Spin accumulation in degenerate semiconductors near modified Schottky contact with ferromagnets: Spin injection and extraction

V. V. Osipov[1,2] and A. M. Bratkovsky[1]
[1]*Hewlett-Packard Laboratories, 1501 Page Mill Road, 1L, Palo Alto, California 94304, USA*
[2]*New Physics Devices, NASA Ames, Moffet Field, California 94035, USA*
(Received 18 April 2005; published 20 September 2005)

We study spin transport in forward and reverse biased junctions between a ferromagnetic metal and a degenerate semiconductor with a δ-doped layer near the interface at relatively low temperatures. We show that spin polarization of electrons in the semiconductor, P_n, near the interface increases both with the forward and reverse current and reaches saturation at certain relatively large current while the spin injection coefficient, Γ, increases with reverse current and decreases with the forward current. We analyze the condition for efficient spin polarization of electrons in degenerate semiconductor near interface with ferromagnet. We compare the accumulation of spin polarized electrons in degenerate semiconductors at low temperatures with that in non-degenerate semiconductors at relatively high, room temperatures.

DOI: 10.1103/PhysRevB.72.115322 PACS number(s): 72.25.Hg

I. INTRODUCTION

The idea of solid state electronic devices using a electron spin has given rise to the field of spintronics.[1,2] Among practically important spintronic effects are the giant magnetoresistance in magnetic multilayers and the tunnel ferromagnet-insulator-ferromagnet (FM-*I*-FM) structures.[3–5] Of particular interest is injection of spin-polarized electrons into semiconductors because of large spin relaxation time[7] and a prospect of using this phenomena for the next generation of high-speed low-power electronic devices[6,8,9] and quantum computing.[1] Relatively efficient spin injection into nonmagnetic semiconductors (*S*) has been demonstrated at low temperatures in ferromagnet-semiconductor heterostructures both with metallic ferromagnets[10–12] and magnetic semiconductors[13] as the spin sources. Theoretical aspects of the spin injection have been studied in Refs. 14–26.

There are several fundamentally different types of FM-*S* junctions with the energy band diagrams shown in Fig. 1. The band diagrams depend on electron affinity of a semiconductor, χ_S, and a work function of a ferromagnet, χ_F, electron density in a semiconductor, n, and a density of surface states at the FM-*S* interface.[27] Usually, a depleted layer and a high Schottky potential barrier form in *S* near metal-semiconductor junction, Figs. 1(a) and 1(b), at $\chi_S < \chi_F$ and even when $\chi_S > \chi_F$, due to the presence of surface states on the FM-*S* interface.[27] In some systems with $\chi_S > \chi_F$, a layer with accumulated electrons can form in *S* near the FM-*S* interface, Figs. 1(c) and 1(d). Such a rare situation is probably realized in Fe—InAs junctions studied in Ref. 12. The barrier height in the usual situation [Figs. 1(a) and 1(b)] is equal to $\Delta \simeq 0.5-0.8$ eV for GaAs and Si in contacts with practically all metals, including Fe, Ni, and Co.[27,11] The barrier width, i.e., the Schottky depleted layer width, is large, $l \gtrsim 30$ nm, for doping donor concentration $N_d \lesssim 10^{17}$ cm^{-3}. The injection of spin-polarized electrons from FM into *S* corresponds to a reverse current in the Schottky contact, when positive voltage is applied to *n*-*S* region. The current in reverse-biased FM-*S* Schottky contacts is saturated and usually negligible due to such large barrier thickness and height, l and Δ.[27] Therefore, a thin heavily doped n^+-*S* layer between FM metal and *S* should used to increase the reverse current determining the spin injection.[19,25] This layer drastically reduces the thickness of the barrier, and increases its tunneling transparency.[27,25] Thus, an efficient spin injection has been observed in FM-*S* junctions with a thin n^+ layer.[11]

In forward-biased FM-*S* Schottky contacts without the thin n^+ layer, the current can reach a large value only at a bias voltage V close to Δ/q, where q is the elementary charge.[27] Realization of the spin accumulation in *S* due to such thermionic emission currents is problematic. Indeed, electrons in FM with energy $F+\Delta$ well above the Fermi level F are weakly spin polarized.

The energy band structure of FM-*S* junctions, their spin-selective and nonlinear properties have not been actually considered in majority of theoretical works on spin injection.[14–24] Authors of these prior works have developed a *linear* theory of spin injection describing the spin-selective properties of FM-*S* junctions by various, often contradictory, boundary conditions at the FM-*S* interface. For example, Aronov and Pikus assumed that a *spin injection coefficient* (spin polarization of current in FM-*S* junctions) $\Gamma = (J_\uparrow - J_\downarrow)/J$ at the FM-*S* interface is a constant, equal to that in the FM metal, and studied spin accumulation in semiconductors considering spin diffusion and drift in applied electric field.[14] The authors of Refs. 15–19 assumed a continuity of both the currents and the electrochemical potentials for both spins and found that a spin polarization of injected electrons depends on a ratio of conductivities of a FM and *S* (the so-called "conductivity mismatch" problem). At the same time, the authors of Refs. 20–24 have asserted that the spin injection becomes appreciable when the electrochemical potentials have a substantial discontinuity at the interface (produced by, e.g., a tunnel barrier).[21] However, they described this effect by the unknown constants, spin-selective interface conductances G_σ, which cannot be found within those theories. In fact, we have shown before that the parameters G_σ are not constant and can strongly depend on the applied bias voltage.[9,25]

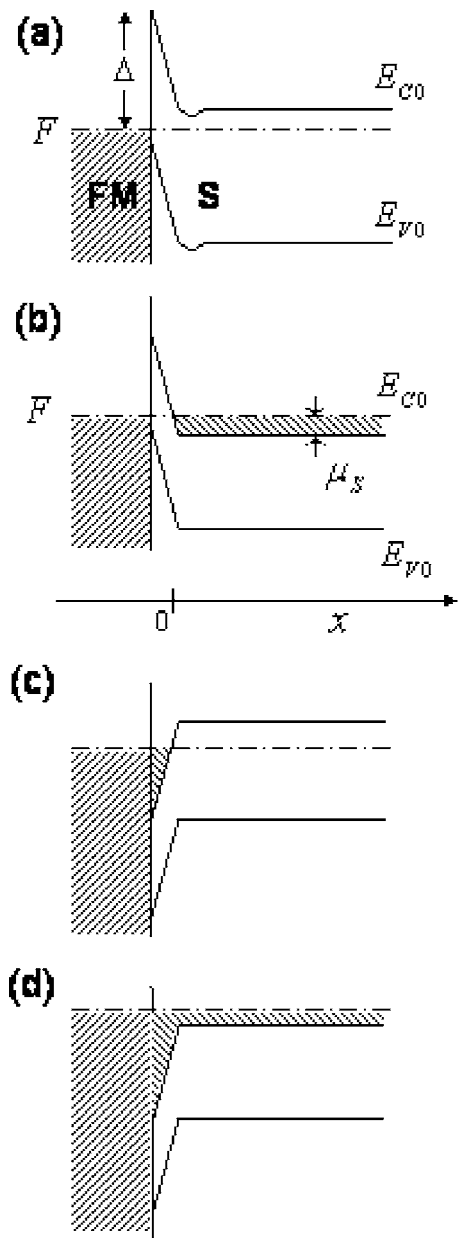

FIG. 1. Energy diagrams of modified ferromagnet-semiconductor (FM-S) junctions at equilibrium: modified Schottky contact of a FM metal with nondegenerate (a) and degenerate (b) semiconductors with a depletion layer in S near the interface. The Schottky contacts are modified by highly doped very thin semiconductor δ-doped layer between FM and S, Δ is the Schottky barrier height, μ_S is the Fermi energy in the degenerate S. Band diagrams (c) and (d) are for modified ohmic contacts of a FM metal with nondegenerate (c) and degenerate (d) semiconductors with an accumulation layer in S.

In our earlier works[9,25,26] we have studied the nonlinear spin injection in nondegenerate semiconductors near modified FM-S Schottky contacts with δ-doped layer, Fig. 1(a), at room temperature and showed that the assumptions made in Refs. 15–19 are not valid at least in that case. Here we derive the boundary conditions and study nonlinear spin injection in degenerate semiconductors near reverse-based and forward-biased FM-S Schottky contacts with an ultrathin heavily doped semiconductor layer (δ-doped layer) between FM and S, Fig. 1(b). In degenerate semiconductors, unlike in nondegenerate semiconductors studied in Refs. 25 and 26, the spin injection can occur at any (low) temperatures. We consider below the case when the temperature $T \ll \mu_S$, where $\mu_S = (F - E_{c0})$ is the Fermi energy of equilibrium electrons in S, where E_{c0} is the bottom of the conduction band in equilibrium, Fig. 1, and T is the temperature in units of $k_B = 1$.

II. SPIN TUNNELING THROUGH THIN δ-DOPED BARRIER AT THE FM-S INTERFACE

We assume that the donor concentration, N_d^+, and thicknesses, l, of the δ-doped layer satisfy the conditions $N_d^+ l^2 q^2 \simeq 2\varepsilon\varepsilon_0\Delta$ and $l \lesssim l_0$, where $l_0 = \sqrt{\hbar^2/(2m_*\Delta)}$ is a typical tunneling length ($l_0 \lesssim 2$ nm for $N_d^+ \sim 10^{20}$ cm^{-3}). The energy band diagram of such a FM-S junction includes a potential δ spike of the height Δ and the thickness l. We assume the elastic coherent tunneling through this δ layer, so that the energy E, spin σ, and the component of the wave vector $\vec{k}$ parallel to the interface, $\vec{k}_\parallel$, are conserved. In this case the tunneling current density of electrons with spin $\sigma = \uparrow, \downarrow$ near the FM-S junction containing the δ-doped layer (Fig. 1) can be written as[28,5,25,26]

$$J_{\sigma 0} = \frac{-q}{(2\pi)^3} \int d^3k [f(E_{k\sigma} - F_{\sigma 0}^f) - f(E_{k\sigma} - F_{\sigma 0}^S)] v_{\sigma x} T_{k\sigma}$$
$$= \frac{q}{h} \int dE [f(E - F_{\sigma 0}^S) - f(E - F_{\sigma 0}^f)] \int \frac{d^2 k_\parallel}{(2\pi)^2} T_\sigma, \qquad (1)$$

where $T_{k\sigma}$ is the transmission probability, $f(E)$ the Fermi function, $v_{\sigma x}$ the x component of velocity $v_\sigma = \hbar^{-1}|\nabla_k E_{k\sigma}|$ of electrons with the wave vector $\vec{k}$ and spin σ in the ferromagnet, the integration includes a summation with respect to a band index. Importantly, one needs to account for a strong *spin accumulation* in the semiconductor. Therefore, we use the *nonequilibrium* Fermi levels, $F_{\sigma 0}^f$ and $F_{\sigma 0}^S$ for electrons with spin $\sigma = \uparrow(\downarrow)$ in the FM metal and the semiconductor, respectively, near the interface, $x = 0$. In particular, the local electron density with spin σ in the degenerate semiconductor at the FM-S junction at low temperatures is given by

$$n_{\sigma 0} = \frac{2^{1/2} m_*^{3/2} M_c}{3\pi^2 \hbar^3} (F_{\sigma 0}^S - E_c)^{3/2}$$
$$= \frac{n}{2\mu_S^{3/2}} (F_{\sigma 0}^S - E_c)^{3/2} = \frac{n}{2}\left(1 + \frac{\Delta F_{\sigma 0}^S}{\mu_S}\right)^{3/2}, \qquad (2)$$

where M_c the number of effective minima of the semiconductor conduction band; E_{c0} and $E_c = E_{c0} + qV$ are the bottom of conduction band in S at equilibrium and at the bias voltage V, $\mu_S = F - E_{c0}$ is the equilibrium Fermi *energy* of the electrons in the semiconductor bulk, with F the Fermi level in FM metal bulk, $F_{\sigma 0}^S$ is the quasi Fermi level in S near the interface (point $x = 0$, Fig. 1), $\Delta F_{\sigma 0}^S = F_{\sigma 0}^S - E_c = F_{\sigma 0}^S - E_{c0} - qV$, $|\Delta F_{\sigma 0}^S| < \mu_S$, n and m_* are the concentration and effective mass of electrons in S. We note that $V > 0$ and current $J > 0$ in forward-biased FM-S junctions, i.e., J flows in x direction from FM to S when $V > 0$ (usual convention),[27] and

$V<0$ and $J<0$ in reverse biased junctions. The current (1) should generally be evaluated numerically for a complex band structure $E_{k\sigma}$.[29] The analytical expressions for $T_\sigma(E,k_\parallel)$ can be obtained in an effective mass approximation, $\hbar k_\sigma = m_\sigma v_\sigma$ where v_σ is the velocity of electrons in the FM with spin σ. This applies to "fast" freelike d electrons in elemental ferromagnets.[30,5] Approximating the δ barrier by a triangular shape, we find

$$T_\sigma = \frac{16\alpha m_\sigma m_* k_{\sigma x} k_x}{m_*^2 k_{\sigma x}^2 + m_\sigma^2 \kappa^2} e^{-\eta\kappa l} = \frac{16\alpha v_{\sigma x} v_x}{v_{\sigma x}^2 + v_{tx}^2} e^{-\eta\kappa l}, \qquad (3)$$

where $\kappa = (2m_*/\hbar^2)^{1/2}(\Delta + F - E + E_\parallel)^{3/2}/(\Delta - qV)$, $E_\parallel = \hbar^2 k_\parallel^2/2m_*$, $v_x = \sqrt{2(E - E_c - E_\parallel)/m_*}$ is the x component of the velocity of electrons in S, $\hbar k_x = v_x m_*$, $v_t = \hbar\kappa/m_*$ the "tunneling" velocity, $\alpha = \pi(\kappa l)^{1/3}[3^{1/3}\Gamma^2(\frac{2}{3})]^{-1} \simeq 1.2(\kappa l)^{1/3}$, $\eta = 4/3$ (for comparison, for a rectangular barrier $\alpha = 1$ and $\eta = 2$), $\theta(x) = 1$ for $x > 0$, and zero otherwise. The preexponential factor in Eq. (3) takes into account a mismatch between effective mass, m_σ and m_*, and velocities, $v_{\sigma x}$ and v_x, of electrons in the FM and the S. Obviously, only the states with $E_{k\sigma} > E_c$ are available for transport.

We obtain the following expression for the current at the temperature $T \ll \mu_S$ with the use of Eqs. (1) and (3), noting that the electron velocity in the semiconductor is singular near $E = E_c$,

$$J_{\sigma 0} = \frac{2\pi q m_* M_c}{h^3}\left[\int_{E_c}^{F_{\sigma 0}^S} dE \int_0^{E-E_c} dE_\parallel T_\sigma - \int_{E_c}^{F_{\sigma 0}^f} dE \int_0^{E-E_c} dE_\parallel T_\sigma\right], \qquad (4)$$

where the second integral corresponds to electrons tunneling from the metal into semiconductor that can only take place when $F_{\sigma 0}^f > E_c$. As a rule, $v_{\sigma x}$ and v_{tx} are smooth functions over E in range $E = F \pm \mu_S$ of interest to us in comparison with a singular v_x. At not very large bias voltages of interest, $|V| \lesssim \Delta/q$ all factors but v_x can be taken outside of integration. We obtain, therefore, from (2) and (4) the expression

$$J_{\sigma 0} = \frac{32\pi\alpha_0 q m_* M_c v_\sigma}{h^3(v_\sigma^2 + v_t^2)} e^{-\eta\kappa_0 l} \times \left[\int_{E_c}^{F_{\sigma 0}^S} dE \int_0^{E-E_c} dE_\parallel v_x - \theta(F_{\sigma 0}^f - E_c)\int_{E_c}^{F_{\sigma 0}^f} dE \int_0^{E-E_c} dE_\parallel v_x\right], \qquad (5)$$

which with use Eq. (2) can be finally written as

$$J_{\sigma 0} = j_0 d_\sigma\left[\left(1 + \frac{\Delta F_{\sigma 0}^S}{\mu_S}\right)^{5/2} - \left(1 + \frac{\Delta F_{\sigma 0}^f - qV}{\mu_S}\right)^{5/2}\theta(\mu_S + \Delta F_{\sigma 0}^f - qV)\right], \qquad (6)$$

where

$$j_0 = \tfrac{4}{5} q n v_F^S \alpha_0 \exp(-\eta\kappa_0 l), \qquad (7)$$

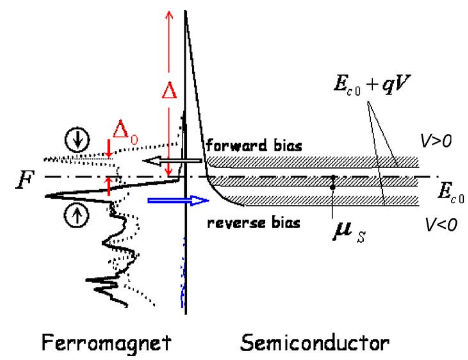

FIG. 2. (Color online) Energy diagram of the modified Schottky junction between a FM metal and an n-type degenerate semiconductor with δ-doped layer at equilibrium (zero bias, $V=0$) and at reverse (forward) bias voltage $qV \simeq \Delta_{\downarrow(\uparrow)}$. F is the Fermi level in FM, Δ is the barrier height, μ_S is the Fermi energy in S, $E_{c0}(x)$ is the bottom of the conduction band of the semiconductor at equilibrium. Left (right) bold horizontal arrows show a flux of electrons at forward (reverse) bias voltage. The corresponding states in FM are dominated by minority (majority) electrons and this may lead to an accumulation of the spins of the same sign in the semiconductor at respective forward and reverse bias voltages.

$$d_\sigma = \frac{v_F v_{\sigma 0}}{v_{t0}^2 + v_{\sigma 0}^2}. \qquad (8)$$

Here $\kappa_0 \equiv 1/l_0 = (2m_*/\hbar^2)^{1/2}(\Delta - qV)^{1/2}$; $\alpha_0 = 0.96(\kappa_0 l)^{1/3}$; $v_F^S = \sqrt{2\mu_S/m_*}$ is the velocity of electrons in the degenerate semiconductor, $v_{\sigma 0} = v_\sigma$ the velocity of electrons in the FM (taken at $E=F$ and $F+qV$ for reverse and forward bias voltages, respectively, see below), $v_{t0} = \sqrt{2(\Delta - qV)/m_*}$, and $\Delta F_{\sigma 0}^f = F_{\sigma 0}^f - F$ is the splitting of the quasi Fermi level $F_{\sigma 0}^f$ for nonequilibrium electrons with spin $\sigma = \uparrow(\downarrow)$ in FM metal. We notice that only spin factor d_σ determines the dependence of current on materials parameters of a ferromagnet. The need for a different choice of $v_{\sigma 0}$ for forward and reverse bias voltage is evident from Fig. 2. At forward bias the electrons tunnel from the semiconductor into the states in the ferromagnetic metal at $E = F + qV$, so there $v_{\sigma 0} \approx v_\sigma(F+qV)$. At reverse bias voltage ($V<0$) the electrons tunnel to the semiconductor in the interval of energies $E_{c0} + qV < E < F$. In this case the effective tunnel barrier height is smallest for electrons with energies $E \approx F$, so $v_{\sigma 0} \approx v_\sigma(F)$. Moreover, at reverse bias a spatial charge starts to buildup in semiconductor and a wide barrier forms at energies $E < E_{c0}$. Therefore, only electrons in narrow energy range $E_{c0} - \mu_S < E < F$ can tunnel, and the reverse current practically saturates at $V < -\mu_S/q$.

Finally, we can present the currents of electrons with spin $\sigma = \uparrow(\downarrow)$ at the interface in the following useful form:

$$J_{\uparrow(\downarrow)0} = \frac{J_{m0}}{2}(1 \pm P_F)\left[(1 \pm P_n)^{5/3} - \left(1 + \frac{\Delta F_{\sigma 0}^f - qV}{\mu_S}\right)^{5/2}\theta(\mu_S + \Delta F_{\sigma 0}^f - qV)\right], \qquad (9)$$

where

$$J_{m0}=(d_\uparrow+d_\downarrow)j_0=\tfrac{4}{5}(d_\uparrow+d_\downarrow)qnv_F^S\alpha_0\exp(-\eta\kappa_0 l) \quad (10)$$

and

$$P_F=\frac{d_\uparrow-d_\downarrow}{d_\uparrow+d_\downarrow}=\frac{(v_{\uparrow0}-v_{\downarrow0})(v_{t0}^2-v_{\uparrow0}v_{\downarrow0})}{(v_{\uparrow0}+v_{\downarrow0})(v_{t0}^2+v_{\uparrow0}v_{\downarrow0})}. \quad (11)$$

As we see below the value of P_F determines maximum spin polarization.

At small bias voltage qV when $\Delta F_{\sigma0}^S$, and $\Delta F_{\sigma0}^f$ are much smaller than μ_S, and by linearizing Eq. (6) we obtain

$$J_{\sigma0}=\tfrac{5}{2}j_0d_\sigma(\Delta F_{\sigma0}^S+qV-\Delta F_{\sigma0}^f)/\mu_S=G_\sigma(\zeta_{\sigma0}^S-\zeta_{\sigma0}^f), \quad (12)$$

where $\zeta_{\sigma0}^S=F+qV+\Delta F_{\sigma0}^S$ and $\zeta_{\sigma0}^f=F+\Delta F_{\sigma0}^f$ are the electrochemical potentials at the FM-S interface in the semiconductor and ferromagnet, respectively, $G_\sigma=\frac{5}{2}j_0d_\sigma/\mu_S$ is the spin-selective interface linear conductance. It is worth noting that if we were to use the assumption of Refs. 15–19 about a continuity of the electrochemical potentials at FM-S junction, $\zeta_{\sigma0}^S=\zeta_{\sigma0}^f$, we must have concluded that no current flows through the junction, $J_{\sigma0}=0$. We note that the boundary condition similar to Eq. (12) was used in a linear theory of spin injection in Refs. 20–22 and 24, where G_σ were introduced as some phenomenological constants. Here, we have found the explicit expressions for the spin conductances G_σ for the FM-S junction under consideration. Obviously, G_σ, as well as $\zeta_{\sigma0}^S$ and $\zeta_{\sigma0}^f$, are not universal and depend on all specific parameters of the junctions, Fig. 1 (cf. Ref. 25). Moreover, the conclusions drawn from the linear approximation strongly differ from the results of a full nonlinear analysis provided below (see also Ref. 25).

Importantly, we can neglect the quasi-Fermi splitting in FM metal compared to that in the semiconductor because the density of electrons in the FM metal is several orders of magnitude larger that in real semiconductors. It is easy to prove that $\Delta F_{\sigma0}^f\ll qV$ for the currents of interest to us (see Appendix A), therefore we can simplify the expression (9) for tunneling currents of spin-polarized electrons as

$$J_{\uparrow(\downarrow)0}=\frac{J_{m0}}{2}(1\pm P_F)\left[(1\pm P_n)^{5/3}-\left(1-\frac{qV}{\mu_S}\right)^{5/2}\theta(\mu_S-qV)\right]. \quad (13)$$

III. INJECTED AND EXTRACTED SPIN POLARIZATION IN A DEGENERATE SEMICONDUCTOR

The assumption of elastic coherent tunneling means a continuity of the currents $J_{\sigma0}$ of spin-polarized electrons through the FM-S junction. In this case the FM-S junction can be characterized by the *spin injection coefficient* Γ according to the definition

$$\Gamma=(J_{\uparrow0}-J_{\downarrow0})/J, \quad (14)$$

where $J_{\sigma0}\equiv J_\sigma(0)$ are the currents of electrons with $\sigma=\uparrow(\downarrow)$ near the FM-S interface, Fig. 1. Notice that Γ is the spin polarization of a current in the FM-S junction, therefore we used symbol P_J instead of Γ in our earlier papers.[9,25,26]

The following derivation of bispin diffusion applies to both semiconductor and ferromagnet based on an assumption of *quasineutrality* (see Appendix A). The current J_σ is given by

$$J_\sigma=\sigma_\sigma E+qD_\sigma dn_\sigma/dx, \quad (15)$$

where $\sigma_\sigma=q\mu_\sigma n_\sigma$, D_σ, μ_σ, and n_σ are the conductivity, the diffusion constant, the mobility and the density of electrons with spin $\sigma=\uparrow(\downarrow)$, respectively, E the electric field in S or FM. We assume *quasineutrality*, $n=n_\uparrow(x)+n_\downarrow(x)=\text{const}$ and later prove that it holds very well indeed (see Appendix A) and a continuity of the total current, $J=J_\uparrow(x)+J_\downarrow(x)=\text{const}$, so that one has

$$\delta n_\uparrow=n_\uparrow-n_\uparrow^0=-\delta n_\downarrow, \quad (16)$$

and for the electric field

$$E=\frac{J}{\sigma}-\frac{q(D_\uparrow-D_\downarrow)}{\sigma}\frac{d\delta n_\uparrow}{dx}, \quad (17)$$

where $\sigma=\sigma_\uparrow+\sigma_\downarrow=q(\mu_\uparrow n_\uparrow+\mu_\downarrow n_\downarrow)$ is the total conductivity of S or FM. Substituting (17) into (15), we find

$$J_{\uparrow(\downarrow)}=\frac{\sigma_{\uparrow(\downarrow)}}{\sigma}J+q\bar{D}\frac{d\delta n_{\uparrow(\downarrow)}}{dx}, \quad (18)$$

where $\bar{D}=(\sigma_\uparrow D_\downarrow+\sigma_\downarrow D_\uparrow)/\sigma$ is the *bispin diffusion* constant for the semiconductor or ferromagnet.

The bispin diffusion that appears in the case of degenerate semiconductors is different in comparison with nondegenerate semiconductor where D_σ and μ_σ do not depend on spin orientation (see Refs. 14, 18, and 25). In degenerate semiconductors we need to account for the density dependence of the diffusion constant. We will assume that the relaxation time of electron momentum τ weakly depends on a quasi-Fermi level (i.e., on electron density). Therefore, the mobility of electrons μ_σ in nonmagnetic semiconductors in question weakly depends on the electron density. In this case we can put $\mu_\sigma=\mu$, $\sigma_\sigma=\sigma n_\sigma/n$, and $D_\sigma=(1/3)v_\sigma^2\tau=D_0(2n_\sigma/n)^{2/3}$ at low temperature, where D_0 and σ are the diffusion coefficient in a nonpolarized semiconductor and the total conductivity of the semiconductor, respectively. The account for a density-dependent diffusion coefficient gives the following expression for the bispin diffusion coefficient:

$$\bar{D}[n]=D_0\left[\frac{n_\uparrow}{n}\left(\frac{2n_\downarrow}{n}\right)^{2/3}+\frac{n_\downarrow}{n}\left(\frac{2n_\uparrow}{n}\right)^{2/3}\right]\equiv D_0u(P_n), \quad (19)$$

where

$$u=\tfrac{1}{2}[(1+P_n)(1-P_n)^{2/3}+(1-P_n)(1+P_n)^{2/3}], \quad (20)$$

and we have introduced the spin polarization of electrons

$$P_n=\frac{n_\uparrow-n_\downarrow}{n_\uparrow+n_\downarrow}=\frac{2\delta n_\uparrow}{n}. \quad (21)$$

When the polarization is small, $P_n\ll1$ (as is always the case at distances $x\gtrsim L_s$ from the interface), the bispin diffusion coefficient has only quadratic corrections to the usual diffusion coefficient, $\bar{D} \approx D_0[1-(7/9)P_n^2]$, and $\bar{D}$ is quite close to the diffusion coefficient in a nondegenerate semiconductor D_0.

In nonmagnetic semiconductors the electron density n_σ is determined by the continuity equation[14,18]

$$dJ_\sigma/dx = q\delta n_\sigma/\tau_s, \tag{22}$$

where $\delta n_\sigma = n_\sigma - n/2$, n is the total density of equilibrium electrons, τ_s is spin-coherence lifetime of electrons in S. The expression for current (18) now gives

$$\frac{J}{n}\frac{dn_\sigma}{dx} + q\frac{d}{dx}\left(\bar{D}[n]\frac{dn_\sigma}{dx}\right) = \frac{q\delta n_\sigma}{\tau_s}. \tag{23}$$

We can rewrite this as an equation for the polarization distribution $P_n(x)$, using $\delta n_\uparrow = -\delta n_\downarrow$ and $n_\uparrow/n = (1+P_n)/2$, as

$$\frac{J}{J_s}\frac{dP_n}{d\tilde{x}} + \frac{d}{d\tilde{x}}\left(u\frac{dP_n}{d\tilde{x}}\right) = P_n, \tag{24}$$

where $\tilde{x} = x/L_s$ is the dimensionless coordinate and

$$L_s = \sqrt{D_0\tau_s}, \quad J_S = \frac{qnD_0}{\tau_s} = \frac{qnL_s}{\tau_s}, \tag{25}$$

are the typical spin-diffusion length and the characteristic current density. It is very convenient to rewrite the spin currents (18) through P_n as

$$J_{\uparrow(\downarrow)} = \frac{J}{2}(1 \pm P_n) \pm \frac{J_s}{2}u\frac{dP_n}{d\tilde{x}}. \tag{26}$$

The spin currents at the interface $x=0$ should be equal to the tunneling spin currents through FM-S junction given by Eq. (13). With the use $J = J_\uparrow(x) + J_\downarrow(x) = \text{const}$, this gives the main boundary condition at the interface

$$\frac{J}{J_s}(P_{n0} - P_F) + u\left(\frac{dP_n}{d\tilde{x}}\right)_{x=0} = \frac{J_m}{2J_s}[(1+P_{n0})^{5/3} - (1-P_{n0})^{5/3}], \tag{27}$$

where

$$J_m = J_{m0}(1-P_F^2), \tag{28}$$

$P_{n0} = P_n(x=0)$ the spin polarization next to the interface. It is easy to see that Eq. (24) becomes linear ($u=1$) away from the interface where $P_n(x) \to 0$. Therefore, it has an asymptotic behavior[14,18,25]

$$P_n(x) = A\exp(-x/L), \quad \text{when } x \gg L, \tag{29}$$

$$L/L_s = \sqrt{1+(J/2J_S)^2} - J/2J_S, \tag{30}$$

where coefficient A would have been equal $A = P_{n0}$ for $u=1$ ($D_\sigma = D_0$ case) like in a nondegenerate semiconductor.[25] The stationary polarization distribution $P_n(x)$ is found from Eq. (24) solved with the boundary conditions (27) and (29).

Interestingly, the effect of *nonlinearity of the diffusion coefficient* in degenerate semiconductors, given by the function $u(P_n)$ in Eq. (20), appears *to be very small*. This is confirmed by comparing the solution of (24) with the case of constant diffusion coefficient, $u=1$, but we first give simple arguments why this is so. Nonlinearity could have only been important in Eq. (24) when the polarization is close to unity, $P_{n0} \approx 1$, so that $u \ll 1$. At the same, relatively large P_{n0} can only be achieved at a large current $J \gg J_S$ and a large polarization in ferromagnet, $P_F \approx 1$ (i.e., for a half-metallic FM),[5] but even in this case P_n remains considerably smaller than P_F, see Fig. 3 and the discussion below. As a result, the polarization dependence of the diffusion changes the polarization profile $P_n(x)$ very little, see Fig. 3 where we compare the exact polarization profile with that for $\bar{D} = D_0$.

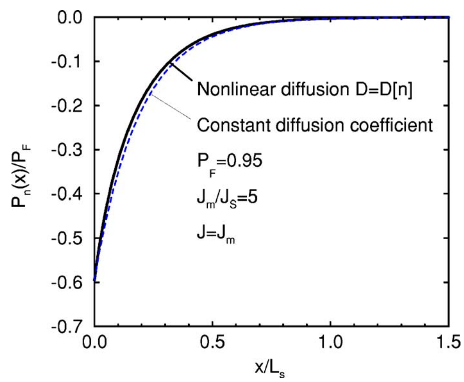

FIG. 3. (Color online) Spatial profiles of accumulated polarization with a full account for nonlinear density dependence of diffusion coefficient ($\bar{D} = \bar{D}[n]$, numerical solution) and for constant diffusion coefficient ($\bar{D} = \bar{D}_0$, analytical solution) for $P_F = 0.95$, $J_m/J_S = 5$ and $J = J_m$ (forward bias). Note that in this case the spin penetration length is $L \approx L_s J_S/J_m = \frac{1}{5}L_s$ so that the spin accumulation layer is squeezed towards the interface.

We study the current dependence of the polarization in Fig. 4. It illustrates two important points: (i) the effect of P_F, the polarization of injected carriers in a semiconductor and (ii) the effect of having different maximal currents through the structure J_m in comparison with the characteristic current density J_S. We see that the difference between the polarization dependent and independent diffusion coefficients is minute at all parameters. A small difference is only present for the spin extraction near maximal current $J \approx J_m$ for $J_m/J_S = 5$ where the nonlinearity in the diffusion coefficient slightly reduces the extracted polarization. In the opposite case of relatively small maximal current, $J_m/J_S = 0.2$, the difference in polarizations is not discernible at all. The case of $J_m/J_S \gg 1$ is of most interest to us, since there the absolute value of the accumulated polarization is maximal. The overall behavior of the injected/extracted polarization with the current is similar to the one we found for nondegenerate semiconductors.[9,26]

Since we have determined that the density dependence of the diffusion coefficient in a semiconductor has little effect, the solution of the kinetic equation (24) reduces to (29) and (30), where the prefactor $A = P_{n0}$. The boundary condition (27) then simplifies to

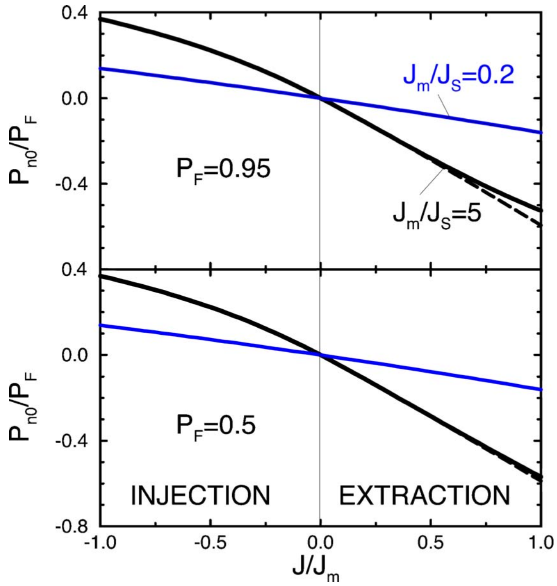

FIG. 4. (Color online) Current dependence of spin polarization near the FM-*S* interface P_{n0}/P_F for two polarizations of a ferromagnet $P_F=0.95$ (top panel) and $P_F=0.5$ (bottom panel) for two values of the dimensionless parameter $J_s/J_m=5$ and 0.2. The broken curve is for P_{n0} for the case where the density dependence of the diffusion coefficient has been neglected ($\bar{D}=D_0$). Although the absolute values of accumulated polarization are very different, the relative polarizations, P_{n0}/P_F are almost independent of P_F.

$$P_{n0}\frac{L}{L_s}+\frac{J_m}{2J_S}[(1+P_{n0})^{5/3}-(1-P_{n0})^{5/3}]=-P_F\frac{J}{J_S}. \tag{31}$$

This is similar to the case of nondegenerate semiconductor, the difference being the term in square brackets, which is specific for the degenerate semiconductor.

General analytical solution for polarization P_{n0} is readily found by noticing that the right hand side of Eq. (31) is very close to a linear function of P_{n0} at all values of parameters. Therefore, a general solution for the polarization in degenerate semiconductor can be written very accurately as

$$P_{n0}=-P_F\frac{3J}{3J_SL/L_s+5J_m}=-P_F\frac{6J}{3(\sqrt{J^2+4J_S^2}-J)+10J_m}. \tag{32}$$

As expected, P_{n0} vanishes with current, $P_{n0}\propto -J$ when $|J|<J_S$, and increases in absolute value when the current approaches maximum. It follows from Eq. (32) that the polarization can reach an absolute maximum only when $J_m \gg J_S$, where the maximal *injected* polarization is $P_{n0}(-J_m)=\frac{3}{8}P_F$, and the maximal *extracted* polarization is $P_{n0}(J_m)=-0.6P_F$.

The solution for P_{n0} (32) together with the expression for current (13) allows one to obtain the *I*-*V* curve. The closed expression for the *I*-*V* curve can be obtained in the case of small bias voltage $|qV|\lesssim\mu_S$, where $|P_{n0}|\ll 1$:

$$J=\frac{J_{m0}(5J_m+3J_SL/L_s)}{5J_{m0}+3J_SL/L_s}\left[1-\left(1-\frac{qV}{\mu_S}\right)^{5/2}\right], \tag{33}$$

where according to (10) J_{m0} and J_m depend on V. Equation (33) is a transcendental one, but at $|qV|\ll\mu_S$ when $|J|\ll J_S$ we have $L/L_s\approx 1$, and it becomes an expression for the current that starts as an Ohmic law

$$J=\frac{5qJ_{m0}(5J_m+3J_SL/L_s)}{2\mu_S(5J_{m0}+3J_SL/L_s)}V \tag{34}$$

and then deviates from it at larger bias.

The behavior of injection coefficient Γ is very different compared to the polarization. Using the relation (26) for $u=1$ (neglecting the polarization dependence of the diffusion coefficient) and Eqs. (32), (25), and (30) we find a relation between the injection coefficient Γ (polarization of current) and the polarization of density P_n,

$$\Gamma\equiv\frac{J_\uparrow-J_\downarrow}{J}=-P_{n0}\frac{J_sL}{JL_s}=3P_F\frac{\sqrt{J^2+4J_S^2}-J}{3(\sqrt{J^2+4J_S^2}-J)+10J_m}. \tag{35}$$

The injection coefficient does not vanish with current, but tends to a finite value

$$\Gamma=\frac{3P_FJ_S}{3J_S+5J_m}\ \text{when } J=0. \tag{36}$$

In order to maximize the polarization P_{n0}, according to Eq. (32), one needs to use the modified Schottky contact with $J_m\gg J_S$ (transparent for tunneling electrons), where the injection coefficient would be very small, $\Gamma(J\to 0)\approx 0.6P_FJ_S/J_m\ll P_F$. In this case, at large forward current $\Gamma(J_m)=\frac{3}{5}P_F(J_S/J_m)^2\ll 1$, so the spin injection coefficient practically vanishes in spin *extraction* regime (in other words, the polarization of *current* vanishes). Very differently, under reverse bias voltage $\Gamma(-J_m)=P_{n0}=\frac{3}{8}P_F$, so that the polarization of the *injected* current is large. Note that here we still assume that the densities of carriers in the FM metal and the degenerate semiconductor are vastly different, so that there is a clear conductivity mismatch and yet the spin injection proceeds very efficiently. On the other hand, if we were to make the contact opaque, where $J_m\ll J_S$, the polarization of electrons, according to Eq. (32), would become minute, $P_{n0}\ll 1$, since the current through the structure becomes very small compared to the characteristic current that polarizes electrons, J_S. But at the same time, the injection coefficient becomes large, $\Gamma=P_F$. This is the same behavior as observed in FM-*I*-FM tunnel junctions:[5] relatively thick tunnel barriers facilitate strong polarization of *current* but the accumulated spin polarization remains very small since the current density is insufficient.

The described behavior of the polarization and the injection coefficient is very important for proper understanding of the behavior of spintronic structures. In particular, we have demonstrated once again an ill-conceived nature of the conductivity mismatch problem.[17] The condition of the maximum spin accumulation in semiconductor, $J_m\gg J_S$, in accordance with Eqs. (10), (28), and (25) can be written down as

$$\alpha_0(1-P_F^2)(d_{\uparrow 0}+d_{\downarrow 0})\frac{\tau_s v_T}{L_s}\exp\left(-\frac{\eta l}{l_0}\right) \gg 1. \qquad (37)$$

This condition can be rewritten with the use of Eq. (33) at $qV \ll \mu_S$ as

$$r_c \ll L_s/\sigma_S, \qquad (38)$$

where $r_c=(dJ/dV)^{-1}$ is the tunneling contact resistance. We emphasize that Eq. (38) is opposite to the condition of maximum of current spin polarization found in Ref. 21 for small currents. At $r_c \gg L_s/\sigma_S$, i.e., when $J_m \ll J_S$, as we noted above, a degree of spin accumulation in the semiconductor is very small, $P_n \ll 1$, but exactly this P_n is the characteristic that determines chief spin effects.[1,6,8,25] Note that the condition (38) does not depend on the electron concentration, therefore it coincides with that for nondegenerate semiconductors (see Ref. 25).

IV. DISCUSSION

We obtained an analytical solution for spin injection/extraction for degenerate semiconductor in addition to numerical results for nonlinear spin diffusion. The nonlinear dependence of the bispin diffusion coefficient in semiconductor on accumulated polarization appears to be small. We emphasize that the value of P_F (11) determining maximum spin polarization of the FM-S junction depends on bias voltage V, because the spin factor d_σ given by Eq. (8) is determined by $v_{\sigma 0}=v_\sigma(F+qV)$. Since usually $v_{\sigma 0}>v_{t0}$, the spin factor $d_\sigma \propto v_{\sigma 0}^{-1}$. In a metal, as a rule, $v_{\sigma 0}^{-1}\propto g_{\sigma 0}=g_\sigma(F+qV)$, therefore $d_\sigma \propto g_\sigma(F+qV)$, where $g_{\sigma 0}=g_\sigma(F+qV)$ is the density of states of the d electrons with spin σ and energy $E=F+qV$ in the ferromagnet. Thus, assuming $m_\sigma=m$ we find from Eq. (11) that $P_F\approx(g_{\uparrow 0}-g_{\downarrow 0})/(g_{\uparrow 0}+g_{\downarrow 0})$. The polarization of d electrons in elemental ferromagnets Ni, Co, and Fe is reduced by the current of unpolarized s electrons rJ_s, where $r<1$ is a factor (roughly the ratio of the number of s bands to the number of d bands crossing the Fermi level). Together with the contribution of s electrons the polarization parameter P_F is approximately

$$P_F=\frac{J_{\uparrow 0}-J_{\downarrow 0}}{J_{\uparrow 0}+J_{\downarrow 0}+J_{s0}} \simeq \frac{J_{\uparrow 0}-J_{\downarrow 0}}{J_{\uparrow 0}+J_{\downarrow 0}+2rg_{s0}}. \qquad (39)$$

We note that such a relation for P_F can be obtained from a standard "golden-rule" type approximation for tunneling current that is supposed to be proportional to the density of states $g_\sigma(E)$ (cf. Refs. 27 and 31–33). The density of states $g_\downarrow$ for *minority* d electrons in Fe, Co, and Ni has a large peak at $E=E_F+\Delta_\downarrow$ ($\Delta_\downarrow\simeq 0.1$ eV), much larger than $g_\uparrow$ for the majority d electrons and g_s for s electrons,[34,35] Fig. 2. Therefore, the spin polarization and spin injection coefficient can potentially achieve a large value of $|P_F|$ in the forward-biased FM-S at a bias voltage $qV=\Delta_\downarrow$ (Fig. 2). In reverse biased junctions the situation is different in that most effective tunneling is by electrons in FM with energies close to the Fermi level, $E\simeq F$ where the polarization of carriers is positive, $P_F=40–50\%$ (Ref. 35) and a good fraction of it may be injected into a semiconductor. In this case the excess of majority spins may be created in semiconductor for both reverse (injection) and forward (extraction) bias voltages. This implies a complex dependence of accumulated spin polarization on a bias voltage.

V. CONCLUSION

Let us compare spin injection in the modified Schottky FM-S junctions with degenerate semiconductor at low temperatures with nondegenerate semiconductors at large (room) temperature. In both cases the process of spin injection/extraction strongly depends on current density and is generally nonlinear. The condition for most efficient spin accumulation is similar in both cases, $J_m \gg J_S$, that sets constraints on materials parameters, see Eq. (37). We have studied this case for both reverse[25] and forward bias voltages.[26]

We have shown that the spin injection in reverse-biased FM-S junctions differs from that in the forward-biased junctions. In the reverse-biased junctions spin polarization of injected electrons, P_{n0}, and spin injection coefficient, Γ, increase with current up to a maximum $P_{n0}(-J_m)=\Gamma(-J_m)=\frac{3}{8}P_F$, where P_F is the polarization of ferromagnet, Fig. 4. In forward-biased FM-S junctions the polarization approaches $P_{n0}(J_m)=-0.6P_F$ at large currents in a shrinking region with the width $L\propto 1/J$. In this case the spin injection coefficient is small, $\Gamma=0.6P_FJ_S/J_m\ll 1$ already at $J=0$, and decreases at large current, $\Gamma(J_m)=0.6P_F(J_S/J_m)^2\ll 1$. Analogous results are obtained in Refs. 25 and 26 for the FM-S junctions with nondegenerate semiconductors, with the only difference that $\Gamma=P_F$ at forward current when the minority electrons are extracted into the energy region with a peak in the density of states. The I-V characteristics for Schottky contacts with degenerate and nondegenerate semiconductors are also quite different.

It is worth mentioning a different dependence of effective polarization of ferromagnet P_F (11) on bias voltage in both cases. In a nondegenerate semiconductor P_F corresponds to the electron energy $E=E_{c0}+qV>F$, whereas in a degenerate semiconductor to $E=F+qV$. The value of $|P_F|$ for the nondegenerate semiconductor can reach its maximum at a reverse bias voltage $qV\simeq E_{c0}-F-\Delta_\downarrow$ ($\Delta_\downarrow\simeq 0.1$ eV) while for degenerate semiconductor P_F can have the same large value at a forward voltage $qV\simeq\Delta_\downarrow$, Fig. 2. In a nondegenerate semiconductor, P_F has the same sign practically independently of the bias while in the degenerate semiconductor P_F may change sign with bias voltage and, at least potentially, can become close to unity at the forward bias $qV\simeq\Delta_\downarrow$, but not at a reverse bias. Under reverse bias voltage, the electrons are injected into the degenerate semiconductor from states in the ferromagnet with energies $E\simeq F$, where their polarization is $\simeq 40\%-50\%$. The predicted strong dependence of accumulated polarization on bias voltage can be exploited in order to reveal possible effect of peaks in the density of states. Indeed, if the filling of the conduction band of the degenerate semiconductor is relatively small, $\mu_S \ll 0.1$ eV$\sim\Delta_\downarrow$, as is usually the case, then by changing the forward bias one could "scan" the density of states in FM with a "resolution" $\mu_S\ll\Delta_\downarrow$, Fig. 2. One may see an increase in current and a maximum in an extracted polarization at

$qV=\Delta_{\downarrow}$. Interestingly, one may expect a sign change of the polarization in FM-S modified Schottky contact with a degenerate semiconductor S.

APPENDIX A: ELECTRONEUTRALITY

A deviation from the quasineutrality is determined by the continuity equations (22) with the Poisson equation (in CGS units)

$$dE/dx = -q\Delta n/4\pi\epsilon, \tag{A1}$$

where ϵ is the dielectric constant of the material and $\Delta n = n_{\uparrow}+n_{\downarrow}-n$ is the deviation of electron density from equilibrium one. We show here that $\Delta n \ll n_{\uparrow}, n_{\downarrow}$ and, therefore, the deviation from electroneutrality Δn can be neglected. To this end, we substitute the expression for the electric field, Eq. (17) into (A1) and obtain the following estimate:

$$\Delta n = \frac{\epsilon}{4\pi q}\frac{dE}{dx} = \epsilon\frac{(D_{\uparrow}-D_{\downarrow})}{4\pi\sigma}\frac{d^2\delta n_{\uparrow}}{dx^2},$$

$$|\Delta n| \sim \frac{\epsilon D_0}{4\pi\sigma}\frac{\delta n_{\uparrow}}{L_s^2} \sim n\left(\frac{L_{TF}}{L_s}\right)^2, \tag{A2}$$

where $L_{TF}=(\epsilon D_0/4\pi\sigma)^{1/2}=(\epsilon/4\pi q g_F)^{1/2}$ is the screening length in the degenerate semiconductor (Thomas-Fermi length). We have used the Einstein relation $\sigma=q^2Dg_F$, where g_F is the density of states at the Fermi level. Finally, the required estimate for deviations from electroneutrality becomes

$$\frac{|\Delta n|}{n} \sim \left(\frac{L_{TF}}{L_s}\right)^2 \ll 1. \tag{A3}$$

For example, in Si at doping $n\sim 10^{17}\ \mathrm{cm}^{-3}$ the screening length is $L_{TF}\sim 30$ Å and with $L_s \sim 1\ \mu$m one obtains $\Delta n/n \sim 10^{-5}$, a very small deviation from electroneutrality indeed that can be safely neglected (cf. this with attempts to account for deviations from electroneutrality in Ref. 2).

APPENDIX B: QUASI-FERMI LEVEL SPLITTING IN FERROMAGNET AND SEMICONDUCTOR

Let us prove that we indeed can neglect the splitting of the quasi-Fermi level in FM metal, $\Delta F_{\sigma 0}^f$, compared to the splitting of the quasi-Fermi level in semiconductor $\Delta F_{\sigma 0}^S$ for the FM-S junction under consideration. Since we can neglect the electric field in FM metal, the distribution of spin polarized electrons is determined by their diffusion: $\delta n_{\uparrow}^f(x) = \delta n_{\uparrow 0}^f \exp(x/L_f)$ in FM, i.e., in the region corresponding to $x<0$, Fig. 1. Thus, according to (18) the currents of spin polarized electrons in FM near FM-S interface are

$$J_{\uparrow(\downarrow)0} = \frac{\sigma_{\uparrow(\downarrow)0}^f}{\sigma}J + (-)\frac{qL_f}{\tau_s}\delta n_{\uparrow 0}^f. \tag{B1}$$

We find from (B1) and (14) that $J_{\uparrow 0}\equiv(1+\Gamma)J/2=(1+P_{FM})J/2+qL_f\delta n_{\uparrow 0}^f/\tau_s^f$, which gives

$$\delta n_{\uparrow 0}^f = J(\Gamma - P_{FM})\tau_s^f/2qL_f, \tag{B2}$$

where we have introduced

$$P_{FM} = (\sigma_{\uparrow}^f - \sigma_{\downarrow}^f)/\sigma^f, \tag{B3}$$

the spin polarization of a current in the FM bulk. Thus, if we were to make the same assumption as Aronov and Pikus in Ref. 14 that $\Gamma=P_{FM}$, we would have obtained $\delta n_{\uparrow 0}^f=0$ and, consequently, $\Delta F_{\sigma 0}^f=0$. In other words, there would be no splitting at all of the Fermi levels in a ferromagnet in Aronov-Pikus approximation. In reality, there is a splitting of the quasi-Fermi levels in FM, but it is usually small compared to the splitting in the semiconductor (see estimates below). This allows us to considerably simplify the description of the spin injection/extraction.

According to Eqs. (B2) and (35),

$$\left|\frac{\delta n_{\uparrow 0}^f}{\delta n_{\uparrow 0}}\right| = \gamma\left|\frac{\Gamma - P_{FM}}{\Gamma}\right|, \tag{B4}$$

where $\gamma=\tau_s^f L_s/(\tau_s L_f)\sim 1$. We have shown that the polarization of current $|\Gamma|<|P_{FM}|$, and it may be $\ll |P_{FM}|$, therefore, $|\delta n_{\uparrow 0}^f/\delta n_{\uparrow 0}| \lesssim 1$.

The ratio of $\Delta F_{\uparrow 0}^S$ and $\Delta F_{\uparrow 0}^f$ is approximately equal to

$$\left|\frac{\Delta F_{\uparrow 0}^f}{\Delta F_{\uparrow 0}^S}\right| \simeq \frac{n\mu^f}{n^f\mu_S}\left|\frac{\delta n_{\uparrow 0}^f}{\delta n_{\uparrow 0}}\right| = \gamma\beta\left|\frac{\Gamma - P_{FM}}{\Gamma}\right| \ll 1, \tag{B5}$$

where $\beta=n\mu^f/(n^f\mu_S)$, μ^f and μ_S are the Fermi energies for electrons in FM and S, respectively. Since the electron density in FM metals, $n^f\simeq 10^{22}\ \mathrm{cm}^{-3}$, is several orders of magnitude larger than in S (typically, $n\lesssim 10^{18}\ \mathrm{cm}^{-3}$), the value $\beta\sim(n/n^f)^{1/3}\ll 1$. Thus, one can see from (B5) that indeed $|\Delta F_{\uparrow 0}^f| \ll |\Delta F_{\uparrow 0}^S|$. We showed above (see also Ref. 26) that Γ is small at very large forward currents, therefore, $\Delta F_{\uparrow 0}^f$ can be on the order of $\Delta F_{\uparrow 0}^S$. However, such current corresponds to the bias voltages of Schottky junctions $qV \gg \Delta F_{\sigma 0}^f$. Due to the condition $\Delta F_{\sigma 0}^f \ll \Delta F_{\sigma 0}^S, q|V|$, we can indeed neglect $\Delta F_{\sigma 0}^f$ in Eq. (9), so the approximation used to derive the Eqs. (9) and (27) is justified.

We emphasize that the conclusion $\Delta F_{\uparrow 0}^f \ll \Delta F_{\uparrow 0}^S$ is valid for FM-S Schottky junctions. Possible exception can only be the FM-S junctions with an accumulation layer, Fig. 1(d). In such FM-S junctions the electron density in S near the FM-S interface can be very large. In such rare case both β and γ can be on the order of unity, perhaps allowing for $\Delta F_{\uparrow 0}^f \simeq \Delta F_{\uparrow 0}^S$ and even $\zeta_{\sigma 0}^S \simeq \zeta_{\sigma 0}^f$. However, this case requires a separate study where one has also to take into account spin selective properties of such a FM-S junctions and a steep spatial variation of electron density in S near the FM-S interface, Fig. 1(d).

[1] *Semiconductor Spintronics and Quantum Computation*, edited by D. D. Awschalom, D. Loss, and N. Samarth (Springer, Berlin, 2002); S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnar, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, Science **294**, 1488 (2001); D. P. DiVincenzo, *ibid.* **270**, 255 (1995); G. A. Prinz, Phys. Today **48**, 58 (1995); N. A. Gershenfeld and I. L. Chuang, *ibid.* **275**, 350 (1997); B. E. Kane, Nature (London) **393**, 133 (1998); H. Ohno, D. Chiba, F. Matsukura, T. Omiya, E. Abe, T. Dietl, Y. Ohno, and K. Ohtani, *ibid.* **408**, 944 (2000); D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).

[2] I. Zutic, J. Fabian, and C. Das Sarma, Rev. Mod. Phys. **76**, 323 (2004).

[3] M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988); A. E. Berkowitz, J. R. Mitchell, M. J. Carey, A. P. Young, S. Zhang, F. E. Spada, F. T. Parker, A. Hutten, and G. Thomas, *ibid.* **68**, 3745 (1992); *Ultrathin Magnetic Structures*, edited by B. Heinrich and J. A. C. Bland (Springer, Berlin, 1994); J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey, Phys. Rev. Lett. **74**, 3273 (1995); T. Miyazaki and N. Tezuka, J. Magn. Magn. Mater. **139**, L231 (1995).

[4] J. C. Slonczewski, Phys. Rev. B **39**, 6995 (1989).

[5] A. M. Bratkovsky, Phys. Rev. B **56**, 2344 (1997).

[6] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990); S. Gardelis, C. G. Smith, C. H. W. Barnes, E. H. Linfield, and D. A. Ritchie, Phys. Rev. B **60**, 7764 (1999).

[7] A. G. Aronov, G. E. Pikus, and A. N. Titkov, Sov. Phys. JETP **57**, 680 (1983); J. M. Kikkawa, I. P. Smorchkova, N. Samarth, and D. D. Awschalom, Science **277**, 1284 (1997); J. M. Kikkawa and D. D. Awschalom, Phys. Rev. Lett. **80**, 4313 (1998); D. Hägele, M. Oestreich, W. W. Rühle, N. Nestle, and K. Eberl, Appl. Phys. Lett. **73**, 1580 (1998); M. Oestreich, J. Hübner, D. Hägele, P. J. Klar, W. Heimbrodt, W. W. Rühle, D. E. Ashenford, and B. Lunn, *ibid.* **74**, 1251 (1999); J. M. Kikkawa and D. D. Awschalom, Nature (London) **397**, 139 (1999); I. Malajovich, J. J. Berry, N. Samarth, and D. D. Awschalom, *ibid.* **411**, 770 (2001); I. Malajovich, J. M. Kikkawa, D. D. Awschalom, J. J. Berry, and N. Samarth, Phys. Rev. Lett. **84**, 1015 (2000); R. M. Stroud, A. T. Hanbicki, Y. D. Park, G. Kioseoglou, A. G. Petukhov, B. T. Jonker, G. Itskos, and A. Petrou, *ibid.* **89**, 166602 (2002).

[8] R. Sato and K. Mizushima, Appl. Phys. Lett. **79**, 1157 (2001); X. Jiang, R. Wang, S. van Dijken, R. Shelby, R. Macfarlane, G. S. Solomon, J. Harris, and S. S. P. Parkin, Phys. Rev. Lett. **90**, 256603 (2003).

[9] A. M. Bratkovsky and V. V. Osipov, Phys. Rev. Lett. **92**, 098302 (2004); V. V. Osipov and A. M. Bratkovsky, Appl. Phys. Lett. **84**, 2118 (2004).

[10] P. R. Hammar, B. R. Bennett, M. J. Yang, and M. Johnson, Phys. Rev. Lett. **83**, 203 (1999); M. Tanaka and Y. Higo, *ibid.* **87**, 026602 (2001); H. J. Zhu, M. Ramsteiner, H. Kostial, M. Wassermeier, H.-P. Schönherr, and K. H. Ploog, *ibid.* **87**, 016601 (2001); W. Y. Lee, S. Gardelis, B.-C. Choi, Y. B. Xu, C. G. Smith, C. H. W. Barnes, D. A. Ritchie, E. H. Linfield, and J. A. C. Bland, J. Appl. Phys. **85**, 6682 (1999); T. Manago and H. Akinaga, Appl. Phys. Lett. **81**, 694 (2002); A. F. Motsnyi, J. De Boeck, J. Das, W. Van Roy, G. Borghs, E. Goovaerts, and V. I. Safarov, *ibid.* **81**, 265 (2002); C. Adelmann, X. Lou, J. Strand, C. J. Palmstrøm, and P. A. Crowell, Phys. Rev. B **71**, 121301(R) (2005).

[11] A. T. Hanbicki, B. T. Jonker, G. Itskos, G. Kioseoglou, and A. Petrou, Appl. Phys. Lett. **80**, 1240 (2002); A. T. Hanbicki, O. M. J. van't Erve, R. Magno, G. Kioseoglou, C. H. Li, and B. T. Jonker, *ibid.* **82**, 4092 (2003).

[12] H. Ohno, K. Yoh, K. Sueoka, K. Mukasa, A. Kawaharazuka, and M. E. Ramsteiner, J. Appl. Phys. **42**, L87 (2003).

[13] V. V. Osipov, N. A. Viglin, and A. A. Samokhvalov, Phys. Lett. A **247**, 353 (1998); Y. Ohno, D. K. Young, B. Beschoten, F. Matsukura, H. Ohno, and D. D. Awschalom, Nature (London) **402**, 790 (1999); R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag, and L. W. Molenkamp, *ibid.* **402**, 787 (1999).

[14] A. G. Aronov and G. E. Pikus, Fiz. Tekh. Poluprovodn. (S.-Peterburg) **10**, 1177 (1976) [Sov. Phys. Semicond. **10**, 698 (1976)].

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

[16] P. C. van Son, H. van Kempen, and P. Wyder, Phys. Rev. Lett. **58**, 2271 (1987); G. Schmidt, G. Richter, P. Grabs, C. Gould, D. Ferrand, and L. W. Molenkamp, *ibid.* **87**, 227203 (2001).

[17] G. Schmidt, D. Ferrand, L. W. Molenkamp, A. T. Filip, and B. J. van Wees, Phys. Rev. B **62**, R4790 (2000).

[18] Z. G. Yu and M. E. Flatte, Phys. Rev. B **66**, 201202(R) (2002).

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

[20] S. Hershfield and H. L. Zhao, Phys. Rev. B **56**, 3296 (1997).

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

[22] A. Fert and H. Jaffres, Phys. Rev. B **64**, 184420 (2001).

[23] C.-M. Hu and T. Matsuyama, Phys. Rev. Lett. **87**, 066803 (2001).

[24] Z. G. Yu and M. E. Flatte, Phys. Rev. B **66**, 235302(R) (2002).

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

[26] A. M. Bratkovsky and V. V. Osipov, J. Appl. Phys. **96**, 4525 (2004).

[27] S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981); R. T. Tung, Phys. Rev. B **45**, 13509 (1992).

[28] C. B. Duke, *Tunneling in Solids* (Academic, New York, 1969).

[29] S. Sanvito, C. J. Lambert, J. H. Jefferson, and A. M. Bratkovsky, Phys. Rev. B **59**, 11936 (1999); O. Wunnicke, Ph. Mavropoulos, R. Zeller, P. H. Dederichs, and D. Grundler, *ibid.* **65**, 241306(R) (2002).

[30] M. B. Stearns, J. Magn. Magn. Mater. **5**, 167 (1977).

[31] J. G. Simmons, J. Appl. Phys. **34**, 1793 (1963); J. G. Simmons, J. Phys. D **4**, 613 (1971); R. Stratton, *Tunneling Phenomena in Solids*, edited by E. Burstein and S. Lundqvist (Plenum, New York, 1969); R. T. Tung, Phys. Rev. B **45**, 13509 (1992).

[32] R. Gomer, *Field Emission and Field Ionization* (Harvard University Press, Cambridge, 1961); A. McConville, *Emission Standards Handbook* (Oxford University Press, New York, 1997).

[33] L. Esaki, Phys. Rev. **109**, 603 (1958); M. Julliere, Phys. Lett. **54A**, 225 (1975).

[34] V. L. Moruzzi, J. F. Janak, and A. R. Williams, *Calculated Electronic Properties of Metals* (Pergamon Press, New York, 1978); S. Chikazumi, *Physics of Ferromagnetism* (Oxford, New York, 1999).

[35] I. I. Mazin, Phys. Rev. Lett. **83**, 1427 (1999).