Strong spin relaxation length dependence on electric field gradients

D. Csontos\textsuperscript{1, 2} and S.E. Ulloa\textsuperscript{2}

\textsuperscript{1}Institute of Fundamental Sciences, Massey University,
Private Bag 11222, Palmerston North, New Zealand
\textsuperscript{2}Nanoscale and Quantum Phenomena Institute, and Department of Physics and Astronomy,
Ohio University, Athens, Ohio 45701-2979, USA

We discuss the influence of electrical effects on spin transport, and in particular the propagation and relaxation of spin polarized electrons in the presence of inhomogeneous electric fields. We show that the spin relaxation length strongly depends on electric field gradients, and that significant suppression of electron spin polarization can occur as a result thereof. A discussion in terms of a drift-diffusion picture, and self-consistent numerical calculations based on a Boltzmann-Poisson approach shows that the spin relaxation length in fact can be of the order of the charge screening length.

PACS numbers: 72.25.Dc, 72.25.Hg, 72.25.Rb, 72.25.Mk

I. INTRODUCTION

Electrical spin injection, transport and detection in diluted magnetic semiconductor (DMS)-nonmagnetic semiconductor (NMS) based systems\textsuperscript{1-5} are three crucial prerequisites for the successful realization of semiconductor spintronics. While the spin degree of freedom naturally is important, the charge degree of freedom plays a significant role in semiconductor spin transport as well, through electric field induced effects. Several experiments\textsuperscript{3-7} have recently shown that the spin injection efficiency is strongly dependent on both applied and intrinsic electric fields, caused by, e.g., inhomogeneous doping. This was theoretically emphasized by Yu and Flatté (YF)\textsuperscript{8} within a drift-diffusion model from which it was shown that the magnitude and sign of an electric field strongly influences the spin relaxation length according to

\begin{equation}
L_{D(U)} = \left\{\begin{array}{l}
-(+) \frac{|eE|}{2k_BT} + \sqrt{\left(\frac{eE}{2k_BT}\right)^2 + \frac{1}{L_s^2}} \\\ \text{if}\ \text{parallel}
\end{array}\right. , \text{1)}
\end{equation}

where $E$ is a homogeneous electric field, and $L_s$ is an intrinsic (electric field-independent) spin diffusion length. According to eq. 1, the electric field enhances(suppresses) the spin relaxation length $L_D(L_U)$ in the direction anti-parallel(parallel) to the direction of the electric field. However, the underlying assumption leading up to eq. 1 was local charge neutrality, and thus homogeneous electric fields. The question is how spin polarized electrons propagate in, e.g., inhomogeneously doped semiconductors where electric fields are inhomogeneous?

In this paper, we use a similar approach as YF as well as self-consistent numerical calculations to study the effects of inhomogeneous electric fields. We find that, in an analogous drift-diffusion picture, a "quasi-local" spin relaxation length in the presence of inhomogeneous electric fields can be defined according to

\begin{equation}
L'_{D(U)} = \left\{\begin{array}{l}
-(+) \frac{|eE|}{2k_BT} + \sqrt{\left(\frac{eE}{2k_BT}\right)^2 + \frac{1}{L_s^2} - \frac{e\nabla E}{k_BT}} \\\ \text{if}\ \text{parallel}
\end{array}\right. , \text{2)}
\end{equation}

from which a strong electric field gradient dependence becomes evident. However, in order to understand the full influence of inhomogeneous electric fields one needs to have access to the self-consistent charge density and electric field profile. We have performed such self-consistent numerical calculations using a Boltzmann-Poisson equation approach for a DMS-NMS inhomogeneously doped semiconductor from which we demonstrate that electric field gradients indeed can play a crucial role in the propagation of spin polarized electrons. Our findings may in particular highlight a possible difficulty in obtaining efficient spin polarized propagation at semiconductor interfaces between low-to-high doping concentration regions.

In the following we will show a derivation of the drift-diffusion model leading to eq. (2) (Section 2), followed by our numerical model (Section 3), and a discussion of our results (Section 4).
that eq. (2) is only defined "locally", over a region where equation for eq. (6) to define up- and down-stream spin diffusion lengths from eq. (6) leading up to eq. (2). Notice \[ \delta \]

For a NMS \( \mu = \mu_\downarrow \), and \( D = D_\downarrow \). Multiplying eq. (5) with \( \sigma_\downarrow(\sigma_\downarrow) \) and substracting them from each other we arrive to the following expression for the spin density imbalance \( \delta_\uparrow \equiv n_\uparrow - n_\downarrow \)

\[ \nabla^2 \delta_\uparrow + \frac{eE}{k_BT} \nabla \delta_\uparrow + \frac{eE}{2k_BT} \delta_\uparrow \nabla \cdot E - \frac{\delta_\downarrow}{L_s} = 0 , \]

where we have used the Einstein relation \( \mu = eD/k_BT \), \( \tau_s \) is the spin relaxation time \( \tau_s^{-1} = \tau_\uparrow^{-1} + \tau_\downarrow^{-1} \) \( (\tau_\uparrow = \tau_\downarrow) \), and \( L_s = \sqrt{D\tau_s} \) is the intrinsic spin diffusion length.

Equation (6) is a drift-diffusion equation for the spin density imbalance \( \delta_\uparrow \) and contains terms depending on both the electric field, and the electric field gradient. We note that in fact eq. (6) resembles the corresponding equations in Refs.\textsuperscript{2,9}, but with an additional term proportional to \( \nabla \cdot E \). Similarly to Refs.\textsuperscript{2,9} we can use the roots of the characteristic equation for eq. (6) to define up- and down-stream spin diffusion lengths from eq. (6) leading up to eq. (6). Notice that eq. (6) is only defined "locally", over a region where \( \nabla \cdot E \) can be considered constant, and where an average value of the electric field is used. Note also that the above equations are also valid for ferromagnetic semiconductors provided the mobility and diffusion constant are replaced with the ones corresponding to the minority-spin species.\textsuperscript{8,2}

A comparison between eq. (6) and Refs.\textsuperscript{8,2} results in that eq. (6) above contains an additional term \(-e\nabla E/k_BT\) in the square root. Naturally, this term plays an important role in inhomogeneously doped semiconductors. We have performed self-consistent calculations and compared them with numerical fits using eq. (6) to verify its applicability.

\section{III. Self-consistent numerical calculations}

Our self-consistent approach is based on the solution of the Boltzmann and Poisson equations using numerical methods developed in Ref.\textsuperscript{10}. Working in a one-dimensional model (choosing the \( x \) direction), the transport of spin-polarized electrons is described by two BTE equations according to

\begin{equation}
-\frac{eE}{m^*} \frac{\partial f_\uparrow(\downarrow)}{\partial v} + v \frac{\partial f_\uparrow(\downarrow)}{\partial x} = -\frac{f_\uparrow(\downarrow) - f_\downarrow(\downarrow)}{\tau_m} - \frac{f_\uparrow(\downarrow) - f_\downarrow(\downarrow)}{\tau_\uparrow(\downarrow)} ,
\end{equation}

where \( f_\uparrow(\downarrow) \) is the electron distribution for the spin-up (down) electrons, \( \tau_m \) is the momentum relaxation time, and \( 1/\tau_\uparrow (1/\tau_\downarrow) \) is the scattering rate for spin-up (down) electrons. The first term on the right-hand side of eq. (7)
describes the relaxation of each nonequilibrium spin distribution to a local equilibrium (spin-dependent), normalized electron distribution function \( f_{↑(↓)}(r) = \frac{n_{↑(↓)}(r)}{\sqrt{2\pi k_B T}} \exp(-mv^2/2k_B T) \), where \( T = 300 \) K is the lattice temperature.

The last term in eq. (7) describes the relaxation of the spin polarization. From the distribution function \( f_{↑(↓)}(r) \) we calculate the local spin density according to \( n = n_{↑} + n_{↓} \), and the spin density imbalance, \( \delta_{↑↓} = n_{↑} - n_{↓} \). In order to take into account inhomogeneous charge distributions and electric fields we solve eq. (7) together with the Poisson equation \( \nabla \cdot \mathbf{E} = e(N_D - n_{↑} + n_{↓})/\varepsilon \varepsilon_0 \), where \( \varepsilon \) is the dielectric constant and \( N_D \) is the donor concentration profile, using finite difference and relaxation methods.\(^{10} \)

IV. RESULTS AND DISCUSSION

We have performed self-consistent, numerical calculations for an inhomogeneously doped DMS-NMS structure schematically depicted in Fig. 1 using \( T = 300 \) K, \( m^* = 0.067m_0 \), \( \tau_m = 0.1 \) ps, \( \tau_s = 0.5 \) ns, \( N_1 = 10^{-21} \) m\(^{-3} \), \( L = 0.2 \) \( \mu \)m and \( V_b = -0.3 \) V.

At the interface between the two doping regions with concentrations \( N_1 \) and \( N_2 \) a built-in field is expected due to the diffusion of carriers from the region with higher to the region with lower doping concentration. This is illustrated in Fig. 2 where we show the electric field profile, as well as the gradient of the electric field (inset) around the interfacial regions, for different doping concentrations \( N_2 = 0.05, 0.5, 1, 5, 20N_1 \). The sign and amplitude of the electric field gradients naturally depend strongly on the doping concentration \( N_2 \) on a length scale of the order of the screening length.

While it is not possible to use eq. (2) directly for a quantitative analysis of the spin transport properties, one can make preliminary estimates of the order of the spin relaxation length around a specific region using linear approximations of the electric field. For example, using a linear fit of \( E \) for \( -0.1 < x < 0.1 \) \( \mu \)m for the \( N_2 = 20N_1 \) curve yields \( \nabla E \approx 2.8 \) V/\( \mu \)m. Furthermore, using a mean value of \( E \approx 2.9 \) kV/cm and \( L_s \approx 1.8 \) \( \mu \)m we obtain from eq. (2) a spin relaxation length value \( L_D \approx 0.16 \) \( \mu \)m along the (charge) direction of transport. Similarly, it is found that \( L_U \approx 0.06 \) \( \mu \)m. In comparison, an evaluation of eq. (1), i.e. without the electric field gradient term, using the same value of the electric field yields \( L_D \approx 36 \) \( \mu \)m, and \( L_U \approx 0.09 \) \( \mu \)m. Thus, the spin relaxation length in the direction of the charge flow is predicted to be strongly influenced by the inhomogeneous electric field around the doping interface.

In Fig. 3 the numerically calculated spin density imbalance, \( \delta_{↑↓} \), and total charge density, \( n \), are shown for the \( N_2 = 20N_1 \) structure considered in the above estimates. The total charge density (dashed line) increases monotonically as expected within a screening length from the low to the high doping concentration region. The spin density imbalance (solid line) follows a similar increase, but is, however, significantly suppressed such that only a maximum of 0.5\( N_2 \) is reached around the interface region, beyond which \( \delta_{↑↓} \) decreases exponentially. The observed suppression is a consequence of the inhomogeneous electric fields.

A crude estimate of the validity of the values for \( L_D' \) can be obtained by comparing our numerical calculations with \( \delta_{↑↓} = n(x) \exp[-(x-x_0)/L_D'] \). In Fig. 4 we show the resulting fits for \( L_D' = 0.16, 0.3, 1 \) and 36 \( \mu \)m, the first and latter values corresponding to the previously estimated values for \( L_D' \) and \( L_D \) obtained from the numerically calculated electric field profiles. We see that the higher values of \( L_D \) indeed yield that \( \delta_{↑↓} \approx n \). In contrast, the \( L_D \) values 0.16

[FIG. 2: Electric field and electric field gradient (inset) profile for different doping concentrations \( N_2 = 0.05, 0.5, 1, 5, 20N_1 \).]
FIG. 3: Total charge density (dashed line) and spin density imbalance (solid line) profiles calculated for $N_2 = 20N_1$. Additional curves for $-0.1 < x < 0.1 \mu\text{m}$ correspond to $\delta_{\uparrow\downarrow} = n(x)\exp[-(x + 0.1)/L_D]$ for different $L_D$ as described in the text. Inset shows $n$ and $\delta_{\uparrow\downarrow}$ for a larger region.

and 0.3 $\mu\text{m}$, which are of the order of the screening length, yield better fits to the numerically calculated data.

Our results and analysis shows that inhomogeneous electric fields can strongly influence the spin relaxation length, and that significant spin polarization suppression can occur as a result thereof. We have also high-lighted a possible mechanism that may inhibit propagation of spin polarized electrons from low-to-high regions of doping concentrations, such as encountered in future semiconductor spintronic devices.

This work was supported by the Indiana 21st Century Research and Technology Fund. Numerical calculations were performed using the facilities at the Center for Computational Nanoscience at Ball State University.

---

1 R. Fiederling et al., Nature 402, 787 (1999); Y. Ohno et al., Nature 402, 790 (1999).
2 G. Schmidt et al., Phys. Rev. Lett. 87, 227203 (2001).
3 G. Schmidt et al., Phys. Rev. Lett. 92, 226602 (2004).
4 P. Van Dorpe et al., Appl. Phys. Lett. 84, 3495 (2004).
5 M. Kohda, Y. Ohno, F. Matsukura, and H. Ohno, Physica E 32, 438 (2006).
6 C. Adelmann et al., J. Vac. Sci. Technol. 23, 1747 (2005).
7 S. A. Crooker, and D. L. Smith, Phys. Rev. Lett. 94, 236601 (2005).
8 Z. G. Yu, and M. E. Flatté, Phys. Rev. B 66, 201202(R) 2002; ibid. 235302 (2002).
9 M. E. Flatté, and J. M. Byers, Phys. Rev. Lett. 84, 4220 (2000).
10 D. Csontos, and S. E. Ulloa, Physica E 32, 412 (2006).