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 radiation-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](image)

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.

![Fig.2. Boron and phosphorus concentration in p-n-p bipolar transistor](image)

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

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

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

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 current transmission coefficient is:

$$k = \frac{J_k}{J_B}$$

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

$J_k$ is the recombination current of the minority carriers (holes) injected from emitter to base. The inverse value of the current transmission coefficient is the recombination losses $R_k$ 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:
(3) \[ p(0) = p_n(0) \cdot e^{-\frac{qU_{EB}}{kT}} \]

where \( p_n(0) \) is the equilibrium hole concentration in base, \( U_{EB} \) is the voltage on the emitter-base junction equalled 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:

(4) \[ p(x) = \frac{n_i^2}{N(0)} \cdot e^{-\frac{qU_{EB}}{kT}} \]

where \( n_i \) is the intrinsic concentration of the carriers in Si, \( n_n \) 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:

(5) \[ p(0) = \frac{n_i^2}{N(0)} \cdot e^{-\frac{qU_{EB}}{kT}} \]

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

(6) \[ p(x) = \frac{J_A}{qS_A L_B} \cdot \frac{1}{N(x)} \cdot N(x) dx \]

where \( D_p \) is the hole diffusion coefficient, \( S_A \) is the square of emitter bordered on the active base, \( W_d \) is the active base thickness.

The distribution of the injected holes in a passive base taking into account the reverse collector voltage is given by:

(7) \[ p(x) = \frac{n_i^2}{N(0)} \cdot \frac{1}{N_P} \cdot \exp\left(\frac{qV_{EB}}{kT}\right) \cdot \exp\left(-\frac{x}{L_p}\right) \]

where \( L_p \) is the average hole diffusion length in the passive base.

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

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

(8) \[ J_A = qS_A \int_0^{W_d} p(x) \frac{1}{\tau_p(x)} dx \]

The recombination current in the passive base is described by:

(9) \[ J_p = qS_A \frac{1}{N_P} \cdot \frac{1}{N_P} \cdot \exp\left(\frac{qU_{EB}}{kT}\right) \]

where \( N_P \) is the average donor impurity concentration in the passive base, \( S_A \) is the passive base area. The relation between the hole diffusion length and the hole lifetime in the base is:

(10) \[ L_p = \sqrt{\frac{D_p \tau_p}{kT}} \]

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 semiconductors, the lifetime of the nonequilibrium holes is the most radiation-sensitive parameter 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

(11) \[ \frac{1}{\tau_\Phi} = \frac{1}{\tau_o} + k_c \Phi \]

where \( \tau_o \) is the initial hole lifetime, \( \tau_o \) is the radiation-induced hole lifetime, \( \Phi \) is the radiation flow, \( k_c \) is the factor of radiation changes of hole lifetime in the base.

The factor \( k_c \) 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:

(12) \[ \frac{1}{k_c} = 4 \cdot 10^{-4} + 5.76 \cdot 10^{-6} \left(\frac{P}{n}\right)^{0.534} \]

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

(13) \[ \Delta R_A(\Phi) = \tau_{t_A} \Phi k_c A \]

where \( \tau_{t_A} \) 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:

(14) \[ k_A = k_c \left(\frac{\tau_{t_A}}{\tau_{t_A} + \tau_{r_A}}\right) \]

where \( \tau_{r_A} \) and \( \tau_{t_A} \) are the average values of donor concentration and injected holes in active base.

The hole transit time for the drift bipolar transistor is:

(15) \[ \tau_{t_A} = \frac{W_p^2}{\eta D_A} \]

where \( \eta \) is the coefficient of base doping heterogeneity that is:

(16) \[ \eta = \ln\left(\frac{N_{BE}}{N_{BC}}\right) \]

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

(17) \[ \Delta R_p(\Phi) = R_{p0}\sqrt{1 + k_c \tau_{r_A} \Phi} - 1 \]

where \( R_{p0} \) is the radiation loss in a passive base before irradiation, \( \tau_{r_A} \) 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.

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 $1 \times 10^5$ Rad, the base current $I_B=0.7$ mA and the collector voltage $U_C=-9$ V. 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 monotonic 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 $2 \times 10^5$ and $5 \times 10^5$ 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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