ELDRS in a wide range of total doses

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Abstract. The ELDRS enhancement factor versus total absorbed dose and dose rate is considered in a wide range of doses.

1. Introduction
The low dose rate effect in bipolar technologies or Enhanced Low Dose Rate Sensitivity (ELDRS) consists of more severe degradation of a bipolar structure’s current gain for a given total dose at low dose rate. The ratio of the sensitive electrical parameter’s degradation at low dose rate to that at some fixed high dose rate for a given total dose is termed as low dose rate enhancement factor (EF) [1]. EF can reach more than 10. Detailed analysis of ELDRS has been performed in early works [1] typically related to space electronics for relatively small total doses. However using modern integrated circuits for the front end electronics of High Energy Physics experiments (such as the ATLAS Detector at the Large Hadron Collider at CERN) changes the situation [2,3]. Total dose in the ATLAS Upgrade Inner Detector’s Middle Region gives dose value near 50 Mrad (SiO$_2$) for the front-end electronics operation during 10 years [4]. This corresponds to the dose rate near 0.25 rad (SiO$_2$)/s taking into account shutdown and inactive periods. The authors of [4] investigating the behavior of the silicon-germanium heterojunction bipolar transistors for ATLAS Detector applications observed the effect of the anomalous recovery of transistor current gain after the total absorbed dose of 30 Mrad (SiO$_2$): reducing the dose rate leads to the decrease of current gain degradation. This means that the enhancement factor EF becomes less than 1. The same result was obtained in [5]. Therefore devices can suffer from ELDRS for small total doses and show recovery dependence for high doses.

The goal of this paper is to describe the enhancement factor EF versus dose-dependence in a wide range of total absorbed doses.

If the excess base current of bipolar transistor is a linear function of excess interface-trap density [6-8], EF can be written as:

$$EF = \frac{\Delta I_b(\text{low dose rate})}{\Delta I_b(\text{high dose rate})},$$

(1)

where $\Delta I_b(\text{low dose rate})$ and $\Delta I_b(\text{high dose rate})$ are the excess base current values at low and high dose rates for a given total dose.

2. Physical model
The most developed model of radiation-induced interface-trap buildup is a two-stage “hydrogen” model [9, 10]. Another model (the so-called “conversion” model [11]) is based on the assumption that...
The generation of interface traps is related to the neutralization of positive charge by the substrate electrons. Experiments [12, 13] have shown that the interaction between hydrogen species and the electrons from substrate is a necessary and important component of the interface-trap build-up. Those results extend the hydrogen model and allow for speaking about a hydrogen-electron model of radiation-induced interface-trap buildup [13].

The concentration of hydrogen in a given microelectronic structure is unknown and depends on a particular manufacturing process. The conversion model allows us to consider the effect of substrate electrons on the interface-trap buildup at any specified hydrogen concentration in the structure. This can be very important for low dose rate applications during a long term device operation, for example, in space. In this work, we assume that the generation of interface traps relates to the oxide trapped charge annealing.

Surface states generation and annihilation can be expressed as follows:

\[
d N_{it} \frac{dt}{dt} = (K_{oi})_{sub} \frac{Q_{ot}}{(\tau_{ann})_{sub}} - \frac{N_{it}}{(\tau_{ann})_{it}},
\]

where \(N_{it}\) is the density of interface states; \(Q_{ot}\) is the oxide trapped charge; \((\tau_{ann})_{sub}\) is the time constant of the annealing of oxide space charge by electrons from the substrate; \((K_{oi})_{sub}\) is the fraction of space charge converted to interface traps due to the interaction with substrate electrons; \((\tau_{ann})_{it}\) is the time constant of \(N_{it}\) annihilation.

The first term on the right-hand side of (2) represents the interface traps buildup through the annealing of trapped charge by the substrate electrons. The second term is responsible for the interface traps annihilation (annealing) [14,15].

Interface traps annihilation is considered from the view of AD-center model [16]. According to [17] time constant of \(N_{it}\) annihilation is

\[
(\tau_{ann})_{it} = \frac{K_{AD}}{P},
\]

where \(K_{AD}\) is a function of thermal velocity, capture cross-section of AD center, generation rate and the radiation induced electrons yield; \(P\) is the dose rate.

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

\[
\frac{dQ_{ot}}{dt} = (K_{acc})_{ot}P - \frac{Q_{ot}}{(\tau_{ann})_{sub}},
\]

where \((K_{acc})_{ot}\) is a coefficient characterizing the accumulation of trapped charge; \(P\) is the dose rate.

Time constant of the annealing process is a function of temperature described by the Arrhenius law:

\[
(\tau_{ann})_{sub} = \tau_{0} e^{\frac{E_A}{kT}},
\]

where \(k\) is the Boltzmann's constant; \(T\) is the temperature; \(E_A\) is the activation energy of the oxide trap thermal excitation; \(\tau_0\) is the pre-exponential coefficient.

3. Shallow and deep traps

According to the ELDRS conversion model [18,19] the inverse S-shaped form of the excess base current versus dose rate [1,6] assumes that there are two kinds of oxide trapped charge at the Si-SiO\(_2\) interface: shallow one \(Q_S\) laying near the edge of Si conduction band, and deep one \(Q_D\) laying near the middle of Si bandgap. The shallow trapped charge has small conversion time constant \((\tau_{ann})_{sub} = \tau_S\) so it is converted to \(N_{it}\) in the first place. Deep trapped charge has relatively large conversion time constant \((\tau_{ann})_{sub} = \tau_D\), so it converts to interface traps much later than the shallow one does. When a device is irradiated with high dose rate just shallow charge has time to convert to interface traps. When the device is irradiated with low dose rate both shallow and deeply trapped charges, convert into interface traps causing more degradation than that at high dose rate.
We assume that the processes of shallow and deep trapped charge conversion are independent of each other, that leads us to two separate sets of differential equations (2) and (4) each one having its values of \( (K_{acc})^S_{ot}, (K_{acc})^D_{ot}, \tau_{ann}^S_{sub} = \tau_S \) and \( (K_{ann})^D_{sub} = \tau_D \).

4. Fitting parameters extraction

Practical use of the model requires extraction of its fitting parameters [18-21]. The model described above has six of them: \( (K_{acc})^S_{ot}, (K_{acc})^D_{ot}, (K_{ot})_{sub}, \tau_S, \tau_D \) and \( K_{AD} \). The extraction procedure includes the following approaches:

- Irradiation at different doses and dose rates at room temperature. The set of experiments can include, for example, three doses and two dose rates.
- Post-irradiation annealing performed in order to extract the activation energy and the pre-exponential coefficient in (5).
- Irradiation at elevated temperature.

Measurements number (i.e. number of equations for extraction procedure) must exceed the number of fitting parameters. This allows for obtaining averaged and thus more reliable values of the fitting parameters.

In Table 1 fitting parameters are presented that we have extracted for LM111 from [22,23].

| Parameter          | Value       |
|--------------------|-------------|
| \( (K_{ot})_{sub} \) | 1           |
| \( K_{AD} \)       | \( 10^4 \) rad |
| \( \tau_S \)       | \( 4.5 \cdot 10^2 \) s |
| \( \tau_D \)       | \( 3.2 \cdot 10^6 \) s |
| \( (K_{acc})^D_{ot}/(K_{acc})^S_{ot} \) | 5.7 |

5. Enhancement factor in a wide range of total doses

Fig. 1 shows the calculated EF versus total dose for LM111. The calculations were made using equation (1) for four dose rate values: 100 rad(Si)/s (reference dose rate), 0.1 rad(Si)/s, 10 mrad(Si)/s and 1 mrad(Si)/s. EF stays approximately constant at doses in the range \( 10^6 - 10^7 \) rad(Si) for dose rates 10 mrad(Si)/s and 1 mrad(Si)/s. At large doses, EF monotonically decreases finally approaching 1. For 0.1 rad(Si)/s and 1 rad(Si)/s dose rates EF has the maximum at \( 10^7 \) rad(Si) and \( 10^6 \) rad(Si) respectively.

6. Discussion

In general, EF versus total dose is a non-monotonic curve. For LM111 at small dose rates (10 mrad(Si)/s and 1 mrad(Si)/s) the enhancement factor stays constant up to \( 10^7 \) rad(Si) and then falls to 1 at higher doses. For dose rates 0.1 rad(Si)/s EF has a plateau for doses \( 10^6 - 10^7 \) rad(Si), becoming smaller outside this range. EF for dose rate 1 rad(Si)/s has the maximum at \( 10^7 \) rad(Si). Decrease of EF at doses smaller than \( 10^5 \) rad(Si) is due to the fact that at these doses exposure time becomes smaller than the deep traps conversion time \( (3.2 \cdot 10^6 \) s, see Table 1) and during the exposure time deep traps convert to interface states only partially, that leads to less base current degradation. For 1 rad/s dose rate, the behavior of EF is the same.

EF decrease at high doses is caused by the interface states annealing. At very large absorbed doses the accumulation of interface states saturates. Note that the saturated \( N_a \) value doesn’t depend on dose rate [14,15], and therefore at doses greater than \( 10^7 \) rad(Si) all EF curves converge. The obtained data tell us that at very large doses the influence of ELDRS is not that critical. The interface states build-up saturation can occur for relatively small doses [24,25]. Therefore the role of ELDRS can reduce even for space electronics devices. This issue requires special analysis.
7. Conclusion

The conversion model of surface traps accumulation and annihilation has been described and based on this model the analysis of enhancement factor versus total dose has been made in a wide range of doses ($10^3$ – $10^9$ rad(Si)). The model has several fitting parameters which can be extracted from experimental data. By the example of LM111, we found that EF versus total dose is a non-monotonic curve. At large doses inherent in the front end electronics of High Energy Physics experiments, the enhancement factor approaches 1 which leads to the lack of ELDRS. The obtained results improve our understanding of the ELDRS physical mechanism and can be useful for bipolar devices’ radiation tolerance estimation for the front end electronics in High Energy Physics experiments.

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