SHUBNIKOV-DE HAAS EFFECT IN SnTe

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We have observed Shubnikov-de Haas oscillations in the longitudinal magnetoresistance of SnTe, a cubically symmetric, extrinsic p-type semiconductor.[1-5] The measurements were made in steady magnetic fields up to 155 kG. Oscillations were detected between 40 and 155 kG, and were seen in samples with carrier concentrations[6] p between 5×10^{19} and 5×10^{20} cm^{-3}. It is very unusual to have observed the Shubnikov-de Haas effect over such a wide range of carrier concentrations. Moreover, the upper limit is some 25 times larger than the highest concentration at which such oscillations have been detected previously in an extrinsic material.[7] It was possible to observe the oscillations at such large carrier concentrations because of the high magnetic field intensities available, and because of the extraordinarily weak "ionized impurity" scattering[8] in SnTe.

The results presented here already suggest (1) the orientation of the Fermi surfaces, (2) the presence of a second, lower-lying valence band, and (3) an explanation for several puzzling electrical and elastic measurements obtained earlier.[2,6,9]

For our as-pulled single crystals, $p\approx5\times10^{20}$ cm^{-3}. We obtained lower p values by diffusion techniques to be described elsewhere. The crystallographic orientations studied included [001], [114], [112], [111], and [110] directions. Measurements were made at 4.2 and 1.4°K. The high, steady magnetic fields were produced in a $1\frac{1}{4}$-inch inner diameter modified Bitter-type solenoid.[10]

The most extensive measurements were made at $p=1.3\times10^{20}$ cm^{-3}. A tracing of part of a record, typical of the data obtained at this carrier concentration, is shown in Fig. 1. At this value of p, two sets of oscillations of different periods were resolved in most orientations, and in some cases doubling of the extrema suggested spin splitting of the Landau levels. Smooth straight lines were obtained from such data when successive integers were plotted versus the reciprocals of the fields at which maxima occurred in each set of oscillations. According to theory,[11] the slopes of these lines are proportional to the extremal cross sections of the Fermi surfaces normal to the magnetic field direction.

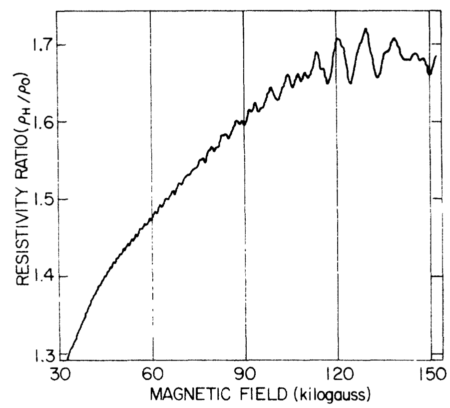

FIG. 1. Resistivity ratio versus magnetic field intensity. Carrier concentration: 1.3×10^{20} cm^{-3}. Magnetic field direction: [110]. Temperature: 4.2°K.

The slopes thus far obtained at the above carrier concentration as a function of magnetic field direction are shown in Fig. 2. As many as 35 oscillations belonging to a given slope were observed, and we estimate that the quan-

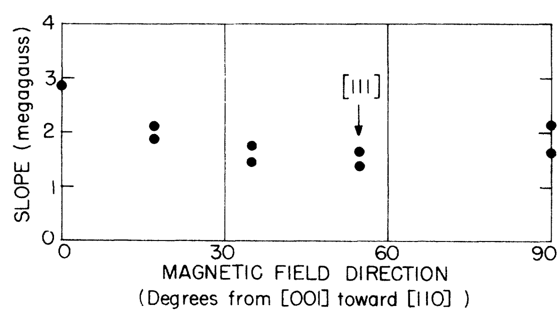

FIG. 2. Slope versus magnetic field direction. Slope (defined in text) is proportional to extremal cross section of Fermi surface normal to magnetic field direction. Carrier concentration: 1.3×10^{20} cm^{-3}. Temperature: 4.2°K or 1.4°K.

tum numbers of the Landau levels crossing the Fermi surface ranged from 10 to 50. The variation of the slopes with magnetic field direction is characteristic of energy surfaces which are elongated in a particular [111] direction. Comparison of the total carrier concentration with the magnitudes of the two slopes obtained when the magnetic field was in that [111] direction suggests the presence of two sets of four ⟨111⟩ "ellipsoids", or four "dumbbell-shaped" surfaces.

A preliminary analysis[12] of the [110] data obtained at this carrier concentration also suggested that ⟨111⟩-oriented surfaces were present. It underestimated their anisotropy by assuming incorrectly that the larger cross section originated from a surface having its [111] direction perpendicular to the magnetic-field direction.

Measurements were also made at one lower and three higher carrier concentrations. At $p = 5\times10^{19}$ cm^{-3}, the observed oscillations were very weak, although the carrier mobility was higher. Apparently the low-temperature anneal designed to reach this carrier concentration did not produce completely homogeneous samples.

At $p = 2.4\times10^{20}$ cm^{-3}, three sets of oscillations were resolved with the magnetic field in a [110] direction. The two larger slopes derived from the data were 2.62 and 2.10 megagauss. These values are in the same ratio as the two obtained at $p = 1.3\times10^{20}$ cm^{-3}, but are about 25% larger. The third slope had the much smaller value of 0.34 megagauss, corresponding to roughly 1×10^{18} carriers cm^{-3}. At $p = 3.6$ and 5.0×10^{20} cm^{-3}, this new slope had increased to 0.56 and 0.67 megagauss, respectively.

We believe this new oscillation offers direct evidence that a second valence band in SnTe is occupied at higher values of p. Its presence had been inferred previously from anomalies in the thermoelectric power and in the temperature dependence of the Hall coefficient, as functions of p.[2-4] These earlier data had suggested that the Fermi level enters the second band at $p \approx 2\times10^{20}$ cm^{-3}.

Considering the high values of total carrier concentration, the number of carriers in valence band 2 is surprisingly small. However, this result does offer an explanation for three puzzling observations: (1) The factor r which relates the weak-field Hall coefficient to the total carrier concentration ($R = r/pe$) is essentially unchanged in the one- and two-band ranges of p;[6] (2) the curve of Hall mobility versus carrier concentration is only slightly perturbed[13] when the Fermi level enters band 2; and (3) the bulk modulus is almost constant, even though the shear moduli are very strong functions of p.[9]

We wish to acknowledge that our interest in this project was stimulated by unpublished results of P. J. Stiles. Some time ago he had detected oscillations in the magnetic susceptibility of one of our SnTe crystals ($p \approx 1\times10^{20}$ cm^{-3}), but was unable to continue the investigation.

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[1]R. S. Allgaier and P. O. Scheie, Bull. Am. Phys. Soc. 6, 436 (1961).

[2]R. F. Brebrick and A. J. Strauss, Phys. Rev. 131, 104 (1963).

[3]J. A. Kafalas, R. F. Brebrick, and A. J. Strauss, Appl. Phys. Letters 4, 93 (1964).

[4]B. B. Houston, Jr., and R. S. Allgaier, Bull. Am. Phys. Soc. 9, 293 (1964).

[5]E. G. Bylander, J. R. Dixon, H. R. Riedl, and R. B. Schoolar, Phys. Rev. (to be published).

[6]Computed from the weak-field Hall coefficient at 77°K, using the formula $p = 0.6/Re$, determined experimentally by B. B. Houston, Jr., R. S. Allgaier, J. Babiskin, and P. G. Siebenmann, Bull. Am. Phys. Soc. 9, 60 (1964).

[7]W. Bernard, H. Roth, W. D. Straub, and J. E. Mulhern, Jr., Phys. Rev. 135, A1386 (1964).

[8]R. S. Allgaier and B. B. Houston, Jr., in Proceedings of the International Conference on the Physics of Semiconductors, Exeter, July, 1962 (The Institute of Physics and the Physical Society, London, 1962), p. 172. In the case of highly nonstoichiometric SnTe, the "impurity" which produces and scatters the extrinsic carriers is a vacancy in the tin sublattice.

[9]B. B. Houston, Jr., and R. E. Strakna, Bull. Am. Phys. Soc. 9, 646 (1964).

[10]R. T. Swim, Rept. Naval Res. Lab. (U.S.) Progr., Nov. 1962, p. 1.

[11]L. Onsager, Phil. Mag. 43, 1006 (1952).

[12]J. R. Burke, Jr., R. S. Allgaier, B. B. Houston, Jr., J. Babiskin, and P. G. Siebenmann, Bull. Am. Phys. Soc. 9, 647 (1964).

[13]There is no indication of any perturbation in the mobility data of references 2 and 3. R. S. Allgaier and B. B. Houston, Jr. (to be published), have detected a slight "droop" in the 77°K mobility between 2 and 5×10^{20} carriers cm^{-3}.