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2008 J. Phys.: Condens. Matter 20 045205

(http://iopscience.iop.org/0953-8984/20/4/045205)

IOP PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **20** (2008) 045205 (3pp) doi:10.1088/0953-8984/20/04/045205

# Multi-channel spintronic transistor design based on magnetoelectric barriers and spin–orbital effects

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Received 4 September 2007, in final form 6 December 2007
Published 8 January 2008
Online at stacks.iop.org/JPhysCM/20/045205

**Abstract**
We present a spin transistor design based on spin–orbital interactions in a two-dimensional electron gas, with magnetic barriers induced by a patterned ferromagnetic gate. The proposed device overcomes certain shortcomings of previous spin transistor designs such as long device length and degradation of conductance modulation for multi-channel transport. The robustness of our device for multi-channel transport is unique in spin transistor designs based on spin–orbit coupling. The device is more practical in fabrication and experimental respects compared to previously conceived single-mode spin transistors.

Semiconductor (SC) based spintronic devices have been the subject of intensive research efforts in recent years. A crucial ingredient in these studies is the spin–orbit coupling (SOC) effect, since it allows the manipulation of spins by purely electrical means. In particular, the experimental demonstration of the gate control of the Rashba SOC parameter [1] in a two-dimensional electron gas (2DEG) structure [2] has spurred interest in the realization of the Datta–Das spin transistor [3]. In that device, a gate bias is used to control the spin precession rate of electrons [4] as they traverse along a 2DEG channel between two ferromagnetic (FM) contacts. Ideally, the transistor should be tuned such that electron spins and the magnetization of the FM collector are parallel (antiparallel) whenever the gate bias is turned 'on' ('off'). This constraint, however, requires the channel length to be of order 1 $\mu$m [4], which is close to two orders of magnitude longer than conventional MOSFET devices. Furthermore, the Datta–Das device can operate optimally (i.e. with maximum conductance modulation) only under restrictive conditions of (i) quasi-one-dimensional (Q1D) channel geometry, and (ii) single-mode or channel electron transport (i.e. a single propagating wavevector). It would typically require elaborate confinement schemes such as the use of split gates [5] to realize Q1D transport in SC heterostructures, whilst single-mode transport will entail stringent constraints on e.g. operating temperature and doping densities. There have been other transistor designs which utilize spin-dependent tunneling of conduction electrons through SC barriers with SOC to induce spin polarization [6]. However, the requirement for single-mode transport still holds, since the spin polarization in such devices will be nullified when one performs an ensemble averaging over the whole Fermi surface, due to time-reversal symmetry.

In this paper, we propose a multi-channel spin-FET device based on a 2DEG trilayer structure with a FM gate electrode, and having a short channel length of the order of 10 nm. The FM gate induces a fringe magnetic field which acts as a barrier to the spin transport, while the Rashba [1] and Dressselhaus SOC [7] within the 2DEG enables gate control of the precessional behavior of the spins. We consider the ballistic transport of electrons injected from a half metallic (HM) source electrode into the 2DEG channel with the SOC, and thence into a ferromagnetic collector with an in-plane magnetization. The in-plane spin component of electrons reaching the collector is tunable through the Rashba SOC parameter, thus enabling transistor action. Interestingly, this spin component is virtually independent of the momentum of the injected electrons when the coupling between the magnetic field and 2DEG channel medium is sufficiently large. This independence is a unique characteristic of our device compared to previous spin transistor designs. Multi-channel transport

 

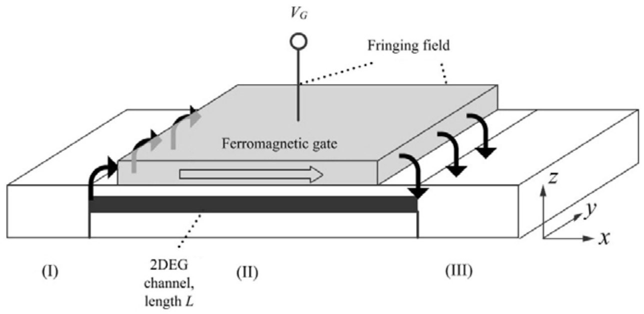


**Figure 1.** Schematic of device under consideration. Electrons are injected from the source electrode (I) into the 2DEG channel (II) with both Rashba and Dresselhaus spin–orbit coupling. The azimuthal spin orientation of electrons reaching the collector region (III) is tunable by varying the Rashba parameter, resulting in spin-FET-like operation.

which involves the injection of an ensemble of electron modes will thus not dilute the conductance modulation and degrade the transistor performance. As such the practical requirements for fabricating and operating such a device may be considerably relaxed.

We consider spin-dependent electron transport under the combined influence of Rashba and Dresselhaus spin–orbit coupling in a two-dimensional electron gas (2DEG), in the presence of external magnetic barriers in the vertical $\hat{z} = [001]$ direction. The Hamiltonian is given by:

$$\mathcal{H} = -\frac{\hbar^2}{2m^*}\nabla_x^2 + \frac{\hbar^2}{2m^*}k_y'^2 + U_0 + \frac{eg^*\hbar}{4m_0}B_z(x)\sigma_z + \alpha(k_y'\sigma_x + \mathrm{i}\sigma_y\nabla_x) + \beta(k_y'\sigma_y + \mathrm{i}\sigma_x\nabla_x), \tag{1}$$

where $g^*$ is the effective Landé factor of the 2DEG channel layer medium, $\sigma_i$ are the Pauli spin matrices, $\alpha$ and $\beta$ are the Rashba and Dresselhaus[3] parameters, and $k_y' = k_y + \frac{e}{\hbar}A_y(x)$. We consider the fringe field from a ferromagnetic gate with in-plane magnetization placed on top of the 2D system. This configuration may be practically realized by the patterning of ferromagnetic or superconducting materials [8]. To a first approximation, the field is modeled as having a delta-function profile in the vertical direction (see figure 1) [8–12]. Thus, for a 2DEG channel with length $L$, the field can be written as $B_z(x) = B[\delta(x) - \delta(x - L)]$. Under the Landau gauge, $B_z(x)$ corresponds to a vector potential $\vec{A}(x) = (0, A_y(x), 0)$ in which $A_y(x) = B[\Theta(x) - \Theta(x - L)]$, where $\Theta(x)$ is the Heaviside step function. The general solutions to the Hamiltonian of (1) are given by $\vec{\xi} = (\pm \mathrm{e}^{\mathrm{i}\chi(\vec{k})}, 1)^T/\sqrt{2}$, where the phase factor $\chi(\vec{k})$ is given by the relation $\tan\chi(\vec{k}) = (\alpha k_x - \beta k_y')(\alpha k_y' - \beta k_x)^{-1}$. For a fixed electron energy $E$, there are four distinct values of the wavevector $k_x$ that are solutions to the equation $E = H_0 \pm [(k_x^2 + k_y'^2)(\alpha^2 + \beta^2) - 4k_x k_y'\alpha\beta]^{1/2}$. In the 2DEG channel (labeled II in figure 1) where spin–orbit coupling is present, the traveling wavefunction can be written as a pure state comprising of a linear combination of eigenspinors $\vec{\xi}_i$, each corresponding to wavevector $k_x = k_i$ [8]:

$$\Psi^{\mathrm{II}}(x) = \sum_{i=1}^{4} a_i\vec{\xi}_i \mathrm{e}^{\mathrm{i}k_i x}. \tag{2}$$

The coefficients in (2) can be found by imposing the condition of flux continuity at the interfaces[4]. For Regions I and III, we represented the electronic wavefunctions $\Psi^{\mathrm{I}}$ and $\Psi^{\mathrm{III}}$ in the basis of the spin–orbit eigenvectors $\vec{\xi}_i$. We assumed the source electrode to be half metallic (HM) and considered injection of electrons in the pure $+|z\rangle$ spin state into the 2DEG, then studied the spin in the collector electrode (region III).

In our numerical calculations, all physical parameters are expressed in dimensionless reduced units (r.u.) for convenience: coordinates $\vec{x} \to l_B\vec{x}$, energy $E \to E_0E$, magnetic field $\vec{B} \to B_0\vec{B}$, magnetic vector potential $\vec{A} \to B_0 l_B\vec{A}$ and spin–orbit coupling parameters $\alpha \to E_0 l_B\alpha$ and $\beta \to E_0 l_B\beta$. Here $B_0$ is an arbitrary magnetic field, $l_B = \sqrt{\hbar/eB_0}$ is the magnetic length, and $E_0 = \hbar\omega_C$ where $\omega_C = eB_0/m^*$ is the cyclotron frequency. We assume indium antimonide (InSb) to be the 2DEG material on account of its large $g^*m^*$ factor, which ensures strong coupling of the electron spin to the magnetic fringing fields, and its requisite zinc-blende structure for Dresselhaus SOC. Unless otherwise stated, we have assumed the following material parameters for a typical InSb 2DEG channel layer [13, 14]: $m^* = 0.0136m_0$, $g^* = 50.6$, $\alpha = 1.2 \times 10^{-11}$ eV m $= 0.077$ r.u. and $\beta = 4.1 \times 10^{-12}$ eV m $= 0.027$ r.u. if $B_0 = 0.5$ T. We also set the following parameters: Fermi level $E_{\mathrm{F}} = 2.5$ meV $= 0.59$ r.u. (corresponding to electron density $n = 1.4 \times 10^{10}$ cm$^{-2}$) and electric potential $U_0 = 1.7$ meV $= 0.4$ r.u.

We consider the injection of electrons in the spin-up $+|z\rangle$ state from the HM source electrode, and analyzed the precession behavior of spins under ballistic transport across the trilayer structure, using the $\vec{S}$ operator, $\vec{S} = \hbar/2\langle\Psi^{\mathrm{III}}|(\sigma_x, \sigma_y, \sigma_z)|\Psi^{\mathrm{III}}\rangle = (s_x, s_y, s_z)$. We find that the azimuthal spin component, $\vec{S}_{xy} = (s_x, s_y)$, which is the component arising from the spin–orbital interactions, can be tuned through the Rashba coefficient over nanoscale channel lengths. In figure 2 (main), we show the strong dependence of $\theta = \arctan(s_y/s_x)$ on the Rashba parameter for channel lengths in range 2 nm $\leqslant L \leqslant$ 20 nm. Since the Rashba parameter can be modulated by around 50% [2], there can be a significant rotation of the in-plane spin component depending on the applied gate bias. The corresponding spin polarization amplitudes $|\vec{S}_{xy}|$ are plotted in figure 2 (inset) as a function of $\alpha$ for the various channel lengths. The spin polarization is found to increase almost linearly with $\alpha$, and shows a sinusoidal variation with $L$ for a fixed $\alpha$, with the peak $|\vec{S}_{xy}|$ value occurring at $L \approx 5$ nm for the range of $\alpha$ considered. In order to achieve a transistor function, one should set the magnetization of the collector electrode to be in the in-plane direction, along $\theta_0 = \arctan(s_y/s_x)$ corresponding to zero gate bias. The zero bias state then corresponds to the 'on' state

[3] The $\vec{k}$-linear Dresselhaus Hamiltonian in equation (1) is an approximation of the full $\vec{k}$-cubic Hamiltonian under a vector potential, $\vec{k} = \vec{k} + e/\hbar\vec{A}$.

[4] Calculation of the particle flux in the source and collector (regions I and III) was based on the standard operator, $j(x) = \hbar/(2mi)(\Psi^*\Psi_x - \Psi\Psi_x^*)$, but with the wavefunctions $\Psi$ expressed in the spinor representation. In Region II, we used $j_{\mathrm{II}}(x) = \sum_{i=1}^{4}|a_i|^2\langle\vec{\xi}_i(x)|\hat{v_x}|\vec{\xi}_i(x)\rangle$ where $\hat{v_x} = \partial\mathcal{H}(\vec{p})/\partial p_x$ from Hamilton's equation.

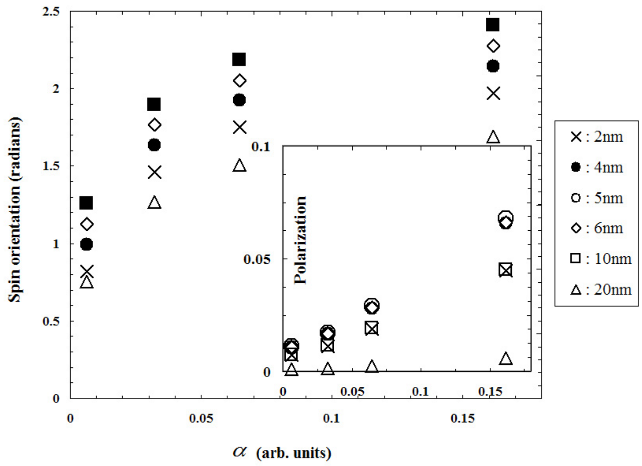


**Figure 2.** The azimuthal spin angle of electrons for various 2DEG channel lengths as a function of Rashba coupling strength, $\alpha$ and (inset) the corresponding spin polarization values. Here, the in-plane wavevector is fixed at $k_y = -0.3/l_B$.

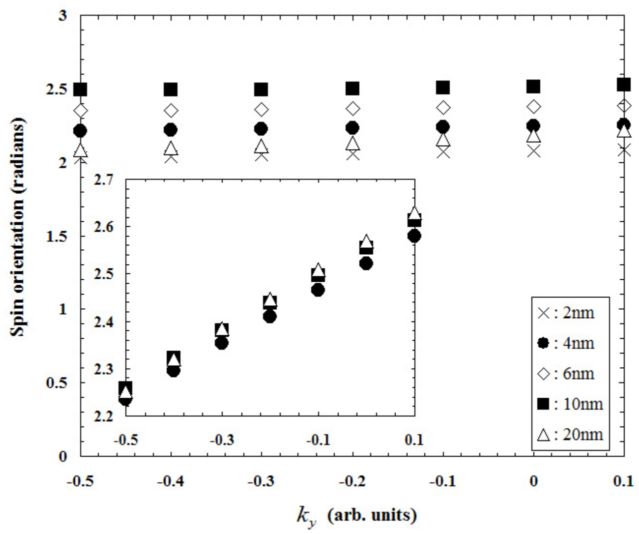


**Figure 3.** Spin orientation of transmitted electrons in azimuthal plane as a function of wavevector $k_y$ (in units of $1/l_B$), at a constant Fermi level, for various 2DEG channel lengths. The main plot corresponds to a strong magnetic field ($\gamma = g^*m^*B = 5.51$) from the FM gate electrode, resulting in uniform precession of spins over a range of $k_y$. This robustness is reduced, however, when the field is not sufficiently strong ($\gamma = 1.38$), as shown in the inset.

of the transistor with a relatively low resistance. Applying a gate bias will cause the electron spins to deviate away from $\theta_0$. The reduced spin polarization along $\theta_0$ will then switch the transistor to the 'off' state with a higher channel resistance. The conductance modulation achievable is smaller compared to that predicted for the Datta–Das device due to the lower spin polarization values. However, the conductance modulation could potentially be increased by enhancing the gate bias variation of the Rashba SOC parameter to beyond the present 50% e.g. with improvements in gate insulation [3].

We now analyze the multi-channel operation of our device. In the presence of a strong $\delta$–$B$ field strength ($\gamma = g^*m^*B \simeq 5.51$ r.u.), the spin precession behavior is found to be nearly uniform with variation in the transverse wavevector $k_y$. There is only a small spread of less than 0.1 rad in the transmitted spin orientation over the whole range of electron transmission modes $k_y$ considered (main figure 3). The robustness of our device to multi-channel transport reduces when a lower $\delta$–$B$ field strength of $\gamma = 1.38$ r.u. is applied. Figure 3 (inset) shows a larger spread of $\Delta\theta \approx 0.35$ rad over the same range of $k_y$. In effect, a strong magnetic field reduces the variance of $\theta$ due to a spread in $\vec{k}$, whilst still permitting $\theta$ to be modulated through $\alpha$. Typically, however, multi-channel transport is detrimental to the performance of spintronic devices which utilize the SOC effect, such as the Datta–Das transistor [3, 15, 16] and spin filter devices [6, 17]. For instance in the former, it is necessary to confine transport to a quasi-one-dimensional channel (i.e. $\langle k_y \rangle = 0$) and to ensure single-mode transport (i.e. a single $k_x$) for maximal conductance modulation. Our proposed device may therefore lead to a new class of multi-channel spintronic devices which are able to utilize the SOC effect. Such devices would avoid the need for elaborate schemes for confinement and wavevector restriction of the injected electrons [16–18] that are difficult to realize experimentally.

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