Spin extraction from a nonmagnetic semiconductor: Tunneling of electrons from semiconductors into ferromagnets through a modified Schottky barrier

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New efficient mechanism of obtaining spin polarization in nonmagnetic semiconductors at arbitrary temperatures is described. The effect appears during tunneling of electrons from a nonmagnetic semiconductor (S) into ferromagnet (FM) through a Schottky barrier modified with very thin heavily doped interfacial layer. We show that electrons with a certain spin projection are extracted from S, while electrons with the opposite spins are accumulated in S. The spin density increases and spin penetration depth decreases with current.

Spintronics, i.e. the manipulation of spin in solid state devices, opens up the possibilities for designing ultrafast scaleable devices [1,2]. Giant and tunnel magnetoresistance effects in magnetic layered systems proved to be practically important phenomena [3–5]. An injection of spin-polarized carriers into semiconductors is of particular interest because of relatively large spin-coherence lifetime of electrons in semiconductors [6] and possibilities for applications in ultrafast devices and quantum computers [1,2]. An efficient spin injection in heterostructures with magnetic semiconductor as a spin source have been reported in Refs. [7]. However, the Curie temperature of the known magnetic semiconductors is substantially below room temperature. In Ref. [8] it was shown that spin injection and extraction in p-n junctions containing magnetic semiconductors can occur in large magnetic fields (at least a few Tesla). Fairly efficient spin injection from ferromagnets (FM) into semiconductors (NS) has been demonstrated recently at low temperatures [9]. The attempts to achieve an efficient room-temperature spin injection from FM into NS have faced substantial difficulties [10]. Optimal conditions of the spin injection from FM into NS have been discussed in Refs. [11]. Spin diffusion and drift in an electric field have been investigated in Refs. [12]. The spin polarization of photoexcited electrons in NS due to reflection off a ferromagnet was studied in Refs. [13].

In this paper we consider a ferromagnet-semiconductor junction with very thin heavily doped semiconductor layer (δ-doped layer) and show that tunnelling of electrons from a nonmagnetic semiconductor into a ferromagnet through the δ-doped layer results in formation of highly spin-polarized electrons in the semiconductor near the interface at room temperature in absence of an external magnetic field. We assume that the δ-doped layer has the thickness l ≲ 2 nm, and the concentration of donors, \( N_d^+ \), satisfying the condition: \( N_d^+ l^2 = \frac{2\varepsilon_0 (\Delta - \Delta_0)}{q^2} \), where \( q \) is the elementary charge, \( \varepsilon_0 \) is the permittivity of the semiconductor (vacuum), \( \Delta_0 = E_c - F \), \( F \) the Fermi level, \( E_c \) the bottom of a semiconductor conduction band, \( \Delta \) the height of potential barrier at the ferromagnetic-semiconductor interface. (Note that for GaAs and Si \( \Delta \approx 0.5 – 0.8 \) eV practically for all metals including Fe, Ni, and Co [14,9]).

The energy band diagram of such a FM–n+–n–S structure includes a δ–spike of height (\( \Delta - \Delta_0 \)) and thickness l (Fig. 1). We consider that due to a smallness of l the electrons can easily tunnel through the δ–spike.

We assume that the electron energy \( E \) and component \( \vec{k}_\parallel \) of the wave vector parallel to the interface are conserved during tunneling through the FM-S interface. The current density of electrons with spin \( \sigma \) from the semiconductor into the ferromagnet at the interface (\( x = 0 \), Fig. 1), which we denote \( J_{\sigma 0} = J_\sigma (0) \), can be written as [15,5]

\[
J_{\sigma 0} = \frac{q}{h} \int dE [f(E - F_{\sigma 0}) - f(E - F)] \int \frac{d^2 \vec{k}_\parallel}{(2\pi)^2} T_\sigma, \tag{1}
\]

where \( f(E - F_{\sigma 0}) - f(E - F) \) is the Fermi function and \( T_\sigma \) is the transmission coefficient.
where \( f(E) = \exp(E - F)/T + 1 \) \(^{-1} \) the Fermi function, \( T \) the temperature (in units \( k_B = 1 \)), \( T_{\sigma \tau} \) the transmission probability, the integration includes a summation with respect to a band index, and we assume that the negative bias voltage \( V \) is applied to the semiconductor. We need to consider, in variance with Refs. \([15,5]\), that electrons with spin \( \sigma \) in the semiconductor can be out of equilibrium with their distribution described by a Fermi function with a quasi-Fermi level \( F_\sigma(x) \). For definiteness, we consider a nondegenerate semiconductor \([16]\) where a total electron density \( n \) and a density of electrons with spin \( \sigma \) near the interface, \( n_\sigma(0) \), are given by

\[
n = N_c \exp \left( -\frac{\Delta_0}{T} \right), \quad n_\sigma(0) = \frac{N_c}{2} \exp \left( \frac{F_\sigma - E_\sigma}{T} \right).
\]

Here \( F_\sigma = F_\sigma(0) \), \( N_c = 2M_c(2\pi m_e T)^{3/2}h^{-3} \) is the effective density of states of the semiconductor conduction band \([14]\), \( m_e \) the effective mass of electrons in the semiconductor, \( M_c \) the number of band minima. The analytical expressions for the transmission probability \( T_{\sigma}(E, k_x) \) can be obtained in an effective mass approximation \( \hbar k_{\sigma \tau} = m_\sigma v_\sigma \) where \( v_\sigma \) and \( m_\sigma \) are the velocity and the mass of electron with spin \( \sigma \). The potential barrier (Fig. 1) has a “pedestal” with a height \( (\Delta_0 + qV) \). For electron energies \( E \gtrsim E_\sigma = F + \Delta_0 + qV \) one can approximate the \( \delta \)-barrier by a triangular shape and find approximately

\[
T_{\sigma} = \frac{16\alpha m_\sigma m_x k_x e^{-\kappa l}}{m_\sigma^2 k_x^2 + m_x^2 \kappa^2} e^{-\kappa l}, \quad \kappa = (2m_e/\hbar^2)^{1/2} (\Delta_0 + qV)^{-1}, \quad E_\sigma = E - E_\parallel, \quad E_\parallel = \hbar^2 k_x^2/2m_x, \quad v_\sigma = \hbar/k_x/m_x, \quad \text{the \"tunneling\" velocity}, \quad v_x(v_\sigma) \text{ is the } x\text{-component of the velocity of electrons } v(v_\sigma) \text{ in the semiconductor (ferromagnet).}
\]

\[
\alpha = \pi(k|x|^{1/2} [3/4]^{-3/2} (\frac{2}{\eta})^{-1}) \approx 1.2 \alpha(k|x|^{1/2} \eta = 4/3 \text{ (cf. } \alpha = 1 \text{ and } \eta = 2 \text{ for a rectangular barrier). The preexponential factor in Eq. (3) accounts for a mismatch of the effective masses, } m_\sigma \text{ and } m_x, \text{ and the velocities, } v_\sigma \text{ and } v_x, \text{ of electrons at the FM-S interface. Note that Eq. (3) is similar to Eq. (2) of Ref. [5].}
\]

In a regime of interest, \( T < \Delta_0 \ll \Delta \text{ and } E \gtrsim E_\sigma = (F + \Delta_0 + qV) > F \) \([16]\), Eqs. (1) and (3) can be written, accounting for a singular energy dependence of \( v_x \) in the nonlinear semiconductor

\[
J_{\sigma 0} = \frac{2^{3/2} \alpha q M_c}{\pi^{3/2} h^3 m_x^{5/2}} \left( e^{\frac{\eta q l}{T}} - e^{-\frac{\eta q l}{T}} \right) \int_0^\infty dk_x^2 \int_{E_\sigma}^{E_1} dE \left[ \frac{v_x}{v_x^2 + v_\sigma^2} (E - E_\sigma - E_\parallel)^{1/2} \exp \left( -\eta q l - \frac{E}{T} \right) \right]
\]

\[
= \frac{2^{3/2} \alpha q M_c}{\pi^{3/2} h^{3/2} m_x^{3/2}} \frac{v_\sigma^{1/2} v_{\sigma 0} T^{5/2}}{v_{\sigma 0}^{2} + v_\sigma^2} e^{-\eta q l - \frac{E}{T}} \left( e^{\frac{\eta q l}{T}} - e^{-\frac{\eta q l}{T}} \right),
\]

where \( \kappa_0 \equiv 1/l_0 = (2m_e/\hbar^2)^{1/2} (\Delta - \Delta_0 - qV)^{1/2} \), \( v_{\sigma 0} = \sqrt{2(\Delta - \Delta_0 - qV)/m_x} \) and \( v_\sigma = v_\sigma(\Delta_0 + qV) \). From Eqs. (2), and (4) we find

\[
J_{\sigma 0} = j d_\sigma \left( \frac{2n_\sigma(0)}{n} - e^{-\frac{\eta q l}{T}} \right), \quad j = \frac{4\alpha_0}{3} q v n_T e^{-\eta q l}. \quad (5)
\]

We have introduced the thermal velocity \( vT \equiv \sqrt{3T/m_e} \), \( \alpha_0 = 1.2(\kappa_0 l_0)^{1/3} \), and the spin factor \( d_\sigma = v_{\sigma 0} (v_{\sigma 0}^2 + v_\sigma^2)^{-1} \). One can see from Eq. (5) that the current of electrons flowing from nonmagnetic semiconductors into ferromagnets \( J_{\sigma 0} \) depends on an electron spin \( \sigma \). Note that the present expression for the current is in stark difference from standard expressions for a current through Schottky metal-semiconductor contact (see Ref. [14]).

The density of electrons with spin \( \sigma \) and their spatial distribution in the semiconductor near the interface is determined by the continuity equation \([14,12]\)

\[
dJ_\sigma/dx = q \delta n_\sigma/\tau_\sigma,
\]

where \( \delta n_\sigma = n_\sigma - n/2 \) and \( \tau_\sigma \) the electron spin-coherence time. The current density of electrons is given by the usual expression

\[
J_\sigma = qD(dn_\sigma/dx) + q \mu n_\sigma E,
\]

where \( D(\mu) \) is the diffusion constant (mobility) of the electrons, \( E \) electric field. Both \( J \) and \( E \) are directed along the \( x \)-axis, and \( \tau_\sigma \gg \tau_\rho \), i.e. \( L_S = \sqrt{D\tau_\sigma} = \lambda / \sqrt{D\tau_\rho} \), \( \tau_\rho \) the relaxation time of electron momentum in the semiconductor. From continuity of the total current, \( J(x) = J_1 + J_L = \text{const} \), and \( n(x) = n_\sigma(x) + n_\sigma(x) = \text{const} \) we have \( E(x) = J/qn \) \text{ const} and \( \delta n_\sigma(x) = -\delta n_\sigma(x) \). Using (6) and (7), we obtain

\[
L_S d^2 \delta n_\sigma/dx^2 + L_E d\delta n_\sigma/dx - \delta n_\sigma = 0,
\]

where \( L_S = \sqrt{D\tau_\sigma} \) and \( L_E = \mu \tau_\rho E = \tau_\rho \mu qn \) are the spin-diffusion and the drift lengths of electrons in a semiconductor, respectively \([12]\). The solution of Eq. (8), satisfying a boundary condition \( \delta n_\sigma \to 0 \) at \( x \to \infty \), is

\[
\delta n_\sigma(x) = \frac{n}{2} e^{-x/L}, \quad L = \frac{1}{2} \left( 4L_S^2 + L_E^2 - L_E \right).
\]

The parameter \( c \) in the above expression is found as follows. We obtain from Eqs. (5), (9)

\[
J_{10} = j_0 d_\sigma(\gamma + c) = \frac{J_0}{2} (1 + P)(\gamma + c),
\]

where \( \gamma = 1 - \exp(-qV/T) \) and we have introduced the effective spin polarization

\[
P = \frac{d_\parallel - d_\perp}{d_\perp + d_\parallel} = \frac{(v_{10} - v_{01}) (v_{10}^2 + v_{10} v_{00})}{(v_{10} + v_{01}) (v_{10}^2 + v_{10} v_{00})},
\]

\[
\gamma = \frac{v_{10}^2 + v_{01}^2}{v_{10}^2 + v_{01}^2 - 2 v_{10} v_{01}}.
\]
which is the spin polarization of current in a tunneling FM-I-FM structure [5]. On the other hand, substituting Eq. (9) into Eqs. (7) and using that $J = q\mu En$, we find

$$J_{\tau_0} = \frac{J}{2} \left[ 1 + c \left( 1 - \frac{D}{\mu EL} \right) \right] = \frac{J}{2} \left( 1 - e^{-\frac{L}{LE}} \right). \quad (12)$$

One obtains a quadratic equation for $c$ from Eqs. (10) and (12), which has a unique physical solution, quite accurately represented as

$$c = -P \frac{EL(1 - e^{-qV/T})}{LE + L(1 - e^{-qV/T})}. \quad (13)$$

One can see from (9) and (13) that at very small bias voltage, $qV \ll T$, and current $J \ll J_s = qnL_s/\tau_s$, when $L_E = \mu \tau_s E = J\tau_s/\epsilon n \ll L_s$, the induced spin polarization in the semiconductor is small, $c/P \approx - (\xi J/J_s)/(1 + \xi)$, where $\xi = L_s/v_T \tau_s \ll 1$. At large voltages $qV \gg T$ and the current $J$ approaching its saturation value $J_{\text{max}} = J_s/\xi \approx J_s$, the polarization of electrons reaches the limiting value $c/P = -2/(1 + \sqrt{1 + 4\xi^2}) \approx -1$, and near the interface $\delta n_{\tau_i}(0) \approx \mp Pn/2$. The spin penetration length is equal to $L = L_E^2/LE = enD/J$. Thus, at $P < 0$ ($d_\uparrow < d_\downarrow$) the electrons with spin $\sigma = \uparrow$ are accumulated, $n_\tau(0) \approx (1 + |P|)n/2$, while the electrons with spin $\sigma = \downarrow$ are extracted, $n_\tau(0) \approx (1 - |P|)n/2$, from a semiconductor. The penetration length of the induced spin polarization area decreases as $L \propto 1/J$ (Fig. 2). For a typical semiconductor parameters at room temperature $D_n \approx 25 \text{ cm}^2/\text{s}$, $\tau_s = 4 \times 10^{-10} \text{ s}$, and $L_s = 1 \mu\text{m}$. Thus, when $J \approx 3J_s$ the spin accumulation/extraction at the interface is $\delta n_{\tau_i}(0) \approx \mp 0.91Pn/2$ and $L = 0.3\mu\text{m}$.

The required spin-relaxation time is obtained from Eq. (5), which yields $J \gg J_s$ at $qV \gtrsim T$ when the $\delta$-doped layer is very thin, $l \lesssim l_0$. The corresponding condition reads

$$\tau_s \gg D \left( \frac{\Delta - \Delta_0}{4\sigma_0^2 v_\sigma T} \right)^2 \exp \frac{2n\hbar}{l_0}. \quad (14)$$

With typical semiconductor parameters at $T \approx 300 \text{ K}$ ($D_n \approx 25 \text{ cm}^2/\text{s}$, $(\Delta - \Delta_0) \approx 0.5 \text{ eV}$, $v_\sigma \approx 10^8 \text{ cm/s}$ [14]) it is satisfied at $l \lesssim l_0$ when the spin-coherence time $\tau_r \gg 10^{-12} \text{ s}$. We notice that $\tau_r$ can be an $\text{ns}$ even at $T \approx 300 \text{ K}$ (e.g. in ZnSe [6]).

We emphasize that $l_0 \propto (\Delta - \Delta_0 - qV)^{1/2}$, $v_\sigma = v_\sigma(F + \Delta_0 + qV)$, and $P$ are all functions of the bias voltage $V$ and $\Delta_0$. Therefore, by adjusting $V$ and $\Delta_0$ one may be able to maximize a spin accumulation. This can be achieved by means of electron tunneling through the $\delta$-doped layer, when the bottom of the conduction band in a semiconductor $E_c = F + \Delta_0 + qV$ is close to a peak in the density of states of minority electrons in the elemental ferromagnet like e.g. Ni, $F + \Delta_4$, $\Delta_4 \approx 0.1 \text{ eV}$ [17], as illustrated in Fig. 1.

![FIG. 2. Spatial distribution of spin polarized electrons $2\delta n_{\tau_\uparrow}(0)/|n|P|$ in the semiconductor at different currents densities $j = J/J_s$, shown next to the lines. $J_s = qnL_s/\tau_s$, at $\xi = L_s/v_T \tau_s = 0.2$ in a structure like the one shown in Fig. 1.](image)

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[16] Spin extraction from degenerate highly doped semiconductors can be achieved at arbitrary temperatures from $T = 0$ to $T \gtrsim 300$K. In this case $E_c$ should be substituted for $F + qV$ in all equations.

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