APPLIED PHYSICS LETTERS VOLUME 82, NUMBER 2 13 JANUARY 2003

Proposal for all-electrical measurement of T_1 in semiconductors

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(Received 14 May 2002; accepted 18 November 2002)

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, in which 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. In a magnetic $p-n$ junction, for which the results can be calculated analytically, it is also possible to extract the g-factor and the degree of injected-carrier spin polarization. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1536270]

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 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, and magnetic and electric fields. It would be highly desirable if the same semiconductor structures that 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, and there are suggestions for employing various transport effects.[4–6]

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,[7,8] introduced in metals by Silsbee and Johnson, to inhomogeneously-doped semiconductors.[4] 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[4,9] as sketched in Figs. 1(a) and 1(b). In the p (n) region, there is a uniform doping with N_a 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,[10] 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 non-

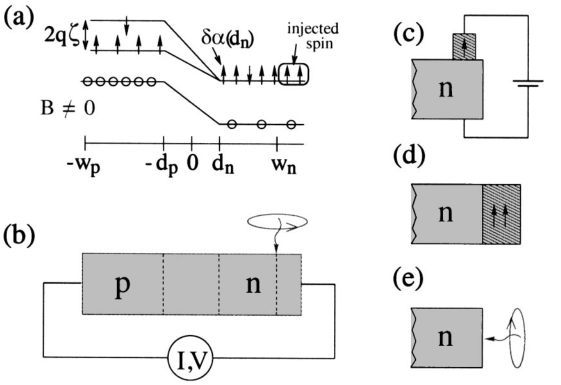

FIG. 1. Scheme of a magnetic $p-n$ junction. (a) Band-energy diagram with spin-polarized electrons (arrows) and unpolarized holes (circles). The spin-splitting $2q\zeta$, the nonequilibrium spin polarization at the depletion edge $\delta\alpha(d_n)$, and the region where the spin is injected, are depicted. (b) Circuit geometry corresponding to panel (a). Using circularly polarized light (photo-excited electron–hole pairs absorb the angular momentum carried by incident photon), nonequilibrium spin is injected transversely in the nonmagnetic n region and the circuit loop for $I-V$ characteristics is indicated. Panels (c)–(e) indicate alternative schemes to inject spin into the n region. Schemes (c) and (d) rely on the magnetic (paramagnetic or ferromagnetic) material to inject spin electrically. Realizations depicted in (b), (c), and (e) are suitable to demonstrate spin-voltaic effect,[4] where: (1) in a closed circuit charge current can flow, even at no applied (longitudinal) bias, in which the direction can be reversed either by $B\rightarrow -B$ or by the reversal of the orientation of the injected spin and (2) for an open circuit, an analogous reversal in B or in the spin orientation would change the sign of the voltage drop across the junction.

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0003-6951/2003/82(2)/221/3/$20.00

degenerate 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.[9] Following the approach from Ref. 4, we consider only the effect of spin-polarized electrons. (It is simple to also include the net spin polarization of holes).[9] The resulting Zeeman splitting of the conduction band [Fig. 1(a)] is $2q\zeta = g\mu_B B$, where g is the g-factor for electrons, μ_B is the Bohr magneton, q is the proton charge, and ζ is the electron magnetic potential.[4]

Nonequilibrium electron and hole densities are n (the sum of spin-up and spin-down components $n_\uparrow + n_\downarrow$) and p, while the spin density and its polarization are $s = n_\uparrow - n_\downarrow$ 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 the temperature. We assume[4] 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 $\delta s(w_n) = \alpha(w_n) N_d$, where $\delta s = s - s_0$ and $\delta\alpha = \alpha - \alpha_0$. [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.[9]] In addition to spin injection by optical means[2,11] [depicted in Figs. 1(b) and 1(e)], an electrical spin injection [Figs. 1(c) and 1(d)] has been reported using a wide range of magnetic materials.[12–19] For a magnetic $p-n$ junction, total charge current (density) J can be decomposed[4,9] 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;[4,9]

$$J_n = q\frac{D_n}{L_n} n_0(-d_p) \coth\left(\frac{\tilde{w}_p}{L_n}\right)(e^{V/V_T} - 1), \tag{1}$$

$$J_p = q\frac{D_p}{L_p} p_0(d_n) \coth\left(\frac{\tilde{w}_n}{L_p}\right)(e^{V/V_T} - 1), \tag{2}$$

$$J_{sv} = q\frac{D_n}{L_n} n_0(-d_p) \coth\left(\frac{\tilde{w}_p}{L_n}\right) e^{V/V_T} \alpha_0(-d_p)\, \delta\alpha(d_n), \tag{3}$$

where D_n (D_p) is the electron (hole) diffusivity, L_n and L_p are the minority diffusion lengths,[20] and $\tilde{w}_p = w_p - d_p$ ($\tilde{w}_n = w_n - d_n$) is the width of the bulk p (n) region. There is an implicit V-dependence of $\tilde{w}_{n,p}$ since for the depletion layer edge[21] $d_{n,p} \propto \sqrt{V_b - V}$, where $V_b = V_T \ln(N_a N_d / n_i^2)$ is the built-in voltage. The derivation of the Eqs. (1)–(3) assumes that the depletion region is highly resistive (depleted from free carriers).[9,21] The voltage drops 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 that will be used to formulate the method for determining T_1. From Eq. (3), 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. 1(a)] that J_{sv} should be sensitive to: (1) $\tilde{w}_n$ 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, that is, $\delta\alpha(w_n)$. Indeed, one can show[4] that

$$\delta\alpha(d_n) = \delta\alpha(w_n)/\cosh(\tilde{w}_n / L_{sn}), \tag{4}$$

which from Eq. (3) implies a high sensitivity of J_{sv} to T_1 (through L_{sn}). In contrast, $J_{n,p}$ 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 $J_{sv} = J_{sv}(T_1)$] implies some limitations. At vanishing bias ($V \ll V_T$), where $J_{n,p} \to 0$, $J \to J_{sv}$ is small, while at higher bias ($V \gg V_T$ and $V < V_b$) J is dominated by J_n and J_p, a large T_1-independent background. For a simple estimate, we assume that the electrons have typically higher mobility than the holes ($J_n \gg J_p$). Consequently, a "signal-to-background ratio" $J_{sv}/J_n \approx \alpha_0(-d_p)\,\delta\alpha(d_n)$, if needed, can be readily increased (even above 10%) by recalling that $\alpha_0(-d_p)$ increases with $1/T$. To fully exploit simple $I-V$ measurements, we note that $T_1 = T_1(|B|)$ (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:

$$J_{n,p}(-B) = J_{n,p}(B), \quad \text{and } J_{sv}(-B) = -J_{sv}(B). \tag{5}$$

This follows if we recall that $\zeta \propto B$, $J_n \propto \cosh(\zeta/V_T)$, J_p is ζ-independent, and $J_{sv} \propto \sinh(\zeta/V_T)$. Consequently, by measuring $J(V,B) - J(V,-B) = 2J_{sv}$, the large T_1-independent background has then been effectively removed. In optical schemes [see Figs. 1(b) and 1(e)] an alternative background subtraction can be performed [recall Eqs. (1)–(3)] by measuring the difference of the total charge current with left- and right-hand circularly polarized light, respectively.

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 that would yield a large difference in J_{sv} as T_1 is changed, that is, large $\partial[\delta\alpha(d_n)]/\partial L_{sn}$ [see Eq. (4)]. For a given L_{sn}, this is achieved with $\tilde{w}_n / L_{sn} \approx 1.5$, and to increase the magnitude of J_{sv} it is favorable to choose a short p region[22] [$J_{sv} \propto \coth(\tilde{w}_p/L_n)$] 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 $\tilde{w}_n$ 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:[20] $D_n = 10 D_p = 103.6\ \mathrm{cm}^2\,\mathrm{s}^{-1}$, $L_n \approx 1.0\ \mu\mathrm{m}$, $L_p \approx 0.3\ \mu\mathrm{m}$, and $n_i = 1.8 \times 10^6\ \mathrm{cm}^{-3}$. Doping with $N_a = N_d = 5 \times 10^{15}\ \mathrm{cm}^{-3}$ at $V = 0$ yields $d_n = d_p \approx 0.4\ \mu\mathrm{m}$. For example, expecting that the spin relaxation time will be within 0.01 and 0.16 ns, to optimize sensitivity, we choose that, for $T_1 = 0.16$ ns (which corresponds to $L_{sn} \approx 1.3\ \mu\mathrm{m}$) $\tilde{w}_n / L_{sn} \approx 1.5$. We set (at $V = 0$) $\tilde{w}_p \approx 0.3\ \mu\mathrm{m}$, which leads [see Figs. 1(a) and 1(b)] to $w_p = 0.7\ \mu\mathrm{m}$ and $w_n = 2.3\ \mu\mathrm{m}$. For the injected spin polarization, we use $\delta\alpha(w_n) = 0.5$, and for the maximum spin splitting $2q\zeta/V_T = 0.2$, where at room temperature and B [Tesla], one can also write $q\zeta/V_T \approx 900 B/g$.[4] The sensitivity of our methods is displayed in Fig. 2, where for approximately an order of magnitude change in T_1, the spin-voltaic current J_{sv} changes by *two* orders of magnitude. Considering

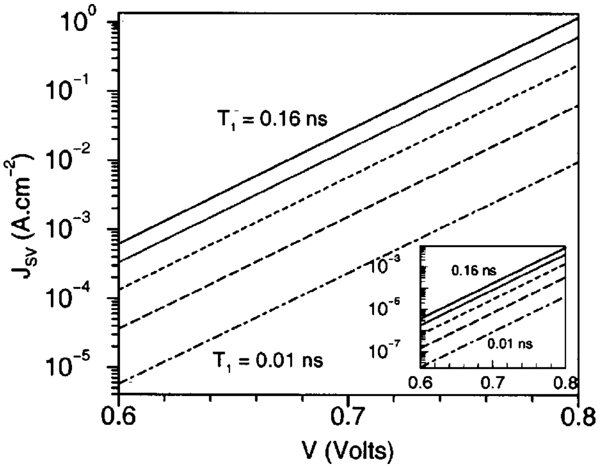

FIG. 2. Calculated spin-voltaic current J_{sv} for the magnetic $p-n$ junction as a function of forward bias (in volts). Lines (top to bottom) correspond to $T_1=0.16$, 0.08, 0.04, 0.02, and 0.01 ns, revealing the high sensitivity for probing the spin relaxation time. The doping is $N_a=N_d=5\times10^{15}$ cm^{-3}. In the inset the results are displayed for $N_a=N_d=5\times10^{17}$ cm^{-3} [23] (all the other parameters remain unchanged), indicating that the high sensitivity to T_1 is preserved at different doping levels.

a sample with a cross-sectional area of 10^{-4} cm^2, a typical current density of $J_{sv}\sim10^{-5}$ A cm^{-2} (see Fig. 2) would imply resolving the current $I_{sv}\sim1$ nA (after the background subtraction) from the total current $I\sim10$ nA, readily observable with the existing experimental techniques.[24] The magnitude of the observed current could be further increased by considering other materials (narrow band III–V semiconductors, Si, etc.) with much larger n_i than in GaAs [see Eqs. (1)–(3), and recall $n_0(-d_p)$, $p_0(d_n)\propto n_i^2$]. Since the gist of the method just outlined relies on the robust symmetry properties of $J_{n,p}$ and J_{sv} with respect to B [see Eq. (5)], it is straightforward to implement our proposal for a wide variety of magnetic $p-n$ junctions for which only a numerical solution is known. For example, higher (degenerate) doping could also be considered, typical for ferromagnetic semiconductors.[10]

With the aid of the analytic solution of Eqs. (1)–(3), it is also possible to illustrate how to extract other quantities of interest. Consider the situation in which we accurately know B and are interested in measuring g-factor in the magnetic p region. Recalling that $2q\zeta=g\mu_BB$, identifying ζ is then equivalent to extracting the g-factor. We know that $J_{n,p}$ is even in B, and measure $J(V,B)+J(V,-B)=2[J_n(V,B)+J_p(V,B)]$. From Eqs. (1) and (2), we note that the only dependence on ζ ($\propto B$) enters through $n_0(-d_p)=(n_i^2/N_a)\cosh(\zeta/V_T)$. Consequently, $J(V,B)+J(V,-B)\equiv a(V)+b(V)\cosh(\zeta/V_T)$, where functions $a(V)$, $b(V)$ are known and are readily expressed in terms of the parameters from Eqs. (1) and (2). It remains then to measure $J(V,B)+J(V,-B)$ for different values of B, and to obtain a one-parameter fit for ζ, that is, for the g-factor. (An attempt to extract ζ from J_{sv} would be more complicated, since it also contains a generally unknown B-dependence in T_1.) If both ζ and T_1 are unknown, this procedure to obtain ζ should then be followed by measuring the spin-voltaic current to extract T_1, as discussed earlier. Finally, our analysis could be extended to determine $\delta\alpha(w_n)$ (in addition to ζ and T_1). We would employ the nontrivial effect of applied bias, which 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.

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 device concepts in semiconductor spintronics, as well as a diagnostic tool for the existing structures.

This work was supported by DARPA, NSF-ECS, and the U.S. ONR.

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