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Modulation of spin dynamics in a channel of a nonballistic spin field effect transistor

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We have investigated the effect of gate control over the spin polarization drag in an $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ heterostructure. The study is motivated by a recent proposal for a nonballistic spin field effect transistor that utilizes the interplay between the Rashba and the Dresselhaus spin-orbit interaction in the device channel. A model that utilizes real material parameters, in order to calculate spin dynamics as a function of the gate voltage, has been developed. From the obtained results, we define the efficiency of the spin-polarization modulation and spin-density modulation. The estimated modulation of the spin polarization at room temperature is of the order of 15–20 %. The results show that the effect is not sufficient for device applications. However, it can be observed experimentally by spatially resolved optical pulse-probe techniques.

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Successful applications utilizing giant magnetoresistance and tunneling magnetoresistance effects in layered ferromagnetic-metal structures for commercial devices[1] have motivated large interest in spin-dependent phenomena in semiconductor structures.[2,3] In comparison with metal-based structures, semiconductor spintronic devices are believed to be compatible with conventional circuits and more flexible in functionality. Many semiconductor spin electronic (spintronic) devices have been proposed recently.[4–14] The optimistic expectation is that such devices could be scalable to smaller sizes, dissipate less power in comparison to conventional devices, and, in addition, utilize the property of spin quantum coherence.[15–17] According to a more skeptic estimation, semiconductor spintronic devices will be limited only to specific applications.[18,19] In order to clarify this controversy the functionality of the various proposed device structures should be analyzed.

We have estimated the efficiency of the gate voltage control over the spatial distribution of the spin polarization in a channel of a nonballistic spintronic field effect transistor[10] (spin-FET) at room temperature, utilizing realistic material parameters. This spin-FET should be stable to effects of electron scattering, in contrast to other spintronic devices that operate in a ballistic transport regime. It utilizes spin relaxation of conduction electrons in III-V or II-VI semiconductor quantum wells (QW) modulated by the gate voltage.[10] In such structures the spin dynamics of the conduction electrons is controlled by spin-orbit interaction.[20,21] Two different spin-orbit terms are present in zincblende semiconductor heterostructures: the Rashba term,[20]

$$H_{\mathrm{R}} = \eta(k_y\sigma_x - k_x\sigma_y), \tag{1}$$

and the Dresselhaus term,[21,22]

$$H_{\mathrm{D}} = \gamma(k_y\sigma_y - k_x\sigma_x). \tag{2}$$

The interplay between these terms makes the spin relaxation strongly anisotropic.[23] It was shown theoretically that for some particular configurations, spin-polarized electrons can be transported without substantial loss of polarization if the spin-orbit coupling constants η and γ are nearly equal.[10,24,25] The external gate voltage controls the difference between the Rashba and Dresselhaus terms (mostly through the variation of the Rashba term[26,27]). As a result, it produces a different spin polarization of electrons in the device channel near the drain contact. The magnetoresistance of the structure is dependent on the value of this spin polarization and its relative orientation with respect to the magnetization of the drain.

In this Rapid Communication, we address the issue of spin-polarization and spin-density modulation by controlling the gate voltage, without taking into account the issues of injection and filtering. The influence of the later subjects on the spin-FET operation will be discussed at the end of this article. Obviously, problems of spin injection and detection are crucial for the design of spin-FETs. In the case of a nonrobust source of spin-polarized electrons, the fabrication of a spin-FET (Ref. 10) is questionable. Direct spin injection from a ferromagnetic metal into a QW showed a small variation of magnetoresistance of the order of 1%.[28] The more promising design is used in spin light-emitting diodes.[29] Recent experimental advances allow efficient electrical spin injection[29] and spin detection[30] at room temperature in such structures. The comprehensive review of recent achievements of spin injection/detection in semiconductor structures can be found in Refs. 3 and 31. The design of a spin source and spin drain can vary for a particular device. For example, both mechanisms of spin injection mentioned above can be utilized in the spin-FET.[4,11] In this case, the study of spin dynamics in the device channel, separately from spin injection and detection, characterizes the gate control mechanism. Experimentally, the control mechanism proposed in Ref. 10 can be investigated independently of the spin-FET geometry, by using spin-galvanic[32] or weak localization effects.[27]

The structure considered in this work is shown in Fig. 1, where the QW is orthogonal to the (0, 0, 1) direction in crystallographic axes. We have assumed that the thermalized spin polarized electrons are injected into the QW at the left boundary, $x=0$. The device channel (x axis) is oriented along the $(1\ -1\ 0)$ crystallographic direction and the initial spin polarization is parallel to $(-1\ 1\ 0)$ direction. Within a drift-diffusion approximation[25,33] the electron spin density at a given position x will be[25]

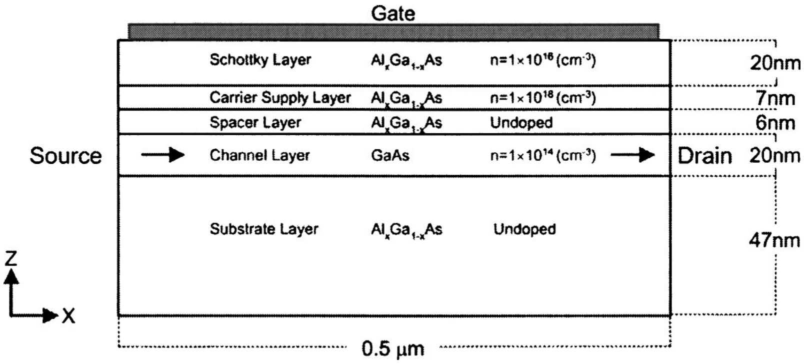

FIG. 1. Schematic diagram of the structure simulated, $x=0.3$.

$$n_s(x) = n_s(0)e^{-x/L_s}. \tag{3}$$

The characteristic spin dephasing length, L_s, is defined as

$$L_s = \left[\frac{\mu E}{2D} + \sqrt{\left(\frac{\mu E}{2D}\right)^2 + \left(\frac{2m^*(\eta - \gamma)}{\hbar^2}\right)^2} \right]^{-1}, \tag{4}$$

where E is the in-plane electric field, m^* is the electron effective mass, μ is the electron mobility, and D is the diffusion coefficient. Within this model,[25] spin polarization is conserved along the channel if the spin-orbit coupling constants are equal. On the other hand, it decays exponentially if they are different. The dependence of L_s on the electric field, E, in Eq. (4) is similar to that obtained in Ref. 34.

A simulation model has been developed based on Ref. 35 to compute the properties of the heterostructure shown in Fig. 1. The algorithm consists of coupled macroscopic and microscopic models. The macroscopic model, which includes the transport and continuity equations, is solved iteratively with the Poisson equation to get the self-consistent electron concentration and electric potential within the whole device. The total number of electrons in the QW is obtained from the concentration distribution. To take into account the quantum effect of the QW, the microscopic model, the Schrödinger equation, is solved self-consistently with the Poisson equation. It refines the distribution of the electron concentrations in the different subbands and the potential in the region of the device where the quantum mechanical effects take place (QW width plus 5 nm in both sides out of the QW). The exact form of the energy-band diagram of the heterointerface is based on the assumption of a continuous vacuum level (known as the Anderson model).[36,37] The resulting electric potential distribution, conduction-band profile, subband energies, and confined electron wave functions are used to calculate the Rashba and the Dresselhaus terms as functions of the gate voltage and the device structure.

In the simulation, the gate-semiconductor interface was assumed to be a Schottky barrier contact and the substrate interface was assumed to be an ohmic contact. The boundary conditions of the device, represented by the voltage and the concentration, were calculated using the equations from Ref. 38. The Schottky barrier height, $\phi_B=1.06$ eV, was obtained from experimental data.[39] In the QW region the three lowest subbands were accounted. Profiles of the doping density and material composition were assumed to vary only in one dimension. Effects of the crystal potential were parameterized by an effective mass, which is constant in each material region, and which changes abruptly at the material interface. The Schrödinger equation, solved for the electrons confined in the QW, is spin independent. This is applicable for middle-gap semiconductor structures.[40]

We have calculated the spin-orbit coefficients for two cases. The first case (case I) is based on the simplified equations, $\eta=\alpha\overline{E}$ (the Rashba constant is independent of the subband index i), and $\gamma_i=\beta\langle k_z^{i^2}\rangle$, where $\alpha=5.33$ eV Å^2 and $\beta=29$ eV Å^3 were fitted from experimental data.[27] $\overline{E}$ is the average electric field in the QW region and $\langle k_z^{i^2}\rangle$ is the expectation value of the wave vector squared. In the second case (case II) we used the model developed by Zawadzki and Pfeffer.[40] The utilized constants were E_0(GaAs)=−1.424 eV, E_0(AlGaAs)=−1.798 eV, Δ_0(GaAs)=−0.34 eV, Δ_0(AlGaAs)=−0.328 eV,[41] E_1(GaAs)=3.04 eV, E_1(AlGaAs)=2.693 eV,[42] P_0=10.493 eV Å, P_1=4.780 eV Å, Q=8.165 eV Å, and $\overline{\Delta}$=−0.050 eV.[43]

The calculated spin-orbit coupling coefficients, presented in Fig. 2, are compatible with the results of experimental measurements and theoretical calculations.[26,27,44–46] According to case I, Fig. 2(a), at $V_g=0.8$ V, the Rashba and Dresselhaus coefficient are equal. In case II, Fig. 2(b), this occurs at a higher gate voltage that was out of the studied range.

It can be seen from the results in Fig. 2(b) that the Rashba coefficient is linear and nearly the same for all the subbands. In both cases $\eta=0$ at $V_g=0.42$ V, where the QW is symmetric. The slope of γ_i in both figures can be explained as the effect of the electric field on k_z. It is more pronounced in the lowest subband, which is highly sensitive to the conduction-band variations.

It can be deduced from the results that it will not be possible to control electron-spin dynamics over all subbands simultaneously. Hence, in order to achieve a bigger spin modulation, the majority of electrons should be transported on the first subband. This corresponds to the conclusions by Pramanik *et al.*[47]

To characterize the efficiency of the spin-density modulation we introduce the ratio between the spin densities at the drain contact, $x=a$, for two different values of gate voltages,

$$\Gamma = \frac{\sum_i n_s^i(a, V_g^{\text{off}})}{\sum_i n_s^i(a, V_g^{\text{on}})}. \tag{5}$$

V_g^{off} and V_g^{on} correspond to the "off" and "on" states of the spin-FET and i is the subband index. Here we assume that

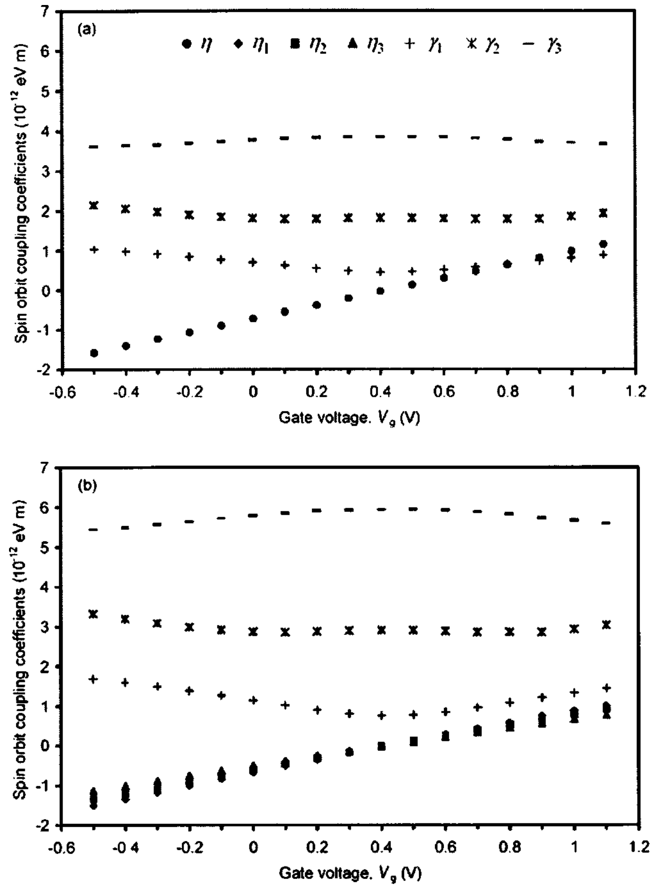

FIG. 2. Rashba, η_i and Dresselhaus, γ_i, spin-orbit coupling coefficients as a function of the gate voltage. Indexes correspond to different subbands. (a) Case I: phenomenological parameters fitted to experimental data (Ref. 27), (b) Case II: parameters calculated according to Ref. 40.

the on state corresponds to a bigger spin density than the off state. The spin density, $n_s^i(a,V)$, in the channel varies due to the change of the electron concentration and the modulation of the spin polarization, $P_i = n_s^i / n^i$. The parameter Γ in Eq. (5) characterizes both of these processes. This ratio is equal to one if the spin density is not controlled by the gate voltage and is close to zero if the control mechanism is efficient. The modulation of the spin polarization can be described by the parameter

$$\Lambda_P = (1 - \Gamma/\Gamma_n) \times 100\,\% . \quad (6)$$

Here, in the same form as Eq. (5), we define Γ_n as the ratio between the average electron charge concentrations, $n^i(a,V_g^{\mathrm{off}})$ and $n^i(a,V_g^{\mathrm{on}})$. The modulation of the spin polarization, Λ_P, varies from zero to 100%. When the gate voltage does not affect the spin dynamics it is zero and 100% when it is most efficient.

To estimate the parameters Γ and Λ_P, the in-plane electric field is specified as $E = -10^5$ V/m. The on and off states of the gate voltage are defined as $V_g^{\mathrm{on}} = 0.4$ V and $V_g^{\mathrm{off}} = 0.3$ V, respectively. The chosen on and off gate voltages, device length, and applied voltage correspond to future trends in semiconductor devices.[48] The calculated values are shown in

TABLE I. Ratio of spin densities for the "off" and "on" states, Γ, and range of spin-polarization variation Λ_P. The results are given for two different sets of spin-orbit coefficients. Case I: phenomenological parameters fitted to experimental data (Ref. 27). Case II: parameters calculated according to Ref. 40.

	Case I	Case II
Γ	0.120	0.114
Λ_P [%]	15.2	19.8

Table I. Similar results for Λ_P were obtained for an inverted structure, in which the QW is located between the gate contact and carrier supply layer. The obtained efficiency of the gate modulation is not sufficient for a device application. However, variation of spin polarization can be observed experimentally at room temperature using optical pulse-probe measurement techniques.[49] The first optical beam should persistently polarize electrons close to the source contact, while the second beam will measure the polarization at drain contact. Both source and drain should be nonmagnetic and acquire an ohmic contact with the semiconductor. In comparison with recent results on the gate modulation of spin relaxation time in QWs,[50] the proposed experiment describes a spatial propagation of the spin polarization rather than its time evolution. Moreover, it operates with an interference of the Rashba and Dresselhaus mechanisms and can be used for (0, 0, 1) QWs.

In realistic device structures, the spin-injection and spin-detection mechanisms will complicate the device operation. In the first approximation a nonideal spin source and drain (for example, injection of electrons with spin polarizations less than 100%) will increase a leakage current through the device rather than affect the value of the spin-polarization modulation, Λ_P (see also the discussion in Ref. 19). A similar effect should be observed, for example, if the device channel is tilted from the $(1,-1,0)$ direction while the magnetization of the contacts remains the same. In this case, the spin-dephasing length will be shorter[24] and the spin density for both on and off states will decrease.

In conclusion, we have studied the effect of the gate voltage on the spin-polarization drag in a spin-FET device using realistic parameters. The spin dynamics in the structure is governed by the spin-orbit interaction. The calculations of the spin-orbit coupling coefficients for a given device structure and gate voltage are based on the self-consistent steady state solution of the Poisson and Schrödinger equations coupled with the transport and continuity equations.

We have shown that it is possible to control the spatial distribution of an electron-spin polarization in a quantum well by the gate voltage at room temperature. The calculated range of the spin-polarization modulation for the on and off states is approximately $\Lambda_P = 15-20\,\%$. The effect can be measured using optical pulse-probe techniques. In order to make it applicable for commercial devices, further improvements in the structure design are required.

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