High-frequency spin valve effect in ferromagnet-semiconductor-ferromagnet structure based on precession of injected spins

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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 at relatively large bias voltage.

72.25.Hg, 72.25.Mk

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 read-out devices and non-volatile 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 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 Refs. [12,13].

In this paper 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 heterostructure 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.

There are known obstacles for an efficient spin injection in FM-S structures. A Schottky barrier with a height ∆ ≳ 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 as a rectangular potential barrier of a height ∆ and a thickness w.

Hence, the current through the FM-S-FM structure is negligible when w ≳ 30 nm. To increase a spin injection current, a thin heavily n−semiconductor layer between the ferromagnet and semiconductor should be used [8,11]. This layer sharply decreases the thickness of the Schottky barriers and increases their tunneling transparency [14]. 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 optimal conditions [11]: the thickness l^{L(R)} ≲ 2 nm, the donor concentration N^{+}_{d} ≳ 10^{20} cm^{−3}, N^{+}_{d}(l^{L})^{2} ≲ 2\varepsilon\varepsilon_{0}(\Delta - \Delta_{0} + rT)/q^2, and N^{+}_{d}(l^{R})^{2} ≲ 2\varepsilon\varepsilon_{0}(\Delta - \Delta_{0})/q^2, where Δ_{0} = E_{c} - F, F is the Fermi level in the equilibrium (in the left FM), E_{c} the bottom of semiconductor conduction band, r ≃ 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. Importantly, there is a shallow potential well of depth ≈ rT next to the left δ−spike. Presence of this mini-well allows to retain the thickness of the left δ−barrier equal to l^{L} ≲ l_{0} and its tunneling transparency high for the bias voltage up to qV_{L} ≃ rT. The δ−spike is transparent for tunneling when l^{L(R)} ≲ l_{0} = h^2/[2m_{s}(\Delta - \Delta_{0})], where m_{s} is the effective mass of electrons in the semiconductor. However, when w ≫ l_{0}, only electrons with energies E ≥ E_{c} = F + \Delta_{0} can overcome the barrier \Delta_{0} due to thermionic emission [11]. We assume w ≫ \lambda, \lambda being the electron mean path in a semiconductor, so one can consider the FM-S junctions independently. We assume the elastic coherent tunneling, so that the energy E and the wave vector k_{∥} in the plane of the interface
are conserved, so the current density of electrons with spin \( \sigma \) through the left and right junctions, including the \( \delta \)-doped layers, can be written as [15,4,11]

\[
J_{\sigma}^{L(R)} = \frac{q}{\hbar} \int dE [f(E - F_{\sigma}^{L(R)}) - f(E - F_{L(R)})] \int \frac{d^2k_{\perp}}{(2\pi)^2} T_{k\sigma}^{L(R)}
\]

(1)

where \( T_{k\sigma} \) is the transmission probability, \( f(E) = (\exp(E - F)/T + 1)^{-1} \) the Fermi function, \( F_{L} = F \) and \( F_{R} = F - qV \) is the left and right Fermi level, Fig. 1, \( q \) 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 \( F_{\sigma} \). 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 \( \sigma, n_{\sigma} \), are given by

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

(2)

where \( N_c = 2M_c(2\pi m_{\sigma}T)^{3/2}e^{-3} \) 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) \( F_{k\sigma}^{L} = F_{\sigma}(0) \) and \( F_{k\sigma}^{R} = F_{\sigma}(w) \). 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 \( v_{\sigma} \) is a velocity of electrons with spin \( \sigma \). The present interface barriers are opaque at energies \( E > E_c \). For energies \( E \gtrsim E_c \) we can approximate the \( \delta \)-doped barrier by a triangular shape and find [11]

\[
T_{k\sigma}^{L(R)} = \frac{16\alpha_{L(R)}^{L(R)}(v_{\sigma}^{L(R)})^4}{(v_{\sigma}^{L(R)})^2 + (v_{\sigma}^{R(L)})^2} \exp \left( -\eta k_{L(R)}^{L(R)} \right),
\]

(3)

where \( E_{||} = \hbar^2 k_{L(R)}^2/(2m_{\sigma}) \), \( v_{\sigma}^{L(R)} = \hbar k_{L(R)}/m_{\sigma} \) the “tunneling” velocity, \( v_{\sigma}^{L(R)} = \sqrt{2(E - E_c - E_0)/m_{\sigma}} \) and \( v_{\sigma}^{L(R)} = \) are the \( x \)-components of electron velocities in a direction of current in the semiconductor and ferromagnets, respectively, \( \alpha_{L(R)}^{L(R)} = (2m_{\sigma}/\hbar^2)^{1/2}(\Delta + F - E + E_{||} - E_0)^{1/2}(\Delta - \Delta_0 \pm qV_{L(R)})^{-1} \), \( \alpha_{L(R)}^{L(R)} = 3^{-1/3}\pi^{-1/3}(\frac{1}{2})^{1/3}k_{L(R)}^{L(R)} \) \( k_{L(R)}^{L(R)} \approx 1.2 \), \( \eta = 4/3 \) (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, \( m_{\sigma} \) and \( m_{\sigma} \), and the velocities, \( v_{\sigma} \) and \( v_{\sigma} \), of electrons at the FM-S interfaces (cf. Ref. [4]). We consider \( qV_0 \ll \Delta_0, T < \Delta_0 \ll \Delta \) and \( E \geq E_c > F + T \), when Eqs. (1),(3) yield the following result for the tunneling-emission current density

\[
j_{\sigma}^{L(R)} = \frac{\alpha qM_{\sigma}T^5/2(8m_{\sigma})^{1/2}v_{\sigma}^{L(R)}(v_{\sigma}^{L(R)})^2}{\pi^{3/2}h^3 \left[ (v_{\sigma}^{L(R)})^2 + (v_{\sigma}^{R(L)})^2 \right]} \times \frac{\exp(-\eta k_{L(R)}^{L(R)} \Delta)}{\exp(-\eta k_{L(R)}^{L(R)} \Delta)},
\]

(4)

where \( k_{L(R)}^{L(R)} = 1/\lambda_{L(R)}^{L(R)} = (2m_{\sigma}/\hbar^2)^{1/2}(\Delta - \Delta_0 \pm qV_{L(R)})^{1/2}, \)

\[
v_{\sigma}^{L(R)} = \sqrt{2(\Delta - \Delta_0 \pm qV_{L(R)})/m_{\sigma}}, \quad v_{\sigma}^{L(R)} = v_{\sigma}(\sigma) \Delta_0 \pm qV_{L(R)} \]. It follows from Eqs. (4) and (2) that the spin currents of electrons with the quantization axis \( \parallel \vec{M}_1 \) in FM1 with \( \sigma = \uparrow \), Fig. 1, and \( \parallel \vec{M}_2 \) in FM2 with \( \sigma' = \pm \) through the junctions of unit area are equal to

\[
J_{\sigma}^{L} = J_{\sigma}^{L,0} \frac{\Delta}{q} \exp(\Delta/2 - 2n_{\sigma}(0)/n),
\]

(5)

\[
J_{\sigma}^{R} = J_{\sigma}^{R,0} \frac{\Delta}{q} \exp(\Delta/2 - 2n_{\sigma}(w)/n),
\]

(6)

\[
J_{\sigma}^{L(R)} = -\alpha_{L(R)}^{L(R)} n\Delta \exp(-\eta k_{L(R)}^{L(R)} \Delta),
\]

(7)
Here we have introduced \( \alpha_0^{L(R)} = 1.6 \left( k_0^{L(R)} t^{L(R)} \right)^{1/3} \), the thermal velocity \( v_T = \sqrt{3T/m_\sigma} \), and the spin factors \( d_{\sigma}^L = v_T \sqrt{1 - \left((v_{L(1)}^0)^2 + (v_{L(2)}^0)^2\right)^{-1}} \) and \( d_{\sigma}^R = v_T \sqrt{1 - \left((v_{R(1)}^0)^2 + (v_{R(2)}^0)^2\right)^{-1}} \).

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 \( dJ_{\sigma}/dx = q\delta n_{\sigma}/\tau \), where \( \delta n_{\sigma} = n_{\sigma} - n/2 \), and \( \tau \) is spin-coherence lifetime of the electrons in the \( n \)-semiconductor, and the current in spin channel \( \sigma \) is given by

\[
J_{\sigma} = q\mu n_{\sigma} E + q D d n_{\sigma}/dx,
\]
where \( D \) and \( \mu \) are diffusion constant and mobility of the electrons, \( E \) the electric field [12,14]. From conditions of continuity of the total current, \( J = J_1 + J_\uparrow \) is const and \( n = n_1 + n_\uparrow = \text{const} \), it follows that \( E(x) = J/q\mu \). We obtain the equation for \( \delta n_{\uparrow}(x) \) [12,13]. Its general solution is

\[
\delta n_{\uparrow}(x) = (n/2)(c_1 e^{-x/L_1} + c_2 e^{-(w-x)/L_2}),
\]
where \( L_1 = 2/L_2 \) and \( L_E = \mu E/\tau \) are the spin diffusion and drift lengths [12,13]. Substituting Eq. (9) into (8), we obtain

\[
J_{\uparrow}(x) = (J/2) \left[ 1 + b_1 c_1 e^{-x/L_1} + b_2 c_2 e^{-(w-x)/L_2} \right]
\]
where \( b_1 = L_1/L_E - L_2/L_E \). We consider the case when \( w \ll L_1 \) and the transit time \( \tau = w^2/(D + \mu E|w|) \) of the electrons through the \( n \)-semiconductor layer is shorter than \( \tau \). In this case spin ballistic transport takes place, i.e. the spin of the electrons injected from the FM layer is conserved in the semiconductor layer, \( \sigma' = \sigma \). Probabilities of the electron spin \( \sigma = \uparrow \) to have the projections along \( \pm \hat{M}_2 \) are \( \cos^2(\theta/2) \) and \( \sin^2(\theta/2) \), respectively, where \( \theta \) is the angle between vectors \( \sigma = \uparrow \) and \( \hat{M}_2 \). Therefore, the spin current through the right junction can be written, using Eq. (6), as

\[
J_{\uparrow}^R = \frac{J(1 + P_\uparrow)(1 + 2\delta n_{\uparrow}(w)/n)}{2}.
\]

It follows from Eqs. (5) and (11) that the total current \( J = J_1 + J_{\uparrow}^L + J_{\uparrow}^R \) through the left and right interfaces is equal, respectively,

\[
J = J_0^L (d_+ + d_-) \gamma_L - 2P_L \delta n_{\uparrow}(0)/n, \tag{12}
\]
\[
J = J_0^R (d_+ + d_-) \gamma_R + 2P_R \cos \theta \delta n_{\uparrow}(w)/n, \tag{13}
\]
where \( \gamma_L = e^{qV/L}/T - 1 \) and \( \gamma_R = 1 - e^{-qV/R}/T \), and

\[
J_{\uparrow}^L = \frac{J(1 + P_L) \gamma_L - 2\delta n_{\uparrow}(0)/n}{\gamma_L - 2P_L \delta n_{\uparrow}(0)/n}, \tag{14}
\]
\[
J_{\uparrow}^R = \frac{J(1 + P_R \cos \theta) \gamma_R + 2\delta n_{\uparrow}(w)/n}{\gamma_R + 2P_R \cos \theta \delta n_{\uparrow}(w)/n}. \tag{15}
\]

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

\[
P_{L(R)} = \frac{v_{\uparrow L(1)}^0 - v_{\downarrow L(1)}^0}{v_{\uparrow L(1)}^0 + v_{\downarrow L(1)}^0} \frac{v_{\uparrow L(1)}^0 - v_{\downarrow L(1)}^0}{v_{\uparrow L(1)}^0 + v_{\downarrow L(1)}^0}. \tag{16}
\]

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]. In general, the parameters \( c_1(2), V_{L(R)} \) 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 larger bias voltages. Indeed, from Eqs. (14),(15) at \( qV_{L(R)} \geq 2T \) we find

\[
J_{\uparrow}^R \sim \frac{J(1 + P_0)(1 + 2\delta n_{\uparrow}(w)/n)}{2}.
\]

where \( P_0 = P_R \cos \theta \). We can obtain the current at \( x = 0 \) (w) from Eq. (10), equate it to \( J_{\uparrow}^R \) assuming negligible spin relaxation at the interface, and then find the unknown \( c_1(2) \) with the use of (9). At \( L_E \gg L_\uparrow \), we have \( b_1 = 1, b_2 = -L_1^2/L_2^2 \) and \( c_1 = P_L, c_2 = -P_0(1 - P_0^2)/(1 - P_L P_0) \). Thus, according to Eqs. (9), the spin densities at the two interfaces are

\[
2\delta n_{\uparrow}(0)/n = P_L - e^{-w/L_\uparrow} P_0(1 - P_0^2)/(1 - P_L P_0), \tag{18}
\]
\[
2\delta n_{\uparrow}(w)/n = (P_L - P_0)/(1 - P_L P_0). \tag{19}
\]

The spin-polarized density profile \( n_{\uparrow}(x) \) is shown in Fig. 2 (bottom panel) for \( w \ll L_\uparrow \). 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, \( \hat{M}_1 || - \hat{M}_2 \), and relatively small accumulation occurs in the case of the parallel configuration, \( \hat{M}_1 \parallel \hat{M}_2 \), Fig. 2.

At \( qV > T \) the current saturates at the value

\[
J = J_0 \left(1 - P_L^2 \cos^2 \theta \right)^{-1}, \tag{20}
\]
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 \( P_L \leftrightarrow P_R \). The current \( J \) is minimal for antiparallel (AP) moments \( \hat{M}_1 \) and \( \hat{M}_2 \) in the electrodes when \( \theta = \pi \) and near maximal for parallel (P) magnetic moments \( \hat{M}_1 \) and \( \hat{M}_2 \). The ratio
allows to find Study of the current oscillations at various bias voltages with an amplitude \( H_0 \) for \( M_{net} \) the magnetization. Eqs. (12), (20) the angle \( \theta_H = \pi \) at \( H \simeq 1 \) kOe. Thus, \( J_H \simeq 1 \) mA at \( J_0 = 25 \) mA, \( P_L P_R \simeq 0.2 \), and \( H \simeq 100 \) Oe. 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 \( t_{tr} = w/|\mu E| = J_s w \tau_s/(J L_s) \), \( t_{tr} \lesssim 10^{-11} \) s for \( w \lesssim 200 \) nm, \( \tau_s \sim 3 \times 10^{-16} \) s, and \( J/J_s \gtrsim 10 \) (\( D \approx 25 \) cm/s at \( T \approx 300 \) K [14]). Thus, the operating frequency \( f = 1/t_{tr} \gtrsim 100 \) GHz \( (\omega = 2\pi/t_{tr} \simeq 1 \) THz) would be achievable at room temperature.

We emphasize that the parameters \( \kappa_0^{L(R)} \), \( P_{L(R)} \) are functions of the bias \( V_{L(R)} \) and \( \Delta \). The efficient spin injection can be achieved when the bottom of 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., minority electrons in the elemental ferromagnet like Fe, Co, Ni (cf. [11]). For instance, in Ni and Fe the peak is at \( F + \Delta_1 \), \( \Delta_1 \approx 0.1 \) eV [16].

In conclusion, we have showed 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.

\[ J_{max}^{(P)} = \frac{1+P_L P_R}{1-P_L P_R} \]

is the same as for the tunneling FM-I-FM structure [3,4], hence, the structure may be also 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 a magnetic sensing. Indeed, spins of the injected electrons can precess in an external magnetic field \( H \) during the transit time \( t_{tr} \) of the electrons through the semiconductor layer \( (t_{tr} < \tau_s) \). In Eqs. (12), (20) the angle between the electron spin and the magnetization \( \vec{M}_2 \) in the FM2 layer is in general \( \theta = \theta_0 + \theta_H \), where \( \theta_0 \) is the angle between the magnetizations \( \vec{M}_1 \) and \( \vec{M}_2 \), and \( \theta_H \) is the spin rotation angle. The spin precesses with a frequency \( \Omega = gH \), where \( H \) is the magnetic field normal to the spin direction, and \( g = g g/(m_e c) \) the gyromagnetic ratio, \( g \) the \( g \)-factor. Therefore, \( \theta_H = \gamma g H t_{tr}(m_0/m_e) \), where \( m_0 \) the mass of a free electron, \( \gamma g = 1.76 \times 10^7 \) Oe\(^{-1} \) 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 \( \Delta H = (2\pi m_e)\gamma g m_0 t_{tr}^{-1} \), Fig. 2 (top panel). Study of the current oscillations at various bias voltages allows 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 \( \theta_H \ll 1 \)

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

\[ K_H = dJ/dH = J_0 P_L P_R \gamma g t_{tr}(m_0/m_e), \quad (22) \]

where \( K_H \) is the magneto-sensitivity coefficient. For example, \( K_H \approx 2 \times 10^{-3} J_0 P_L P_R A/\Omega \) for \( m_0/m_e = 14 \) (GaAs) and \( g = 2 \), \( t_{tr} \sim 10^{-11} \) s, and the angle \( \theta_H = \pi \) at \( H \simeq 1 \) kOe. Thus, \( J_H \simeq 1 \) mA at \( J_0 = 25 \) mA, \( P_L P_R \approx 0.2 \), and \( H \approx 100 \) Oe. 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 \( t_{tr} = w/|\mu E| = J_s w \tau_s/(J L_s) \), \( t_{tr} \lesssim 10^{-11} \) s for \( w \lesssim 200 \) nm, \( \tau_s \sim 3 \times 10^{-16} \) s, and \( J/J_s \gtrsim 10 \) (\( D \approx 25 \) cm/s at \( T \approx 300 \) K [14]). Thus, the operating frequency \( f = 1/t_{tr} \gtrsim 100 \) GHz \( (\omega = 2\pi/t_{tr} \simeq 1 \) THz) would be achievable at room temperature.

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