APPLICATION NOTE

Silicon Carbide (SiC) MESFET Reliability

Summary

This applications note describes the reliability characteristics of Cree SiC MESFET technology. Two products, CRF24010 (a 10W device) and CRF24060 (a 60W device), have been evaluated using accelerated lifetest methods, RFHTOL (operational life) testing, and High Temperature Reverse Bias (HTRB) stress. Applications guidance is provided in terms of selecting a channel temperature for a desired reliability level. During testing, DC and RF parameters are measured periodically so that any change in these parameters can be observed. Failure is reached when a DC characteristic changes by 20%, or an RF parameter changes by 1dB, of its initial value. Lifetests are continued until at least 75% of the devices have failed, in accordance with JEDEC publication JEP 118. The methods used to calculate reliability metrics are described in detail in this report. Activation energy (Ea), median time to failure (MTTF), and failure unit (FIT) results are presented in terms of channel temperatures for the 10W and 60W products. Table 1 is a summary of select reliability results.

Parameter	Value	Unit
Activation Energy (Ea)	1.27	eV
Median Time to Failure (MTTF) (worst case)	2.2×10^6	Hours
Median Time to Failure (MTTF) (typical)	4.1×10^8	Hours
Failure Unit (FIT) (RFHTOL)	10.7	

Table 1. SiC MESFET Reliability Summary

Background- The Semiconductor Lifecycle

The lifecycle of a semiconductor device (a.k.a. "the bathtub curve") has three phases: early-life, constant failure rate, and wearout (Fig. 1). Early-life failures are usually dominated by out-of-family manufacturing defects that are not detected during the course of electrical testing and wafer acceptance procedures. For a high quality manufacturing operation, the probability of failure during early life is only slightly higher than the constant failure rate period, which is dominated by random failures inherent to the manufacturing process. At the end of device life, wearout failures occur due to degradation processes inherent to the materials used in the technology.

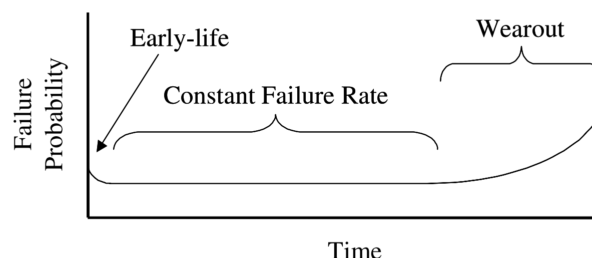

Figure 1. The Bath Tub Curve

In terms of reliability metrics, failure unit (FIT) values describe the average time between failures in the early and constant failure rate portions of the life cycle. Median-time-to-failure (MTTF) values describe the time at which 50% of the devices are expected to reach the wearout phase of the life cycle. In both cases, an activation energy that relates failure to operating conditions is required as an input to the calculation. The activation energies for the FIT and MTTF calculations are likely to be different since different failure modes are involved.

Results & Discussion

A comprehensive assessment of reliability was performed on Cree SiC MESFET technology. The data are presented here, along with the methods used to arrive at the various calculated values.

Thermal Activation Energy

Thermal activation energy (E_a) relates temperature to the rate of progression of a failure mechanism, and is expressed in electron volts (eV). Failure mechanisms that are primarily temperature driven are typically diffusion controlled, and therefore, follow an exponential relationship with time. This relationship is given by the Arrhenius equation (Eq. 1):

$$t = A * e^{\frac{E_a}{k}\left(\frac{1}{T}\right)}$$

Equation 1: A Form of the Arrhenius Equation

where A is an empirical constant (units of time), k is Boltzman's constant (8.6 x 10^{-5} eV/K), and T is temperature (in Kelvin). Activation energy can be determined by taking the ratio of the median time to failure at two temperatures, as shown in Equation 2.

$$\frac{t_1}{t_2} = e^{\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$

Equation 2: Arrhenius Relationship Between Two Temperatures.

A third temperature is used to calculate statistical confidence, and to verify that the activation energy is constant over a wide temperature range. Since modern semiconductors are designed for high reliability, the three temperatures selected are well above the normal operating condition of the device, creating the basis for an accelerated life test. Due to the degree of acceleration necessary to complete a test in a practical

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timeframe, only the wearout phase of the lifecycle can be determined using this method (in a high quality device). Three temperature accelerated life testing was performed on production SiC MESFET devices. The only modifications were that the devices were unlidded (due to thermal limitations of the lid seal epoxy), and a higher temperature die attach material was used to mount the die to the package. The data show that for Cree SiC MESFET technology, E_a = 1.27 eV (± 0.04 eV). Failure analysis identified an increase in ohmic contact resistance as the primary failure mode. In the course of additional reliability testing, electric field and current density acceleration did not produce a significant shift in device parameters relative to thermal acceleration.

Median Time to Failure (MTTF)

Median-Time-To-Failure (MTTF) is the time required for 50% of the devices in a population to fail*. The *median* time is used because statistical uncertainty is minimized at the median of a population, even if that population is not normally distributed.

* Often the term MTTF, in the context of semiconductor reliability, is defined as mean-time-to-failure. This may simply be due to non-conventional terminology, or the author may be representing a different calculation altogether.

The Arrhenius plot (Fig.2) is used to estimate MTTF at the intended use temperature from the measured MTTF values at the accelerated temperature splits of a 3-temperature life test. It also provides a derating curve to estimate the time to wearout at an application's maximum channel temperature.

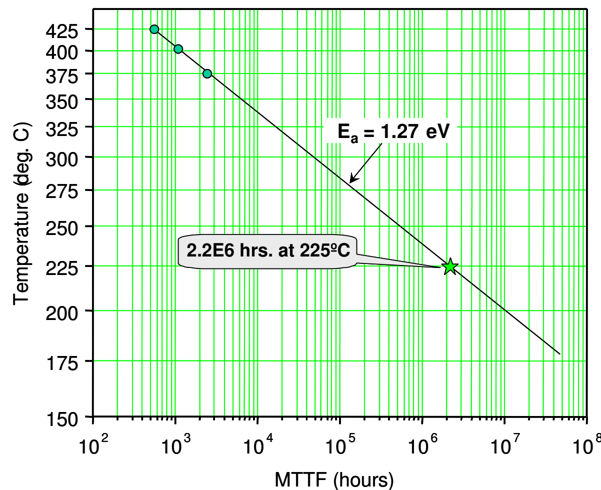

Fig. 2. Arrhenius Plot Example (Data are from CREE's standard Gen2 MESFET process).

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There is no consensus on a reference channel temperature when reporting MTTF values. Some vendors use the worse case scenario of 100% dissipated power under maximum bias conditions at the maximum channel temperature of the device. Others use a typical operating condition under RF drive. Table 2 shows the MTTF of Cree MESFET technology at the maximum specified channel temperature and at various commonly reported channel temperatures.

$T_{CHANNEL}$	MTTF
225 °C	2.2×10^{6} hours
150 °C	4.1×10^{8} hours
140 °C	9.5×10^{8} hours
140 °C	3.6×10^{9} hours

Table 2. MTTF at Various Channel Temperatures

It is especially important to state the statistical confidence limits for accelerated life test calculations since exponential relationships are involved. For these data, the 80% lower confidence limits for the MTTF calculations in Table 2 are no less than 60% of the stated value. For example, based on the parts used for accelerated life testing, MTTF is 3.6×10^{9} hours at a channel temperature of 125°C. It is 80% certain that the MTTF of all devices produced will be at least 2.2×10^{9} hours at a channel temperature of 125°C.

FIT

Failure unit (FIT) is a measure of the failure rate of a device, assumes a constant failure rate, and has units of "failures per billion device hours". Since the failure rate is decreasing in early life, and increasing during the wearout phase, FIT only strictly applies to the middle portion of the bathtub curve (Fig.1). However, in a high quality manufacturing operation, the early life failure rate should be only slightly higher than the mid-life failure rate, so a FIT rate calculated during early life should be a good approximation (albeit conservative) of the failure rate until wearout. FIT is given by (Eq. 3):

$$FIT_{LCL} = \frac{\chi^{2}_{1-\alpha,2F+2} * 10^{9}}{2 * N * t * AF}$$

Equation 3. FIT equation†

† FIT is generally reported in terms of its 60% lower confidence limit.

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where χ^2 is a statistical estimator (having confidence level α at an observed number of failures, F), N is the number of devices in the sample, t is the weighted average time of operation, and AF is the ratio between use time and accelerated stress time, of the form given in Equation 2.

The activation energy of the random failures in the constant failure rate portion of the bathtub curve is unknown, and cannot be practically determined. Therefore, a conservative value of 0.7eV is used by convention.

To determine the FIT value for SiC MESFET technology, production devices were operated under typical RF drive conditions, at a moderately accelerated channel temperature. This test was performed on 15 devices at an accelerated channel temperature of 250°C for 5600 hours at 2.6GHz (CW) under 2.5dB compression. Normal (i.e., unaccelerated) channel temperature under these conditions is 150°C. There were no failures observed (in fact, there was no degradation of any kind), resulting in a FIT rate of less than 11 failures per billion device hours‡. This test was repeated for 2500 hours at a normal operational channel temperature of 150°C to verify that no hot electron effects exist. An additional 200,000 device hours of DCHTOL testing at maximum bias conditions was also performed with a larger sample size (1000 parts). No degradation in device parameters was observed.

Robustness Testing

A series of tests were performed to evaluate the robustness of SiC MESFET technology. These tests are not predictive of lifetime, but do give an assessment of how resistant the products are to electrical over-stress (EOS) and electrostatic discharge (ESD). These results are detailed in Table 3.

Test	Result
PFAST (130 V_{DG})	2 x 10^6 device-hours (no failures)
VSWR	10:1 (all phase angles)
ESD-HBM	Class 1C (1000V to <2000V)
ESD-CDM	Class IV (>1000V)
ESD-MM	Class M3 (200V to <400V)
IDSS at 50 V	96 hours (no failures)
Forward Gate Bias	3000 mA for 10 s (no failures)

Table 3. Robustness test results.

PFAST (Peak Field Accelerated Stress Test) was conducted in three-terminal mode at VD = 115V and VG = -15V, at a temperature of 175°C. This test is meant to simulate peak electric field stress in RF

‡ A typical industry goal for a microwave power amplifier is FIT<120

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overdrive conditions.

ESD testing was conducted on a standard CRF24010 product. Please refer to JESD 22-A114-B (Human Body Model), A115-A (Machine Model) and C101-A (Charged Device Model) for a description of these test methods.

Conclusion

Reliability and robustness testing has demonstrated the suitability of SiC MESFET technology to microwave power amplifier applications. Worst-case MTTF values are in excess of 2.2×10^6 hours (150 years) at maximum spec sheet operating conditions. In addition, the integrity of the process has been demonstrated by RF and DC operational tests, from which a FIT rate of <11 failures per billion device hours has been demonstrated.

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