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Field lifetime estimation of power modules using Active Power Cycling

Executive summary

The design of power electronics modules and power packages is heavily influenced by thermal concerns. New substrate materials, thinner and thermally more conductive attachment materials are used to decrease the thermal resistance of a given module. When a new material or technology is applied, its reliability has to be tested thoroughly before the module can be considered for production.

The reliability or the expected lifetime of the module can be expressed as the number of temperature or power cycles the system can withstand. These numbers however make more sense if they can be linked to the foreseen lifetime of the application where the power module will be used. Under multiple pressures, including the imperative to keep costs down, power module design no longer aims to achieve the maximum possible lifetime, but rather it is determined by the application itself as a compromise between reliability and cost, weight, volume, etc., the objective being to minimize these factors while ensuring the necessary lifetime for the application with a high degree of confidence.

Contents

Introduction

In this whitepaper we discuss how active power cycling measurements can be used to help designers to predict the expected lifetime of power modules in an application, taking into account how the parts will be used. The individual steps involved are summarized.

Power electronics modules, such as IGBTs or MOSFETs are used ever more widely in applications like automotive and railway traction, power generation and power conversion. The most critical design requirement for these packages in the application is their time-to-failure. High reliability and safety critical target applications demand power electronics modules that will be long-lasting given the demands of the application, and the application environment [1].

The major contributor to wear out is the thermo-mechanical stresses arising within the structure from the different coefficients of thermal expansion of the different materials. These stresses are induced by changes in temperature within the module, which in turn are caused by the varying power profile the devices are exposed to.

Temperature changes within different parts of a power module, and rate of change, are accelerating factors for the dominant failure mechanisms. These include degradation of the heat conduction path, such as die attach delamination or cracking within the base-plate solder; or deterioration of the bond wires [2]. The most straightforward way to limit thermally induced failures is to limit the junction temperature excursion during operation, by minimizing the package's thermal resistance.

The module's thermal resistance can be evaluated by thermal transient testing [3, 4]. This can reveal not only the total thermal resistance for the package, but the partial thermal resistances of the constituent parts, including any spreading resistances as the heat passes from the die down to and through the baseplate.

Accelerated testing strategies

The two commonly used lifetime tests for power modules are Temperature Cycling and Active Power Cycling. Both test methods introduce a thermal load by periodically changing the device temperature, but are fundamentally different.

In Temperature Cycling the device is unpowered. Temperature change is achieved by placing the part in a thermostatically-controlled environment such as an oven, which both heats and cools the part. Hence the heating is externally applied. The heating and cooling rates are relatively slow, of the order of several minutes, so the temperature within the part remains fairly uniform as it heats and cools. Temperature Cycling is mainly used to evaluate solder joints between the Direct Bonded Copper (DBC) substrate and the module's baseplate.

By contrast, in Active Power Cycling the part is heated internally, by passing current through the semiconductor device, thereby using it as a dissipating element. Heat is dissipated at the same location heat is dissipated during normal operation, resulting in a temperature distribution within the part that is similar to the application. As the heating is localized, significant temperature gradients result. These can be controlled by changing the rate of heating by changing the supplied current.

By using a low current and long heating and cooling times, Active Power Cycling can also be used to heat the solder joints between the DBC and module baseplate. Normally, Active Power Cycling uses shorter cycle times with heating times of just a few seconds. High currents are used to elevate the chip junction temperature in order to stress the bond wires and die attach solder joint. Hence the long term reliability of a package can be comprehensively investigated using Active Power Cycling. As temperature variations within the thermal structure trigger the various types of degradation, the effect on electrical parameters such as collector-emitter (drain-source) voltage drop or gate leakage current can be observed at each cycle. Degradation in the thermal stack can also be monitored by performing transient thermal testing periodically. The combination of the two allows reliability engineers to fully assess the evolution of the various interrelated damage mechanisms within a module.

Approach to lifetime prediction

Active Power Cycling testing cannot be done at the operating frequency of the device. Parameters affected by the degradation process cannot be measured accurately during high-speed switching. A further problem is that testing parts under operational conditions would mean that the lifetime tests themselves would approach the expected lifetime of the part, with little scope to accelerate the testing time. However, such tests can be used to determine the rate and magnitude of junction temperature change the part will experience in the application environment.

During normal operation the frequency with which power electronics devices are switched is constant. However, the proportion of the cycle that the part is on (fill factor) varies. When the part is off it does not dissipate any power. When it is switched (either on or off) there is a discrete switching loss, which varies with the switching frequency, and when it is on it has a lower constant conduction loss. Due to the thermal inertia of the structure the effect of these changes in heat dissipation within a cycle are negligible, with the thermal structure effectively experiencing the time-averaged amount of heat dissipated over the cycle.

Once this information is known, the part can be tested by opening the device and applying a constant current through it, thereby using the conduction loss to replicate the time-averaged heating experienced in operation. This can be accelerated by applying a higher cur-

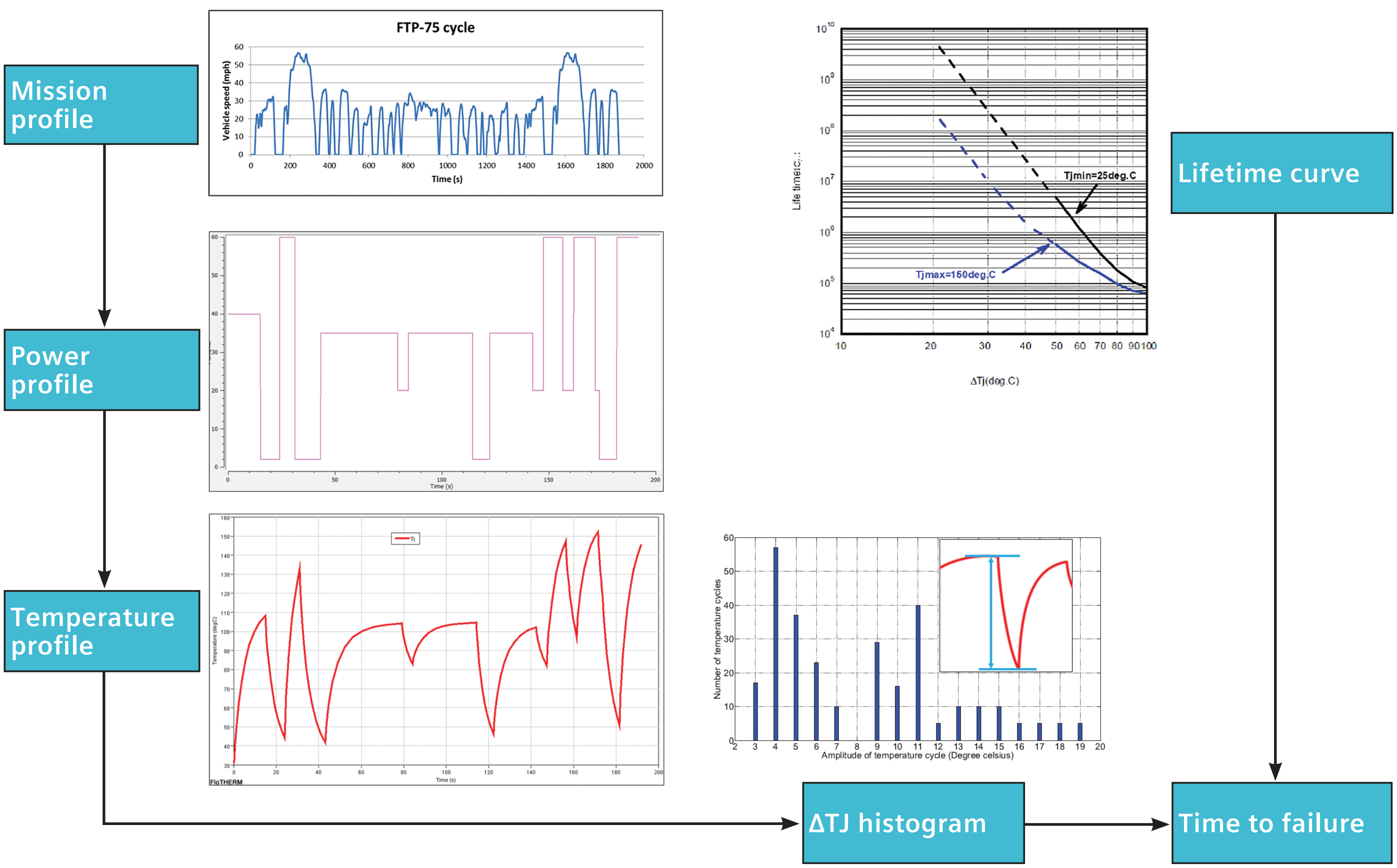

Figure 1: Overall process for estimating system time-to-failure.

rent, and the power-on and power-off times can be adjusted to give the desired junction temperature swing.

Prediction of the expected lifetime in the final application is a complicated task. It requires knowledge of its operational duty cycle, in other words its 'mission profile' [5]. Having this information, the optimal 'power profile' can be calculated, which is required to drive the module to its desired operating state within the equipment being designed.

Having the proper description of the input power profile as well as the mechanical construction of the package and the targeted thermal environment, transient thermal simulations can predict the temperature variations in the device junction during the operation of the final system [6]. The different temperature changes have a different impact on the lifetime of the package. 'Lifetime curves' can be accurately prepared based on the active power cycling data collected at a number of pre-set junction temperature swings [7].

Description of the process

The lifetime of a power module depends not only on the devices it contains (IGBTs, MOSFETs, diodes, etc.), the packaging design and manufacturing, but also a host of external factors. Besides the thermo-mechanical design of the module and the environmental conditions (temperature, humidity, and vibration) that the device has to withstand, the heat generated by the device itself and the characteristics of the cooling system are two of the most important factors determining the lifetime.

Defining the mission profile

In order to describe the typical load on a module, a specific characteristic task has to be described that the module has to fulfil repeatedly during its lifetime. This mission profile is typically a time function of a variable that is directly related to the load the module experiences. The most straightforward, but rarely available, mission profile is P(t) - the power dissipation as a function of time for each device in the IGBT module, that can be used directly for further calculations.

It is more usual to define the mission profile as a time function of the state of the whole system and then calculate P(t) using a mechanical and electrical model of the system. In the automotive industry the typical use cases for a vehicle provide v(t) – the velocity vs. time profiles defined for standard fuel economy tests. The United State Environmental Protection Agency's Urban Dynamometer Driving Schedule (UDDS) driving profile is taken to represent city driving conditions for light duty vehicles. This is shown in figure 2.

Based on the mechanical model of an electric vehicle, the load on the electric motor, and finally the power loss on the driving circuits, can be calculated to give the P(t) profile.

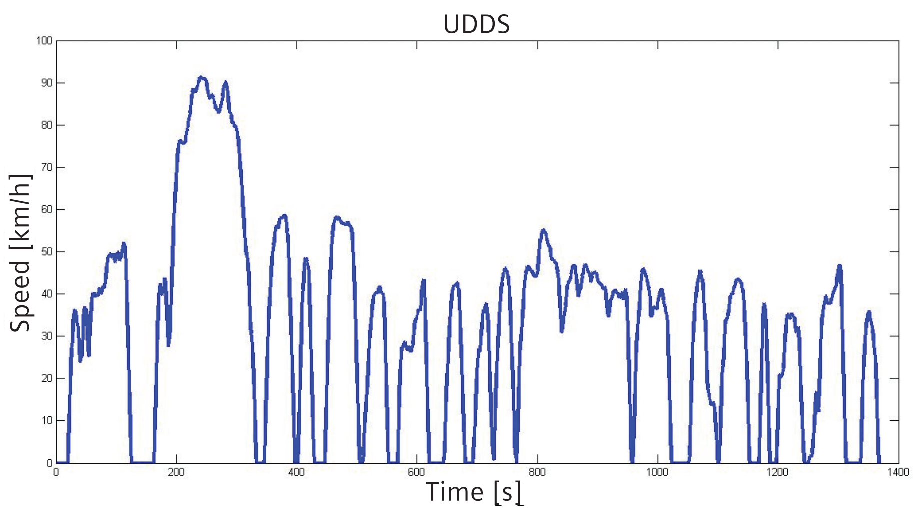

Figure 2: Urban Dynamometer Driving Schedule (UDDS).

Determining the thermal load

The most frequent cause of failure of a power module is the cracking or delamination of different layers due to the thermally-induced stresses that arise from periodic cycling. The magnitude of the thermal stress is proportional to the temperature change induced by the power dissipated by the semiconductor devices. Consequently the next step is to turn the P(t) mission profile into a temperature vs. time function. As the dissipation is not constant, but rather a complex time function, the temperature function cannot be analytically calculated either. Most modern 3D thermal simulators can do transient simulations, and there are some that can handle arbitrary dissipation profiles as well. Even in case of quite complex package structures a detailed 3D model can be built, as shown in figure 3.

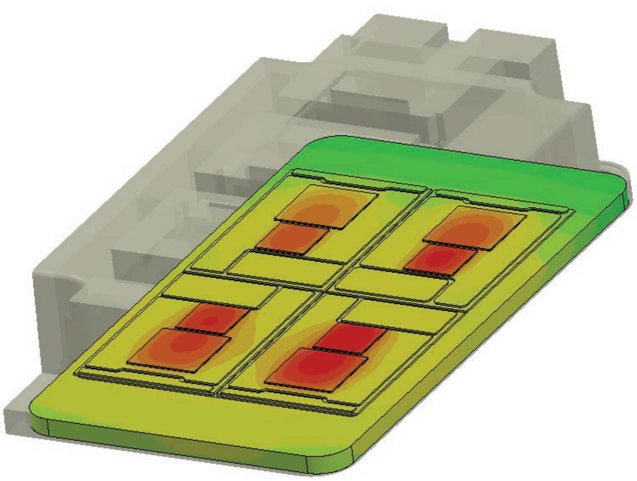

Figure 3: Detailed thermal model of IGBT in Simcenter Flotherm™ XT.

Before the simulation model can be used to support reliability studies it needs to be calibrated so the transient behaviour exactly matches with experimental results [9]. The importance of accurate control of parameters affecting the lifetime during the experiment should not be underestimated. Figure 4 shows active power cycling tests on identical IGBT samples to give a controlled change in junction temperature over the cycle. When the junction temperature change was increased from 110°C to 120°C (a 9% increase), the lifetime was shortened from ~57500 cycles to ~39000 cycles (a ~37% decrease).

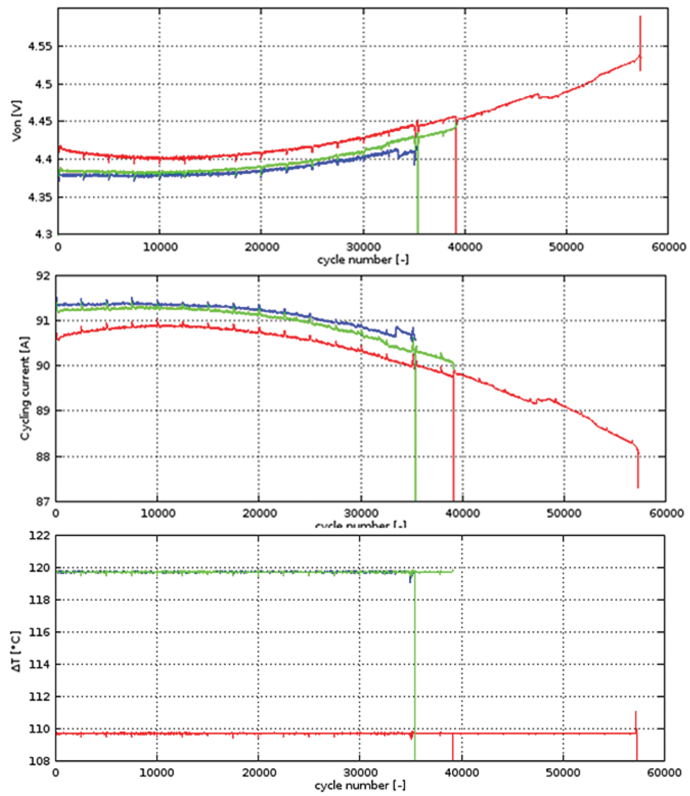

Figure 4: IGBT lifetimes resulting from a 10C difference in junction temperature swing under power cycling.

As the lifetime is highly dependent on the junction temperature swing, it follows that the simulation model must be able to predict the junction temperature swing resulting from the load profile P(t) with high accuracy if it is to be used for lifetime prediction. A significant challenge when building high-fidelity thermal models of chip packages is ensuring that the models incorporate the correct thermal properties for the materials of construction and thicknesses of bond lines and soldered interfaces, such as the die attach layer. As a result, the simulated thermal response to a power step will be different to that observed in practice.

Precise calibration of the model requires highly accurate test data, having a high resolution in both temperature and time, makes it possible to convert the temperature time response into a Structure Function, showing the cumulative thermal capacitance vs resistance along the heat flow path. Figure 5 compares the thermal response of an IGBT modeled in Simcenter Flotherm™ [10] with the physical part measured with Simcenter T3STER™ thermal characterization hardware, Simcenter T3STER [8], as the model is initially set up (left) and after calibration (right). It is important that all parts of the curves match with high accuracy to ensure that all time constants along the heat flow path within the package are correct, ensuring the correct temperature rise is predicted irrespective of the length of the applied heat pulse.

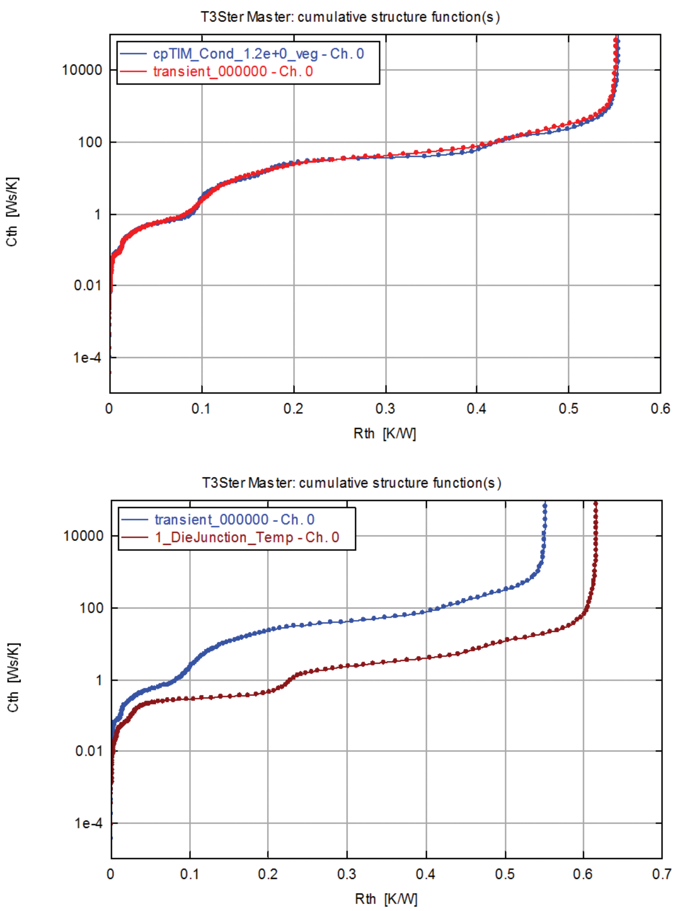

Figure 5: Structure functions for IGBT before and after model calibration.

Figure 6 shows a short section of the temperature-time function of a single chip in an IGBT module obtained by thermal simulation using a detailed model of the structure after calibration using the Structure Function generated by Simcenter T3STER.

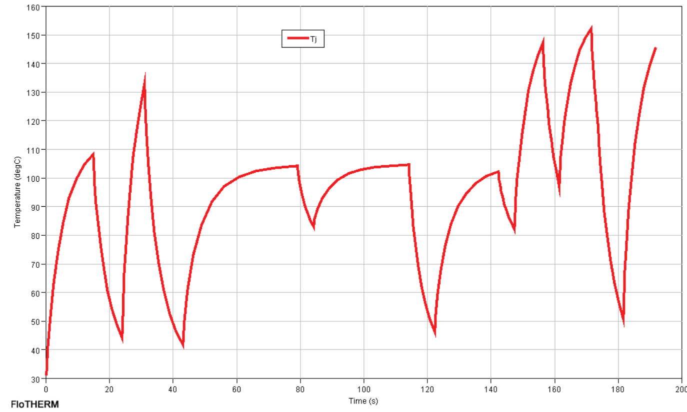

Figure 6: Simulated IGBT chip temperature for a given power profile.

After the temperature curves corresponding to the junction temperature of the chips within the module have been generated, the local minimum and maximum values of the function need to be identified, and the temperature change calculated. The number of occurrences of each degree of temperature change (to within ± 0.5°C) are counted and their distribution plotted as a histogram. An example histogram is shown in figure 7.

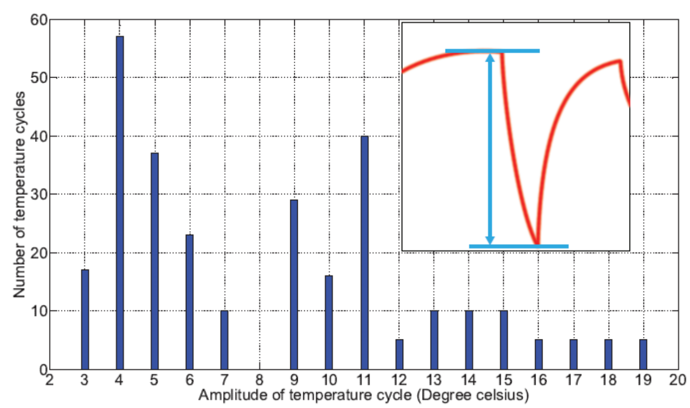

Figure 7: Histogram of junction temperature swing.

This histogram has two roles. First, it helps in selecting parameters for power cycling tests. Second, normalizing the number of occurrences of each temperature cycle change by the total number of temperature swings, gives weighting factors for the different magnitudes of temperature change that can used later for the total lifetime calculation.

Module lifetime curves

In the above sections we used calculations and simulations to find what temperature changes are stressing the devices. To investigate the lifetime of a device at a certain load, there is no better way than using actual lifetime tests, for example using Simcenter POWERTESTER™ 1500A [11].

In order to be able to calculate the proper lifetime curves that eliminate the effect of random failures, a statistically significant amount of data is needed. This requires a significant number of experiments. As the lifetime experiments are time-consuming, the test parameters have to be chosen carefully and maintained accurately during the whole duration of the test. Some of the most important parameters are the temperature swing, the maximum temperature achieved and the time period of the cycle.

The power cycling has to be continued until a device failure occurs. The outcome of the test is the number of cycles elapsed until device failure (Nf) for a certain set of test parameters. It is practically impossible to test the device at all possible load conditions; however, by testing the device at a number of characteristic loads, the lifetime may be approximated for all other loads by curve fitting (Figure 8).

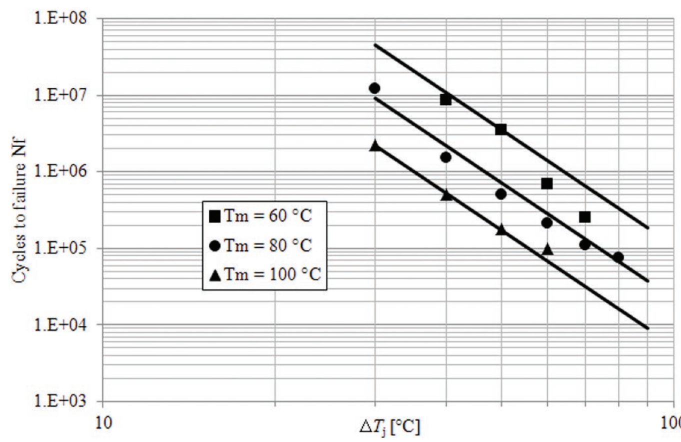

Figure 8: Experimental results and fitted failure models.

Developing failure models

There are number of models that take into account many more parameters, but the base of all these models is the well-known Arrhenius model that was primarily elaborated to describe chemical reaction rates:

$$N_f = e^{\left(\frac{E_a}{k_b \cdot T}\right)} \quad (1)$$

Where E_a is the activation energy, k_b is the Boltzmann constant, and T is the absolute temperature. This equation only takes into account the mean temperature. In order to take into account the empirical fact that the larger the temperature swing is, the shorter the lifetime will be, a ΔT_j term can be added to the formula [10], yielding the thermo-mechanical stress model:

$$N_f(\Delta T) = A \cdot (\Delta T_j)^{\alpha} \cdot e^{\left(\frac{E_a}{k_b \cdot T}\right)} \quad (2)$$

Where ΔTj is the junction temperature change, and A and α are coefficients that are calculated using curve fitting.

Despite the fact that this model can give a fair approximation to the failure rate, it is also known that the cycle time also affects the lifetime. The same junction temperature change can be achieved either with a short high-power heating pulse, or a longer lower power heating pulse, but the choice influences the lifetime.

If the heating power is high, some features in the package do not have enough time to heat up during this short time. Shorter heating pulses primarily stress the chip itself, the die-attach and the wire bonds. If the heating power is lower, requiring a longer heating time to achieve the same temperature change, the heat can spread further down into the DBC substrate and base plate, so the change in the temperature distribution within the package is quite different, despite both producing the same junction temperature swing. Longer pulses therefore stress solder layers further way from the junction. To account for this, a further term, fβ is added to the above formula resulting in the Norris-Landzberg model [12]:

$$N_f(\Delta T) = A \cdot f^{\beta} \cdot (\Delta T_j)^{\alpha} \cdot e^{\left(\frac{E_a}{k_b \cdot T}\right)} \quad (3)$$

Where f is the cycle time and β is another coefficient calculated using curve fitting. A similar model is reported to be used by some companies manufacturing power modules, e.g. in one of their application notes, Infineon published a calculation in which they are using a similar expression for lifetime modeling, with the slight difference being that they take into account only the heating time rather than the whole cycle period [13]. There are also more complex models available in the literature, that take into account even more parameters (e.g. electrical load conditions: current and voltage), however those cannot increase the accuracy of the prediction, because these parameters are not regulated in the same way during operation as they can be during reliability testing.

Calculating service lifetime

In the previous section it was shown how the lifetime of a device can be modeled based on the experimental power cycling results, but the resulting Nf lifetime only predicts the device lifetime at a certain constant load (at which it was calculated).

To calculate the expected total lifetime of the device, taking account of the variable load caused by the selected mission profile, the overall effect of the different load conditions has to be estimated. A commonly-used equation to sum the aging effects from different loads that arise in parallel is the following [15]:

$$N_{f\_sum} = \frac{1}{\sum_{k=1}^{n} w_i \frac{1}{N_{f\_i}}} \quad (4)$$

where N_{f_sum} is the number of times the load corresponding to the mission profile can be applied to the device until it is expected to fail, and the wi are the weight factors calculated from the histogram.

Finally, if we multiply this aggregated cycle number N_{f_sum} by the duration of the mission profile, the operation lifetime can be calculated:

$$t_{operation} = N_{f\_sum} \cdot t_{cycle} \quad (5)$$

Conclusion

Mission profile based power module design is becoming the state-of-the-art design method in the power electronics industry. To get an accurate prediction of the lifetime of a thermal system, a number of parameters have to be known, such as the mission profile, the mechanical properties of the system and the reliability characteristics of the power modules used. The accurate definition of these parameters, combined with calibration of the thermal model, allows the proper calculation of the temperature changes in the power device's junction using numerical methods. This information can then be combined with the data in the lifetime curves to give a fair lifetime prediction. Predicting the lifetime of a system based on a given mission profile may give power module designers greater confidence in their time-to-failure estimates, supporting new product introductions, and cost reduction efforts efforts, and opening up new applications and cooling solutions.

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