Proposal for all-electrical measurement of $T_1$ in semiconductors

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In an inhomogeneously doped magnetic semiconductor spin relaxation time $T_1$ can be determined by all-electrical measurements. Nonequilibrium spin injected in a magnetic p-n junction gives rise to the spin-voltaic effect where the nonequilibrium spin-induced charge current is very sensitive to $T_1$ and can flow even at no applied bias. It is proposed that $T_1$ can be determined by measuring the I-V characteristics in such a geometry. For a magnetic p-n junction where the results can be calculated analytically, it is in addition possible to extract the $g$-factor and the degree of injected carrier spin polarization.

In examining the properties of spin-polarized transport in solid state systems one of the key physical quantities is the characteristic spin relaxation time $T_1$ and the related length scale, spin diffusion length $L_s$, both describing the decay of nonequilibrium spin. These spin relaxation parameters play crucial roles in various novel spintronic applications [1]. Unlike in the conventional charge-based electronics, spintronic devices rely on manipulating nonequilibrium spin. Since $T_1$ and $L_s$ determine “spin memory” they effectively set an upper limit on the time required to perform various device operations and the possible optimal size of spintronic devices. In semiconductor spintronics [1], spin relaxation of carriers (electrons and holes) is a complex process [2,3]. For a given temperature and doping, several different mechanisms contribute to spin relaxation which is sensitive [2,3] to strain, dimensionality, magnetic and electric fields. It would be highly desirable if the same semiconductor structures which hold promise for spintronic applications could also be used to probe spin relaxation. Previous methods [2,3] to measure $T_1$ have typically used optical techniques or electron spin resonance.

In this letter we discuss a proposal to determine $T_1$ by all-electrical measurements from the I-V characteristics. This method can be viewed as a generalization of the concept of spin-charge coupling [4,5], introduced in metals by Silsbee and Johnson, to inhomogeneously doped semiconductors [6,7]. We show how several features, specific to semiconductors (bipolar transport—by both electrons and holes, bias-dependent depletion region, and highly nonlinear I-V characteristics), can be exploited to provide a sensitive probe for $T_1$.

To illustrate our proposal we consider a magnetic p-n junction [6,7] as sketched in Fig. 1a,b. In the p (n) region there is a uniform doping with $N_n$ acceptors ($N_d$ donors). Within the depletion region ($-d_p < x < d_n$) we assume that there is a spatially dependent spin splitting of the carrier bands. Such splitting, a consequence of doping with magnetic impurities, can occur in different situations. For example, in ferromagnetic semiconductors [8] or, in the presence of magnetic field $B$, the spin splitting could arise from either having inhomogeneous $g$-factors or by applying an inhomogeneous magnetic field. While
our method is applicable to all of these cases, we focus here on the last two instances and further assume that the carriers obey the nondegenerate Boltzmann statistics. In the low injection regime it is possible to obtain the results for spin-polarized transport analytically and to decouple the contribution of electrons and holes \( \delta_s \). Following the approach from Ref. \( \delta_s \), we consider only the effect of spin-polarized electrons. (It is simple to also include the net spin polarization of holes \( \delta_s \).) The resulting Zeeman splitting of the conduction band (Fig. 1b) is 2\( \nu = \mu_B B \), where \( g \) is the \( g \)-factor for electrons, \( \mu_B \) is Bohr magneton, \( q \) is the electron magnetic potential \( \nu \).

Nonequilibrium electron and hole densities are \( n \) (the sum of spin up and spin down components \( n_+ + n_- \)) and \( p \), while the spin density and its polarization are \( s = n_+ - n_- \) and \( \alpha = s/n \), respectively. Equilibrium values (with subscript "0") satisfy \( n_0 p_0 = n_i^2 \cosh(\zeta/V_T) \) and \( \alpha_0 = \tanh(\zeta/V_T) \), where \( n_i \) is the intrinsic (nonmagnetic) carrier density and \( V_T = k_B T/q \), with \( k_B \) being the Boltzmann constant and \( T \) temperature. We assume \( \nu \) equilibrium values (ohmic contacts) for minority carriers at \( x = -w_p, w_n \) and at \( x = -w_p \) for spin density. To characterize the spin injection, at \( x = w_n \) we impose \( \delta(s(w_n)) = \alpha(w_n) \), where \( \delta = s - s_0 \) and \( \alpha = \alpha_0 \).

Neglecting \( \delta p(w_n) \), which can accompany \( \delta s(w_n) \), is an accurate approximation while \( (w_n - d_n) \) is greater than the hole diffusion length \( L_n \). In addition to spin injection by optical means (depicted in Fig. 1a,b,c), an electrical spin injection (Fig. 1d) has been reported using a wide range of magnetic materials \( \delta s \). For a magnetic p-n junction total charge current \( J \) can be decomposed \( \delta s \) as the sum of equilibrium-spin electron \( J_n \) and hole \( J_p \) currents, and spin-voltaic current \( J_{sv} \), which originates from the interplay of the equilibrium magnetization (i.e., equilibrium spin polarization in the \( p \) region) and the nonequilibrium spin (injected in the \( n \) region).

The individual contributions of \( J \) as a function of applied bias \( V \) and \( B \) (recall that \( \zeta = \zeta(B) \)) are \( \delta s \)

\[
\begin{align*}
J_n &= q \frac{D_n}{L_n} n_0 (-d_p) \coth \left( \frac{\bar{w}_n}{L_n} \right) \left( e^{V/V_T} - 1 \right), \\
J_p &= q \frac{D_p}{L_p} p_0 (d_n) \coth \left( \frac{\bar{w}_n}{L_p} \right) \left( e^{V/V_T} - 1 \right), \\
J_{sv} &= q \frac{D_n}{L_n} n_0 (-d_p) \coth \left( \frac{\bar{w}_n}{L_p} \right) e^{V/V_T} \alpha_0 (-d_p) \alpha(d_n),
\end{align*}
\]

where \( D_n (D_p) \) is the electron (hole) diffusivity, \( L_n \) and \( L_p \) are the minority diffusion lengths \( \delta s \), and \( \bar{w}_n = w_p - d_p \) is the width of the bulk \( p \) (\( n \)) region. There is an implicit \( V \)-dependence of \( \bar{w}_n \) since for the depletion layer edge \( \delta s \), \( d_n \propto \sqrt{V_0 - V} \), where \( V_0 = V_T \ln(N_n N_d/n_i^2) \) is the built-in voltage. The derivation of the Eqs. \( \delta s \) assumes that the depletion region is highly resistive (depleted from free carriers) \( \delta s \). The voltage drop between the two ends of the junction (see Fig. 1) and between \( x = -w_p \) and \( x = w_n \) can then be identified.

We next explore some properties of charge current which will be used to formulate the method for determining \( T_1 \). From Eq. \( \delta s \) we note \( J_{sv} \propto \delta \alpha(d_n) \), the spin-voltaic part of the charge current is related to the nonequilibrium spin. For a given injected spin, represented by \( \delta \alpha(w_n) \), it follows (see Fig. 1b) that \( J_{sv} \) should be sensitive to:

1) \( \bar{V}_n \), the separation between the source of spin injection and the depletion layer edge, and
2) the spin diffusion length \( L_{sn} = \sqrt{D_n T_1} \), characterizing the spin decay, i.e., \( \delta \alpha(w_n) \). Indeed, one can show \( \delta s \) that

\[
\delta \alpha(d_n) = \delta \alpha(w_n)/\cosh(\bar{w}_n/L_{sn}),
\]

which from Eq. \( \delta s \) implies a high sensitivity of \( J_{sv} \) to \( T_1 \) (through \( L_{sn} \)). In contrast, \( J_{np} \) do not contain the nonequilibrium spin and thus have no \( T_1 \) dependence. A direct measurement of total charge current to identify \( T_1 \) (based on \( J_{sv} \)) implies some limitations. At vanishing bias \( (V \ll V_T) \), where \( J_{np} \rightarrow 0 \), \( J \rightarrow J_{sv} \) is small, while at higher bias \( (V \gg V_T \text{ and } V < V_b) \) \( J \) is dominated by \( J_n \) and \( J_p \)—large \( T_1 \)-independent background. To fully exploit simple I-V measurements we note that \( T_1 \) (or \( T_1(B) \)) (the precise \( B \)-dependence differs for various spin-relaxation mechanisms). We also use the symmetry properties of the individual contributions to the charge current with respect to the applied magnetic field: \( J_{np}(-B) = J_{np}(B) \), and \( J_{sv}(-B) = -J_{sv}(B) \). Consequently, by measuring \( J(V,B) - J(V,-B) = 2J_{sv} \) the large \( T_1 \)-independent background has then been effectively removed. To optimize the experimental sensitivity we assume that, with the exception of \( T_1 \), all the material parameters are known and consider variable sample size which would give large difference in \( J_{sv} \) as \( T_1 \) is changed, i.e., large \( \partial \delta \alpha(d_n)/\partial L_{sn} \) (see Eq. \( \delta s \)). For a given \( L_{sn} \) this is achieved with \( \bar{w}_n/L_{sn} \approx 1.5 \) and to increase the magnitude of \( J_{sv} \) it is favorable to choose a short \( p \) region \( \delta s \) (\( J_{sv} \propto \coth(\bar{w}_n/L_p) \)) and to consider forward bias \( V \gg V_T \), while still remaining in the low bias (low injection) regime \( (V < V_b) \). Since a priori we can only estimate a range of expected values for \( T_1 \) the choice of \( \bar{w}_n \) should maximize the corresponding values of \( \partial \delta \alpha(d_n)/\partial L_{sn} \). The results obtained by this procedure are illustrated in Fig. 2.

The material parameters are based on GaAs \( \delta s \), \( D_n = 10D_p = 103.6 \text{ cm}^2\text{s}^{-1} \), \( L_n \approx 1.0 \mu \text{m} \), \( L_p \approx 0.3 \mu \text{m} \), \( n_i = 1.8 \times 10^8 \text{ cm}^{-3} \). Doping with \( N_n = N_d = 5 \times 10^{15} \text{ cm}^{-3} \) at \( V = 0 \) yields \( d_n = d_p \approx 0.4 \mu \text{m} \). For example, expecting that the spin relaxation time will be within \( 0.01 \text{ and } 0.16 \text{ ns} \), to optimize sensitivity, we choose that for \( T_1 = 0.16 \text{ ns} \) (which corresponds to \( L_{sn} \approx 1.3 \mu \text{m} \)) \( \bar{w}_n/L_{sn} \approx 1.5 \). We set \( \bar{w}_n = 0.3 \mu \text{m} \), which leads (see Fig. 1a,b) to \( w_p = 0.7 \mu \text{m} \), \( w_n = 2.3 \mu \text{m} \).
remains then to measure where functions $a(V)$, $b(V)$ are known and readily enters through factor. We use that identifying in the magnetic p-n variety of magnetic p-n junctions we are interested in measuring $T_1$, as discussed above. Finally, we consider the situation where $\zeta$, $T_1$, and $\delta\alpha(w_n)$ are all unknown. Again we first extract $\zeta$ from $J(V, B) + J(V, -B)$ and subsequently the spin-voltaic current by measuring $J(V, B) - J(V, -B)$. It follows from Eq. 3 that the value of $\delta\alpha(d_n)$ can then be determined. However, $\delta\alpha(d_n)$ (see Eq. 4) still contains two unknown quantities: $T_1(L_{sn})$ and $\delta\alpha(w_n)$ which influence needs to be decoupled. We assume (as it was implicitly done throughout the paper) that $\delta\alpha(w_n)$ is $V$-independent. We recall that change of applied bias modifies $d_n$. Effectively, we are changing the separation between the point of spin injection and spin “detection,” since at the depletion edge $x = d_n$ the remaining nonequilibrium spin can be detected by its measurable effect on charge current. To eliminate influence of $\delta\alpha(w_n)$ we evaluate $f(V) = \delta\alpha[d_n(V_0)]/\delta\alpha[d_n(V)]$ for a range of applied bias and fixed $V_0$. In our case, it is suitable to choose $V \in [-0.8, 0.8]$ and $V_0 = -0.8$. Variation of $f(V)$ changes monotonically with $T_1$ and can be used to extract the spin relaxation time. However, the resulting sensitivity will be smaller that the one achieved in Fig. 2 under the assumption that $T_1$ is the only unknown quantity. [For $T_1 = 0.16$ ns $\Delta f(V) = [f(0.8) - f(-0.8)]/f(-0.8) \approx 0.25$, while for $T_1 = 0.01$ ns $\Delta f(V) \approx 1.7$.] After $T_1$ is extracted we use then Eq. 4 to obtain $\delta\alpha(w_n)$, the only remaining unknown quantity.

We have proposed here how all-electrical measurements can be used to identify several quantities fundamental to the understanding of spin-polarized transport in semiconductors. The general principle that the nonequilibrium injected spin can produce measurable effects on charge current should be useful both for developing novel device concepts in semiconductor spintronics, as well as a diagnostic tool for the existing structures.

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