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ELDRS in SiGe transistors for room and low-temperature irradiation

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ABSTRACT

The possible physical mechanism of ELDRS effect in the silicon-germanium (SiGe) bipolar transistors for room and low-temperature irradiation is described. The mechanism is connected with narrowing of the bandgap in transistor base region due to Ge content.

1. Introduction

The silicon-germanium heterojunction bipolar transistors (SiGe HBT) are an attractive candidate for an operation in extreme environments including satellite systems and front-end electronics for high energy physics experiments [1–4]. It is connected with their high gain and fast processing capability at relatively low power consumptions. A significant radiation tolerance during long time operation (10–15 years) is one of the main requirements for using these devices in space and for particle physics applications [5–8]. The test procedure for selection of devices for these applications, usually, is fulfilled at high dose rate from 10 rad (SiO_2)/s to 300 rad (SiO_2)/s. In real operation, the dose rate is several orders of magnitude less, than in the test procedure. At this condition, the effect of enhanced low dose rate sensitivity (ELDRS) [9] can lead to a significant reduction of the operation time of electronics without failures.

The analysis of experimental data in [1] allows to say: "and to first order, enhanced low dose rate sensitivity (ELDRS) is NOT observed in SiGe HBTs, which is clearly good news since it is a traditional concern in most Si BJT technologies" [1, page 2001]. This statement is agreed with experimental data of [3] and [10]. Authors of [3] presented experimental data concerning current gain degradation of SiGe heterojunction bipolar transistors for ^{60}Co gamma irradiation at dose rate from 0.25 rad (SiO_2)/s to 200 rad (SiO_2)/s. It was shown that for total dose, 0.65 Mrad (SiO_2), gain degradation is constant in this range of dose rates. This effect is an indication that investigated SiGe devices are ELDRS-free.

The same experimental results were presented on NSREC-2014 [10]. The results in this paper cover new and previous SiGe technology generations in order to incorporate a broader view of dose rate effects in SiGe HBT's. No indication of ELDRS was found in any technology generation.

All known experimental data about the absence of ELDRS in SiGe HBTs can indicate only specific features of investigated devices because some conventional Si bipolar transistors are ELDRS-free as well as SiGe. The main goal of this work is to search an answer for the following question: is ELDRS the inherent property of most generation of SiGe transistors or not. We propose, for the first time, physical mechanism, according which ELDRS effect doesn't occur in SiGe transistors at room temperature irradiation. It connects with narrowing of the bandgap in HBT base region due to Ge content. This approach was spread for study of the ELDRS effect in SiGe transistors at low-temperature irradiation. This paper contains the qualitative description of the proposed physical mechanism for ELDRS in SiGe transistors for room and low-temperature irradiation.

2. Background

The radiation-induced gain degradation in bipolar transistors is dominated by the formation of interface traps Nit at the Si/SiO_2 interface above base region [9]. Because the excess base current is proportional to the concentration of interface traps. The analysis of this work is based on conversion model [11,12] of the interface trap buildup. According to this

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model the generation of interface traps connects with the neutralization of positive charge by the electrons from the semiconductor substrate, i.e. due to the conversion of positive charge to interface traps during the annealing. Based on this assumption in [13] the ELDRS so-called conversion model was proposed. To explain the reversibility of annealing effect [14] it is necessary to introduce the rechargeable oxide charge, which must occupy energy levels lying opposite the Si forbidden gap. Direct substrate electron tunneling to positive centers Q_{ot} located opposite the silicon forbidden gap is impossible because the tunneling electron energy must be constant (according to basic principles of quantum mechanics). But tunneling substrate electrons to thermally excited positive charge can lead to interface-trap buildup (Fig. 1,a). The positive charge can be neutralized by hole emission to silicon valence band (Fig. 1,b). The case of an interaction of positive charge and electron (Fig. 1,a) will be considered below.

The probability of the oxide positive center excitation up to the conduction band depends on its energy depth in oxide relatively Si forbidden gap. The oxide traps near conduction band convert to interface traps in a short time while the traps opposite to the middle of Si forbidden gap need much more time for conversion.

It is supposed that there are two kinds of oxide traps: shallow traps $(Q_{ot})_S$ with small time of conversion, which are responsible for the degradation at high dose rates, and deep traps $(Q_{ot})_D$, which determine the excess base current increasing at long-time irradiation, i.e. at low dose rates (Fig. 2). The shallow traps convert with time constant τ_S; the conversion time of the deep traps is τ_D. Essentially, the conversion time of the deep traps τ_D is responsible for ELDRS.

At high dose rate (>10 rad (SiO$_2$)/s) for small time irradiation, only shallow traps have the possibility to be converted. Therefore, the degradation of base current at high dose rate (small time of irradiation) is determined by accumulation and conversion of shallow oxide traps only.

With dose rate decreasing excess base current begins to increase (ELDRS effect). This is connected with the effect of the deep traps conversion: together with irradiation time, the density of interface traps increases due to the additional conversion of deep traps. At very low dose rate ($<10^{-3}$ rad (SiO$_2$)/s) or high irradiation time all deep traps have time to be converted, therefore, the excess base current reaches some saturation value.

The conversion time τ_D depends on the temperature and is described by Arrhenius law:

$$\tau_D = \tau_{D0}\, exp(E_A/kT), \tag{1}$$

where τ_D is conversion time of deep traps; T is the temperature; E_A is the activation energy of the oxide trap thermally excitation; k is the Boltzmann's constant; τ_{D0} is pre-exponential coefficient.

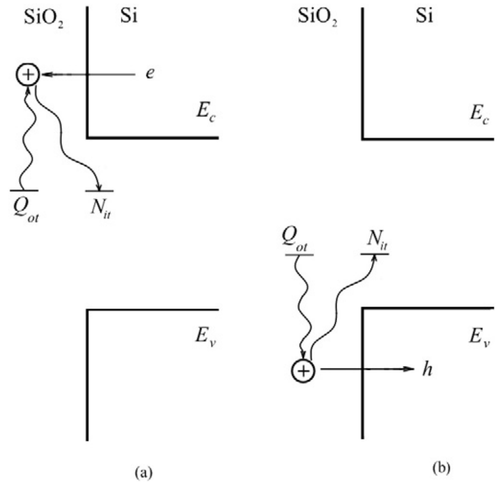

Fig. 1. Conversion of oxide charge Q_{ot} to interface trap N_{it}: the capture of an electron e (a), emission of a hole h (b). E_c and E_v are energy levels of Si conduction and valence band.

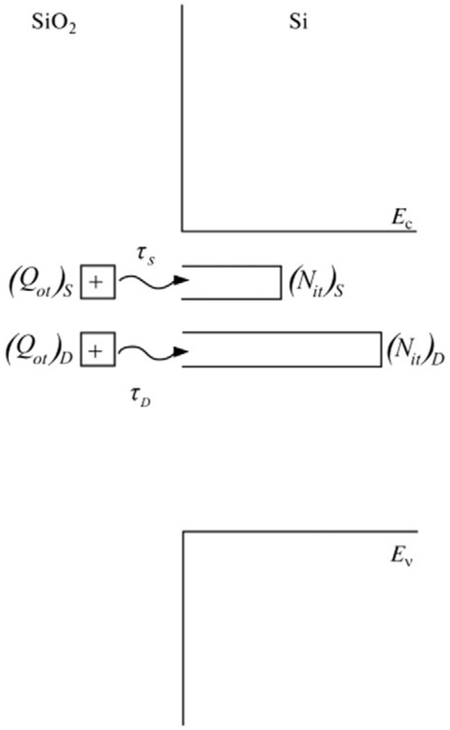

Fig. 2. Shallow $(Q_{ot})_S$ and deep $(Q_{ot})_D$ traps in oxide with conversion time τ_S and τ_D.

The activation energy of deep positive oxide center with energy $(E_{ot})_D$ in the oxide (Fig. 3) can be presented as the sum of the energy of thermal excitation ΔE_D to energy level of conduction band E_c and energy of elastic coupling of positive center with lattice atoms E_{latt}:

$$E_A = \Delta E_D + E_{latt}, \tag{2}$$

where E_A is the activation energy of the positive oxide trap; $\Delta E_D = E_c - (E_{ot})_D$; E_c is the electron energy at conduction band edge; $(E_{ot})_D$ is energy level of the positive trap in the oxide; E_{latt} is the energy of elastic coupling of positive center with lattice atoms.

3. Effect of bandgap narrowing on ELDRS

In SiGe HBTs due to the Ge content, the narrowing bandgap in the base region takes place. The narrowing of the bandgap ΔE_G leads to reducing the energy interval $(\Delta E_D)_{SiGe}$ which is needed for an interaction

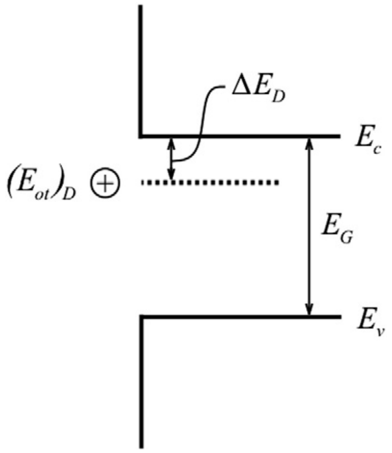

Fig. 3. The energy of thermal excitation ΔE_D from the level of the positive trap in the oxide $(E_{ot})_D$ to conduction band edge E_c. E_G is bandgap of the semiconductor.