# Accelerated Effects of Hydrogen on GaAs MESFETs

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## Abstract

Several experiments were conducted which have all indicated that moderate to high levels of hydrogen causes distinct changes in MESFETs under accelerated temperatures. The changes were found to be generally opposite of those previously reported for hydrogen degradation. The changes also took significantly longer to manifest than has been reported for other processes. The changes were found to occur on devices constructed with either platinum or palladium included in the gate metals, with some differences noted between the two barrier metals. Temperature and hydrogen concentration were found to accelerate the changes caused by hydrogen.

## Purpose

The primary motivation of this study was determine if the "hydrogen effect" [ref 1 & 2] could be observed. If the effect was observed, the experiment was designed to also investigate any differences between platinum and palladium barrier metallizations in a standard titanium-gold gate metal stack. Because of the historical data, indicating a lack of hydrogen effect on this particular process, conditions were selected to represent the worst case scenario. For example, samples investigating hydrogen interactions were purposely sealed in a 100% hydrogen belt furnace, resulting in approximately 10-40% hydrogen inside the package cavities. The experiment was also designed with six different FET configurations, in various DC bias schemes. Once the hydrogen effect was observed at 185°C (channel temperature), additional samples were added at higher acceleration conditions without bias. Even more samples were subsequently added which allowed hydrogen to evolve naturally inside the package, representing more typical amounts of hydrogen expected during use. Testing of all parts of the experiment is continuing, with additional results expected before presentation in October 1994.

## Experimental Description

The entire population of devices used for this experiment began with 120 specially prepared samples. The structure implemented is a Technology Characterization Vehicle (TCV) in which (3) 300um wide FETs and (3) 50um wide FETs are bonded out for measurement. In all cases, the TCVs were mounted inside a 24 pin ceramic sidebraze Dual In-line Package (DIP) using a silver-filled epoxy die attach material. The devices were fabricated using TriQuint's HA MESFET process, which is capable of half micron long gates. Half of the samples were constructed with a gate metal stack of Ti-Pd-Au and the other half had Ti-Pt-Au. All other processing was conducted identically in the same lot and per standard procedures for the HA process. Half of the samples were eutectically sealed in a 100% hydrogen belt furnace and have between 10% and 40% hydrogen inside the package from time zero. The remaining half of the population was split between being sealed in a normal 100% nitrogen belt furnace, and left unsealed. These splits generated a low hydrogen level (virtually unaccelerated in terms of hydrogen concentration) and a package cavity incapable of containing any significant amount of hydrogen, respectively. Initial testing was started on 18 samples at 185°C with various DC bias configurations. At the onset of a distinct observable change due to high concentration of hydrogen, five additional tests were sequentially started. All of the five subsequent tests have been conducted without bias, but with higher temperature accelerations. The original test has accumulated 3,500 hours so far. A description of the experimental matrix is shown in Table 1.

## Results

<u>Measurement Methods.</u> The effect of the hydrogen changes was observed by making DC parametric measurements primarily on MESFETs. The test system used for measurements is a PC-controlled Keithley S-900 parametric tester. Each FET had five key parameters measured. Channel current (Idss) is measured with 2.5 Volts from drain to source, and 0 Volts on the gate. Pinchoff (Vp) is also measured with 2.5 Volts from drain to source. It is an iterative test to find the gate bias required to reduce the channel current to 50 uA. Gate leakage (Igss), Breakdown Voltage (BV), and forward Voltage (Vf) are measured with the source and drain shorted to ground. For gate leakage, the gate is biased to -5.5 Volts, and the resulting gate current is measured. Breakdown is measured as the gate voltage required to force the reverse gate current to 50 uA. Forward voltage is measured as the bias Voltage required to force 50 uA forward current in the gate.

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Additional measurements were made on several samples. In particular, channel current was measured for a range of gate bias, and typical "curve trace" data was collected. The curve trace data measures channel currents for swept drain voltages and stepped gate biases.

**Table 1 - Experiment Description to Examine the GaAs "$H_2$ Problem"**

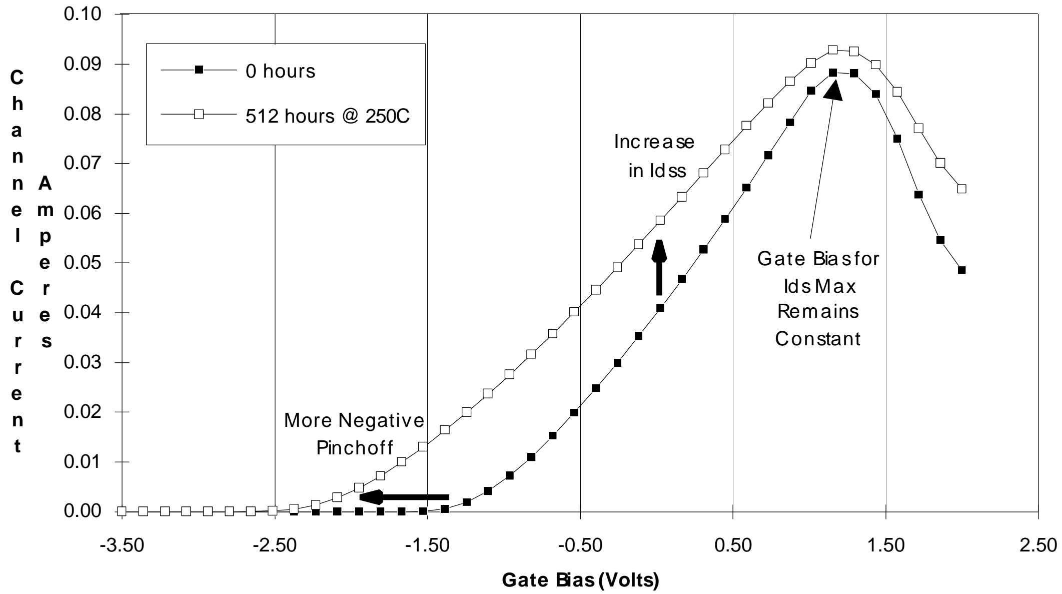
| Test Name | T1 | X | T2 | Z | T3 | T4 |
|---|---|---|---|---|---|---|
| 24 Pin Dips | 18 | 2 | 18 | 7 | 18 | 18 |
| Ambient Temp | 175°C | 250°C | 225°C | 275°C | 200°C | 250°C |
| Static Bias | Yes | No | No | No | No | No |
| Room Cntl Pkg | 8 | 8 | 8 | 8 | 8 | 8 |
| Air Control Pkg | 9 | 1 | 6 | 2 | 6 | 6 |
| High $H_2$ Pkg | 9 | 1 | 6 | 2 | 6 | 6 |
| Low $H_2$ Pkg | 0 | 0 | 6 | 2 | 6 | 6 |
| Pd Pkg | 9 | 0 | 9 | 3 | 9 | 9 |
| Pt Pkg | 9 | 2 | 9 | 4 | 9 | 9 |
| Test FETs | 90 | 12 | 108 | 42 | 108 | 108 |
| Small FETs | 36 | 6 | 54 | 21 | 54 | 54 |
| Large FETs | 54 | 6 | 54 | 21 | 54 | 54 |
| 1/2 um FETs | 36 | 4 | 36 | 14 | 36 | 36 |
| Pt Gate, Small FETs | 18 | 12 | 27 | 9 | 27 | 27 |
| Pt Gate, Small FETs, High $H_2$ | 8 | 6 | 9 | 6 | 9 | 9 |
| Pt Gate, Small FETs, Low $H_2$ | 0 | 0 | 9 | 3 | 3 | 9 |
| Pd Gate, Small FETs | 18 | 0 | 27 | 9 | 27 | 27 |
| Pd Gate, Small FETs, High $H_2$ | 10 | 0 | 9 | 3 | 9 | 9 |
| Pd Gate, Small FETs, Low $H_2$ | 0 | 0 | 9 | 3 | 9 | 9 |
| Pt Gate, Large FETs | 27 | 12 | 27 | 9 | 27 | 27 |
| Pt Gate, Large FETs, High $H_2$ | 12 | 6 | 9 | 6 | 9 | 9 |
| Pt Gate, Large FETs, Low $H_2$ | 0 | 0 | 9 | 3 | 3 | 9 |
| Pd Gate, Large FETs | 27 | 0 | 27 | 9 | 27 | 27 |
| Pd Gate, Large FETs, High $H_2$ | 15 | 0 | 9 | 3 | 9 | 9 |
| Pd Gate, Large FETs, Low $H_2$ | 0 | 0 | 9 | 3 | 9 | 9 |
| Pd Gate, Lg=1um , High $H_2$ | 5 | 0 | 3 | 1 | 3 | 3 |
| Current Hours Completed | 3500 | 2500 | 700 | 700 | 600 | 600 |

Failure Criteria. Wearout failure mechanisms typically affect MESFETs most significantly by gradually reducing channel current (Idss). The failure criteria for these Idss changes is usually set at 20%. "Degradation" in this study generally produced an increase in channel current. These increases often lead to oscillations in the MESFETs which are occasionally present initially, but confuse the data as the FETs developed more drive. Because of these anomalies, pinchoff was selected as the parameter of interest since the FETs do not oscillate while being turned-off. Because of the increased stability of the measurements, a change of 10% was used as a failure criteria to determine predictive estimates on the hydrogen effect. Although this is considered a more conservative failure criteria, it was selected in order to allow the classification of more samples as "failures" for the purposes of this analysis.

Onset Time. The length of time to observe hydrogen shifting was the first difference found in this experiment from other published data. In general, hydrogen degradation had been previously observed in one week or less at 125°C. The original test in this experiment, using accelerated hydrogen concentrations, remained unaffected by hydrogen for nearly 1000 hours at 185°C.

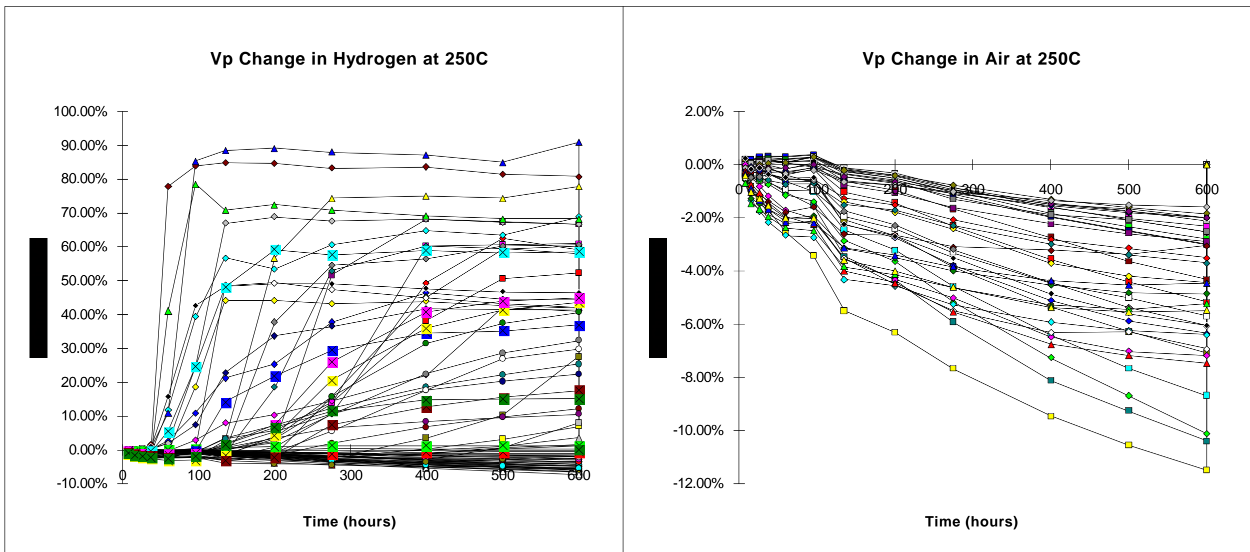
"Degradation." Since wearout and the changes caused by hydrogen occur in opposite directions, the hydrogen effect is termed "degradation." In many operational situations, the hydrogen "degradation" would be considered beneficial, especially if it counteracted the normal changes observed because of wearout. Figure 1 is included to more fully describe the observed changes than classification merely as an increase in channel current. As shown, the channel current in a FET affected by hydrogen increases at ALL gate biases. The gate bias point for maximum channel current remains stable. Clearly, the most significant effect is the increase in channel current near pinchoff. A FET affected by hydrogen requires much more negative bias to be turned-off.

**Figure 1 - Changes in FET Channel Currents Over A Range of Gate Biases.**



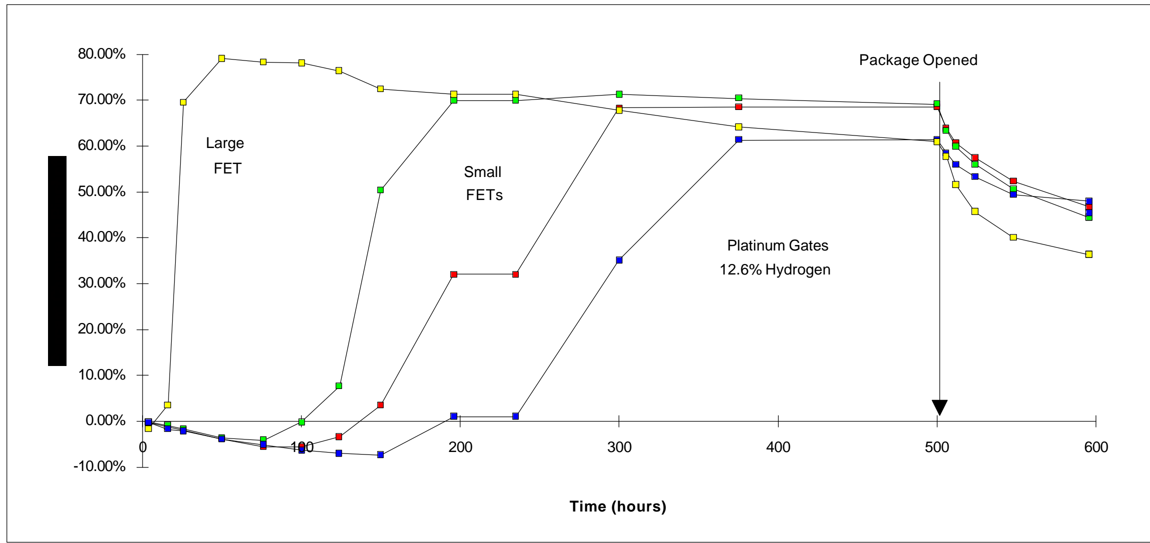

Parametric Changes. Figure 2 shows the characteristic shifts in pinchoff caused by the hydrogen effect. For comparison purposes, data is shown for samples in hydrogen and in air. Please note the different scales between the hydrogen and non-hydrogen results. Unlike the gradual and continuous degradation of wearout, the hydrogen shifts are abrupt and discrete. The hydrogen effect seems to saturate rapidly. It is also obvious that normal wearout degradation is observed on hydrogen affected FETs before and after the abrupt shifting takes place. Increases in channel current occur simultaneously with the pinchoff shifts. Some other improvements were noted in gate leakage and reverse breakdown parameters. Gate leakage decreased and reverse breakdown increased simultaneously with the channel current and pinchoff shifts. Forward Voltage characteristics were unchanged by the presence of hydrogen, and slowly wore out identically to the control devices in air.

**Figure 2 - Changes in Pinchoff for FETs in Hydrogen and Air at 250°C**



Device Recovery. Similarly to other reported data, the shifts measured in this study were found to recover after removal of the hydrogen. Figure 3 shows the characteristic pinchoff shifts for a single sample aged at 275°C. After 500 hours, all the FETs had experienced shifts in pinchoff due to hydrogen, and the device was submitted for Residual Gas Analysis (RGA). The package was found to contain 12.6% hydrogen at that point. Testing was continued at 275°C with the RGA sample hole in the package lid. Following the RGA testing, the degradation shifted in the opposite direction of the initial changes with the hydrogen in the cavity. These recovery shifts begin at a rate similar to the original shifts, but seem to approach a value between the starting pinchoff and the maximum shift, less than a complete recovery.

**Figure 3 - Initial Vp Changes and Recovery at 275°C.**




Big FETs Vs Small FETs. A significant difference in onset time to hydrogen shifts between FETs was noted in every sample. Particularly, the larger interdigitated FETs (300 um wide) shifted first, and the small single gate stripe FETs (50 um wide) shifted much later. The key physical feature to describe these different results is assumed to be the airbridge metal employed in the design of the larger FETs. The airbridge provides an alternate path for hydrogen to reach the FET ohmic contacts (close proximity to the gates) other than directly though the nitride dielectrics. The airbridge also thins the nitride over the gates from a total of 6000 angstroms to roughly 5000 angstroms because of shadowing during the final passivation application. An example of the different onset times for hydrogen "degradation" for different FET sizes is evident in Figure 3. The large FET changes completely in less than 24 hours at 275°C, while it takes 125 hours before the first small FET begins it's degradation. All FETs shown in Figure 3 were in the same package, on the same TCV. An estimate of the accelerating affect of FET size is shown in Table 2.

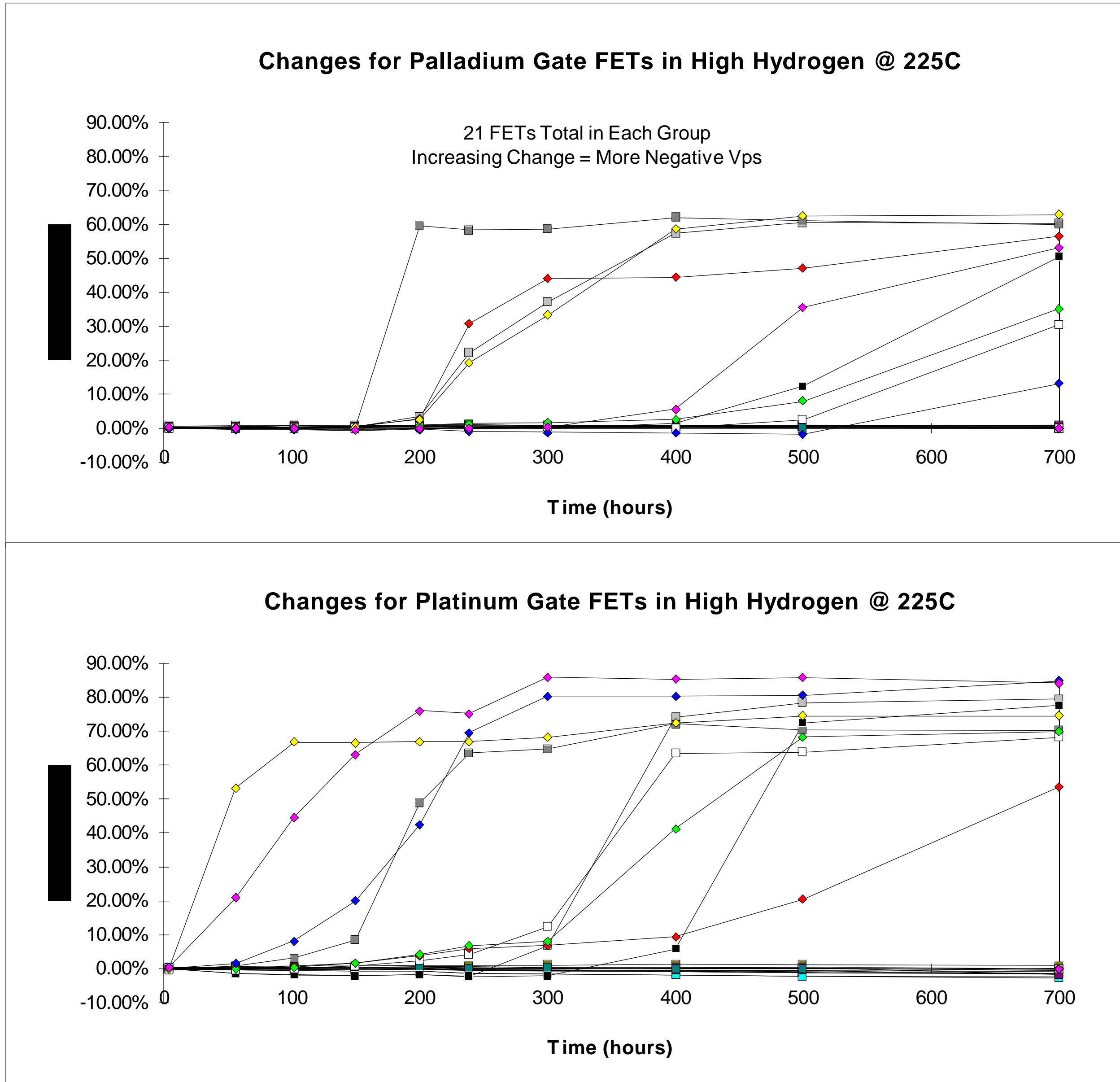
**Table 2 - Effect of FET Size (Path Length) on Hydrogen Shifting**

| Test | T4 | Z |
|---:|:---:|:---:|
| Temperature: | 250°C | 275°C |
| Gate Metal Type: | Pt | Pt |
| Large FET Median Life (hours): | 96 | 50 |
| Small FET Median Life (hours): | 700 | 300 |
| Acceleration Factor Observed On FET Size: | 7.29x | 6x |

Separation of Variables. Because testing was conducted in multiple discrete packages, the potential of findings influenced by various concentrations of hydrogen is likely to be significant. Until all the testing is completed and the devices have been analyzed to determine each one's individual hydrogen amount, the effect of hydrogen concentration cannot be completely separated from other variables under investigation. Although the effect of hydrogen concentration was studied as a separate acceleration variable, it cannot be specifically determined until all RGA testing is completed. Gate metal and temperature variables were not completely separable from hydrogen concentration.

Platinum Vs. Palladium. Effects due to hydrogen were observed in samples with either platinum or palladium barrier metal in the gates. In most cases, the samples with platinum gates shifted earlier, and to a greater extent than the samples with palladium gates. This difference is shown in Figure 5, where data is shown for both types of FETs at 225°C.

**Figure 5. Shifts in Pinchoff Observed for Platinum and Palladium Gates.**




Thermal Acceleration. Tests were conducted over a range of five temperatures: 185°C, 200°C, 225°C, 250°C, and 275°C. Acceleration of the hydrogen "degradation" was observed at each increase in temperature. The activation energy of the hydrogen effect was measured over the full range. Failures were insufficient at 200°C, but estimates of activation energy using various combinations of all the other temperatures range from 0.2eV to 1.2eV, with the best estimate at 0.8eV for both platinum and palladium gate metals.

Hydrogen Concentration Acceleration. In an attempt to measure the accelerating effect of hydrogen concentration, samples were assembled in three basic forms. High concentration samples were made by sealing in a belt furnace with 100% hydrogen. Preliminary measurements have found that method results in hydrogen levels from 10% to 40% inside each package cavity. The second assembly method involved sealing in a normal manner using 100% nitrogen in a belt furnace. Preliminary measurements indicate this method results in hydrogen levels from 2% to 10%. The final method of sample preparation involves no cavity seal. To maintain consistent thermal history, the unsealed packages were exposed to the same sealing temperatures as the hydrogen samples without attaching a lid. Table 3 indicates an estimate of the hydrogen concentration effect for several conditions.

**Table 3 - Effect of Hydrogen Concentration on Shifting**

| Test | T4 | T4 | Z |
|---|---|---|---|
| Temperature: | 250°C | 250°C | 275°C |
| Gate Metal Type: | Pd | Pt | Pt |
| Low Hydrogen Median Life (hours): | 135 | 96 | 50 |
| High Hydrogen Median Life (hours): | 275 | 500 | 375 |
| Acceleration Factor of Hydrogen Concentration: | 2.04x | 5.21x | 7.5x |

## Summary

Six relatively long lifetests have now been conducted at highly accelerated temperature conditions. So far, less than 1/3 of all devices tested in hydrogen atmospheres have been affected. At this point, the affected devices exhibit rapid, abrupt increases in channel current with corresponding large negative shifts in pinchoff (threshold) voltages. As these shifts occur, the magnitude of breakdown voltages increase, and leakage currents decrease. Schottky forward voltage parameters remain relatively stable. For all parameters except Vp, these parametric changes are generally perceived as improvements in device parameters. Upon removal of hydrogen, the shifts will partially recover. Passivation (silicon nitride) seems to inhibit the onset of the hydrogen "degradation" as evidenced by the differences observed between FET designs with different path lengths through the dielectric to the gates. Both platinum and palladium barrier metals are affected by hydrogen. Gates with platinum barrier metal seem to shift earlier, and certainly to a greater extent, than gates with palladium barrier metal. The hydrogen effect is certainly accelerated by temperature, but to a lesser degree than most GaAs FET wearout mechanisms. A strong accelerating effect of hydrogen concentration was also observed.

## Impact

Since many findings here are contrary to those previously reported, this study clearly shows that the effects of hydrogen on GaAs MESFETs can be very different for different processes. Testing was conducted on packaged devices with accelerated or normally evolved amounts of hydrogen, instead of in large chambers with various partial pressures of virtually unlimited amounts of hydrogen. For the TriQuint standard MESFET process in particular, this study found:

1. Hydrogen can cause parametric shifts in MESFETs with either platinum or palladium gate metals.
2. Ingress path lengths (evidenced by FET size) affect the onset time of hydrogen shifting.
3. Temperature and hydrogen concentration are accelerating factors for the hydrogen effect.
4. Observed parametric changes are opposite of expected wearout degradation.
5. Onset times are much longer than previously reported.

The result of these last three conclusions indicate that hydrogen "degradation" may not be a factor during normal operation of devices. In fact, the effect of low to moderate hydrogen concentration levels and normal temperature operation is likely to moderate the hydrogen changes to the extent that they may be matched or offset by the normal wearout degradation resulting in more stable devices over long term operation.

## References

1. W.O. Camp, et.al. "Hydrogen Effects on Reliability of GaAs MMICs," 1989 GaAs IC Symposium, Pg.203.
2. P.C. Chao, et.al. "HEMT Degradation in Hydrogen Gas," IEEE Electron Device Letters, May 1994, Pg.151.