# Practical Approaches to Remediation of Hydrogen Poisoning in GaAs Devices

Anthony A. Immorlica Jr., Stephen B. Adams, and Axel R. Reisinger

Sanders, a Lockheed Martin Company
65 Spit Brook Road, Nashua, NH 03060


## ABSTRACT

**A number of approaches have been investigated for remediation of the deleterious effects of exposure of GaAs Field Effect Transistors to hydrogen gas. Understanding the degree of risk and mission lifetime requirements is key to selection of the most appropriate remediation approach. A new metric, *hydrogen exposure*, which is the product of partial pressure and time, and an associated *degradation exposure*, which relates to a defined failure point, are useful in engineering a practical solution. While use of a properly designed, irreversible hydrogen getter is felt to be the best approach at this time, other remedies such as controlled leaks, package bakeout, and bias compensation can also be effectively employed in certain situations.**

## INTRODUCTION

It is well known that hydrogen can significantly degrade GaAs Field Effect Transistors, particularly for devices incorporating Schottky barrier gates employing Pt or Pd [1]. Because many common microwave packaging materials can outgas hydrogen, hydrogen poisoning poses a significant reliability risk, particularly for devices which are hermetically packaged or employ hydrogen based reducing gases in the packaging process. The purpose of this work is to examine practical approaches to dealing with hydrogen effects remediation. New insights have been gained into understanding the degree of hydrogen exposure, both during the manufacturing process and useful life, and into the interpretation of hermeticity.

### *Outline of Paper*

This paper will first briefly review the causes and effects of hydrogen poisoning in GaAs Field Effect Devices and then focus on describing approaches that have been successfully employed to remediate hydrogen poisoning effects. Before choosing a remediation approach, however, it is important to understand the risk of failure that a device will incur over its design life as a result of its exposure to hydrogen. Assessing risk can, in fact, dictate the most practical and cost effective way to deal with the problem.

## UNDERSTANDING HYDROGEN EXPOSURE AND RELIABILITY PREDICTION

It is important to recognize that in most situations the hydrogen concentration, most conveniently expressed in terms of partial pressure of hydrogen, is far from constant and is continually changing with time. Earlier workers have measured hydrogen content in packaged parts by Residual Gas Analysis, and found several percent partial pressure [2]. However, as will be shown, the evolution of hydrogen from package materials, which is governed by classical diffusion equations, can take considerable time to build up to dangerous levels, and can, in fact, reverse as the slope of the concentration gradient becomes negative [3].

One technique often used for estimating reliability in hydrogen environments assumes that the total amount of hydrogen in the package materials is released into the package cavity at time t = 0 and remains there for the life of the device. This gives a somewhat pessimistic or worst case result. An alternative methodology which is also useful for estimating mission life using familiar reliability equations, is to define a metric, *hydrogen exposure*, E, which is the product of the exposure partial pressure and exposure time. For the packaged device, $E_p$ is defined as:

$$E_p(\text{atm-hr}) = Q(\text{cm}^3\text{-atm}) * t(\text{hr}) / V(\text{cm}^3) \qquad (1)$$

where Q is the total hydrogen released into the package cavity up to time t, and V is the volume of the package cavity. Q can be estimated by measuring the total hydrogen content of the packaging materials by methods such as meltdown techniques, giving the worst case result, or determined by measuring the time evolution of hydrogen from outdiffusion measurements of the actual package material; this can also be calculated if the appropriate constants, diffusivity and solubility, are known for the materials. One utility of this metric is that it can also be used to account for exposures during the manufacturing process; for example, exposures to forming gas during die attach can be accounted for by adding a constant term to equation (1).

Similarly, one can define a *degradation exposure*, D, which will degrade a device to a defined failure criterion. For example, the Mean Time to Failure (MTTF) of PHEMTs exposed to a constant hydrogen partial pressure, p, and temperature, T, is given by:

$$\text{MTTF(hr)} = A \exp\{E_a/kT\}/p^n \qquad (2)$$

where $E_a$ is the activation energy for hydrogen induced degradation, k is Boltzmann's constant and A is a pre-exponential constant; the dimensionless constant n~1 [4]. Then,

$$D(\text{atm-hr}) = p^*\text{MTTF} = A \exp\{E_a/kT\}. \qquad (3)$$

Degradation exposure can be determined by accelerated life measurements at constant hydrogen pressure and can vary considerably among various device technologies and manufacturers. Degradation exposures for GaAs devices reported in the literature range from 1 to $10^4$ atm-hr at T=373K.

If we assume hydrogen induced failures are log normal distributed, we can predict hydrogen failures using the ratio $E_t$/D using the same methodology as that used in predicting reliability using the time ratio of MTTF to mission life. Now, $E_t$ is the total hydrogen exposure, including any exposure the device might see during the manufacturing process, such as die attach. The cumulative failure, F, can be shown to be [5]:

$$F = (1-R) = ½ + ½ \text{ erf } [\ln ((E_t/D)/\sigma\sqrt{2})] \qquad (4)$$

Figure 1 is a plot of the failure probably, F, versus *fractional dose* $E_t$/D for various values of the log normal sigma, σ.

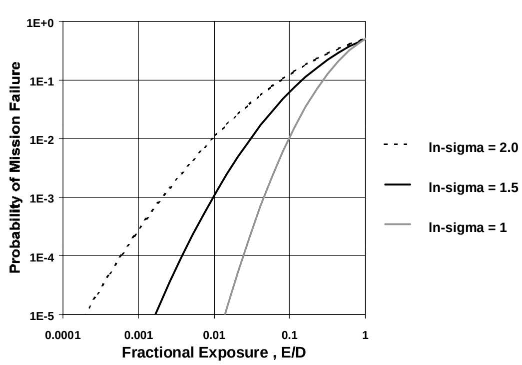


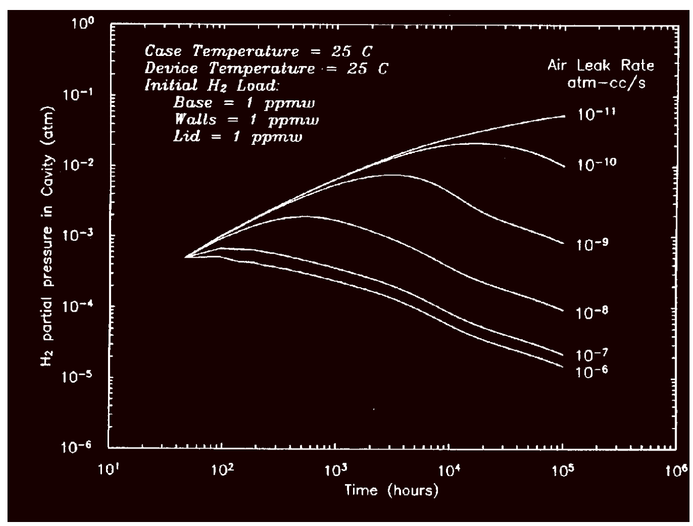

Fig. 1. Failure probability versus fractional dose for various log normal standard deviation values

Thus, $E_t$/D is the key to prediction of the risk of failures due to hydrogen poisoning, and *is independent of the time evolution of hydrogen into the package cavity*.

DEFINING HERMETICITY

"Hermeticity" is normally defined in terms of an acceptable "leak rate," implying that a truly hermetic package is difficult, if not impossible, to achieve. For typical microwave packages, the maximum leak rate is given as ~$10^{-8}$ standard cc/sec for a package to be considered hermetic. Thus, while hydrogen is constantly diffusing from the package materials into the package cavity, it is also leaking from the cavity at the package leak rate. Indeed, this may be the reason for the often observed spread in RGA data of hydrogen partial pressures in packages which were otherwise thought to be identical. Thus, it is important to understand the dynamics of effusion and leaks in order to accurately determine the total exposure.

In order to estimate the effects of constant leaks, we have modeled a "generic" microwave Kovar® based package, and solved the diffusion equations for time varying boundary conditions at the inside of the package wall. Figure 2 shows the hydrogen partial pressure as a function of time for




various leak rates. For "large" leak rates, the

Fig. 2. Evolution of partial pressure with time in a generic package as a function of package leak rate

pressure falls within 100 hours, while for "small" leak rates, it continues to monotonically increase throughout the time scale of the calculation. Note that at the intermediate leak rates, the hydrogen pressure exhibits a maximum. Results of integrating this behavior with the expression for MTTF for

PHEMTs (Eq. 2) is given in Figure 3. It is intuitive that at high leak rates, the total exposure is lessened and the MTTF will increase. What is surprising and of interest, is that the transition is relatively steep and occurs in the vicinity of a leak rate of $10^{-8}$ standard cc/sec. This can be exploited by introducing controlled leaks in the package structure as discussed below.

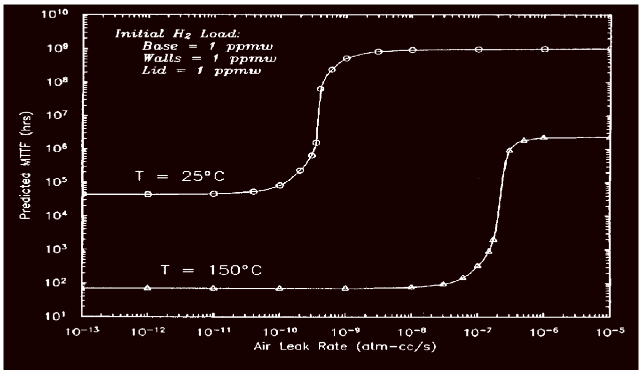



Fig. 3. Modeled MTTF of a hermetically packaged PHEMT versus package leak rate; results for two different package temperatures are shown.

## REMEDIATION APPROACHES

A number of approaches are being utilized to reduce or eliminate the reliability risk of hydrogen exposure during the design life. The balance of this paper will discuss these approaches and offer guidelines for their application.

*1. Hydrogen Getters* - Gettering techniques have been used in the semiconductor industry for some time in dealing with problems such as moisture and loose particulate. A number of laboratories are working on hydrogen getters and commercial getters are available. Device lifetest results using a proprietary Lockheed Martin getter are shown in Figure 4.

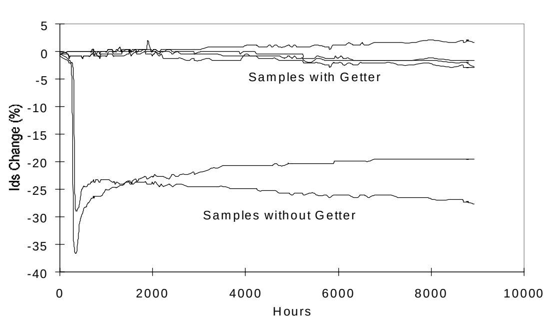



Fig. 4. Lifetest data comparing $I_{dss}$ of GaAs PHEMTs in gettered and ungettered packages. The getter was designed for a 15 year mission life at 125C

The key to proper application of hydrogen getters, regardless of their composition or physical mechanism,* is knowledge of a.) the getter capacity and b.) the getter pumping speed. We can define a characteristic pumpdown time as:

$$\tau(hr) = V(cm^3) / S(cm^3/hr) \quad (5)$$

where V is volume and S is pumping speed. It can be shown that with adequate capacity and for $\tau << t$, the getter reduces the device exposure by the ratio of $\tau$ to mission life, t, or:

$$E = E_p * \tau / t. \quad (6)$$

Thus, with a gettered device, the total device exposure is reduced by $\tau/t$ and reliability can be predicted by multiplying the component of E representing the packaged exposure in Figure 1 with the ratio $\tau / t$.

In order to successfully employ a getter, it is important to 1. know the robustness of the device technology being used (i.e., the value of D) and 2. insure that the getter capacity, C, exceeds the exposure dose Q. Generally, since the pumping speed of a getter degrades as the capacity is approached, it is vitally important that C>>Q in order for the inequality $\tau << t$ to be satisfied.

. *2. Controlled Leaks* - One obvious conclusion that can be drawn from Figure 3 is that at high enough leak rates, hydrogen exposure ceases to be a reliability risk and other known mechanisms will prevail. In fact, it is generally accepted that no hydrogen remediation is needed for devices in "non-hermetic" packages. For cases in which hermeticity is desired to eliminate intrusion of moisture and other higher molecular weight gasses, it is feasible to introduce a "controlled leak." Materials exist which allow permeation of hydrogen, but highly attenuates permeation of other heavier or larger gas molecules. This approach is under investigation. To be used effectively, the dynamics of the hydrogen effusion from the package materials must be understood.

*3. Package Bakeout* - Another approach to reducing risk is to eliminate or reduce the amount of hydrogen in the package environment by judicious selection of package materials or by bakeout of the packages prior to incorporation of the semiconductor device. For example, aluminum as a packaging material does not appreciably outgas hydrogen, but anti-corrosive plating such as Ni defeat use of Al for this purpose. Some workers have reported to

* It is, of course, assumed that the getter reaction to hydrogen is permanent and irreversible

use bakeout successfully and we have employed baking in conjunction with gettering. Starting materials must be well characterized and controlled with respect to hydrogen content, and care must be taken to maintain desirable package properties, such as solderability, during the baking process.

*4. Bias Compensation* - In some cases, hydrogen poisoning does not result in catastrophic device failure, but a shift is device characteristics. For PHEMTs for example, hydrogen poisoning results is a shift in $V_{po}$ to more positive values, a drop in $I_{dss}$, and a shift in the peak $g_m$ [6]. For

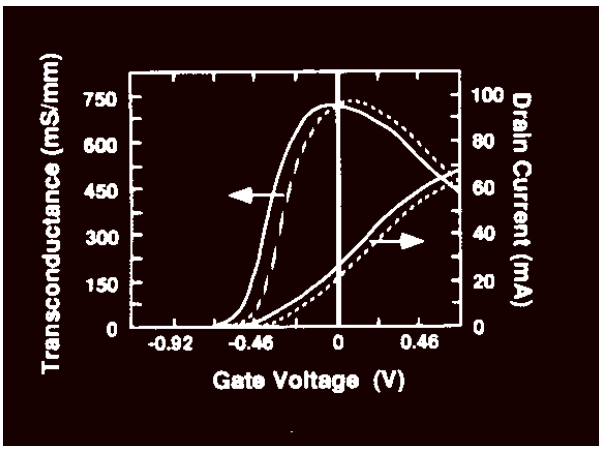



Fig. 5. Typical effects of hydrogen exposure to PHEMTs before ( — ) and after ( --- ) exposure to 4% $H_2$ for 10 min at 270C (after [6] ). In some applications, the design current and transconductance can be recovered by re-biasing the device.

small signal applications, it is possible in some instances to change the operating point of the device to recover the desired operating conditions. Automatic bias compensation circuits can be employed to accomplish this. While this is a somewhat pragmatic approach, it has been successfully employed in situations where it was judged not practical or desirable to rework modules which have been on the shelf for many years prior to detailed investigation of the hydrogen effects.

*5. Alternative Gate Technology* - Finally, we and other workers are pursuing metallization technologies which result in devices insensitive to hydrogen. There is evidence, for example, that GaAs FETs with aluminum gates are not effected by hydrogen exposure [6]. While an alternative gate technology may provide the ultimate solution, it is difficult to abandon a technology which has a mature manufacturing heritage and is well established in the industry. It is more likely that alternative gate technologies will be incorporated in emerging technologies such as InP HEMTs.

## SUMMARY

This paper describes approaches which are being used today to remediate the reliability risk of hydrogen poisoning of GaAs Field Effect Devices in hermetically sealed packages. A new metric, hydrogen exposure, is introduced, which can account for exposures during the manufacturing as well as testing and useful life, and the effect of hermetic leak rate on hydrogen poisoning vulnerability is discussed. While we feel that the best approach at this time is application of a hydrogen getter, it is essential that the capacity and pumping speed be adequately accounted for, and that, as in any approach, that the total exposure and degradation exposure be known or estimated.

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