Journal of New Technology and Materials
JNTM
Vol. 01, N°00 (2011)63-65

OEB Univ. Publish. Co.

Spin polarized transport in semiconductor

A. Boudine[a], K. Benhizia[b] and L. Kalla[a]
[a] *Université Larbi ben M'Hidi, 04000-Oum El Bouaghi, Algérie*
[b] *Université Mentouri, Route Ain El Bey, Constantine 25017, Algérie*
Received: 23 May 2011, accepted: 30 September 2011

Abstract
In this paper, we study two-dimensional spin polarized transport in semiconductors. Based on the some semiclassical considerations and taking account of the spin relaxation. We determined the relationship of the polarization as a function of time and the distance. And we have also established the relationship of the drain current in a 2D channel of a transistor called "spin-FET" where it was matter to highlight this type of transport.
This study was crowned with a numerical study of the characteristics of spinFET 2D transistor depending on the external field and internal characteristics of the semiconductor.
Keywords: Spin polarized transport, spintronic, spinfet, Semiconducteur

1. Introduction

The study of spin-polarized transport across interfaces is a subject of long history [1, 2]. The recent advent of semiconductor-based electronic devices at the nanoscale has revived the interest in transferring, controlling and detecting spin currents. This research area has been termed spintronics due to the exciting possibility of future, successful spin-based electronic technology [3]. Nevertheless, spintronics is interesting as well for fundamental physics, both experimentally and theoretically, as its basic constituent—the spin—is of quantum nature only.

In the ideal situation where spin (or its projection along a direction) is conserved, spin current is simply defined as the difference between the currents of electrons in the two spin states. This concept has served well in early study of spin-dependent transport effects in metals. The ubiquitous presence of spin-orbit coupling inevitably makes the spin non-conserved, but this inconvenience is usually put off by focusing one's attention within the so-called spin relaxation time. In recent years, it has been found that one can make very good use of spin-orbit coupling, realizing electric control of spin generation and transport [3, 4, 5, 6, 7, 8, 9]. The question of how to define the spin current properly in the general situation therefore becomes urgent.

2. Hamiltonian And Theoretical Approaches

In semiconductor spintronic structures, where spin is carried by electrons and/or holes, the spin dynamics is controlled by magnetic interactions. Some of these are surveyed below.

-Interaction with an external magnetic field.

An external magnetic field $\vec{B}$ exerts a torque on a magnetic dipole and the magnetic potential energy is given by Zeeman term

$$U = \frac{g^* \mu_B}{2} \vec{\sigma}.\vec{B} \qquad (1)$$

where g^* is the effective g -factor, and σr represents a vector of the Pauli spin matrices, used in the quantum-mechanical treatment of spin ½, see [10]. The interaction (1) leads to the spin precession around the external magnetic field. This interaction is important in all system where a magnetic field is present. Moreover, fluctuations of $\vec{B}$ could lead to noise contributing to spin relaxation.

-Interaction with magnetic impurities, nuclei and other spin carriers.

An electron located in a semiconductor experiences different kinds of spin-spin interactions including direct dipole-dipole interactions with nuclear spins and other (free and localized) electrons, and the exchange interaction. The latter, in fact, is the result of the electrostatic Coulomb interaction between electrons, which becomes spin-dependent because of the Pauli exclusion principle [10]. Usually, at room temperatures in sufficiently clean, low-doped non-magnetic semiconductors these interactions are not very important.

3. Spin-orbit interaction

The spin-orbit (SO) interaction arises as a result of the magnetic moment of the spin coupling to its orbital degree of freedom. It is actually a relativistic effect, which was first found in the emission spectra of hydrogen. An electron moving in an electric field, sees, in its rest frame, an effective magnetic field. This field, which is dependent on the orbital motion of the electron, interacts with the electron's magnetic moment.

The Hamiltonian describing SO interaction, derived from the four-component Dirac equation [11], has the form

$$H_{SO} = \frac{\hbar^2}{4m^2c^2}\left(\vec{\nabla} \times V\right).\vec{\sigma} \qquad (2)$$

where m is the free electron mass, rp is the momentum operator, and is the gradient of the potential energy, proportional to the electric field acting on the electron. When dealing with crystal structures, the spin orbit interaction, Eq. (2), accounts for symmetry properties of materials. Here we emphasise two specific mechanisms that are considered to be important for spintronics applications. The Dresselhaus spin-orbit interaction [1] appears as a result of the asymmetry present in certain crystal lattices, e.g., the zinc blende structures. For a two-dimensional electron gas in semiconductor heterostructures with an appropriate growth geometry, the Dresselhaus SO interaction is of the form

$$H_D = \frac{\beta}{\hbar}(\sigma_x p_x - \sigma_z p_z). \qquad (3)$$

Here, β is the coupling constant.

The Rashba spin-orbit interaction [13] arises due to the asymmetry associated with the confinement potential and is of interest because of the ability to electrically control the strength of this interaction. The latter is utilized, for instance, in the Datta-Das spin transistor [13]. The Hamiltonian for the Rashba interaction is written [38] as

$$H_R = \frac{\alpha}{\hbar}(\sigma_x p_z - \sigma_z p_x), \quad (4)$$

where α is the coupling constant. Other possible sources of spin-orbit interaction are non-magnetic impurities, phonons [14], sample inhomogeneity, surfaces and interfaces. In some situations these could play a role in spin transport and spin relaxation dynamics.

Consider the two-dimensional channel of a Spin Field Effect Transistor (SPIN-FET) in the x-z plane with current flowing in thex-direction. An electron's wavevector components in the channel are designated as kx and kz, while the total wavevector is designated as kt. Note that $k_t^2 = k_X^2 + k_Z^2$.

The gate terminal induces an electric field in the y-direction which causes Rashba interaction. The Hamiltonian operator describing an electron in the channel is

$$H = \frac{p_x^2+p_z^2}{2m^*}[\mathbf{I}] + \alpha[V_G](\sigma_x p_z - \sigma_z p_x) \quad (5)$$

where the *p*-s are the momentum operators, the *σ*-s are the Pauli spin matrices and **[I]** is the 2×2 identity matrix. Since this Hamiltonian is invariant in both *x*- and *z*-coordinates, the wavefunctions in the channel are plane wave states $e^{i(k_x x+k_z)}$. Consequently, in the basis of these states, the Hamiltonian is

$$H = \begin{bmatrix} \frac{\hbar^2 k_t^2}{2m^*} + \alpha[V_G]k_x & -\alpha[V_G]k_z \\ -\alpha[V_G]k_z & \frac{\hbar^2 k_t^2}{2m^*} - \alpha[V_G]k_x \end{bmatrix} \quad (6)$$

Diagonalization of this Hamiltonian yields the eigen energies and the eigen-spinors in the two spin-split bands in the two-dimensional channel:

$$E_l = \frac{\hbar^2 k_t^2}{2m^*} - \alpha[V_G]k_t \quad \text{(lower band)}$$
$$E_u = \frac{\hbar^2 k_t^2}{2m^*} + \alpha[V_G]k_t \quad \text{(upper band)} \quad (7)$$

And

$$[\Psi]_l = \begin{bmatrix} sin\theta \\ cos\theta \end{bmatrix} \quad \text{(lower band)}$$
$$[\Psi]_u = \begin{bmatrix} sin\theta \\ cos\theta \end{bmatrix} \quad \text{(upper band)} \quad (8)$$

where $\theta = (1/2)arctan\,(k_z/k_x)$. Note that an electron of energy E has two different wave vectors in the two bands given by $k_t^{(1)}$and $k_t^{(2)}$.

We will assume that the source contact of the SPINFET is polarized in the+*x*-direction and injects +*x*-polarized spins into the channel under a source-to-drain bias. We also assume that the spin injection efficiency at the source is 100%, so that only +*x*-polarized spins are injected at the complete exclusion of −*x*-polarized spins. An injected spin will couple into the two spin eigenstates in the channel. It is as if the x-polarized beam splits into two beams, each corresponding to one of the channel eigenspinors. This will yield:

$$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix} = C_1 \begin{bmatrix} sin\theta \\ cos\theta \end{bmatrix} + C_2 \begin{bmatrix} -cos\theta \\ sin\theta \end{bmatrix}$$

+*x*- polarized (9)

where the coupling coefficients C_1 and C_2 are found by solving Equation (9).

The result is

$$C_1 = C_1\,(k_x, k_z) = sin\,(\theta + \pi/4)$$
$$C_2 = C_2(k_x, k_z) = -cos\,(\theta + \pi/4) \quad (10)$$

Note that the coupling coefficients depend on k_x and k_z.

At the drain end, the two beams recombine and interfere to yield the spinor of the electron impinging on the drain. Here, we are neglecting multiple reflection effects between the source and drain contacts in the spirit of ref. [1]. Since the two beams have the same energy *E* and transverse wavevector k_z (these are good quantum numbers in ballistic transport), they must have different longitudinal wavevectors $k_X^{(1)}$and $k_X^{(2)}$ since $k_t^{(1)} \neq k_t^{(2)}$. Therefore, these two beams have slightly different directions of propagation in the channel. In other words, the channel behaves like a "birefrigent" medium where waves with anti-parallel spin polarizations travel in slightly different directions.

Hence, the spinor at the drain end will be:

$$[\Psi]_{drain} = C_1 \begin{bmatrix} sin\theta \\ cos\theta \end{bmatrix} e^{i\left(k_X^{(1)}L+k_z W\right)} + C_2 \begin{bmatrix} -cos\theta \\ sin\theta \end{bmatrix} e^{i\left(k_X^{(2)}L+k_z W\right)}$$
$$= e^{ik_z W} \begin{bmatrix} sin\left(\theta + \frac{\pi}{4}\right) sin\theta e^{ik_X^{(1)}L} + cos\,(\theta + \pi/4) cos\theta e^{ik_X^{(2)}L} \\ sin\left(\theta + \frac{\pi}{4}\right) cos\theta e^{ik_X^{(1)}L} - cos\,(\theta + \pi/4) sin\theta e^{ik_X^{(2)}L} \end{bmatrix}$$

(11)

Where *L* is the channel length (distance between source and drain contacts) and *W* is the transverse displacement of the electron as it traverses the channel.

Since the drain is polarized in the same orientation as the source, it transmits only +x-polarized spins, so that spin filtering at the drain will yield a transmission probability $|T|^2$ where *T* is the projection of the impinging spinor on the eigenspinor of the drain. It is given by

$$T = \frac{1}{\sqrt{2}}[1 \quad 1] \times \begin{bmatrix} sin\left(\theta + \frac{\pi}{4}\right) sin\theta e^{ik_X^{(1)}L} + cos\,(\theta + \pi/4) cos\theta e^{ik_X^{(2)}L} \\ sin\left(\theta + \frac{\pi}{4}\right) cos\theta e^{ik_X^{(1)}L} - cos\,(\theta + \pi/4) sin\theta e^{ik_X^{(2)}L} \end{bmatrix} e^{ik_z W}$$

$$= e^{ik_z W}\left[sin^2\left(\theta + \frac{\pi}{4}\right) e^{ik_X^{(1)}L} + cos^2\,(\theta + \pi/4) cos\theta e^{ik_X^{(2)}L}\right] \quad (12)$$

Here, we have assumed 100% spin filtering efficiency.

Therefore,

$$|T|^2 = cos^4\left(\theta + \frac{\pi}{4}\right)\left|1 + tan^4\left(\theta + \frac{\pi}{4}\right) e^{i\left(k_X^{(1)} - k_X^{(2)}\right)L}\right|^2$$

$$= cos^4\left(\theta + \frac{\pi}{4}\right) + sin^4\left(\theta + \frac{\pi}{4}\right) + \frac{1}{2}cos(2\theta)cos(\theta L) \quad (13)$$

where $\Theta = k_X^{(1)} - k_X^{(2)}$.

From Equation (8), we get that:

$$k_t^{(1)} - k_t^{(2)} = -\frac{2m^*\alpha[V_G]}{\hbar^2}$$

Expressing the wavevectors in terms of their *x*- and *z*-components, we get:

$$\Theta = \frac{-\frac{2m^*\alpha[V_G]}{\hbar^2 k_t^{(2)}}+2(m^*)^2\alpha^2[V_G]/\hbar^4}{\left[k_X^{(1)}-k_X^{(2)}\right]/2} \qquad (14)$$

Now, if α [V_G] is small, then $\left[k_X^{(1)} - k_X^{(2)}\right]/2 \approx \sqrt{k_0^2 - k_Z^2}$, where $k_0 = \sqrt{2m^*E}/\hbar$. Substituting theseresults in Equation (14), we get

$$\Theta = \frac{-\frac{2m^*\alpha[V_G]\sqrt{2m^*E}}{\hbar^3}-(m^*)^2\alpha^2[V_G]/\hbar^4}{\sqrt{\sqrt{2m^*E}/\hbar^2-k_Z^2}} \qquad (15)$$

The current density in the channel of the SPINFET (assuming ballistic transport) is given by the Tsu-Esaki formula:

$$J = \frac{q}{W_y}\int_0^\infty \frac{1}{h} dE \int \frac{dk_Z}{\pi} |T|^2 [f(E) - F(E + qV_{SD})] \qquad (16)$$

where q is the electronic charge, W_y is the thickness of the channel (in the y-direction), V_{SD} is the source-to-drain bias voltage and $f(\eta)$ is the electron occupation probability at energy η in the contacts. Since the contacts are at local thermodynamic equilibrium, these probabilities are given by the Fermi-Dirac factor.

In the linear response regime when $V_{SD} \to 0$, the above expression reduces to

$$J = \frac{q^2 V_{SD}}{W_y}\int_0^\infty \frac{1}{h} dE \int \frac{dk_Z}{\pi} |T|^2 \left[-\frac{\partial f(E)}{\partial E}\right] \qquad (17)$$

This yields that the channel conductance G is

$$G = \frac{I_{SD}}{V_{SD}} = \frac{q^2 W_Z}{\pi h}\int_0^\infty dE \int dk_Z\, |T|^2 \left[-\frac{\partial f(E)}{\partial E}\right] (18)$$

we finally get that the channel conductance is

$$G \approx G_0 + \frac{q^2 W_z}{2\pi h}\int_0^\infty dE \int dk_Z \left[1 - \frac{\hbar^2 k_Z^2}{2m^*E}\right] cos(\Theta L) \left[-\frac{\partial f(E)}{\partial E}\right] \qquad (19)$$

4. Conclusion

In this work we have studied the transport of two-dimensional spin-polarized, we have established a relation giving the expression of the source-drain current as a function of the parameters of the semiconductor used, and the electric field across the control grid and polarization of injected spins, then we have calculated the associated transconductance G. This model is based on semiclassical consédérations with the holders of spin injected with ballistic trajectories inside the conduction channel.

References

[1] P.M. Tedrow and R. Meservey, Phys. Rev. Lett. 26, 192 (1971).
[2] M. Julliere, Phys. Lett. A 54, 225 (1975).
[3] M.I. Dyakonov and V.I. Perel, JETP 33, 1053 (1971).
[4] J. E. Hirsch, Phys. Rev. Lett. 83, 1834 (1999).
[5] S. Zhang, Phys. Rev. Lett. 85, 393 (2000).
[6] S. Murakami, N. Nagaosa, and S.C. Zhang, Science 301,1348 (2003).
[7] J. Sinova et al., Phys. Rev. Lett. 92, 126603 (2004).
[8] Y.K. Kato et al., Science 306, 1910 (2004).
[9] J. Wunderlich, B. Kaestner, J. Sinova, T. Jungwirth, Phys. Rev. Lett. 94, 047204 (2005).
[10] Landau L.D., and Lifshitz, E.M.: 'Quantum Mechanics' (Butterworth-Heinemann, Oxford, 1997)
[11] Condon, E.U., and Shortley, G.H.: 'The Theory of Atomic Spectra' (Cambridge University Press, Cambridge, 1953)
[12]Dresselhaus, G.: 'Spin-orbit coupling effects in zinc blende structures', Phys.Rev., 1955, 100, pp. 580-586
[13] Bychkov, Yu., and Rashba, E.I.: 'Oscillatory effects and the magnetic susceptibility of carriers in inversion layers', J. Phys. C, 1984, 17, pp. 6039-6045
[14] Gantmakher, V.F., Levinson, Y.B.: 'Carrier scattering in metals and semiconductors' in 'Modern Problems in Condensed Matter Science' v. 19. Series editors Agranovich, V.M., Maradudin, A. A. (North-Holland, New York 1987)