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Bounding the Total-Dose Response of Modern Bipolar Transistors^{††}

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Abstract

The base current in modern bipolar transistors saturates at large total doses once a critical oxide charge is reached. The saturated value of base current is dose-rate independent. Testing implications are discussed.

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I. INTRODUCTION

The response of modern bipolar transistors to ionizing radiation has received recent attention in the literature [1 – 6]. However, predicting the response of these devices in space radiation environments is currently not possible with laboratory dose-rate irradiations [3]. Testing techniques for predicting the low-dose-rate response of MOS devices are not applicable to bipolar devices [3] due to the fundamentally different physics that determine bipolar device gain degradation [1]. Indeed, high temperature annealing following irradiation actually improves the characteristics of the bipolar device [3], in contrast to the enhanced degradation for MOS devices, which exhibit threshold-voltage rebound [7].

The increase in base current of modern bipolar devices at low total doses is dose-rate dependent [3, 6], with lower dose rates causing more device degradation than higher dose rates. Testing at extremely low dose rates is unattractive, however, due to the large amount of time required to obtain reasonable total doses. If, however, the worst-case increase in base current can be ascertained from laboratory irradiations, it would be possible for system designers to ensure bipolar circuit total-dose reliability in space or other low-dose-rate applications.

In this paper we demonstrate that positive oxide charge is the primary factor determining the worst-case response in modern bipolar devices, in contrast to earlier modeling efforts [8]. In addition, the maximum degradation that may occur in the device is independent of dose rate. Thus, although it may take different amounts of total ionizing dose to reach the necessary amount of oxide charge to cause the worst-case increase in base current, the maximum current that can flow once this condition is met is *independent* of dose rate. Based on these observations, implications for hardness assurance and testing of modern bipolar devices are discussed.

II. EXPERIMENTAL DETAILS

A representative cross-section of devices from technology A is shown in figure 1. These devices are polysilicon emitter NPN bipolar transistors from a complementary bipolar process described in [9]. Technology B is a re-

Figure 1. Representative cross-section of devices from technology A.

Table 1. Relevant device parameters.

Quantity	Technology A	Technology B	Technology C
Emitter Type	polysilicon	polysilicon	silicon
Emitter Size	1.5 x 1.5 μm	1.5 x 1.5 μm	1.5 x 1.5 μm
Int. Base Surf. Doping	$9 \times 10^{17} \text{ cm}^{-3}$	$7.8 \times 10^{17} \text{ cm}^{-3}$	$1 \times 10^{18} \text{ cm}^{-3}$
Active Base Width	0.8 μm	0.8 μm	0.8 μm
Int. Base Length	1.5 μm	1 μm	1.5 μm
Oxide Thickness	545 nm	55 nm	545 nm
Nominal Current Gain	70 A/A	200 A/A	40 A/A

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lated BiCMOS process, and technology C is a standard emitter process that is very similar to technology A, except for the emitter type. Relevant device parameters for all technologies are summarized in table 1. The devices were irradiated in a Pb/Al box with a Co-60 source at various dose rates with all pins grounded.

III. EXPERIMENTAL RESULTS

The excess base current at a base-emitter voltage, V_{BE} , of 0.6 V is plotted in figure 2 versus total ionizing dose for technologies A, B, and C. The excess base current is defined as $\Delta I_B = I_B - I_{B,pre-rad}$. For all technologies, the excess base current increases exponentially with total dose for low total doses, but tends to saturate for very large total doses. Note that the value of excess base current at saturation is different for technologies A and B. Also note that although technology C exhibits much more excess base current at low total doses than either technology A or B, the currents merge at high total doses. Finally, although the dose rates for the different technologies are slightly different, there is no dose-rate effect buried in figure 2, as discussed below.

In figure 3, ΔI_B at $V_{BE} = 0.6$ V is plotted versus total dose for several dose rates for devices from technology A. For low total doses, the degradation is most severe at the lowest dose rates, as reported in [3]. This difference has recently been linked to the difference in oxide charge buildup as a function of dose rate [6]. Note that there is little dose-rate effect at low total doses for dose rates larger than approximately 100 rad(SiO₂)/s, as reported in [3]. For high total doses, the excess base current saturates at a value that is independent of dose rate. This fact allows high dose rates to be used to obtain the worst-case excess base current.

Figure 2. Excess base current at $V_{BE} = 0.6$ V versus total dose for technologies A, B, and C.

Figure 3. Excess base current at $V_{BE} = 0.6$ V versus total dose for technology A at three different dose rates.

IV. MODELING

In figure 4, PISCES-simulated [10] ΔI_B at $V_{BE} = 0.6$ is plotted versus net positive oxide charge, N_{ox} for technologies A and B. The excess base current increases exponentially for small values of N_{ox} , but saturates at a particular value of N_{ox} , $N_{ox}(transition)$. Physically, when $N_{ox} > N_{ox}(transition)$, the recombination current flows primarily below the oxide-silicon interface [1]. When this occurs, the current is insensitive to additional surface damage [6]. The excess base current may be written in this case as $\Delta I_B(subsurface)$, given by

$$\Delta I_B(subsurface) = \frac{q n_i}{2 \tau} \Delta x A_{IB} \exp \left[\frac{\beta V_{BE}}{2} \right]. \quad (1)$$

In this expression, n_i is the intrinsic carrier concentration, q is the magnitude of the electronic charge, $\beta = q/kT$ is the inverse thermal voltage, Δx is the effective recombination width, A_{IB} is the surface area of the intrinsic base, and τ is the bulk minority-carrier lifetime. An estimate for Δx is the depletion-layer width induced by the positive oxide charge in the depletion approximation, $\Delta x < N_{ox}/N_s$.

Equation (1) indicates that $\Delta I_B(subsurface)$ is proportional to the intrinsic base area, as shown in [1] and inversely proportional to the recombination lifetime. Recall from figure 2 that technology A had a higher value of saturation excess base current than technology B. This trend is reproduced in the PISCES simulations in figure 4. The difference is explained by noting that the intrinsic base area for technology A is larger than technology B, and the intrinsic base is more heavily doped at the surface, which leads to a shorter recombination lifetime. These effects combine to produce a larger $\Delta I_B(subsurface)$ in

Figure 4. PISCES-simulated excess base current at $V_{BE} = 0.6$ V versus positive oxide charge for technologies A and B.

technology A than technology B.

Technology C exhibits much larger excess base current at low total doses than either technologies A and B, which is attributable to differences in the charge trapping properties of the oxide in this technology. Evidently, technology C accumulates positive charge more rapidly than either technology A or B. Since technology C has the same intrinsic base area as technology A and similar intrinsic base surface doping, it is not surprising that the excess base currents for technologies A and C merge at high total doses.

The dose-rate independence of $\Delta I_B(\text{subsurface})$ evident from figure 2 is also easily understood from figure 4. Although the total dose required to exceed $N_{ox}(\text{transition})$ depends upon dose rate, $\Delta I_B(\text{subsurface})$ is only a weak function of N_{ox} beyond $N_{ox}(\text{transition})$. Thus, although $\Delta I_B(\text{subsurface})$ is reached at lower total doses for low dose-rate irradiations, eventually the devices irradiated at higher dose rates accumulate enough N_{ox} to reach $\Delta I_B(\text{subsurface})$ as well.

In the full paper, we will examine the bias dependence of the worst-case base current, with the expectation that the worst-case base current is independent of bias as well as dose rate. In addition, our model for worst-case base current will be compared to the model presented in [8], which overestimates the excess base current by more than an order of magnitude for typical device geometries.

V. CONCLUSIONS

From the previous discussion and figure 3, it is evident that the rate at which the charge builds up does not affect the worst-case excess base current. This implies that any

convenient laboratory dose rate may be used to obtain the worst-case response of the device, as long as a high enough total dose is used to observe a saturation in ΔI_B . It should be noted that at the high total doses required to observe saturation in ΔI_B , failure modes other than gain degradation of the transistors may limit circuit performance. This fact does not affect the worst-case nature of the method proposed above, however.

When the worst-case excess base current flows in a modern bipolar transistor, the current gain is still sufficient for many digital circuit applications [11, 12]. The results presented above indicate a fast, reliable means to qualify bipolar devices in digital circuits for space applications.

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