Magnetic bipolar transistor

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A magnetic bipolar transistor is a bipolar junction transistor with one or more magnetic regions, and/or with an externally injected nonequilibrium (source) spin. It is shown that electrical spin injection through the transistor is possible in the forward active regime. It is predicted that the current amplification of the transistor can be tuned by spin.

We propose a novel device scheme—the magnetic bipolar transistor (MBT)—which builds on the existing technology (bipolar junction transistor), adding spin degrees of freedom to the current carriers. An MBT is a bipolar spintronic device: its functionality is defined by the transport properties of electrons, holes, and their spins. While bipolar spintronics still relies rather on experimentally demonstrated fundamental physics concepts (such as spin injection, spin filtering, or semiconductor ferromagnetism) than on working devices, recent experiments on spin injection through bipolar tunnel junctions prove the potential of the spin-polarized bipolar transistor for both fundamental physics and useful technological applications. Here we analyze MBTs (other types of spin transistors were proposed in Refs. 18, 19, 20, 21, 22, 23, 24), with a magnetic base and a source spin in the emitter. We predict that spin can accumulate in the collector due to the electrical spin injection, and that the current amplification of MBTs can be controlled by spin.

Crucial to MBTs is the use of magnetic semiconductors where the splitting of the carrier bands produces spin-polarized electrons or holes with the spin polarization perhaps 10% or more. The carrier band splitting can be of the Zeeman or the exchange type. The former arises from large g factors (for example, in Cd$_{0.95}$Mn$_{0.05}$Se the g factor exceeds 500), while it is as large as 50 in InSb at room temperature), and an application of a magnetic field, while the latter comes from the exchange coupling in ferromagnetic semiconductors (about 10 meV). In addition to the equilibrium spin, a nonequilibrium (source) spin can be generated in the emitter by an external spin injection, electrical or optical.

Our model is described in Fig. 1. We consider an npn structure doped with $N_{dc}$ donors in the emitter, $N_{ab}$ acceptors in the base, and $N_{dc}$ donors in the collectors. There are two depletion layers, one between the emitter and the base, the other between the base and the collector. The transistor is a three terminal device: there is a contact with an external electrode at each region, generating bias $V_{bc}$ across the emitter-base and $V_{dc}$ across the base-collector depletion layer. The base is magnetic. For simplicity only electrons are spin polarized. The equilibrium spin polarization in the base is $\alpha_{0b} = \tanh(q\zeta/k_BT)$, where $2q\zeta$ is the conduction band spin splitting and $k_BT$ is the thermal energy. The nonequilibrium spin polarization injected externally into the emitter is $\alpha_c$. The equilibrium number of electrons in the base depends on the equilibrium spin polarization:}

$$n_{0b} = (n_i^2/N_{ab})(1/\sqrt{1-\alpha_{0b}^2}), \quad (1)$$

where $n_i$ is the intrinsic carrier density. The equilibrium number of holes in the emitter is $n_{0e} = n_i^2/N_{dc}$. For simplicity we assume that the electron and hole diffusivities $D_e$ and $D_p$ are uniform, similarly for the electron and hole diffusion lengths $L_e$ and $L_p$, and for the electron spin diffusion length $L_s$. The effective widths $w$ (which depend on the biases as well as on $\alpha_{0b}$) of the three bulk regions are defined in Fig. 1.

We consider the most useful forward active (also called amplification) regime of the transistor, where the emitter-base depletion layer is forward biased, $V_{be} > 0$, and the base-collector junction is reverse biased, $V_{bc} < 0$, as shown in Fig. 1. Furthermore, we assume the small injection limit where the excess (injected) electron densities anywhere in the structure are smaller than the equilibrium densities determined by the doping. The resulting flow of electrons and holes is depicted in the bottom part of Fig. 1. Take electrons first. As the barrier between the emitter and the collector is lowered by $V_{be}$, the electrons flow easily to the base, forming the electron emitter current $j_{ne}^n$. In the base the excess electrons either recombine with holes, producing the base recombination current $j_{rb}^n$, or diffuse towards the base-collector depletion layer. This layer is reverse biased so that all the electrons reaching it from the base are swept by the large electric field to the collector, forming the collector current $j_{nc}^n$. Holes need to be supplied from the base to go in the forward direction to the emitter, forming the hole base, $j_{rb}^p$, and the hole emitter, $j_{ma}^p$, currents. The total emitter current is $j_e = j_{ma}^p + j_{nc}^n$ and the total collector current is $j_c = j_{ma}^p$. The base current is $j_b = j_e - j_c$. The current amplification coefficient (gain) is defined as $\beta = j_c/j_b$, being about...
indicated by the shading of the arrows.

densities are shown. The electron flow is spin-polarized, as input signal), there is a large variation in \( j \) are indicated and the regions labels (spin) in the collector, proving the possibility of the electrons and holes is depicted (part of the base current, flow to the emitter. The flow of electrons and holes, which are the large \( j_b \) in the base-collector region (base) and source spin densities in the p region (base). This is the case of a magnetic solar cell, since the electron and the source spin densities in the p region mimic the carrier and spin generation by light. For this case our theory gives

\[
\alpha \approx \gamma_1 s_{be} = \gamma_1 n_{be} \exp(V_{be}/k_B T) (\alpha_{ob} + \alpha_e),
\]

where \( \gamma_1 \approx (L_e/w_b) \tanh (w_c/L_s) \). The accumulated spin polarization, which is the measure of the electrical spin injection efficiency, is \( \alpha_e = s_e/N_{dc} \). Typically the spin diffusion length in the collector \( L_{sc} \gg w_b \), which means that \( \alpha_e \) can be a considerable fraction (say, 10%) of \( \alpha_e \) or \( \alpha_{ob} \). What is interesting in Eq. (4) is the fact that \( \alpha_{ob} \) plays the same role as \( \alpha_e \) in the spin injection: the equilibrium spin can cause spin accumulation in the low injection limit, because it leads first to nonequilibrium spin \( s_{be} \). This has no analog in magnetic diodes, where spin accumulation cannot result from the presence of just an equilibrium spin polarization.

Spin control of current amplification. When written in terms of \( n_{be} \), the formulas for the currents \( j_e \) and \( j_c \) are the same as for the standard (nonmagnetic) bipolar transistors derived by Shockley. After we write those formulas for the active forward regime, we substitute Eq. (2) for \( n_{be} \) and obtain the dependence of the currents (and of \( \beta \)) on \( \alpha_e \) and \( \alpha_{ob} \).

The emitter current is

\[
j_e = j_{ge}^n (n_{be}/n_{ob}) + j_{ge}^p (p_c/p_{oe}),
\]

where \( j_{ge}^n \) is the electron generation current \( (qD_n/L_n) n_{ob} \coth (w_b/L_n) \), the hole generation current \( j_{ge}^p \) is \( (qD_p/L_p) p_{be} \coth (w_c/L_p) \), and the injected hole density in the emitter \( p_c = p_{oe} \exp (V_{be}/k_B T) \). The collector current comprises only electrons (Fig. 1):

\[
j_c = j_{gc}^n (n_{be}/n_{ob}) \coth (w_b/L_n).
\]
After evaluating $j_b = j_e - j_c$ and substituting Eq. (2) for $n_{be}$, it is straightforward to show that in the narrow base limit ($w_b \ll L_n, L_s$) the gain is

$$\beta = 1/\left(\alpha_T' + \gamma'\right),$$

(7)

where we use the standard transistor notation [3]:

$$\alpha_T' = \left(w_b/L_n\right)^2/2,$$

(8)

$$\gamma' = \frac{N_s D_p}{N_e D_n} \frac{w_b}{L_p \tanh(w_e/L_p)} \left(1 + \alpha_e \alpha_{ob}\right).$$

(9)

The factor $\alpha_T'$ determines how much electrons will recombine in the base, thus not reaching the collector. This factor is not affected by the presence of spin, and is the same as in the standard transistors. The factor $\gamma'$ is related to the emitter injection efficiency, since it measures the proportion of the electron flow in the emitter current (where both electrons and holes contribute). This factor does depend on the spin. To get the maximum amplification, both $\alpha_T'$ and $\gamma'$ need to be small. For the most efficient spin control of $\beta$, one needs $\alpha_T' \lesssim \gamma'$, the case of Si-based transistors which have slow carrier recombination. In this case

$$\beta(\alpha_e, \alpha_{ob}) = \beta(\alpha_e = 0, \alpha_{ob} = 0) \times \frac{1 + \alpha_e \alpha_{ob}}{\sqrt{1 - \alpha_{ob}^2}}.$$  

(10)

The current amplification is affected by both $\alpha_e$ and $\alpha_{ob}$.

As an illustration we calculate $\beta$ as a function of $\alpha_{ob}$ for an MBT with $\alpha_e = 0.9$ and with generic materials parameters, specified for a Si-like transistor. The nominal widths of the emitter, base, and collector are 2, 1.5, and 2 μm, respectively. The dopings are $N_e = 10^{17}$, $N_b = 10^{16}$, and $N_c = 10^{15}$ cm$^{-3}$. Electron (hole) diffusivities at room temperature are taken to be $D_n = 100$ and $D_p = 10$ cm$^2$/s. The bias voltages are $V_{be} = 0.5$ and $V_{bc} = 0$ volts. The intrinsic carrier density $n_i = 10^{10}$ cm$^{-3}$ and the dielectric constant (needed to calculate the effective widths $w_i$) is 12. The carrier and spin diffusion lengths (note that Si has long recombination and spin relaxation times [29]) are taken to be $L_n = 30$ μm, $L_p = L_s = 10$ μm. The calculated $\beta$ varies strongly with the spin, following closely the approximate $\beta$ given by Eq. (10). The amplification is largest (smallest) for the parallel (antiparallel) orientation of the source and equilibrium spins.

We conclude that spin can be injected through MBTs and that current amplification can be controlled by both the source and the equilibrium spin, making MBTs attractive for spintronic applications.

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