Is Silicon a Glass? Measurements of the Mechanical Properties of Boron-Doped and Single-Crystal Silicon

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The low-temperature mechanical properties of single-crystal silicon have been studied by Kleiman et al. [1] (KAB). A high-purity (110) wafer, with ρ = 20K Ω-cm and a few ppm non-electronic impurities was used to fabricate the oscillator. They observed a temperature independent dissipation to 100mK, decreasing linearly for T < 100mK. The frequency shift shows softening below 60mK, with a log T dependence near the frequency maximum. Such a mechanical response is qualitatively similar to that of glasses [2]. KAB propose that glassy defects are intrinsic to silicon, and estimate a defect concentration ~1% of that found in vitreous silica. Other explanations have been offered for the mechanical response. [3,4] Keyes proposed that electronic states, split by a small energy, would fit the frequency shift data at a much smaller concentration.

Such electronic states are known to exist in the acceptor hole states of semiconductors, and strongly scatter thermal and ultrasonic phonons. [5,6] We have measured oscillators made from boron doped silicon to determine the importance of the Keyes mechanism. The oscillators were fabricated into the double-paddle geometry of KAB, using the same anisotropic etching technique. We used (100) wafers because this orientation offers geometrically cleaner post-etch corners, believed to yield lower background dissipation. The oscillators had boron concentrations of 6 x 10^{13} cm^{-3}, 1.4 x 10^{15} cm^{-3}, 1.1 x 10^{16} cm^{-3}, and 5.7 x 10^{16} cm^{-3}, corresponding to resistivities of 200, 7, 1, and 0.2 Ω-cm. The oxygen and carbon content were similar for all samples, at ~10^{18} and 4 x 10^{16} cm^{-3} respectively.

The low temperature dissipation and resonant period shift at strain levels of 10^{-6} is shown in Figure 1. The dissipation increases with doping level and drops rapidly at low temperatures. The period shift shows crystal softening up to at least 1K and also increases with doping level. Period measurements for the two highest doping samples were taken to a temperature of 20K, both showing a log T dependence up to 1K and softening up to 10K.

For the three highest doped samples, the period shift data is consistent with the analysis of Keyes. The presence of softening to 10K suggests that there is a distribution of energy splittings. The log T dependence indicates the distribution width of about 1K. Keyes estimates that N_a holes with an energy splitting from -U to +U will produce a period shift given by $(P-P_o)/P_o = D^2 (N_a/3U)(1/c_{44})$, where D is an elastic coupling constant and c_{44} the shear elastic constant. Our measured period shift is described well by this relation for a coupling constant of 3 eV, consistent with values measured elsewhere. [6,7]

The dissipation of these three samples also appears to originate in the boron hole states. The scattering of ultrasonic phonons has been calculated by Isawa

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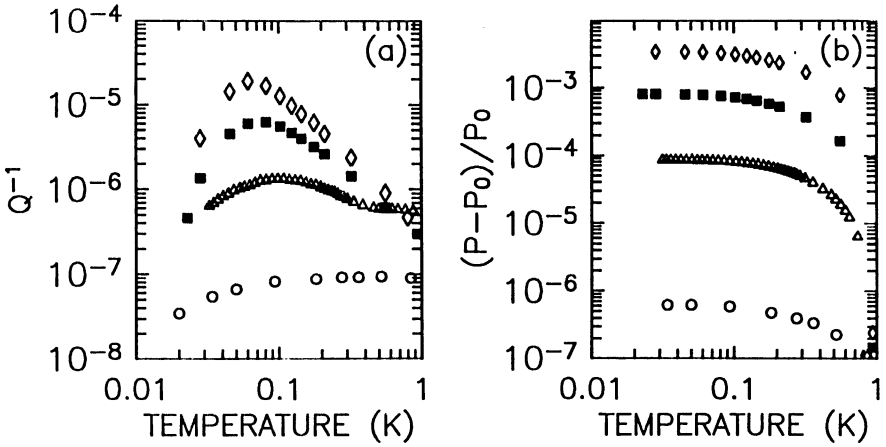

Fig. 1. The dissipation (Fig. 1a) and period change (Fig. 1b) for the four doped silicon oscillators (◇) 0.2 Ω-cm, (□) 1.0 Ω-cm, (△) 7 Ω-cm, (○) 200 Ω-cm.

et al. [8], and should be valid for audio frequency vibrations introduced by the oscillator's motion. The dissipation data can be fit reasonably well using these expressions with a distribution of splitting values. Unfortunately, the dissipation is dominated by the smallest energy splittings; consequently, it is difficult to obtain detailed information on the distribution.

In summary, the mechanical response of our three highest dopant samples is determined by acceptor hole states. The scattering is very strong. The energy splittings appear to arise from elastic introduced by the oxygen impurities.

Our lowest dopant sample's dissipation is qualitatively similar, but an *order of magnitude smaller* than that of the KAB oscillator. In the glass model, the dissipation is proportional to the concentration of glassy defects, implying that our sample has a much lower defect concentration than that of KAB. This is unlikely, since our sample has much higher concentrations of both electronic and nonelectronic impurities. Thus we conclude that glassy defects as proposed by KAB are not intrinsic to silicon. The additional loss observed by KAB may originate in the torsion rod corners from their geometry.

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