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# CONVERSION MODEL OF THE RADIATION-INDUCED INTERFACE-TRAP BUILDUP AND ITS HARDNESS ASSURANCE APPLICATION

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**Abstract**. *The model, which confirms that the interaction of trapped positive charges (hydrogenous species) in the oxide and electrons from the substrate is an important component of radiation-induced interface-trap buildup, is presented. The "one-to-Koi" relationship between the number of trapped holes annealed and number of interface-trap generated is used for prediction of MOS device response in space environment. The model of enhanced low dose rate effect (ELDRS) is proposed. ELDRS conversion model is based on the assumption that there are two types of traps: shallow and deep. The time constants of these traps are different and correspond to interface-trap buildup at high dose rates for shallow traps and at low dose rates for deep traps. The possible physical mechanism of ELDRS effect elimination in the silicon-germanium (SiGe) bipolar transistors is described. The original mechanism of interface-trap buildup saturation based on radiation-induced charge neutralization (RICN) effect is presented.*

**Key words**: *MOS device, bipolar device, interface trap, conversion model, ELDRS, hardness assurance*

## 1. INTRODUCTION

Total ionizing dose effects in MOS and bipolar devices for space electronics connect with radiation-induced positive oxide trapped charge Qot and interface-trap Nit buildup. Electron-hole generation, initial hole yield, continuous-time-random-walk, deep hole trapping and annealing is described in detailed in [1]. Physical model [1] is commonly used. The most developed model of radiation induced interface-trap buildup is a two-stage "hydrogen" model [2-3]. The other model (so called "conversion" model [4,5]) is based on the assumption that the generation of interface traps connects with the neutralization of positive charge by the substrate or radiation-induced electrons. In this work the conversion model of interface trap buildup is used for the estimation of long time operation MOS and bipolar devices in space environment. The introducing of

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quantitative relationship between two physical processes gives us the possibility to develop numerical prediction methods for the estimation of long time operation MOS and bipolar devices in space mission. The use of the conversion model for the description of low dose rate effect in SiGe transistors and interface-trap buildup saturation are described.

## 2. Conversion Model of Interface-trap Buildup

Radiation induced buildup of interface traps Nit is a problem that has been known for the last 35 years [2,3]. In addition to the works [4] where interface trap generation is connected with electron capture by trapped holes, none widely known experimental results described in [5]. The experimental dependencies of the threshold voltage shift $\Delta V_{it}$ (caused by the interface-trap buildup) versus the annealing time for different four tests are presented in Fig. 1. A maximum change of $\Delta V_{it}$ is observed in test 1, when both electrons and hydrogenous species are presented near the surface. In other cases, when there are no electrons (test 2) or no hydrogen species (test 3) or both are near the interface (test 4), shift $\Delta V_{it}$ is essentially reduced. These experimental data confirms the hypothesis that only the presence of hydrogen is not enough for an effective interface trap buildup. The interaction between hydrogen complexes and electrons from substrate is an important component of this process.

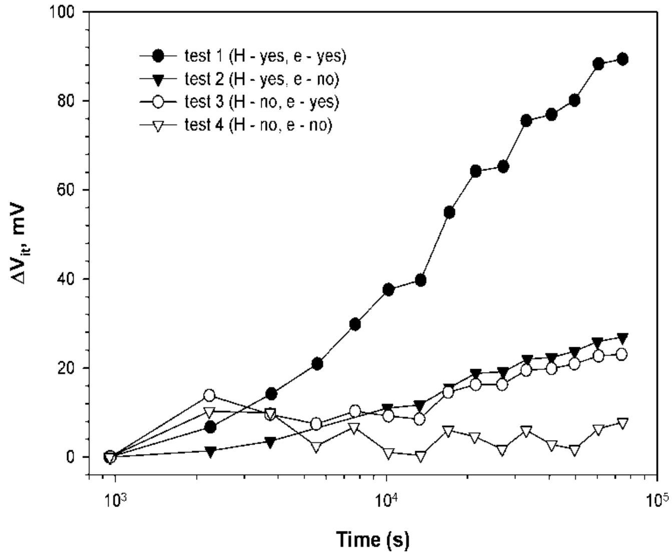


**Fig.1** Interface-trap component of the threshold voltage shift ΔVit versus the annealing time in the hydrogen atmosphere (After Ref. [5])

## 3. PREDICTION OF MOS DEVICES RESPONSE IN SPACE ENVIRONMENT

Total radiation induced threshold voltage shift $\Delta V_{th}$ is usually separated to the components due to oxide trapped ($\Delta V_{ot}$) and interface trap ($\Delta Vit$) charge buildup

$$\Delta V_{th} = \Delta V_{ot} + \Delta V_{it} \tag{1}$$

To separate accumulation and annealing effects which occur simultaneously during irradiation, the technique of linear response theory can be used. At time $t$ the $\Delta V_{ot}$ response to an arbitrary irradiation starting at $t = 0$ and described by the dose rate function $\gamma(t)$ which can be obtained through the convolution integral [6]

$$\Delta V_{ot} = \int \gamma(t)\Delta V_r(t-t')dt' \tag{2}$$

where $\Delta V_r(t-t')$ is the impulse response function.

To describe the annealing process we use the equation for $\Delta V_r$ introduced in [6]. If after the end of irradiation at $t \to \infty$ all trapped holes are completely annealed, the impulse response function $\Delta V_r$ is given by [6]

$$\Delta V_r(t) = -V_0 /(1 + t/t_0)^{\nu} , \tag{3}$$

where $\Delta V_0$, $t_0$ and $\nu$ are fitting constant.

For irradiation time $t_{ir}$ using this impulse response function with $\gamma(t) = \gamma_0$ for $t < t_{ir}$ and $\gamma(t) = 0$ for $t > t_{ir}$ we have

$$\Delta V_{ot}(t) = -C[(1 + t/t_0)^{1-\nu} - 1], t < t_{ir} , \tag{4a}$$

$$\Delta V_{ot}(t) = -C[(1 + t/t_0)^{1-\nu} - (1 + (t - t_{ir})/t_0)^{1-\nu}], t > t_{ir} \tag{4b}$$

where $C = \gamma_0 t_0 \Delta V_0 /(1-\nu)$

Similar equations were derived in [6].

If no annealing occurs ($\nu = 0$), the threshold voltage shift would reach its maximum value

$$\Delta V_{ot\_\max}(t) = V_0 D , \tag{5}$$

where $D$ is the total absorbed dose.

The threshold voltage shift $\Delta V_{it}$ includes fast and slow components. We suppose that for times greater than about $10^{-3}$ s the fast component is proportional to the dose

$$\Delta V_{it\_fast}(t) = \Delta V_i D , \tag{6}$$

where $\Delta Vi$ is the fitting constant.

According to conversion model of interface buildup, the interface state density is proportional to decrease of positive charge, i.e. there is some conversion coefficient $K_{oi}$ which reflects strong correlation between the accumulation of slow interface states and trapped hole annealing. Following this approach we can write for slow interface density component $\Delta Nit\_slow$:

$$\Delta V_{it\_slow} = K_{oi}(\Delta N_{ot\_\max} - \Delta N_{ot}) , \tag{7}$$

where $\Delta Not\_max$ corresponds to $\Delta Not\_max$.

In this case for slow component we have:

$$\Delta V_{it\_slow} = K_{oi}(\Delta V_{ot\_\max} - \Delta V_{ot}) , \tag{8}$$

Note, that the process of interface annealing is ignored, because at room temperature they decay with a time constant of several years.

Finally, we have the analytical equations for interface voltage shift:

$$\Delta V_{it} = K_{oi}(\Delta V_o + \Delta V_i)D + K_{oi}\Delta V_{ot} , \tag{9}$$

The practical formula for hardness assurance application of MOSFET voltage shift response can be derived from equation (1):

$$\Delta V_{th} = K_{oi}(\Delta V_o + \Delta V_i)D + (1 + K_{oi})\Delta V_{ot} , \tag{10}$$

where $\Delta V_{ot}$ is calculated using (4a).

Equation (10) has five fitting parameters: $K_{oi}$, $\Delta V_o$, $\Delta V_i$, $t_0$ and $\nu$, which can be found numerically using experimental data obtained in laboratory tests with high dose rate irradiation. There are several approaches to fitting procedure: solving of nonlinear least squares problem for five unknown parameters, implementation of separation techniques and so on. More convenient approach is to find three constants $\Delta V_o$, $t_0$ and $\nu$ using the experimental data on $\Delta V_{ot}$ and two constants $K_{oi}$ and $\Delta V_i$ from analysis of $\Delta V_{it}(t)$. The constants can be extracted from at least three experimental points $\Delta V_{ot}$ and $\Delta V_{it}$ versus $t$. The reasonable value for the first measurement is taken to be equal to 1s after the end of irradiation. The Monte-Carlo simulation shows that the second point can correspond to interval 2 $t_{ir}$ and the third measurement can be done at 100 $t_{ir}$ [7].

The results of parameter extraction for our experimental data as well as for data taken from [8-11] are listed in Table 1.

**Table 1** Parameters extracted from experimental data (After Ref. [7]).

| Data | $V_g$ (V) | $\Delta V_0$ (V/rad) $10^{-6}$ | $t_0$ (s) | $\nu$ | $K_{oi}$ | $\Delta V_i$ (V/rad) $10^{-7}$ |
|---|---|---|---|---|---|---|
| [8], fig 2 | 5.0 | 0.35 | 26 | 0.082 | 0.0 | 0.6 |
| [9], fig 1 | 6.0 | 14 | 1.5 | 0.081 | 0.73 | 2.5 |
| [9], fig 4 | 6.0 | 3.6 | 0.018 | 0.078 | 0.44 | 4.5 |
| [10], fig 5 | 5.0 | – | 8900 | 0.405 | 0.25 | – |
| [11], fig 13 | 2.5 | 21 | 110 | 0.1 | 0.41 | 12 |
| Experiment: | 0 | 1.1 | 0.0004 | 0.074 | 0.0 | 1.5 |
| n-channel, | 2.5 | 0.83 | 0.0016 | 0.083 | 0.12 | 0.14 |
| 30nm | 5.0 | 0.6 | 0.019 | 0.092 | 0.12 | 0.0028 |
| Experiment: | 0 | 20 | 15 | 0.026 | 1.0 | 56 |
| n-channel, | 2.5 | 23 | 16 | 0.035 | 1.0 | 59 |
| 100nm | 5.0 | 22 | 48 | 0.078 | 1.0 | 98 |

## 4. Low Dose Rate Effect in Bipolar Devices

The low dose rate effect in bipolar transistors or the Enhanced Low-Dose-Rate Sensitivity (ELDRS) consists in more serve degradation of bipolar structure current gain for the given total dose following the low dose rate [12]. The ELDRS model in the given work is based on the hydrogen-electron (H-e) conversion model. The motivation of this development is the creation of a model that is allowed to obtain a quantitative numerical estimation of radiation degradation of bipolar transistor current gain for the arbitrary dose rate and temperature. Because the H-e model is based on the conversion of a radiation-induced positive trapped charge to interface traps, the model described below is called the ELDRS conversion model.

To explain the classical radiation-induced positively charge annealing [13] and the reversibility of annealing effect [14], it is necessary to consider two positions of positive centers in the oxide forbidden gap: the non-rechargeable centers located about 1 eV above $SiO_2$ valence band [12], and the rechargeable parts of the oxide trapped charge located opposite the silicon forbidden gap [13]. Direct substrate electron tunneling to positive centers, located opposite the silicon forbidden gap, is impossible because the tunneling electron energy must be constant (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 (Fig. 2,a). The positive charge can be neutralized by hole emission to silicon valence band (Fig. 2,b). Below the case of an interaction of positive charge and electron (Fig. 2,a) will be considered.

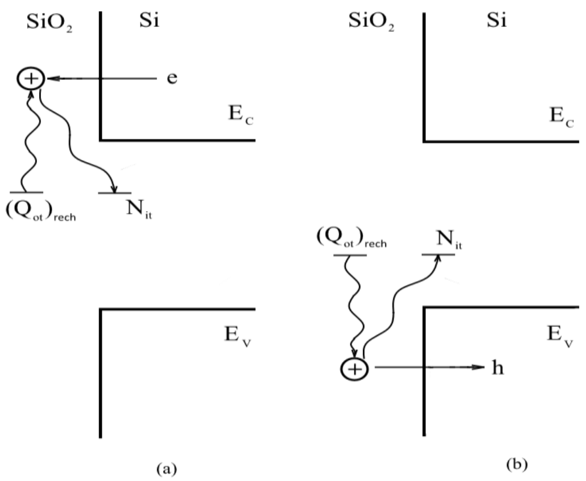


**Fig. 2** Conversion of oxide charge $(Q_{ot})_{rech}$ to interface trap $N_{it}$: capture of an electron e (a), emission of a hole h (b). $E_c$ and $E_v$ are energy levels of Si conduction and valence band

An interaction of thermally excited rechargeable positive charges and tunneling substrate electrons leads, according to conversion model, to interface-trap buildup. The physical nature of the conversion process can be connected with changing a distance between positive Si+ and neutral SiO atoms ($E_\gamma'$ center, hole trap) after electron capture by $E_\gamma'$ center [15].

The probability of the oxide positive center excitation up to conduction band depends on its energy depth in oxide relatively Si forbidden gap. The shallow oxide traps (near conduction band) are converted for short time, while the deep traps (opposite to middle of Si forbidden gap) need much more time for conversion.

For simplicity, it is supposed that there are two kinds of oxide traps: shallow traps with small time of conversion, responsible for the degradation at high dose rates, and deep traps determining the excess base current increasing at long times of irradiation, i.e. at low dose rates (Fig. 3). The shallow traps are converted with time constant $\tau_S$; the conversion time of the deep traps is $\tau_D$. Essentially, the conversion time of the deep traps or constant $\tau_D$ is responsible for ELDRS.

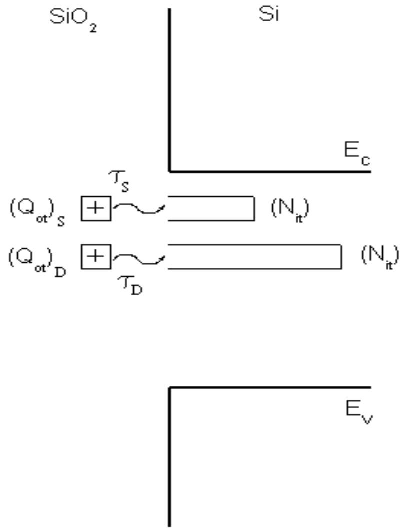


**Fig. 3** The shallow $(Q_{ot})_S$ and deep $(Q_{ot})_D$ oxide trapped charges with conversion time $\tau_S$ and $\tau_D$

As shown in [16], the degradation of the base current as a function of dose rate (for irradiation time much more than 1 s) can be written as:

$$\Delta I_B = (K_D + K_S) \cdot D + \gamma \cdot K_D \cdot \tau_D \left( e^{-D/\gamma \cdot \tau_D} - 1 \right), \qquad (11)$$

where $K_S$ is excess base current per unit dose at high dose rate; $K_D$ is excess base current per unit dose at low dose rate; $\gamma$ is dose rate; $D$ is the total dose.

A conversion of oxide charge to interface traps is a thermal stimulating process. To consider a temperature effect on base current degradation, dependence of deep trap conversion time from temperature is introduced. Temperature dependence of time constant $\tau_D$ can be described by Arrhenius equation:

$$\tau_D = \tau_{D0} \exp(E_A / kT), \qquad (12)$$

where $\tau_D$ is conversion time of deep traps; $T$ is temperature; $E_A$ is the activation energy of the oxide trap thermal excitation; $k$ is the Boltzmann's constant; $\tau_{D0}$ is pre-exponential coefficient.

Thus ELDRS conversion model has 4 fitting parameters: $K_{S,}$ $K_{D,}$ $E_A$ and $\tau_{D0}$. Their extractions are performed by the following steps presented in [17]:

1. Constant $K_S$ determining the contribution of shallow trapped charge conversion to base current degradation is estimated as a ratio of base current degradation to the specified total dose at 10 rad($SiO_2$)/s irradiation.
2. The deep traps conversion time or constant $\tau_D$ is estimated from data of post-irradiation anneal following high dose rate irradiation to the specified total dose. Pre-exponential constant $\tau_{D0}$ and activation energy $E_A$ in (12) are derived from the data for two different temperatures of elevated temperature post-irradiation anneal.
3. Constant $K_D$ determining the contribution of deep trapped charge conversion to base current degradation at low dose rate is estimated from elevated temperature irradiation data. Constant $K_D$ is derived from (11), where the constant $\tau_D$ for using elevated temperature is calculated from (12) (values of $\tau_{D0}$ and activation energy $E_A$ are determined on step 2).

The ELDRS conversion model was validated by comparison with previously reported experimental data. Two examples are shown below. In fig. 4 calculated and experimental results obtained from relationship (11) and [18] are shown. Relationship (11) well describes experimental data [18] for values of fitting constants: $K_S = 1.35 \cdot 10^{-3}$ $nA/rad(SiO_2)$, $K_D = 8.65 \cdot 10^{-3}$ $nA/rad(SiO_2)$, $\tau_D = 2.2 \cdot 10^5 s$ (for lateral pnp) and $K_S = 0.16 \cdot 10^{-3}$ $nA/rad(SiO_2)$, $K_D = 1.49 \cdot 10^{-3}$ $nA/rad(SiO_2)$, $\tau_D = 5.0 \cdot 10^5 s$ (for substrate pnp). The same results for [19] are shown in fig. 5. Fitting constants for that case are: $K_S = 0.33 \cdot 10^{-3}$ $nA/rad(SiO_2)$, $K_D = 6.33 \cdot 10^{-3}$ $nA/rad(SiO_2)$, $\tau_D = 3.0 \cdot 10^5 s$.

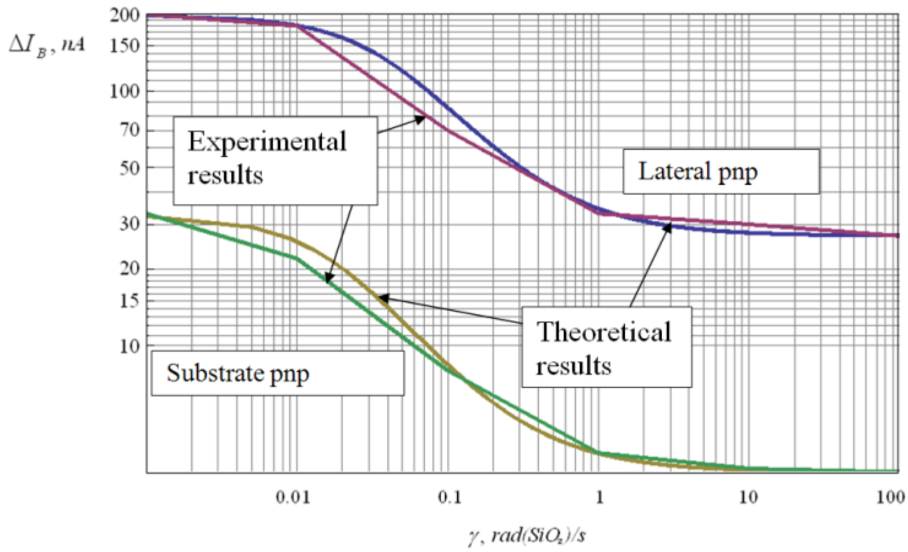


**Fig. 4** Excess base current versus dose rate. Experimental [18] and calculated data from relationship (11).

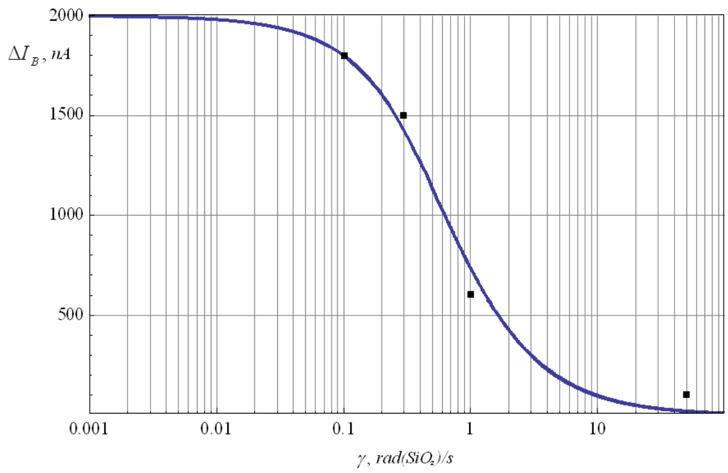


**Fig. 5** Excess input base current LM158 versus dose rate. Experimental [19] (dots) and calculated data from conversion model (11).

The conversion model proposed also explains why the base current starts growing $10^5$ s after the cessation of the short-term, high dose rate irradiation [19]. The reason is that the charge at the deep oxide traps has no time to be converted into interface traps during the short-term, high dose rate irradiation. It is not accidental that the measured value $\tau_D = 3.0 \cdot 10^5$ s is of the same order of magnitude as the started delay in [19].

## 5. ELDRS IN SIGE TRANSISTORS

The activation energy of deep positive oxide center with energy $E_{ot}$ in the oxide (Fig. 6) can be presented as the sum of the energy of thermal excitation $\Delta E_D$ from $E_{ot}$ to electron energy at conduction band edge $E_c$ and energy of elastic coupling of positive center with lattice atoms:

$$E_A = \Delta E_D + E_{latt}, \tag{13}$$

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

In SiGe HBTs due to the Ge content, the bandgap narrowing in base region takes place. The bandgap narrowing $\Delta E_G$ leads to a reducing of the energy interval $(\Delta E_D)_{SiGe}$ which is needed for an interaction of the thermal exited deep oxide traps and tunneling substrate electrons. It leads to a reducing of deep trap conversion time and during any dose rate irradiation all oxide trapped charges have time to be converted into interface traps. As a result, deep traps can act as shallow traps, and ELDRS is eliminated. The reducing of a necessary exited energy for conversion of deep traps in SiGe transistors depends on bandgap narrowing $\Delta E_G$ of base region under base spacer interface:

$$(\Delta E_D)_{SiGe} = (\Delta E_D)_{Si} - \Delta E_G, \tag{14}$$

where $(\Delta E_D)_{SiGe}$ is the thermal exited energy for conversion of the oxide deep traps in SiGe transistor; $(\Delta E_D)_{Si}$ is the thermal exited energy for conversion of the oxide deep traps in conventional Si transistor; $\Delta E_G$ is bandgap narrowing of base region under base spacer interface of SiGe HBT.

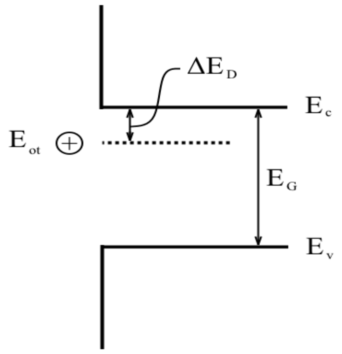


**Fig. 6** The energy of thermal excitation $\Delta E_D$ from level of positive trap in the oxide $E_{ot}$ to conduction band edge $E_c$ . $E_G$ is bandgap of semiconductor.

It can be shown using results of [16] that for conventional bipolar devices the deep trap location is near 0.21eV – 0.29 eV below the edge of conduction band. Fig.7 presents the effect of bandgap narrowing on the exited energy $\Delta E_D$ which is enough for conversion of deep traps into interface traps. The line 1 in Fig. 7 corresponds to initial value $\Delta E_D$ = 0.29eV, line 2 corresponds the initial value $\Delta E_D$ = 0.21 eV. The dotted line shows the boundary between ELDRS region and region where ELDRS is absent (ELDRS-free).

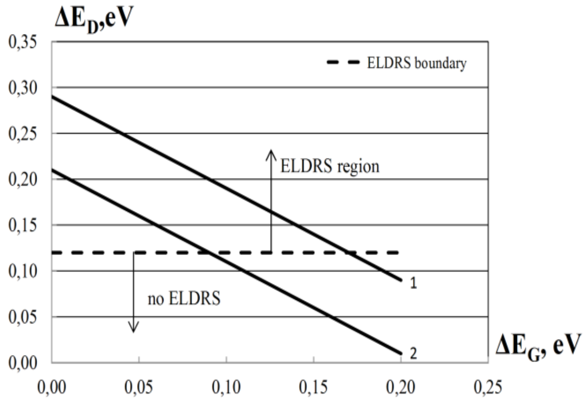


**Fig. 7** The effect of bandgap narrowing $\Delta E_G$ on the exited energy $\Delta E_D$. The dotted line presents the boundary between ELDRS region and region where ELDRS is absent (ELDRS-free).

We consider that the ELDRS boundary (existence or absence ELDRS) corresponds to $\Delta E_D$ = 0.12 eV. It connects with following physical reason. A spreading of the energy location of the positive oxide traps by temperature excitation can be estimated as ±(2-3) *kT*. It means that shallow and deep energy levels can be separated as different traps if the energy gap between their locations more than approximately 5 *kT* or 0.0125 eV. For $\Delta E_D$ more than 0.12 eV the shallow and deep oxide traps act as the different traps and ELDRS can be observed (above dotted line in Fig.7). For $\Delta E_D$ less than 0.12 eV the shallow and deep oxide traps are equivalent one trap and ELDRS cannot be observed (under dotted line in Fig.7).

In SiGe HBTs the value of bandgap narrowing has order 0.1eV – 0.2 eV. Fig. 8 shows valence band offset as a function of Ge content [20, Fig.9].

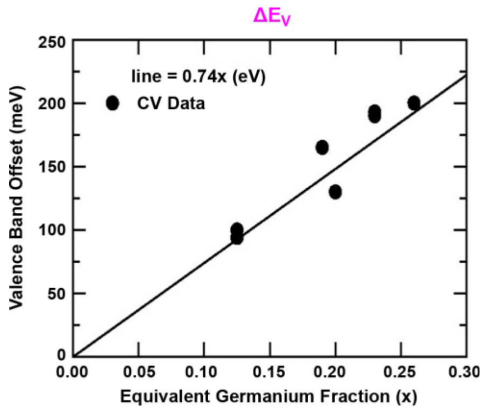


**Fig. 8** Valence band offset as a function of Ge content (After Ref. [20]).

Therefore, for SiGe devices ELDRS will be not observed (no ELDRS region in Fig. 7) if bandgap narrowing more than 0.1 eV or 0.18 eV. It is very probable that parameters of the modern SiGe HBTs lay within “no ELDRS” region. This conclusion agrees with experimental data of [20], where was said: “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” [20, page 2001]. The ELDRS conversion model can give physical explanation of this statement.

## 6. Saturation of the Radiation-induced Interface-trap Buildup

The analysis of this section is based on the assumption that the positive charge of trapped holes in oxide is transformed through electron capture into a new defect (the AD center) with two energy states in forbidden gap of Si [21]. This is point defect, for which the high energy level is acceptor-like and lower energy level is donor-like. The following process of AD center generation and annihilation is proposed. The strained Si-Si bond (oxygen vacancy) serves as precursor for this radiation-induced defect. This precursor can be treated as a non-activated donor center D. The radiation induced holes are captured by deep D traps creating a positive charged $D^+$ center: $D + h = D^+$. Free electron capture by $D^+$ center causes its transformation to the two-level AD center: $D^+ + e = A^0D^0$. The AD defect can be found in four different states: $A^0D^0$ , $A^-D^0$ , $A^0D^+$ , $A^-D^+$ . The superscripts after A and D designate charge state of the acceptor and donor levels respectively: $A^0D^0$ – acceptor level is empty, donor level is occupied; $A^-D^0$ – acceptor and donor levels are occupied; $A^0D^+$ – acceptor and donor levels are empty; $A^-D^+$ – acceptor level is occupied, donor level is empty. The charge exchange of the $A^0D^0$ with radiation induced or substrate electrons leads to $A^-D^0$ and $A^0D^+$. The charge state $A^-D^+$ cannot be stable and is assumed to immediately relax back to the D precursor due to energy released during electron transition from higher (A) to lower (D) levels. Therefore, the appearance of the $A^-D^+$ state leads to the annihilation of the AD center.

The saturation can be explained by two competitive processes: accumulation and annihilation (annealing). At mathematical form it can be written

$$dN_{it} / dt = G - N_{it} /(\tau_{ann})_{it} , \tag{15}$$

where $G$ is accumulation rate of interface trap; $N_{it}$ is density of interface traps; $(\tau_{ann})_{it}$ is the time constant of interface state annihilation.

In saturation, $dNit/dt = 0$ and Nit reaches a saturated value

$$(N_{it})_{sat} = G \cdot (\tau_{ann})_{it} , \tag{16}$$

The accumulation rate of $N_{it}$ buildup is proportional to the dose rate

$$G = (K_{acc})_{it} \gamma , \tag{17}$$

where $(K_{acc})_{it}$ is a coefficient characterizing interface trap accumulation; γ is the dose rate.

Therefore

$$(N_{it})_{sat} = (K_{acc})_{it} \cdot (\tau_{ann})_{it} \cdot \gamma , \tag{18}$$

The value of $(N_{it})_{sat}$ is proportional the dose rate $\gamma$ if $(K_{acc})_{it}$ and $(\tau_{ann})_{it}$ are constants. But, as follows from experimental data, the value interface trap concentration in saturation $(N_{it})_{sat}$ is very weak function of the dose rate. The changing of the dose rate at more than 4 orders in region from 300 krad (Si)/min to 13 rad (Si)/min leads to very small variation of $(N_{it})_{sat}$ [22]. The same result is obtained in [23,24], where the saturation of $N_{it}$ was observed for the changing of the dose rate from 333 rad ($SiO_2$) to 5.25 rad ($SiO_2$).

The coefficient $(K_{acc})_{it}$ is very weak function of the dose rate. It follows from linear dependence of $N_{it}$ buildup at small total doses, that agrees with numerous experimental data reported by [22, 24, 25]. The value $(N_{it})_{sat}$ is not dependent at the dose rate $\gamma$ if $(\tau_{ann})_{it}$ is inversely proportional γ or an annihilation (annealing) of interface traps depend on the dose rate. It is necessary to consider radiation induced charge neutralization (RICN) effect. Usually RICN effect concerns to the annealing of oxide trapped charge. In given work we suppose using RICN effect as basic mechanism of interface-trap annealing.

Consider the case when annihilation takes place from $A^0D^+$ configuration after capture radiation-induced electron. The $A^0D^+$ state transforms to $A^-D^+$ state, which is not stable and is assumed to immediately relax back to the D precursor. The Nit annihilation process can be described by the relationship from recombination theory of Shockly- Read-Hall [26]

$$(dN_{it} / dt)_{ann} = -v_{th} \sigma_t n \cdot N_{it} , \tag{19}$$

where $\upsilon_{th}$ is the thermal velocity; $\sigma_t$ is the capture cross-section of AD center; $n$ is concentration of radiation induced electrons.

Concentration of radiation induced electrons equal

$$n = K_p K_y \gamma \,, \tag{20}$$

where $K_p$ is generation rate per unit dose rate; $Ky$ is electron yield; $\gamma$ is the dose rate.

Result of substituting (20) in equation (19) is

$$(dN_{it} / dt)_{ann} = -v_{th}\sigma_t K_p K_y \gamma \cdot N_{it} = -N_{it} /(\tau_{ann})_{it} \,, \tag{21}$$

where

$$(\tau_{ann})_{it} = K_{AD} / \gamma \,, \tag{22}$$

$$K_{AD} = 1/ v_{th}\sigma_t K_p K_y \,, \tag{23}$$

It means from (18) that

$$(N_{it})_{sat} = (K_{acc})_{it} \cdot K_{AD} \,, \tag{24}$$

The value of density of interface trap in saturation, as follows from (24), depends on product of interface trap accumulation rate $(K_{acc})_{it}$ and constant $K_{AD}$ which is function of thermal velocity, capture cross-section of AD center, generation rate and electron yield of radiation induced electrons.

Consider the analysis of the some results of work [25], using relationship (24). Two vendors (vendor "A" and vendor "B") of n-channel Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) were irradiated with X-ray. The vendors had different initial values of interface trap density and were irradiated at different dose rates, which presented in table 2 with estimated value of $(K_{acc})_{it}$ and $K_{AD}$.

**Table 2** Experimental conditions and estimation results for transistor venders from [25].

| | Dose rate (rad($SiO_2$)/s) | Initial $N_{it}$, $cm^{-2}$ | $(K_{acc})_{it}$, (rad($SiO_2$)$^{-1}$cm$^{-2}$) | $K_{AD}$, rad($SiO_2$) | $(Nit)_{sat}$, $cm^{-2}$ |
|---|---|---|---|---|---|
| Vendor "A" | 170 | $2*10^{10}$ | $6.4*10^4$ | $1.6*10^7$ | $1*10^{12}$ |
| Vendor "B" | 1700 | $2*10^{11}$ | $1.15*10^6$ | $1.7*10^7$ | $2*10^{13}$ |

The values of $K_{AD}$ for different venders are the same despite different initial $N_{it}$ values and irradiation dose rate. It means that model, presented in this work, is able to describe physical mechanism of interface-trap buildup saturation correctly. Value of $(K_{acc})_{it}$ is determined by initial $N_{it}$ buildup rate and depends on parameters of manufacture technology process and irradiation dose rate. The additional information concerning interface-trap buildup saturation can be find in [27].

## 7. Conclusion

The ELDRS conversion model for modeling the radiation-induced degradation of bipolar device parameters for the impact of low dose rate irradiation is described. The model is based on the concept that the radiation-induced interface-trap buildup connects with the hydrogen-electron mechanism, where both hydrogenous species and electrons are responsible for radiation-induced interface-trap formation. The interaction of trapped positive charges (hydrogenous species) and electrons from the substrate leads to the formation of interface traps. The main feature of the ELDRS conversion model includes the fitting parameter extraction techniques. The model was validated by comparing it with the previously reported experimental data for different technologies and devices. According to conversion model of interface trap buildup, bandgap narrowing of the SiGe bipolar transistor base region leads to reducing of deep trap conversion time and, as a result, during irradiation at any dose rate all oxide trapped charges have enough time to be converted into interface traps. Therefore, there is no difference between test dose rate and low dose rate irradiation (ELDRS-free). The interface-trap buildup saturation is explained by an interaction of the radiation-induced electrons with centers which were formed during conversion process.

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