Magnetic field effects on boron-doped Si oscillators

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We have measured the mechanical properties of single-crystal silicon doped with boron (acceptor) impurities. A low-temperature doping-dependent increase in dissipation is observed, accompanied by a period shift. With increasing magnetic field, the dissipation and period shift are eliminated. These results confirm an electronic origin for the dissipation, consistent with the attenuation observed elsewhere in ultrasound in boron-doped silicon. [S0163-1829(97)07545-0]

I. INTRODUCTION

Single-crystal microfabricated mechanical oscillators are sensitive detectors of force and mechanical loss.[1] Single-crystal cantilevers have been used for sensitive magnetic measurements as torque deflection magnetometers,[2] as oscillating ac magnetometers,[3] and as magnetic force microscope and magnetic resonance force microscope cantilevers.[4,5]

Several groups have studied the intrinsic properties of silicon oscillators with resonant frequencies in the kilohertz range.[6,7] They observed a feature in dissipation at temperatures around 100 mK. A simultaneous shift in resonant frequency was observed, indicating a softening of the spring constant and decrease in the sound velocity. Keyes[8] suggested that these features might be due to electronic defects and Mihailovich and Parpia[9] later observed a peak in dissipation proportional to the level of boron (acceptor) impurities. Similar features in the energy dissipation have long been known to occur in ultrasound in bulk p-type silicon.[10] It seems likely that the same mechanism is responsible for both observations.

The attenuation of ultrasonic waves has been explained as due to scattering of phonons from holes bound to acceptor impurities. These impurities have a fourfold $J=3/2$ degenerate ground state that is split by the presence of local strains into two states $J_z=\pm 1/2$ and $J_z=\pm 3/2$. These two states form a two-level system that can scatter phonons resulting in glasslike sound attenuation and silicon oscillator dissipation at low temperatures. A magnetic field should cause Zeeman splitting, creating four distinct energy levels whose spacing eventually increases beyond the regime where they can effectively scatter phonons.

Strong suppression of ultrasound attenuation with magnetic field was observed by Ishiguro[11] in his ultrasound experiments on boron-doped silicon. To support or disprove the postulate that dissipation in these two frequency regimes have a common origin, we studied the magnetic field dependence of the observed dissipation peak and period shift in oscillators fabricated from acceptor-doped silicon. We present here data taken from oscillators fabricated from boron-doped silicon wafers with room-temperature resistivities of 16 and 0.2 Ω cm, corresponding to acceptor impurity levels of 7.1×10^{14} and 5.7×10^{16} cm^{-3}, respectively.

II. EXPERIMENT

The details of oscillator fabrication have been described elsewhere.[9,12] Two different techniques were employed to pattern metal electrodes on the silicon oscillators. After etching, the 16-Ω cm oscillators were attached to a backing layer with a few drops of photolithographic resist. This allowed a second level of photolithography to be carried out without cracking the fragile oscillators. The upper torsion rod as well as many fine fingers on the wings were covered with photoresist, which was dissolved after copper was evaporated onto the oscillator, lifting the copper off these regions. This ensured the upper torsion rod, a region of high stress, would not suffer from dissipation due to a copper overlayer and also minimized eddy current dissipation due to the motion of the wings through a magnetic field. The 0.2-Ω cm oscillators were simply placed in a machined aluminum mask to keep the copper film off the upper torsion rod and oscillator head. The copper overlayer was thin ($\sim$200 Å). It was used as a ground plane for capacitive drive and position detection. After evaporation the 16-Ω cm oscillators were released from their backing wafer as the excess copper was lifted off in an acetone bath.

The oscillators were mounted on a ^{3}He cryostat with the paddles perpendicular to an applied magnetic field. The oscillators have two rotational masses (stages), a smaller inertial mass (the head) connected by a torsion rod to the main inertial mass (the wings), which itself is connected by another torsion rod to a base (see Fig. 1). This is clamped in place, providing a path to electrical ground and good thermal contact to the sample platform of the cryostat. A copper ground plane covers the wings, the lower torsion rod, and the

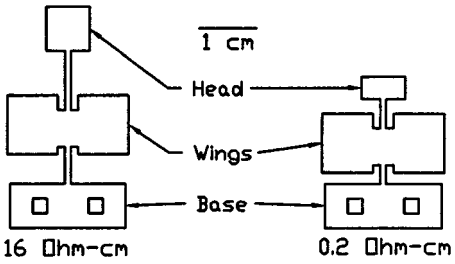

FIG. 1. Schematic of the oscillator geometry. The high-Q antisymmetric mode involves the head and paddles moving 180° out of phase about the axis of the torsion rods.

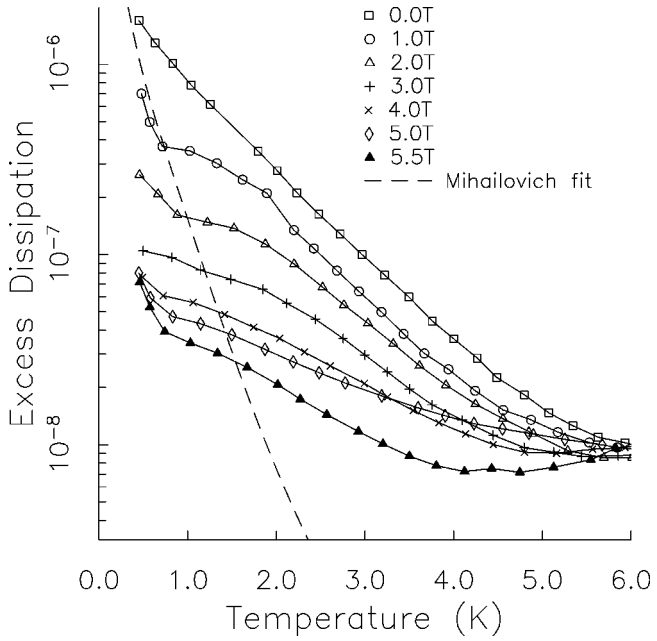

FIG. 2. Temperature dependence of 0.2-Ω cm oscillator's dissipation at several magnetic fields. Also shown is the fit obtained by Mihailovich.

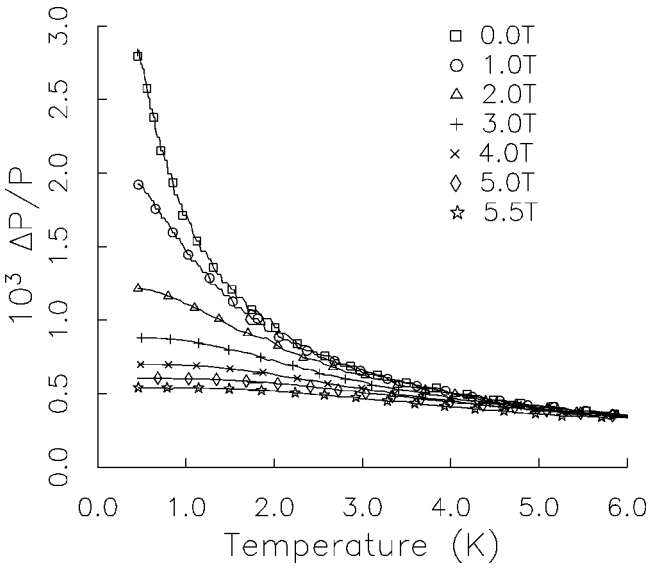

FIG. 3. Temperature dependence of 0.2-Ω cm oscillator's period at several magnetic fields.

base. Biased electrodes are brought up to the main stage to drive and detect the oscillator motion.

The oscillators were driven at resonance using a phase-locked loop in their antisymmetric torsional mode. This mode has a high Q (as high as 10^7), as it minimizes the motion of the lower stage, thereby minimizing the losses due to stresses where the oscillator is clamped. The oscillators' amplitude and frequency were measured while they were cooled to approximately 500 mK, then slowly warmed to 10 K. This was repeated in a variety of magnetic fields.

With no applied magnetic field, we measured the high-temperature tail of the dissipation peak and period shift that had been observed in other experiments.[9] As the magnetic field was increased, both the period increase and the excess dissipation were reduced (Figs. 2 and 3). The effect was observed in both the 0.2- and 16-Ω cm oscillators. Similar behavior was noted at other resonant modes. We focus on the asymmetric torsional mode in this paper since it is a well-defined mode with the highest Q. For the geometries used in this experiment, this mode has a frequency of 3500 and 2200 Hz in the 0.2- and 16-Ω cm oscillators, respectively.

III. DISCUSSION

Isawa *et al.*[13] have derived an expression for the acoustic attenuation due to relaxation in this system that is applicable in the low-frequency limit. The origin of the dissipation is individual dopant atoms contributing holes whose ground states are split by an energy Δ by the presence of strain in the (111) direction. For a dopant concentration N_a, the attenuation due to relaxation is given by

$$\alpha_{rel}(\Delta,T)=\beta\frac{8N_aN_1N_2D_{u'}^{a2}|f(q)|^2}{9\rho_0 v_t^3 kT}\frac{\omega^2\tau}{1+\omega^2\tau^2}, \quad (3.1)$$

where N_1 and N_2 are the populations of the ground and excited states, respectively, τ is longitudinal relaxation time, ω corresponds to the ultrasound angular frequency or the angular frequency of the oscillator, ρ_0 is the silicon density, v_t is the transverse sound velocity, and $D_{u'}^a$ is the off-diagonal coupling between the strain and total hole spin. $f(q)$ is a cutoff function that falls off for phonons whose wavelength is small compared to the Bohr radius of the bound hole. For the case described above, $\beta=1$, but it can be taken to be a geometric parameter of order one if, as is the case in our experiments, the strain is not uniformly aligned in the (111) in direction. Theoretically, resonant attenuation is also present, but is insignificant at the frequencies with which we are concerned.

Note that the attenuation is proportional to the population of the excited states and so states with $\Delta \gg T$ will not contribute to the dissipation. Isawa *et al.* derived an expression for τ,

$$\tau^{-1}=\frac{2\pi}{\hbar^2}\sum_{\mathbf{q},\lambda}\delta\left(\omega_{q\lambda}-\frac{1}{\hbar}\Delta\right)\left(\frac{\hbar\omega_{q\lambda}}{2\rho_0 V v_{q\lambda}^2}\right)|C_{q\lambda}^{12}|^2(2n_{q\lambda}+1), \quad (3.2)$$

where $\omega_{q\lambda}$ and $v_{q\lambda}$ are the phonon frequency and velocity and $n_{q\lambda}$ is the average number of phonons in the mode q,λ for a particular temperature. $C_{q\lambda}^{12}$ is the phonon-hole scattering amplitude. V is the volume of the sample. This relaxation time calculation does not take into account indirect (Raman) scattering effects, which are splitting independent and become significant at ~ 2 K. They will cause a decrease in the relaxation time.

Oscillator dissipation and attenuation are related linearly to each other via the equation

$$Q^{-1}=0.2303\left(\frac{v}{\omega}\right)\alpha, \quad (3.3)$$

where Q^{-1} is the dissipation of an oscillator with angular frequency ω and α is the attenuation of sound with a veloc-

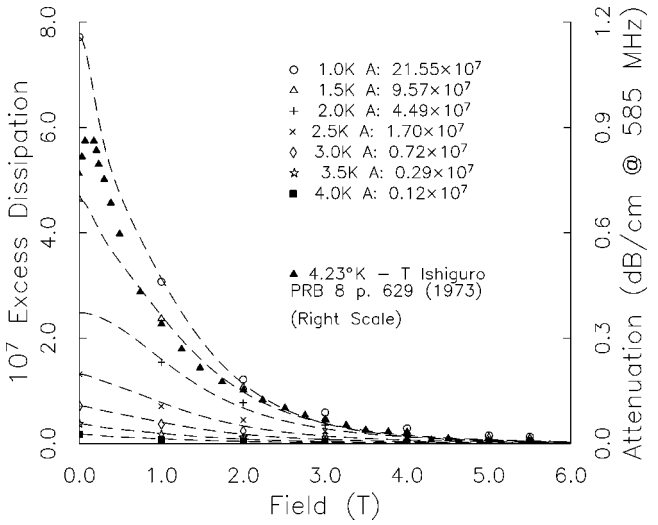

FIG. 4. Dependence of dissipation on the magnetic field at several temperatures. Dashed lines are fits to Eq. (3.4). For comparison, data obtained by Ishiguro using ultrasound attenuation experiments are also shown. Note the similar shape despite very different frequency regimes.

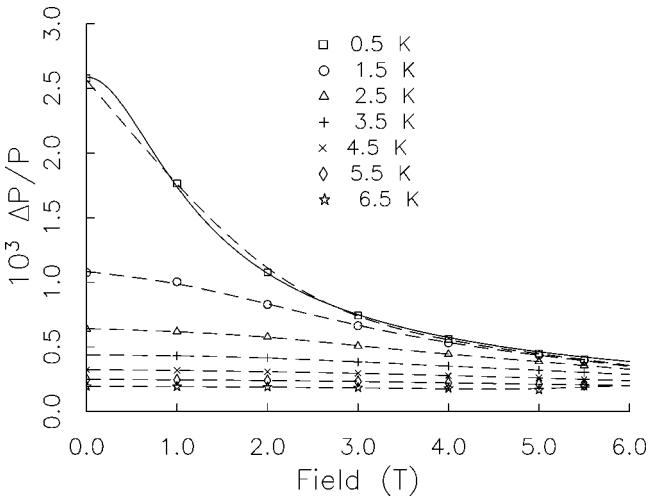

FIG. 5. Dependence of the period shift on the field at several temperatures. The solid line is the simple functional form described in the text for comparison. Dashed lines are guides to the eye.

ity v. Mihailovich found a maximum dissipation at about 80 mK. Using the Isawa-Takeuti-Mikoshiba model, he was able to fit a dissipation curve to his data assuming the single value of the splitting $\Delta = 0.125$ K.[14] The peak observed, according to this analysis, is due to the competition between thermal activation (through the N_2 term) of the attenuation and the increasing relaxation rate as temperature increases. Systems with greater energy splittings might be present, but at kilohertz frequencies their contribution to dissipation is masked by the increase in relaxation at temperatures lower than those at which they are thermally activated.

The dissipation features we observe are actually the high-temperature tail of the peak observed by Mihailovich and Parpia.[9] The dissipation at these temperatures is enhanced over the $\Delta = 0.125$ K fit, probably because of the thermal activation of holes with greater energy splittings. The analysis of ultrasound measurements in Ref. 11 indicates that typical splitting distributions are centered at about 1 K and have a width of about 1 K, so holes with greater energy splittings are expected to be present, though their contribution to the attenuation is overwhelmed by holes with smaller energy splittings.

The application of a magnetic field complicates the system, further splitting the levels so the scattering is from four-level systems rather than two-level systems. In addition, the quantization axis of the spin aligns with the magnetic field, possibly altering the geometric factor β. Since the distribution of splittings is not known, it is in any case impossible to do a precise fit to the data. However, a respectable fit is obtained by assuming that the primary effect of the magnetic field is to increase the energy splitting. (See Fig. 4.) The increased splitting will lead to an increase in the relaxation rate and a depopulation of the excited state, reducing dissipation. This ignores the complications mentioned above and so should not be viewed as exact, but rather as a semiempirical fit.

Given that $\omega \ll \tau^{-1}$, we take for the attenuation the simplified form

$$\alpha(\Delta,T) = A(T) N_1(\Delta,T) N_2(\Delta,T) / [2n(\Delta,T)+1] \tag{3.4}$$

at low temperatures (<2 K). At higher temperatures, Raman scattering becomes significant, and the simplified form is no longer valid. We assume the splitting due to the field adds to the splitting due to strains in quadrature, so that $\Delta = \sqrt{\Delta_0^2 + \gamma^2 H^2}$. The splitting in the absence of a field (Δ_0) and the splitting independent scaling factor (A) are taken as parameters. We take $\gamma = \mu_B$. Note that the overall amplitude of our fits scales approximately inversely with temperature at low temperatures, as expected from examining Eq. (3.1). At higher temperatures, in the Raman regime, the overall amplitude should fall roughly as T^{-6}.[15] A crossover to this regime is observed. The same behavior of the dissipation (scaled by number of acceptor impurities) was observed in the oscillator with fewer impurities, but the signal-to-noise ratio was less.

Shown in Fig. 5 is the fall in the period shift with applied field. A detailed analysis is beyond the scope of this paper. We will simply note here that the period shift is suppressed with field, although its suppression is more gradual than that of the dissipation. The degree of period shift seems to be proportional to Δ^{-1}. We plot a curve of the form

$$\Delta P/P_0 = B/\sqrt{(\gamma' H)^2 + \Delta_0^2} \tag{3.5}$$

for comparison, where B (in ergs) is a constant with units of energy, and we have taken $\gamma' = 2\mu_B$ and $\Delta_0 = 1.22$ K. This behavior was closely reproduced in the sample with higher resistivity when relative period shift was scaled by the number of impurities.

It is interesting to note that the behavior of the dissipation with applied field found here is similar to that found by Ishiguro in his ultrasonic measurements. [See Fig. 4. His data, however, were taken with the field in the (111) direction and the phonons were propagating in the (111) direction.]

IV. CONCLUSION

In conclusion, we have demonstrated that the magnetic field behavior of boron-doped silicon is consistent with phonon scattering by holes bound to acceptor impurities whose ground state is split due to local strains and thus demonstrates that the dissipation originates in the electronic states associated with the acceptor impurities. Oscillator studies allow us to examine the very-low-frequency limit of this scattering and make measurements of the stiffness of this material in this regime. This is of some importance since many of the applications of mechanical oscillators involve magnetic fields. We have demonstrated that a magnetic field may have the salutary effect of reducing the temperature dependence of dissipation at temperatures on the order of 1 K when dissipation features have an electronic origin.

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[1] R. N. Kleiman *et al.*, Rev. Sci. Instrum. **56**, 2088 (1985).

[2] M. Chaparala, O. H. Chung, and M. J. Naughton, in *Superconductivity and its Applications*, edited by H.-S. Kwok, O. T. Shaw, and M. J. Naughton, AIP Conf. Proc. 273 (AIP, New York, 1993), p. 407.

[3] P. A. Crowell *et al.*, Rev. Sci. Instrum. **67**, 4161 (1996).

[4] Y. Martin and H. K. Wickramasinghe, Appl. Phys. Lett. **50**, 1455 (1987); J. J. Sáenz *et al.*, J. Appl. Phys. **62**, 4293 (1987).

[5] D. Rugar, C. S. Yannoni, and J. A. Sidles, Nature (London) **360**, 563 (1992).

[6] T. Klitsner, Ph.D. thesis, Cornell University, 1987 (unpublished); T. Klitsner and R. O. Pohl, Phys. Rev. B **34**, 6045 (1986).

[7] R. N. Kleiman, G. Agnolet, and D. J. Bishop, Phys. Rev. Lett. **59**, 2079 (1987).

[8] R. W. Keyes, Phys. Rev. Lett. **62**, 1324 (1989).

[9] R. E. Mihailovich and J. M. Parpia, Phys. Rev. Lett. **68**, 3052 (1992).

[10] W. P. Mason and T. B. Bateman, Phys. Rev. Lett. **10**, 151 (1963).

[11] T. Ishiguro, Phys. Rev. B **8**, 629 (1973).

[12] G. Kaminsky, J. Vac. Sci. Technol. B **3**, 1015 (1985).

[13] Y. Isawa, Y. Takeuti, and N. Mikoshiba, Phys. Rev. B **15**, 4907 (1977).

[14] R. E. Mihailovich, Ph.D. thesis, Cornell University, 1992 (unpublished).

[15] K. Suzuki and N. Mikoshiba, Phys. Rev. Lett. **28**, 94 (1972).