GaN HEMT Lifetesting – Characterizing Diverse Mechanisms

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Keywords: failure analysis, gallium nitride, HEMTs, life testing, semiconductor device reliability.

Abstract

We describe a conceptually simple technique for estimating the contributions of individual degradation mechanisms to the wearout of RF GaN HEMT. This is important because most "physics of failure" studies on such devices report several distinct mechanisms that operate simultaneously. As a result, the overall degradation rate for a given GaN HEMT technology does not have a well-defined thermal activation energy (i.e. the effective E_a varies with time), so it is not possible to extrapolate MTTF's from elevated-temperature lifetests to application temperatures. Rather, it is necessary to quantify each mechanism separately.

INTRODUCTION

Because GaN HEMT is a relatively new technology, there is still a variety of distinct degradation mechanisms present in devices from most laboratories. Therefore, to qualify these devices, it is not sufficient to simply lifetest them till they fail – one must measure all the competing mechanisms, and determine their net overall effect at the end of the mission life. This contrasts markedly with the present-day situation for GaAs-based technologies, where the devices from a given laboratory usually wear out by only one well-characterized mechanism. In this paper, we illustrate why simple lifetesting is not sufficient, and briefly outline a technique (based on standard lifetest methods) that allows one to develop a picture of the various mechanisms, and their contributions at any time and temperature.

THE PROBLEMS

One problem is illustrated in Fig. 1: if one does an RF lifetest, one mechanism might dominate the observed changes initially, but another (with a different E_a) might take over later. The net δP_{out} has contributions from both, so it is very difficult to extrapolate to different temperatures and times.

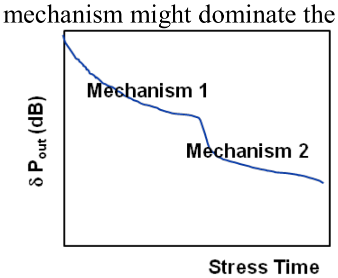

Fig. 1. Hypothetical RF lifetest, illustrating possible effect when two mechanisms with different E_a's are operating. This makes extrapolation to failure at a different temperature very difficult. In this example, one mechanism has been delayed, as sometimes occurs, to emphasize the effect.

If one does a DC lifetest instead, this problem may still be present, and there is the additional problem of relating the DC stress to the stress that is present during RF operation. Finally, lifetests can completely hide some mechanisms; this is illustrated for a hypothetical DC lifetest in Fig. 2. In the

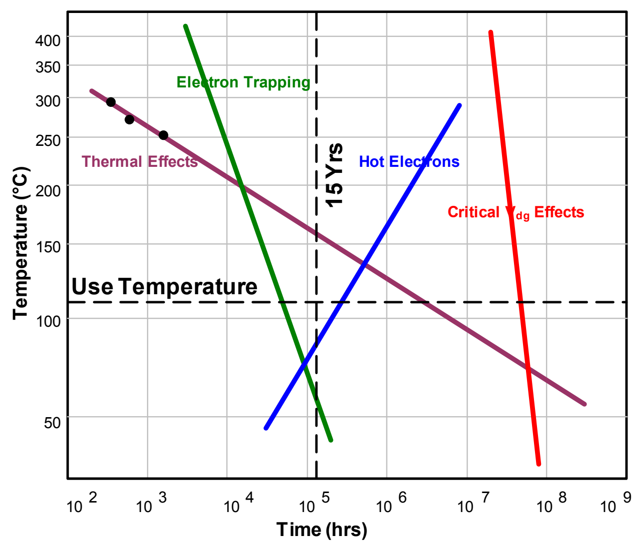

Fig. 2. Hypothetical DC lifetest, illustrating the risks when several different degradation mechanisms are operating. The names of mechanisms have been assigned arbitrarily.

figure, the 3 black dots on the "Thermal Effects" line indicate the mean times to failure (MTTF's) measured in a typical elevated-temperature DC lifetest, which is most sensitive to thermal degradation mechanisms. At these high temperatures it is the thermal effects that cause failure first. Then, extrapolating these data to a typical use temperature (say 110 °C) we read off an MTTF of 3 x 10^6 hrs, which is reasonable for some applications. But we notice that at the use temperature, other mechanisms may actually cause failure before the thermal effects: electron trapping effects will be fatal at about 4 x 10^4 hrs, and even if these can be tolerated, hot electron effects could cause failure at 3 x 10^5 hrs. Thus, while one effect may occur first in accelerated tests, it's very important to characterize other mechanisms that may be present, as in this hypothetical (but entirely plausible) scenario.

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OUR SOLUTIONS

Our technique is as follows:

1. Identify the significant degradation mechanisms, and DC parameters that each scale with one mechanism alone (known as "signature parameters"). This may require considerable study, including step-stress experiments, lifetests, literature studies, and physical analyses. Possible examples are threshold voltage to track charge trapping close to the gates, leakage current to track "reverse piezoelectric" effects, and maximum current to track surface pitting. Note the precise method for measurement of the signature parameters may be critical to keeping them "uncontaminated" by other mechanisms. Also, they will surely lose specificity as wearout becomes severe, but they are only needed till the failure criterion for the application is reached. This is typically equivalent to a degradation of P_{out} by only 1 dB.

2. Identify the failure criteria for each of the signature parameters, alone. This can be done by modeling.

3. Identify zones in the drain I-V plane where each mechanism will be observed most easily: either it is at a maximum, or it is well-separated from the peaks of other mechanisms.

4. Conduct DC lifetests to find the MTTF versus temperature and thermal activation energy of each mechanism, in its zone. This way, the time for the lifetests will be minimized.

5. Conduct an RF lifetest (preferably on a single-stage amplifier) at the highest power that would be used in the application, but with thermal acceleration. Measure the degradation rates of all of the signature parameters. Note this does not require running the lifetest to all the failure criteria – only long enough to find the degradation rates.

6. Find the ratio of RF degradation rate to DC degradation rate (scaled to the same channel temperature with the known E_a's), for each signature parameter. Then use the inverse of this number (known as the "scaling factor") to scale the measured MTTF's in the DC lifetests to the conditions of RF operation. They are likely to be large numbers (> 10) because RF operation takes the device through a wide range of biases, so it will remain in the zone for any given mechanism for only a short time.

7. Finally, conduct several checks: did the expected mechanisms continue, or did others arise? Are the thermal analyses consistent with well-defined E_a's?

If the checks are successful, one can now draw an Arrhenius plot of the MTTF under RF operation versus temperature <u>for each mechanism.</u>

This approach has the following advantages:

a. We study each mechanism with biases where that mechanism is strong. This improves efficiency and helps to elucidate otherwise-hidden mechanisms.

b. We use mostly DC lifetests (simple and economical), and only one RF lifetest (complex and expensive).

c. If we move to another application with different RF biases or frequency, we may only need to repeat the RF lifetest.

The main challenges are as follows:

a. Do the signature parameters reflect a single mechanism during both DC and RF lifetesting? (Our extensive study suggested they do, for one particular technology in our laboratory; other technologies may require slightly different signature parameters.)

b. Are the mechanisms different under DC and RF stress? For example, since RF generates a large range of stresses, several of them might be strong at the same time, unlike the situation during our "zoned" DC lifetests. Then defects generated by one mechanism may interact with defects caused by the other, i.e. they may "catalyze" or "inhibit" each other. (Any change in magnitude from such an effect will be measured in the scaling factor, but we do assume the temperature dependences do not change. Perhaps this is reasonable because diffusion mechanisms do not change.)

c. Is the scaling factor independent of temperature and time? (This mostly requires that the RF load line remains constant, and we adjust our RF inputs throughout lifetests so this is probably achieved to a sufficient degree.)

These, and several other assumptions and approximations are described in detail elsewhere, and associated uncertainties are estimated [1]. The net overall uncertainties are relatively large: - 35 %, + 100 % in MTTF. But this is adequate for a high reliability parts evaluation, where a margin of at least 10x (900 %) is required. And it is a big improvement over the previous situation where the individual degradation rates of the various mechanisms operating during RF drive were unknown.

AN EXAMPLE

We show some results with a 2011-vintage GaN HEMT technology with 0.15 µm gates and no field plates. Burn-ins were completed before testing began. In the description below, we use the same step numbers as in the previous section.

1. The only observed degradation mechanisms were:

a. Surface pitting and associated extended defects beneath them, with signature parameter δI_{dmax}, i.e. maximum drain current, measured with µs pulsing.

b. Hot electron damage, with signature parameter δG_{mp}, the peak of the transconductance, plotted against V_g.

c. Electron trapping, with signature parameter δV_{th}, the threshold voltage.

The studies that established these signature parameters are reported in [2]. We were unable to observe sudden increases of gate leakage, attributed to the "reverse piezoelectric" mechanism [3, 4, 5], under RF operation. Therefore, if this mechanism is present in normal operation of this technology, our technique clearly cannot handle it; rather an analogous approach will be needed, which scales the high DC electric fields and long durations that are reported to be necessary to see this phenomenon, to the much lower biases and shorter time intervals present in RF operation.

2. The failure criterion was 1 dB drop in the output power, at 62 GHz. This corresponded to a 27 % drop in G_{mp}, a 730 mV increase in V_{th}, or a 10 % drop in I_{dmax}.

3. Bias zones were chosen after preliminary experiments [2] as follows:

Hot electron zone: (I_d, V_d) = (267 mA/mm, 12).
Electron trapping zone: (I_d, V_d) = (0, 20).
Surface pitting zone: (I_d, V_d) = (33 mA/mm, 20).

4, 5. DC lifetests were conducted on single transistors, and RF lifetests were conducted on 1-stage amplifiers. Fig. 3 shows examples of DC lifetest results for G_{mp} and V_{th}. Dashed curves are for control specimens. Fig. 4 shows analysis of the failure times for G_{mp}, assuming a log-normal distribution.

6. Fig. 5 shows an example of degradation under RF stress, compared with degradation of the same signature parameter, under DC stress.

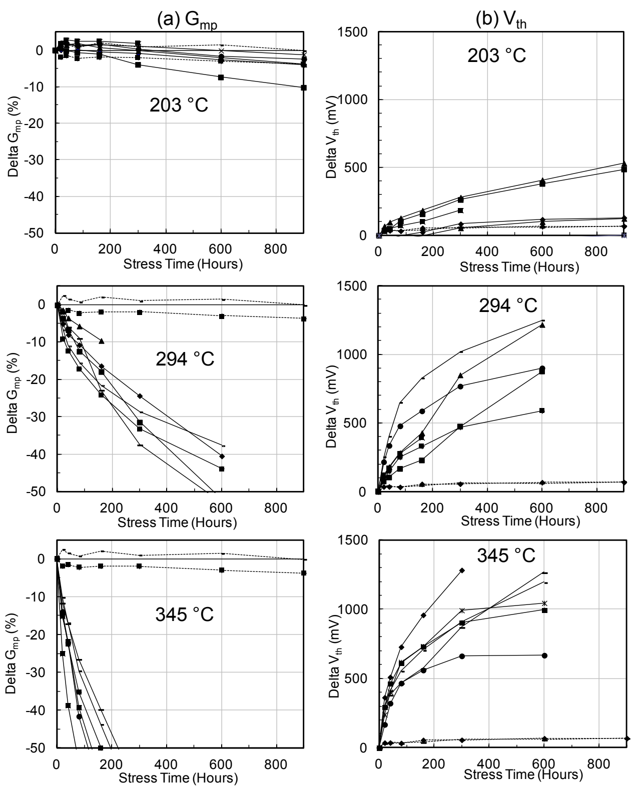

Fig. 3. Examples of data from a DC lifetest. This was a DC lifetest with stresses in the hot electron zone. Delta's in G_{mp} and V_{th} are shown. Each curve is for a separate specimen, and the dotted curves are for controls that were not stressed. Some electron trapping is present, even though we called this bias area the "hot electron zone".

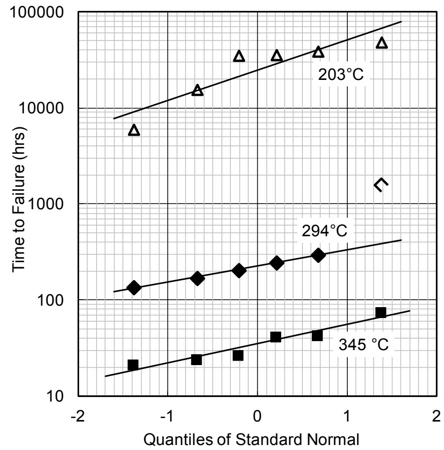

Fig. 4. Log-normal analysis of the failure times from Fig. 3. (a). Open symbols indicate extrapolations beyond the lifetest time, and hence, larger uncertainties.

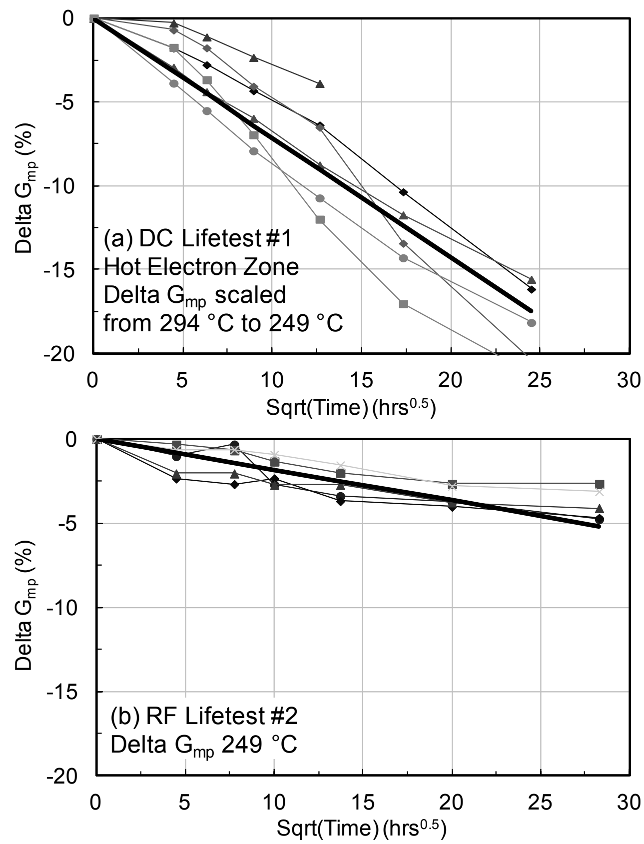

Fig. 5. Illustration of degradation versus √(time), and determination of a scaling factor. The heavy lines indicate the means of the specimens, found from log-normal analyses. The curves in (a) have been scaled from the original DC lifetest temperature, to the RF lifetest temperature, with the known thermal activation energy. The respective gradients are a and b; the Scaling Factor is $(a/b)^2 = 16.4$.

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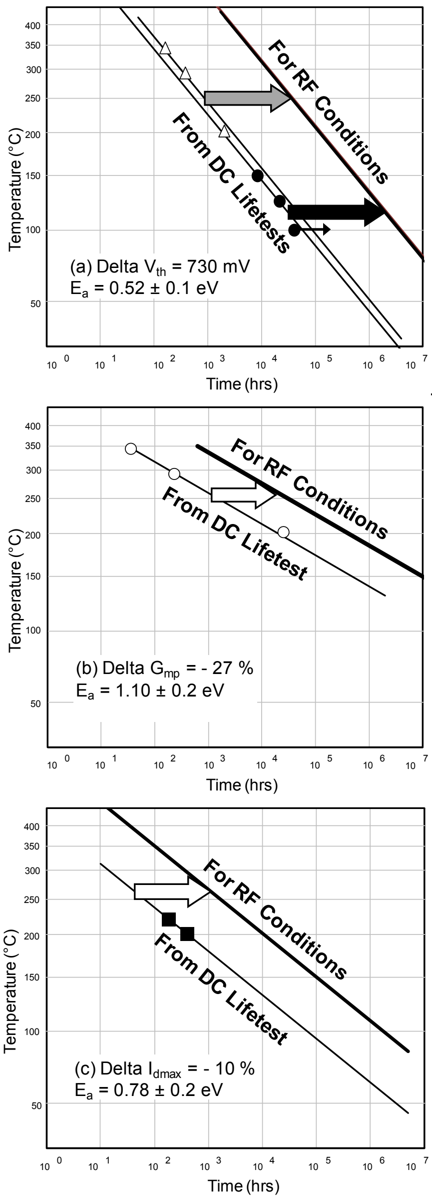

Fig. 6. Arrhenius plots for all signature parameters, with the scaling factors applied, as indicated by the large horizontal arrows. The resulting lines are the MTTF's predicted for typical RF operation. In (a), the triangles are for the hot electron zone, and the filled circles are for the electron trapping zone.

Fig. 6 shows the Arrhenius plots for the various DC lifetests, with scaling applied.

7. Cross sections, and other checks showed good consistency. Finally, Fig. 7 shows the overall Arrhenius plot for failure of the RF operation, with the curves for each of the mechanisms. We see in Fig. 7 that surface pitting defines the reliability at most temperatures, but below about 80 °C electron trapping will probably cause failure first. We note that if the surface pitting vulnerability is reduced with process improvements, it is quite likely that one of the other mechanisms will then dominate the reliability.

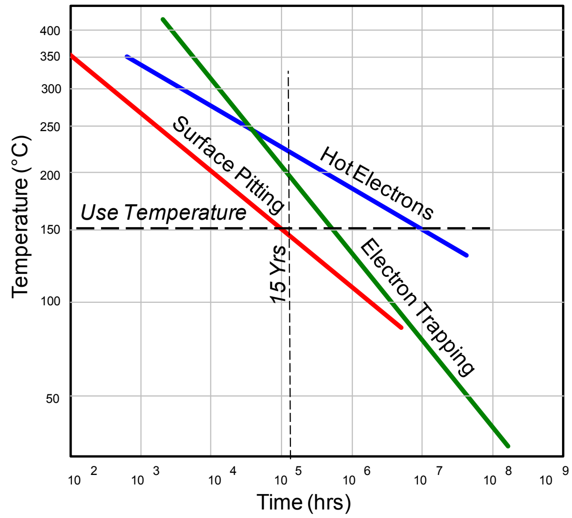

Fig. 7. Arrhenius plots for the various mechanisms. Note the limiting mechanism, and the relevant E_a, depend on the temperature of operation.

ACKNOWLEDGEMENTS

Instrumentation and assembly support were provided by Bartley J. Price and Sang Nguyen of Boeing. Test support was provided by Larry R. Duncan. Valuable consultations were provided by Dr. Andy C. Chen, John R. Grebliunas and Dr. Stephen Thomas III of Boeing.

This work was supported by a Technology Investigation Agreement between the Air Force Research Laboratory, contract # FA8650-11-2-1187 (Lois Kehias), and the Boeing Network and Space Systems Internal Research and Development program (Remy Hiramoto).

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ACRONYMS

HEMT: High Electron Mobility Transistor
MTTF: Mean time to failure
E_a: Thermal activation energy
GaN: Gallium nitride