Experiments on the Localization Effects in Bulk Semiconductor

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§1 A scaling approach of Abrahams, Anderson, Ricciardello and Ramakrishnan[1] established a view point which enables one to look at various aspects of the localization effects in disordered systems in a unified way. It is shown that the anomalous properties, which have been considered characteristic of the metallic impurity conduction, can be interpreted as a precursor effect of localization. Modern techniques of perturbation theory provide a useful device to obtain quantitative results for these weakly localized regime problems, especially for the case of two dimensional systems[2], and now the experimental results can be discussed quantitatively by comparing with these theories. As for the problems related with the strongly localized regime, such as the metal-nonmetal transitions, mathematical device is not strong enough to provide full understanding of the experiments.

With these backbrounds, two problems are discussed in the present article. One is related with the anomalous temperature and magnetic field dependences of electrical resistivity in metallic samples where the precursor effect of localization is effective. Another is related with the thermal and magnetic properies in samples near the metal-nonmetal transition where the localization effects appear in a more direct way.

§2 Since its first observation in InSb, negativemagnetoresistance effect has been reported to exist in various kind of doped semiconductors.[3] It was pointed out that this effect is most predominant in just metallic and becomes smaller with increasing donor concentration, and that the effect shows anisotropy which is consistent with that of cyclotron mass of cubic crystals oriented in magnetic field. Together with the negative magnetoresistance an anomalous temperature variation was also noticed to exist. Fig.1[4] shows this anomaly observed in a Ge:Sb sample. The negative sign of magnetoresistance which is observed in the liquid helium temperature region turns into positive when the temperature is reduced below 1 K.

Recently developed scaling approach explains these features as follows[5]: To begin with, we discuss the one electron problem at 0 K. There is a growing tendency of localization among the electrons with increasing disorder in a metallic sample. A measure of the localization is a characteristic length which describes the size of localized states. When the size of a sample becomes comparable to this length, the effect of localization will appear in a way that it becomes impossible to define the conductivity as a material constant. If the sample is a cube of side length L, the conductivity is obtained from the conductance G of the cube measured with the electrodes on the opposite faces of it as

$$\sigma = G/L \tag{1}$$

σ being a function of L. σ as the material constant is usually obtained from the cube conductance when it is large compared to a universal constant $e^2/2\pi^2\hbar$ ($\simeq 10^{-5}$ mho). When the measrued cube conductance becomes smaller than this, the effect of localization is expected to appear. In the case of three dimension this effect reveals itself as a correction to the conductivity expressed by

$$\sigma = \sigma_0 + \frac{e^2}{2\pi^2\hbar} aL^{-1} \tag{2}$$

at zero Kelvin. The second term of the right hand is the correction due to the precursor effect of the localization.

L is the sample size when we consider the effect at zero K. It must be replaced other lengths which are determined by the experimental conditions. At finite temperatures L should be replaced by the diffusion length of electrons limited by the inelastic scattering $\sqrt{D\tau_{in}}$, D being the diffusion constant and τ_{in} the inelastic scattering relaxation time. Under a magnetic field L is replaced by the Landau orbit radius $\sqrt{c\hbar/eH}$. The introduction of these length reflects the distirbance of localization of electrons induced by the thermal inelastic scattering or the time reversal symmetry breaking. This way of approach enables one to expain the anomalies as seen in Fig.1. Analysing the experimental results [5] it was shown that the magnetoconductance increases in proportion to $H^{1/2}$ over a wide range of the magnetic field and semiquantitative agreement of its magnitude with $(e^2/2\pi^2\hbar)(eH/c\hbar)^{1/2}$ was obtained. When, however, we go into the lower temperature region, this agreement becomes unsatisfactory. Contrary to the theoretical expectation, the conductivity decreases with the increase of temperature and magnetic field. A resolution of this controversy was given by taking the effect of Coulomb interaction among the electrons into account. In a disordered system the interaction results in an anomaly of the

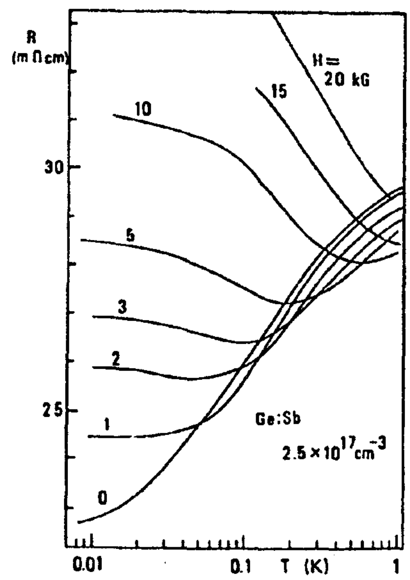

Fig.1 Low temperature resistivity in a metallic Ge:Sb sample with $N_D = 2.5 \times 10^{17}$ cm^{-3}, with magnetic field the parameter.

the density of states of electrons around the Fermi level which is proportional to $\sqrt{|E - E_F|}$[6]. With this anomaly a $T^{1/2}$ temperature dependence appears in physical quantities. With inclusion of this anomaly the correction to the conductivity turns to be

$$\delta\sigma = 0.46\frac{e^2}{2\pi^2\hbar} A \frac{kT}{\hbar D} + BT \tag{3}$$

Here A is a constant depending upon the range of the electron -electron interaction and becomes negative for the screened Coulomb interaction. The second term comes from the delocalization effect due to the electron-electron inelastic scattering and the sign of B is positive.

Fig.2 is a replot of the experimental result shown in Fig.1, with the conductivity as a function of $T^{1/2}$. The experimental results in zero magnetic field can be fitted to Eq.3 with a negative A and positive B values. As for the magnitudes of A and B, quantitative agreement between theory and experiment is not satisfactory at present. This problem will be discussed by Ootuka and Katsumoto[7] in a following articles of this issue.

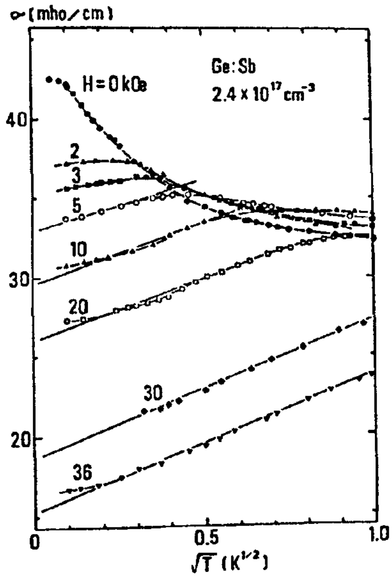

Fig.2 Replor of resistivity versus temperature relation of metallic Ge:Sb sample into conductivity versus $T^{1/2}$ relation.

When magnetic field is applied, the conductivity is affected through both the Zeeman splitting and orbital motion of electrons. After a complicated arguement[8] it is concluded that the coefficient of $T^{1/2}$ in Eq.3 changes the sign and magnitude in higher magnetic field where

$$g\mu_B H \gtrsim kT, \quad D\tau_{in} \gtrsim c\hbar/eH \tag{4}$$

when these conditions are satisfied, the conductivity is represented as

$$\sigma = \sigma_0 + CT^{1/2} - DH^{1/2} \tag{5}$$

with positive coefficients C and D. In higher temperature region or lower magnetic fields where the condition (4) are not satisfied, the effect of magnetic field is silght. General features of these arguements are illustrated in Fig.3, which resembles quite well with the experiments shown in Fig.2. That is , the position of the hump of respective curve seems consistent with the condition (4), and the

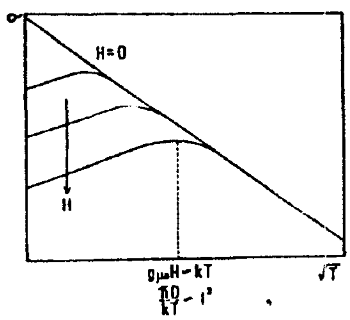

Fig.3 Schematic drawing of conductivity variation expected from interaction theory.

the gradient of the low temperature side of respective curves in nearly the same. As for the magnitude of C and D a discussion will be given also in the article by Ootuka and Katsumoto[7].

§3 We now examine the localization effects which are observed directly in less metallic and nonmetallic samples. The materials being discussed are magnetic and thermal properties in Si:P crystals in which the metal-nonmetal transition occurs at $N_C = 3.2 \times 10^{18}\ cm^{-3}$.

Fig.4[9] illustrates the low temprature specific heat of Si:P. Except for the lowest temperature region of relatively lightly doped samples, experimental points are situated on lines represented by

$$C = \gamma T + AT^3 \qquad (6)$$

which is typical of normal metals. The magnitude of the coefficient γ gives the density of states at the Fermi level $N(E_F)$ of the electron band

$$\gamma = \frac{1}{3}\pi^2 k^2 TN(E_F) \qquad (7)$$

In Fig.5[10] the γ values are shown as a function of N_D. The dotted line in the Figure represents the γ values expected from the degenerate semiconductor picture. It is observed that the experimental γ values vary with N_D well in accordance with the degenerate semiconductor picture, for samples even in the nonmetallic region with N_D's from 1.7 to 2.7 times $10^{18}\ cm^{-3}$. For another nonmetallic sample with $N_D = 5.3 \times 10^{17}\ cm^{-3}$ the γ value is negligibly small, so that it is considered that a finite energy gap exists for electronic exitation. It is interesting to observe that continuum of electronic exitation

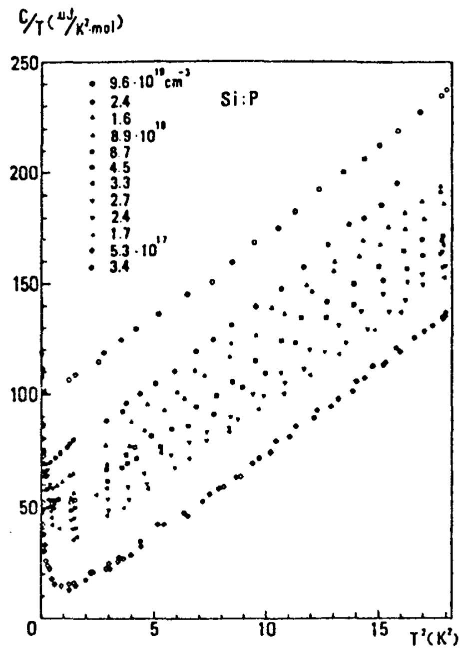

Fig.4 Specific heat in Si:P system. The donor concentration covers whole range of non-metal to metal.

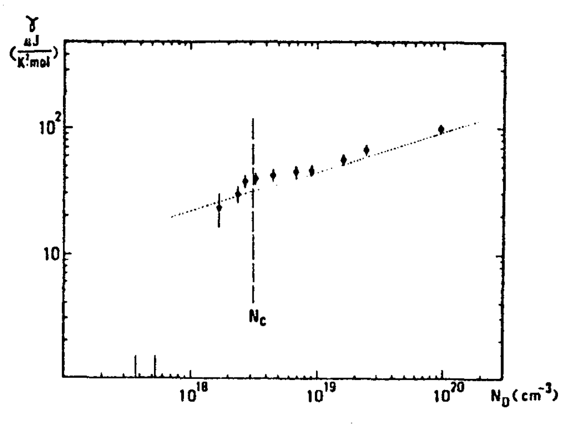

Fig.5 γ values of Si:P system. For samples with $N_D = 1.7 \times 10^{18}\ cm^{-3}$ varies with N_D in accordance with the degenerate semiconductor picture indicated by a dotted line.

exists even in nonmetallic samples just below the transition, and this is what can be expected from the Mott-Anderson picture that the transition occurs when the position of the Fermi level becomes lower and crosses over the mobility edge. Around the transition concentration, the electrons are considered to stay in the conduction band whether they are localized or not.

As is shown in Fig.4 an additional specific heat appears in the lowest temperature region for samples with N_D's smaller than 4.5×10^{18} cm^{-3}. Fig.6 illustrates the electronic specific heat observed in a nonmetallic sample with $N_D = 1.7 \times 10^{18}$ cm^{-3}. It is suggested that the specific heat approaches zero as T^s as $s \lesssim 1$, and not as $\exp(-T/T_0)$ in the lowest temperature region. Thus, it is conjectured that the density of states is enchanced forming a hump around the Fermi level. When magnetic field is applied the specific heat is suppressed in low temperarure side while enchanced in high temperature side, and is described satisfactorily by the Schottky formula with the Zeeman energy corresponding to $g = 2$ and $S = 1/2$. The entropy due to this additional specific heat is kept constant over the magnetic field region from rero to 10 kG. Such a feature is observed in samples with N_D's ranging from 0.5 to 2 times N_C, including both metallic and non-metallic samples. Curie-Weiss paramagnetism is also observed in these samples as illustrated in Fig.7.[12] It should be noted that the number of free spins estimated from the Curie-Weiss component of paramagnetism is consistent with the entropy calculated from the anomaly of specific heat.

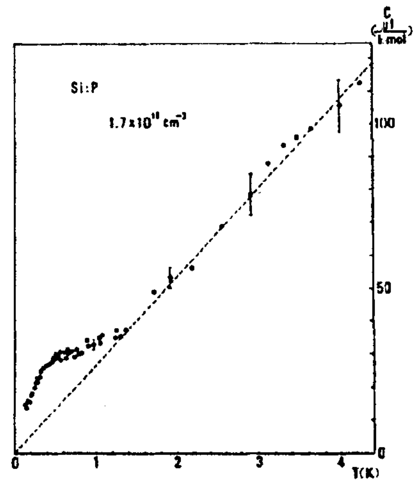

Fig.6 Specific heat of a non-metallic Si:P sample with $N_D = 1.7 \times 10^{18}$ cm^{-3} in the lowest temperature region.

If we are to explain the metal-nonmetal transition in terms of the Mott-Anderson picture, the concept of the mobility edge must be modified so that free sipns are allowed to exist even when the Fermi level is situated above the mobility edge. Usually free spins can appear on localized states with finite values of intra=state Coulomb energy. A possibility[13] of co-existence of localized and extended states in metallic samples was pointed out so that the

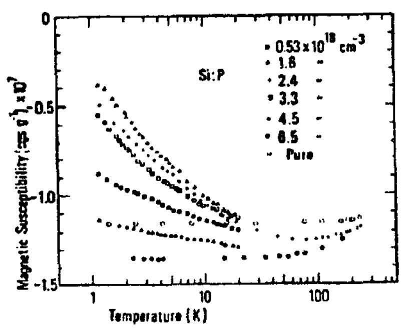

Fig.7 Static magnetic suscepti-bility in Si:P system.

the observed scaling relation [14] of the conductivity in just metallic samples can be explained.

More careful studies on the localized states around the mobility egde should be needed before we get through understanding of the transition.

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