Reliability of Advanced Power Modules for Extended Maximum Junction Temperatures
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In the early days of power electronics, lifetime assessment was restricted to maximum load conditions and generous margins. Today, application specific mission profiles, which reflect the dynamic behavior of the load and of the cooling system, are evaluated to estimate the lifetime of power electronic systems. This approach improves the prediction quality, but it requires better and more refined lifetime models. How such a lifetime model can be derived for advanced power modules will be presented.

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The demand for extended maximum junction temperatures above 150°C in power semiconductor components gained growing attention in the beginning of this century driven by 3 major factors: the high coolant temperatures in hybrid electrical vehicles, the potential of wide band gap devices to operate at much higher temperatures, and the enhanced current capability of silicon devices when operated at junction temperatures up to 200°C. This required a considerable increase in lifetime of the package, because a component must fulfill the same lifetime expectation at extended junction temperature to be acceptable for applications. Depending on the exact operation conditions and the lifetime model applied, an increase in lifetime of a factor of 5 is necessary for each 25°C increase of the maximum junction temperature as a rule of thumb, resulting in a required lifetime increase of a factor 25 for 200°C maximum junction temperature.

The progress in the last decade has delivered improved interconnection technologies with the potential to reach this target. Ag diffusion sintering and transfer liquid phase bonding are candidates for replacing the traditional solder die attachment. And Cu wire bonds or Al cladded Cu wire bonds are enhancing the lifetime of the top side chip contact considerably compared to the classical Al wire bonds.

When such improved technologies are introduced along with first lifetime test results to demonstrate their potential, the demand for a consistent lifetime model arises to evaluate the advantage for specific applications based on mission profiles. However, the generation of experimental data to establish a new lifetime model for improved technologies requires a test vehicle from controlled series production and years of lifetime testing.

The following discussion will present a power cycling lifetime model for an advanced power module named SKiM63. This module, which was introduced to the market in 2008, is a 100% solder-free design [1]. The silicon chips are attached to the DBC substrates by Ag diffusion sintering, thus eliminating solder fatigue. The top side contact of the chip is connected by 300μm Al wire bonds with improved bond loop geometry. Mechanical fatigue tests on heavy Al wire bonds had already shown the increase of lifetime by an enhanced aspect ratio, which is the ratio of wire bond loop height to the distance between bond stitches [2]. However, this improvement potential was limited by solder fatigue in the classical module design [3].

The SKiM63 module design is based on the pressure contact technology and thus does not contain a base plate. This feature improves the temperature cycling capability by eliminating the stress between the ceramic substrate and the base plate. Tests have proved a cycling capability beyond 1000 cycles in a two chamber temperature cycling test between -40°C and 125°C [4]. The design without base plate also eliminates potential fatigue between substrate and base plate in active power cycling. The load contacts are formed as bus bars with multiple pressure contacts to simultaneously establish the electrical contacts as well as the thermal contact between substrate and heat sink. Spring contacts are implemented to transmit the control and auxiliary signals to the substrates. An explosion view of the SKiM63 is shown in Figure 1.

This SKiM63 module was selected as a vehicle to establish the first empirical power cycling lifetime model for sintered devices with Al wire bonded top side contacts. Since solder fatigue is completely eliminated, only wire bond heel cracks and wire bond liftoff are found as failure modes. For a consistent lifetime model, all important parameters of the power cycling tests had to be investigated. Variation of these parameters allows to model their influence on the lifetime in real applications.

Figure 1: Explosion view of the SKiM63 module architecture
It is known from the first lifetime models that the magnitude of the temperature swing has a significant impact on the component lifetime during power cycling. However, degradation of the device contacts can affect the thermal resistance and/or the electrical contact resistance and thus can lead to an increase of the temperature swing during the test. Therefore, the control strategy is important for the evaluation of the test result [5]. Some authors propose to control the test conditions to maintain constant losses or even constant temperature swings. Since these control strategies are not relevant for most applications, all power cycling tests presented here were conducted with constant current pulses and constant pulse length $t_{\text{on}}$ and pause length $t_{\text{off}}$. The characteristic temperature swing is always the value obtained at the beginning of the test after stationary thermal conditions are reached.

In the power cycling test program the temperature swing $\Delta T_j$ varied between 64K and 113K and the number of cycles to failure $n_f$ observed by experiment ranged between 31,000 cycles and 7.7 million cycles (Figure 2). The medium junction temperature $T_{jm}= T_{j,\min} + \frac{\Delta T_j}{2}$ was varied between 32.5°C and 122°C to investigate the impact of the Arrhenius term (Figure 3). It should be pointed out that some test were also performed with minimum junction temperatures below 0°C to include the effect of cold start situations. The aspect ratio of the Al wire bond was selected between 0.19 and 0.42 to analyze the potential of wire bond geometry optimization (Figure 4). The general form of the lifetime model is based on the well-known LESIT model [6], which determines the number of cycles to failure $n_f$ from a fundamental scaling factor $A$, a Coffin-Manson term for the impact of the temperature swing $\Delta T_j$ and an Arrhenius term for the impact of the medium junction temperature $T_{jm}$. Two additional new factors were added to the model to account for the impact of the wire bond aspect ratio $ar$ and for the impact of the power pulse duration $t_{\text{on}}$. Earlier investigations had shown that the advantage of higher wire bond loops is more pronounced for smaller temperature swings, so that the exponent of this parameter is assumed to be a linear function of the temperature swing. The impact of the power pulse duration $t_{\text{on}}$ is described by a function, which approaches an asymptotic value for increasing pulse durations, but reflects the increasing number of cycles for short (~1s) and very short (~0.1s) pulse durations.

Finally, a factor was added to account for differences found between tests on IGBTs and diodes. As was already reported by Bayerer et al. in the CIPS2008 model [7], the voltage class of the devices has an impact on the power cycling lifetime. This is in fact attributed to the thickness of the silicon devices used for different voltage classes. In the experimental data base, 1200V Infineon IGBTs with a device thickness of 120μm were implemented together with 1200V CAL diodes with a thickness of 260μm. According to the
CIPS2008 model, an increase of device thickness from 120µm to 260µm would result in a lifetime reduction to 59%. The experimental determined diode factor of ~0.62 corresponds well with this prediction. However, since no further variation of device thickness was integrated in the test data base, only a simple scaling factor for the diode test was applied.

\[ n_f = \frac{\Delta T_j}{T_{j,m}} = \frac{\Delta T_j}{T_{j,m}} \cdot \frac{C + T_{j,m}}{C + 1} \cdot \exp \left( -\frac{E_n}{k_B T_{j,m}} \right) \cdot f_{\text{diode}} \]

The coefficients for the SKiM63 lifetime model were determined by a least square fit to the experimental test data set. The results are displayed in Table 1. A comparison between the experimental results and the model prediction is shown in Figure 6. For this illustration, the SKiM63 lifetime model prediction for each test parameter set was sorted for increasing number of cycles to failure and displayed together with the experimental results. As expected for a least square fit procedure, some experimental results are higher and some are lower than the predicted lifetime. Therefore, an additional margin factor of 0.8 is added to the final SKiM63 lifetime model. As is discussed in more detail in [8], this margin factor represents a module failure rate of 15% or a survival probability of 85%.

![Figure 6: Comparison of the model prediction and the experimental power cycling results](image)

**Table 1: Parameter of the SKiM63 lifetime model**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Experimental data range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.4368E14</td>
<td>64K ≤ ΔT_j ≤ 113K</td>
</tr>
<tr>
<td>α</td>
<td>-4.923</td>
<td>0.19 ≤ ar ≤ 0.42</td>
</tr>
<tr>
<td>β_1</td>
<td>-9.012E-3</td>
<td>0.97 ≤ t_on ≤ 63s</td>
</tr>
<tr>
<td>β_0</td>
<td>1.942</td>
<td>0.97 ≤ t_on ≤ 63s</td>
</tr>
<tr>
<td>C</td>
<td>1.434</td>
<td>32.5°C ≤ T_{j,m} ≤ 122°C</td>
</tr>
<tr>
<td>γ</td>
<td>-1.208</td>
<td>113K ≤ ΔT_j ≤ 113K</td>
</tr>
<tr>
<td>E_n [eV]</td>
<td>0.06606</td>
<td></td>
</tr>
<tr>
<td>f_{diode}</td>
<td>0.6204</td>
<td></td>
</tr>
</tbody>
</table>

In Figure 7, characteristic lifetime curves for the SKiM63 are shown. With the margin factor of 0.8 and a wire bond aspect ratio of 0.31, the number of cycles to failure \( n_f \) is shown as the function of temperature swing \( \Delta T_j \) for different load pulse durations \( t_{on} \).

This new lifetime model now allows to calculate the estimated lifetime for application specific mission profiles. Therefore it is necessary to extrapolate the lifetime curves to smaller temperature swings outside the area of tested parameter variation. This is a general problem of lifetime estimation for power modules, since power electronic applications demand for lifetimes of 20 years and more. We must be aware, that such extrapolation cannot be validated by experiment. Even if a power cycling test would be started today for such a parameter combination, the test results received after two decades would only be of historical interest, since the power device generations will probably not be available anymore. This general limitation of empirical models can only be solved by physics based fatigue models, which could be used to verify the relative increase in lifetime for reduced stress.

![Figure 7: Lifetime curves for the SKiM63 module with a margin factor of 0.8 as a function of \( \Delta T_j \) for different load pulse durations](image)

From Figure 7 we can estimate the lifetime of a SKiM63 module for a temperature swing of 110K at a medium temperature of 115°C, i.e. for a temperature swing between 60°C and 170°C. For a power pulse duration of 1s we obtain 5.8·10^4 cycles to failure, for a power pulse duration of 10s we can still expect 3.6·10^4 cycles to failure. For a classical industrial module with a copper base plate, solder chips and non-optimized Al wire bonds, a lifetime of 3.5·10^3 cycles to failure can be expected. This comparison shows, that the SKiM63 module is suitable for extended junction temperatures up to 175°C.

For an increase of the maximum junction temperature to 200°C, further improvements of the chip top side contact are required. Cu wire bonds or Al cladded Cu wire bonds, but also sintered Cu sheet contacts are potential candidates, which have proved their potential in first demonstration tests. However, no series products with these technologies are available today and it will take years to perform the power cycling tests to establish a consistent lifetime model for power modules with rated maximum junction temperatures of 200°C.

**References:**


