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Modeling Low-Dose-Rate Effects in Irradiated Bipolar-Base Oxides

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R.J. Graves[1], C.R. Cirba[1], R.D. Schrimpf[1], R.J. Milanowski[1], A. Michez[2],
D.M. Fleetwood[3], S.C. Witczak[4], and F. Saigne[1]

[1]Vanderbilt University, ECE Department, Nashville, TN 37235-1683 USA
[2]CEM2 Universite Montpellier II, 34095 Montpellier Cedex 5, FRANCE
[3]Sandia National Laboratories, Albuquerque, NM 87185-1083 USA
[4]The Aerospace Corporation, Los Angeles, CA 90009-9257 USA

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ABSTRACT

A physical model is developed to quantify the contribution of oxide-trapped charge to enhanced low-dose-rate gain degradation in BJTs. Simulations show that space charge limited transport is partially responsible for the low-dose-rate enhancement.

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DISCLAIMER

I. INTRODUCTION

In 1991, Enlow, *et al.* first reported enhanced low-dose-rate current gain degradation ($\beta = I_C / I_B$) for some types of advanced NPN bipolar junction transistors (BJTs) exposed to ionizing radiation [1]. Dose rate dependence has since been studied for several bipolar technologies, using individual devices [2-8] and integrated circuits [9,10]. Physical models have been proposed for enhanced current gain degradation at low dose rates for both NPN [6] and PNP [5] transistors. These models have been verified and extended, using charge separation methods [11] coupled with MOS capacitor test results [12,13], to show that the low-dose-rate base current gain degradation in advanced bipolar devices is sensitive to the quality of the relatively thick, ion-implanted, thermally grown emitter-base screen oxide.

Gain degradation in irradiated BJTs is caused by the interactive effects of oxide-trapped charge (N_{OX}), interface-trapped charge (N_{it}), and surface recombination velocity. In this work we develop a quantitative model for dose-rate-dependent charge transport and hole trapping in irradiated bipolar-base oxides, based on the studies of Fleetwood, *et al.* [12,13]. We show that in the low dose rate case, more holes are trapped near the Si-SiO_2 interface, compared to the high dose rate case, resulting in a larger midgap voltage shift (ΔV_{mg}) for low dose rate. We believe that this is the first physically-based oxide simulation model which has produced low-dose-rate sensitivity for trapped charge in a bipolar-type oxide. Using a multiple-trapping-detrapping (MTD) simulator [14,15], we model the oxide, in one dimension, as a wide-bandgap semiconductor with an abrupt heterojunction at the Si-SiO_2 interface, and multiple energy level trap sites at each oxide node in the simulation mesh. Previous MTD models yield good agreement with experimental results [16,17] and with the generally accepted stochastic polaron-hopping model [18]. This simulator also accounts for electric-field-dependent electron-hole-pair recombination. Electron tunneling at the Si-SiO_2 interface is not currently modeled.

Current Gain Degradation in BJTs

NPN devices exposed to ionizing radiation exhibit an increase in base current, and relatively constant collector current. Excess base current (ΔI_B), defined as $\Delta I_B = I_B - I_{B0}$ where I_{B0} is the pre-irradiation base current, results from increased recombination in the emitter-base depletion region. Experimental and simulated plots of ΔI_B vs. N_{OX} are shown in Figure 1, for an advanced-process NPN device. Note the strong dependence, $\sim \exp(N_{OX}^2)$, for lower values of oxide-trapped charge, and the saturation at higher values, after a critical transition value of N_{OX}. Comparison of irradiated poly-emitter NPN BJTs and MOS capacitors with similar oxides shows that N_{OX} is responsible for most of the current gain degradation in these devices [6]. In lateral PNP transistors, N_{OX} also plays an important role, with the effects depending strongly on the details of device design [8]. Lateral PNP transistors are most sensitive to interface-trap formation, which increases the surface recombination velocity in the base at low total doses. In this work, we focus on the effects of dose rate on the buildup of oxide-trapped charge.

II. SIMULATION RESULTS

The physical mechanisms included in the model are *charge trapping*, *emission*, *compensation*, and *transport*. Holes are *trapped* at two discrete energy levels in the oxide: (1) shallow traps are distributed uniformly throughout the oxide to simulate retarded hole transport in the bulk; and (2) deep traps are distributed spatially as a gaussian function, peaked at the Si-SiO_2 interface. The distributions of free and shallow-trapped carriers modify carrier transport, due to field and potential barrier changes during irradiation, and the deep-trapped holes are still present after irradiation, leading to a change in the midgap voltage. Figure 2 is a plot of simulated ΔV_{mg} vs. dose rate, showing a larger shift for low dose rate, 0V bias, room temperature irradiation. Hole trapping and emission are modeled with constant capture cross-sections, and the trapping is proportional to the instantaneous current. Carrier *emission* occurs with a characteristic lifetime τ, which is an exponential function of activation energy and the attempt-to-escape frequency. *Compensation* is modeled as electron trapping at a site already occupied by a trapped hole, forming a dipole [12,13]. Carrier *transport* is modeled by drift-diffusion equations, mediated by trapping and detrapping at the shallow trap sites.

Deep-Trapped Hole Density

A key result for understanding the dose rate sensitivity of BJT current gain degradation is the simulated density of holes in deep traps (p_{td}) shown in Figure 3. The simulated device structure is an MOS capacitor with a p-type substrate and a 600 nm oxide. Note that at the Si-SiO$_2$ interface, the low-dose-rate trapped hole density is ~ 14% greater than at high dose rate. For NPN devices operating at low total doses in the superlinear region of Figure 1, where $\Delta I_B \sim \exp(N_{OX}^2)$, a 14% increase in N_{OX} can cause a 35% increase in ΔI_B. The simulation results of Figure 3 are in agreement with the trends of Figure 1, that low dose rates can give larger excess base currents, due to larger trapped oxide charge densities near the Si-SiO$_2$ interface, which deplete the surface and increase Shockley-Read-Hall recombination [5,6]. The origin of the dose-rate dependence of N_{OX} will be discussed next.

Dose-Rate Dependence of N_{ox}

Figure 4 shows the simulated electric field in the oxide during irradiation for ~ 200 krad exposure at both high and low dose rates. For the low dose rate (1 rad/s) case, the field is constant and positive throughout the oxide, so generated holes tend to move toward the Si-SiO$_2$ interface. Both cases show perturbation of the field near the interface due to the net positive charge (N_{OX}) trapped there. For the high dose rate case (500 rad/s), note the point of electric field reversal near the midpoint of the oxide, confirming the models for space charge limited transport in previous work [12,13]. This situation is illustrated schematically in Figure 5, for an oxide with a uniform positive charge distribution. The electric field dependence on dose rate comes directly from Poisson's Equation. At high dose rates, there is a large density of transporting holes in the oxide. This increases the slope of the internal electric field, causing field reversal for high charge densities. Figure 6 shows the potential in the oxide.

After an initial transient time, the density of transporting holes in shallow traps dominates the field and current characteristics in the oxide bulk. The deep-trapped hole density in the oxide is quite small, except for the 100 nm region near the interface, as shown in Figure 3.

Electron Compensation

Once a hole is trapped at a deep site, it may be compensated by a trapped electron, rather than recombining. Previous studies [12,13] indicate that most deep-trapped holes are compensated in both low and high dose rate irradiations of bipolar-base oxides. This simulation accounts for electron compensation; however, the density of compensating electrons is negligible compared to the density of trapped holes. This result is likely due to uncertainties in physical parameters such as trap densities, distributions, and capture cross sections. We expect that for heavily process-damaged bipolar-base oxides, trap densities may be higher and differently distributed than the currently simulated values, the electric field dependence of capture cross sections may be significant, and electron tunneling may occur near the Si-SiO$_2$ interface.

Temperature and Bias Dependence

The consistency of the model was checked by simulating the temperature and bias dependence of ΔV_{mg} vs. dose rate. For irradiation at high dose rate and high temperature, the resulting ΔV_{mg} is the same as that obtained at low dose rates and room temperature. This is the result of a more rapid detrapping of holes from shallow traps. Application of 3V bias to the capacitor during irradiation is also sufficient to eliminate the dose-rate dependence of the charge transport. These results are consistent with experimental trends [13] which show that the enhanced low-dose-rate effect is maximum for low oxide fields.

III. CONCLUSIONS

Simulated irradiation of MOS capacitor structures with oxides similar to bipolar-base oxides shows a dose rate dependence of ΔV_{mg}, a measure of trapped oxide charge density. We show that in the low dose rate case, more holes are trapped near the Si-SiO$_2$ interface, compared to the high dose rate case, resulting in a larger midgap voltage shift for low dose rates. The additional oxide trapped charge near the interface causes an exponential increase in excess base current, and resultant decrease in current gain, for some advanced NPN bipolar technologies. Space charge effects due to transporting holes are likely to affect interface trap formation as well, if the mechanism is related to proton release and transport. We plan to show additional effects due to compensating electrons in the final paper.

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V. FIGURES

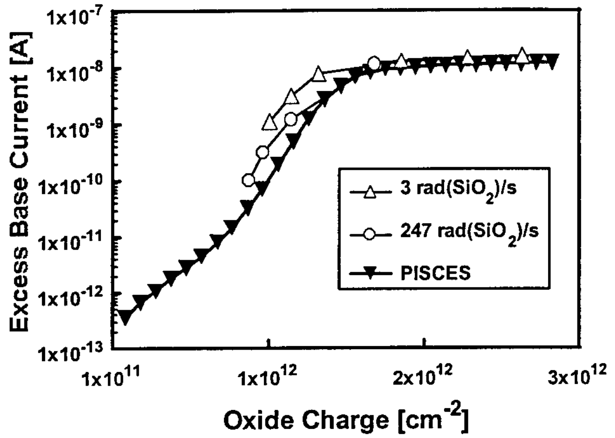

Figure 1. Experimental ΔI_B vs. net oxide charge density from charge separation and PISCES simulation. Data from NPN BJTs irradiated to 1 Mrad total dose at 0V bias, 300 K, $V_{BE} = 0.6V$. After [5].

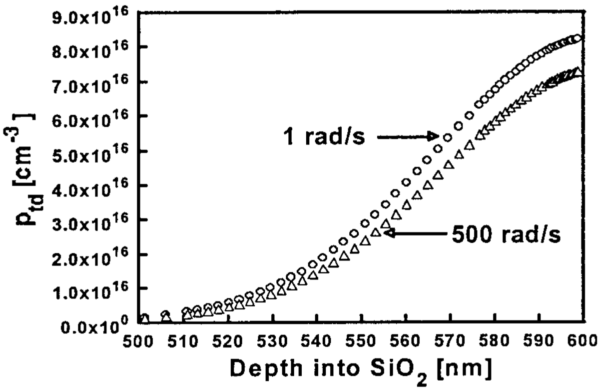

Figure 3. Density of holes in deep traps vs. oxide depth, near the Si-SiO$_2$ interface, at two dose rates. The electrode is at the origin, or 0 nm position, not shown. Simulated irradiation conditions are the same as in Figure 2.

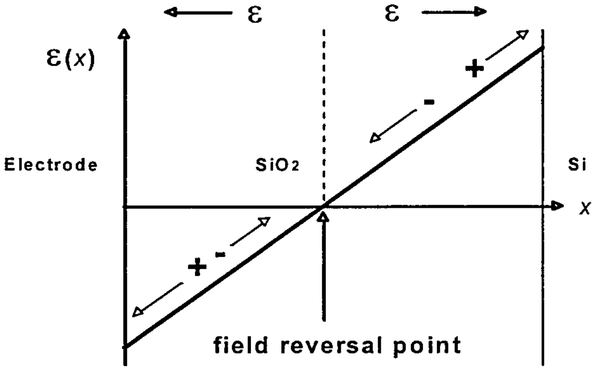

Figure 5. Schematic of the oxide electric field for a uniform distribution of holes in the space charge limited transport condition. Field directions, reversal point, and carrier drift transport directions are shown. After [12,13].

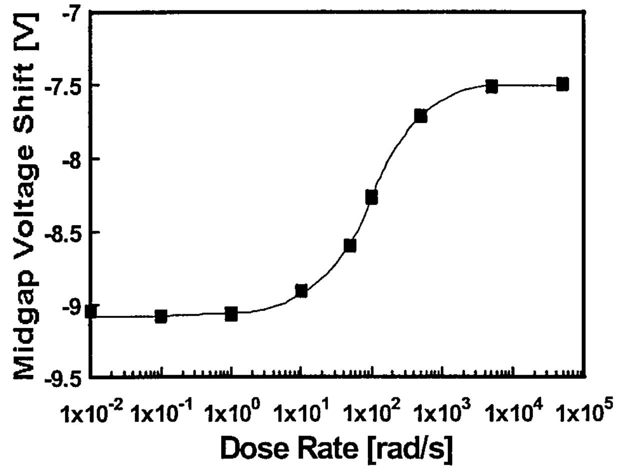

Figure 2. Simulated ΔV_{mg} vs. dose rate for 600 nm oxide in MOS capacitor structure. Note the higher midgap voltage shift at lower dose rates. Irradiation to ~ 200 krad total dose at 0V bias, 300 K.

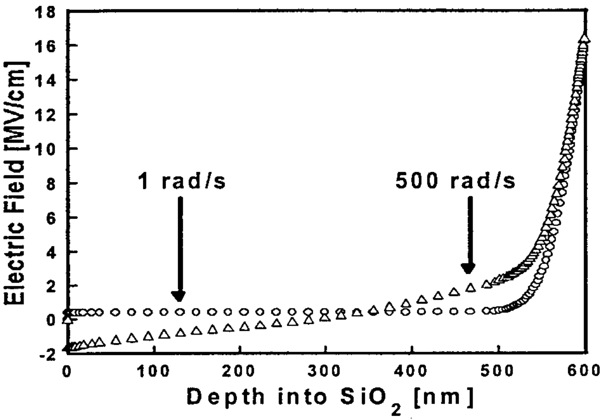

Figure 4. Electric field vs. depth into oxide, at two dose rates. The electrode is at the origin. Simulated irradiation conditions are the same as in Figure 2.

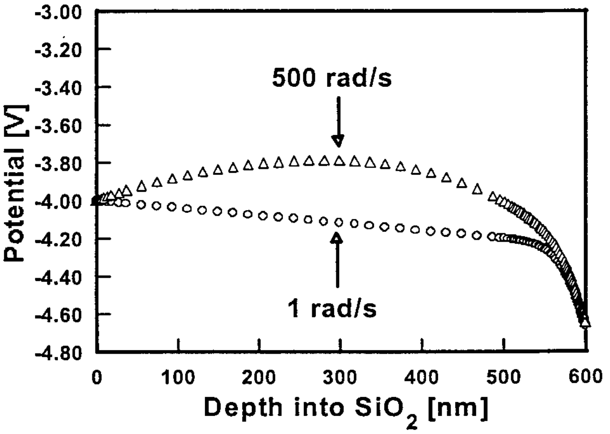

Figure 6. Simulated potential vs. depth into oxide, at two dose rates. Simulated irradiation conditions are the same as in Figure 2.

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