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EVALUATION OF TEMPERATURE-ENHANCED GAIN DEGRADATION OF VERTICAL NPN AND LATERAL PNP BIPOLAR TRANSISTORS

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ABSTRACT

The effect of dose rate on radiation-induced gain degradation is compared for vertical npn and lateral pnp bipolar transistors. High dose rate irradiations at elevated temperatures are more effective at simulating low dose rate degradation in the lateral pnp transistors.

I. INTRODUCTION

Ionizing radiation degrades the current gain of vertical npn bipolar junction transistors by introducing net trapped positive charge and interface traps into the oxide overlying the base[1]. The positive oxide trapped charge spreads the emitter-base depletion region into the extrinsic base, which leads to increased recombination current in the base under forward-biased operation of the junction. Radiation-induced interface traps, especially those near midgap, serve as generation-recombination centers through which recombination current in the base is further increased due to enhanced surface recombination velocity.

The defects primarily responsible for radiation-induced gain degradation in lateral pnp bipolar transistors are interface traps[2]. Because current flow in lateral devices is along the Si surface, interface traps can pose especially severe problems for these devices. Lateral pnp transistors have been identified as the cause of radiation-induced failures in a variety of linear integrated circuits[3], including operational amplifiers, comparators and voltage regulators, where they are used as input devices, level shifters, current sources or part of start-up circuitry. In contrast to the case for vertical pnp transistors, radiation-induced positive oxide trapped charge can mitigate gain degradation in lateral pnp bipolar transistors by creating an imbalance in carrier concentrations at the surface of the base[2].

Degradation of many types of bipolar transistors and circuits is known to depend strongly on dose rate, such that, for a given total dose, degradation is more severe following low dose rate exposure than following high dose rate exposure[4]. This dose rate effect recently has been attributed to space charge effects in the base oxide associated with metastable hole traps[5,6]. Since, in space applications, the transistors are subjected to low dose rate irradiation, this complicates the task of performing accelerated tests for hardness assurance and can lead to an overestimation of device lifetime in space. Of the various approaches tried to date for hardness assurance testing, high dose rate irradiation at elevated temperatures has been the most promising for simulating low dose rate degradation for a variety of bipolar processes[6,7]. Although previous work has examined temperature-enhanced gain degradation for individual bipolar technologies, to date, there has not been a direct comparison made at the transistor level of the utility of high-temperature irradiations in simulating low dose rate gain degradation for different bipolar processes.

In this work, a comparison of temperature-enhanced gain degradation is made for vertical npn and lateral pnp bipolar transistors from different technologies. High dose rate irradiations at elevated temperatures are found to simulate low dose rate gain degradation more effectively in the lateral pnp device than in the vertical npn device. The results are explained in terms of the different roles that radiation-induced positive oxide trapped charge plays in degrading current gain in the two devices. The results imply that a hardness assurance approach utilizing high temperature irradiations works best for bipolar devices whose radiation response is dominated by interface traps.

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II. EXPERIMENT

Lateral pnp and vertical npn bipolar transistors from different technologies were studied in this work. The pnp transistors 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]. The npn devices were processed on bonded (100) silicon-on-insulator wafers in a complementary bipolar process[9]. Relevant device parameters for the technologies are shown in Table I.

Transistors from each technology were irradiated with ^{60}Co γ-rays in two separate experiments. Details of the measurement results for the lateral pnp devices can be found elsewhere[7]. High dose rate irradiations of the vertical npn devices were performed at 294 rad(Si)/s and seven different temperatures between 25 and 240 °C. Each transistor received a total dose of 400 krad(Si), during which the irradiations were 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 400 krad(Si) irradiations verified that negligible annealing occurred during the warm-up period prior to each incremental irradiation. To account for part-to-part variations in gain degradation, several transistors were tested at each irradiation temperature. Low dose rate irradiations as low as 10 mrad(Si)/s were performed at 25 °C for the vertical npn devices. All device terminals were grounded during the irradiations.

In Fig. 1(a), representative current gain characteristics are shown for vertical npn transistors irradiated to 100 krad(Si) at the high dose rate, where irradiation temperature is a parameter. Each curve is normalized by its corresponding pre-irradiation peak current gain. A pre-irradiation 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. At 100 krad(Si), gain characteristics for vertical npn devices irradiated above approximately 135 °C exhibited decreasing degradation with increasing temperature and were excluded from the figure for clarity.

Fig. 1(b) shows that the temperature dependence of current gain degradation is reflected in the base current. Here excess base current is plotted as a function of base-to-emitter voltage for the devices from the previous figure, where excess base current is defined as the increase in base current due to radiation exposure. Regardless of the base-to-emitter voltage, excess base current increases markedly with temperature 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.

In Fig. 2, excess base current for the vertical npn transistor is plotted as a function of irradiation temperature, where total dose is a parameter. Each value of excess base current shown represents the mean of all data acquired at a given dose and temperature. The curves in the figure are fourth-order polynomial fits to the data (although fits of other functions may also be appropriate). 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 dose. The peak in the excess base current moves to lower irradiation temperatures with increasing total dose.

In Fig. 3, ambient temperatures corresponding to maximum radiation-induced gain degradation at 294 rad(Si)/s are shown as a function of total dose for the vertical npn transistors. The temperatures plotted in the figure were obtained from the peaks in the excess base current characteristics of the previous figure. In agreement with previously reported results for the lateral pnp transistor[7], the optimum irradiation temperature for degradation enhancement depends approximately logarithmically on total dose over the range of doses examined.

Excess base current in the npn device following a total dose of 100 krad(Si) is shown in Fig. 4 for four dose rates between 0.01 and 294 rad(Si)/s. The symbols in the figure denote means of measurement results on all replicate samples irradiated. Excess base current increases sharply for dose rates below about 0.1 rad(Si)/s. The difference in excess base currents measured at the extreme dose rates is approximately 2.3. Enhancement of the gain degradation at low dose rates has not yet saturated by 0.01 rad(Si)/s.

In Figs. 5(a) and 5(b), excess base current induced at 294 rad(Si)/s for the full range of irradiation temperatures examined is compared with excess base current resulting from room temperature irradiations at 10 mrad(Si)/s for the vertical npn and lateral pnp devices, respectively. Although the enhancement in degradation due to dose rate is not saturated for either device at 10 mrad(Si)/s, this rate is useful for such a comparison given the similarity in the dose rate dependences of the devices[7]. The comparisons are made at $V_{BE} = 0.6$ V for the npn device and $V_{EB} = 0.7$ V for the pnp device following 100 krad(Si) exposures. The different biases for the two devices were chosen out of convenience and have no affect on the resulting comparison. At 100 krad(Si), excess base current in the more radiation-tolerant npn device is large compared to the pre-irradiation base current, and the optimum irradiation temperatures for degradation enhancement are similar for the npn and pnp devices. The amount of excess base current resulting from maximum high dose rate degradation of the npn device is approximately 61% of that incurred at 10 mrad(Si)/s, while, for the pnp device, approximately 88% of the low dose rate excess base current is compensated by the high-temperature exposure. The difference in the effectiveness with which high-temperature irradiations simulate low dose rate degradation in the two devices can be explained by the in situ annealing of oxide trapped charge at the elevated irradiation temperatures.

III. DISCUSSION

High-temperature irradiation is most effective at simulating low dose rate degradation in the pnp device, because the gain degradation is dominated by the effects of interface traps on surface recombination velocity. Annealing of interface trapped charge typically is not very significant over the temperature range for maximum enhanced degradation considered here[10]. On the other hand, radiation-induced gain degradation of the npn device is strongly associated with oxide trapped charge. Since the annealing of oxide trapped charge is quite important at temperatures over 100 °C[10], the temperature-related enhancement of degradation in the npn transistors is moderated by accelerated annealing of oxide trapped charge. This result is quite general: that is, high-temperature irradiations are most effective at simulating the low dose rate response of devices whose degradation is dominated by interface traps. Since lateral pnp transistors typically are especially radiation-sensitive, this result is encouraging for the use of high-temperature irradiations to predict low dose rate degradation of bipolar circuits or systems made with different device types or from different technologies.

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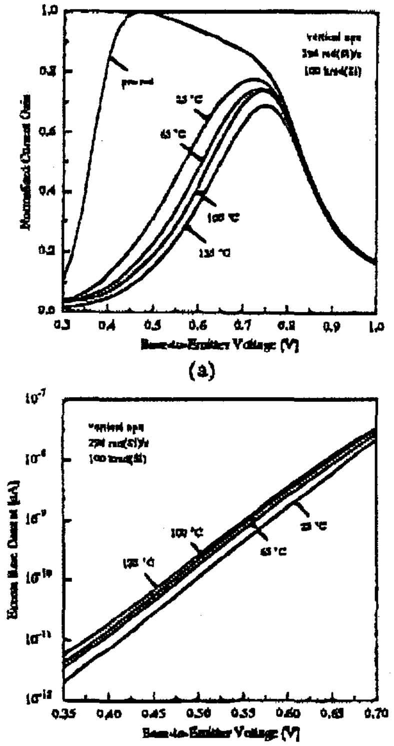
Table I. Relevant Device Parameters

	vertical npn	lateral pnp
Emitter Size	1.5 x 1.5 μm^2	1.2 x 1.2 μm^2
Base Doping	8 x 10^{17} cm^{-3}	1 x 10^{16} cm^{-3}
Base Width	0.8 μm	2.6 μm
Oxide Thickness	55 nm	570 nm
Peak Gain	200	40



(a)

(b)

Fig. 1. Effect of temperature on radiation-induced (a) gain degradation and (b) excess base current in the npn device.

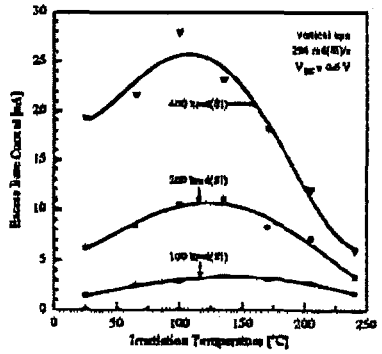


Fig. 2. Effect of temperature on radiation-induced excess base current in the npn transistor.

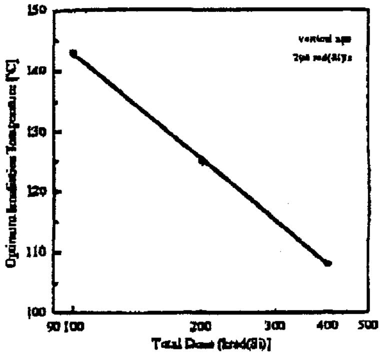


Fig. 3. Effect of total dose on the optimum irradiation temperature in the npn transistor.

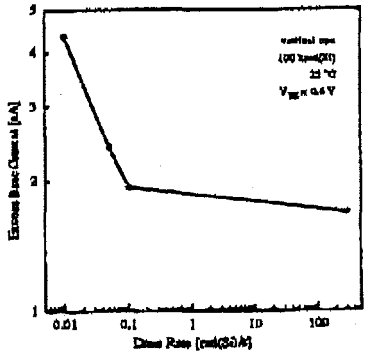
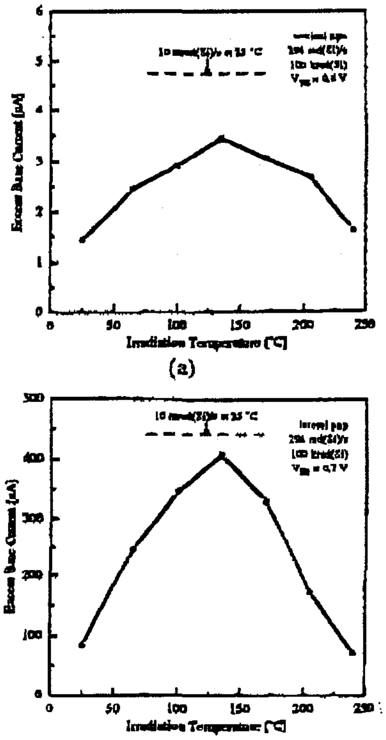


Fig. 4. Effect of dose rate on excess base current in the npn transistor.



(a)

(b)

Fig. 5. Comparison of high-temperature degradation and low rate degradation in the (a) npn and (b) pnp devices.