The Effects of Hydrogen in Hermetically Sealed Packages on the Total Dose and Dose Rate Response of Bipolar Linear Circuits

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***Abstract*—It is demonstrated with test transistors and circuits that a small amount of hydrogen trapped in hermetically sealed packages can significantly degrade the total dose and dose rate response of bipolar linear microelectronics. In addition, we show that when exposed to an atmosphere of 100% molecular hydrogen dies with silicon nitride passivation are unaffected, whereas dies with silicon carbide or deposited oxides become very soft at high and low dose rate.**

***Index Terms*—Dose rate, enhanced low-dose-rate sensitivity, hydrogen, interface traps, radiation effects, temperature transducer, total ionizing dose, voltage comparator.**

I. Introduction

HYDROGEN, trapped inside hermetically sealed packages, has been shown to affect the total dose and post-irradiation annealing response of radiation hardened 1 μm CMOS devices and circuits [1]. The primary effect is an increase in the interface traps and the effect is significantly increased when the parts are in a 100% hydrogen atmosphere [1]. In a recent paper [2] it was also shown that the Analog Devices AD590K temperature transducer in flatpack packages with $\sim$0.6% hydrogen, as determined by residual gas analysis (RGA), degraded much more than the same parts packaged in TO-52 cans, which showed non-detectable levels of hydrogen [2]. When the flatpack lids were removed for several days the radiation response was similar to that of the cans [2]. There are several processes by which molecular hydrogen (H_2) can accumulate inside a hermetically sealed package, including reaction of moisture in the package with Si [3], out-gassing from gold plating [4] and oxidation of polyimide, sometimes used as an alpha particle barrier [5]. While many hermetic packages may contain no detectable levels of H_2, other packages may reach 2%–4% H_2. 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 normally no specification limit put on H_2, even though it has been shown to affect the reliability of GaAs microwave devices [6].

In this paper we will show how a small percentage of H_2 in hermetically sealed packages can affect both the total dose and low dose rate response of bipolar linear devices and circuits. In addition total dose irradiations were conducted on parts in a sealed 100% H_2 environment to measure the saturated H_2 induced degradation. New data are presented for experiments with package lids sealed and open as well as unsealed parts in 100% H_2.

II. Experimental Description

Bipolar linear test transistors and circuits were characterized in the course of this investigation. The test transistors are part of an enhanced low-dose-rate sensitivity (ELDRS) test chip designed to study the buildup of oxide trapped charge and interface traps in the National Semiconductor Corp. (NSC) linear circuit technology in Arlington, TX [7]. The test chip includes gated lateral pnp transistors, as well as an npn transistor and an non-gated lateral pnp transistor. The gated lateral pnp transistor (glpnp) is used to separately measure radiation induced increases in oxide trapped charge (ΔN_{ot}) and interface trap (ΔN_{it}) densities. The circuits characterized in this study included the Analog Devices Inc. (ADI) AD590 temperature transducer and the Texas Instruments (TI) LM139 quad voltage comparator. The ELDRS test chips came from a single wafer lot of parts fabricated with the NSC LM124 process in Arlington, TX. This special wafer lot was fabricated with several different combinations of the final passivation [7]–[9], [13], [14]. Measurements were taken on parts with the standard passivation, consisting of silicon nitride (Si_3N_4) over phosphorus doped oxide (p-glass), no passivation, silicon carbide (SiC), and p-glass only. The ELDRS test chip samples were packaged either by Golden Altos in 14 lead dual in-line packages (DIPs) with sealed KOVAR lids or by Sandia Labs in 14 lead DIPs using a room temperature die attach and taped on lids. Sealed KOVAR lid packages were analyzed with RGA and shown to have $\sim$ 1.2% to 1.4% H_2 in the cavity. The AD590s came from several different date code lots in two different packages, a two lead flatpack and a three lead TO-52 can, with the military and space level parts coming from a wafer bank of 4-in wafers fabricated in Santa Clara and the commercial parts

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Fig. 1. Picture of parts mounted in glass tube with 100% H_2.

coming from a 6-in line in Wilmington, MA. All of the parts in this study are commercial parts. The final passivation for all of the AD590s is a deposited silicon oxide. As discussed in the introduction, the flatpack packages showed 0.6% H_2 in the cavity by RGA, whereas the cans had an undetectable level of H_2. The TI LM139s are from a single date code lot fabricated in Sherman, TX, and were packaged in ceramic 14 lead DIPs. RGA of the LM139 package showed an undetectable level of H_2. The final passivation for the TI LM139s is silicon nitride.

The irradiations were carried out at NAVSEA Crane in a Shepherd 484 Co-60 Irradiator and at Arizona State University (ASU) in a Gammacell 220 Co-60 room source. All irradiations were conducted with all leads shorted. The irradiations in 100% H_2 were conducted with the parts inside a sealed glass tube that was evacuated and then filled with H_2 to atmospheric pressure. A picture of the glass tube is shown in Fig. 1. The electrical measurements on the ELDRS test chip glpnps were taken with a parameter analyzer and consisted of base current versus gate voltage for fixed $V_{\rm be}$ and $V_{\rm cb}$ and emitter (drain) current versus gate voltage for the transistor biased as a pMOS transistor [7]. The AD590 was characterized for $I_{\rm out}$ versus $V_{\rm in}$ at room temperature using programmable power supplies and meters [2]. The LM139 was characterized for all dc specification parameters using an Eagle linear circuit tester. The high dose rate tests were performed at dose rates between 20 and 100 rad/s and the low dose rate tests at 12–13 mrad/s.

III. Experimental Results- ELDRS Test Chip

In the first experiment, samples of the ELDRS test chip with no passivation, packaged in 14 lead ceramic DIPs with sealed KOVAR lids were irradiated in the ASU Co-60 source at 26 rad/s to a total dose of 30 krad. Along with these samples, parts with the sealed lids removed and parts from the same wafer that had never been sealed were exposed. Some of the de-lidded parts had taped on KOVAR lids and others had taped on ceramic lids during irradiation. The never sealed parts had taped on ceramic lids during exposure. In addition, an experiment was performed to measure the response of unsealed parts versus the time between lid removal and total dose exposure. Parts with sealed lids had the lids removed for 1 hour, 13 hours, and 1 week prior to exposure. The results of these experiments are shown in Fig. 2. On the left the increase in interface traps, $\Delta N_{\rm it}$, extracted from the glpnp data [7], is shown versus dose for the various samples. On the right $\Delta N_{\rm it}$ is shown versus time after lid removal for the 30 krad exposure. Data at 0 hours are for sealed lid parts and, for comparison, data at 1 week are also shown for never sealed parts.

The results shown in Fig. 2 on the left for the ELDRS test chip glpnp transistors demonstrate that the parts in the sealed KOVAR lid packages with 1%–2% H_2 degrade much more than the parts with lids removed or parts that have never been sealed. The increase in $N_{\rm it}$ is directly proportional to the increase in base current, which causes gain degradation in lateral pnp transistors [7]. Note that there is a slight difference between the parts with taped on KOVAR lids and taped on ceramic lids, which is probably due to dose enhancement from the KOVAR. The data on the right of Fig. 2 (note linear vertical scale) show that the H_2 can out-diffuse rather rapidly when the lids are removed. For the glpnp the decrease in $N_{\rm it}$ buildup leveled out after about 13 hours. Recall that these parts had no passivation.

In a second set of experiments, performed at NAVSEA Crane, exposures were made at a high dose rate (HDR) of 50 rad/s to 30 krad in 100% H_2, in sealed packages (1%–2% H_2) and open air (<0.0005% H_2), and at a low dose rate (LDR) of 12.8 mrad/s to 24 krad, in 100% H_2 and in open air. The parts in the glass tube with 100% H_2 and the open air samples were irradiated at the same time for each dose rate. The irradiations included parts with silicon carbide (SiC), no passivation, p-glass only and standard passivation (nitride over p-glass). The parts in 100% H_2 were allowed to soak for 1 week prior to irradiation with lids off. The parts with 1%–2% H_2 were taken from the same packaging lot as in the first experiment, i.e., with sealed KOVAR lids. The parts in air with lids not sealed had the lids taped on. The results are shown in Fig. 3 for SiC on the left and no passivation on the right. Fig. 4 shows similar results for p-glass on the left and nitride over p-glass on the right. These results compare degradation at high and low dose rate for saturated diffusion in 100% H_2, 1%–2% H_2 and $\sim$0%H_2.

The results in Figs. 3 and 4 for the glpnp show that: 1) parts with silicon carbide or no passivation are hard at HDR and LDR in air, 2) parts with p-glass are hard at HDR but soft at LDR in air (ELDRS), 3) parts with silicon carbide, no passivation or p-glass degrade about a factor of two higher in a sealed package with 1%–2% H_2 than parts in air at HDR, 4) parts with silicon nitride

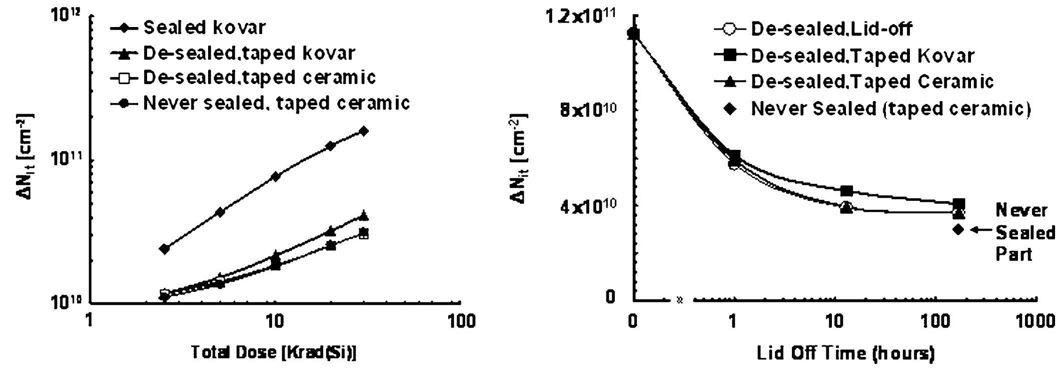

Fig. 2. Data for ELDRS test chip glpnps in various packaging configurations showing Δ N_{it} versus dose on the left and Δ N_{it} versus time between lid removal and irradiation on right.

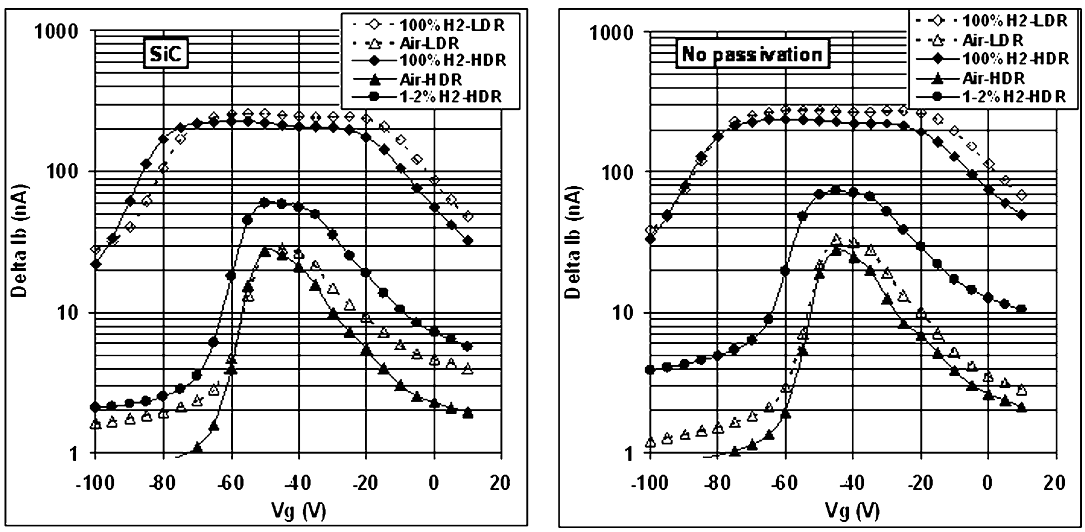

Fig. 3. Increase in base current versus gate voltage for ELDRS test chip glpnps with silicon carbide passivation (left) and no passivation (right) for high dose rate to 30 krad and low dose rate to 24 krad with different levels of H_2.

are soft at HDR and LDR in air, and 5) parts with any of the passivations are soft at HDR and LDR when exposed in 100% H_2. While all of the data in Figs. 3 and 4 are new, the results in 1), 2), and 4) were presented in [7], whereas the results in 3) and 5) are new results. TEOS is used as a passivation for many technologies, and was included in the wafer splits for the ELDRS test chip, however none of the TEOS parts were included in this experiment. It is interesting to note that while SiC solves the problem of ELDRS when there is no H_2 in the package [12], the parts start degrading at HDR with only 1%–2% H_2 in the package and become soft at HDR and LDR with 100% H_2. The parts with silicon nitride over p-glass are soft and show about the same amount of degradation at HDR and LDR in air and at HDR in 100% H_2. Hence soaking the SiN parts in 100% H_2 did not seem to increase the amount of degradation at HDR. This could be because the degradation has saturated at this dose or the H_2 is unable to penetrate the silicon nitride. The results on the LM139, discussed below, would imply that the H_2 is unable to penetrate the silicon nitride. In summary, the results for the NSC glpnp devices show that even for a passivation that apparently solves the ELDRS problem, the parts will lose their hardness when the package contains H_2, and the amount of degradation will increase as the percentage of H_2 increases.

IV. Experimental Results- AD590

In [2], we showed that the AD590 temperature transducers packaged in flatpacks degraded much more than parts packaged in TO-52 cans, across several date code lots of each package type. We further showed with RGA that the flatpacks had 0.6% H_2 in the cavity and the cans had no detectable H_2, and that removing the lid on the flatpack for several days improved the degradation at 30 krad and LDR by a factor of 10 [2]. Additional tests have been conducted at LDR to 24 krad with both the flatpacks and cans exposed in 100% H_2, as well as with the lids sealed and open to air. The new results are shown in Fig. 5 as average $I_{\rm out}$ versus $V_{\rm in}$ on the left and as the absolute value of the average radiation induced change in $I_{\rm out}$ $(\Delta I_{\rm out})$ versus $V_{\rm in}$ on the right (on a semilog scale to enhance the differences). The output current is proportional to the absolute temperature, with the proportionality constant of 1 μA $=$ 1 K. Hence, for example, at room temperature (72 °F) $I_{\rm out}$ is equal to $\sim$ 295 μA. Pre-irradiation the input voltage where the circuit starts to work properly is about 2.5 V. This is like a "threshold" voltage for proper operation. The value of this parameter can increase with radiation, as seen with the can part in 100% H_2 and the flatpack part in air. For the flatpack parts sealed and in 100% H_2

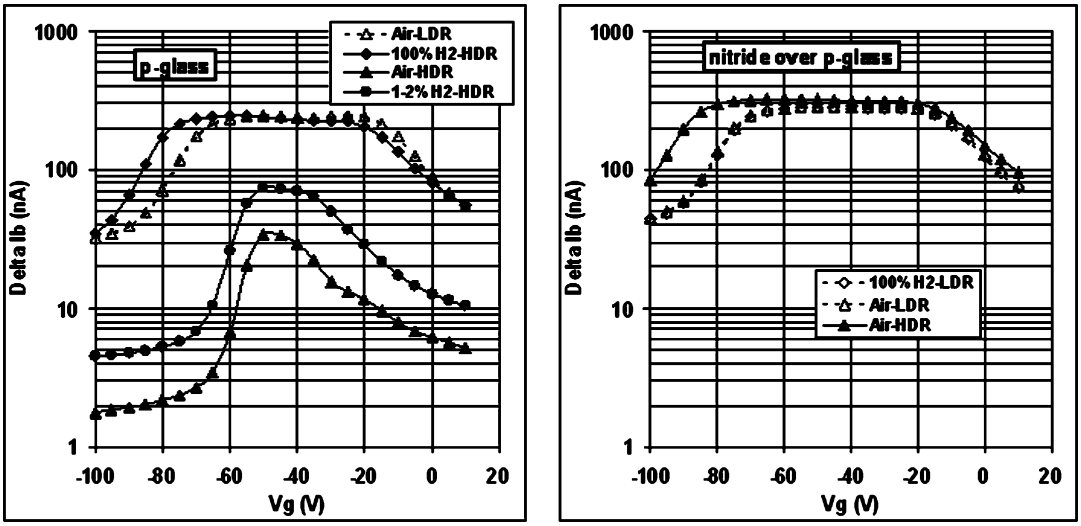

Fig. 4. Increase in base current versus gate voltage for ELDRS test chip glpnps with p-glass passivation (left) and standard passivation (right) for high dose rate to 30 krad and low dose rate to 24 krad with different levels of H_2.

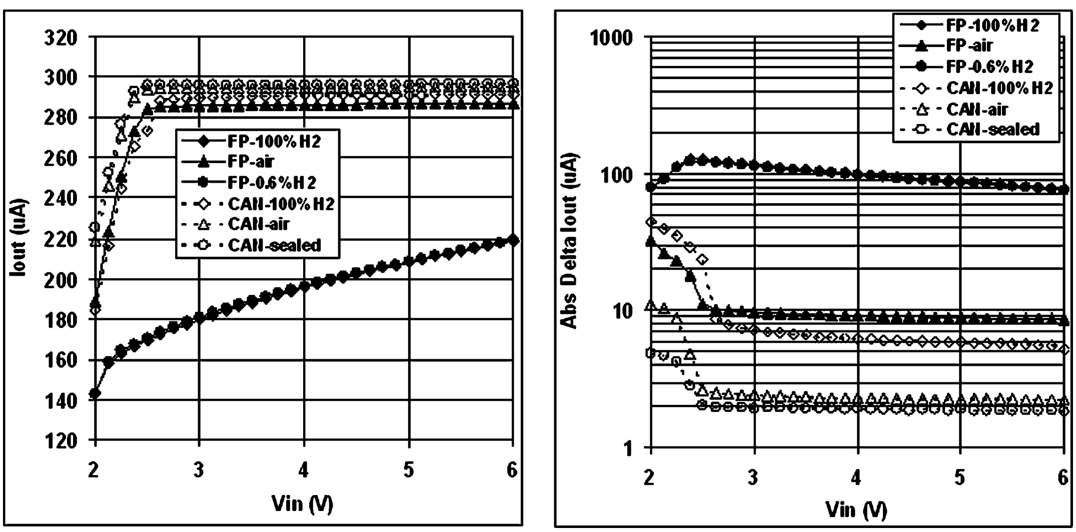

Fig. 5. AD590 average output current versus input voltage (left) and absolute radiation induced change in output current versus input voltage (right) for irradiation to 24 krad at 12.8 mrad/s for flatpacks and cans sealed, open to air and in 100% H_2.

this "threshold" voltage is greater than 6 V, so over this range of $V_{\rm in}$, the part is essentially non-functional. The slope of $I_{\rm out}$ versus $V_{\rm in}$ is a measure of the power supply rejection.

It was shown previously [2] for the AD590 that a small amount of hydrogen in the flatpack caused the parts to be soft at LDR. What Fig. 5 shows is that the amount of degradation for flatpacks at LDR with 100% H_2 is essentially the same as for 0.6% H_2. As discussed above, over this range of $V_{\rm in}$ these parts are non-functional. Based on SPICE simulations, the failure appears to be the result of the gain degradation of lateral pnp current sources that feed the npn transistor pair that sets $I_{\rm out}$ [2]. What is interesting to note is that the parts in the *cans* that had their lids removed and were exposed to 100% H_2 only degraded a factor of 2–3 more than the parts with sealed lids, as shown in Fig. 5 on the right. Since the parts in cans with 100% H_2 degraded less than parts in flatpacks in air, it would appear that there are distinct differences in the fabrication of the parts. However, as indicated previously the only difference in the fabrication of the AD590s is whether they are Military/Aerospace or commercial parts. Both of these lots are commercial, so the difference may be a lot to lot variation in response. In a follow-up test one of the can parts was exposed in 100% H_2 and irradiated at HDR to 100 krad and failed functionally.

V. Experimental Results- LM139

Previous investigations have shown that the TI LM139 voltage comparator exhibits ELDRS [11]. Experiments were conducted for irradiation at a high dose rate of 100 rad/s, irradiation at several low dose rates and elevated temperature irradiation to validate the ELDRS test procedures of MIL-STD-883/Test Method 1019.6. These tests included a) irradiation at low dose rates of 2.6 and 10 mrad/s, b) elevated temperature irradiation at 100 °C for dose rates of 0.5 and 5 rad/s, and c) 1000 hour irradiations for assumed specification

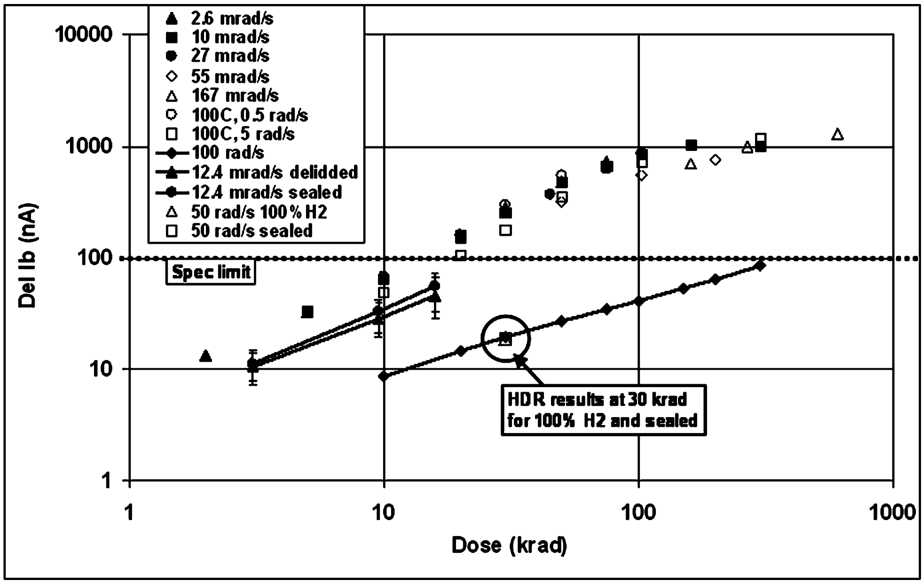

Fig. 6. Increase in input bias current versus total dose for TI LM139 for several dose rates and with packages open and in 100% H_2.

total dose values of 50, 100, and 300 krad (dose rates of 26, 55, and 167 mrad/s). The current version of the test method, TM1019.7, does not include baseline radiation tests at elevated temperature or the 1000 hour test of TM1019.6. The results of the investigation showed that the TI LM139 was quite total dose tolerant at 100 rad/s but for any dose rate at or below 167 mrad/s, or for irradiation at elevated temperature, the parts degraded much more, with ratios of low dose rate to high dose rate response equal to 10 or more at 100 krad [11]. Additional tests have been conducted on the same date code lot of parts used for the experiments of [11]. Irradiations were performed at 12.4 mrad/s to 16 krad and at 50 rad/s to 30 krad. The LDR test was performed on both sealed parts and parts that had the lids removed for a week prior to irradiation. Since the RGA on the sealed parts indicated non-measurable H_2 in the package cavity, the results for sealed and open packages should give the same result. The HDR test was performed on both sealed parts and delidded parts in the glass tube with 100% H_2. The new results are shown in Fig. 6, compared to the data presented in [11]. For the low dose rate test there was a lot of scatter in the data so the average of all four comparators for three packages (12 comparators) is shown with errors bars representing the minimum and maximum values. The results for the HDR test to 30 krad are the same for parts sealed and exposed to 100% H_2 and are the same as the results previously obtained for irradiation at HDR to 30 krad.

The results for the TI LM139, shown in Fig. 6, demonstrate that a part with silicon nitride passivation (verified by TI) is essentially immune to H_2 in the package. This was demonstrated by removing the lids and exposing the parts to 100% H_2 for a week and then irradiating the parts at HDR to 30 krad. The result was that the sealed part with no H_2 in the package, as shown by RGA, degraded the same as the part in 100% H_2. This result implies that the H_2 cannot penetrate the silicon nitride, even though silicon nitride incorporates a large amount of hydrogen when it is formed [9]. However, the part clearly exhibits ELDRS, as shown in Fig. 6 for dose rates at or below 167 mrad/s and for elevated temperature irradiation at dose rates of 0.5 and 5 rad/s. While the NSC parts with nitride are soft at HDR and LDR, the TI parts with nitride are only soft at LDR, i.e., exhibit ELDRS.

VI. Discussion and Conclusion

The results presented herein demonstrate a wide range of behavior of bipolar linear circuit technologies in the presence of molecular hydrogen. RGA investigations by Golden Altos and similar investigations at NAVSEA Crane have shown that many package types contain H_2 in small percentage amounts. There are many sources of H_2 in packages, but it can be eliminated with proper anneals, as demonstrated by the packages we analyzed that had H_2 below the detectable level. Our results have shown that degradation with 1%–2% H_2 can be intermediate between no H_2 and 100% H_2 (NSC glpnp), that 0.6% H_2 can cause as much degradation as 100% H_2 (ADI AD590 in flatpacks), or that 100% H_2 can result in no further degradation (TI LM139). The results depend primarily on what type of final passivation is used. It appears that silicon nitride acts as a barrier to H_2 since it does not let the H_2 either penetrate from the outside or escape from the underlying oxides, even though the silicon nitride itself usually contains a large amount of hydrogen. It was demonstrated in an earlier experiment that removing the silicon nitride from a NSC LM111 allowed the H_2 to escape and greatly reduce the degradation [8].

These results have led us to the conclusion that many bipolar linear circuits that show ELDRS may be quite hard at high and low dose rate as processed through metallization. We demonstrated this with the NSC process that had no final passivation [7]. It is often the things that are done after metal that degrade the total dose hardness. The hardness can be degraded by the final passivation [8], [9], [12], and [14], the thermal cycles that occur in packaging and preconditioning, e.g., burn-in [8], [13], and the presence of molecular hydrogen in the package [2], [10]. Based on these results the recommended approach to hardening bipolar linear circuits with poor total dose response is to characterize the high and low dose rate response of the part as processed through metallization. This can be done by pulling a wafer before final passivation and packaging the chips with a room temperature die attach and not sealing the lids. It may also be done using wafer level irradiations since the parts would not need to be biased during irradiation. If this "baseline" total dose response is acceptable, then those factors occurring after metal that degrade the hardness can be identified and mitigated.

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REFERENCES

[1] R. A. Kohler, R. A. Kushner, and K. H. Lee, "Total dose radiation hardness of MOS devices in hermetic ceramic packages," *IEEE Trans. Nucl. Sci.*, vol. 35, no. 6, pp. 1492–1496, Dec. 1988.

[2] R. L. Pease, D. Platteter, G. Dunham, J. E. Seiler, and S. McClure, "Total dose and dose rate response of an AD590 temperature transducer," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 4, pp. 1049–1054, Aug. 2007.

[3] M. L. White, K. M. Striny, and R. E. Sammons, "Attaining low moisture levels in hermetic packages," *IEEE Proc. IRPS*, p. 253, 1982.

[4] R. K. Lowry, "Sources of volatile gases hazardous to hermetic electronic enclosures," *IEEE Trans. Electron. Packag. Manuf.*, vol. 22, no. 4, pp. 319–323, Oct. 1999.

[5] Interpretation of RGA data including observations on the outgassing of materials 1994, Oneida Research Services. Sophie Antipolis, France [Online]. Available: www.orsfr.com

[6] R. R. Mutha, D. P. Rancour, S. A. Kayali, and W. T. Anderson, "Modeling of hydrogen effects in GaAs FETs," in *Proc. GaAs Reliability Workshop*, 1997, pp. 72–76.

[7] R. L. Pease, D. G. Platteter, G. W. Dunham, J. E. Seiler, H. J. Barnaby, R. D. Schrimpf, M. R. Shaneyfelt, M. C. Maher, and R. N. Nowlin, "Characterization of enhanced low dose rate sensitivity (ELDRS) effects using gated lateral PNP transistor structures," *IEEE Trans. Nucl. Sci.*, vol. NS-51, no. 6, pp. 3773–3780, Dec. 2004.

[8] M. R. Shaneyfelt, R. L. Pease, J. R. Schwank, M. C. Maher, G. L. Hash, D. M. Fleetwood, P. E. Dodd, C. A. Reber, S. C. Witczak, L. C. Riewe, H. P. Hjalmarson, J. C. Banks, B. L. Doyle, and J. A. Knapp, "Impact of passivation layers on enhanced low-dose-rate sensitivity and thermal-stress effects in linear bipolar ICs," *IEEE Trans. Nucl. Sci.*, vol. NS-49, no. 6, pp. 3171–3179, Dec. 2002.

[9] J. E. Seiler, D. G. Platteter, G. W. Dunham, R. L. Pease, M. C. Maher, and M. R. Shaneyfelt, "Effects of passivation on the enhanced low dose rate sensitivity of National LM124 operational amplifiers," in *IEEE Radiation Effects Data Workshop Rec.*, 2004, p. 42.

[10] X. J. Chen, H. Barnaby, B. Vermeire, R. Pease, D. Platteter, G. Dunham, J. Seiler, and S. McClure, "Mechanisms of enhanced radiation-induced degradation due to excess molecular hydrogen in bipolar oxides," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, Dec. 2007.

[11] R. L. Pease and J. Seiler, "Evaluation of MIL-STD-883/Test Method 1019.6 for bipolar linear circuits," *J. Radiat. Effects: Res. Eng.*, 2005, submitted for publication.

[12] M. R. Shaneyfelt, J. R. Schwank, P. E. Dodd, M. C. Maher, and R. L. Pease, "Elimination of Enhanced Low-dose-rate sensitivity in linear bipolar devices using silicon-carbide passivation," *IEEE Trans. Nucl. Sci.*, vol. NS-53, no. 4, pp. 2027–2032, Aug. 2007.

[13] M. R. Shaneyfelt, J. R. Witczak, J. R. Schwank, D. M. Fleetwood, R. L. Pease, P. S. Winokur, L. C. Riewe, and G. L. Hash, "Thermal-stress effects on enhanced low dose rate sensitivity in linear bipolar ICs," *IEEE Trans. Nucl. Sci.*, vol. NS-47, no. 6, pp. 2539–2545, Dec. 2000.

[14] M. R. Shaneyfelt, R. L. Pease, M. C. Maher, J. R. Schwank, S. Gupta, P. E. Dodd, and L. C. Riewe, "Passivation layers for reduced total dose effects and eldrs in linear bipolar devices," *IEEE Trans. Nucl. Sci.*, vol. NS-50, no. 6, pp. 1784–1790, Dec. 2003.