Relaxation of electron spin during high-field transport in GaAs bulk

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Abstract. A semiclassical Monte Carlo approach is adopted to study the multivalley spin depolarization of drifting electrons in a doped n-type GaAs bulk semiconductor, in a wide range of lattice temperature (40 K < T_L < 300 K) and doping density (10^{13} \text{ cm}^{-3} < n < 10^{16} \text{ cm}^{-3}). The decay of the initial non-equilibrium spin polarization of the conduction electrons is investigated as a function of the amplitude of the driving static electric field, ranging between 0.1 and 6 kV cm^{-1}, by considering the spin dynamics of electrons in both the \Gamma-valley and the upper valleys of the semiconductor. Doping density considerably affects spin relaxation at low temperature and weak intensity of the driving electric field. At high values of the electric field, the strong spin–orbit coupling of electrons in the L-valleys significantly reduces the average spin polarization lifetime, but, unexpectedly, for field amplitudes greater than 2.5 kV cm^{-1}, the spin lifetime increases with the lattice temperature. Our numerical findings are validated by a good agreement with the available experimental results and with calculations recently obtained by a different theoretical approach.

Keywords: driven diffusive systems (theory), stochastic particle dynamics (theory), transport processes/heat transfer (theory), Boltzmann equation
1. Introduction

The processing of the high volumes of information and worldwide communication is, at present, based on semiconductor technology, whereas information storage devices rely on multilayers of magnetic metals and insulators. Semiconductor spintronics offers a possible direction for technological research towards the development of hybrid devices that could perform logic operations, communication and storage, within the same material technology: information could be stored in a system of polarized electron spins [1]–[11], transferred attached to mobile carriers and finally detected. The possibility of obtaining long spin relaxation times or spin diffusion lengths in electronic materials makes spintronics a viable prospective technology. Nevertheless, the designers of spin devices have to worry about the loss of spin polarization (spin coherence) before, during and after the necessary manipulations. In particular, efficient injection, transport, control and detection of spin polarization must be carefully treated [2]. Electron spin states depolarize by scattering from imperfections or elementary excitations of the medium, such as phonons. Furthermore, the miniaturization process forces the system to experience very intense electric fields, even when the applied voltages are very low. This means that, for the operability of prospective spintronic devices, the features of spin relaxation at relatively high electric fields should first be understood. In recent years there has been a proliferation of experimental works in which the influence of transport conditions on the relaxation of spins in semiconductors has been investigated [12]–[18]. All these works are focused on the study of coherent spin transport at low temperatures ($T_L < 30$ K) and under the influence of weak electric fields ($F < 0.1$ kV cm$^{-1}$), except for a few [12, 13] in which spin depolarization has been investigated with driving fields up to $6$ kV cm$^{-1}$.

The temporal evolution of the spin and the evolution of the momentum of an electron cannot be separated. The spin depolarization rates are functions of the electron distribution function in momentum space which continuously evolves with time when an
electric field is applied to drive the transport. Thus, the dephasing rate is a dynamic
variable that needs to be treated self-consistently in step with the dynamic evolution of
the electron’s momentum. A way to solve this problem is to describe the transport
of spin polarization by making use of Boltzmann-like kinetic equations. This can
be done within the density matrix approach [19], methods of non-equilibrium Green’s
functions, as the microscopic kinetic spin Bloch equation approach [20]–[24], [11], or
Wigner functions [25, 26], where the spin property is accounted for starting from quantum
mechanics equations.

Another way is to use a semiclassical Monte Carlo approach, by taking into account
the spin polarization dynamics with the inclusion in the code of the precession mechanism
of the spin polarization vector [27]–[34].

Both methods allow one to include the relevant spin relaxation phenomena for electron
systems and take into account the details of electron scattering mechanisms, material
properties and specific device design; their predictions have been demonstrated to be in
good agreement with experiments.

Theoretical descriptions of the transport of spin-polarized electrons have also been
achieved by the drift–diffusion approximation. The existing drift–diffusion schemes can
be classified into two approaches accounting differently for the spin degree of freedom: the
two-component drift–diffusion model and the density matrix based approximations [35]–
[37]. General conditions for the applicability of these approximations are not different
from the usual conditions of applicability of drift–diffusion approximations.

Despite decades of study, most theoretical or simulation research has considered only
the central valley $\Gamma$, since the spin–orbit coupling parameters of the upper conduction
bands have only recently been theoretically calculated by Fu et al [38]. Monte Carlo
approaches have been widely adopted by groups of scientists to study spin-polarized
transport in 2D channels, heterostructures, quantum wells, and quantum wires [27,28],
[30]–[33]. However, to date, to the best of our knowledge, in semiconductor bulk
structures a theoretical investigation of the influence of transport conditions on the spin
depolarization in the presence of high electric fields, with the comprehensive effects of
both lattice temperature and impurity density, is still lacking.

The aim of this work is to numerically estimate the spin lifetimes of an ensemble
of initially polarized electrons drifting in doped n-type GaAs bulks, with the lattice
temperature, doping density and electric field amplitude over a wide range of values,
focusing on the effects due to the inclusion of the upper valleys of the semiconductor on
the mechanism of depolarization.

The paper is organized as follows: in section 2 we briefly describe the multivalley
model, used for the study of the spin depolarization dynamics and the Monte Carlo
simulator; in section 3 the numerical results are given and discussed. Final comments and
conclusions are given in section 4.

2. Theory and Monte Carlo approach

2.1. Spin dynamics and multivalley model

Spin dephasing may be caused by interactions with local magnetic fields originating
from nuclei and spin–orbit interactions or magnetic impurities. The most relevant spin
Relaxation mechanisms for an electron system under the non-degenerate regime are: (i) the Elliott–Yafet (EY) mechanism, in which electron spins have a small chance to flip during each scattering, due to the spin mixing in the conduction band \[39,40\]; (ii) the Dyakonov–Perel (DP) mechanism, based on the spin–orbit splitting of the conduction band in non-centrosymmetric semiconductors, in which the electron spins decay due to their precession around the k-dependent spin–orbit fields (inhomogeneous broadening) during the free flight between two successive scattering events \[41,42,7\]; (iii) the Bir–Aronov–Pikus (BAP) mechanism, in which electrons exchange their spins with holes \[43\]. The hyperfine interaction is another mechanism, usually important for spin relaxation of localized electrons, but ineffective in the metallic regime where most of the carriers are in extended states \[44–46\].

Previous theoretical \[24,11\] and experimental \[47\] investigations indicate that the EY mechanism is totally irrelevant to electron spin relaxation in n-type III–V semiconductors. Hence, in this work we analyze the spin depolarization of drifting electrons in n-type GaAs semiconductors by considering only the Dyakonov–Perel process.

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

\[ H_{\text{SO}} = \frac{\hbar}{2} \vec{\sigma} \cdot \vec{\Omega}. \]  

(1)

It represents the energy of electron spins precessing around an effective magnetic field \[ \vec{B} = \hbar \vec{\Omega}/\mu_B g \] with angular frequency \( \vec{\Omega} \), which depends on the orientation of the electron momentum vector with respect to the crystal axes. Near the bottom of each valley, the precession vector can be written as \[46,38\]

\[ \vec{\Omega}_\Gamma = \beta_\Gamma \left[k_x (k_y^2 - k_z^2) \hat{x} + k_y (k_z^2 - k_x^2) \hat{y} + k_z (k_x^2 - k_y^2) \hat{z}\right] \]  

(2)

in the \( \Gamma \)-valley, and

\[ \vec{\Omega}_L = \frac{\beta_L}{\sqrt{3}} \left[ \hat{x}(k_y - k_z) + \hat{y}(k_z - k_x) + \hat{z}(k_x - k_y) \right] \]  

(3)

in the \( L \)-valleys, located along the [111] direction of the crystallographic axes. In equations (2) and (3), \( k_i \ (i = x, y, z) \) are the components of the electron wavevector. \( \beta_\Gamma \) and \( \beta_L \) are the spin–orbit coupling coefficients, crucial parameters for the simulation of spin polarization. Here, we assume \( \beta_L = 0.26 \text{ eV Å}^{-1} \times 2/\hbar \), as recently theoretically estimated \[38\]. In the \( \Gamma \)-valley we consider the effects of nonparabolicity on the spin–orbit splitting by using \[46\],

\[ \beta_\Gamma = \frac{\alpha \hbar^2}{m \sqrt{2m E_g}} \left( 1 - \frac{E(\vec{k}) (9 - 7\eta + 2\eta^2)}{E_g} \right) \]  

(4)

where \( \alpha = 0.029 \) is a dimensionless material-specific parameter, \( \eta = \Delta/(E_g + \Delta) \), with \( \Delta = 0.341 \text{ eV} \) the spin–orbit splitting of the valence band, \( E_g \) the energy separation between the conduction band and valence band at the \( \Gamma \) point, \( m \) the effective mass and \( E(\vec{k}) \) the electron energy.

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The quantum-mechanical description of electron spin evolution is equivalent to that of the classical momentum $\vec{S}$ experiencing the effective magnetic field, as described by the equation of motion

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}.$$ (5)

Every scattering event changes the orientation of the effective magnetic field $\vec{B}$ (which strongly depends on $\vec{k}$) and the direction of the spin precession axis.

### 2.2. The Monte Carlo algorithm

The Monte Carlo approach is one of the most powerful methods to simulate the transport properties in semiconductor devices beyond the quasi-equilibrium approximations [48]–[50]. In fact, owing to its flexibility, the Monte Carlo method presents the remarkable advantage of giving a detailed description of the particle motion in the semiconductor by taking into account the details of collisions with impurities, phonons, etc, specific device design and material parameters, and allows us to obtain all the needed information, such as the average velocity of electrons, temperature, current density, etc, directly without the need of calculating first the electron distribution function. In simulations, between two successive scattering events, each electron propagates along a classical trajectory and, according to the classical equations of motion, it is affected by the presence of external fields. The time interval between two collisions (time of free flight), the scattering mechanisms, the collisional angle, and all the parameters of the problem are chosen in a stochastic way, making a mapping between the probability density of the given microscopic process and a uniform distribution of random numbers.

In our code the conduction bands of GaAs are represented by the $\Gamma$-valley and by four equivalent $L$-valleys. We do not consider the $X$-valleys because, even for the highest value of the driving field ($F = 6$ kV cm$^{-1}$), the percentage of electrons in these valleys is always lower than 0.1%. The algorithm includes: (i) the intravalley scattering with acoustic phonons, ionized impurities, acoustic piezoelectric phonons, polar optical phonons, and for the $L$-valleys also the scattering with optical nonpolar phonons; (ii) the intervalley scattering with the optical nonpolar phonons between the two valleys. The complete set of n-type GaAs parameters used in our calculations is listed in [51]. The scattering probabilities are calculated by the Fermi Golden Rule and assumed to be both field and spin independent; accordingly, the influence of the external fields is only indirect through the field-modified electron velocities. Nonlinear interactions of the field with the lattice and bound carriers are neglected. We also neglect electron–electron interactions and consider electrons to be independent [27]. The spin polarization vector is included in the Monte Carlo algorithm and calculated for each free carrier. From equation (5), the Monte Carlo (MC) simulator calculates the electron spin precession, by taking into account the scattering-induced deviations of the precession vector suffered after each collision.

All simulations are performed by using a temporal step of 10 fs and an ensemble of $5 \times 10^4$ electrons to collect spin statistics. We assume that all donors are ionized and that the free electron concentration is equal to the doping concentration $n$. 

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Figure 1. Average electron spin polarization $\langle S_x \rangle$ as a function of time, by considering only the electrons drifting into the $\Gamma$-valley (dashed line), into the $L$-valleys (dotted line) and into both the $\Gamma$-valley and the $L$-valleys (solid line). $F = 5$ kV cm$^{-1}$, $n = 10^{13}$ cm$^{-3}$ and $T_L = 300$ K.

3. Numerical results

3.1. Spin lifetime calculation

The initial non-equilibrium spin polarization decays with time as the electrons, driven by a static electric field, move through the medium, experiencing elastic and inelastic collisions. Since scattering events randomize the direction of $\vec{\Omega}$ during the motion, the polarization vector of the electron spin experiences a slow angular diffusion. The dephasing of each individual electron spin produces a distribution of spin states that results in an effective depolarization, which is calculated by ensemble-averaging over the spin of all the electrons.

The simulation of the spin relaxation starts with all the electrons of the ensemble initially polarized ($\langle \vec{S} \rangle = 1$) along the $\hat{x}$-axis at the injection plane ($x_0 = 0$). After a transient time of typically $10^4$ time steps, long enough to achieve the steady-state transport regime, the electron spins are initialized, the spin relaxation begins and the quantity $\langle \vec{S} \rangle$ is calculated as a function of time. In order to extract the characteristic time $\tau$ of the spin relaxation, the obtained trend of the spin dephasing is fitted by the following exponentially time decaying law

$$\langle S_x \rangle(t) = A \cdot \exp(-t/\tau),$$

with $A$ a normalization factor.

In figure 1 we show the average electron spin polarization, $\langle S_x \rangle$, in the presence of a driving electric field, with amplitude $F = 5$ kV cm$^{-1}$ and directed along the $\hat{x}$-axis, with density $n = 10^{13}$ cm$^{-3}$ and lattice temperature $T_L = 300$ K. This value of field amplitude is high enough to allow almost 21% of all electrons to visit the $L$-valleys. The curves represent the decreasing trend of $\langle S_x \rangle$ versus time by firstly considering only the electrons drifting into the $\Gamma$-valley (dashed line), secondly, by solely taking into account the electrons moving into the $L$-valleys (dotted line) and, finally, by considering the electrons moving into both the $\Gamma$-valley and the $L$-valleys (solid line). We find a significant reduction of the average spin polarization lifetime caused by the spin–orbit coupling in $L$-valleys stronger.

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Figure 2. Spin lifetime $\tau$ as a function of the electric field amplitude $F$, at $T_L = 77$ K (blue lines) and $T_L = 300$ K (red lines), for three values of doping density, namely $n = 10^{13}$, $10^{15}$ and $10^{16}$ cm$^{-3}$, with the electrons drifting in both the $\Gamma$-valley and the $L$-valleys.

with respect to that in $\Gamma$-valley, according to the theoretical results obtained by Zhang et al [23] on quantum wells. The transition of about 21% of electrons to the $L$-valleys leads to an increase of efficacy of the dephasing mechanism, which brings about a reduction of $\langle S_x \rangle$ over time in the range 15–20%.

3.2. Effects of temperature and doping density on spin relaxation

In figure 2, we show the spin depolarization time $\tau$ as a function of the electric field amplitude $F$, for two values of the lattice temperature, namely $T_L = 77$ (blue curves) and 300 K (red curves) and three values of doping density $n = 10^{13}$, $10^{15}$ and $10^{16}$ cm$^{-3}$; respectively, leaving the electrons free to drift in both the $\Gamma$-valley and the $L$-valleys. Except for the case at the doping density $n = 10^{13}$ cm$^{-3}$ and $T_L = 77$ K, we find that $\tau$ is always a monotonic decreasing function of $F$. In fact, when the field amplitude becomes larger, the electron momentum $k$ increases, causing a stronger effective magnetic field, as expected by equations (2) and (3). Consequently, the electron precession frequency becomes higher, inducing a faster spin relaxation [41].

For field amplitudes greater than 2.5 kV cm$^{-1}$, at $T_L = 300$ K we find depolarization times longer than those obtained at $T_L = 77$ K. In order to avoid that the observed behavior could be ascribed only to stochastic fluctuations of MC computations, we have calculated the statistical error associated with our simulated data. We have repeated our simulations ten times, finding a maximum spread of 0.05 ps, which corresponds to about 1% of the observed variation of $\tau$ with the temperature.

We have investigated the counterintuitive behavior of longer average spin lifetimes obtained for hotter electrons, by adopting the proportionality law of Perel [41]:

$$\frac{1}{\tau} \propto \Omega^2 \tau_p,$$

(7)

where $\Omega$ is the spin precession frequency and $\tau_p$ the momentum characteristic relaxation time, corresponding to the timescale of the scattering events. We have calculated the spin

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precession frequency and the momentum characteristic scattering time for each electron of our ensemble and, in figure 3, we show the average momentum scattering time $\tau_p$ (panel (a)) and the average spin precession frequency $\Omega$ (panel (b)) as a function of the electric field amplitude $F$, at $T_L = 77$ K and $T_L = 300$ K, for the three values of doping density $n = 10^{13}, 10^{15}$ and $10^{16}$ cm$^{-3}$.

Panel (a) of figure 3 shows that $\tau_p$ is a monotonically decreasing function of $F$ for every value of $n$ and $T_L$. At the higher temperature ($T_L = 300$ K) we find low values of $\tau_p$, because electrons experience a greater number of scattering events, both in the $\Gamma$-valley and in the $L$-valleys. Moreover, the curves at room temperature are characterized by only a slight slope, because in this case the thermal energy of the electrons is dominant with respect to the drift kinetic energy. At $T_L = 77$ K and for very low values of the electric field amplitude, since the scattering events are mainly due to ionized impurities, $\tau_p$ is greatly dependent on $n$, increasing its value at lower densities. At $T_L = 300$ K, $\tau_p$ is nearly independent on the doping density since the dominant scattering mechanism is due to the optical phonons.

Panel (b) of figure 3 shows that the spin precession frequency $\Omega$ is an increasing monotonic function of $F$. For $F < 3$ kV cm$^{-1}$, independently on the values of the doping density, the values of $\Omega$ obtained at room temperature are larger than those obtained at $T_L = 77$ K. The increase of the spin precession frequency for electrons moving at higher temperatures is explained by the increasing number of electron transitions from the $\Gamma$-valley to the $L$-valleys, the value of the spin–orbit coupling coefficient in the $L$-valleys being one order of magnitude greater than that of the $\Gamma$-valley. At $T_L = 77$ K, for $F < 3$ kV cm$^{-1}$, the percentage of electrons in the central valley $\Gamma$ is practically unitary and the spin precession frequency increases as the third power of electron momentum $\vec{k}$, which increases with $F$ according to equation (2). When $F$ is greater than $3$ kV cm$^{-1}$, the percentage of electrons in the $L$-valleys is high enough to lead $\Omega$ to have a nearly linear trend (see equation (3)). At $T_L = 300$ K, for $F < 3$ kV cm$^{-1}$, the term of thermal energy is dominant with respect to the drift kinetic energy and $\Omega$ versus $F$ shows a slighter increase.
For $F > 3$ kV cm$^{-1}$, independently of the values of $T_L$ and $n$, the action of $F$ overcomes the disorder due to the lattice temperature. In fact, except for the data obtained at $T_L = 300$ K and $n = 10^{16}$ cm$^{-3}$, which show lower values of $\Omega$, all curves coincide. The detached curve $T_L = 300$ K and $n = 10^{16}$ cm$^{-3}$ is ascribed to a strong reduction of the percentage of electrons present in the $L$-valleys.

The calculation of the square of the spin precession frequency times the momentum relaxation time as a function of the electron energy for each electron of the ensemble shows that for $F > 2.5$ kV cm$^{-1}$ the average value of $\Omega^2 \tau_p$ obtained at $T_L = 77$ K is greater than that at $T_L = 300$ K. This finding explains the longer lifetimes observed at higher temperatures for field amplitudes greater than 2.5 kV cm$^{-1}$.

To highlight the nonmonotonic electric field dependence of $\tau$, observed at the doping density $n = 10^{13}$ cm$^{-3}$, we have investigated the spin lifetime dependence on $F$ also for different values of the lattice temperature, namely $T_L = 77, 150, 220, 300$ K (see figure 4). Up to $T_L = 150$ K the decoherence times slightly depend on the temperature and are characterized by a marked maximum. The presence of a maximum in the spin depolarization time can be explained by the interplay between two competing factors, both due to the increase of the electric field. In the momentum space, at greater field amplitudes, the electrons occupy states with larger $\vec{k}$, characterized by a stronger spin–orbital coupling, causing an enhancement of the spin inhomogeneous broadening. On the other hand, a larger electric field also brings about an increase of the number of scattering events, giving rise to a reduction of the momentum relaxation time. This in turn causes an increase of the spin relaxation time, as follows from equation (7).

At low values of temperature and for electric field amplitudes $0.1$ kV cm$^{-1} \leq F \leq 0.5$ kV cm$^{-1}$ the inhomogeneous broadening is still marginal and the spin relaxation phenomenon is dominated by the momentum scattering. In particular, the number of electron scattering events, which are mainly due to interactions with acoustic phonons at very weak electric fields, increases its value because of the triggering of the scattering mechanism by ionized impurities, causing a reduction of $\tau_p$. For field amplitudes greater than $\approx 0.5$ kV cm$^{-1}$, the enhancement of the spin–orbit coupling, which is $k$-cubic
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Figure 5. Temperature dependent measurements of the spin relaxation rate from the experiment (sample B) in [52] (circles) and numerical data obtained from our Monte Carlo code (solid curve), \( n = 2.7 \times 10^{15} \text{ cm}^{-3}, \beta_\Gamma = 19 \text{ eV A}^3 \).

3.3. Comparison with experiments and with other theoretical approaches

Unfortunately, to date, experimental investigations of the ultrafast relaxation of electron spin during drift transport in bulk semiconductors, at both sample temperatures higher than 30 K and applied field amplitudes greater than 0.1 kV cm\(^{-1}\), are still lacking.

Although the main aim of this work is the investigation of the influence of transport conditions on the spin relaxation of electrons driven by high-intensity electric fields, including the effects of choosing both the lattice temperature and impurity density in a wide range of values, in order to validate the prediction capability of our MC code, we have performed a comparison between our numerical spin relaxation times and very recent experimental results on the electron-spin-relaxation rate, obtained by [52]. These experiments were carried out by performing spin noise spectroscopy on a sample of n-type GaAs at a doping concentration of \( n = 2.7 \times 10^{15} \text{ cm}^{-3} \), without any driving field and for lattice temperatures \( T_L \) between 4 and 80 K. In figure 5 we plot the temperature dependence of the spin relaxation rate calculated from our code (solid line), together with the experimental data (circles, sample B in [52]). In order to best fit the experimental points with our numerical trend, we have utilized the spin–orbit coupling coefficient in the \( \Gamma \)-valley \( \beta_\Gamma \) as a free parameter, obtaining the best agreement with \( \beta_\Gamma = 19 \text{ eV A}^3 \). This value is only slightly different from the value (23.8 eV A\(^3\)), recently estimated using the tight binding theory [38]. However, this value is still within the reasonable range of values calculated and measured via various methods, as reported in [53]. For sample temperatures greater than 45 K, our numerical trend agrees well with the experimental data, while at lower temperatures a considerable discrepancy is found, probably due to neglecting the electron–electron scattering mechanism. In fact, as shown in [24] at \( T_L = 40 \text{ K} \), the assumption of neglecting the Coulomb term gives spin lifetime values
smaller (hence relaxation rates higher) than those obtained from the full calculation including all scattering mechanisms.

In order to further test the effectiveness of our code we have compared our one-valley numerical data with the calculation of the effects of a low-amplitude electric field \( (F \leq 2 \text{kV cm}^{-1}) \) on spin relaxation in n-type III–V semiconductor bulks, recently obtained from the fully microscopic kinetic spin Bloch equation (KSBE) approach [24]. To the best of our knowledge, that paper is the only one in which the electric field dependence of spin lifetime has been investigated. In figure 6, we plot the ratio of the spin relaxation time under electric field to the electric-field-free one \( \tau(F)/\tau(F = 0) \) and the ratio between the hot-electron temperature and the lattice temperature \( T_e/T_L \), as a function of the applied field obtained from our Monte Carlo code for a GaAs bulk with \( n = 10^{16} \text{ cm}^{-3} \) at \( T_L = 300 \text{ K} \). These results are compared with the calculations from the KSBEs (see fig. 15(b) of [24]). Our finding for the spin lifetime agrees well with the theoretical results over the whole range investigated, while the values of the electron temperature are systematically slightly lower than those obtained from the KSBE approach. This small deviation could be due to the fact that the Coulomb scattering is neglected in our computation. In fact, the electron–electron \( (e-e) \) scattering is very important in determining the hot-electron temperature, which influences both the electron-longitudinal optical \( (e-LO) \) phonon and the electron-impurity scattering. Hence the e–e scattering effectively influences the spin relaxation. However, since at high temperatures the e–e scattering is weak compared to e-LO phonon scattering, it leads only to a marginal decrease in the spin relaxation [23]. Moreover, Römer et al [52] have experimentally shown that, for doping concentrations below the metal-to-insulator transition, the electron–electron interaction is weaker at low impurity densities. In our finding this decrease is surely negligible for the two lower values of donor concentrations, namely \( n = 10^{13} \) and \( 10^{15} \text{ cm}^{-3} \).

The analysis of the influence on the spin lifetime of the intravalley and intervalley Coulomb scattering at high lattice temperatures is a very interesting problem which deserves further detailed investigations and will be the subject of a forthcoming paper.

\[
\tau(F)/\tau(F = 0) \quad \text{and} \quad T_e/T_L
\]

**Figure 6.** Ratio of the spin relaxation time under electric field to the electric-field-free one \( \tau(F)/\tau(F = 0) \) and ratio between the hot-electron temperature and the lattice temperature \( T_e/T_L \) as a function of the applied field obtained from our Monte Carlo code, \( n = 10^{16} \text{ cm}^{-3} \), \( T_L = 300 \text{ K} \).
4. Conclusions

A full understanding of the role played by the lattice temperature, the doping density and the amplitude of high-intensity electric field on the electron spin dynamics in semiconductors is essential for the design and fabrication of spintronic devices.

In this work we have studied the spin lifetimes of an ensemble of conduction electrons, drifting in doped n-type GaAs bulk crystal, by using a semiclassical Monte Carlo transport model. The spin depolarization is investigated over a wide range of lattice temperatures and doping densities by simulating the electrons driven by an electric field with amplitude $0.1 \text{kV cm}^{-1} < F < 6 \text{kV cm}^{-1}$, including both the $\Gamma$-valley and the $L$-valleys in the spin dephasing dynamics.

Our results show that the electron spin lifetime is not marginally influenced by the driving electric field, the lattice temperature and the impurity density, which hence represent key parameters in the depolarization process. We find a significant reduction of the average spin polarization lifetime at high values of the electric field, caused by the stronger spin–orbit coupling of electrons in the $L$-valleys. In the non-degenerate regime the doping density considerably affects spin lifetimes at liquid nitrogen temperature and the weak intensity of the driving electric field. Moreover, for field amplitudes greater than $2.5 \text{kV cm}^{-1}$, we observe spin lifetimes longer at room lattice temperatures with respect to those observed at $T_L = 77$ K.

The prediction capability of our numerical code has been positively validated through a comparison with the available experimental results and with the calculations obtained by a different theoretical approach.

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