The concept of a magnetic bipolar transistor (MBT) is introduced. The transistor has at least one magnetic region (emitter, base, or collector) characterized by spin-splitting of the carrier bands. In addition, nonequilibrium (source) spin in MBTs can be induced by external means (electrically or optically). The theory of ideal MBTs is developed and discussed in the forward active regime where the transistors can amplify signals. It is shown that source spin can be injected from the emitter to the collector. It is predicted that electrical current gain (amplification) can be controlled effectively by magnetic field and source spin.

The theory of magnetic bipolar transistors

Jaroslav Fabian¹, Igor Žutić², and S. Das Sarma²

Institute for Theoretical Physics, Karl-Franzens University, Universitätsplatz 5, 8010 Graz, Austria
Condensed Matter Theory Center, Department of Physics, University of Maryland at College Park, College Park, Maryland 20742-4111, USA

The concept of a magnetic bipolar transistor (MBT) is introduced. The transistor has at least one magnetic region (emitter, base, or collector) characterized by spin-splitting of the carrier bands. In addition, nonequilibrium (source) spin in MBTs can be induced by external means (electrically or optically). The theory of ideal MBTs is developed and discussed in the forward active regime where the transistors can amplify signals. It is shown that source spin can be injected from the emitter to the collector. It is predicted that electrical current gain (amplification) can be controlled effectively by magnetic field and source spin.

PACS numbers: 72.25.Dc, 72.25.Mk

Ideally, novel electronics applications build on the existing technologies with as little added complexity as possible, while providing greater capabilities and functionalities than the existing devices. Such is the promise of semiconductor spintronics which aims at developing novel devices utilizing electron spin, in addition to charge—which would provide spin and magnetic control of electronics and, vice versa, electronic control over spin and magnetism. Potential applications of semiconductor spintronics range from nonvolatile computer memories to spin-based quantum computing. One particular promising implementation of semiconductor spintronics is bipolar spintronics which combines spin and charge transport of both electrons and holes in (generally magnetic) semiconductor heterostructures to control electronics. In this Letter we propose a novel device scheme—magnetic bipolar (junction) transistor (MBT)—which, while in design a minor modification of the existing charge-based heterojunction transistor (in fact, materials needed to fabricate MBTs are already available), has a great potential for extending functionalities of the existing device structures, since, as is demonstrated here, its current gain (amplification) characteristics can be controlled by magnetic field and spin.

As semiconductor spintronics itself, bipolar spintronics still relies rather on experimentally demonstrated fundamental physics concepts (such as spin injection, spin filtering, or semiconductor ferromagnetism) than on demonstrated working devices. But the recent experiments on spin injection through bipolar tunnel junctions clearly prove the potential of spin-polarized bipolar transport for both interesting fundamental physics and useful technological applications. We have recently shown theoretically that indeed spin-polarized bipolar transport is a source of novel physical effects and device concepts. In particular, we have analyzed the properties of magnetic junction diodes, demonstrating spin injection, spin capacitance, giant magnetoresistance, and a spin-voltaic effect. Here we formulate an analytic approach to study magnetic bipolar transistor (which is a very different structure from the earlier spin transistors), incorporating two magnetic p-n junctions in sequence. The step from a diode to a transistor is nontrivial conceptually as it introduces new phenomena, most notably current amplification. Our two major findings are: source spin can be injected across a transistor and electrical gain can be controlled by spin and magnetic field.

A scheme of MBT is shown in Fig. 1. We consider an npn transistor with spin-split conduction bands (the splitting is proportional to magnetic field and is amplified by magnetic doping) and with source spin (which is incorporated here through boundary conditions) injected, in principle, to any region. Source spin, in addition to applied bias, brings about nonequilibrium carrier population and thus electrical current. In the following we generalize the theory developed for magnetic p-n junctions to study magnetic transistor structures. All the assumptions of that theory apply here. Most important, carriers obey nondegenerate Boltzmann statistics, nonequilibrium carrier densities are smaller than the doping densities (the low injection or low bias limit), and carrier recombination and spin relaxation is neglected in the depletion layers. Further, we express voltages in the units of thermal energy $k_BT$, and make them positive for forward biasing.

Our first task is to obtain the electron and spin densities at the two depletion layers. Once these are known, the density profiles can be calculated using the formulas provided in Tab. II of Ref. 13. In the following the quantities at the emitter-base (collector-base) depletion layer edges carry index 1 (2). To simplify complex notation we adopt terminology that is useful in treating an arbitrary array of magnetic p-n junctions, though here we limit ourselves to MBT which is the smallest nontrivial array of such kind. We denote by scalar $u$ the nonequilibrium spin density in the $n$ regions (here emitter $e$ and collector $c$), and by vector $v$ the nonequilibrium electron (the first component) and spin (the second component) densities in the $p$ regions (here only base $b$). The boundary

...
conditions are specified by \( u \) and \( v \) at the emitter and collector contacts to the external electrodes. In our case the boundary spin densities are \( u_0 \) and \( u_3 \) which are to be treated as input parameters. The notation inside the array follows the indexing of the junctions. For example, \( v_2 \) is the nonequilibrium density vector in the \( p \) side at the second depletion layer edge (in our case it is the density in the base at the \( b-c \) depletion layer). The values of \( u_1 \), \( v_1 \), etc. need to be obtained self-consistently requiring \( 2 \) that the (spin-resolved) chemical potentials and spin currents are continuous across the depletion layers. The following is the basic set of equations describing the coupling of charge and spin (the coupling is both intra- and inter-junction) in the magnetic transistor system \( 13 \):

\[
\begin{align*}
  u_1 &= \gamma_{0,1} u_0 + C_1 \cdot v_2, \\
  v_1 &= v^0_1 + D_1 u_1,
\end{align*}
\]

for junction 1, and

\[
\begin{align*}
  u_2 &= \gamma_{0,2} u_3 + C_2 \cdot v_1, \\
  v_2 &= v^0_2 + D_2 u_2,
\end{align*}
\]

for junction 2. The notation goes as follows. For a general junction \( V^0 = [\exp(V) - 1](n_{0p}, s_{0p}) \) is the nonequilibrium density vector due to applied bias (across the junction) \( V \) (but no source spin). \( C = [\gamma_2(\gamma_2 - 1), \gamma_1] \), and

\[
D = \frac{n_{0p} e^V}{N_d} \frac{1}{1 - \alpha_{0n}} (\alpha_{0p} - \alpha_{0n}, 1 - \alpha_{0p} \alpha_{0n}).
\]

Symbol \( n_{0p} \) (\( s_{0p} \)) stands for the electron (spin) equilibrium density in the \( p \) region of the junction. \( N_d \) is the donor doping density of the \( n \)-region, and \( \alpha_{0n} \) (\( \alpha_{0p} \)) is the equilibrium electron spin polarization (the ratio of spin and electron density) in the \( n \) \( (p) \) region adjacent to the junction. The geometric/transport factors \( \gamma_0 \) through \( \gamma_2 \) are determined from carrier diffusivities, carrier recombination and spin relaxation times, and effective widths of the adjacent bulk regions \( 13 \). We note that equations analogous to Eqs. \( 1 \) \( 2 \) can be written for holes, if their polarization is taken into account. The solution to Eqs. \( 1 \) \( 2 \) is

\[
u_2 = \gamma_{0,1} (C_2 \cdot D_1) u_0 + \gamma_{0,2} u_3 + C_2 \cdot v^0_1,
\]

where we have neglected terms of order \( [n_{0p} \exp(V)/N_d]^2 \), consistent with the small injection limit. The formulas for \( u_1 \), \( v_1 \), and \( v_2 \) can be obtained directly by substituting Eq. \( 2 \) for \( u_2 \) into Eqs. \( 1 \) through \( 2 \).

Equation \( 2 \) describes spin injection through MBT, since \( u_2 \) is the nonequilibrium spin in the collector at the depletion layer with the base. The first term on the right-hand side (RHS) of Eq. \( 2 \) represents transfer of source spin \( u_0 \) from the emitter to the base. Indeed, for a nonmagnetic transistor (the equilibrium spin polarizations are zero) the transferred source spin is \( u_3 = \gamma_{0,1} \gamma_{1,2} n_{0b} \exp(V_1) u_0 \). Here \( \gamma_0 \) describes the transfer of source spin through the emitter–majority carrier spin injection. Once the spin is in the base, it becomes the spin of the minority carriers [hence the minority density factor \( n_{0b} \exp(V_1) \)], diffusing towards the \( b-c \) depletion layer. The built-in electric field in this layer sweeps the spin into the collector, where it becomes the spin of the majority carriers again, by the process of minority-carrier spin pumping \( 10 \) \( 13 \). Can the injected spin polarization in the collector be greater than the source spin polarization? The answer is negative in the low-injection regime. It would be tempting to let the spin diffusion length in the collector to increase to large values to get a greater pumped spin. But that would increase the importance of electric field in the \( n \)-regions and the theory (which is based on charge and spin diffusion and not spin drift) would cease to be valid. However, the spin density in the collector can be greater than that in the base (as illustrated in the example below), demonstrating that spin spatial decay is not, in general, monotonically decreasing.

The second term on the RHS of Eq. \( 2 \) results from diffusion of the source spin in the collector (described by \( \gamma_{0,2} \)). Finally, the third term, which is independent of source spin, results from the (intrinsic) spin pumping by the minority channel of nonequilibrium spin generated in the base by the forward current through junction 1. This term vanishes if the base is nonmagnetic (\( \alpha_{0b} = 0 \)).

To illustrate spin injection across MBT we plot in Fig. 2 the calculated electron and spin density profiles in a Si-based magnetic \( npm \) transistor with magnetic base (and nonmagnetic emitter and collector) and with source spin in the emitter. The geometry of the device is depicted at the top of the figure. The emitter, base, and collector are doped (respectively) with \( N_e = 10^{17} \), \( N_b = 10^{16} \), and \( N_c = 10^{15} \) donors, acceptors, and donors per cm\(^3\). The carrier and spin relaxation times are taken to be 0.1 \( \mu \)s (it is not clear what spin relaxation times of conduction electrons in Si should be \( 18 \), but due to the small spin-orbit coupling they are expected to be on the
The intrinsic carrier concentration is of the order of sub-microseconds, rather than sub-nanoseconds. The densities inside the depletion layers are not calculated, and are shown here (with no justification beside guiding the eye) as straight lines connecting the densities at the depletion layer edges.

FIG. 2: Calculated electron and spin density profiles in a Si-based npn transistor with magnetic base and source spin in the emitter. The transistor geometry is shown at the top. The transistor is at room temperature. The applied bias is $V_1 = V_{bc} = 0.5$ volts and $V_2 = V_{bc} = -0.2$ volts. The spin splitting of the base conduction band is $2\zeta_b = 2$ (in $k_B T$), yielding the equilibrium spin polarization $\eta_{0b} = \tanh(\zeta_b) = 0.76$; the source spin polarization at the emitter (at $x = 0$) is $\eta_0/N_D = 0.9$. Finally, we assume charge and spin ohmic contact at $x = 3$, meaning that both carrier and spin densities are at their equilibrium levels. Figure 2 demonstrates that spin injection is possible all the way from the emitter, through the base, down to the collector. The density of the injected spin in the collector depends on many factors, most notably on the forward bias $V_{bc}$ and on the spin diffusion lengths in the base and in the collector. The spin density (but not spin polarization) even increases as one goes from the base to the collector, consistent with our notion of spin amplification [10, 21]. The injected spin polarization $\eta_2/N_c$ in the above example is about 2%, but it would be greater for higher $V_{bc}$, longer spin relaxation times, and smaller base widths.

We now turn to the question of current gain (amplification) and its control by magnetic field (through $\zeta_b$) and source spin (through $\delta\alpha_c$, the nonequilibrium spin polarization in the emitter at junction 1). Electric currents are readily evaluated once the nonequilibrium carrier densities at the depletion layers are known. Thus the emitter current

$$j_e = j_{gb}^n \frac{\delta n_{be}}{n_{0b}} - j_{gb}^p \frac{1}{\cosh(\tilde{w}_b/L_{nb})} \frac{\delta n_{bc}}{n_{0b}} + j_{ge}^p \frac{\delta p_{be}}{p_{0e}}. \tag{7}$$

and the collector current

$$j_c = -j_{gb}^p \frac{\delta n_{be}}{n_{0b}} + j_{gb}^n \frac{1}{\cosh(\tilde{w}_b/L_{nb})} \frac{\delta n_{bc}}{n_{0b}} + j_{ge}^n \frac{\delta p_{be}}{p_{0e}}, \tag{8}$$

where we denote the generation currents for electrons and holes (with the indexing of the appropriate region) respectively as $\delta n_{be}$ and $\delta p_{be}$, the nonequilibrium electron (hole) densities at the corresponding depletion layer. In the active control regime ($V_{bc} > 0$ and $V_{bc} < 0$) the hole collector current and the current driven by the nonequilibrium density $\delta n_{be}$ becomes negligible. Finally, the base current is given by the current continuity (see Fig. 1) as $j_b = j_e - j_c$.

The current amplification factor $\beta$ is the ratio of the collector current to the base current (if $\beta$ is large, typically about 100, small changes in $j_b$ lead to large variations in $j_e$). For illustration we consider only the case of magnetic base and emitter source spin, and consider (as is typically done in transistor physics) thin bases ($\tilde{w}_b \ll L_{nb}, L_{sh}$) where $L_{sh}$ is the spin diffusion length in the base). The gain of MBT can then be written as

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

where

$$\alpha_T' = (\tilde{w}_b/L_{nb})^2/2, \tag{9}$$

and

$$\gamma' = \frac{N_b D_{pe}}{N_c D_{sh} L_{pe} \tanh(\tilde{w}_e/L_{pe})} \frac{1}{\cosh(\zeta_b)(1 + \delta\alpha_c \eta_{0b})}. \tag{10}$$

The two factors $\alpha_T'$ and $\gamma'$ are related to the usual base transport $\alpha_T$ and emitter efficiency factor $\gamma$ by $\alpha_T = 1/(1 + \alpha_T')$ and $\gamma = 1/(1 + \gamma')$. They represent, respectively, the contribution to the gain by the carrier recombination in the base and by the efficiency of the electrons injected by the emitter to carry the total charge current in the emitter (for a standard reference on nonmagnetic transistors see, for example, [17]). In MBT the base transport cannot be controlled by either spin or magnetic field, since it is related only to carrier recombination in the base (one can, however, consider more specific cases where $L_{nb}$ depends on $\zeta_b$, in which case even $\alpha_T'$ could be controlled). The emitter efficiency, on the other hand, varies strongly with both $\zeta_b$ and $\delta\alpha_c \eta_{0b}$.

Under what circumstances can we control $\beta$ by magnetic field and spin most effectively? The answer lies in the relative magnitudes of $\alpha_T'$ and $\gamma'$. In GaAs-base...
transistors the two might have similar amplitudes, since the carrier recombination is rather fast, although additional band structure engineering (making heterojunctions) usually significantly enhances \( \gamma' \) at which point \( \gamma' \) might dominate. The situation is much more favorable in Si (or Si/Ge) based transistors, which have long carrier recombination times and it is the emitter efficiency \( \gamma' \) which determines the gain. In this case \( \beta = 1/\gamma' \) and

\[
\beta \sim \cosh(\zeta_b)(1 + \delta \alpha_{be} \alpha_{ob}). \tag{11}
\]

The gain varies exponentially with \( \zeta_b \) and is asymmetrically modulated by the magnetic field, depending on the relative orientation of the magnetic field and source spin polarization. The physics behind Eq. 11 is quite illuminating. The emitter efficiency is the ratio of the electron emitter current to the total emitter current (which includes the hole current). The electron part of the current depends linearly on the electron minority carrier density in the base. This density is modulated, separately, by \( \zeta_b \), which changes the effective band gap in the material and thus the equilibrium minority carrier density—according to \( n_{ob} = n_{i}^2 \cosh(\zeta_b)/N_b \) \[12\] \[13\], and by the amount of nonequilibrium spin (through the spin-voltaic effect \[12\] \[13\]). Similar control of gain could be achieved by having a magnetic emitter. In such a case it would be the equilibrium minority hole density (and thus the hole emitter current) which would be modified by magnetic field, changing the emitter efficiency. All the effects associated with the conduction band spin splitting can be also observed when the splitting is (also) in the valence band.

To illustrate the gain control of magnetic field and spin we calculate \( \beta \) for the same \( npn \) geometry as in Fig. 2, but now with two different sets of materials parameters. Figure 3 top part, is for GaAs (with \( n_i = 1.8 \times 10^6 \) cm\(^{-3} \), dielectric constant of 11, and recombination and relaxation times of 1 ns, keeping all the other parameters unchanged), while the bottom part is for Si. The calculated gain as a function of conduction band spin splitting \( \zeta_b \) in the base is shown in Fig. 3. The source spin polarization \( \nu_0/N_0 \) at the emitter is set to 0.9 (which is roughly also \( \alpha_{be} \)). The figure shows that current gain (amplification) is significantly influenced by magnetic field (which controls the splitting), but much more in Si than in GaAs, for the reasons stated earlier.

Magnetic bipolar transistor could be also called magnetic heterostructure transistor. Indeed, MBT’s functionality is based on tunability of electronic properties by band structure engineering. In contrast to the standard (nonmagnetic) heterostructure transistors, however, MBT’s band structure (the spin-split conduction band) is not a fixed property, but can change on demand, during the device operation, by changing the magnetic field. One can also have magnetic heterostructure transistors with variable spin splitting in the base producing magnetic drift \[13\] of the spin carrying minority carriers (as in drift-base transistors) to further enhance spin current and the resulting spin injection into the collector. Interesting effects could be observed by using ferromagnetic semiconductors for the base. Similarly to optical induction of ferromagnetism by optical injection of carriers \[12\], emitter can inject (presumably in the high injection limit which goes beyond the scope of our theory) high density carriers into the base, changing the base’s magnetic state (on and off, depending on the density of the nonequilibrium minority electrons, or twisting the magnetic moment orientation, if the injected electrons are spin-polarized). This could be an alternative electronic way of switching (or modifying) semiconductor ferromagnetism \[20\] \[21\], which could lead to numerous novel functionalities.

This work was supported by DARPA, the NSF-ECS, and the US ONR.

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