Charge and spin transport in spin valves with anisotropic spin relaxation

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We investigate effects of spin-orbit splitting on electronic transport in a spin valve consisting of a large quantum dot defined on a two-dimensional electron gas with two ferromagnetic contacts. In the presence of both structure and bulk inversion asymmetry a giant anisotropy in the spin-relaxation times has been predicted. We show how such an anisotropy affects the electronic transport properties such as the angular magnetoresistance and the spin-transfer torque. Counterintuitively, anisotropic spin-relaxation processes sometimes enhance the spin accumulation.

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I. INTRODUCTION

Conventional microelectronics makes use of the electron charge in order to store, manipulate, and transfer information. The potential usefulness of the spin, the intrinsic angular momentum of the electron, for electronic devices has been recognized by a large community after the discovery of the giant magnetoresistance (GMR) in 1988.[1–3] The integration of the functionalities of metal-based magnetoelectronics with semiconductor-based microelectronics is an important challenge in this field.[4]

A central device concept in magnetoelectronics is a spin valve consisting of a normal conductor (N) island that is contacted by ferromagnets (F) with variable magnetization directions. An applied bias injects a spin accumulation into the island that affects charge and spin transport as a function of the relative orientation of the two magnetizations. We consider here a spin-valve structure in which the island is a large semiconductor quantum dot, i.e., a patch of two-dimensional (2D) electron gas, weakly coupled to the ferromagnetic contacts. In order to observe spin-related signals the injection of spins from the ferromagnet into the quantum dot must be efficient and the injected spin accumulation must not relax faster than the dwell time of an electron on the island.

Spin injection from ferromagnets into metals has been achieved by Johnson and Silsbee in 1988 (Ref. 5), but early attempts to fabricate devices based on injection of spins from metallic ferromagnets into semiconductors have not been successful. The reason for these difficulties turned out to be inefficient spin injection in the presence of a large difference between the conductances of the metallic ferromagnet and the semiconductor, i.e., the conductance mismatch problem.[6] These technical difficulties, however, appear to be surmountable.[7] Effective spin injection into a semiconductor can, e.g., be achieved using a magnetic semiconductor.[8] Schottky or tunneling barriers to a metallic ferromagnet can overcome the conductance mismatch problem,[9–11] as has been confirmed by using optical techniques.[12–16] Recently, all-electric measurements of spin injection from ferromagnets into semiconductors have been reported. Chen *et al.* used a magnetic *p-n* junction diode to measure the spin accumulation injected from a ferromagnet into a bulk *n*-GaAs via a Schottky contact.[17] Spin accumulation in a GaAs thin film has been injected and detected by Fe contacts in a nonlocal four-point configuration.[18]

Spin-relaxation mechanisms lead to decay of the spin accumulation and restore the equilibrium on the island. The main origin for spin-flip scattering in *n*-doped quantum well structures[4] is the Dyakonov-Perel mechanism[19] due to spin-orbit interaction, which is efficient when the spatial inversion symmetry is broken causing the spin-orbit coupling to split the spin-degenerate levels.[20] The relaxation arises because spins are subject to a fluctuating effective magnetic field due to frequent scattering. The inversion symmetry may be broken by a bulk inversion asymmetry (BIA) of the zinc-blende semiconductor material such as GaAs (Ref. 21) or structure inversion asymmetry (SIA) in the confinement potentials of heterostructures[22] that can be modulated externally by gate electrodes.[34,35] The SIA and BIA induced spin-orbit coupling terms linear in the wave vector often dominate the transport properties of electrons in III–V semiconductors and are known as Bychkov-Rashba and Dresselhaus terms, respectively. Their relative importance can be extracted, e.g., from spin-resolved photocurrent measurements.[23] The growth direction of the quantum well affects the strength of the spin-orbit coupling terms. This gives rise to differences in spin-relaxation times as observed for GaAs quantum wells using optical measurements.[24] In general, the spin-relaxation processes in semiconductor quantum wells are anisotropic, i.e., the spin-relaxation rate depends on the direction of the spin accumulation. When the coupling constants in the Bychkov-Rashba and Dresselhaus terms in [001] grown quantum wells are equal, the interference of the spin-orbit interactions give rise to suppression of the Dyakonov-Perel spin-relaxation mechanism for the [110] crystallographic direction. This leads to a giant anisotropy in the spin lifetimes of up to several orders of magnitude.[25–27] The phenomenon can be rationalized in terms of a SU(2) spin rotation symmetry that protects a spin helix state.[28] Similar behavior is expected for the [110] Dresselhaus model.[28]

Datta and Das proposed a spin-transistor based on the coherent rotation of spins by the SIA spin-orbit interaction that is tuned by a gate field.[29] An alternative transistor concept that relies on a gate-controlled suppression of the spin-relaxation by tuning of the SIA vs BIA spin-orbit interaction is believed to work for wider channels and to be more robust

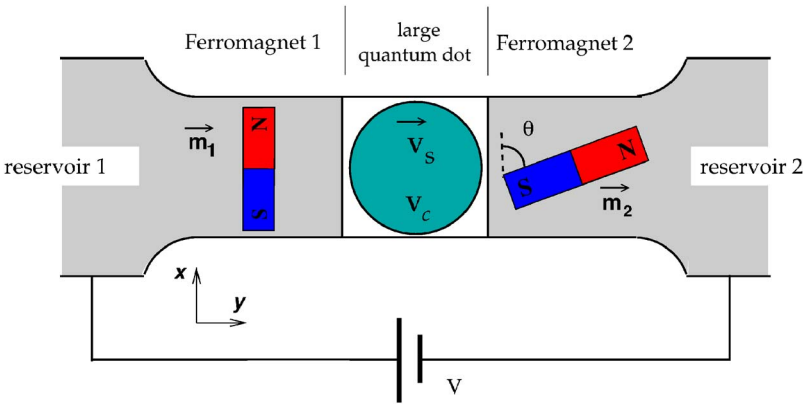

FIG. 1. (Color online) Schematic picture of the spin-valve structure. A voltage bias $V=V_1-V_2$ drives charge and spin currents through a layered ferromagnet-quantum dot-ferromagnet system. The magnetizations $\mathbf{m}_1$ and $\mathbf{m}_2$ point in arbitrary directions in the 2D plane of the large quantum dot. The ferromagnets inject a spin accumulation $\mathbf{V}_s$ into the dot. The coordinate system is chosen so that x axis is parallel to $\mathbf{m}_1$ and z is perpendicular to the plane of the quantum dot.

against impurity scattering than the original Datta-Das proposal.[30,31] A review of the effect of spin-orbit interactions on transport can be found in Ref. 32.

In the present work we use magnetoelectronic circuit theory[33] to calculate the transport properties of spin valves in the presence of anisotropic spin-relaxation processes. Circuit theory has been found to be applicable in both metal and semiconductor-based magnetoelectronics. It was used to describe the spin transfer through a Schottky barrier between a ferromagnetic metal and a semiconductor.[38] In this work we find that anisotropic spin-relaxation processes leave clear marks on the transport properties such as the angular magnetoresistance and the spin-transfer torque. We obtain, e.g., the counterintuitive result that anisotropic spin relaxation may enhance rather than destroy the current-driven spin accumulation on the island. In Sec. II we introduce our model system and the theories of spin transport and relaxation. In Sec. III we identify the electrical signatures of anisotropic spin relaxation. The enhancement of spin accumulation due to anisotropy is discussed in Sec. IV. We present conclusions in Sec. V.

II. MODEL FOR SPIN AND CHARGE TRANSPORT

The spin valve in this work consists of a large quantum dot island between two ferromagnets. The quantum dot is assumed to be in contact with the ferromagnets by tunneling barriers, with contact resistances much larger than the resistance of the island. We derive the transport equations for a general case, and as an example discuss a quantum dot made in a [001] grown quantum well in GaAs/AlGaAs. The Dyakonov-Perel mechanism becomes then the leading source of spin relaxation and emergence of a giant anisotropy in spin relaxation has been predicted in such systems.[26,27] A gate electrode on top of the quantum dot can be used to tune the relative strengths of the SIA and BIA spin-orbit interactions which effectively changes the degree of anisotropy in the system. The model device is sketched in Fig. 1.

We model the spin and charge transport in the spin valve using the magnetoelectronic circuit theory,[33] which describes spin-dependent transport in an electronic circuit with ferromagnetic elements. The contacts between metallic or ferromagnetic nodes are parametrized as 2×2 conductance tensors in spin space. Their diagonal elements are the conventional spin-dependent conductances $G^{\uparrow}$ and $G^{\downarrow}$, whereas the nondiagonal ones are occupied by the complex mixing conductance $G^{\uparrow\downarrow}$ (and its conjugate). The mixing conductance is the material conductance parameter that governs spin currents transverse to the magnetization and becomes relevant when magnetization vectors are not collinear. The electric currents driven through the system are small and current-induced spin polarizations[36] may be disregarded. The island should be diffuse or chaotic, such that its electron distribution function is isotropic in momentum space. The quantum dot is supposed to be large enough so that Coulomb charging effects can be disregarded, although the calculations can be readily extended to include the Coulomb blockade, at least in the orthodox model.[37]

We focus here on a symmetric spin-valve device, i.e., the conductances of the majority and minority spin channels $G^{\uparrow}$ and $G^{\downarrow}$ and the polarization, defined as $P=(G^{\uparrow}-G^{\downarrow})/(G^{\uparrow}+G^{\downarrow})$, are the same for both the source and the drain contacts to the dot. In the tunneling regime, the real part of the mixing conductance $\mathrm{Re}\, G^{\uparrow\downarrow}\to G/2$, where $G=G^{\uparrow}+G^{\downarrow}$ is the total contact conductance. The imaginary part of the mixing conductance is believed to be significant for ferromagnet-semiconductor interfaces.[38]

The charge current $I_{c,i}$ into the quantum dot through contact $i=1,2$ is (Ref. 33)

$$I_{c,i}/G = V_c - V_i + P\mathbf{V}_s\cdot\mathbf{m}_i, \tag{1}$$

where V_i is the potential of reservoir i, V_c and $\mathbf{V}_s$ are the charge and spin potentials in the quantum dot, and $\mathbf{m}_1$ and $\mathbf{m}_2$ are the magnetizations of the left and right ferromagnet, respectively. Equations for the spin currents through the interfaces into the island read (in units of A) (Ref. 33)

$$\mathbf{I}_{s,i} = \mathbf{m}_i[\mathbf{V}_s\cdot\mathbf{m}_i + P(V_c - V_i)]G + 2\,\mathrm{Re}\, G^{\uparrow\downarrow}\mathbf{m}_i\times(\mathbf{V}_s\times\mathbf{m}_i) + 2\,\mathrm{Im}\, G^{\uparrow\downarrow}\mathbf{V}_s\times\mathbf{m}_i. \tag{2}$$

A transverse spin current cannot penetrate a ferromagnet but they are instead absorbed at the interface and transfer the angular momentum to the ferromagnet. This gives rise to the spin-transfer torques (Ref. 39)

$$\tau_i = \frac{\hbar}{2e}\mathbf{m}_i \times (\mathbf{m}_i \times \mathbf{I}_{s,i}) \tag{3}$$

on the magnetization $\mathbf{m}_i$. When the spin-transfer torque is large it may cause a switching of the magnetization direction.

The charge and spin conservation in the steady state implies that

$$\sum_{i=1,2} I_{c,i} = 0, \tag{4}$$

$$\frac{d\mathbf{V}_s}{dt} = \left.\frac{\partial \mathbf{V}_s}{\partial t}\right|_{\text{precess}} + \left.\frac{\partial \mathbf{V}_s}{\partial t}\right|_{\text{relax}} + \sum_{i=1,2} \mathbf{I}_{s,i}/2e^2\mathcal{D} = 0, \tag{5}$$

where $\mathcal{D}$ is the density of states at the Fermi energy of the quantum dot, which is assumed to be constant and continuous on the scale of the applied voltage and the thermal energy. The Bloch equation[4,40] (5) describes changes in the spin accumulation due to spin precession and spin-relaxation processes and the spin currents. In the standard approach, spin relaxation is parametrized in terms of an isotropic, phenomenological spin-flip relaxation time. However, when the spin is coupled to orbital and structural anisotropies, spin relaxation can be anisotropic. Anisotropic spin-relaxation processes can be taken care of by replacing the spin-flip relaxation-rate constant by a tensor $\mathbf{\Gamma}$, that, given a spin-orbit coupling Hamiltonian and disorder, can be calculated with perturbation theory. In the presence of anisotropic spin-relaxation processes and external magnetic field $\mathbf{B}$ the terms in the Bloch equation (5) read

$$\left.\frac{\partial \mathbf{V}_s}{\partial t}\right|_{\text{precess}} = \gamma_g(\mathbf{V}_s \times \mathbf{B}), \qquad \left.\frac{\partial \mathbf{V}_s}{\partial t}\right|_{\text{relax}} = -\mathbf{\Gamma}\cdot\mathbf{V}_s, \tag{6}$$

where γ_g is the electron gyromagnetic ratio. Comparison of Eqs. (2)–(5) with Eq. (6) show that the imaginary part of the mixing conductance $\mathrm{Im}\, G^{\uparrow\downarrow}$ acts like a magnetic field and gives rise to a precession around the direction determined by the magnetization vectors $\mathbf{m}_i$.

The quantum dot and the magnetizations are supposed to be in the xy plane. The spin accumulation can have a component perpendicular to the quantum dot (z direction) by the imaginary part of the mixing conductance. The spin-relaxation tensor $\mathbf{\Gamma}$ is diagonal in a coordinate system defined by $U=(\mathbf{u}_l,\mathbf{u}_s,\mathbf{u}_z)$, where (column) vector $\mathbf{u}_l$ denotes the direction corresponding to the longest spin lifetime $\tau_{\mathrm{sf},l}$ in the plane of the quantum dot, $\mathbf{u}_s$ denotes the direction where the in-plane spin lifetime $\tau_{\mathrm{sf},s}$ is shortest and $\mathbf{u}_z$ denotes the direction perpendicular to the system with spin lifetime $\tau_{\mathrm{sf},z}$. In the xyz-coordinate system the $\mathbf{\Gamma}$ tensor then reads

$$\mathbf{\Gamma} = U\mathbf{\Delta}U^T = U\begin{pmatrix} 1/\tau_{\mathrm{sf},l} & 0 & 0 \\ 0 & 1/\tau_{\mathrm{sf},s} & 0 \\ 0 & 0 & 1/\tau_{\mathrm{sf},z} \end{pmatrix}U^T. \tag{7}$$

We introduce a spin-flip conductance, which is effectively a measure of the spin-relaxation rate, as follows:

$$G_{\mathrm{sf},i} = \frac{e^2}{2}\frac{\mathcal{D}}{\tau_{\mathrm{sf},i}}, \tag{8}$$

for $i \in s,l,z$. The spin-valve effect depends nonmonotonously on the contact resistance. When the resistance is too small, the magnetoresistance is suppressed by the conductance mismatch. When it is too large, all spins relax because the dwell time is longer than the spin-flip times,[10] i.e., when $G \ll G_{\mathrm{sf,i}}$. Defining the dwell time as $G=e^2\mathcal{D}/(2\tau_{\mathrm{dwell}})$, we require that $\tau_{\mathrm{dwell}} \ll \tau_{\mathrm{sf},i}$, i.e., the spin lifetime must be long enough so that at least one component of the spin persists before the electrons tunnel out of the dot.

We discuss now the special case of a large quantum dot defined on a gated 2D electron gas in GaAs. We assume a [001] growth direction and use an effective mass $m^*=0.067m_e$ and an electron density $N=4\times10^{11}/\mathrm{cm}^2$. In the [001] quantum wells $\mathbf{u}_l=\frac{1}{\sqrt{2}}(1,1,0)$ and $\mathbf{u}_s=\frac{1}{\sqrt{2}}(-1,1,0)$ when the electric field points in the [001] direction.[27,41] Analytic expressions for the spin-relaxation rates in quantum wells dominated by the Dyakonov-Perel spin-relaxation mechanism are given by Averkiev *et al.*[41] They used a Hamiltonian with linear spin-orbit coupling terms

$$H = \frac{\hbar^2k^2}{2m^*} + \frac{\alpha}{\hbar}(\sigma_x k_y - \sigma_y k_x) + \frac{\beta}{\hbar}(\sigma_x k_x - \sigma_y k_y), \tag{9}$$

where α and β are SIA and BIA spin-orbit coupling constants and m^* is the effective electron mass. A variational calculation for a triangular model potential and the perturbation theory was then used to extract the spin-relaxation rates. In the case of short-range scattering and degenerate electron gas they found

$$\frac{1}{\tau_\pm} = \frac{2\tau_{\mathrm{tr}}}{\hbar^2}\left[k_F^2(\pm\alpha-\beta)\left(\pm\alpha-\beta+\frac{\gamma}{2}k_F^2\right)+\frac{\gamma^2k_F^6}{8}\right], \tag{10}$$

$$\frac{1}{\tau_z} = \frac{4\tau_{\mathrm{tr}}}{\hbar^2}\left[k_F^2(\alpha^2+\beta^2)-\frac{\gamma\beta k_F^4}{2}+\frac{\gamma^2k_F^6}{8}\right], \tag{11}$$

where $+,-$ and z denote [110], [$\bar{1}$10], and [001] directions, respectively, and τ_{tr} denotes the transport relaxation (scattering) time. The material parameter $\gamma=\beta/\langle k_z^2\rangle=27$ eV Å^3 for GaAs. The calculations leading to (10) and (11) are valid only when the mean free path $l=v_F\tau_{\mathrm{tr}}$, where v_F is the Fermi velocity, is much smaller than the size of the quantum dot.

The Bychkov-Rashba term is expected to be linearly dependent on the gate-electrode induced electric field $\mathbf{E}=E\mathbf{z}$ so that $\alpha=\alpha_0 eE$, where $\alpha_0=5.33$ Å^2 for GaAs/AlGaAs. The E dependence of the expectation value for the perpendicular component of the wave vector $\langle k_z^2\rangle=0.78(2m^*eE/\hbar^2)^{2/3}$ in triangular asymmetric quantum wells.[42] Equation (10) shows a significant reduction of the spin-relaxation rate for the [110] direction when $\alpha\simeq\beta$, whereas the spin-relaxation rate for [$\bar{1}$10] is not reduced. The spin-relaxation process is thereby strongly insotropic in this regime. A more accurate numerical analysis of the anisotropy based on a self-consistent calculations in a multiband envelope-function approximation has been carried out by Kainz *et al.* and gives qualitatively similar results.[27] When $\alpha\simeq\beta$, the most stable

spin direction [110] can have a lifetime that is several orders of magnitude longer than in the $[\bar{1}10]$ and [001] directions, i.e., $\tau_{\mathrm{sf},l} \gg \tau_{\mathrm{sf},s}$ and $\tau_{\mathrm{sf},l} \gg \tau_{\mathrm{sf},z}$.

As shown in Eqs. (10) and (11) the spin-relaxation rate of the Dyakonov-Perel mechanism is proportional to the transport relaxation time. Spin-relaxation times are therefore expected to increase with temperature and disorder in the sample. The enhancement of spin-relaxation times with temperature has been recently demonstrated experimentally.[43] For $\tau_{\mathrm{tr}}=0.1$ ps, Averkiev *et al.* predicted that the spin-relaxation times in GaAs typically range from picoseconds to nanoseconds.[41]

III. SIGNATURES OF ANISOTROPY

Equations (1)–(5) can be solved analytically, but general expressions are lengthy. We therefore study transport in the limiting case of strong anisotropy

$$G_{\mathrm{sf},s} \gg G \gg G_{\mathrm{sf},l}. \tag{12}$$

By fixing the direction of the magnetization of the left ferromagnet along the x axis the problem contains only two variables, the angle θ between the magnetizations and angle ϕ between the x axis and $\mathbf{u}_l$, i.e., the eigenvector of the spin-relaxation rate matrix (7) corresponding to the most stable spin-accumulation direction. We present here the results for the spin-valve angular conductance, spin-transfer torque, and spin accumulation on the island and identify signatures of the anisotropy which could be probed in all-electric measurements. In experiments the dependence of the currents on the angle between the magnetizations and the orientation of the anisotropy axes could be probed, e.g., by depositing strips of ferromagnets at different angles on the same sample wafer. Alternatively, the magnetization of a magnetically soft ferromagnet can be rotated using a magnetic field.

Figure 2 shows the current of the device versus the angle θ with anisotropic and isotropic spin-relaxation processes in the central island. The results are compared to the current $I_{\mathrm{Ohmic}}=GV/2$ through two nonmagnetic interfaces with conductance G in series. For isotropic spin-relaxation the curve is symmetric with a single minimum at the center [Fig. 2(a)]. The θ dependence is gradually suppressed when the spin-relaxation rate increases and in the limit of very fast spin relaxation the transport is governed solely by interface conductances. In the presence of anisotropic spin-relaxation processes the magnetoconductance depends strongly on the relative orientations of the magnetization axes with respect to the anisotropy axis. When one of the magnetizations is oriented perpendicular to the axis of the fastest relaxing spin component $\mathbf{u}_s$ (i.e., $\phi=\pi/2$) the magnetoresistance shows two minima in the limit of strong anisotropy [Fig. 2(b)]. When the spin is injected along a stable magnetization direction ($\phi=0$) the shape of the magnetoresistance curve only weakly depends on the spin-relaxation rate in the perpendicular direction [Fig. 2(c)]. For $0<\phi<\pi/2$ the magnetoresistance generally contains two minima of unequal heights [Fig. 2(d)]. Thus, the formation of a double minimum is a characteristic signature of the anisotropy in the system. It should be noted that such a double minimum is also possible in a system with isotropic spin relaxation, but only when the contact polarizations of the spin valve are significantly different.[44]

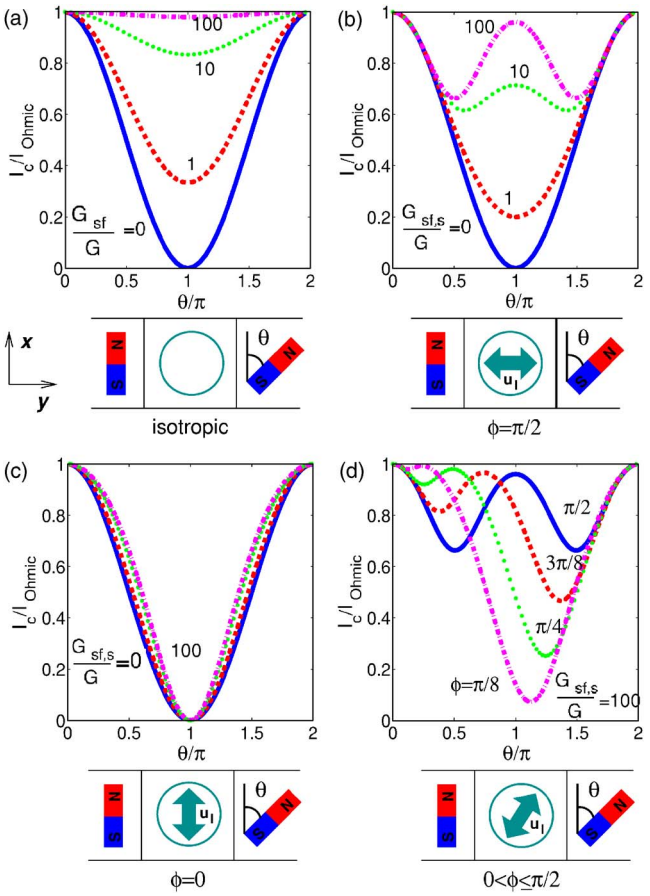

FIG. 2. (Color online) The charge current through the device relative to $I_{\mathrm{Ohmic}}=GV/2$ in the presence of anisotropic spin relaxation depends strongly on the angle θ between the spin-injecting magnetizations and the angle ϕ between left magnetization and the direction of the most stable spin orientation. (a) In the case of isotropic spin relaxation the magnetoresistance shows a single minimum. (b) When the spin is injected parallel to the axis of the most short-lived spin orientation ($\phi=\pi/2$) the rapid relaxation of spin accumulation near $\theta=\pi$ causes a shift of current towards I_{Ohmic}. (c) When the spin is injected parallel to the axis of the most stable spin orientation ($\phi=0$) the spin accumulation persists and there is little change in the charge current. (d) In the case of strong anisotropy and $0<\phi<\pi/2$ the magnetoresistance generally shows two minima with unequal heights. In (b)–(d) $G_{\mathrm{sf},l}=0$, $P=1$ and the curves are plotted for different relative spin flip conductances $G_{\mathrm{sf},s}/G$.

Since the spin relaxation affects the spin currents, anisotropic spin relaxation is expected to change the spin-transfer torque on the magnetization as a function of the relative orientation of the magnetizations and the anisotropy axes. The torque on the right ferromagnet τ_2 in the case of strong anisotropy (12) is shown in Fig. 3. Equations (2) and (3) show that the spin torque on the ferromagnet i is proportional to $|\mathbf{m}_i \times \mathbf{V}_s|$. When the left ferromagnet injects spin parallel to the axis of the longest spin lifetime the spin-transfer torque increases compared to the case of no spin relaxation. On the

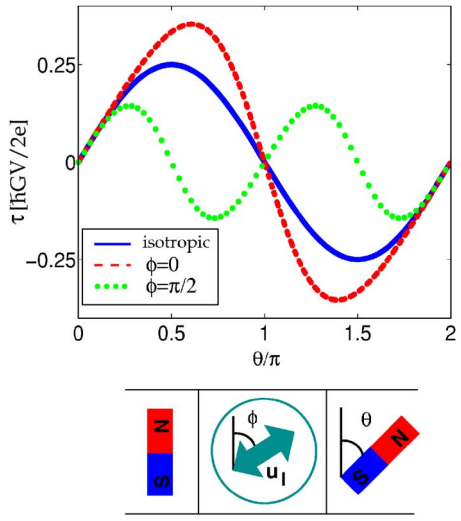

FIG. 3. (Color online) The spin torque on ferromagnet 2 as a function of the angle θ between left and right magnetization in the absence of spin relaxation processes (solid line) and in the presence of giant spin-relaxation anisotropy with $G_{\mathrm{sf},s}=\infty$, $G_{\mathrm{sf},l}=0$ (dashed and dash-dotted lines). In the latter case the left ferromagnet injects spin parallel to $\mathbf{u}_l$ ($\phi=0$, dashed line) or $\mathbf{u}_s$ ($\phi=\pi/2$, dash-dotted line), respectively. The polarization is here $P=1$ and $\mathrm{Im}\, G^{\uparrow\downarrow}=0$.

other hand, when the left ferromagnet injects spin perpendicular to this direction the spin torque decreases as a consequence of the loss of spin accumulation. Moreover, in this configuration the spin torque is found to change sign at $\theta=\pi/2$. This effect is due to decay of the perpendicular component of the spin accumulation. At $\theta=\pi/2$ the magnetization $\mathbf{m}_2$ is therefore parallel to $\mathbf{V_s}$ and $\tau_2=\mathbf{0}$.

Another way to detect anisotropy electrically is by modulating the spin-relaxation rates via the spin-orbit interaction. We discuss this within the model system introduced in Sec. II and use the spin-relaxation times Eqs. (10) and (11) to calculate charge current as a function of gate-voltage induced electric field E (Fig. 4).

The magnetizations of the left and right ferromagnets are set in the $\mathbf{u}_l$ and $\mathbf{u}_s$ directions, respectively, to maximize the effect of the spin-orbit interaction. We have used $\mathrm{Re}\, G^{\uparrow\downarrow}=G/2$ and $\mathrm{Im}\, G^{\uparrow\downarrow}=-G/2$ for the ferromagnet-semiconductor interface as suggested by *ab initio* studies of Fe-InAs interfaces.[38] Since the spin-relaxation time perpendicular to the plane of the quantum dot τ_z is of the same order of magnitude as $\tau_{\mathrm{sf},s}$ a finite imaginary part of the mixing conductance is detrimental to the spin accumulation. The results as shown in Fig. 4 are not particularly sensitive to the values of these parameters, however. By setting $\mathrm{Im}\, G^{\uparrow\downarrow}=0$ the result differs significantly only in low gate fields $E<200$ kV/cm as shown by the dashed lines in Fig. 4. Due to rapid spin relaxation in the $[\bar{1}10]$ and $[001]$ directions the spin accumulation is along the $[110]$ direction to a good approximation for $E>200$ kV/cm. At the dip in the current the contributions from the SIA and BIA spin-orbit couplings are approximately equal ($\alpha\simeq\beta$), and the anisotropy is largest.

We focus now on the analytical expressions which can be obtained in the limit of weak polarization ($P\ll 1$) and $\mathrm{Im}\, G^{\uparrow\downarrow}=0$. As a consequence the z component of the spin

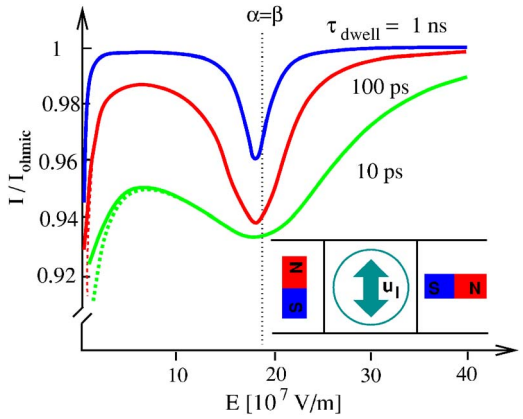

FIG. 4. (Color online) Calculated current through a device as a function of gate voltage induced electric field E for three different dwell times τ_{dwell} and using spin-relaxation rates as given by Eqs. (10) and (11). The magnetizations of the left and right ferromagnetic contacts are in the $[110]$ and $[\bar{1}10]$ directions, respectively. The polarization is set to $P=50\%$ and $\mathrm{Re}\, G^{\uparrow\downarrow}=G/2$. The solid lines correspond to $\mathrm{Im}\, G^{\uparrow\downarrow}=-G/2$ and the dashed lines correspond to $\mathrm{Im}\, G^{\uparrow\downarrow}=0$.

accumulation vanishes. The spin accumulation to lowest order in P reads

$$\mathbf{V}_s=\frac{VP}{2}\left(\frac{\sin\left(\phi+\frac{\theta}{2}\right)\sin\left(\frac{\theta}{2}\right)}{1+2G_{\mathrm{sf},l}/G}\mathbf{u}_l-\frac{\cos\left(\phi+\frac{\theta}{2}\right)\sin\left(\frac{\theta}{2}\right)}{1+2G_{\mathrm{sf},s}/G}\mathbf{u}_s\right)+\mathcal{O}(P^3). \tag{13}$$

Equations (1) and (4) give the charge current through the system

$$I_c=\frac{G}{2}[V-P\mathbf{V}_s\cdot(\mathbf{m}_1-\mathbf{m}_2)]. \tag{14}$$

This can be combined with (13) to obtain the charge current to the second order in P. The $GV/2$ term in (14) is given by Ohm's law for two nonmagnetic interfaces and the second term gives the lowest order correction.

These results help to develop an intuitive picture of the effects of anisotropic spin-relaxation processes on transport. To linear order in P the components of the spin accumulation along $\mathbf{u}_l$ and $\mathbf{u}_s$ depend only on the spin-relaxation rates along these directions but do not depend on the spin-relaxation rates along perpendicular directions. This lowest-order result explains the physics when the polarization is small. When the polarization is larger, the current and spin accumulation have a more complicated interdependence.

IV. ENHANCEMENT OF SPIN ACCUMULATION DUE TO ANISOTROPY

Fast spin-relaxation is supposed to be detrimental for the spin accumulation in the central node of a spin valve. In anisotropic systems, however, this is not necessarily the case. Anisotropic spin-relaxation processes can also enhance the spin accumulation when there is at least one direction with a

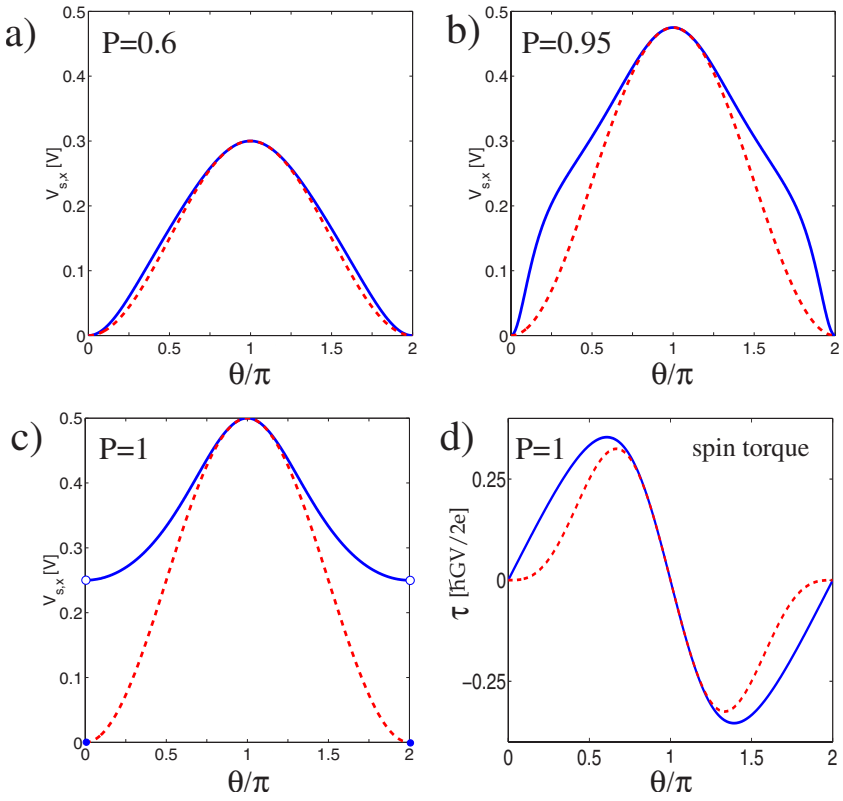

FIG. 5. (Color online) (a)–(c) The component of spin accumulation in the direction of the injecting magnetization $V_{s,x}$ is enhanced in the presence of fast spin relaxation in the perpendicular direction ($\phi=0$, $G_{\mathrm{sf},s}=\infty$). The solid line presents the results from the circuit theory (16) and the dashed line shows the spin accumulation in the linear-order approximation (13). The spin accumulation is not assumed to decay in the direction of the injecting magnetization ($G_{\mathrm{sf},l}=0$). The enhancement of the spin accumulation strongly depends on the magnetization polarization P. (d) Enhancement of the spin accumulation is also reflected by the spin-transfer torque on the right ferromagnet as shown here for $P=1$.

long spin lifetime. We demonstrate this in a spin-valve configuration in which the injected spin accumulation is dominantly along the stable direction. Spin relaxation in the perpendicular direction then may enhance the spin accumulation.

In the absence of spin-relaxation processes the angle dependence of the x component of the spin accumulation is

$$V_{s,x}(\theta,P)=\frac{VP}{2}\sin^2(\theta/2) \tag{15}$$

as shown by dashed lines in Fig. 5. Assume now that a fast spin-relaxation process is switched on in the y direction only and the x component of the spin accumulation does not decay, i.e., $\mathbf{u}_s=(0,1,0)$, $\tau_{\mathrm{sf},s}=0$ and $\mathbf{u}_l=(1,0,0)$, $\tau_{\mathrm{sf},l}=\infty$. The decay of the spin accumulation in the y direction induces a larger current through the system for the same bias voltage. This implies a larger spin current and, as a consequence, an enhanced spin accumulation in the x direction. Since to linear order in the contact polarization circuit theory predicts no enhancement of the spin accumulation [Eq. (13)], we have to work out the solution for arbitrary P. In the above limit of $G_{\mathrm{sf},s}=\infty$ and $G_{\mathrm{sf},l}=0$, the solution to the set of equations (1)–(5) is

$$V_{s,x}(\theta,P)=\frac{2VP(\cos\theta-1)}{P^2(\cos\theta+\cos 2\theta+3)-8}, \tag{16}$$

as shown by solid lines in Fig. 5. The results prove that spin accumulation in the x direction may be enhanced due to spin relaxation in the y direction. The y component of the spin accumulation decays but the total modulus of the spin accumulation vector may increase as a result of the spin relaxation. The enhancement of the spin accumulation is substantial in the limit of high polarization $P>0.9$. At lower polarizations, the increased spin current and reduced y component of the spin compete and the phenomenon disappears in the low P limit in Eq. (13). In the limiting case of 100% polarization the spin enhancement is discontinuous at $\theta=0$ [Fig. 5(c)]. There is no spin accumulation at $\theta=0$, in line with the results from collinear circuit theory, but infinitely close to this point the spin accumulation jumps to 1/2 of the maximum value at $\theta=\pi$. The enhancement of the spin accumulation has an impact on the spin-transfer torque on the ferromagnets as well. Figure 5(d) shows an increase in the spin torque on ferromagnet 2 at $P=1$ compared to the spin torque calculated from the linear-order approximation (13).

V. CONCLUSIONS

Magnetoelectronic circuit theory has been used to calculate the spin and charge transport through a spin valve with a diffuse or chaotic quantum dot in the presence of anisotropic spin-relaxation processes. Analytical expressions for charge current, spin accumulation, and spin-transfer torques in the tunneling regime illustrate the sensitivity of the charge current on the relative orientation of the anisotropy axes and the magnetizations of the ferromagnets. Signatures of anisotropy have been identified in the magnetoresistance. The anisotropy can be probed either by rotating the magnetization directions of the ferromagnets or alternatively by using a gate electrode to change the spin-relaxation rates. Counterintuitively, anisotropic spin-relaxation processes may enhance

the spin accumulation. This effect is attributed to an increased charge current due to removal of one component of the spin, which increases the spin-injection rate in the perpendicular direction. The enhancement was found to be remarkably large in the limit of high polarization.

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