Electronic Transport in Metallic Ge:Sb at Low Temperature

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The metallic impurity conduction is a typical example of the transport in the disordered metal. It shows anomalous transport at low temperature [1]. After the developement of the perturbation theory of transport in "weakly localized region"[2], these anomalies are interpreted to be the appearance of the effects of localization and electron-electron interaction in dirty metal. The theories explain the characteristic features of temperature and magnetic field dependence of conductivity, but quantitatively there remain some disagreements between theory and experiment [3].

In this paper, we report the measurement of low temperature transport properties in the metallic impurity conduction of Ge:Sb, especially stressing the anisotropy of magnetoconductance.

I. 4-valley Ge

I-i) Temperature and magnetic field dependence of conductivity

Fig.1 shows the conductivity of the sample with the donor concentration N of $2.4\times10^{17}\mathrm{cm}^{-3}$ in various magnetic fields. The conductivity increases steeply as temperature is lowered below 1K. In the magnetic field it increases first and at low temperature it begins to decrease, forming a hump in the temperature dependence. This hump of conductivity shifts to higher temperature as the magnetic filed is increased. The magnetoconductance is positive at around 1K and is negative at lower temperature.

Localization and electron-electron interaction are two important mechanisms in the disordered metals. The former gives the tendency to localization remaining even in the metallic phase and gives a positive magnetoconductance. The latter treates the Coulomb interaction which is modified by the diffusive character of electron in disordered material and gives a negative magnetoconductance.

The expressin of conductivity which takes multivalleys and anisotropy effects is [2,4]

$$\delta\sigma = \frac{e^2}{2\pi^2\hbar}\left(\Delta_{LOC} + \Delta_{INT}\right) \qquad (1)$$

$$\Delta_{LOC} = \begin{cases} \sum_{i=1}^{\nu} \alpha_i \,(D\tau_\varepsilon)^{-1/2} & \text{when } H=0 \\ \sum_{i=1}^{\nu} 0.605\, \alpha_i / \ell_c^i & \text{when } \frac{eH}{c\hbar} \gg \frac{1}{D\tau_\varepsilon} \end{cases}$$

$$\Delta_{INT} = \begin{cases} \sum_{i=1}^{\nu} 0.46\, \frac{\alpha_i}{\nu}\left(\frac{4}{3}-3F\right)\sqrt{\frac{T}{\hbar D}} & \text{when } H=0 \\ \sum_{i=1}^{\nu} 0.46\, \frac{\alpha_i}{\nu}\left(\frac{4}{3}-F\right)\sqrt{\frac{T}{\hbar D}} - \sum_{i=1}^{\nu} \frac{\alpha_i}{\nu}\frac{F}{\ell_c^i}\left[f(\lambda_i)+\sqrt{\frac{\lambda_i}{2}}\right] \cdot & \text{when } g\mu_B H,\ \frac{DeH}{c} \gg 2\pi kT \end{cases}$$

where $l_c = \left(\frac{c\hbar}{eH}\frac{m_c}{m_a}\right)^{1/2}$, $\frac{1}{m_c^2} = \frac{1}{m_t}\left(\frac{\cos^2\theta}{m_t} + \frac{\sin^2\theta}{m_l}\right)$, $\alpha = m_a\left(\frac{1}{m}\right)_{\mu\mu}$, $m_a = (m_l m_t^2)^{1/3}$

$\lambda = \frac{c\mu_B}{4eD}\frac{(HgH)}{H^2}\frac{m_c}{m_a}$ and $f(\lambda) \rightarrow 0.65$ (when $\lambda \ll 1$), $\sqrt{\lambda/2}$ (when $\lambda \gg 1$).

The parameters of D, τ_ε, F, m_l, m_t, g, ν and θ are the diffusion constant, the inelastic scattering time, the screening parameter, the longitudinal and transverse effective mass, the g-factor of electron, number of conduction band valleys and the angle between magnetic field and the cylindrical axis of a conduction band valley.

These theories are consistent with the features in Fig.1. The observed positive magnetoconductance at high temperature can be attributed to localization and the negative one at low temperature to interaction. In magnetic field, conductivity varies as $T^{1/2}$ at low temperature with a coefficient almost independent of H. The magnetic field dependence is approximately $H^{1/2}$. Therefore, the conductivity in the amgnetic field can be expressed as

$$\delta\sigma = m_1 T^{1/2} + J H^{1/2} \tag{2}$$

In zero field we can fit the temperature dependence as

$$\delta\sigma = m_0 T^{1/2} + B T \tag{3}$$

The similar T and H dependence is observed in other samples with N = 2 - 6 $\times 10^{17}$cm^{-3}. Donor concentration dependence of coefficients m_0, m_1, J and B are given in Fig.2. The theoreticel values of m_0 and m_1 are also given in the figure. In the concentration range of N = 2 - 3 $\times 10^{17}$cm^{-3}, there are discrepancy of the factor of 2 - 7 between theory and experiment.

The observed magnetoconductance at low temperature is negative, while in the theory the negative magnetoconductance due to interaction is not large enough to predominate over the positive one due to localization. Here we should note that the values of $m_0$and m_1 are larger than the prediction of the interaction theory. On the other hand, the positive magnetoconductance is smaller than the prediction of the localization theory by 1/4 to 1/10. Therefore it is conjectures that the present theory of localization overestimates , while that of the interaction

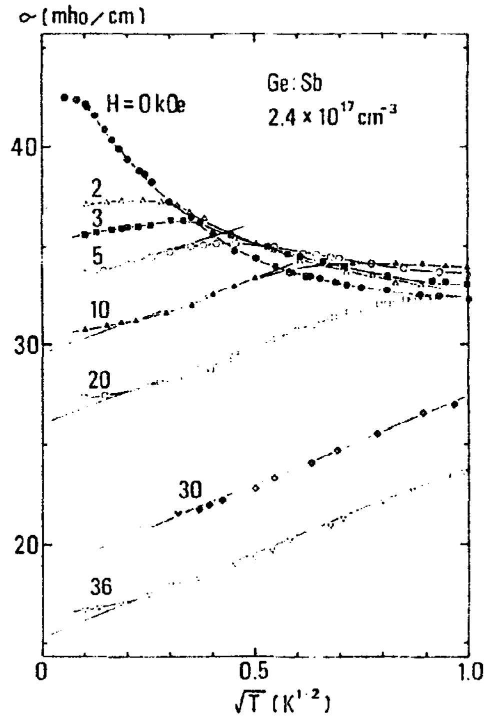

Fig.1 Conductivity of the sample with N=2.4x10^{17}cm^{-3} as a function of $T^{1/2}$.

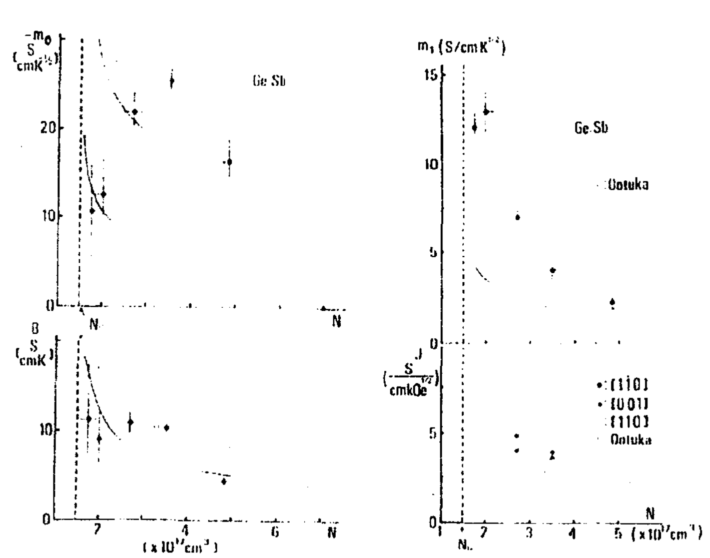

Fig.2 Donor concentration dependence of fitted values of m_0, m_1, J and B in Eqs.(2) and (3). The solid curves are the theoretical predictions.

underestimates the effects. If it is the case, low temperature magnetoconductance could be negative.

I-ii) Anisotropy of magnetoconductance

According to the theories, the magnetoconductance has anisotropy reflecting the anisotropy of effective mass and g-factor. This will be a clue to understand the origin of the magnetoconductance.

Fig.3 shows the anisotropy of positive magnetoconductance measured at 4.2K. The donor concentration is $2.7\times10^{17}cm^{-3}$, the current direction is $[1\bar{1}0]$ and the magnetic field is rotated in the plane (001). The anisotropy in low magnetic field was analyzed by Kawabata [4] and he found that it is explained by the localization theory very well, which is confirmed by our experiment also. At higher field the anisotropy changes. The theoretical expression of anisotropy given by Eq.(1) is shown in Fig.4, where we use the values of m_l=1.59m and m_t=0.082m. The characteristic "dip" in magnetoconductance at H // [110] is consistent with the experiment, although quantitative disagreements exist.

The anisotropy of negative magnetoconductance at low temperature is shown in Fig.5. Here the fitting parameter J in Eq.(2) is plotted as a function of magnetic field direction. The current is along $[1\bar{1}0]$ and the magnetic field is rotated in planes of $(1\bar{1}0)$ in (a) and [001] in (b). Although the anisotropy of (b) is resembling that of the Zeeman energy term of the interaction theory. The anisotropy of (a) seems not to consistent with it. The detailed analysis is being done now.

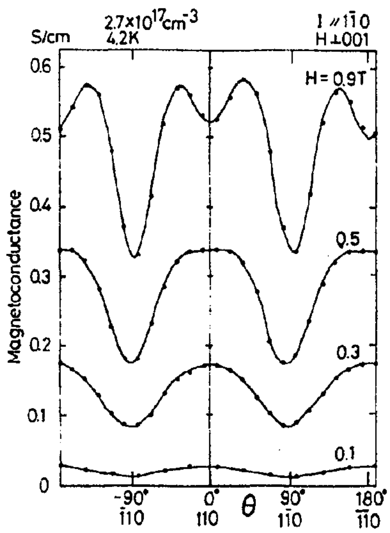

Fig.3 Anisotropy of positive magneto-conductance of the sample with $N=2.7\times10^{17}cm^{-3}$. The conductivity is measured along $[1\bar{1}0]$ and the magnetic field is rotated in the plane (001).

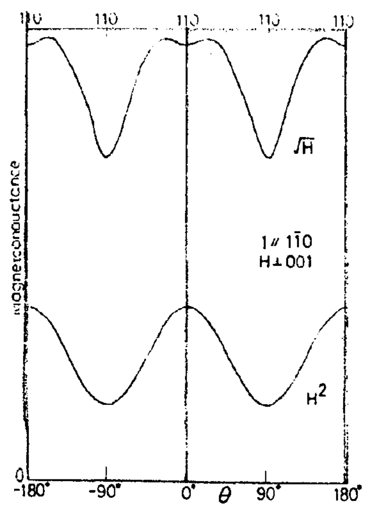

Fig.4 Positive magneto-conductance predicted by the localization theory. The current is along $[1\bar{1}0]$ and the magnetic field is rotated in the plane (001). The upper curve indicates the anisotropy at high H, and the lower one at low H.

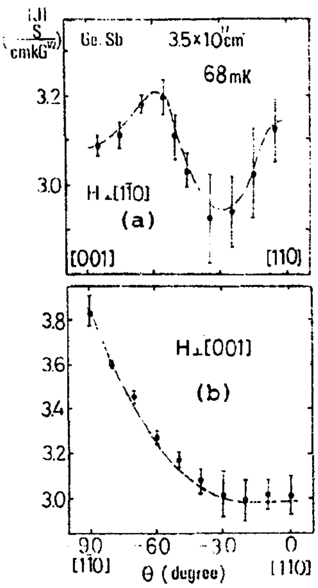

Fig.5 Anisotropy of negative magnetoconductance of the sample with $N=3.5\times10^{17}cm^{-3}$ at 68mK. The current is along $[1\bar{1}0]$ and H is rotated in the plane $(1\bar{1}0)$ in (a), and (001) in (b).

II. 1-valley Ge

Ge has equivalent four valleys of conduction band. Uniaxial compression along the [111] direction shifts the [111] valley down and the remaining three valleys up in energy [5]. Hence, when the compression is strong enough, electrons distribute only in the lowest valley. This is a 1-valley metal with strong anisotropy. This system is thought to give us clearer informations on low temperature conduction, because the anisotropy is large and the intervalley scattering which complicates the situation is not need to be considered.

Fig.6 shows the temperature dependence of conductivity of 1-valley Ge below 1K. They resemble that of 4-valley Ge and positive magnetoconductance at liquid He temperature, negative magnetoconductance at lower temperature and $T^{1/2}$ and $H^{1/2}$ dependence of conductivity in magnetic field are seen.

II-i) Positive magnetoconductance

Magnetic field dependence of positive magnetoconductance at 4.2K is shown in Fig.7. Conductivity is measured along the direction of [111]. The magnetic field is rotated in the plane of $(1\bar{1}0)$. Anisotropy is very large. Little anisotropy is seen when the magnetic field is rotated in the plane of (111), which is consistent with the symmetry of the system. Magnetoconductance varies as H^2 at $H \lesssim 0.2T$. At higher field magnetic field dependence is weaker than H^2.

According to the localization theory, magnetoconductance reflects the anisotropy of cyclotron energy and is largest when the cyclotron mass is lightest, i.e. $H /\!/ [111]$. This is consitent with the experiment. Quantitatively, theory says the anisotropy equals to the effective mass ratio at low field and to the power of the one-forth of the effective mass ratio at high field. This means the magnetoconductance ratio of $H /\!/ [111]$ to $H \perp [111]$ is 1:0.05 at low field and 1:0.48 at high field, as shown in

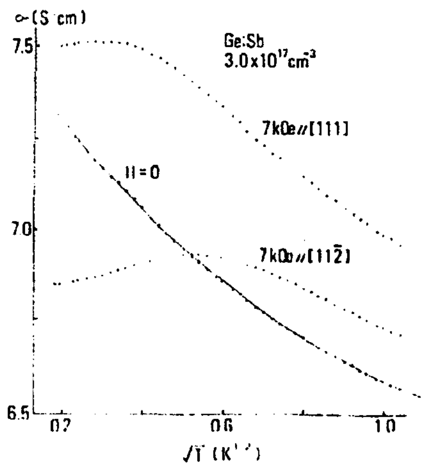

Fig.6 Conductivity of 1-valley Ge with $N=3.0\times10^{17}cm^{-3}$ as a function of $T^{1/2}$ in the magnetic fields of 0 and 0.7T. The current is along [111].

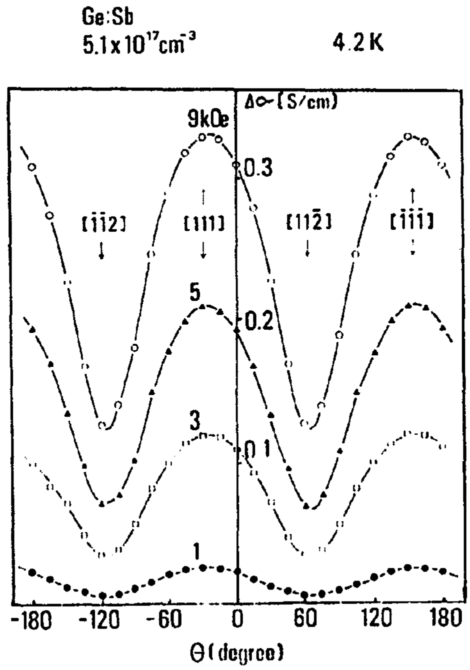

Fig.7 Anisotropy of positive magnetoconductance of 1-valley Ge with $N=5.1\times10^{17}cm^{-3}$ at 4.2K. The conductivity is measured along [111] and the magnetic field is rotated in the plane of $(1\bar{1}0)$.

Fig.8. The experimental ratio is 1: 0.01 at low field and 1:0.37 at 0.9T. Concerning this discrepancy, we point out the anisotropy of the relaxation time τ. In the present theory, it is assumed that τ is isotropic, but it is not realistic. For example, the anisotropy of the electron mobility is $\mu_\perp/\mu_{//}$ = 5 ~ 10 [6] and is rather small compared with that of the effective mass. Hence, we have to consider the anisotropy of relaxation time and the above discrepancy is expected to be explained by this.

As for the absolute value of positive magnetoconductance, the theoretical value is about 1.5 times larger when H // [111], and 0.6 times smaller when H ⊥ [111] than the experiment. This discrepancy also is thought to be improved by considering the relaxation time anisotropy.

In 1-valley Ge, positive magnetoconductance can be explained rather well by the localization theory, on the other hand in 4-valley Ge absolute value of positive magnetoconductance is smaller by 1/4 to 1/10 than the theory as mentioned above. We conjecture here that the intervalley scattering is important in 4-valley Ge. In theory the electrons behave as if they moved in "one band" and positive magnetoconductance becomes small when there exist frequent intervalley scatterings. This makes the discrepancy small. But if it is the case, it is puzzling that the anisotropy of positive magnetoconductance does not vanish but shows the anisotropy which can be explained very well by the theory ignoring the intervalley scattering.

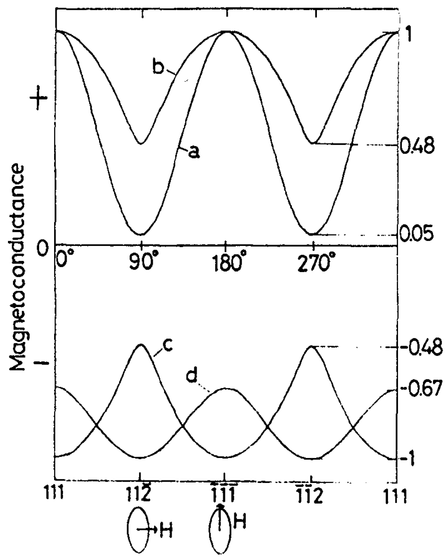

Fig.8 Theoretical predictions of magnetoconductance anisotropy of 1-valley Ge. The magnetic field is rotated in the plane (1$\bar{1}$0). The meaning of each curves is as follow; (a):localization theory in low H, (b): localization theory in high H, (c):orbital term of interaction theory in high H and (d):spin-Zeeman term of interaction theory in high H. Magnetoconductance is isotropic in the plane (111).

II-ii) Negative magnetoconductance

The general trend of conduction of 1-valley Ge shown in Fig.6 is similar to that of 4-valley Ge. Hence we analyze the conduction using the same formulae as Eqs.(2) and (3) and obtains the fitting parameters of m_0= -1.53, m_1 = 0.4, J = -0.10 ~ -0.28 and B = 0.54 for the sample shown in Fig.6. The value of J dependes the direction of the magnetic field as is discussed below. On the other hand, the interaction theory gives the values of m_0 = -0.19 and m_1 = 0.04 for this sample. Discrepancy between theory and experiment which is same or larger than in the case of 4-valley Ge exists. We can point out, however, that the theoretical values depend strongly on the anisotropies of effective mass and relaxation time and that the agreement is improved if the anisotropy of the system is smaller than that of mass as is the case with positive magnetoconductance.

Next we examine the anisotropy of negative magnetoconductance. Fig.9 shows the magnetic field direction dependence of J of the sample with N=3.0x$10^{17}$$cm^{-3}$ at T = 67.7mK. Magnetoconductance is largest when H ⊥ [111] and smallest when H // [111].

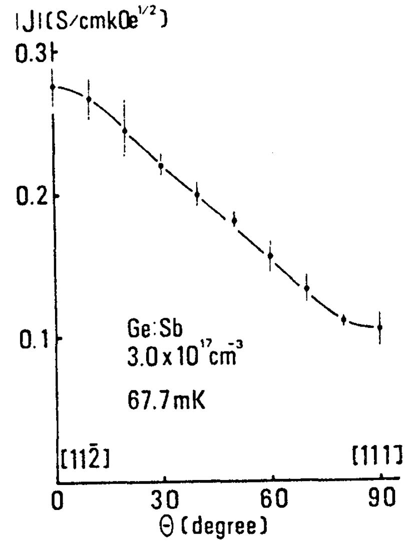

Fig.9 Anisotropy of negative magnetoconductance of 1-valley Ge with N=3.0x10^{17} cm^{-3} at 67.7mK. The current is along [111] and the magnetic field is rotated in the plane (1$\bar{1}$0).

This is contrary to the positive magnetoconductance shown in Fig.7.

According to the interaction theory, two processes are important in magnetoconduction at low temperature: one is due to the spin Zeeman effect and the other due to the interplay of the Zeeman and the orbital motion effects. The latter shows the anisotropy which varies depending on the ratio of Zeeman energy to orbital energy, λ. In our sample, λ is estimated small and this magnetoconductance shows the anisotropy reflecting the mass anisotropy. This is shown in Fig.8(c). Magnetoconductance is largest when H // [111]. The origin of anisotropy of Zeeman term is the g-value. The g-value of an electron in conduction band of Ge is 0.87 along [111] and 1.92 along [1$\bar{1}$0] and [11$\bar{2}$]. Therefore, the effect of magnetic field is largest when H ⊥ [111] as shown in Fig.8(d).

By using these theories, the experimental anisotropy is expressed as
0.73x(negative M.C. with the anisotropy of Zeeman term) + 0.27x(positive M.C. with the anisotropy of orbital, or localization term). The experiment suggests that the dominant contribution to low temperature magnetoconductance is the Zeeman term of the interaction theory. This is consitent with the theory, where the positive magnetoconductance due to localization almost cancels the negative one due to the orbital term of the interaction theory and only the spin Zeeman term remains.

By this experiment, it becomes clear that the positive magnetoconductance is originated by the localization effect and that the intervalley scattering and the anisotropy of the relaxation time need to be considered. The contribution of the Zeeman term of the interaction theory is dominant in the negative magnetoconductance of 1-valley Ge at low temperature. But the theory cannot explain the absolute value of temperature dependent conductivity even in 1-valley case. This is a future problem.

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