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Cyclotron resonance experiments on rare-earth monopnictides

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Abstract
Cyclotron resonance (CR) measurements on high-quality single crystals of rare-earth monopnictides have been performed in the frequency range from 50 to 190 GHz. We have successfully observed CR signals for a strongly correlated electron system, CeSb, as well as other rare-earth monopnictides, LaSb and PrSb. We have also observed Doppler-shifted CR including nonlinear behaviour in the frequency–field diagrams.

1. Introduction

Cyclotron resonance (CR) is considered to provide the best method for obtaining the effective masses of conducting substances. By means of CR measurements, we can directly determine the cyclotron effective mass m^*_{CR} from the relation between the frequency of the microwave and the resonance field. It should be interesting to directly determine m^*_{CR} for strongly correlated electron systems (SCES) and to compare it with the mass m^*_{QO} estimated from de Haas–van Alfven (dHvA) effect measurements [1, 2]. However, there have been only a few reports on m^*_{CR} for SCES of metallic or semimetallic compounds due to the difficulty of the CR experiments.

Some of the rare-earth monopnictides RX (R = rare earth; X = N, P, As, Sb, and Bi) with NaCl-type crystal structure show anomalous physical properties such as dense Kondo behaviour, valence fluctuational behaviour, heavy-fermion states, and complicated magnetic states [3, 4]. It is known that these compounds are typical SCES with low carrier density. In this paper, we give our recent results from CR experiments on single crystals of LaSb, PrSb, and CeSb.

2. Experimental details

In order to observe CR signals, we prepared high-quality single crystals of LaSb and CeSb. A high-quality single crystal of PrSb was grown in Ames Laboratory, Iowa State University [6].

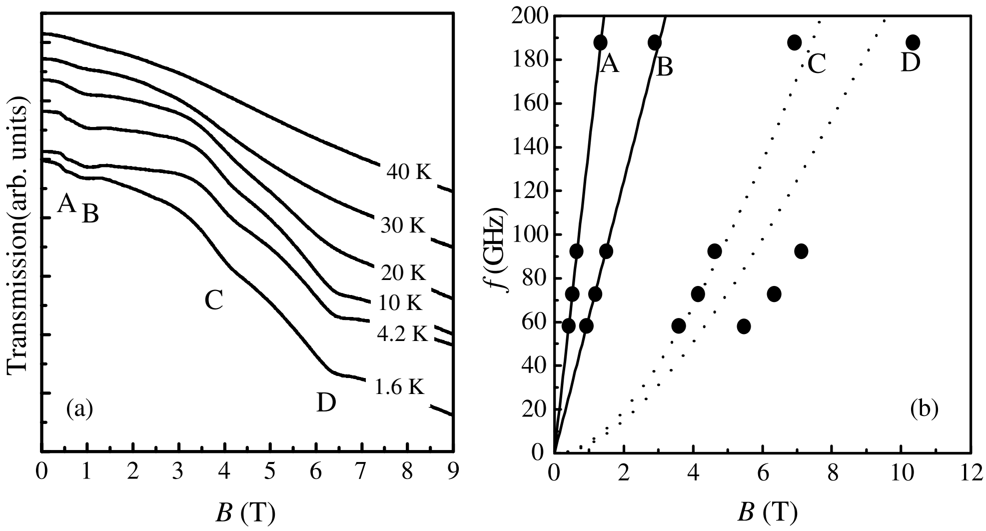

Figure 1. (a) Cavity transmissions for LaSb at various temperatures at 72.8 GHz for $\boldsymbol{B} \parallel [001]$. (b) The frequency–field diagram of LaSb at 1.6 K for $\boldsymbol{B} \parallel [001]$.

The typical residual resistivity ratio of the single crystals is about 500, which indicates about 5–10 times higher quality than those in previous reports. CR measurements have been performed using a vector network analyser (AB Millimeter Company, Limited) and a resonant cavity in the frequency region from 50 to 190 GHz in magnetic fields up to 14 T using a superconducting magnet. The experimental method is described in detail in [5].

3. Results and discussion

Figure 1(a) shows the cavity transmissions for LaSb at various temperatures from 1.6 to 40 K at 72.8 GHz for $\boldsymbol{B} \parallel [001]$. The transmissions decrease with increasing magnetic field, which seems to be an effect of the surface impedance due to increase of the transverse magnetoresistance. In figure 1(a), we can see four absorption lines at 1.6 K, and these absorption lines are labelled as 'A', 'B', 'C', and 'D'. All the absorption lines become broader with increasing temperature and are undetectable above 40 K. This indicates that these absorption lines originated from the cyclotron motion of the carriers in LaSb.

Figure 1(b) shows the frequency–field diagram for LaSb for $\boldsymbol{B} \parallel [001]$. The resonance points 'A' and 'B' are indicated by the straight lines crossing the origin. From the angular dependence, the absorption lines 'A' and 'B' are identified as relating to CR of the carriers in the α-branch and the γ-branch, respectively [5]. The m^*_{CR} determined are 0.20 and 0.45 m_0 for the α- and γ-branch, respectively. On the other hand, the resonance frequencies of 'C' and 'D' show nonlinear behaviour with respect to the magnetic field. In addition, their resonance fields are very large. That is, if we assume these 'C' and 'D' resonances as CR lines, the m^*_{CR} are estimated to be over 1.0 m_0 and these values are much larger than the expected masses in LaSb [7, 8].

These 'C' and 'D' absorption lines are identified as Doppler-shifted cyclotron resonance (DSCR) with Alfven waves which propagate in LaSb [9]. DSCR is concerned with carriers which have velocity components along the direction of the Alfven wave propagation. In this case, a carrier sees a Doppler-shifted frequency depending on the velocity. As a result, the

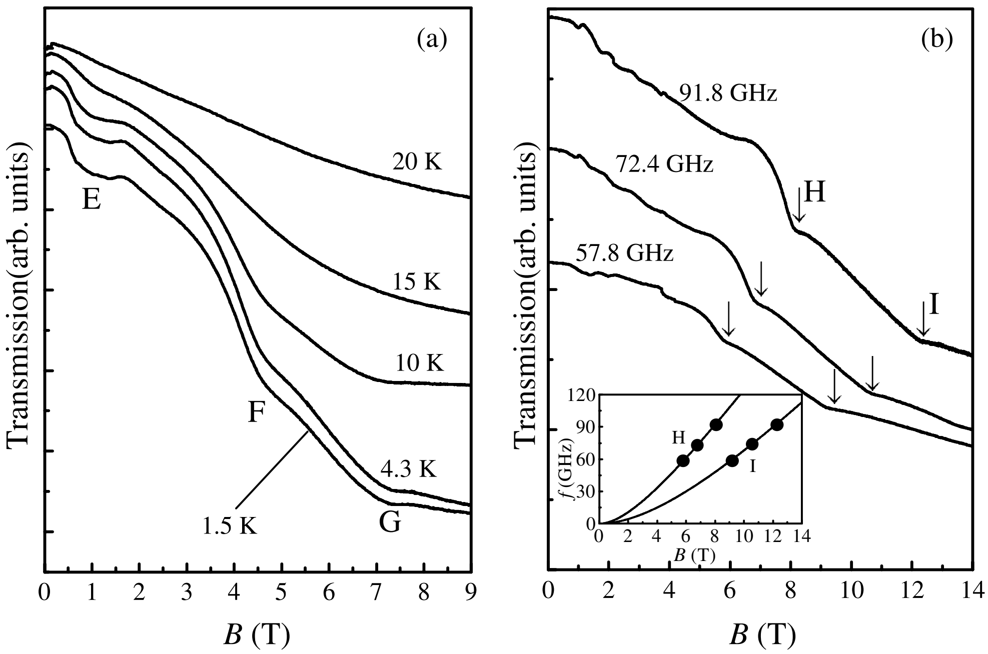

Figure 2. (a) Cavity transmissions for PrSb at various temperatures at 72.7 GHz for $\boldsymbol{B} \parallel [001]$. (b) Cavity transmissions for CeSb at various frequencies at 1.6 K for $\boldsymbol{B} \parallel [001]$. The inset shows the frequency–field diagram of CeSb at 1.6 K for $\boldsymbol{B} \parallel [001]$.

absorption line is observed far from the magnetic field position of the 'normal' CR at a fixed frequency [10, 11]. The magnetic field dependence of the resonance frequency ω_c' for DSCR is given by

$$\omega_c' = \frac{\omega_c}{1 + (v_F\sqrt{\mu \sum n_j m_j})/B}, \tag{1}$$

where ω_c is the cyclotron frequency, μ the magnetic susceptibility, v_F the Fermi velocity, n_j the density of the jth carrier, and m_j its mass [10, 11]. The dotted curves in figure 1(b) are calculated from equation (1) using parameters expected from experiments [5, 7, 8], and correspond to the γ-branch and $\alpha_\parallel$-branch ($\alpha_\parallel$: the longitudinal axis of the spheroid is perpendicular to the [001] direction). The agreement between the experimental data for 'C' and 'D' and the calculated lines is qualitatively good. Therefore, we conclude that the 'C' and 'D' lines are due to DSCR of the carriers at the edge of the γ-branch and the $\alpha_\parallel$-branch, respectively. Since the resonance condition of DSCR depends on the effective mass and on the Fermi velocity v_F, we can estimate v_F from DSCR measurements if the effective mass parameters are completely determined.

CR and DSCR signals are also observed in PrSb and CeSb. Figure 2(a) shows the cavity transmissions for PrSb at various temperatures from 1.5 to 20 K at 72.7 GHz for $\boldsymbol{B} \parallel [001]$. Three absorption lines are observed at 1.5 K, and these absorption lines are labelled as 'E', 'F', and 'G'. The resonance field of the absorption line 'E' is about 1 T, which corresponds to the m^*_{CR}-value of 0.4 m_0. However, the absorption line 'E' has some structure; that is, the line seems to consist of several absorption lines. On the other hand, the resonance fields of the absorption lines 'F' and 'G' are 4.8 and 7.2 T, respectively, which are much larger than the resonance fields expected from the effective masses estimated from dHvA measurements. The absorption lines 'F' and 'G' are considered to be related to DSCR in the same way as for LaSb.

Figure 2(b) shows the cavity transmissions for CeSb for various frequencies at 1.6 K for $\boldsymbol{B} \parallel [001]$. We can see two large absorption lines which are labelled as 'H' and 'I'. The inset of figure 2(b) shows the frequency–field diagram for the absorption lines 'H' and 'I'. The resonance points are not shown by any straight lines crossing the origin, but are represented by the solid curves in the inset of figure 2(b). These curves are calculated by the DSCR resonance condition equation (1). Therefore, the absorption lines 'H' and 'I' are considered to be related to DSCR of the carriers in CeSb. As seen in figure 2(b), small dips and anomalies are also observed below 4 T in each spectrum. These dips and anomalies are due to 'normal' CR or changes in the magnetic permeability or the electric resistivity with the magnetic phase transitions. The estimated m^*_{CR} are in the range of 0.3–1.5 m_0, which indicates that m^*_{CR} are considerably enhanced, like the m^*_{QO}. Detailed results for the 'normal' CR in CeSb have been reported in [12].

4. Summary

We have performed CR measurements on high-quality single crystals of rare-earth monopnictides (LaSb, PrSb, and CeSb) in the frequency range from 50 to 190 GHz. We have observed CR signals for these compounds and the m^*_{CR} are estimated to be in the range of 0.2–1.5 m_0. We have also observed DSCR signals, including the nonlinear behaviour in the frequency–field diagrams.

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