SiC Power Diode Reliability

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ABSTRACT

Cree introduced its *Zero Recovery*® line of SiC power rectifiers three years ago into mainstream switching power supply applications, and is pleased to announce an outstanding record of reliability performance in the field. This paper explains why Cree SiC products are expected to be inherently reliable, discusses Cree's approach to reliability assessment, and presents the expected lifetime of SiC power diodes under various operational and environmental conditions.

SiC Schottky Diode Reliability

SUMMARY

Cree's 600V family of Schottky diodes have accumulated nearly 12 billion device-hours in fielded industrial and consumer applications. Overall, the FIT value (expressed as failures per billion device hours) is less than 1.4, which is typical of a FIT value for traditional high voltage silicon power diodes.

Historical concerns regarding crystal and epitaxial quality in large volume SiC products have been allayed, as only one field failure related to a crystal defect has ever been observed. This is equivalent to a FIT of less than 0.2 for crystal related failures, indicating extremely high crystal quality in fielded Cree diodes.

WHY IS SIC SO RELIABLE?

By its nature, SiC has long been believed to be an ideal material for high power, high reliability semiconductor devices. SiC is highly corrosion resistant, has very low dopant diffusivity, exhibits high mechanical robustness, possesses a high breakdown field strength (10 times that of silicon), and provides thermal conductivity similar to that of copper.

To take advantage of these natural properties, several engineering challenges were successfully met in the areas of ion implantation, epitaxial growth, and device design. Cree holds a number of design and process patents that are critical to the high reliability performance of its devices.

Cree's Approach to Reliability Assessment

BACKGROUND

Cree's approach to reliability assessment begins in the laboratory with a series of robustness and operational stress tests. Once the materials and device design are proven to be reliable, a series of qualification tests are applied to verify that the new product meets Cree's rigorous quality standards. Finally, ongoing assessments of reliability are made in fielded products. Field data represent the most straightforward picture of device reliability, and are only meaningful after a significant number of device hours are achieved in actual applications. Now that the product has sufficient experience in the field, Cree SiC Schottky diodes have an established record of high reliability and robustness in all phases of reliability assessment.

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 (Figure 1). For a high quality manufacturing operation, the probability of failure during early life is only slightly higher than the constant failure rate period. At the end of device life, wearout failures occur due to degradation processes inherent to the materials used in the technology.

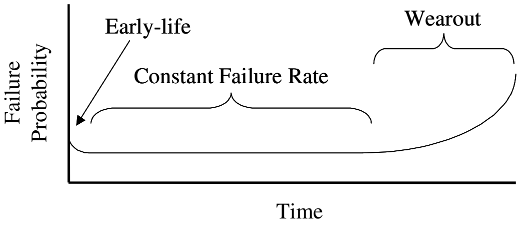

Figure 1: The "bathtub curve".

In terms of reliability metrics, failure unit (FIT) values describe the average failures per unit time 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.

SERVICE LIFE FAILURE RATE CALCULATIONS

Early life failures, sometimes referred to as "infant mortality" failures, are typically related to quality control issues. In a high quality manufacturing operation, the early life failure rate should therefore be only slightly higher than the mid-life failure rate. Thus, a FIT rate calculated during early life should be a conservative approximation of the failure rate until wearout. FIT is given by (Equation 1):

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

Equation 1. FIT equation[†]

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, and t is the weighted average time of operation. The acceleration factor (AF) is the ratio between use time (t_1) and accelerated stress time (t_2), at temperatures T_1 and T_2, given by (Equation 2):

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

Equation 2: Acceleration factor.

where k is Boltzman's constant. The activation energy (E_a) of the random

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

failures in the constant failure rate portion of the bathtub curve is unknown, and cannot be practically determined. Therefore, a conservative value of 0.6eV is used by convention. For field data, AF=1, since the data represent the unaccelerated operation of the device.

In the laboratory, new products are exposed to a series of critical reliability tests that stress the devices to the extremes of their operational envelope. These accelerated tests can be categorized as survivability tests in which specific aspects of device operation are evaluated. The desired outcome of survivability tests is to accumulate as many "device-hours" as possible with few failures. Table 1 shows the results of the most critical survivability tests for power diodes.

Table 1. Survivability Test Data

Laboratory Stress Testing Results			
Stress Test	**Conditions**	**Device Hours**	**Fails**
Thermal Cycle	-55C to +155C, 1000 cycles (3 cycles/hour)	425,000	0
Power Cycle	7 minute 50% duty cycle, P_{max}, 1000h, T_j=150C	1,807,300	0
HTRB	V_{RRmax} at Tj=200C, 1000h	2,383,480	0
H3TRB	85%RH, 85C 1000h	154,000	0

Combining these results, the predicted FIT value is less than 6.0 failures per billion device-hours, according to laboratory data. In addition to estimating FIT values, these data also demonstrate that Cree SiC devices are quite robust with regard to thermal, electric field, power density, and thermo-mechanical stresses that are well in excess of what a typical application would require.

While laboratory data are useful in evaluating devices for new product introduction, a more accurate understanding of practical reliability behavior can only be determined after many hours of device use in actual fielded applications. The larger number of devices and longer duration of operation reduces the statistical uncertainty associated with FIT calculations, and the uncertainty involved in simulating the severity of stresses the devices encounter in actual use is eliminated. Table 2 details the practical reliability performance of Cree's SiC 600V Schottky diodes in switching power supply applications.

Table 2. Field Reliability Performance

Field Failure Rate Data		
Product	**Device Hours**	**FIT**
CSD10060A	7,914,475,778	1.5
CSD06060A	4,001,452,800	1.6
Total	11,915,928,578	1.4

FAILURE AT WEAROUT

The final portion of the semiconductor device lifecycle is known as wearout, and is an inherent characteristic of the materials used to construct the device. All devices will undergo wearout – the goal is to ensure that wearout occurs well after the designed service life of the product.

Operational wearout

For Cree Schottky diodes, the dominant failure mechanism at wearout is driven by temperature[*], which can be described in terms of a thermal activation energy (E_a), and is expressed in electron volts

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[*] No significant changes occurred during electric field and current density acceleration tests.

(eV). Activation energy can be derived by taking the ratio of the median time to failure at two temperatures, as previously shown in Equation 2. A third temperature is used to calculate statistical confidence, and to verify that the activation energy is constant over a wide temperature range.

Three-temperature accelerated life tests were performed on SiC MESFETs (a Schottky gated device), since higher power densities and junction temperatures can be generated on this type of device relative to a Schottky diode. The data show that for Cree's SiC Schottky-based technology, the dominant failure mode has an activation energy of Ea = 1.27 eV (± 0.04 eV).

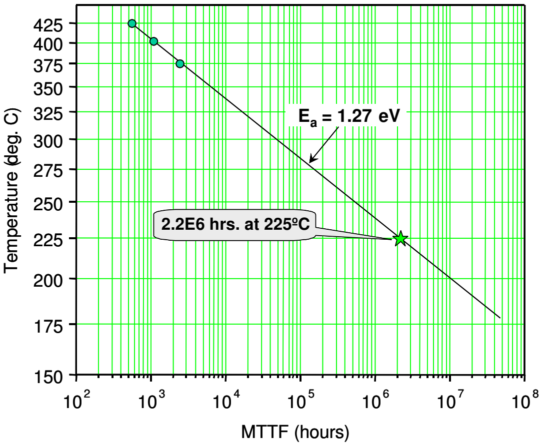

Figure 2. Arrhenius plot of wearout

The Arrhenius plot (Figure 2) is used to estimate MTTF at the intended use temperature. These data show that Cree SiC technology can operate at active region temperatures as high as 225°C and still meet the internal 250 year goal (2.2 x 10^6 hours) for wearout reliability. MTTF is 6.0 x 10^7 hours at a junction temperature of 175°C, which is the maximum rated temperature for a Schottky diode in a power supply application.

Environmental Reliability

For Cree Schottky diodes, the primary environmental failure mode is humidity related, and involves electrochemical degradation due to moisture. Laboratory results (Figure 3) show that devices will perform for over 50 years in any climate controlled environment.

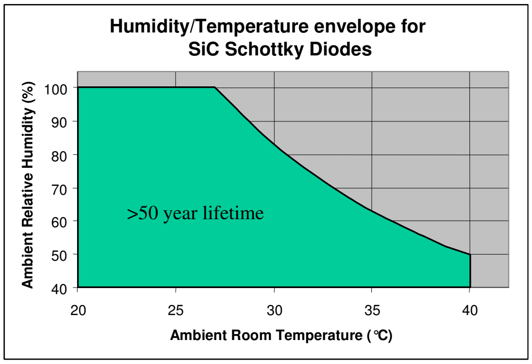

Figure 3. Humidity/Temperature Envelope for Cree SiC Schottky Diodes

Conclusion

This paper has presented operational and accelerated life test data that indicate a low failure rate in a variety of stress conditions. In the field, Cree 600V Schottky diodes have demonstrated FIT values below 1.6 failures per billion device hours, which is highly competitive with other power diode technologies. With a wear-out lifetime estimated to be in excess of 50 years in the most stringent environmental conditions, Cree Schottky diodes are expected to perform well beyond the design life of their system-level applications.