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A resonant spin lifetime transistor

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We present a device concept for a spintronic transistor based on the spin relaxation properties of a two-dimensional electron gas (2DEG). The device design is very similar to that of the Datta and Das spin transistor. However, our proposed device works in the diffusive regime rather than in the ballistic regime. This eases lithographical and processing requirements. The switching action is achieved through the biasing of a gate contact, which controls the lifetime of spins injected into the 2DEG from a ferromagnetic emitter, thus allowing the traveling spins to be either aligned with a ferromagnetic collector or randomizing them before collection. The device configuration can easily be turned into a memory and a readout head for magnetically stored information. © 2003 American Institute of Physics. [DOI: 10.1063/1.1601693]

If the current pace of electronic device miniaturization is to continue, it is reasonable to think that the good use of the quantum properties of the electron will play a role in making this possible. Traditionally it has been the wave character of the electron that has been put to this use, resulting in devices such as the resonant tunnel diode and the single electron transistor. Another quantum property of the electron that only recently has received attention for its potential for information storage and processing is its spin. One of the most promising proposals for a spin electronic (spintronic) device is the spin transistor by Datta and Das. In that device, electrons are injected from a ferromagnetic contact into a two-dimensional electron gas (2DEG) and another ferromagnetic contact is used to collect the traveling electrons and analyze their spin. Switching action is achieved by the application of an external electric field, which affects the spin of the ensemble through the Rashba effect.

In this letter we see how, by making minimal changes to the device configuration proposed by Datta and Das, and by considering the bulk inversion asymmetry (BIA) effects, we can create a family of information processing, storing, and retrieving devices. We start reviewing the effects in the 2DEG band structure and spin alignments of the combination of BIA and structural inversion asymmetry (SIA), and the consequences for the spin lifetime of the electrons in the 2DEG. Then, we describe our proposal for a spin transistor and make some estimates of its performance. Finally, we also describe two kinds of memory cells and a read head based on these effects.

For zinc-blende semiconductor heterostructures we can easily write a Hamiltonian describing both the SIA and BIA contributions to the 2DEG lowest conduction subbands of a [001]-grown structure

\[
H = H_0 + \alpha_{\text{BIA}}(\sigma_x k_x - \sigma_y k_y) + \alpha_{\text{SIA}}(\sigma_x k_y - \sigma_y k_x)
\]

\[
= H_0 + \sigma_z(\alpha_{\text{SIA}} k_x + \alpha_{\text{BIA}} k_y) - \sigma_y(\alpha_{\text{BIA}} k_x + \alpha_{\text{SIA}} k_y),
\]

where \(H_0\) is the spin degenerate part of the Hamiltonian, \(\alpha_{\text{SIA}}\) parameterizes the importance of the BIA (SIA) contribution—\(\alpha_{\text{SIA}}\) is commonly referred to as the Rashba coefficient—to the lowest nonvanishing order, \(\sigma_i\) are the Pauli matrices and \(k_i\) are the components of the in-plane electron wave vector \(k\).

For our forthcoming considerations it is important to study the spin configuration in \(k\) space that results from Eq. (1). When \(\alpha_{\text{BIA}} = 0\), the electron spins point in the 2DEG plane and perpendicular to \(k\) (see, for example, Fig. 1 in Ref. 8). Figure 1 shows the spin expectation values for electrons with wavevector in the 2DEG plane and a magnitude \(k = 0.012\) \(\pi/\alpha\). The expectation values have been calculated from the eigenstates of Hamiltonian (1). For \(\alpha_{\text{BIA}}/\alpha_{\text{SIA}} = 0.25\) we see that the spins are slightly tilted respect to the tangential configuration for the case of \(\alpha_{\text{BIA}} = 0\). However, the usual time reversal requirement that states

\[
\bar{H}(\sigma_{\text{BIA}} k_x - \sigma_{\text{SIA}} k_y) = \bar{H}(\sigma_{\text{SIA}} k_x + \sigma_{\text{BIA}} k_y),
\]

where \(\bar{H}\) is the Hamiltonian for the reversed spin configuration.
The spin configuration in Fig. 1 for \( \alpha_{\text{BIA}}/\alpha_{\text{SIA}} = 1 \) is much more interesting. In it, eigenstate spins can only point in one of two possible directions, namely \([1\bar{1}0]\) and \([\bar{1}10]\), depending on the angle \( \theta \) between \( \mathbf{k} \) and the \([100]\) direction. The boundary of the two regions is at \( \theta = -\pi/4 \) and \( \theta = 3\pi/4 \). The condition \( \alpha_{\text{BIA}} = \alpha_{\text{SIA}} \) might be achieved by tuning the value of \( \alpha_{\text{SIA}} \) through the application of an external electric field perpendicular to the 2DEG. The value of \( \alpha_{\text{BIA}} \) is primarily determined by the intrinsic properties of the constituent materials, and its magnitude can only be affected by the thickness of the 2DEG.

In this particular configuration, the component along \([1\bar{1}0]\) of an injected spin will always be aligned with the effective magnetic field \( \mathbf{B} \) irrespective of \( \mathbf{k} \) and, therefore, will not suffer from the different rates and axes of precession as described by the D'yakonov–Perel’11 (DP) mechanism of spin relaxation. Averkiev and Golub12,13 have computed the DP spin lifetimes of the different components for electrons in the \([001]\) 2DEG. In particular, assuming the validity of Eq. (1), they see that the lifetime for spins along \([1\bar{1}0]\) is proportional to \((\alpha_{\text{SIA}} - \alpha_{\text{BIA}})^{-2}\). Figure 2 shows the spin lifetimes plotted from Eq. (19) in Ref. 13, where \( \tau_i \) is the lifetime of the spin component along \( i \). The values used in the computation are \( k_F = 0.01 \) Å\(^{-1}\) (a degenerate 2DEG is assumed), a momentum scattering time \( \tau_p = 0.2 \) ps and \( \alpha_{\text{BIA}} = 15 \times 10^{-10} \) eV cm. From this figure, we see clearly the resonant behavior of the lifetime when \( \alpha_{\text{SIA}} = \alpha_{\text{BIA}} \). In what follows, we will describe how, by driving this component of the spin in and out of resonance through the action of an external bias, we can construct a series of spintronic devices.

Figure 3 shows the operating principle of the resonant spin lifetime transistor (RSLT). The device layout is very similar to the Datta–Das3 device, except that the ferromagnetic contacts must be designed so that their magnetization points in the \([1\bar{1}0]\) direction, as per Fig. 1. Since the resonant spin direction points in the 2DEG plane, this may be easily achieved with a thin bar as in the figure. At first, an ensemble of spins pointing along \([\bar{1}10]\) is injected in the 2DEG. The gate bias drives the lifetime of the injected spins on- or off-resonance by setting \( \alpha_{\text{BIA}} = \alpha_{\text{SIA}} \) or \( \alpha_{\text{BIA}} \neq \alpha_{\text{SIA}} \), respectively. In the on state the spins would arrive aligned with the ferromagnetic collector, thus resulting in low resistance. In the off state, the spins are randomized before reaching the collector and a high resistance is measured.

There are other kinds of devices that can be constructed with these building blocks. If the gate bias in Fig. 3 is ap-
plied through a charged/uncharged floating gate, the device would behave as a flash memory. A different nonvolatile memory configuration is shown in Fig. 4. In it, the gate bias is set to the resonance condition only during the read cycle and remains off at other times, thus reducing power consumption. Then, the “0” or “1” states would be given by the relative orientation of the magnetization of the emitter and the collector. The performance would improve because this memory can operate in the ballistic mode. Finally, we can envision a magnetic information readout head based on the configuration in Fig. 4. Similar to giant magnetoresistance readout heads,20 the magnetization of one contact would be pinned while the other follows some stored pattern.

Note added in proof. We have recently become aware of a similar work by Schliemann, Egues and Loss.21 Their work emphasizes the treatment of quantum point contacts, which have different implications for the collection of spins from the extended contacts we consider in this work.

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FIG. 4. Operating principle of the resonant spin lifetime memory. The gate bias is fixed in the resonant condition. Different memory states are stored by the relative orientation of the emitter and collector magnetizations. The reading of the state is obtained by the application of a current and measurement of the resistance.

2 K. K. Likharev, Prog. IEEE 87, 606 (1999), and references therein.