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STRONGLY CORRELATED STATE OF ELECTRON AND HOLE LANDAU LEVELS IN BISMUTH AT LOW TEMPERATURES

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Peculiar anomalies have been found in the temperature and frequency dependences of the attenuation coefficient of sound waves in bismuth in a low magnetic field region. These anomalies appear only in a narrow region of magnetic field direction. Assuming that there exists a strongly correlated but incoherent state of electrons and holes, these anomalies are tentatively explained on the basis of Kuramoto's theory which takes into account short range correlation interaction between carriers.

I. Introduction

Giant quantum attenuation of sound waves in Bi at low temperatures was investigated under the conditions: $\vec{q} \parallel$ trigonal axis (z-axis), $\vec{H} \parallel$ trigonal-bisectrix axes plane (zy-plane), $\theta = \vec{q} \wedge \vec{H} \sim -23°$ ($\vec{q}$ is the wave number vector of sound waves and $\vec{H}$ the magnetic field vector) [1~3]. When bc(0+) and h(1-) approach simultaneously to the Fermi level, the attenuation coefficient at the peak, $\alpha(T,H_p)$, shows anomalous temperature and frequency dependences [4,5],

$$\alpha(T,H_p) \propto T^{-\kappa} f^{\mu}, \quad (\kappa \simeq 1.6 \text{ and } \mu \simeq 2.0). \tag{1}$$

On the other hand, in a normal case it takes $0<\kappa<1.0$ and $\mu \simeq 1.0$. Here, bc(ns) means the level with the Landau quantum number n and the spin one s for the electrons in b- and c-pocket, and h means that for the holes. These anomalies could be explained if a correction with q-dependence is added to the correlation terms in Kuramoto's attenuation formula [4,6].

On the other hand, similar anomalies were observed in the direction of $|\theta - 90°| \sim 2°$ in a low field region [7]. Further we have investigated in detail the anomalies in this region and found an extremum in the $\alpha(T,H_p)$ versus T plot.

II. Experimental Results

The measurement procedures are the same as the ones described in [7].

2-1. Temperature Dependence

Figure (1) shows the plot of $\alpha(T,H_p)$ versus T. The attenuation peak due to b(1-) is located at H_p=20 kG. The peaks due to b- and c-electrons are slightly separated because $\vec{H}$ is

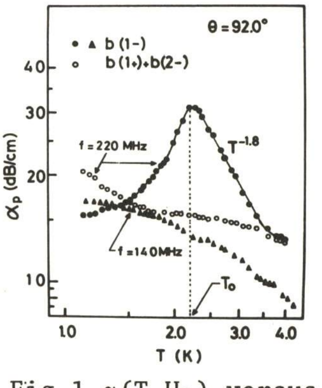

Fig.1 $\alpha(T,H_p)$ versus T plot for the sample No.1

slightly tilted from the exact zy-plane. The characteristics in behavior are as follows:
(1) $\alpha(T,H_p)$ due to b(1-) at f=220 MHz increases rapidly, goes through a maximum at T=2.3 K and then decreases with decreasing temperature.
(2) $\alpha(T,H_p)$ at H_p=10 kG due to b(1+) and b(2-) does not exhibit any anomalies.
(3) $\alpha(T,H_p)$ versus T plot at f=140 MHz does not show any anomalies.

Figure (2) shows one more result in another experimental run for the same sample. In this case, the peaks due to b(0+) and to b(1-) are not separated since the spin splitting does not exist. $\alpha(T,H_p)$ due to b(0+) and b(1-) also exhibits the same anomalies. Thus we can conclude that the occurrence of anomalies are not dependent on whether b(0+) and b(1-) are degenerated or not.

Figure (3) shows the $\alpha(T,H_p)$ versus T plot for another sample. The data indicated by circles were obtained for the sample which experienced one thermal cycle after the data of dots were taken. The values of T_o and κ (in the higher region than T_o) decrease after one thermal cycle.

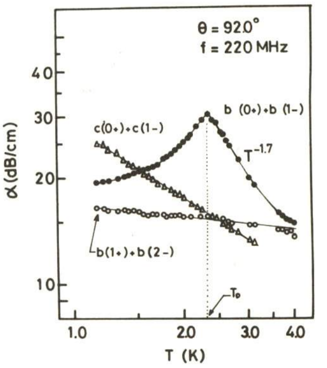

Fig.2 Another plot of $\alpha(T,H_p)$ versus T for the sample No.1

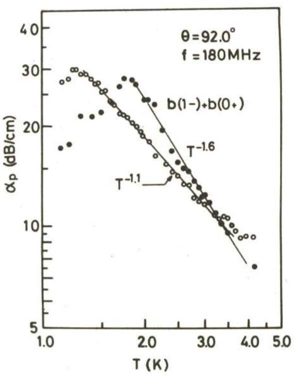

Fig.3 $\alpha(T,H_p)$ versus T plot for the sample No.2

2-2. Frequency Dependence

Figure(4) shows a frequency dependence of $\alpha(T,H_p)$ due to the same b(1-) as in Fig.(1). The power index μ at T=2.0 K is much larger than at T=4.2 K and the dependence at T=1.15 K is not represented by a simple power. Thus, the anomalous frequency dependence coexists with the anomalous temperature dependence.

2-3. Angular Dependence

The $\alpha(T,H_p)$ versus θ for b-electrons was also measured. The remarkable behavior in the plot for b(1-) at T=1.15 K is that

$$\alpha(2.04\mathrm{K},H_p) > \alpha(1.15\mathrm{K},H_p) \text{ for } 91.4°\lesssim\theta\lesssim92.3°.$$

This inequality suggests that the anomalous temperature dependence as in Figs. (1) and (2) certainly appears at least in this region.

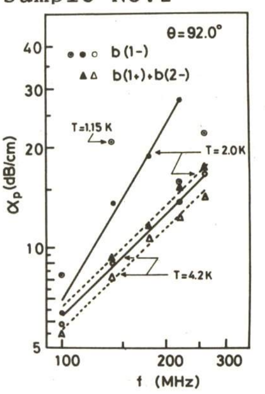

Fig.4 $\alpha(T,H_p)$ versus f plot for the sample No.1

III. Discussions

In the present low field region also, a few hole levels certainly exist closely to b(1-) as shown in Fig.(3) in [7]. It is very difficult to explain the anomalies by using any theories for the electron-hole system based on the one electron model. Then we try to explain the anomalies by assuming a new model which seems to contain most of the characteristics of the phenomenon [8].

3-1. Emulsion Model

It seems that at least the next two conditions are required for the occurrence of anomalies.
(a) An electron Landau level and a hole Landau level approach simultaneously to the Fermi level.
(b) The parallel mass $m_{/\!/}$ of electrons becomes anomalously large because of a local anomaly of the electron Fermi surface in a special direction. Therefore, although electrons have a finite momentum $\hbar k_{/\!/}$ in the direction of $\vec{H}$, the drift velocity $v_{/\!/} = \hbar k_{/\!/}/m_{/\!/}$ is almost zero and the electrons are easily captured temporarily even by a shallow potential well.

Under these conditions the absorber electrons with large $m_{/\!/}$ are quasi-captured in the neighborhood of each dislocation core with deep well, and forms a space with carriers of higher density than that in its surrounding. In that case, the charge neutrality in the space with a high density electrons and holes is held through the Coulomb and short range correlation interactions between carriers. We imagine such an emulsion state that in a spatially uniform reservoir electron-hole liquid there exist many quasi-coagulations of electrons and holes in a high density, which are regarded as immobile colloids. This state has the following properties.
(1) The effective diameter of a colloid, D(T), decreases with decreasing temperature because of very weakness of the attractive force.
(2) D(T) decreases with increasing f because of stripping the surface due to a friction between a colloid and the surrounding reservoir liquid.
(3) The spatial inhomogeneity becomes weaker with increasing the dislocation density, A, due to the overlapping among colloids.
(4) The density of carriers in a colloid is inhomogeneous due to a variable gradient of the potential well.

3-2. Attenuation Coefficient

The attenuation coefficient is represented by the following formula when the longitudinal sound waves propagate along z-axis of bismuth as discussed in [6],

$$\alpha(T,H) = \alpha_o[C_{zz}^{(e)} - C_{zz}^{(h)}]^2 \text{ Im } W, \tag{3}$$

where

$$W = \frac{\Xi_{ee}\cdot\Xi_{hh} - \Xi_{eh}^2}{\Xi_{ee} + \Xi_{hh} + 2\Xi_{eh}}, \quad \hat{\Xi} = \hat{\pi}[1 + \hat{J}\hat{\pi}]^{-1}. \tag{4}$$

$\hat{\pi}$ is a conventional polarization function [9] and $\hat{J}$ originates from a short range correlation interaction between carriers [6]. In order to explain all anomalies systematically, we assume that the spatial inhomogeneity of the carrier concentration enhances the sound attenuation and its effect is phenomenologically taken into account by introducing the temperature and frequency dependent term into J_{ij}. This assumption may be reasonable, since it is proved that some spatial inhomogeneity of carriers in Bi-Sb alloys increases the attenuation, though a mechanism to cause the inhomogeneity is different from that in the present case [10]. Then J_{ij}'s are supposed to be represented by the followings,

$$J_{ii}=J_{ii}^{o}[1 + a(q/q_o)^2], \quad J_{ij}=J_{ij}^{o}[1 + b(q/q_o)^2], \quad (i,j=e \text{ or } h), \tag{5}$$

$$a, b = a_o, b_o \exp(-\sqrt{A}\lambda)[1 - \exp(-D(T)/\lambda)], \quad q_o=10^5 \text{ cm}^{-1}, \tag{6}$$

where λ is the sound wave length. A characteristic temperature T_o related with D(T) is introduced through the following equation:

$$\exp[-D(T_o)/\lambda] \sim 0.1, \text{ i.e. } \lambda \sim 0.4D(T_o) \quad (\lambda \approx 9\ \mu m \text{ at } f=220 \text{ MHz}). \quad (7)$$

3-3. Qualitative Explanations

Next we will explain the experimental results qualitatively on the basis of this emulsion model and eqs. (3)~(7).
(i)In the region of $T>T_o$(i.e. $\lambda<D(T)$), a and b have the maximum values:

$$a = a_o \exp(-\sqrt{A}\lambda), \quad b = b_o \exp(-\sqrt{A}\lambda). \quad (8)$$

Then, the large values of κ and μ in a temperature region in Figs. (1)~(4) are reproduced.
(ii) In the region of $T<T_o$(i.e. $\lambda>D(T)$), a and b become as follows:

$$a \sim a_o \cdot \exp(-\sqrt{A}\lambda)[D(T)/\lambda] \to 0, \quad b \sim b_o \cdot \exp(-\sqrt{A}\lambda)[D(T)/\lambda] \to 0. \quad (9)$$

Then the excess part of $\alpha(T,H_p)$ which has increased in the region of $T>T_o$, continues to decrease with decreasing T. At a=b=0 $\alpha(T,H_p)$ reaches the normal value and the f dependence also becomes normal.
(iii) $\alpha(T,H_p)$ has a maximum in the vicinity of $T \sim T_o$.
(iv) $\alpha(T,H_p)$ becomes smaller with increasing A, because a and b approach to zero. Then the temperature and frequency dependences become normal and the maximum in $\alpha(T,H_p)$ versus T curve disappears.
(v) T_o becomes larger as f increases, because D(T) decreases as was expressed in 3-1.

IV. Conclusions

We have found peculiar anomalies in the temperature and frequency dependences of $\alpha(T,H_p)$ in a low field region. These anomalies are well explained qualitatively by introducing a new model for the electron-hole system and assuming a new mechanism of sound attenuation.
However, the present interpretation is only tentative, because the experimental data such as the dislocation dependence of anomalies are not enough and because there are no theories which can be applied to a system with spatial inhomogeneity of the carrier density.

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