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ORIGIN OF FAR-INFRARED MAGNETO-OSCILLATIONS OF ELECTRON-HOLE DROP IN Ge

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Time-resolved observation of the magneto-oscillation in far-infrared (97-233 μm) absorption by electron-hole drops created in germanium gives evidences that the phenomenon originates from the oscillatory carrier pair density.

I. Introduction

For electron-hole drops (EHD) created in germanium, magneto-oscillatory features have been observed at various experiments of luminescence and far-infrared (FIR) works [1]. Keldysh and Silin suggest the dependence of carrier pair density on the magnetic field as the principal mechanism of the oscillations [2]. This suggestion has been strongly supported by Betzler et al. [3] from the side of luminescence measurement. Thus it is generally accepted now that magneto-oscillations in luminescence are due to oscillatory carrier pair density. There exists, on the other hand, only a small amount of information about the origin of magneto-oscillations in FIR absorption. We have measured time dependent FIR absorption and interpret the data with the help of theory based on the density variation.

II. Experiments

The pure Ge sample placed in the 7 T superconducting magnet is illuminated at 2.0 K by argon ion laser radiation chopped at the frequency of 60 Hz and having the pulse width of 200 μs. The source of FIR radiation is an optically pumped laser, containing vapor of CH_3OH, CH_3OD or CD_3OD whose emitting wavelengths range from 97 to 299 μm. The FIR radiation is chopped at 60 Hz in synchronization with photoillumination and to make the pulse width of 1 ms. The detector of FIR radiation is an n-InSb embedded in a persistent-current-driven superconducting magnet.

III. Magneto-oscillation of FIR Absorption

The observed magneto-oscillations in the FIR absorption by EHD in the course of excitation are shown in Fig.(1) for the wavelengths 97 to 299 μm. The magnetic fields where dips occur are independent of laser wavelength. The relative amplitude of oscillations starts decreasing for the laser frequency somewhat higher than the plasma resonance frequency $\omega_p/\sqrt{3}$ (138 μm). The frequency dependence of the relative oscillation amplitude suggests that the oscillation is not caused by the change in EHD radius due to oscillatory work function.

Next we will try to interpret the oscillation in terms of oscillatory carrier pair density. According to Keldysh and Silin, the carrier pair density n is calculated from the condition that the free

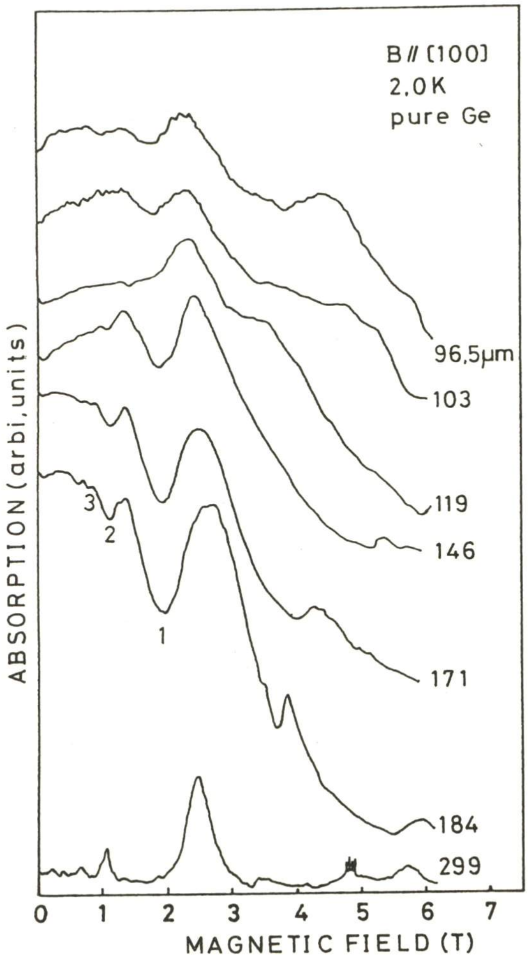

Fig.(1) Magnetoabsorption by EHD in pure Ge obtained at the geometry B // [100] is shown for various FIR wavelengths. Numbers 1, 2 and 3 indicate the Landau numbers of the light electron.

energy becomes minimum, and at low magnetic fields the oscillation amplitude of the exchange term is larger than that of the kinetic term. From the result of numerical calculation of n, the fields of carrier pair density maxima are given by

$$E_F = (\ell + 0.534)\hbar\omega_c \ , \qquad (1)$$

where E_F is the Fermi energy, ℓ is integer and ω_c is the cyclotron frequency. Since the magnetic fields of the Fermi level intersecting the Landau levels are calculated from $E_F=(\ell+0.5)\hbar\omega_c$, the crossing field should come very close to the magnetic field of the density maximum. The correction Δn of the carrier pair density due to the magnetic field induces the variation of the FIR absorption coefficient $\Delta\alpha$. When the radius of EHD is small compared with laser wavelength and excitation level is high enough above the threshold of EHD formation, the ratio of $\Delta\alpha$ to the zero field absorption value α_0 is

$$\frac{\Delta\alpha}{\alpha_0} = \left(-2 - \frac{Cn_0}{B+Cn_0} + \frac{\omega^4-\frac{1}{9}\omega_p^4+\omega^2/\tau^2}{(\omega^2-\frac{1}{3}\omega_p^2)^2+\omega^2/\tau^2}\right)\frac{\Delta n}{n_0} \ , \qquad (2)$$

where B and C are radiative and Auger recombination coefficients, respectively, ω the frequency of FIR radiation, ω_p the plasma frequency and τ the relaxation time. Making use of the values $n_0=2.1\text{x}10^{17}$ cm^{-3}, $B=3\text{x}10^{-14}$ cm^3 s^{-1} and $C=4\text{x}10^{-31}$ cm^6 s^{-1} [3], we may calculate $\tilde{\alpha}(\omega)=(\Delta\alpha/\alpha_0)/(\Delta n/n_0)$ as a function of ω (see Fig.(2)). We find that $\tilde{\alpha}(\omega)$ undergoes a drastic change near the plasma resonance frequency. This change of $\tilde{\alpha}(\omega)$ explains the frequency dependence of the relative oscillation amplitude shown in Fig.(2). With $\hbar/\omega$=2meV, for example, $\tilde{\alpha}(\omega)$ is changing from -6.1 at 171 µm to 2.2 at 119 µm. At magnetic fields satisfying Eq.(1) the FIR absorption is indeed minimized for 171 µm. We calculate the Fermi energy E_F from the magnetic fields of dips with the help of Eq.(1). If the possible mass renormalization is included ($m_t^*=1.15m_t$ and $m_\ell^*=0.96m_\ell$ for transverse and longitudinal masses [4]), E_F and n become

2.2meV and 2.1×10^{17} cm^{-3}, respectively. These values agree well with those obtained from various measurements at zero magnetic field [1].

IV. Amplitude of Magneto-oscillation

The damping feature of the oscillation amplitude as observed for B // [100] and shown in Fig.(1) is almost the same as that calculated, suggesting that the broadening of each Landau level due to collisions is small in comparison with the temperature broadening.

Now that n changes from n_0 to $n_0+\Delta n$, the relative variation of luminescence intensity becomes

$$\frac{\Delta I}{I_0} = -\frac{Cn_0}{B+Cn_0}\frac{\Delta n}{n_0} = -0.74\,\frac{\Delta n}{n_0} \quad . \tag{3}$$

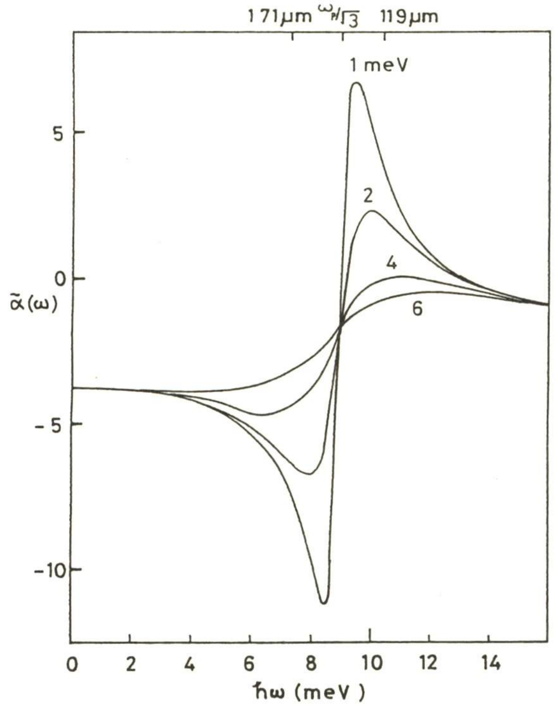

Fig.(2) The calculated value of $\tilde{\alpha}(\omega)=(\Delta\alpha/\alpha_0)/(\Delta n/n_0)$ is given as a function of FIR frequency ω for various damping constants $\hbar/\tau$.

When the oscillation amplitude of FIR absorption at 171 μm is compared with that of luminescence, the former is larger than the latter. In our calculation the amplitude ratio between FIR absorption and luminescence is about 8. Comparing our FIR data with Skolnick and Bimberg's luminescence data [5], we find the ratio to be about 5. Thus the experimental ratio of oscillation amplitude between FIR absorption and luminescence is of the same order as that calculated.

According to our calculation of the density oscillation for B // [111], magneto-oscillations due to the heavy electron should appear even at low magnetic fields. In our experiments, however, no signals arising from the heavy electron are observed. This fact indicates that the Keldysh-Silin type calculation overestimates the contribution of the heavier cyclotron mass electron.

The ratio of the oscillation amplitude to the total absorption $\Delta\alpha/\alpha_0$ is about 0.16 at B=1 T and for B // [100]. In the calculation by Keldysh and Silin [2], one finds $\Delta n/n_0$=0.33 for the same conditions. Combined with Eq.(2), $\Delta\alpha/\alpha_0$ is predicted to be -1.9. This value is much larger in magnitude than the experimental value 0.16.

V. Time-resolved Magneto-oscillations

The decay profiles of magneto-oscillations at 171 μm are shown in Fig.(3) for B // [100]. Inversion of dips and peaks reported by

Betzler et al. [3] in their luminescence measurement is not observed for all three magnetic field directions. The relative oscillation amplitude $\Delta\alpha/\alpha_0$ changes little in the course of decay after shutting off the excitation light. This can be explained as follows. Time dependent relative amplitude for 171 μm is written by

$$\frac{\Delta\alpha(t)}{\alpha_0(t)} = - \frac{\Delta n}{n_0} (a + b\,t) \quad . \tag{4}$$

with a=6.1 and $b=4.2\times10^4\ s^{-1}$. The time dependent part of the oscillation is thus smaller in magnitude, say for t < 100 μs, than the time independent part so that the inversion of peaks and dips will not be observable.

It is true that there still remain some other possibilities for interpreting the magneto-oscillation of FIR absorption; e.g., in terms of change in plasmon damping in the presence of a magnetic field. But such a mechanism fails to explain the oscillation observed in luminescence measurement. The magneto-oscillation of FIR absorption can thus be explained most likely in terms of oscillation in carrier pair density. Contribution of plasmon damping, if any, is considered quite small.

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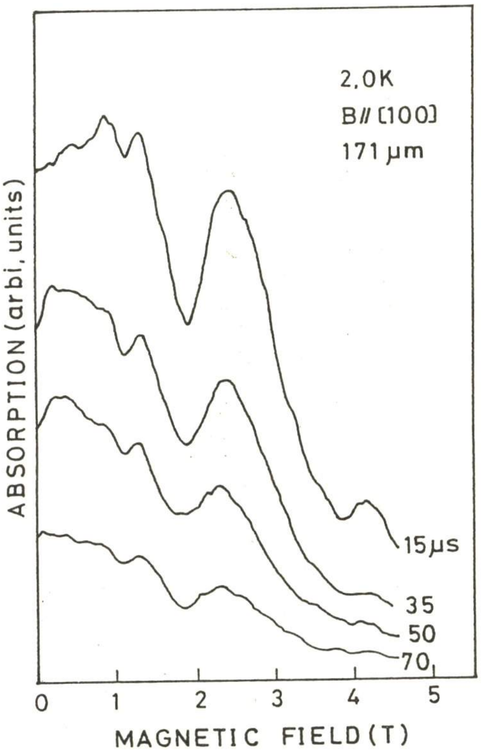

Fig.(3) Time-resolved magneto-oscillations observed for 171 μm after the end of 0.2 ms excitation. Delay-times are indicated on the right.

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