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Density Dependence of Electron Spin Relaxation Time in GaA

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Abstract

The electron density dependence of the electron spin relaxation time in a system of electrons interacting with phonons through phonon-modulated spin-orbit coupling was calculated using the formula for electron spin resonance derived by the projection-reduction method. The electron spin relaxation time in GaAs increased with increasing electron density, and the electron density was found to affect the electron spin relaxation differently according to temperature. The electron spin in GaAs was relaxed mainly by optical phonon scattering at high electron densities and piezoelectric phonon scattering at relatively low electron densities.

Keywords

1. Introduction

Electron spin relaxation in semiconductors has attracted considerable attention because of its essential role in the application of spintronic devices [1]-[3]. Important electron spin relaxation mechanisms include the Elliot-Yafet (EY) [4] [5] and "Dyakonov-Perel" (DP) [6] mechanisms. For larger gap materials, the DP mechanism has been shown to dominate the spin relaxation at high temperatures [7]-[10], whereas Dzhioev *et al*. [11] report that the dependence of the spin-relaxation rate on the electron mobility in lightly doped n-GaAs bulk crystals disagrees with the results predicted by the DP mechanism. They attribute the spin relaxation to the electron-electron interaction. Many studies have examined the temperature and magnetic field dependence of the spin relaxation time [11]-[15], whereas the dependence of the spin relaxation time on the carrier concentration has received relatively little attention [9] [16]. Murdin *et al*. [16] show that the carrier density dependence of the spin lifetime in InAs is reversed at $n_e = 1 \times 10^{23}$ m^{-3} and suggest that electron-electron interaction affects the dependence of the spin lifetime on the carrier concentration.

This study calculates the electron density dependence of the electron spin relaxation time in a system of electrons interacting with piezoelectric acoustic and polar optical phonons through phonon-modulated spin-orbit coupling using the formula for the electron spin resonance obtained using the Kang-Choiprojection-Reduction (KCPR) method [17]. In spintronics, preserving the information injected into spin over a practical timescale is important for spintronics devices. Therefore, it is important to understand how the Planck distribution function for phonons and the Fermi distribution function for electrons are included in the spin relaxation time because the density and temperature dependence of the spin relaxation time are caused by the distribution functions. The formula used in this paper includes two distribution functions in multiplicative forms (not in simple additive forms), which is physically acceptable because electrons and phonons belong to different categories in a quantum-statistical classification. Therefore, the absorption and emission processes of phonons and photons in all electron transition processes can be explained in an organized manner, and the spin flipping and conserving processes can be interpreted from a fully microscopic point of view [18].

This paper investigates the effects of piezoelectric acoustic and optical phonon scatterings on the electron spin relaxation. For that purpose, the electron density and temperature dependence of the spin relaxation time in GaAs are calculated and the results are discussed by a comparison with the experimental data.

2. Review of Theory

An electron transferred from a spin down state with a lower energy to a spin up state with a higher energy by absorbing electromagnetic radiation must return to the spin down state by an interaction with the background. This process is characterized by the electron spin relaxation time, T_1, which is related to the line shape function, $\Gamma(\omega)$, where ω is the angular frequency of the electromagnetic wave, as $\hbar/T_1 = 2\mathrm{Im}\{\Gamma(\omega)\}$, where it means "the imaginary part of". $\Gamma(\omega)$ is contained in the electron spin resonance formula.

The electron spin relaxation time in a system of electrons interacting with phonons through phonon-modulated spin-orbit coupling is expressed as [17] [18]

$$
\begin{aligned}
\frac{1}{T_1} = \frac{2\pi}{\hbar(f_{\alpha-} - f_{\alpha+})} \sum_{q,\gamma} \Big[& \{T_+(\alpha-,\gamma+) + T_-(\alpha-,\gamma+)\} |C_{\gamma+,\alpha+}(q)|^2 \\
& + |C_{\alpha-,\gamma+}(q)|^2 \{T_+(\gamma+,\alpha+) + T_-(\gamma+,\alpha+)\} \\
& + \{T_+(\alpha-,\gamma-) + T_-(\alpha-,\gamma-)\} |C_{\gamma-,\alpha+}(q)|^2 \\
& + |C_{\alpha-,\gamma-}(q)|^2 \{T_+(\gamma-,\alpha+) + T_-(\gamma-,\alpha+)\} \Big]
\end{aligned}
\tag{1}
$$

Here $f_{\alpha s_\alpha}$ is the Fermi distribution function for an electron with energy E_{α,s_α} and spin s_α, $T_+(\alpha-,\beta+)[T_-(\alpha-,\beta+)]$ means the clockwise (counterclockwise) spin flipping process between the states, $\alpha-$ and $\beta+$, and $T_+(\alpha\pm,\beta\pm)[T_-(\alpha\pm,\beta\pm)]$ is the clockwise (counterclockwise) spin conserving process between the states, $\alpha\pm$ and $\beta\pm$ [17]. The energy eigenvalue under a static magnetic field, B, applied along the z-axis can be written as

$$
E_{\alpha,s_\alpha} = (n_\alpha + 1/2)\hbar\omega_c + \hbar^2 k_{z\alpha}^2/2m_l + g\mu_B B s_\alpha/2,
\tag{2}
$$

where $n_\alpha = 0,1,2,\cdots$, $\omega_c = eB/m_t$ is the cyclotron frequency, $k_{z\alpha}$ is the z-component of the electron wave vector, g is the electron g-factor, μ_B is the Bohr magneton, $s_\alpha = +(-1)$ for an up (down) spin, and m_t (m_l) is the transverse (longitudinal) effective mass. In Equation (1), the electron-phonon coupling factor, $C_{\alpha s_\alpha, \beta s_\beta}(q)$, is given as [4] [5]

$$
C_{\alpha s_\alpha, \beta s_\beta}(q) = \frac{\hbar}{4m_e^2 c^2} \langle \alpha s_\alpha | [\nabla V_{ep} \times (\boldsymbol{p} + e\boldsymbol{A})] \cdot \boldsymbol{\sigma} | \beta s_\beta \rangle,
\tag{3}
$$

where m_e is the effective mass of an electron, c is the speed of the light, $\boldsymbol{p}$ is the momentum operator of an electron, $\boldsymbol{A} = (0, Bx, 0)$ is the vector potential, $\boldsymbol{\sigma}$ is the Pauli spin matrix, and V_{ep} is the electron-phonon interaction potential that depends on the mode of the phonons.

The first two terms in Equation (1) can be interpreted as follows: $T_\pm(\alpha-,\gamma+)$ means an implicit spin flipping process between an initial spin down state ($\alpha-$) and an implicit spin upstate ($\gamma+$). Photon absorption or

emission processes and phonon absorption or emission processes are included in $T_{\pm}(\alpha-,\gamma+)$ (**Figure 1(a)**) corresponds to $T_{+}(\alpha-,\gamma+)$. These processes form loops because the phonon absorption process maintains balance with the emission process. $C_{\gamma+,\alpha+}(q)$, which is denoted by a blue (right) spring in **Figure 1(a)**, means that an implicit spin up state is induced from a final spin up state ($\alpha+$) by an electron-phonon interaction. The implicit spin up state and down state ($\gamma-$) are thus named because they are included only in the relaxation time, not in the electron spin resonance formula. The second two terms correspond to the spin conserving processes, *i.e.*, $T_{\pm}(\gamma+,\alpha+)$ means an implicit spin conserving process between an implicit spin up state and a final spin up state, and $C_{\alpha-,\gamma+}(q)$ means that the implicit spin up state is induced from the initial spin down state (**Figure 1(b)**) corresponds to $T_{+}(\gamma+,\alpha+)$. The other four terms in Equation (1) can be interpreted in a similar manner [18].

3. Numerical Results

Piezoelectric acoustic and polar optical phonon interactions are the dominant scattering mechanisms at high temperatures in III-V compounds. The acoustic strain induced by pressure in a crystal whose lattice lacks inversion symmetry gives rise to a macroscopic electric field, which is assumed to be proportional to the derivative of the atomic displacement, $\boldsymbol{u} = \sum_q \sqrt{\hbar/2\rho_m V_0 \omega_q} \left(b_q + b_{-q}^+\right) e^{iq\cdot r} \hat{\boldsymbol{e}}_q$, where ρ_m is the mass density, V_0 is the volume of the system, $\hat{\boldsymbol{e}}_q$ is the polarization vector, and $b_q (b_q^+)$ is the annihilation (creation) operator for a phonon with energy $\hbar\omega_q$. In contrast, ∇V_{ep} is proportional to the polarization for the optical mode because the electric displacement is proportional to the polarization. Then, Equation (3) can be expressed as follows:

$$C_{\alpha s_\alpha,\beta s_\beta}(q) = \frac{\hbar D_q}{4m_e^2 c^2}\left\langle \alpha s_\alpha \left|\left[\nabla e^{iq\cdot r} \times (\boldsymbol{p} + e\boldsymbol{A})\right]\cdot\boldsymbol{\sigma}\right|\beta s_\beta\right\rangle \tag{4}$$

Here, $D_q = P_{po}q\sqrt{\hbar/2\rho_m V_0 \omega_q}\big/\left(q^2 + q_d^2\right)$ for polar optical phonon scattering and $D_q = \sqrt{\hbar/2\rho_m V_0 \omega_q} \times P_{pe}q^2\big/\left(q^2 + q_d^2\right)$ for piezoelectric phonon scattering, where two proportional constants, P_{po} and P_{pe}, are used as the fitting parameters, $q_d = \sqrt{n_e e^2/\epsilon\epsilon_0 k_B T}$ is the reciprocal of the Debye screening length, and ϵ and n_e are the static dielectric constant and electron density, respectively. D_q (screening effect) decreases (increases) with increasing electron density.

The electron spin relaxation time in GaAs was calculated numerically for $n_\alpha = 0$ at the sub and edge ($k_{z\alpha} = 0$) in the quantum limit. **Figure 2** shows the electron density dependence of the electron spin relaxation times by piezoelectric acoustic and optical phonon scattering at $T = 300$ K for $B = 0.1$ T, $P_{pe} = 5.7 \times 10^{24}$ eV/m, and $P_{po} = 3.9 \times 10^{26}$ eV/m^2, where Matthiessen's rule [19] was adopted to add the relaxation time by piezoelectric phonon scattering (T_1^{pe}) and that by optical phonon scattering (T_1^{op}) to the total spin relaxation time (T_1) as $1/T_1 = 1/T_1^{pe} + 1/T_1^{op}$. The spin relaxation time increases with increasing electron density because the spin relaxation time is proportional to the inverse of the relaxation rate, which decreases with increasing screening effect as the electron density is increased. The electron spins are relaxed mainly by optical phonon scattering at high electron densities and piezoelectric phonon scattering at relatively low electron densities.
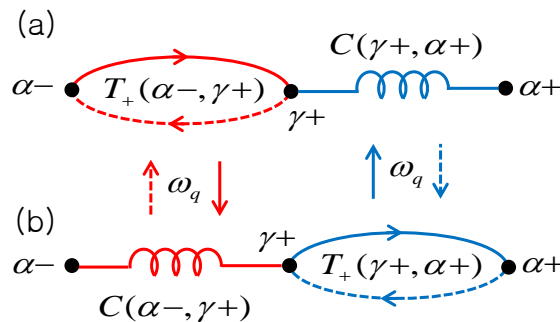

Figure 1. Diagrammatic representation of the first and third terms in Equation (1). A photon with frequency ω is absorbed (emitted) during the forward (backward) process in a loop and a phonon with frequency ω_q is absorbed (emitted) from (to) the spring during the lower (upper) half circle process. The red (left) and blue (right) processes correspond to the spin flipping and conserving processes, respectively.
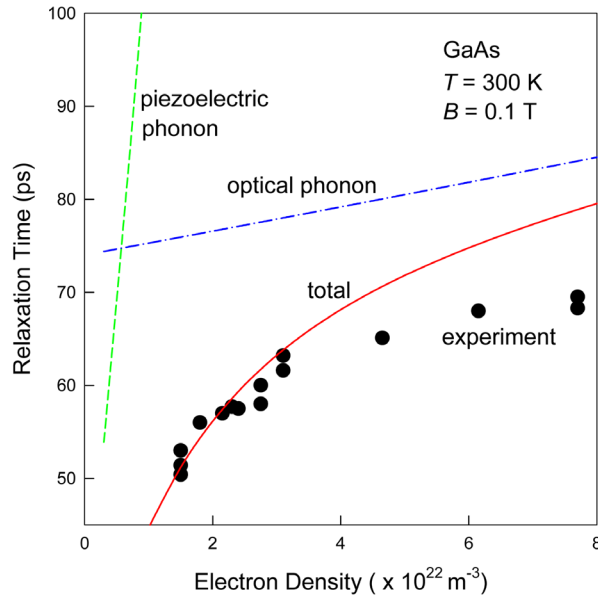
Figure 2. Electron density dependence of the electron spin relaxation time in GaAs at $T = 300\,\text{K}$ and $B = 0.1\,\text{T}$. The electron spins are relaxed mainly by the piezoelectric phonons at relatively low electron densities and the optical phonons at high electron densities. The black circles denote the results reported by Oertel *et al*. [9]

The energy of optical phonon is almost constant and that of piezoelectric phonon is dependent on the wave vector as $\hbar\omega_q = \hbar v_s q$ where v_s is the speed of sound. Therefore, $D_q \propto q^{3/2}/\left(q^2 + q_d^2\right)$ for piezoelectric phonon scattering and $D_q \propto q/\left(q^2 + q_d^2\right)$ for optical phonon scattering. **Figure 3** and **Figure 4** show the q-dependence of D_q for several electron densities. The spin relaxation times by piezoelectric phonon and optical phonon scattering increase because D_q decreases with increasing electron density. The spin relaxation time increases with increasing number of phonons and the number of piezoelectric phonon decreases within creasing q, whereas the number of optical phonons is independent of q. Therefore, the spin relaxation time by piezoelectric phonon scattering increases more sharply than that by optical phonon scattering because the maximum points of D_q are shifted to the right and the number of piezoelectric phonon contributing strongly to the spin relaxation decreases with increasing electron density.

The electron density dependence of the spin relaxation time at relatively low electron densities is similar to the experimental result reported by Oertel *et al*. [9] (the black circles in **Figure 2**). On the other hand, some experimental results [20]-[22] showed that the spin relaxation time increases with increasing carrier density and then decreases after reaching a maximum value at approximately $n_e = 1 \times 10^{23}\,\text{m}^{-3}$. Therefore, the discrepancy at relatively high electron densities ($> n_e = 1 \times 10^{22}\,\text{m}^{-3}$) can be corrected if the electron-electron interaction is considered because the spin relaxation time (rate) by the electron-electron interaction decreases (increases) with increasing electron density. **Figure 5** shows the temperature dependence of the relaxation relaxation times for different electron densities. The spin relaxation time decreases with increasing temperature because the number of phonons increases with increasing temperature. The spin relaxation time by piezoelectric phonon scattering decreases more sharply with increasing electron density than that by optical phonon scattering for the same reason shown in **Figure 2**.

4. Conclusions

This study calculated the electron spin relaxation time in a system of electrons interacting with piezoelectric acoustic and optical phonons through phonon-modulated spin-orbit coupling using the formula for the electron spin resonance obtained using the Kang-Choiprojection-Reduction (KCPR) method. The electron density dependence of the spin relaxation time was determined by D_q and the distribution functions. The electron spin re-
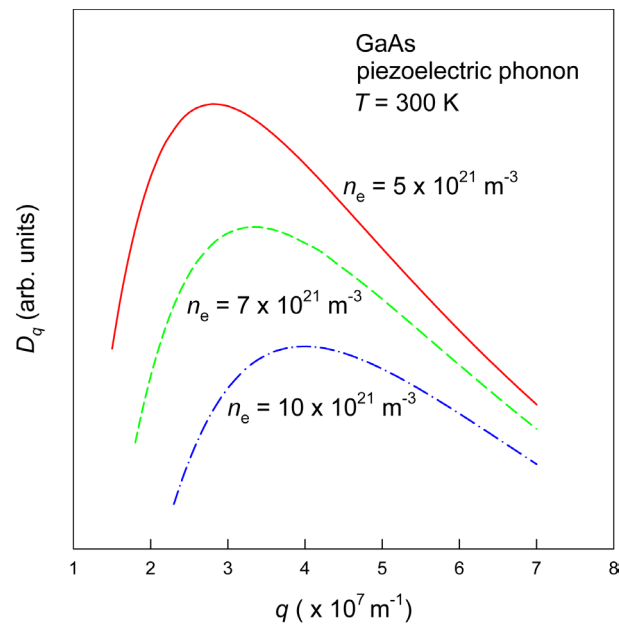
Figure 3. q-dependence of D_q for piezoelectric phonon scattering in GaAs at $T = 300\,\text{K}$. D_q decreases and the maximum point of D_q shifts to the right with increasing electron density.
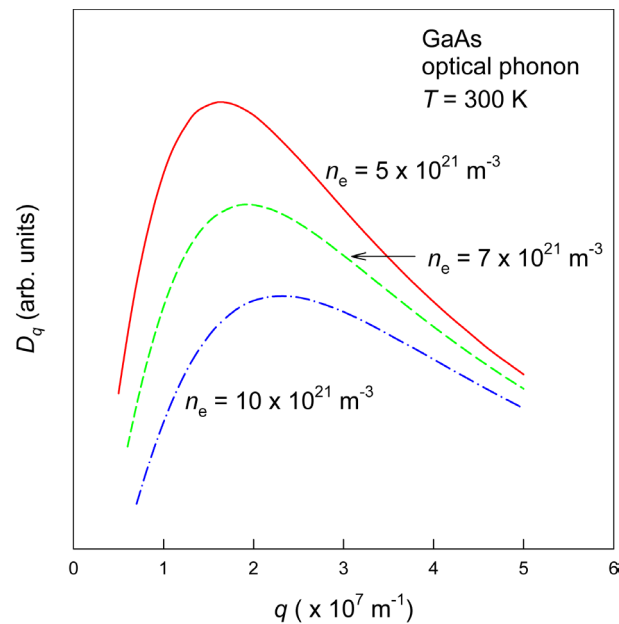

Figure 4. q-dependence of D_q for optical phonon scattering in GaAs at $T = 300\,\text{K}$. D_q decreases and the maximum point of D_q shifts to the right as the electron density is increased.

laxation in GaAs was caused mainly by optical phonon scattering at high electron densities and piezoelectric phonon scattering at relatively low electron densities. The spin relaxation time decreased with increasing temperature and the electron density affected the electron spin relaxation differently according to temperature. The spin relaxation time increased with increasing electron density due to the screening effect. The meaning of two fit
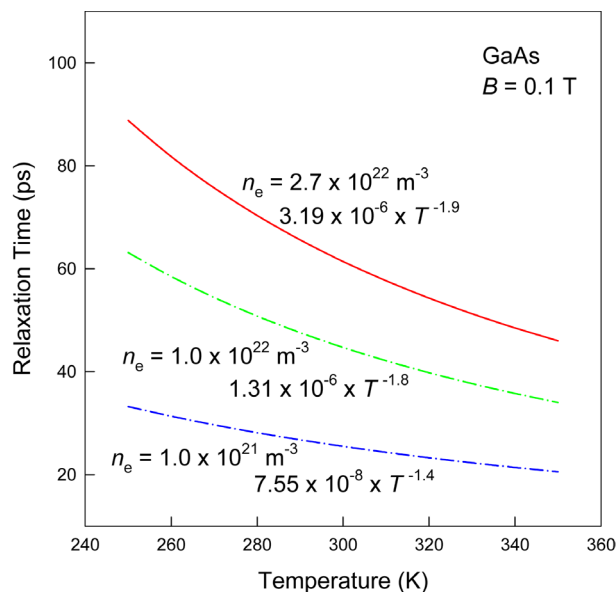
Figure 5. Temperature dependence of the electron spin relaxation times in GaAs for several electron densities at $B = 0.1\,\text{T}$. The relaxation times decrease with different exponents for different electron densities as the temperature is increased.

ting parameters, P_{pe} and P_{po}, was unclear at the present time. They affected the magnitude of the spin relaxation and it was inferred that they were related with the piezoelectric coupling constant ($\bar{K}^2$) and Fröhlich coupling constant (α), respectively.

On the other hand, the spin relaxation time will decrease if the electron-electron interaction is considered at high electron densities. Therefore, it is expected that the electron spin relaxation time will increase with increasing electron density and then decrease after reaching a maximum value. Although it has been reported that the DP mechanism is important in a metallic regime [3] [23] for bulk III-Vn-type semiconductors, it is inferred that the DP mechanism can be quenched by an applied magnetic field or the (Dresselhaus) spin-orbit coupling term in conduction band can be suppressed at low electron densities. The formula used in this paper is applicable to the phonon-modulated spin-orbit interaction, which is dominant scattering mechanism at low electron density. Therefore, the formula is applied to GaAs at low electron density. By the Matthiessen's rule, the total spin relaxation time (T^{tot}) is given by $1/T^{\text{tot}} = 1/T^{\text{EY}} + 1/T^{\text{other}}$, where T^{EY} is the spin relaxation time by the EY mechanism and T^{other} is the spin relaxation times by the other mechanisms including the "Dyakonov-Perel" (DY) mechanism. Therefore, small spin relaxation time corresponds to the dominant spin relaxation mechanism and the spin relaxation time by a single spin relaxation mechanism must exceed the experimental result. In conclusion, this paper shows that the dominant spin relaxation mechanism in bulk GaAs at low electron density is EY mechanism (**Figure 1**). The discrepancy between the present result and the experimental data [9] at high electron density may be corrected if other spin relaxation mechanisms such as electron-electron interaction and the DY mechanism or Marqulis and Marqulis (MM) mechanism [24] are considered. These will be examined using the present KCPR method in the future.

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