Complete spin extraction from semiconductors near ferromagnet-semiconductor interfaces

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Abstract

We show that spin polarization of electrons in nonmagnetic semiconductors near specially tailored ferromagnet-semiconductor junctions can achieve 100%. This effect is realized even at moderate spin injection coefficients of the contact when these coefficients only weakly depend on the current. The effect of complete spin extraction occurs at relatively strong electric fields and arises from a reduction of spin penetration length due to the drift of electrons from a semiconductor towards the spin-selective tunnel junction.

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Combining carrier spin as a new degree of freedom with the established bandgap engineering of modern devices offers exciting opportunities for new functionality and performance. This new field of semiconductor physics is referred to as semiconductor spintronics [1, 2]. The injection of spin-polarized electrons into nonmagnetic semiconductors (NS) is of particular interest because of the relatively large spin-coherence lifetime, $\tau$, and the promise for applications in both ultrafast low-power electronic devices [1, 2, 3, 4, 5] and in quantum information processing [2, 6, 7]. The main challenge is to achieve a high spin polarization, $P_n$, of electrons in NS. The characteristics of the spintronic devices dramatically improve when $P_n \rightarrow 100\%$.

It has been concluded in all previous theoretical works on spin injection [8, 9, 10, 11, 12, 13, 14] that $P_n$ cannot exceed either the spin polarization of the carriers in the spin source or the spin injection coefficient, $\gamma$, of the ferromagnet-semiconductor junction [15]. This conclusion does not contradict existing experiments in which different magnetic materials such as magnetic semiconductors, half-metallic ferromagnets, and ferromagnetic metals (FM) have been used as spin sources [1, 2]. FM are widely used in semiconductor technology. The Curie temperatures of these materials are usually much higher than the room temperature. The greatest value of $P_n \simeq 32\%$, was achieved for Fe-based junctions [16, 17] with approximately the same polarization of the source.

One of the obstacles for the spin injection from FM into NS is a high and wide Schottky barrier that usually forms at the metal-semiconductor interfaces [18]. The spin injection corresponds to a reverse current of the Schottky FM-S junction. This current is usually extremely small [18]. Therefore, a thin heavily doped $n^+$-S layer between FM and S must be used to increase the current [12, 13, 14, 16, 18]. This layer greatly reduces the thickness of the barrier and increases its tunneling transparency. The greatest values of $P_n$ were found in such FM- $n^+-n$-S structures [16].

Thus, the spin injection is the tunneling of spin polarized electrons from FM into NS in reverse-biased FM-S structures. Since the tunneling is a symmetric process the spin selective transport must also occur in the forward-biased junctions when electrons are emitted from NS into FM [14]. In these junctions the electrons with a certain spin projection can be efficiently extracted from NS while the opposite spin electrons will accumulate in NS near FM-S interface [14]. Spin extraction from NS was predicted by I. Zutic et al. [19] for forward-biased p-n junctions containing a magnetic semiconductor and was experimentally
found in forward-biased MnAs/GaAs Schottky junction [20]. However the predicted and observed values of $P_n$ were rather small.

In this letter we demonstrate a possibility for achieving complete spin polarization of electrons in NS near forward-biased FM-S junctions with moderate spin injection coefficient, $\gamma$. The effect is based on spin extraction and nonlinear dependence of the nonequilibrium spin density on the electric field. We consider a FM-$n^+-$n-S structure containing a heavily doped degenerate $n^+$-S layer, Fig. 1. We use a standard assumption of spin injection [8, 9, 10, 11, 12] that $\gamma$ of the FM-$n^+$-S contact only weakly depends on the total current $J$ due to a high density of degenerate electrons in the $n^+$-S layer (see below). In the forward-biased structure unpolarized electrons drift from the bulk of NS to the contact. Because of the spin selectivity of the contact the electrons with spin $\sigma = \uparrow$ (up-electrons) at $\gamma > 0$ are extracted from NS, i.e. $\delta n_{\uparrow} = (n_{\uparrow} - n_s/2) < 0$, and electrons with spin $\sigma = \downarrow$ (down-electrons) are accumulated, i.e. $\delta n_{\downarrow} = (n_{\downarrow} - n_s/2) > 0$, near the contact [14]. Here $n_s$, $n_{\uparrow}$ and $n_{\downarrow}$ are the equilibrium electron density in NS and densities of up-and down-electrons, respectively, at the boundary between the $n^+$-S layer and high-resistant NS region ($x = l$ in Fig. 1(a)). The quantity $|\delta n_{\uparrow}|$ increases with the electric field, $E$ [14]. In sufficiently strong fields, the drift efficiently compresses the spin polarized electrons to the boundary. As a result [11, 14], the spin penetration length $L$ decreases with the current $J$ [cf. white and red curves in Fig. 1(a)]. Note, that due to $\delta n_{\downarrow} = -\delta n_{\uparrow}$, the diffusion flow of up-electrons is directed along the electron drift while the diffusion flow of down-electrons is in the opposite direction, Fig. 1(a). The superlinear increase of the spin diffusion flows with $J$ can be compensated only by an increase of the spin density $n_{\downarrow}$ up to $n_s$ and a decrease of $n_{\uparrow}$ down to zero. In other words, spin polarization of the electrons in NS near FM- $n^+$-S contact $|P_{nl}| = |\delta n_{\uparrow} - \delta n_{\downarrow}|/n_s = 2|\delta n_{\uparrow}|/n_s$ can reach 100% when the current is sufficiently large.

Let us consider for simplicity the case when the diffusion constant and mobility of up- and down-electrons are the same constants: $D_{\uparrow} = D_{\downarrow} = D$ and $\mu_{\uparrow} = \mu_{\downarrow} = \mu$. This standard assumption [8, 9, 10, 11, 12] is valid for nondegenerate NS (the peculiarities of degenerate NS are discussed below). In this case the currents of up- and down electrons with $\sigma = \uparrow, \downarrow$ are given by the equations [8, 11, 13, 14]

$$J_{\sigma} = q\mu n_{\sigma}E + qD\frac{d\delta n_{\sigma}}{dx}, \quad (1)$$

$$dJ_{\uparrow}/dx = q(n_{\uparrow} - n_{\downarrow})/2\tau_s, \quad (2)$$
FIG. 1: (a) FM-$n^+-n$-S heterostructures containing a thin heavily doped degenerate semiconductor layer ($n^+-S$) sandwiched between the ferromagnetic metal (FM) and donor doped degenerate nonmagnetic semiconductor (NS) region ($n$-S). White and red curves display spatial distributions of densities $n^\uparrow$ and $n^\downarrow$ at small and large currents, respectively; (b) Energy diagrams of equilibrium (dashed curves) and forward biased (solid curves) FM-$n^+-S$ junction for the case of a “narrow”-bandgap $n^+-S$ layer and a “wide”-bandgap $n$-S region. $F$ is the Fermi level; $w$ and $l$ are the thicknesses of the Schottky barrier and $n^+-S$ layer, respectively; $E_C(x)$ and $E_V(x)$ are the bottom of the conduction band and top of the valence band, respectively.
where \( q \) is the magnitude of the elementary charge. It follows from conditions of the continuity of the total current and electroneutrality that \( J(x) = J_\uparrow + J_\downarrow = \text{const} \), and \( n(x) = n_\uparrow + n_\downarrow = n_s = \text{const} \). This means that \( E(x) = J/qmn_s = \text{const} \) and \( \delta n_\uparrow(x) = -\delta n_\downarrow(x) \). Then the solution of Eqs. (1)-(2) reads 8, 11, 13, 14.

\[
\delta n_\uparrow(x) = P_{nl} \frac{n_s}{2} \exp\left[-(x-l)/L\right], \tag{3}
\]

where \( L = (1/2) \left( \sqrt{4L^2_s + L_E^2} \pm L_E \right) \). \( \delta n_\uparrow \) is the spin polarization of the up-electrons at \( x = l \) (Fig. 1), \( L_s = \sqrt{D\tau_s} \) and \( L_E = \mu \tau_s |E| = L_s |J|/J_s \) are the spin diffusion and drift lengths, respectively, and \( J_s = qn_SD/L_s \). The signs \( \pm \) correspond to the reversed, \( J < 0 \), and forward biases, \( J > 0 \), respectively. From Eqs. (1)-(3) we find that the currents at \( x = l \) are

\[
J_{\uparrow,\downarrow} = \frac{J}{2} \pm \frac{\delta n_\uparrow}{n_s} + qD\frac{\delta n_\uparrow}{L} = \frac{J}{2} \pm \frac{J_s}{L_s}L_Pnl. \tag{5}
\]

It follows from Eq. (5) that the electron spin polarizations, \( P_{nl} = 2\delta n_\uparrow/n_s \), and the spin injection coefficient, \( \gamma_l = (J_\uparrow - J_\downarrow)/J \), near the boundary are related by the equation

\[
P_{nl} = -\gamma_l \frac{JL_s}{J_sL} = \frac{-2J\gamma_l}{\sqrt{(2J_s)^2 + J^2} \pm |J|}. \tag{6}
\]

Thus, we see that for the case of the spin injection (reversed bias, sign +) \( |P_{nl}| < |\gamma_l| \) in accordance with previous works 8, 11, 13. Another situation is realized in the forward-biased FM-S junctions, sign \( - \) in Eq. (5). Here the spin penetration depth \( L \) decreases with the current \( J \) and according to (6) \( |P_{nl}| \) approaches 1 (100%) when

\[
J \rightarrow J_\uparrow \equiv J_s (|\gamma_l| + \gamma_l^2)^{-1/2} \tag{7}
\]

and \( L \rightarrow L_\uparrow \equiv L_s \sqrt{|\gamma_l|/(1 + |\gamma_l|)} \). \( \tag{8} \)

In degenerate NS the diffusion constants depend on electron densities: \( D_{\sigma}/\mu_\sigma = (D/\mu)(2n_\sigma/n_s)^{2/3} \) at low temperatures \( T \ll \mu \). In this case we can find \( E \) from Eqs. (1) and \( J = J_\uparrow(x) + J_\downarrow(x) \). Then, substituting \( E \) into Eq. (1), we obtain \( J_\uparrow \). Using this \( J_\uparrow \) and Eq. (2) we find a diffusion-drift equation for \( \delta n_\downarrow(x) \) with a bi-spin diffusion constant,

\[
D(P_n) = (D/2) (1 - P_n^{2/3}) \left[ (1 + P_n)^{1/3} + (1 - P_n)^{1/3} \right], \tag{9}
\]

which depends on \( P_n = 2\delta n_\downarrow/n_s \). One can see that \( D(P_n) \rightarrow 0 \) when \( |P_n| \rightarrow 1 \). It means that the effective spin diffusion length \( L_\downarrow(P_n) = [D(P_n)\tau_s]^{1/2} \) decreases with the current because \( |P_{nl}| \rightarrow 1 \) near \( x = l \).
Thus, an additional mechanism of a decrease of the spin penetration length $L$ with current $J$ occurs in a degenerate NS. As a result, the decay of $P_{nl}(x)$ is sharper, particularly near $x=l$, as shown in the inset in Fig. 2. Therefore, in degenerate NS the condition of complete spin extraction, $|P_{nl}|=1$, can be reached at lower threshold currents and greater spin lengths as compared with those given by (7) and (8) for nondegenerate NS. For instance, numerical analysis shows that the threshold values $L_{\sigma}/\mu_{\sigma}=(D/\mu)(2n_{\sigma}/n_{s})^{2/3}$ while $J_{t}=1.6J_{s}$ and $L_{t}=0.48L_{s}$ for the case $D_{\sigma}/\mu_{\sigma}=\text{const}$.

The effect of complete spin extraction from a degenerate NS can be illustrated based on spatial and current dependences of quasi-Fermi levels $F_{\uparrow}$ and $F_{\downarrow}$ for up- and down-electrons, respectively (Fig. 2). Indeed, due to the spin extraction the difference between $F_{\uparrow}$ and $F_{\downarrow}$ near the FM-$n^+$-S contact increases with the current. Therefore, the value $F_{\uparrow}$ can reach the bottom of the conduction band $E_{c}$ in NS at $x=l$ (Fig.2) at the current $J=J_{t}$. This implies that $\Delta F_{\uparrow}=F_{\uparrow}-F=-\mu_{s}$ at this point and $n_{\uparrow\downarrow} \propto (F-E_{c}+\Delta F_{\downarrow}) \rightarrow 0$, $n_{\downarrow\downarrow}=(n_{s}-n_{\uparrow}) \rightarrow n_{s}$, i.e. $|P_{nl}| \rightarrow 1$. Here $\mu_{s}=F-E_{c}$ and $F$ are the Fermi energy and the equilibrium Fermi level of electrons in NS, respectively.

In reality, however, our theory, which is based on the consideration of two nonequilibrium ensembles of the up- and down-electrons, becomes invalid when $n_{\uparrow\downarrow} \rightarrow 0$. Our approach is justified only when the time of electron-electron collisions within each of these systems is much less than $\tau_{s}$. Moreover, at large currents $J>J_{t}$ the value of $|P_{nl}|=2|\delta n_{\downarrow\downarrow}|/n_{s}=2n_{\downarrow\downarrow}-n_{s}/n_{s}$ becomes greater than 1 (see e.g. (3)), i.e. spin density $n_{\downarrow\downarrow}$ at $x=l$ exceeds the equilibrium electron density, $n_{s}$. Therefore, the condition of local electroneutrality $n_{\uparrow\downarrow}+n_{\downarrow\downarrow}=n_{s}$ is violated and a space charge arises near $x=l$ in Fig.1. This charge will change the field $E(x)$ and the total electron density in the vicinity of $x=l$. The complete set of equations consists of Eqs. (1)-(2), $J=J_{\uparrow}(x)+J_{\downarrow}(x)=\text{const}$, and Poisson’s equation: $\varepsilon\varepsilon_{0}dE/dx=\rho$, where $\rho=q(n_{s}-n_{\uparrow}+n_{\downarrow})$ and $\varepsilon\varepsilon_{0}$ is the permittivity of the NS. Our calculations for the case of $\gamma_{l}=\text{const}$ show that, as expected, the characteristic scale of the nonuniform-field region is determined by a relatively short screening length and the value of $|P_{nl}|$ in the degenerate NS is close to 1 near $x=l$ at $J \approx J_{t}$.

One can see from (7) and (8) that the spin injection coefficient of FM-$n^+$-S contact, $\gamma_{l}$, determines the threshold current, $J_{t}$, and spin penetration depth, $L_{t}$. However our main finding that $|P_{nl}| \rightarrow 1$ at $J \rightarrow J_{t}$ remains valid at any reasonable value of $\gamma_{l}$. The only required condition is a relatively weak dependence of $\gamma_{l}$ on $J$ (see [21]). This can be realized in a
FIG. 2: Spatial dependences of the quasi-Fermi levels $F_\uparrow$ and $F_\downarrow$ for up- and down-electrons, respectively, at the threshold current $J = J_t$. The inset shows electron spin polarizations, $P_n(x)$ ($x$ is in units of $L_s$), for cases $D_\sigma/\mu_\sigma = \text{const}$ (solid curves) and $D_\sigma/\mu_\sigma = (D/\mu)(2n_\sigma/n_s)^{2/3}$ (dashed curves) at $\gamma = 0.3$ and currents $J = 1.6J_s$ (curves 1, solid line), $J = 1.3J_s$ (curves 1, dashed line), and $J = 0.8$ (curves 2). Dashed curves are the numerical solutions of the diffusion-drift equation for $\delta n_\downarrow(x)$ with a bi-spin diffusion constant $D(P_n)$ (see text).

FM-$n^+-$S junction containing a heavily doped $n^+-$S layer. The donor concentration, $N_{d^+}$, and thickness, $l$, of this layer must satisfy the following conditions: $l \gtrsim 3w$ and $N_{d^+}w^2q^2 \simeq 2\varepsilon \varepsilon_0 \Delta$, where $\Delta$ and $w$ are the height and width of the depletion Schottky layer, Fig. 1. The electron gas has to be highly degenerate in a certain part of the $n^+-$S layer contiguous $n-$S layer. The transition between the $n^+-$S and $n-$S layers should have a discontinuous jump $\Delta_0 = (E_c - E_c^+)$ shown in Fig.1(b). This is realized when the $n^+-$S layer has a narrower energy bandgap than that of the $n-$S region. A similar diagram can also be realized when $n^+-$S and $n-$S regions are made of the same semiconductor, but an additional, acceptor-doped, ultrathin layer is formed between the $n^+-$S and $n-$S regions. The acceptor concentration $N_a$ and thickness $l_a$ of this layer have to satisfy the conditions: $N_a l_a^2 q^2 \simeq 2\varepsilon \varepsilon_0 \Delta_0$ and $l_a \ll l$.
To demonstrate the weak dependence of $\gamma_l$ upon the current $J$ through FM-$n^+$-S junction we use the common assumption that the electron energy $E$, spin $\sigma$, and the lateral component $\vec{k}_{||}$ of the wave vector $\vec{k}$ are conserved during tunneling. Then the current density of electrons with spin $\sigma=\uparrow, \downarrow$ tunneling through the Schottky barrier, i.e. between the points $x=w$ and $x=0$ in Fig. 1, can be expressed as [13, 14]:

$$J_{\sigma w} = \frac{q}{h} \int dE [f(E - F_{\sigma w}^+) - f(E - F)] \int \frac{d^2k_{||}}{(2\pi)^2} T_{k\sigma},$$

(9)

where $f(E - F)$ is the Fermi function, $F$ the Fermi level in FM, $F_{\sigma w}^+$ quasi-Fermi levels up- and down-electrons in $n^+$-S layer near the FM-S interface ($x=w$ in Fig.1), and $T_{k\sigma}$ is the transmission probability. We also assume that the temperature $T \ll \mu_s^+/k_B$, and $\mu_s^+ = (F - E_{c0}^+)$ is the Fermi energy of degenerate equilibrium electrons of the $n^+$-S layer.

In this case the nonequilibrium density of the electrons with spin $\sigma$ at $x=w$ reads

$$n_{\sigma w}^+ = \frac{n^+}{2(\mu_s^+)^{3/2}} (F_{\sigma w}^+ - E_{c0}^+ - qV)^{3/2} = \frac{n^+}{2} \left[ 1 + \frac{\Delta F_{\sigma w}^+}{\mu_s^+} \right]^{3/2},$$

(10)

where $n^+$ is the equilibrium electron density at $x=w$; $E_{c0}^+$ is the bottom of conduction band in the $n^+$-S region in equilibrium, $V$ is the bias voltage, and $\Delta F_{\sigma w}^+ = (F_{\sigma w}^+ - F - qV)$. Using the approximate expression for $T_{k\sigma}$ [13, 14], and Eqs. (9) - (10) at $T \ll \mu_s/k_B$, $|qV| < \mu_s^+$ and $w \geq 3l_0$ we obtain

$$J_{\sigma w} = j_0 d_{\sigma} T_0 (\mu_s^+)^{-5/2} \left[ (\mu_s^+ + \Delta F_{\sigma w}^+)^{5/2} - (\mu_s^+ - qV)^{5/2} \right]$$

(11)

where $j_0 = qn_s^+ v_F \alpha_0$, $\alpha_0 \approx 0.96(\kappa_0)^{1/3} \approx 1$ and $T_0 = \exp \left[ -\eta w (\Delta - \mu_s^+ - qV)^{1/2} \right]$ and $d_{\sigma} = v_F v_{\sigma 0}/(v_{\sigma 0}^2 + v_{\sigma 0}^2)$ is the tunneling transparency and the spin selection factor of FM-$n^+$-S contact; $\eta \approx 4/3$, $l_0 = (h^2/2m_s \Delta)^{1/2}$ is a tunneling length, $v_{\sigma 0} = \sqrt{2(\Delta - qV)/m_s}$, $v_{\sigma} = v_{\sigma}(F + qV)$ and $v_F = \sqrt{3\mu_s^+/m_s}$ are velocities of electrons with spin $\sigma$ and the energies $F + qV$ and $\mu_s^+$ in FM and $n^+$-S regions, respectively, and $m_s$ effective mass of electrons in $n^+$-S layer.

Let us consider the case when the thickness of the $n^+$-S layer $l \ll L_s^+$, but $l \gtrsim 3w$. Here $L_s^+ = \sqrt{D^+\tau_s^+}$ is the spin diffusion length in the $n^+$-S layer. Due to the condition $l \ll L_s^+$ the quasi-Fermi levels, $F_\uparrow$ and $F_\downarrow$ and the spin currents change very weakly in the $n^+$-S layer (Fig. 2). Therefore we can put $J_{\sigma w} \simeq J_{\sigma l}$ and $\gamma_{lw} \simeq \gamma_l$. We noticed above that in degenerate $n^+$-S $|\Delta F_{\sigma w}^+| \simeq \mu_s = (E_c - F)$ at $x = w$ when $J \to J_l$. Due to $n_s^+ \gg n_s$ the value $\mu_s^+ \propto (n_s^+)^{2/3} \gg \mu_s$, therefore we can neglect $|\Delta F_{\sigma w}^+|$ in Eq. (11) in comparison
with \(\mu^+\) when \(qV \simeq \mu^+\) at \(J \simeq J_t\). In this case we find that the spin injection coefficient,

\[
\gamma_w = \frac{(J_{\uparrow w} - J_{\downarrow w})}{J},
\]

and the total current of the FM-S junction are equal

\[
\gamma_0 = \frac{(d_\uparrow - d_\downarrow)}{(d_\uparrow + d_\downarrow)},
\]

\[
J = J_0 T_0 \left[ 1 - \left( 1 - qV / \mu^+ \right)^{5/2} \right].
\]

Here \(J_0 = (d_\uparrow + d_\downarrow)j_0\) and \(\gamma_0\) depend weakly on \(V\) and \(J\) (\(\gamma_0\) can increase with \(V\) \cite{14}). We note that \(J_0 \propto n^+_s = N^+_d\) while \(J_t \propto n_s = N_d\), and, therefore \(J_0 \gg J_t\). We see that \(\gamma_t \simeq \gamma_w = \gamma_0\) in the forward-biased FM-\(n^+-n\)-S structures when \(L^+_s > l \gtrsim 3l_D\), \(J_0 \gg J_t\), and \(J_0 T_0 \sim J_t\) at \(qV \simeq \mu^+\). In other words we suppose that Rashba’s condition \cite{10} is valid for the FM-\(n^+-S\) junction and therefore the spin injection coefficient \(\gamma_t\) only weakly depends on the current at \(J \lesssim J_t\). In this case, as we have shown above, the spin polarization of electrons in degenerate \(n\)-S region near the \(n^+-S\) layer, \(P_{nl} \to 100\%\) as \(J \to J_t\).

In real ferromagnets the situation is much more complex. In FMs there are spin-polarized heavy d-electrons and nonpolarized light s-electrons with very involved energy spectrum. Nonetheless our conclusion about the weak dependence of the spin injection coefficient \(\gamma_t\) on the current remains valid for any complex spectrum. This conclusion is based on the fact that the perturbations of the quasi-Fermi levels in \(n^+-S\) layer are small: \(\Delta F^+_s \ll qV \leq \mu^+_s\). The latter inequality follows from a very large mismatch of the carrier concentrations in the heavily doped \(n^+\)-S layer and NS region with higher resistivity: \(n_s/n^+_s = N_d/N^+_d \ll 1\).

In conclusion, we emphasize that we have demonstrated a possibility of achieving 100% spin polarization in NS via electrical spin extraction, using FM-S contacts with moderate spin injection coefficients that weakly depend on the current. The highly spin-polarized electrons, according to the results of Ref. \cite{22}, can be efficiently utilized to polarize nuclear spins in semiconductors. They can also be used to spin polarize electrons on impurity centers or in quantum dots located near the FM-S interface. These effects are important for spin-based quantum information processing \cite{2, 6, 7}. The considered FM-\(n^+-n\)-S heterostructures and FM-\(n^+-S\) contacts can be used as very efficient spin polarizers or spin filters in most of the spin devices proposed to date \cite{1, 2, 3, 4, 5}. In particular, such devices as spin-based high-frequency spin-transistors, square law detectors, frequency multipliers, magnetic sensors \cite{3}, spin-light emitting diodes (spin-LEDs) \cite{16, 23}, and spin-resonant tunneling
diodes (spin-RTDs) can be modified to significantly enhance their performance.

[1] I. Zutic, J. Fabian, and S. Das Sarma, *Spintronics: Fundamentals and applications*, Rev. Mod. Phys. 76, 323 (2004).

[2] *Semiconductor Spintronics and Quantum Computation*, edited by D. D. Awschalom, D. Loss, and N. Samarth (Springer, Berlin, 2002).

[3] S. Datta and B. Das, Appl. Phys. Lett. 56, 665 (1990); S. Gardelis, *et al.*, Phys. Rev. B 60, 7764 (1999).

[4] R. Sato and K. Mizushima, Appl. Phys. Lett. 79, 1157 (2001); X. Jiang, *et al.*, Phys. Rev. Lett. 90, 256603 (2003).

[5] V. V. Osipov and A. M. Bratkovsky, Appl. Phys. Lett. 84, 2118 (2004); A. M. Bratkovsky and V. V. Osipov, Phys. Rev. Lett. 92, 098302 (2004) and Appl. Phys. A 80, 1 (2005).

[6] M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum information* (Cambridge University Press, Cambridge, 2000).

[7] J. M. Taylor, A. Imamoglu, M. D. Lukin, Phys. Rev. Lett. 90, 246802 (2003); J. M. Taylor, C. M. Marcus, M. D. Lukin, *ibid.* 89, 206803 (2002).

[8] A. G. Aronov and G. E. Pikus, Fiz. Tekh. Poluprovodn. 10, 1177 (1976) [Sov. Phys. Semicond. 10, 698 (1976)].

[9] M. Johnson and R. H. Silsbee, Phys. Rev. B 35, 4959 (1987); M. Johnson and J. Byers, *ibid.* 67, 125112 (2003).

[10] E. I. Rashba, Phys. Rev. B 62, R16267 (2000).

[11] Z. G. Yu and M. E. Flatte, Phys. Rev. B 66, R201202 and 235302 (2002).

[12] J. D. Albrecht and D. L. Smith, Phys. Rev. B 66, 113303 (2002).

[13] V. V. Osipov and A. M. Bratkovsky, Phys. Rev. B 70, 205312 (2004).

[14] A. M. Bratkovsky and V. V. Osipov, J. Appl. Phys. 96, 4525-4529 (2004).

[15] Note that $\gamma$ is denoted as $P_J$ in Refs. [3, 13, 14] and is called the spin polarization of current in FM- S contacts.

[16] A. T. Hanbicki, *et al.*, Appl. Phys. Lett. 80, 1240 (2002); A. T. Hanbicki, *et al.*, *ibid.* 82, 4092 (2003).

[17] H. Ohno, *et al.*, Jpn. J. Appl. Phys. 42, L1 (2003).
[18] S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981).

[19] I. Zutic *et al.*, Phys. Rev. Lett. **88**, 066603 (2002).

[20] J. Stephens *et al.*, Phys. Rev. B **68**, 041307 (2003); cond-mat/0404244 (2004).

[21] This condition is not valid for tunneling FM-S junctions containing a $\delta$–doped layer and nondegenerated semiconductor layer near FM-S interface [14].

[22] R.K. Kawakami, *et al.*, Science **294**, 131 (2001); J. Strand, *et al.*, Phys. Rev. Lett. **91**, 036602 (2003).

[23] A. M. Bratkovsky and V. V. Osipov, Appl. Phys. Lett. **86**, 1111 (2005).

[24] A. G. Petukhov, *et al.*, Phys. Rev. Lett. **89**, 107205 (2002); A. G. Petukhov, *et al.*, Phys. Rev. B **68**, 125332 (2003).