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ABSTRACT

Recent enhanced low dose rate sensitivity (ELDRS) investigations carried out by RLP Research, Crane, Arizona State University (ASU), and Jet Propulsion Laboratory (JPL) have shown significant differences in the degradation of bipolar microcircuits with total dose in the presence of molecular hydrogen (H₂) in packages. This has a significant impact on radiation hardness assurance and opens up opportunity to improve device performance.

The objectives of this program are 1) to investigate and confirm the causal relationship between packaging recipes, hydrogen contamination, and total dose response of linear bipolar microcircuits; and 2) to develop a guideline that will take into account these effects at the radiation level for future NASA space missions. This program is geared to benefit all future NASA space missions using bipolar or BiCMOS linear devices.

A close collaboration between JPL, ASU, Crane, and RLP Research led to the following set of investigations:

1. JPL tasks included investigations into the source of hydrogen in common packages, low dose rate and high dose rate testing of vendor packaged devices and residual gas analysis (RGA) to identify the correlation between their packaging recipes, hydrogen contamination and total dose response.
2. JPL funded ASU to develop physical models that take into account the participation of hydrogen into the mechanism of creation of interface traps (i.e., enhanced the degradation of linear bipolar microcircuits).
3. JPL and Crane collaborated to obtain data from high dose rate and low dose rate testing in a hydrogen environment.

SUMMARY OF THE HYDROGEN WORK

In 1991, it was shown that bipolar test transistors from a microcircuit process technology exhibited a true dose rate effect. For the true dose rate effect, the degradation at a low dose rate is much greater than the degradation at a higher dose rate plus a room temperature anneal for a period of time equal to or greater than the exposure time at low dose rate. It was shown that this effect had severe consequences for the total dose test method in MIL-STD-883, Method 1019, which allowed for all testing on bipolar parts to be conducted at a high dose rate of 50–300 rad/s. The test for metal oxide semiconductor (MOS) parts, which exhibit a time dependent effect and not a true dose rate effect, is not applicable to bipolar parts that exhibit the true dose rate effect. In 1994, several papers were presented that demonstrated the true dose rate effect in bipolar linear circuits, including op amps, voltage comparators, and voltage regulators. Before the mechanisms of the true dose rate effect were known, the effect became known as enhanced low dose rate sensitivity (ELDRS), although it was later shown that the more accurate terminology would have been reduced high dose rate sensitivity (RHDRS), since the phenomenon is actually a mitigation of the degradation at high dose rate. However, the term ELDRS has been maintained. MIL-STD-883, Method 1019 has been revised to include a test for ELDRS and a testing protocol for parts that exhibit ELDRS.

In the 1990s, most of the work on ELDRS was directed at characterization of many bipolar linear circuit part types and investigations to develop an accelerated test for ELDRS. A number of accelerated test methodologies have been proposed, including (1) irradiation at an elevated temperature and a moderate dose rate, (2) irradiation at a high dose rate with negative power supply bias, (3) switched dose rate testing, and (4) multiple cycles of high dose rate testing followed by elevated temperature anneals. None of these techniques have proven universally adequate, so characterization to determine an accelerated technique for a specific part type was added to Method 1019. A space experiment was run in the late 1990s on the microelectronics and photonics test bed (MPTB) that demonstrated that testing at a constant low dose rate correlates with the highly variable dose rate in space for selected op amps and comparators.

In the early 2000s, experiments were conducted to examine the effect of final passivation on the total dose and ELDRS response. It was shown that, at least for one process technology, parts with no final passivation were quite total dose hard and did not exhibit ELDRS. It was also shown that for parts that did exhibit ELDRS, pre-irradiation thermal stress would affect the low dose rate enhancement factors and in some cases would eliminate ELDRS.

In the last few years, a new experiment to characterize ELDRS in space has been designed using special test structures that employ a metal gate over the base region of a lateral pnp transistor. This structure can be used to separately measure oxide trapped charge and interface states. The use of these test chips in space will provide more basic information about the total dose degradation of bipolar linear circuits than the MPTB experiments. This ELDRS experiment is being conducted on the NASA Living with a Star Space Environments Testbed Program by Arizona State University (ASU). The ELDRS test chips for this experiment were taken from a special wafer lot of test chips and LM124 op amps fabricated by National Semiconductor in Arlington, Texas using many different final passivation layers, as well as wafers with no passivation. For these wafers, it has been shown that parts with the standard passivation of nitride over p-glass are soft at high and low dose rates, parts with p-glass only exhibit ELDRS, and parts with no passivation or SiC are hard at high and low dose rates. The space experiment was designed to use the p-glass parts to study ELDRS in space and the no-passivation or SiC parts as controls. ASU had test chip samples packaged by Golden Altos in 14-pin, dual in-line packages with sealed kovar lids. When the ground radiation tests were run by ASU to verify the previous irradiation test results, it was discovered that the p-glass parts did not exhibit ELDRS and the no-passivation parts were soft. With these results, the space experiment would not have met the test objectives. An investigation was launched to determine the

cause of the unexpected results. After eliminating a number of possible explanations, it was suggested by NAVSEA Crane to run a residual gas analysis (RGA) on the packages from Golden Altos. It was discovered that the packages contained 1–2% molecular hydrogen (H_2). This discovery led to a series of tests to determine the effects of external sources of H_2 on the total dose response of bipolar linear circuits and test transistors. Crane developed a technique to irradiate parts in the presence of 100% H_2 by placing the parts in a sealed glass tube that had been pressurized with pure H_2 . Additional experiments were conducted on the parts that were packaged by Golden Altos in which the KOVAR lids were removed for several days and then taped back on during irradiation. It was shown that when the lids were removed, allowing the H_2 to escape, the radiation response was the same as for the parts originally tested by Crane, which had been packaged by Sandia Labs with unsealed, taped-on lids. Further experiments demonstrated that, for the gated lateral pnp transistors with the p-glass or with no passivation, the amount of degradation at high dose rate was proportional to the amount of H_2 that the part was exposed to.

In experiments conducted by Crane, Raytheon, Boeing, and TRW (now Northrop Grumman), it was shown that the Analog Devices AD590 temperature transducer exhibits ELDRS when irradiated without bias and when packaged in a flatpack. The part is available in both a flatpack and a can. Several lots of both cans and flatpacks have been tested and the flatpacks all exhibited ELDRS and the cans were hard at both high and low dose rates. After seeing the results on the National ELDRS test chip, it was suggested that an RGA be run on the AD590 flatpacks. The RGA showed that the flatpack had on the order of 0.6% H_2 . This amount of hydrogen was apparently enough to cause the flatpack parts to degrade significantly at low dose rate under zero bias. Tests run on the AD590 with 100% H_2 did not show any greater degradation than the parts with 0.6% H_2 indicating a saturating effect with the smaller amount of hydrogen. However, these results were obtained with parts from different diffusion lots and, therefore, the claim of a causal relationship between H_2 and total ionizing dose (TID) sensitivity needed to be confirmed. Results are presented in this document. Additional work has focused on developing an analytical model that would relate radiation response to the ambient H_2 concentration and fit experimental data from measurements on gated lateral pnp (GLPNP) bipolar devices

Based on the results for the National ELDRS test chip and the AD590, other parts that exhibit ELDRS were investigated. The Jet Propulsion Laboratory (JPL) performed a more general investigation on a selection of parts from different manufacturers. The results of this investigation are reported in this document. The results show that a correlation exists between different packaging recipes, hydrogen content, and total dose response. Also, testing by Crane on the Texas Instruments (TI) LM124 op amp and LM139 comparator had shown that both of these parts exhibited ELDRS. TI informed us that the parts had a nitride passivation. When an RGA was run on the 14-pin DIP packages no H_2 was found. Irradiation tests on unsealed parts in a 100% H_2 environment did not show any greater degradation than with no H_2 . This led to the conclusion that nitride is a barrier to H_2 and parts with a nitride final passivation should not be affected by H_2 in the package. If nitride is a barrier to H_2 , then it should also prevent any H_2 below the nitride from escaping. This assumption has been verified by results previously published by Sandia on an LM111 comparator. In those tests it was shown that a part with the standard nitride over p-glass passivation is soft at high and low dose rates. Several samples of the LM111 had the nitride removed by plasma etching. These parts proved to be hard at high and low dose rates. Since there is a lot of hydrogen incorporated in the under layers during the nitride deposition (silane and ammonia), it may be assumed that after the nitride is removed, the H_2 is allowed to escape, rendering the parts hard. The presence of excess hydrogen in the under layers of National parts with nitride was verified by Crane using secondary ion mass spectrometry (SIMS).

In further experiments (fiscal year 2008 [FY08]), we are attempting to show that many bipolar linear circuit process technologies are hard to total dose at high and low dose rates as processed through metallization. It is likely that soft and ELDRS parts become that way as a result of the final passivation, pre-conditioning, and packaging, or a combination of these factors. If this can be demonstrated, the task

of hardening the parts is limited to discovering which of the post-metal factors degrade the hardness and developing processes that preserve the hardness.

1.0 INTRODUCTION

The residual hydrogen content in hermetically sealed packages is a significant reliability issue for electronic components that are used for space applications. Previous work in the area reported that hydrogen gas quantities as low as 0.5% of ambient atmosphere can cause significant performance degradation at temperature of 125°C in a relatively short period of time (500 hrs) [1]. The problem is somewhat involved since device type, fabrication process, feature size, gate structure/metallurgy, and operating ambient temperature, all can impact the sensitivity to the hydrogen level.

There are several likely sources of H₂:

1. In many cases, piece parts are pre-seal baked or fired and/or sealed in a reducing environment of forming gas containing > 4% H₂ in N₂.
2. H₂ can also outgas from grain boundaries or structural imperfections in iron-nickel alloy (Kovar, Alloy42) lead frame materials.
3. Electro-plated metal components such as plated gold or nickel films are major sources of dissolved hydrogen; H₂ can be trapped during this process.
4. Moisture is often present and results from the absorption or adsorption of H₂O 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, the problem exists and there is no clear guideline or limit as to what level of hydrogen might be considered acceptable in hermetically 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 put on H₂.

This lack of specification introduces another unknown when dealing with the radiation response of commercial linear bipolar devices. Their total ionizing dose (TID) response and their sensitivity to enhanced low dose rate sensitivity (ELDRS) might be affected. Indeed, it has been shown that hydrogen transport and reactions play key roles in the radiation response and long-term reliability of bipolar microelectronics technologies. Due to its high mobility, hydrogen can diffuse into SiO₂ over-layers and participate in the creation of interface traps upon ionizing radiation exposure, thereby enhancing the total dose degradation of bipolar devices.

Recent work has shown that Analog Devices linear bipolar temperature transducers (AD590s) in flatpacks degrade significantly more than same parts packaged in TO-52 cans in response to ionizing radiation. The difference was attributed to the higher molecular (H₂) content in the gas ambient within the flatpack, which was determined through residual gas analysis (RGA) to be 0.6%. No detectable levels of H₂ were measured in TO-5 cans. However, these results were obtained with parts from different diffusion lots and, therefore, the claim of a causal relationship between H₂ content and TID sensitivity needed to be confirmed. Additional work has focused on developing an analytical model that would relate radiation response to the ambient H₂ concentration and fit experimental data from measurements on GLPNP bipolar devices.

This document reports, for the first time, the impact of hydrogen contamination on the total dose response of two linear parts from the same diffusion lots: the AD590 terminal temperature transducer from Analog Device and the HSYE-117RH linear voltage regulator from Intersil. This report states the first conclusions about the correlation of hydrogen content, different packaging characteristics, and total

dose degradation. In addition, results are provided on the modeling effort that was performed at ASU. Finally, an approach to hardening bipolar linear circuits with poor total dose response is introduced.

2.0 HYDROGEN CONTENT, PACKAGING, AND PASSIVATION STUDY

2.1 Parts Investigations and First Conclusions

A general investigation was performed on a selection of 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. Results were analyzed to determine if, for the set of parts selected, a correlation exists between the different packaging characteristics, hydrogen content, and total dose degradation. All the information obtained about the amount of hydrogen, passivation, and packaging characteristics are summarized in Table 1.

Table 1. Devices description with associated characteristics
(hydrogen content, passivation, and package information)

	Hydrogen Content (%)	Water	Oxygen	Gas	TID Response	Passivation	Package
HYSE117RH 5962F9954701VYC DC: 03/03 S/N: 8142	<u>2.96</u>	0.06	0.006	Dry nitrogen	ELDRS Bias dependency (unbiased worst performer)	Oxide	Ceramic surface mounted, brazed kovar lids with gold plating
HYSE117RH 5962F9954701VYC DC: 03/43 S/N: 8151	<u>1.78</u>	0.051	0.009	Dry nitrogen	ELDRS Bias dependency (unbiased worst performer)	Oxide	Ceramic surface mounted, brazed kovar lids with gold plating
OP484 59620051701VDA DC: 0123A S/N: 065	0.043	0.251	16.2	Dry air	No ELDRS No bias dependency	Thin nitride over oxide or oxynitride	Ceramic glass frit No kovar No gold
OP484 59620051701VDA DC: 0123A S/N: 1682	0.0394	0.242	17.2	Dry air	No ELDRS No bias dependency	Thin nitride over oxide or oxynitride	Ceramic glass frit No kovar No gold
LP2953 59629233601 DC: 0228 S/N: 332	0.0394	0.204	11.1	Dry air	ELDRS Fails specification (LDR)<5-20 krad	Nitride	Ceramic glass frit
AD590 5962R8757104VXA DC: 0419F S/N: k1023	0.2	0.31	0.18	Dry nitrogen	ELDRS Bias dependency (unbiased worst performer)	Oxide	Ceramic package with Gold/Nickel/Tungsten metallization; kovar lid with Gold/Nickel plating
AD590 5962R8757104VXA DC: 0419F S/N: k1024	<u>0.275</u>	0.22	0.19	Dry nitrogen	ELDRS Bias dependency (unbiased worst performer)	Oxide	Ceramic package with Gold/Nickel/Tungsten metallization; kovar lid with Gold/Nickel plating
AD590 5962R8757104VXA DC: 0419F S/N: k1025	<u>0.88</u>	0.245	0.1987	Dry nitrogen	ELDRS Bias dependency (unbiased worst performer)	Oxide	Ceramic package with Gold/Nickel/Tungsten metallization; kovar lid with Gold/Nickel plating

	Hydrogen Content (%)	Water	Oxygen	Gas	TID Response	Passivation	Package
LM193 JM35/11202BPA DC: 9950 S/N: PO357	0.025	0.156	19.26	Dry air	ELDRS Bias dependency at HDR/LDR	Nitride	Ceramic glass frit No kovar No gold
LT1006 596289933026A DC: 9626 S/N: 307	0.0007	0.396	0.0123	Dry nitrogen	ELDRS No bias dependency (LDR) Fails the spec for bias/HDR at 10- 15 krad	Nitride	Metal can
LT1006 596289933026A DC: 9626 S/N: 321	0	0.378	0.128	Dry nitrogen	ELDRS No bias dependency (LDR) Fails the spec for bias/HDR at 10- 15 krad	Nitride	Metal can

2.2 AD590 and HSYE-117RH Results

The HSYE-117RH shows a significant amount of hydrogen content, close to 3%. It presents some interesting packaging characteristics that are potential sources of hydrogen such as brazed kovar lids with gold plating and dry nitrogen gas. It is also likely that a large amount of hydrogen was introduced during the sealed process in a reducing environment of forming gas, containing some H₂ in N₂. It also has an oxide passivation layer.

The AD590 presents some very interesting characteristics as well. Varying levels of H₂ have been detected through RGA (0.2%, 0.27%, and 0.88%) for the flatpack ceramic package devices. It has several potential sources of hydrogen (Gold/Nickel/Tungsten metallization) and kovar lids with gold nickel plating. It has been shown that devices in cans do not contain any hydrogen and have a seal process that does not introduce hydrogen. A typical sealing method follows a welded process. This means that parts are usually pre-baked for a certain period of time (~several hours). The parts are then removed from the vacuum oven and placed in a weld station nitrogen purged dry box without being exposed to air. This eliminates any potential for the hydrogen to be gettered by the gold if the parts are exposed to air.

2.3 Conclusion

The results of this investigation clearly indicate that there is a correlation between packaging characteristics and hydrogen content. Indeed, it suggests that by only looking at the package characteristics, it is possible to evaluate which category of device is likely to have a significant amount of hydrogen in the package and consequently sensitivity to total-dose and low-dose-rate enhancement.

As expected, devices in cans exhibit low amounts of hydrogen. Ceramic frit glass devices show negligible amounts of hydrogen. Parts that also have a nitride passivation layer do not show a significant quantity of hydrogen, though there is not necessarily a correlation here. As previously shown by Pease et al. [2], parts with nitride may exhibit ELDRS independent of and unaffected by the presence of hydrogen in the package.

In the present work, both cases of ELDRS and non-ELDRS were found for nitride coated devices. It is interesting to note that while silicon nitride is a very good barrier to hydrogen diffusion, the deposition processes are known to introduce hydrogen into device passivation layers. It is also known that some nitride processes have been optimized to eliminate the presence of hydrogen in passivation layers. Thus,

we believe it is critical to investigate the mechanisms of hydrogen absorption/desorption in nitride passivation.

3.0 EFFECT OF H₂ ON THE TOTAL DOSE RESPONSE OF THE AD590 AND HYSE-117RH

Since it has been identified that the HYSE-117RH and AD590 show a significant amount of hydrogen in their packages, further experiments were conducted to identify the relationship between hydrogen content and total dose response [3].

Twelve space-qualified, screened parts were provided for this test by Analog Devices. Irradiated AD590 was from the same diffusion lot and had a minimum of 240 hours of burn-in. Three flatpacks and three cans 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. All irradiated parts were unbiased during irradiation with all leads grounded or in conductive foam.

Two parts of the HYSE-117RH were available for this test. Parts were from the same wafer lot and were irradiated unbiased at a dose rate of 0.05 rad/s. One part had been opened for more than a week to release the hydrogen content.

Parts were electrically tested with an LTS2020 mixed signal automated test system located adjacent to the C0-60 range source. Pre- and post-irradiation tests were performed at ambient temperature according to the DC test parameters listed in the vendor or military specifications. Special precautions were taken to allow the temperature of the AD590 and HYSE-117RH to stabilize before electrical testing was conducted. The total dose source is compliant to MIL-STD-883, Method 1019 respectively. The testing procedure follows the MIL-STD-883, Method 1019 condition C (the dose rate agreed to by the parties to the test; in this case, 50 mrad/s).

Test groups and conditions of irradiation about the AD590 and HYSE-117RH are defined in Tables 2 and 3.

Table 2. AD590 testing conditions

Group	SS	Bias	Package	Dose Rate	Approximate Test Levels
1	3	Unbiased	FP	0.01 R/s	2.5, 5, 10, 15, 20, 25, and 30 Krad
2	3	Unbiased	FP	0.01 R/s	2.5, 5, 10, 15, 20, 25, and 30 Krad
3	3	Unbiased	Can	25 R/s	2.5, 5, 10, 15, 20, 25, 30, 50, and 100 Krad
4	3	Unbiased	Can	25 R/s	2.5, 5, 10, 15, 20, 25, 30, 50, and 100 Krad

Table 3. HSYE-117-RH testing conditions

Group	SS	Bias	Package	Dose Rate	Approximate Test Levels
1	2	Unbiased	FP	0.05 R/s	2.5, 5, 10, 15, 20, 25, 30, 35, 40, 50, and 70 Krad

4.0 EXPERIMENTAL RESULTS

4.1 AD590 Experimental Results

The results of irradiation performed on the four groups of AD590 are shown in Figure 1. The output current (~error in temperature) was measured for four values of supply voltage ($V_{cc} = 5, 10, 15, 20$ V). However, only results for $V_{cc} = 20$ V are shown; experimental results for a $V_{cc} = 20$ V is sufficient to verify that flatpacks degrade significantly more than cans at low dose rate (LDR) and high dose rate (HDR) when irradiated unbiased. Indeed, Figure 1 shows very interesting results; at high dose rate the degradation in the output current (or error in temperature) tracks the increase in hydrogen content (0.2%, 0.27% and 0.88%) and at low dose rate it seems that the impact of hydrogen is even worse on the degradation (see 0.33% and 1.04% of H_2 for the LDR case). These results also indicate a correlation between hydrogen content and total dose response.

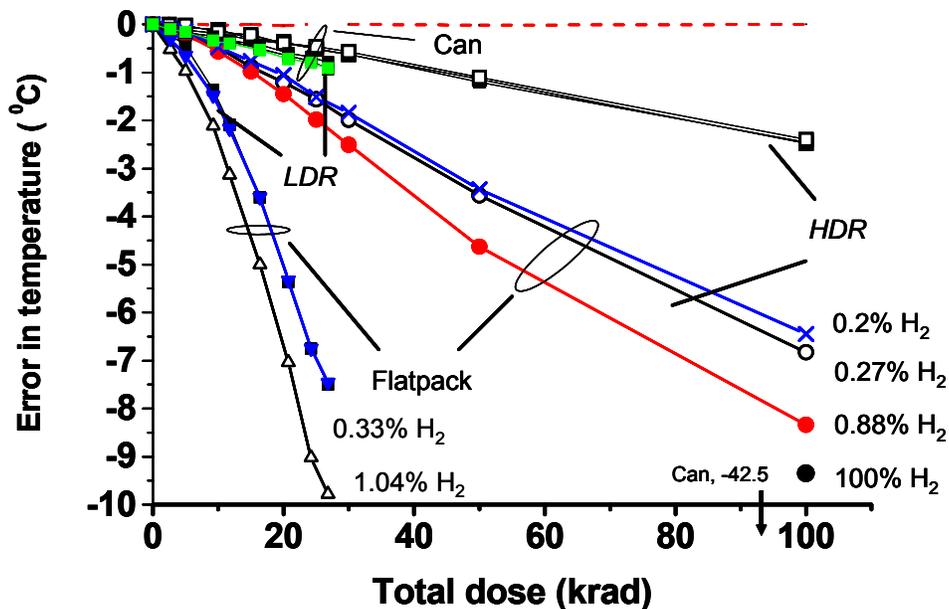


Figure 1. Degradation of the AD590 output current as a function of total dose. Two groups of three flatpacks and three cans were irradiated unbiased at both high and low dose rates (respectively, 25 rad/s and 0.01 rad/s). Residual gas analysis (RGA) was performed after irradiation on the flatpack devices to evaluate the amount of hydrogen. The error in temperature was measured for a supply voltage $V_{cc} = 20$ V.

Further experiments were performed at NAVSEA Crane on an AD590 die that was packaged in a can from the single wafer lot. The one can part was delidded and exposed to 100% H_2 for 48 hours and then irradiated to 100 krad at HDR (80 rad/s). As indicated in Figure 2, the part showed severe degradation, with some recovery after voltage sweeps and anneals.

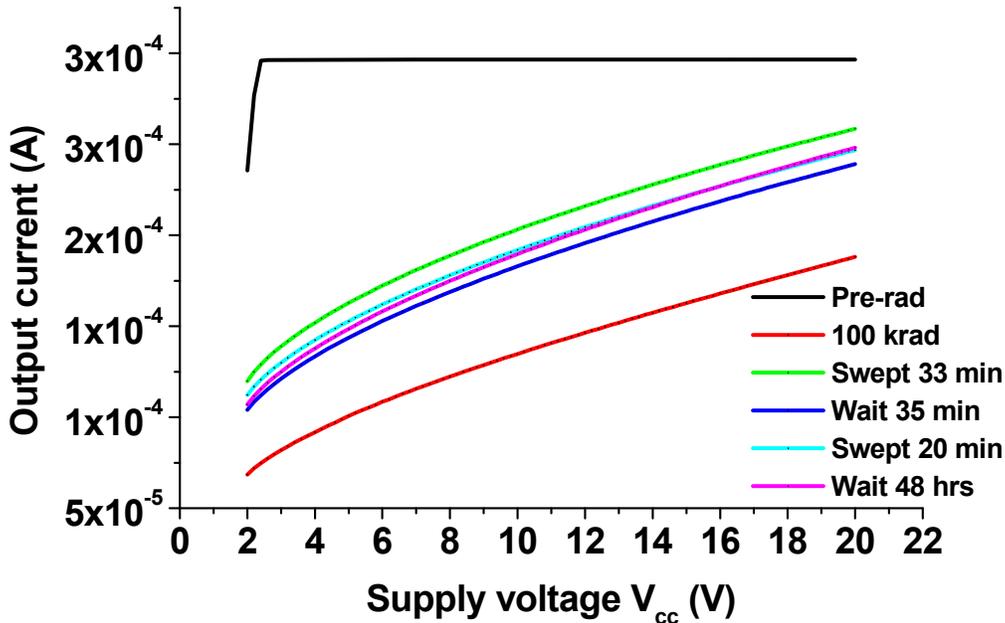


Figure 2. Delidded AD590 can exposed to 100% H_2 for 48 hours and irradiated unbiased at 80 rad/s to 100 krad. This result verifies that the can device can be made to degrade similar to the flatpack (FP) when the die is exposed to H_2 .

These results show that the die in cans do exhibit severe degradation, even at HDR, when exposed to H_2 .

4.2 HSYE-117RH Experimental Results

Three critical parameters have been considered to assess the total dose response of the HYSE-117RH linear voltage regulator: changes in V_{ref} , I_{out} , and V_{out} . Degradation of I_{out} is a good indicator of the loss of gain in the output transistor, which, in this case is a vertical pnp. V_{out} and V_{ref} are also good parameters to be considered so that the DC regulation of the device can be estimated. The results, shown in Figs. 3, 4, and 5, clearly indicate significant differences in the response between the sealed part (~3% of hydrogen content) and the open one (~0%). First, as shown in Figure 3, the voltage reference starts degrading at 100 krad. This is not surprising since this process is a “hardened” process so large variations below 100 krad were not expected. Small variations in the voltage reference have a non-negligible effect on the DC regulation of the linear regulator.

The most significant difference is shown for the output current change and dropout voltage. From the results shown in Figure 8 and Figure 9, a very large difference is observed between the two parts: 1) an approximate 200 mA difference at 150 krad for the output current and 2) an approximate 0.9 V difference at 150 krad in the dropout voltage. These results clearly indicate a correlation between hydrogen content, packaging, and total dose response, with a significant increase in degradation when hydrogen is present.

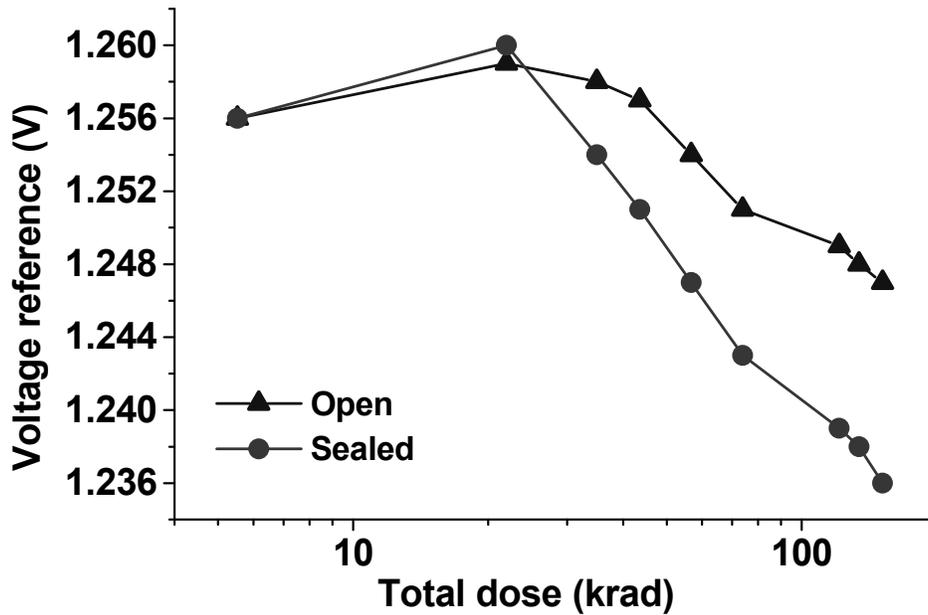


Figure 3. Reference voltage degradation as a function of total dose for the HYSE-117RH regulator. Two devices were tested: sealed package with ~3% hydrogen and open package with ~0% hydrogen. The dose rate was 0.05 rad/s.

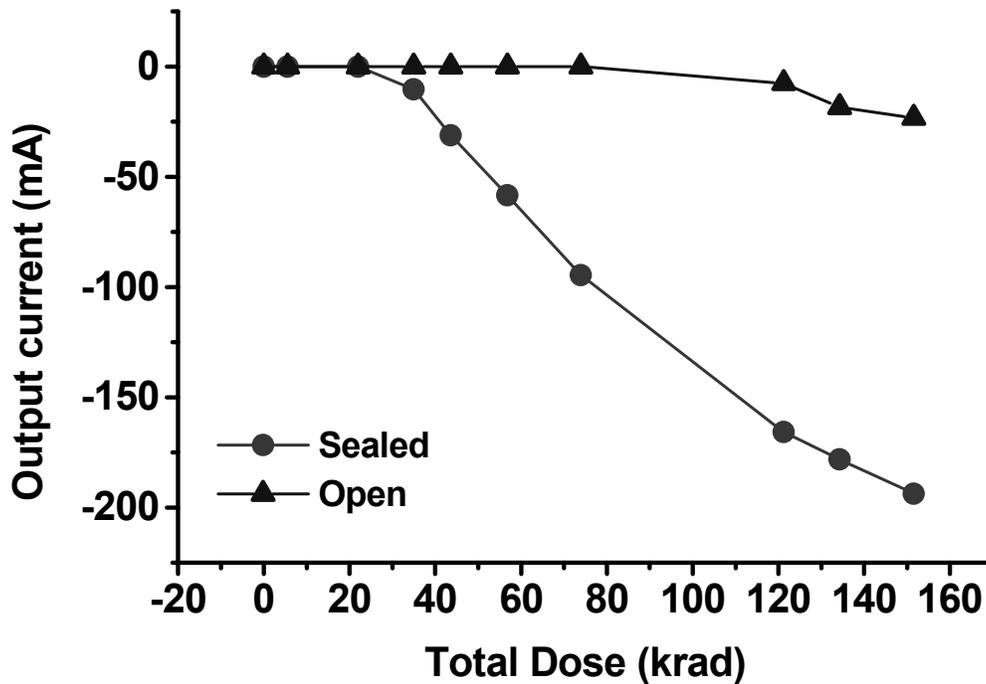


Figure 4. Maximum output current variation as a function of total dose for the HYSE-117RH regulator. Two devices were tested: 1) sealed package with ~3% of hydrogen and 2) open package with ~0% of hydrogen. The dose rate was 0.05 rad/s.

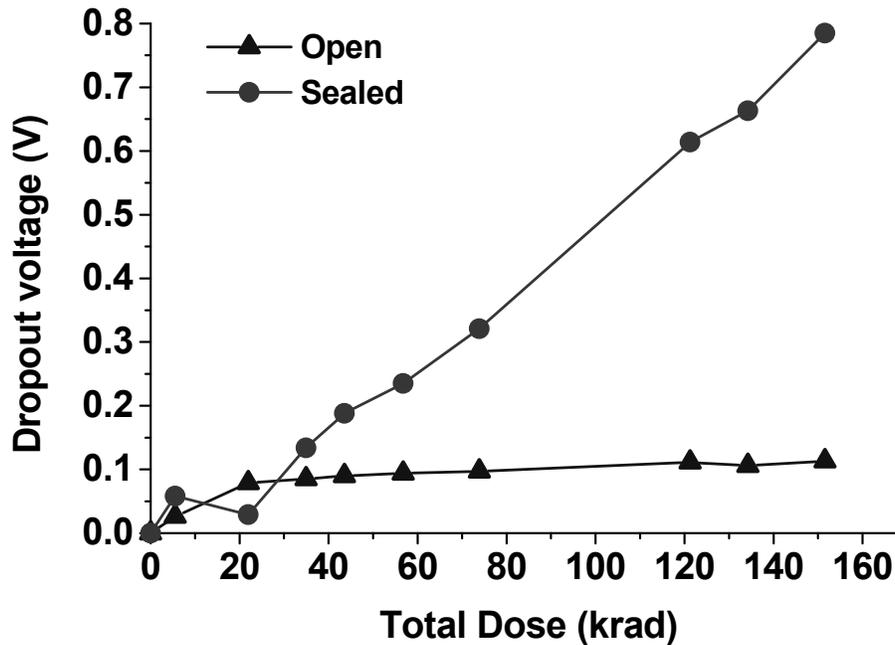


Figure 5. Dropout voltage variation as a function of total dose for the HYSE-117RH regulator. Two devices were tested: 1) sealed package with ~3% of hydrogen and 2) open package with ~0% of hydrogen. The dose rate was 0.05 rad/s.

4.3 Conclusion

The main results that can be extracted from this study on the AD590 and HSYE-117RH are:

1. Flatpack devices degrade much more at low and high dose rates compared to the cans due to hydrogen contamination. As a result, Vendor RLAT tests performed in cans can underestimate damage and affect total dose evaluation.
2. The devices in the high and low dose rate case degrade more as the amount of hydrogen content increases.
3. The can device can be made to degrade similar to the flatpack when the die is exposed to H₂.
4. These results have a significant impact on radiation hardness assurance and opens up opportunity to improve device performance by eliminating hydrogen during packaging phase or passivation process.
5. Experimental results and packaging investigations on these two parts clearly show and confirm the correlation between total dose response, packaging, and hydrogen contamination. They indicate that parts that have an oxide passivation are more affected by molecular hydrogen (H₂) in packages.

5.0 MODELING UNDERLYING MECHANISM

The modeling effort helps explain the underlying physical mechanisms that relates to the role of hydrogen contamination in the total dose response of linear bipolar microcircuits. To explain these effects, a combination of modeling and experiments have been planned and conducted on GLPNP bipolar devices fabricated at National Semiconductor.

5.1 Effect of H₂ on Device Response after Ionizing Radiation Exposure

The modeling and experimentation on the effects of molecular hydrogen on the radiation response of bipolar devices started with radiation experiments conducted on specially designed GLPNP bipolar fabricated in National Semiconductor's standard linear bipolar process and packaged in hermetically sealed packages. In the first set of experiments, measurements were conducted on samples with four different package conditions: 1) hermetically sealed with 1% H₂ in package, 2) lid/seal removed but with metal lid taped back on, 3) lid/seal removed but with ceramic lid taped back on, and 4) never sealed package with taped-on lid. Figure 6 shows the radiation response of these devices after 30 krad of total ionizing dose exposure. Time dependent experiments were also conducted to study the diffusion of hydrogen over time from the packages as the package lids are removed. Figure 7 shows the decrease in radiation damage as H₂ is diffused out of the packages.

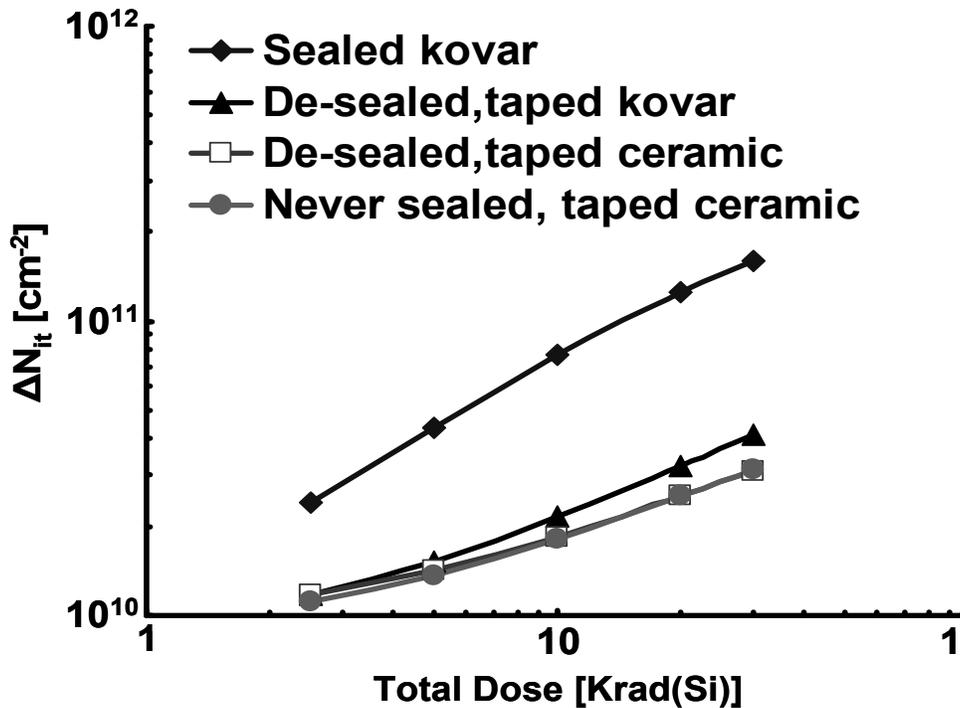


Figure 6. Radiation-induced interface trap build-up in devices with unsealed and hermetically sealed packages

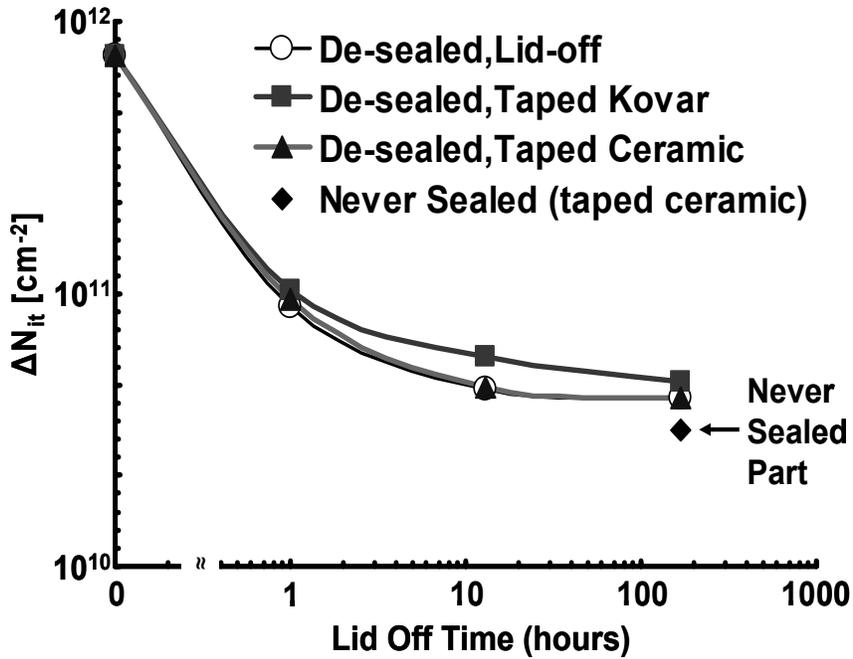


Figure 7. Decrease of radiation induced interface traps as H₂ diffuses out of the sealed package over time

Further experiments were conducted on GLPNP devices with different ambient concentrations of H₂. The relationship between excess ambient H₂ concentration and radiation-induced interface trap density (N_{it}) were established using analytical modeling [4]. The experimental results in Figure 3 shows monotonic increase of both radiation-induced interface trap and oxide trapped charge formation as ambient H₂ concentrations are increased.

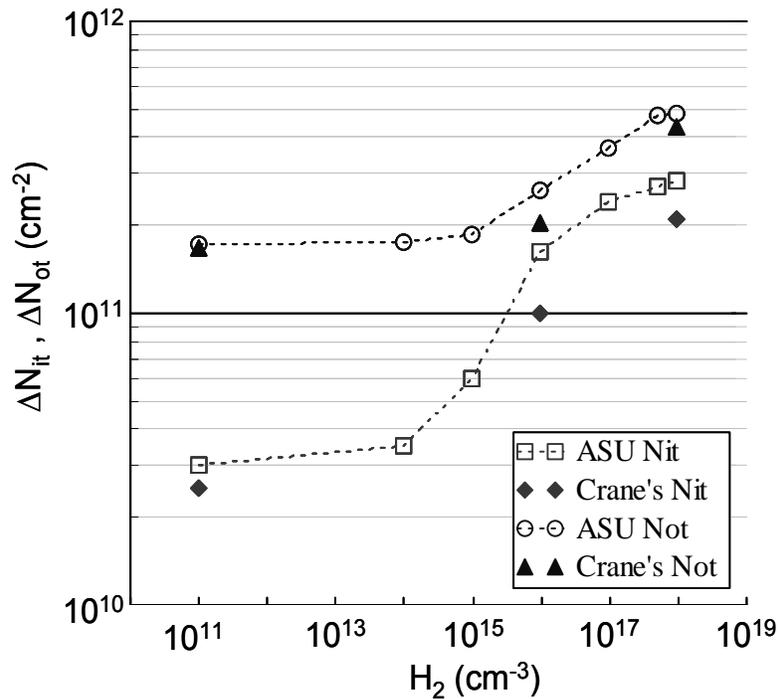


Figure 8. Radiation-induced oxide trapped charge (N_{ot}) and interface trap (N_{it}) buildup

In Figure 9, the analytical model provided excellent fit to the N_{it} data obtained from the radiation experiments conducted in various ambient H_2 environments. A detailed derivation of this model can be found in [6].

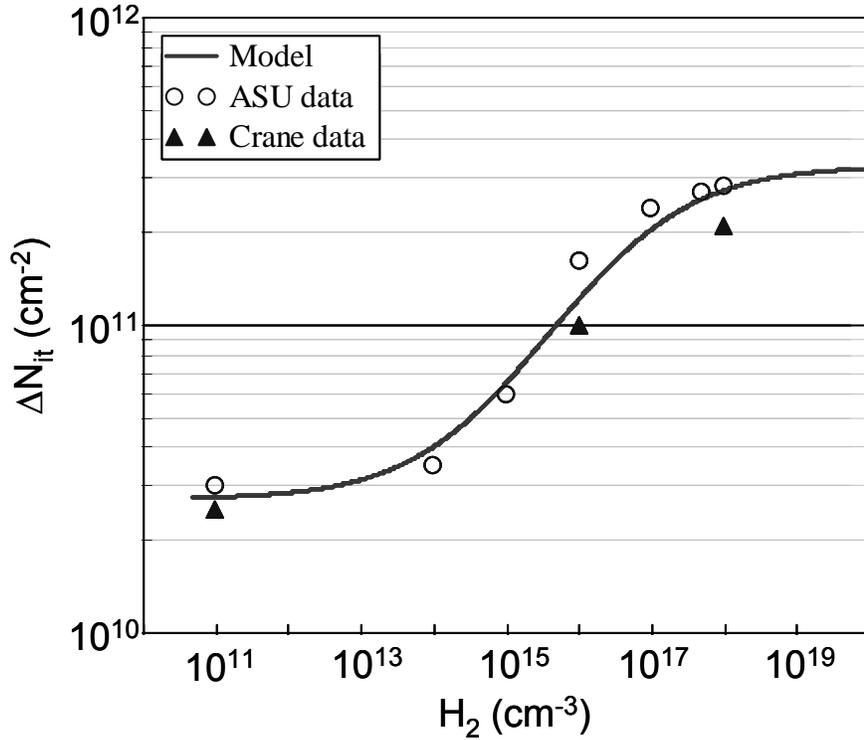


Figure 9. Fit of analytical model describing interface trap formation due to excess H_2

5.2 Annealing Behavior of Radiation Induced Defects Generated in Excess H_2 Environment

Post-irradiation annealing experiments were conducted in room temperature for GLPNP devices irradiated both in air and in 100% H_2 environments [5]. The annealing experiments took place both in air and in 100% H_2 environment. Higher temperature anneal were also conducted in air for samples irradiated in 100% H_2 as well. The annealing results indicate that changes in interface trap and oxide trapped charge densities are strong functions of molecular hydrogen content in both exposure and post-exposure ambient. For devices irradiated in air, Figure 10 shows the annealing behaviors of a 60-day air anneal followed by a 3-day 100% H_2 anneal. The decrease of both N_{it} and N_{ot} after 60-day air anneal agrees with past results. After a 3-day 100% H_2 anneal, a decrease in N_{ot} corresponding to an increase in N_{it} was observed in these devices. This annealing behavior shows that molecular hydrogen reacts at trapped hole sites to anneal N_{ot} and produce additional H^+ to enhance N_{it} generation during annealing.

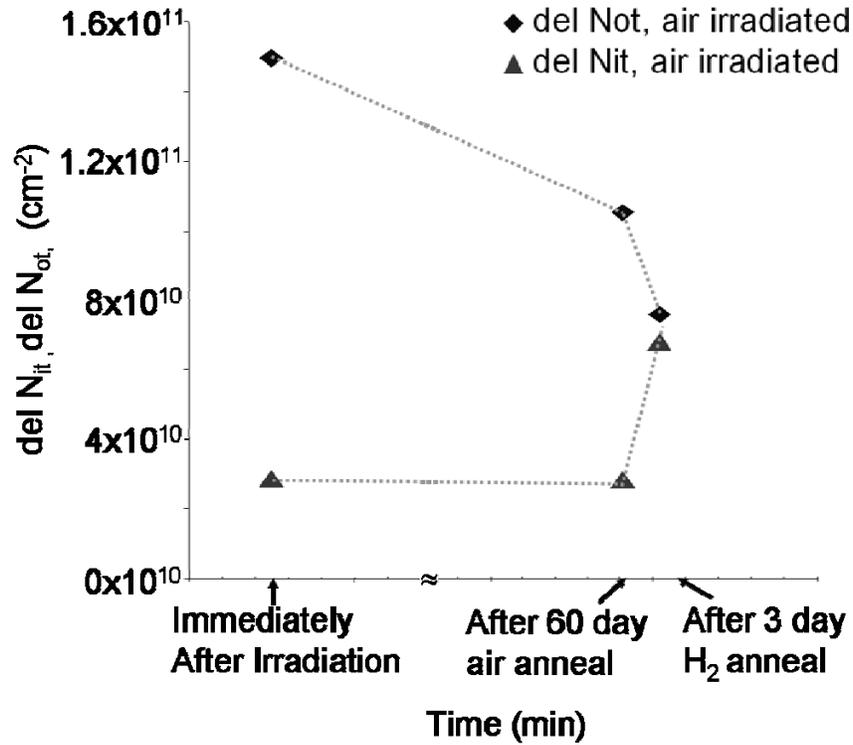


Figure 10. Extracted ΔN_{it} and ΔN_{ot} values for GLPNP devices irradiated in air, then annealed first in air for 60 days and then in 100% H₂ for 3 days.

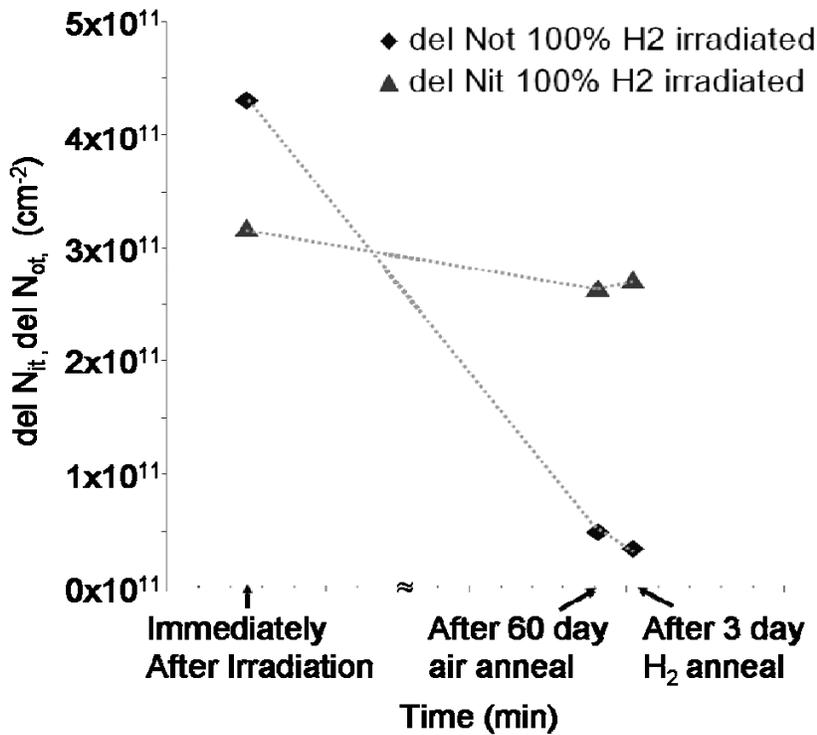


Figure 11. Extracted ΔN_{it} and ΔN_{ot} values for GLPNP devices irradiated in 100% H₂, then annealed first in air for 60 days and then in 100% H₂ for 3 days.

5.3 Effect of Deuterium vs. Hydrogen

Further investigation is needed to explain the annealing behavior of samples irradiated in 100% H₂ environment. As indicated in Figure 11, during the 3-day 100% H₂ anneal, the device behaves similarly as those irradiated in air. However, during the 60-day air anneal, the radiation induced N_{ot} annealed significantly as compared to the air-irradiated devices. At this point, it is suggested that this behavior is either the annealing behavior of a chemically different species having the same electrical signature as traditional oxide trapped charge, or a direct result of excess H₂ reacting with N_{ot} during annealing. In order to directly confirm the role of H₂ in this reaction, comparative irradiation and anneal tests with deuterium and hydrogen are suggested.

6.0 RADIATION HARDNESS ASSURANCE IMPLICATIONS

To our knowledge, there is no clear radiation hardness methodology that addresses the impact of hydrogen contamination on the total dose response of linear bipolar microcircuits. There is strong evidence that many bipolar circuits may be quite hard at high and low dose rates as processed through metallization. A first good example was the response of National Semiconductor devices as previously reported in [6]. The hardness can be degraded by the final passivation, the thermal cycles that occur in packaging and preconditioning, and the presence of molecular hydrogen in the package [6-8].

“Through metallization” testing can be performed by pulling a wafer before final passivation and packaging the chips with a room temperature die attach and not sealing the lids. If this baseline total dose response is acceptable, then those factors occurring after metal that degrade the hardness can be identified and mitigated. We judge critical to systematically add some post-metal manufacturing steps to the dies to isolate causes of increased degradation, starting with final passivation. For example, an approach would be to start with the standard passivation used by the vendor, package samples at room temperature with taped on lids, and test five samples with worst case bias at low dose rate to a sufficient total dose to see if the degradation has increased. If so, then investigate alternate passivation processes to restore baseline response. If the standard passivation does not degrade the response, package the parts in the standard vendor’s package(s) and test five samples with worst case bias at low dose rate. If the parts show increased degradation, perform residual gas analysis (RGA) to determine the level of hydrogen in the packaging. If the standard passivation and package do not degrade the part, then subject the part to the elevated temperature preconditioning steps and repeat the low dose rate test. Using this approach may establish post-metal manufacturing procedures that will maintain the baseline total dose response.

7.0 CONCLUSION

Significant differences in hydrogen content for various package types of different commercial linear bipolar microcircuits have been shown. Six part types were evaluated. It was demonstrated that the HSYE-117RH and AD590, which have oxide passivation, are affected by hydrogen in the packages. With the AD590, it was shown that the greater the amount of hydrogen the greater the total dose degradation. Four of the part types had a nitride passivation and nearly undetectable levels of hydrogen in the packages. Previous testing of the LT1006, LM193, and LP2953 has shown that all three part types exhibit enhanced low dose rate sensitivity (ELDRS). New data on the OP484 show that the part does not exhibit ELDRS. Suggestions on how to evaluate the total dose and dose rate hardness of bipolar linear circuits have been proposed. In addition, radiation experiments were performed on gated bipolar test structures to study the effect of molecular hydrogen on the radiation response of these devices. The experimental results show 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 model was proposed to describe the relationship between interface trap formation and excess molecular hydrogen concentration in gaseous

ambient during radiation exposure. This first order model provides an excellent fit to the data obtained from the experiments.

8.0 FUTURE WORK

The current and future tasks planned for the Jet Propulsion Laboratory (JPL), Arizona State University (ASU), and RLP Research for fiscal year 2008 (FY08) are listed below.

8.1 JPL Current and Future Tasks

- Develop the capability at JPL to perform high dose rate, low dose rate, bias and unbiased irradiation in a hydrogen environment.
- Focus on the impact of nitride passivation and hydrogen contamination on the total dose response of the LM193/OP484/LM117 linear microcircuits. Several experiments will be performed as listed below:
 1. High dose rate (HDR) and low dose rate (LDR) irradiation on the LM193/OP484/LM117 unbiased.
 2. HDR and LDR irradiation on the LM193/OP484/LM117 unbiased after removing the silicon nitride passivation using plasma etch techniques.
 3. Irradiation at different hydrogen concentration on unpassivated parts (1% and 100%).
 4. Post-irradiation measurements after 60 days annealing in air and an extra 3 days annealing in 100% H₂.
 5. High temperature annealing for parts irradiated in 100% H₂ (60°C, 80°C, 100°C, and 160°C)
- Work with Intersil to solve their issue with the HSYE-117RH. Twelve parts will be provided by Intersil for this test. Efforts will be to confirm some of the modeling results developed at ASU.
- Provide a radiation hardness assurance guideline.
- Work with RLP and Sandia on some package parts with different passivation layers (to be defined).

8.2 ASU Current and Future Tasks

- Perform deuterium experiments to compare the behavior of the response between H₂ and D₂, which would provide critical information about the reaction kinetics between H₂ and defects in the oxide to generate interface defects in these devices.
 1. D₂ ambient irradiation experiments.
 2. D₂ ambient annealing experiments.

- Perform Fourier Transform Inferred Spectroscopy experiments to directly measure D-H defects in the oxide (samples will be either be spared wafers from National's linear bipolar process or from other sources).
 1. If no spare wafers from Crane or Sandia, wafers will be purchased and oxide will be thermally grown at ASU's NanoFab)
 2. Direct FTIR (direct beam penetration through the oxide).
 3. Multiple-reflection FTIR (angled beam reflected at the edges of the device sample).
- Perform LDR experiments to study the defect formation in H₂ under low dose rate irradiations.
 1. Low dose rate irradiation on p-glass (ELDRS chips) and no-pass chips in H₂ ambient.
 2. Post-LDR irradiation annealing experiment.
 3. Establish the relationship between ELDRS and the effect of H₂.
- High temperature/low temperature irradiation experiments in H environments to study the effect of temperature on the reactions between H₂ and oxide defects.
 1. High temperature irradiation in H₂ environment.
 2. Low temperature irradiation in H₂ environment.

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14. ABSTRACT Recent enhanced low dose rate sensitivity (ELDRS) investigations carried out by RLP, Crane, ASU, and JPL have shown significant differences in the degradation of bipolar microcircuits with total dose in the presence of molecular hydrogen (H2) in packages. This has a significant impact on radiation hardness assurance and opens up opportunity to improve device performance. The objectives of this program are 1) to investigate and confirm the causal relationship between packaging recipes, hydrogen contamination and total dose response of linear bipolar microcircuits, and 2) to develop a guideline that will take into account these effects at the radiation level for future NASA space missions. This program is geared toward benefiting all future NASA space missions using bipolar or BiCMOS linear devices.					
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