# Test-to-Fail Methodology for Accurate Reliability and Lifetime Evaluation of eGaN Devices in Solar Applications

*Modern solar panels are demanding increasingly higher power density and longer operating lifetimes. Solar applications including power optimizers and panels with built-in microinverter are becoming the prevailing trend for an increasing number of solar customers, where low voltage GaN power devices ($V_{DS}$ < 200 V) are extensively used.*

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Greater than 25 years of reliable operation is a typical requirement for solar installations. The test-to-fail methodology stresses devices to failures quickly. By understanding the intrinsic underlying failure mechanisms, physics-based lifetime models can be developed to accurately predict the lifetime under all mission profiles [1-5]. In this report, we use these physical insights and apply them to the unique demands of solar applications.

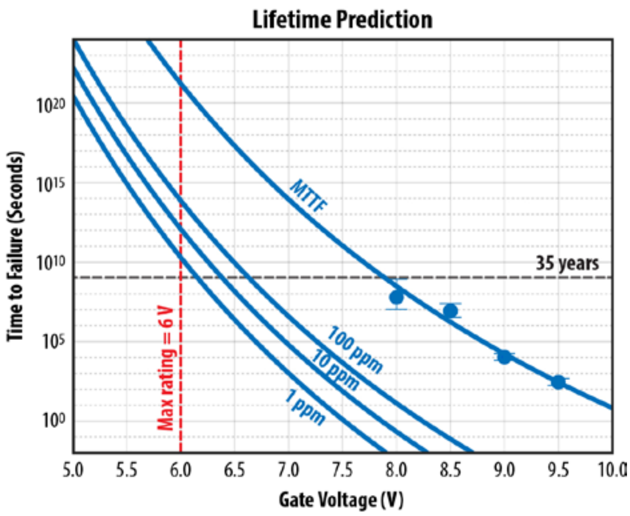


*Figure 1: EPC2212 time to failure vs. $V_{GS}$ at 25°C MTTF (and error bars) are shown for four different voltage legs.*

**Gate Stress:**

Representative discrete GaN devices (EPC2212) showed excellent long-term gate reliability. Failure analysis was conducted on multiple failures from the study, and a consistent failure mode was found between the gate metal and the metal field plate. By understanding the underlying failure mechanism, a first-principles model was developed to explain all observations. This model can be used to predict the lifetime under different gate biases, temperatures, and duty cycles. The lifetime equation is plotted against the measured accelerated data for EPC2212 in Figure 1. Figure 1 shows that EPC2212 has less than 1ppm failure rate projected over more than 35 years of lifetime under continuous DC gate bias at the maximum rated gate voltage ($V_{GS}$ = 6 V). This projected result is also consistent with EPC's field experience for gate failures.

**Drain Stress:**

One common concern for GaN is dynamic on-resistance. This is a condition whereby the on-resistance of a transistor increases when the device is exposed to high drain-source voltage ($V_{DS}$). By understanding hot electrons trapping mechanism, a hard switching topology circuit was developed and implemented to accelerate this failure mechanism by providing more hot electrons at maximum rated $V_{DS}$ [2,6-8] and beyond. Using the characterization test results from this development, a physics-based lifetime model was developed to describe the dynamic $R_{DS(on)}$ effects in eGaN FETs under all bias and temperature stress conditions.

Flyback is one of the most used topologies for the microinverters in solar applications where the EPC2059, a 170 V max $V_{DS}$ rated product, is frequently selected by solar customers for such applications. Figure 2 shows an EPC2059 device that was operated under continuous hard switching at 136 V (80% of the max rated drain bias of 170 V) while the case temperature was modulated at 80°C, where 80°C is considered a nominal operation temperature for solar applications. The measured data and the corresponding model predict the $R_{DS(on)}$ increase due to continuous hard switching in 35 years is expected to be approximately 10%.

Another popular option for solar applications is to use a DC-DC converter in the primary stage (typically a full bridge) of a microinverter. This topology is frequently used in a power optimizer, which has been increasingly adopted by solar providers due to its superior efficiency. GaN devices such as 100 V-rated EPC2218, EPC2088, and EPC2302, among others, are a good fit for this application. Fig-

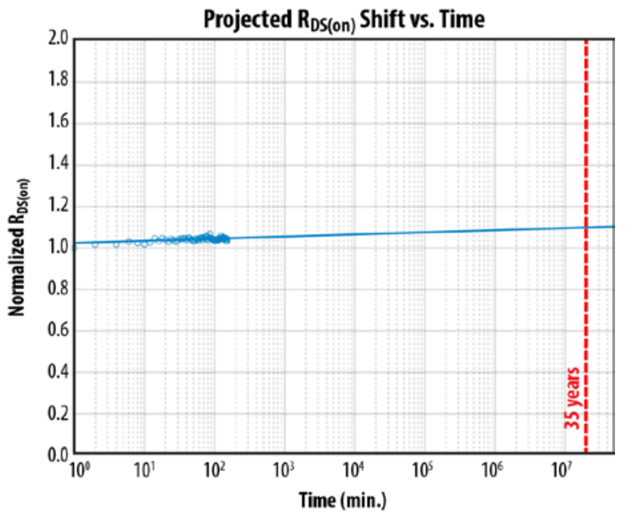


*Figure 2: Projected $R_{DS(ON)}$ shift of EPC2059, a 170 V rated device, in 35 years of continuous hard-switching operation is expected to be approximately 10%.*

ure 3 shows the projected $R_{DS(on)}$ increase of an EPC2218 device is expected to be 10% in 35 years of continuous hard switching operation at 80 V, ambient temperature.

Therefore, eGaN devices demonstrate good robustness in dynamic on-resistance with more than 25 years of lifetime and beyond.

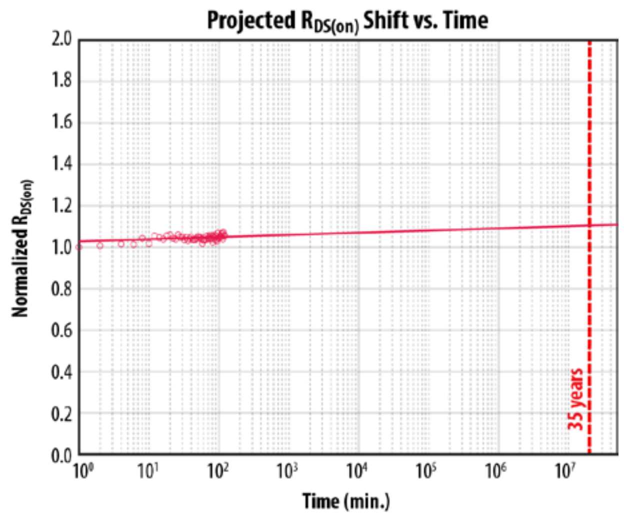


*Figure 3: Projected $R_{DS(ON)}$ shift of EPC2218, a 100 V rated device in 35 years of continuous hard-switching operation is expected to be approximately 10%.*

**Thermo-mechanical stress:**
Thermo-mechanical reliability is another critical area of particular interest in solar applications. Solar panels are placed outside and experience significant ambient temperature change. A similar test-to-fail approach was used to study the board level thermo-mechanical reliability of EPC2218A.

Three different combinations of test conditions are studied as shown below.

- TC1 condition without underfill: −40°C to 125°C
- TC2 condition without underfill: −40°C to 105°C.
- TC1 condition with underfill: −40°C to 125°C, where the underfill manufacturer is HENKELS and the part number is ECCOBOND-UF 1173.

All parts were mounted on test coupons consisting of a 2-layer, 1.6 mm thick, FR4 board using SAC305 solder paste, and water-soluble flux. A group of 88 devices was tested for each leg, and all three test legs used similar ramp rate and dwell time at the two temperature extremes. After every temperature cycling interval, electrical

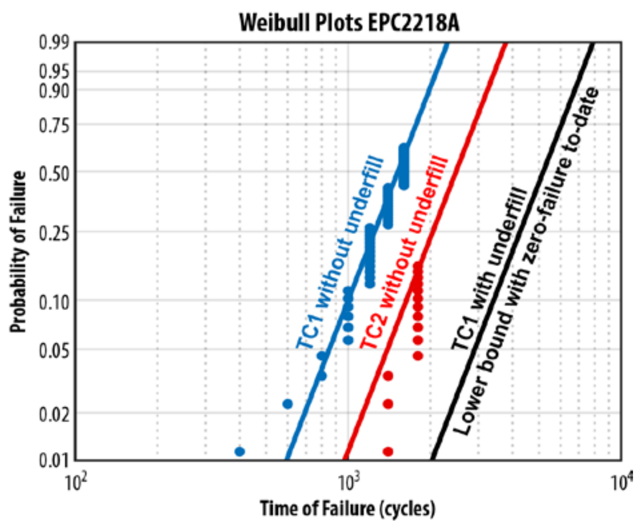


*Figure 4: Weibull plots of temperature cycling results for EPC2218A.*

screening was performed, where exceeding datasheet limits was used to determine failures. Physical cross-sectioning and SEM inspection followed to further examine the electrical test failures. Solder joint cracking was found to be the single failure mode throughout all failures analyzed.

Figure 4 shows Weibull failure distribution of the temperature cycling results. The failure distribution was analyzed using a 2-parameter Weibull distribution for each temperature cycling leg using maximum likelihood estimation (MLE) [9]. The fits are indicated by solid lines in the graph.

From TC1 (−40°C to 125°C) to TC2 (−40°C to 105°C) without underfill, a strong acceleration was found. Two primary failure mechanisms are responsible for the significant acceleration. First, the difference in ΔT of two testing conditions leads to the acceleration of the solder fatigue failure mechanism [10,11]. However, this failure mechanism alone is insufficient to explain the acceleration observed. A second mechanism, creep solder joint failure mechanism, is introduced. Creep is believed to be the main effect during the dwell period at the hot temperature extreme [11-16].

After 1800 cycles of TC1 (−40°C to 125°C) with underfill, no failures have been found to-date. This shows that applying proper underfill material can significantly improve the thermo-mechanical capability of the chip-scale package devices. Based on the test results, a more general TC lifetime model was developed.

$$N = A \cdot f^{-\alpha} \cdot \Delta T^{-\beta} \cdot \exp\left(\frac{E_a}{kT_{Max}}\right) \qquad \text{equation (1)}$$

Where is the number of cycles to fail, $f$ is the cycling frequency and $\alpha$ is the frequency exponent, at -1/3 [12-17]. This frequency term is to describe the frequency of usage. $\Delta T$ is the range of temperature change and $\beta$ is the temperature exponent. Since SAC305 solder is used, $\beta$ is 2.0 [12-17]. The last variable is an Arrhenius term that models the creep failure mechanism, where $E_a$ is the activation energy, $k$ is the Boltzmann constant, and $T_{max}$ is the maximum temperature in Kelvin units (°K). By comparing the mean-time-to-fail between TC1 and TC2 without underfill, the $E_a$ was calculated to be 0.2 eV.

In real world application, solar panels experience varying temperature profiles. As a result, a more general lifetime model is warranted to include all mission profiles. An empirical equation is therefor developed in equation 2.

$$\frac{1}{N_{Total}} = \frac{a}{N_{\Delta T_a}} + \frac{b}{N_{\Delta T_b}} + \cdots + \frac{i}{N_{\Delta T_i}} \qquad \text{equation (2)}$$

Where $N_{Total}$ is the total calculated lifetime of number of cycles, $N_{\Delta Ti}$ corresponds to cycles-to-failure for the condition of $\Delta T_i$ and $i$ is the fraction of time the device was operational under $\Delta T_i$ .

Now let's examine a real-world example to estimate the lifetime by applying different mission profiles. The first assumption is that the solar panels are installed in Phoenix, Arizona, where solar is well-suited for the climate that has long sun exposure, but also demands stringent thermo-mechanical requirements. Using the year 2023 forecast as an example [18] and then adding 30 °C of device self-heating on top of each ambient mission profile, the projected lifetime of EPC2218A with underfill material at 0.1% failure rate is estimated to be approximately 42 years due to temperature cycling stress.

**Conclusions:**

Based on the discussions above, making use of EPC's 100 V rated generation 5 product family with underfill for real-world solar application vastly reduces thermal cycling reliability risk while giving excellent lifetimes that significantly exceed the expected 25 years.

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