Spin drift and spin diffusion currents in semiconductors

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Abstract
On the basis of a spin drift-diffusion model, we show how the spin current is composed and find that spin drift and spin diffusion contribute additively to the spin current, where the spin diffusion current decreases with electric field while the spin drift current increases, demonstrating that the extension of the spin diffusion length by a strong field does not result in a significant increase in spin current in semiconductors owing to the competing effect of the electric field on diffusion. We also find that there is a spin drift-diffusion crossover field for a process in which the drift and diffusion contribute equally to the spin current, which suggests a possible method of identifying whether the process for a given electric field is in the spin drift or spin diffusion regime. Spin drift-diffusion crossover fields for GaAs are calculated and are found to be quite small. We derive the relations between intrinsic spin diffusion length and the spin drift-diffusion crossover field of a semiconductor for different electron statistical regimes. The findings resulting from this investigation might be important for semiconductor spintronics.

Keywords: semiconductor, drift-diffusion, electrical properties, spintronics

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Utilization of the electron spin as an information carrier in conventional electronic devices is a promising trend for future spin-based electronics (spintronics) [1–3]. It is generally expected that the addition of a spin degree of freedom in information processing will extend the functionality of conventional devices and allow the development of novel electronic devices (spintronic devices) with potentially lower power consumption, faster operation and smaller size. Recent interest has been motivated by successful examples of metallic spintronic devices, such as ferromagnetic metal-based reading heads for hard disc drives and magnetic RAM [4, 5]. These first metallic spintronic (passive) devices 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). In comparison with metal-based spintronics, the utilization of semiconductors promises more versatile design owing to the ability to adjust the potential and spin polarization in the device by, for example, varying the external voltage and device structure. The first active semiconductor spintronic device was proposed by Datta and Das in 1990 [6], which was an electronic analogue of an electro-optical modulator, that was later termed a ‘spin field-effect transistor (SFET)’, in a two-dimensional electron gas in contact with two ferromagnetic electrodes: one as a source for the injection of spin-polarized electrons and the other as an analyser for electron-spin polarization. The Datta–Das SFET device relies on the basic concept of modulating the transistor’s source-to-drain current by varying the Rashba interaction in the channel through the gate voltage. The necessary requirements for such an active device are the efficient
generation or injection of spin-polarized electrons into a semiconductor, their reliable transport over reasonable distances, i.e. without spin-flipping or spin relaxation and then their detection. Much effort has thus been dedicated [5] to understanding these important issues. The injection and detection of spin-polarized or spin currents in semiconductors have been achieved either optically or by electrical methods with varying degrees of success [5, 7, 8].

Despite much effort and substantial progress, a further major obstacle to the practical implementation of semiconductor spintronics is the lack of a proper understanding of spin transport in semiconductors [5]. Although a number of promising spin-based devices, very similar to the Datta–Das SFET, in semiconductors have recently been proposed [9–11], the advantages of these models in practical devices, compared with the conventional electronic devices, have not yet been clearly established [12]. Furthermore, detailed spin transport parameters in semiconductors have still not been thoroughly studied. To fully understand the spin transport and to successfully implement the device concepts, substantial research in this area is required.

The diffusion equation for the electrochemical potential has been widely used to model spin transport in semiconductors [13–16]. In spin transport studies of semiconductors in the diffusive regime, the spin polarization is usually assumed to obey the same diffusion equation for the electrochemical potential as that used to describe its diffusion in metals, where there are no electric-field effects and the spin polarization decays exponentially on a length scale of the intrinsic spin diffusion length from the point of spin generation or injection. In semiconductors, in contrast to metals, the field remains partially unscreened. Thus, it is necessary to study the spin transport in the drift-diffusion regime.

Recently, Yu and Flatté [17] used a drift-diffusion equation that takes into account electric-field effects and nondegenerate electron statistics to study spin transport in a ferromagnet-semiconductor (FM-S) structure. They showed that spin injection from a ferromagnetic metal into a semiconductor is enhanced by several orders of magnitude and that for sufficiently high fields the spin polarization can be transported over distances significantly exceeding the intrinsic spin diffusion length. Pershin and Privman [18, 19] also used a drift-diffusion-type equation to investigate spin transport and to compress and amplify the spin polarization density by the inhomogeneous doping of semiconductors. They showed that electron spin transport through the boundary between semiconductor regions with different doping levels can lead to electron spin polarization amplification near the boundary.

In the present study, we derive a more general drift-diffusion equation that takes into account electric-field effects and both nondegenerate (Boltzmann) and degenerate (Fermi–Dirac) electron statistics. Using this drift-diffusion model, we deduce expressions for the spin drift and spin diffusion current densities and show that the extension of the spin diffusion length by a strong electric field does not result in a significant increase in spin current in semiconductors owing to the competing effect of the electric field on diffusion, which is a refinement of the second finding by Yu and Flatté, as mentioned earlier, and by others [20]. We find that there is a spin drift-diffusion crossover field for a process in which the drift and diffusion contribute equally to the spin current, which suggests a possible method of identifying whether the process for a given electric field is in the drift or diffusion regime. An examination of the drift and diffusion contributions to the spin current in different electron statistical regimes suggests a possible method of enhancing the spin current by using a semiconductor degenerate regime. We also derive expressions that relate the spin drift-diffusion crossover field to the intrinsic spin diffusion length of a semiconductor for all electron statistical regimes.

2. Theory

We start from the continuity relation that takes into account spin relaxation,

$$\frac{\partial \sigma_{\uparrow \downarrow}(\vec{r}, t)}{\partial t} = \vec{\nabla} \cdot \vec{j}_{\uparrow \downarrow}(\vec{r}) + \frac{e \left[ c_{\uparrow}(\vec{r}, t) - c_{\downarrow}(\vec{r}, t) \right]}{\tau_{\uparrow \downarrow}(\vec{r})},$$

(1)

where $e$ is the electron charge; $c_{\uparrow}(\vec{r}, t)$ and $\tau_{\uparrow \downarrow}(\vec{r})$ denote, respectively, density, current density and spin relaxation time with spin-up (spin-down) electrons. Assuming that there is no space charge and that the material is homogeneous, the expression for the current density of a spin species, including the drift and diffusion contributions, can be written as

$$\vec{j}_{\uparrow \downarrow}(\vec{r}) = \sigma_{\uparrow \downarrow}(\vec{r}) \vec{E} + eC_{\varepsilon,\tau}(\vec{r}) \vec{\nabla} c_{\uparrow \downarrow}(\vec{r}),$$

(2)

with $\sigma_{\uparrow \downarrow}(\vec{r}) = eC_{\varepsilon,\tau}(\vec{r})$, where $\mu_{\uparrow \downarrow}(\vec{r})$, $\sigma_{\uparrow \downarrow}(\vec{r})$ and $C_{\varepsilon,\tau}(\vec{r})$ are the mobility, Drude conductivity and diffusion coefficient for spin-up (spin-down) electrons, respectively. We assume that the transport is unipolar (e.g. an n-doped semiconductor) so that the recombination process can be neglected. Carefully applying the local charge neutrality constraint ($e \uparrow + e \downarrow = 0$), we obtain from equations (1) and (2)

$$\frac{\partial c_{\uparrow \downarrow}(\vec{r}, t)}{\partial t} = \frac{\mu_{\uparrow \downarrow}(\vec{r}) \vec{E} \cdot \vec{\nabla} c_{\uparrow \downarrow}(\vec{r}, t)}{\tau_{\uparrow \downarrow}(\vec{r})} + C_{\varepsilon} \vec{\nabla}^{2} \left[ c_{\uparrow}(\vec{r}, t) - c_{\downarrow}(\vec{r}, t) \right]$$

$$- \frac{c_{\uparrow}(\vec{r}, t) - c_{\downarrow}(\vec{r}, t)}{\tau_{\uparrow \downarrow}(\vec{r})},$$

(3)

where we have assumed that the mobility and diffusion coefficient are equal for spin-up and spin-down carriers ($\mu_{\uparrow} = \mu_{\downarrow}$ and $C_{\varepsilon,\uparrow} = C_{\varepsilon,\downarrow}$) and used ($\tau_{\uparrow \downarrow})^{-1} = (\tau_{\uparrow})^{-1} + (\tau_{\downarrow})^{-1}$. Defining the spin density as $s(\vec{r}, t) = c_{\uparrow}(\vec{r}, t) - c_{\downarrow}(\vec{r}, t)$, we now obtain from equation (3)

$$\frac{\partial s(\vec{r}, t)}{\partial t} = \frac{\mu_{\uparrow} \vec{E} \cdot \vec{\nabla} s(\vec{r}, t) - s(\vec{r}, t)}{C_{\varepsilon} \tau_{\uparrow \downarrow}(\vec{r})},$$

(4)

where $L_{s,0} = \sqrt{C_{\varepsilon} \tau_{\uparrow \downarrow}}$ is the intrinsic spin diffusion length. Equation (4) is a two-component (spin-up and spin-down) drift-diffusion relation for the spin transport.
We now refer to the conceptual device depicted in the insert of figure 1. We take the electric field to be along the negative x-direction and consider y to be the transverse direction. Suppose that a continuous spin unbalance is generated or injected at the left of the device at x = 0 with the spin polarization axis taken to be either z or −z. From the experimental standpoint, such a spin polarization can be created locally in the bulk of a semiconductor, e.g. by using ferromagnetic-metal scanning tunnelling microscopy tips, or by optical excitation. For the optical excitation of bulk zinc-blende semiconductors, such as GaAs, with photon energy slightly above the band gap, because of the selection rules [21] governing optical transitions from heavy-hole or light-hole states to conduction band states, right circular polarization (σ^+) generates spin-down electrons (c↓) with three times the density of spin-up electrons (c↑), and vice versa for left circularly polarized light (σ−). Hence, the initial electron spin polarization (p0) generated by a circularly polarized beam in a zinc-blende semiconductor, defined as \( p(\vec{r}, t) = (c↓(\vec{r}, t) - c↑(\vec{r}, t)) / (c↓(\vec{r}, t) + c↑(\vec{r}, t)) \), is ±0.5 (50%). Optical excitation with σ^− (σ−) injects spins along the direction parallel (antiparallel) to the direction of the light propagation, i.e. along +z (−z) (figure 1 insert).

Once an electron spin imbalance is injected into a semiconductor, electrons undergo spin-dependent interactions with the environment, which cause their spin relaxation. For technologically important semiconductors, such as n-doped GaAs, the spin relaxation is mainly by the Dyakonov–Perel (DP) mechanism [22]. The DP spin relaxation is due to the spin precession about a momentum-dependent intrinsic magnetic field \( \vec{h}(k) \) induced by the presence of the spin–orbit interaction in a zinc-blende structure. During transport in the electric field, electrons are accelerated to higher velocities at higher fields (where the electron temperature, \( T_e \), increases sharply due to the dominant energy relaxation process via the longitudinal polar optical phonon scattering [23]). The increased electron momentum (or \( T_e \)) at higher current densities brings about a stronger \( \vec{h}(k) \), and consequently, the electron spin precession frequency \( \omega_0(k) \) increases. Momentum-dependent spin precession described by the DP Hamiltonian [23], together with momentum scattering characterized by the momentum relaxation time, leads to the total DP spin relaxation.

Although the total current is preserved when the electrons propagate through the device, the spin density or polarization decreases as the distance from the point of injection increases, and the length scale associated with this decrease is governed by the spin diffusion length, which can be obtained from the steady-state \( [\partial(c↓ - c↑) / \partial t] = 0 \) solution of equation (4). The general solution restricting one-dimensional variation to the positive x-direction is found to be

\[
s(x) = R e^{-\left(\sqrt{\rho^2 E^2 + 2 / \rho E} - \rho E\right) x},
\]

where \( \rho E = \mu E / (2C_e) \) and R is a constant of integration to be determined by the initial conditions. If the spin density at the injection point, \( x = 0 \), is \( s_0 = c↓(0) - c↑(0) \), then \( R = s_0 \) and equation (5) becomes

\[
s(x) = s_0 e^{-\left(\sqrt{\rho^2 E^2 + 2 / \rho E} - \rho E\right) x},
\]

where the quantity \( \left(\sqrt{\rho^2 E^2 + 2 / \rho E} - \rho E\right)^{-1} \) is the spin diffusion length, \( L_{s,E} \), i.e. the distance over which the carriers move in the downstream direction within the spin lifetime, \( \tau_s \), in the presence of the electric field. In the absence of the electric field (\( \rho E = 0 \)), \( L_{s,E} \) is equal to the intrinsic spin diffusion length, \( L_s \). Equation (6) gives the spin density distribution along the positive x-direction and shows that the stronger the field is, the further the spin density can be shifted, which can be over distances significantly exceeding \( L_s \).

As mentioned earlier, this field effect has been demonstrated in [17, 20]. However, we will show here that the extension of the spin diffusion length in this way does not result in a significant increase in spin current owing to the competing effect of the electric field on diffusion.

The relation between the position dependences of the spin current density and the spin density or polarization can be obtained from equation (2):

\[
\vec{j}_s(\vec{r}) = \vec{j}_↑(\vec{r}) - \vec{j}_↓(\vec{r}) = e(\mu \vec{E} + C_e \vec{v}) s(\vec{r}),
\]

where \( s(\vec{r}) \) is the spin polarization density defined as

\[
p(\vec{r}) = (c↑(\vec{r}) - c↓(\vec{r})) / (c↑(\vec{r}) + c↓(\vec{r})) = s(\vec{r}) / c(\vec{r})
\]

and

\[
c(\vec{r}) = c↑(\vec{r}) + c↓(\vec{r})
\]

The expression for the spin current density (x-dependent) in terms of the spin polarization becomes

\[
\vec{j}_s(x) = p_0 \left[-ec(\mu \vec{E} + C_e \vec{v}) \left(\sqrt{\rho^2 E^2 + 2 / \rho E} - \rho E\right) x\right] \times e^{-\left(\sqrt{\rho^2 E^2 + 2 / \rho E} - \rho E\right) x},
\]
shows, the current, and thus the spin diffusion current, is zero through the expression derived for the ↓ species. Thus, for the electron diffusion coefficient, we obtain
\[ C_e = -\frac{\mu_e}{e\beta} \int_0^\infty D_{\downarrow,d}(\epsilon) f(\epsilon) \, d\epsilon, \] (16)
where \( \beta \) is the inverse of the thermal energy \( E_T = k_B T \), \( D_{\downarrow,d}(\epsilon) \) is the density of states for the minority spin with energy \( \epsilon \), measured from the bottom edge of the conduction band for the spin ↓, which for a bulk parabolic band is given by \( D_{\downarrow,d}(\epsilon) = (\sqrt{3}/\hbar)^3 \sqrt{2E}/\pi^2 \), and \( f \) is the Fermi–Dirac distribution function (and \( \partial_x f \) is its partial derivative with respect to \( \epsilon \)). For degenerate systems, equation (16) can be approximated as
\[ C_e = -\frac{\mu_e}{e\beta} I_{1/2}(\Lambda), \] (17)
Here \( \Lambda = (\epsilon_f - \epsilon_0,\downarrow) \) is the reduced Fermi level, \( \epsilon_0,\downarrow \) is the bottom edge of the conduction band for the spin ↓, \( \epsilon_f \) is the Fermi level and \( I_{1/2}(\Lambda) \) are the Fermi integrals. Equation (17) is the generalized Einstein relation in terms of the Fs, which are widely used in problems concerning semiconductors and metals, where Fermi–Dirac statistics are involved. They can be evaluated analytically in two limiting cases: (i) when \( \Lambda \ll 1 \), \( I_{1/2}(\Lambda) \approx \exp(\Lambda) \), which applies to the Maxwell–Boltzmann statistics and suffices for the description of the electronic and transport properties of nondegenerate systems, or in the low-density limit, and equation (17) simply gives the Einstein relation
\[ C_e = \frac{\mu_e}{(e\beta)}, \] (18)
and (ii) when \( \Lambda \gg 1 \), which is the case for highly degenerate systems, \( I_{1/2}(\Lambda) \sim \Lambda^{-1/2} \) and the expression for \( C_e \) reduces to
\[ C_e = \frac{2 \mu e \Lambda}{3 e \beta} = \frac{2 (\epsilon_f - \epsilon_0,\downarrow)}{3} = \frac{\mu e h^2 (3\pi^2 e)^{2/3}}{3 e m^*}. \] (19)
where \( m^* \) is the effective electron mass, which shows that \( C_{HDG} \gg C_e^{NDG} \). This can also be seen from figure 2, where \( \chi = e\beta C_e/m^* \), calculated for GaAs with \( \zeta = 0.067 \) (\( \zeta \) is the ratio of the effective electron mass to the free electron mass, \( m_0 \) in the degenerate regime \( T = 4K \), is plotted as a function of electron density. As figure 2 shows, \( C_e \) (equation (17)) increases in the degenerate regime and with increasing electron density at a given temperature. From a \( x \)-T plot, it can also be shown that \( C_e \) increases with decreasing temperature for a given electron density.

Given that diffusion is considered to be driven by a gradient in the chemical potential, caused by an increase in carrier density, this result can be seen as a consequence of the faster increase of chemical potential with density owing to the Fermi pressure (the Fermi energy strongly depends on the carrier density) [24]. The condition \( C_{HDG} \gg C_e^{NDG} \) suggests a possible method of enhancing the spin current. An increase in the electric field will increase the drift current but will, in

3. Results and discussion
It is interesting to note that the spin current has two components. The first term in the square bracket of equation (9), \( j(x) = -e\mu E \xi \), corresponds to the total drift current density, and the second term corresponds to the total diffusion current density, \( \tilde{j}_{d}(x) = -eC_\xi \left( \sqrt{\rho_{\xi}^2 + 1/L_{\xi,0}^2} - \rho_\xi \right) \tilde{x} \); both terms contribute additively to the total spin current \( \tilde{j}_s(x) \). The spin drift current density \( j_{s,dr} \), spin diffusion current density \( j_{s,di} \), and the total spin current density are therefore
\[ \tilde{j}_{s,dr}(x) = -eC_\xi \left( \sqrt{\rho_{\xi}^2 + 1/L_{\xi,0}^2} - \rho_\xi \right) \tilde{x}, \] (11)
\[ \tilde{j}_{s,dr}(x) = -eC_\xi \left( \sqrt{\rho_{\xi}^2 + 1/L_{\xi,0}^2} - \rho_\xi \right) p(x) \tilde{x}, \] (12)
\[ \tilde{j}_s(x) = \tilde{j}_{s,dr}(x) + \tilde{j}_{s,di}(x). \] (13)
The diffusion current decreases with the electric field while drift current increases, and if we define a spin drift-diffusion crossover field \( E_{sc} \) as
\[ eC_\xi E_{sc} = eC_\xi \left( \sqrt{\rho_{\xi}^2 + 1/L_{\xi,0}^2} - \rho_\xi \right), \] (14)

where the spin drift and spin diffusion mechanisms contribute equally to the spin current, we obtain
\[ E_{sc} = \frac{1}{\sqrt{2} \mu L_{\xi,0}}. \] (15)

Equation (15) is important because it relates the spin drift-diffusion crossover field with the intrinsic spin diffusion length and temperature. When \( E \) is very large \( (\rho_\xi \gg 1/L_{\xi,0}, 0, \sqrt{\rho_{\xi}^2 + 1/L_{\xi,0}^2} - \rho_\xi \approx 0 \) and the diffusion current, and thus the spin diffusion current, is zero \( (\tilde{j}_{s,di} = 0) \) so that only the drift current contributes to the spin current \( [\tilde{j}_s(x) \propto j(x) \approx \tilde{j}_{s,dr}(x) = -eC_\xi E p(x) \tilde{x}] \). This point is shown in figure 1, where it can be seen that \( \tilde{j}_{di} \) decreases with the electric field while \( j \) increases, and that there is a spin drift-diffusion crossover field at each temperature, which suggests a possible method of identifying whether the process for a given field is in the spin drift \( (E > E_{sc}) \) or spin diffusion \( (E < E_{sc}) \) regime.

To quantify conditions for enhancing the spin diffusion contribution, we consider the relationship between the mobility and the diffusion coefficient. Since the diffusion and mobility of both spin and charge in doped semiconductors are approximately determined by the properties of a single (spin) carrier species, specifically, the lower-conductivity spin species, usually the minority spins (here spin-down, ↓) [24], one can relate the diffusion coefficient with the mobility

\[ p(x) = s(x)/c = p_0 e^{-\left(\sqrt{\rho_{\xi}^2 + 1/L_{\xi,0}^2} - \rho_\xi \right)x}. \] (10)
principle, decrease the diffusion current, making it difficult to increase the spin current by increasing the external field. Since for degenerate systems \( C_4^{HDG} \gg C_4^{NDG} \), a method of increasing the spin current for a given field would be to use the degenerate regime by, for example, lowering the temperature. Increasing the diffusion coefficient in this way would increase the diffusive contribution without any change in the drift contribution. Although it is easy to adjust the value of \( e\beta C_c/\mu \) in a semiconductor by doping, it is difficult to control in a metal, suggesting that a semiconductor degenerate regime should also be considered for room-temperature applications.

The semiconductor degenerate regime extends to higher densities when the applied electric field is increased. In semiconductors, in contrast to metals, the electric field remains partially unscreened. However, by increasing the carrier density, the system will eventually enter the metallic regime, in which the electric-field effects in the transport processes are effectively zero and need not be considered.

We now calculate \( E_{sc} \) for GaAs \( (L_{s,0} = 2 \, \mu m) \) for various temperatures in the nondegenerate regime. Table 1 shows the results. \( E_{sc} \) for \( T = 4 \, K \) is 0.12 mV \( \mu m^{-1} \) and increases with increasing temperature with a room-temperature (300 K) value of 9.00 mV \( \mu m^{-1} \). Figure 2 obtained from equations (15) and (17) shows that \( E_{sc} \) in the degenerate regime increases with increasing electron density at a given temperature (with \( L_{s,0} = 2 \, \mu m \) for GaAs). A typical value of \( E_{sc} \), calculated for GaAs in the degenerate regime, is found to be 6 mV \( \mu m^{-1} \) at 4 K for an electron density of \( c = 1 \times 10^{17} \, cm^{-3} \). It can also be shown that \( E_{sc} \) in the degenerate regime increases with increasing temperature for a given electron density for \( L_{s,0} = 2 \, \mu m \). Since the spin drift-diffusion crossover field is quite small, in order for the diffusion or spin diffusion contribution to become significant, the field must therefore be weak (i.e. the spin diffusion regime is within the low field of the spin transport), but not beyond the fields under which spintronic devices can realistically operate [8].

![Figure 2. \( \chi \) as a function of electron density in the degenerate regime. It can be seen (equation (17)) that \( C_4 \) increases in the degenerate regime and with increasing electron density at a given temperature. From equations (15) and (17), it can also be shown that \( E_{sc} (L_{s,0} = 2 \, \mu m) \) at a given temperature increases with increasing electron density in the degenerate regime.](image)

### Table 1. Spin drift–diffusion crossover field \( E_{sc} \) calculated for GaAs with \( L_{s,0} = 2 \, \mu m \), for different temperatures in the nondegenerate regime.

| \( T \) (K) | \( E_{sc} \) (mV \( \mu m^{-1} \)) |
|------------|----------------------------------|
| 4          | 0.12                             |
| 10         | 0.30                             |
| 20         | 0.61                             |
| 40         | 1.20                             |
| 70         | 2.20                             |
| 100        | 3.00                             |
| 140        | 4.40                             |
| 180        | 5.80                             |
| 220        | 6.90                             |
| 260        | 8.00                             |
| 300        | 9.00                             |

From equation (15) and equations (17)–(19), expressions for the intrinsic spin diffusion lengths of a semiconductor in different electron statistical regimes can be obtained as

\[
L_{s,0} = \begin{cases} 
DG : & \frac{1}{\sqrt{2e\beta E_{sc}}} \frac{f_{1/2}^{2}}{f_{-1/2}^{2}} \\
HDG : & \frac{1}{\sqrt{3\sqrt{2}E_{sc}}} \frac{h^2(3\pi^2e)^{2/3}}{e\xi m_0} \\
NDG : & \frac{1}{\sqrt{2e\beta E_{sc}}} 
\end{cases} \tag{20}
\]

where DG, HDG and NDG, respectively stand for degenerate, highly degenerate and nondegenerate regimes. For the highly degenerate systems, \( L_{s,0} \) is independent of temperature. Equation (20) shows that \( L_{s,0} \) can be determined from \( E_{sc} \) if the temperature, electron density and both the temperature and electron density, respectively, are known for the nondegenerate, highly degenerate and degenerate systems.

### 4. Conclusions

Starting from a two-component drift-diffusion equation, we showed how the spin current is composed and found that the spin drift and spin diffusion currents contribute additively to the spin current and that there is a spin drift-diffusion crossover field for a process in which the drift and diffusion contribute equally to the spin current, which suggests a possible method of identifying whether the process for a given electric field is in the drift or diffusion regime. We calculated the spin drift-diffusion crossover fields for GaAs and found them to be quite small but not beyond the fields under which spintronic devices can realistically operate. We derived expressions for the spin drift and spin diffusion current densities. We also derived the relations between the intrinsic spin diffusion length and spin drift-diffusion crossover field of a semiconductor for all electron statistical regimes. The results will be useful for obtaining the transport properties of the electron’s spin, in particular, the intrinsic spin diffusion lengths of semiconductors. This investigation, however, highlights the need for further experiments to measure the spin drift-diffusion crossover field in semiconductors. It was also
shown that a possible method of enhancing the spin current for a given field would be to use a degenerate regime.

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