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Temperature and magnetic field dependences of resistivity in metallic *n*-InSb below 100 mK

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It is shown that the resistance of three-dimensional metallic *n*-InSb below 100 mK can be explained by the effects of the anomalous correction due to Coulomb interactions. A clear comparison of the experiment with the theory is made possible by resistance measurements over a wide range of the carrier concentration. The theoretical results show better agreement with the experimental ones in metallic *n*-InSb than those in metallic Si-P.

Sasaki and his co-workers[1,2] have investigated the anomalous temperature and magnetic field dependences of resistivities in three-dimensional metallic Ge-Sb and Si-P at low temperatures. On the other hand, we have measured[3,4] the resistivity in three-dimensional metallic *n*-InSb at low temperatures and have observed the $\ln T$ dependences of the resistivity and the strong positive magnetoresistance in the sample with low carrier concentration $n\,(=N_D-N_A)$. Three of us[5] have pointed out the possibility that the $\ln T$ dependences come from the interplay of Coulomb interactions with the randomness due to impurities. However, as $n\,(=N_D-N_A)$ increases, the $\ln T$ dependences of the observed resistivity become not clear and the different temperature dependences are revealed. These temperature dependences appearing with the increase of n and the behavior of the strong positive magnetoresistance may be due to the lower-order diagrams relevant to Coulomb interactions than those giving the $\ln T$ term for three-dimensional disordered system.

In the following, we examine this possibility from the comparison of the experimental results of *n*-InSb with the theoretical ones by Altshuler *et al.*,[6,7] and Lee and Ramakrishnan.[8]

Altshuler *et al.*[6,7] and Rosenbaum *et al.*[9] calculated analytically the resistivity in a three-dimensional system with Coulomb interactions in the presence of random impurity scattering in the weakly localized regime ($k_F l \gg 1$). The contribution from the vertex correction due to particle-hole (p-h) ladder in $H=0$ Oe is given by

$$\rho=\rho_0-2\alpha(\tfrac{2}{3}-F)[T(\mathrm{K})]^{1/2}\ (\Omega\,\mathrm{cm})\ , \tag{1}$$

$$\alpha=1.08\times10^{-7}\rho_0^{5/2}[n(\mathrm{cm}^{-3})/T_F(\mathrm{K})]^{1/2}\ (\Omega\,\mathrm{cm}\,\mathrm{K}^{-1/2})\ , \tag{2}$$

$$F=(1/x)\ln(1+x),\quad x=(2k_F/\kappa)^2\ , \tag{3}$$

where k_F is the Fermi wave number, $l=v_F\tau$ is the electron mean free path. v_F is the Fermi velocity, τ is the relaxation time due to impurity scattering, T_F is the Fermi temperature, and κ^{-1} is the Thomas-Fermi screening length.

Recently, Kawabata[10] has pointed out that the Zeeman effect gives rise to positive magnetoresistance proportional to $H^{1/2}$ in the strong magnetic field, i.e., $|g|\mu_B H \gg 2\pi kT$. Lee and Ramakrishnan[8] (LR) have given the explicit expression for the contribution due to p-h ladder as follows

$$\rho=\rho_0-2\alpha\left(\frac{2}{3}-\frac{F}{2}\right)[T(\mathrm{K})]^{1/2}+0.77\alpha F(|g|\mu_B/k)^{1/2}[H(\mathrm{Oe})]^{1/2}\ \ (\Omega\,\mathrm{cm})\ , \tag{4}$$

where g is the g factor of conduction electron, μ_B is the Bohr magneton, and k is the Boltzmann constant. Equation (4) was first published in Ref. 11, but is explained in Ref. 8.

Rosenbaum *et al.*[11,12] measured the magnetoresistance of three-dimensional metallic Si-P down to 3 mK up to 10 kOe and compared with the Coulomb interaction theories calculated by Altshuler *et al.* and LR. Similar measurement and analysis have been done by Chui *et al.*[13] on three-dimensional granular aluminum. However, the following problems remain for the agreement of the experiments with the theory. (1) Although the $T^{1/2}$ effect was observed over almost three decades in T and confirms the theoretical results, the $H^{1/2}$ behavior is seen over a much narrower region and is therefore less certain. (2) There is a significant difference in the magnitude of the observed and predicted effects in Ref. 11, which the authors attribute to intervalley scattering. Although the theory includes this effect, in principle, the scattering rates are unknown. Therefore, it is important to compare the theory with the experiments in n-InSb which is a single valley semiconductor.

Resistivities of seven metallic n-InSb with high mobilities were measured.[4] The excess donor concentrations n $(=N_D-N_A)$ were determined by measuring the strong magnetic field Hall coefficient at 77 K.[14] The values of $k_Fl=\hbar(3\pi^2)^{2/3}/(e^2\rho_0 n^{1/3})$

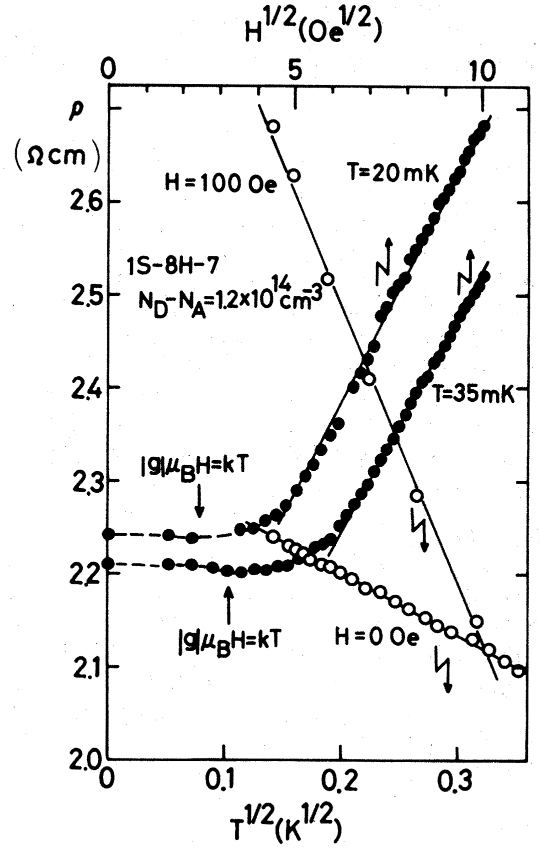

FIG. 1. ρ vs $H^{1/2}$ at 20 and 35 mK, and also ρ vs $T^{1/2}$ at $H=0$ and 100 Oe for metallic n-InSb with $N_D-N_A=1.2\times10^{14}$ cm^{-3} and $k_Fl=0.36$. Solid lines show ρ to be nearly linear in $H^{1/2}$ or $T^{1/2}$.

in seven samples, where ρ_0 is determined from the resistivities using Eq. (1), are $k_Fl=0.24$, 0.36, 1.15, 1.25, 2.17, 2.44, and 5.13, respectively.

Figure 1 shows the resistivities for a metallic n-InSb with the carrier concentration of $N_D-N_A=1.2\times10^{14}$ cm^{-3} ($k_Fl=0.36$). The resistivity is approximately independent of the configurations of magnetic field within the experimental error. The resistivities below 100 mK in $H=0$ Oe and $H=100$ Oe are nearly proportional to $T^{1/2}$ down to the measured lowest temperature $T=20$ mK. The magnetic field coefficient of $H^{1/2}$ is nearly independent of the temperature consistent with the calculated result of Eq. (4). The sign of the temperature coefficient a in $H=0$ Oe is the same as the calculated result $[a\equiv2\alpha(\frac{2}{3}-F),\ F=0.47]$, and also the sign of a' in $H=100$ Oe is the same as the calculated result $[a'\equiv2\alpha(\frac{2}{3}-F/2)]$. The temperature coefficients a in $H=0$ Oe and a' in $H=100$ Oe, and the magnetic field coefficient b are estimated by assuming $T^{1/2}$ or $H^{1/2}$ dependences. Then, the quantity b_c $(b_c\equiv b-\Delta\rho_l/H^{1/2})$, where the localization effect $[\Delta\rho_l\equiv-2.9\times10^{-2}\times\rho_0^2H\ (\mathrm{Oe})^{1/2}]$ (Refs. 15 and 16) is subtracted from the magnetic field coefficient b, is also evaluated. The quantities a, a', and b_c are now compared with Coulomb interaction theories. Figure 2 shows the temperature coefficient a in $H=0$ Oe as a function of $\rho_0^{5/2}(n/T_F)^{1/2}$. Closed and open circles

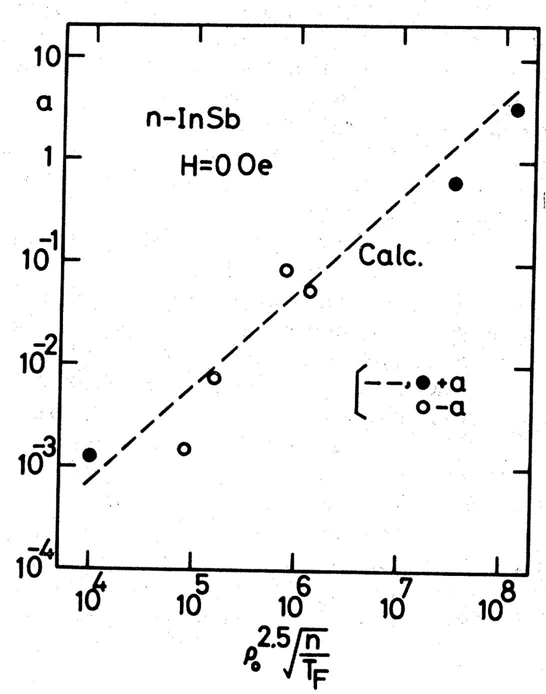

FIG. 2. Temperature coefficient a of resistivities in $H=0$ Oe when fitted by $T^{1/2}$ as a function of $\rho_0^{5/2}(n/T_F)^{1/2}$. Closed and open circles show experimental data of a and $-a$, respectively. The broken line is a calculated line of a.

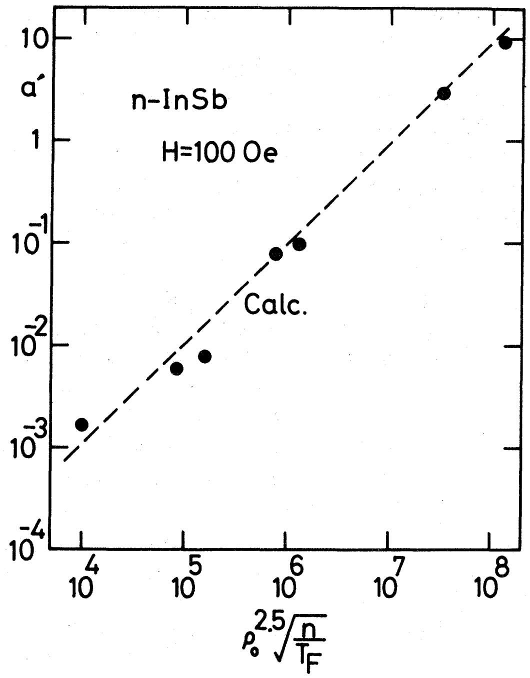

FIG. 3. Temperature coefficient a' of resistivities in 100 Oe when fitted by $T^{1/2}$ as a function of $\rho_0^{5/2}(n/T_F)^{1/2}$. Closed circles show experimental data of a'. The broken line is a calculated line of a'.

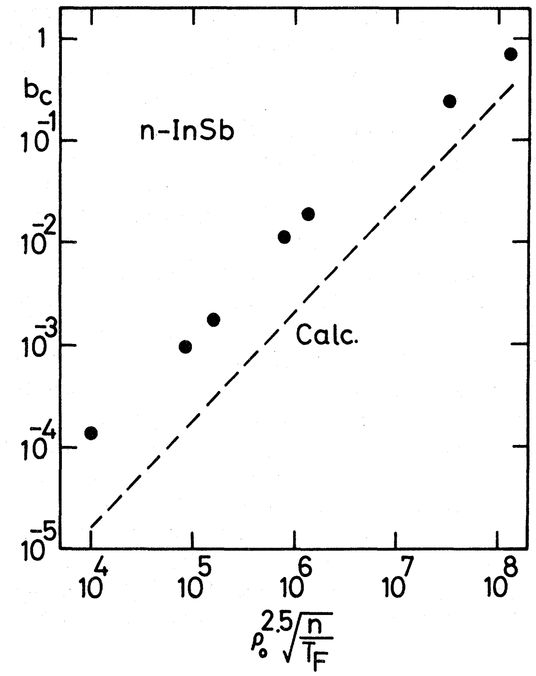

FIG. 4. Magnetic field coefficient b_c of resistivities when fitted by $H^{1/2}$ as a function of $\rho_0^{5/2}(n/T_F)^{1/2}$. Closed circles show experimental data of b_c. The broken line is a calculated line of b_c.

are experimental values of a and $-a$. The change in sign of the temperature coefficient a in $H=0$ Oe for $k_Fl \lesssim 1$ was also observed in metallic Si-P by Rosenbaum *et al.*[9] However, they did not report the change in sign in higher carrier concentration ($k_Fl > 1$). In spite of twice changing the sign of the temperature coefficient a, the absolute values show semiquantitative agreement with the calculated broken line over nearly three orders of magnitude. Figure 3 shows the temperature coefficient a' in $H=100$ Oe as a function of $\rho_0^{5/2}(n/T_F)^{1/2}$. Experimental data of closed circles have the same sign as the calculated broken line, and the absolute values coincide with the calculated results over nearly four orders of magnitude. Figure 4 shows the magnetic field coefficient b_c caused by Coulomb interactions as a function of $\rho_0^{5/2}(n/T_F)^{1/2}$. Experimental data of closed circles have the same sign and tendency as the calculated broken line [$b_c \equiv 0.77\alpha F(|g|\mu_B/k)^{1/2}$], although the absolute values do not agree with the calculated results. The agreements between theory and experiment in Figs. 2–4 give a strong evidence that Coulomb interactions play an important role in the resistivity of n-InSb at low temperatures. The calculated values of a and a' agree within the factor of $2 \sim 3$ with the experimental ones in n-InSb in contrast with the difference of the factor of 8 in Si-P.[17]

The differences between the theoretical results and the experimental ones in metallic n-InSb may arise from the following facts. (1) The calculated results of Eqs. (1)–(4) include the contribution only from p-h ladder.[8] Inclusion of particle-particle ladder produces a new magnetic field effect caused by the orbital motion of the electrons.[18,19] (2) The experimental values of k_Fl and magnetic field do not satisfy the theoretical assumptions of $k_Fl \gg 1$ and $|g|\mu_BH \gg 2\pi kT$.

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