

Theory of semiconductor magnetic bipolar transistors

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(Received 19 December 2003; accepted 28 April 2003)

Bipolar transistors with a ferromagnetic base are shown theoretically to have the potential to generate almost 100% spin-polarized current injection into nonmagnetic semiconductors. Optical control of ferromagnetism and spin splitting in the base can lead to either long-lived or ultrafast switching behavior. Fringe field control of the base magnetization could be used for information transfer between metallic magnetoelectronics and conventional semiconducting electronics. © 2003 American Institute of Physics. [DOI: 10.1063/1.1586996]

One motivation for semiconductor spin electronics has been the seminal suggestion of Datta and Das of a “spin transistor.”¹ A burst of recent activity demonstrating controllable fabrication of ferromagnetic semiconductors and their incorporation into heterostructures has led to several additional device suggestions. These include a “spin filter,”² “spin-resonant-tunneling-diode,”³ “unipolar spin transistor,”⁴ “magnetic Zener tunnel diode,”⁵ and “magnetic p - n diode.”⁶ At the same time, progress on the problem of spin injection into nonmagnetic semiconductors has been reported, both from magnetic semiconductors^{7,8} and from magnetic metals.^{9–11} Hybrid transistor devices incorporating both semiconductors and ferromagnets, such as the spin-valve transistor,¹² have demonstrated magnetoresistances exceeding 300%, but suffer from low efficiency for current transport through the base to the collector. Additional hybrid systems are also under development.¹³

Here, we propose a general class of semiconductor devices, based on bipolar (junction) transistors,¹⁴ but enhanced in functionality by the use of a magnetic semiconductor in one or more regions of the device. Although improvements may be achieved by this substitution for any transistor region, (emitter, collector, or base) we will emphasize the dramatically enhanced functionality when a magnetic semiconductor (indicated by the subscript \uparrow or \downarrow , oriented along the direction of magnetization) is used as the base of a bipolar transistor while the emitter and collector remain nonmagnetic. We will focus our description on n - p_{\uparrow} - n transistor structures (shown in Fig. 1), although p - n_{\uparrow} - p transistors will behave in an analogous way. While (Ga,Mn)As grown as a random alloy is p type, recent advances in the synthesis of digital ferromagnetic heterostructures allow independent control of electronic and magnetic properties.¹⁵ This should allow for the implementation of either transistor geometry.

In this structure, three general spin-selective processes can potentially cause minority electrons in the p -doped base, which were injected from the nonmagnetic n -doped emitter, to become spin polarized before passing into the collector.

The first is a dramatic spin-filtering effect on carriers passing from the emitter to the p_{\uparrow} base, the second is spin-selective conduction electron spin flipping within the p_{\uparrow} region, and the third is spin-selective recombination within the p_{\uparrow} region. The result is a large current of highly spin-polarized electrons into the nonmagnetic collector of the device. This spin-polarized current can be controlled by any scheme which controls the orientation or magnitude of the base magnetization. The influence of these processes on the spin polarization of the collector current is calculated within “generalized Shockley approximations,” namely that the transport in the emitter, base, and collector is diffusive,¹⁶ transport through the depletion layers is ballistic, and recombination and spin flipping can be neglected in the depletion regions.

The spin-filtering effect originates from the spin splitting of the minority (conduction electron) band edges in the p_{\uparrow} base (shown in Fig. 1). The valence band is spin split in a p -doped magnetic semiconductor such as GaMnAs, and estimates of this spin-splitting range from 20–100 meV. The conduction band should be split as well through hybridiza-

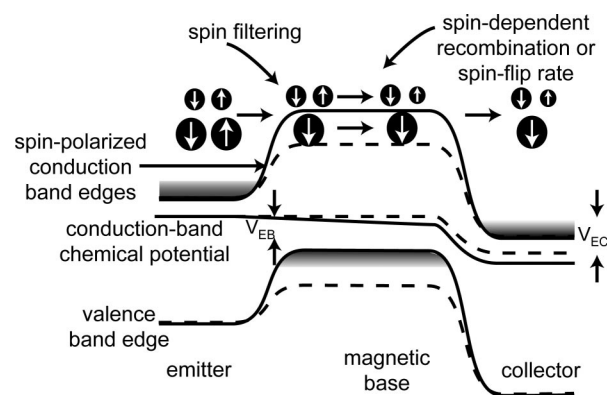


FIG. 1. n - p_{\uparrow} - n transistor. Thermally excited unpolarized electrons in the emitter are filtered at the emitter–base interface and can be further polarized through spin relaxation or carrier recombination in the base. The result is a highly spin-polarized current in the nonmagnetic collector. The spin-split conduction- and valence-band edges are shown in the magnetic base, as well as the conduction-band quasi-chemical potential. Dashed (solid) lines are for spin down (spin-up). Occupied states (electron or hole) are indicated with shading.

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tion with the valence band and the d levels, by an energy S_c . Studies of II–VI magnetic semiconductors indicate that S_c will be a factor of 5 smaller than that of the valence band.¹⁷ The influence of the conduction-band spin splitting on our proposed device is quite dramatic even for small splittings, for

$$\frac{n_{B\downarrow o} - n_{B\uparrow o}}{n_{B\downarrow o} + n_{B\uparrow o}} = \tanh(S_c/2k_B T), \quad (1)$$

where n_{Bso} is the equilibrium density of spin s conduction electrons in the base. When the device is biased the Shockley approximations fix the minority carrier quasichemical potential on the emitter side of the base equal to the chemical potential in the emitter (Fig. 1). In an ordinary transistor this gives rise to the exponential dependence of the minority carrier density of the base on the emitter–base voltage, V_{EB} . For a magnetic base, the enhanced minority carrier densities n_{Bs} injected from the emitter will likewise increase exponentially, and retain the spin polarization of Eq. (1),

$$\frac{n_{B\downarrow}}{n_{B\uparrow}} = \frac{n_{B\downarrow o}}{n_{B\uparrow o}}. \quad (2)$$

If the band alignment is as shown in Fig. 1 then $n_{B\downarrow} > n_{B\uparrow}$. The degree of spin polarization is considerably more dramatic than that expected for tunneling through a spin-split barrier,¹⁸ and occurs in any base region thick enough to eliminate tunneling from the emitter to the collector.

The other two effects may dominate when the base is thick enough either for spin flipping or for selective carrier recombination to substantially modify the minority carrier spin polarization. Spin-selective conduction electron spin flipping can originate, e.g., from the spin polarization of the hole sea via an electron–hole scattering process. If $n_{B\downarrow}/\tau_{\downarrow\uparrow} = n_{B\uparrow}/\tau_{\uparrow\downarrow}$, and neglecting spin-selective carrier recombination, then there is a quasi-equilibrium electron spin polarization in the base given by

$$\frac{n_{B\downarrow} - n_{B\uparrow}}{n_{B\downarrow} + n_{B\uparrow}} = \frac{\tau_{\downarrow\uparrow} - \tau_{\uparrow\downarrow}}{\tau_{\downarrow\uparrow} + \tau_{\uparrow\downarrow}}. \quad (3)$$

Near equilibrium, the polarization from Eq. (3) will equal that from Eq. (1) due to detailed balance. For $n_B \gg n_{Bo}$, however, the values could be different, as $\tau_{\downarrow\uparrow}$ and $\tau_{\uparrow\downarrow}$ are dependent on the densities n_{Bs} . As a result, even though the chemical potential of minority electrons is not spin split at the emitter side of the base [giving rise to Eq. (1)], because the electrons are out of equilibrium with the holes, the spin-relaxation processes of the electron and hole spin densities could result in a spin-split electron chemical potential. Again, for a thick enough base, this minority spin polarization [Eq. (3)] would determine the spin polarization of the collector current.

Spin-selective carrier recombination most likely will occur due to the spin polarization of the hole sea, and a simple model predicts $\tau_{R\downarrow}/\tau_{R\uparrow} = p_{\uparrow}/p_{\downarrow}$. Unlike the other mechanisms, spin polarization generated this way will continue to increase as the base region thickness is increased, however the transport efficiency across the base will suffer.

As the collector current is proportional to the minority carrier density in the base, for the case of a thin base and in the absence of other spin dependences in carrier transport,

the collector current spin polarization will be given simply by Eq. (1), and for a thick base if recombination can be neglected, by Eq. (3). If $S_c \gg k_B T$ in Eq. (1), the spin polarization of the collector current approaches 1, even though the spin polarization of holes in the magnetic base may not be close to 1. For more general cases, the spin-selective transport can be described by one-dimensional drift–diffusion equations for the minority electrons^{6,19}

$$E\nu_{\uparrow} \frac{\partial n_{\uparrow}}{\partial z} + D_{\uparrow} \frac{\partial^2 n_{\uparrow}}{\partial z^2} = \frac{n_{\uparrow}}{\tau_{\uparrow\downarrow}} - \frac{n_{\downarrow}}{\tau_{\uparrow\downarrow}} + \frac{n_{\uparrow}}{\tau_{R\uparrow}}, \quad (4)$$

$$E\nu_{\downarrow} \frac{\partial n_{\downarrow}}{\partial z} + D_{\downarrow} \frac{\partial^2 n_{\downarrow}}{\partial z^2} = \frac{n_{\downarrow}}{\tau_{\uparrow\downarrow}} - \frac{n_{\uparrow}}{\tau_{\uparrow\downarrow}} + \frac{n_{\downarrow}}{\tau_{R\downarrow}}. \quad (5)$$

These equations must be solved self-consistently with the Poisson equation.

We obtain analytic solutions for the device properties from Eqs. (4) and (5) for the simplified (but plausible) case of negligible spin relaxation in the base. Spin-relaxation times measured in highly ($2.8 \times 10^{19} \text{ cm}^{-3}$) p -doped GaAs indicated spin-relaxation times of ~ 50 ps at room temperature.²⁰ Transit times much lower than this (~ 1 ps) can be achieved with a sufficiently thin base. Then, the coupling between Eqs. (4) and (5) can be neglected, and the decay of the two spin components in the base is determined by the differing mobilities, diffusion constants, and recombination times. We write $J_{E\uparrow}$ and $J_{E\downarrow}$, where the charge current is the sum of these and the spin-polarized charge current is the difference of the two. We neglect the drift field in the base and denote the diffusion lengths $L_s = \sqrt{D_s \tau_{R_s}}$. Hence, the spin-polarizing effect of spin-selective carrier recombination is contained within the diffusion lengths, and the spin-filtering effect at the emitter–base interface manifests itself through the equilibrium carrier density. The emitter current density for spin direction s is

$$J_{Es} = - \frac{qD_{Bs}n_{Bso}}{L_{Bs} \sinh(W/L_{Bs})} [(e^{-qV_{EB}/kT} - 1) \cosh(W/L_{Bs}) - (e^{-qV_{CB}/kT} - 1)] - \frac{qD_E p_{Eo}}{L_E} [e^{-qV_{EB}/kT} - 1], \quad (6)$$

the collector current is

$$J_{Cs} = - \frac{qD_{Bs}n_{Bso}}{L_{Bs} \sinh(W/L_{Bs})} [(e^{-qV_{EB}/kT} - 1) - (e^{-qV_{CB}/kT} - 1) \cosh(W/L_{Bs})] + \frac{qD_C p_{Co}}{L_C} [e^{-qV_{CB}/kT} - 1], \quad (7)$$

and the base current is

$$J_{Bs} = J_{Es} - J_{Cs}. \quad (8)$$

The base width is W , the voltage between emitter and base is V_{BE} , and the voltage between collector and base is V_{CB} . When W/L_{Bs} is small, $J_{Bs} \ll J_{Cs}$, which is the desired situation for transistor operation (current gain $J_C/J_B \gg 1$). We assume that a sufficiently wide-gap emitter material has been employed and, therefore, we neglect hole current into the emitter (emitter efficiency $\gamma \sim 1$). For appropriate values of V_{EB} and V_{CB} ($V_{EB} < 0$ and $V_{CB} > 0$),

$$J_{Cs} = - \frac{qD_{Bs}n_{Bs0}(e^{-qV_{EB}/kT} - 1)}{L_{Bs} \sinh(W/L_{Bs})}, \quad (9)$$

$$J_{Es} = - \frac{qD_{Bs}n_{Bs0}(e^{-qV_{EB}/kT} - 1)}{L_{Bs} \tanh(W/L_{Bs})}. \quad (10)$$

We now analyze the spin polarization of the emitter and collector currents. For Eqs. (9) and (10), for $W/L_{Bs} \ll 1$, the spin polarization of each of these currents is

$$\frac{J_{\uparrow} - J_{\downarrow}}{J_{\uparrow} + J_{\downarrow}} = \frac{n_{B\uparrow o} - n_{B\downarrow o}}{n_{B\uparrow o} + n_{B\downarrow o}}. \quad (11)$$

Hence, we have verified our expectations guided by Eq. (1) for thin bases. The spin polarization of the collector current can be larger or smaller than this for thicker bases but the difference between the collector current and emitter current grows, indicating a larger (undesirable) base current.

The magnitude and orientation of the collector current spin polarization are also controllable. Magnetic techniques for controlling the base magnetization are available through standard magnetic domain writing technology. We now describe some more unusual electrical and optical techniques for controlling the base magnetization in this device. Control of the base magnetization permits control of the conduction-band spin splitting and the hole sea spin polarization (hence, the spin-selective recombination and spin-relaxation rates). These properties control the degree of spin polarization of the collector current.

Electrical control of the Curie temperature in the magnetic semiconductor InMnAs has been demonstrated.²¹ An implementation relevant to the spin transistor proposed here is for the magnetic base to be in contact with a nonmagnetic *p*-doped semiconductor material. If a voltage is applied between this semiconducting material and the base, then holes can be depleted from the base. That will reduce the Curie temperature²² without significantly affecting minority carrier (electron) transport through the base. As S_c depends on the hole density, this voltage also will directly affect the collector current spin polarization.

Optical injection of real carriers into the base²³ or the optical Stark effect^{24,25} could be used for optical control of the base magnetization or spin-filtering properties. If the base layer had a band gap smaller than the emitter or collector, the photon energy could be set for maximal absorption in the base. Electrons optically injected into the base would be rapidly swept out toward the emitter or collector, leaving behind the holes. As the Curie temperature and magnetization of such magnetic semiconductors increases with increasing hole density,²² this optical injection process could drive the base into the ferromagnetic phase (a transition requiring only a $5 \times 10^{18} \text{ cm}^{-3}$ change in hole density).²¹ If sufficient spin-polarized holes were injected optically, the orientation of the resulting base magnetization in the ferromagnetic phase might be set by the injected hole polarization. As the electrons injected into the base are swept out and are not easily available to recombine with the base holes, the nonequilibrium hole population can persist for a considerable time.

The spin-selective optical Stark effect permits much faster manipulation of the spin polarization in the collector through enhancing or reducing the spin splitting in the base.

Virtual transitions induced by subresonant photons create shifts in the energies of the conduction-band edge in the base. If the illumination is by circularly polarized light, then the shifts will differ for the two spin directions. Depending on whether the polarization of the subresonant light is parallel or antiparallel to the spin orientation of the lowest conduction band, the spin splitting will either decrease or increase. This effect persists only as long as the optical field is on and, hence, could permit rapid manipulation of the spin polarization of the collector current. Illumination with polarization oblique to the base magnetization would produce coherent precession of electrons passing through the base.

This work was supported in part by DARPA/ARO DAAD19-01-0490, DARPA/ONR N00014-99-1-1096, and the ARO MURI DAAD19-01-1-0541.

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