High-Frequency Spin-Valve Effect in a Ferromagnet-Semiconductor-Ferromagnet Structure Based on Precession of the Injected Spins

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(Received 18 September 2003; published 4 March 2004)

A new mechanism of magnetoresistance, based on tunneling emission of spin-polarized electrons from ferromagnets (FM) into semiconductors (S) and precession of electron spin in the semiconductor layer under external magnetic field, is described. The FM-S-FM structure is considered, which includes very thin heavily doped (δ-doped) layers at FM-S interfaces. At certain parameters the structure is highly sensitive at room temperature to variations of the field with frequencies up to 100 GHz. The current oscillates with the field, and its relative amplitude is determined only by the spin polarizations of FM-S junctions.

DOI: 10.1103/PhysRevLett.92.098302 PACS numbers: 85.75.–d, 85.35.–p

Manipulation of an electron spin may lead to breakthroughs in solid state ultrafast scalable devices [1]. Spintronic effects, like giant and tunnel magnetoresistance (TMR), are already widely used in readout devices and nonvolatile memory cells [1,2]. Theory of TMR junctions has been considered in Refs. [3,4]. A large ballistic magnetoresistance of Ni and Co nanocontacts was reported in Refs. [5]. The injection of spin-polarized carriers into semiconductors provides a potentially powerful mechanism for field sensing and other applications, which is due to the relatively large spin-coherence lifetime of electrons in semiconductors [1,6]. Different spintronic devices, including magnetic sensors, are considered in detail in [1]. The efficient spin injection into nonmagnetic semiconductors has been recently demonstrated from ferromagnets [7,8] and magnetic semiconductors [9]. Conditions for efficient spin injection have been discussed in Refs. [10,11]. Spin diffusion and drift in electric field have been studied in Ref. [12]. A new class of spin injection-precession ultrafast devices is described in Ref. [13].

In this Letter we study a new mechanism of magnetoresistance, operational up to 100 GHz frequencies. We consider a heterostructure comprising a n-type semiconductor (n-S) layer sandwiched between two ferromagnetic (FM) layers with ultrathin heavily n^+-doped (δ-doped) semiconducting layers at the FM-S interfaces. Magnetoresistance of the structure is determined by the following processes: (i) injection of spin-polarized electrons from the left ferromagnet through the δ-doped layer into the n-S layer; (ii) spin ballistic transport of spin-polarized electrons through that layer; (iii) precession of the electron spin in an external magnetic field during a transit through the n-S layer; (iv) variation of conductivity of the system due to the spin precession.

We notice that a Schottky barrier with a height $\Delta \gtrsim 0.5$ eV usually forms in a semiconductor near a metal-semiconductor interface [14]. The energy band diagram of a thin FM-S-FM structure looks like a rectangular potential barrier of a height Δ and a thickness w. Hence, the current through the FM-S-FM structure is negligible when $w \gtrsim 30$ nm. To increase a spin injection current, a thin heavily doped n^+-semiconductor layer between the ferromagnet and semiconductor should be used [8,11]. Recently an efficient injection was demonstrated in FM-S junctions with a thin n^+ layer [8].

We consider a heterostructure, Fig. 1, where left (L) and right (R) δ-doped layers satisfy the following conditions [11]: the thickness $l^{L(R)} \lesssim 2$ nm, the donor concentration $N_d^+ \gtrsim 10^{20}$ cm^{-3}, $N_d^+(l^L)^2 \simeq 2\varepsilon\varepsilon_0(\Delta - \Delta_0 + rT)/q^2$, and $N_d^+(l^R)^2 \simeq 2\varepsilon\varepsilon_0(\Delta - \Delta_0)/q^2$, where $\Delta_0 = E_c - F$, F is the Fermi level in the equilibrium (in the left FM), E_c the bottom of the semiconductor conduction band, $r \simeq 2$–3, and T the temperature (we use the units of $k_B = 1$). The value of Δ_0 and the relevant profile of $E_c(x)$ can be set by choosing N_d^+, $l^{L(R)}$, and a donor concentration, N_d, in the n semiconductor. The energy diagram of such a FM-n^+-n-n^+-FM structure is shown in Fig. 1. There is a shallow potential well of depth $\approx rT$ next to the left δ spike. The presence of this miniwell allows one to retain the thickness of the left δ barrier equal to $l^L \lesssim l_0$ and its tunneling transparency high for the bias voltage up to $qV_L \simeq rT$. The δ spike is transparent for tunneling when $l^{L(R)} \lesssim l_0 = \sqrt{\hbar^2/[2m_*(\Delta - \Delta_0)]}$, where m_* is the effective mass of electrons in the semiconductor. However, when $w \gg l_0$, only electrons with energies $E \geq E_c = F + \Delta_0$ can overcome the barrier Δ_0 due to thermionic emission [11]. We assume $w \gg \lambda$, λ being the electron mean free path in a semiconductor, so one can consider the FM-S junctions independently.

We assume the elastic coherent tunneling, so that the energy E, spin σ, and the wave vector $\vec{k}_\parallel$ in the plane of the interface are conserved, so the current density of electrons with spin σ through the left and right junctions, including the δ-doped layers, can be written as [4,11,15]

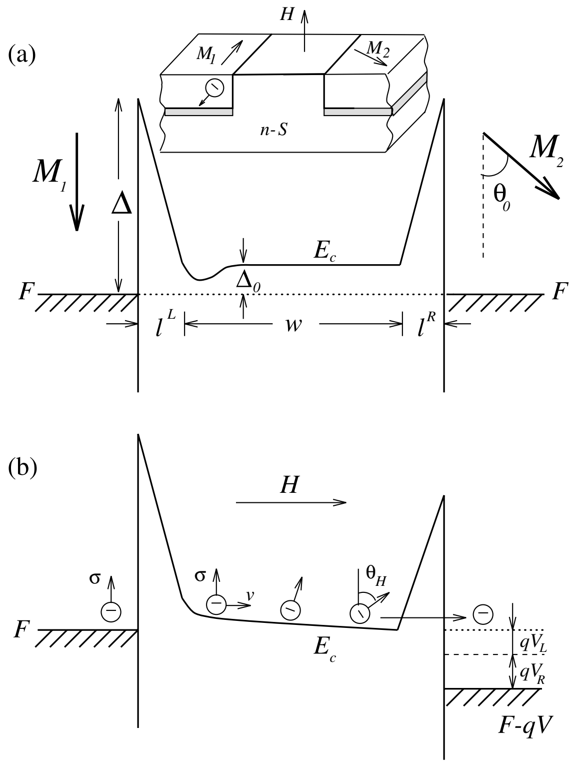

FIG. 1. Energy diagram of the FM-S-FM heterostructure with δ-doped layers in equilibrium (a) and at a bias voltage V (b), with V_L (V_R) the fraction of the total voltage drop across the left (right) δ layer. F marks the Fermi level, Δ the height, $l^{L(R)}$ the thickness of the left (right) δ-doped layer, Δ_0 the height of the barrier in the n-type semiconductor (n-S), E_c the bottom of conduction band in the n-S, w the width of the n-S part. The magnetic moments on the FM electrodes $\vec{M}_1$ and $\vec{M}_2$ are at some angle θ_0 with respect to each other. The spins, injected from the left, drift in the semiconductor layer and rotate by the angle θ_H in the external magnetic field H. Inset: schematic of the device, with an oxide layer separating the ferromagnetic films from the bottom semiconductor layer.

$$J_\sigma^{L(R)} = \frac{q}{h}\int dE[f(E - F_\sigma^{L(R)}) - f(E - F_{L(R)})] \times \int \frac{d^2k_\parallel}{(2\pi)^2} T_{k\sigma}^{L(R)}, \quad (1)$$

where $T_{k\sigma}$ is the transmission probability, $f(E) = [\exp(E - F)/T + 1]^{-1}$ is the Fermi function, $F_L = F$ and $F_R = F - qV$ are the left and right Fermi levels (Fig. 1), q is the elementary charge, and integration includes a summation with respect to a band index. We take into account the spin accumulation in the semiconductor described by the Fermi functions with the nonequilibrium quasi-Fermi levels F_σ. The condition $\Delta_0 = E_c - F > 0$ means that the semiconductor is nondegenerate, so that the total electron density, $n = N_d$, and a density of electrons with spin σ, n_σ, are given by

$$n = N_c \exp\left(-\frac{\Delta_0}{T}\right) = N_d, \quad n_\sigma = \frac{N_c}{2}\exp\left(\frac{F_\sigma - E_c}{T}\right), \quad (2)$$

where $N_c = 2M_c(2\pi m_* T)^{3/2}h^{-3}$ is the effective density of states in the semiconductor conduction band and M_c the number of the band minima [14]. The left (right) junctions are at $x = 0$ (w), so that in Eq. (1) $F_\sigma^L = F_\sigma(0)$ and $F_\sigma^R = F_\sigma(w)$. The analytical expressions for $T_{k\sigma}^{L(R)}$ can be obtained in an effective mass approximation, $\hbar k_\sigma = m_\sigma v_\sigma$, where v_σ is a velocity of electrons with spin σ. The present interface barriers are opaque at energies $E < E_c$. For energies $E \gtrsim E_c$ we can approximate the δ-doped barrier by a triangular shape and find [11]

$$T_{k\sigma}^{L(R)} = \frac{16\alpha^{L(R)} v_{\sigma x}^{L(R)} v_x^{L(R)}}{(v_{\sigma x}^{L(R)})^2 + (v_{tx}^{L(R)})^2}\exp(-\eta\kappa^{L(R)} l^{L(R)}), \quad (3)$$

where $E_\parallel = \hbar^2 k_\parallel^2/2m_*$, $v_{tx}^{L(R)} = \hbar\kappa^{L(R)}/m_*$ is the "tunneling" velocity, $v_x^{L(R)} = \sqrt{2(E - E_c - E_\parallel)/m_*}$ and $v_{\sigma x}^{L(R)}$ are the x components of electron velocities in a direction of current in the semiconductor and ferromagnets, respectively, $\kappa^{L(R)} = (2m_*/\hbar^2)^{1/2}(\Delta + F - E + E_\parallel)^{3/2}(\Delta - \Delta_0 \pm qV_{L(R)})^{-1}$, $\alpha^{L(R)} = 3^{-1/3}\pi\Gamma^{-2}(\frac{2}{3})[\kappa^{L(R)} l^{L(R)}]^{1/3} \simeq 1.2[\kappa^{L(R)} l^{L(R)}]^{1/3}$, and $\eta = 4/3$ (for a rectangular barrier $\alpha = 1$ and $\eta = 2$), where $V_{L(R)}$ is the voltage drop across the left (right) barrier (Fig. 1). The preexponential factor in Eq. (3) takes into account a mismatch between the effective masses, m_σ and m_*, and the velocities, $v_{\sigma x}$ and v_x, of electrons at the FM-S interfaces (cf. Ref. [4]). We consider $qV_b \lesssim \Delta_0$, $T < \Delta_0 \ll \Delta$, and $E \gtrsim E_c > F + T$, when Eqs. (1) and (3) yield the following result for the tunneling-emission current density:

$$j_\sigma^{L(R)} = \frac{\alpha q M_c T^{5/2}(8m_*)^{1/2} v_{0\sigma(\sigma')}^{L(R)} \exp(-\eta\kappa_0^{L(R)} l^{L(R)})}{\pi^{3/2}\hbar^3[(v_{\sigma(\sigma')}^{L(R)})^2 + (v_{t0}^{L(R)})^2]}\left(e^{\frac{F_\sigma^{L(R)} - E_c}{T}} - e^{\frac{F_{L(R)} - E_c}{T}}\right), \quad (4)$$

where $\kappa_0^{L(R)} \equiv 1/l_0^{L(R)} = (2m_*/\hbar^2)^{1/2}(\Delta - \Delta_0 \pm qV_{L(R)})^{1/2}$, $v_{t0}^{L(R)} = \sqrt{2(\Delta - \Delta_0 \pm qV_{L(R)})/m_*}$, and $v_{\sigma(\sigma')}^{L(R)} = v_{\sigma(\sigma')}(\Delta_0 \pm qV_{L(R)})$. It follows from Eqs. (4) and (2) that the spin currents of electrons with the quantization axis $\parallel \vec{M}_1$ in FM_1 with $\sigma = \uparrow (\downarrow)$, Fig. 1, and $\parallel \vec{M}_2$ in FM_2 with $\sigma' = \pm$ through the junctions of unit area are equal to

$$J_\sigma^L = J_0^L d_\sigma^L[e^{\frac{qV_L}{T}} - 2n_\sigma(0)/n], \quad (5)$$

$$J_{\sigma'}^R = J_0^R d_{\sigma'}^R[2n_{\sigma'}(w)/n - e^{-\frac{qV_R}{T}}], \quad (6)$$

$$J_0^{L(R)} = -\alpha_0^{L(R)} n q v_T \exp(-\eta\kappa_0^{L(R)} l^{L(R)}). \quad (7)$$

Here we have introduced $\alpha_0^{L(R)} = 1.6(\kappa_0^{L(R)} l^{L(R)})^{1/3}$, the thermal velocity $v_T \equiv \sqrt{3T/m_*}$, and the spin factors $d_\sigma^L = v_T v_\sigma^L[(v_{t0}^L)^2 + (v_\sigma^L)^2]^{-1}$ and $d_{\sigma'}^R = v_T v_{\sigma'}^R[(v_{t0}^R)^2 + (v_{R\sigma'})^2]^{-1}$.

Now we can find the dependence of current on a magnetic configuration in FM electrodes and an external magnetic field. The spatial distribution of spin-polarized electrons is determined by the kinetic equation $dJ_\sigma/dx = q\delta n_\sigma/\tau_s$, where $\delta n_\sigma = n_\sigma - n/2$, τ_s is the spin-coherence lifetime of the electrons in the n semiconductor, and the current in spin channel σ is given by

$$J_\sigma = q\mu n_\sigma E + qD dn_\sigma/dx, \tag{8}$$

where D and μ are the diffusion constant and mobility of the electrons, and E the electric field [12,14]. From conditions of continuity of the total current, $J = J_\uparrow + J_\downarrow =$ const and $n = n_\uparrow + n_\downarrow =$ const, it follows that $E(x) = J/q\mu n =$ const and $\delta n_\uparrow = -\delta n_\downarrow$. Note that $J < 0$, thus $E < 0$. With the use of the kinetic equation and Eq. (8), we obtain the equation for $\delta n_\uparrow(x)$ [12]. Its general solution is

$$\delta n_\uparrow(x) = (n/2)(c_1 e^{-x/L_1} + c_2 e^{-(w-x)/L_2}), \tag{9}$$

where $L_{1(2)} = (1/2)[\sqrt{L_E^2 + 4L_s^2} + (-)L_E]$, and $L_s = \sqrt{D\tau_s}$ and $L_E = \mu|E|\tau_s$ are the spin diffusion and drift lengths [12]. Substituting Eq. (9) into (8), we obtain

$$J_\uparrow(x) = (J/2)[1 + b_1 c_1 e^{-x/L_1} + b_2 c_2 e^{-(w-x)/L_2}] \tag{10}$$

where $b_1 = L_1/L_E$ ($b_2 = -L_2/L_E$). We consider the case when $w \ll L_1$ and the transit time $t_{tr} \simeq w^2/(D + \mu|E|w)$ of the electrons through the n-semiconductor layer is shorter than τ_s. In this case spin ballistic transport takes place, i.e., the spin of the electrons injected from the FM_1 layer is conserved in the semiconductor layer, $\sigma' = \sigma$. Probabilities of the electron spin $\sigma = \uparrow$ to have the projections along $\pm\vec{M}_2$ are $\cos^2(\theta/2)$ and $\sin^2(\theta/2)$, respectively, where θ is the angle between vectors $\sigma = \uparrow$ and $\vec{M}_2$. Therefore, the spin current through the right junction can be written, using Eq. (6), as

$$J_{\uparrow(\downarrow)}^R = J_0^R[2n_{\uparrow(\downarrow)}(w)/n - \exp(-qV_R/T)] \times [d_{+(-)}\cos^2(\theta/2) + d_{-(+)}\sin^2(\theta/2)]. \tag{11}$$

It follows from Eqs. (5) and (11) that the total current $J = J_\uparrow^L + J_\downarrow^L = J_\uparrow^R + J_\downarrow^R$ through the left and right interfaces is equal, respectively,

$$J = J_0^L(d_\uparrow + d_\downarrow)[\gamma_L - 2P_L\delta n_\uparrow(0)/n], \tag{12}$$

$$J = J_0^R(d_- + d_+)[\gamma_R + 2P_R\cos\theta\delta n_\uparrow(w)/n], \tag{13}$$

where $\gamma_L = e^{qV_L/T} - 1$ and $\gamma_R = 1 - e^{-qV_R/T}$, and

$$J_\uparrow^L = \frac{J}{2}\,\frac{(1 + P_L)[\gamma_L - 2\delta n_\uparrow(0)/n]}{\gamma_L - 2P_L\delta n_\uparrow(0)/n}, \tag{14}$$

$$J_\uparrow^R = \frac{J}{2}\,\frac{(1 + P_R\cos\theta)[\gamma_R + 2\delta n_\uparrow(w)/n]}{\gamma_R + 2P_R\cos\theta\delta n_\uparrow(w)/n}. \tag{15}$$

Here we have introduced the spin polarization $P_{L(R)} = (d_\uparrow^{L(R)} - d_\downarrow^{L(R)})(d_\uparrow^{L(R)} + d_\downarrow^{L(R)})^{-1}$ for the left (right) contact, which is equal to

$$P_{L(R)} = \frac{(v_\uparrow^{L(R)} - v_\downarrow^{L(R)})[(v_{t0}^{L(R)})^2 - v_\uparrow^{L(R)}v_\downarrow^{L(R)}]}{(v_\uparrow^{L(R)} + v_\downarrow^{L(R)})[(v_{t0}^{L(R)})^2 + v_\uparrow^{L(R)}v_\downarrow^{L(R)}]}. \tag{16}$$

Importantly, this $P_{L(R)}$ is determined by the electron states in FM *above* the Fermi level, at $E = E_c > F$, which may be substantially more polarized compared to the states at the Fermi level [11]. The parameters $c_{1(2)}$ and $V_{L(R)}$ are determined by Eqs. (10), (5), (6), and (12)–(15).

The current through the structure is Ohmic at small bias, $J \propto V$ at $|qV| < T$, and saturates at bias voltages $qV > 2T$. Indeed, from Eqs. (14) and (15) at $qV_{R(L)} \gtrsim 2T$ we find $J_\uparrow^L = \frac{J}{2}(1 + P_L)$ and

$$J_\uparrow^R = \frac{J}{2}\,\frac{(1 + P_\theta)[1 + 2\delta n_\uparrow(w)/n]}{1 + 2P_\theta\delta n_\uparrow(w)/n}, \tag{17}$$

where $P_\theta \equiv P_R\cos\theta$. We can obtain the current at $x = 0$ (w) from Eq. (10), equate it to $J_\uparrow^L$ ($J_\uparrow^R$), and then find the unknown $c_{1(2)}$ with the use of (9). At $L_E \gg L_s$, we have $b_1 = 1$, $b_2 = -L_s^2/L_E^2$ and $c_1 = P_L$, $c_2 = -P_\theta(1 - P_L^2)/(1 - P_L P_\theta)$. Thus, according to Eqs. (9), the spin densities at the two interfaces are

$$2\delta n_\uparrow(0)/n = P_L - e^{-w/L_2}P_\theta(1 - P_L^2)/(1 - P_L P_\theta), \tag{18}$$

$$2\delta n_\uparrow(w)/n = (P_L - P_\theta)/(1 - P_L P_\theta). \tag{19}$$

The spin-polarized density profile $n_\sigma(x)$ is shown in Fig. 2 (bottom panel) for $w \ll L_s$. One can realize from Eqs. (9), (18), and (19) that large accumulation of the majority injected spin occurs when the moments on the magnetic electrodes are antiparallel, $\vec{M}_1 \parallel -\vec{M}_2$, and relatively small accumulation occurs in the case of the parallel configuration, $\vec{M}_1 \parallel \vec{M}_2$ (Fig. 2).

At $qV > T$ the current saturates at the value

$$J = J_0(1 - P_R^2\cos^2\theta)(1 - P_L P_R\cos\theta)^{-1}, \tag{20}$$

where $J_0 = J_0^R(d_+ + d_-)$, as follows from Eqs. (18) and (13). For the *opposite* bias, $qV < -T$, the total current J is given by Eq. (20) with the replacement $P_L \rightleftharpoons P_R$. The current J is minimal for antiparallel (AP) moments $\vec{M}_1$ and $\vec{M}_2$ in the electrodes when $\theta = \pi$ and near maximal for parallel (P) magnetic moments $\vec{M}_1$ and $\vec{M}_2$. The ratio $\frac{J_{\max}(\mathrm{P})}{J_{\min}(\mathrm{AP})} = \frac{1 + P_L P_R}{1 - P_L P_R}$ is the same as for the tunneling FM-I-FM structure [3,4]; hence, the structure may also be used as a memory cell.

The present heterostructure has an additional degree of freedom, compared to tunneling FM-I-FM structures, which can be used for an ultrafast *magnetic sensing.* Indeed, spins of the injected electrons can precess in an external magnetic field H during the transit time t_{tr} of the

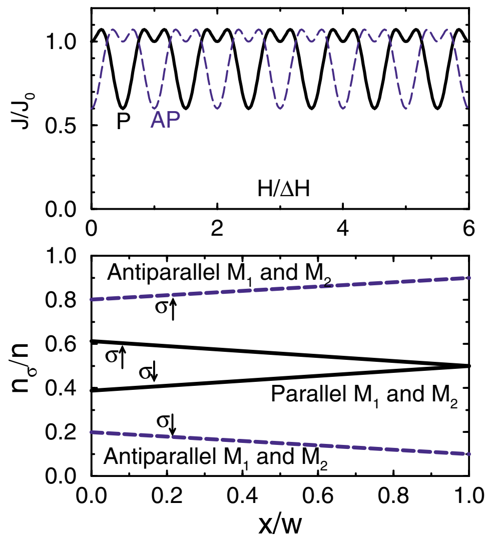

FIG. 2 (color online). Oscillatory dependence of the current J through the structure on the magnetic field H (top panel) for parallel (P) and antiparallel (AP) moments M_1 and M_2 on the electrodes (Fig. 1), and $P_L = P_R = 0.5$. Spatial distribution of the spin polarized electrons $n_{\uparrow(\downarrow)}/n$ in the structure for different configurations of the magnetic moments M_1 and M_2 in the limit of saturated current density J, $w = 60$ nm, $L_2 = 100$ nm (bottom panel).

electrons through the semiconductor layer ($t_{\rm tr} < \tau_s$). In Eqs. (12) and (20) the angle between the electron spin and the magnetization $\vec{M}_2$ in the FM_2 layer is in general $\theta = \theta_0 + \theta_H$, where θ_0 is the angle between the magnetizations M_1 and M_2, and θ_H is the spin rotation angle. The spin precesses with a frequency $\Omega = \gamma H$, where H is the magnetic field normal to the spin direction, and $\gamma = qg/(m_* c)$ the gyromagnetic ratio, with g the g factor. Therefore, $\theta_H = \gamma_0 g H t_{\rm tr}(m_0/m_*)$, where m_0 is the mass of a free electron, and $\gamma_0 g = 1.76 \times 10^7\ \mathrm{Oe}^{-1}\,\mathrm{s}^{-1}$ for $g = 2$ (in some magnetic semiconductors $g \gg 1$). According to Eq. (20), with increasing H the current *oscillates* with an amplitude $(1 + P_L P_R)/(1 - P_L P_R)$ and period $\Delta H = (2\pi m_*)(\gamma_0 g m_0 t_{\rm tr})^{-1}$ [Fig. 2 (top panel)]. A study of the current oscillations at various bias voltages allows one to find P_L and P_R.

For magnetic sensing one may choose $\theta_0 = \pi/2$ ($\vec{M}_1 \perp \vec{M}_2$). Then, it follows from Eq. (20) that, for $\theta_H \ll 1$,

$$J = J_0[1 + P_L P_R \gamma_0 g H t_{tr}(m_0/m_*)] = J_0 + J_H, \quad (21)$$

$$K_H = dJ/dH = J_0 P_L P_R \gamma_0 g t_{tr}(m_0/m_*), \quad (22)$$

where K_H is the magnetosensitivity coefficient. For example, $K_H \simeq 2 \times 10^{-3} J_0 P_L P_R$ A/Oe for $m_0/m_* = 14$ (GaAs) and $g = 2$, $t_{tr} \sim 10^{-11}$ s, and the angle $\theta_H = \pi$ at $H \simeq 1$ kOe. Thus, the signal current $J_H S \simeq 1$ mA at $J_0 S = 25$ mA, $P_L P_R \simeq 0.2$, and $H \simeq 100$ Oe, where S is the area of the device perpendicular to current. The maximum operating speed of the field sensor is very high, since redistribution of nonequilibrium injected electrons in the semiconductor layer occurs over the transit time $t_{tr} \simeq w/\mu|E| = J_s w \tau_s/(J L_s)$, $t_{\rm tr} \lesssim 10^{-11}$ s for $w \lesssim 200$ nm, $\tau_s \sim 3 \times 10^{-10}$ s, and $J/J_s \gtrsim 10$ ($D \approx 25\ \mathrm{cm}^2/\mathrm{s}$ at $T \simeq 300$ K [14]). Thus, the operating frequency $f = 1/t_{\rm tr} \gtrsim 100$ GHz ($\omega = 2\pi/t_{\rm tr} \simeq 1$ THz) would be achievable at room temperature.

We emphasize that the parameters $\kappa_0^{L(R)}$ and $P_{L(R)}$ are functions of the bias $V_{L(R)}$ and Δ_0. The efficient spin injection can be achieved when the bottom of the conduction band in a semiconductor E_c near both FM-S junctions is close to a peak in a density of spin-polarized states, e.g., of minority electrons in the elemental ferromagnet like Fe, Co, Ni (cf. [11]).

In conclusion, we have shown that (i) the present heterostructure can be used as a sensor for an ultrafast nanoscale reading of an inhomogeneous magnetic field profile, (ii) it includes two FM-S junctions and can be used for measuring spin polarizations of these junctions, and (iii) it is a *multifunctional* device where current depends on mutual orientation of the magnetizations in the ferromagnetic layers, an external magnetic field, and a (small) bias voltage, thus it can be used as a logic element, a magnetic memory cell, or an ultrafast read head.

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