INTRODUCTION

The parameters of microelectronic transistor structures used in integrated circuits of the spaceborne equipment on aerospace stations experience degradation under the action of ionizing cosmic radiation. The entire range of problems emerging in this connection is described in [1]. However, some problems remain urgent even now, which follows from the papers of leading national and international conferences held in this field in recent years. In particular, the so-called low-intensity effect in bipolar integrated circuits remains unclear [2]. The essence of this effect is that a decrease in the intensity of ionizing radiation enhances the degradation of the amplification factor of bipolar transistors after accumulation of the same absorbed dose. This enhancement may be stronger than an order of magnitude. A generally accepted physical model of the effect has not been developed and, which is most important, no methods for simulating the effect in laboratory conditions, in which sources with a relatively high intensity must be used, have been worked out (e.g., a radiation source with an intensity of 3–4 orders of magnitude higher than the cosmic radiation intensity is required for simulating the ten-year operation of a microcircuit in the orbit if the duration of the laboratory experiment is several hours).

Under the action of cosmic radiation, the degradation of bipolar transistors is due to an enhancement of surface recombination or an increase in the surface component of the base current. Recombination losses increase because of accumulation of positive charge in the bulk of the passivating oxide and due to embedding of surface states at the oxide–semiconductor interface. A relation of the surface recombination current with the charge in the oxide and the density of surface states was derived in [3]. However, the authors of this publication disregarded the effect of the charge of surface states on the surface potential and, hence, on the recombination loss current. This factor is of fundamental importance since its disregard makes impossible the description of radiation-induced degradation of NPN and PNP transistors from a unified point of view.

This study aims at calculating the surface recombination current of bipolar transistors as a function of the charge of surface states, which is determined by the position of Fermi quasi-levels under direct bias of the emitter junction. The relations derived here can form the basis for a physical model of the effect of low intensity in bipolar transistors.

BASIC ASSUMPTIONS

Figures 1 and 2 show the cross section of a bipolar transistor with a lateral dielectric insulation (SiO₂) and the boundary region of the base under the passivating oxide. The geometry of the boundary region (see Fig. 2) forms the basis of further analysis since it is typical of the most advanced technologies (e.g., ISOPLANAR-S, ISAC, and SST) used for preparing bipolar large-scale integration (LSI) devices. The x coordinate is directed to the bulk of the base from the SiO₂–Si (passivating oxide–base) interface. Zero value of the y coordinate corresponds to the boundary (2) of the space charge region of the emitter–base junction. The distance to the wall of the insulating oxide along the y coordinate is denoted by W_s.

The surface recombination current is calculated under the following assumptions.
(1) We assume that the surface recombination current is given by

$$I_s = j_s \Pi_E,$$

where $I_s$ is the surface recombination current, $j_s$ is the specific density of the surface recombination current (per unit length of the emitter), and $\Pi_E$ is the perimeter of the emitter.

The action of ionizing radiation leads to structural distortions in the bulk of the semiconductor, the formation of radiation-induced charge $Q_{br}$ in the bulk of the passivating oxide, and the introduction of surface states $N_{it}$ at the oxide–semiconductor interface. The specific feature of the effect of ionizing cosmic radiation is that the degradation of parameters of bipolar transistors is mainly associated with processes in the passivating oxide and at the interface between the passivating oxide and the base. The role of structural distortions in the bulk of silicon is insignificant. For this reason, the calculation of the surface recombination current makes it possible to describe degradation of the amplification factor of bipolar transistors under the action of ionizing radiation.

(2) The problem of calculation of recombination losses in the passive region of the base is basically two-dimensional since the variation of the concentration of