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Effects of Oxide Charge and Surface Recombination Velocity on the Excess Base Current of BJTs

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Abstract

The role of net positive oxide trapped charge and surface recombination velocity on excess base current in BJTs is identified. The effects of the two types of damage can be detected by plotting the excess base current versus base-emitter voltage. Differences and similarities between ionizing-radiation-induced and hot electron-induced degradation are discussed.

I. Introduction

The current gain I_C/I_B of bipolar transistors is degraded when the oxide over the emitter-base junction is damaged. This can occur when the emitter-base junction is reverse-biased [1], as it is in normal BiCMOS circuit operation [2], or when the device is exposed to ionizing radiation [3 - 5]. The damage typically leads to excess base current in the device, ΔI_B , and no change in the collector current. Until now, authors have assumed that ΔI_B is caused primarily by interface states created during the stress [6 - 9]. The effects of net trapped positive charge, N_{ox} , have not been considered. Thus, the effects of N_{ox} on the current gain of the device have not been identified.

In this work, the separate effects of N_{ox} and surface recombination centers on the current gain of BJTs are identified. It is shown that ionizing radiation causes a large increase in net positive oxide charge and a relatively small increase in surface recombination velocity. Hot electron stressing, on the other hand, causes a relatively small increase in net positive oxide charge and a large increase in surface recombination velocity. Since the current gain depends on the product of the two stress-induced defects, both types of stress can lead to qualitatively similar changes in the current gain of the device.

II. Experimental Details

The devices studied in this work are oxide-isolated polysilicon emitter bipolar transistors fabricated in a complementary bipolar process closely related to that described in ref. [10]. A representative cross-section of the devices is shown in figure 1. Relevant structural information is summarized in table 1. For the irradiation study, the devices were irradiated with 10 keV x-rays at a dose rate of 1.7 krad(SiO₂)/s up to a total dose of 1

Figure 1. Representative cross-section of the devices studied in this work.

Table 1. Values of relevant device parameters.

Device Parameter	Value	Units
Emitter-Base Junction Depth	0.3	μm
Intrinsic Base Surface Doping	7.5×10^{17}	cm^{-3}
Oxide Thickness	550	$\text{\AA}$
Emitter Size	3 x 3	μm
Nominal Current Gain	200	A/A

Mrad(SiO₂). All pins were grounded during irradiation. For the hot electron stress, a constant reverse current of 6 mA was applied through the emitter-base junction of unirradiated devices for a total of 2048 seconds. A Hewlett-Packard 4145B Semiconductor Parameter Analyzer was used for device characterization.

III. Analysis

The common-emitter current gain, I_C/I_B , is plotted versus base-emitter voltage, V_{BE} , in figure 2 for increasing values of stress. Figure 2a shows the current gain for increasing values of total ionizing dose, while figure 2b shows the current gain for increasing values of hot electron stress time. The current gain degrades substantially for both types of stress, and the degradation is most severe at lower values of V_{BE} . Note that the current gain degradation tends to saturate for large values of total ionizing dose, but shows no tendency to saturate for the stress times shown here. The trend, however, is qualitatively similar

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Figure 2. Common emitter current gain for increasing stress levels. a) Increasing total ionizing dose (units are rad(SiO₂)). b) Increasing hot electron stress time.

for both types of stress.

The collector current remains approximately constant throughout both radiation and hot electron stressing. The current gain degrades because the base current increases. The base current is written as $I_B = I_{B,pre} + \Delta I_B$, where the excess base current, ΔI_B , is recombination current in the emitter-base depletion region. The recombination current can be obtained analytically from Shockley-Read-Hall (SRH) recombination theory [11, 12]. Assuming equal electron and hole capture cross-sections, a single trap level at midgap, and moderate forward bias, ΔI_B can be written as

$$\Delta I_B = \alpha v_{surf} \exp\left[\frac{\beta V_{BE}}{2}\right] \gamma(N_{ox}, V_{BE}) \quad (1)$$

where $\beta = q/kT$ is the inverse thermal voltage, and v_{surf} , α , and γ are given by

$$v_{surf} = \sigma v_{th} N_T \quad (2)$$

$$\alpha = \frac{1}{2} q n_i P_E \quad (3)$$

$$\gamma(N_{ox}, V_{BE}) = \int_0^{y_B} \frac{dy}{\cosh[\beta(\psi_s(y) - V_{BE}/2)]} + \frac{2\pi}{P_E} \int_0^{r_B} \frac{r dr}{\cosh[\beta(\psi_s(r) - V_{BE}/2)]} \quad (4)$$

In these expressions, v_{surf} is the surface recombination velocity, N_T is the trap density, σ is the effective capture cross-section, v_{th} is the thermal carrier velocity, q is the electronic charge, n_i is the intrinsic concentration, P_E is the perimeter of the emitter, y is the lateral position variable, $r_B = \sqrt{2} y_B$, and ψ_s is the surface potential.

The dependence of ΔI_B on surface recombination velocity is easily seen in equation (2): v_{surf} merely scales ΔI_B multiplica-

Figure 3. Surface potential (top) and surface recombination rate (bottom) versus lateral position, y , obtained from S-PISCES 2B simulations of the emitter-base junction. The metallurgical junction is at 1.16 μm . After reference [5].

tively. The effect of positive oxide charge is not so easily seen. The positive charge affects ΔI_B by increasing the value of the γ integral. This integral is seldom considered when analyzing recombination current, but it is crucial to take the contribution of this term into account in order to account for the effect of positive oxide charge. Positive charge raises the surface potential ψ_s in the base of the BJT. This increases the surface recombination rate throughout the base. In terms of the γ integral, the integrand becomes a less sharply peaked function as oxide charge increases [5]. These trends are illustrated in figure 3, where PISCES-simulated surface potential and surface recombination rate are plotted versus lateral position for a fixed forward voltage and varying amounts of positive oxide charge.

Recombination current in PN junctions varies as $\Delta I_B = \Delta I_{B0} \exp$

Figure 4. Excess base current versus base-emitter voltage for increasing values of total ionizing dose. The data correspond to those in figure 2a.

Figure 5. Oxide charge and surface recombination velocity versus total ionizing dose.

Figure 6. Excess base current versus base-emitter voltage for increasing values of hot electron stress time. The data correspond to those in figure 2b.

$[\beta V/n]$, where n , the ideality factor, depends upon oxide charge and forward voltage. The shape of the integrand in the γ integral is what determines the ideality factor in the diode equation. In [5] it is shown that the value of oxide charge can be determined by plotting the excess base current versus base emitter voltage, as in figure 4. Three transition voltages, V_{tr} , are also identified. The transition voltages mark the transition between predominantly surface and predominantly subsurface recombination. These transition voltages are readily related to oxide charge [5]. In figure 5, oxide charge calculated from the transition voltages is plotted versus total ionizing dose. Oxide-trapped charge, N_{OT} , measured from MOS capacitors and surface recombination velocity measured from gated diodes from the same process is also plotted for comparison. It is seen that degradation due to ionizing radiation is caused by increases in both positive oxide charge and surface recombination velocity, in contrast to hot-electron damage, which is dominated by increases in surface

Figure 7. Normalized peak current gain versus intercept current ΔI_{B0} (at $V_{be} = 0$) for radiation and hot electron stress.

recombination velocity.

In figure 6, ΔI_B is plotted versus V_{BE} for several values of increasing stress time. The ideality factor is roughly two for all stress times, and no transition voltage can be determined for any stress level. This indicates that the maximum recombination rate is at the surface for all values of forward voltage, and thus that the oxide charge remains small for all stress times. This is the assumption made by several authors, but until now, no direct evidence of this was available.

Additional evidence for the existence of distinctly different defects for each type of stress is shown in figure 7, where the normalized peak current gain is plotted versus ΔI_{B0} . If the magnitudes of the stress induced defects were the same for both types of stress, these curves would lie on top of one another. The difference is a result of the large amounts of positive oxide charge induced in the oxide by the radiation stress. The curves approach one another for large intercept currents because the ideality factors for both types of stress are approximately two.

IV. Summary and Conclusions

For hot electron stressing, the positive oxide charge remains small for all stress levels, indicating that the increase in base current is due primarily to increased surface recombination velocity. For radiation stressing, however, the increase in base current is due to both increased surface recombination velocity and increased positive oxide charge. The two types of stress lead to qualitatively similar changes in current gain, although the individual contributions of surface recombination velocity and positive oxide charge are different in each case.

The separate contributions of net positive charge and surface recombination centers are detected by plotting the excess base current as a function of forward-bias base emitter voltage. By graphically finding the transition from a diode ideality factor of two to an ideality factor less than two, the amount of oxide charge can be obtained. The presence of oxide charge can also be detected by plotting the normalized peak current gain against the extrapolated intercept ($V_{BE} = 0$) of the excess base current for both types of stress.

Despite the fact the radiation and hot electron stressing produce qualitatively similar changes in current gain, the magnitudes of stress-induced defects for each type of stress differ considerably. These differences must be taken into account when designing stress-tolerant processes and correlating hot electron and radiation stress results.

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