QUANTUM LIMIT CYCLOTRON RESONANCE IN GaAs AND Ge

H. KOBORI, T. OHYAMA, and E. OTSUKA

Department of Physics, College of General Education, Osaka University, Toyonaka, Osaka 560, Japan

ABSTRACT

A study of quantum limit cyclotron resonance linewidth has been carried out in n-GaAs and pure Ge. The relaxation time in the quantum limit derived from cyclotron resonance linewidth has been examined for neutral donor scattering in GaAs and for acoustic deformation potential scattering in Ge. Time-resolved far-infrared (513 to 84 μm) laser cyclotron resonance has been performed in pulsed band gap excitation. It is found that (1) The inverse relaxation time for neutral donor scattering is proportional to neutral donor concentration and the reciprocal of the square root of magnetic field, and independent of temperature. (2) The same for acoustic deformation potential scattering is proportional to temperature and the square root of magnetic field.

1. INTRODUCTION

Cyclotron resonance has been used as a forcible means for studying carrier scattering mechanisms as well as band structures. Particularly, the cyclotron resonance linewidth has yielded direct information concerning the momentum relaxation mechanisms of carriers. In the classical limit, \( \hbar \omega_c < k_BT \) ( where \( \omega_c \) : cyclotron angular frequency), many experimental studies of the cyclotron resonance, especially those in Ge and Si, have been reported at microwave frequencies. So far theoretical study for neutral impurity scattering in the quantum limit is not available. Meyer [15] first pointed out that, under quantum region, the cyclotron resonance linewidth for acoustic deformation potential scattering cannot be expressed in terms of the relaxation time. Arora-Spector [16] have attained the formulas for various scatterings, including electron-phonon system, using the density operator method. Suzuki-Choi-Fujita [17] have derived the formula for electron-acoustic phonon scattering, starting from the Kubo formula [19] and employing the proper connected diagram expansion. They have assumed an elastic scattering approximation. Afterwards, Suzuki-Dunn [18] have removed the assumption of elastic scattering approximation by taking numerical analysis. The results of Suzuki-Choi-Fujita and Arora-Spector are equivalent to each other besides apart from a constant multiplying factor. They are, however, different from Meyer’s prediction. Pink-Braunstein [9] have carried out far-infrared cyclotron resonance experiments in n-Ge of a wavelength of 337 μm. They have got temperature dependence of cyclotron resonance linewidth between 30 and 100 K. The inverse relaxation time shows an indication to increase and saturate above 60 K. However, there is a possibility that their experimental results include the contribution of ionised impurity and/or electron-electron scatterings to a degree not negligible. To obtain carriers by thermal excitation, they had to employ n-Ge sample with a doping level of \( 10^{14} \text{cm}^{-3} \). Furthermore, since \( \hbar \omega_c/k_B = 42.7\text{ K} \) for 337 μm, temperature above 42.7 K is under classical region. Maure-Kido-Chikazumi [10] have performed far-infrared (119 μm) and infrared (10.8 μm) cyclotron resonance experiments, using steady and pulsed magnetic fields, respectively, at 300 K.

In this paper, we present the relaxation time in the quantum limit obtained from cyclotron resonance linewidth for neutral donor scattering in GaAs as a function of neutral donor concentration, temperature and magnetic field, and for acoustic deformation potential scattering in Ge as a function of temperature and magnetic field. We have carried out time-resolved far-infrared (513 to 84 μm) laser cyclotron resonance experiments in pulsed band gap excitation. The magnetic field is swept over a range of 0 to 100 kG, and temperature is varied between 1.7 and 4.2 K for GaAs and 10.0 and 160 K for pure Ge.

2. EXPERIMENTAL

The impurity concentrations of the employed n-GaAs and pure Ge samples are given in Table I. We have used time-resolved far-infrared cyclotron resonance method in pulsed band gap excitation. The employed far-infrared laser is of discharge (H<sub>2</sub>O and D<sub>2</sub>O) and optically pumping (HCOOH) types, and produces pulses at a repetition of 30 Hz in synchronised combination with intrinsic photoexcitation using a xenon flash lamp. The excitation light is guided to the sample through a self-focussing dual-core glass rod. The far-infrared light transmitting the sample is detected by an n-InSb Puttley detector accompanied...
Table I. List of n-GaAs and pure Ge samples

<table>
<thead>
<tr>
<th>sample</th>
<th>type</th>
<th>N_d (x10^15 cm^-3)</th>
<th>N_a (x10^15 cm^-3)</th>
<th>growth method</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs-1</td>
<td>n</td>
<td>0.75</td>
<td>0.5</td>
<td>MBE</td>
</tr>
<tr>
<td>GaAs-2</td>
<td>n</td>
<td>1.0</td>
<td>0.6</td>
<td>MOCVD</td>
</tr>
<tr>
<td>GaAs-3</td>
<td>n</td>
<td>1.5</td>
<td>1.0</td>
<td>VPE</td>
</tr>
<tr>
<td>GaAs-4</td>
<td>n</td>
<td>4.6</td>
<td>3.7</td>
<td>LPE</td>
</tr>
<tr>
<td>GaAs-5</td>
<td>n</td>
<td>5.5</td>
<td>1.5</td>
<td>MBE</td>
</tr>
<tr>
<td>pure Ge</td>
<td>p</td>
<td>N_a - N_d ≤ 10^12 cm^-3</td>
<td>Floating Zone</td>
<td></td>
</tr>
</tbody>
</table>

with a persistent current solenoid. These experiments have been carried out in the Faraday configuration. The temperature is between 1.7 and 160 K and the magnetic field is applied up to 100 kG. The pulse width of the excitation light is ~ 1 µs and the average power on the sample surface is ~3 mW/cm^2. The temperature rise of the sample due to photoexcitation is kept less than 0.5 K for measurement at 4.2 K.

The signal is led to a two channel boxcar integrator with a logarithmic amplifier and the aperture of the boxcar integrator is open for 0.5 µs. The absorption spectra are obtained as

$$\Delta a = \ln(I_0/I_R)/d$$  \hspace{1cm} (1)

where $\Delta a$ is the change in absorption coefficient, $I_R$ and $I_0$ are transmitted far-infrared light intensities with and without excitation, respectively, and $d$ is the sample thickness.

3. RELAXATION TIME OF NEUTRAL DONOR AND ACOUSTIC DEFORMATION POTENTIAL SCATTERINGS IN THE QUANTUM LIMIT

The inverse relaxation time has been derived making use of the relation

$$1/\tau = \omega_c R/2B$$  \hspace{1cm} (2)

where $\omega_c = eB/m^*c$ is the cyclotron angular frequency, $m^*$ the effective mass of the conduction electron, $R$ the cyclotron resonance linewidth, $B$ the resonance magnetic field. The bracket represents an appropriate average over the electron energy distribution.

In the classical limit, $h\omega_c < kT$, we consider the next well-known two cases with neutral donor and acoustic deformation potential scatterings

(1) Neutral donor scattering in the classical limit: The inverse relaxation time is expressed by Erginsoy's formula (20)

$$1/\tau_{ND}^D = 20\hbar R_n^m N_{ND}/\kappa^*$$  \hspace{1cm} (Erginsoy)

$$1/\tau_{ND}^D = 3.4 \times 10^{-4} N_{ND}^m s^{-1} \quad \text{(GaAs)}$$  \hspace{1cm} (4)

($\kappa^*$ classical prediction by Erginsoy)

(2) Acoustic deformation potential scattering in the classical limit: Bardeen-Shockley [22] gives the following relation

$$1/\tau_{AD}^D = 3\kappa^*^3/2\hbar^2 (k_B T)^{3/2}/2^{3/2} \ 1/2\hbar^2 \rho_m v_s^2$$  \hspace{1cm} (Bardeen-Shockley)

where $\kappa^*$ is the acoustic deformation potential, $\rho_m$ the density of mass and $v_s$ the sound velocity. Substituting typical values for Ge into (5) when magnetic field is applied (111) direction, $\kappa^* = 0.22$ and $v_s = 5.6 \times 10^3$ cm/s, we have

$$1/\tau_{AD}^D = 3.1 \times 10^8 \ k_B T$$  \hspace{1cm} (5)

Relation (6) has confirmed by D.C. [23] and microwave cyclotron resonance [1]-[5] experiments. Next we consider the experimental results of cyclotron resonance linewidth in the quantum limit.

(1) Neutral donor scattering in GaAs in the quantum limit: On account of intrinsic photoexcitation by xenon flash lamp, ionized donors and acceptors are completely neutralized. Re-ionization is very slow below 4.2 K.

![Fig. 1. Dependence on the neutral donor concentration of the inverse relaxation time in GaAs-1-GaAs-5 samples for the wavelength of 220 µm at 4.2 K. The classical prediction by Erginsoy is shown for comparison.](image-url)
The contribution of carrier-carrier scattering has been eliminated by taking signal at a sufficiently long interval between photoexcitation and aperture, when the resonance linewidth becomes constant in time. Figure 1 shows the inverse relaxation time against the neutral donor concentration for the wavelength of 220 µm at 4.2 K. We find \( E_{\text{ND}}/k_B = 65.3 \) K so that the quantum limit conditions are well satisfied at 4.2 K. Neutral donor concentration ranges from 7.5 \( \times 10^{14} \) to 5.5 \( \times 10^{15} \) cm\(^{-3}\). The effective Bohr radius of shallow donor with typical binding energy of 5.8 meV is 99 Å and according to the postulate that neutral donor should be isolated. As showing in Fig. 1, the inverse relaxation time is proportional to the neutral donor concentration.

These experimental results also indicate that contribution of electron-phonon scattering can be neglected for the neutral donor concentration above 7.5 \( \times 10^{14} \) cm\(^{-3}\) in GaAs. Erginsoy's prediction is shown in Fig. 1 for comparison. The inverse relaxation time for neutral donor scattering in GaAs and GaAs-3 samples at 4.2 K is shown in Fig. 3. Wavelengths used in these experiments are 513 to 84 µm, corresponding to \( E_{\text{ND}}/k_B = 28.1 \) to 170 K. The inverse relaxation time is found to be proportional to the reciprocal of the square root of magnetic field. As mentioned above, we have the following relation for neutral donor scattering in GaAs in the quantum limit.

\[
\frac{1}{\tau_{\text{ND}}} = 1.1 \times 10^{-2} N_{\text{ND}} B^{-1/2} \ 	ext{s}^{-1} \ 	ext{(GaAs)}
\]

(2) Acoustic deformation potential scattering in Ge in the quantum limit: This is expected to be dominant in pure Ge over a temperature range 10.0 and 160 K. We have removed the contribution of carrier-carrier scattering by the same method as mentioned in the section of neutral donor scattering in GaAs. Figure 4 indicates the dependence of the inverse relaxation time for a wavelength of 172 µm over a temperature range between 10.0 and 160 K. For comparison, the classical limit experiments and prediction are shown in Fig. 4. As \( E_{\text{ND}}/k_B = 121 \) K, T=120 K corresponds to the classical region. As seen from Fig. 4, the inverse relaxation time is found to be proportional to temperature. This is in deviation from the classical prediction (\( \propto T^{1/2} \)) and, in addition, the magnitude is larger than that in the classical limit. Figure 5 shows magnetic field dependence at 20.0 K for wavelengths of 220, 172 and 119 µm or for effective temperatures of \( E_{\text{ND}}/k_B = 56.3, 83.7 \) and 121 K, respectively. The quantum limit conditions are met at 20.0 K. The inverse relaxation time is shown to be proportional to the square root of the magnetic field. Consequently, we get for acoustic deformation scattering in Ge.

\[
\frac{1}{\tau_{\text{DA}}} = 2.4 \times 10^{-7} T B^{1/2} \ 	ext{s}^{-1} \ 	ext{(Ge[111])}
\]

This is qualitatively explained by Meyer's prediction (\( \propto T B^{1/2} \)) for moderate temperatures when the wavelength is 119 µm. Arora-Spector's and Suzuki-Chol-Pujita's predictions (\( \propto T B^{1/2} \)) cannot be applied to our experimental results. The formula (8) agrees excellently well with Miura-Kido-Chikazumi's experimental results in Ge for the wavelength of 10.8 µm at 300 K. Ohyama-Murase-Otsuka have carried out microwave (71 GHz, \( E_{\text{ND}}/k_B = 34 \) K) cyclotron resonance experiment in pure Ge below 1 K. They have found that the inverse relaxation time tends to be independent of temperature below 1 K for acoustic deformation potential scattering and this result corresponds to Meyer's prediction for very low temperature. The inverse relaxation time is found to be proportional to temperature. We have for GaAs, \( \frac{1}{\tau_{\text{ND}}} = 1.1 \times 10^{-2} N_{\text{ND}} B^{-1/2} \ 	ext{s}^{-1} \) against the classical prediction.

CONCLUSIONS

The relaxation time has been obtained from the cyclotron resonance linewidth in the quantum region: neutral donor scattering in GaAs and acoustic deformation potential scattering in Ge. It is found that (1) the inverse relaxation time for neutral donor scattering is proportional to neutral donor concentration and the reciprocal of the square root of magnetic field. It is independent of temperature. We have for GaAs, \( \frac{1}{\tau_{\text{ND}}} = 1.1 \times 10^{-2} N_{\text{ND}} B^{-1/2} \ 	ext{s}^{-1} \).
The same for acoustic deformation potential scattering is proportional to temperature and the square root of $\gamma_{GD} = 2.4 \times 10^{-4}$ NND (s$^{-1}$) (Erginsoy). (2) We have for Ge, $1/\tau_{AD} = 2.4 \times 10^{-2}$ TB (s$^{-1}$) against the classical prediction $1/\tau_{AD} = 3.1 \times 10^{5}$ T$^{3/2}$ (s$^{-1}$) (Bardeen-Shockley).

5. ACKNOWLEDGEMENTS

This work has been supported by Grant in Aid for Scientific Research from the Ministry of Education, Science and Culture.

6. REFERENCES