ELECTRICAL RESISTANCE OF ANTIMONY IN A MAGNETIC FIELD UP TO 420 kOe AT LIQUID HELIUM TEMPERATURE

N. B. BRANDT, E. A. SVISTOVA, and T. V. GORSKAYA

Moscow State University

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The magnetoresistance of single-crystal antimony samples was measured in fields up to 420 kOe at liquid helium temperature. It was found that the monotonic component of the magnetoresistance increased as $H^{1.7}$ throughout the whole field range. It was shown that in fields of the order of 400 kOe antimony did not reach the ultra-quantum limit. Quantum oscillations (Shubnikov–de Haas effect) were observed at positions which did not agree with the effective mass and Fermi energy values for antimony usually cited in the literature.

1. AN earlier investigation of the magnetoresistance of Bi in fields up to 450 kOe at a temperature of 4.2°K [1] has led to the discovery of several anomalies associated with basic changes in the structure of the energy spectrum of Bi in the ultra-quantum region.[2, 3] A characteristic feature of Bi is that the band overlap increases in strong magnetic fields of all possible orientations and, therefore, a transition to the dielectric state in a field is impossible.

In view of these observations, it seemed interesting to investigate another semimetal—Sb—under the same conditions. Tsidil'kovskiĭ, Sokolov, and Aksel'rod investigated the magnetoresistance of Sb in fields up to 350 kOe at 77°K [2] and concluded that the band overlap of Sb decreased in magnetic fields, so that at 350 kOe an energy gap appeared in the spectrum of Sb. As far as the present authors are aware, the magnetoresistance of Sb has not yet been investigated in strong fields at liquid helium temperatures. Like Bi, Sb is a compensated semimetal with a relatively small band overlap. The electron part of the Fermi surface of Sb consists of three isolated surfaces, which differ considerably in shape from triaxial ellipsoids. The average principal axis of each "ellipsoid" lies along the binary axis and the direction of greatest ellipticity makes an angle of $\approx 4°$ with the basal plane. The surfaces transformed into one another by a 120° rotation about the trigonal axis. The hole part of the Fermi surface consists of six isolated surfaces, which are also of non-ellipsoidal shape and whose shortest axes are directed along the binary axes, the directions of ellipticity making an angle of $\approx 36°$ with the basal plane.

The cyclotron effective masses of electrons and holes in Sb have been investigated in detail by Datars[4] and are tabulated here for the principal orientations of the field. Practically nothing is known about the spin effective mass of electrons and holes. In the only paper on this subject, Smith, Galt, Merritt,[5] who have investigated the spin resonance of Sb, find that the spin splitting of the Landau levels in a magnetic field oriented along the bisector axis is approximately equal to the orbital splitting. Unfortunately, it is not possible to say to which cyclotron mass this result applies.

2. Measurements of the magnetoresistance of Sb were carried out at 4.2°K using magnetic field pulses with a half-period of 360 μsec. The measurement method was similar to that described in [1]. Samples, in the form of rectangular parallelepipeds, $0.4 \times 0.5 \times 3$ mm, were cut from a single-crystal Sb ingot of purity higher than 99.9999%. The electrical resistance of the mounted samples decreased by a factor of 800–1500 when temperature was lowered from 300 to 4.2°K. A special method of mounting ensured minimum induced strays and good reproducibility of the results.

The measurements were carried out using various orientations of the field and current with respect to the crystallographic axes of the samples. The accuracy with which the orientation of the crystallographic axes was determined was 2–3°.

3. Figures 1 and 2 give, by way of example, the dependences of the relative resistivity $r \equiv \Delta\rho/\rho_0$ on the field for four samples for the principal orientations of the field and current. The dependences of r on H could conveniently be considered as consisting of monotonic and oscillatory (Shubnikov–de Haas effect) components. Over the whole range of the field the monotonic components of the r(H) curves increased, on the average, as $H^{1.7}$. In contrast to Bi,[1] no saturation was ob-

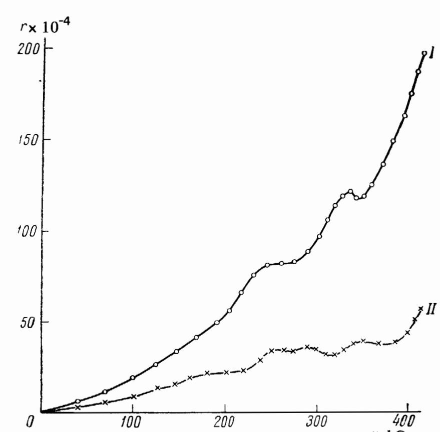

FIG. 1. Electrical resistivity of Sb in a magnetic field at liquid helium temperature: curve I – the field parallel to the bisector axis and the current parallel to the trigonal axis; curve II – the field parallel to the binary axis and the current parallel to the trigonal axis.

	m^*		
	$H \parallel c_2$	$H \parallel c_1$	$H \parallel c_3$
Electrons	{0.215, 0.080	0.214, 0.0715	0,100
Holes	{0.32, 0.097	0.160, 0.089	0,32

served and there was no transition to an exponential dependence on the field, which was reported in [2] and which would have indicated the appearance of a gap in the spectrum of Sb. Clearly visible oscillations were superimposed on the monotonic component and, in some cases (for example, when the field was oriented parallel to the binary axis and the current was parallel to the trigonal axis, as in Fig. 1), these oscillations much distorted the shape of the monotonic component.

For the same orientation of the magnetic field, the nature of the observed oscillations and their amplitude changed when the direction of the measuring current (curves denoted by I in Figs. 1 and 2) was altered. This was evidently due to a change in the contributions of individual constant-energy surfaces to the electrical conductivity when the direction of the current was altered.

4. To analyze the oscillations and to deduce from such an analysis the data on the dispersion law of carriers in Sb, it was necessary to know exactly—for each constant-energy surface—the numbers of the Landau levels corresponding to given oscillations. In order to find these numbers, we had to know (in addition to the cyclotron masses) the Fermi energies of electrons and holes and the values of the spin splitting of levels for the principal orientations of the field. At present, neither these energies nor the splittings are known. The values of the Fermi energies of electrons and holes calculated from the formula[5]

$$E_F = \frac{S_{mi}}{m_i^*}\frac{e\hbar}{c}$$

(S_{mi}, m_i^* represent the i-th extremal cross section and the corresponding cyclotron mass), valid for a quadratic dispersion law, should be regarded only as estimates since the values of S_{mi}/m_i^* vary by up to 70% for electrons and up to 30% for holes.[6] Therefore, the results obtained in the present investigation can be used only to estimate the degree of approximation to the ultraquantum limit $\hbar\omega = e\hbar H/m^*c \approx E_F$ reached at 420 kOe. Using the cyclotron mass values listed in the table and the approximate values $E_f^e \approx 0.11$ eV (for electrons) and $e_F^h = 0.8$ eV (for holes), taken from a paper of Epstein and Juretschke,[7] and assuming that the spin splitting is either small or equal to the orbital splitting, we can find how far these data agree with the observed quantization pattern.

When the field is oriented parallel to the trigonal axis, the value of the hole mass m_h^* is more than three times larger than the electron mass m_e^*. Therefore, the oscillations in curve II (Fig. 2) should be attributed to electrons. The minimum in curve II at 380 kOe evidently corresponds to the crossing of the Fermi level by the second Landau level. When the field is oriented parallel to the binary axis, the minimum at H = 380 kOe may be attributed to the electron and hole levels with n = 1 or n = 2. When the field is oriented parallel to the bisector axis, the minimum at H > 400 kOe may be attributed to electron and hole levels with n = 1 and n = 2. Thus, the maximum possible change in the band overlap of Sb in a field of the order of 400 kOe does not exceed 15%. It is also found that the values of the cyclotron masses and Fermi energies employed here and the assumptions made about the value of the spin splitting cannot account for the general pattern of the observed oscillations; this indicates that the known parameters of the energy spectrum of antimony are inaccurate.

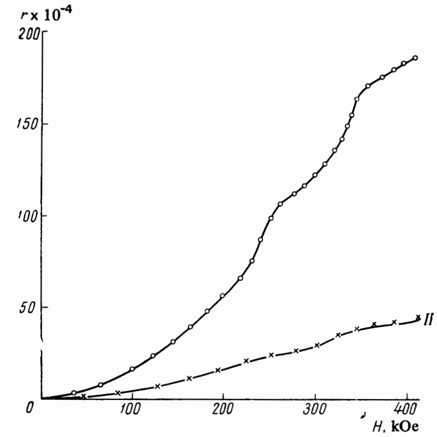

FIG. 2. Electrical resistivity of Sb in a magnetic field at liquid helium temperature: curve I – the field parallel to the bisector axis, the current parallel to the binary axis; curve II – the field parallel to the trigonal axis, the current parallel to the binary axis.

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