Elimination of Enhanced Low-Dose-Rate Sensitivity and Thermal-Stress Effects in Linear Bipolar Devices

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ABSTRACT

Passivation layers are shown to have a major impact on the total dose hardness of bipolar technologies. Selecting the correct passivation layers can eliminate the PETS and ELDRS effects in at least some bipolar technologies.

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I. INTRODUCTION

Developing hardness assurance methods for predicting the radiation response of bipolar devices for use in low dose rate radiation environments remains a very challenging issue facing the radiation effects community. It has been shown over the past ten years that many bipolar devices used in space-based systems exhibit enhanced low dose rate sensitivity (ELDRS) at low electric fields [1]. Unfortunately, high dose rate irradiation followed by room temperature annealing, which can accurately estimate the radiation response of CMOS devices at low dose rates [2], [3], does not accurately estimate the low dose rate response of many types of bipolar devices [4], [5], [6]. This has made it difficult to develop a quick and accurate total-dose hardness assurance test method for predicting the radiation response of bipolar devices. Currently, the most promising method involves the use of an elevated temperature irradiation at relatively low dose rates (≤ 1 rad(SiO_2)/s). However, the optimum irradiation temperature for this procedure may vary from technology to technology and the required dose rate is significantly lower than the current dose rate range (50 to 300 rad(SiO_2)/s) used for qualifying CMOS technologies. As a result, manufacturers do not have a reliable laboratory test guideline for timely assessment of the radiation hardness of their bipolar technologies.

Although a considerable amount of work has been performed in an attempt to identify the mechanisms for ELDRS, no process modifications during device fabrication have been identified that substantially reduce or eliminate ELDRS. If one could eliminate the ELDRS effect by process optimization, developing a hardness assurance guideline for ELDRS would no longer be needed for manufacturers that implement these optimizations. Obviously, this would be the preferred approach.

Recently, it has been shown that there is a link between ELDRS and preirradiation elevated temperature stress (PETS) effects [7]. Both MOS and bipolar devices subjected to PETS have been shown to exhibit increased radiation-induced degradation for some technologies. The mechanisms for PETS have been investigated [7], [8], but to date no conclusive model for the mechanisms has been developed. However, just as for the ELDRS effect, it is likely that both hydrogen and radiation-induced oxide defects play a role in the mechanisms for PETS. If process techniques could be identified that could eliminate or reduce ELDRS effects, it is also possible that the same techniques could eliminate or reduce PETS effects.

In this paper, we investigate the effects of different ambient gases on PETS effects and passivation layers on ELDRS and PETS effects of bipolar linear devices fabricated by National Semiconductor. Specifically, we focus on the impact of process steps associated with the final passivation layers. It is shown that by modifying these steps we can substantially reduce or eliminate both ELDRS and PETS effects in these devices and thus, significantly ease the task of qualifying bipolar devices for space applications.

II. EXPERIMENTAL DETAILS

LM111 voltage comparators were taken from a single wafer supplied by National Semiconductor from their United Kingdom bipolar linear fabrication line. Note that this wafer came from the same wafer lot used in a prior study of ELDRS in LM111s [9]. Selected die were subjected to unbiased PETS up to 450 °C for times as long as 600 s. Die were heated using a hot chuck, standard convection oven, or 4" vertical tube furnace. The temperature limit of the hot chuck and oven is ~315 °C. For the hot chuck and oven no attempt was made to control the ambient (i.e., we used room ambient). The furnace is capable of reaching temperatures in excess of 700°C with a forming gas (10% H_2/90% N_2) ambient. In addition, LM139 quad input comparators were taken from a single wafer lot supplied by National Semiconductor from their Arlington, Texas, bipolar linear fabrication line.

Following elevated temperature stress, the die were packaged at room temperature in 14-pin ceramic dual-in-line packages. The die were attached to the package using a thermoplastic that cures at room temperature, and the lids were attached with tape. As a result, die were not subjected to the numerous thermal cycles used during typical integrated circuit (IC) packaging. This eliminates the possibility that thermal cycles normally used in packaging could have affected the results.

The packaged devices were irradiated with all pins shorted at dose rates of 83.3 rad(SiO_2)/s using a ^{60}Co gamma source and 0.01 rad(SiO_2)/s using a ^{137}Cs gamma source. In general, three devices per irradiation and anneal condition were characterized. The devices were irradiated at room temperature up to a maximum of 500 krad(SiO_2) in steps. The packaged ICs were characterized using an Analog Devices LTS2020 linear IC tester. All standard electrical parameters were measured, including input bias and offset currents, offset voltage, and power supply current. Pre-irradiation electrical parameters measured on packaged die not subjected to any thermal cycles (controls) and packaged die subjected to thermal cycles agreed to within experimental uncertainty, indicating that PETS did not alter the pre-irradiation electrical response.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Based on existing models, hydrogen interactions in oxides are likely involved in ELDRS and PETS effects [6] - [8], [10]. To explore the effects of exposing fully processed bipolar devices to hydrogen, LM111s were stressed at 250°C in different ambients for 600 s and then irradiated at a dose rate of 83.3 rad(SiO_2)/s. Figure 1 is a plot of the positive input bias current (I_{B+}) for LM111s versus total dose for devices not subjected to PETS and devices stressed prior to irradiation on the hot chuck, in the oven, and in the furnace. The hot chuck and oven stresses were performed in the room ambient, with no attempt to control the gases over the parts. The furnace anneals were performed in a forming gas ambient. As shown in previous work [1], [7], input bias current is a good metric for characterizing ELDRS and PETS in these devices. As shown in the figure, the devices with PETS exhibited significantly more degradation in I_{B+} (up to 3x) with dose than the control samples. However, to within experimental uncertainty, there is no difference in input bias current for the devices exposed to the different anneal conditions. For each case, input bias current peaks at an average current level of approximately 900 nA at a total dose of 100 krad(SiO_2) and decreases at higher total dose levels. These results suggest that the ambient used during the stresses has a negligible effect on input bias current. The room ambient contains some hydrogen and we cannot rule out the possibility that part of the increase in input bias current for the hot chuck and oven anneals results from exposure to hydrogen. Nevertheless, the data show that annealing in a hydrogen-rich environment does not have a significant effect on the amount of radiation-induced degradation for these devices. Consistent with previous work, the increase in I_{B+} for the devices with PETS is due primarily to the temperature and time of the stress as opposed to the ambient.

The LM111s have a composite passivation layer consisting of a 1-µm oxide capped with a 1-µm nitride. Nitride passivation layers are well known to act as a diffusion barrier to hydrogen, but they can also act as a source for hydrogen. In addition, others have observed that some bipolar devices with nitride passivation layers are more sensitive to PETS effects than devices without nitride passivation [11]. To investigate the effect of the nitride passivation layer on PETS and ELDRS effects we removed the nitride passivation layers from some of the die using a wet chemical process. Figure 2 is a scanning electron microscope (SEM) cross section taken after wet etching a die. Note that not all of the nitride layer could be removed without etching into the underlying oxides. As a result some residual nitride was left on the die. After the nitride was etched the die were packaged without exposing them to any thermal cycles. Removing the nitride caused a slight increase in the preirradiation input bias current (from ~25 nA to ~40 nA), which is likely due to an increase in surface leakage current.

Devices with and without the nitride layer removed were irradiated unbiased at dose rates of 0.01 and 83.3 rad(SiO_2)/s. The results are shown in Figure 3, which plots I_{B+} versus total dose. At a dose rate of 83.3 rad(SiO_2)/s, I_{B+} for devices with nitride passivation increased from an average 25 nA to ~330 nA at 50 krad(SiO_2). Irradiating to higher dose levels caused no further increase in input bias current. Irradiating devices with nitride passivation at a dose rate of 0.01 rad(SiO_2)/s resulted in considerably higher increases in input bias current with dose. After irradiating to a total dose of 50 krad(SiO_2), I_{B+} increased to ~1432 nA. The large difference (a factor of 4.3 at 50 krad(SiO_2)) in I_{B+} between the low- and high-dose-rate irradiations is consistent with previously reported results [7] and is a classic example of ELDRS. A much smaller increase in I_{B+} with dose was observed for the devices with the nitride removed irradiated at dose rates of 83.3 and 0.01 rad(SiO_2)/s. The maximum value of input bias current was 204 nA after irradiating to 100 krad(SiO_2). Within experimental uncertainty there is no difference between the low and high dose rate irradiations. *Thus, removing the nitride not only mitigated the ELDRS effect but it also improved the overall total-dose response of the devices.*

It has been shown previously that there is a link between the ELDRS and PETS effect [7]. If removing the nitride layer eliminates the ELDRS effect, one might ask what effect it will have on the PETS effect? LM111 die with and without the passivation layer removed were exposed to PETS of 250 and 450 °C for 200 s. Figure 4 is a plot of I_{B+} versus dose for devices irradiated at 83.3 rad(SiO_2)/s. For the die with nitride passivation, PETS caused a large increase in I_{B+} with dose. At 250 and 450 °C the peak degradation in I_{B+} was ~940 and ~1567 nA, respectively, while the control sample with nitride passivation that was not exposed to PETS had a peak I_{B+} of ~330 nA. On the other hand, for the devices without the nitride passivation PETS had no significant impact on the radiation-induced increase in I_{B+}. The change in I_{B+} for these devices was identical to the control sample without nitride that was not exposed to PETS. *These results clearly show that both the PETS and ELDRS effects can be eliminated in this technology by removing the nitride passivation layer.*

It is possible that the results shown in Figures 3 and 4 are not associated with the lack of a nitride passivation but instead are related to the wet etch procedure. To verify that the results are only due to the absence of the nitride passivation layer, a lot of LM139s was fabricated by National with various passivation layers: no passivation, a p-glass (2.5% P) passivation, and two different oxide/nitride passivation layers. For one of the oxide/nitride passivation layers the nitride was deposited using processing techniques that reduce the amount of hydrogen incorporated in the nitride compared to the baseline process (although this was not experimentally verified). Die from this wafer lot were packaged without exposure to any PETS before, during, or after packaging. The devices were irradiated unbiased at a dose rate of 211 rad(SiO_2)/s using a ^{60}Co source. The type of passivation layer had a significant impact on the radiation-induced change in I_{B+} for these devices as shown in Figure 5. For devices with no passivation or a p-glass passivation the increase in I_{B+} was less than 125 nA after irradiating to 100 krad(SiO_2) with the unpassivated samples showing slightly smaller increases in I_{B+} at the lower total dose levels. Significantly larger increases were observed for the devices with both types of oxide/nitride passivation. The largest increase in I_{B+} was for devices with the baseline oxide/nitride passivation, which showed a peak I_{B+} of 985 nA at 70 krad(SiO_2). The devices with reduced hydrogen concentration in the nitride showed less degradation with dose for all total dose levels examined than the devices with the baseline oxide/nitride passivation; however, the degradation was still much larger than for the devices with no passivation or a p-glass passivation. While these results clearly indicate that the passivation layer plays a key role in determining the total dose hardness of these devices, experiments to irradiate these devices at low dose rates are in progress to address the ELDRS issues. The results of these irradiations will be shown in the final paper.

As was suggested in an earlier paper [7], a possible mechanism for the correlation between ELDRS and PETS effects could be the activation of additional metastable trap sites in the bulk of the oxide overlying the base region via the release of hydrogen that had previously passivated the site. These additional metastable trap sites impact the space charge fields produced in the oxide, which reduces the amount of hole trapping and interface trap buildup by retarding hole and H^+ transport to the interface [6], [10]. The fact that the concentration of hydrogen in the nitride can impact the hardness of the device may suggest that the diffusion of molecular hydrogen or other hydrogen related species from the nitride plays a key role in the depassivation of metastable trap sites in the base oxide by reacting with hydrogen at the passivated trap sites. Without the nitride passivation there is no additional source of hydrogen available to depassivate the metastable trap sites and thus we see no PETS or ELDRS in devices without nitride passivation. However, we also cannot rule out the possibility that the absence or removal of the nitride passivation has changed the mechanical stress on the die. Thermal cycling previously has been shown [12], [13] to affect the mechanical stress in MOS structures causing changes in radiation-induced charge buildup. It is possible that changes in the mechanical stress could also enhance the activation of hydrogen from passivated trap sites [14]. The mechanisms for the elimination or reduction of ELDRS and PETS effects will be discussed in more detail in the full paper.

Regardless of the detailed microscopic mechanisms for ELDRS and PETS, we have shown that the final passivation layer plays a critical role in determining the total dose response of some bipolar linear devices. By selecting appropriate passivation layers, one can eliminate PETS and ELDRS effects in some bipolar technologies. This can mitigate the difficult and challenging undertaking of developing improved hardness assurance tests methods for qualifying devices sensitive to PETS and ELDRS. While it might appear that eliminating any nitride passivation layers on the die is the easiest approach, this may not be practical for manufacturers or users that want or need devices packaged in plastic packages. In these cases, nitride passivation layers are commonly used as a moisture barrier. However, it might be possible to develop nitride passivation layers with reduced hydrogen concentrations that do not significantly degrade the total dose hardness of bipolar linear ICs.

IV. SUMMARY

We have demonstrated that final passivation layers can have a significant impact on ELDRS and PETS for devices fabricated in National Semiconductors bipolar linear process. By eliminating the nitride passivation layer, we can eliminate or reduce ELDRS and PETS sensitivities in these devices. Others have also observed that nitride passivation layers can impact the PETS sensitivity of bipolar devices [11]. This suggests that PETS and ELDRS effects may also be eliminated in other kinds of bipolar technologies produced by different manufacturers if the final passivation layers are modified. Eliminating PETS and ELDRS effects in bipolar technologies would significantly ease the task of qualifying bipolar devices for space applications.

V. ACKNOWLEDGMENTS

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VI. REFERENCES

[1] R. L. Pease et al., Workshop Record of the 2001 IEEE Radiation Effects Data Workshop, pp. 127-133, Vancouver, Canada.
[2] J. R. Schwank et al., IEEE Trans. Nucl. Sci. 31, 1434, (1984).
[3] D. M. Fleetwood et al., IEEE Trans. Nucl. Sci. 36, 1963, (1989).
[4] E. W. Enlow et al., IEEE Trans. Nucl. Sci. 38, 1342, (1991).
[5] D. M. Fleetwood et al., IEEE Trans. Nucl. Sci. 41, 1871, (1994).
[6] S. C. Witczak et al., IEEE Trans. Nucl. Sci. 45, 2339, (1998).
[7] M. R. Shaneyfelt et al., IEEE Trans. Nucl. Sci. 47, 2539, (2000).
[8] M. R. Shaneyfelt et al., IEEE Trans. Nucl. Sci. 43, 865, (1996).
[9] J. Krieg et al., IEEE Trans. Nucl. Sci. 46, 1627, (1999).
[10] D. M. Fleetwood et al., IEEE Trans. Nucl. Sci. 43, 2537, (1996).
[11] J. L. Gorelick and S. S. McClure, 2000 IEEE Radiation Effects Data Workshop, pp. 6-10, Reno, Nevada.
[12] M. R. Chin and T. P. Ma, Appl. Phys. Lett. 42, 883, (1983).
[13] V. Zekeriya and T. P. Ma, IEEE Trans. Nucl. Sci. 31, 1261, (1984).
[14] A. P. Karmarkar et al., accepted for publication, IEEE Trans. Nucl. Sci. 48, (2001).

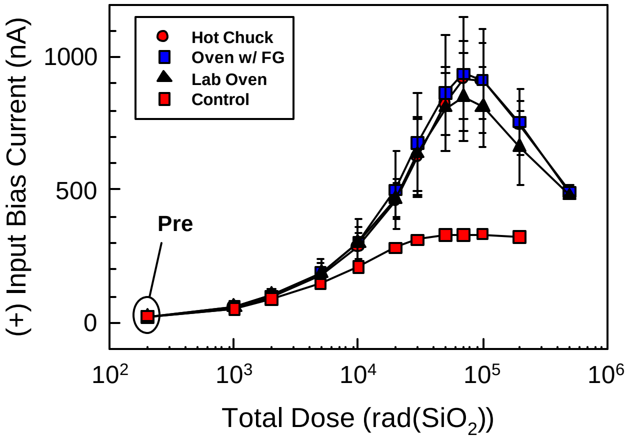

Fig. 1: I_{B+} versus total dose for LM111s irradiated at 83.3 rad(SiO$_2$)/s with all pins grounded. The LM111 were subjected to a 250 °C, 600 s PETS using three different temperature sources.

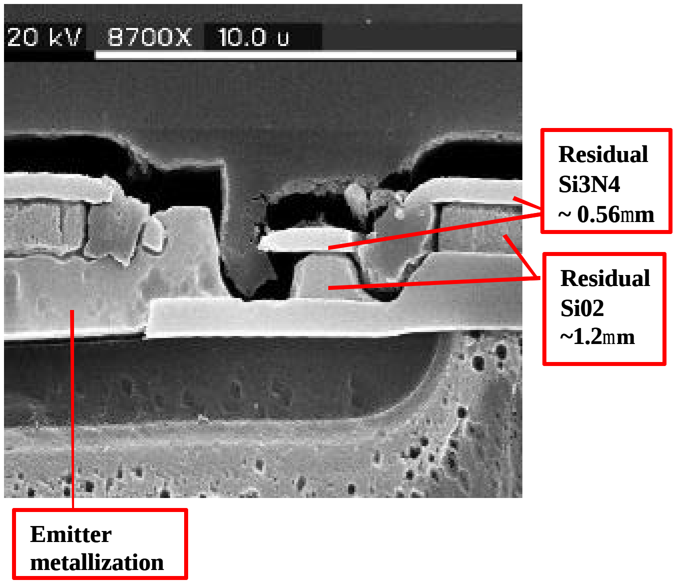

Fig. 2: SEM cross section of LM111 die after using a wet chemical process to remove a significant amount of the nitride passivation layer.

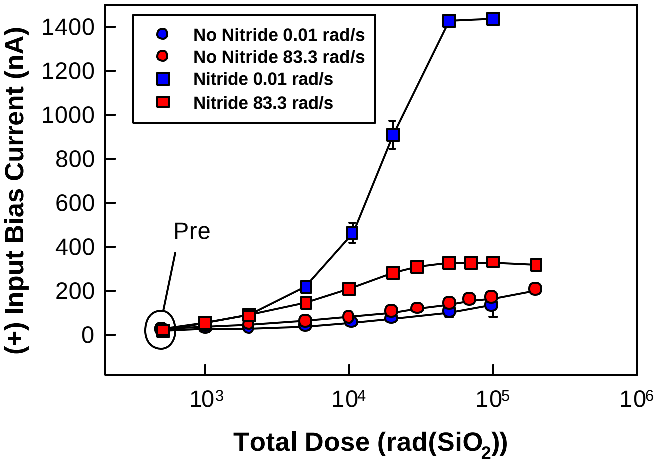

Fig. 3: I_{B+} versus total dose for LM111s with and without the nitride passivation layer irradiated at 0.01 or 83.3 rad(SiO$_2$)/s with all pins grounded.

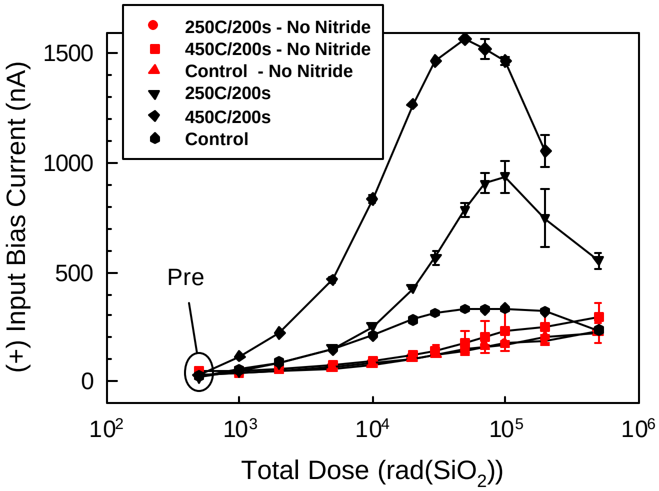

Fig. 4: I_{B+} versus total dose for LM111s exposed to PETS for 200s at a temperature of either 250 or 450 °C. The devices were irradiated at 83.3 rad(SiO$_2$)/s with all pins grounded. Devices with (black symbols) and without (red symbols) the nitride passivation layer removed were examined.

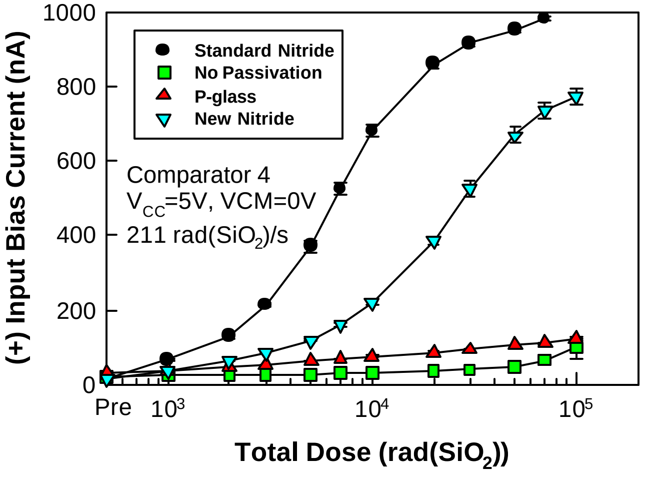

Fig. 5: I_{B+} versus total dose for LM139s with different passivation layers. The devices were irradiated at 83.3 rad(SiO$_2$)/s with all pins grounded.