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ACCELERATED TESTS FOR BOUNDING THE LOW DOSE RATE RADIATION RESPONSE OF LATERAL PNP BIPOLAR JUNCTION TRANSISTORS †

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ABSTRACT

Low dose rate gain degradation of lateral pnp bipolar transistors can be simulated by accelerated irradiations performed at approximately 135 °C. Degradation enhancement is explained by temperature-dependent radiation-induced interface trap formation above the transistor's base.

I. INTRODUCTION

Lateral pnp bipolar junction transistors are known to exhibit extreme sensitivity to ionizing radiation[1,2]. Their intolerance to radiation is so severe that failures of many integrated circuits used in radiation environments have been attributed to their degradation. Such circuits include operational amplifiers[3,4], comparators[3] and voltage regulators[5], where lateral pnp transistors are used as input devices, level shifters, current sources or part of start up circuitry. The acute susceptibility of lateral pnp transistors to radiation makes accurately predicting the total dose tolerance of these devices a crucial issue, since the lifetime of lateral pnp transistors in a radiation environment often determines the time to failure of the circuits or systems in which the transistors are used.

Degradation of lateral pnp transistors[1,2,5] and circuits using lateral pnp transistors[6,7] has been shown to be strongly dose rate dependent, such that, for a given total dose, degradation is more severe following low dose rate exposure than following high dose rate exposure. Since, in space applications, lateral pnp transistors are subjected to low dose rate irradiation, this complicates the task of performing accelerated tests for device failure analysis and can lead to an overestimation of the device's lifetime in space. Of the various approaches tried to date for hardness assurance testing[2,7], high dose rate irradiation at elevated temperatures has been the most promising for simulating low dose rate degradation in lateral pnp transistors[2].

In this work, the effect of temperature on high dose rate radiation-induced gain degradation in lateral pnp bipolar junction transistors is thoroughly investigated. The results constitute strong evidence that low dose rate gain degradation in lateral pnp transistors can be approximated over a wide range of total doses by low-cost accelerated irradiations performed at approximately 135 °C. In conjunction with characterization of the transistors, metal-oxide-silicon (MOS) capacitors fabricated from the same bipolar process are found to exhibit a similar temperature dependence for radiation-induced interface trap formation, suggesting that the enhancement of high dose rate transistor gain degradation at elevated temperatures can be explained by an increase in surface recombination due to the formation of interface traps in the oxide overlying the transistor's base. so why wouldn't a rebound test work?

II. EXPERIMENT

A. LATERAL PNP BIPOLAR JUNCTION TRANSISTORS

The lateral pnp transistors investigated in this work come from a Si bipolar process developed for low noise amplifiers, power amplifiers, mixers and radio frequency (RF) switches used in consumer RF and microwave communications applications[8]. A representative cross-section of the device is shown in Fig. 1. The process features poly-crystalline emitter technology and low-capacitance junction isolation. The transistor's emitter consists of either a 1.2 μm × 1.2 μm square diffusion area or five such square areas connected in parallel. Its active base width is 2.6 μm, and doping at the surface of the base is 1.0×10^{16} cm^{-3}. The thickness of the oxide covering the transistor's base is 5700 Å. The transistor's peak current gain is approximately 40 and occurs at an emitter-to-base voltage of about 0.65 V before irradiation. The test chips containing the devices were packaged in 14-pin dual-in-line ceramic packages for ease of biasing and handling.

Transistors of both geometries were irradiated with ^{60}Co γ-rays at two dose rates. High dose rate irradiations were performed at 294 rad(Si)/s and seven temperatures between 25 and 240 °C. Each transistor

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received a total dose of 100 krad(Si), during which the irradiation was interrupted periodically to perform Gummel measurements. All Gummel measurements were taken at 21±1 °C after allowing the devices to cool from their respective irradiation temperatures. The temperatures were monitored with a calibrated thermocouple taped to the device packages. Gummel measurements following one-shot 100 krad(Si) irradiations at each experimental temperature verified that negligible annealing occurred during the warm-up period prior to each incremental irradiation. To compensate for experimental uncertainties, several transitors were tested at each irradiation temperature. Low dose rate irradiations were performed at 0.01 rad(Si)/s and 25 °C. All device terminals were grounded during the irradiations.

In Fig. 2(a), representative current gain characteristics are shown for transistors of the small size irradiated to 20 krad(Si) at the high dose rate, where the irradiation temperature is a parameter. Each curve is normalized by its corresponding pre-radiation peak current gain. A pre-radiation gain characteristic is shown for comparison. The gain characteristics are such that degradation grows significantly worse as the irradiation temperature is increased through 135 °C. Gain characteristics for irradiation temperatures above 135 °C exhibited decreasing degradation with increasing temperature and were excluded from the figure for clarity.

Fig. 2(b) shows the temperature dependence of the current gain degradation to be manifested in the base current. Here excess base current is plotted as a function of emitter-to-base voltage for the devices from the previous figure, where excess base current is defined as the increase in base current due to radiation. Excess base current increases markedly with temperature for all emitter-to-base voltages through 135 °C, after which it decreases with further heating. Changes in collector current due to radiation were negligible. Qualitatively similar trends in temperature were observed for all other total doses investigated.

High dose rate data taken at all of the irradiation temperatures and total doses investigated are shown in Fig. 3. Each curve in the figure represents excess base current as a function of total dose for a different irradiation temperature. The excess base currents were measured at an emitter-to-base voltage of 0.7 V and are normalized by their respective pre-radiation base currents to offset part-to-part variations. Normalizing in such a way has the added advantage of accounting for the different emitter geometries, so that excess base currents for devices of both sizes can be compared directly. Each data point in the figure represents the average of results obtained from several transistors of each size. Enhancement in the excess base current due to elevated irradiation temperatures occurs over the entire range of total doses investigated. At 4 krad(Si), the enhancement factor varies between approximately three and four for temperatures from 65 to 240 °C and depends little on temperature. For increasing total doses, however, the enhancement factor grows increasingly dependent on temperature due to the temperature's effect on accelerating the onset of saturation in base current. At approximately 135 °C, the enhancement of excess base current due to temperature is at a maximum independent of total dose and varies between approximately four and eight over the range of total doses investigated.

In Fig. 4, excess base current following the high dose rate irradiation at 135 °C is compared as a function of total dose with excess base current incurred at the low dose rate. Excess base current due to the high dose rate irradiation at 25 °C is included for comparison. The figure clearly illustrates the dose rate effect in these transistors, where excess base currents for the different dose rates differ by a factor of between three and five for the 25 °C irradiations. The high dose rate irradiation at 135 °C closely approximates and, in fact, bounds the low dose rate response over the entire range of total doses examined. This result is of great importance with regard to hardness assurance testing, as it shows for the first time that the low dose rate radiation response of lateral pnp bipolar transistors can be reliably predicted using a low-cost accelerated test.

The effect of irradiation temperature on gain degradation and the utility of elevated temperature irradiations to simulate the low dose rate response of lateral pnp transistors is most clearly illustrated in Fig. 5. Here excess base current is shown as a function of temperature for the small and large transistors separately following high dose rate irradiations to 20 krad(Si). The horizontal dashed line represents an interpolation of the low dose rate response in the previous figure. At 135 °C, the enhancement in excess base current by a factor of more than five is sufficient to bound the low dose rate response.

B. MOS CAPACITORS

To provide physical insight into the radiation response of the transistors, MOS capacitors from the same bipolar process were characterized for damage following high-temperature irradiations similar to those received by the transistors. The dielectric material in the capacitors consists of the oxide overlying the base in the transistors. While grounded, the capacitors received 100 krad(Si) of ^{60}Co γ-radiation at a dose rate of 294 rad(Si)/s. The irradiation temperatures varied between 25 and 275 °C. Following irradiation, the capacitors were measured for capacitance-voltage (C-V) characteristics at a frequency of 1 MHz, from which energy distributions of interface trap densities were generated[9].

Fig. 6 shows energy distributions of interface trap densities for capacitors irradiated at four temperatures between 25 and 135 °C. The effect of raising the irradiation temperature is to increase the number of interface traps generated throughout the entire Si bandgap. For temperatures above 135 °C, the interface trap densities decreased and were excluded from the figure for clarity.

This effect of temperature on radiation-induced interface trap formation is illustrated in another form in Fig. 7, where interface trap densities at midgap are plotted as a function of irradiation temperature for all of the capacitors tested. A distinct peak in the density of interface traps occurs near a temperature of 135 °C. Increasing the irradiation temperature from 25 to 135 °C leads to an increase in the density of interface traps by a factor of almost three.

The similarities in temperature dependence for radiation-induced gain degradation in the lateral pnp bipolar transistors and interface trap formation in the MOS capacitors are striking. Interface trap formation in the oxide overlying the base is a dominant mechanism for radiation-induced gain degradation in lateral pnp bipolar transistors[1]. Interface traps increase the base current by increasing the recombination rate at the surface of the base. Surface recombination can be a severe problem for lateral pnp transistors, especially for devices with large base widths, since current flow in the device is primarily along the surface of the base. The measurement results for the MOS capacitors are consistent with a physical model that explains the high dose rate radiation response of the lateral pnp bipolar transistors in terms of a strong temperature dependence of interface trap formation above the transistor's base.

III. SUMMARY

The possibility of bounding the low dose rate radiation response of lateral pnp transistors with elevated temperature high dose rate irradiations was investigated. Characterization was performed on transistors of two emitter geometries irradiated with ^{60}Co γ-rays to various total doses up to 100 krad(Si). High dose rate irradiations were given at 294 rad(Si)/s and seven temperatures ranging from 25 to 240 °C. The low dose rate irradiations were performed at 0.01 rad(Si)/s and 25 °C. Significantly enhanced gain degradation was observed for high dose rate irradiations performed over the entire range of temperatures investigated. Above 65 °C, the enhancement is nearly independent of temperature at total doses as low as 4 krad(Si) but grows increasingly temperature dependent with increasing total dose. Gain degradation is at a maximum for irradiation temperatures near 135 °C independent of total dose. Furthermore, high dose rate gain degradation at 135 °C closely approximates and, in fact, appears to bound room-temperature low dose rate degradation over the entire range of total doses investigated. These important results strongly support the utility of elevated temperature accelerated stress tests as a viable low-cost means of accurately predicting the low dose rate radiation response of lateral pnp bipolar junction transistors and lend important insight into better understanding the dose rate problem in bipolar transistors.

In conjunction with the transistor measurements, MOS capacitors fabricated from the oxide covering the transistor's base were irradiated to 100 krad(Si) at the same high dose rate and temperatures as the transistors. Energy distributions of interface trap densities generated from measured high-frequency C-V characteristics of the capacitors revealed a temperature-dependent enhancement in radiation-induced interface traps very similar to that seen in the gain degradation of the transistors. These results are consistent with the notion that the enhancement of high dose rate transistor gain degradation at elevated temperatures results from increased surface recombination due to radiation-induced interface traps above the transistor's base.

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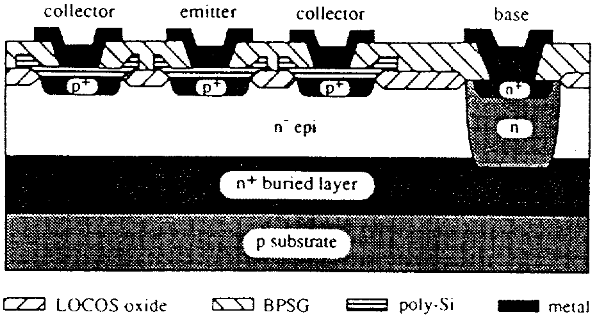

Fig. 1. Cross-section of the lateral pnp bipolar junction transistor.

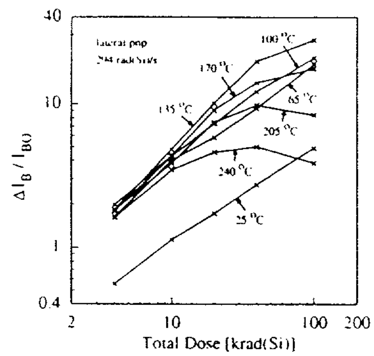

Fig. 3. Effect of temperature on the total dose response of the lateral pnp bipolar transistors.

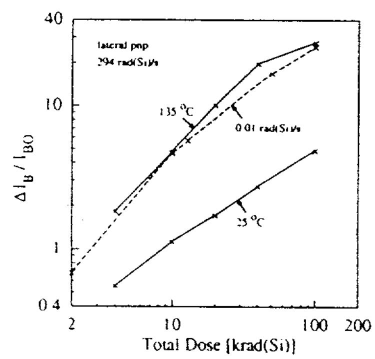

Fig. 4. Comparison of degradation for the low and high dose rate irradiations.

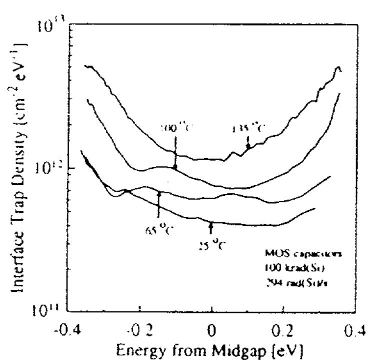

Fig. 6. Effect of irradiation temperature on the distribution of interface trap densities in the MOS capacitors.

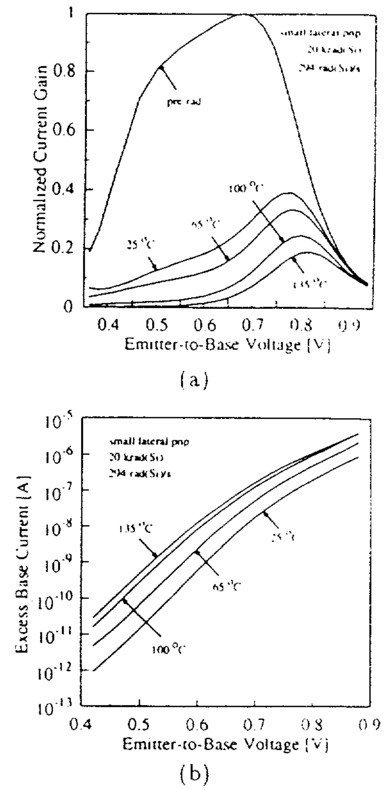

Fig. 2. Effect of temperature on radiation-induced (a) gain degradation and (b) excess base current.

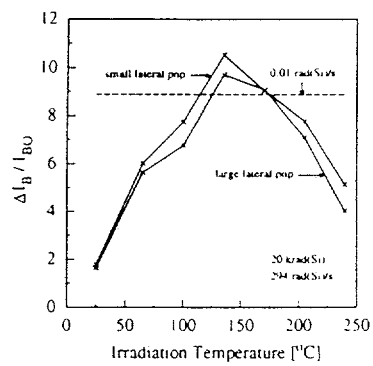

Fig. 5. Effect of temperature on radiation-induced excess base current.

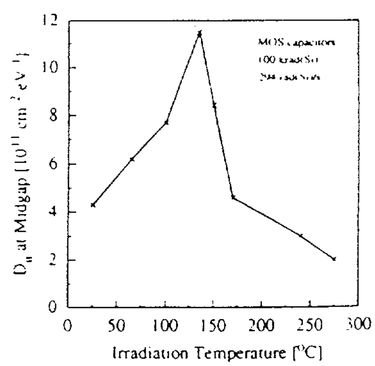

Fig. 7. Effect of irradiation temperature on the midgap interface trap densities in the MOS capacitors.

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