RESISTANCE ANOMALY IN n-TYPE InSb AT VERY LOW TEMPERATURES

Yoshifumi Katayama and Shoji Tanaka

Department of Applied Physics, University of Tokyo, Bunkyo-Ku, Tokyo, Japan
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A resistance anomaly at low temperatures has been reported in dilute magnetic alloys[1] and in heavily doped germanium.[2]

In n-type InSb, we have found a strong resistance anomaly and negative magnetoresistance between 0.1 and 4.2°K, which are more remarkable than those in dilute magnetic alloys and in germanium. The experimental results and their interpretation are reported in the present paper.

The samples measured in the present experiments were single crystals of n-type InSb whose carrier concentrations were in the range of $1.8\times10^{14}\sim 3.3\times10^{17}$ cm^{-3} and were cut with dimensions $3\times1\times10$ mm^3. The carrier concentrations were determined from measurements of the Hall effect in weak magnetic fields (less than 70 Oe) between 1.3 and 4.2°K, and in this temperature range the Hall coefficients do not show any temperature dependence. The resistivity and the magnetoresistance were measured between 0.1 and 4.2°K; the lowest temperatures were attained through adiabatic demagnetization of chromium alum.

The resistivity increases rapidly below 1°K as the temperature is lowered, for the samples with small carrier concentrations. The temperature dependence of the resistivity becomes weaker as the carrier concentration increases. For the sample containing $n = 3.3\times10^{17}$ cm^{-3}, a temperature dependence of the resistivity was not observed. An example of the observed temperature dependence of the resistivity is shown in Fig. 1. The resistivity is seen to increase logarithmically as the temperature decreases and to approach saturation at very low temperatures. Empirically the following expression for the temperature dependence of the resistivity was obtained:

$$\rho = a - b\log_{10}(T+T_0), \qquad (1)$$

where a, b, and T_0 are positive parameters which depend on the carrier concentration n. The above expression fits the data from all the samples very well, and the carrier-concentration dependences of these parameters are, approximately,

$$a \propto n^{-2}, \quad b \propto n^{-2.5}, \quad T_0 \propto n^{1.5}. \qquad (2)$$

The transverse magnetoresistance is negative in weak magnetic fields, reaches its minimum value at about 500 Oe, and then becomes positive gradually, as the magnetic field increases. In weak magnetic fields less than 50 Oe, the magnetoresistance can be expressed in the form

$$\frac{\Delta\rho}{\rho} = \frac{\rho(H)-\rho(0)}{\rho(0)} = -S(T)H^2. \qquad (3)$$

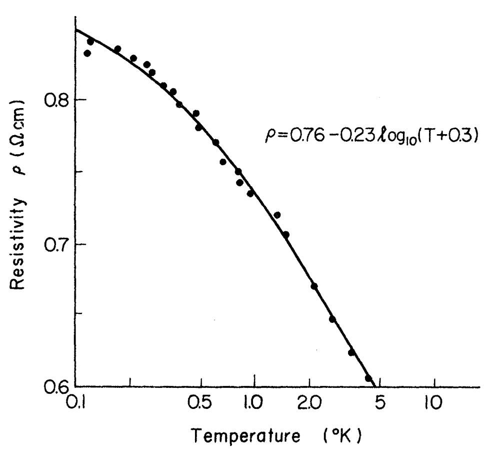

FIG. 1. The temperature dependence of the resistivity of n-type InSb at low temperatures (sample No. 2).

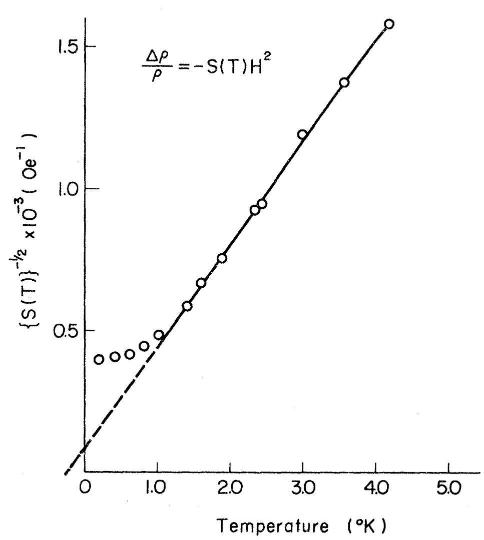

FIG. 2. The temperature dependence of the low-field magnetoresistance of n-type InSb at low temperatures (sample No. 1).

Table I. Parameters for resistivity [Eq. (1)] and magnetoresistance [Eq. (3)] of n-InSb at low temperatures.

Sample No.	Carrier concentration (cm^{-3})	Hall mobility at 4.2°K (10^5 cm^2/V sec)	Fermi energy (meV)	a (Ω cm)	b (Ω cm)	T_0 (°K)	T_0' (°K)
1	1.8×10^{14}	1.0	0.9	3.47	2.53	0.08	0.1
2	6.0×10^{14}	1.1	2.0	0.75	0.23	0.3	0.3
3	6.5×10^{14}	1.0	2.1	0.38	0.25	0.5	0.8
4	1.6×10^{15}	0.93	3.8	9.6×10^{-2}	4.5×10^{-2}	1.0	a
5	2.8×10^{15}	0.80	5.7	3.2×10^{-2}	3.5×10^{-3}	3.8	a
6	5.0×10^{15}	0.85	8.5	1.3×10^{-2}	1.8×10^{-3}	10	10
7	2.0×10^{16}	0.40	21	9.1×10^{-3}	5.0×10^{-4}	6	a
8	3.3×10^{17}	0.37	135	4.8×10^{-5}	...	...	...

[a]The magnetoresistance was not symmetric when the direction of the magnetic field was reversed.

The parameter $S(T)$ depends on n and T. As shown in Fig. 2, $\{S(T)\}^{-1/2}$ is proportional to $(T+T_0')$ above 1°K and is almost constant below 1°K. It is interesting that the values of the parameter T_0' are fairly close to those of the parameter T_0 of Eq. (1). The values determined for T_0 and T_0' are given in Table I.

In weak magnetic fields, where the magnetoresistance is negative, the longitudinal magnetic field gives just the same results as in the transverse magnetic field.

Since the carrier concentration is independent of temperature below 4.2°K, the observed resistance anomaly and the negative magnetoresistance must arise from the scattering of the electrons, which are degenerate in conduction band.

Kondo[3] showed that the logarithmic temperature dependence of the electrical resistivity in dilute alloys comes from the scattering of the conduction electrons by localized paramagnetic spins through s-d interactions. The resemblance between the temperature dependences of the resistivity in n-type InSb and those in the dilute alloys seems to suggest that a similar electron-scattering mechanism contributes to the resistivity in n-type InSb. Actually, Toyozawa[4] discussed the possibility of the existence of the localized spins in semiconductors.

It was pointed out by Yoshida[5] that, theoretically, the negative magnetoresistance in dilute alloys should be proportional to the square of the magnetization of the total spins. If we assume paramagnetic localized spins in n-type InSb, $(-\Delta\rho/\rho)^{1/2}$ should then be given by a function of H/T. $(-\Delta\rho/\rho)^{1/2}$ is plotted against $H/(T+T_0')$ as shown in Fig. 3. It should be noted that the experimental values of $(-\Delta\rho/\rho)^{1/2}$ are better described by a function of $H/T+T_0'$) than of H/T. The existence of the parameters T_0 and T_0' suggests the presence of the interaction among the localized spins via conduction electrons.

Khosla and Sladek[6] have very recently reported the observation of an anomalous thermoelectric power in n-type InSb and have proposed the localized spin model in the interpretation of their experimental results.

Details of our experiments and their interpretation will be reported shortly at greater length.

We are sincerely grateful to Professor

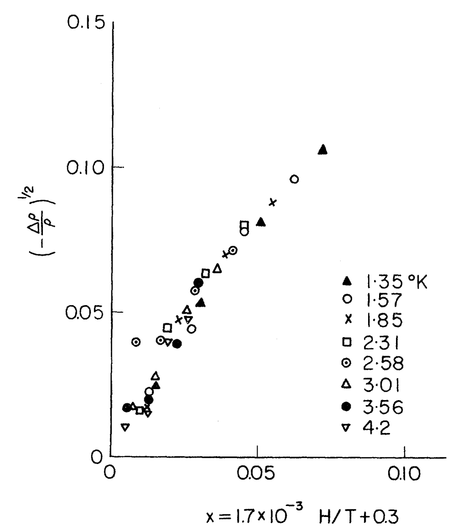

FIG. 3. The magnetoresistance as a function of the parameter $x=1.7\times10^{-3}H/T+T_0'$), where H is in Oe, T and T_0' in °K, and the numerical factor is tentatively selected (sample No. 2).

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RECENTLY PROPOSED RELATIONSHIP FOR SUPERCONDUCTORS

J. Grunzweig-Genossar and M. Revzen

Physics Department, Technion-Israel Institute of Technology, Haifa, Israel

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Utilizing an approximate expression for the specific heat of superconductors, Lewis[1] obtained a general thermodynamic relation between the energy gap of a superconductor and the slope of the critical field at the critical temperature (T_c). It was emphasized by Schafroth[2] that Lewis's expression is insensitive to the exact form chosen for the specific heat. Noting this, and the fact that Lewis's implied energy gap can be approximately[3] identified with the energy gap at zero temperature [$\Delta(0)$], it is shown below that numerically Lewis's expression approximates a relationship which was recently proposed by Toxen[4] [see Eq. (3) below]. This indicates, we believe, that Toxen's relation is a numerical coincidence rather than a fundamental relationship for superconductors.

We now outline briefly Lewis's method. The specific heat (C_s) for superconductors in our adopted approximation is given by

$$C_s/\gamma T_c = A\exp(-\alpha T_c/T). \tag{1}$$

Here $\alpha \approx \Delta(0)/kT_c$,[3] k is the Boltzmann constant, and A is a parameter. (We remark that a weak temperature dependence of A will not affect the argument.) γ is given by the electronic specific heat of the normal metal (C_n) at low temperatures, i.e.,

$$C_n \simeq \gamma T.$$

Equating the entropy of the normal and superconducting metal at T_c, we get

$$\int_0^{T_c} C_s \frac{dT}{T} = \gamma T_c,$$

or

$$AE(\alpha) = 1,$$

where

$$E(\alpha) = \int_\alpha^\infty \frac{e^{-x}}{x} dx.$$

This determines A. A somewhat more complicated, but straightforward, thermodynamic argument gives[1,2]

$$-\left(\frac{dH_c}{dT}\right)_{T_c} \frac{T_c}{H_0}\Bigg|_{\text{theor}} = \left[\frac{e^{-\alpha} - E(\alpha)}{2e^{-\alpha} - (1+2\alpha)E(\alpha)}\right]^{1/2} \equiv F(\alpha). \tag{2}$$

Here H_0 is the critical field at zero temperature and $(dH_c/dT)_{T_c}$ is the slope of the critical field at T_c; $F(\alpha)$ is defined by the above equa-

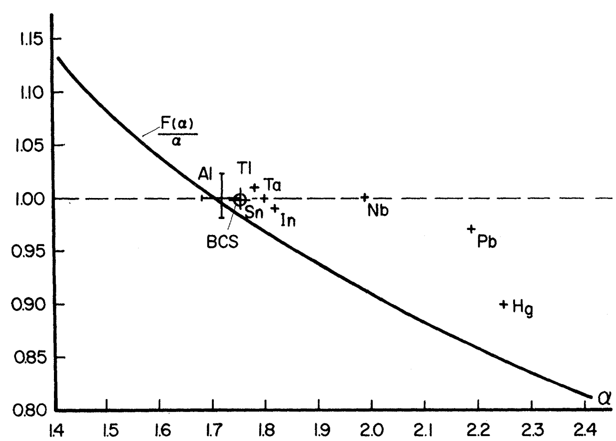

FIG. 1. Solid line depicts $F(\alpha)/\alpha$ as a function of α [see Eq. (2)]. Dashed line shows Toxen's relationship [see Eq. (3)]. The experimental points plotted are $-(dH_c/dT)_{T_c}[kT_c^2/\Delta(0)H_0]$ as a function of $\alpha \simeq \Delta(0)/kT_c$. The BCS value in the weak-coupling limit is shown by a circle.