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Office of Safety and Mission Assurance

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ABSTRACT

An accelerated total ionizing dose (TID) hardness assurance test for enhanced low-dose-rate-sensitive (ELDRS) bipolar linear circuits, using high-dose-rate tests on parts that have been exposed to molecular hydrogen, has been proposed and demonstrated on several ELDRS part types. In this study, several radiation-hardened ELDRS-free part types have been tested using this same approach to see if the test is overly conservative. Radiation hardness assurance implications are discussed.

SUMMARY

Molecular 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 forming gases during packaging processes [2]. H_2 can outgas from grain boundaries or structural imperfections in iron-nickel alloy (kovar, Alloy42) lead frame material. Electroplated 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 moisture within the sealing gas itself.

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 available for 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 enhanced low-dose-rate sensitivity (ELDRS) are 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.), it is possible to evaluate which category of device is likely to have a non-negligible amount of hydrogen (~0.5–3%) 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 absorption/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 showing a significant amount of hydrogen (~0.6–3 %) in their package. Further experiments were conducted to identify the relationship between ***hydrogen content and total dose response***. Twelve screened space-qualified AD590s were irradiated at both high and low dose rates (LDRs) unbiased with all leads grounded. Three flat packs (with 0.4–1% H_2) and three cans (~0% H_2) were irradiated up to 30 krad(Si) with a low dose rate (LDR) of 0.01 rad(Si)/s. Three flatpacks and three cans were

irradiated up to 100 krad(Si) with a high dose rate (HDR) of 25 rad(Si)/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(Si)/s. One part was opened for more than a week to release the hydrogen content. The results led to the following conclusions: 1) flat pack devices degrade much more at both low and high dose rates compared to the cans due to hydrogen contamination; 2) devices in the HDR and LDR case degrade more as the amount of hydrogen content increases; 3) cans devices can be made to degrade similarly to the flat pack when the die is exposed to H_2; 4) the devices in the HDR and LDR 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 12 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 relate 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 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 on 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 in 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 LDR, and 2) it increases the dose rates region where the transition from HDR to LDR 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 LDR. However, further experiments at a lower dose rate were suggested to completely validate the results. The following 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 ensures an 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(Si)/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 within the FY10 timeframe.
3. An accelerated hardness assurance test method was suggested by testing parts at HDR (100 rad(Si)/s) in a 100% H_2 atmosphere to set an upper bound to the LDR response in space [3]. The technique is to irradiate parts with package lids removed in a glass tube pressurized with high concentration 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 test transistor and one circuit type; Figure 1 displays the results.

In FY10, the proposed method of accelerated testing using HDR irradiations in environments with elevated concentrations of H_2 was 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 were very promising. Such a technique may have a large beneficial impact on radiation hardness assurance for bipolar linear technologies. Compared to LDR testing, hydrogen-enhanced testing at HDRs 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 LDR 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.

In FY11, further experiments were required to consolidate the method proposed particularly for non-ELDRS parts. This report evaluates if the method is too conservative for radiation-hardened, ELDRS-free parts and discusses radiation hardness implications.

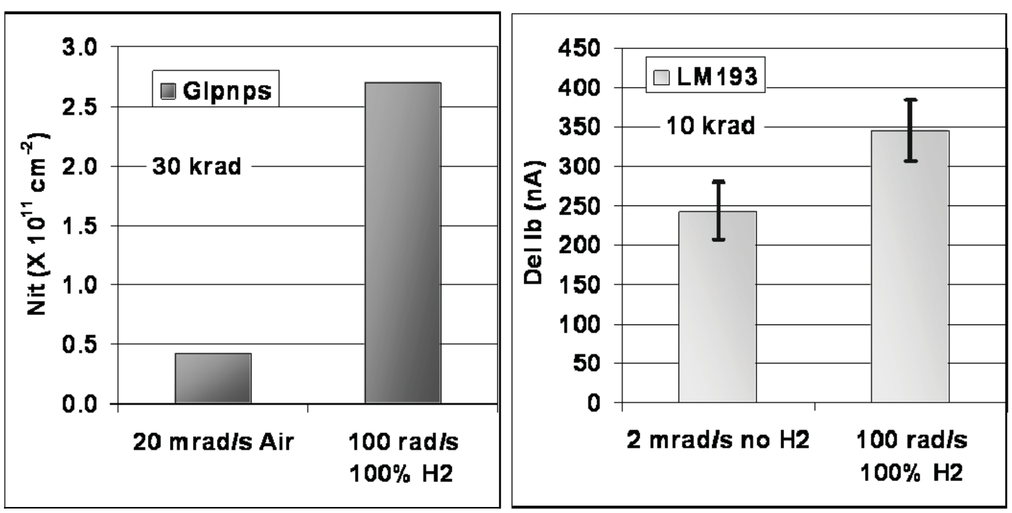

Figure 1. Comparison of post-irradiation interface traps (Nit) for a gated lateral PNP (GLPNP) transistor irradiated to 30 krad(Si) at 20 mrad(Si)/s in air to irradiation at 100 rad(Si)/s in 100% H_2 (left), and delta Ib of an LM193 from NSC to 10 krad(Si) at 2 mrad(Si)/s in air to irradiation at 100 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 [4–7]. While early test results and modeling seemed to indicate that the phenomenon of ELDRS was a result of the processing and thickness of the base oxide, later studies have shown that the dominant factors that affect dose rate sensitivity and the total dose response are the final passivation [8–10], packaging and post-packaging thermal treatments [11], and the amount of hydrogen that may be trapped in the package [12–14]. 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 [12], unless there is a barrier such as nitride [13].

In FY08, we reported that hydrogen is a dominant factor determining both the total dose and dose rate characteristics of linear bipolar circuits. Experiments conducted on both transistor structures and linear circuits to measure their response as a function of the externally introduced molecular hydrogen (H_2) concentration indicated that the percent of hydrogen: 1) increases the degradation at low dose rate (LDR) and 2) increases the dose rate region where the transition from a high dose rate (HDR) response to an enhanced LDR 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 LDR 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. [15] and investigated by others [16–18]; 2) alternate HDR irradiation and elevated temperature anneals, initially proposed by Freitag and Brown [19] and further investigated by Pershenkov et al. [20]; and 3) switched dose rate experiments proposed by Boch et al. [21, 22]. 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 HDR irradiation and elevated temperature anneal approach, Freitag and Brown found that for two types of op amps the following procedure worked: irradiation at HDR to half the specification dose, followed by an elevated temperature anneal at 100°C for 3 hours, followed by an additional irradiation at HDR to half the specification dose, followed by another elevated temperature anneal at 100°C for 4.4 hours [19]. The switched dose rate technique consists of irradiation at HDR to increasing values of total dose and then switching to LDR and continuing the irradiation [21, 22]. The results at LDR are then transposed along the dose axis to construct the LDR 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. Hence, a characterization would be required to establish the parameters and procedures for each process technology and part type to bound the LDR 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. Combining this approach with an overtest will usually not work. Nevertheless, the development of an accelerated hardness assurance method is highly desired because of the cost and time constraints associated with LDR testing.

In FY09, we investigated 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, LDR responses of linear bipolar circuits. An argument for hydrogen-based accelerated testing was presented by providing both an examination of the LM193 response as 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 its effect on the dose rate response (saturation at LDR and transition dose rate between HDR and LDR degradation) was qualitatively explored using a 2-D finite element simulator: COMSOL Multiphysics. Four core processes are considered with this model: 1) space charge effects [11], 2) free electron-hole recombination [15], 3) hole-hydrogen defect reactions in the oxides, and 4) proton de-passivation 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 [14, 3].

The proposed method was tested on six different ELDRS 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 were very promising. It was judged that such a technique may have a large beneficial impact on radiation hardness assurance for bipolar linear technologies. Compared to LDR testing, hydrogen-enhanced testing at HDRs 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 LDR 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.

In FY10, further experiments were required to consolidate the method proposed particularly for non-ELDRS parts. This report evaluates if the method is too conservative for radiation-hardened, ELDRS-free parts and discusses the implications of such results.

2.0 EXPERIMENTAL DETAILS

The accelerated hardness assurance technique using molecular hydrogen (H_2) is best utilized on parts that are packaged in hermetic packages. The package lids must be removed so that the microcircuit die can be exposed directly to H_2. If plastic packages are used, the plastic must be etched away over the surface of the die. Parts with a silicon nitride passivation must have the nitride removed, for example, by plasma etching. The exposure to H_2 is done in evacuated glass tubes (10^{-5} torr), shown in Figure 2, that are backfilled to various controlled partial pressures of H_2. In these experiments, exposures to H_2 were done at three different pressures to achieve H_2 concentration such as 1%, 10%, or 100%. Several space-qualified, ELDRS-free part types were selected and obtained from National Semiconductor Corporation (NSC). These included the LM136 voltage reference, the LM2941 low-dropout voltage regulator, the LM124 quad operational amplifier, and the LM139 quad voltage comparator. LDR data on the LM2941 and LM136 were published in the Radiation Effects Data Workshop last year by NSC [25, 26]. LDR data on the LM124 and LM139 were published in 2008 [6]. All four of these part types have been demonstrated to be hard to 100 krad(Si) at both HDR (50–300 rad(Si)/s) and LDR (10 mrad(Si)/s) for irradiation under both biased and unbiased conditions [25–27]. In addition, the LM2941 was tested at 1 mrad(Si)/s up to 20 krad(Si) and was shown to be ELDRS-free.

To ensure that the results are not unique to one process technology, several ELDRS-free part types from other manufacturers were added. One ELDRS-free RH1009 voltage reference was obtained from Linear Technologies, and two radiation-hardened discrete bipolar transistors, a 2N2222A and a 2N2907A, were obtained from Semicoa.

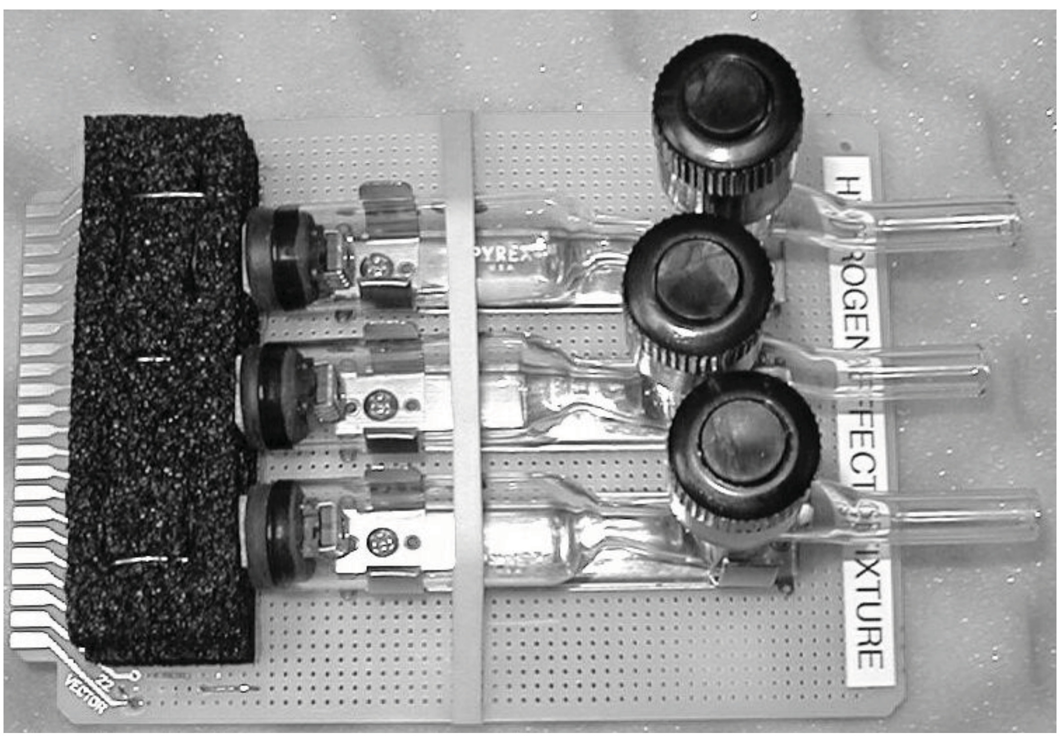

Figure 2. Picture of glass tubes used by JPL for exposure in H_2.

Samples of three to six parts of each type were delidded and placed inside evacuated glass tubes. Note that all the parts have no silicon nitride passivation, which is a barrier to hydrogen. Parts were soaked in the H_2 gas ambient for a minimum of 48 hours before irradiation. The electrical parameters that were monitored, before and after exposure to H_2 and after each irradiation step, were the same ones used by the manufacturers in their irradiation testing. All irradiations were performed with all leads shorted at dose rates of 1 rad(Si)/s or 10 rad(Si)/s using a Shepherd 81 cobalt-60 source at JPL. Post-irradiation electrical measurements were made at several intermediate dose levels up to 100 krad(Si).

Table 1 lists the part types, manufacturers, package types, dose rates, percent H_2 used, and step-stress dose levels.

Table 1. List of part types used in the study along with irradiation information.

Manufacturer	Part Type	Package	Date Code	H_2 (%)	Dose Rate (rad/s)	Dose (krad)	Sample Size
NSC	RM124AJRQMLV	14 pin CDIP	*0514*	100	10	10, 20, 30, 50	3
NSC	RM139AJRQMLV	14 pin CDIP	*0527*	1	10	10, 20, 30, 50, 75, 100	6
NSC	RM139AJRQMLV	14 pin CDIP	*0527*	100	10	10, 20, 30, 50	3
NSC	RH136AH2.5RQMLV	TO-46		100	1	10, 20, 30, 40, 50, 75, 100	3
NSC	RM2941JXQMLV	16 pin CDIP	*0911*	100	1	10, 20, 30, 40, 50, 75, 100	3
Linear Tech	RH1009MW	10 pin FP	*0649*	1	10	10, 20, 30, 50, 75, 100	6
Semicoa	2N2222A	TO-18	*0739*	10	10	10, 20, 30, 50, 75, 100	6
Semicoa	2N2907A	TO-18	*0804*	10	10	10, 20, 30, 50, 75, 100	6

3.0 EXPERIMENTAL RESULTS—OP AMP AND COMPARATOR

3.1 NSC LM124

The LM124 quad operational amplifier is a general-purpose amplifier that can be operated either single sided at 5 V or with ±15 V supplies. The NSC part has been extensively characterized for ionizing radiation response and was the basis for the ELDRS study using a specially designed test chip that included GLPNP transistors [26]. NSC has since produced an ELDRS-free version of this part that is qualified for space application by modifying the final passivation and making some circuit design changes [25]. The HDR and LDR data taken by NSC on "ELDRS-free" parts for the unbiased case are used for comparison to the results for exposure of parts from the same wafer lot subjected to 100% H_2 and irradiated at 10 rad(Si)/s.

The two most sensitive parameters for the LM124 are the input bias current and the input offset voltage. Figure 3 shows the total dose response of the increase in positive input bias current, $\Delta Ib+$, for the HDR and LDR response measured by NSC for the space qualified packaged parts compared to parts soaked in 100% H_2 before exposure. Note that the scale is log-log. In all of the plots to follow, the average ±1 standard deviation is shown for either three or six samples (sample size shown in Table 1). Exposure to H_2 results in over an order of magnitude increase in degradation.

Figure 4 shows a comparison of the NSC ELDRS-free data to parts soaked in 100% H_2 for the increase input offset voltage, ΔV_{io}. Again there is over an order of magnitude increase in the degradation for the parts soaked in H_2 and the difference increases with increasing dose.

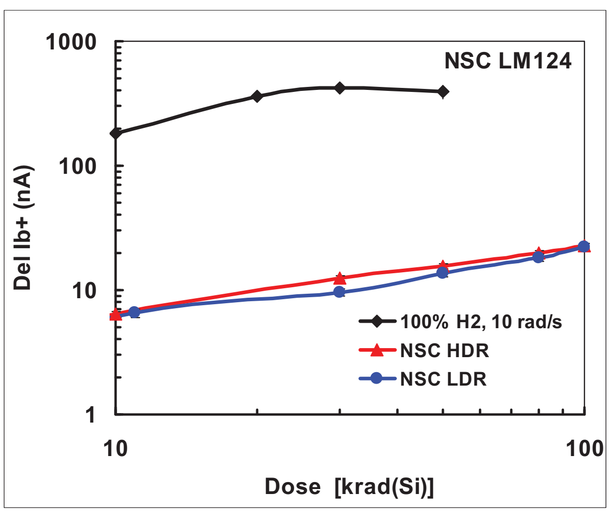

Figure 3. Increase in input bias current for the NSC LM124, comparing NSC data to exposure to 100% H_2.

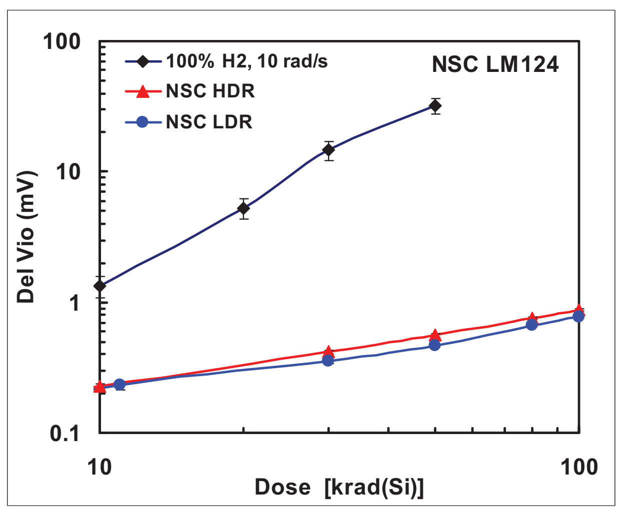

Figure 4. Increase in input offset voltage for the NSC LM124, comparing NSC data to exposure to 100% H_2.

3.2 NSC LM139

The quad comparator, LM139, is another bipolar linear circuit that has been extensively characterized for total dose and dose rate response [5, 28, 29]. This part was also modified by process and circuit design to be ELDRS-free [26]. For unbiased irradiation, the two most sensitive parameters are the input bias current, Ib+, and the sink current, I_{sink}. The LM139 was irradiated at 10 rad(Si)/s for two values of H_2 soaking, 100% and 1%. Figures 5 and 6 show the increase in ΔIb+ and I_{sink}, respectively, versus dose, compared to the HDR and LDR NSC ELDRS-free data.

As for the LM124, the exposure to 100% H_2 prior to irradiation resulted in well over an order of magnitude increase in the degradation. What is more significant is that with only a 1% H_2 exposure, the increase in degradation over the ELDRS-free parts was still over an order of magnitude for ΔIb+ and about a factor of eight for I_{sink}.

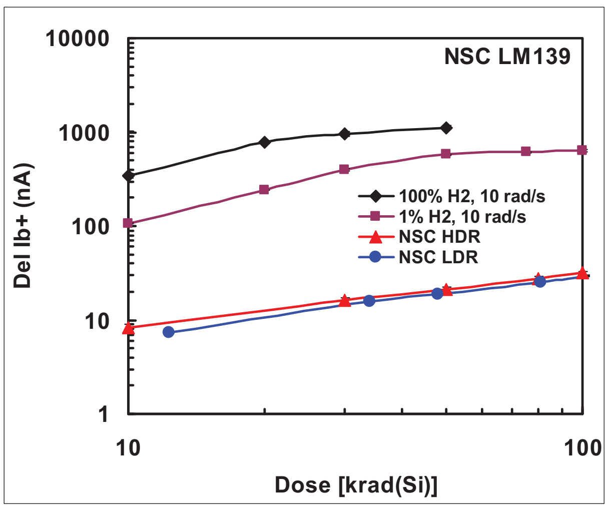

Figure 5. Increase in input bias current for the NSC LM139, comparing NSC data to exposure to 100% and 1% H_2.

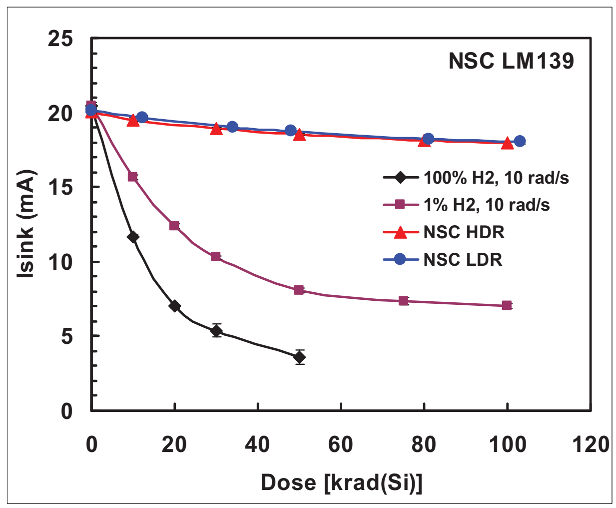

Figure 6. Increase in sink current for the NSC LM139, comparing NSC data to exposure to 100% and 1% H_2.

4.0 EXPERIMENTAL RESULTS—VOLTAGE REFERENCES AND REGULATORS

4.1 NSC LM136-2.5 and LTC RH1009

The NSC LM136 and LTC RH1009 are both 2.5 V references. NSC offers an ELDRS-free version of this reference as described in [25]. The RH1009 was radiation tested by ICS at high (50 rad(Si)/s) and low (8.2 mrad(Si)/s) dose rates both biased and unbiased and demonstrated to be ELDRS-free. This section compares the results of the HDR and LDR tests on the ELDRS-free parts to irradiation at 1 rad(Si)/s after exposure to 100% H_2 for the LM136 and to irradiation at 10 rad(Si)/s after exposure to 1% H_2 for the RH1009. Figures 7 and 8 show the results for the average change in V_{ref} (at 1 mA) for the LM136 and RH1009, respectively.

Comparing the two references we see that the V_{ref} decreases with irradiation for the LM136 and increases for the RH1009. With only 1% H_2, the RH1009 shows a significant increase in V_{ref} compared to the parts not exposed to H_2. The changes are much greater at 100% H_2 for the LM136.

Another parameter that is sensitive for the reference is the change in V_{ref} between two different current values. For these 2.5 V references, this parameter, BVR, is measured between currents of 400 µA and 10 mA. This parameter is also known as load regulation. Figures 9 and 10 show the results for BVR versus dose for the LM136 and RG1009, respectively.

Again with BVR or load regulation, the degradation with H_2 is much greater than for the packaged ELDRS-free parts and the changes are in the opposite direction for the two part types.

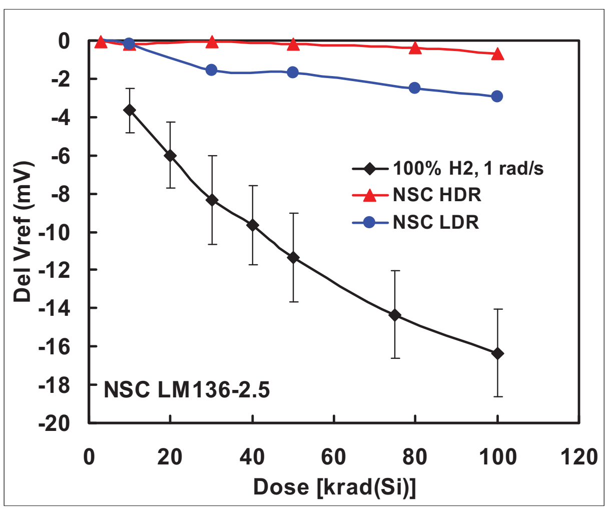

Figure 7. Change in V_{ref} versus dose for LM136, comparing NSC data to exposure to 100% H_2.

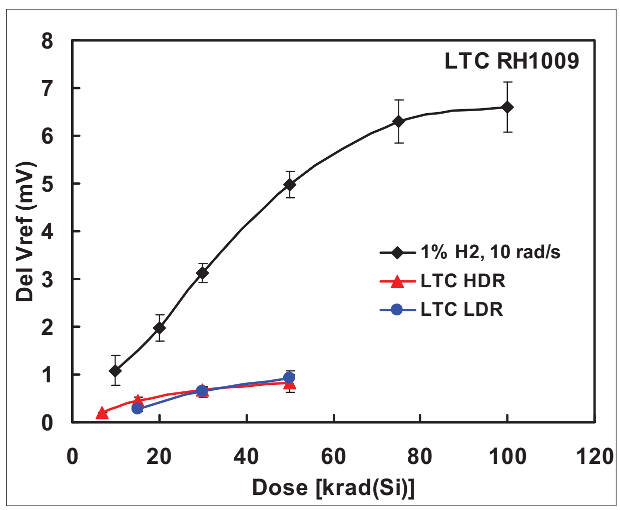

Figure 8. Change in V_{ref} versus dose for RH1009, comparing LTC (ICS) data to exposure to 1% H_2.

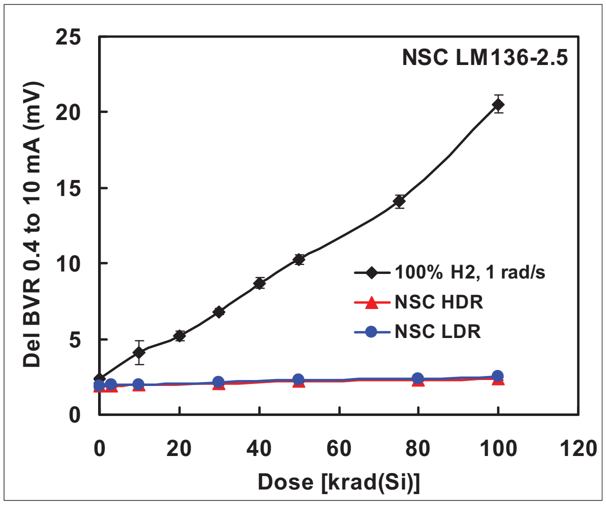

Figure 9. Change in BVR (0.4–10 mA) versus dose for LM136, comparing NSC data to exposure to 100% H_2.

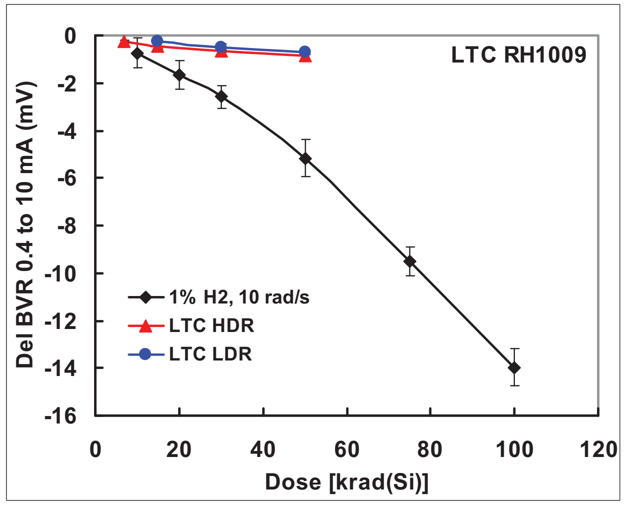

Figure 10. Change in BVR (0.4–10 mA) versus dose for RH1009, comparing LTC (ICS) data to exposure to 1% H_2.

4.2 NSC LM2941

The LM2941 is a 1 A positive, adjustable low-dropout regulator. The ELDRS-free version is described in [25]. This part was exposed to 100% H_2 prior to irradiation and irradiated at 10 rad/s. The output voltage was set at 5 V for the electrical tests. The reference voltage, measured at the adjust pin, is typically 1.275 V. The average change in V_{out} versus dose is shown in Figure 11 and the average change in V_{ref} is shown versus dose in Figure 12.

While there are only a few mV changes at HDR and LDR for the ELDRS-free parts, there are several hundred mV changes in V_{out} at 5 V for the parts exposed to 100% H_2 prior to irradiation. The changes in V_{ref} reflect the changes in V_{out} since $V_{out} \propto V_{ref}$.

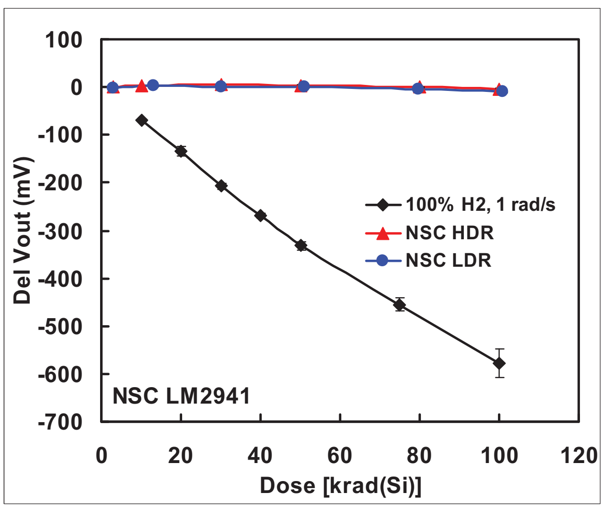

Figure 11. Average change in output voltage versus dose for the LM2941, comparing NSC data to exposure to 100% H_2.

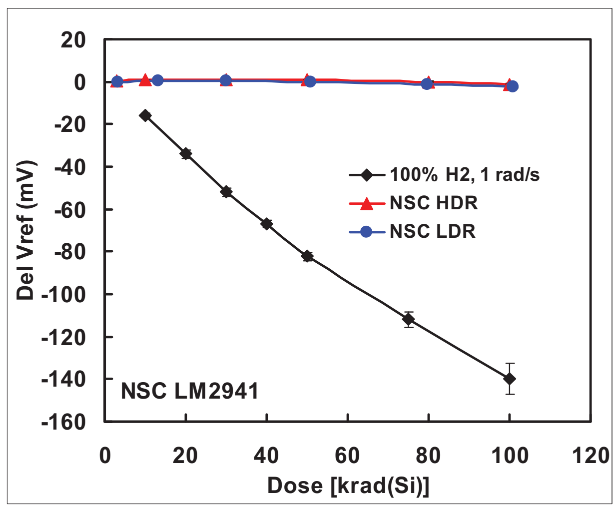

Figure 12. Average change in reference voltage versus dose for the LM2941, comparing NSC data to exposure to 100% H_2.

5.0 EXPERIMENTAL RESULTS—DISCRETE BIPOLAR TRANSISTORS

Radiation-hardened versions of the widely used discrete bipolar transistors, the NPN 2N2222A and the PNP 2N2907A were obtained from Semicoa. The HDR and LDR data on the parts not exposed to H_2 were taken by Semicoa. Delidded samples were subjected to 10% H_2 and irradiated, unbiased, at 10 rad(Si)/s at JPL. The primary parameters affected by total dose are the forward current gain, H_{fe}, and the collector-emitter saturation voltage, $V_{ce(sat)}$. The degradation of H_{fe} is a function of the collector current and degrades much more at low collector current. The change in $1/H_{fe}$ versus total dose at 1 mA collector current is shown in Figure 13 for the 2N2222A and Figure 14 for the 2N2907A for the baseline Semicoa data at HDR and LDR and the parts soaked in 10% H_2 and irradiated at 10 rad(Si)/s.

The amount of degradation with 10% H_2 is greater than for the baseline parts, and the effect is much greater for the PNP device than for the NPN device. If we assume that the amount of oxide-trapped charge is roughly the same with and without the added H_2, then the primary difference would be in the amount of interface traps generated from the excess H_2. PNP transistors are more affected by interface traps than NPN transistors, which would explain why there is relatively more degradation with H_2 for the 2N2907A [30]. Note that in the case of the 2N2907A the baseline degradation (no added H_2) at LDR is actually less than at HDR.

The average normalized percent increase in $V_{ce(sat)}$ (I_c = 500 mA and I_b = 50 mA) versus dose is shown in Figure 15 for the 2N2222A and Figure 16 for the 2N2907A. Comparing Figures 15 and 16, we see that the increase in $V_{ce(sat)}$ for the H_2 exposed parts is much greater for the 2N2907A, than for the 2N2222A; although in both cases the exposure to H_2 does result in enhanced degradation. These results are consistent with the H_{fe} results shown in Figures 13 and 14.

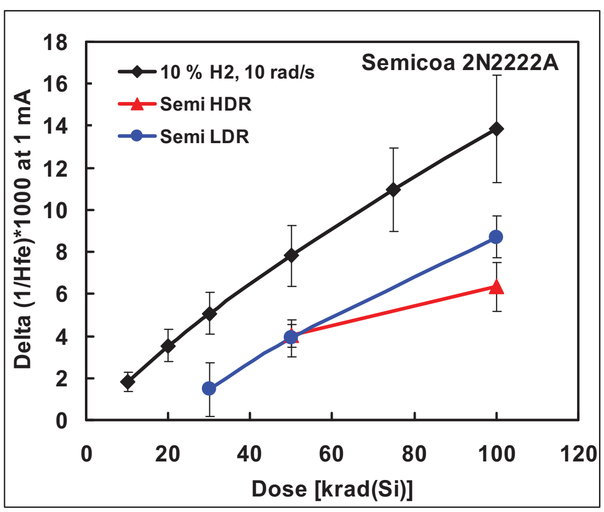

Figure 13. Average change in one over H_{fe} at 1 mA for 2N2222A exposed to 10% H_2 compared to baseline Semicoa data.

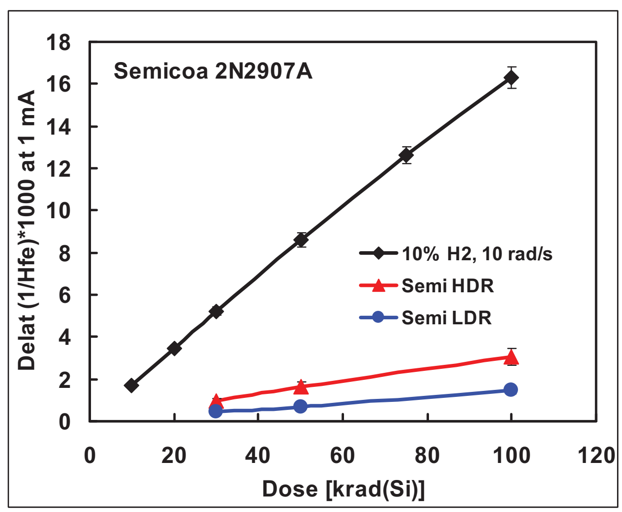

Figure 14. Average change in one over H_{fe} at 1 mA for 2N2907A exposed to 10% H_2 compared to baseline Semicoa data.

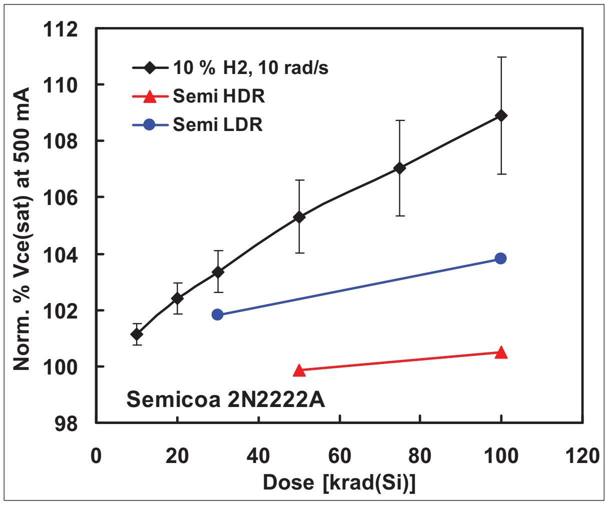

Figure 15. Average normalized percent increase of $V_{ce(sat)}$ for 2N2222A exposed to 10% H_2 compared to baseline Semicoa data.

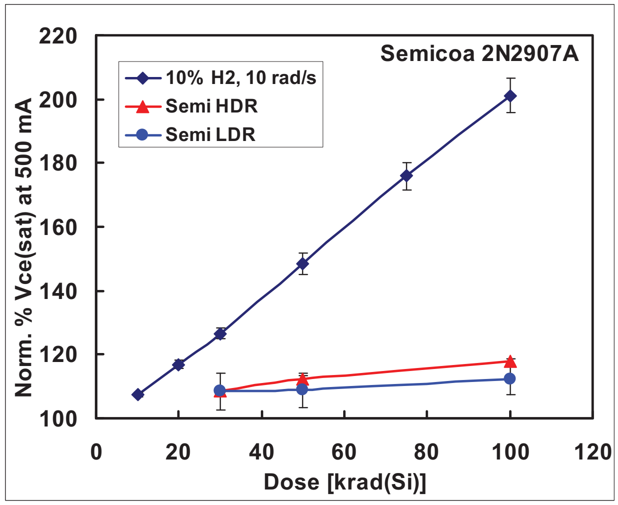

Figure 16. Average normalized percent increase of $V_{ce(sat)}$ for 2N2907A exposed to 10% H_2 compared to baseline Semicoa data.

6.0 DISCUSSION

In previous experiments to investigate the viability of exposure to molecular hydrogen prior to irradiation (at medium to high dose rate), as an accelerated hardness assurance approach, the part types were all known to be ELDRS [23, 24]. At the time, it was thought that using the same approach for radiation-hardened, ELDRS-free parts may be overly conservative [23]. This study investigated the approach on ELDRS-free parts from three manufacturers, looking at a variety of circuit types (operational amplifier, comparator, voltage references, and low dropout regulator) as well as NPN and PNP discrete bipolar transistors. The H_2 exposure was varied between 1% and 100% and the dose rates varied between 1 and 10 rad(Si)/s. In all cases, the exposure to H_2 resulted in an increase in the amount of degradation of sensitive electrical parameters. The amount of enhanced degradation over the baseline HDR and LDR degradation varied from a few percent for the 2N2222A to orders of magnitude for some of the ELDRS-free circuits. It is clear that, for characterization, this technique is not applicable as an accelerated technique for the purpose of determining whether a part is ELDRS. In other words, if the only data on a part is at HDR (Condition A of MIL-STD-883, Method 1019), and one wanted to do an accelerated test to determine if the part is ELDRS, this test might produce overly conservative results. However, as an accelerated test to bound the LDR response of a known ELDRS part, it can still be effective, if correlated to the LDR response.

Although the accelerated test using H_2 does not work for ELDRS-free parts, it does illustrate the importance of hydrogen in increasing the amount of degradation in bipolar linear circuits and discrete transistors. In a previous publication [24], we demonstrated that increasing the amount of hydrogen affected the total dose and dose rate response of bipolar linear circuits. With increased hydrogen, the transition dose rate for enhanced LDR degradation moved to higher dose rates and the saturation degradation at LDR increased. Based on this mechanism, we proposed that parts that did not show a significant LDR enhancement factor at 10 mrad(Si)/s might begin to show enhanced degradation at dose rate below 10 mrad(Si)/s. In a review of ELDRS [31], data on several bipolar circuits were shown where the LDR enhancement factor continued to increase at dose rates below 10 mrad(Si)/s. Experiments are currently being conducted to investigate the very LDR response of several ELDRS-free bipolar circuits to see if the enhancement factors increase down to dose rates of 0.5 mrad(Si)/s [32]. To date, the dose levels achieved at 0.5 mrad(Si)/s are not sufficiently high to determine whether these ELDRS-free parts will show increased enhanced degradation for dose rates below the current LDR test of MIL-STD-883, Test Method 1019.8, Test Condition D of 10 mrad(Si)/s.

This investigation shows that if ELDRS-free parts are purchased in die form for use in a hybrid microcircuit, or are packaged in a different package from what the manufacturer used for the ELDRS-free qualification, then the parts may not be total dose hard or ELDRS-free if they are subjected to molecular hydrogen in the new package form. We have shown in several previous studies [13, 33, 29] that many hermetic package types may have as much as 2% to 4% H_2 in the package due to outgassing from gold or kovar and that these parts show enhanced degradation compared to parts in packages without H_2. These results suggest that anyone buying ELDRS-free dies for subsequent packaging should test the packages for molecular hydrogen and ensure that the concentration is at or below the detection level.

7.0 CONCLUSIONS

In this study, we performed experiments on a number of ELDRS-free bipolar linear circuits, delidded the parts, and exposed the dies to molecular hydrogen at various concentrations from 1% to 100% H_2, prior to irradiation. The total dose response of these parts was compared to the HDR and LDR response of the packaged samples not exposed to H_2. The results, in all cases, were that the degradation was significantly higher for the parts subjected to H_2, even at 1%. The increased degradation ranged from a few percent to over two orders of magnitude. While the use of H_2 exposure followed by medium- to high-dose-rate irradiation, as an accelerated test for ELDRS-free parts, is shown to be overly conservative, the results demonstrate that the radiation hardness of the parts will be compromised if the parts are purchased in die form and packaged in a package that contains even small amounts of H_2. This would be the case for hybrids, dies assembled by third-party packaging companies, or other non-manufacturer packaging options.

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