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ABSTRACT

High dose rate irradiation with hydrogen stress is proposed as an accelerated total dose test method for bipolar linear circuits. The method is validated across process and circuit technologies with five parts that are commonly used in space: a comparator (LM193 from National Semiconductor), a voltage regulator (HSYE-117 RH from Intersil), a voltage reference (LT1019 from Linear Technology), a JFET input op amp (OP42 from Analog Devices) and a temperature transducer (AD590 from Analog Devices). The testing technique could rapidly establish an upper bound to the low dose rate response of parts in space and help with the part selection process in the design phase of a mission. The technology dependence and the viability of this technique are qualitatively explored using a physical model describing the dose rate response and the effect of hydrogen in bipolar technologies. The model uses four core processes: 1) space charge effects, 2) free electron/hole pair recombination, 3) hole-hydrogen defect reactions in the oxides and 4) proton depassivation of dangling bonds at the Si/SiO_2 interface. Radiation hardness assurance implications are discussed.

SUMMARY

Hydrogen (H_2) is ubiquitous in today's semiconductor integrated circuit (IC) fabrication and packaging processes [1]. During IC fabrication, it is present in wafer cleaning procedures, film depositions, etches, high and low temperature anneals and an assortment of other processes. During IC packaging, it is introduced during die attach and by gases formed during packaging processes [2]. H_2 can outgas from grain boundaries or structural imperfections in iron-nickel alloy (kovar, Alloy42) lead frame material. Electro-plated metal components such as plated gold or nickel films are major sources of dissolved hydrogen. Moisture is often present and results from the absorption or adsorption of H_2O on the internal surfaces of the package prior to sealing or from the sealing gas itself that is moist.

Solutions to hydrogen contamination have been reported and include: thermal treatment, the use of package materials with low hydrogen absorption, a change of barrier materials in gates, and the use of hydrogen getters inside the packaging to absorb the hydrogen. However, there is no clear guideline or limit as to what level of hydrogen might be considered acceptable in sealed packages. The military standard test method for internal gas analysis, MIL-STD-883 Test Method 1018, was designed to look for moisture and not hydrogen or other gas impurities. There is no specification limit out on H_2. This lack of specification introduces another unknown when dealing with the radiation response of commercial linear bipolar devices. As it will be shown in this report, their total ionizing dose (TID) response and their sensitivity to enhance low dose rate sensitivity (ELDRS) is affected.

In FY07, we reported on the impact of hydrogen contamination on the total dose response of linear circuits. A general investigation was performed on a selection of key parts from different manufacturers that both exhibit ELDRS as well as differences in the total dose degradation with bias conditions and dose rates. Residual gas analyses (RGAs) and die passivation analyses were performed on these devices. The results of this study clearly indicated that there is a correlation between ***packaging characteristics and hydrogen content***. They suggested that by only looking at the package characteristics (ceramic package with or without gold plating, with or without kovar lids, can package, passivation layers, etc.), is it possible to evaluate which category of device is likely to have a non-negligible amount of hydrogen (~0.5 to 3%) in the package and, consequently, might be sensitive to total-dose and low-dose-rate enhancement. We showed that 1) devices in can packages exhibit low amounts of hydrogen; 2) ceramic frit glass devices show negligible amounts of hydrogen; 3) parts that also have a nitride passivation layer do not show a significant quantity of hydrogen, though there is not necessarily a correlation here and 4) both cases of ELDRS and non-ELDRS were found for nitride coated devices. While silicon nitride is a very good barrier to hydrogen diffusion, the deposition processes are known to introduce hydrogen into device passivation layers. Thus, we believe it is critical to investigate the mechanisms of hydrogen asorbtion/desorption in nitride passivations.

In addition, two parts, the HSYE-117RH linear voltage regulator from Intersil and the AD590 temperature transducer from Analog Devices, were identified as parts showing a significant amount of hydrogen (~0.6 - 3%) in their package. Further experiments were conducted to identi-

fy the relationship between ***hydrogen content and total dose response***. Twelve screened space-qualified AD590s were irradiated at both high and low dose rates unbiased with all leads grounded. Three flatpacks (with 0.4 - 1% H_2) and three cans (~0% H_2) were irradiated up to 30 krad with a low dose rate (LDR) of 0.01 rad/s. Three flatpacks and three cans were irradiated up to 100 krad with a high dose rate (HDR) of 25 rad/s. In addition, two parts of the HYSE-117RH (~3 % H_2) from the same wafer lot were irradiated unbiased at a dose rate of 0.05 rad/s. One part was opened for more than a week to release the hydrogen content. The results led to the following conclusions: 1) flatpack devices degrade much more at both low and high dose rates compared to the cans due to hydrogen contamination; 2) devices in the high dose and low dose rate case degrade more as the amount of hydrogen content increases; 3) cans devices can be made to degrade similar to the flatpack when the die is exposed to H_2; 4) The devices in the high and low dose rate case degrade more as the amount of hydrogen content increases and 5) parts that have an oxide passivation are more affected by molecular hydrogen (H_2) in packages. The results clearly confirmed the correlation between ***total dose response, packaging, and hydrogen contamination***. For the HSYE-117 case, the same trends were observed but more experiments were needed with more devices to confirm. During FY09, an evaluation of twelve additional devices in three different packages (i.e., with different concentrations of H_2) was performed to compare the HDR and LDR behavior. Results, presented in this report, show the same impact of hydrogen on the total dose response.

In order to explain the underlying mechanisms that relates to the role of ***hydrogen contamination in the total dose response of linear bipolar microcircuits,*** additional work was performed at Arizona State University. A combination of modeling and experiments were conducted on gated lateral pnp (GLPNP) devices fabricated at National Semiconductor. These devices were specifically designed to study ELDRS. Experimental results showed a monotonic increase in radiation-induced interface traps (as well as oxide trapped charge) with increasing molecular hydrogen concentration in the ambient atmosphere during irradiations. Using chemical kinetics and previously developed models for interface trap formation, a first order model was proposed to describe the relationship between interface trap formation and excess molecular hydrogen concentration in gaseous ambient during radiation exposure. This model provided an excellent fit to the data obtained from the experiments.

In FY08, we focused our effort by providing a better understanding of how hydrogen impacts the ***total dose and dose rate response of linear bipolar circuits and its correlation with ELDRS***. Because hydrogen is a dominant factor determining both the total dose and dose rate responses of linear bipolar circuits, we have conducted experiments on both transistor structures and linear circuits to measure their response as a function of the externally introduced hydrogen concentration. The results of these experiments showed that the amount of hydrogen does two things: 1) it increases the degradation at low dose rate and 2) it increases the dose rates region where the transition from high dose rate to low dose rate enhancement occurs. The mechanisms for these trends were explored with a code that incorporates the basic drift-diffusion, as well as kinetic processes for hydrogen cracking and free electron hole recombination. The results from this model also indicate the saturation at low dose rate. However, further experiments at a lower dose rate were suggested to completely validate the results. Here are the main conclusions drawn from the FY08 study: 1) bipolar linear circuits should be processed and packaged with a minimum amount of hydrogen to achieve reasonable total dose hardness and minimize ELDRS. If the amount of hydrogen introduced during processing through metallization assures acceptable response, then the post metal processes should be designed to minimize any further introduction of

hydrogen; 2) if the amount of hydrogen, both initially in the base oxide and introduced after metallization is low, then the transition to ELDRS may occur at a very low dose rate. Hence, some parts that have only been tested at dose rates as low as 10 mrad/s may show enhanced degradation when taken to even lower dose rates. If this turns out to be the case, it would have severe implications for MIL-STD-883, Test Method 1019. Experiments conducted by NASA Goddard Space Flight Center are underway to explore this possibility and results will be provided in the FY10 timeframe; 3) an accelerated hardness assurance test method was suggested by testing parts at high dose rate (100 rad/s) in a 100% H_2 atmosphere to set an upper bound to the low dose rate response in space [2]. The technique is to irradiate parts, with package lids removed, in a glass tube pressurized with high concentrations of H_2 (10-100%). Parts with nitride layers will prevent any penetration of externally applied hydrogen. To use this approach for such parts, the nitride layer has to be removed. This approach has only been demonstrated on a GLPNP and one circuit type; see Fig. 1 for results.

In FY09, we proposed to investigate if FY08 results are reproducible on other part types and see if a more general method of accelerated testing using hydrogen stress could be developed. Several candidates have been selected to cover a wide range of circuit types and manufacturers. In addition, further improvements of the model have been implemented and new simulation results help us qualitatively explain the differences observed in the experiments. We investigate the impact of process variables (i.e. technology dependence) and their effect on the dose rate response in the presence of hydrogen, and demonstrate why this accelerated testing method is a viable method.

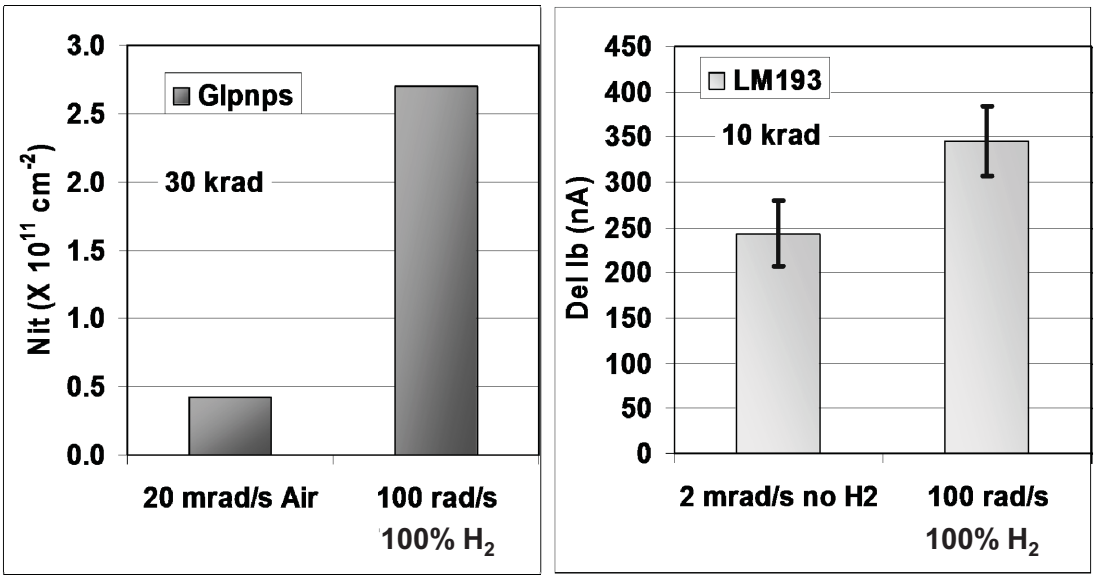

Fig. 1. Comparison of post irradiation interface traps (N_{it}) for a GLPNP transistor irradiated to 30 krad(Si) at 20 mrad(Si)/s in air to irradiation at 100 rad(Si)/s in 100% H_2 (left) and delta Ib of an LM193 from National Semiconductor to 10 krad(Si) at 2 mrad(Si)/s in air to irradiation at 100 rad(Si)/s in 100% H_2 (right).

1.0. INTRODUCTION

Enhanced Low Dose Rate Sensitivity (ELDRS) in bipolar linear circuits has been a major topic of research since it was first reported [3]-[6]. While early test results and modeling seemed to indicate that the phenomena of ELDRS was a result of the processing and thickness of the base oxide, later studies have shown that the dominate factors that affect dose rate sensitivity and the total dose response are the final passivation [7]-[9], packaging and post packaging thermal treatments [10] and the amount of hydrogen that may be trapped in the package [11]-[13]. Certain types of final passivation steps may introduce large amounts of hydrogen into the base oxide, such as the low temperature nitride process, which uses ammonia and silane. Thermal treatments can both drive hydrogen into the base oxide and alter the means by which it is incorporated in the oxide. Moreover, external sources of hydrogen can rapidly diffuse through intervening passivation layers into the base oxide [11], unless there is a barrier such as nitride [12].

In FY09, we reported that hydrogen is a dominant factor determining both the total dose and dose rate characteristics of linear bipolar circuits. Experiments conducted on transistor structures and linear circuits to measure their response as a function of externally introduced hydrogen (H_2) concentration indicated that the percent of hydrogen 1) increases the degradation at low dose rate and 2) increases the dose rate region where the transition from a high dose rate response to an enhanced low dose rate response occurs. These results suggest that a new accelerated hardness assurance test method might be possible, whereby parts are tested at a higher dose rate while exposed in a rich H_2 environment. Data obtained from such a method could rapidly establish an upper bound to the low dose rate response in space. If these results are reproducible in other part types, then a general method of accelerated testing using hydrogen stress may be developed and help in the parts selection for systems designed for space. ***This could be a major step toward a cost-effective approach in the part qualification process for space missions***. ***While it seems conservative, this approach could be a very powerful radiation hardness assurance tool***. Up to now, several accelerated testing methods have been proposed: 1) Elevated Temperature Irradiation (ETI) initially proposed by Fleetwood, et al. [16] and investigated by others [17-19]; 2) alternate high dose rate irradiation and elevated temperature anneals initially proposed by Freitag and Brown [21] and further investigated by Pershenkov, et al. [22] and 3) switched dose rate experiments proposed by Boch, et al. [23], [24]. In the ETI technique irradiation is usually performed at a temperature of ~100 °C at a dose rate of 1 rad(Si)/s or less. In the alternate high dose rate irradiation and elevated temperature anneal approach, Freitag and Brown found that for two types of op amps the following procedure worked: irradiation at high dose rate to ½ the specification dose followed by an elevated temperature anneal at 100°C for 3 hours, followed by an additional irradiation at high dose rate to ½ the specification dose, followed by another elevated temperature anneal at 100 °C for 4.4 hours [21]. The switched dose rate technique consists of irradiation at high dose rate to increasing values of total dose and then switching to low dose rate and continuing the irradiation [23, 25]. The results at low dose rate are then transposed along the dose axis to construct the low dose rate response. Although it takes many more test samples to use this approach, the total irradiation time is reduced by the number of steps used.

All of these techniques are useful; however, they all have their limitations. The number of part types investigated for each of the techniques is limited and, at least for the first two techniques,

there is no set of variables that is universal. A characterization would be required to establish the parameters and procedures for each process technology and part type to bound the low dose rate response. Also, in the case of the ETI technique the total dose is limited because irradiation at elevated temperature for extended times results in annealing that competes with the additional degradation. Hence, combining this approach with overtest will usually not work. Nevertheless, accelerated hardness assurance method development is highly desired because of the cost and time constraints associated with low dose rate testing.

Here, we investigate the extent to which molecular H_2 can be used more generally to accelerate the degradation induced by higher-rate laboratory sources in order to bound or perhaps predict the low dose rate responses of linear bipolar circuits. An argument for hydrogen-based accelerated testing is presented by providing an examination of the LM193 response as both a case study and a theoretical basis for the approach by examining one of the prevailing models in detail. The impact of process variables (i.e., technology dependence) and their effect on the dose rate response (saturation at low dose rate and transition dose rate between high and low dose rate degradation) is qualitatively explored using a 2-D finite element simulator: COMSOL Multiphysics. Four core processes are considered with this model: space charge effects [10], free electron-hole recombination [16], hole-hydrogen defect reactions in the oxides and proton depassivation of dangling bonds at the Si/SiO_2 interface. The last two processes are based on the two-stage hydrogen transport model of interface trap formation developed over the years [13, 15].

The test method is validated by providing experimental evidence on four other ELDRS sensitive candidates commonly used in space: the LT1019 voltage reference from Linear Technology, the HSYE-117 linear voltage regulator from Intersil, and the AD590 temperature transducer and OP42 JFET-input operational amplifier from Analog Devices. These five part types represent a wide range of manufacturer process technologies and circuit designs. The implications for radiation hardness assurance methodologies are discussed.

2.0. MECHANISM FOR HYDROGEN ASSISTED DOSE RATE EFFECTS

Ionizing radiation primarily degrades bipolar transistors by increasing the density of oxide trapped charge (N_{ot}) and Si-SiO_2 interface traps (N_{it}). Most of the older bipolar linear circuit technologies (still widely used today) that exhibit ELDRS use lateral and substrate pnp transistors. It is these transistors that usually dominate the degradation at low dose rate, and their degradation is dominated by N_{it}. The processes that relate interface trap buildup to bipolar transistor and circuit degradation have been studied extensively and are well understood [25-28]. Efforts to model dose rate effects have focused more on identifying the processes governing radiation-induced interface trap formation [29-34]. It is generally accepted that interface traps are formed when hydrogen-passivated dangling bonds, *Si-H*, at the oxide silicon interface react with transporting protons [42]. The well known reaction,

$$SiH + H^+ \rightarrow Si^+ + H_2 \tag{1}$$

describes this process, where Si^+ represents the generated interfacial defects. N_{it} creation is dependent on the presence of free hydrogen ions near the interface. Most theories contend that the sources of protons are hydrogen containing defects (*DH* centers) in the oxide that release H^+ upon reactions with radiation induced holes (p^+). While there are several models that describe proton release in oxides [32, 33, 35], the simplest model [24] is described by the reaction equation,

$$p^+ + DH \rightarrow D + H^+ \tag{2}$$

According to (2), the liberation of protons and therefore the generation of interface traps is dependent on both the density of *DH* centers and the probability that generated holes will survive and transport close enough to the fixed defect to react.

The combined impact of dose rate and molecular hydrogen on the generation of H^+ can be summarized, with some approximations, by the following rate equation:

$$\frac{\partial N_{H^+}}{\partial t} = k_1 p(dr) N_{DH}(H_2) - k_2 N_{H^+} N_{SiH} - \frac{\partial f_{H^+}}{\partial x}. \tag{3}$$

In (3), N_H^+ is the concentration of protons, N_{SiH} is the concentration of passivated dangling bonds, $N_{DH}(H_2)$ is the concentration of *DH* centers (function of H_2), and $p(dr)$ is the hole density in the oxide (function of dose rate). The parameters k_1 and k_2 are the reaction rate constants and f_H^+ is the proton flux. Solving (3) simultaneously with $N_{DH}(H_2)$ and $p(dr)$ enables the density of protons reacting at the interface to be calculated as a function of both dose rate and molecular hydrogen concentration. Fig. 2 plots the results of the calculation. As the figure clearly shows, *an increase in H_2 percentage accelerates the dose rate signature* by shifting the response curve upward and to the right.

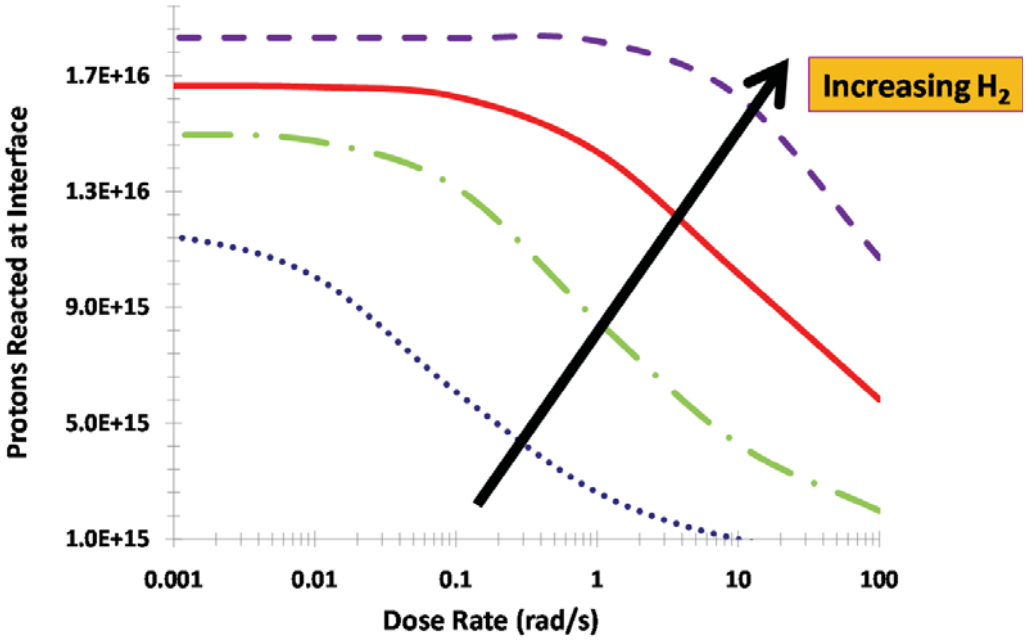

Fig. 2. Protons reacted at interface at 30 krad as a function of dose rate for different hydrogen levels based on the model defined by equation 3.

While the model presented above provides a reasonable assumption and analytical evidence that hydrogen can be used to accelerate the total dose degradation of linear devices, it is critical to demonstrate experimentally the proposed effect. In FY08, we reported the results of ionizing radiation experiments on an LM193 linear bipolar dual comparator [14]. The data, plotted in Fig. 3, represents the average increase in input bias current, Ib, versus dose rate (three or four parts for each data point) after a total dose exposure of 10 krad(Si). The four curves represent the dose rate response characteristics of: 1) unmodified COTS parts with a nitride over p-glass final passivation (nitride), 2) parts with nitride stripped off (p-glass left intact) and irradiated in a natural air environment with ~ 0% H_2 (air), 3) parts soaked in 1.0% H_2 (1%) and 4) parts soaked in 100% H_2 (100%). One data point at 1 mrad (Si)/s for the parts with nitride over p-glass has been added this year and shows the predicted saturation at low dose rate. The data presented as they are in Fig. 3 are qualitatively similar to the model results shown in Fig. 2 and provide an excellent illustration of how molecular hydrogen can be used to accelerate the dose rate response characteristics. The unmodified part's bias current represents a typical dose rate profile. At the higher rate exposures, ΔIb for the COTS part is fairly low (well within the specification limit of the part). At a dose rate near 100 mrad(Si)/s, called the transition dose rate, excess current increases dramatically. Near 2 mrad(Si)/s, the degradation seems to be saturating. This type of leveling off in the dose rate behavior is consistent with most ELDRS signatures [29, 36, 37].

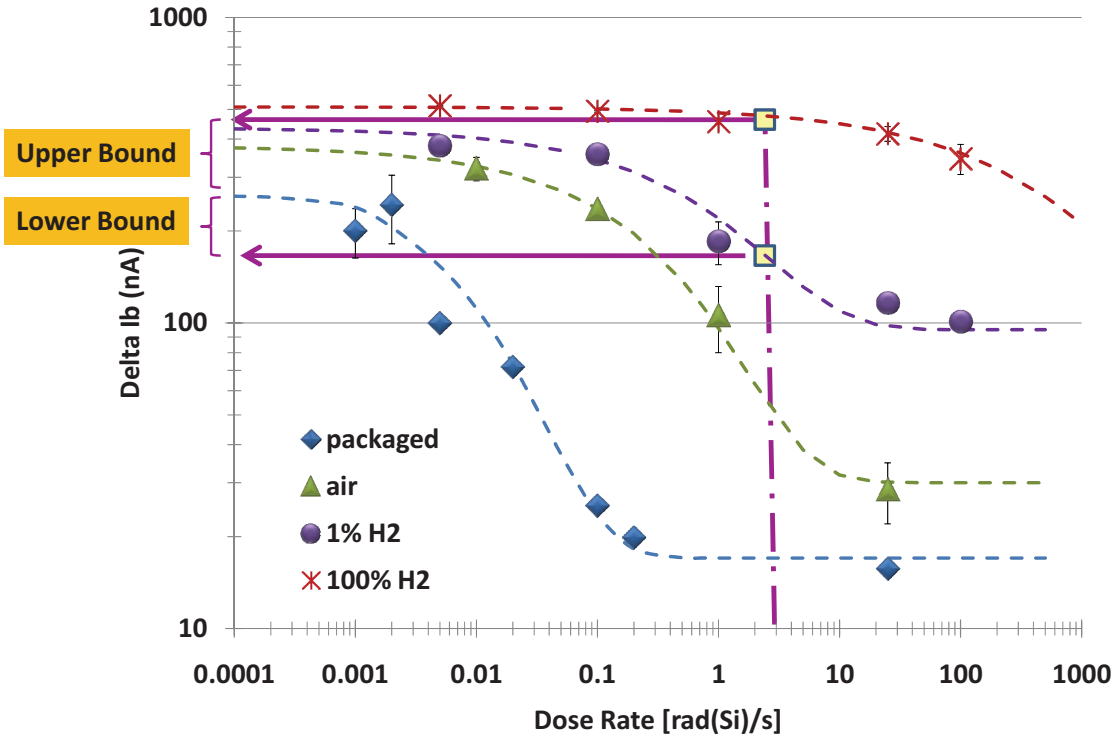

Fig. 3. Increase in input bias current vs dose rate for irradiation to 10 krad for the LM193s, with p-glass and different % H_2 and for nitride with no H_2. At 1 rad/s the 1% H_2 underestimates the low dose rate response whereas the 100% H_2 bounds it.

Irradiations performed in open air and in the hydrogen pressurized glass tubes show an upward shift in both the transition and saturation dose rates. These shifts are attributed to the diffusion of H_2 from the external gas ambient into the bipolar base oxide [15, 29]. According to [20], molecular hydrogen, after reaching an equilibrium concentration in the oxide, reacts with process-related defects (*D*) to form the hydrogen containing defect centers (DH). *The increase in DH centers accelerates degradation by increasing the rate of proton release*, Eq. (2), hastening degradation of the part.

3.0. ACCELERATED TESTING VALIDATION

Experimental data presented in this section were taken at the Jet Propulsion Laboratory (JPL). Low dose rate (LDR) and high dose rate (HDR) irradiations were performed using a Shepherd 81 Co-60 range irradiator. The irradiations with concentrations of H_2 (1-100%) were all conducted with the parts inside a sealed glass tube that was evacuated and then filled with H_2 to the appropriate partial pressure. The vacuum level in each tube before being soaked by H_2 was 10^{-3} torr. All the parts in the glass tube were soaked in the H_2 gas ambient for a minimum of 48 hours before irradiation. All dc specification parameters were measured at each dose step using an LTS2020 or ETS300 linear circuit tester.

To validate the method across technologies and circuit designs, several parts from different manufacturers were evaluated: the LT1019 voltage reference from Linear Technology, the HSYE-117 RH linear voltage regulator from Intersil, and the AD590 temperature transducer and OP42 JFET input operational amplifier from Analog Devices. Additional modeling results help provide a qualitative explanation of the experimental results observed and the different behavior between parts. A closer look at the mechanism of carrier drift/diffusion and recombination before proton release and N_{it} formation demonstrates how process variables (technology dependence) can affect the dose rate responses as a function of hydrogen, consequently impacting the selection of adequate dose rate and H_2 concentration for the proposed method.

3.1 Experimental validation on four candidates (LT1019, HSYE-117RH, AD590 and OP42)

Fig. 4 shows experimental data obtained from irradiations performed on the LT1019 voltage reference from Linear Technology. The change in reference voltage as a function of total dose is plotted for five different conditions of irradiation: HDR (50 rad/s), LDR (10 mrad/s) and HDR (50 rad/s) with 1, 10 and 100% H_2. Irradiations were performed unbiased with all leads grounded. Every data point is an average of 2-3 samples. At 30 krad, the ratio between the HDR-100% data point and the LDR data point is about 1.9. The ratio between HDR-10% data point and the LDR data point is about 1, indicating that 10% could be a more appropriate testing choice since it is much less conservative.

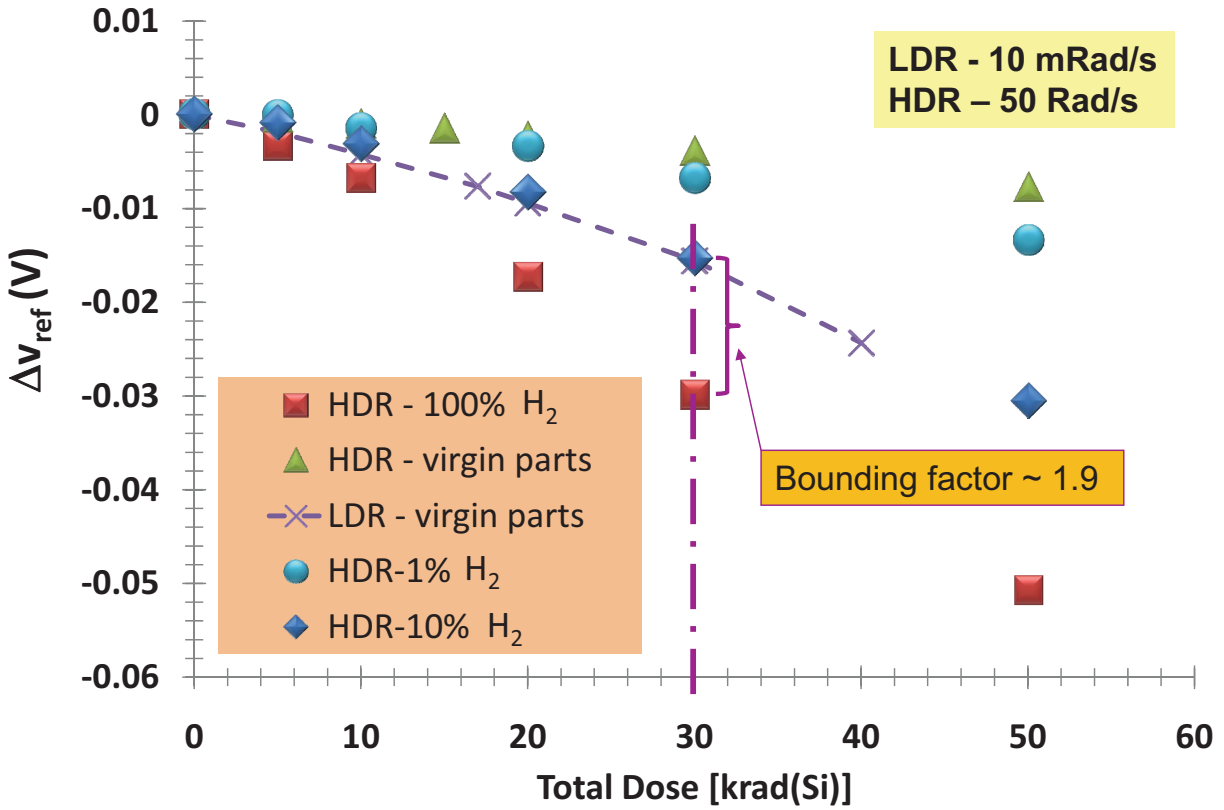

Fig. 4. Change in reference voltage for the LT1019 as a function of total dose for four irradiation conditions: HDR (50 rad/s), LDR (10 mrad/s) and (50 rad/s with 1, 10 and 100 % H_2).

Fig. 5 is a plot of experimental data obtained from irradiation performed on the HSYE-117 linear voltage regulator from Intersil. The dropout voltage at 100mA load current is plotted as a function of total dose for two conditions of irradiation: 1) twelve parts in three different packages (can TO-39 with 0% H_2, TO-220 with ~1.66% H_2 and Flatpack-SCC with ~1.9% H_2) were irradiated unbiased at a dose rate of 0.05 rad/s, and 2) two additional TO-220 parts (with the lid off and nitride removed) were irradiated with 100% H_2 at a dose rate of 50 rad/s. Once again, the HDR-100% H_2 data bound the LDR responses for all dose steps. This also applies to other susceptible parameters that exhibit enhanced degradation at low dose rate, such as the reference voltage,V_{ref}, and adjust current, I_{adj}. The interesting result is that unlike other parts, the response between the ~2% and 100% hydrogen data is saturating. The fact that Intersil uses a hardened (RSG) process with better oxide properties (possibly lower numbers of passivated interfacial bonds limiting N_{it} creation or fewer defect centers in the oxide to release protons in the presence of H_2) might explain the results. In addition, these results could indicate that the dose rate used for these experiments was somewhat high, and going to a lower dose rate (i.e., 1 rad/s) could have shown a bounding factor > 1.

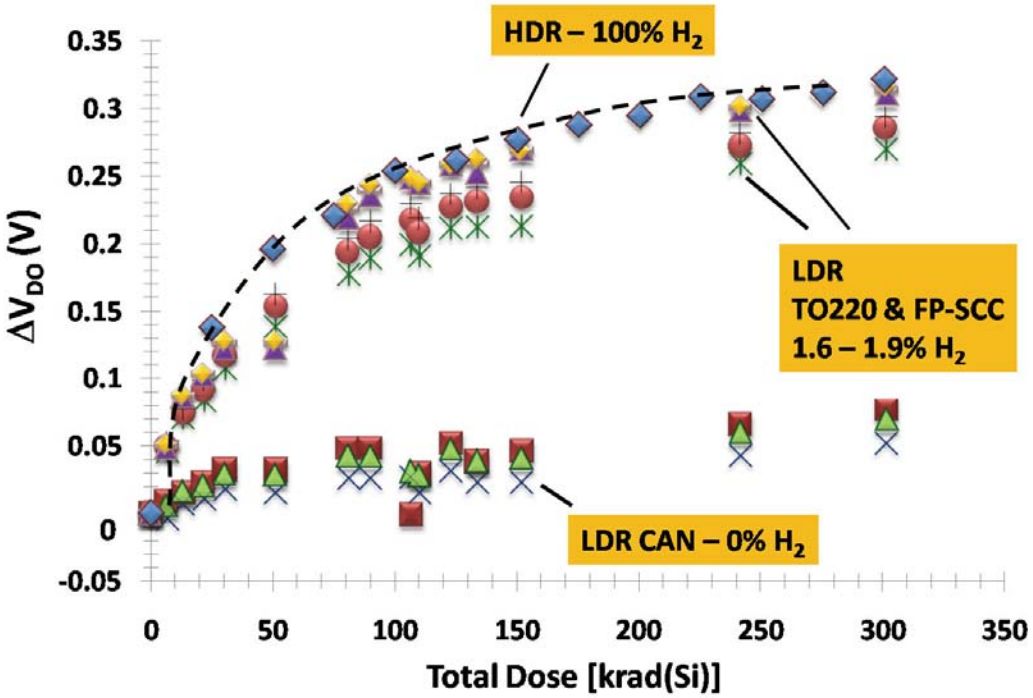

Fig. 5. Change in dropout voltage versus total dose for the HSYE-117 linear voltage regulator in three different packages (TO39, TO-220 and FP-SCC). Twelve parts were irradiated at LDR (0.05 rad/s). Two additional parts (TO-220) with the lid off were irradiated at HDR (50 rad/s) with 100% H_2.

The AD590 temperature transducer has been shown to exhibit ELDRS when irradiated in a flat-pack containing H_2 and with all leads shorted [14]. Additional tests have been performed on AD590s in both cans (no H_2) and flatpacks. Initially, twelve screened space-qualified AD590s were irradiated at both high (25 rad/s) and low (10 mrad/s) dose rates with all leads grounded. Three flatpacks (with 0.4 - 1% H_2) and three cans (~0% H_2) were irradiated up to 30 krad. The results in Figure 6 show that flatpacks degrade significantly more than cans at LDR and HDR when irradiated unbiased because of the amount of hydrogen introduced in the package. The results are compared to an accelerated test and show similar trends as those observed for the other devices. Indeed, the AD590 in cans (~0% H_2) were made to degrade similarly to the flatpacks when the die was exposed to 100% H_2 with a dose rate of 1 rad/s. Unlike with the LT1019 and HSYE-117, the HDR exposure in H_2 had to be lowered to 1 rad/s to bound the LDR response. Once again, the HDR-100% H_2 data bounds the low dose rate response for all dose steps. Note that the parts irradiated after being soaked with 100% H_2 failed earlier (dashed line on Fig. 6) than the flatpacks.

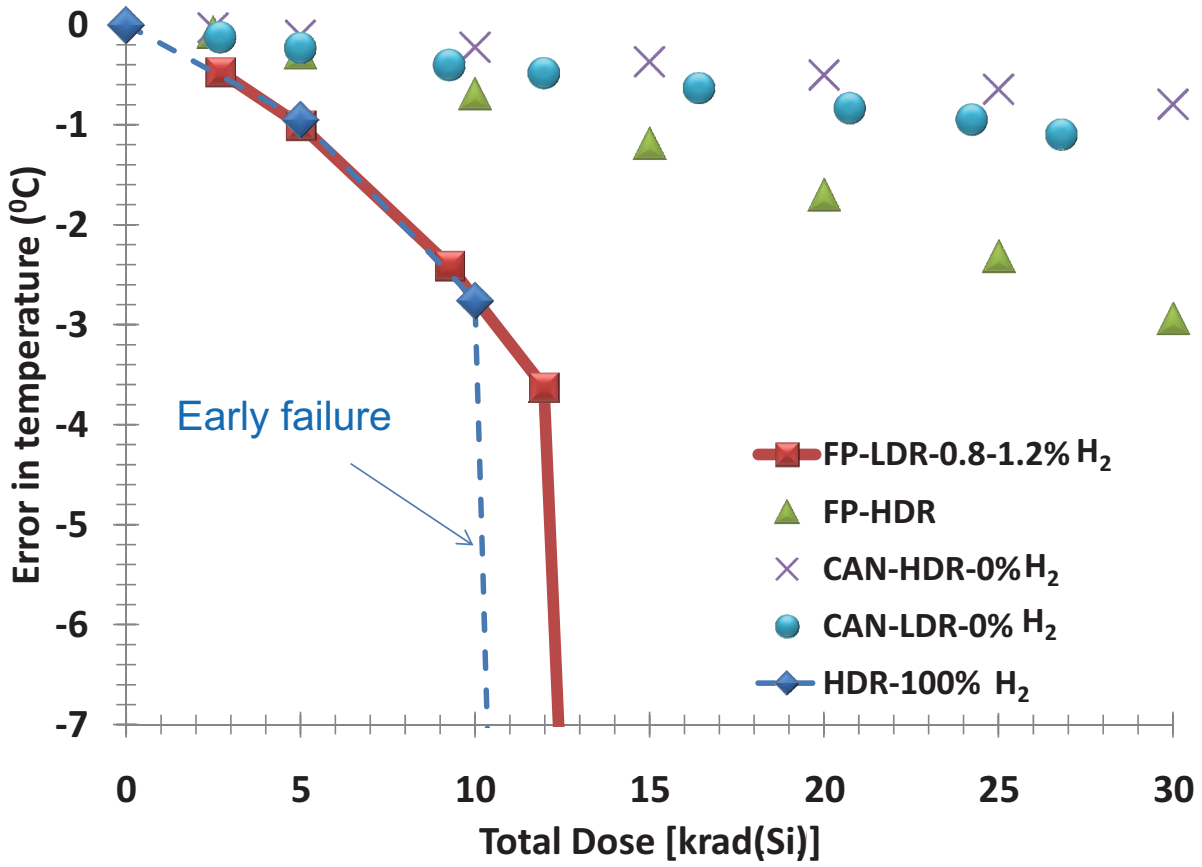

Fig. 6. Degradation of the AD590 temperature error as a function of total dose. Two groups of three flatpacks and three cans were irradiated unbiased at both high and low dose rate (respectively 25 rad/s and 0.01 rad/s). RGA was performed after irradiation on the flatpack devices to evaluate the amount of hydrogen. Three additional parts (cans) with the lid off were irradiated at HDR (1 rad/s) with 100% H_2.

Finally, a set of irradiations were performed on the OP42 JFET input op-amps from Analog Devices. Irradiation conditions were similar to the ones used in [38, 39], which was a voltage follower configuration with +/- 15 V on the supply pins. The offset voltage under biased irradiations is the critical parameter to look at, since this is the only parameter that shows an ELDRS effect and only under bias [29]. Four samples were soaked in 100% H_2 and irradiated with a dose rate of 1 rad/s. As shown in Figure 7, the hydrogenated devices show an ELDRS effect compared to the HDR response. The LDR curve at 0.04 rad/s also shows an ELDRS effect. In this case the bounding factor between the LDR curve and the HDR-H_2 curve is about 1. Once again, using hydrogen stress during irradiation at HDR can make the part degrade similarly to the one irradiated at LDR. We should indicate that additional testing is needed to find out if these OP42 devices behave the same way as compared to data presented in [38, 39]. If, for lower dose rate (< 0.04 rad/s) the device shows a larger ELDRS effect, then additional data at a lower dose rate (< 1 rad/s) will be needed to bound the LDR response. (Note that this op-amp has JFET input transistors and that irradiations were performed under bias; two different conditions compared to the other bipolar devices evaluated for this study.)

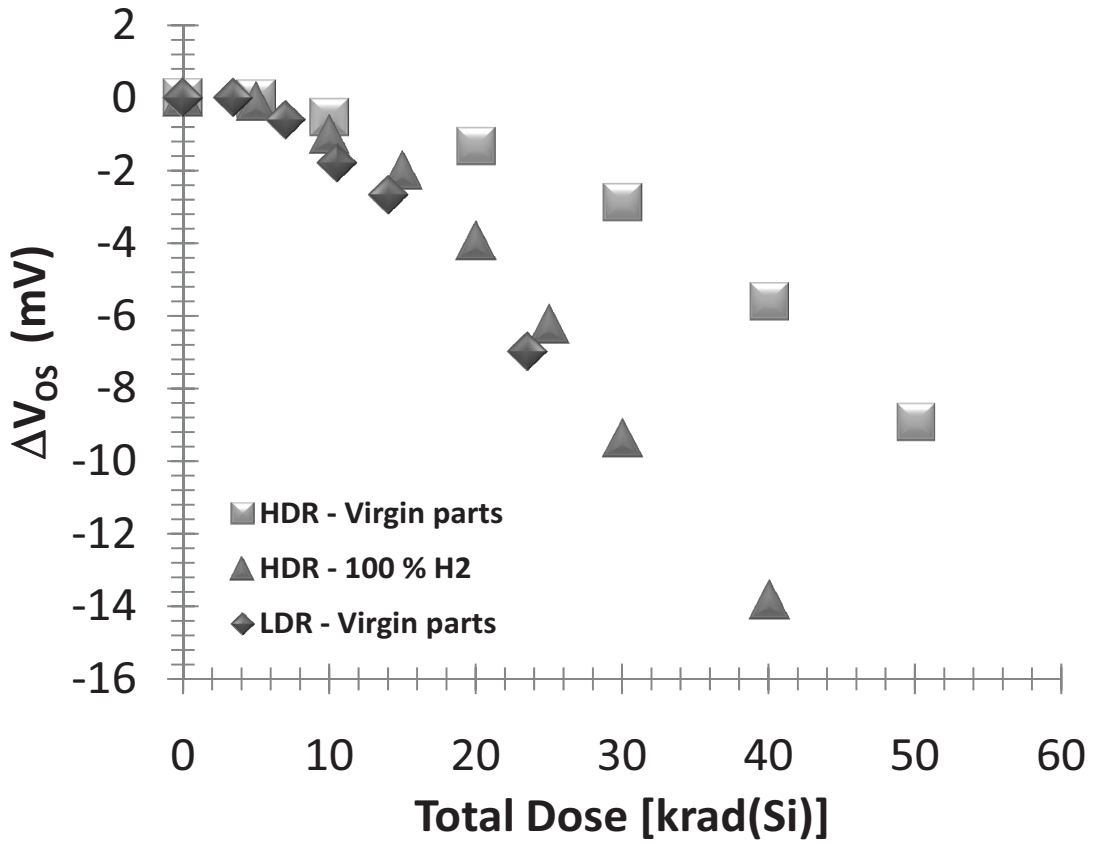

Fig. 7. Change in offset voltage versus total dose for the Analog Devices OP42. The HDR results are shown for irradiation at 50 rad/s (HDR – virgin parts) and 1 rad/s in 100% H_2 (HDR – 100% H_2), as well as a LDR result at 0.04 rad/s (LDR- virgin parts).

3.2 Experimental interpretation using 2-D simulation with COMSOL Multi-physics

Experimental results on the six parts examined in this study indicate that the bounding factor between the hydrogenated device and the virgin device at low dose rate can vary between technologies. While the LM193, LT1019, HSYE-117 and GLPNP data demonstrate that the virgin device LDR response is bounded by the 100% H_2 test at an HDR of 50-100 rad/s, this is not the case for the AD590 and OP42. Considering the data on the six part types, it is shown that using this accelerated technique there are two variables that must be adjusted to optimize the result; % H_2 and dose rate. As an example, by looking at the data in Fig. 3, one could conclude that any irradiation with 100% H_2 and a dose rate between 1 rad/s and 100 rad/s would bound the low dose rate response (dashed line) with at least a factor of 2. By looking at the 1% H_2 curve, a dose rate of 0.1 rad/s will bound the LDR response, whereas a dose rate of 1 rad/s will not (see Fig. 3). This indicates that a tradeoff exists between the high dose rate selection and the concentration of hydrogen when performing an accelerated hydrogen-based test. In this particular case, a higher concentration of H_2 would have to be selected to bound the low dose rate response. As far as other devices are concerned, there is a case (LT1019) where the data show that a 10% H_2 irradiation at a dose rate of 50 rad/s is sufficient to bound the LDR response, whereas in another case (AD590) it is not. An irradiation with a dose rate of 1 rad/s with 100% H_2 was necessary for the AD590. The main conclusion of this experimental study is that we were able to provide an upper bound for all devices considered. In addition, ***all the experimental results for this set of five circuits would indicate that a maximum dose rate of 1 rad/s associated with an hydrogen soaking of 100% are reasonable values to consider for this accelerated testing method.***

However, we observed quite a bit of difference in response between circuit types and process from different manufacturers. One could expect that devices fabricated by different technologies would most likely encounter different concentrations of hydrogen at different processing steps. In addition, it could also result in parts with drastically different oxide quality. One measure of the oxide quality is the density of oxygen vacancies. Because oxygen vacancies can react with hydrogen species [41], they can directly influence the amount of hydrogen defects that can be generated in the device. Furthermore, variations in processing temperature across different technologies can also influence the density of hydrogen species, since oxygen vacancy formation, hydrogen diffusion, hydrogen defect generation are all strong functions of temperature. The influence of temperature may be directly related to the dose rate response differences in devices with and without pre-irradiation thermal stress during burn-in or packaging [10]. The effect of passivation layers on dose rate response observed in [8] can also be attributed to hydrogen, as different passivation layers not only contain different concentrations of hydrogen—some also act as barriers to hydrogen diffusion. A layer of silicon nitride, for example, can prevent hydrogen from diffusing in and out of the device oxide because molecular hydrogen diffusivity in this material is extremely low. Different passivation layers may also require different temperatures for deposition, and this again may influence the amount of hydrogen defects generated in the device oxide. For instance, the HSYE-117 and AD590 do not have silicon nitride passivation compared to other devices tested. It is expected that parts with nitride get more stresses during the processing.

To qualitatively capture this technology dependence, we performed simulations using a finite element simulator (COMSOL Multi-physics) that captures the essential mechanism of ELDRS and the effect of hydrogen on ELDRS by modeling the transition dose rate curve on a 2-D rec-

tangular SiO_2 structure with a thickness of 1μm (representative of bipolar technology) by three main competing processes [41]: 1) carrier recombination, 2) hydrogen reaction and 3) space charge effects (more details are provided in the Appendix). Devices fabricated by different technologies would most likely encounter different concentrations of hydrogen at different processing steps. While the first order reactions (described in II) of drift/diffusion of protons and interface trap formation are valid, we took a closer look at carrier drift and diffusion, electrostatics, H_2 diffusion, and chemical reactions of H_2 cracking at oxygen vacancies before proton generation and (N_{it}) formation. Based on the two stage H-transport model [40], the simulations integrate all of the space charge effects included in the conventional space charge model by solving the Poisson's equation,

$$\frac{\partial E_{ox}}{\partial x} = \frac{q}{\varepsilon_{ox}}(p^+ - n^- + N_{H^+}), \tag{4}$$

where E_{ox} is the oxide electric field, ε_{ox} is the permittivity of SiO_2, p^+ and n^- are hole and electron concentrations, respectively, and N_{H+} is the proton concentration in conjunction with hole and electron transport/reaction equations that incorporate all of the electron-hole recombination reactions,

$$\frac{\partial p^+}{\partial t} = g_o \dot{R}_D - \sigma_{recomb} n^- p^+ - r_{H^+} p^+ N_{DHo} - \frac{\partial f_{p^+}}{\partial x}, \tag{5}$$

where R_D is the dose rate and σ_{recomb} is the electron/hole recombination constant. According to Chen et al [41], H_2 affects DH and σ_{recomb} terms in eq. 5 (see Appendix) and, consequently, the hole yield after carrier generation induced by radiation. The subsequent proton generation/transport and interface trap formation processes share the same basic equations as the hydrogen transport model presented in section 2.

Figure 8 shows the first simulation results of (N_{it}) formation as a function of dose rate for different hydrogen concentrations. Simulations show that as the hydrogen concentration is increased (by increasing DH) from DH4 to DH1, the ELDRS saturation limit increases. It also shows that by increasing σ_{recomb} (eq. 5) the transition region shifts to higher dose rates. By looking at Fig. 8, assuming that DH1 (by analogy to experimental data) is the ELDRS curve at 0% or some level of H_2, any selected dose rate between 1 and 100 rad/s on the DH4 curves (corresponding to a high level of H_2) bounds the LDR response. This is an ideal case and very representative of the LM193 data. However, it is expected that significant differences in dose rate response will be seen across technologies with different process variables, since oxide properties will directly affect σ_{recomb} and how H_2 is converted to DH (eq. 5). As a result, from part-to-part, the transition dose rate curves could be in some cases close to each other, independent of the level of H_2.

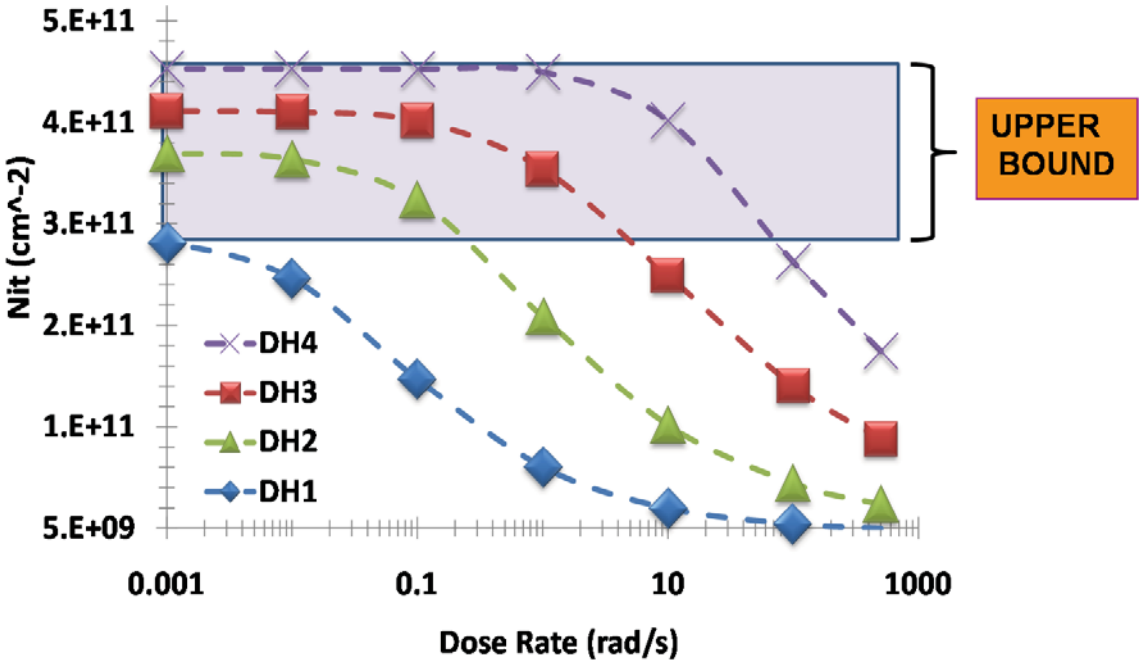

Fig. 8. Simulation of N_{it} formation as a function of dose rate for different hydrogen concentrations. Simulations capture the right shift of transition dose rates and the increase of low dose rate saturation limit. In these simulations, *DH4* > *DH3* > *DH2* > *DH1* and $\sigma 4 < \sigma 3 < \sigma 2 < \sigma 1$.

A second set of simulations was performed to illustrate how the transition dose rate curve is changed by fixing DH2 and DH3 at the same value and changing the σ_{recomb} term with a small value (representative of a process variation). The results clearly show the increase in transition dose rate when $\sigma 3 < \sigma 2$ and DH2 and DH3 are equal.

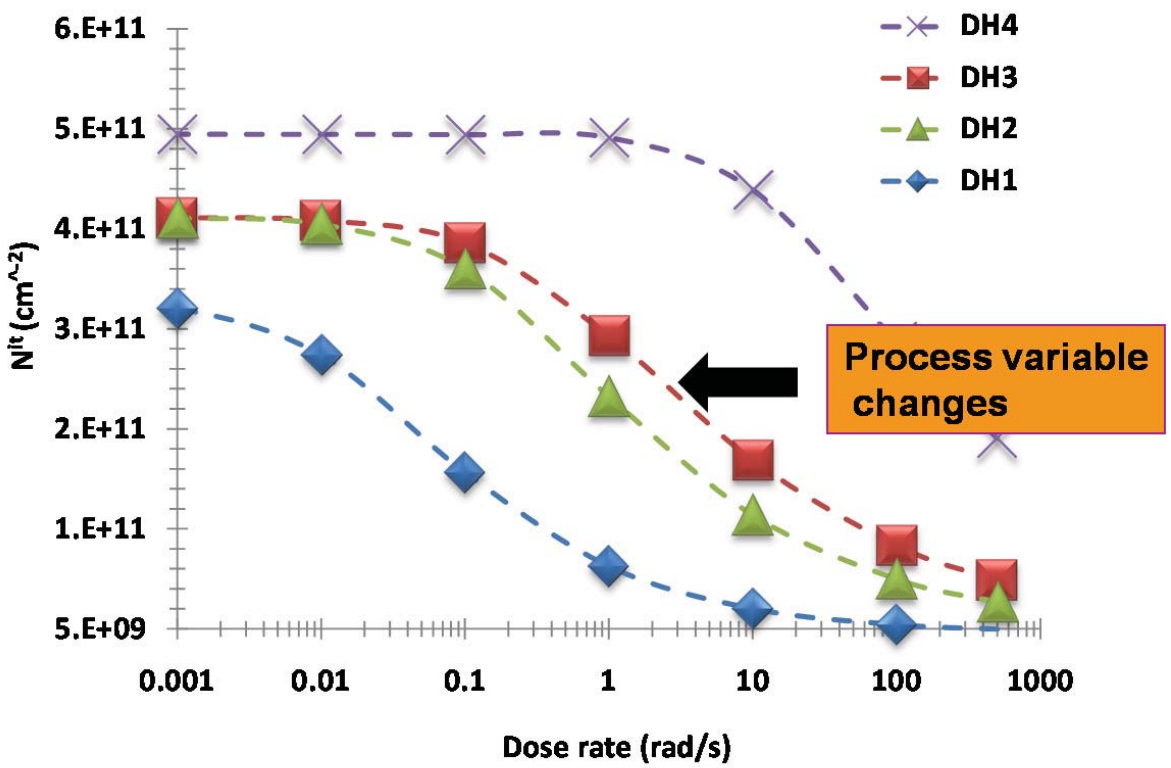

Fig. 9. Simulation of N_{it} formation as a function of dose rate for different hydrogen concentrations. In these simulations, there are *DH4* > *DH3* = *DH2* > *DH1* and $\sigma 4 < \sigma 3 < \sigma 2 < \sigma 1$.

Fig. 10 shows a third case where all DH values are constant and the σ_{recomb} term vary with a larger value capturing the right shift of the transition dose rate curve.

3.3 Conclusion

To conclude, it appears that the proposed hydrogen-based accelerating testing technique is a viable technique because there is no case where we were unable to bound the LDR response with a reasonable dose rate and concentration of H_2. However, because of the process variables (technology dependence) a characterization would be required for each process and circuit type to establish the appropriate dose rate and H_2 concentration for the test. Using the effect of hydrogen, the model can produce different variations of ELDRS observed in literature. By changing the hydrogen defect densities in the oxide, and/or adjusting its functional relationship with e^-/h^+ recombination coefficient in (10), different combinations of dose rate responses can be produced by the simulator.

4.0. RADIATION HARDNESS ASSURANCE IMPLICATIONS

The proposed hydrogen-based testing method could fit with Condition E of the US standard test method for total ionizing dose, MIL-STD-883/Test method 1019. This standard is based on a characterization of ELDRS parts to demonstrate an accelerated test method and is widely used by agencies. A flow diagram for ELDRS testing is shown in Fig. 11.

The test to determine if a part is ELDRS sensitive involves testing parts at high and low dose rate to the specification level and comparing the degradation at low dose rate to high dose rate. If the ratio (enhancement factor) for any sensitive parameter is > 1.5, the part is considered ELDRS. The main question about the baseline low dose rate ELDRS test is whether the dose rate of 10 mrad(Si)/s is low enough. This dose rate was chosen based on a large database including the data presented in various ELDRS data compendia [39-41]. Data presented in section 2, Fig. 3, indicate that the LM193 does not exhibit a large increase in low dose rate enhancement factor until the dose rate is below 10 mrad(Si)/s. Data also show that degradation saturates below 2 mrad(Si)/s (see fig. 3). Several tests are currently being performed on many part types below 10 mrad(Si)/s to see how serious this issue may be. Testing at 10 mrad(Si)/s requires an irradiation time of about 6 months to 150 krad(Si) to qualify a part to 100 krad(Si) using Condition D of TM1019. Reducing the dose rate requirement would be an even greater inconvenience for qualification and lot acceptance of ELDRS parts. *The desired solution is the development of an accelerated test*.

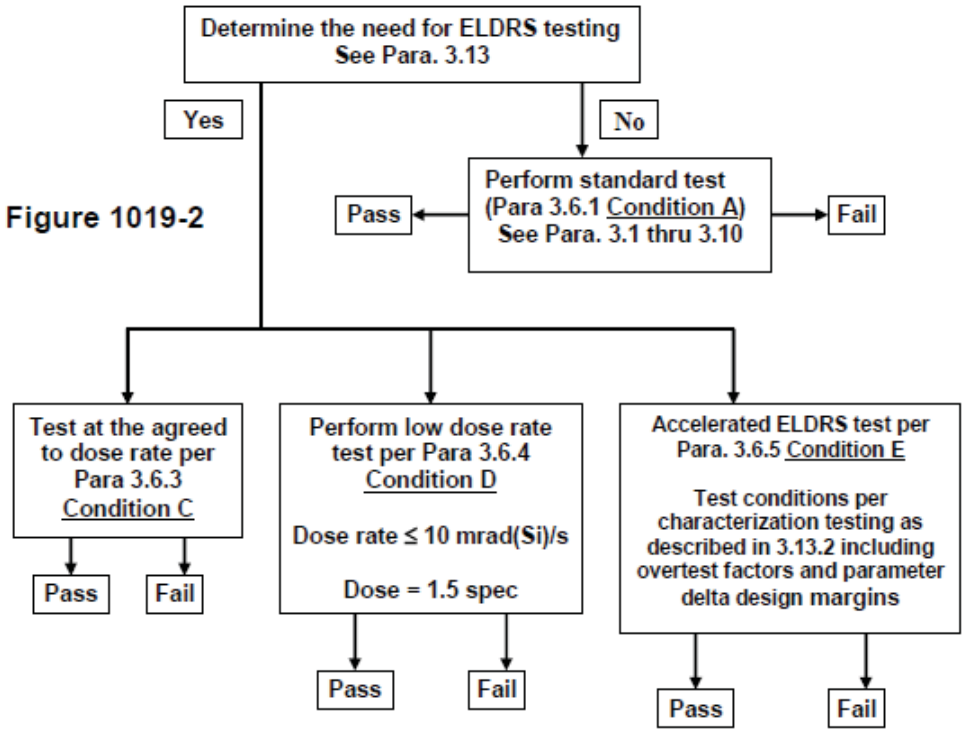

Fig. 10. Flow diagram for ELDRS testing from Test Method 1019.7

The proposed accelerated hardness assurance test method, where parts are tested at a higher dose rate while exposed in a rich H_2 environment, is proposed as an alternative to these other existing accelerated test techniques [16-24]. While at this point we cannot claim that this technique will be universal, we showed that it can be used as a screen for bipolar linear circuits in the part selection process in the early design phase of a space system. When used in this manner it is suggested that the test be performed at a dose rate of ***1 rad/s in 100% H_2***. If the parts show unacceptable degradation alternative parts may be selected.

The technique may also be used as an accelerated qualification or lot acceptance test for parts that exhibit ELDRS. In this case the parts would be tested under Condition E of Test Method 1019. A characterization test would need to be performed to establish the dose rate and H_2 concentration for the test so that the result would bound the LDR response. Based on the results shown here a starting point would be a dose rate of 1 rad/s and an H_2 concentration of 100%. If the parts have a final passivation layer of nitride, it would need to be removed before exposure to the H_2 environment. To assure adequate margin over the low dose rate response, one could incorporate an overtest and/or a parameter delta design margin as described in the test method. There should be no problem with an over-test such as the problem with the ETI approach.

CONCLUSION

The proposed method of accelerated testing using high dose rate irradiations in environments with elevated concentrations of H_2 have been tested on six different parts types representing a wide variation in manufacturer, process technology and circuit design (GLPNP, LM193, AD590, LT1019, OP-42 and HSYE-117). In all cases, results are very promising. Such a technique may have a large beneficial impact on radiation hardness assurance for bipolar linear technologies. Compared to low dose rate testing, hydrogen-enhanced testing at high dose rates can be a very cost effective approach for part selection during the design phase of space systems. It also may be considered for missions that require higher dose levels for qualification where low dose rate testing is not practical. For use as a qualification or lot acceptance test method, a characterization test would need to be performed to establish the optimum dose rate and H_2 concentration to bound the LDR response. Further experimental data are required to consolidate the method proposed. For example tests need to be performed on rad hard non-ELDRS parts to show that the proposed test would not result in rejection of those parts. Additional tests on parts whose low dose rate response is dominated by npn transistors need to be performed as well.

The experimental work is supported by a physical model that is based on four core mechanisms describing the dose rate response and the effect of hydrogen in bipolar technologies. These core mechanisms are: space charge effect, free electron-hole recombination, hole-hydrogen defect reaction in the oxide, and proton depassivation of dangling bond at the Si/SiO_2 interface. Simulation results show that the change in hydrogen concentration in the device oxide causes shifts in low dose rate saturation limit as well as in transition dose rates. These changes provide strong evidence that variations observed in bipolar device dose rate behaviors across different technologies are due to the effects of hydrogen, the common ingredient in many fabrication and packaging technologies.

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APPENDIX: MORE DETAILED PHYSICAL MODEL

When a bipolar transistor is exposed to ionizing radiation, electron/hole pairs are generated uniformly throughout the isolation oxides above the active silicon layers (primarily base region). At higher dose rates, large local E-fields in these oxides induced by substantial space charge buildup not only limit the transport of charged species, they also stimulate competition of other processes that can reduce the generation of interface traps and trapped charge. Such processes include: free electron/hole recombination, trapped electrons recombining with free holes [43], and free electrons recombining with trapped holes 32]. While, relative to holes, electrons in oxides are highly mobile, because of the high localized E-fields induced at high dose rates, electrons can be confined in the oxide for extended periods. As more electrons are confined in the oxide, the probability of their being trapped and/or recombining with holes becomes higher. The model presented here treats free electron/hole recombination as a core mechanism for dose rate effects.

Model description:

In this model, the free electron/hole recombination reaction is coupled with carrier transport (modeled as drift and diffusion). This process can be described by

$$\frac{\partial p^+}{\partial t} = g_o \dot{R}_D - \sigma_{recomb} n^- p^+ - r_{H^+} p^+ N_{DH} - \frac{\partial f_{p^+}}{\partial x} \tag{1}$$

and

$$\frac{\partial n^-}{\partial t} = g_o \dot{R}_D - \sigma_{recomb} n^- p^+ - \frac{\partial f_{n^-}}{\partial x}, \tag{2}$$

where $\dot{R}_D$ is the dose rate, g_o is the dose rate to carrier generation rate conversion factor, σ_{recomb} is the electron/hole recombination reaction coefficient, N_{DH} is the density of hydrogen-containing defects, r_{H+} is the hole-hydrogen defect reaction rate constant, and f_n- and f_{p+} are the fluxes of electrons and holes which are modeled with drift and diffusion components as follows,

$$f_{n^-} = \mu_{n,ox} n^- E_{ox} + D_{n,ox} \frac{dn^-}{dx} \tag{3}$$

and,

$$f_{p^+} = \mu_{p,ox} p^+ E_{ox} - D_{p,ox} \frac{dp^+}{dx} \quad . \tag{4}$$

The second key process for the proposed model is the hole/hydrogen defect reaction coupled with proton transport.

This process was first proposed by [44], and can be described by the continuity equation

$$\frac{\partial H^+}{\partial t} = N_{DH} \sigma_{DH} p^+ - \left[N_{Si-H} - N_{it}(t)\right] \sigma_{it} H^+ - \frac{\partial f_{H^+}}{\partial x}, \tag{5}$$

where H^+ is the density of protons, σ_{DH} is the hole/hydrogen defect reaction rate constant, and f_{H+} is the proton flux,

$$f_{H^+} = \mu_{H^+,ox} N_{H^+} E_{ox} - D_{H^+,ox} \frac{dN_{H^+}}{dx}. \tag{6}$$

The term N_{it} is the density of interface traps, N_{Si-H} is the density of passivated dangling bonds, and σ_{it} is the reaction rate constant associated with the well-known interface trap generation process between protons and passivated dangling bonds at the Si/SiO_2 interface. Trap generation is described by

$$\frac{\partial N_{it}}{\partial t} = \left[N_{Si-H} - N_{it}(t)\right] \sigma_{it} H^+ - \frac{N_{it}(t)}{\tau_{it}}, \tag{7}$$

where τ_{it} is lifetime associated with the annealing of interface traps. Finally, the effect of space charge generated in the device oxide is also modeled through Poisson's equations,

$$\frac{\partial E_{ox}}{\partial x} = \frac{q}{\varepsilon_{ox}}(p^{+} - n^{-} + H^{+}) \tag{8}$$

where E_{ox} is the electric field and ε_{ox} is the permittivity of the oxide.

There are certainly other processes that likely occur during irradiation. The trapping/detraping processes of electrons, holes and protons, the reactions of molecular hydrogen with oxygen vacancies [41], the trapping of holes at neutral sites (e.g., oxygen vacancies) and subsequent cracking of H_2 and proton release [32], the passivation reaction of silicon dangling bonds and more. However, in these processes may be considered secondary because, as simulation results indicate, the core processes described here can still reasonably describe the dose rate response of bipolar devices.

Modeling the effect of hydrogen:

Using this model, the effect of molecular hydrogen can be implemented as a disturbance to the core processes responsible for the dose rate response, particularly the recombination process of electrons and holes in eqs. (1) and (2), and the hole/hydrogen defect reaction process in (3). In recent TID studies on the effects of H_2 [41, 29] , it was demonstrated that H_2 can diffuse into device oxide and react at defect centers (conceivably shallow level oxygen vacancies) to generate shallow level hydrogen defects. According to Henry's law [45], the saturated hydrogen concentration in the bipolar oxide can be as high as 10^{18} cm^{-3}. High concentrations of hydrogen defects in the oxide can have significant impact on two key terms in the model: 1) proton generation rate and 2) electron/hole recombination coefficient due to competition with carrier hoping [46]. The e^{-}/h^{+} recombination process described here is assumed to be a bimolecular recombination process and therefore can be described by the rate equations (continuity equations) in (1) and (2). According to [46], the total rate of recombination can be attributed to two factors, one is the rate at which an electrons and holes transport toward one another, and the other is the efficiency with which an electron and hole recombine at close proximity. The rate constant for bringing free carriers in close proximity is defined by

$$\beta = \frac{q(\mu_n + \mu_p)}{\varepsilon_{ox}} \tag{9}$$

where, according to ionic recombination theory [47], μ_n and μ_p are respective effective mobilities of electrons and holes in the oxide. The recombination efficiency is defined as, η, which is determined by the competition between carrier recombination and carrier hopping through localized defects. If it is assumed that the increase in hydrogen defects enhances competition between hopping and recombination, the overall recombination coefficient expressed in eq. (1) and (2) can be written as,

$$\sigma_{rcomb} \approx \beta(\mu_n, \mu_p) \cdot \eta(H_2) \tag{10}$$

where the recombination efficiency, η, is now a decreasing function of hydrogen density. Using this approach in combination with the effect of hydrogen on proton generation rate, the simulation of the effect of hydrogen on the dose rate response can be performed.

The effect of hydrogen was thus implemented in the COMSOL simulator without increasing the number of simultaneous equations to minimize complexity and simulation time. This means that the model does not take into account the process of molecular hydrogen diffusion, and the reaction that generates hydrogen defects. Instead, the hydrogen defect concentration, N_{DH} in eqs. (1) and (5), is assumed to be distributed uniformly in the oxide and increases with the molecular hydrogen concentration used during soaking experiment or during processing. It should be noted also that the simulation results from the physical model presented here are only obtained with steady state assumptions to reduce complexity and

simulation time. The steady state assumption is most accurate at low dose rates, but become less accurate at high dose rates due to dramatic changes in concentrations of species over time. Nonetheless, the simulation results are in excellent qualitative agreement with experimental data.