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Rapid note

Gate-induced spin precession in an $In_{0.53}Ga_{0.47}As$ two dimensional electron gas

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Abstract. We report a study of the gate-induced spin precession in an $In_{0.53}Ga_{0.47}As$ two dimensional electron gas, using a Monte-Carlo transport model. The precession vector originates from the spin-orbit coupling existing at a III-V hetero-interface, usually denoted as Rashba interaction. Contrary to the case of a one dimensional electron gas, the precession vector is randomized by the scattering events, which leads to a non negligible loss of spin coherence for an initially spin-polarized electron population moving along a conduction channel. However, we show that by operating at the liquid nitrogen temperature, or by reducing the channel width to a value close to 0.1 μm, the gate-controlled spin-polarization remains high enough to enable the investigation of the physics of spin-related phenomena in a ferromagnet/semiconductor structure.
PACS. 85.90.+h Other topics in electronic and magnetic devices and microelectronics – 71.70.Ej Spin-orbit coupling, Zeeman and Stark splitting – 73.40.-c Electronic transport in interface structures

1 Introduction

A new topic has recently induced a growing interest: the magnetoelectronics, based on properties of ferromagnetic materials relative to the electron spin orientation [1]. So, Datta and Das [2] have proposed a particular structure of high electron mobility transistor (HEMT) that applies such properties to a semiconductor device. They propose to replace the usual source and drain materials by ferromagnetic contacts that act as spin polarizer and spin detector. Indeed, such contacts inject, or collect, preferentially electrons with a specific spin orientation, depending on the magnetic moment of the ferromagnetic material [1,3]. Furthermore, the control of the electron spin orientation by the gate voltage is possible in the conduction channel of a gated III-V heterostructure, through a spin-orbit coupling effect usually denoted as the Rashba mechanism [4]. Recently, two research teams [5,6] have experimentally demonstrated the possibility to control the strength of the Rashba spin-orbit coupling in such structures.

The spin-HEMT is therefore a device in which the current is controlled "magnetically" by the gate voltage, in addition to the classical field effect control which consists into the modulation of the electron density in the channel. The magnitude of the drain current depends actually on the orientation of the spin of the electrons reaching the drain with respect to the orientation of the magnetic moment of this contact. Rather than a new electronic device, this structure may be very suitable for the exploration of the physics of spin-polarized transport and of the spin-dependent injection in semiconductor/ferromagnet structures.

However, after Datta and Das [2], the gate-control of spin orientation would be efficient only in the case of a one dimensional electron gas (1DEG). They explain that in a two dimensional electron gas (2DEG), no current modulation due to the gate-induced spin precession should be expected, because of the distribution of the carrier wave vector in the plane of the channel. The aim of this paper is to check this assertion.

2 Model of spin polarized transport

2.1 Rashba precession

The Rashba interaction is a spin-orbit coupling existing in asymmetric quantum wells [4]. In III-V heterostructures, this term appears in the effective mass Hamiltonian of the 2DEG formed close to the heterointerface in the narrow bandgap semiconductor. Its magnitude depends on the confining electric field E_y perpendicular to the heterointerface (xz-plane). Contrary to spin-relative interactions which lead to instantaneous spin flip events, *e.g.* the Elliott-Yafet and the Bir-Aronov-Pikus mechanisms [8],

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the Rashba mechanism corresponds to a slow spin dephasing process [7,9]. The spin rotation period related to the Rashba mechanism is actually less than, or comparable to, the momentum relaxation time. Therefore, this process has to be considered as a continuous spin precession in the time duration between scattering events by the lattice, and not as a scattering mechanism.

Moreover, the Rashba coupling is expected to be the dominant mechanism related to the electron spin in III-V heterostructures with a narrow band gap semiconductor, as $In_{0.53}Ga_{0.47}As$ [10], and even in AlGaAs/GaAs heterostructures [11]. The Rashba mechanism is thus the only spin-related process that we consider in this work.

During free-flights, the electron spin orientation changes under the influence of a pseudomagnetic field $\mathbf{B_R}$, related to the Rashba interaction. After expression of Rashba Hamiltonian given by Lommer *et al.* [10], we have for a 2DEG in the xz-plane:

$$\mathbf{B_R} = \frac{2a_{46}E_y}{\hbar\gamma}(k_x\mathbf{u}_x - k_x\mathbf{u}_z) \quad (1)$$

where γ is the electron gyromagnetic factor, E_y the gate-induced perpendicular electric field at the heterostructure interface, a_{46} is a constant depending on the band structure of the channel material, k_x (resp. k_z) is the electron wave vector component in x-direction (resp. z-direction), and $\mathbf{u_z}$ (resp. $\mathbf{u_x}$) is a unitary vector in z-direction (resp. x-direction). In $In_{0.53}Ga_{0.47}As$, we have $a_{46} = 4.4 \times 10^{-38}$ C m^2.

It should be noted that we use an expression for the Rashba Hamiltonian depending only on the perpendicular electric field E_y. In fact, the recent studies realized about the Rashba mechanism [5,11] show that the boundary conditions for the wave function in the quantum well formed at the heterointerface lead to an additional effect. This term does not degrade *a priori* the gate-control of the Rashba spin-orbit coupling, but seems in the contrary to reinforce it [5].

The electron spin $\mathbf{S}$ precession is driven by the following law:

$$\frac{d\mathbf{S}}{dt} = \boldsymbol{\Omega}_\mathbf{R} \times \mathbf{S} \quad (2)$$

where $\boldsymbol{\Omega}_\mathbf{R} = -\gamma\mathbf{B_R}$ is the precession vector. This differential equation is related to the rotation of $\mathbf{S}$ about $\boldsymbol{\Omega}_\mathbf{R}$, with the angular frequency $|\boldsymbol{\Omega}_\mathbf{R}|$. In the case of the Rashba precession, it should be noted that the precession vector is perpendicular to the electron wave vector.

In a 1DEG with the x-axis as the direction of current propagation, the component k_z of the electron wave vector vanishes. The direction of $\boldsymbol{\Omega}_\mathbf{R}$ remains thus always the same. If we assume that the electrons are injected by the source contact with a spin orientation along the x-axis, the spin orientation rotates only in the xy-plane, with an angular frequency proportional to k_x. Assuming a parabolic energy band, a deterministic relation can be established between the spin orientation and the distance along the x-axis. The spin polarization $P(x)$ along the 1D-channel is simply given by the following expression [7]:

$$P(x) = P_0 \cos\left(\frac{E_y x}{V_R}\right) \quad (3)$$

where P_0 is the spin polarization imposed by the ferromagnetic source contact at $x = 0$, and V_R is a parameter homogeneous to a voltage and equal to $\hbar^2/(2m^*a_{46})$. In $In_{0.53}Ga_{0.47}As$, we have $V_R = 3.4$ V.

If an analytical approach is sufficient in a 1DEG, the situation is completely different in a 2DEG. The equation (1) shows actually the strong dependence of the pseudomagnetic field $\mathbf{B}_R$ on the wave vector direction. Electron wave vector orientation is stochastically distributed after scattering with lattice imperfections. Therefore, the scattering events tend to randomize the precession vector, *i.e.* to randomize the rotation of the spin orientation during the electron free-flights. As the scattering events experienced by different electrons are non correlated events, the spin polarization imposed by the ferromagnetic source is relaxed as soon as each electron undergoes a sufficiently large number of scatterings. The current modulation due to gate-induced precession vanishes then in a 2DEG, as predicted by Datta and Das [2]. This spin relaxation phenomenon is similar to the mechanism described by D'yakonov and Perel [12]. The pseudomagnetic field studied by these authors is not related to the Rashba term, but to the bulk inversion term existing in a noncentrosymmetric crystal. A statistical approach is necessary to quantify the influence of the scatterings on the spin precession and spin relaxation in a 2DEG. Here, we propose to quantify the gate-induced spin precession phenomenon in an $In_{0.53}Ga_{0.47}As$ 2DEG, using a Monte-Carlo transport model.

2.2 Transport model and description of the 2DEG

A Monte-Carlo transport model [13] is based on a microscopic description of conduction phenomena: the current results of the collective motion of individual particles. Their motion is described as a succession of free-flights, under the influence of the electric field, interrupted by scatterings which correspond to instantaneous collisions between charge carriers and the host crystal. A Monte-Carlo algorithm consists into following carriers free-flights during a sufficiently long time duration, to obtain the statistical laws driving the studied structure. The free-flights durations and the type of the scatterings which interrupt the free-flights are chosen randomly with the help of scattering rates, computed from the Fermi golden rule.

In this frame, it is easy to take into account the Rashba mechanism. We define the spin orientation of each particle by its spherical coordinates. In the simulation, the electrons are injected at $x = 0$ in a channel of length L_x with a spin orientation up or down along x-axis according to the spin polarization P_0 imposed by the ferromagnetic source contact. To study the evolution of the spin polarization $P(x)$ along the channel, we solve numerically equation (2) during all free-flights.

To describe the 2DEG, we assume that the electrons are confined in a triangular potential well in the Γ valley.

As we restrict our study to longitudinal field E_x up to 0.5 kV/cm, the carrier energy remains close to the thermal value, and then the non-parabolicity of the Γ valley can be ignored. Moreover, the separation between the first two subbands of the well is high enough for E_y greater than or equal to 100 kV/cm (80 meV between the first and the second subband at $E_y = 100$ kV/cm) to allow the use of a single-subband model. As the highest perpendicular field in a HEMT is about 300 kV/cm, we carry out simulations for E_y varying between 100 kV/cm and 300 kV/cm. In the lateral z-direction, the potential is assumed to be constant everywhere in the width Z of the channel.

Finally, our transport model takes into account the most important scattering mechanisms in $In_{0.53}Ga_{0.47}As$ for temperatures lying between 77 K and 300 K, *i.e.* the electron/phonon scattering (with acoustic or polar optical phonons) and the alloy scattering. The Coulomb scattering on impurities is actually neglected, because we assume a non intentionally doped channel layer, separated from doping impurities of the wide bandgap top layer by a thick enough spacer, which is a non intentionally doped wide bandgap layer inserted into the heterostructure.

3 Simulation results

3.1 How to characterize Rashba spin precession?

In a spin-HEMT, the drain current is modulated by the variations of $P(L_x)$ with the perpendicular field E_y, *i.e.* with the gate voltage V_G. These variations are pseudo-periodical, with the electric pseudo-period $E_{y0} = 2\pi V_R/L_x$, and their magnitude increases with the spin polarization P_0 imposed by ferromagnets [7]. The value of P_0 remains till now unknown. From experimental data [3,14,15], we cannot expect P_0-values close to 100%. If a value of about 30% seems to be more realistic [3,15], it could be in fact much weaker [14]. That is the reason why the spin-related current modulation has to be experimentally characterized by its electric pseudo-period, rather than by its magnitude.

For a given channel length L_x, the maximum value of E_y has to be actually greater than two electric pseudo-periods E_{y0}, for the latter quantity to be experimentally determined. If the HEMT-channel is realized with $In_{0.53}Ga_{0.47}As$, its length has to be then greater than or equal to 1.4 μm. Under these conditions, the field-induced spin precession could even lead to significant electrical effects [7]. In order to evaluate the influence of the spin relaxation on $P(L_x)$-modulation in a 2DEG, results presented below focused on a channel with length $L_x = 1.4$ μm.

We simulate an electron population with an initial spin up orientation for all particles at $x = 0$, which corresponds to $P_0 = 100\%$. If the electrons injected by a ferromagnet in a semiconductor are two nonintermixing populations, with spin up or down, results for other values of P_0 can be obtained from this single case.

3.2 Spin relaxation in a channel of infinite width

In this part, we report simulation results for a 2D-channel with infinite width in the lateral z-direction. We study first

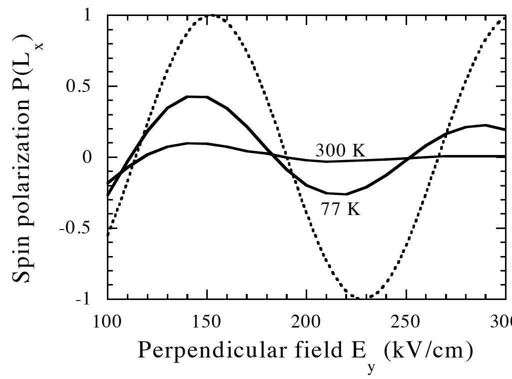

Fig. 1. Spin polarization $P(L_x)$ at the end of the channel against perpendicular electric field E_y. Data from Monte-Carlo simulation at 300 K and 77 K for a 2D-channel of length $L_x = 1.4$ μm and of infinite width (solid lines), and analytical expression (Eq. (3)) in the 1D-case (dashed line). $P_0 = 100\%$, $E_x = 0.5$ kV/cm.

the variation with the time of the spin polarization of an electron population with spin up orientation at $t = 0$, in a 2D-channel with infinite length and for $E_x = 0$ kV/cm. After Monte-Carlo calculations, the electrons lose rapidly their spin coherence in these conditions: the spin relaxation time is about 1 ps at room temperature, and about 2 ps at liquid nitrogen temperature for $E_y = 240$ kV/cm. These values are of the same order of magnitude as the typical transit times for conduction electrons in the channel of a HEMT. So, the spin relaxation may degrade the spin coherence of electrons moving in a 2D-channel.

We verified this prediction by studying the spin polarization P at $x = L_x$. In Figure 1, we plot the variation of the spin polarization $P(L_x)$ with the perpendicular field E_y for $L_x = 1.4$ μm, obtained by simulation at 77 K and 300 K for a 2DEG for $E_x = 0.5$ kV/cm (solid lines), and analytically for a 1DEG (Eq. (3), dashed line). For both temperatures, the magnitude of the oscillations of the spin polarization in the 2DEG is strongly attenuated by the spin relaxation. The magnitude of $P(L_x)$-modulation by E_y is very weak at 300 K for $L_x = 1.4$ μm, which should lead to non observable modulation of the drain current in a HEMT. However, the spin coherence remains high enough at 77 K to be perceptible. At liquid nitrogen temperature, the pseudo-period of the modulation of the spin polarization, almost the same as in a 1DEG, may be observable in a 2DEG. Consequently, a 2DEG structure with an infinite width is usable to study the physics of the spin-related phenomena at 77 K, but not at 300 K.

When the temperature decreases, the electron drift velocity increases, so the electron transit time in the channel decreases. The electrons experience then a weaker number of scatterings. Therefore, the effect of the spin relaxation is less high. The increase of the longitudinal field E_x may have the same influence on the transit times. If we compare the results obtained at 77 K for $E_x = 0.1$ kV/cm and for $E_x = 0.5$ kV/cm, we observe indeed an improvement of the spin coherence with the increase of the applied field E_x, but it remains weak. At 300 K, the variations obtained for the different values of E_x are almost identical.

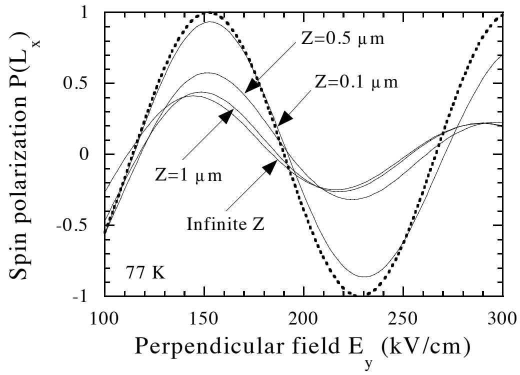

Fig. 2. Spin polarization $P(L_x)$ at the end of the channel against perpendicular electric field E_y. Data from Monte-Carlo simulation at 77 K for 2D-channels of length $L_x = 1.4$ μm and of different widths (solid lines), and analytical expression (Eq. (3)) in the 1D-case (dashed line). $P_0 = 100\%$, $E_x = 0.5$ kV/cm.

The number of scatterings remains high enough at 300 K, whatever the value of E_x, to lead to the complete relaxation of the spin coherence imposed by the spin polarizer.

3.3 Influence of a finite channel width

In the previous section, we have compared the spin-polarized transport in a "pure" 2DEG, where the Rashba precession is degraded by a significant spin relaxation phenomenon, and in a 1DEG, where the spin relaxation phenomenon does not exist. We investigate in this part the transition between these two extreme cases, by studying a 2DEG formed in a channel with a finite width Z. For the simulation, we assume that the lateral boundaries of the conduction channel are perfectly reflecting: an electron colliding with these boundaries experiences a specular reflection.

Figure 2 shows the variation of the spin polarization $P(L_x)$ with the perpendicular field E_y obtained by simulation for 2D-channels of different widths Z (solid lines), still in comparison with the results obtained in a 1DEG (dashed line). The length of these channels is $L_x = 1.4$ μm, and the temperature is equal to 77 K. For values of the width Z lying between infinity and 3 μm (results not depicted in Fig. 2), no change is remarkable. For $Z = 1$ μm, a small improvement in spin coherence is observable for E_y less than 200 kV/cm. But, there is almost no change for E_y greater than this value. For $Z = 0.5$ μm, the improvement in spin coherence is more significant for E_y less than 200 kV/cm and it begins to appear also for greater values of E_y. Finally, for $Z = 0.1$ μm, the spin relaxation phenomenon becomes really negligible for E_y less than 200 kV/cm. The values of spin polarization are very close to the values in a 1DEG. For E_y greater than 200 kV/cm, a difference still exists between 2D-values and 1D-values, but it is much reduced in comparison with the case of a channel with infinite width.

When the channel width is short enough, the spin polarization in a 2DEG tends thus continuously to its value in a 1DEG. It is in fact sufficient to limit the lateral displacements of the electrons to a value of the same order of magnitude of their mean free path. In this case, the sign of the component k_z of the electron wave vector can change many times during the time duration between two scattering events. As the perturbing term for the spin orientation varies with k_z (see Eq. (1)), its contribution during one free-flight tends to zero as the number of reflections increases. In a 2D-channel of width close to 0.1 μm, the spin coherence remains thus high enough to enable the experimental investigation of the spin-polarized transport.

4 Conclusion

The randomization of the Rashba precession vector by the scattering events in an $In_{0.53}Ga_{0.47}As$ 2DEG yields a non negligible spin relaxation for electrons moving within a conduction channel with an infinite channel width. But it is possible to increase the spin diffusion length by operating at the liquid nitrogen temperature, or by reducing the channel width to a value close to 0.1 μm. Therefore, a spin-HEMT with a 1DEG is not absolutely necessary to enable the investigation of the physics of the spin-relative phenomena in a ferromagnet/semiconductor structure.

Work is in progress to:

(i) study experimentally and theoretically the spin-dependent injection and collection phenomena at a ferromagnet/semiconductor interface, which appears now as the key point for the viability of the spin-HEMT;

(ii) realize and characterize a spin-HEMT, or simplified structures based on the same concept.

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