

Reliability Assessment of Production SiC MESFETs

A. Ward, S.T. Allen, and J. Palmour

Cree, Inc., 4600 Silicon Drive, Durham, NC 27703, Allan.Ward@cree.com, Phone: (919) 313-5833

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Abstract

Testing was performed to assess the wear-out reliability and robustness of production SiC MESFETs. Parametric failures ultimately occurred due to Ti/Pt/Au interconnect degradation after 730 hours at a junction temperature of 410°C. However, no degradation was observed in the properties of the SiC semiconductor itself, nor in the gate and ohmic interface to SiC, demonstrating the suitability of this technology for applications that require high reliability at both standard and elevated operating temperatures. Accelerated life test data using production SiC MESFETs indicates MTTF = 2.0×10^6 hours at a junction temperature of 175°C.

INTRODUCTION

SiC transistor technology is quickly gaining acceptance in both military and commercial applications due to the bandwidth and power characteristics of production-level devices [1,2]. Such devices are available as discrete transistors (up to 60W), and as higher power MMICs through an available foundry service. Although this technology has previously passed internal reliability requirements during the research and development process, this is the first public report of reliability characteristics on production devices. The focus of this paper is on the use-life and wear-out characteristics of reliability, and the methods of ensuring reliability on production SiC transistors.

SiC MESFET RELIABILITY PERFORMANCE

Accelerated Life Test Method

The wear-out reliability of SiC MESFET technology was assessed by performing tests in which electric field, current density, and junction temperature were increased to force failure within 1000 hours in air. The failure criteria used were a change in data sheet DC parameters of greater than 10% or a change in data sheet RF parameters of greater than 0.5dB. Before and after stressing, a sub-set of devices from the run was tested on a load-pull system to characterize any impedance shifts due to stressing. Device DC characteristics were monitored in-situ during the accelerated life test (ALT), and all devices were bench-tested under CW conditions at intermediate points during the test.

Samples of 10W MESFET devices (randomly selected out of the production work flow prior to die attach) were used as the characterization vehicle for ALT. The only

differences between accelerated life test samples and production devices (Cree part number CRF24010) are that the accelerated life test samples were attached with Au/Ge solder rather than Au/Sn solder, and that the ALT parts are unlidded. Using a die attach material with a higher eutectic point (356°C for Au/Ge compared to 280°C for Au/Sn) allows testing at higher accelerating temperatures. The ALT devices are unlidded because the lid seal epoxy on production parts cannot withstand ambient temperatures above 200°C for extended periods of time. Otherwise, the same package and packaging methods were used to assemble the ALT devices.

The high thermal conductivity of SiC results in a much lower junction-to-case temperature rise than would be experienced by other technologies operating at the same power density. This presents a unique challenge for reliability assessment because the ambient or flange temperature must be increased to a much greater extent for a desired junction temperature than would be required for a GaAs or Si device. Further exacerbating the reliability assessment problem is that, to the authors' knowledge, no commercially available test system is available that can simultaneously provide sufficiently high thermal heat sinking for the power densities involved, enough power for the required number of devices tested per run, and prevent oscillation problems in the test fixtures. Therefore, a custom reliability test system was designed and constructed to meet these requirements. By running the ALT device at the test system maximum of 33W dissipated power, the highest T_j that can be achieved for reliability testing is 410°C. Standard 10W production devices without lids and Au/Sn die attach can be tested up to $T_j = 340^\circ\text{C}$.

Accelerated Life Test Results

No change in any DC or RF parameter was observed within 1000 hours unless the stress conditions exceeded the simultaneous application of $V_{DS}=60\text{V}$, $I_{DS}=550\text{mA}$, and a flange temperature of 255°C in air. At this stress condition, 50% of devices met the failure criteria for I_{DSS} degradation of 10% and P_{3dB} of -0.5dB in 730 hours of continuous operation. The maximum unaccelerated operating condition of the device, as defined by its data sheet, is $V_{DS} = 48\text{V}$, $I_{DS}=500\text{mA}$, and a flange temperature of 90°C. An Arrhenius plot projecting MTTF = 2×10^6 hours at

$T_j=175^\circ\text{C}$ is shown in Figure 1. The lognormal shape factor for these data is 0.6, indicating good manufacturing control.

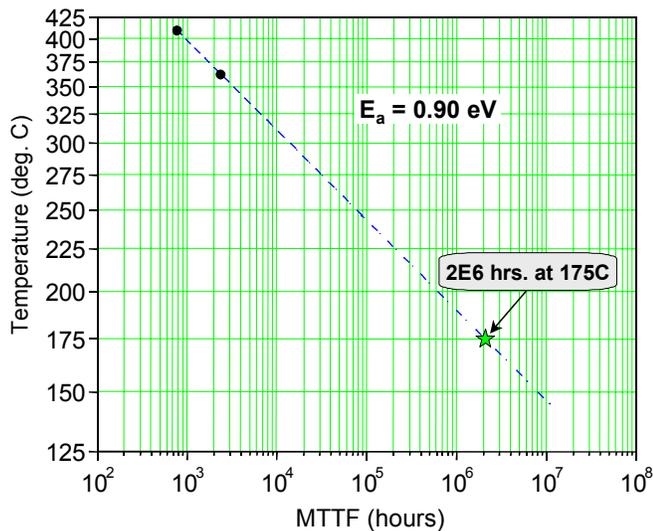


Fig 1. Arrhenius plot of production 10W SiC MESFETs.

Load-pull data shows a purely resistive shift on the Smith chart, which has been correlated with the increasing R_{DS} that is apparently responsible for lower I_{DSS} and P_{3dB} values in failed devices. Failure analysis was performed to determine the nature of this resistance increase.

FAILURE ANALYSIS

Failure analysis was performed on post-ALT devices using Focused Ion Beam cross sectioning, Scanning Transmission Electron Microscope imaging, and Energy Dispersive X-ray element analysis. The results show (Fig.2) that the root cause of failure is dissolution of

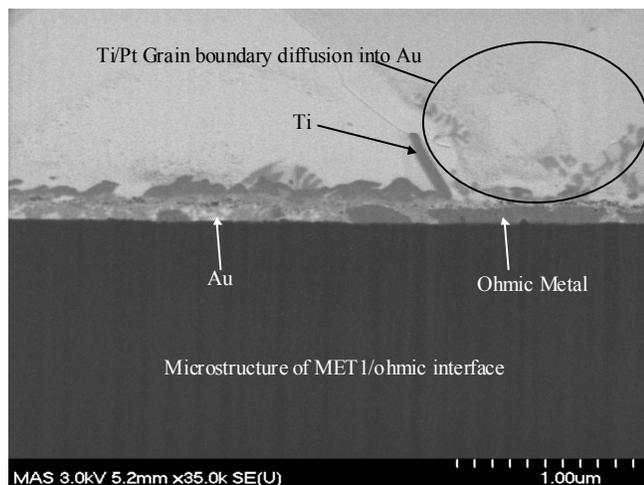


Fig 2. Cross-sectional image of failed device after 730h at $T_j=410^\circ\text{C}$.

the platinum diffusion barrier at the interface of the interconnect and ohmic metals as the platinum migrated into the adjacent gold layer by grain boundary diffusion. Once the platinum barrier metal is breached, the titanium adhesion layer also mixes into the gold layer, allowing direct interaction between the gold and nickel silicide ohmic contact material.

No degradation was apparent in the gate region or the passivation/SiC interface. Also, in areas of certain devices where gold did not penetrate the diffusion barrier, no ohmic contact degradation was observed. Therefore, it appears that gold diffusion into the ohmic contact is the primary failure mode at $T_j = 410^\circ\text{C}$. The root cause of failure appears to be failure of the Pt diffusion barrier in the Ti/Pt/Au interconnect metal, which is expected at these temperatures.

ELEMENT TESTING

Element tests were performed in an attempt to duplicate the failure mode observed in the actual device. TLM structures were fabricated with and without interconnect metal to assess the reliability on the ohmic metal itself, and to verify that gold migration through a failed diffusion barrier increases contact resistance. These structures were stressed in air at 500°C and 600°C until the contact resistance of the structure increased 100%, which is well below the resistance change necessary to impact device performance. Figure 3 shows the results of the TLM test with ohmic metal and Ti/Pt/Au interconnect metal. From these data, $E_a = 0.93 \text{ eV}$, with an $\text{MTTF} = 1.3 \times 10^7$ hours at $T_{\text{ambient}} = 175^\circ\text{C}$ was calculated.

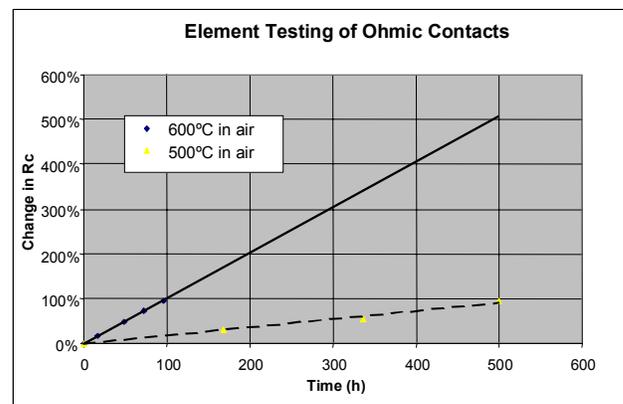


Fig 3. Element test results of TLM with ohmic metal and interconnect.

Failure analyses from TLM structures with Ti/Pt/Au interconnect metal showed the same failure mode as the ALT devices, verifying the root-cause analysis. For the TLM without interconnect metal, $E_a = 1.1 \text{ eV}$ with an $\text{MTTF} = 2 \times 10^8$ hours at $T_{\text{ambient}} = 175^\circ\text{C}$ was calculated.

OPERATIONAL LIFE TESTING

In addition to DC accelerated testing, operational life tests were performed. The devices used for operational tests were randomly sampled from production (and therefore have Au/Sn die attach and are lidded). Devices were biased at the maximum Q-point of 48V and 500mA at the drain.

RF High Temperature Operational Life Testing

An RF High Temperature Operating Life (RFHTOL) test was performed using 20 production CRF24010 devices operating at 2.6 GHz under P_{2dB} compression and a 90°C flange temperature for 5,000 hours. The purpose of this test is to identify drift or degradation in the device due to trapping phenomena (such as hot electrons) when operated at unaccelerated temperatures under RF drive. Typical results from RFHTOL testing are shown in Figure 4.

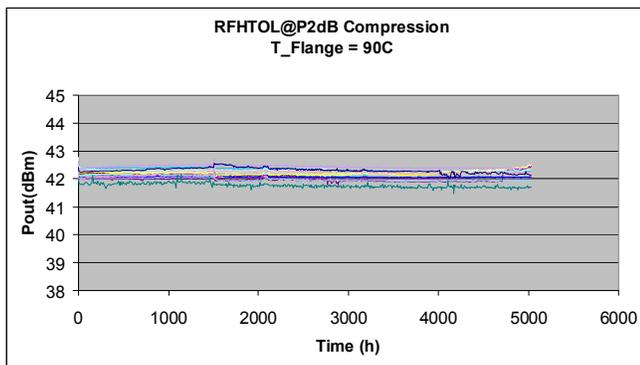


Fig 4. Long-term RFHTOL test on production 10W SiC MESFETs.

No degradation was observed in any DC or RF parameter after 5,000 hours of RFHTOL testing, which confirms pre-production conclusions that hot electron and other trapping phenomena are not significant in the SiC MESFETs tested.

DC Operational Life and Robustness Testing

To verify the repeatability of the SiC MESFET process with regard to reliability, DC High Temperature Operating Life (DCHTOL) tests were performed on CRF24010 devices randomly selected from ten different processing lots over the course of the past 24 months. These devices were tested under the maximum specified operating conditions of 48V on the drain terminal, 90°C flange temperature, and 500mA drain-to-source current. These conditions result in a junction temperature of 172°C, at which the devices were operated collectively for 100,000 device-hours with no die failures. No change in any DC or RF parameters was observed. For normal operating conditions, FIT = 14 at the lower 80% confidence boundary, and MTBF = 7.1×10^7 hours.

In addition to steady state DC testing, DC power cycle stressing and High Temperature Reverse Bias (HTRB) testing were also performed as robustness tests. The purpose of the power cycling test is to stress the device to identify any unexpected thermo-mechanical and trap effects in the active region of the device. With a constant drain voltage of 48V, gate switching is used to pinch-off the device and return it to its Q-point 1000 times. The fixture has been designed to allow a 50% overshoot of drain current at 48V before settling at the target Q-point (settling time = 8ms). This procedure is also performed at wafer level on sampled devices for 100,000 power cycles per device as part of our wafer acceptance criteria. No power cycling failures have been observed in production devices to date.

HTRB testing is performed at $V_{DG} = 130$ V (812 kV/cm) for 1000 hours at a flange temperature of 175°C. The purpose of the HTRB test is to ensure that the devices are robust to dielectric breakdown failure modes and ion migration. Collectively, CRF24010 production devices have passed over 1.2 million device-hours of HTRB stressing without failure or degradation in any DC or RF parameter.

DISCUSSION

The superior robustness of SiC MESFET technology to temperature acceleration is primarily due to the lack of semiconductor-to-metal interaction at both the gate and ohmic interfaces, and the high temperature stability of the semiconductor itself (i.e., no significant dopant diffusion or defect formation). Further improvement of SiC MESFET reliability will likely occur as interconnect metal is improved for high temperature robustness. However, the current state of operational reliability and wear-out reliability in Cree SiC MESFETs has been shown to exceed the requirements for commercial and military microwave power amplifiers.

CONCLUSIONS

Production SiC MESFET devices were tested to determine operational and wearout reliability. Devices were operated collectively for 100,000 device-hours with no failures in DCHTOL testing and 100,000 device-hours with no failures in RFHTOL testing. No change in any DC or RF parameters was observed. For normal operating conditions, FIT = 14 at the lower 80% confidence boundary, and MTBF = 7.1×10^7 hours during the “constant failure rate” portion of the product life cycle. The wearout reliability has been shown to have a lognormal shape factor of 0.6 and an MTTF of 2.0×10^6 hours at maximum specified operating conditions.

Failure analysis was performed using Focused Ion Beam cross sectioning, STEM imaging, and EDX element analysis. The results show that the root cause of failure is

dissolution of the platinum diffusion barrier at the interface between the Ti/Pt/Au interconnect and ohmic metals. Subsequent diffusion of gold into the ohmic metal results in high contact resistivity, and thereby, a decrease in I_{DSS} .

The current state of operational reliability and wear-out reliability in Cree SiC MESFETs has been shown to exceed the requirements for commercial and military microwave power amplifiers.

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ACRONYMS

SiC: Silicon Carbide
MESFET: Metal Semiconductor Field Effect Transistor
FIT: Failure Unit (failures per billion device-hours)
MTTF: Median Time to Failure
MMIC: Monolithic Microwave Integrated Circuit
ALT: Accelerated Life Test
MTBF: Mean Time Between Failures
HTRB: High Temperature Reverse Bias
TLM: Transmission Line Model