PHYSICAL REVIEW B VOLUME 10, NUMBER 2 15 JULY 1974

Thermal conductivity of deformed germanium below 1 K[†]

M. P. Zaitlin[*] and A. C. Anderson
Department of Physics and Materials Research Laboratory, University of Illinois, Urbana, Illinois 61801

(Received 21 March 1974)

The thermal conductivity of pure deformed Ge has been measured below 1 K. There is no evidence for resonant scattering of phonons by dislocations, which is consistent with the presence of a relatively large Peierls potential.

The preceding paper[1] discusses evidence from a number of materials for the existence of localized lattice modes or resonances associated with dislocations, and also the theoretical models proposed to explain these resonances. The work reported in the present paper was an attempt to test one of these models.

The potential energy of a dislocation in a covalently bonded material varies greatly as a function of position in the lattice. A dislocation at a minimum in the potential might undergo vibrations of frequency[1] $\nu_0 \approx (1/2\pi)(\sigma_p/\rho b^2)^{1/2}$, where σ_P is the Peierls stress or spatial derivative of the potential, ρ is the mass density, and b is the Burgers vector. For germanium,[2] $\sigma_P = 2\times 10^{10}$ dyn/cm^2, so $\nu_0 \approx 2.4\times 10^{11}$ Hz. A minimum should then occur in the phonon mean free path near 2.4 K due to the resonant absorption and reradiation of phonons. This would be in contrast to the other materials studied,[1] in which the resonance occurs at temperatures of less than 1 K. It should be noted that we are here concerned with a dislocation which remains in thermal equilibrium with the lattice at low temperatures, and thus has the smallest possible motional amplitude.

We have measured the thermal conductivity of pure (i.e., undoped) Ge to search for a possible resonance. The experimental techniques have been described elsewhere.[3] Two single-crystal samples were used. In both cases the heat flux was parallel to the $\langle 111 \rangle$ axis. One sample had a thickness of 0.122 cm and a width of 1.003 cm. The surfaces of this sample were abraded with silicon carbide paper to prevent specular reflection of phonons from these surfaces. The other sample was 0.159 cm thick and 0.899 cm wide. The surfaces were chemically polished to a high luster. Phonons should be specularly reflected from these surfaces and thus act as a more sensitive detector of other phonon-scattering mechanisms in the bulk of the sample. This sample was then deformed in vacuum at ≈600 °C using W anvils. From the radius of curvature of the bend, a *minimum* dislocation density of $>6\times 10^6$ cm^{-2} is obtained.[4]

The data for the two samples are shown in Fig. 1. The thermal conductivity κ of the abraded sample was calculated from Ref. 3 assuming no specular reflection of phonons from the surfaces. The calculations also assumed an isotropic material with a Debye temperature of 374 K. The result of this calculation is shown in Fig. 1, and is in good agreement with the data. Specular reflection of phonons in the polished sample resulted in an order-of-magnitude-larger thermal conductivity near 0.1 K.

The phonon mean free paths l have been obtained from the data of Fig. 1 using $l = 3.08\kappa T^{-3}$. These are shown in Fig. 2 along with the calculated mean free path due to boundary scattering in the abraded sample. The dotted line is a calculated mean free path in the abraded sample, assuming phonons are

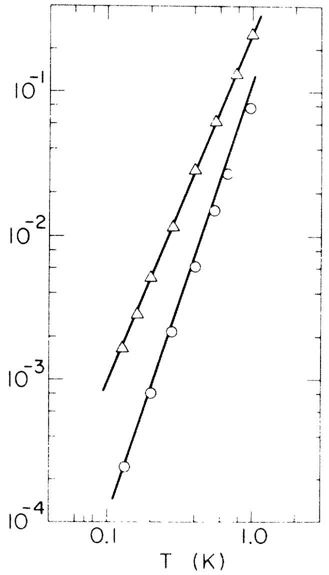

FIG. 1. Thermal conductivity of two pure Ge samples. ○, abraded surfaces. The line through these data has been calculated from Ref. 3, assuming no specular reflection of phonons from the surfaces. △, polished sample, deformed by bending. The curves through these data are intended as an aid to the eye.

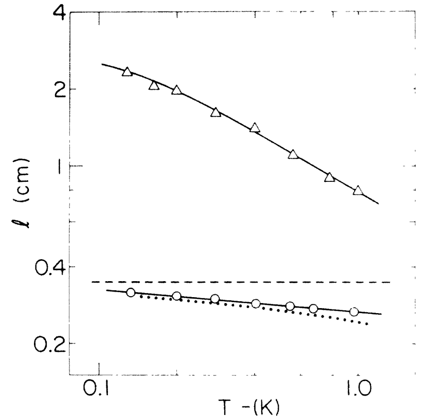

FIG. 2. The phonon mean free path for the two Ge samples. The symbols are the same as in Fig. 1. The dashed line is the mean free path caused by non specular phonon reflection from the abraded surfaces. The dotted curve is explained in the text.

scattered (i) by the boundaries *and* (ii) by whatever mechanism scatters phonons in the polished sample. The dotted line lies within 4% of the actual data for the abraded sample. In other words, the same internal phonon-scattering mechanism is present in both samples. An internal phonon-scattering mechanism similar in magnitude and temperature dependence has been observed before in pure Ge,[5–7] and it has been suggested that at least part of this scattering may be attributed to isotopic impurities.[8]

If the scattering within both samples is the same, then if follows that the dislocations introduced into the bent sample do not reduce the phonon mean free path significantly. Indeed, we would not expect the scattering of phonons by the static-strain fields of dislocations in the bent sample to be evident at temperatures below ≈ 10 K.[9] A resonance of the dislocations in a Peierls well should produce a mean free path of $\lesssim 0.1$ cm if the resonance occurred at 1 K, and a shorter mean free path at lower temperatures.[1] It is obvious from Fig. 2 that there is no evidence for such a resonance below 1 K.

The rough calculation at the beginning of the paper predicted a resonance near 2.4 K. In this temperature range two problems developed. First, for a dislocation density of $\approx 10^7$ cm^{-2}, the scattering becomes comparable with the internal scattering normally present in nominally pure Ge. Second, the refrigerator was somewhat unstable above 1 K, so we have not included data obtained at higher temperatures. These higher temperature data did, however, follow an extrapolation to higher temperatures of the curve in Fig. 2 for the polished sample with no suggestion of an additional scattering mechanism. Also, the half-width of the minimum in l caused by any noncooperative resonance mechanism must be at least T_m wide, where T_m is the temperature at which the minimum in l occurs. From this it follows that there is no resonance in the range $0.08 < T < 2$ K. A definitive search for resonant scattering above 2 K would require a greater density of dislocations and, presumably, an isotopically pure sample of Ge.

All other strained materials studied in this laboratory have exhibited some evidence for a dislocation resonance at temperatures below 1 K. These include ionically bonded materials[9] and bcc,[1,10] fcc,[1,11] or tetragonal[12] metallically bonded materials. In this respect, deformed Ge is unique, since no resonance is observed below ≈ 2 K. This result is consistent with the assumed existence of a large Peierls lattice potential in covalently bonded materials.

We thank H. K. Birnbaum for providing the samples used in this study.

---

[*] National Science Foundation Graduate Fellow.

[†] Research supported in part by the National Science Foundation under Grant No. GH-33634.

[1] S. G. O'Hara and A. C. Anderson, Phys. Rev. B 10, B 10, 574 (1974).

[2] H. Alexander and P. Haasen, in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic, New York, 1968), Vol. 22, p. 27.

[3] J. E. Robichaux and A. C. Anderson, Phys. Rev. B 2, 5035 (1970).

[4] A. H. Cottrell, *Dislocations and Plastic Flow in Crystals* (Oxford U. P., London, 1953), p. 29.

[5] A. M. Toxen, Phys. Rev. 122, 450 (1961).

[6] J. A. Carruthers, J. F. Cochran, and K. Mendelssohn, Cryogenics 2, 160 (1962).

[7] B. L. Bird and N. Pearlman, Phys. Rev. B 4, 4406 (1971).

[8] J. Callaway, Phys. Rev. 113, 1046 (1959).

[9] A. C. Anderson and M. E. Malinowski, Phys. Rev. B 5, 3199 (1972).

[10] A. C. Anderson and S. C. Smith, J. Phys. Chem. Solids 34, 111 (1973).

[11] S. G. O'Hara and A. C. Anderson, Phys. Rev. B 9, 3730 (1974).

[12] S. G. O'Hara and A. C. Anderson, J. Phys. Chem. Solids (to be published).