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NEW MODEL FOR SPINFET TRANSISTOR

A.Boudine[a], L. Kalla[a], K. Benhizia[b],M.Zaabat[a]
M. draidi[a] and I. Zerrouk[a]

[a]*Université Larbi ben M'Hidi, 04000-Oum El Bouaghi, Algéria*
[b]*UniversitéMentouri,* ***Route Ain El Bey, 25000 Constantine, Algéria***

Abstract

In this work we present the study of spin polarized transport in semiconductors as new type of current transmission in semiconductor devices, we built a 2deg model for so- called SPINFET transistor.

We chose the spinFET transistor or the transistor at spin rotation as a better implementation because it is a type of HEMT transistor in which we replace the source and drain by ferromagnetic contacts. The source contact acts as a spin polarizer for electrons injected into the conduction channel of the transistor and the drain contact is a spin analyzer to those (spins) which have reached the end of the canal. We establish the expression of drain current in function of orientations of the spin of electrons at the end of the canal and the magnetization of the drain contact, taking in account, the possibility to control the current through the grid voltage.

As application we have presented a simple model in the 1D and 2D channel formed in $In_{0,53}Ga_{0,47}As$ a spin FET transistor .

Keywords: Spin polarized transport, spintronic, spinfet, Semiconductor

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1. Introduction

The spin electronics, or "spintronics" Prinz (1999), is a new research theme has been booming since the late 80s. The first structures studied in this area are made of ferromagnetic metal multilayers, separated by insulators or "tunnel" or by non-magnetic metal films. Their operating principles are related to a property of ferromagnetic metals on the spin of electrons: they inject or collect preferentially carriers whose spin is polarized along the direction of their magnetic moment. In 1990, Datta and Das has proposed a transistor named Spin FET " rotation spin transistor". This device looks at first sight to the classical field effect transistor, and has a current source, a drain and a channel with a conductance controllable via a gate voltage, Vg, however, comparison stops there. The spin transistor is based on spin selective contacts, that is to say capable of injecting or collecting a given spin orientation. The injection and the collection of spin-polarized current is carried by ferromagnetic electrodes (Fe, for example). To modulate the drain current, Datta and Das proposed to control the rotation of the "bundle" of spin in the channel using the spin-orbit Rashba coupling to be a function of voltage applied to the gate Rashba (1960), The drain current reaches a maximum value when the spin orientation is parallel to the magnetization of the electrodes and injection manifold. It reaches a minimum value when they are opposed. This concept also implies a transistor coherent transmission, i.g without loss of spin between the injector (source) and collector (drain).

2. The spinorbit coupling

Thekey mechanismthat can affectthe orientation of theelectron spininsemiconductorsis whatis called thespin-orbit coupling. When the structurestudiedthislack ofsymmetry, thespin-orbit couplingleads tothe appearance ofan effective fieldmakingprecess(orrotate)thespin vectorforfreeflightselectrons.Insemiconductor structures, it has essentiallythe couplingofRashbaspin-orbitand ofDresselhauss[1].

In quantum mechanics, a particle of spin 1/2 (electron) immersed in a potential V can be described by a wave function ψ $=(\psi^{\uparrow}, \psi^{\downarrow})$. Components $\psi^{\uparrow}$and $\psi^{\downarrow}$ represent the wave functions of particles with spin-up and spin-down respectively. ψfunction verifies the Schrödinger equation as follows [2]:

$$i\,\hbar\partial_t\,\psi = (H_0 + H_{SO})\,\psi \tag{1}$$

Where $H_0$is the Hamiltonianofthestandardkinetic energyplus the energypotential

$$H_0 = \left(-\frac{\hbar^2}{2m*}\Delta_x + V\right) I_2 \tag{2}$$

m∗is the effective massof an electron andI_2isthe identity matrix ofC_2.According to [3, 4] thehamitonianofthespin-orbitinteraction, thederivativeDirac equationhas four componentsis given by:

$$H_{SO} = \frac{\hbar^2}{4m^2c^2}\left(\vec{\nabla} \times V\right).\vec{\sigma} \tag{3}$$

$\vec{\sigma}$is the Pauli matrices vector.

Thespin-orbit interactionmixesstates ofspin-upanddown.Instantaneousinteractionsbetween theparticles andthe crystal (or the environment) can then be accompanied bya reversal ofthe orientation of thespin vector, according to the mechanism calledElliot-Yafet[2].Although interactionswithspin flippingarerare eventsin thesemiconductor, they may be sufficientinareas of lowmobility (orhigh density)to remove thespincoherence(ortorelax thespin vector).

2.1. Thespin-orbit Rashba coupling:

The spin-orbit Rashba is a strong asymmetry in the quantum well which confines the two dimensional electron gas (2DEG). This term is designated by a phrase: "structure inversion asymmetry" and is often noted SIA. The Rashba interaction is a particular type of interaction spin-orbit. It is important only in the two-dimensional systems in which a uniform electric field is present, perpendicular to the plane in which the electrons move. The strong perpendicular field is present in systems in which the electrons are confined in an asymmetric potential well. This electric field is inter facial example inside a modulation-doped heterojunction as the heterojunctionInGaAs / InAlAs proposed and studied by Datta and Das.

TheRashbaHamiltonianis usually writtenas follows[2,5]:

$$H_R = \alpha\left(\vec{\sigma} \times \vec{k}\right).\vec{u}_y \tag{4}$$

Where α is the parameter of the spin - orbit interaction which depends linearly on the normal electric field to the surface and Ey is a function of the semiconductor gap and the effective mass, including the direction of the electric field applied via the grid and the $\vec{k}$ wave vector of the electron. The total Hamiltonian assuming Rashba effect dominates all other factors of the spin coupling is:

$$H_{tot} = H_k + H_R \tag{5}$$

Where$H_k$isthe kinetic energy ofthe electron.

2.2. Dresselhauss coupling [6]:

The spin-orbit interaction gives rise to a term that is responsible for the lifting of spin degeneracy. The existence of this term is due to the absence of a center of inversion of the zinc blende crystal structure. Because of this absence, this term is designated by a phrase: "bulk inversion asymmetry" and is often noted BIA. In 1955, in a famous paper journal "Physical.Review." G. Dresselhaus introduced the term spin-orbit coupling which is proportional to the cube of the wave vector with a coefficient of proportionality, hence the name "Dresselhaus term" is often attributed to him. The expression of this term:

$$H_D = \gamma.\vec{\sigma}.\vec{B}(k) \tag{6}$$

With

$$B(k) = k_x\left(k_y^2 - k_z^2\right)e_x + k_y(k_z^2 - k_x^2)e_y + k_z\left(k_x^2 - k_y^2\right)e_z \tag{7}$$

Where$\boldsymbol{e_x}$, $\boldsymbol{e_y}\boldsymbol{e_z}$ are the unit vectors of an orthonormal basis selected following the crystallographic axes andγ is the coefficient corresponding to the band in question and it depends on thematerial. Other spin relaxation mechanisms exist in the literature.

The quantum model

Consider the case of an electron gas 1D in the channel of a transistor A spin (spin FET). Electrons are

confined vertically (in the direction normal to the hetero-interface) and laterally (along the z direction) under the influence of the gate potential (that is to say, consider the 1D quantum transport son) It was in this case a structure or electrons, free to move along the x direction, are confined in a well as y and z according.
Taking into account the spin-orbit interaction of Rashba, the Hamiltonian of an electron moving in this structure is given by:

$$H = \frac{p_x^2}{2m^*} + \frac{\alpha}{\hbar}(\sigma_z p_x) \tag{8}$$

where$m^*$is the effective massof the electron and P momentum operator .
The Hamiltonianis

$$H = \begin{bmatrix} \frac{\hbar^2 k_x^2}{2m^*} + \alpha k_x & 0 \\ 0 & \frac{\hbar^2 k_x^2}{2m^*} - \alpha k_x \end{bmatrix} \tag{9}$$

The existence of thecouplingcausesthe lifting ofRashbaspin degeneracyinthe conduction bandenergy, the stateis splitdoubly degenerateunder the influence oftwo statesin$H_R$nondegenerateenergy:

$$E_- = \frac{\hbar^2 k_x^2}{2m^*} - \alpha k_x \qquad \text{(spin down)}$$

$$E_u = \frac{\hbar^2 k_x^2}{2m^*} + \alpha k_x \quad \text{(spin up)}$$

The sign of the spin splitting energy αk_x depends on the spin of the electron. The eigenvectors (eigen-spinors) of the electron in the presence of Rashba effect are:

$$[\Psi]_- = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \text{(spin down)}$$

$$[\Psi]_+ = \begin{bmatrix} -1 \\ 0 \end{bmatrix} \qquad \text{(spin up)}$$

Thewave vectorsof the electron inthe twodifferent bands are

$$k_x^{\overset{+}{-}} = \frac{-\,\mathrm{m}^*\alpha}{+\ \hbar^2} + \sqrt{\left(\frac{\mathrm{m}^*}{\hbar^2}\right)^2 + k^2}$$

If the source contact (ferromagnetic) requires the injection of electrons directed along the spin axis with a polarization x + 100%, the electron beam polarized along x is divided into two beams, each corresponding to one of the eigenvectors channel. At the end of the drain, the two beams recombine to give the spinor of the electron impinging on the drain. The effects of reflection between source and drain are negligibles, if L is the channel length:

$$[\Psi]_{drain} = C_1 \begin{bmatrix} 0 \\ 1 \end{bmatrix} e^{i\left(k_X^{(-)} L\right)} + C_2 \begin{bmatrix} -1 \\ 0 \end{bmatrix} e^{i\left(k_X^{(+)} L\right)}$$

C_1, C_2 are coupling coefficients

$$[\Psi]_{drain} = \begin{bmatrix} \frac{1}{\sqrt{2}} e^{ik_X^{(+)} L} \\ \frac{1}{\sqrt{2}} e^{ik_X^{(-)} L} \end{bmatrix}$$

Since thedrainis polarized inthe same direction asthesource, it transmits only the spinspolarized along+x,thetransmission coefficientTis given by:

$$T = \left[\frac{1}{2} e^{ik_X^{(-)} L} + \frac{1}{2} e^{ik_X^{(+)} L}\right] \tag{11}$$

Therefore, the probability of transmission is:

$$|T|^2 = \frac{1}{2}(1 + cos(\theta L))$$

With:

$$\Theta \;=\; k_X^{(-)} - k_X^{(+)}$$

In cases where$\alpha$is small

$$k_X^{(-)} \approx k_X^{(+)} \approx k_0 = \sqrt{}2\mathrm{m}^*\mathrm{E}/\hbar$$

We obtain:

$$\Theta \;= \frac{-\frac{2\mathrm{m}^*\alpha\sqrt{2\mathrm{m}^*\mathrm{E}}}{\hbar^3}+2(\mathrm{m}^*)^2\alpha^2/\hbar^4}{\sqrt{2m{*}E/\hbar^2}} \tag{12}$$

Thenetcurrent densityin thechannelspin-FET is given by theformulaTsu-Esaki [7]:

$$J = \frac{q}{4\pi^3}\frac{1}{\hbar}\int_0^\infty dk_l \int_0^\infty dk_t\,[f(E) - f(E')]T^*T\,\frac{\partial E}{\partial k_t} \tag{13}$$

E the energy of the incident electron and E ', the electron transmitted energy.
The transmission coefficient depends only on the longitudinal energy, and a result of a separation of variables, the expression of the current can be integrated in the transverse direction, we have:

$$J = \frac{q}{2\pi^2}\frac{m{*}kT}{\hbar^3}\int_0^\infty T^*T\;ln\left(\frac{1+exp\left[\left(E_f-E_l\right)/kT\right]}{1+exp\left[\left(E_f-E_l-eV\right)/kT\right]}\right)dE_l \tag{14}$$

If $T \rightarrow 0$theabove expressionbecomes

$$J = \left(\frac{qm^*}{2\pi^2\hbar^3}\right)\int_0^{E_f}\left(E_f - E_l\right)T^*TdE_l\;, \qquad\qquad V \geq\; E_f \tag{15}$$

$$J = \left(qm^*/2\pi^2\hbar^3\right)\left[V\int_0^{E_f-V}T^*T\;dE_l + \int_{E_f-V}^{E_f}\left(E_f - E_l\right)T^*TdE_l\right]V < E_f \tag{16}$$

Vthe potential appliedbetween the sourceand the drain (V_{SD})

Thechannel conductanceGis given by

$$G = \frac{I_{SD}}{V_{SD}} = \frac{J\,S}{V_{SD}}$$

S is thecross-sectional area
therefore:

$$G = \frac{q}{2\pi^2}\frac{m{*}kTS}{\hbar^3 V_{SD}}\int_0^\infty T^*T\;ln\left(\frac{1+exp\left[\left(E_f-E_l\right)/kT\right]}{1+exp\left[\left(E_f-E_l-eV\right)/kT\right]}\right)dE_l \tag{17}$$

The Conductancewithoutthe constant factor$(\frac{q}{2\pi^2}\frac{m{*}}{\hbar^3})$

$$G' = G(\frac{q}{2\pi^2}\frac{m{*}}{\hbar^3})^{-1} = \frac{kTS}{V_{SD}}\int_0^\infty T^*Tln\left(\frac{1+exp\left[\left(E_f-E_l\right)/kT\right]}{1+exp\left[\left(E_f-E_l-eV\right)/kT\right]}\right)dE_l \tag{18}$$

Finally, weobtain the following formulaforchannel conductance

$$G' \approx G_0 + \frac{kTS}{2V_{SD}}\int_0^\infty cos(\Theta L)\;ln\left(\frac{1+exp\left[\left(E_f-E_l\right)/kT\right]}{1+exp\left[\left(E_f-E_l-eV\right)/kT\right]}\right)dE_l \tag{19}$$

Conclusion

In this work we have studied theoretically the spin polarized transport in the case of a 1D channel of a transistor called a spin rotation (spin-FET). We have established a relationship giving the expression of the current in the channel based on the parameters used in the semiconductor, the electric field through the control gate and the transmission coefficient of the injected spins, then we calculated the conductance associated.

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