz sample (background) as seen in Fig. 2b. With increasing peak strain amplitude, the oscillator exhibits behavior typical for a nonlinear harmonic oscillator including hysteresis (not shown). The frequency shift expected from the vibrational heating, shown as the dotted line, is less than 10% of the shift observed. At 10.6 and 7 mK, however, (see Figs. 2c and 2d) the nonlinear behavior differs dramatically. With increasing strain amplitudes, the frequency response becomes discontinuous with jumps, plateaus, oscillations, and no obvious hysteresis. Since the background oscillator showed no such behavior, we conclude that the tunneling entities in a-SiO_2 are responsible. This is the first evidence that the tunneling entities themselves may change their behavior at ≈10 mK. We do not understand the nature of the tunneling entities that can bring about this new kind of nonlinearity.

The internal friction was determined only when the frequency dependence of the oscillator was clearly in the linear regime, i.e., fit a Lorentzian curve well (solid curves in Fig. 2). In the linear regime, the internal friction was found to be independent of the driving power and ΔT to be negligible. At larger strain amplitudes (in the nonlinear regime), the fits yielded higher internal frictions and speeds of sound. As an example, consider Fig. 2c; for a peak $\epsilon_A = 1.4 \times 10^{-8}$ and a power $= 8 \times 10^{-14}$ W, using a half-width of the non-Lorentzian, discontinuous curve would lead to an erroneous increase of the internal friction by a factor of 2, while increasing the speed of sound by only ~1 ppm.

With the previously identified experimental problems avoided, Fig. 3 shows the internal friction, Q^{-1}, and the relative change of the transverse speed of sound, $\frac{\Delta v}{v_0}$ [as defined in Eq. (1)] of a-SiO_2 which were determined from the Lorentzian frequency responses (solid curves in Fig. 2). Sample heating was always less than 0.5% of the temperature. Note the excellent agreement of the data from the two cryostats. Below 10 mK, the internal friction approaches a nearly temperature independent value very close to that measured on the quartz sample (dashed line). This close agreement is also evidenced in Figs. 2c and 2d with the frequency responses obtained on both samples (solid and dashed Lorentzians). From this we

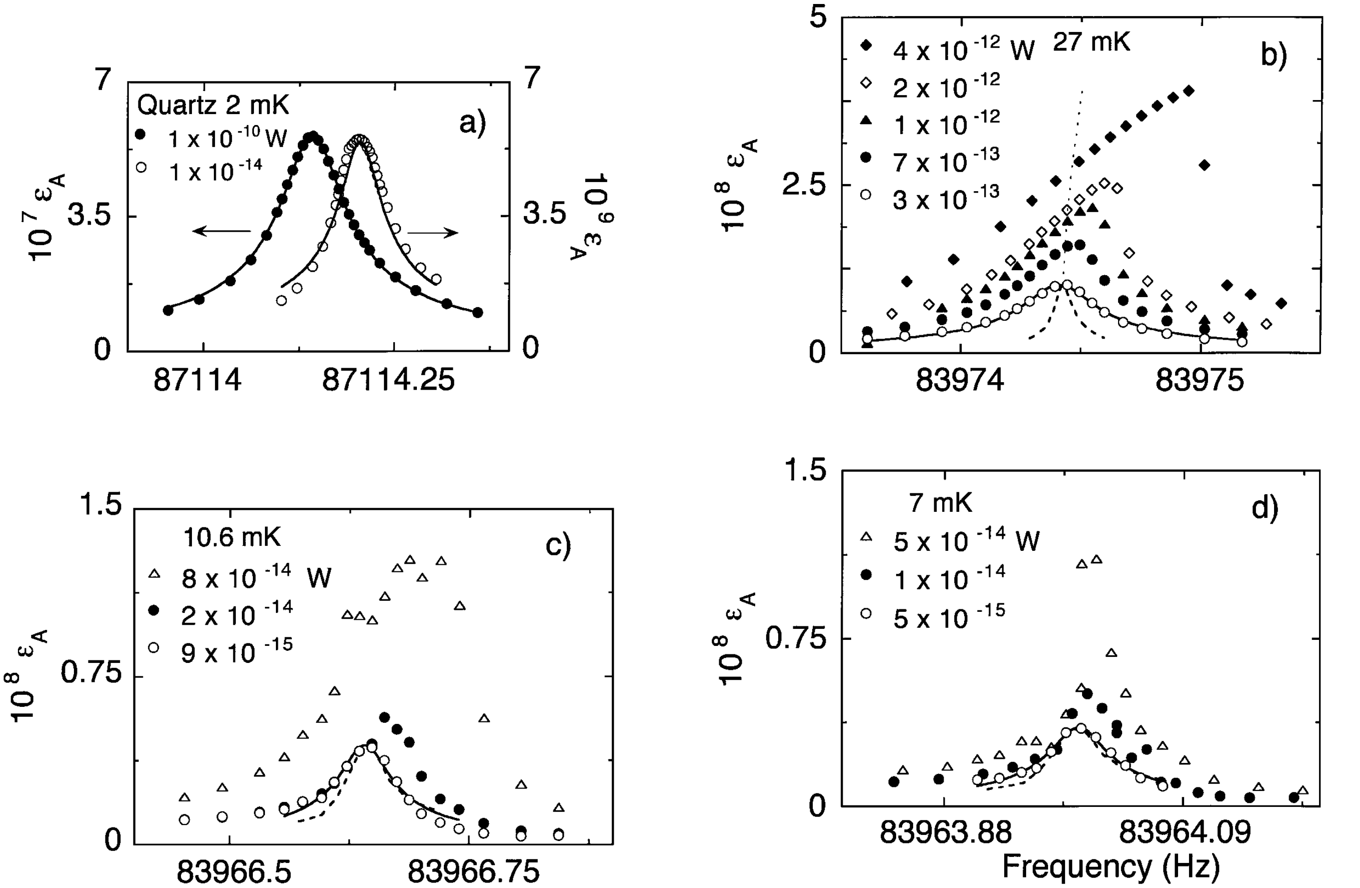

FIG. 2. Frequency response of the background (quartz) and of a-SiO_2. Solid curves are Lorentzian fits to the data and the powers are those dissipated at the peak. (a) Lorentzian line shapes of quartz measured at $\sim$2 mK. Note the different scales on the y axes. (b)–(d) Frequency response of a-SiO_2 at 27, 10.6, and 7 mK for different peak powers. Dashed curves are normalized background Lorentzians. Dotted curve in (b) is the trajectory of peak shifts expected from heating calculated from R_{th}, the peak power dissipation, and the stiffening expected at the resulting higher temperatures using the data in Fig. 3b.

conclude that the internal friction measured on the a-SiO_2 sample below 10 mK is dominated by the background, and we use the dashed line to derive the internal friction of the a-SiO_2 without this background, shown as $\times$'s in Fig. 3a, following the method outlined in Ref. [3]. No such correction needs to be applied to the speed of sound, because the background frequency shift is independent of temperature (dashed line in Fig. 3b). Equally small changes have been observed in similar experiments on crystal quartz, lightly doped fluoride crystals, and annealed metals [3,18,20,21]. The two solid curves in Fig. 3 are fits to the TM using a tunneling strength $C = 3.1 \times 10^{-4}$ and a crossover temperature $T_{co} = 0.08$ K, both identical to our previous published values based on the measurements above 50 mK [3]. The internal friction shows no deviation from the TM prediction (below 15 mK, separating background from the internal friction by the tunneling states would involve large errors). The speed of sound also agrees with the TM prediction between 25 and 500 mK. The deviation of $\frac{\Delta v}{v_0}$ for $T > 500$ mK is experimentally well established [9], indicating the existence of channels for defect relaxation other than by single phonon emission. Very remarkable and new, however, is the deviation of $\frac{\Delta v}{v_0}$ from the logarithmic temperature dependence below 25 mK which is unambiguous at least to 10 mK (the uncertainty below 10 mK is due only to the thermometer calibration as discussed earlier). This deviation is consistent within the standard TM assuming a cutoff $\Delta_{0,\min}/k_B$ of the energy distribution of the tunneling states, which affects the speed of sound v [2]:

$$\frac{v(T) - v_0}{v_0} = \frac{\Delta v}{v_0} = C\left(\ln\frac{T}{T_0} + \frac{\Delta_{0,\min}/k_B}{2T}\right), \quad (1)$$

where v_0 is the speed of sound at some reference temperature T_0 and C is the tunneling strength. The long-dashed curve, calculated with $\Delta_{0,\min}/k_B = 6.6$ mK, fits the data in Fig. 3b well. Including this cutoff energy does not affect the TM fit of the internal friction; see Fig. 3a. Evidence for a cutoff energy has also been obtained from heat pulse measurements of a-SiO_2 ($\Delta_{0,\min}/k_B = 3.1$ mK) [22], and from dielectric measurements on sputtered a-SiO_x (3.3 mK) [7] and on a multicomponent alumosilicate glass (12.2 mK) [23]. While such a cutoff may indeed be caused by interaction between the tunneling defects, our

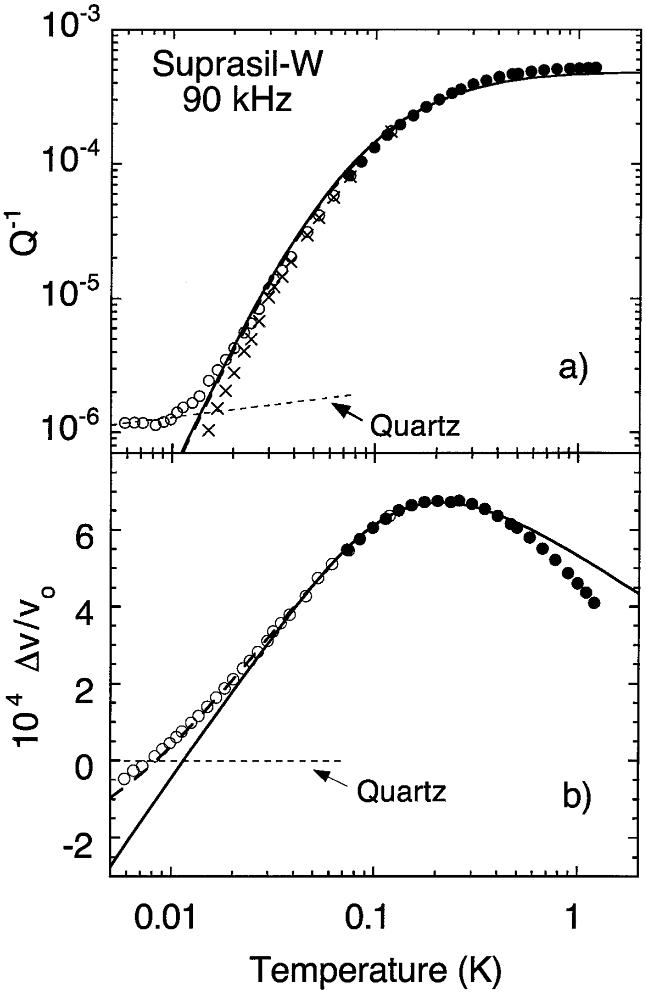

FIG. 3. (a) Internal friction and (b) relative change of the transverse speed of sound of a-SiO_2 (Suprasil-W) at 90 kHz. Solid circles, in dilution cryostat; open circles, in demagnetization cryostat; $\times$'s, after subtraction of the background. Dashed lines, quartz sample (background). Solid curves, TM prediction with parameters from sound velocity measurements. Long dashed curves, TM prediction including a cutoff energy of $\Delta_{0,\min}/k_B = 6.6$ mK.

data above 25 mK show no evidence for the effects of such interactions.

In conclusion, our measurements have shown no evidence above 25 mK for a deviation from the predictions of the standard tunneling model. Below 25 mK, a deviation is observed which can be described with a cutoff energy $\Delta_{0,\min}/k_B = 6 \pm 0.5$ mK. Our results disagree with the earlier studies [5,6,8,10] in which much weaker temperature dependences of both internal friction and speed of sound than predicted by this model had been observed, and there was no evidence of a cutoff energy, although at different frequencies ($\leq$14 kHz). Those measurements had been interpreted as evidence for defect interactions at temperatures of 100 mK and higher. If we ignore the potential experimental problems explored here, our results and those reported recently [8] show a very remarkable frequency dependence of the acoustic properties of this glass: At 90 kHz, evidence for a deviation from the standard TM is observed only below ~25 mK, which can be described phenomenologically with a cutoff energy. In measurements at and below 14 kHz a deviation can be observed already at 100 mK, and no evidence for a cutoff energy is seen [8]. Clearly, more work is needed to resolve the fascinating issue of interacting tunneling defects.

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