Draft Guidelines for Space Qualification of GaN HEMT Technology

John Scarpulla and Caroline M. Gee

The Aerospace Corporation, 2310 E. El Segundo Blvd., El Segundo, CA 90245
john.scarpulla@aero.org 310-336-7998

Keywords: GaN HEMT, space qualification, reliability, screening, mission assurance

Abstract

This paper is a synopsis of a draft document that has been written by The Aerospace Corporation to provide some guidelines for qualifying GaN HEMT technologies for space missions. The purpose of the draft document is to set forth recommended tests and test protocols that will enable GaN semiconductor technologies to become qualified for use in US DOD (Dept. of Defense) and NSS (National Security Space) class A or B space applications. The status of the draft (available now) and its ongoing maturation into a standard will also be reviewed.

INTRODUCTION

The properties of the GaN HEMT technology make it especially attractive for many high-reliability space applications and missions, especially in the areas of communications, sensors, power amplifiers, and radars. The combination of its ability to operate at high temperature, to be capable of supporting high voltage and handling a high current density are properties that are particularly valuable. Commercial products have been developed that exploit these properties and perform useful functions. The open question at this time is whether the GaN technology will be sufficiently reliable for the long term and hazardous space missions to which it could be well suited. US Military missions are long, measured in years or decades, and the space environment is challenging with temperature extremes, vibration and ionizing radiation(s). It is believed that with adequate testing and evaluation on the ground it will be possible to recommend GaN technologies for high reliability space missions.

GOALS & SCOPE OF A DRAFT GAN GUIDELINE

The purpose of this guidance document [1] is to set forth recommended tests and test protocols that will enable GaN semiconductor technologies to become qualified for use in US DOD (Dept. of Defense) and NSS (National Security Space) class A or B space applications [2]. GaN is a technology that has been in development for approximately 20 years. Useful applications for this technology are in the areas of RF/microwave transistors and MMICs, especially for higher power applications. The GaN technologies are also being applied to power conversion and power switching applications. This document only addresses the former set of applications - RF/microwave uses of GaN. The power supply applications are sufficiently different to warrant a somewhat different set of qualification tests, and are not addressed here. These considerations will possibly be addressed in a future revision. Furthermore, the express purpose of this document is to address conventional AlGaN/GaN HEMTs or HEMT-like devices (having a metal Schottky barrier gate) or similarly based MMICs. The substrates may be SiC, Si, sapphire, native GaN or other substrates. Newer MIS- (Metal Insulator Semiconductor) HEMTs or IG- (Insulated Gate) HEMTs are specifically not included herein. These devices have not yet achieved mainstream status. This situation is rapidly changing and an update to this document may be needed soon. These newer HEMT technologies have sufficiently different qualification concerns especially related to the reliability of the gate insulator. These concerns are not addressed in this document.

APPROACH

GaN is a compound semiconductor that appears at first blush to be similar in many ways to its main predecessor GaAs technology. There are many similarities. However GaN is uniquely suited to high power applications that are beyond the domain of the GaAs technologies. The realm of high power RF/microwave operation requires a different set of considerations for qualifying the technology for space. It is important to understand the differences and to properly account for them. It would be a mistake to simply perform the same tests on GaN devices that have enabled previous space qualification of GaAs devices. The failure mechanisms and methods of acceleration of these failures are now known to be different between the technologies [3]-[5]. It is important to understand these mechanisms for space qualification of the GaN technologies.

In mature semiconductor technologies such as Si and GaAs, one of the most important milestones in qualification of a device or fabrication line is the HTOL (high temperature operating life). In this test the device is operated at DC or sometimes with RF or pulsed RF, and is subjected to 1000 hours of elevated ambient temperature, typically 125°C or 150°C, accompanied usually by a much higher channel temperature. Then afterwards, the devices are tested, and the number of failures determined. Often this number is zero. Then using a series of assumptions, the failure rate can be computed. The assumptions are:

- a single dominant failure mechanism
- with a known activation energy (typically 0.7 eV or 1 eV)
- constant failure rate, equivalent to an exponential cumulative failure distribution
- failure rate then determinable using a chi-square distribution
- constant usage channel temperature of 105°C (sometimes more or less)

While this approach works well for mature semiconductor technologies, it is not appropriate for new technologies where these assumptions are not valid. In particular for GaN HEMT devices, the failure rates are not constant, the activation energies are not necessarily known, and there may be more than one failure mechanism. A different approach is needed for establishing the reliability for stringent long duration high reliability space missions.

HIGHLIGHTS OF THE DRAFT GUIDELINES

Table I lists the topics covered in the draft guideline. Here are brief highlights of a few key items. The first is in regard to competing intrinsic failure mechanisms. There have only been a few attempts [3]–[5] to address the issue of competing multiple failure mechanisms in GaN HEMTs. The exact mixture of failure modes that might be experienced under actual spaceflight usage conditions depends upon the particular RF/microwave load line (more correctly the load figure) and/or the matching and loading impedances.

Fig. 1 shows IV curves from DC and pulsed IV measurements for a typical microwave power HEMT. Superimposed on these curves are three possible bias/loading conditions of the infinitude of possibilities. The first is an ideal or resistive Class A load line. In practice, a load line is not resistive since especially at high frequencies the reactance and parasitics become important. For this reason, under a more realistic Class A operation, the load line becomes elliptical as shown.

Also shown for comparison is a Class F^{-1} (inverse Class F) load figure, which is considerably more complex. The Class F^{-1} amplifier approach is one of many that improves narrowband efficiency by controlling the harmonics—in this case tuning the impedance at the odd harmonics to be a short circuit and the even harmonics to be an open circuit—thus dissipating zero harmonic power. The Class F^{-1} load figure passes through different regions of the IV plane than the Class A load figure.

Therefore if there are different failure mechanisms extant at different operating points in the IV plane, this load figure would be expected to produce different reliability results. This in fact has been observed for certain GaN devices, with conventional DC testing sometimes producing unduly optimistic reliability predictions. It is highly recommended that GaN HEMT reliability testing be performed under different DC operating conditions as well as under RF-driven conditions.

RECOMMENDED DC LIFETEST PROTOCOL

It is recommended that at least four DC operating points be chosen for reliability testing. Fig. 1 shows these four points (Q1 through Q4):

- Point Q1 is a high power operating point. It is similar to one commonly chosen for DC three temperature lifetests. It is in the center of the IV plane, provides a maximum temperature rise through self-heating, and provides high thermal acceleration. This is the approach usually taken for GaAs lifetesting.
- Point Q2 is a high current low voltage operating point.
- Point Q3 is a high voltage low current operating point.
- Point Q4 is a high voltage pinched off operating point with essentially zero drain current.

It is recommended that DC tests be devoted to these four operation points, tailored appropriately to the voltage and current rating to the particular GaN HEMT or technology of interest. For each stress condition, it is recommended to devote a sample size of 20 burned-in parts at two temperatures (minimum) for a total of 20 parts × 2 temperatures × 4 stressing biases = 160 parts (minimum). If any failures occur, the exact causes should be determined using physical failure analysis techniques. The DUTs should be drawn from three lots of wafers.

Fig. 2 shows some typical test data in the form of an Arrhenius plot. Multiple samples of this particular GaN HEMT were subjected to stressing at a DC operating point similar to Q1. At various intervals, the RF output power in a test fixture was measured at room temperature (or a selected measurement temperature). Three stress channel temperatures were chosen, and the median time to failure for each was plotted for each group of samples. The failure criterion was that the RF power degraded by 1dB. The three points are extrapolated to an acceptable MTTF of 5×10^6 hours at a usage channel temperature of 200°C. Statistical variation should be included in the estimated MTTF value. The distribution of the times to failure at each of the test temperatures should be evaluated using appropriate probability plotting methods or maximum likelihood analysis. A lognormal failure distribution or a Weibull failure distribution are usually used and can be evaluated for their appropriateness using statistical techniques. The variability of the MTTF is expressed using the lognormal shape factor or the Weibull shape coefficient.

POSSIBLE PITFALLS

Suppose however that there are two other "hidden" failure mechanisms that reveal themselves under different conditions (these are for illustration only of the pitfalls of conventional lifetests, and are not actual data plots). The first one, with an activation energy of 0.5eV (as a pessimistic guess for surface pitting for example) is not observable at the three temperature-accelerated test conditions chosen. Its MTTF is unobservable at the three test channel temperatures. However at the 200°C usage channel temperature, it dominates the MTTF, making this HEMT unusable for a space satellite mission of 10–15 years (green shaded area). A second mechanism with an activation energy of 1.0eV (as a guess for a catastrophic gate leakage effect) also may exist, and is also not observable at the three test temperatures. Instead, it might be driven by high electric fields more strongly than temperature. It gives a MTTF at usage conditions of 4×10^5 hours, not generally acceptable for hi-rel space applications, especially with a catastrophic failure mechanism. This example shows why conventional lifetesting may not always ensure satisfactory reliability.

RECOMMENDED RF LIFETEST PROTOCOL

Although much more difficult than DC stressing, a large signal RF-driven lifetest should be done as part of the qualification process. This is because DC stressing may accelerate some failure mechanisms differently (either more strongly or more weakly) than under more realistic RF usage. For example, depending upon the nature of the RF load line, the surface pitting mechanism may occur reducing the drain current; hot electrons may be generated producing drain lag or drain current collapse; the Schottky gate may be affected thus changing the threshold voltage; the source/drain contacts may become more resistive due to high currents. At this time it is not possible to recommend exactly how to electrically accelerate a correct mixture of failures with DC or pulsed testing that occur under actual RF-driven conditions. However, at least one proposed method [3] of translating from DC to RF tests is now under consideration. The following have been reported or suggested as modes of RF-driven acceleration:

- High levels of RF overdrive
- Increased drain voltage below catastrophic breakdown
- Elevated temperature
- Temperature cycle to induce mechanical stress

The RF driven lifetest should be tailored to the usage or application with as much acceleration as possible from each of these accelerants. Device loading should be similar to its anticipated usage as much as possible. It is recommended that at least one elevated temperature test be performed on a minimum of 8 devices. (A two temperature RF driven lifetest with 8 devices per temperature is highly recommended). The temperature(s) should be selected to have sufficient acceleration to test for RF stress induced degradation without inducing high temperature failure mechanisms not seen in normal operation. The RF drive should encompass the proposed usage of the device, with as much overdrive as possible. If the anticipated usage of the HEMT is in a pulsed application, then a realistic pulse or signal waveform should be used. If the anticipated usage is CW, then the actual drive level with some additional overdrive or compression is recommended. Other general requirements are as follows:

- Frequent or continuous monitoring of the output power, DC input power (voltage and current) and baseplate or die mount temperature
- Real time estimation of the channel temperature from the thermal resistance × dissipated power (dissipated power is DC input power less RF output power)
- Frequent or continuous adjustment of the RF input power so as to maintain a constant channel temperature despite possible reductions in RF output power as the device degrades
- Alternatively, frequent or continuous adjustment of the RF input power so as to maintain a constant RF output power, despite changes in channel temperature and power dissipation as the device degrades
- Periodic interruptions for cool down to room temperature (or a selected measurement temperature) where the device electrical measurements are made.

In performing this RF driven lifetest, a realistic combination of device degradation mechanisms can be established. These should be compared with those observed during the DC stressing at the four DC bias conditions. Where similar degradation mechanisms occur in comparing the DC to RF tests, Arrhenius parameters (activation energy and time scale factor) may be estimated. There will likely be a mixture of Arrhenius relationships for temperature at work along with electrical (current, voltage or electric field) relationships such as power law, Eyring relationships or others. These relationships should be separated and analyzed individually.

RECOMMENDED TLYF ("TEST LIKE YOU FLY") PROTOCOL

The final proof of the reliability of HEMT operation is to perform a "test like you fly" (TLYF) test. This test should be conducted under realistic RF usage conditions with device loading as similar to its anticipated usage as much as possible. The test considerations should be similar to those for the RF driven lifetest as described above. However there should be no acceleration or only mild acceleration. For example the junction temperature should be similar to that anticipated under usage conditions. The test should be conducted for a long duration—at least 15%—of the anticipated usage or mission time. For example, for a 10 year mission, a minimum 1.5 year duration test is recommended. A minimum device quantity of 10 devices each from 3 wafer lots is recommended. The purpose of this test is to eliminate the possibility of any hidden or "sneak" failure mechanisms, not necessarily accelerated by temperature. It is important to ensure that unanticipated low activation energy mechanisms are not present in long duration applications. This test should include periodic measurements of RF and DC parameters. The actual performance parameters of the device under test are most appropriate for consideration for a TLYF test.

STATUS

Many other recommendations are covered in the draft guidelines [1] available from the authors on request. Soon after this guideline was first proposed, a weekly working group of industry, government and academic representatives led by The Aerospace Corporation was held in the latter half of 2017. Based upon the many excellent comments and discussion, this document is under extensive revision and will soon be made available to the community as a standard.

ACKNOWLEDGEMENTS

We acknowledge the support of the Aerospace Technical Investment Program, The Aerospace Corporation. (All materials previously approved for public release: OTR 2018-00299 and ATM-2017-01782)

REFERENCES

[1] Scarpulla, J., and Gee, C., "Draft Guidelines for Space Qualification of GaN HEMT Technology" The Aerospace Corporation, El Segundo, CA. Report No. ATR-2017-01782, May 23, 2017

[2] Johnson-Roth, G., "Mission Assurance Guidelines for A-D Mission Risk Classes" The Aerospace Corporation, El Segundo, CA. Report No. TOR-2011(8591)-21, June 3, 2011

[3] Paine, B., S. Polmanter, V. Ng, N. Kubota, and C. Ignacio, "Lifetesting GaN HEMTs With Multiple Degradation Mechanisms" IEEE Trans. On Device And Materials Reliability, Vol. 15, No. 4, December 2015, p. 486

[4] Chini, A., V. Di Lecce, F. Fantini, G. Meneghesso, and E. Zanoni, "Analysis of GaN HEMT Failure Mechanisms During DC and Large-Signal RF Operation" IEEE Trans. On Electron Devices, Vol. 59, No. 5, May 2012, p. 1385

[5] Coutu Jr., R., R. Lake, B. Christiansen, E. Heller, C. Bozada, B. Poling, G. Via, J. Theimer, S. Tetlak, R. Vetury and J. Shealy, "Benefits of Considering More than Temperature Acceleration for GaN HEMT Life Testing" Electronics 2016, 5, 32; doi:10.3390/electronics 5030032, www.mdpi.com/journal/electronics, (MDPI, Basel Switzerland open access journal)

TABLE I GAN SPACE QUALIFICATION TOPICS ADDRESSED

Robustness
- SOA (safe operating area)
- Gate burnout
- RF burnout
- ESD
- Temperature cycling
- Power cycling
- Off-state voltage screening

Intrinsic Reliability
- DC lifetesting (4 Q-points)
- RF lifetesting
- Step stressing
- TLYF (Test Like You Fly)
- Thin film resistors
- Electromigration

Environmental Effects
- Moisture warmth
- Hydrogen sensitivity
- Air Sensitivity

Extrinsic Defects
- MIMCAPs
- Gate Defects
- Airbridge Defects
- Backside Via defects

Mechanical
- Backside metal adhesion
- Bondpull tests
- Die shear tests
- Step Coverage
- Low Frequency Oscillations

Radiation Effects
- Total Ionizing Dose
- Dose Rate
- Singe Event Effects
- Displacement Damage

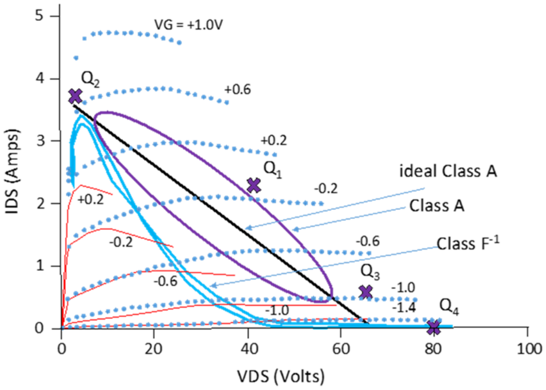

Fig. 1. DC (lines) and pulsed IV (points) characteristics of a RF power GaN HEMT, and representative load lines, with four proposed operating Q-points for DC reliability testing.

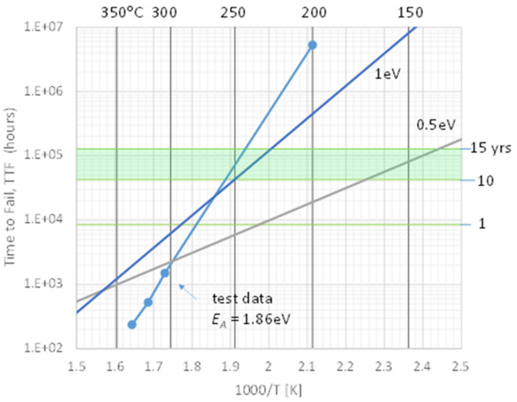

Fig. 2. Arrhenius plot of high temperature test data extrapolated to a lower usage temperature of 200°C, along with alternate unobserved failure modes that may actually determine the life.