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Spin-dependent transport phenomena in a HEMT

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Abstract

After reviewing the spin-dephasing mechanisms appearing in III–V heterostructures, we study theoretically spin-dependent transport in the channel of a original architecture of high electron mobility transistor, the spin-FET. We investigate particularly the spin relaxation associated to Rashba spin precession.

Keywords: HEMT; Spin–orbit coupling; Spin precession

A particular concept of field-effect transistor, the spin-FET, was proposed [1]. This structure consists of a high electron mobility transistor (HEMT) where highly doped source and drain regions are replaced by ferromagnetic (FM) contacts. FM contacts inject and collect mainly electrons with a specific spin depending on their magnetic moment. Moreover, spin rotation in HEMT channel is controlled by gate voltage V_G through Rashba spin–orbit coupling [2], resulting from the asymmetry of the conduction band, i.e. a structure inversion asymmetry (SIA). So, drain current I_D depends on gate-controlled spin of electrons reaching this contact with respect to drain magnetic moment, in addition to classical field-effect control by V_G.

In order to study theoretically spin-polarized transport in spin-FET channel, we review first the main spin-dephasing effects in such a structure. These effects are (i) the SIA term, (ii) the spin–orbit term due to the lack of inversion symmetry of the zinc-blende crystal [3], i.e. a bulk inversion asymmetry (BIA), and (iii) the spin–orbit interaction due to impurities or phonons, denoted as Elliott–Yafet (EY) mechanism [3]. SIA and BIA terms lead to continuous spin precession during electron free-flights [4]. EY mechanism corresponds to instantaneous scatterings with simultaneous "spin flip" [3]. We compare their influences by evaluating the "spin flip" times T_{sf} associated to each of them. For SIA and BIA precessions, we obtain T_{sf} by dividing π by the magnitude of precession vector Ω. We deduce Ω_{SIA} and Ω_{BIA} expressions from Ref. [5]. We calculate finally $T_{sf\ EY}$ by inverting spin flip scattering rate, which we calculate following Ref. [3].

In Fig. 1, we plot the variations with electron kinetic energy of $T_{sf\ SIA}$, $T_{sf\ BIA}$ and $T_{sf\ EY}$ at 77 K in a two-dimensional electron gas (2DEG) formed in $In_{0.53}Ga_{0.47}As$ (solid lines). We plot in dashed line the inverse of total scattering rate, which gives roughly electron free-flight times. $T_{sf\ EY}$ is at least two orders of magnitude higher than $T_{sf\ SIA}$ and

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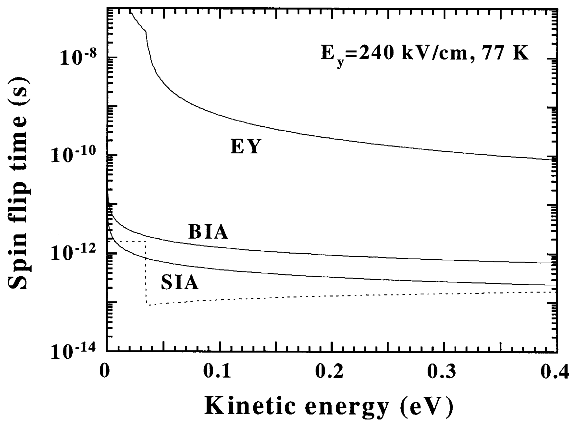

Fig. 1. Spin flip times $T_{\mathrm{sf\ SIA}}$, $T_{\mathrm{sf\ BIA}}$ and $T_{\mathrm{sf\ EY}}$ against electron kinetic energy in an $In_{0.53}Ga_{0.47}As$ 2DEG (continuous lines). Dashed line: inverse of total scattering rate.

T_{sfBIA}. This remark remains valid at 300 K. Spin flip scattering events are actually scarce in semiconductors in comparison with spin conserving scatterings. So, we do not have to take into account EY. SIA precession is faster than BIA one, but the ratio of $T_{\mathrm{sf\ BIA}}$ to T_{sfSIA} does not exceed 3. The comparison between influences of BIA and SIA terms in III–V heterostructures has in fact induced a large controversy for 15 years (see Ref. [4] and references therein). After recent experimental and theoretical results, SIA term is however really predominant in comparison with BIA [6]. The SIA term is thus the only spin-dephasing effect that we must consider.

We have for SIA in a 2DEG formed in xz-plane [5]:

$$\Omega_{\mathrm{SIA}} = \frac{2a_{46}E_y}{\hbar}(-k_z\boldsymbol{u}_x + k_x\boldsymbol{u}_z), \tag{1}$$

where E_y is the electric field along y-axis normal to the 2DEG, $\boldsymbol{u}_i$ is a unitary vector along i-axis, k_i the i-component of electron wave vector $\boldsymbol{k}$ and a_{46} a constant depending on channel material. So, this vector is in the 2DEG plane and is normal to $\boldsymbol{k}$. Its magnitude increases with the increase of E_y, which is roughly proportional to V_G in a HEMT. As $\boldsymbol{k}$ is randomized by scatterings, Ω_{SIA} is also randomized by such events in whole xz-plane. Thus, the spin polarization imposed by FM source in the spin-FET can be relaxed before electrons reach drain as soon as each electron undergoes a large number of scatterings. In a 1DEG along x-axis, k_z vanishes and Ω_{SIA} has always the same direction. Then, the scatterings cannot relax spin and electron spin rotates coherently with an angular pulsation proportional to E_y and k_x. We derive an analytical model to calculate I_D variations in this case [4].

A transport Monte Carlo (MC) model is used for 2DEG formed in $In_{0.53}Ga_{0.47}As$ to quantify accurately the effect of scatterings on spin [7]. In Fig. 2, we combine I_D expression obtained in 1DEG with MC results in 2DEG to plot I_D variations with "gate voltage" in different 2D-channels of length $L = 1.4$ μm (continuous lines). The "gate voltage" corresponds in fact to polar angle of spin at the end of a 1D-channel, which is roughly proportional to V_G. We plot for comparison the case of a classical HEMT (dashed line). At 300 K for infinite channel width W (wide 2DEG), the spin relaxation is very strong: no spin-related effect is observable. But this relaxation is reduced at 77 K, or better by using a narrow enough channel (narrow 2DEG), i.e. $W =$ 0.1 μm. The curve plotted for narrow 2DEG concerns results obtained at 77 K, but results at 300 K are almost identical, i.e. very close to variations obtained in a 1DEG. The gate-induced spin precession leads then to significant pseudo-periodical current oscillations. For wide 2DEG at 77 K, the

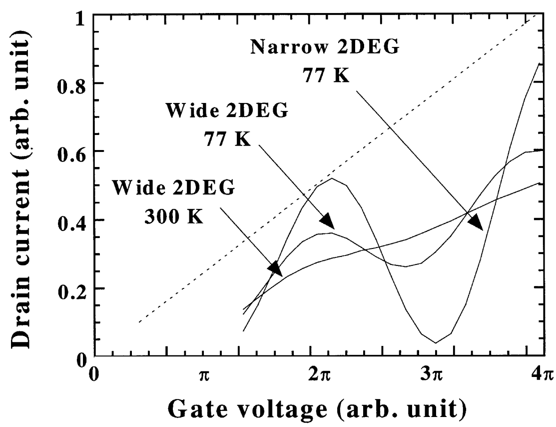

Fig. 2. I_D against V_G in different $In_{0.53}Ga_{0.47}As$ 2D-channels (continuous lines). Wide 2DEG: infinite channel width W, narrow 2DEG: $W = 0.1$ μm. Dashed line: classical HEMT. $L = 1.4$ μm, $E_x = 0.5$ kV/cm, spin polarization P_0 imposed by source and drain = 100%.

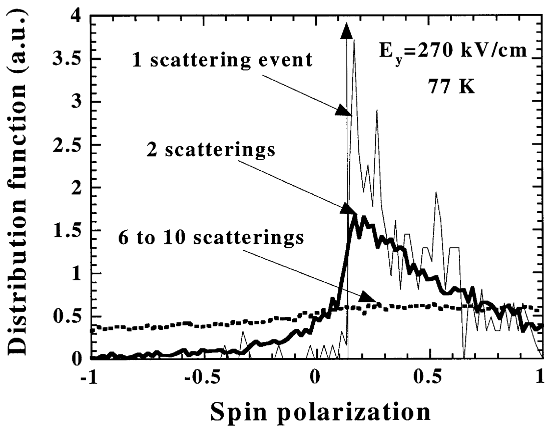

Fig. 3. Spin polarization spectra at the end of a wide $In_{0.53}Ga_{0.47}As$ 2D-channel for electrons undergoing different numbers of scatterings between source and drain. The vertical arrow is the Dirac peak obtained in a 1D-channel. $L = 1.4$ μm, $E_x = 0.5$ kV/cm, $P_0 = 100\%$.

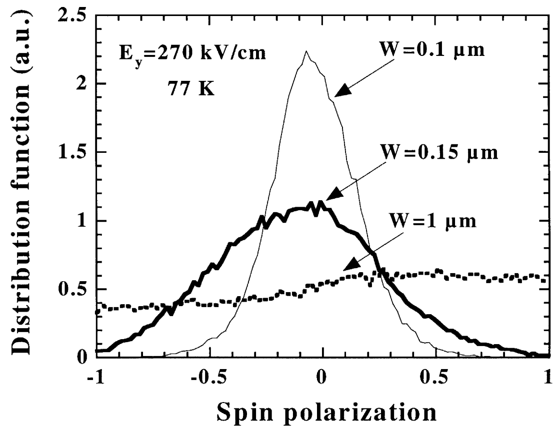

Fig. 4. Spin polarization spectra at the end of $In_{0.53}Ga_{0.47}As$ 2D-channels of different widths W for electrons undergoing 6–10 scatterings. $L = 1.4$ μm, $E_x = 0.5$ kV/cm, $P_0 = 100\%$.

measurement of this pseudo-period would constitute a very interesting way to characterize SIA term [7]. For narrow 2DEG, the oscillations are stronger. In particular, I_D exhibits a marked minimum for V_G equal to 3π, which corresponds to spin of electrons reaching drain opposite to spin preferentially collected by this contact. On the contrary for V_G equal to 2π and 4π, these spin orientations are parallel and I_D presents a marked maximum. This yields an increase of transconductance for V_G between 3π and 4π, or negative transconductance effect for V_G between 2π and 3π.

To illustrate the effect of scatterings on spin coherence, we plot in Fig. 3 three spin polarization distributions for electrons undergoing, at 77 K, only one scattering between source and drain in a wide 2DEG, two scatterings and 6 to 10 scatterings. In the first case, a significant peak of spin coherence appears close to 1D Dirac peak. The spin polarization of these electrons is not relaxed but it is very minor (0.2% of the population). In the second case (7% of the population), the peak of coherence is weaker and the distribution spreads out. The two undergone scatterings have indeed reduced the spin coherence. The third distribution (42%) is fully randomized. At 77 K, the spin coherence under these conditions is in fact only due to electrons undergoing less than 3 scatterings, which represent only 14% of the population. At 300 K, all electrons experience at least 5 scatterings and lose their spin coherence between source and drain.

We plot finally in Fig. 4 distributions concerning electrons undergoing 6–10 scatterings for different widths W. When W is small enough, the effect of scatterings on spin precession decreases with the reduction of W. The spin polarization distribution tends gradually to 1D Dirac distribution. At 300 K, these comments remain valid for electrons undergoing many scatterings. In narrow 2DEG, such electrons do not lose their spin coherence, in spite of the scatterings undergone. Spin coherence is then higher than for wide 2DEG, in which only few electrons undergoing a weak number of scatterings carry the spin polarization.

So, it is not necessary to confine the electrons in a 1DEG to make the spin relaxation vanish. It is sufficient to limit electrons lateral displacements Δz to a value close to their mean free path. To explain it qualitatively, if the term proportional to k_x appearing in Ω_{SIA} carries the information in a 1DEG, the term proportional to k_z is perturbing for the spin in a wide 2DEG. During a free-flight of duration t_v, perturbing variation of spin orientation varies roughly as $k_z t_v$, that is as Δz. In a narrow

2DEG, Δz vanishes. Then, the spin relaxation decreases gradually when W decreases.

In conclusion, we point out the spin relaxing effect of spin conserving scatterings in a spin-FET with 2D-channel. This effect of scatterings on spin precession vanishes when the width of the channel is reduced sufficiently, which yields significant electrical effects.

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