Equivalent Circuit Model For Switching Performance of Bipolar Spin Transistor

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We have suggested an equivalent circuit model for switching performance of bipolar spin transistor composed of a nonmagnetic metal film (N) sandwiched between two ferromagnetic metal films (F1 and F2). The "ON" or "OFF" operation of this equivalent circuit model is simulated by depending on the orientation of the magnetization of F1 and F2 rather than the strength of the external magnetic filed. Changing the coupling coefficient, turn number of two inductances, (L1:L2) like a transformer, and parallel variable resistance R4 connected to L2 at the collector region, we can explain the magnetic characteristics and the dependence of magneto resistance ratio on the orientation of spin-polarized electrons.

1. Introduction

Recently, bipolar spin transistor consisted of two ferromagnetic films sandwiched with a non-magnetic metal thin film has been proposed as one of the interesting spintronic devices. From 1985, Mark Johnson has proposed a bipolar spin transistor using spin tunneling effect and spin injection technique [1,2]. This bipolar spin transistor was composed of CoFe (20Å)- Al_2O_3 (16Å)- CoFe (20Å). Two CoFe layers (F1 and F2) are the emitter (E) and the collector (C), respectively, and Al_2O_3 (N) is the base (B) in the bipolar transistor. In this spin bipolar transistor, the switching operation is controlled by depending on the orientation of the magnetization of F1 and F2 rather than the strength of the external magnetic field. Therefore, for the spin operation, when the magnetizations of F1 and F2 have parallel orientation, input spin electrons are driven from the emitter (E) into the collector (C) across the nonmagnetic base (B). In this case the output voltage (or current) of spin transistor is "ON" state, but at the opposite case, such as antiparallel state, the output is "OFF" state. In this work, we have designed an equivalent circuit of the bipolar spin transistor using PSPICE simulation parameters based on the basic concept and the physical operation principle of the bipolar spin transistor. With this equivalent circuit, we have tried to explain the physical operating of the bipolar spin transistor.

2. Equivlent Circuit for Bipolar Spin Transistor

2.1 Concept of equivalent circuit

Figure 1 shows the basic physical operation and electrical concept to design the inner equivalent circuit of the bipolar spin transistor. Figure 1 shows the physical operating principle of the bipolar spin transistor to be adapted to the electrical analysis method and a proposed circuit network to explain the operation principle of the bipolar spin transistor. In this equivalent circuit, two inductances, L1 and L2 are proposed to model the changes of MR ratio between the two ferromagnetic metal films (F1 and F2) according to the orientation of magnetization. In order to explain the spin tunneling effect between E and C of bipolar transistor, we have introduced the mutual inductance of transformer between two coils, coupling coefficient of transformer since the density of induced magnetization between two coils of transformer depends on the turns of ratio and coupling coefficient of the transformer. Eventually, we can explain the variation of MR ratio according to the orientation of magnetization with the equivalent mutual inductance and the ratio of coil turns. The orientation of F1 and F1 according to the orientation of magnetization is represented by the turn ratio of two inductances (L1 and L2). When the orientation of magnetization of F1 and F2 is parallel, the ratio of L1 and L2 is equal to the same ratio. Whereas, F1 and F2 is antiparallel, the L1 is not changed, but the L2 is slowly changed form high to low level.

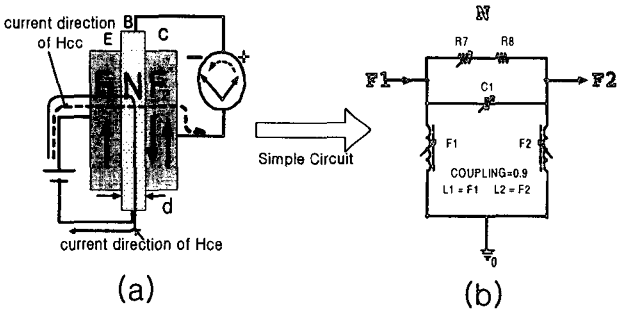

Fig. 1. (a) Phyical operation principle of bipolar spin transistor and (b) equivalent circuit to describe the physical operation principle of the bipolar spin transistor.

2.2 Design to the equivalent circuit of spin transistor

Figure 2 shows that the PSPICE simulation parameters in this full equivalent circuit are obtained with the data from the MTJ sample proposed by R. C. Sousa *et. al.* The followings are the detail description of PSPICE parameters :

- L3 and R5 are the inductance to be equivalent to the characteristics of frequency response time and the resistance of lead line at the E layer, respectively.
- L1 and L2 are equivalent to the MR ratio that is changed with the magnetization orientation of two ferromagnetic metal films (C and E) according to the external magnetic field. In order to be 1:1 corresponding to the characteristics of the ferromagnetic metal films included the magnetic flux density $B = \mu_0(1+\chi)H = \mu H$, the magnetic susceptibility χ

is equivalent to the turns ratio of two inductances. The permeability, μ, which is changed by the kind of magnetic material, is equivalent to the coupling coefficient of L1 and L2.

The values of each parameter at the B layer was measured by the current-voltage curve of Al_2O_3 base layer. The input voltage and current were 1.23V and about 4 μA, the total resistance of this layer was about 308 kΩ. Therefore R7 is 308 kΩ, and R8 is 1Ω which is the film resistance of base layer. The N between F1 and F2 acts as the capacitance of junction area. Therefore, the junction capacitance of the base layer is given as follows:

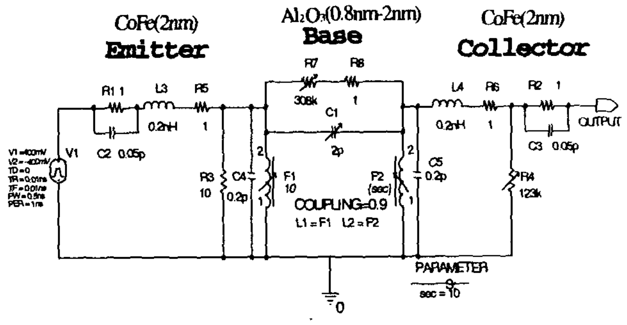

Fig. 2. A full equivalent circuit of the bipolar spin transistor.

$$C[F]=8.85\times10^{-12}[F/m]\times C_{oxide}\times10^{-2}\times(Area[\mu m^2]/t_0[nm])$$

Where t_o is oxide thickness using to design, *Area* is the junction area, and C_{oxide} is a oxide dielectric constant. According to the experiment result of R. C. Sousa *et. al.*, the oxide dielectric constant is 9 for Al_2O_3, the Area is $24\mu m^2$, and t_o is 0.8 ~ 2 nm for tunneling. Substituting these values into the above equation, the junction capacitance, C1 is about 2pF. Also, when the thickness of of CoFe film is 2nm and Area is $5\mu m^2$, then capacitances, C5 and C6 are each 0.2pF. R3 and R4 is 10Ω that is required as the minimum value for the tunnel junction resistance.

The resistance of MR signal measured at low bias voltage changes slowly from 123 kΩ to 155 kΩ according to the orientation of magnetization and external magnetic field. When the MR signal is 123 kΩ, it is "OFF" state because of parallel state. When this signal is 155 kΩ, it is "ON" state because of antiparallel state. We explained "ON" or "OFF" state with the ratio of L1 and L2. When the MR ratio changes from 123 kΩ to 155 kΩ, L2 changes from 0 to 10. At this time the orientation of spin-polarization slowly rotates from antiparallel state to parallel state, and the direction of detector connected to C layer is also slowly changed to positive state because of "ON" state. At the opposite case, L2 changes form 10 to 0, and the bipolar spin transistor will be "OFF" state. In both cases, the coupling coefficient of L1 : L2, which represents, the permeability of the ferromagnetic metal film, is fixed at 0.9.

3. Simulation Result of Equivlent Circuit for Bipolar Spin Transistor

Figure 3 is the simulation result of the the detector according to the ratio of L1:L2. In this figure, we can understand how the "ON" or "OFF" state of the designed equivalent circuit changes according to the variation of ratio of L1:L2 from 10 to 0 or from 0 to 10.

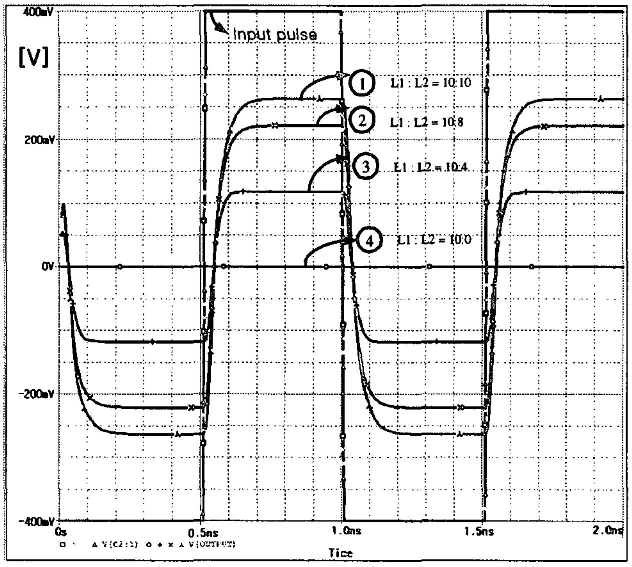

Fig. 3. Simulation result of the equivalent circuit of the bipolar spin transistor corresponding to the orientation of magnetization.

4. Conclusions

Since the direction of the collector current is switched by flipping the orientation of the magnetizations in the two magnetic films (F1 and F2), we have proposed that L2 in the equivalent circuit changes with the external magnetic field. Therefore, the on/off states of switch can be controlled by the coupling ratio of L1 to L2. i.e., the upspin electrons move from the emitter (F1) to the collector (F2) across the base (N) at the on state and at the off state the downspin electrons move from F2 to N.

References

[1] Johnson. M, and R. H. Silsbee: Phys. Rev. Lett. *55*, 170 (1985).

[2] Johnson. M, and R. H. Silsbee: Phys. Rev. B 37, 5326 (1988)