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THE SYNTHESIS OF MATHEMATICAL MODEL FOR MAGNETOTRANSISTOR USING PSPICE SOFTWARE

Keywords: magnetotransitor, simulation, SPICE software, equivalent circuit

We present the methods for synthesis of magnetotransistor mathematical model based on dual-collector structure of lateral transistor using PSPICE software. The complexity of magnetotransistor model is caused by special effects which concern these transistors. We considered main special effects such as parasitic carrier extraction from epitaxial layer into substrate and dependence of magnetotransistor parameters on base accelerating field.

1. INTRODUCTION

The design process of electronic devices is always accompanied with study using mathematical simulation. The PSPICE application package is one of the most popular software for circuitrical simulation and modeling. However just only small amount of primary transducers can be synthesized using this program. As example we can say about model of temperature transducers [1]. In this paper we consider problem of synthesis of mathematical model for magnetotransistors which are the most promising measuring transducers for magnetic field [2, 3].

The model should allow not only field and temperature characteristics of magnetotransistor but also special effects. It means influence on output signal of parasitic transistor structure formed by integrated circuit substrate and accelerating electrical field in base formed by voltage between two base electrodes [4].

2. MAGNETOTRANSISTOR EQUIVALENT CIRCUIT

The equivalent circuit which allows all above-mentioned effects is presented in Fig. 1. Similarly to magnetodiode model this circuit consists of three basic subcircuits: subcircuit for temperature simulation "Temperature" which is based on thermistor RT = 1 K with linear resistance temperature coefficient TKR = 1, current supply source IT = 1 mA and voltage source for primary biasing VT = 300 V (temperature translation from Celsius degree to Kelvin degree – in SPICE software the initial parameters of elements' base is set default at 27 ^{0}C, i.e. approximately at 300 K); subcircuit for simulation of magnetic field induction "Induction" which is based on voltage sources VB, VB0 (primary bias) and load resistor RB = 1 K; subcircuit for voltage-current characteristic formation. The subcircuit for voltage-current characteristic formation is symmetrical and left (L) and right (R) section form output signal which is difference between currents of left (Collector-L) and right (Collector-R) collectors of lateral dual-collector magnetotransistor. Third subcircuit includes:

- driving transistors QBL, QBR (Q is mandatory first symbol of bipolar transistor for PSPICE program) which form voltage-current characteristic without granting field dependence and its temperature coefficient;
- non-linear controlled current sources BBL, BBR which form magnetotransistor field characteristic and its temperature coefficient;
- driving transistors QGL, QGR which form voltage-current characteristic of parasitic transistor structure (these transistors have G symbol in description) without taking into consideration of field characteristic and its temperature coefficient;
- non-linear controlled current sources BGL, BGR which form field characteristic of parasitic transistor and its temperature coefficient;
- auxiliary zero voltage sources VBL, VGL, VBR, VGR with output current which is input signal for controlled current sources;
- resistors RBH, RB0, RBL, RBR which represent distributed structure of magnetotransistor base (for analyzing in strong magnetic field the influence of field on base resistance can be realized by substitution of resistors RBH, RB0, RBL, RBR on non-linear voltage controlled current sources which are used in resistive type sensor models).

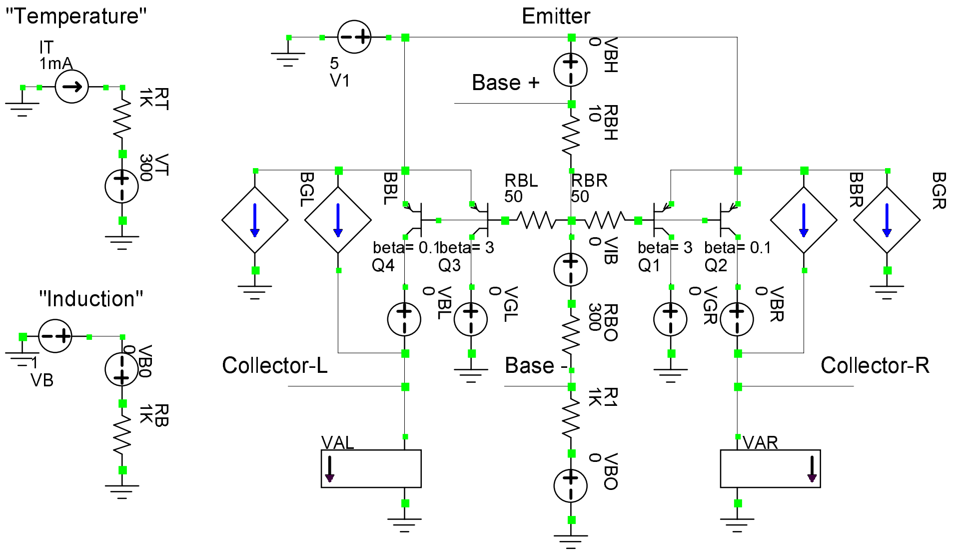

Рис. 1. Model (equivalent circuit) for magnetotransistor in "B2 Spice A/D 2000" software

The rest elements are subsidiary and serve for magnetotransistor supply and for investigations of its characteristics. Voltage sources V1, VBH, VB0 supply emitter and base circuits and amperemeters VAL, VAR measure currents of magnetotransistor two collectors.

The magnetotransistor model can be described as (below you can find mathematical equations just only for QBL transistor to shorten details)

$$I_{Ei} = I_{Ci} + I_{Bi}\,;\; I_{EMT} = I_{EBL} + I_{EGL} + I_{EBR} + I_{EGR} + I_{BBL} + I_{BGL} + I_{BBR} + I_{BGR}\,;$$

$$I_{CBL} = \frac{I_S}{q_{bB}} e^{\frac{qV_{BEL}}{\eta_{fB}kT}} - \frac{I_S}{q_{bB}} e^{\frac{qV_{BCL}}{\eta_{rB}kT}} - \frac{I_S}{\beta_{rB}}\left(e^{\frac{qV_{BCL}}{\eta_{rB}kT}} - 1\right) - I_{SCB}\left(e^{\frac{qV_{BCL}}{\eta_{cB}kT}} - 1\right);$$

$$I_{BBL} = I_S\left[\frac{1}{\beta_{fB}}\left(e^{\frac{qV_{BEL}}{\eta_{fB}kT}} - 1\right) + \frac{1}{\beta_{rB}}\left(e^{\frac{qV_{BCL}}{\eta_{rB}kT}} - 1\right)\right] + I_{SE}\left(e^{\frac{qV_{BEL}}{\eta_{cB}kT}} - 1\right) + I_{SCB}\left(e^{\frac{qV_{BCL}}{\eta_{cB}kT}} - 1\right);$$

$$I_{BBL} = \psi_{BBL}(I_{CBL}, E, B, T)\,; \quad I_{BGL} = \psi_{BGL}(I_{CGL}, E, B, T)\,;$$

$$I_{BBR} = \psi_{BBR}(I_{CBR}, E, B, T)\,; \quad I_{BGR} = \psi_{BGR}(I_{CGR}, E, B, T)\,,$$

where I_{Ei}, I_{Ci}, I_{Bi} are, correspondingly, emitter, collector and base currents for transistor number i; I_{EMT} is magnetotransistor emitter current; I_{EBL}, I_{EGL}, I_{EBR}, I_{EGR} are emitter currents for transistors QBL, QBR, QGL, QGR, correspondingly; I_{CBL}, I_{CGL}, I_{CBR}, I_{CGR} are collector currents for transistors QBL, QBR, QGL, QGR, correspondingly; I_{CBL}, I_{CGL}, I_{CBR}, I_{CGR} are base current for transistors QBL, QBR, QGL, QGR, correspondingly; I_{BBL}, I_{BGL}, I_{BBR}, I_{BGR} are currents for controlled current sources BBL, BBR, BGL, BGR, correspondingly, which define magnetotransistor field characteristic and its temperature coefficients; V_{BEi}, V_{BCi}, V_{BGi} are voltages on emitter, collector and insulating p-n junctions of transistor number i, correspondingly; q is electron charge; k is Boltzmann constant; T is absolute temperature; I_S is p-n junction saturation current; I_{SE}, I_{SC} are leakage currents for emitter and collector p-n junctions; β_{fi}, β_{ri} are current gain factors for transistor number i in forward and reverse bias, correspondingly; η_{fi}, η_{ri} are emission coefficients for p-n junctions in forward and reverse bias, correspondingly; η_{Ci} is emission coefficient for leakage current in collector p-n junction; E is electrostatic intensity in base layer.

Functions ψ_i, which define dependence of magnetotransistor voltage-current characteristic on accelerating field in base, field characteristic and its temperature coefficient as dependence of currents I_{BBL}, I_{BGL}, I_{BBR}, I_{BGR} for controlled sources BBL, BBR, BGL, BGR on collector currents of transistors QBL, QBR, QGL, QGR, can be specified by two method. First method is based on interpretation of physical processes which influence on magnetotransistor operation, e.g. using known equation for magnetosensitivity

$$\Delta I_C = AE\left(1 + \frac{E\mu_p Baq}{2kT}\right)\cdot\left(1 - 0.5\mu_p{}^2 B^2\right)\cdot\left(1 + \frac{\mu_p BW_0}{0.5l_E + \Delta l}\right),$$

where ΔI_C is change of collector current caused by magnetic field with induction B; A is constant coefficient; μ_p – hole mobility in base layer; a is distance between collector and transistor symmetry axis; W_0 is base effective length; l_E is emitter width; Δl_E the value which indicates increase of injected carrier flow caused by diffusion and diffusion in simplified form is as follows $\Delta l = \sqrt{2D \cdot W_0 / \mu_p E}$, where D is diffusion coefficient.

3. THE APPROXIMATION OF CHARACTERISTICS

Let us consider the description of functions by approximation polynomials based on experimental data on four variables I_{Ci}, E, B, T, at that variable I_{Ci} represents the result of iterative calculations of dependence of collector current on transistor parameters such as gain ratio, Erly voltage, imperfection of p-n junctions etc. Thus, mathematical model is rather simple but it allows simulation of all aspects of magnetotransistor structure.

Accelerating electrical field in base can be defined by total base current which includes recombination current I_{Bi} and current which caused by base biasing on two electrodes (Base +, Base -). The total current is measured by auxiliary voltage zero source which is mounted in base circuit. Quantitative values of magnetic field induction and temperature are imaged in "Induction" (as voltage drop on resistor RB) and “Temperature” (as sum of voltages on temperature-dependent resistor RT and voltage source VT, which allow to translate temperature from Celsius to Kelvin scale) subcircuits.

Functions ψ_{BGL} and ψ_{BGR}, which describe current of parasitic transistor structure formed by substrate can be simplified. In comparison to other factors, e.g. position of buried layer, these function possesses low dependence on magnetic field. Thus they are equal in left and in right parts $\psi_{BGL} = \psi_{BGR}$. Temperature dependence of parasitic transistor structure can be imaged by QGL, QGR transistor models. We show that with error no more than 5 %

$$I_{BGL} = I_{BGR} = -\frac{I(VIB)}{I(VIB) + I_Z} \cdot I(VG),$$

where I(VIB) is current through voltage zero source VIB in magnetotransistor base circuit, which allows to determine electrical field value I(VIB) ~ E; I_Z is empirical approximation value which defines influence of electrical field in base on current of parasitic transistor structure (typical value of I_Z is in limits from $I_Z = 0.5 \cdot I(VIB)_{MAX}$ for transistors in which electrical field in base leads to large decrease of current in parasitic transistor structure to $I_Z = 5 \cdot I(VIB)_{MAX}$ – for opposite case); $I(VG) = I(VGL) = I_{CGL} = I(VGR) = I_{CGR}$ is collector current of transistors QGL, QGR, i.e. parasitic current into substrate of integrated circuit.

Functions ψ_{BBL} and ψ_{BBR}, which define magnetotransistor field characteristic and its temperature dependence can be simplified to

$$I_{BBL} = I(VBL) \cdot \frac{I(VIB)}{I_{B0} + I(VIB)} \cdot (a_{B0T0} + a_{B1T0} U_B + a_{B1T1} U_B U_T + a_{B1T2} U_B U_T^2 +$$
$$+ a_{B2T0} U_B^2 + a_{B2T1} U_B^2 U_T + a_{B2T2} U_B^2 U_T^2);$$

and in similar way for I_{BBR}, where $I(VBL) = I_{CBL}$, $I(VBR) = I_{CBR}$ are collector currents of driving transistors QBL, QBR, correspondingly; I(VIB) is current through voltage zero source VIB in base circuit; I_{B0}, a_{B0T0} are empirical approximation coefficients which are defined with no magnetic field; a_{B1T0}, a_{B1T1}, a_{B1T2}, a_{B2T0}, a_{B2T1}, a_{B2T2} are empirical coefficients which are defined by magnetotransistor characteristic approximation at three magnetic field induction points and three temperature points.

The simulation results for magnetotransistor voltage-current characteristic are shown in Fig. 2.

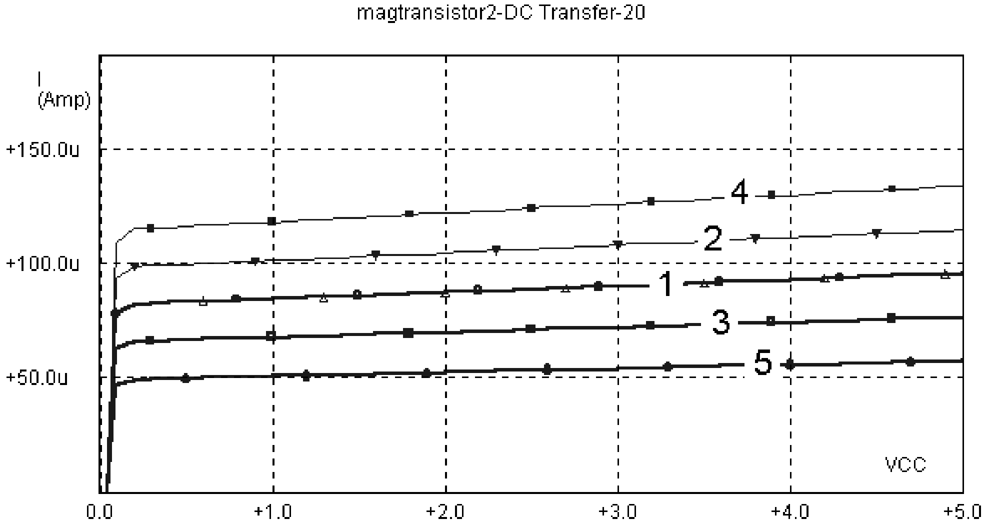

Fig. 2. The results of magnetotransistor characteristic modeling:
1– $I_{CL} = I_{CR}$ *(B = 0); 2 –* I_{CL} *(B = 0.2 T); 3 –* I_{CR} *(B = 0.2 T);*
4 – I_{CL} *(B = 0.5 T); 5 –* I_{CR} *(B = 0.5 T)*

4. CONCLUSIONS

The methods for synthesis of magnetotransistor model, which allows field, temperature and special effects, for PSPICE software are elaborated. Special effects, which are necessary to account for magnetotransistor output signal, are parasitic transistor structure formed by IC substrate and accelerating field in magnetotransistor base, which is caused by voltage between two base electrodes.

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