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Decay of spin-polarized hot carrier current in a quasi-one-dimensional spin-valve structure

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We study the spatial decay of spin-polarized hot carrier current in a spin-valve structure consisting of a semiconductor quantum wire flanked by half-metallic ferromagnetic contacts. The current decays because of D'yakonov-Perel' spin relaxation in the semiconductor caused by Rashba and Dresselhaus spin–orbit interactions in multi-channeled transport. The associated relaxation length is found to decrease with increasing lattice temperature (in the range from 30 to 77 K) and exhibit a nonmonotonic dependence on the electric field driving the current. The relaxation lengths are several tens of microns which are at least an order of magnitude larger than what has been theoretically calculated for two-dimensional structures at comparable temperatures, spin-orbit interaction strengths, and electric fields. This improvement is a consequence of one-dimensional carrier confinement that does not necessarily suppress carrier scattering, but nevertheless suppresses D'yakonov-Perel' spin relaxation.
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Ever since the discovery of the spin-valve (SV) effect,[1] there has been considerable interest in studying spin transport in nonmagnetic materials in which spin-polarized (SP) carriers are injected from a ferromagnetic (FM) contact and detected by another FM contact. The SV structure has also been employed to devise spintronic devices, such as the so-called spin field-effect transistor,[2] in which an electron's spin (rather than its charge) is employed to elicit transistor action.

The basic SV geometry is shown in the top panel of Fig. 1. It consists of a semiconductor channel [assumed to be quasi-one-dimensional (1D) for this study] flanked by two half-metallic FM contacts. One contact (called the ''source'') injects SP current into the channel and thus acts as a ''spin polarizer.'' The other contact acts as a ''spin analyzer'' and is termed the ''drain.'' Carriers drift from the source to the drain under the influence of a driving electric field. When they arrive at the drain, they are transmitted with a probability $|T|^2=\cos^2(\theta/2)$ where θ is the angle between the electron's spin polarization at the drain end and the drain's magnetization.[2] With increasing degree of spin depolarization in the channel (caused by spin relaxation), the average ''misalignment angle'' θ (for the electron ensemble) increases and consequently the transmitted current decreases. Ultimately, when there is no residual spin polarization in the current (i.e., carriers are equally likely to have their spins aligned parallel or antiparallel to the drain's magnetization), the transmitted current will fall to 50% of its maximum value. We are interested in finding how the (transmitted) SP current falls off with distance along the channel at different driving electric fields and temperatures.

Spins depolarize in the channel primarily because of spin–orbit interactions caused by bulk inversion asymmetry (Dresselhaus spin–orbit coupling)[3] and structural inversion asymmetry (Rashba spin–orbit coupling).[4] These spin–orbit couplings are momentum dependent, and because different electrons have different momenta that change randomly due to scattering, the spins become randomized by scattering and the *ensemble averaged* spin and SP current decay with distance. This mechanism of spin relaxation is the D'yakonov-Perel' mechanism[5] which is overwhelmingly dominant in quasi-1D structures over the Elliott–Yafet[6] or Bir-Aronov–Pikus[7] mechanisms. The spatial decay of spin due to D'yakonov-Perel' mechanism was studied in the past by Bournel *et al.*[8] and Saikin *et al.*[9] in two-dimensional (2D) channels. They mostly dealt with low driving electric fields so that transport is linear or quasilinear. In contrast, we have studied the spatial decay in quasi-1D structures of both spin and SP current at high driving electric fields of 1–10 kV/cm, which result in hot carrier transport and nonlinear effects.

In a 1D structure, the SP current due to one electron is proportional to $q\nu_x|T|^2$ where ν_x is the ensemble averaged velocity of the electrons along the channel. As stated before, the quantity $|T|^2$ depends on the component of the electron's spin polarization along the magnetization of the drain. We will assume that the source and drain are both magnetized along the channel's axis (x axis). This results in the initial spin orientation to be along the channel axis. Accordingly,

$$|T|^2=\cos^2(\theta/2),$$
$$\cos(\theta)=S_x/\sqrt{S_x^2+S_y^2+S_z^2}=\overline{S_x}, \quad (1)$$

where S_n is the spin component along the n axis and $\overline{S_x}$ is the normalized value of S_x.

The ensemble averaged SP current at any position x is given by

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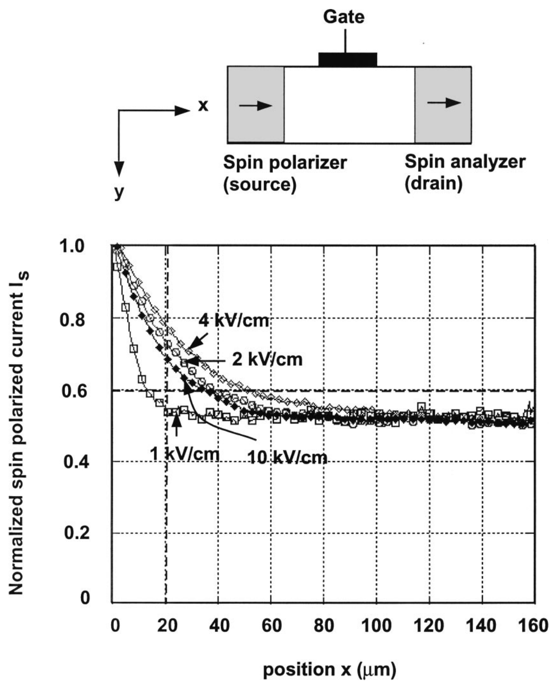

FIG. 1. Spatial decay of the normalized SP current in a GaAs quantum wire channel of rectangular cross section 30 nm×4 nm. The results are shown for four different channel electric fields of 1, 2, 4, and 10 kV/cm at an electron temperature of 30 K. The top panel shows schematic of a SV with a quasi-1D channel. The half-metallic FM source and drain contacts act as spin polarizers and analyzers, respectively, while the gate terminal is used to apply a transverse electric field on the channel to induce a Rashba effect.

$$I_s(x) = q \sum_{\nu_x, \overline{S_x}} f(\nu_x, \overline{S_x}, x)\, \nu_x |T(\overline{S_x})|^2, \tag{2}$$

where the velocity (ν_x)- and spin $(\overline{S_x})$- dependent distribution function $f(\nu_x, \overline{S_x}, x)$ at any position x is found directly from the Monte Carlo simulator described in Ref. 10 (all pertinent details of the simulator can be found in Ref. 10 and will not be repeated here). We only mention that in the simulator, we use a parabolic energy versus velocity dispersion relation $E = (\hbar^2/2m^*)(n\pi/W_z)^2 + (\hbar^2/2m^*)(\pi/W_y)^2 + (1/2)m^*\nu_x^2$ (n is the subband index in the z direction), neglecting any band-structure nonparabolicity, which is not important in the energy ranges encountered.[11] This dispersion relation allows us to calculate the velocity ν_x from the carrier energy E and subband index n (which are tracked in the simulator) very easily. If instead we used the energy versus wave-vector relation (which is traditional) and then attempted to find ν_x from the velocity versus wave-vector relation, it would have been immensely complicated. The reason is that the velocity (or energy) versus wave-vector relation is *spin dependent* in the presence of the Rashba effect[12] and becomes even more complicated if the Rashba effect is strong which leads to spin mixing effects.[13] These complications would have been overwhelming in our case since we have a continuous distribution of spin and hence would have been faced with a denumerably infinite number of energy versus wave-vector relations. The way to avoid this daunting complication (and the associated numerical cost) is to use the energy–velocity relation, which is *spin independent*, instead of the energy–wave-vector relation which is *spin dependent*.

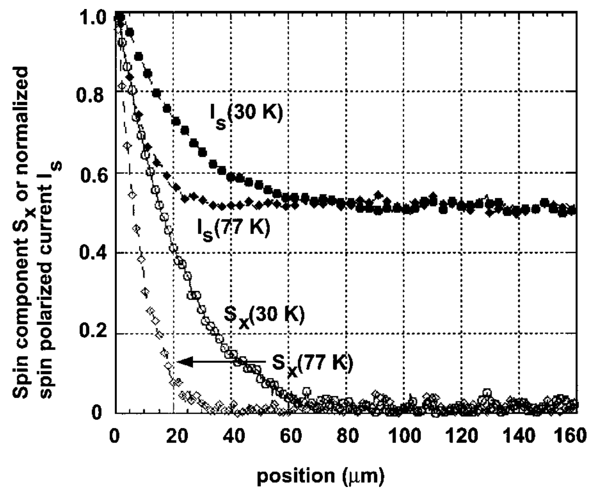

FIG. 2. Spatial decay of the normalized SP current and the injected spin vector in the channel of Fig. 1. The results are shown for two different temperatures of 30 and 77 K at a channel electric field of 2 kV/cm.

In the simulation, carriers are injected into a quasi-1D GaAs channel of rectangular cross section 30 nm×4 nm (see top panel of Fig. 1). We have assumed that there is a transverse electric field of 100 kV/cm (in the y direction) that gives rise to a structural inversion asymmetry and induces a Rashba effect in the channel. This field perturbs the subband energies in the channel but only slightly. The transverse voltage drop over a 4-nm-wide channel due to this field is 40 meV, while the lowest subband energy is 355 meV. Therefore, the perturbation is 11% for the lowest subband and progressively decreases for higher subbands. Consequently, we neglect this perturbation. Electrons are injected from a Fermi–Dirac distribution with their spins all aligned along the channel axis (x axis) in order to simulate the spin polarizer. At any given position x, we find the spin vector $\overline{S_x}$ and compute the quantity $|T(\overline{S_x})|^2$ for every electron using Eq. (1). We also find the velocity ν_x for every electron at position x and then compute the SP current I_s by performing the ensemble averaging given by Eq. (2). We have found I_s versus position x for four different channel electric fields of 1, 2, 4, and 10 kV/cm and two different temperatures of 30 and 77 K.

In Fig. 1, we show the spatial decay of the normalized SP current I_s for the four different (x directed) channel electric fields at a temperature of 30 K. In Fig. 2, we show the same quantity (along with the spatial decay of the ensemble-averaged spin component $\overline{S_x}$) at an electric field of 2 kV/cm at temperatures of 30 and 77 K. Spin depolarization is complete when I_s reaches a value of 0.5. At this point, an electron is equally likely to have its spin aligned parallel or antiparallel to the drain's magnetization (and therefore it is equally likely to be transmitted or blocked). We can define a "relaxation length" as the distance over which the injected SP current decays to 50% of its value (i.e., becomes completely depolarized). Table I gives the relaxation lengths at different electric field strengths and different temperatures.

As expected, the relaxation length decreases with increasing carrier temperature because of increased scattering that causes increased spin depolarization. The electric field, on the other hand, has two opposing effects. The scattering rate increases slowly with the electric field, but so does the

TABLE I. Spin-relaxation length dependence on temperature and driving electric field.

Electric field (kV/cm)	Temperature (K)	Spin relaxation (μm)
1.0	30	20
2.0	30	60
4.0	30	100
10.0	30	50
2.0	77	30

ensemble averaged carrier drift velocity until the saturation velocity is reached. A larger drift velocity makes the carriers travel a greater distance before getting depolarized. Consequently, the relaxation length at first increases with increasing electric field, but once the drift velocity begins to saturate, the increased scattering takes over and the relaxation length starts to decrease with increasing electric field. The dependence of relaxation length on the electric field is therefore nonmonotonic.

Based on the data in Table I, we find that the relaxation length for SP current is very large (between 20 and 100 μm for the cases considered). This is at least an order of magnitude larger than what was calculated for 2D structures[11,12] at comparable temperatures and driving electric fields. This difference is not due to any suppression of scattering. In fact, even though elastic scattering is suppressed in quasi-1D structures,[14] inelastic scattering is not,[15] and the calculated mobility in 1D structures in this temperature range is less than that in bulk.[16] The true origin of the difference lies in the fact that Dresselhaus and Rashba interactions cause a carrier's spin to precess slowly (during free flight) about a so-called ''spin precession vector'' that is defined by the carrier's momentum.[11] In a 1D structure, a carrier is free to move only along one direction, and therefore the Rashba or the Dresselhaus spin precession vector always points along one particular direction. Scattering can change its magnitude, but not its direction. This leads to slow spin relaxation. In contrast, scattering can change both the magnitude and the direction of the spin precession vector in two- or three-dimensional structures. Therefore, spin depolarizes much faster in multi dimensional structures.

Before concluding this letter, we should mention that in the type of structures considered here, there is always a magnetic field in the channel caused by the FM contacts. This field, however weak, ensures that the eigenstates in the channel are not spin eigenstates.[17] Therefore, even nonmagnetic scatterers can cause spin relaxation.[18] This mechanism has not been considered here, since we have not considered the channel magnetic field. In the absence of this mechanism, we have shown that spin relaxation length of carriers is very large in quasi-1D structures, even at elevated temperatures and high electric fields. Large spin relaxation lengths have been observed before in multidimensional structures, but only at low driving electric fields and low temperatures.[19] One-dimensional confinement can extend the range to high electric fields and elevated temperatures, which are required for realistic device applications.

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