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ENHANCED LOW DOSE RATE SENSITIVITY (ELDRS) AND REDUCED LOW DOSE RATE SENSITIVITY (RLDRS) IN BIPOLAR DEVICES*

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Abstract. *Possible physical mechanism of enhanced low dose rate sensitivity (ELDRS) and reduced low dose rate sensitivity (RLDRS) in bipolar devices is described. Modification of the low dose rate conversion model is presented. The enhanced or reduced sensitivity can be connected with a specific position of the effective Fermi level relatively acceptor and donor radiation-induced interface traps. The qualitative and quantitative analysis of the low dose rate effects is presented. The effect of the oxide trapped charge on the value of the oxide electric field and the yield of the oxide charge were taken into account. It leads to dependence of the accumulation of radiation-induced oxide charge and interface traps on the dose rate. In enhancement version the ELDRS and RLDRS conversion model describes the low dose rate effect in as "true" dose rate effect.*

Key Words: *total dose, low dose rate, bipolar devices, ELDRS, conversion model.*

1. INTRODUCTION

The main ideas of this paper were presented in [1]. Several types of bipolar devices demonstrate enhanced degradation during low dose rate (LDR) irradiation in comparison with irradiation at high dose rate (HDR) for the same total dose level. These devices are known as ELDRS-susceptible (Enhanced Low Dose Rate Sensitivity) [2]. Since the physical mechanism of the ELDRS effect [3] is connected with suppressing of the accumulation of the radiation defects at high dose rate we can consider the effect as Reduced High Dose Rate Sensitivity (RHDRS) [4]. Nevertheless the term ELDRS is used for these devices in literature.

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Recent research of bipolar technology shows [5] that reducing degradation with decreasing of the dose rate is an inherent property of devices which are not susceptible to ELDRS effect. We can consider these devices as ELDRS-free [6]. The decreasing of the radiation degradation at low dose rate irradiation, as a rule, is not considered during hardness assurance tests of devices for space applications. It can lead to significant underestimation of the operation life time of these devices in real space environment.

Since devices which demonstrate reduced degradation at low dose rate irradiation are usually considered as ELDRS-free, it will be useful to single them out into a separate class using the term RLDRS (Reduced Low Dose Rate Sensitivity).

The purpose of this work is to describe possible physical mechanism of ELDRS and RLDRS effect using the low dose rate conversion model [7, 8, 9], which enables to numerically estimate the degradation of electrical parameters of bipolar devices during specified space mission.

In this work the low dose rate conversion model is shortly described. The qualitative and quantitative models of the ELDRS and RLDRS effects are considered.

2. CONVERSION MODEL

The model is based on the assumptions that the ELDRS effect in bipolar devices is directly connected with increasing of the surface recombination current due to interface trap buildup at SiO_2/Si interface near emitter junction. We suppose that the interface trap buildup can be described by H-e model [10, 11]. According to the model the interface trap buildup is connected with positive oxide trapped charge conversion due to the interaction with substrate electrons and not with the action of hydrogen ions only. Nevertheless, the H-e model is not in conflict with the most popular hydrogen model [12]. The H-e model takes into account the contribution of substrate electrons to interface trap buildup process [13].

To check the hypothesis that interface-trap buildup is connected with the interaction between the positive charge in the oxide and electrons tunneling from the substrate, a special experiment was performed [10, 11]. The *n*-channel MOS transistors with a 30-nm gate oxide were used in the experiment. These devices were irradiated by Cu-target X-rays sourced with a 1 krad (SiO_2)/s dose rate to 3 Mrad (SiO_2) total dose. The gate voltage was +5 V during irradiation. For one hour after the end of irradiation the devices were annealed in a molecular hydrogen atmosphere for 24 hours. The interface-trap buildup was registered during this annealing time. Four different tests were investigated. The tests were chosen so that the field in the oxide might have a positive or negative value to provide motion for the positively charged hydrogenous species to the Si/SiO_2 interface and from the Si/SiO_2 interface. Electron concentration on the substrate near the surface was changed by varying the gate voltage, substrate bias or forward bias of the source-substrate and drain-substrate junctions. This allows us to provide an enhancement or depletion mode for electrons near the substrate surface. Thus, different combinations of hydrogenous species and electrons present near the interface were varied in tests 1 through 4.

The experimental dependencies of the threshold voltage shift ΔV_{it} (caused by the interface-trap buildup) versus the annealing time for all four tests are presented in Fig. 1. A maximum change of ΔV_{it} is observed in test 1, when both electrons and hydrogenous species are presented near the surface. In other cases, when there are no hydrogen species (test 3) or no electrons (test 2) or both near the interface (test 4), shift ΔV_{it} is essentially reduced.

The presented experimental data confirms the hypothesis that the presence of hydrogen has some effect on interface-trap buildup. But the interaction of hydrogenous species and electrons from the substrate is the most important component of this process. In hydrogen-electron concept, both components – hydrogenous species and electrons – are factors that can restrict the rate of interface-trap buildup.

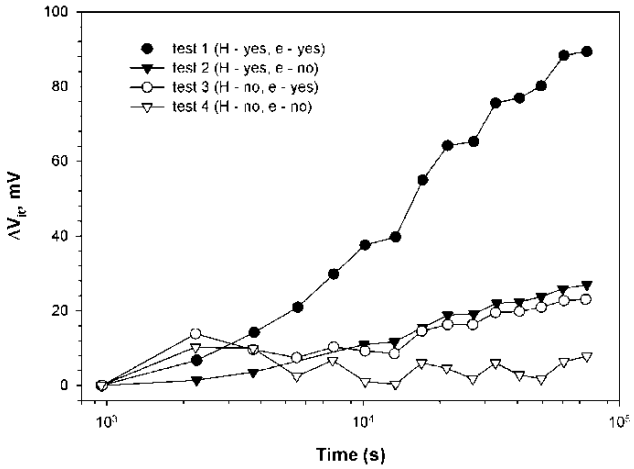

Fig. 1 The interface-trap component of the threshold voltage shift ΔV_{it} versus the annealing time in the hydrogen atmosphere (after [11])

The post-irradiation relaxation of a positive oxide charge ("annealing") is traditionally considered as the superposition of two independent processes: a tunneling of electrons from the substrate and a thermal excitation of electrons from the oxide valence band. The effect of the reversibility of annealing [14] could not be explained by these models.

It is supposed in [7, 8, 9] that interface trap buildup is connected with a conversion of rechargeable part of trapped positive charge located opposite the silicon forbidden gap [14]. Direct substrate electron tunneling to positive centers, 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 to the thermally activated positive centers is still possible. The positive centers energy level can reach the silicon conduction band due to a thermally excited vibration of the lattice. An interaction of thermally excited rechargeable positive charge Q_{ot} and tunneling substrate electrons leads to interface trap buildup (Fig. 2a). The positive charge Q_{ot} can be neutralized by hole emission to silicon valence band (Fig. 2b).

The interaction of the oxide defects and electrons from the substrate includes the thermal excitation of the defect and tunneling of the electron. Simplistically speaking, the thermal atom fluctuation leads to the oscillation of energy levels. When the energy level of the defect in the oxide corresponds to the allowed electron level in Si, it is possible that the tunneling transitions the electron from the substrate to the defect. In that case, the probability w of the tunneling transition of an electron with energy E_e to the defect energy level E_t is a function of temperature T:

$$w \sim \exp\left(-\frac{x}{\lambda}\right) \cdot \exp\left(-\frac{1}{kT}\frac{(E_e - E_t)^2}{E_0}\right), \quad (1)$$

where x is the distance from the defect to the interface Si/SiO_2; k is the Boltzmann constant; λ, E_0 are the tunneling parameters.

From the relationship(1), the recharge rate depends on the space and energy defect location. The defect located close to interface Si/SiO_2 but with deep energy levels within the silicon forbidden gap (with large activation energy) is recharged during a long time interval. However, after electron capture and defect reconstruction, its energy level shifts and the defect acts as an interface-trap. For example, the typical transition time of the electron to the defect located on the depth 1 nm from the silicon interface and with an activation energy of 0.65 eV is greater than 10^6 s. However, the defect located at the same distance but with an activation energy of 0.1 eV has a recharge time less than 1 ms and acts as an interface-trap.

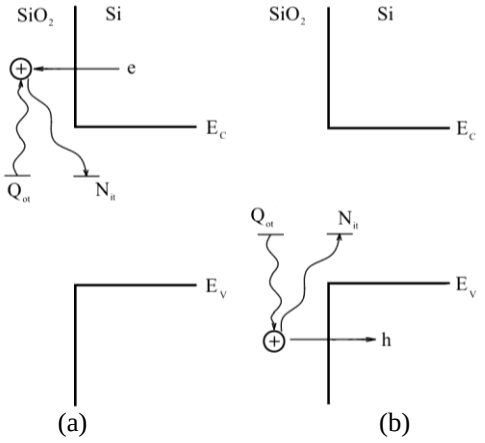

Fig. 2 Conversion of rechargeable oxide charge Q_{ot} to interface traps N_{it}: capture of an electron e (a); emission of a hole h (b), E_c and E_v are energy levels of Si conduction and valence band

The conversion mechanism of trapped positive charge or E'_γ center to interface state can be the following. According to the model [15], positively charged Si atom in the E'_γcenter is sp2-hybridized (planar configuration), while neutral Si^0 atom is sp3-hybridized (tetrahedral configuration). The electron energy levels in this defect strongly depend on the distance between Si^+ and Si^0 atoms [16, 17]. When this distance is large, these levels are located in the oxide close to the Si midgap [16]. When these two atoms are bonded and the distance between them is small, the energy levels of bonding electrons are close to the edges of SiO_2 bandgap. The first electron capture to the E'_γcenter changes defect configuration [15, 16] which results in the electron energy levels shift from Si midgap toward the Si valence or conduction bands, the distance between Si atoms being of intermediate value. The electrons in this transformed defect are expected to be in the intermediate sp2-sp3 configuration and could form diffusion orbital (it is the orbital which extends toward neighbor Si further than ordinal sp3 one) [17]. This defect

configuration may be assumed stable and electron energy levels are proposed to remain unchanged when one of the electrons is removed.

The probability of thermal excitation of the oxide trap energy level up to conduction band depends on the depth of its location opposite the silicon forbidden gap. Than close trap energy level to the middle of the forbidden gap than less the probability of the conversion process. In time scale, the shallow traps (near conduction level) are annealed first, after that the annealing front spreads to more deep energy levels.

For simplicity it is supposed in [7, 8, 9] there are two types of oxide traps: shallow traps with a short time of conversion responsible for the degradation at high dose rates, and deep traps that determine the excess base current at greater times of irradiation or low dose rates. The duration of HDR irradiation process is relatively short, not enough to convert all radiation-induced positive charge to interface traps. Therefore at long-time LDR irradiation we can observe the increasing of the degradation.

3. Physical Model of ELDRS and RLDRS

3.1. The qualitative physical model

The surface recombination current, which is responsible for a radiation degradation of the base current, depends on the concentration of interface traps and the surface potential on interface screen oxide-base region along emitter junction perimeter. Its value is integral on the total surface of the passive base region under oxide (Fig. 3):

$$I_S = q \int_S U_s \, dS, \tag{2}$$

where q is electronic charge; Us is surface recombination rate; S is the surface area of the passive base region under oxide.

The surface recombination rate changes as far as injected carriers expand through the base region surface. For estimation of the maximum value of excess base current (worst case) it is possible to use the value of the recombination rate on the edge of emitter junction ($y = 0$), where a concentration of injected carriers are maximal. In that case relationship (2) can be rewritten:

$$I_s = qU_s(0)S, \tag{3}$$

where $Us(0)$ is the surface recombination rate on emitter junction edge (y = 0) (Fig. 3).

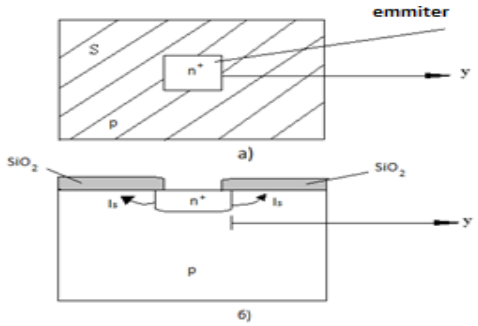

Fig. 3 The schematic structure of emitter – base junction of n-p-n bipolar transistor: top view (a); cross section (b). The shade is the surface area of the passive base region S

Using the well known assumption, we consider that in the top half the interface traps act as acceptors, while in the bottom half they act as donors (Fig. 4). The empty acceptor-like traps are neutral, the filled acceptor-like traps are negatively charged. The empty donor-like traps are positively charged and the filled donor-like traps are neutral. The capture cross section of a neutral trap is approximately 10^{-15} cm^2 the order of atomic dimensions. The capture cross section of a charged trap is one-two orders greater (10^{-14} - 10^{-13} cm^{-2}) due to columbic interaction with injected to base minority carriers. The charge state of trap depend on its position relatively Fermi level on the surface.

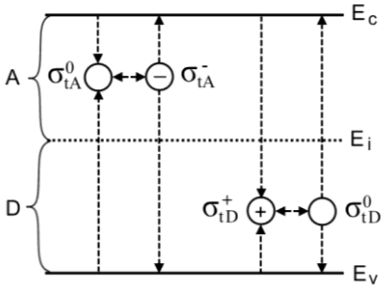

Fig. 4 Acceptor-like (A) and donor-like (D) interface traps

In this work we suppose that interface traps in the top and bottom half of the silicon forbidden gap occupy some effective mono levels E_{tA} and E_{tD}. Fig. 5 shows energy location of these traps in the forbidden gap for p-base region of npn transistor (the real possible distribution of these traps in the forbidden gap is shown by dotted lines). The solid lines correspond to any effective energy level of acceptor-like E_{tA} and donor-like E_{tD} surface traps. The acceptor-like traps in the top half of the forbidden gap always is empty for any location of Fermi level in p-base region. The capture cross section of the neutral acceptor-like traps $\sigma_{tA}{}^0$ equals approximately 10^{-15} cm^2.

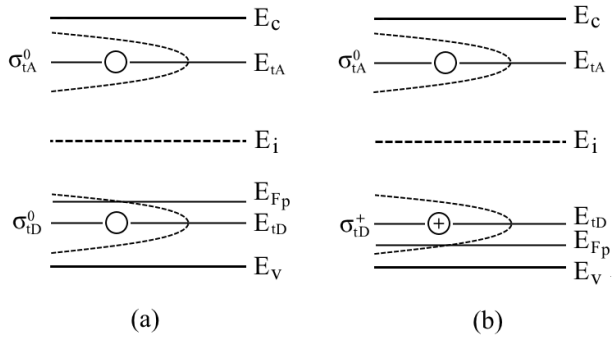

Fig. 5 The energy location of the acceptor-like and donor-like traps relatively Fermi level E_{FP} in the forbidden gap for p-base region of npn transistor: Fermi level E_{FP} is located above the effective mono levels of the donor-like traps E_{tD} (a); E_{FP} is located below level E_{tD} (b). The dotted lines show the real possible distribution of interface traps in the forbidden gap

The capture cross section of the donor-like traps strongly depends on their position relatively Fermi level E_{FP}. In Fig. 5a Fermi level is located above the effective mono levels of the donor-like traps E_{tD}, but in Fig. 5b it lies below level E_{tD}. The charge state of the donor-like traps depends on their position relatively Fermi level. The filled donor-like traps below Fermi level are neutral and their capture cross section corresponds neutral traps σ_{tD}^{0} (approximately 10^{-15} cm^2) (Fig. 5a). The empty donor-like traps above Fermi level are positively charged (Fig. 5b) and their capture cross section essentially increases. The capture cross section of the positively charged traps may be equal 10^{-14} - 10^{-13} cm^2.

We suppose that the main difference of ELDRS and RLDRS devices is connected with Fermi level position in base region relatively energy levels of radiation-induced surface traps in silicon forbidden gap.

The case of Fig. 5, a is feature for RLDRS devices. In that case the acceptor-like and donor-like traps are neutral. The recombination rate of injected from emitter electrons connects with their capture on traps with relatively small capture cross section (10^{-15} cm^2). For this reason at low dose rate irradiation the excess base current is relatively small in spite of all trapped oxide charges are converted to interface traps during long time irradiation. The increasing of dose rate (the reducing of the irradiation time) leads to increasing of the non converted trapped positive charge and the increasing of the excess base current (Fig. 6a). Qualitatively it is explained by that: a greater positive charge attracts the injected electrons to the surface that leads to increasing of the recombination rate. The saturation of the excess base current degradation at the high dose rate (Fig. 6a) connects with a contribution of the conversion of the shallow traps[7, 8, 9], when the conversion of deep traps becomes insignificant.

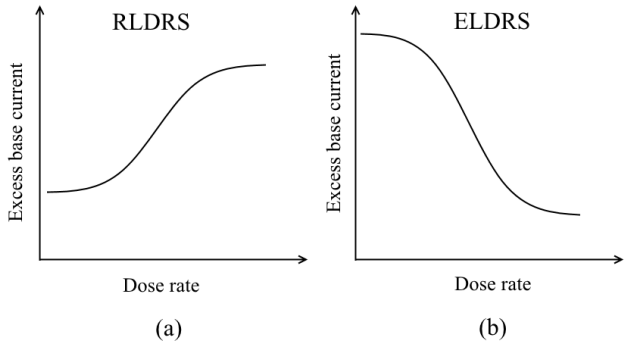

Fig. 6 The excess base current versus dose rate for RLDRS (a) and ELDRS (b) devices

The case of Fig. 5b is a feature of ELDRS devices. In that case the acceptor-like traps are neutral while the donor-like traps are positively charged. The recombination rate of injected from emitter electrons connects with their capture on the positively charged traps with relatively large capture cross section (10^{-14} - 10^{-13} cm^{-2}). Therefore the excess base current is large. According to conversion model [7, 8, 9] the increasing of dose rate (the reducing of the irradiation time) leads to decreasing of the interface trap concentration and the excess base current reduces (Fig. 6b). The increasing of the trapped positive charge yield at HDR, like RLDRS devices, has not significant effect since the recombination is

connected essentially with a capture of electrons on positively charged interface traps. Besides, the increasing of the dose rate leads to reducing of trapped positive charge yield due to RICN (Radiation Induced Charge Neutralization) effect [18].

The position of Fermi level in p-base depends on a specific feature of the manufacturing process: a doping level in p-base region and a value of the initial positive trapped charge in screen oxide above base. The case of Fig. 5, a is characterized by a low level of p-base doping or a large value of the initial positive trapped charge in screen oxide. This positive charge shifts the energy level of the donor-like traps E_{tD} below Fermi level E_{FP} (Fig. 7a).

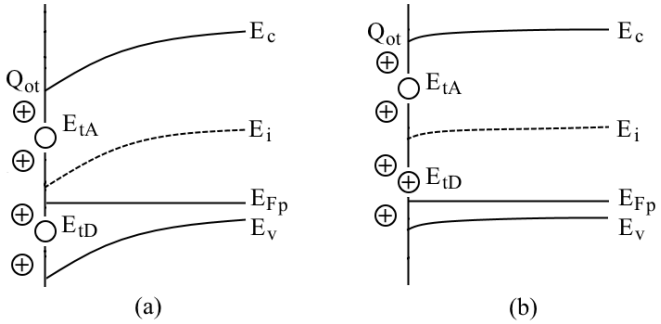

Fig. 7 Relation of Fermi level E_{FP} location to the position of donor-like traps E_{tD} on surface: (a) for case Fig. 7a (feature for RLDRS devices); (b) for case Fig. 7b (feature for ELDRS devices)

The case shown in Fig. 5b is realized when the p-base region is strongly doped or the screen oxide has a small technological positive charge. It corresponds the position of the donor-like traps E_{tD} above Fermi level E_{FP} (Fig. 7b).

The initial features corresponding Fig. 5a or Fig. 5b can be used for classification ELDRS and RLDRS devices.

A similar mechanism can be described for n-base region of pnp bipolar structures using acceptor-like traps in top half of the silicon forbidden gap.

3.2. The quantitative model

We suppose that the accumulation and annealing of the positive oxide trapped charge Q_{ot} are described by the following equation:

$$\frac{dQ_{ot}}{dt} = K_{ot}P - \frac{Q_{ot}}{\tau_D} - K_{RICN}Q_{ot}P, \tag{4}$$

where Q_{ot} is the oxide trapped charge; K_{ot} is a coefficient characterizing the accumulation of trapped charge; P is dose rate; τ_D is the conversion time of deep traps; K_{RICN} is coefficient connected with charge neutralization by RICN effect [18].

First term in the right-hand side of (4) represents the trapped charge accumulation in thick oxide by dispersion transport of radiation-induced holes. Second term is responsible for the neutralization of deep trap charge by electrons from substrate. Third term characterizes the annealing of the positive charge by radiation-induced electrons (RICN effect).

The interface trap buildup N_{it} can be expressed as follows:

$$\frac{dN_{it}}{dt} = \frac{1}{q}\frac{Q_{ot}}{\tau_D} + \frac{1}{q}K_{RICN}Q_{ot}P. \tag{5}$$

First and seconds terms in the right-hand side of (5) represent the interface traps buildup through the conversion of trapped charge by the substrate electrons and radiation-induced electrons.

The total concentration of interface traps equals the sum of donor-like and acceptor-like traps[19]

$$N_{it} = N_{tA} + N_{tD} \tag{6}$$

where N_{tA} is the concentration of the acceptor-like traps in the top half of the forbidden gap; N_{tD} is the concentration of the donor-like traps in the bottom half of the forbidden gap.

The excess base current ΔI_b equals anincrease of the surface recombination:

$$\Delta I_b = \Delta Is. \tag{7}$$

The recombination through the acceptor-like and the donor-like traps is described by Shockley-Read-Hall theory [20-22] and includes 4 processes: electron capture (the rate r_a); electron emission (the rate r_b); hole capture (the rate r_c); hole emission (the rate r_d). Following [22] we can obtain

$$r_{aA} = \upsilon_T \sigma_{tA}^0 N_{tA}(1 - f_{tA})n_s, \tag{8}$$

$$r_{bA} = \upsilon_T \sigma_{tA}^0 N_{tA} f_{tA} n_{tA}, \tag{9}$$

$$r_{cA} = \upsilon_T \sigma_{tA}^- N_{tA} f_{tA} p_s, \tag{10}$$

$$r_{dA} = \upsilon_T \sigma_{tA}^- N_{tA}(1 - f_{tA})p_{tA}, \tag{11}$$

where $\upsilon_T$is the thermal velocity; σ^0_{tA} is capture cross section of the empty (neutral) acceptor-like trap; N_{tA} is the effective concentration of the acceptor-like traps; σ^-_{tA} is capture cross section of the filled (negative charged) acceptor-like trap; n_s and p_s are the electron and hole surface concentrations;

$$n_{tA} = n_i e^{\frac{E_{tA}-E_i}{kT}};\ p_{tA} = n_i e^{\frac{E_i-E_{tA}}{kT}};\ f_{tA} = \frac{1}{1+e^{\frac{E_{tA}-E_{Feff}}{kT}}}, \tag{12}$$

where n_i is intrinsic electron concentration; E_{tA} is the effective energy level of acceptor-like traps; E_{Feff} is the effective Fermi level.

Similar equations can be received for donor-like traps.

Final relationship for the surface recombination rate *Us* has view:

$$U_s = \upsilon_{therm}\sigma_{tA}^0 N_{tA}(1 - f_{tA})n_s + \upsilon_{therm}\sigma_{tD}^+ N_{tD}(1 - f_{tD})n_s - \upsilon_{therm}\sigma_{tA}^0 N_{tA} f_{tA} n_{tA} - \upsilon_{therm}\sigma_{tD}^+ N_{tD} f_{tD} n_{tD} =$$

$$= \upsilon_{therm}\sigma_{tA}^- N_{tA} f_{tA} p_s + \upsilon_{therm}\sigma_{tD}^0 N_{tD} f_{tD} p_s - \upsilon_{therm}\sigma_{tA}^- N_{tA}(1 - f_{tA})p_{tA} - \upsilon_{therm}\sigma_{tD}^0 N_{tD}(1 - f_{tD})p_{tD}, \tag{13}$$

where σ^{+}_{tD} is capture cross section of the empty (positive charged) donor-like trap; σ^{0}_{tD} is capture cross section of the filled (neutral) donor-like trap; $n_{tD} = n_i e^{\frac{E_{tD}-E_i}{kT}}$; $p_{tD} = n_i e^{\frac{E_i-E_{tD}}{kT}}$; $f_{tD} = \frac{1}{1+e^{\frac{E_{tD}-E_{Feff}}{kT}}}$.

It can be shown that the effective Fermi level equals:

$$E_{Feff} = kTln(\frac{1}{2(A_A+A_D-B_D-B_A)}(\sqrt{\left(A_D e^{\frac{E_{tD}}{kT}} + A_A e^{\frac{E_{tA}}{kT}} - (B_D + B_A)\left(e^{\frac{E_{tD}}{kT}} + e^{\frac{E_{tA}}{kT}}\right)\right)^2 + 4(B_D + B_A)e^{\frac{E_{tD}+E_{tA}}{kT}}(A_A + A_D - B_D - B_A)} + (B_D + B_A)(e^{\frac{E_{tD}}{kT}} + e^{\frac{E_{tA}}{kT}}) - A_D e^{\frac{E_{tD}}{kT}} - A_A e^{\frac{E_{tA}}{kT}})), \quad (14)$$

where $A_A = N_{tA}(\sigma^{-}_{tA}(p_s + p_{tA}) + \sigma^{0}_{tA}(n_s + n_{tA}))$;$A_D = N_{tD}\big(\sigma^{0}_{tD}(p_s + p_{tD}) + \sigma^{+}_{tD}(n_s + n_{tD})\big)$;$B_A = N_{tA}(\sigma^{-}_{tA}p_s + \sigma^{0}_{tA}n_s)$;$B_D = N_{tD}(\sigma^{0}_{tD}p_s + \sigma^{+}_{tD}n_s)$.

The relationships for U_S (13) and E_{Feff} (14) include the electron and hole concentrations n_s and p_s which depend on forward bias of emitter-base junction U_{eb} and on value of the surface potential φ_s. For n-p-n transistor can be written [23]:

$$n_s = \frac{n_i^2}{N_a} e^{\frac{U_{eb}}{\varphi_T}} e^{\frac{\varphi_s}{\varphi_T}}, \quad (15)$$

$$p_s = N_a e^{-\frac{\varphi_s}{\varphi_T}}, \quad (16)$$

where N_a is the acceptor concentration on the base region surface; U_{eb} is emitter-base bias; $\varphi_T = kT/q$ is thermal potential; φ_s is the surface potential.

The surface potential φ_s is determined from a charge balance on the Si/SiO_2 interface [23]. Taking into account the charge of the interface traps Q_{it} [19] we can write:

$$Q_{ot} + Q_{it} = \sqrt{2\varepsilon_{Si}\varepsilon_0 kT}\sqrt{(e^{\frac{\varphi_s}{\varphi_T}} + \frac{\varphi_s}{\varphi_T} + 1) + \frac{n_i^2}{N_a^2} e^{\frac{U_{eb}}{\varphi_T}}(e^{\frac{\varphi_s}{\varphi_T}} - \frac{\varphi_s}{\varphi_T} - 1)}, \quad (17)$$

where Q_{ot} is the oxide trapped charge; Q_{it} is the charge on the interface traps; ε_{Si} and ε_0 are the permittivity of silicon and free space.

The charge on the interface traps depends on a position of the effective Fermi level and can be equal zero or positive or negative. For example, for p-base of n-p-n transistor charge Q_{it} = 0 if the effective level of donor-like trap lies low with respect to the effective Fermi level since the donor traps is filled by electrons. If the effective Fermi level locates lower than effective energy level of donor-like traps, that is the donor traps are empty, the charge Q_{it}>0. (Note that empty acceptor-like traps have zero charge and relatively small capture cross section).

The values E_{Feff} and φ_s are interconnected. The surface potential φ_s is included in equation (14) for the effective Fermi level E_{Feff}. The charge Q_{it} depending on the effective Fermi level E_{Feff} enters in equation (17). Therefore the values E_{Feff} and φ_s can be estimated by combined solution of (14) and (17). It can be done by numerical procedure only.

The relationships (13-16) allow to calculate the exact value of the excess base current from (3) and (7).

For simplicity it is possible to use the approach described in [7,8,9]. In this case the degradation of the base current as a function of the dose rate (for irradiation time essentially more than 1 s) can be written as:

$$\Delta I_b = (K_D + K_S) \cdot D + P \cdot K_D \cdot \tau_D (e^{-D/P \cdot \tau_D} - 1), \quad (18)$$

where K_S is the excess base current per unit dose at a high dose rate; K_D is the excess base current per unit dose at a low dose rate; P is a dose rate; τ_D is conversion time of the deep traps; and D is a total dose.

3.3. True dose rate effect

The relationship (18) follows from the combined solution of (4) and (5). The parameters K_S and K_D in (18) depend on the coefficient K_{ot} in (4) characterizing the accumulation of the oxide trapped charge for shallow and deep traps. For ELDRS and RLDRS devices the main factor is an accumulation of the deep traps, which determines parameter K_D.

The accumulation of the oxide trapped charge is the strong function of an electric field in oxide. The effect of the electric field consists at separation of radiation induced electron-hole pairs and obstacle their initial recombination. At low electric field the electron-hole pairs do not separate, the recombination is great and the yield of the oxide trapped charge is small. The thick screening oxide above the passive transistor base region does not have any metallization, so the value of the oxide electric field is small and depends on the oxide trapped charge. Usually it is assumed that the initial build-in electric field in bipolar thick oxide is positive and equals several units of 10^5 V/cm [24]. An accumulation of the positive trapped charge in oxide near Si/SiO_2 interface leads to reducing of the oxide electric field. Using Gauss theorem, the value of reduction of the oxide electric field can be estimated as Q_{ot} /$\varepsilon_{SiO2}\varepsilon_0$ (ε_{SiO2} and ε_0 are the dielectric permittivity of oxide and vacuum).

Because the initial built-in oxide electric field E_0 is positive, an accumulation of the positive trapped charge in oxide near Si/SiO_2 interface leads to reducing of the oxide electric field:

$$E_{ox} = E_0 - \frac{\alpha Q_{ot}}{\varepsilon_{SiO_2}\varepsilon_0}, \quad (19)$$

where E_{ox} is the oxide electric field; E_0 is the initial built-in oxide electric field; α is the fitting parameter [24], characterizing a fraction of the charge electric field connected with the reducing the initial built-in oxide electric field.

At small electric field the effective trapped charge yield is linear function of the electric field [25]. Therefore it can be written:

$$K_{ot} = \beta(E_0 - \frac{\alpha Q_{ot}}{\varepsilon_{SiO_2}\varepsilon_0}), \quad (20)$$

where β is constant characterizing the accumulation of the trapped charge.

The charge yield for low and high dose rates is quite different. For LDR the value of the positive trapped charge is relatively small due to its conversion during long-time irradiation, as a result the reduction of the oxide electric field is low and the yield of the oxide trapped charge is relatively large. Since the duration of HDR irradiation is relatively short and time

for the conversion is small, the value of the positive trapped non converted charge increases. It leads to decreasing of the oxide electric field and reduction of the total of the oxide charge yield. Therefore the reduction of the oxide electric field at LDR is less than in case of HDR. It leads to increasing the value of positive charge yield for LDR (more electric field relates less initial recombination) and increasing the value of interface traps due to converted the greater positive charge. The "true" effect connects with the dependence of coefficient K_{ot}in (4) from the dose rate due to the different oxide charge yield at LDR and HDR irradiations. It means that the coefficient K_D in (18) is function of the dose rate. For this reason ELDRS is "true" dose rate effect because the accumulation of oxide charge and interface traps depends on the dose rate. Note that the ELDRS and RLDRS conversion model in form (18) has time-dependent nature for given dose rate.

The oxide charge yield is less for the high dose rate. Therefore HDR irradiation leads to an accumulation of the smaller oxide trapped charge in comparison with LDR irradiation. High temperature annealing after HDR irradiation leads to the accumulation of the smaller value of interface traps due to conversion of the smaller positive charge. It means that the degradation measured at the end of a low dose rate irradiation is greater than the degradation after irradiation at high dose rate followed by a high temperature anneal ("true" dose rate effect).

The constant K_D is proportional to the coefficient characterizing the accumulation of trapped charge K_{ot}. According to the extraction technique the value K_D is estimated from elevated temperature irradiation data. As the main goal of the conversion model is a prediction of the transistor parameter degradation for the extremely low dose rate in the space environment, the elevated temperature installs 100^0C – 120^0C when all radiation-induced deep oxide charges are converted to interface traps. It means that the conversion model correctly predicts the degradation for the small dose rate. The degradation at the high dose rate is estimated very easy during test laboratory experiment. Therefore the error of the description of the radiation degradation in the wide range of the dose rates using the low dose rate conversion model [7, 8, 9] takes place only in the middle interval of the dose rates. But it has not any practical interest.

The correct description of the radiation degradation for any dose rate requires the extraction of the constant K_D for the each dose rate. It can be done using elevated temperature irradiation in range 40^0C – 90^0C. The constants K_D are estimated from these experimental data correspond to not full conversion of the oxide trapped charge and in a first order describe the dependence K_D at the dose rate P. Using the value K_D in (18) as a function of the dose rate P the low dose rate conversion model really describes the ELDRS and RLDRS as "true" dose rate effect.

3.4. Fitting parameter extraction

The conversion time of the deep traps τ_D can be described by the Arrhenius law:

$$\tau_D(T) = \tau_{D0}\exp\left(\frac{E_A}{kT}\right), \tag{21}$$

where T is the absolute temperature; E_A is the activation energy of deep oxide trap thermal excitation; k is the Boltzmann constant; τ_{D0} is a pre-exponential coefficient.

The model based on (18) and (21) has four effective fitting parameters: K_S; K_D; E_A and τ_{D0}.

The experimental extraction of effectiveparameters can be performed by the following steps [26]:

1) The constant K_S is estimated as the ratio of base current degradation to the specified total dose at high dose rate irradiation.
2) The pre-exponential constant τ_{D0} and activation energy E_A in (21) are derived from the experimental data for two different temperatures of elevated temperature post-irradiation annealing.
3) The constant K_D is estimated from elevated temperature irradiation data (100^0C – 120^0C).

It is very important to note that the extraction technique is established on the application of the high dose rate irradiation and can be fulfilled during relatively short time testing.

The extraction technique is invariant relatively ELDRS and RLDRS devices and can be used as universal approach. The extraction of four effective fitting parameters allows to describe the behavior of the radiation-induced excess base current for arbitrary dose rate, total dose and temperature. The successful using this technique was demonstrated in [7,8,9] for several types of ELDRS devices. The additional experimental work is needed for evidence of validity of here proposed in given work physical mechanism for RLDRS devices. It can be done in our future work.

4. Conclusion

The possible physical mechanism of the enhanced low dose rate sensitivity (ELDRS) and reduced low dose rate sensitivity (RLDRS) in bipolar devices can be connected with specific position of Fermi level in base region relatively radiation-induced interface traps in forbidden gap. Acceptor- and donor-like interface traps may be neutral or charged according to their position relatively Fermi level. The capture cross section of a charged trap is one-two orders greater than a neutral trap due to columbic interaction with injected to base minority carriers. For RLDRS devices interface traps are neutral while for ELDRS devices they are charged. As a result the effect of low dose rate irradiation is quite different for these devices.

The qualitative and quantitatively models of ELDRS and RLDRS are presented. The ELDRS and RLDRS conversion model describes the low dose rate effect in as “true” dose rate effect. The quantitatively model involves the fitting parameters extraction technique that allows to numerical estimate of the radiation degradation for arbitrary dose, dose rate and temperature.

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