Monte Carlo modelling of spin relaxation in a III-V two dimensional electron channel

A. Bournel, P. Dollfus, P. Bruno*, P. Hesto

Institut d'Electronique Fondamentale, CNRS URA22, Université Paris Sud, Bât. 220, F-91405 Orsay cedex, France

*Present address: Max-Planck Institut für Mikrostrukturphysik, Weinberg 2, D-06120 Halle, Germany

Abstract

By using a Monte Carlo transport model, we investigate the feasibility of the control of the electron spin rotation by a perpendicular electric field in a III-V two dimensional electron gas. At room temperature, this control is made difficult because of an important spin relaxation phenomenon due to the scattering events between the carriers and the host crystal. However, we show that the loss of spin coherence can be decreased by operating at liquid nitrogen temperature, or even almost eliminated by reducing the electrons lateral displacements.

1. Introduction

This work is motivated by a new concept of structure proposed by Datta and Das [1]: it consists of a high electron mobility transistor (HEMT) with ferromagnetic source and drain contacts. The new concept appearing in this structure is the modulation of the drain current by a gate-control of electron spin orientation in the HEMT-channel. The existence of a gate-controlled spin-orbit coupling term in asymmetric quantum wells [2] makes actually feasible the control of the electron spin precession in the channel layer of a HEMT. This term, depending on the perpendicular electric field at the HEMT-heterointerface, is often denoted as the Rashba mechanism [3]. Moreover, the ferromagnetic source and drain contacts should act as spin polarizer and analyzer: they inject or collect preferentially electrons with a spin orientation in accordance with their magnetic moments [4].
However, after Datta and Das [1], the gate-control of spin orientation would be only efficient if free electrons in the channel form a one dimensional electron gas (1DEG). After describing in a previous work a first approach for the modelling of a spin-HEMT with a 1DEG [5], we want to check Datta and Das assertion by studying the Rashba spin precession in a two dimensional electron gas (2DEG).

2. Model of spin polarized transport

The Rashba spin precession is a slow spin dephasing process [5,6]. This phenomenon has to be considered as a continuous spin rotation during electron free-flights, about a precession vector Ω_R. The expression of this vector is

$$\Omega_R = \frac{a_{46}E_y}{\hbar}\left(k_x u_z - k_z u_x\right) \qquad (1)$$

where E_y is the gate-controlled perpendicular electric field at the HEMT-heterointerface, a_{46} is a parameter depending on the energy band structure of the narrow bandgap semiconductor of the heterostructure, and $\mathbf{k}=k_x\mathbf{u}_x+k_z\mathbf{u}_z$ is the electron wave vector ($\mathbf{u}_x$ and $\mathbf{u}_z$ are unitary vectors). In case of parabolic energy bands, the spin orientation rotates then about a direction perpendicular to the electron trajectory with an angular frequency depending on the electron wave vector.

If the electrons form a 1DEG with the x-axis as propagation direction, the value of the wave vector component k_z vanishes. The direction of the precession vector is always the z-axis. 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. Therefore, it is possible to determine an analytical expression for the variation of the spin polarization P with the distance x [5], where the spin polarization P is defined as the mean value of the spin component along x (with the spin vector normalized to unity). If the electrons are injected at x=0 with a spin up orientation, we get in this case

$$P(x)=\cos\left(\frac{E_y x}{V_R}\right) \tag{2}$$

where V_R is a parameter homogeneous to a voltage and equal to $\hbar^2/(2m^*a_{46})$.

In a 2DEG, the scattering events between an electron and the host crystal randomize the electron wave vector **k**. The electron trajectory is then randomized. As the precession vector is perpendicular to **k**, the spin rotation during the electron motion is also a "random walk". The scatterings lead then to a spin relaxation phenomenon. The current modulation related to the spin precession could thus vanish in the structure proposed by Datta and Das if the conduction electrons form a 2DEG.

To quantify this phenomenon, we use a Monte Carlo transport model. The electron spin orientation S is defined by two variables associated to the simulated particles: φ and θ its polar and azimuthal angles. The law driving the spin precession is

$$\frac{dS}{dt}=\Omega_R\times S \tag{3}$$

Using the spherical coordinates, Eq. (3) becomes

$$\begin{cases}\dfrac{d\varphi}{dt}=\dfrac{a_{46}E_y}{\hbar}k_x+\dfrac{a_{46}E_y}{\hbar}k_z\dfrac{\cos\theta\cos\varphi}{\sin\theta}\\[2mm] \dfrac{d\theta}{dt}=\dfrac{a_{46}E_y}{\hbar}k_z\sin\varphi\end{cases} \tag{4}$$

If the longitudinal field E_x is equal to zero, the analytical resolution of Eq. (3) during one free-flight is possible, otherwise this resolution is difficult, or even impossible without approximation. Then, we solve numerically Eq. (4) for all free-flights of each particle. Finally, the spin polarization P is the mean value of $\cos\varphi\times\sin\theta$.

3. Simulation results

We study the evolution of the spin polarization of electrons injected at x=0 with a spin up orientation, moving along a 2D-channel of length L_x=1.4 μm in $In_{0.53}Ga_{0.47}As$, under the influence of a low electric field E_x. In $In_{0.53}Ga_{0.47}As$, we have V_R=3.4 V.

In Fig. 1, we plot the variations of the spin polarization obtained from Monte Carlo simulation at 77 K and 300 K in a 2D-channel of infinite width Z (solid lines), in comparison with those obtained from the analytical expression in a 1D-channel (Eq. (2), dashed line). At room temperature, a significant spin relaxation phenomenon is noticeable.

In fact, the spin coherence is completely lost for distances greater than 1 μm. In these conditions, one cannot expect any current modulation. At liquid nitrogen temperature, the spin relaxation is still non negligible, but significantly reduced in comparison with the case of room temperature. In fact, the spin coherence at $x=L_x$ remains high enough to enable the study of spin-relative phenomenons in such a structure.
We investigate also the influence of a reduced channel width Z on the spin relaxation, still in the case of a 2D-channel. We consider that an electrons colliding the lateral boundaries of the channel experiences a specular reflection. In Fig. 2, we plot the variations of the spin polarization obtained from Monte Carlo simulation at 77 K in 2D-channels with different widths Z (solid lines), still in comparison with the 1D-results (Eq. (2), dashed line). For Z=1 μm, the variations of the spin polarization are almost identical to those obtained in a channel with infinite width. For Z=0.5 μm, value close to the electron mean free path at this temperature, we remark an improvement in the spin coherence, but it remains weak. However, for Z=0.1 μm, the variations of the spin polarization are almost the same as in the case of a 1DEG, which may allow spectacular electrical effects. So, it is not necessary to confine the electrons in a pure 1DEG to make vanish the spin relaxation phenomenon. In fact, it is 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 changes many times during the time duration between two scattering events. As the perturbative terms for the spin orientation vary with k_z (see Eq. (4)), their contribution during one free-flight tends to zero with the number of reflections.

4. Conclusion

We have developed a Monte Carlo model for the simulation of the spin-polarized transport in a 2DEG. Our results show that it is not necessary to confine the electrons in the two directions perpendicular to the propagation axis of a spin-HEMT. It is possible indeed to reduce the spin relaxation phenomenon that degrades the control of the spin precession in a 2DEG, by operating at the liquid nitrogen temperature, or by reducing sufficiently the lateral displacements of the electrons.
This work is in progress for the modelling of a complete structure, with taking into account the spin polarized injection/collection by ferromagnetic contacts. This phenomenon may be in fact the bottleneck for the spin-HEMT viability.

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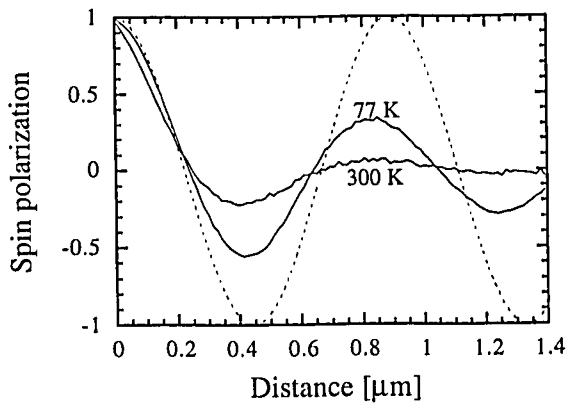

Figure 1: Spin polarization variations along the $In_{0.53}Ga_{0.47}As$-channel. Data from Monte Carlo simulation at 300 K and 77 K for a 2D-channel with an infinite width (solid lines) and analytical expression in the 1D-case (Eq. (2), dashed line). L_x=1.4 μm, E_x=0.5 kV/cm, E_y=240 kV/cm.

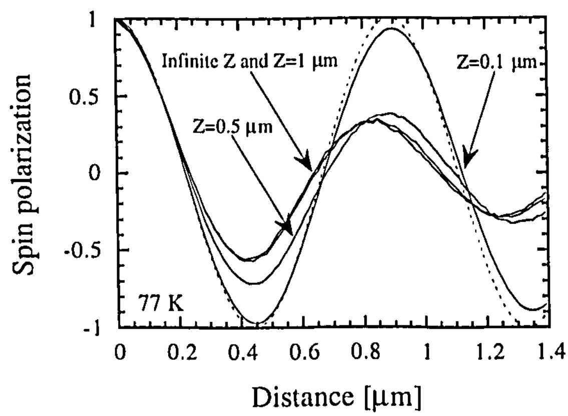

Figure 2: Spin polarization variations along the $In_{0.53}Ga_{0.47}As$-channel for different channel widths Z. Data from Monte Carlo simulation at 77 K for a 2D-channel (solid lines) and analytical expression in the 1D-case (Eq. (2), dashed line). L_x=1.4 μm, E_x=0.5 kV/cm, E_y=240 kV/cm.