Reduced ballistic spin scattering in a spin-FET using stray electric fields

G. A. Nemnes
University of Bucharest, Faculty of Physics,
“Materials and Devices for Electronics and Optoelectronics” Research Center,
P.O. Box MG-11, 077125 Magurele-Ilfov, Romania
E-mail: nemnes@solid.fizica.unibuc.ro

A. Manolescu
School of Science and Engineering,
Reykjavik University, Menntavegur 1, IS-101 Reykjavik, Iceland

V. Gudmundsson
Science Institute,
University of Iceland, Dunhaga 3, IS-107 Reykjavik, Iceland

Abstract. The quasi-bound states which appear as a consequence of the Rashba spin-orbit (SO) coupling, introduce a strongly irregular behavior of the spin-FET conductance at large Rashba parameter. Moreover, the presence of the bulk inversion asymmetry, i.e. the Dresselhaus SO coupling, may compromise the spin-valve effect even at small values of the Rashba parameter. However, by introducing stray electric fields in addition to the SO couplings, we show that the effect of the SO induced quasi-bound states can be tuned. The oscillations of the spin-resolved conductance become smoother and the control of the spin-FET characteristics becomes possible.

1. Introduction
The practical realization of the spin field effect transistor (spin-FET) suggested by Datta and Das [1] in the 90’s was first met with serious challenges concerning the efficient spin injection using metallic ferromagnetic contacts and the attainment of the ballistic regime. Since then, a number of studies, both theoretical and experimental, reported significant progress.

Some theoretical studies suggested several improvements: enhanced spin control due to interband coupling [2] or large magnetocurrent due to the spin-filter effect of Schottky junctions [3]. Other design elements that are shown to play a key role are channel orientation and boundary effects [4] and the effects of stray magnetic fields [5]. Recently, the operation of the Datta-Das transistor was investigated in the ballistic [6] and nonballistic regimes [7, 8, 9].

An experimental realization of a transit-time spin-FET [10], making use of magnetic fields for spin precession has been achieved. Other spin-FETs with different operation principles than the Datta-Das transistor were reported, indicating a giant negative magnetoreistance effect.

Published under licence by IOP Publishing Ltd
Figure 1. Schematics and functionality of a spin-FET with stray electric fields. The device structure is depicted together with the diagram of the first energy levels inside the leads ($\Omega_{S/D}$) and the scattering region ($\Omega_0$). The combined action of the Rashba SO coupling and stray electric fields is indicated.

[11], tunneling through a magnetic domain wall [12], or the possibility of optical control of a quantum dot transistor [13]. Experimental devices investigated electric field tuning of the spin-orbit coupling [14], and the performance of a spin-valve transistor [15]. Recently, the concrete integration of spin-FETs with magnetic tunnel junctions to produce nonvolatile static random access memory has been analyzed [16] and the electrical control in a spin-FET using Rashba spin-orbit coupling was achieved in the experimental setup of Koo et al. [17].

From the theoretical point of view, some performance limitations were predicted, which are due to the inter-band ballistic scattering and spin interference effects in the large SO coupling regime [18]. This is due to the coupling of propagating modes to the quasi-bound states, which result following the SO interaction, leading to an uncontrollable sequence of minima and maxima in the conductance.

In this study we point out the possibility of using stray electric fields in order to diminish the effects introduced by the quasi-bound states and thus recover a controllable characteristics for the spin-FET, including the spin-valve regime. Calculations including the Dresselhaus SO coupling and an embedded point contact are also discussed, and they support the idea of using stray electric fields for obtaining a reasonable spin control.

2. Model
The transistor model considered is based on the spin-FET configuration proposed by Datta and Das [1]. As depicted in Fig. 1, the device is a usual field effect transistor, with the major difference that the source and drain contacts are ferromagnetic materials. The spins of electrons injected by the source contact will have the same orientation with the source contact magnetization, while the drain electrode acts as a spin filter and collects electrons with spins aligned with the drain contact magnetization. The electrons passing from source to drain are subject of spin-orbit interaction, also called the Rashba effect [19]: the electric field produced by the gate, perpendicular on the channel direction, causes a “structural inversion asymmetry”, which leads to the precession of the electron-spins. In this way, the orientation of the spins at the drain contact can be controlled by electrical means, simply by applying a gate voltage.

It is known that the Rashba SO coupling produces an effective quantum well as indicated schematically in Fig. 1, and it also provides the inter-subband coupling. The two effects
combined are detrimental for the source-drain current, as inter-band scattering between the free traveling states and the quasi-bound states accommodated in the effective quantum well lead to uncontrollable characteristics. One way to overcome this undesired result is to introduce a potential step, to counterbalance the effect of the Rashba SO coupling. This is achieved by means of stray electric fields which naturally occur in a spin-FET structure between the source/drain contacts and the gate. The electric field components along the transport direction can be adjusted by varying the potential difference between source/drain and the gate, while the electric field which generates the Rashba effect is controlled by the potential difference between gate and back-gate.

We assume the device is based on a InAs heterojunction, which is a typical material for spintronic applications, due to a relatively high Rashba parameter \( \alpha \approx 10 \text{ meV nm} \). The effective mass is \( m^* = 0.023m_0 \). The two dimensional electron gas (2DEG) has a parabolic confinement in the \( y \)-direction (see Fig. 1), given by the level spacing \( \hbar \omega_0 = 0.01 \text{ meV} \), which leads to an effective confinement length \( l_0 = \hbar/\sqrt{m^*\hbar\omega_0} \). The length of the Rashba active region is \( 8l_0 \).

The key element in this approach – the stray electric fields – introduces a shift \( (V_0) \) in the energy levels inside the active region (2DEG), which is opposite to the effect produced by the Rashba SO coupling. The value \( V_0 \) is set by matching the first Wigner-Eisenbud energy \( E_{2D}^{2DEG}(x) = c_1 \) (see next section) with the first subband in the semi-infinite source/drain leads \( E_{2S,I}^0 = E_{2D}^{2DEG} \). This matching condition implicitly means that \( V_0 \) must depend on \( \alpha \):

\[
V_0(\alpha) = E_{2S,I}^0 - E_{2S,I}^{2DEG}(\alpha). \tag{1}
\]

3. The R-matrix scattering formalism

The spin-resolved conductance is obtained using the R-matrix scattering formalism, which has already proved its efficiency in a number of studies regarding charge transport in mesoscopic systems \[20, 21, 22, 23\].

The scattering problem is described by the two-dimensional Schrödinger equation defined in the \((x, y)\) plane of the 2DEG, with asymptotic boundary conditions corresponding to incoming electrons from either source or drain:

\[
\mathcal{H}\Psi(\vec{r}) = E\Psi(\vec{r}), \tag{2}
\]

where \( \mathcal{H} = T + W + H_R + H_D + V_0(\alpha) \) is the total Hamiltonian composed by the following terms: kinetic energy \( T = -\hbar^2/(2m^*)\Delta \), potential energy \( W = W(\vec{r}) - \) which includes the parabolic confinement in the \( y \)-direction, Rashba SO interaction \( H_R = \alpha/\hbar(p_y\sigma_x - p_x\sigma_y) \), Dresselhaus SO interaction \( H_D = \beta/\hbar(p_z\sigma_x - p_x\sigma_y) \) and the add-on potential due to the stray electric fields \( V_0(\alpha) \).

The device is partitioned as usual in leads \((\Omega_s)\), which are uniform in the transport direction, and the scattering region \((\Omega_s)\), which includes the channel and the regions containing the stray electric fields. The wavefunctions inside the leads take the general form of traveling waves modulated by the confinement potential:

\[
\Psi_s(\vec{r} \in \Omega_s, E) = \sum_i \Psi_{\nu}^{in} \exp(-ik_{\nu}s)\Phi_{\nu} + \sum_i \Psi_{\nu}^{out} \exp(ik_{\nu}s)\Phi_{\nu}, \tag{3}
\]

with \( \Phi_{\nu} = \sum_{\sigma} \Phi_{\nu,\sigma}(\vec{r}_{\perp,s})|\sigma\rangle \), where \( \sigma \) denotes the electron spin. Following notations from Ref. [23], the wavevectors are given by \( k_{\nu} = \sqrt{2m^*/\hbar^2}(E - E_{\nu}^0) \), where \( \nu = (s, i) \) is a composite index denoting channel \( i \) from lead \( s = S, D \) and \( E_{\perp}^0 \) are the energies of transverse modes \( \Phi_{\nu} \) inside the leads.
The scattering matrix relates the complex coefficients of incoming and outgoing functions, \( \tilde{\Psi}_{\text{out}} = S \tilde{\Psi}_{\text{in}} \), and it is given by the R-matrix
\[
S = -\frac{1 + \frac{i}{m} R_k}{1 - \frac{i}{m} R_k},
\]
where \( k \) is the diagonal matrix given by the wavevectors \( k_\nu \). The R-matrix is defined as
\[
(R)_{\nu \nu'}(E) = \sum_{\sigma, \sigma'} \int_{\Gamma_s} d\Gamma_s' \int_{\Gamma_s} d\Gamma_s \Phi_{\nu, \sigma}(\vec{r}_{\perp; s}) \Phi_{\nu', \sigma'}(\vec{r}_{\perp; s'}) R_{\sigma, \sigma'}(\vec{r} \in \Gamma_k; \vec{r}' \in \Gamma_{s'}; E),
\]
where \( \Gamma_s = \Omega_s \cap \Omega_0 \) are the interfaces between the leads and the scattering region. One should note that the R-function has now an explicit dependence on the electron spin:
\[
R_{\sigma, \sigma'}(\vec{r}; \vec{r}'; E) = -\frac{\hbar^2}{2} \sum_{l=1}^{\infty} \chi_{l, \sigma}(\vec{r}) \chi_{l, \sigma'}(\vec{r}') \frac{1}{E - \epsilon_l}, \quad \vec{r}, \vec{r}' \in \Omega_0,
\]
where \( \chi_{l} \) and \( \epsilon_{l} \) are the Wigner-Eisenbud functions and energies, respectively. The Wigner-Eisenbud problem is defined as usual:
\[
H \chi_{l}(\vec{r}) = \epsilon_{l} \chi_{l}(\vec{r}), \quad \vec{r} \in \Omega_0,
\]
with the boundary conditions on \( \Gamma_s \):
\[
\left[ \frac{\partial \chi_{l}}{\partial x_s} \right]_{\Gamma_s} = 0.
\]
Using the S-matrix one can extract directly the total transmission between leads \( s \) and \( s' \):
\[
T_{ss'}(E) = \sum_{i, i'} \Theta(E - E_{i+}') \Theta(E - E_{i'}') |\tilde{S}_{\nu \nu'}(E)|^2,
\]
where \( \tilde{S} = k^{1/2}Sk^{-1/2} \). The \( \Theta \)-functions ensure that the summation is performed on the open channels only.

4. Results and discussion

The spin-FET conductance as a function of the Rashba parameter was analyzed for three spin polarizations of the contacts in the \( z \) direction: unpolarized, parallel, and anti-parallel.

In a first run, by varying the Rashba parameter \( \alpha \), the source-drain conductance is determined for the three contact polarizations and the positions of the first Wigner-Eisenbud energies are recorded. Then, using Eq. (1), one obtains the parametric dependence \( V_0(\alpha) \), which is added to the Hamiltonian, and after that a second run is performed.

In Fig. 2(a) and 2(b) the results for the source-drain conductance are depicted, for one and five propagating modes, respectively. The number of participating channels \( N \) is set by the energy of the incident electrons. For one mode one obtains, as in Ref. [18], a chaotic behavior (upper plot) above a value of the Rashba parameter \( \alpha \approx \hbar \omega_0 l_0 = 5.75 \text{ meV nm} \), for all three contact polarizations. When the additional potential, \( V_0(\alpha) \), is included in the Hamiltonian, the irregular oscillations are replaced by a more predictable characteristics. Increasing the number of modes to five (see Fig. 2(b)), one obtains a similar behavior as in Ref. [18]: the conductance oscillations drop in amplitude, although the onset of the irregular regime is still visible and, in the limit of large \( \alpha \), the conductance approaches the value of \( N/2 \). Including the term \( V_0(\alpha) \) the
Figure 2. Conductance as function of the Rashba parameter, for the following test cases: (a) one mode, (b) five modes, (c) additional Dresselhaus SO coupling and (d) embedded point contact, for unpolarized (black/solid), parallel polarized (red/dotted), anti-parallel polarized (green/dashed) contacts. In each case, in the lower plots are depicted the improved characteristics, which follow from the inclusion of the stray electric fields, i.e. the term \( V_0(\alpha) \).

oscillations are further smoothed and for the systems with polarized contacts an enhancement of the spin-valve effect can be observed.

For some materials, the Dresselhaus spin-orbit coupling becomes equally important. For the one mode case, by introducing a Dresselhaus SO parameter \( \beta = 3.5 \text{ meV nm} \) (as for InAs), one finds that the spin-valve effect is seriously affected at even smaller values of the Rashba parameter \( \alpha \) (see Fig. 2(c)). The two SO couplings, i.e. Rashba and Dresselhaus, act in a similar way, i.e. they both produce an effective quantum well and, in addition, they generate the coupling between different subbands. By including the stray electric fields, i.e. \( V_0(\alpha) \), according to Eq. (1), one obtains a nearly ideal characteristics, indicating a high quality spin valve-effect. The low conductance for both unpolarized and polarized contacts is a consequence of the relatively high potential shift \( V_0 \), which now compensates the effective quantum well produced by both Rashba and Dresselhaus SO couplings.

Including embedded systems is commonly done for improving spin injection or designing efficient spin filters. Here, a sharp point contact of length \( 4l_0 \) and aperture \( 2l_0 \), placed in the middle of the Rashba active region was considered. Fig. 2(d) (upper plot) shows the conductance in the presence of the point contact, which acts as an effective potential step, as the wire confinement is locally increased. Consequently, it follows that for all contact polarizations the
conductance is low at small $\alpha$, while overall, the oscillations are better defined as compared to Fig. 2(a). Applying the same recipe of additional stray electric fields in this case, one also obtains an improvement in the spin control.

5. Conclusions
The undesired effects introduced by the quasi-bound states are diminished by adding proper stray electric fields. The spin-FET characteristics is improved in single and multi-channel case, without adjusting the wire confinement. The procedure is robust even in the presence of Dresselhaus spin-orbit coupling or after including an embedded system like a sharp point contact. The spin-valve effect is also restored.

Acknowledgments
This work was supported by the Romanian National Authority for Scientific Research, CNCS-UEFISCDI, project number PN-II-RU-PD-2011-3-0044 and by the Icelandic Research Fund. We are thankful to Roxana and Paul Racec for instructive discussions on the R-matrix theory.

References
[1] Datta S and Das B Appl. Phys. Lett. 1990 56 665
[2] Egues J C, Burkard G and Loss D 2003 Appl. Phys. Lett. 82 2658
[3] Sugahara S and Tanaka M 2004 Appl. Phys. Lett. 84 2307
[4] Liu M H and Chang C R 2006 Phys. Rev. B 73 205301
[5] Koo H C, Eom J, Chang J and Han S H 2009 Solid-State Electronics 53 1016
[6] Jiang K M, Yang J, Zhang R and Wang H 2008 J. Appl. Phys. 104 053722
[7] Schliemann J, Egues J C, and Loss D 2003 Phys. Rev. Lett. 90 146801
[8] Cartoixa X 2003 Appl. Phys. Lett. 83 1462
[9] Ohno M and Yoh K 2008 Phys. Rev. B 77 045323
[10] Huang B, Monsma D J and Applebaum I 2007 Appl. Phys. Lett. 91 072501
[11] Gurzhi R N et al. 2003 Appl. Phys. Lett. 83 4577
[12] Vignale G and Flate M E 2002 Phys. Rev. Lett. 89 098302
[13] Lu H F, Guo Y, Zu X T and Zhang H W 2009 Appl. Phys. Lett. 94 162109
[14] Nakamura H and Kimura T 2009 Phys. Rev. B 80 121308
[15] Huang Y W et al. 2005 J. Appl. Phys. 97 10D504
[16] Shuto Y, Yamamoto S and Sugahara S 2009 J. Appl. Phys. 105 07C933
[17] Koo H C, Kwon J H, Eom J, Chang J, Han S H and Johnson M 2009 Science 325 1515
[18] Gelabert M M, Serra L, Sanchez D and Lopez R 2010 Phys. Rev. B 81 165317
[19] Yu A Bychkov et al. 1984 J. Phys. C: Solid State Phys. 17 6039
[20] Nemnes G A, Wulf U and Racec P N 2004 J. Appl. Phys. 96 596
[21] Nemnes G A, Wulf U and Racec P N 2005 J. Appl. Phys. 98 084308
[22] Nemnes G A, Ion L and Antohe S 2009 J. Appl. Phys. 106 113714
[23] Nemnes G A, Ion L and Antohe S 2010 Physica E 42 1613