A class of spin injection-precession ultrafast nanodevices

V.V. Osipov and A.M. Bratkovsky

Hewlett-Packard Laboratories, 1501 Page Mill Road, 1L, Palo Alto, CA 94304

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Spin valve ultrafast spin injection devices are described: an amplifier, a frequency multiplier, and a square-law detector. Their operation is based on injection of spin polarized electrons from one ferromagnet to another through a semiconductor layer and spin precession of the electrons in the semiconductor layer in a magnetic field induced by a (base) current in an adjacent nanowire. The base current can control the emitter current between the magnetic layers with frequencies up to several 100 GHz.

Spintronic devices is a very active area of research [1]. The devices based on giant- and tunnel magnetoresistance [2] are used in a number of applications. The injection of spin-polarized electrons into semiconductors is of particular interest because of relatively large spin-coherence lifetime, and a prospect of using this phenomenon in spintronic devices and quantum computers [1]. Devices of that type have been suggested before based on the Rashba spin-orbital splitting of 2D electrons under a gate electric field [3]. The schemes involving reflection of semiconductor electrons off a ferromagnetic layer have also been discussed [4].

In the present paper we describe a spintronic mechanism of ultrafast amplification and frequency conversion, which can be realized in heterostructures comprising a metallic ferromagnetic nanowire surrounded by a semiconductor (S) and a ferromagnetic (FM) thin shells, Fig. 1(a). Practical devices may have various layouts, with two examples shown in Fig. 1(b),(c). Let us consider the principle of operation of the spintronic devices with the layout shown in Fig. 1(a). We assume that the thickness $w$ of the $n$-type semiconductor layer is not extremely small ($w \gtrsim 30$ nm), so that a tunneling through this layer is negligible. The base voltage $V_b$ is applied between the ends of the nanowire. The base current $J_b$, flowing through the nanowire, induces a cylindrically symmetric magnetic field $H_b = J_b/(2\pi \rho)$ in the S layer, where $\rho$ is the distance from the center of nanowire. When the emitter voltage $V_e$ is applied between FM layers, the spin polarized electrons are injected from the first layer (nanowire FM$_1$) through the semiconductor layer into the second (exterior) ferromagnetic shell, FM$_2$. We assume that the transit time $t_{tr}$ of the electrons through the S layer is less than the spin relaxation time, $\tau_s$ (i.e. we consider the case of a spin ballistic transport). We show below that in this case the emitter current $J_e$ between FM$_1$ and FM$_2$ layers depends on the angle $\theta$ between the magnetization vectors $\vec{M}_1$ and $\vec{M}_2$ in these layers approximately in the same way as in the tunneling FM-I-FM structures [5,6]:

\[ J_e = J_{eo}(1 + P_1 P_2 \cos \theta). \]  

(1)

However, in comparison with the tunneling structures, the described heterostructures have an additional degree of freedom. Spins of injected electrons will precess in the radially symmetric induced magnetic field $H_b = J_b/(2\pi \rho)$ during the transit of electrons through the semiconductor layer ($t_{tr} < \tau_s$). Therefore, $\theta = \theta_0 + \theta_H$ in Eq. (1), where $\theta_0$ is the angle between $\vec{M}_1$ and $\vec{M}_2$, and $\theta_H$ is the angle of the spin rotation. The spin precesses with the frequency $\Omega = \gamma H_\perp$, where $H_\perp$ is the magnetic field component normal to the spin and $\gamma$ is the gyromagnetic ratio [7,8]. One can see from Fig. 1(a) that $H_\perp = H_b$. Thus, the angle of the spin rotation is equal to $\theta_H = \gamma H_\perp t_{tr} = \gamma t_{tr} J_b/2\pi \rho S$, where $\rho_s$ is the characteristic radius of the S layer. According to Eq. (1),

\[ J_e = J_{eo}[1 + P_1 P_2 \cos(\theta_0 + \theta_H)]. \]  

(2)

where $k_j = \gamma t_{tr}/2\pi \rho S = \gamma /\omega \rho S$ and $\omega = 2\pi /t_{tr}$ is the frequency of a variation of the base current, $J_b = J_e \cos(\omega t)$. Equation (2) shows that, when the magnetization $M_1$ is perpendicular to $M_2$, $\theta_0 = \pi/2$, and $\theta_H \ll \pi$,

\[ J_e = J_{eo}(1 + k_j P_1 P_2 J_b), \quad G = dJ_e/dJ_b = J_{eo} k_j P_1 P_2. \]  

(3)

Thus, the amplification of the base current occurs with the gain $G$, which can be relatively high even for $\omega \gtrsim 100$ GHz. Indeed, $\gamma = q/(m_e c) \approx 2.2(m_0/m_e)10^5$ m/A-s [7,8], where $m_0$ is the free electron mass, $m_e$ the effective mass of electrons in the semiconductor, and $c$ the velocity of light. Thus, when $\rho S \simeq 30$ nm, $m_0/m_e = 14$ (GaAs) and $\omega = 100$ GHz, the factor $k_j \simeq 10^3$ $\text{A}^{-1}$, so that $G > 1$ at $J_{eo} > 0.1 \text{mA}/(P_1 P_2)$.

When $M_1$ is collinear with $M_2$ ($\theta_0 = 0, \pi$) and $\theta_H \ll \pi$, then, according to Eq. (2), the emitter current is

\[ J_e = J_{eo}(1 \pm P_1 P_2) \mp \frac{1}{2} J_{eo} P_1 P_2 k_j^2 J_b^2. \]  

(4)

Therefore, the time-dependent component of the emitter current $\delta J_e(t) \propto J_b^2(t)$, and the device operates as

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a square-law detector. When \( J_b(t) = J_\text{lo} \cos(\omega_0 t) \), the emitter current has a component \( \delta J_e(t) \propto \cos(2\omega_0 t) \), and the device works as a frequency multiplier. When \( J_b(t) = J_h \cos(\omega_h t) + J_s \cos(\omega_s t) \), the emitter current has the components proportional to \( \cos(\omega_h \pm \omega_s) t \), i.e. the device can operate as a high-frequency heterodyne detector with the conversion coefficient \( K = J_\text{lo} J_h P_1 P_2 k_s^2/4 \). For \( k_s = 10^3 \) \( \text{A}^{-1} \) the value of \( K > 1 \) when \( J_\text{lo} J_h > 4(\text{mA})^2/(P_1 P_2) \). Let us now consider the present spintronic devices in greater detail. One can see from Fig. 1 that the devices in the cross-section \( a - a \) are the FM-n-FM heterostructures, where \( n \) marks the \( n- \)type semiconductor layer. It is well known that a large potential barrier, so-called depleted Schottky layer, forms at the metal-semiconductor interface [9]. Therefore, the spin injection current from FM into S in such a FM-n-FM structure is negligibly small when \( w > 30 \) nm. To increase the current, a thin heavily doped \( n^+ - \)semiconductor layer (so-called \( \delta \)-doped layer) between the ferromagnet and semiconductor should be used [10,11]. This layer screens the interface potential barriers, sharply decreases their thickness, and increases the tunneling transparency [11]. This is why the considered heterostructures have to comprise two \( \delta \)-doped layers, between the S and FM layers. Thickness of the \( \delta \)-doped layers \( l_{1(2)} \) and the donor concentration \( N_d^+ \) there have to satisfy the following conditions [11]:

\[
N_d^+ l_{1(2)}^2 \approx 2\epsilon \varepsilon_0 (\Delta - \Delta_0 + r T)/q^2 \quad \text{and} \quad N_d^+ l_{1(2)}^2 \approx 2\epsilon \varepsilon_0 (\Delta - \Delta_0)/q^2,
\]

where \( \epsilon (\varepsilon_0) \) the dielectric permittivity of semiconductor (vacuum), \( \Delta_0 = E_c - F > 0 \), \( F \) the equilibrium Fermi level, \( E_c \) the bottom of a semiconductor conduction band, the parameter \( r \approx 2 - 3 \), and \( T \) the temperature (we use the units of \( k_B = 1 \)). The energy diagram of such a FM-n+ -n -n^+ -FM structure includes two potential \( \delta \)-barriers of the height \( (\Delta - \Delta_0) \) and the thicknesses \( l_{1(2)} \) and a low wide barrier of the height \( \Delta_0 \) and the thickness \( w \) in the \( n- \)semiconductor region (Fig. 2). We assume that the electrons easily tunnel through the \( \delta \)-spike barriers due to a smallness of \( l_{1(2)} \). However, only electrons with the energy \( E \geq E_c \) can overcome the low wide barrier \( \Delta_0 \) by way of a thermionic emission-tunneling [11]. We assume that the electron energy \( E \), spin \( \sigma \) and the wave vector \( \vec{k}_\parallel \) parallel to the interface are conserved during tunneling. The current density of electrons with spin \( \sigma \) through FM-S junctions, including the \( \delta \)-layers, Fig. 2, can be written as [12,6,11]

\[
J_\sigma^{1(2)} = \frac{q}{\hbar} \int dE \left[ f(E - F_{1(2)}) - f(E - F_{1(2)}) \right] \int \frac{d^2 k_\parallel}{(2\pi)^2} T_{k_\sigma},
\]

where \( T_{k_\sigma} \) is the transmission probability, \( f(E) = [\exp(E - F_{1(2)})/T + 1]^{-1} \) the Fermi function, the left (right) Fermi levels are \( F_1 = F \) and \( F_2 = F - qV \), respectively, where \( V \) is the bias voltage on the device, and the integration includes a summation with respect

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**FIG. 1.** Schematic of the spin injection-precession devices having cylindrical (a), semi-cylindrical (b), and planar shape (c). Here FM\(_1\) and FM\(_2\) are the ferromagnetic layers; \( n-S \) the \( n \)-type semiconductor layers; \( w \) the thickness of the \( n-S \) layer; \( \delta \) the \( \delta \)-doped layers; NW the highly conductive nanowires; \( I \) the insulating layers. The directions of the magnetizations \( \vec{M}_1 \) and \( \vec{M}_2 \) in the FM\(_1\) and FM\(_2\) layers, as well as the electron spin \( \sigma \), the magnetic field \( \vec{H}_s \), and the angle of spin rotation \( \theta \) in S are also shown.
to a band index. We take into account that the spin polarized electrons in the semiconductor are not out of equilibrium and their distribution is described by a nonequilibrium Fermi function with the quasi-Fermi level $F_\sigma(x)$. In Eq. (5) $F_1 = F_\sigma(0)$ and $F_2 = F_\sigma(w)$. The condition $\Delta_0 = E_c - F > 0$ means that the semiconductor is nondegenerate, so the total electron concentration and the concentration of electrons with spin $\sigma$ are given by

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

where $N_c = 2M_c(2\pi m_s T)^{3/2}h^{-3}$ is the effective density of states of the conduction band of the semiconductor, $m_s$ the effective mass of electrons in the semiconductor, and $M_c$ the number of the band minima [9]. The analytical expressions for $T_{k\sigma}$ can be obtained in an effective mass approximation, $\hbar k \approx m_\sigma v_\sigma$. For energies of interest, $E \gtrsim F + \Delta_0 \equiv qV_{1(2)}$, we can approximate the $\delta$–barrier by a triangular shape and find that, when the voltage drops across the first and the second junctions $V_{1(2)}$ satisfy the condition $2T \lesssim qV_{1(2)} \lesssim \Delta_0 \ll \Delta$, the currents of electrons with spins $\sigma = \uparrow (\downarrow)$ and $\sigma' = \pm$ through the junctions of a unit area are approximately equal to [11]

$$J_{1\sigma} = J_{01}d_\sigma \exp(qV_{1(2)}/T), \quad J_{2\sigma'} = 2J_{02}d_\sigma n_\sigma(w)/n, \quad J_{01(2)} = -\frac{\alpha^{(2)}_0}{T} q \sqrt{\kappa^{(2)}_0}$$

where the spins $\sigma = \uparrow$ and $\sigma' = +$ are parallel to the magnetizations $\vec{M}_1$ and $\vec{M}_2$, respectively,

$$\kappa^{(2)}_0 \equiv 1/\alpha^{(2)}_0 = (2m_s/\hbar^2)^{1/2}(\Delta - \Delta_0 \pm qV_{1(2)})^{1/2}, \quad \alpha^{(2)}_0 = 1.2 \left( \kappa^{(2)}_0 l_{1(2)} \right)^{1/3},$$

$$d_\sigma = \frac{v_T v_{\sigma(\sigma')}}{v_{\sigma(\sigma')}} = \frac{(v_{\uparrow(\downarrow)} + v_{\downarrow(\uparrow)})^2}{(v_{\uparrow(\downarrow)} + v_{\downarrow(\uparrow)})},$$

$$v_{\sigma(\sigma')} = v_{\sigma(\sigma')} (\Delta_0 \pm qV_{1(2)}),$$

$$v_{\uparrow(\downarrow)} = \sqrt{2(\Delta - \Delta_0 \pm qV_{1(2)})/m_s}$$

and

$$v_T = \sqrt{3T/m_s}.$$

In the case of a spin ballistic transport ($t_{tr} < \tau_s$), the spin of injected electrons is conserved in the semiconductor layer, $\sigma' = \sigma$, where the spins $\sigma$ is determined by the direction $\vec{M}_1$. Therefore, the angle between the spin $\sigma$ and the magnetization $\vec{M}_2$ is $\theta = \theta_0 + \theta_H$, where $\theta_0$ is the angle between $\vec{M}_1$ and $\vec{M}_2$ and $\theta_H$ the angle of spin precession in the magnetic field $H_0 = J_0/2\pi R_S$. Probabilities of an electron spin $\sigma$ to have a projection onto the axes $\pm \vec{M}_2$ are $\cos^2(\theta/2) \sin^2(\theta/2)$, respectively [7]. Therefore, using Eqs. (7), the spin current through the second (right) junction can be written as

$$J_{2\uparrow(\downarrow)} = J_{02} \left( \frac{2a^{(2)}_T(w)}{a^{(2)}_T} \right) \left( d_{\uparrow(-)} \cos^2 \frac{\theta}{2} + d_{\downarrow(+)} \sin^2 \frac{\theta}{2} \right).$$

(9)

Considering the total current density $J = J_{\uparrow} + J_{\downarrow}$, it follows from Eqs. (7) and (9) that

$$J_{\uparrow} = (J/2)(1 + P_1), \quad J_{\downarrow} = \frac{J}{2} \frac{1 + (2\delta n_t(w)/n)P_2 \cos \theta}{1 - (2\delta n_t(w)/n)P_2 \cos \theta},$$

(10)

Here $P_{1(2)}$ are the spin factors

$$P_{1(2)} = \frac{d_{\uparrow(\downarrow)} - d_{\downarrow(\uparrow)}}{d_{\uparrow(\downarrow)} + d_{\downarrow(\uparrow)}}, \quad \frac{(v_{\uparrow(\downarrow)} + v_{\downarrow(\uparrow)})(v_{\uparrow(\downarrow)}^2 - v_{\downarrow(\uparrow)}^2)}{(v_{\uparrow(\downarrow)} + v_{\downarrow(\uparrow)})(v_{\uparrow(\downarrow)}^2 + v_{\downarrow(\uparrow)}^2)}.$$

(11)

which coincide with spin polarization of a current in tunneling FM-I-FM structures [6].

The spatial distribution of spin polarized electrons is determined by the usual equation $dJ_{\sigma}/dx = q\delta n_\sigma/\tau_s$, where $\delta n_\sigma = n_\sigma - n/2 [9,13]$. Integrating this equation over $x$ along the semiconductor layer of thickness $w$ we obtain $J_{\uparrow} - J_{\downarrow} = q\tau^{-1}_s \int \delta n_\sigma dx < qnw/\tau_s$. Therefore, when $J_{\uparrow} \gg J_{\downarrow} 
\gg J_{\uparrow}$, Eqs. (10),(11) yield

$$\frac{\delta n_t(w)}{n} = \frac{(P_1 - P_2 \cos \theta)/(1 - P_1P_2 \cos \theta)}{J_{02}(d_+ + d_-)} \left( 1 - P_2 \cos \theta \right)^{-1}.$$

(13)

$$J = J_{02}(d_+ + d_-) \left( 1 - P_2 \cos \theta \right)^{-1}.$$

(14)

One can see that Eq. (14) gives the same qualitative behavior as Eqs. (3),(4), so indeed the effects described above can be realized in the heterostructures shown in Fig. 1.

We note that both $\kappa^{(2)}_0$ and $P_{1(2)}$ are the functions of the bias $\Delta_0$ and $V_{1(2)}$. Therefore, by adjusting $\Delta_0$ and $V_{1(2)}$ one can maximize a polarization of the injected current [11]. This may be achieved when the bottom of the conduction band in a semiconductor, $E_c$, is close to a peak in the density of (minority) electron states in the elemental
ferromagnet like Fe, Co, Ni (cf. [11], for example, in Ni and Fe \( \Delta_1 \approx 0.1 \text{ eV} \) [14]).

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