Evaluation of an Accelerated ELDRS Test Using Molecular Hydrogen

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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.**

***Index Terms*—Dose rate, enhanced low-dose-rate sensitivity (ELDRS), Radiation effects, Total ionizing dose, Hydrogen, Bipolar linear circuits, Discrete bipolar transistors**

I. Introduction

The phenomena of a true dose rate effect in bipolar technologies was first reported in 1991 [1] on bipolar microcircuit transistors. It was later reported by several researchers on bipolar linear circuits [2-4] and became known as enhanced low dose rate sensitivity (ELDRS). Since that time the effect has been studied extensively and many investigations have sought an accelerated test method to provide an upper bound of the low dose rate response of ELDRS parts in a space radiation environment. The first technique that was investigated was elevated temperature irradiation at high dose rate [5]. This technique is not universal and requires extensive characterization to select the optimum dose rate and irradiation temperature to provide an upper bound of the low dose rate response for those parts where the technique does work. Since then other methods have been suggested including repeated high dose rate irradiations followed by elevated temperature anneals [6], switched dose rate testing to reduce the total test time at low dose rate [7], and high dose rate irradiation on parts that have been exposed to molecular hydrogen [8, 9]. While the multiple cycles of high dose rate irradiation plus elevated temperature anneal seemed promising, the technique was only demonstrated on a few part types and sensitive parameters. The switched dose rate technique requires a large number of samples to reduce the total test time and depends on a well behaved population for good statistics. The use of molecular hydrogen as an accelerated hardness assurance technique is very recent [8] and characterization using this approach continues. In this paper the evaluation of ELDRS-free parts is investigated to determine if the technique is too conservative for radiation hardened ELDRS-free parts.

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II. Experimental Description

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 Fig. 1, 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 Corp. (NSC). These included the LM136 voltage reference, the LM2941 low-dropout voltage regulator, the LM124, quad operational amplifier, and the LM139, quad voltage comparator. Low dose rate data on the LM2941 and LM136 were published in the Radiation Effects Data Workshop last year by NSC [10, 11]. Low dose rate data on the LM124 and LM139 were published in 2008 [13]. All four of these part types have been demonstrated to be hard to 100 krad at both high dose rate (50-300 rad/s) and low dose rate (10 mrad/s) for irradiation under both biased and unbiased conditions [10, 11, 12]. In addition the LM2941 was tested at 1 mrad/s up to 20 krad and was shown to be ELDRS free.

To assure that the results are not unique to one process technology, we added several "ELDRS-free" part types

from other manufacturers: 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.

Samples of 3-6 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/s or 10 rad/s using a Co-60 source at JPL. Post irradiation electrical measurements were made at several intermediate dose levels up to 100 krad.

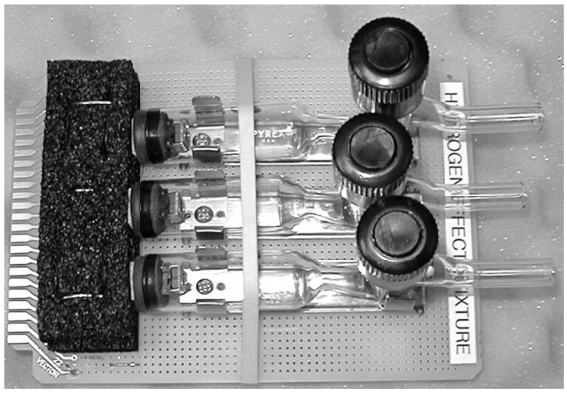

Figure 1. Picture of glass tubes used by JPL for exposure in H_2.

A list of the part types, manufacturers, package types, dose rates, % H_2 used and step-stress dose levels is summarized in Table I.

III. Experimental Results- Op amp and comparator

NSC LM124. The LM124 quad operational amplifier is a general purpose amplifier that can be operated either single sided at 5V or with +/- 15V supplies. The National Semiconductor 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 gated lateral pnp transistors [13]. 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 [12]. The high and low dose rate 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/s.

The two most sensitive parameters for the LM124 are the input bias current and the input offset voltage. Fig. 2 shows the total dose response of the increase in positive input bias current, ΔIb+, for the high and low dose rate 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 3 or 6 samples (sample size shown in Table I). Exposure to H_2 results in over an order of magnitude increase in degradation.

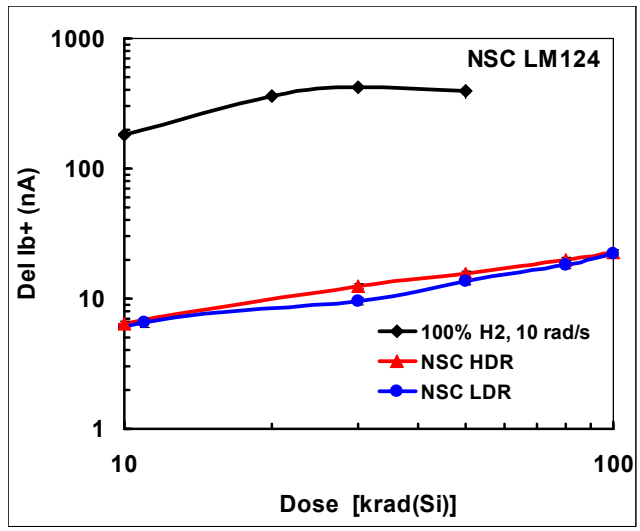

Figure 2. Increase in input bias current for the NSC LM124, comparing NSC data to exposure to 100% H_2.

Fig. 3 shows a comparison of the NSC ELDRS-free data to parts soaked in 100% H_2 for the increase input offset voltage, ΔVio. 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.

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

Manufacturer	Part type	Description	Package	Date code	H2 (%)	Dose rate (rad/s)	Dose (krad)	Sample size
NSC	RM124AJRQMLV	quad op amp	14 pin CDIP	*0514*	100	10	10,20,30,50	3
NSC	RM139AJRQMLV	quad comparator	14 pin CDIP	*0527*	1	10	10,20,30,50,75,100	6
NSC	RM139AJRQMLV	quad comparator	14 pin CDIP	*0527*	100	10	10,20,30,50	3
NSC	RH136AH2.5RQMLV	2.5 V reference	TO-46		100	1	10,20,30,40,50,75,100	3
NSC	RM2941JXQMLV	LDO regulator	16 pin CDIP	*0911*	100	1	10,20,30,40,50,75,100	3
Linear Tech	RH1009MW	2.5V reference	10 pin FP	*0649*	1	10	10,20,30,50,75,100	6
Semicoa	2N2222A	npn BJT	TO-18	*0739*	10	10	10,20,30,50,75,100	6
Semicoa	2N2907A	pnp BJT	TO-18	*0804*	10	10	10,20,30,50,75,100	6

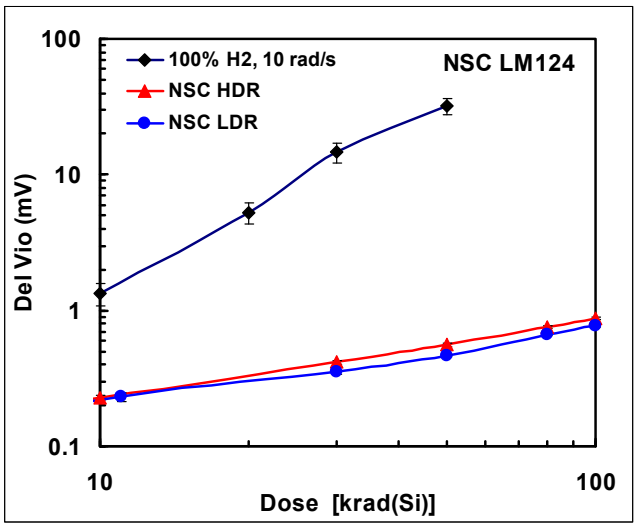

Figure 3. Increase in input offset voltage for the NSC LM124, comparing NSC data to exposure to 100% H_2.

NSC LM139. The quad comparator, LM139, is another bipolar linear circuit that has been extensively characterized for total dose and dose rate response [2, 14, 15]. This part was also modified by process and circuit design to be ELDRS-free [12]. For unbiased irradiation the two most sensitive parameters are the input bias current, Ib+, and the sink current, Isink. The LM139 was irradiated at 10 rad/s for two values of H_2 soaking, 100% and 1%. Figs. 4 and 5 show the increase in ΔIb+ and ΔIsink, respectively, versus dose, compared to the high and low dose rate NSC ELDRS-free data.

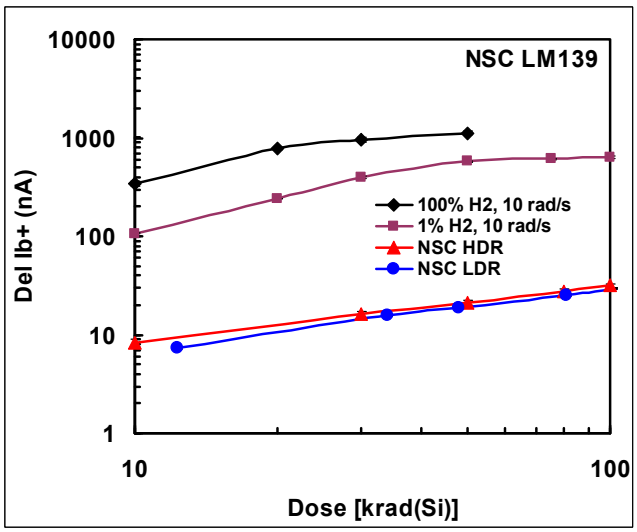

Figure 4. Increase in input bias current for the NSC LM139, comparing NSC data to exposure to 100% and 1% H_2.

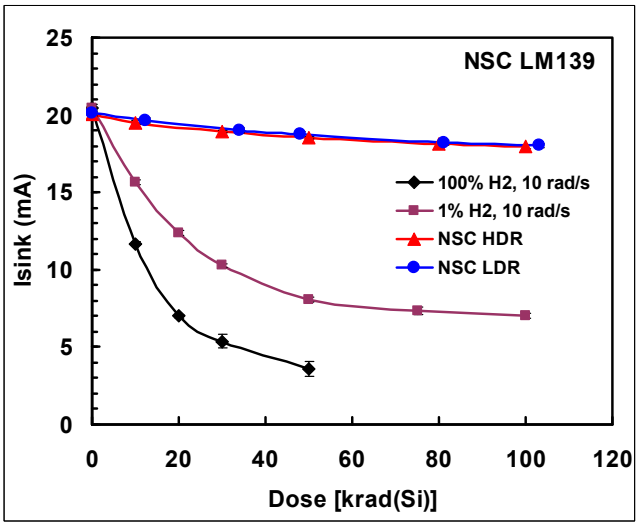

Figure 5. Increase in sink current for the NSC LM139, comparing NSC data to exposure to 100% and 1% H_2.

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 8 for Isink.

IV. Experimental Results- Voltage References and Regulators

NSC LM136-2.5 and LTC RH1009. The NSC LM136 and LTC RH1009 are both 2.5V references. NSC offers an ELDRS-free version of this reference as described in [11]. The RH1009 was radiation tested by ICS at high (50 rad/s) and low (8.2 mrad/s) dose rates both biased and unbiased and demonstrated to be ELDRS-free. We compare the results of the HDR and LDR tests on the ELDRS-free parts to irradiation at 1 rad/s after exposure to 100% H_2 for the LM136 and to irradiation at 10 rad/s after exposure to 1% H_2 for the RH1009. Figs. 6 and 7 show the results for the average change in Vref (at 1 mA) for the LM136 and RH1009, respectively.

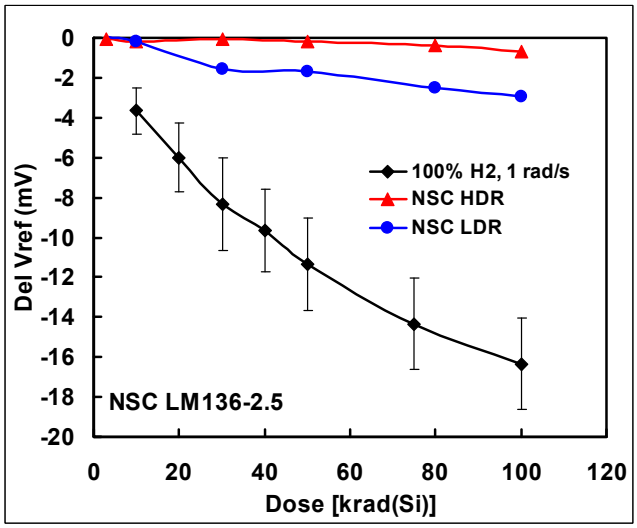

Figure 6. Change in Vref versus dose for LM136, comparing NSC data to exposure to 100% H_2.

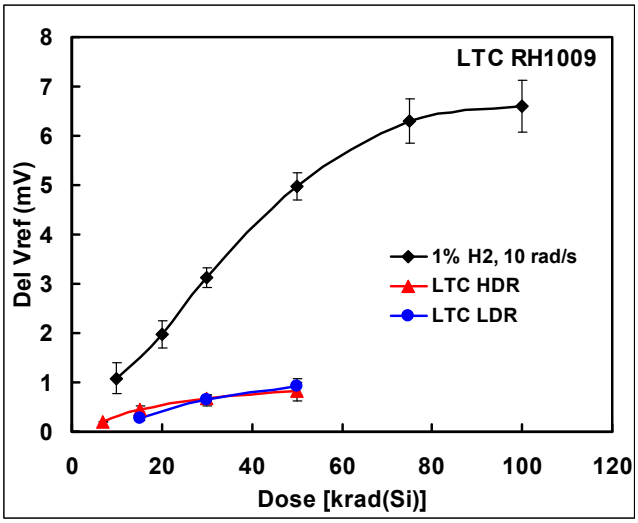

Figure 7. Change in Vref versus dose for RH1009, comparing LTC (ICS) data to exposure to 1% H_2.

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 Vref 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 2.5V references this parameter, BVR, is measured between currents of 400 µA and 10 mA. This parameter is also known as load regulation. Figs. 8 and 9 show the results for BVR versus dose for the LM136 and RG1009, respectively.

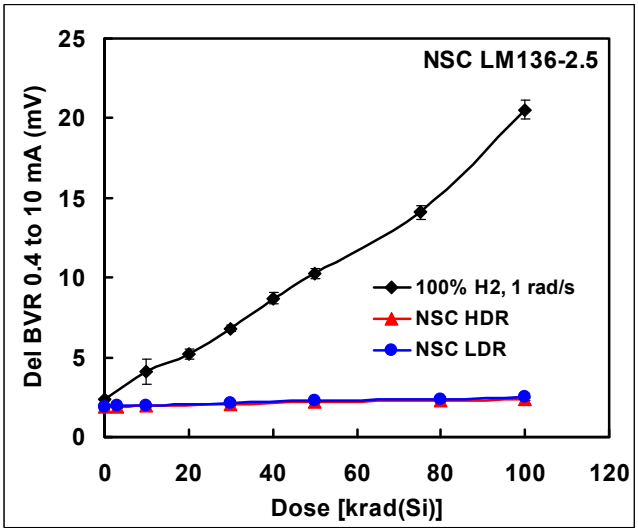

Figure 8. Change in BVR (0.4 to 10 mA) versus dose for LM136, comparing NSC data to exposure to 100% H_2.

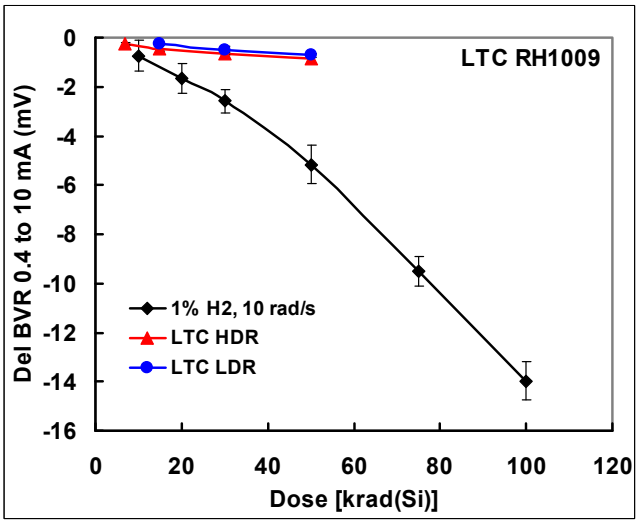

Figure 9. Change in BVR (0.4 to 10 mA) versus dose for RH1009, comparing LTC (ICS) data to exposure to 1% H_2.

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

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

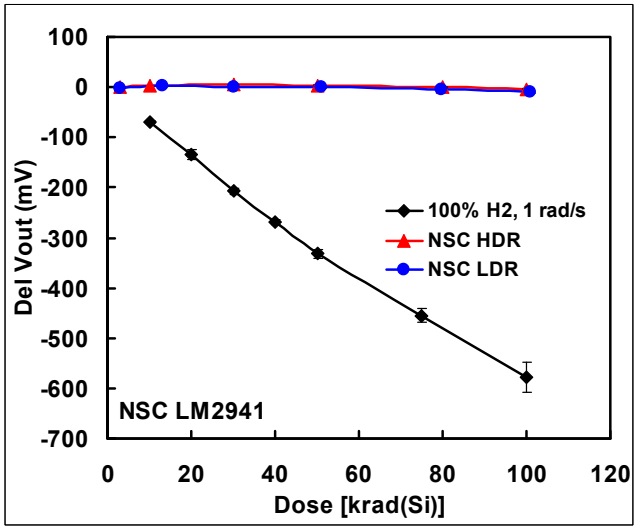

Figure 10. Average change in output voltage versus dose for the LM2941, comparing NSC data to exposure to 100% H_2.

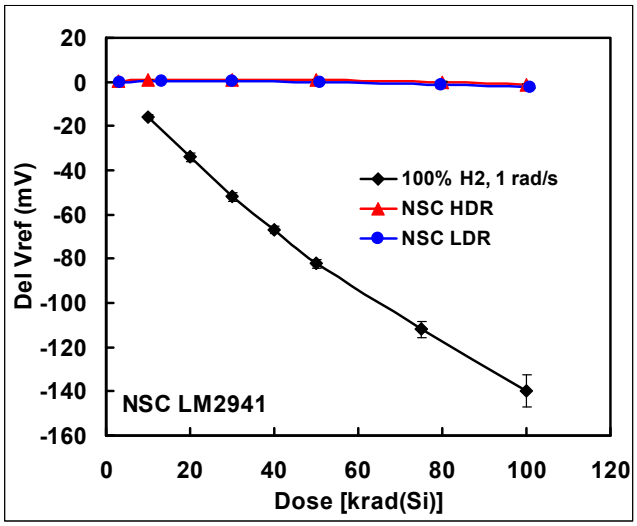

Figure 11. Average change in reference voltage versus dose for the LM2941, comparing NSC data to exposure to 100% H_2.

While there is only a few mV change at high and low dose rate for the ELDRS-free parts, there is several hundred mV change in Vout at 5V for the parts exposed to 100% H_2 prior to irradiation. The changes in Vref reflect the changes in Vout since Vout ∝ Vref .

VI. 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 high and low dose rate 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/s at JPL. The primary parameters affected by total dose are the forward current gain, Hfe, and the collector-emitter saturation voltage, Vce(sat). The degradation of Hfe is a function of the collector current and degrades much more at low collector current. The change in 1/Hfe versus total dose at 1 mA collector current is shown in Fig. 12 for the 2N2222A and Fig. 13 for the 2N2907A for the baseline Semicoa data at high and low dose rate and the parts soaked in 10% H_2 and irradiated at 10 rad/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 [19]. Note that in the case of the 2N2907A the baseline degradation (no added H_2) at low dose rate is actually less than at high dose rate.

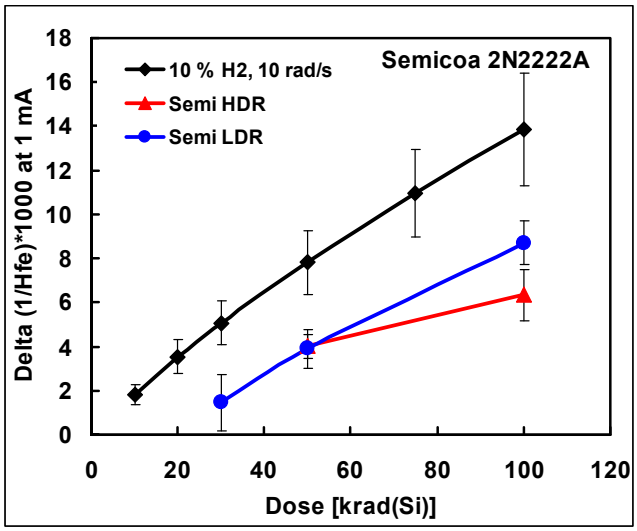

Figure 12. Average change in one over Hfe at 1 mA for 2N2222A exposed to 10% H_2 compared to baseline Semicoa data.

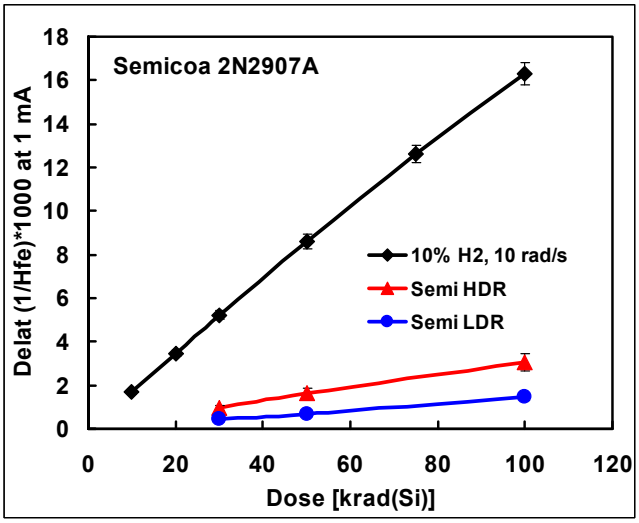

Figure 13. Average change in one over Hfe at 1 mA for 2N2907A exposed to 10% H_2 compared to baseline Semicoa data.

The average normalized % increase in Vce(sat) (Ic=500 mA and Ib=50 mA) versus dose is shown in Fig. 14 for the 2N2222A and Fig. 15 for the 2N2907A. Comparing Figs. 14 and 15, we see that the increase in Vce(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 Hfe results shown in Figs. 12 and 13.

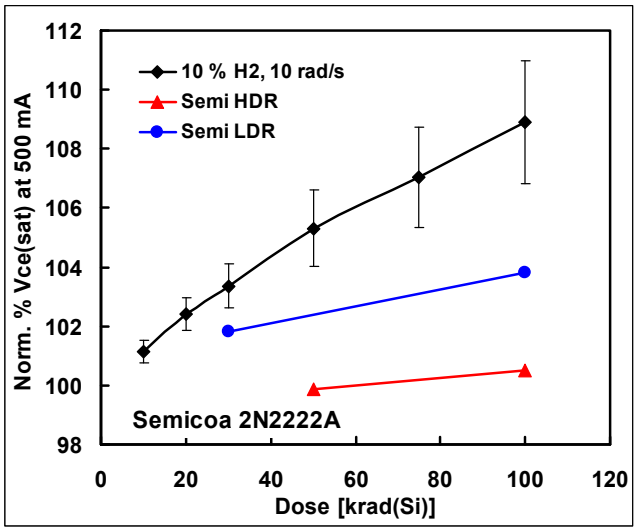

Figure 14. Average normalized % increase of Vce(sat) for 2N2222A exposed to 10% H_2 compared to baseline Semicoa data.

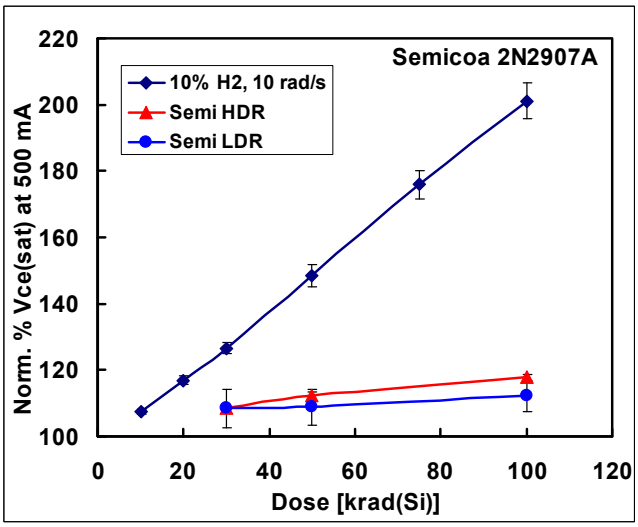

Figure 15. Average normalized % increase of Vce(sat) for 2N2907A exposed to 10% H_2 compared to baseline Semicoa data.

VII. 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 [8, 9]. At the time it was thought that using the same approach for radiation hardened, "ELDRS-free" parts may be overly conservative [8]. In this study we have 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/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 high and low dose rate degradation varied from a few % 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 high dose rate (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 low dose rate response of a known ELDRS part, it may 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 [9] 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 low dose rate degradation moved to higher dose rates and the saturation degradation at low dose rate increased. Based on this mechanism we proposed that parts which did not show a significant low dose rate enhancement factor at 10 mrad/s, might begin to show enhanced degradation at dose rate below 10 mrad/s. In a review of ELDRS [20], data on several bipolar circuits were shown where the low dose rate enhancement factor continued to increase at dose rates below 10 mrad/s. Experiments are currently being conducted to investigate the very low dose rate response of several "ELDRS-free" bipolar circuits to see if the enhancement factors increase down to dose rates of 0.5 mrad/s [21]. To date the dose levels achieved at 0.5 mrad/s are not sufficiently high to determine whether these "ELDRS-free" parts will show increased enhanced degradation for dose rates below the current low dose rate test of MIL-STD-883, Test Method 1019.8, Test Condition D of 10 mrad/s.

What our investigation has shown is that if ELDRS-free parts are purchased in die form for use in a hybrid microcircuit, or to be 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 [16-18] that many hermetic package types may have as much as 2-4% H_2 in the package due to out-gassing 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 assure that the concentration is at or below the detection level.

VIII. Conclusions

We have performed experiments on a number of "ELDRS-free" bipolar linear circuits, de-lidded the parts and exposed the dice 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 high and low dose rate 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 % 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.

IX. Acknowledgements

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