Taking into account the space environments variability for prediction of dose response in bipolar devices

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Abstract. The aim of this paper is modelling and simulation of impact of space variability on dose rates and total ionizing dose (TID) effects in space-borne electronics. It has been shown that the simultaneous thermal annealing may lead to non-stationary relaxation after dose-rate peaks and steady state degradation saturation depending on thermal and electrical operating modes.

1. Introduction
Most testing experiments on the total ionizing dose (TID) have been typically performed with a constant dose rate. However, the space environment can be highly variable. Dose rates are commonly orders of magnitude larger during solar bursts [1,2]. The influence of the space radiation environment variability on spacecraft can affect total dose effects in spaceborne microelectronic parts.

Onboard measurements of dose-rate variations can be conducted through different kinds of monitoring systems. NASA Space Weather Prediction Center contains various sets of data regarding solar activity and particle fluxes measurements. Most of space weather missions require complex equipment to obtain copious data sets, although simple dose detectors could be located on almost any spacecraft. For example, some data presented in [3] was obtained via space-borne segment, containing a set of small-size n-MOSFET based dosimeters with telemetric sub-systems for real-time transfer to Earth. One should note that it may be useful to collect onboard temperature data available considering RADFET temperature sensitivity drift.

Space weather variability makes dose response predictions for onboard devices difficult, in particular, because simultaneous time-dependent anneal effects, which could significantly modify radiation response in IC, especially for bipolar technology, under the solar flares against the long-term low dose-rate radiation background. The main objective of this report is to improve knowledge of space radiation variability impact on the circuit radiation response via considering approaches for degradation prediction modelling.

2. Rate equation approach in modelling
The radiation-induced defect build-up in the insulation layers and at the Si-SiO$_2$ interfaces is the common cause of parameter degradation in bipolar and CMOS technology components. The time-dependent thermal annealing of these defects has found to be a general effect, and the devices of all technologies to some degree are prone to it, although the annealing parameters (activation energies and the time constants) vary for different technologies, and even for different lots of devices.

The rate equation of the criterion parameter change can be written in the linear response approximation as:
\[ \frac{d\Delta \Pi(t)}{dt} = A\eta_{\text{eff}} \left[ P(t), T_{\text{irr}}(T), E_{\text{ox}}(t) \right] P(t) - \frac{\Delta \Pi(t)}{\tau_{\text{a}}[T_{\text{irr}}(t)]} \]  

(1)

where \( A \) is a technology and lot dependent normalized factor, \( \eta_{\text{eff}} \) is the effective charge yield function, generally dependent on the electric field in the oxides \( E_{\text{ox}} \), irradiation temperature \( T_{\text{irr}} \), and a dose rate \( P \). However, radiation-induced modification of electrical fields, which is considerable at high (~Mrad) doses, was described elsewhere [4]. The simultaneous thermal annealing model is elaborated in [5] in different cases of one or few types of defects and corresponding amount of temporal annealing constants.

Equation (1) has a general solution for arbitrary profile of dose rate \( P(t) \):

\[ \Delta \Pi(t) = A \int_0^t \eta_{\text{eff}} \left[ P(t'), T_{\text{irr}}(t'), E_{\text{ox}}(t') \right] e^{-t/t_{\text{a}}[T_{\text{irr}}(t)']} P(t') dt' \]

(2)

This solution expressly shows that the radiation degradation may be represented as a functional (a convolution) of the previous dose-rate, electric and thermal history of the object exposed. This means that parameters degraded under irradiation are affected by any non-stationary variation in dose-rate environments, thermal and electric conditions via transient effects.

3. Space Dose Rate Variations And Time-dependent effects

3.1. ELDRS problem

An increase in charge yield (\( \eta_{\text{eff}} \)) with decreasing dose rate in the bipolar transistors and ICs is known as the ELDRS effect [6]. The explicit form of this relation was found in [5,6]. According to [5], the increased \( \eta_{\text{eff}} \) at low dose rate is possible due to a decrease in electron-hole recombination (Langevin mechanism) through steady-state and dose-rate dependent density of localized holes. This recombination is not observed in the gate oxides of the MOSFETs due to suppression by strong electric fields in the insulating oxides. However, considering ELDRS as a property of thick layers of an amorphous insulator with low electric fields, it may be observed in the thick oxides of p-MOSFET based dosimeters [7].

One should note that even large-scaled dose-rate temporal fluctuations in the cosmic range of \( 10^{-6}-10^{-3} \) rad/s do not change the charge yield significantly. The charge yield evaluates the magnitudes near the maximum at a given temperature and electric field in the oxide. This means that ELDRS effect is a problem of the ground test adequacy (choice of fitting \( P(t) \) for irradiation), rather than a problem of space radiation environment.

3.2. Thermal anneal effects

In bipolar circuits, elevation of irradiation temperatures to a moderate amount (up to 100 °C) results in enhancement of degradation due to increase in charge yield \( \eta_{\text{eff}} \) [5]. This is true for short-term exposure, when the time-dependent anneal did not have time to become noticeable. However, under the long-term irradiation, the degradation is limited by simultaneous anneal effects for all types of devices. Result of competition between enhancement of the charge yield and the simultaneous thermal annealing appear to show the remarkable degradation maximum as a function of irradiation temperature in bipolar transistors [8]. Thereby a noticeable reduction in the conservatism of the hardness assessment may be achieved by taking into account the thermal annealing during the prediction procedure.

Particularly, the simultaneous thermal annealing shows the time-dependent phenomena of the accumulated degradation relaxation after the dose-rate peaks. As an example, Fig. 1 shows the simulation results for the bipolar IC degradation calculated for the actual dose-rate profile derived from the various satellite data.
It is also important to notice that elevated operation temperatures may result in occurrence of quasi-steady-state saturation of degradation due to dynamic compensation of the radiation-induced buildup and the simultaneous annealing processes. Particularly, the level of degradation saturation generally depends on dose rate, irradiation temperature and electric mode, implying that non-stationary and non-monotonic effects could be observed after variation in conditions. Quasi-steady-state saturation in degradation may also point out at sensitivity to operation temperature variations. An example of anti-correlation between operating temperature and RADFET readings was demonstrated in [9].

4. Conclusion
For estimation of degradation space-borne devices using data obtained from ground testing, one should consider variability of the space environment. By modeling dose rate variations and time-annealing effects, it has been shown that the real degradation in onboard devices, is a functional of its radiation, electric and thermal history. Simultaneous anneal effect is also should be taken into account as it is shown to relatedevice operation temperature and degradation magnitude level.

Acknowledgements
This work was supported by the Competitiveness Program of NRNU MEPhI.

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Figure. 1: A common dose rate temporal profile on high circular orbit (left figure) and simulated degradation curve (right figure), calculated in arbitrary units for different irradiation temperatures. Temporal annealing constants used in simulation were obtained in [6] based on experimental data at different operation temperatures. Dashed lines show simulation result for average dose rate values.