MAGNETIC BIPOLAR TRANSISTOR UNDER SPINTRONICS ANALYSES

George MAHALU *mahalu@eed.usv.ro*

Adrian GRAUR *adriang@eed.usv.ro*

"Ştefan cel Mare" University of Suceava, Str.Universităţii nr.13, RO-720229 Suceava

Abstract. *In this paper are presented some aspects by the theory of ideal MBTs developed in the forward active regime where the transistors can amplify signals. Because many authors shown that source spin can be injected from the emitter to the collector, it is predicted that electrical current gain can be controlled effectively by magnetic field and source spin. The working paper is ending with some results about the current gain featuring. This is depending of some pointed conditions, like as the equilibrium or nonequilibrium spin.*

Keywords: *spin, bipolar transistor, junction, magnetoamplification, charge density, spin splitting.*

Introduction

The Shockley theory about the bipolar transistor's internal mechanism in amplification process can be completed with the electron's spin effect. Same generalisation can be conduct to different knowledge meaning intrinsic processes at the low level (in structural sense). Physically, this theory must describe electron and hole carrier and spin diffusion in the bulk region, limited by the electron-hole recombination and spin relaxation [8].

At base of theoretical building will be considered the magnetic *p-n* junction's processes.

The BT (Bipolar Transistor) model

A conventional spin-unpolarized bipolar *npn* transistor consists into *n-p-n* structure of semiconductor regions which are connected in series. The first region, named *emitter*, is typically with the higher donor doping. The one *n* region is called *collector*. The *base* is the *p* region (here doped with acceptors) sandwiched in between.

The most useful mode of operation of the transistor is the so called amplification mode, where the emitter-base junction is forward biased. In this mode, the electrons are easily injected into the base. Together with the opposite flow of holes, they form the emitter current j_e. The electrons injected into the base diffuse towards the collector. The base-collector junction is reversing biased. This way allowing to any electron reaching the junction from the base to sweep by the electric field in the depletion layer to the collector. Thus, is formed the electron current where the hole's contribution is negligible [4]. The base current consists in difference: $j_b=j_c - j_e$. This difference comes from two sources. First, from the hole current which is present in the emitter but not in the collector. Second, from the electron-hole recombination in the base, which diminishes the number of electrons that makes it to the collector. These two factors form the generally small j_b. The current gain, noted β, is defined as the ratio of the large collector current to the small base current.

The MBT (Magnetic Bipolar Transistor) model

The MBT is a bipolar junction transistor with equilibrium spin due to spin-split carrier bands, as well as with a nonequilibrium source spin introduced, for example, by external electrical spin injection or optical orientation. The equilibrium spin can be a result of the Zeeman splitting in an applied magnetic field or of the exchange splitting due to ferromagnetic semiconductors integrated into the device structure [3]. For our purposes the equilibrium spin splitting should be on the order of thermal energy for the spin-charge coupling to be significant. If no equilibrium spin is present, this restriction becomes irrelevant, but the spin effects are limited to electrical spin injection. An MBT in equilibrium is described in figure 1.

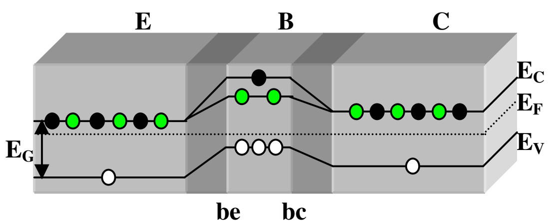

Figure 1. The *npn* MBT structure for equilibrium state

In figure were noted the conduction band E_C, the valence band E_V and the Fermi level E_F. The conduction band is populated mostly with electrons (filled circles) in the emitter and collector. In this example the base is considered magnetic with the conduction band spin split by $2q\zeta$, where with q we have noted the proton charge and the ζ is the Zeeman's split potential. The valence band E_V, separated by the energy gap E_G from the conduction band is populated mostly by holes (empty circles) in the base [6]. The dark (spin down) and light (spin up) shadings indicate the electron's spin. The Fermi level (chemical potential) E_F is uniform. The shaded areas signify the depletion layers in the base-emitter and base-collector junctions.

In the emitter the majority carriers are electrons whose number is essentially N_{de}, the donor density. Similarly in the collector, where the donor density is N_{dc}. Holes are the minority carriers in the two regions. The base is doped with N_{ab} acceptors. Holes are the majority and electrons are the minority carriers. We assume that only electrons are spin polarised. In many important semiconductors (such as GaAs) holes lose their spin orientation very fast and indeed can be treated as unpolarized. Note that the electron density is $n=n_\uparrow+n_\downarrow$, the spin density is $n=n_\uparrow - n_\downarrow$, and the spin polarisation is $\alpha=s/n$ [1,3,5].

The equilibrium in MBTs can be disturbed by applying a bias as well as by introducing a nonequilibrium source spin. Figure 2 depict the nonequilibrium physics and introduces the relevant notation. We assume that the source spin is injected into the emitter within the spin diffusion length from the *BE* depletion layer so that enough spin can diffuse to the base. At the *BE* depletion layer the electrons feel a spin-dependent barrier. Thus, the barrier is smaller for the spin up and larger for the spin down electrons. As in the conventional bipolar transistors there is a significant accumulation of the minority carriers around the forward biased *BE* depletion layer, while there are few carriers around the reverse biased *BC* layer [1,3]. The widths *w* of the bulk regions depends on the applied voltage as well as on the equilibrium spin polarisation.

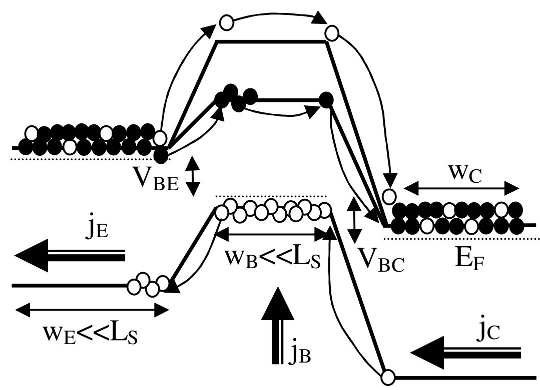

Figure 2. The *npn* MBT structure for amplification mode

The *BE* junction is forward biased with $V_{BE}>0$, lowering the barrier and reducing the depletion layer width. The *BC* junction is reverse biased with $V_{BC}<0$, raising the barrier and increasing the depletion layer width. The corresponding changes to the Fermi level E_F are indicated. The emitter has a spin source, indicated here by the incident circularly polarised light generated nonequilibrium electron spin well within the spin diffusion length L_S from the *BE* depletion

layer. The electron and hole flow gives the emitter (j_E), base (j_B) and collector (j_C) charge currents. Also shown are the effective widths of the emitter (w_E), base (w_B) and collector (w_C).
We assume that the electron-hole recombination, occurring mostly in the emitter and the base is spin independent, a reasonable approximation for unpolarised holes [7]. We also assume that the spin splitting is uniform in the bulk regions, eliminating magnetic drift. Other assumptions are those of the standard Shockley theory:

- temperature is large enough for all the donors and acceptors to be ionised;
- the carriers obey the nondegenerate Boltzmann statistics;
- the injected minority carrier densities are much smaller than the equilibrium densities;
- the electric fields in the bulk regions are small eliminating electrical drift.

Furthermore, we neglect the carrier recombination and spin relaxation inside the depletion layers.
The contacts with the external electrodes are ohmic, maintaining the carrier densities in equilibrium.

The junction-spin theory

In the following we present selected results of the theory of magnetic *p-n* junctions. In figure 3 both the *p* and *n* regions are in general magnetic, biased with voltage *V*. The nonohmic contact which simulating the conditions at the transistor's base, at the *p* region maintains nonequilibrium electron n_p and spin s_p densities. Similarly, there are nonequilibrium densities n_L and s_L at the left of the depletion layer. In the *n* region electrons are the majority carriers whose densities can be considered fixed by the donor density N_d [9]. However, the spin density can vary, being s_R at the right of the depletion layer and s_n at the contact with the external ohmic electrode. We use subscript *0* to denote equilibrium quantities. The equilibrium minority densities are n_{0p} (electrons in *p*), p_{0n} (holes in *n*) and s_{0p} (electron spin in *p*).

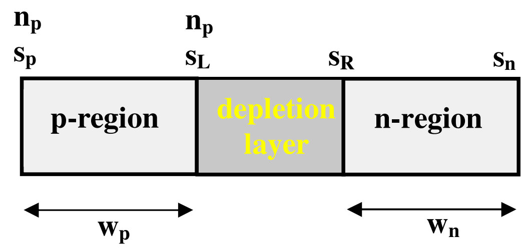

Figure 3. The magnetic *p-n* junction

Is possible to demonstrate [1] that:

$$\alpha_L = \frac{\alpha_{0p}(1-\alpha_{0n}^2) + \delta\alpha_R(1-\alpha_{0p}\alpha_{0n})}{1-\alpha_{0n}^2 + \delta\alpha_R(\alpha_{0p}-\alpha_{0n})} \quad (1)$$

This equation is referred in technique to as the *magnetic p-n junction equations* [1].

Influence of the equilibrium spin in the magnetoamplification effect

Some specific area studies were shown that magnetoamplification coefficient amounts to the expression:

$$\beta = \frac{1}{\gamma}\sqrt{\frac{1-\alpha_e^2}{1-\alpha_b^2}} \quad (2)$$

where γ is the emitter efficiency of a conventional *npn* bipolar transistor, and α_e and α_b is the equilibrium spin polarization in the emitter and in the base respectively.
In order to shown the dependency between the β gain and (α_e,α_b), can be considerate the graphics from figure 4. Here, is presented 3D diagram of evolution for β when (α_e,α_b) varying between (*0,0*) and (*0.9,0.9*).
In the presence of a nonequilibrium spin density $\delta\alpha_e$, the gain factor becomes (Silsbee-Johnson):

$$\beta = \frac{1}{\gamma}\sqrt{\frac{1-\alpha_e^2}{1-\alpha_b^2}}\left[1+\delta\alpha_e(\alpha_e-\alpha_b)/(1-\alpha_e)\right] \quad (3)$$

The spin-charge coupling is described by the products $\delta\alpha_e\alpha_e$ and $\delta\alpha_e\alpha_b$ respectively.

In figure 5 is presented 3D diagram of evolution for β in the same conditions but in the presence of a nonequilibrium spin density $\delta\alpha_e$.

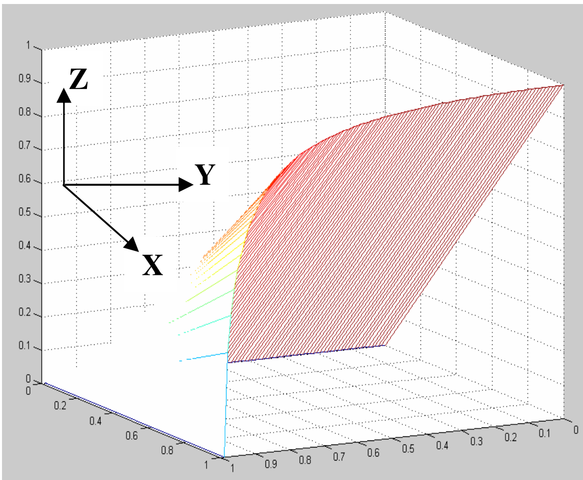

Figure 4. The β gain into the equilibrium spins condition

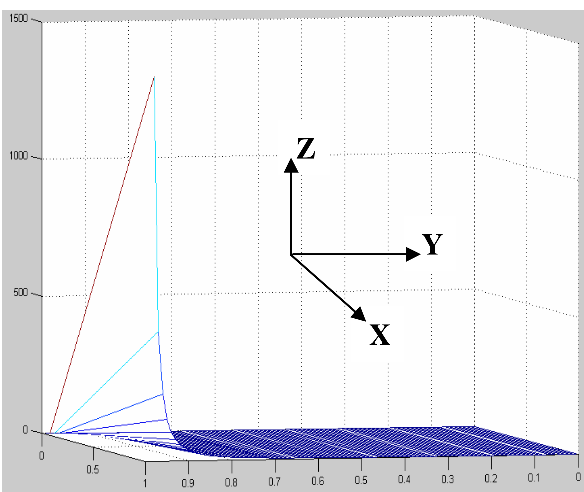

Figure 5. The β gain into the nonequilibrium spins condition

In both figure 4 and figure 5 diagrams were be noted the right orthogonal system axes with x, y and z. The significance of this notation is following: The x and y axes note the α_b and α_e variation respectively. Evidently, the z axe is in correspondence with the β gain.

Conclusions

These above remarks were focused on the physical considerations about the spintronics phenomenon which can be involved into a new designing electronic device like a MBT type. Because the research in this interest area is beginning now, many of these theoretical results will be practical confirmed in a small or a big percent in the near future.

References

[1] Fabian, J. *Spin-polarized current amplification and spin injection in magnetic bipolar transistor*, Cond-Mat/0311456 v1, 19 November 2003.

[2] Zutic, I., Fabian, J. and Das Sarma, S. *Spin-polarized transport in inhomogeneous magnetic semiconductors: theory of magnetic /nonmagnetic p-n junctions*, Cond-Mat/0106085 v2, 04 December 2001.

[3] Fabian, J. *Magnetic bipolar transistor*, Cond-Mat/0307014 v1, 01 July 2003.

[4] Fabian, J., Zutic, I. and Das Sarma, S. *Theory of magnetic bipolar transistor*, Cond-Mat/0211639 v1, 27 November 2002.

[5] Koiller, B., Hu, X., Drew, H.D. and Das Sarma, S. *Disentangling the exchange coupling of entangled donors in the Si quantum computer architecture*, Cond-Mat/0207455 v2, 17 February 2003.

[6] Hu, X. and Das Sarma, S. *Interplay of qubit inhomogeneity and imperfect gates in a double quantum dot*, Cond-Mat/0301612 v2, 04 February 2003.

[7] Das Sarma, S., Hwang, E.H. and Kaminski, A. *How to make semiconductors ferromagnetic: A first course on spintronics*, Cond-Mat/0304219 v1, 09 April 2003.

[8] De Sousa, R. and Das Sarma, S. *Electron spin coherence in semiconductors: Considerations for a spin-based solid state quantum computer architecture*, Cond-Mat/0203101 v3, 10 February 2003.

[9] Das Sarma, S., Fabian, J., and Zutic, I. *Spin-polarized bipolar transport and its applications*, Cond-Mat/0256045 v1, 27 Juny 2002.