Electron Spin Relaxation under Drift in GaAs

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Based on a Monte Carlo method, we investigate the influence of transport conditions on the electron spin relaxation in GaAs. The decay of initial electron spin polarization is calculated as a function of distance under the presence of moderate drift fields and/or non-zero injection energies. For relatively low fields (a couple of kV/cm), a substantial amount of spin polarization is preserved for several microns at 300 K. However, it is also found that the spin relaxation rate increases rapidly with the drift field, scaling as the square of the electron wavevector in the direction of the field. When the electrons are injected with a high energy, a pronounced decrease is observed in the spin relaxation length due to an initial increase in the spin precession frequency. Hence, high-field or high-energy transport conditions may not be desirable for spin-based devices.

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Recently, there has been an increasing interest in the emerging field of spintronics (spintronics), where the electron’s spin degree of freedom is exploited. Many devices and applications, including giant-magnetoresistive structures and magnetic random access memories, have been suggested with varying degrees of success. Furthermore, the suggestion of utilizing electron spin for quantum information processing is a natural extension of spintronics since the electron provides an ideal condition for a qubit.

Of the potential applications, the hybrid devices that combine “traditional” semiconductor electronics with the utilization of the spin state are currently at the center of attention for their increased functionality and the ease of integration. Electron spin states in semiconductor structures relax (depolarize) by scattering with imperfections or elementary excitations such as other carriers and phonons. Therefore, to realize any useful spintronic devices, it is essential to understand and have control over spin relaxation such that the information is not lost before a required operation is completed. So far, most of the studies on spin relaxation have been focused on electrons with a thermal or near-thermal distribution. However, electron spins in the spin-based devices can be subject to highly non-thermal transport conditions including high drift fields for high-speed transfer of spin information.

In this work, we investigate the influence of transport conditions on electron spin relaxation in n-type GaAs. A Monte Carlo approach is used to simulate electron transport, including the evolution of spin polarization, to determine spin relaxation lengths and times. A non-parabolic energy-band model (with Γ − L − X valleys) is used along with the relevant momentum relaxation mechanisms such as polar optical and acoustic phonon deformation potential scattering. Of the three main spin relaxation mechanisms [i.e., Bir-Aronov-Pikus, Elliot-Yafet, and D’yakonov-Perel’ (DP) mechanisms, we only consider the DP processes since this is the dominant mechanism in the regime of interest, namely GaAs at 300K. It is also important to note that the current study is limited to the low energy cases, such that electrons are found only in the Γ valley. This is due to the lack of material parameters on spin-orbit splitting in higher energy valleys.

The DP Hamiltonian due to spin-orbital splitting of the conduction band may be written as

\[ H = \frac{\hbar}{2} \sigma \cdot \vec{\Omega}_{\text{eff}} \]

and

\[ \vec{\Omega}_{\text{eff}} = \frac{\alpha \hbar^2}{m \sqrt{2mE_g}} [k_x (k_y^2 - k_z^2) \hat{x} + \text{cyclic perm.}] \]

where \( \alpha \) is a dimensionless, material-specific parameter which gives the magnitude of the spin-orbit splitting \( \alpha \approx 4\eta m/\sqrt{3 - 3\eta}m_0 \) and \( \eta = \Delta/(E_g + \Delta) \), \( m \) is the effective mass, \( \vec{k} \) is the electron wave vector, \( E_g \) is the energy separation between the conduction band and valence band at the Γ point, and \( \Delta \) is the spin-orbit splitting of the valence band. The material parameters for GaAs are listed in Table I.

The quantum mechanical description of the evolution of the spin 1/2 is equivalent to the evolution of the classical momentum \( \vec{S} \) under an effective magnetic field \( \vec{\Omega}_{\text{eff}} \) with the equation of motion

\[ \frac{d\vec{S}}{dt} = \vec{\Omega}_{\text{eff}} \times \vec{S}. \]

| \( m/m_0 \) | \( \hbar\omega_0 \) | \( E_l \) | \( E_g \) | \( \alpha_{np} \) | \( \Delta \) |
|-----------|------------|--------|--------|--------|------|
| 0.067 | 0.0354 | 7.0 | 1.424 | 0.616 | 0.341 |

TABLE I. Material Parameters for GaAs. \( m/m_0 \) is the Γ valley effective mass ratio, \( \hbar\omega_0 \) is the optical phonon energy, \( E_l \) is the acoustic phonon deformation potential, \( E_g \) is the energy band gap separation at the Γ point, \( \alpha_{np} \) is the non-parabolicity factor in the Γ valley, and \( \Delta \) is the spin-orbit splitting of the valence band.
Figure 1 depicts the average polarization \( < P > \) of electrons as a function of distance in GaAs. The simulation follows the evolution of \( 1 \times 10^4 \) spin-polarized electrons from an injection plane. Although all electrons are initially polarized (\( < P_0 > = 1 \)), polarization at \( x = 0 \) in this figure is not exactly unity due to the averaging over a finite mesh size. Clearly, \( < P > \) decays nearly exponentially with an order of magnitude drop (to 0.1) in approximately 4 \( \mu \text{m} \) to 7 \( \mu \text{m} \) (5.5 \( \mu \text{m} \) to 9 \( \mu \text{m} \) when the non-parabolicity is not considered).

The observed dependence of decay on the applied electric field is non-monotonous with the result of 2.5 \( \mu \text{m} \) (to 0.1) in approximately 4 \( \mu \text{m} \) to 7 \( \mu \text{m} \) (5.5 \( \mu \text{m} \) to 9 \( \mu \text{m} \) when the non-parabolicity is not considered).

The solid line in Fig. 2 provides the fitted non-parabolic band. This finding indicates that the common assumption of constant polarization \( < P > \) for the parabolic energy band is not valid in the non-parabolic case for fields higher than approx. 1.5 \( \text{kV/cm} \). The values for \( \tau_s \) at the low fields agree well with those obtained for near thermal electrons.

The dependence of spin relaxation on electric field can be best understood by considering the functional form of the effective magnetic field in Eq. (2). When the applied electric field is along the \( x \) direction, the interaction Hamiltonian reduces approximately to

\[
H \propto (k_z \hat{z} - k_y \hat{y}) k_x^2.
\]

Since the average values of \( k_y \) and \( k_z \) remain small, it is reasonable to assume that \( \tau_s^{-1} \) will scale as \( < k_x^2 > \). The solid line in Fig. 2 provides the \( < k_x^2 > \) scaling for the non-parabolic band, which clearly illustrates good agreement over the entire field range under consideration. This finding indicates that the common assumption of electron temperature \( T \) to the third power dependence \([i.e., 1/\tau_s^{DP} \propto (k_BT)^3 \tau_p]\), where \( \tau_p \) is the momentum relaxation time)\[^{7,10}\] substantially overestimates the spin relaxation rates in the drift regime. Considering the nature
of drift in this case, the $T^2$ scaling may be more appropriate.

However, the applicability of this scaling rule is also limited. As the electron temperature increases, it is clear that one needs to take into account the effect of non-parabolicity on the spin-orbit splitting (i.e., DP Hamiltonian) itself. By ignoring the higher band contributions, Pikus and Titkov obtained the following estimation in place of $\alpha m^{-3/2}$ in Eq. (2) with the rest of the terms unchanged:

$$\alpha(E)m^{-3/2}(E) = \alpha m^{-3/2} \left(1 - \frac{E(\vec{k})}{E_g} \frac{9 - 7\eta + 2\eta^2}{3 - \eta}\right).$$

(6)

At the constant electric field of 2.5 kV/cm, Eq. (6) results in $\alpha(E)m^{-3/2}(E)$ that is smaller than $\alpha m^{-3/2}$ by approximately 10%. The deviation shrinks as the electric field decreases, leading to a minor change in the $T^2$ scaling of $\tau_s^{-1}$. For the fields beyond the range currently under consideration (0.5–2.5 kV/cm), the influence of the additional term in Eq. (6) can become crucial.

In addition to the influence of the drift field, we also investigate spin transport and relaxation with varying injection energies. As mentioned earlier, one of the fundamental challenges in spintronics has been the electrical injection of spin polarized current into a semiconducting material. Noting recent suggestions for the utilization of tunnel injection, we may anticipate relatively high electron energies at the injection point.

In Fig. 3 we plot the results of simulations where the injection energy and applied electric field are changed. It can be seen that the electrons quickly lose the extra energy and their momentum distribution stabilizes within 1 µm or so, even in the cases of higher energy injection ($200 \text{ meV}$). Therefore, we have two distinct slopes. The first is a more rapid decay in the non-local transport region, corresponding to a large $\vec{K}$ and subsequently a large precession vector $\vec{\Omega}_{eff}$. Once thermalization occurs, the slope becomes smaller and eventually coincides with those shown in Fig. 1 with corresponding electric fields. For the 200 meV case with an applied field of 1 kV/cm, the reduction in depolarization length is fairly significant, approximately 20%.

In summary, we have investigated spin-dependent transport in GaAs in the drift regime. Specifically, we calculated the spin relaxation time and characteristic decay lengths based on a Monte Carlo model. The decay of electron spin polarization is found to be nearly exponential and the length at which spin relaxation/depolarization occurs was found to be relatively large, on the order of 5–10 µm. It is also found that the spin relaxation depends strongly on the drift conditions, scaling as the square of the electron wavevector in the direction of the field. Hence, the commonly assumed $T^3$ scaling is not applicable in the drift regime. When the electrons are injected with a high-energy, a significant reduction is observed in the spin relaxation length. Our calculation results are in good agreement with the data available in the literature.

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