A spin field effect transistor for low leakage current

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Abstract

In a spin field effect transistor, a magnetic field is inevitably present in the channel because of the ferromagnetic source and drain contacts. This field causes random unwanted spin precession when carriers interact with non-magnetic impurities. The randomized spins lead to a large leakage current when the transistor is in the “off”-state, resulting in significant standby power dissipation. We can counter this effect of the magnetic field by engineering the Dresselhaus spin-orbit interaction in the channel with a backgate. For realistic device parameters, a nearly perfect cancellation is possible, which should result in a low leakage current.

Key words: Spintronics, Spin field effect transistors, spin orbit interaction

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Much of the current interest in spintronic transistors is motivated by a well-known device proposal due to Datta and Das [1] that has now come to be known as a Spin Field Effect Transistor (SPINFET). This device consists of a one-dimensional semiconductor channel with half-metallic ferromagnetic source and drain contacts that are magnetized along the channel (Fig. 1). Electrons are injected from the source with their spins polarized along the channel’s axis. The spin is then controllably precessed in the channel with a gate voltage that modulates the Rashba spin-orbit interaction [2]. At the drain end, the transmission probability of the electron depends on the component of its spin vector along the channel. By controlling the angle of spin precession in the channel with a gate voltage, one can control this component, and hence control the source-to-drain current. This realizes the basic “transistor” action [3].

In their original proposal [1], Datta and Das ignored two effects: (i) the magnetic field that is inevitably present in the channel because of the ferromagnetic source and drain contacts, and (ii) the Dresselhaus spin orbit interaction [4] arising from bulk (crystallographic) inversion asymmetry. In the past, we analyzed the effect of the channel magnetic field and showed that it could cause weak spin flip scattering via interaction with non-magnetic elastic scatterers [5]. The flipped spins, whose precession angles have been randomized by the spin flip scattering events, will lead to a large leakage current when the device is in the “off”-state. This is a serious drawback since it will lead to an unacceptable standby power dissipation in a circuit composed of Spin Field Effect Transistors. In order to eliminate the leakage current, we must eliminate the unwanted spin flip scattering processes. In other words, we must find ways to counter the deleterious effect of the channel magnetic field. The purpose of
Fig. 1. A spin field effect device with a one-dimensional channel. (a) side view showing a top gate for modulating the spin precession via the Rashba interaction and a back gate for modulating the channel carrier concentration. The substrate will be p⁺ if we want to deplete the channel with the back-gate, and n⁺ if we want to accumulate it. (b) top view showing the split gate configuration required to produce a one-dimensional channel, as well as the top gate. A positive voltage is applied to the top gate to increase the interface electric field that modulates the Rashba interaction and produces the conductance modulation, whereas a negative voltage is applied to the split gates to constrict the one-dimensional channel.

This paper is to explore how this can be achieved.

In a strictly one-dimensional structure, where transport in single channeled, there is no D’yakonov-Perel spin relaxation [6]. Therefore, the only agents that can cause spin randomization are hyperfine interactions with the nuclei

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and spin mixing effects caused by the channel magnetic field [5]. In order to eliminate the latter (which is the stronger of the two agents), we can adopt one of two options: either eliminate the magnetic field by using non-magnetic spin-injector (source contact) and detector (drain contact) [7], or counteract the effect of the magnetic field with some other effect. The former approach presents a formidable engineering challenge. The latter can be implemented more easily, and, as we show in this paper, is achieved by countering the effect of the magnetic field with the Dresselhaus interaction. Calculations based on realistic parameters for InAs transistor channels show that this is indeed possible.

Consider the one-dimensional channel of the device in Fig. 1. Because of the magnetized source and drain contacts, a magnetic field exists along the wire in the x-direction. We will assume that the channel (x-direction) is along the [100] crystallographic axis.

The effective mass Hamiltonian for the wire, in the Landau gauge $\mathbf{A} = (0, -Bz, 0)$, can be written as

$$
H = \left(\frac{p_x^2 + p_y^2 + p_z^2}{2m^*} + \frac{eBz p_y}{m^*} + \frac{e^2 B^2 z^2}{2m^*} - \frac{g/2}{\mu_B} B \sigma_z \right) + V(y) + V(z) + 2a_{42} [\sigma_x \kappa_x + \sigma_y \kappa_y + \sigma_z \kappa_z] + \eta [\frac{p_z}{\hbar} \sigma_z - \frac{p_z}{\hbar} \sigma_z]$$

where $g$ is the Landè g-factor, $\mu_B$ is the Bohr magneton, $V(y)$ and $V(z)$ are the confining potentials along the y- and z-directions, $\sigma$-s are the Pauli spin matrices, $2a_{42}$ is the strength of the Dresselhaus spin-orbit interaction ($a_{42}$ is a material parameter) and $\eta$ is the strength of the Rashba spin-orbit interaction.

The quantities $\kappa$ are defined in ref. [8]. We will assume that the wire is narrow enough and the temperature is low enough that only the lowest magneto-
electric subband is occupied. Since the Hamiltonian is invariant in the \(x\)-coordinate, the wavevector \(k_x\) is a good quantum number and the eigenstates are plane waves traveling in the \(x\)-direction. Accordingly, the spin Hamiltonian (spatial operators are replaced by their expected values) simplifies to

\[
H = \left(\frac{\hbar^2 k_x^2}{2m^*}\right) + E_0 + (\alpha k_x - \beta)\sigma_x + \eta k_x \sigma_z
\]

(2)

where \(E_0\) is the energy of the lowest magneto-electric subband, \(\alpha(B) = 2a_4 \langle < k_y^2 > - < k_z^2 > + (e^2 B^2 < z^2 > / \hbar^2)\rangle\), \(\psi(z)\) is the \(z\)-component of the wavefunction, \(\phi(y)\) is the \(y\)-component of the wavefunction, \(< k_y^2 > = (1/2) \langle \phi(y) \rangle - (\partial^2 / \partial y^2) \psi(y) \rangle >, < k_z^2 > = (1/\hbar^2) \langle \psi(z) \rangle - (\partial^2 / \partial z^2) |\psi(z)\rangle >\), and \(\beta = (g/2)\mu_B B\).

Since the potential \(V(z)\) is parabolic \((V(z) = (1/2)m^*\omega_c^2 z^2)\), it is easy to show that \(< k_z^2 > = m^* \omega / (2\hbar)\) and \(< z^2 > = \hbar / (2m^* \omega)\) where \(\omega^2 = \omega_0^2 + \omega_c^2\) and \(\omega_c\) is the cyclotron frequency \((\omega_c = eB/m^*)\). Furthermore, \(E_0 = (1/2)\hbar \omega + E_\Delta\) where \(E_\Delta\) is the energy of the lowest subband in the triangular well \(V(y)\).

Diagonalizing this Hamiltonian in a truncated Hilbert space spanning the two spin resolved states in the lowest subband yields the eigenenergies [9]

\[
E_\pm = \frac{\hbar^2 k_x^2}{2m^*} + E_0 \pm \sqrt{(\hbar^2 / \eta^2 + \alpha^2) \left( k_x - \frac{\alpha \beta}{\eta^2 + \alpha^2} \right)^2 + \frac{\eta^2}{\eta^2 + \alpha^2} \beta^2}
\]

(3)

and the corresponding eigenstates

\[
\Psi_+ (B, x) = \begin{bmatrix} \cos(\theta_{k_x}) \\ \sin(\theta_{k_x}) \end{bmatrix} e^{ik_xx} \quad \Psi_- (B, x) = \begin{bmatrix} \sin(\theta_{k_x}) \\ -\cos(\theta_{k_x}) \end{bmatrix} e^{ik_xx}
\]

(4)

where \(\theta_{k_x} = (1/2)\arctan[(\alpha k_x - \beta)/\eta k_x]\).
The dispersion relations given by Equation (3) can be found plotted in ref. [9]. The dispersions are clearly nonparabolic and could be asymmetric about the energy axis. More importantly, note that the eigenspinors given in Equation (4) are functions of \( k_x \) because \( \theta_k \) depends on \( k_x \). Therefore, the eigenspinors are not fixed in any subband, but change with \( k_x \). In other words, neither subband has a definite spin quantization axis and the orientation of the spin vector of an electron in either subband depends on the wavevector. Consequently, it is always possible to find two states in the two subbands with non-orthogonal spins. Any non-magnetic scatterer (impurity, phonon, etc.) can then couple these two states and cause a spin-relaxing scattering event. It is this spin flip process that leads to a non-zero off-conductance (and leakage current) and needs to be eliminated.

It is easy to see that the way to eliminate the spin flip process is to enforce the condition:

\[
\alpha k_x = \beta
\]  
(5)

In this case, the dispersion relations become

\[
E_\pm = E_0 - \frac{\hbar^2}{2m^*} k_R^2 + \frac{\hbar^2}{2m^*} (k_x \pm k_R)^2
\]  
(6)

where \( k_R = m^* \eta / \hbar^2 \), and the eigenstates become

\[
\Psi_+(x) = \begin{bmatrix} 1 \\ 0 \end{bmatrix} e^{i k_x x} \quad \Psi_-(x) = \begin{bmatrix} 0 \\ 1 \end{bmatrix} e^{i k_x x}
\]  
(7)

The dispersion relation in Equation (6) is parabolic (two parabolas displaced
horizontally from the origin by \( \pm k_R \) and each has a definite (wavevector-independent) spin quantization axis which is \(+z\)-polarized in the first subband and \(-z\)-polarized in the second subband. Since the two subbands have orthogonal spin polarizations at any wavevector, no non-magnetic scatter can couple them and cause a spin flip event. Therefore, we can successfully eliminate the unwanted spin flip processes when we enforce the condition in Equation (5).

Equations (6) and (7) are the dispersions and eigenstates employed in ref. [1]. They are correct only if we counteract the channel magnetic field with the Dresselhaus interaction as embodied by the condition in Equation (5).

We now proceed to estimate realistic values of \( \alpha \) and \( \beta \) to see if the condition in Equation (5) can be realized. This equation can be recast as

\[
2a_{42} \left[ \langle k_y^2 \rangle - \frac{m^* \omega}{2\hbar} + \frac{e^2 B^2}{2m^* \hbar \omega} \right] k_F = \frac{g\mu_B B}{2}
\]

(8)

where we have assumed that \( k_x = k_F \), the Fermi wavevector.

We will assume a 0.2 \( \mu \)m long channel where the magnetic field can be as large as 1 Tesla [10,11]. Table 1 lists the parameters used for various quantities used in Equation (8) (along with the citations for the sources when appropriate).

Using these parameters, we find that in order to counter a magnetic field of 1 Tesla through the Dresselhaus interaction, we need \( k_F = 2.47 \times 10^9 \text{ m}^{-1} \), which corresponds to a linear carrier concentration \( n_l \) of \( 1.54 \times 10^9 \text{ m}^{-1} \). A larger magnetic field would require a larger Fermi wavevector and a larger carrier concentration.

The purpose of the backgate in Fig. 1 now becomes clear. We can tune the
carrier concentration and Fermi wavevector $k_F$ in the channel to the optimum value with a backgate voltage. The top gate can then be used exclusively to modulate the Rashba interaction which leads to conductance modulation of the transistor. As we swing the top gate voltage to switch the transistor from “on” to “off”, or vice versa, this gate voltage swing $\Delta V_G$ will also induce some unavoidable fluctuation in $k_F$. We need to ensure that this fluctuation $\Delta k_F$ is a small percentage of $k_F$, so that the act of switching the device does not nullify the balance between the Zeeman splitting (magnetic field) and the Dresselhaus interaction.

In ref. [12], we found that $\Delta V_G$ required to induce a spin precession of $\pi$ radians in an ideal 0.2 $\mu$m long InAs SPINFET channel is about 50 mV if the gate insulator thickness $d$ (see Fig. 1) is 20 nm [13]. This is the voltage swing required to switch such a SPINFET from “on” to “off”, or vice versa. Using standard metal oxide semiconductor field effect device theory, the change in the (two-dimensional) carrier concentration $\Delta N_S$ induced by a gate voltage

Table 1

Parameters for a InAs spin interferometer

| Parameter | Value |
|-----------|-------|
| $a_{42}$  | $1.6 \times 10^{-29}$ eV·m$^3$ [15] |
| $-g-$     | 14.4 [16] |
| $\hbar \omega_0$ | 10 meV [17] |
| $m^*$     | $0.034 \times 9.1 \times 10^{-31}$ Kg |
| $\langle k_F^2 \rangle$ | $10^{16}$ m$^{-1}$ |
swing $\Delta V_G$ is given by

$$e\Delta N_s = (\epsilon/d)\Delta V_G \quad (9)$$

Assuming that the gate insulator is AlAs, for which $\epsilon = 8.9$ times the permittivity of free space [14] and $d = 20 \text{ nm}$, we find that for $\Delta V_G = 50 \text{ mV}$, $\Delta N_s = 1.375 \times 10^{15} \text{ m}^{-2}$. The corresponding fluctuation in the linear carrier concentration is found by multiplying this quantity with the effective width $W_{\text{eff}}$ of the InAs channel which is $\sqrt{\hbar/(2m^*\omega)}$. For $\hbar\omega = 10 \text{ meV}$, $W_{\text{eff}} = 22 \text{ nm}$. Therefore the fluctuation in the linear carrier concentration $\Delta n_l$, sustained during switching the SPINFET from “on” to “off”, or vice versa, is about $3 \times 10^7 \text{ m}^{-1}$. This is only 2% of $n_l$. Therefore, the modulation of the top gate voltage, during switching, does not affect the channel carrier concentration (or $k_F$) significantly. Accordingly, it does not seriously affect the balance between the magnetic field and the Dresselhaus interaction.

0.0.0.1 **Which way should the contacts be magnetized?** Before concluding this paper, we bring out an important issue. It is obvious by looking at Equations (3) and (4) that the dispersion relations and the eigenspinors depend not only on the magnitude but also the sign of $\beta$. Therefore, the “cancellation effect” discussed in this paper and embodied in Equation (8) is possible only if the magnetization of the contacts is directed in a certain way. For example, if the left hand side of Equation (8) is positive, then the contacts should be magnetized along the direction of current flow provided the g-factor is positive. If the g-factor is negative, then the contacts should be magnetized against the direction of current flow. The exact opposite is true if the left hand side of Equation (8) is negative. To our knowledge, no work
on the Spin Field Effect Transistor has ever addressed the issue of which way
the contacts should be magnetized. Here we show, for the first time, that this
matter is important.

In conclusion, we have shown how the deleterious effect of the channel mag-
netic field in a Spin Field Effect Transistor can be countered with the Dres-
sselhaus interaction. In deriving this result, we have also shown that for the
cancellation to happen, there is an optimum channel carrier concentration $n_t$
that depends on the confinement energy $\hbar \omega$ in the channel, the channel mag-
netic field, the strength of the Dresselhaus interaction $a_{42}$, the effective mass
and Landé g-factor of the channel material, and the degree of confinement
of the two-dimensional electron gas at the heterointerface represented by the
quantity $< k^2_y >$. Since normally many of these parameters will be unknown in
any given sample, it will be necessary to vary the carrier concentration in the
channel with a backgate till optimum performance is achieved. To our knowl-
edge, no experimental attempt at demonstrating this device has considered
using a backgate to improve performance. This may however be an important
consideration.

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References

[1] S. Datta and B. Das, Appl. Phys. Lett., 56, 665 (1990).

[2] E. I. Rashba, Sov. Phys. Semicond., 2, 1109 (1960); Y. A. Bychkov and E. I. Rashba, J. Phys. C, 17, 6039 (1984).

[3] Datta and Das appropriately called their device “an electronic analog of the electro-optic modulator” rather than a “spin field effect transistor”. This device may not have all the attributes of a useful transistor and is probably not competitive with state-of-the-art silicon transistors in terms of speed or power dissipation (see reference 12).

[4] G. Dresselhaus, Phys. Rev., 100, 580 (1955).

[5] M. Cahay and S. Bandyopadhyay, Phys. Rev. B, 69, 045303 (2004).

[6] S. Pramanik, S. Bandyopadhyay and M. Cahay, www.arXiv.org/cond-mat/0403021. Also to appear in IEEE Trans. Nanotech.

[7] T. Koga, J. Nitta, H. Takayanagi and S. Datta, Phys. Rev. Lett., 88, 126601 (2002); K. C. Hall, et al., Appl. Phys. Lett., 83, 1462 (2003).

[8] B. Das, S. Datta and R. Reifenberger, Phys. Rev. B, 41, 8278 (1990).

[9] S. Bandyopadhyay, S. Pramanik and M. Cahay, www.arXiv.org/cond-mat/0310115. Also to appear in Superlat. Miscostruct.

[10] M. Cahay and S. Bandyopadhyay, Phys. Rev. B, 68, 115316 (2003).

[11] J. Wróbel, et. al., Physica E, 10, 91 (2001).

[12] S. Bandyopadhyay and M. Cahay, www.arXiv.org/cond-mat/0404339. Also to appear in Appl. Phys. Lett.
[13] We have used the theoretical value of the gate voltage modulability of the Rashba interaction in InAs/AlAs heterostructures. The experimental value reported in J. Nitta, et al, Phys. Rev. Lett., 78, 1335 (1997) is 60 times smaller.

[14] G. Yu, N. L. Rowell, D. J. Lockwood and Z. R. Wasilewski, Appl. Phys. Lett., 83, 3683 (2003).

[15] B. Jusserand, D. Richards, G. Allan, C. Priester and B. Etienne, Phys. Rev. B, 51, 4707 (1995).

[16] E. A. de Andrade e Silva, G. C. La Rocca and F. Bassani, Phys. Rev. B., 50, 8523 (1994).

[17] G. L. Snider, M. S. Miller, M. J. Rooks and E. L. Hu, Appl. Phys. Lett., 59, 2727 (1991); S. J. Koester, C. R. Bolognesi, E. L. Hu. H. Kroemer, M. J. Rooks and G. L. Snider, J. Vac. Sci. Technol., B11, 2528 (1993).