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GIANT QUANTUM ATTENUATION OF SOUND IN BISMUTH BELOW 1 K

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Giant quantum attenuation of sound waves in Bi was investigated down to 0.03 K in the directions of the magnetic field in the vicinity where the electron and hole Landau levels cross the Fermi level simultaneously at about 90 kOe. Temperature and frequency dependences of the attenuation peaks at very low temperatures are discussed in comparison with what are expected in the fluctuation region of the gas-liquid type transition of the electron-hole system.

I. Introduction

Several anomalous behaviors have been found in giant quantum attenuation of sound waves in Bi[1]-[3], when two attenuation peaks, one due to an electron pocket and the other due to a hole pocket, coincide in strong magnetic fields. One of the anomalies is a strong temperature dependence of the attenuation coefficients at the peak positions α_p, that is, $\alpha_p \propto T^{-\mu}$, $\mu > 1$ in $1.5\ K \leq T \leq 4\ K$, contrary to simple one-electron theories[4],[5] ($\mu \leq 1$). This anomaly was, at first, analyzed as a fluctuation effect of an excitonic phase transition[1], but its critical temperature was evaluated to be, at most, of the order of 0.2 K[6] and considered to be too low to explain the anomaly observed above 1 K. Later, it was shown that the density fluctuation associated with the gas-liquid type transition (GL transition) may cause the strong temperature dependence of α_p far above its critical temperature T_c ($\sim$0.1 K)[7]-[9]. On the other hand, it was shown[10] that the electron-hole correlation plays a crucial role in bringing about this anomaly without considering any kind of phase transition (see also [11]). Recent experimental data[12] on the anomalies with respect to the temperature and frequency dependences above 1 K were discussed based on the theory of the electron-hole correlation[10].

In order to clarify the true physical origin of the anomalies mentioned above, we have measured giant quantum attenuation of sound waves in Bi at very low temperatures down to 0.03 K.

II. Experimental

The measurements were performed with a dilution refrigerator which had the attainable lowest temperature of 6 mK. Longitudinal waves were propagated along the trigonal axis (z-axis). The experimental procedure was almost the same as that in [13] except for a sample rotation system. The Bi single crystal used in the measurements had the residual resistance ratio of 627. Magnetic field up to 100 kOe was applied using a superconducting magnet. In order to vary the direction of the magnetic field, the Bi single crystal was rotated around the x-axis (one of three binary axes) by using a gear system driven by a superconducting stepping motor of which one step corresponded to the sample rotation of 0.05°. The angle θ which defined the direction of the field, was measured from the z-axis to the y-axis (one of three bisectrix axes) through the ΓL direction of the Brillouin zone.

III. Results and Discussion

Figure (1) shows the inverse magnetic fields $1/H_p$ of the peak fields H_p, defined as the fields where the attenuation coefficients take the maximum values, and the attenuation coefficient α_p at the peak field vs the angle θ. We denote a principal electron pocket located in the yz-plane as a-pocket and the other two as b- and c-pockets. The Landau levels due to these pockets and the hole pocket are denoted as e_a, e_b, e_c (n, ±) and h(n, ±), respectively, where n is the Landau quantum number and ± means the spin quantum number s=±1. A small amount of misalignment of the sample rotation axis splits the degenerated b- and c-branches. In the neighborhood of θ=-6°, two attenuation peaks due to e_a (0, +) and h(1, -) become close to each other and the attenuation becomes very large. The peak attenuation α_p takes the maximum at θ=-6.35°, where the magnetic field at which h(1, -) crosses the Fermi level is higher than that of e_a(0, +) by about 3 kOe[14]. The direction of the magnetic field where these two Landau levels cross the Fermi level simultaneously is estimated as θ=-6.15°. We focus our attention to the differences between results at θ=-6.35° and those at θ=-6.15° (these two directions are indicated by arrows in Fig. (1)). Figure (2) shows line-shapes of the attenuation peaks at various temperatures and for various frequencies of sound waves. Temperature dependences of the peak attenuation α_p are shown in Fig. (3). We obtain following results from these figures.

1) Temperature dependences of α_p are expressed as $\alpha_p \propto T^{-\mu}$ for $T \gtrsim 1$ K and $\omega/2\pi$=135 MHz with

μ=1.21 for θ=-6.35°,
μ=1.07 for θ=-6.15°.

In the lower temperature range ($T \lesssim 1$ K), the values of α_p tend to saturate against T and below 0.1 K, they take almost constant values.

2) Frequency dependences of α_p are expressed as

$\alpha_p \propto \omega^{\nu}$, ν=1 for $T \gtrsim 1$ K

for the both directions, which is consistent with the previous

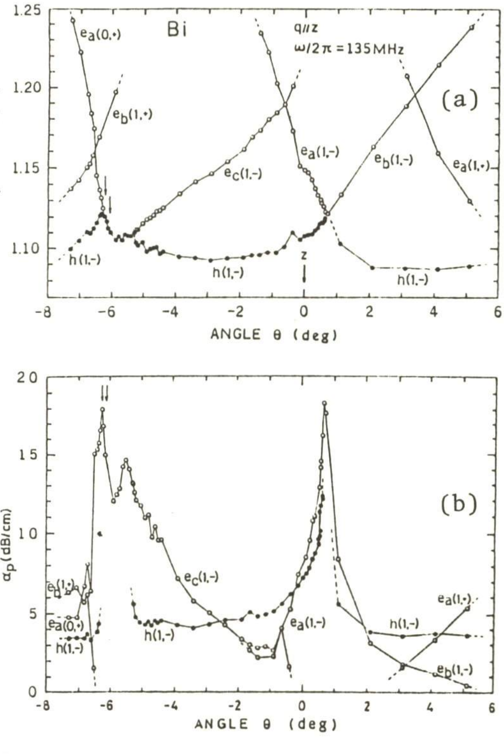

Fig. 1 (a) The inverse magnetic fields of the peak positions and (b) the peak attenuation coefficient at T~0.2 K as a function of the angle θ

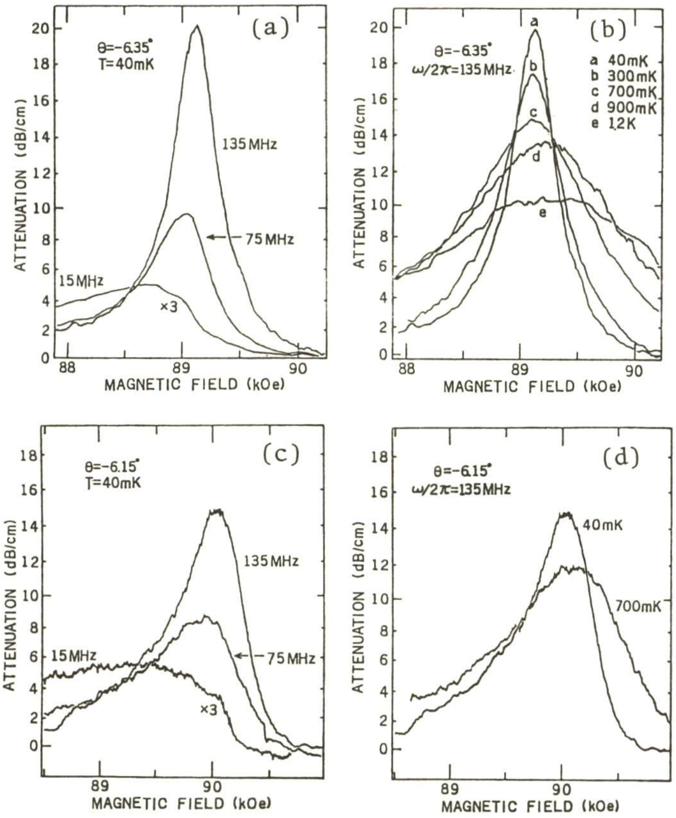

Fig. 2 Traces of the attenuation peaks for various frequencies and at various temperatures

result[2]. On the other hand, in the lower temperature range ($T \lesssim 1$ K) the values of ν increase with decreasing temperature. At T=0.04 K we obtain

$\nu=1.40$ for $\theta=-6.35°$,
$\nu=1.12$ for $\theta=-6.15°$.

3) Temperature dependence of the half-width ΔH is expressed as

$\Delta H \propto T^{1.0}$ for $T \gtrsim 0.7$ K,

which is also consistent with the previous result[2]. Below 0.7 K, the values of ΔH tend to saturate. The saturation values are

$\Delta H=0.50$ kOe for $\theta=-6.35°$,
$\Delta H=0.75$ kOe for $\theta=-6.15°$.

4) The half-width becomes small with increasing frequency of sound. This tendency is enhanced with decreasing temperature. Frequency dependence of ΔH is stronger for $\theta=-6.15°$ than for $\theta=-6.35°$.

5) The lineshape of the attenuation peak becomes asymmetric with decreasing frequency. Frequency dependence of the asymmetry becomes strong with decreasing temperature.

6) The ratio of the half-width in the lower field side of H_p to that of the higher field side, namely $\Delta H_L/\Delta H_H$, takes a nearly constant value of 1.2 for $\theta=-6.35°$ and $\omega/2\pi=135$ MH_z in the temperature range 2 K$\geq T \geq$0.04 K, while $\Delta H_L/\Delta H_H$ for $\theta=-6.15°$ increases from 1.4 to 1.8 with decreasing temperature from 2 K to 0.04 K.

7) The peak field H_p decreases with decreasing temperature and takes an almost constant value below 0.3 K. The temperature dependence is stronger for $\theta=-6.35°$ than for $\theta=-6.15°$.

8) The value of H_p increases with increasing frequency. Frequency dependence is weaker for $\theta=-6.35°$

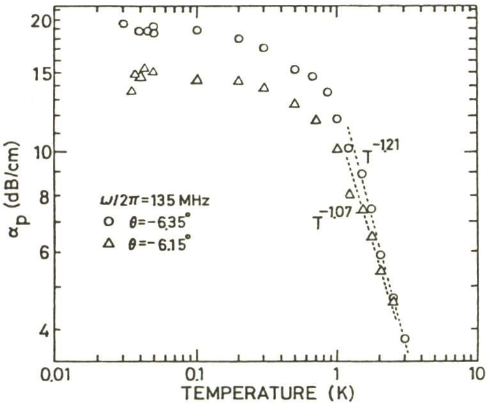

Fig. 3 Temperature dependences of the peak attenuations at $\theta=-6.35°$ and $\theta=-6.15°$

than for θ=-6.15°.

According to the theory of GL transition, a lineshape of the attenuation peak below T_c becomes very asymmetric with a discontinuous change of attenuation constant at the higher field side of the peak. Above T_c, the attenuation peak has following characteristics [14]: a) When the temperature approaches T_c, the fluctuation is enhanced and the frequency dependence of α_p becomes strong with decreasing temperature. b) The highest T_c is obtained in the direction of the field where $e_a(0, +)$ and $h(1, -)$ cross the Fermi level simultaneously. On the other hand, the largest value of α_p is expected in the direction of the field where the edge of $h(1, -)$ crosses the Fermi level at higher field than the cross field of $e_a(0, +)$ by about 3 kOe. c) The attenuation peak becomes symmetric with increasing frequency and with the separation of the cross fields.

We have not observed the discontinuous change of the attenuation with hysteresis. So, we have not observed the GL transition itself. However, our experimental results are consistent with what are expected in the fluctuation region of the GL transition in following respects: i) The temperature dependences of α_p and ΔH. ii) The increase of the value of ν with decreasing temperature. iii) The asymmetry of the attenuation peak for θ=-6.15° is more enhanced than for θ=-6.35° and increases with decreasing temperature. On the other hand, the θ dependences of the values of μ and ν contradict the theory of GL transition. According to the theory the values of μ and ν in the direction with the higher T_c should be larger; in our case, if there were T_c, the values of μ and ν for θ=-6.15° should be larger than those for θ=-6.35°. These contradict our experimental results described in 1) and 2).

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