The Fitting Parameters Extraction of Conversion Model of the Low Dose Rate Effect in Bipolar Devices

Alexander BAKERENKOV

National Research Nuclear University (MEPhI), Moscow, Russia

as_bakerenkov@list.ru

***Abstract* - The Enhanced Low Dose Rate Sensitivity (ELDRS) in bipolar devices consists of in base current degradation of NPN and PNP transistors increase as the dose rate is decreased [1]. As a result of almost 20-year studying, the some physical models of effect are developed, being described in [2] in detail. Accelerated test methods, based on these models use in standards [3, 4]. In [5] the conversion model of the effect, that allows to describe the inverse S-shaped excess base current dependence versus dose rate, was proposed. This paper presents the problem of conversion model's fitting parameters extraction.**

Index Terms – **Enhanced Low Dose Rate Sensitivity, ELDRS. bipolar devices, hardness assurance.**

I. THE CONVERSION MODEL OF LOW DOSE RATE EFFECT

The conversion model is based on the assumption that the positive charge accumulated by ionizing radiation is converted to interface traps. The shallow and deep positive charge traps are supposed to exist. During short period of high dose rate irradiation only shallow traps are converted. An additional conversion of deep traps occurs during long period of low dose rate irradiation. This leads to increase of base current degradation. Conversion process operates like a pump, pumping radiation induced trapped holes charge into interface traps continuously. Mathematically base current degradation dependence versus dose rate is described by the following expression:

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

where ΔI_B is excess current, K_D is excess base current per unit absorbed dose at low dose rate, K_S is excess base current per unit dose at high dose rate, D is total absorbed dose, γ is a dose rate, τ_D is deep traps conversion time.

Relationship (1) has an inverse S-shaped form (fig. 1). During high dose rate irradiation shallow oxide traps have time to be converted into interface traps only, because of small time of irradiation. Therefore, excess base current is determined by accumulation and conversion of shallow traps at high dose rates. At such conditions the value of excess base current is $K_S D$.

Since some values of dose rate (mean times of irradiation) the base current degradation starts to increase. This is associated with the deep trap conversion with increase of irradiation time the density of interface traps increases due to additional conversion of deep traps. Transition time interval is about $\left(3\div 5\right)\tau_D$. The range of dose rates, where excess base current degradation increases is $\left(10^{-2}\div 1\right)D/\tau_D$.

At very low dose rates or in other words at very large irradiation time, all deep traps have time to be converted, so base current degradation reaches some constant value again. This increase in base current degradation is greater than that for high dose rate by the value of $K_D D$. The total excess base current at very low dose rate is determined by total contribution of shallow and deep traps conversion.

Thus the conversion model has three fitting constants: K_S, K_D and τ_D. Knowledge of these constants allows to evaluate full inverse S-shaped characteristic and to predict the base current degradation for any dose rate at given total absorbed dose.

II. HIGH TEMPERATURE POST-IRRADIATION ANNEAL

The dependence of excess base current versus time at the stages of irradiation and 40ºC, 60ºC, 100ºC post- irradiation anneal is presented in . 2.

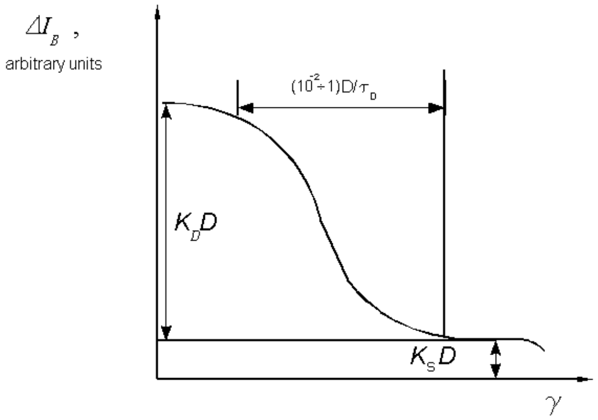

Fig.1. Schematic representation of the dependence of the excess base current versus dose rate.

These dependences are typical for investigated NPN and

PNP discrete transistors and input transistors of operational amplifiers. The surface recombination component of the base current depends on interface states density N_{it} at the SiO_2/Si interface, positive charge in oxide Q_{ot} and interface traps charge Q_{it} at forward bias of emitter junction. Energy diagram of the SiO_2/Si interface is presented in fig. 3, where neutral interface states N_{it}, positive oxide charge Q_{ot} and interface traps charge Q_{it} (formed due to capture of carriers injected into base by interface traps) are designated. It is supposed that interface states located above middle of forbidden gap are acceptor like, i.e. they are negatively charged (Q_{it}<0), being located below quasi-Fermi level for electrons $E_{Fn,}$ (fig.3, a). Interface states located below the middle of forbidden gap donor like, therefore they are charged positively (Q_{it}>0) if they are free, being located above quasi-Fermi level for holes E_{Fp}, (fig. 3, b). Effective charge at the interface is $Q_{eff} = Q_{ot} + Q_{it}$.

The surface recombination current of NPN transistor is directly-proportional to interface states density and increases with the increase of effective interface positive charge (positive charge attracts the injected electrons, that leads to a recombination loss increase).

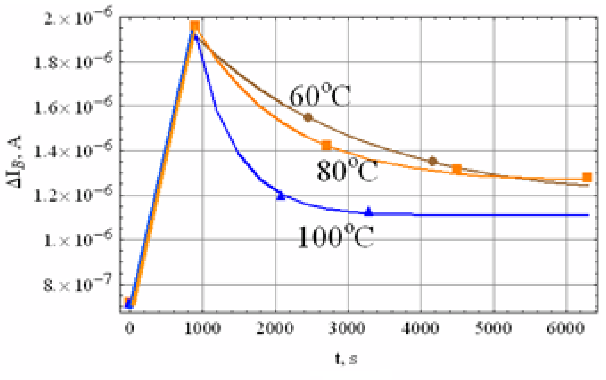

Fig.2. Excess base current versus time (0-1000s – irradiation; more 1000s – annealing) for SWB99 PNP transistor.

Therefore a decrease of the base current on the stage of post-irradiation anneal may be associated with decrease of Q_{ot} or increase of Q_{it}, because $Q_{eff} = Q_{ot} - Q_{it}$ in NPN transistors. At elevated temperature stress charge Q_{ot} is annealed and charge Q_{it} may grow due to conversion of the annealed charge. In case of PNP transistor surface recombination current is also proportional to interface states density, but it decreases if the interface effective charge increase (positive charge repulse injected holes away from the surface, that leads to a recombination loss decrease). Base current decrease during post-irradiation anneal in that case may be associated with increase of interface states charge Q_{it} only (in effective charge $Q_{eff} = Q_{ot} + Q_{it}$ component Q_{ot} decreases, but component Q_{it} increases). In both cases the increase of interface states density plays a secondary role, not leading to surface recombination current increase.

The general feature of NPN and PNP transistors is that base current decrease at elevated temperature post-irradiation anneal is associated with the annealing of trapped positive charge. Therefore an investigation of base current behavior during post-irradiation anneal allows to estimate activation energy of this process and to measure deep traps conversion time τ_D (shallow ones are annealed during the irradiation).

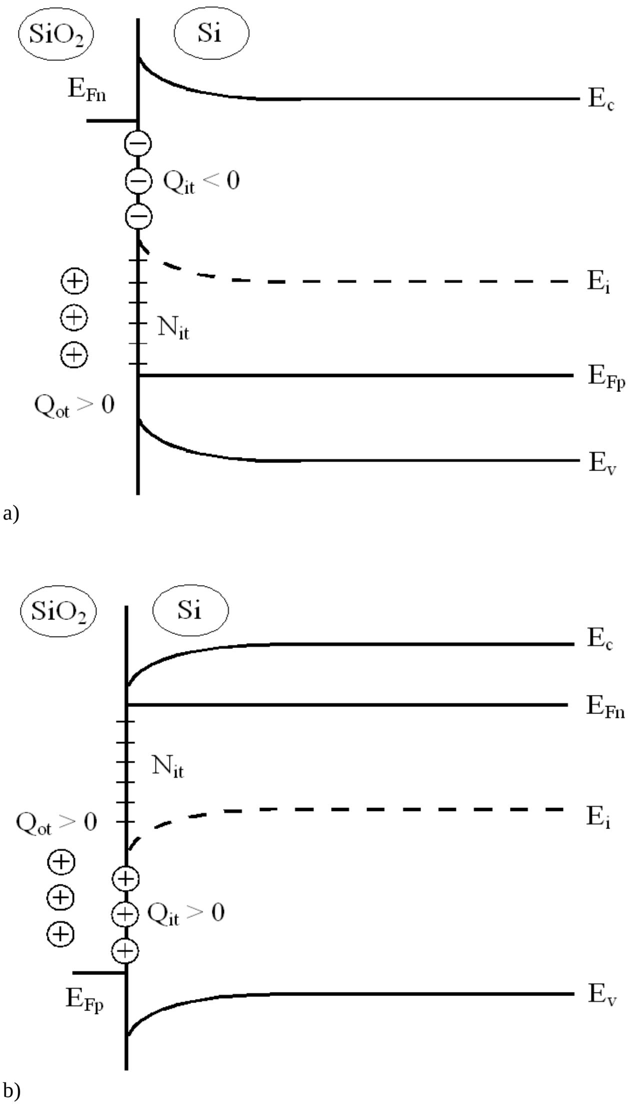

Fig.3. Energy diagram SiO_2/Si interface on forward bias emitter junction.

The annealing time constant is described the Arrhenius law

$$\tau_D = \tau_{D0} Exp\left(\frac{W_A}{kT}\right), \quad (2)$$

where τ_{D0} is a pre-exponential constant, W_A is an activation energy of deep traps anneal.

Pre-exponential constant τ_{D0} and activation energy W_A in (2) are derived from the data for two different temperatures of elevated temperature post-irradiation anneal.

Only insignificant part of radiation induced trapped positive charge is annealed during elevated temperature post-irradiation anneal following high dose rate irradiation (fig.2). This may be associated with the absence of photoelectrons on the post-irradiation phase or space charge effect on at high dose rate irradiation (more detail in full version of paper). The small part annealed charge leads to impossibility to estimate a total value of deep trapped oxide charge and extract the constant $K_{D.}$ For extraction of K_D we need some conditions, when deep trapped charge participates in the process of annealing. For that we suppose to use elevated temperature irradiation, when the annealing of all accumulated charge occurs.

III. ELEVATED TEMPERATURE IRRADIATION

High temperature irradiation leads to significant increase of base current degradation and it is used for accelerated tests on ELDRS [3, 4]. The contributions of deep traps charge to base current degradation is estimated in this work rely on the results of irradiation at several different temperatures.

Temperature elevation leads to a shift of the inverse S-shaped curve to the direction of greater dose rates as illustrated on fig. 4.

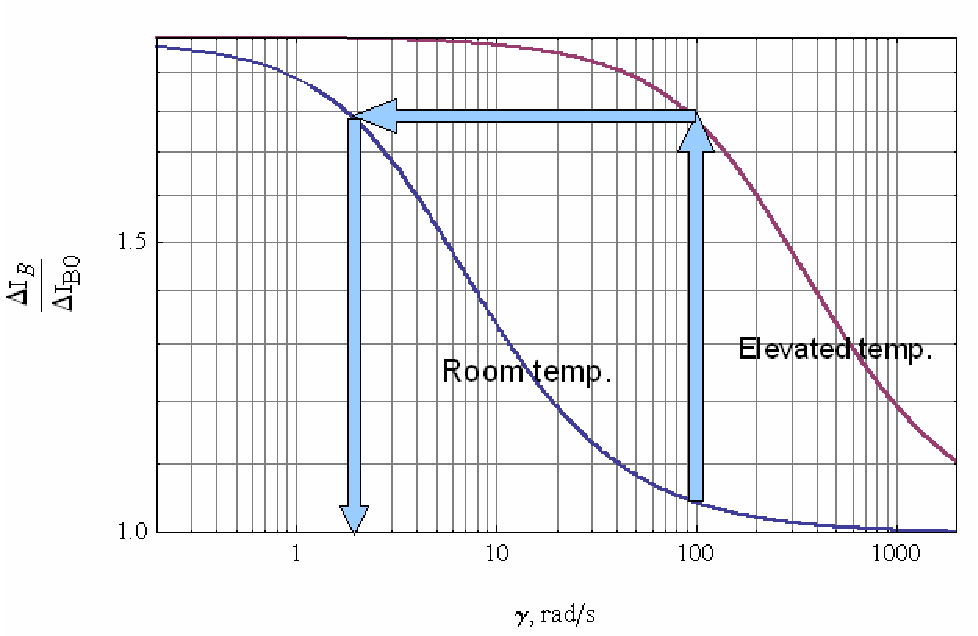

Fig. 4. Inverse S-shaped curve of a device for room and elevated temperature.

It is clear from fig. 4, that irradiation temperature elevation is equal to the dose rate decrease. Thus if we want to model low dose rate irradiation we have to irradiate a device at certain elevated temperature. Knowing τ_{D0} and W_A we can calculate this temperature. In turn we can derive the values of τ_{D0} and W_A from the annealing at different temperatures.

IV. FITTING PARAMETER EXTRACTION TECHNIQUE

Fitting constants extraction was performed by the following way:

1. Constant KS determining the contribution of shallow trapped charge conversion to base current degradation is estimated as a ratio of base current degradation to the specified absorbed dose at 400 rad(SiO2)/s irradiation.
2. The deep traps conversion time or constant τD is estimated from data of post-irradiation anneal following high dose rate irradiation to the specified absorbed dose. Pre-exponential constant τD0 and activation energy WA in (2) 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.

It is desirable that this irradiation temperature corresponds to the maximum base current degradation at elevated temperature irradiation.

Constant K_D is derived from (1), where the constant τ_D for using elevated temperature is calculated from (2) (values of τ_{D0} and activation energy W_A are determined on stage 2).

V. CONCLUSION

The technique for extraction fit parameters of ELDRS conversion model in bipolar transistors was proposed. Presents of dip and shallow positive charge traps in silicon dioxide is assumed. ELDRS is explained by conversion of dip traps. Extraction technique is based on employment elevated temperature post-irradiation annealing for determination of dip traps conversion time constant. Parameter relevant with deep traps concentration obtains from elevated temperature irradiation experiment. Description of ELDRS S-spare characteristic is the result of fit parameters extraction. It provides way to prediction radiation-inducted base current degradation at dose rate that actual in space environment.

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