Conversion model of radiation-induced interface-trap buildup and the some examples of its application

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Abstract. It is supposed that the rechargeable radiation-induced positive centers in the oxide must have energy levels within the Si forbidden gap. These assumptions served as the basis for the physical model of the interface-trap build-up and enhanced low dose rate sensitivity (ELDRS) in bipolar devices. As examples of using the proposed conversion model is considered for bipolar devices space application.

1. Introduction
In this paper, we describe the conversion model of interface-trap buildup which integrates conventional hydrogen and hydrogen-electron approaches. The experimental data confirming the validity of this type of combined model are presented. The energy level location of positive centers and its recharge mechanism using the reversibility of annealing mechanism is described. An account of the interaction of trapped positive charges and electrons from the substrate allows the development of the numerical model for the enhancement low dose rate sensitivity (ELDRS) effect in bipolar devices. The demonstration of using the conversion model for the numerical estimation of bipolar device behavior during a hypothetical space mission is presented.

2. Mechanism of interface-trap buildup
The radiation-induced interface-trap buildup is one of the major problems in the radiation physics of metal-oxide-semiconductor (MOS) structures. In the previous 30 years, two physical models with a description of the process for the radiation-induced interface-trap buildup were proposed. The first model was the hydrogen model (H-model) [1]. The second model was a conversion model where trapped holes are converted to interface traps by electron capture [2]. The last model is not well regarded today.

The hydrogen model proposed an active participation of various hydrogen species for an interface-trap generation. According to [1], the protons produced in bulk oxide by radiation move to the Si interface. When the protons reach the interface, they react, breaking the Si-H bonds, forming H_{2} and a trivalent Si defect according to the reaction.

The hydrogen model successfully explains the field dependence of interface-trap buildup at constant and switching electric fields in the oxide. However, this concept, unfortunately, does not explain all known experimental data. The series of experimental results cannot be unambiguously interpreted by the traditional hydrogen model.

The second group of models is based on experimental data, and interface traps are formed by positive trapped charge annealing [2], when trapped holes are converted to interface traps. In [2],
an injection of electrons into the oxide and a compensation of trapped holes led to interface-trap buildup. It allowed us to make an empirical assumption [2] that the process of recombining the positively charged defect with the electron can lead to the interface-trap formation ("conversion" model). The effect of the hydrogen species on interface-trap buildup was outside of the conversion mechanism. Meanwhile, even in early experiments [2,3], it was shown that the conversion process had a strong dependence on hydrogen concentration in the oxide.

3. Experiment
To check the hypothesis that interface-trap buildup is connected with the interaction between the positively charged hydrogen species in the oxide and electrons tunneling from the substrate, a special experiment was performed [4]. The result of this experiment is presented below.

The n-channel MOS transistors with a 30-nm gate oxide were irradiated by Cu-target X-rays sourced with a 1 krad(SiO2)/s dose rate to 3 Mrad (SiO2) total dose. 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 different combinations of hydrogenous species and electrons present near the interface were varied in 4 tests. A maximum change of $\Delta V_{ir}$ 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 $\Delta V_{ir}$ is essentially reduced.

The presented experimental data confirms the hypothesis that the presence of hydrogen is sufficient for effective interface-trap buildup. The interaction of hydrogenous species and electrons from the substrate is an 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.

The presented approach corresponds to experimental data for the "conversion" concept and a large experimental basis for hydrogen models. It allows us to discuss the common hydrogen-electron (H-e) model of radiation-induced interface-trap buildup, which consolidates hydrogen and conversion concepts.

4. Thermoactivated tunneling mechanism
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. In [5], the effect of the reversibility of annealing was described, which could not be explained by previous models. The model [6] supposed that an interaction of the oxide defects and electrons from the substrate include 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.

The thermoactivated tunneling model describes the main features of the oxide charge relaxation, and it is the most important part of the interface-trap buildup mechanism presented above. In the framework of the hydrogen-electron model, the interface-trap formation at a long time interval is determined by electron tunneling from the substrate. On the other hand, the oxide defect can exhibit some characteristics of interface-traps if it is located close enough to the interface Si/SiO2 (less than 1 nm). Therefore, there is some contradiction between a long time electron transition to a defect during interface-trap formation and a short recharge time for the interface-trap after the buildup. The thermoactivated tunneling model eliminates this contradiction. The center located close to interface Si/SiO2 but with 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 at 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.

5. Conversion model
The low dose rate effect in bipolar transistors or the enhanced low dose rate sensitivity (ELDRS) effect is a more severe degradation of the bipolar structure current gain for a given total dose following a low dose rate. All aspects concerning this effect (mechanisms, modeling, and testing recent developments in ELDRS) are analyzed comprehensively in [7]. The ELDRS model is given the work is based on the hydrogen-electron 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 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.

The key concept of the ELDRS conversion model is as follows. We suppose that there are two types of traps that are located in the oxide interface opposite the silicon forbidden gap: 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.

As shown in [8], the degradation of the base current as a function of the dose rate (for irradiation time substantially more than 1 s) can be written as:

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

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

The ELDRS conversion model includes an experimental procedure for fitting parameters extraction. This feature is a distinguishing characteristic of the model that allows the reception of a quantitative numerical estimation for radiation degradation of a bipolar transistor base current for arbitrary dose rate and temperature.

A conversion of oxide charge to interface traps is a thermally stimulated process. To consider the temperature effect on the base current degradation, dependence on the deep trap conversion time from temperature is introduced. The temperature dependence of time constant $τ_D$ can be described by the Arrhenius law:

$$τ_D(T) = τ_{D0} \cdot \exp\left(\frac{E_A}{kT}\right),$$  \hspace{1cm} (2)

where $T$ is the temperature; $E_A$ is the activation energy of deep oxide trap thermal excitation; $k$ is Boltzmann's constant and $τ_{D0}$ is pre-exponential coefficient.

6. Examples of using the conversion model for numerical estimation of bipolar device radiation degradation in space application
The conversion model can be used for a description practical and interesting applications when the dose rate and temperature are not constant. This takes place during real operating conditions for the on-board space apparatus when the dose rate cyclically varies when crossing the radiation belts of Earth and temperature changes according to the sun apparatus position. It is probable that short high-intensity radiation receives impacts from a solar flare. Below, the conversion model for the quantitative numerical hypothetical analysis of the radiation degradation LM111 comparator (as an example) for a possible on-board space apparatus operation is described. The technical details of this approach were described in [9].

6.1. Dose rate variation
Usually, the ELDRS analysis [7] is performed using a constant dose rate. In real operations, a periodical short increasing dose rate connects by crossing the radiation belts of Earth with the space apparatus.
The selection of averaged dose rates for estimating radiation degradation bipolar devices that are on-board is not obvious.

In the analyzed example, the dose rate varies from 10 mrad(SiO2)/s during 1 hour to less than $10^{-6}$ rad(SiO2)/s during 11 hours [10]. The averaged dose rate was 0.8 mrad(SiO2)/s. A simulation of the dose dependence at 25°C for the input current of the LM111 comparator, is presented in Fig. 1. For comparison, in Fig. 2, the excess input current versus the total dose is shown for the constant averaged dose rate. Fig. 1 shows changes in the input current on a larger scale. The results are practically the same for both cases. This means that for the case of periodic variation in the dose rate and short periods of dose rate variations compared to the total irradiation time, it is correct to use the averaged dose rate for the estimation of radiation degradation.

The obtained data shows, it is possible to use the averaged value of the dose rate during a space apparatus flight on orbit as the in-flight dose rate after switching the dose rate from high to low.

![Figure 1](image-url)

6.2. Cyclic temperature variation

The effect of environment temperature on bipolar device operation during a long space mission was investigated, for example, with a sinusoidal temperature variation from 268 K (-5 °C) to 328 K (+55 °C) with the 12-hour period of variation. The average temperature during the period is 298K (25 °C).

As illustrated, the results of the simulation when using the ELDRS conversion model are presented in Fig. 2 for variable and constant averaged temperatures. The obtained results mean that using the averaged temperature can lead to a large error. From the illustration in Fig. 2, the total dose level of a 1.6 krad(SiO2) estimation error may be more than 300% when the averaged temperature level is used instead of the real dependence temperature on time. If the parametric failure level for the comparator input current is defined as 100 mA, the failure total dose level could be overestimated more than three times when using the averaged temperature value.
Consider the application of the result obtained above for the technique of a thermal annealing approach for regenerated electrical characteristic devices [11]. The technique of [11] is efficient on a thick oxide when electrical characteristic degradation is mainly caused by an oxide-trapped charge. Radiation-induced bipolar transistor gain degradation connects with processes in a thick oxide above the base region and is dominated by the formation of interface traps at the Si/SiO2 interface. For these devices, cycling elevated temperature annealing can lead to an increase in interface trap concentration and an increase in degradation. The following conclusion can be made: the technique for a thermal cycling annealing approach that extends electronic device lifetimes exposed to very high total dose [11] can be used for devices in which a role of radiation-induced interface trap buildup is not significant. It concerns the bipolar devices in which the ELDRS effect takes place, and the role of the interface-trap buildup is important. Using this technique [11] for these types of devices should be performed with caution.

7. Conclusion

The 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 experimental data confirming the validity of this type of combined model is presented. To explain the reversibility effect of annealing, a thermoactivated tunneling mechanism of the defect recharge was proposed. It is supposed that the rechargeable positive centers in the oxide must have energy levels within the Si forbidden gap.

The applicability of the proposed conversion model for the estimation of the radiation degradation of bipolar devices on the impact of low dose rate irradiation is demonstrated. For one type of IC (LM111 comparator) for which the fitting parameters of the ELDRS conversion model were extracted,
we try to demonstrate a numerical estimation of this circuit behavior during a space mission. The numerical analysis of the comparator input current radiation degradation during a long operation in space is simulated during a dose rate variation corresponding to the 12-hour orbit and cyclic device temperature variation. All of these quantitative numerical results may have practical application.

It was shown that in the case of a variable dose rate during a space mission, the averaged value of the dose rate could be used. However, using the averaged temperature can lead to essential error. The correct estimation of radiation-induced degradation should be accurate when considering the temperature time dependence during device operation.

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