GaN Reliability – Where We Are and Where We Need to Go

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Abstract

AlGaN/GaN High Electron Mobility Transistors (HEMTs) offer significant performance advantages over competing technologies for RF applications, but lingering questions about long term reliability persist. This paper will discuss where the state of GaN reliability is and offer suggestions on where the industry needs to go to address remaining reliability concerns.

INTRODUCTION

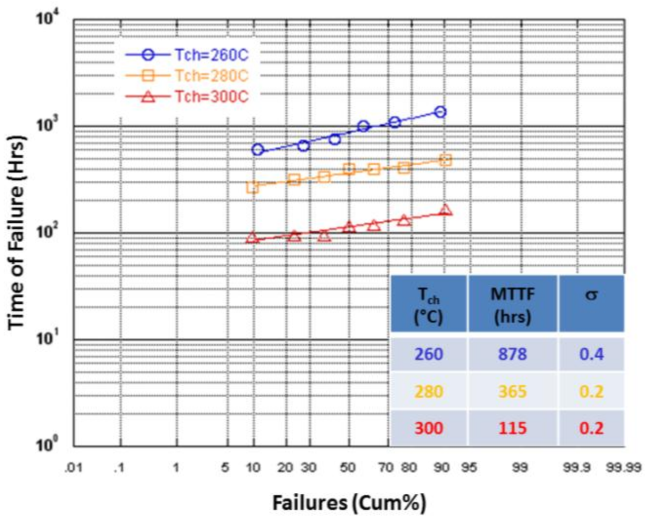
In the early days of AlGaN/GaN HEMT development, dc and RF performance was often benchmarked on the initial test because subsequent measurements frequently yielded degraded results. Lifetimes could be measured in real time as devices degraded in minutes or hours. As the technology matured, many groups were able to demonstrate continuous on-wafer operation, both dc and RF, for 100s and even 1000s of hours with minimal change in performance. At this point, accelerated life tests (ALT) of fixtured devices and standard evaluation circuits (SECs) were initiated. Numerous accelerated life test results have been reported over the years. This ALT data has been compiled and analyzed. Relevant trends and correlations in the data will be presented. Given the critical role accelerated life tests play in the assessment of a technology's long term performance, a brief description of accelerated life test methodology and Arrhenius analysis will be presented.

BACKGROUND AND RESULTS

The basis for semiconductor lifetime prediction is accelerated life testing. The JEDEC JEP118 publication *Guidelines for GaAs MMIC and FET Life Testing* [1] provides a reference for how to conduct these accelerated life tests and develop lifetime predictions.

> "The standard method for predicting device lifetime where this value is too large to be measured directly is to run a series of life tests. Generally, only one parameter, usually the device temperature, is varied. A lifetime is obtained at each temperature. These values are then extrapolated to the temperature of interest."

To summarize, a collection of representative devices from a technology being evaluated are operated (stressed) at elevated temperatures. The time to reach a predefined failure criterion, such as a 20% change in drain current or a 1 dB change in output power, is recorded as in Figure 1 [2]. This time to failure (TTF) data yields an estimate of the mean time to failure (MTTF) for each temperature population. A line fitted to the MTTF data plotted versus the inverse of the channel temperature yields extrapolated lifetime predictions and an activation energy (Ea) via an Arrhenius relationship (Figure 2). This is a ***very*** simplified explanation of the process. There are subtleties in how the parts are selected, how stress conditions are determined, and how the data statistics are applied and interpreted that need to be considered when conducting life tests. In addition, the accuracy of channel temperature estimates and their influence on lifetime predictions needs to be understood when interpreting accelerated life test results. Often lifetime estimates are extrapolated several orders of magnitude from actual test times. If channel temperature estimates are inaccurate or if temperature dependence of thermal conductivities of material being evaluated are not accounted for then the slope of the MTTF fit could shift resulting in a significant change in extrapolated lifetimes. While not a perfect instrument, accelerated life testing provides a means to estimate lifetime at use conditions without having to test for extended periods of time.



T_{ch} (°C)	MTTF (hrs)	σ
260	878	0.4
280	365	0.2
300	115	0.2

Figure 1: Sample Cumulative Failure Plot

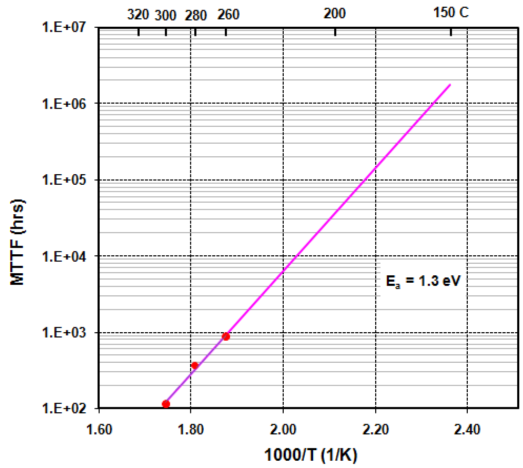


Figure 2: Sample Arrhenius Plot

For this assessment of where the state of GaN reliability is, a survey of industrially published or reported accelerated life test results for AlGaN/GaN High Electron Mobility Transistors (HEMTs) on SiC was performed. This data was compiled and is presented as a composite Arrhenius plot in Figure 3. This plot represents multiple-temperature dc or RF accelerated life tests. Channel temperatures tested ranged from 250C to over 400C with drain voltages spanning 20 V to 65 V. Mean time to failure (MTTF) times ranged from as little as a few 10s of hours to over 10,000 hours. The vast majority of the data presented predicts MTTF in excess of 10^6 hours at a use condition (channel temperature) of 150C with activation energies ranging from 1.0 eV to over 2.5 eV. Looking at the data set as a whole, it is interesting to note that mean time to failure projections (Figure 4) and activation energies (Figure 5) are increasing over time. Figure 6 shows that projected MTTF at use conditions is correlated with activation energy.

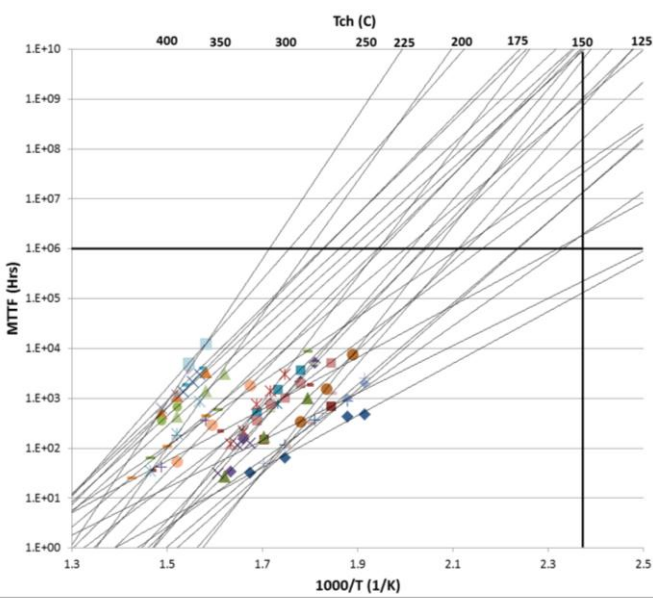


Figure 3: Composite Arrhenius Plot

Figure 4: MTTF Projections Over Time

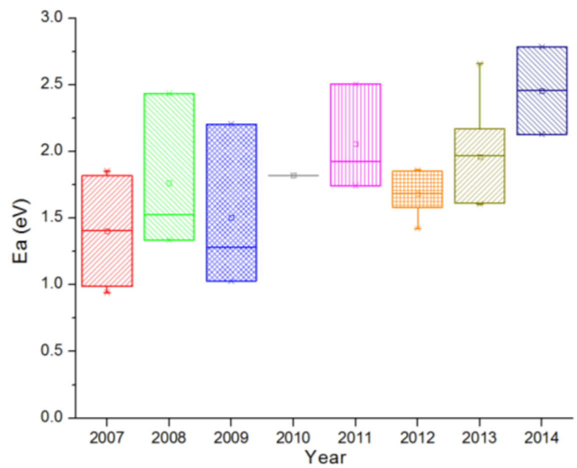


Figure 5: Activation Energy (Ea) Over Time

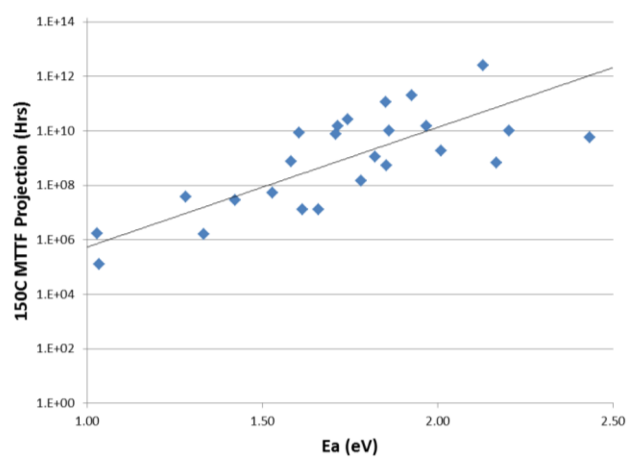


Figure 6: 150C MTTF Projection versus Activation Energy

Using activation energy as a figure of merit, correlation with other parameters is examined. In Figure 7, activation energy is shown as a function of device periphery (Wg). For the data analyzed, there is no strong correlation between device periphery and activation energy. Figure 8 shows activation energy as a function of gate length. Unlike with device periphery, gate length does appear to influence activation energy. Shorter gate lengths are correlated with lower activation energies and as shown in Figure 6, will likely have lower life time predictions. Activation energy plotted versus drain bias for the data sets analyzed (Figure 9) shows no correlation. However, activation energy as a function of whether the accelerated life test was performed under dc only or was RF driven (Figure 10) does show a correlation. RF tests result in lower activation energies and, as shown previously, will have lower lifetime predictions.

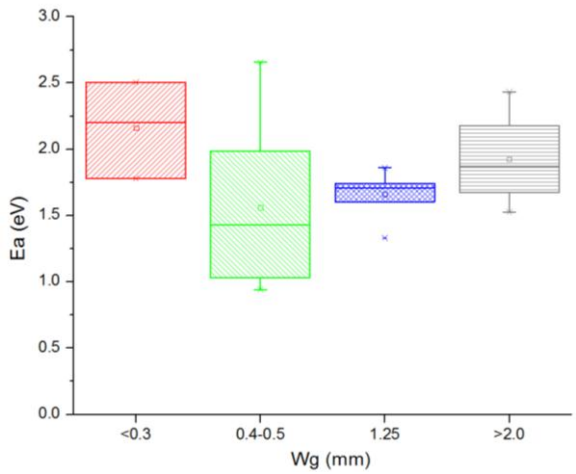


Figure 7: Activation Energy versus Device Periphery (Wg)

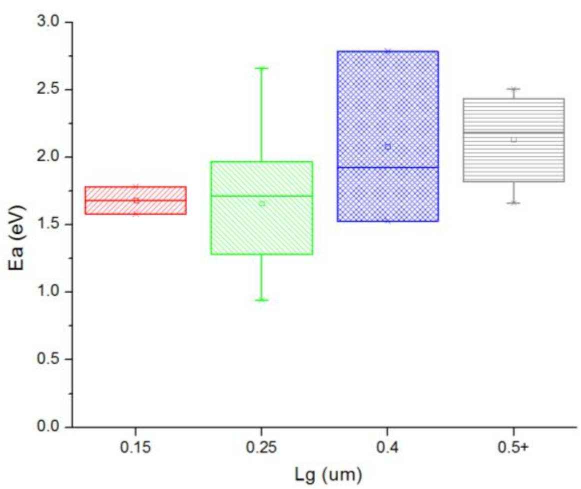


Figure 8: Activation Energy versus Gate Length (Lg)

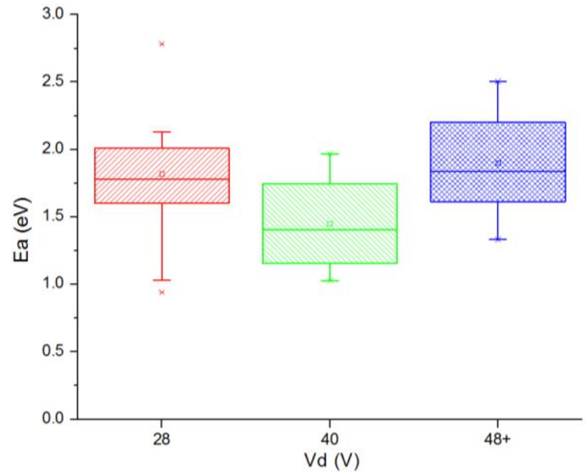


Figure 9: Activation Energy versus Drain Bias

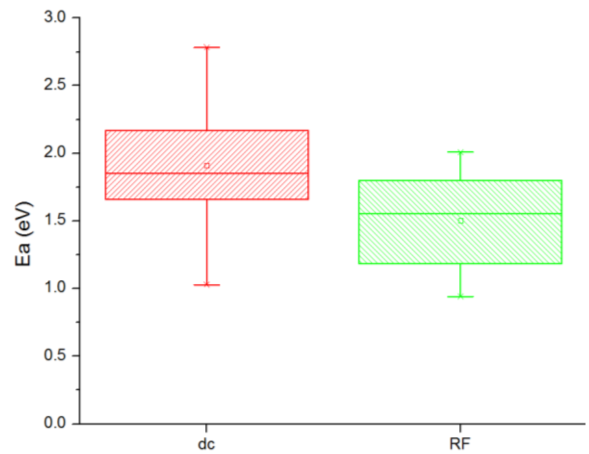


Figure 10: Activation Energy versus Type of Life Test

What can be taken away from this snapshot of the state of GaN reliability? There is significant accelerated life test data from numerous sources that suggests that AlGaN/GaN HEMTs on SiC are very robust. Extrapolated MTTF times are in excess of 10^6 hours at a use condition of 150C. For many of the studies, there are orders of magnitude margin in MTTF at 150C that could be traded off for higher operating temperatures while still achieving a 10^6 hour MTTF threshold. The ALT data is compelling, but there are lingering issues that need to be considered. For example, much of the data presented is based on accelerated life tests of relatively small sample sizes. In addition, population statistics are not commonly reported, thus confidence bounds on extrapolated lifetimes cannot be determined. This is important, as it is not the mean time to failure (t_{50}) that is of primary interest, but rather the predicted time to first or one percent failure (t_1) that will determine insertion readiness for mission critical systems. Larger sample sizes would improve statistics, and more thorough reporting would increase end user confidence in published results.

Another concern about GaN reliability is that the test conditions required (extremely high channel temperatures) to make GaN devices degrade in a reasonable amount of time are inducing failure modes/mechanisms that are not representative of what will ultimately be observed during wearout. Figure 11 provides an example of why this is a concern. The 3-temperature data yields an activation energy of 1.86 eV with an extrapolated MTTF at 150C of nearly 10^{10} hours, however, analyzing just the two lower temperatures of the test results in a much different conclusion. The 2-temperature analysis yields an activation energy of 0.97 eV with an extrapolated MTTF at 150C of just over 10^{6} hours. While the 2T results meet a million hour MTTF threshold, the estimate is several orders of magnitude lower than the 3T analysis, and the activation energy is much lower. The extremely high temperatures used to degrade the devices under test could be masking lower activation energy failure modes which might result in early life failures. Lower temperature testing and/or the addition of a fourth temperature population could help mitigate concerns over buried failure modes. Long term operational tests could also help validate accelerated life test results.

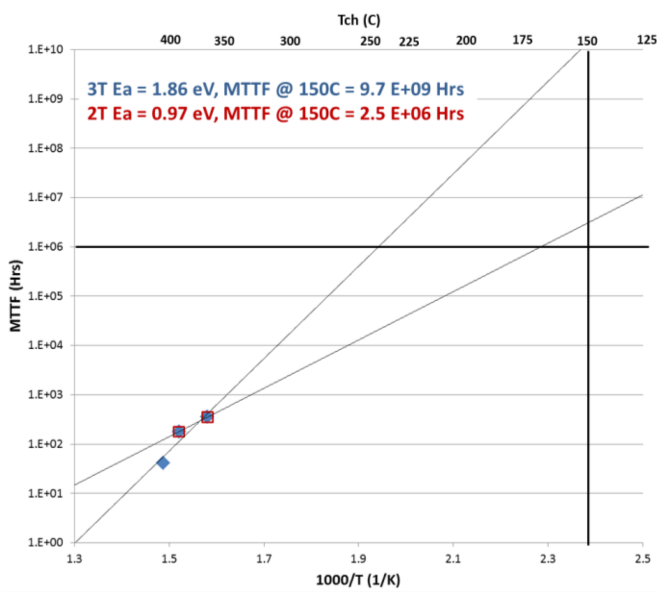


Figure 11: Comparison of 3T and 2T ALT Analysis

There is also lingering concern about the accuracy of dc based accelerated life test predictions on RF wearout. As seen in Figure 10, dc and RF ALT yield different activation energies and thus extrapolated lifetimes (Figure 12). Additional RF accelerated life tests could provide more accurate "under use" lifetime estimates and long term RF operational life tests help validate accelerated life test results.

One final issue hindering acceptance of GaN reliability is the lack of consensus in the community on dominant failure mechanisms. Unfortunately, much of the reported data analyzed here did not discuss the failure mechanisms observed during accelerated life testing. However, a review of the open literature can provide insight into the current understanding of failure mechanisms for AlGaN/GaN HEMTs. While space does not permit a discussion of degradation physics here, the topic will be addressed in the oral presentation. More thorough root-cause analysis and subsequent reporting will aid the industry in converging on a set of well documented and well understood failure mechanisms. This enhanced understanding will help gain user acceptance and help define the trade space between operational use conditions and lifetime.

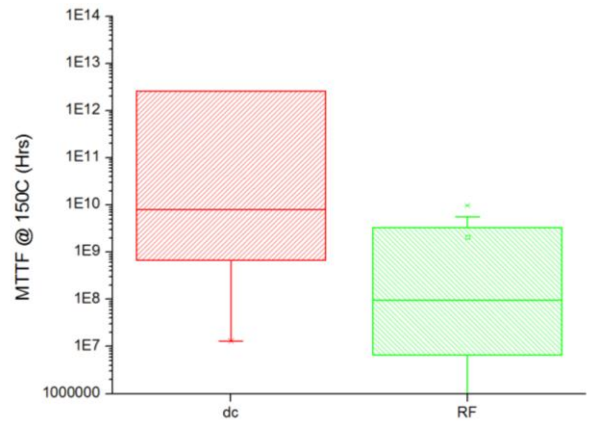


Figure 12: MTTF Prediction versus Type of Life Test

CONCLUSIONS

Accelerated life test data for AlGaN/GaN HEMTs on SiC is quite compelling. Numerous studies indicate this technology is very robust with predicted lifetimes at a use condition of 150C or higher in excess of a million hours. While this may be sufficient for commercial applications, there are some lingering issues that need to be addressed for mission critical insertions. Longer term, lower temperature testing and focused RF assessments along with more thorough reporting of degradation statistics and root cause analysis will go a long way toward building the confidence needed in GaN reliability for military applications.

REFERENCES

[1] www.JEDEC.com
[2] J. A. Mittereder, *et al.*, *RF Arrhenius Life Testing of X-band GaN HEMTs*, ROCS Workshop Proceedings, 2008.

ACRONYMS

ALT: Accelerated Life Test
Ea: Activation Energy
HEMT: High Electron Mobility Transistor
MTTF: Mean Time To Failure
TTF: Time To Failure
SEC: Standard Evaluation Circuit