

Doping Dependence of Spin Dynamics of Drifting Electrons in GaAs Bulks

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We study the effect of the impurity density on lifetimes and relaxation lengths of electron spins in the presence of a static electric field in an *n*-type GaAs bulk. The transport of electrons and the spin dynamics are simulated by using a semiclassical Monte Carlo approach, which takes into account the intravalley scattering mechanisms of warm electrons in the semiconductor material. Spin relaxation is considered through the D'yakonov–Perel mechanism, which is the dominant mechanism in III–V semiconductors. The evolution of spin polarization is analyzed by computing lifetimes and depolarization lengths as a function of the doping density in the range $10^{13} \div 5 \times 10^{16} \text{ cm}^{-3}$, for different values of the amplitude of the static electric field ($0.1 \div 1.0 \text{ kV/cm}$). We find an increase of the electron spin lifetime as a function of the doping density, more evident for lattice temperatures lower than 150 K. Moreover, at very low intensities of the driving field, the spin depolarization length shows a nonmonotonic behaviour with the density. At the room temperature, spin lifetimes and depolarization lengths are nearly independent on the doping density. The underlying physics is analyzed.

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1. Introduction

Spin dynamics is one of the central focuses of semiconductor spintronics. In fact, in order to make spintronics an usable technology, spin signal is required to sustain enough long time and/or enough long distance during transport. This is necessary to control and detect the spin polarization in logic operations, communication and storage of information. The loss of spin polarization before, during and after the necessary operations is a crucial point in spin device design. Therefore, a complete understanding of the effect of temperature, driving field amplitude and doping density on the spin dephasing is essential [1, 2].

Until now, the experimental investigation of the doping density influence on the ultrafast spin dynamics in bulk semiconductors have been performed at low temperature ($T < 80 \text{ K}$) [3–7]. In the detailed work of Dzhioev et al. [5], the dependence of the spin lifetime on the donor concentration at very low temperatures ($T < 5 \text{ K}$) shows a very unusual behavior, characterized by the presence of two maxima, ascribed to the predominance of one of the three different spin-relaxation mechanisms: hyperfine interaction, anisotropic exchange interaction, and the D'yakonov–Perel (DP) mechanism. Recently, Römer et al. [6] have measured the electron–spin relaxation in

bulk GaAs for doping densities close to the metal-to-insulator transition, finding that at temperatures higher than 30 K and densities lower than $8.8 \times 10^{16} \text{ cm}^{-3}$, all measurements are consistent with DP spin relaxation of free electrons since all electrons are delocalized and other spin-relaxation mechanisms can be neglected. From a theoretical point of view, by using a fully microscopic kinetic spin Bloch equation approach, a nonmonotonic dependence of the spin relaxation time on the donor concentration has been predicted, showing that the maximum spin relaxation time occurs at the crossing between the degenerate regime and the non-degenerate one [8, 9].

In this work, we study the impurity density effect on the fast process of relaxation of non-equilibrium electron spin polarization in GaAs bulks, by using a semiclassical Monte Carlo technique to solve the Boltzmann equation. We analyze the spin depolarization of drifting electrons at different lattice temperatures T by considering only the DP mechanism, which is dominant in *n*-type III–V semiconductors [1, 10]. This mechanism, effective in the intervals between the collisions, is related to the spin–orbit splitting of the conduction band in non-centrosymmetric semiconductors like GaAs [10].

2. Spin dynamics model and Monte Carlo approach

In a semiclassical formalism, the term of the single-electron Hamiltonian which accounts for the spin–orbit interaction can be written as

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$$H_{\text{SO}} = \frac{\hbar}{2} \boldsymbol{\sigma} \cdot \boldsymbol{\Omega}. \quad (1)$$

It represents the energy of electron spins precessing around an effective magnetic field [$\mathbf{B} = \hbar\boldsymbol{\Omega}/\mu_B g$] with frequency $\boldsymbol{\Omega}$, which depends on the orientation of the electron momentum vector with respect to the crystal axes [10]. The quantum-mechanical description of electron spin evolution is equivalent to that of a classical momentum \mathbf{S} experiencing the effective magnetic field, as described by the equation of motion

$$\frac{d\mathbf{S}}{dt} = \boldsymbol{\Omega} \times \mathbf{S}. \quad (2)$$

Every scattering event reorients the direction of the precession axis, making the orientation of the effective magnetic field \mathbf{B} (that strongly depends on \mathbf{k}) random and trajectory-dependent, thus leading to spin dephasing [10, 11].

The Monte Carlo code used here follows the procedure described in Ref. [12]. The spin polarization vector has been incorporated into the algorithm as an additional parameter and calculated for each free carrier, by following the procedure described in Ref. [11] with the difference that in the present paper we assume the spin-orbit coupling coefficient in Γ -valley (β_Γ) equal to 8.2 eV \AA^3 , as used in Ref. [9] to obtain a better fit with the experimental work of Kikkawa and Awschalom [3].

In our simulations we use a temporal step Δt of 10 fs and a 5×10^4 electron ensemble to collect spin statistics. To achieve the steady-state transport regime, we run the simulation code for a transient time (typically 10^4 time steps). After that, all the spin electrons are initialized, the spin relaxation begins and we collect data. All simulations are performed in an n -type GaAs bulk with a free electrons concentration varying in the range $10^{13} \div 5 \times 10^{16} \text{ cm}^{-3}$ (non-degenerate regime) by assuming that all donors are ionized. By an exponential fitting of the decay of the spin polarization we estimate the spin lifetime τ and the spin depolarization length L [11]. These parameters satisfy the relation $L = v_d \tau$, where v_d is the average drift velocity.

3. Numerical results and discussions

In Fig. 1, we show the electron spin lifetime τ as a function of the doping density n , for different values of applied electric field F , namely 0.1, 0.5 and 1.0 kV/cm. In each panel, we show four curves at the following values of lattice temperature T : 40, 77, 150 and 300 K.

Up to $T = 150 \text{ K}$, the electron spin lifetime is nearly independent of n until $n \approx 10^{15} \text{ cm}^{-3}$, then τ increases with the doping density. For $n > 10^{15} \text{ cm}^{-3}$ and for each value of the applied field, the longest value of τ is obtained at $T = 77 \text{ K}$ ($\tau_{\text{MAX}} \approx 14 \text{ ns}$ at $F = 0.1 \text{ kV/cm}$). At the room temperature (300 K), the spin lifetimes are almost insensitive to the impurity density. In the investigated range of n , the system is non-degenerate, i.e. the electron plasma temperature is much greater than the Fermi temperature ($T_e \gg T_F$). Hence the inhomogeneous broadening $\langle |\boldsymbol{\Omega}(\mathbf{k})|^2 \rangle$ is little sensitive to n , while

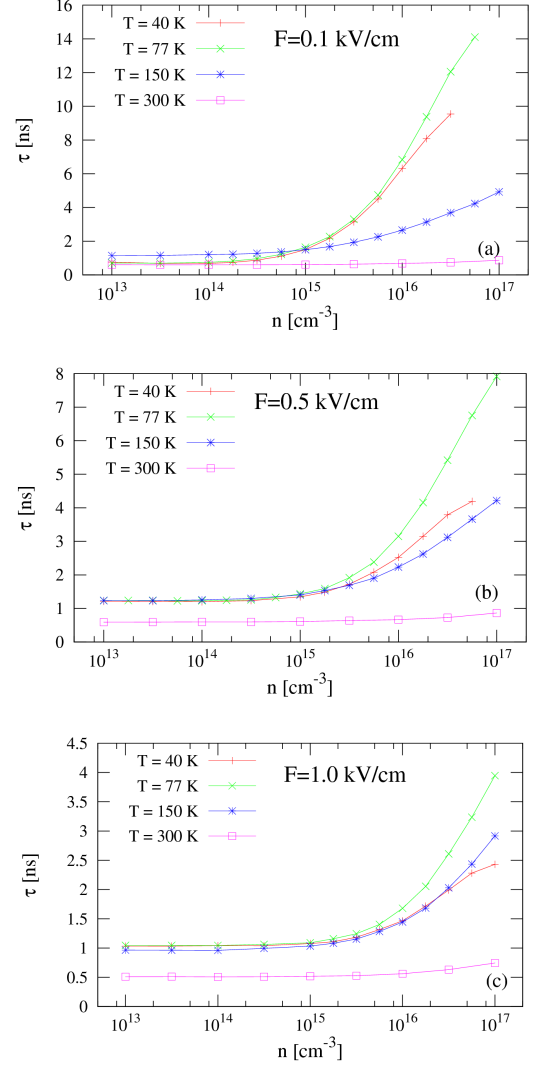


Fig. 1. Electron spin lifetimes τ as a function of the doping density n , for different amplitudes of the applied electric field, namely (a) $F = 0.1 \text{ kV/cm}$, (b) 0.5 kV/cm and (c) 1.0 kV/cm , and four different values of lattice temperature, namely $T = 40, 77, 150, 300 \text{ K}$.

the momentum scattering rate τ_p^{-1} is proportional to a linear function of n [9]. So, in accordance with the DP classical relation $\tau \propto (\langle |\boldsymbol{\Omega}(\mathbf{k})|^2 \rangle \tau_p)^{-1}$, for high values of n the spin lifetime τ increases with the doping density [10]. Moreover, for all the investigated intensities of the driving field, the relaxation time τ has a nonmonotonic behavior as a function of the temperature.

In Fig. 2, we show the electron spin depolarization length L as a function of the doping density n at the same values of applied electric fields and lattice temperatures used in Fig. 1. In particular, in part (a), i.e. for $F = 0.1 \text{ kV/cm}$, for $T < 150 \text{ K}$, L appears to be a nonmonotonic function of n , by showing a minimum at $n \approx 2 \times 10^{14} \text{ cm}^{-3}$. At higher temperatures, L is nearly independent of the doping density. For higher amplitudes

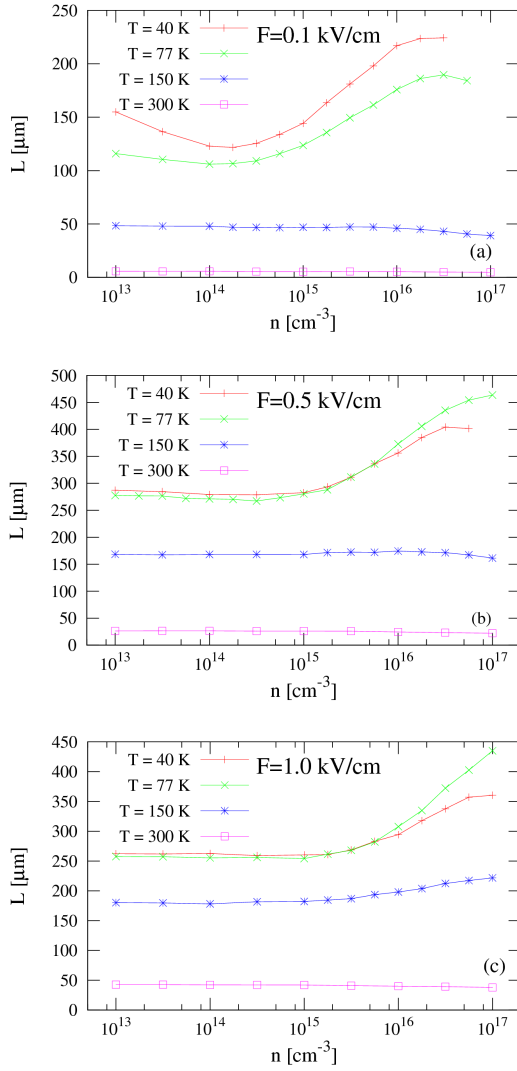


Fig. 2. Electron spin depolarization length L as a function of the doping density at different amplitudes of the applied electric field, namely (a) $F = 0.1$ kV/cm, (b) 0.5 kV/cm and (c) 1.0 kV/cm, and four different values of lattice temperature, namely $T = 40, 77, 150, 300$ K.

of the electric field (parts (b) and (c)), up to $T = 77$ K, L is insensitive to both the temperature and the doping density until $n \approx 10^{15}$ cm^{-3} and slightly increasing for higher values of n . For $T \geq 150$ K the effect of the doping density is marginal. To understand the behaviour of L as a function of n it is necessary to consider the interplay between τ and v_d in the relation $L = v_d \tau$. In fact, in the investigated range of n , the spin lifetime τ always increases with n ; on the contrary, v_d is a decreasing function of n . The nonmonotonic behavior of L , observed at

$F = 0.1$ kV/cm and T in the range $40 \div 77$ K, arises from the fact that for $10^{13} < n < 2 \times 10^{14}$ cm^{-3} , v_d decreases more rapidly than τ increases. Vice versa, for $n > 2 \times 10^{14}$ cm^{-3} , τ increases more quickly and hence L increases, too.

In conclusion, we studied the effect of the doping density on the ultrafast spin dynamics during drift transport in a n -type GaAs bulk below the metal-to-insulator transition. For lattice temperatures $T \leq 150$ K, the electron spin lifetime is an increasing function of the doping density, in accordance with the results reported in other works using different theoretical approaches [8, 9] and with the recent experimental results of Römer et al. [6]. Moreover, for very low intensities of the driving field, the spin depolarization length shows a nonmonotonic behaviour with the density. At the room temperature, the spin relaxation tends to be insensitive to the donor concentration.

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