p-ISSN 2089 – 0133 e-ISSN 2477-6416
URL : https://jurnal.uns.ac.id/ijap/article/view/86965
Indonesian Journal of Applied Physics (IJAP) Vol. 14 No. 2 page 326
DOI : https://doi.org/10.13057/ijap.v14i2.86965

KINETICS OF OPTICAL PHONONS AND DP DEPOLARIZATION OF SPINS IN DRIFT TRANSPORT: HOT CARRIER SPIN EFFECT IN SEMICONDUCTORS

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Received 27-05-2024, Revised 14-09-2024, Accepted 18-10-2024,
Available Online 18-10-2024, Published Regularly October 2024

ABSTRACT

Spin-conserving transport of carriers is an essential requirement for the practical semiconductor-based spintronic devices. Kinetics of optical phonons and Dyakonov-Perel (DP) depolarization of spins in drift transport in semiconductor gallium arsenide (GaAs) is theoretically investigated. We consider electrons in n-type bulk GaAs subjected to a strong electric field to be appropriate for the drifted Maxwellian. The hot phonons in the drifted Maxwellian are incorporated via the longitudinal polar optical phonon mechanism in the momentum relaxation. It is found that a finite phonon lifetime can reduce the momentum relaxation rate, which results in a delay in the runaway to higher fields, where the effect increases with the electron density. The electron spin is found to relax with the DP relaxation frequencies, and the DP spin lifetimes are found to decrease with increasing the drift field. It is also found that the DP spin precession frequency decreases with decreasing electron temperature or increasing electron density in the range considered. The findings resulting from this investigation may find potential applications in semiconductor-based spintronic devices working in moderate temperature and carrier density regimes.

Keywords: Spin transport; DP Spin relaxation; Polar optical phonon; Hot phonons

Cite this as: Miah, M. I. 2024. Kinetics of Optical Phonons and DP Depolarization of Spins in Drift Transport: Hot Carrier Spin Effect in Semiconductors. *IJAP: Indonesian Journal of Applied Physics*, *14*(2), 326-338. doi: https://doi.org/10.13057/ijap.v14i2.86965

INTRODUCTION

Spintronics, or spin physics in fundamental and a broader sense, having its root in magnetotransport or magnetoelectronics has been known since the discovery of the anisotropic magnetoresistance effect in 1857 [1] is a revolutionary new class of electronics based on the spin degree of freedom of the electron in addition to, or in place of, the charge and is an emerging research field in condensed matter physics. However, recent interest has been motivated by successful examples of metallic (metal-based) spintronic devices, such as read heads for hard disc drives and magnetoresistive random access memory, based on ferromagnetic metals in which, as first suggested by Mott [2], the electrical current is carried by independent majority and minority spin channels (Mott's two-carrier approximation). These first metallic spintronic devices (passive components), discovered in 1988 [3,4] (available as the first commercial product in 1994 [5]), were sandwiched structures consisting of alternating ferromagnetic and nonmagnetic metal layers whose electric resistance depends strongly on the external magnetic field. Depending on the relative orientation of the magnetizations in the magnetic layers, the device resistance changes from small (parallel magnetizations) to large

(antiparallel magnetizations). This change in resistance is large enough to be called a giant magnetoresistance (GMR), a quantum mechanical effect in layered magnetic thin-film structures. The impact of the discovery of GMR was enormous mainly due to two reasons: first, possible applications were found in the development of new generation of magnetic devices and sensors based on the GMR effect with much more sensitivity than the existing conventional technologies, and second, the discovery of GMR drew the attention of the scientific community towards the so far neglected spin property of electron in the field of electronics [6].

However, the first active semiconductor spintronic device was suggested by Datta and Das in 1990 [7], where they proposed an electronic analogue of an electro-optical modulator, that was later termed "spin field effect transistor" (spin-FET), in a two-dimensional (2D) electron gas contacted with two ferromagnetic electrodes: one as a source for the injection of spin polarized electrons (because magnetic materials are natural sources of spin polarized electrons) and the other as an analyser (detector) for electron-spin polarization. The Datta-Das spin-FET device relies on the basic concept of modulating the transistor's source-to-drain current by varying the Rashba interaction in the channel with a gate voltage, i.e. the Datta-Das spin-FET is a scheme to control the electronic spin with an electric field via the gate while it is traveling through the 2D transport channel. Since then, their proposal has been believed to be the most promising and led to an intense focus on realizing the semiconductor-based spintronic devices. However, due to the experimental difficulties in the efficient spin injection for a successful detection, the Datta-Das spin-FET is yet to be implemented in an efficient way. On the other hand, the optimization of the electron spin lifetimes and the detection of spin coherence are the major challenges in the area of electron-spin-based qubit (quantum bit) control in quantum computations.

Semiconductor spintronics was greatly motivated by the observations of long spin lifetime (τ_s) or spin diffusion length (δ_s) (δ_s=2 μm obtained by optical [8] and δ_s=1.7 μm by electrical measurements [9]) in semiconductors. However, one of the important requirements necessary in developing semiconductor spintronic devices is the detection of spin current or spin in a semiconductor [10,11]. For a reliable detection, the efficient transport (without spin-flipping or spin relaxation, or the loss of the spin polarization) of spin-polarized carriers through a semiconductor over reasonable distances that are comparable to the device dimensions is required. This is because if spin relaxes too fast, the distance traveled by an electron without losing its spin state will be too short to perform any practical purpose or operation in spintronic devices. Recently, high spin polarization in semiconductors was obtained optically by multi-photon pumping [12,13].

In the previous investigations, we theoretically study the spin relaxation due to polar optical phonon (POP) [14] and hot phonon effect in Dyakonov-Perel (DP) spin relaxation employing the Ehrenreich's variational approach in semiconductors [15]. The electron spin was found to relax with a sub-THz rate and the spin lifetime was found to decrease with increasing the strength of the drifting field. It was also found that a high field completely destroyed the electron spin due to an increase of the electron temperature via the POP scattering. The POP mediated high-field spin and charge transport in semiconductor GaAs was also studied experimentally [16]. A similar DP spin relaxing feature was obtained.

Here, in the present investigation, we analytically study the dynamics of optical phonons and DP depolarization of electron spins in GaAs. Our approach is to consider electrons in *n*-type bulk GaAs subjected to a strong electric field to be appropriate for the drifted Maxwellian approach. We focus on the kinetics of optical phonons and DP depolarization of spins under drift for exploring the hot carrier spin effect in semiconductors, which was not done in

Ehrenreich's variational approach previously employed. Here, the electron distribution is assumed to be drifted Maxwellian due to strong electron-electron interaction in the drift transport of the hot carriers. The momentum drift of this distribution results in the enhanced drift velocity, and electrons with the corresponding energy emit optical hot phonons in the transport process. Stating from the rate of change of phonon occupancy in a relaxation time approximation, the electronic power dissipated in a drifted Maxwellian distribution is obtained. Here hot phonons are incorporated via the POP mechanism in the momentum relaxation. The electron spin is calculated and is found to relax due to an increase of the DP spin precession frequency of the hot electrons in the POP scattering process. It is found that the DP spin precession frequency decreases with decreasing electron temperature or increasing electron density in the moderate range. The results are discussed in comparison with those obtained in earlier experimental and theoretical studies with different approaches.

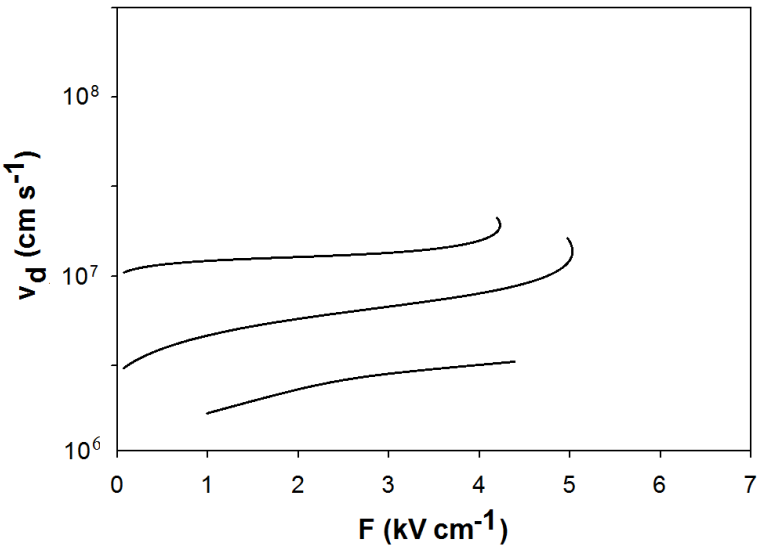

Figure 1. Drift velocity as a function of the drift field for different electron densities: $n = 10^{16}$ cm^{-3} (upper), $n = 10^{17}$ cm^{-3} (middle) and $n = 10^{18}$ cm^{-3} (lower).

METHOD

Momentum Relaxation Mechanisms

The momentum relaxation time τ_p includes four contributions from polar optical phonon scattering ($\tau_{p,op}$), ionized impurity scattering ($\tau_{p,ii}$), piezoelectric scattering ($\tau_{p,pe}$) and acoustic phonon deformation potential scattering ($\tau_{p,ap}$). If Mathiessen's rule is applied

$$\frac{1}{\tau_p} = \frac{1}{\tau_{p,op}} + \frac{1}{\tau_{p,ii}} + \frac{1}{\tau_{p,pe}} + \frac{1}{\tau_{p,ap}} . \quad (1)$$

The polar optical phonon scattering contribution to the momentum relaxation time $\tau_{p,op}$ is obtained according to the Ehrenreich's variational approach [15]

$$\tau_{p,op} = \frac{4\hbar}{3}\sqrt{\frac{\beta}{\pi R_0 \kappa}}\left(\frac{\varepsilon_0 \varepsilon_\infty}{\varepsilon_0 - \varepsilon_\infty}\right)\frac{\exp\Theta_{POP} - 1}{\Theta_{POP}} G_{POP} \exp(-\xi) , \quad (2)$$

where $\Theta_{POP} = \theta_{POP} / T$, $\kappa = m^*/m_0$ is the ratio of the electron's effective mass to its rest mass (for instance, for GaAs $\kappa = 0.076$), θ_{POP} is the longitudinal polar optical phonon frequency (in

units of temperature), R_0 is the Rydberg constant (≈ 13.6 eV) and $G_{POP}(\in,\theta)$ in general is a factor depending on the scattering mechanisms, the average inertial masses associated with the mobility and the sign of the charge carrier. Here, $\in = \xi\beta = \xi / k_B T$, $\beta = 1/k_B T$ is the inverse of the thermal energy, ξ is the Fermi energy and $\theta = \hbar\beta\theta_{POP} = \hbar\theta_{POP} / k_B T = \hbar\Theta_{POP} / k_B$. The function $G_{POP}\exp(-\xi)$ is calculated, as in [17], as a function of the carrier temperature and density.

The ionized impurity scattering contribution $\tau_{p,ii}$ is obtained from the Brooks–Herring equation [18] as

$$\tau_{p,ii} = \frac{1}{3\pi^{3/2}}\sqrt{\kappa}\,\frac{\varepsilon_0^2 / a_0^3}{2N_m + n}\,\frac{\hbar\beta^{-3/2}}{R_0^{5/2}}\int_0^\infty \frac{\in^3 e^{-\in}}{g(n,T,\in)}d\in, \tag{3}$$

where a_0 is the Bohr radius (≈ 0.53 Å), N_m is the concentration of minority impurities (acceptors for *n*-type materials and donors for *p*-type materials) and ϵ is a dimensionless quantity defined earlier and $g(n,T,\epsilon)$ is described by $g(n,T,\in) = \ln(1+b) - b/(1+b)$ with $b = (1/2\pi)\kappa(\varepsilon_0 / a_0^3 n)(R_0\beta)^{-2} \in$.

The piezoelectric scattering contribution $\tau_{p,pe}$ can be obtained from Meijer and Polder [18] as

$$\tau_{p,pe} = \frac{280\sqrt{\pi}}{3}\hbar\sqrt{\frac{\beta}{R_0\kappa}}\,\frac{R_0 a_0 / e^2}{h_{14}^2(4/c_t + 3/c_l)}, \tag{4}$$

where h_{14} is the one independent constant, and c_l and c_t are the average longitudinal and transverse elastic constants and are given by $c_l = (3c_{11} + 2c_{12} + 4c_{44})/5$ and $c_t = (c_{11} - c_{12} + 3c_{44})/5$ [19]. Finally, the acoustic phonon deformation potential scattering contribution to the momentum relaxation time $\tau_{p,ap}$, as showed by Bardeen and Shockley [20], is obtained as

$$\tau_{p,ap} = \frac{8\sqrt{\pi}}{3}\hbar\left(\frac{R_0\beta}{\kappa}\right)^{3/2}\frac{a_0^3 c_l}{E_l^2}, \tag{5}$$

where E_l is the deformation potential. The free-carrier concentration *n* (where electrons for *n*-type materials and holes for *p*-type materials) is calculated from

$$\frac{n(n+N_m)}{(N_M - N_m - n)} = \frac{N}{2}\exp(-\beta E_i), \tag{6}$$

where N_M is the majority impurity concentration and E_i is the ionization energy for the majority impurity and is given by

$$E_i = \frac{R_0}{\varepsilon_0^2}\frac{m}{m_0},$$

where *m* represents m_c for *n*-type materials and m_v for *p*-type materials, respectively. Here *N* is given by

$$N = \frac{1}{4}\left(\frac{2m}{\pi\hbar^2\beta}\right)^{3/2}.$$

Spin Relaxation Mechanisms

Once a spin imbalance is injected into (generated in, for optical case) a semiconductor, spin-carriers experience spin-dependent interactions with the environment, i.e. with impurities and excitations or phonons, which cause spin relaxation. The main spin relaxation mechanisms for conduction electrons in semiconductors (in the absence of magnetic impurities — which can lead to spin-flip scattering also) discussed in the literature are the hyperfine-interaction, Elliott-Yafet (EY), Bir-Aronov-Pikus (BAP), and DP [21]. From the experimental standpoint, the relative importance of the four mechanisms depends on sample structure and experimental conditions (doping profile, sample temperature, etc). The hyperfine interaction is the magnetic interaction between magnetic moments of the electrons and nuclei since atomic nuclei have finite spins. The spin dephasing owing to the hyperfine interaction is shown to be important in low-dimensional semiconductor structures but rather weak in bulk semiconductors.

In the EY mechanism, important either in metals or narrowband gap semiconductors (e.g. InSb), the spin-orbit (SO) interaction leads to a mixing of wave functions of opposite spin, which results in a nonzero electron spin-flip due to impurity and phonon scattering. The EY spin relaxation time ($\tau_{s,EY}$) is given by [21]

$$\frac{1}{\tau_{s,EY}} = C\left(\frac{\eta}{\beta E_g}\frac{1-\eta/2}{1-\eta/3}\right)^2\frac{1}{\tau_p}, \qquad (7)$$

where $\eta = \Delta/(E_g+\Delta)$ with band gap E_g and the SO splitting of the valence band Δ, and C is a dimensional constant and varies from 2 to 6 depending on the dominant scattering mechanisms for momentum relaxation (i.e. for τ_p), as discussed earlier.

The BAP mechanism, important in either *p*-doped or insulating semiconductors and at very low injection energies, is due to the electron-hole exchange interaction. Finally, the DP mechanism, important in *n*-type III-V semiconductors (such as GaAs) or II-VI semiconductors (such as ZnSe), is due to SO coupling in semiconductors lacking inversion symmetry [21].

The origin of the field-dependent efficient electron spin relaxation in *n*-doped GaAs is discussed based on the DP spin relaxation mechanism [22]. The DP mechanism is due to SO coupling in semiconductors lacking inversion symmetry. In III-V semiconductors, for example, the degeneracy in the conduction band is lifted for $\vec{k} \neq 0$ due to the absence of inversion symmetry. Without inversion symmetry the momentum states of spin-up ($\uparrow$) and spin-down ($\downarrow$) electrons are not degenerate, i.e. $E_{\vec{k}\uparrow} \neq E_{\vec{k}\downarrow}$, where $E_{\vec{k}\uparrow}(E_{\vec{k}\downarrow})$ is the momentum-dependent electron energy with spin $\uparrow(\downarrow)$. The resulting energy difference, for electrons with the same $\vec{k}$ but different spin states, plays the role of an intrinsic $\vec{k}$ -dependent magnetic field, known as the effective magnetic field [21],

$$\vec{h}(\vec{k}) = \frac{\alpha\hbar^2}{\sqrt{2em^*E_g}}[k_x(k_y^2-k_z^2)\hat{x} + k_y(k_z^2-k_x^2)\hat{y} + k_z(k_x^2-k_y^2)\hat{z}], \qquad (8)$$

where $\hbar$ is the Planck constant (h) divided by 2π or the reduced Planck constant and α is a dimensionless, material-specific parameter which gives the magnitude of the SO splitting and is given by $\alpha \approx (4\eta/\sqrt{3-\eta})\kappa$, induced by the presence of the Dresselhaus (due to the bulk inversion asymmetry) [24] SO interaction in a zinc-blende structure, acting on the spin with its magnitude and orientation depending on $\vec{k}$ and results in spin precession (spin relaxation) with intrinsic Larmor frequency $\omega_s(\vec{k})$ during the time between collisions, according to the relation $d\vec{P}/dt = \omega_s(\vec{k}) \times \vec{P}$, where $\omega_s(\vec{k}) = (e/m^*)\vec{h}(\vec{k})$ and $\vec{P}$ is electron spin polarization vector. The corresponding Hamiltonian term due to spin-orbital splitting of the conduction band (CB) describing the precession of electrons in the CB is $H_{DP}(\vec{k}) = (\hbar/2)\vec{\sigma} \cdot \omega_s(\vec{k})$, where $\vec{\sigma}$ is the vector of Pauli spin matrices. In a quantum well (QW), for example, the DP Hamiltonian $H_{DP}(\vec{k})$ is composed of the Dresselhaus and Rashba [21] terms. The Rashba term appears if the self-consistent potential within a QW is asymmetric along the growth direction and is therefore referred to as structural inversion asymmetry contribution.

The increased electron momentum at higher electric fields brings about a stronger $\vec{h}(\vec{k})$ and, consequently, the electron precession frequency $\Omega_s(\vec{k})$ becomes higher. The effective magnetic field depends on the underlying material, on the geometry of the device, and on $\vec{k}$. Momentum-dependent spin procession described by the DP Hamiltonian $H_{DP}(\vec{k})$, together with momentum scattering characterized by the momentum relaxation time leads to DP spin relaxation. Since the magnitude and the direction of $\vec{k}$ changes in an uncontrolled way due to electron scattering with the environment, this process contributes to spin relaxation, given by [22]

$$\frac{1}{\tau_{s,DP}} = \gamma \left(\frac{\alpha}{\hbar}\right)^2 \frac{\tau_p}{E_g \beta^3}, \tag{9}$$

where γ is a dimensionless factor and ranges from 0.8 to 2.7 depending on the dominant momentum relaxation process. For example, for scattering by polar optical phonon or piezoelectric phonons $\gamma \approx 0.8$, while scattering by ionized impurities gives $\gamma \approx 1.5$, and scattering by acoustic phonons deformation potential $\gamma \approx 2.7$.

The DP spin relaxation in a bulk zinc-blende structure occurs due to the spin precession about the effective magnetic field $\vec{h}(\vec{k})$ induced by the presence of the Dresselhaus SO interaction. A higher field produces hotter electrons. During transport in the electric field realm, electrons are accelerated to higher velocities at higher fields, where the temperature increases sharply due to the energy-independent nature of the dominant energy relaxation process via the longitudinal polar optical phonon scattering (≈ 0.8). The resulting high temperature leads to enhanced DP spin relaxation ($1/\tau_{s,DP} \propto \tau_p/\beta^3 = \tau_p (k_B T)^3$) because they have large kinetic energy between successive collisions.

Kinetics Of Phonons and Hot Carrier Transport

We consider a high-field electronic transport in *n*-typed bulk GaAs, where the electrons are drifted under the influence of a strong electric field. Here the electron distribution in the process is assumed to be drifted Maxwellian due to strong electron-electron interaction. The enhanced momentum drift of this distribution results in the drift velocity, and electrons with the corresponding energy emit optical hot phonons. The kinetics of hot phonons then explores the kinetics of hot electrons taking into account of their spins. We start from the rate of change of phonon occupancy $f(\mathbf{k})$ in a relaxation time approximation and write for the net rate of emission of a phonon of wave vector **k** by the electron population

$$\frac{df(\mathbf{k})}{dt}+\frac{f(\mathbf{k})-f_0(\mathbf{k})}{\tau_{ph}}=\chi_{ph}(\mathbf{k}), \tag{10}$$

where the wavevector *k* is such that the phonon energy $\hbar\omega = E_k = \hbar^2k^2/2m^*$ in the phase-matched mode condition, $f_0(k)$ is the occupancy at thermodynamic equilibrium and equals to $f_0(\omega)$, and τ_{ph} is the phonon lifetime (~7 ps). For a degenerate statistics within polar interaction, the phonon emission rate by the electron population can be written as

$$\chi_{ph}=\sqrt{\frac{\hbar\omega}{4\tau_{pop}^2E_k^3}}\left[\{f(k)+1\}\int_{E_1}^{\infty}\zeta(E)\{1-\zeta(E-\hbar\omega)\}\,\mathrm{d}E-f(k)\int_{E_2}^{\infty}\zeta(E)\{1-\zeta(E+\hbar\omega)\}\,\mathrm{d}E\right] \tag{11}$$

where $\zeta(E)=(n/D_e)\exp(-E\beta)$, $E_1=(\hbar\omega+E_k)^2/4E_k$, $E_1=(\hbar\omega-E_k)^2/4E_k$, $D_e(T)$ is the electron effective density of states, *n* is the electron density, and τ_{pop} is the characteristic time for the polar interaction and is given by

$$\frac{1}{\tau_{pop}}=\frac{e^2\omega}{h}\sqrt{\frac{m^*}{2\hbar\omega}}\left(\frac{1}{\varepsilon_\infty}-\frac{1}{\varepsilon_c}\right), \tag{12}$$

where $\varepsilon_c(\varepsilon_\infty)$ is the static or low-frequency (high-frequency) permittivity and is different from the zero-frequency or vacuum permittivity ε_0 (ε_c =12.9 ε_0 and ε_∞ =10.6 ε_0). Integrating Eq. (11) over energy, we get for the phase-matched mode

$$\chi_{ph}(\omega)=\frac{\rho}{\tau_{pop}}\exp(-\Gamma)\left[1-f(\omega)\{\exp(\Gamma)-1\}\right], \tag{13}$$

where $\Gamma=\hbar\omega\beta=\hbar\omega/k_BT$ and $\rho=n/2D_e\Gamma$. In use of the above equation in Eq. (10) for the steady-state becomes

$$f(\omega)=\frac{f_0(\omega)+\tau_r\rho\exp(-\Gamma)}{1+\tau_r\rho\{1-\exp(-\Gamma)\}}, \tag{14}$$

where $\tau_r = \tau_{ph} / \tau_{pop}$. The above equation is a generalized expression for the photon occupancy and is an important derivation because it contains all the desirable qualities. For examples, for $\tau_{ph} \to \infty$, $f(\omega) = 1/\{\exp(\Gamma) - 1\}$ and for $n \to 0$ or $T \to T_L$, $f(\omega) \to f_0(\omega)$. Following Stratton [23] for the electronic power dissipation in a drifted Maxwellian distribution, the expression for the drift velocity (v_d) can be obtained as

$$v_d = \sqrt{\frac{2}{\pi}} \frac{\hbar\omega}{\tau_{pop} eF} \left\{ \left(f(\omega) + 1 \right) \exp(-\Gamma) - f(\omega) \right\} \sqrt{\frac{\Gamma}{2}} \exp(\Gamma/2) B_0(\Gamma/2) \quad , \qquad (15)$$

where F is the electron drift field and $B_0(\Gamma/2)$ is the zeroth order Bessel function of $\Gamma/2$. After incorporating the hot phonon effect by eliminating $f(\omega)$ in Eq. (14) one can obtain v_d as

$$v_d = \frac{\sqrt{2}\hbar\omega}{\sqrt{\pi} e \tau_{ph,ef} F} \left\{ \left(1 + f_0 \right) e^{-\Gamma} - f_0 \right\} \sqrt{\Gamma/2} B_0 e^{\Gamma/2} \quad , \qquad (16)$$

where $\tau_{ph,ef} = \tau_{pop} + \tau_{ph}(n / 2D_e\Gamma)\{1 - \exp(-\Gamma)\}$ is the effective time constant manifesting the hot phonon effect. Since $D_e(T) = 2(2\pi m^* k_B T / h^2)^{3/2}$, $D_e \to T^{3/2}$, and so this time constant is not a constant with respect to T, but varies weakly as $\tau_{ph,ef} \to T^{-1/2}$. To relate T with F we use the expression for v_d, which is obtained from solving the momentum balance equation and replacing the phonon occupancy $f(\omega)$ by $f_0(\omega)$ obtained from the steady-state solution of the equation describing the rate of change of $f(\omega)$ in the relaxation time approximation

$$v_d = \frac{3\sqrt{\pi} e \tau_{ph,ef} F}{m^* \Gamma^{3/2}} \left[\left\{ \left(1 + f_0 + \tau_r \left(\frac{n}{D_e \Gamma} \right) \right) e^{-\Gamma} + f_0 \right\} B_1 e^{\Gamma/2} + \left\{ (1 + f_0) e^{-\Gamma} - f_0 \right\} B_0 e^{\Gamma/2} \right]^{-1} \qquad (17)$$

where B_1 is the first-order Bessel function of $\Gamma/2$.

RESULTS AND DISCUSSION

The polar phonon-assisted drift velocity as a function of the drift field for different electron densities and at T = 50 K is shown in Fig. 1. As can be seen, the curves cut off at low fields for the higher densities where electron statistics becomes degenerate. Here the elect of hot phonon is clearly seen, as the curves display the runaway effect, where the enhanced scattering rate reduces the drift velocity so that the field at which runaway occurs is increased in order to achieve the necessary power input. Hot phonons (polar optical) thus tend to stabilize the polar interaction and the reduction of drift velocity is on as a consequence of the drift field effect.

The hyperfine coupling is due to the interaction between the nuclear spin and electron spin, and the spin depolarization owing to this interaction is dominated in low-dimensional semiconductor structures (e.g. quantum wells, quantum wires, quantum dots) but rather weak in bulk semiconductors. For a III-V semiconductor (such as GaAs), for example, the EY relaxation is less effective due to the large E_g and low scattering rate, and for an *n*-type material, as holes are rapidly recombined with electrons due to the presence of a large number of electrons, the spin relaxation due to the BAP mechanism is usually blocked. Finally, the DP is

the dominated spin relaxation mechanism in *n*-type bulk GaAs. The DP relaxation process is via the longitudinal polar optical phonon scattering ($\gamma \approx 0.8$) [21]. As discussed earlier (in Section 3), the DP spin relaxation in a bulk zinc-blende structure occurs due to the spin precession about the effective magnetic field induced by the presence of the SO interaction.

We include the polar optical phonon scattering contribution to the momentum relaxation time $\tau_{\mathrm{p,op}}$ in our calculation. In order to evaluate the DP spin lifetime quantitatively, we carry out a calculation of $\tau_{s,DP}$ as functions of both T and E. We use the relation [18]

$$T = T_L + \frac{2ev_d F}{3k_B} \frac{\left\langle E_{\vec{k}} \right\rangle}{\left\langle E_{\vec{k}} / \tau_{E_{\vec{k}}} \right\rangle}, \tag{18}$$

where T_L is the lattice temperature and $\tau_{E_{\vec{k}}}(E_{\vec{k}})$ is the energy relaxation rate. The angular brackets in the equation denote the averaging over the thermal distribution. Values of the material parameters used in the calculation are taken from [19,20] for GaAs. Figures 2-4 show the calculated results. The DP spin lifetime as a function of T for different electron densities: $n = 1\times10^{16}$ cm^{-3}, 6×10^{16} cm^{-3}, 1×10^{17} cm^{-3} and 1×10^{18} cm^{-3} are displayed in Fig. 2. As can be seen, the DP spin lifetime increases with increasing the electron density up to $n = 1\times10^{17}$ cm^{-3}. However, it decreases at high electron densities. It is also seen that the DP spin lifetime decreases with increasing electron temperature.

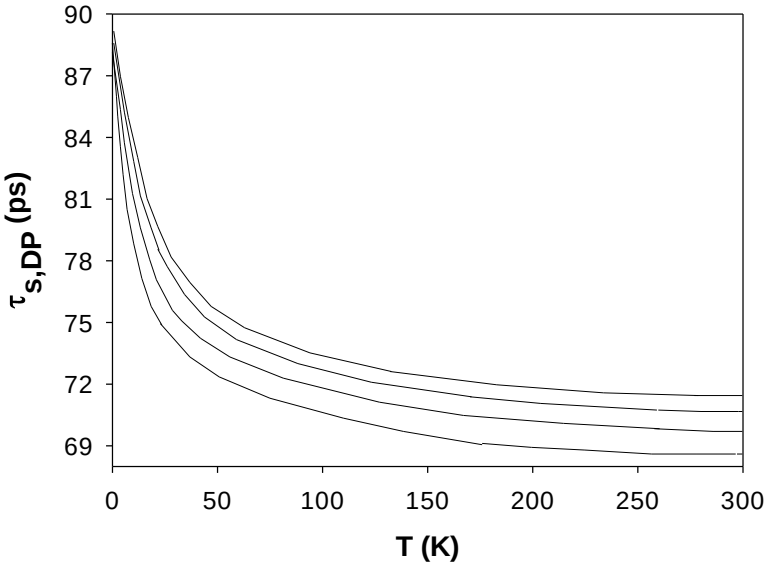

Figure 2. DP spin lifetime as a function of T for different electron densities: $n = 1\times10^{18}$ cm^{-3}, $n = 1\times10^{16}$ cm^{-3}, $n = 6\times10^{16}$ cm^{-3} and $n = 1\times10^{17}$ cm^{-3} (curves are serially from the bottom to top).

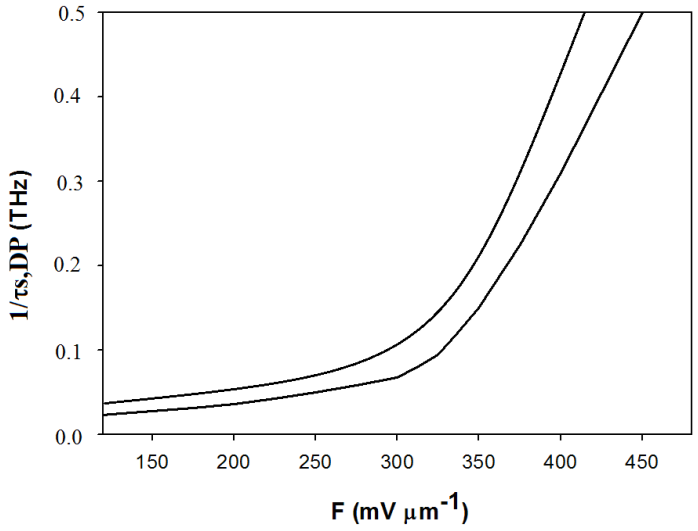

Figure 3. DP spin relaxation as a function of the drift field at different temperatures: 100 K (lower) and 150 K (upper).

The DP spin relaxation frequency as a function of drift field at different temperatures is plotted in Fig. 3. As can be seen, the DP spin relaxation frequency increases with *F* at the moderate fields. However, it is rapid at higher fields and is almost infinite for field higher than 300 mV μm^{-1}, which might be the result of increase of the electron temperature at higher fields and, consequently, the higher DP spin relaxation frequency. This field-dependence agrees well with those of the spin transport experiment reported in [16,24], where authors showed that the photo-generated spins could travel without losing their initial spin orientation as long as *E* was below 100 mV μm^{-1} and the spin relaxation rate increased rapidly with *E* and the polarization disappeared at ~350 mV μm^{-1}. The results are also consistent with the results of the Monte Carlo simulation performed by others [25]. They showed that for relatively low fields up to 100 mV μm^{-1}, a substantial amount of spin polarization is preserved for several microns at 300 K and the DP spin relaxation frequency increased rapidly for fields higher than 150 mV μm^{-1}.

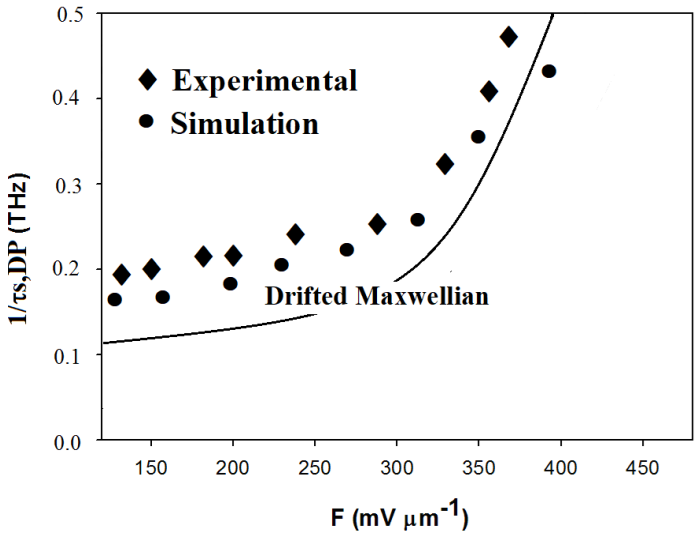

Figure 4. DP spin relaxation frequency as a function of electric field for n=1.5 ×10^{16} cm^{-3} at room temperature (T =300 K), obtained in the present analytical study based on the drifted Maxwellian approach (solid line). Closed circles and diamonds show the trends, as obtained in a Monte Carlo numerical simulation [25] and a spin transport experiment [26], respectively.

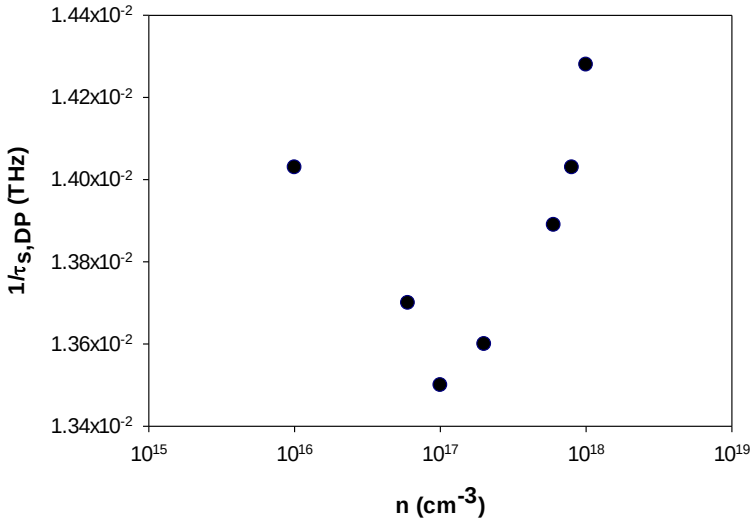

Figure 5. DP spin relaxation as a function of the electron density. The spin relaxation is higher both at lower and higher density regimes.

Figure 4 shows the room-temperature (T =300 K) DP spin relaxation frequency as a function of electric field for n=1.5 ×10^{16} cm^{-3}. This figure also shows the room-temperature DP spin relaxation frequencies, obtained in [26]. As can be seen, the results obtained from the present study based on the drifted Maxwellian approach show the similar trend, as obtained in the earlier experimental [24,26] and theoretical investigation based on Monte Carlo simulation [25]. The results also consistence with those obtained in variational approach [14,15].

The DP spin relaxation frequency as a function of the electron density is shown in Fig. 5. As can be seen, $1/\tau_{s,DP}$ is higher both at lower and higher density regimes and decreases with increasing n in the moderate range. It is found to increase with increasing n in the high density limit because of the scattering in the nondegenerate electronic statistical realm. The introduction of n-type dopants within the moderate limit in semiconductors increases the DP spin lifetime ($\tau_{s,DP}$), because the electronic spin polarization in these systems survives for longer times. Studies of spin precession in GaAs reveal that moderately n-type doping yields significantly extended $\tau_{s,DP}$ and show that $\tau_{s,DP}$ increases with decreasing T [27]. A similar trend was observed in another experiment of bias dependence of the spin-polarization of electrons, where it was shown that several percentage of polarization increased by increasing the n-type doping in the moderate range, near n = 1×10^{17} cm^{-3} [8]. The results, however, demonstrate the hot carrier effect in the spin transport, consisted with those obtained in the literature [28]. A similar trend within the moderate density was also obtained in earlier studies, where the experimentally obtained drift velocity was used to calculate the electron temperature and the DP spin precession frequency [25].

CONCLUSION

We investigated the kinetics of hot phonons and electrons, and spin in n-type bulk GaAs subjected to a strong electric field. Stating from the rate of change of phonon occupancy in a relaxation time approximation, the electronic power dissipated in a drifted Maxwellian distribution was obtained and studied. In the scattering process, hot phonons were incorporated via the POP mechanism in the momentum relaxation. It was found that a finite phonon lifetime could reduce the momentum relaxation, resulting in a delay in the runaway to higher fields. The electron spin was found to relax with the DP relaxation frequencies, and the DP spin

lifetimes were found to decrease with increasing the drift field. However, a high field completely depolarized the electron spin due to an increase of the DP spin precession frequency of the hot electrons via the POP process. It was also found that the DP spin precession frequency decreases with decreasing electron temperature or increasing electron density in the moderate range. On comparison, the field-dependence of the DP depolarization frequency showed the similar trend as obtained in the earlier experimental and theoretical investigations with different approaches. The results were discussed on the basis of the DP spin depolarization mechanism and the hot carrier effect in high field spin transport.

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