MEASUREMENT BIAS DEPENDENCE OF ENHANCED BIPOLAR GAIN DEGRADATION
AT LOW DOSE RATES

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ABSTRACT

Oxide trapped charge, field effects from emitter metallization, and high-level injection phenomena moderate enhanced gain degradation of lateral pnp transistors at low dose rates. Hardness assurance tests at elevated irradiation temperatures require larger design margins for low power measurement biases.

I. INTRODUCTION

Radiation-induced degradation of many types of bipolar transistors[1-5] and circuits[6-10] is more severe following low dose rate exposure than following high dose rate exposure. Since microelectronics devices in space are generally subjected to low dose irradiation, this complicates the hardness assurance testing of linear circuits and can lead to an overestimation of device lifetime in space. Of the various approaches tried to date for hardness assurance testing, the most promising has been high dose irradiation at elevated temperatures with some measure of margin to account for in situ annealing[2,4,5,7,8,11].

Due to their keen sensitivity to radiation, lateral pnp transistors have been the focus of much of the recent work in this area[2-5]. Ionizing radiation degrades the current gain of lateral pnp transistors by introducing interface traps and net positive oxide trapped charge into the oxide overlying the emitter-base junction[3,12]. Radiation-induced interface traps, especially those near midgap, act as recombination centers, which increase surface recombination in the base. Net positive oxide trapped charge can moderate the effect of interface traps by creating an imbalance in carrier concentrations at the base. Base recombination obtained at high dose rates is enhanced with increasing irradiation temperature while simultaneously being moderated by in situ annealing[4,5,8,11]. The amount of design margin required to bound low dose rate degradation is known to depend to varying degrees on total dose, irradiation temperature, device geometry, irradiation bias[10,13] and the dose rate at which testing is performed[8,11].

In this work, we report that the amount of enhancement at low dose rates or elevated temperatures diminishes significantly with increasing measurement bias between the emitter and the base. As a consequence, larger design margins are required to bound low dose rate degradation of devices operating at low power. Mechanisms contributing to the reduction in enhancement include field effects from oxide trapped charge and emitter metallization, base series resistance, and high-level carrier injection.

II. EXPERIMENT

A. DETAILS

This work draws on an extensive data set introduced elsewhere[4,5] that relates gain degradation of the Analog Devices RF25 lateral pnp transistor to dose rate and irradiation temperature. This device is fabricated in a Si bipolar process with a highly doped emitter (-9 x 10¹⁹ cm⁻³) and a base oxide thickness of 570 nm[14]. All irradiations were performed with a ⁶⁰Co γ-source and the device terminals grounded. Lids on the device packages were removed to avoid dose enhancement from photon scattering[15], and Pb-AI shields were used to filter low energy photons and electrons. Further details concerning the experimental procedure are provided elsewhere[4,5].

B. BIAS DEPENDENCE OF DEGRADATION ENHANCEMENT AT LOW DOSE RATES

A typical example of the effect of dose rate on excess base current is shown in Fig. 1(a)[4], where excess base current is defined as the increase in base current due to radiation exposure. The excess base current is plotted as a function of emitter-to-base voltage for devices irradiated to 20 krad(Si) at four dose rates between 0.001 and 294 rad(Si)/s. Base recombination increases monotonically with decreasing dose rate for any emitter-to-base voltage examined. However, the magnitude of this increase diminishes rapidly with increasing bias. Furthermore, the slope of the excess base current characteristics at any given dose rate decreases with bias.
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This result is illustrated more clearly in Fig 1(b), where excess base current at 20 krads(Si) is plotted as a function of dose rate for four emitter-to-base voltages between 0.5 and 0.8 V. The excess base currents are normalized by their respective values at 294 rad(Si)/s. At any bias, excess base current undergoes a sharp transition at intermediate dose rates and levels off at the extreme dose rates examined. The ratio of excess base currents at the extreme dose rates increases from approximately six at 0.8 V to approximately 35 at 0.5 V. This bias dependence of degradation enhancement at low dose rates is qualitatively similar for other total doses through 200 krads(Si).

C. BIAS DEPENDENCE OF DEGRADATION ENHANCEMENT AT ELEVATED TEMPERATURES

In Fig. 2(a), representative excess base current characteristics are shown for lateral pnp devices irradiated to 20 krads(Si) at a high dose rate and four temperatures between 25 and 135°C[4]. For any emitter-to-base voltage, degradation increases monotonically with temperature. However, similarly to the case for dose rate, the amount of degradation enhancement diminishes rapidly with increasing bias. Furthermore, the excess base current characteristics at any temperature tend to fall off at large biases.

This result is illustrated in another form in Fig. 2(b), where normalized excess base current is plotted as a function of irradiation temperature for several emitter-to-base voltages. The enhancement in degradation due to temperature is moderated by in situ annealing such that a distinct peak in the excess base current occurs for a given bias. This peak moves to lower irradiation temperatures with increasing bias. The factor by which excess base current is maximally enhanced increases from approximately eight at 0.7 V to more than 23 at 0.5 V. Qualitatively similar trends in the bias dependence of degradation enhancement at elevated temperatures are observed at other total doses.

III. HARDNESS ASSURANCE IMPLICATIONS

Fig. 3 illustrates the relationship between irradiation temperature and design margin required to bound low dose rate degradation of the test device at 20 krads(Si), where emitter-to-base voltage is a parameter. The figure was constructed by comparing excess base currents obtained at high dose rate and elevated temperatures to those obtained at 0.001 rad(Si)/s. The ordinates represent safety factors by which the high-temperature data must be multiplied in order to approximate the low dose rate response. Because gain degradation and the underlying mechanisms can vary widely among technologies and device types, it should be emphasized that the optimum values of temperature and margin implied by this figure apply strictly to the device studied.

At any irradiation temperature considered, the amount of design margin required to bound low dose rate degradation increases with decreasing emitter-to-base voltage. The dependence of design margin on bias generally grows stronger as the irradiation temperature moves away from its range of optimum values. These trends suggest that larger design margins may be required to bound degradation of relevant circuit level parameters when the transistor is used for low power applications than when it is biased for optimum performance.

IV. MECHANISMS FOR THE BIAS DEPENDENCE OF DEGRADATION ENHANCEMENT

A. OXIDE TRAPPED CHARGE

Excess base current in the lateral pnp transistor results primarily from surface recombination within the emitter-base depletion region. The amount of excess base current flowing at the Si surface is obtained from

$$\Delta I_b = q \int_S U dS,$$

where $q$ is the electronic charge, $U$ is the recombination rate per unit area, and $S$ is the surface area over which recombination takes place. The rate of recombination typically is at a maximum near the emitter-base metallurgical junction, where the carrier concentrations are comparable.

Integration of (1) yields a bias dependence for excess base current that can be approximated by

$$\Delta I_b \propto \exp \left[ \frac{\beta (V_{EB} - V_{acc})}{m} \right],$$

where $\beta$ is the reciprocal of the thermal voltage, $V_{EB}$ is the applied emitter-to-base voltage, $V_{acc}$ represents the potential drop across the accumulation layer in the neutral base, and $m$ is defined as the ideality factor. Recombination far from the E-B junction contributes an ideality factor of one. For recombination occurring at the maximum rate (near the E-B junction), an ideality factor greater than one results. The excess base current, therefore, exhibits a weaker dependence on applied bias when the function $U$ is more sharply peaked near the E-B junction.

Radiation-induced net positive oxide trapped charge moderates degradation enhancement at large biases by reducing recombination away from the E-B junction. In Fig. 4, the surface recombination rate is shown as a function of
distance from the E-B junction for several densities of positive oxide trapped charge. Positive oxide trapped charge reduces both the E-B depletion width and recombination in the neutral base by exacerbating the imbalance in surface carrier concentrations[3,12]. Since reduced recombination in the neutral base leads to a larger ideality factor, the enhancement in excess base current at low dose rates is reduced with increasing emitter-to-base voltage.

B. EMITTER METALLIZATION

In most devices (including the one studied here), the emitter metallization covers the base oxide over a portion of the E-B depletion region. This overlap functions as a field plate similar to a gate electrode in an MOS capacitor. As the emitter-base junction is forward biased, charge added to the metal layer reduces the region of high recombination in the underlying depletion region while increasing the potential drop across the accumulated neutral base (V_{acc} in (2)). The excess base current, therefore, is reduced to a value below that which would exist without the presence of the field plate. Since the relative reduction increases with the amount of charge on the field plate, the excess base current characteristics are stretched out for large emitter-to-base voltages. The effects of the field plate and positive oxide trapped charge are conceptually the same; that is, each acts to moderate the effect of near-midgap interface traps by increasing the surface potential in the Si.

C. HIGH-LEVEL INJECTION AND BASE SERIES RESISTANCE

At large forward currents, such that the number of minority carriers injected into the base approaches the majority carrier concentration, non-negligible electric-fields can result in significant ohmic drops across the bulk emitter and base regions[16]. The amount of potential drop increases with current so as to limit further injection of carriers. Since the rate of recombination in the depletion region depends on the concentration of injected carriers, excess base current increases more slowly with emitter-to-base voltage at large levels of current. Sufficiently high-level injection can yield an ideality factor that approaches two.

Base series resistance also contributes to the convergence of excess base current at large biases. An appreciable distributed resistance generally is present in the quasi-neutral region of the base[16]. This resistance often is significant in lateral pnp transistors due to the separation of the base electrode from the device active region. Since majority carriers in the base must flow into the active area to facilitate recombination and back-injection into the emitter, the applied emitter-to-base voltage is divided across the E-B depletion region and the base bulk. The metal-to-silicon contact at the terminal likewise behaves like a small resistor that adds to the voltage drop. The effect of series resistance is represented in (2) by expressing the junction voltage as V_{EB} = V_{acc} - I_b R_b, where I_b R_b represents the potential drop across the base.

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REFERENCES

Fig. 1(a). Effect of emitter-to-base voltage on excess base current, where dose rate is a parameter. (After [4].)

Fig. 1(b). Effect of dose rate on excess base current, where emitter-to-base voltage is a parameter.

Fig. 2(a). Effect of emitter-to-base voltage on excess base current, where temperature is a parameter. (After [4].)

Fig. 2(b). Effect of temperature on excess base current, where emitter-to-base voltage is a parameter.

Fig. 3. Relationship between temperature and design margin required to bound low dose rate degradation.

Fig. 4. Effect of positive oxide trapped charge on the surface recombination rate.