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Simulation of neutron irradiation influence on p-n-p bipolar transistor characteristics

Abstract. *We have developed numerical model and software to simulate the ionizing radiation influence on the bipolar transistor parameters. The software allows to calculate the input and output characteristics, the current transmission coefficient and other parameters under the irradiation for various temperatures, base and collector voltages.*

Streszczenie. *Opracowaliśmy model numeryczny i oprogramowanie do symulacji wpływu promieniowania jonizującego na parametry tranzystorów bipolarnych. Oprogramowanie pozwala obliczyć parametry wejściowe i wyjściowe, aktualny współczynnik transmisji i inne parametry na podstawie napromieniowania dla różnych temperatur, napięć bazy i kolektora.* ***(Symulacja wpływu promieniowania neutronowego na charakterystyki p-n-p tranzystorów bipolarnych)****.*

Keywords: bipolar transistors, neutron flow, transmission coefficient, output characteristics.
Słowa kluczowe: tranzystor bipolarny, przepływ neutronów, współczynnik transmisji, charakterystyki wyjściowe.

Introduction

Nowadays, the bipolar transistors are extensively used in many sectors of micro- and nanoelectronics as the amplifiers, generators, keys, regulators etc. Their operation in the radiation environment, e.g. in the open space, on the nuclear power plants, during the nuclear blast etc. can be difficult through the radiation-induced changes in operating parameters. The forecasting of these changes is a one of the main problems of development and production of the radiadiation-resistant hardware. The computer simulation is the most optimal method to resolve this problem.

The subject

We consider the *p-n-p* bipolar transistor that is the part of integral structure shown in figure 1.

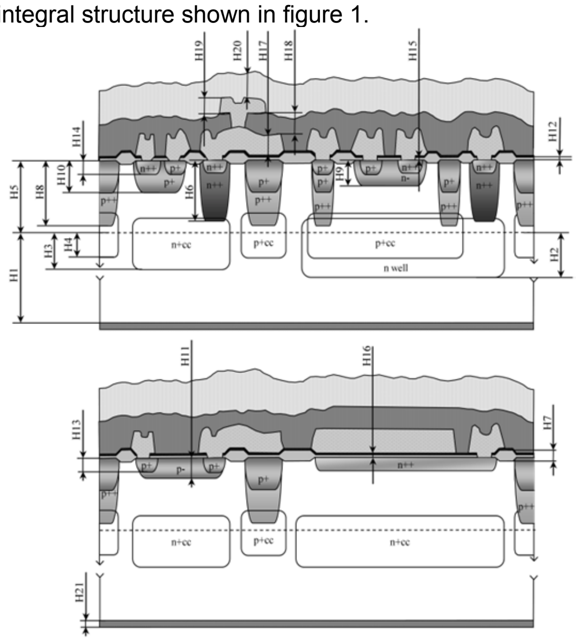

Fig.1. Analysed integral bipolar transistor structure

The impurity distribution, the chip layout and the electric characteristics are based on the real developed device. The transistor is made by the diffusion technology thus the impurity distributions are inhomogeneous and shown in figure 2.

It induces the built-in electric field E(x) in base:

$$E(x) = -\frac{kT}{q}\frac{1}{N(x)}\frac{dN(x)}{dx} \qquad (1)$$

where $N(x)$ is the donor concentration in base, k is the Boltzmann constant, T is the absolute temperature, q is the electron charge.

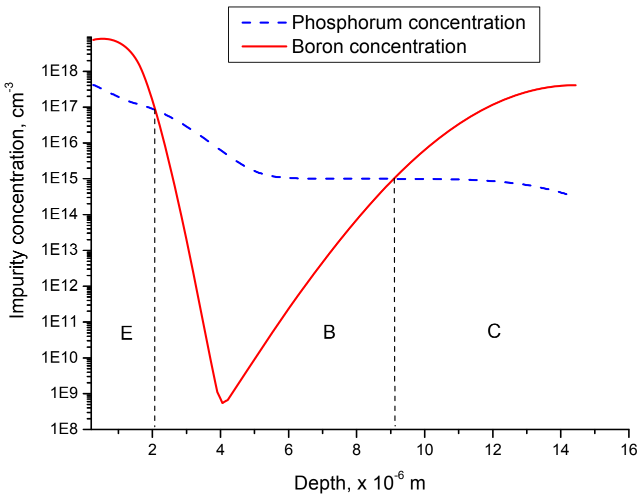

Fig.2. Boron and phosphorus concentration in p-n-p bipolar transistor

The model

The current transmission coefficient is the main parameter of bipolar transistor operating in the active mode. We consider the common-emitter circuit, thus the carrent transmission coefficient is:

$$k = \frac{J_K}{J_B} \qquad (2)$$

where: J_k is the collector current, J_B is the base current.

J_B is the recombination current of the minority carriers (holes) injected from emitter to base. The inverse value of the carrent transmission coefficient is the recombination losses R_B of minority carriers in base.

The nonequilibrium concentration of the holes injected to the base on the p-n junction border in accordance with [1] is described as:

$$p(0) = p_n(0) \cdot e^{\frac{qU_{EB}}{kT}} \tag{3}$$

where $p_n(0)$ is the equilibrium hole concentration in base, U_{EB} is the voltage on the emitter-base junction equaled to the base voltage U_B. The origin of coordinates is positioned at the border of the emitter space-charge region and the base. This border is unsteady and depended on the base voltage. The emitter-base junction is unsymmetrical one because the emitter acceptor concentration is two-order higher than the base donor concentration. Thus, the electron injection from base to emitter is insignificant in comparison with the hole injection from emitter to base so we have the one-side injection [2].

The equilibrium hole concentration in the n-base can be determined by the formula:

$$p(x) = \frac{n^2}{n_n(x)} \tag{4}$$

where n_i is the intrinsic concentration of the carriers in Si, $n_n(x)$ is the electron concentration in the base. We consider the device operating at the normal temperature, so the majority carrier concentration is equal to the dopant (phosphorus) concentration $N(x)$. In accordance with [3], the equation (3) is transformed to:

$$p(0) = \frac{n_i^2}{N(0)} \cdot e^{\frac{qU_{EB}}{kT}} \tag{5}$$

The distribution of the injected holes in active base taking into account the built-in electric field is described in [4]:

$$p(x) = \frac{J_K}{qS_A\overline{D}_P} \frac{1}{N(x)} \int_0^{W_A} N(x)dx \tag{6}$$

where D_p is the hole diffusion coefficient, S_A is the square of emitter bordered on the active base, W_A is the active base thickness.

The distribution of the injected holes in a passive base taking into account that the passive base width $W_P >> W_A$ is:

$$p(x,y) = n_i^2 (\overline{\frac{1}{N_P}}) \exp(\frac{qV_{EB}}{kT}) \exp(-\frac{y}{\overline{L}_P}) \tag{7}$$

where $\overline{L_p}$ is the average hole diffusion length in the passive base.

We suppose that the nonequilibrium hole concentration on the base-collector border is zero $p(W_A) = p(W_P) = 0$. The active base thickness W_A is depended on the reverse collector voltage, so we have to allow it during the calcualtions.

The recombination current in active base in accordance with [2] is described by:

$$J_A = qS_A \int_0^{W_A} \frac{p(x)}{\tau_p(x)} dx \tag{8}$$

The recombination current in the passive base is described by:

$$J_P = \frac{qS_P\overline{D}_P n_i^2}{\overline{L}_P} \frac{1}{\overline{N}_P} \exp(\frac{qU_{EB}}{kT}) \tag{9}$$

where $\overline{N_P}$ is the average donor impurity concentration in the passive base, S_P is the passive base area. The relation between the hole diffusion length and the hole lifetime in the base is:

$$L_P = \sqrt{D_P \tau_P} \tag{10}$$

The full base current excepting the electron injection, the surface losses and the emitter losses is the sum of the recombination currents in active and passive base J_A and J_P.

The irradiation causes the generation of electron-hole pairs and the point defects. According to [1] and [4] describing the radiation influence on the semicoductors, the lifetime of the nonequilibrium holes is the most radiation-sensitive papameter of bipolar transistors. The change of carrier concentration is the insignificant parameter and can be neglected in the calculations. The hole lifetime under the irradiation in accordance with [1] is

$$\frac{1}{\tau_\phi} = \frac{1}{\tau_o} + k_\tau \phi \tag{11}$$

where τ_0 is the initial hole lifetime, τ_Φ is the radiation-induced hole lifetime, Φ is the radiation flow, k_τ is the factor of radiation changes of hole lifetime in the base.

The factor k_τ depends on the hole injection level and the irradiation mode. E.g. this factor for the neutron flow with the average neutron energy 1.4 MeV by [4] for the n-base is determined as:

$$\frac{1}{k_\tau} = 4 \cdot 10^4 + 5{,}76 \cdot 10^6 (\frac{p}{n})^{0{,}534} \tag{12}$$

The change of recombination losses in active base under the irradiation according to [1] is:

$$\Delta R_A(\phi) = t_A \phi k_A \tag{13}$$

where t_A is the hole transit time, k_A is the factor of radiation defects in active base.

The factor of radiation defects is presented in [1] as:

$$k_A = k_\tau (\frac{\overline{p}_A}{\overline{N}_A + \overline{p}_A}) \tag{14}$$

where $\overline{N}_A$ and $\bar{p}_A$ are the average values of donor concentration and injected holes in active base.

The hole transit time for the drift bipolar transistor is:

$$t_A = \frac{W_A^2}{\eta \overline{D}_A} \tag{15}$$

where η is the coefficient of base doping heterogeneity that is:

$$\eta = \ln(\frac{N_{BE}}{N_{BC}}) \tag{16}$$

The change of recombination losses in passive base under the irradiation is presented by the expression [1]:

$$\Delta R_P(\phi) = R_{P0}(\sqrt{1 + k_\tau \bar{\tau}_{P0} \phi} - 1 \tag{17}$$

where R_{P0} is the recombination losses in a passive base before irradiation, $\bar{\tau}_{P0}$ is the average hole lifetime in this passive base.

Thus, our problem is to adapt the theory from [1] and [4] to the specific device topology. Calculating data according to the (6) and (7) expressions for various geometry and impurity distribution we find $p(x)$ then can calculate another integral characteristics of bipolar transistor e.g. the input and output voltages, currents, the current transmission coefficient etc.

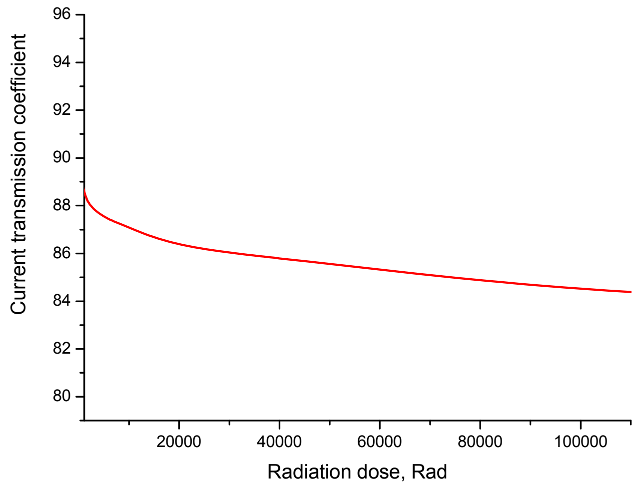

Fig.3. The change of the current transmission coefficient under the neutron irradiation

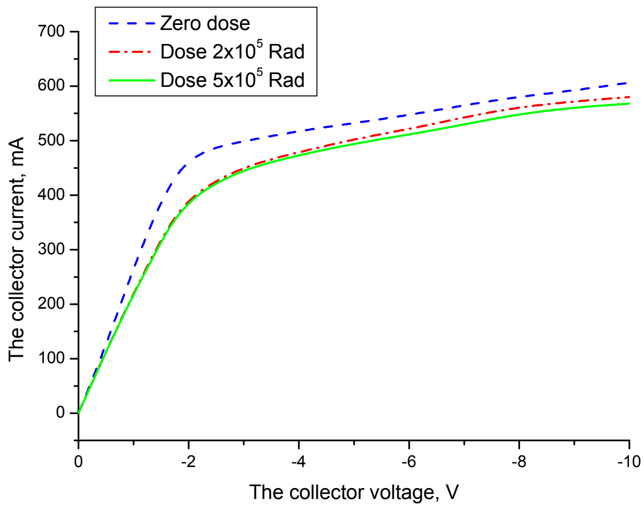

Fig.4. The output characteristics of bipolar transistor

The results of simulation

To calculate the radiation-induced change of the current transmission coefficient we use the following data: the radiation flow is in the range of 0 to 1×10^5 Rad, the base current I_B=0.7 mA and the collector voltage U_C=-9 B. The results of calculation presented in fig. 3 show the significant change of the current transmission coefficient even under the low radiation dose of fast neutrons. But the further irradiation causes the monotonous fall of the current transmission coefficient.

The output characteristics of the p-n-p bipolar transistor were calculated for the constant base voltage U_B=0.5 V, the radiation doses 2×10^5 and 5×10^5 Rad and shown in figure 4

Conclusions

We developed the software based on the models of radiation-induced changes in semiconductor devices to simulate the p-n-p bipolar transistor operating in radiation environment. This software allows to calculate changes of the current transmission coefficient, input and output characteristics under the neutron irradiation. The simulation was implemented and their results are shown in figures 3 and 4.

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