New Failure Mode in a High-Reliability GaN HEMT Technology

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Abstract

We have identified and quantified a new failure mode, which dominates in an advanced, highly-robust power-RF GaN HEMT technology. DC lifetests were effective at channel temperatures near 300 °C, thanks to setting the stress drain voltage close to the peak experienced by a highly-compressed RF waveform. RF lifetests were conducted at temperatures near 400 °C. We scaled the DC results to the actual range of voltages experienced in RF operation, by our previously-published technique. Apart from small increases of threshold voltage, none of the previously-published mechanisms was significant; instead, a new mechanism occurred. The electrical symptoms were sudden drops of output power, by at least 1 dB, increase of gate resistance, and/or sudden complete failures. SEMs revealed that gold was missing from several-micron-long sections of the gates. The thermal activation energy was found to be 2.0 ± 0.2 eV, and the mechanism is accelerated by drain bias. It is likely it involves failure of the passivation, or a diffusion barrier, under very high stress. But even with our small sample sizes (5 specimens per condition in the RF lifetests), we find the 90 % confidence limit for operation at 200 °C is 1.5 x 10^7 hrs, which is excellent reliability.

INTRODUCTION

We have observed a new degradation mechanism in a high-performance commercial L- to C-band GaN HEMT technology. It appears it is detectable because all of the common degradation mechanisms have been eliminated by advanced materials and processing. Initially we observed no degradation despite considerable stress. But eventually we observed failures, all of which had consistent symptoms. We call the mechanism "missing Au", because the failures seem to correlate with loss of 50 to ~ 100 % of the Au from sections of the gate fingers. They often occur as rapid burn-outs without much warning. But sometimes they result in a sudden drop of drain current, and output power, without complete failure. We do not pursue the physics of this mechanism in detail; rather we concentrate on it's symptoms, and it's rate of occurrence versus temperature under normal RF operation, found by our previously-reported technique [1].

EXPERIMENT

The GaN HEMT devices were manufactured by a commercial vendor; this technology was marketed successfully for several years, but has since been superseded. The devices were constructed on SiC substrates, with MOCVD-grown epitaxial layers. Gates were mostly Au, with no separate field plates; the base of each gate contained a diffusion barrier of chemically-inert material ~ 0.1 um thick, on the GaN cap, with no gate recesses. Multiple layers of SiN_x passivation were applied.

We used 4 GHz, 2 W FETs consisting of a single layout cell – larger FETs in this product line were designed by repeating this cell. They were assembled in hermetic modules with the same processes as for the large FETs. We provided stabilization and matching outside the modules.

We measured channel temperatures adjacent to the gates, directly on a specially-fabricated test FET by the gate end-to-end resistance technique [2]; then we used these results to calibrate a finite-difference model which we applied to the FET geometries, assembly configurations, and desired temperatures for our lifetests.

The stress conditions and quantities of specimens are illustrated in Fig. 1. Conditions of each part during the stresses were recorded every hour. Stress was paused at exponentially-increasing time intervals, for detailed characterizations at room temperature. Static I-V characterization was done with an HP 4142B Modular DC Source/Monitor for the DC lifetests, and an Agilent B1500A Semiconductor Parameter Analyzer for the RF lifetests. Drain I-V, I_d vs V_g and gate I-V curves were recorded and more than 15 basic FET parameters were extracted and monitored. These parameters included the following, all with the sources grounded. None of the tests caused any irreversible change.

(a) With V_d = 10 V: I_{dss} is I_d at V_g = 0 V; G_{mp} is peak transconductance; V_{peak} is V_g where G_{mp} occurs; I_{peak} is I_d at the V_g where G_{mp} occurs; $V_{th} = V_{peak} - I_{peak}/G_{mp}$, R_{on} = (0.5 V)/(I_d at V_d = 0.5 V) with V_g = -1 V; CC = (I_{de} - $I_{df)}/I_{de}$ for V_g = -1 V. (The e and f subscripts indicate “traps empty” and “traps full” pre-treatments. See Ref. [3])

(b) With V_d = 2 V: I_{dmax} = I_d at I_g = 10 mA/mm;

(c) With $V_d = 0$ V: $V_{gon} = V_g$ when $I_g > 0.1$ mA/mm; barrier height and ideality have the usual definitions; $R_g = (V_{g2} - V_{g1})/(I_{g2} - I_{g1})$, where 1 and 2 are points where $I_g = 6$ and 8 mA/mm respectively.

(d) RF power out versus RF power in, stepped from very low power to 3 dB compression.

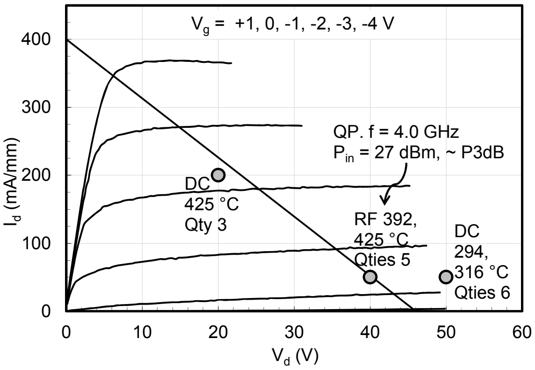

Fig. 1. Stress conditions for DC and RF lifetests, and the starting quantities of specimens. The atmosphere was dry N_2. The straight line is a nominal load line for RF operation.

RESULTS AND EVALUATION

The first unusual symptoms we observed were sudden drops in RF power in the RF lifetest, with no warning evident in our hourly stress monitoring (Fig. 2). Most of the parts stopped functioning completely, and optical inspection showed major melting which obliterated the FET structures. But two of the 10 specimens (SN's 6 and 9) continued functioning with lower output power, and our detailed characterizations showed the gate resistance increased from about 20 Ω.mm to several hundred Ω.mm (Fig 3). On the latter, scanning electron microscope (SEM) studies showed near-complete loss of Au from sections of the gates of the order of tens of micrometers long (inset in Fig. 3). Cross sections confirmed that the Au had disappeared completely, but the thin contact layer remained. The locations appeared to be random, not concentrated near the gate feeders, where the current density along the gate metal is the largest. The morphology of the remaining sections of gate metal, viewed through the passivation, did not appear changed. Several analyses of unstressed specimens showed completely intact gates and negligible density of artifacts of any kind.

In the DC lifetest we could not monitor P_{out}, but we eventually recorded complete functional failures, and most of them were sudden, without any obvious precursor, just as in the RF lifetest, and major melting was visible across the FET patterns. But three specimens out of 13 declined by increasing gate resistance, and SEM images again showed gold missing from parts of the gates. One of the latter suffered a complete failure a few hours after the R_g increase, but several gate sections escaped the melting, allowing us to see the areas of missing Au. This was the only instance when we were lucky enough to catch a definite symptom of missing Au just before a sudden failure. So we cannot say unequivocally that missing Au and sudden complete failure are symptoms of the same mechanism. But we will assume this is the case, because it seems highly likely that a large increase of R_g in a section of a gate would lead to loss of gate control, local heating and rapid melting.

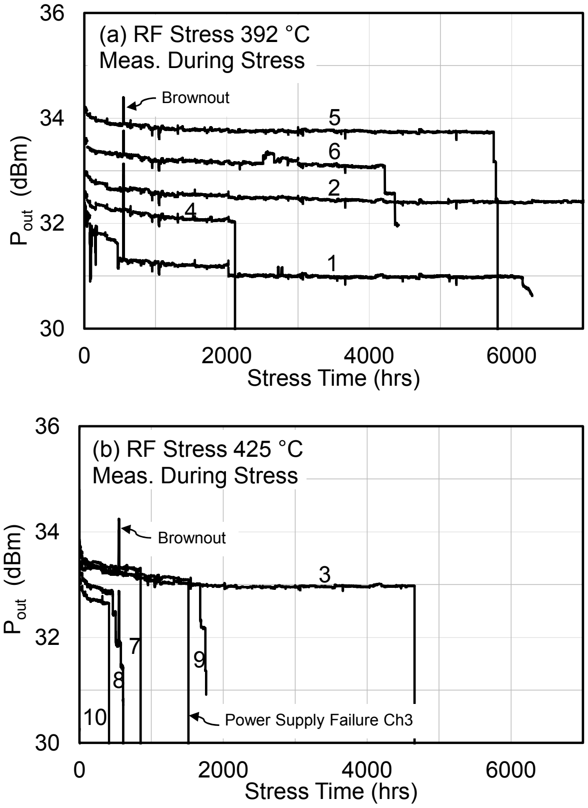

Fig. 2. Compressed output powers in the RF lifetest, versus stress time, for all specimens. Their channel numbers, and the causes of some artifacts are identified.

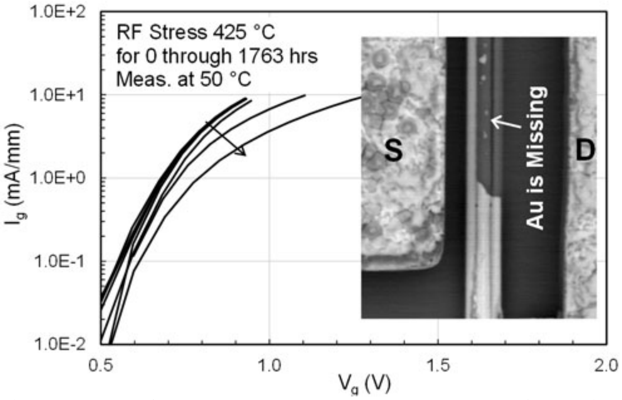

Fig. 3. Forward gate I-V curves ($V_s = V_d = 0$ V) for a single specimen as the lifetest progresses. The arrow indicates the progression with stress time. Inset: 20 kV backscatter SEM image of a gate after large R_g increase. This is close to the end of the gate, at the opposite end from the gate feeder.

To quantify the rate of this new phenomenon, we defined the following joint "signature parameters" and their failure criteria:

Compressed RF output power, P3dB: δ P3dB < -1.0 dB.
Gate resistance, R_g: δ R_g > 10 Ω.mm.
Complete functional failure: I_d < 0.1 mA/mm.

All specimens exhibited increases of threshold voltage, which is a signature for electron trapping. But the increases slowed and stopped at 300 to 400 mV, which is not nearly sufficient to cause failure in a compressed power amplifier application [1]. Apart from the observations already mentioned, there were no changes in any parameters, of more than a few percent (after correction for the effects of the V_{th} increases), before the failures.

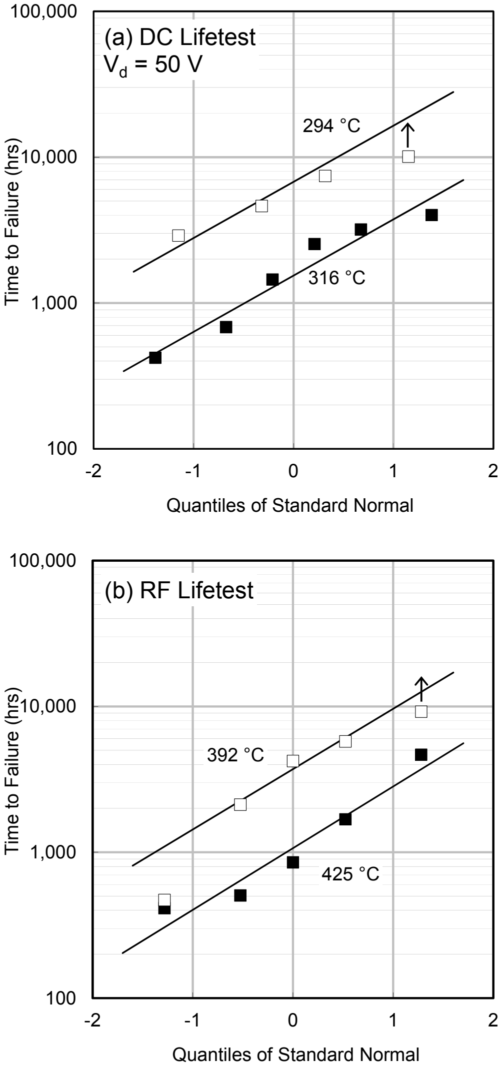

Fig. 4. Log-normal plots for the main lifetests. The failure criterion is missing Au, detailed in the text. A symbol with a vertical arrow indicates that the part has been on stress for the indicated time, but has not yet failed.

Log-normal plots of the failure times are shown in Fig. 4, for the 50 V DC lifetest, and the RF lifetest. Although the last specimen in each low-temperature group has not yet failed, the data can be fitted to find the mean times to failure, with fairly good accuracy. The results of these, plus the 20 V DC lifetest, are plotted in Arrhenius form in Fig. 5.

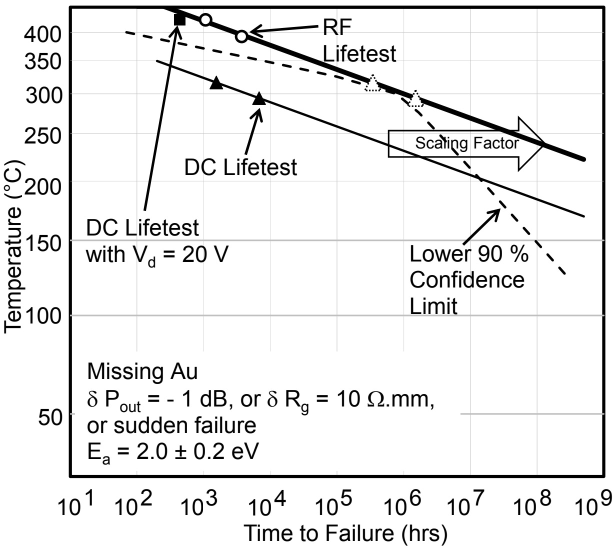

Fig. 5. Arrhenius plot for the missing Au mechanism. The thin line is a fit to the DC lifetest MTTFs; the thick line is the result of scaling this to the RF conditions, by means of the RF lifetest results. The scaled DC MTTF's are indicated with dotted symbols. The MTTFs for the RF lifetests are indicated with open circles. The result of the DC lifetest at V_d = 20 V is indicated by a filled square.

According to our technique [1], we rely on the DC lifetests, with biases chosen to maximize the failure mechanism of interest, to find it's thermal activation energy (E_a) and mean times to failure (MTTF's), indicated by the filled triangles in Fig. 5. From these we determine the failure rates versus temperature. Then we utilize the RF lifetest to find the degradation rate under normal RF operation, of the same signature parameter, and hence a scaling factor between the DC lifetest, and normal RF operation. This is constant with temperature because the two lifetests have the same E_a's for this mechanism (a fairly safe assumption [4], and consistent with our data), and it incorporates any acceleration due to different voltages in the two lifetests. The symbols with dotted outlines are the results of the DC lifetests, scaled to the RF conditions as indicated by the large arrow. Important conclusions are as follows:

1. The E_a for missing Au is 2.0 ± 0.2 eV.
2. After scaling for temperature, the rate of the missing Au mechanism is about 150 x lower in the V_d = 20 V lifetest, than it was in the 50 V lifetest. Since the respective currents were 200 and 50 mA/mm, we

conclude that missing Au is driven by electrical voltage, not current.

3. The lower 90 % confidence limit curve for the missing Au indicates a mean time to failure with T_{ch} = 200 °C of 1.5 x 10^7 hrs. This is competitive with the best reliability reported for any GaN HEMT technology.

We now consider the possible origin of this new degradation mechanism. Random manufacturing defects, like dust particles or debris, are unlikely to be the cause, because missing Au appeared in many gates, at many locations, whereas SEM images (plan view and FIB cross sectioned) of as-fabricated specimens were always completely free of the slightest irregularity. Degradation of the Schottky barrier is also unlikely to be the triggering mechanism, because the largest gate currents we observed corresponded to only 95 A/cm^2, when averaged over the total area of the gate contact. Likewise, electromigration seems an unlikely origin because at the highest-density points in the FET layouts, with the highest I_g during stress, the current density was less than 1.0 x 10^4 A/cm^2; this is well below the typical threshold for electromigration in evaporated Au gates at similar temperatures, of > 1 x 10^6 A/cm^2 [5, 6]. The maximum current density during characterization was 10x higher, but it was at room temperature, for milliseconds only. Also, the missing Au was not correlated with the locations of high current density. Therefore we speculate that the triggering mechanism may have been a breaching of the gate diffusion barrier as reported in [7], or the passivation, by diffusing Au atoms.

Finally, we consider whether this mechanism, which requires temperatures near 400 °C, or constant high electric fields, to be detectable in practical laboratory tests, will be relevant to operation under the conditions of a typical application. This may not be so if the very high temperature triggers some other accelerant, eg. high gate current, or a phase change in one of the materials. We can only report that we have examined wide-ranging electrical parameters, as well as SEM and transmission microscopy photos of stressed parts, and found no evidence of changes of this nature. Therefore it seems likely that missing Au will be the dominant degradation mechanism under normal operating conditions.

CONCLUSIONS

The reliability of the GaN HEMT technology, that we report on here, is extremely high – so much so that it proved difficult to quantify. After considerable effort, we were able to apply sufficient stress, for a long enough time, to cause enough failures for a systematic study. We found that the failures occurred with consistent symptoms (more than simply melting), which convinced us that they were all occurring by the same mechanism, and we were able to determine the temperature and voltage acceleration with reasonable accuracy. We concluded that this technology is mostly immune to the widely-reported aging phenomena in GaN HEMTs. Rather it eventually degrades by loss of gold from the gates. But the E_a is about 2.0 eV, and the MTTF at 200 °C, with 90 % confidence, is 1.5 x 10^7 hrs, making this technology an excellent candidate for high-reliability applications.

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ACRONYMS

HEMT: High electron mobility transistor
SEM: Scanning electron microscope
MOCVD: Metal-organic chemical vapor deposition