Thermal Interface
A Key Factor in Improving Lifetime in Power Electronics

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Abstract

Increased demand in lifetime is an ongoing trend especially in applications like e-mobility or renewable energies. Likewise, the demand in power density is increasing as well, leading to contradicting effects. As higher power densities lead to increased temperature levels, higher temperatures result in higher stress levels thus threatening to reduce the lifetime. Though new developments in power electronic components target to increase the lifetime [1][4], thermal management becomes more important to fully exploit the benefits fr0m these modern devices. The present paper focuses on the influence of thermal interface materials as a key parameter in thermal management. Measurements and test results are presented showing the influence to both, thermal and lifetime situation.

1 Introduction

Two basic things are most common to semiconductors in all power electronic applications:

- Switching and forward losses lead to temperature increase
- Temperature swing in form of active and passive thermal cycles leads to stress limiting the lifetime

While power cycling is an effect taking place in the range of seconds, thermal cycling is related to longer periods of time. Though the two effects trigger different failure mechanisms, both are characterized by the temperature swing, given in Kelvin, and the maximum temperature reached. A lifetime prediction for a specific design can best be done based on an accurate load profile. Detailed knowledge about load current development, cooling conditions and power semiconductor itself is mandatory to precisely calculate the temperature and temperature swing in the setup, leading to a reliable statement about the expected lifetime.

2 Simplified thermal model

To evaluate the thermal performance of a given power electronic component based on a load profile, a simplified model as depicted in figure 1 becomes helpful.

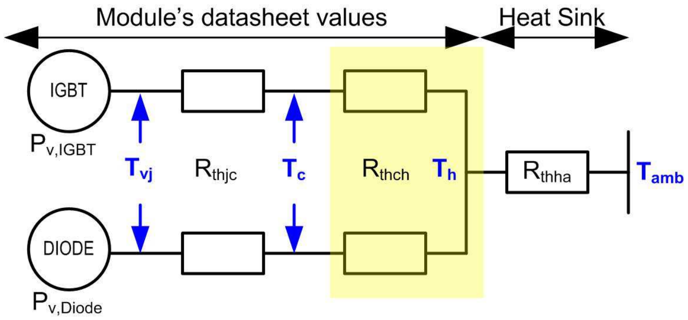

Figure 1: Simplified thermal model of a power electronic setup

The model includes the two sources for heat, the IGBT and the diode die. The dies as a source of losses drive a certain power P_v through the chain of thermal resistances towards ambient. In case the resistances are known exactly, the junction temperature can be calculated from the according values:

$$T_{vj} = T_{amb} + P_v \cdot \sum R_{th} \qquad (1)$$

Up to the base plate, the module's construction is responsible for the thermal transfer and therefore defines the thermal performance. The shaded box in figure 1 introduces the thermal path from the module's case to the heat sink R_{thch}. In simulations and calculations, this value is often spuriously considered to be the datasheet value of a thermal grease defined by its bulk conductivity and layer thickness. Experimental results however substantiate that this is a misleading approach.

3 Evaluating the thermal situation

Today, converters in industrial applications are designed to last for at least 10 years or 80.000 operating hours. In windmill applications 20 years are considered. Traction and automotive applications are even more demanding. Reworking the inverter in these fields just because a malfunctioning thermal interface was detected is an expensive and therefore highly unwanted option. A thermal interface material dedicated to power electronic has to cope with these demands.
During the development of a new thermal interface material (TIM) especially dedicated to power electronics, returned material analysis was done on power modules that were destroyed during operation due to exceeding the temperature limits. The analysis also focused on the question what kind of TIM was used. However, first investigations done to pinpoint the failure mechanisms of TIM were inconclusive. It turned out to be difficult to get reliable information in short-term tests. As a consequence, a whole set of reliability tests was done on specimen consisting of power modules mounted to a commercially available heat sink in conjunction with TIM. Environmental tests done included:

- High Temperature Reverse Blocking (HTRB): DUT is stored at 85^oC with reverse voltage applied. A change in leakage current can be used to determine damage to the device
- H3TRB, a test that applies humidity $\geq 85\%$ at temperatures $\geq 85^oC$ with reverse voltage applied
- H2S, Corrosive gas tests with sulfurus atmosphere

All these tests were passed without noteworthy changes to the thermal capabilities of the tested setups. Active Thermal Cycling as an electrical stress test followed. The modules were periodically heated by current flowing through the IGBT. 100.000 cycles were done. Using a thermographic camera, chip temperatures in a test setup were recorded. The setup consists of three blocks, each carrying two power electronic modules mounted to a common forced air cooled heat sink. The test included six final TIM candidates chosen from more than 80 alternatives that were initially considered [2]. Due to series connection, both modules on one block carry identical currents during power cycling stress. A typical measurement result is depicted on the left side of figure 2.

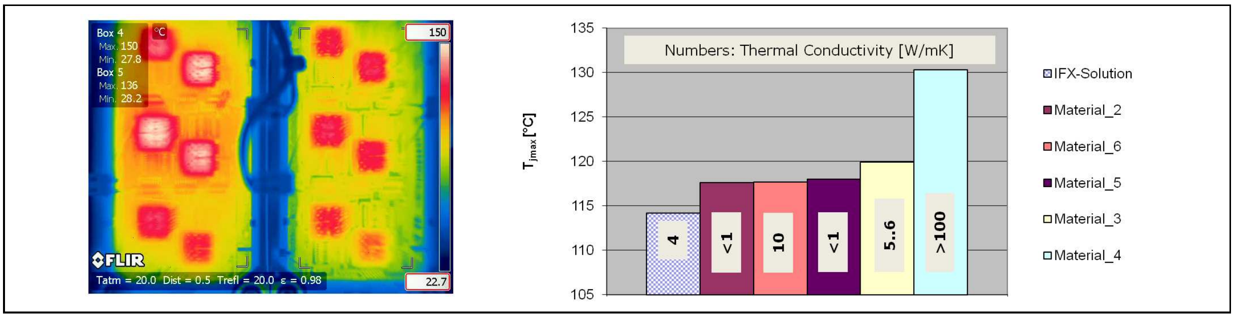

Figure 2: Thermographic measurement of chip temperatures using different thermal interfaces along with data gathered from six different materials

Of utmost interest is the maximum temperature reached within the modules. The measurement equipment allows to mark the area to be investigated and determines the maximum temperature within this area; four measurements are taken per square milimeter. The diagram on the right side of figure 2 summarizes the thermal results gathered from this experiment in a 100.000 cycle test run. It can clearly be seen that there is no relation between the datasheet value given for thermal conductivity and the chip temperature reached in the experiment.
A cycling test like the one conducted gives a good first insight whether or not a material produces an acceptable result in thermal aspects. In addition it allows to observe mechanical aspects. TIM may not be pumpt out from below the modules as a consequence of thermal mechanical movement. It may as well not start to flow in vertically mounted conditions if heated to common operating temperatures and in no case should seperate due to capillary effects caused from the heat sinks microscopic surface structure. All these effects can easily be investigated in the setup described. However especially for power electronics, a reliable statement regarding long-term stability of the material is mandatory.
It is of great importance for the lifetime calculations, that the die's temperature at a given point of operation remains at constant levels throughout the predicted lifetime. The final test conducted was related to higher temperature levels. In High Temperature Storing Test (HTS) the modules are subjected to 125^oC for a duration of 1000 hours. The initial thermal behavior is recorded and once a week the measurement is repeated.
If a change in temperature occoured within these tests it can without a doubt clearly be related to degrading of the thermal interface material. Different, partially unexpected effects became visible. The test results for four materials are depicted in figure 3.

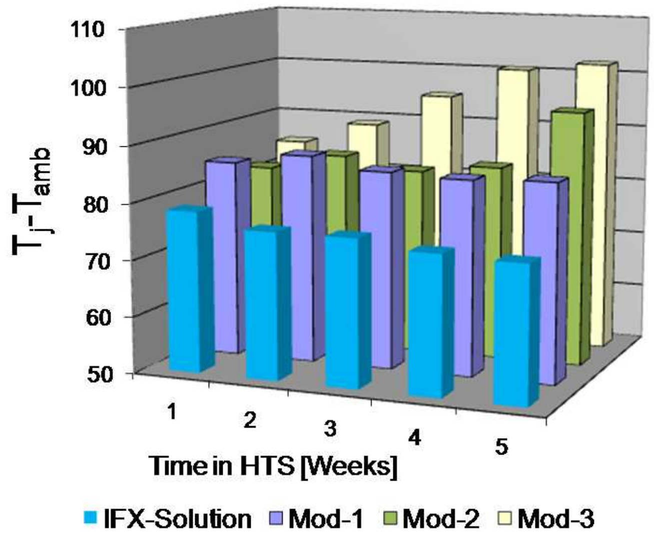

Figure 3: Thermal results from the 1000h HTS-Test

The material labeled Mod-3 shows continuous degradation as a consequence of ageing. Drying, separation or loss of flexibility are reasons for this effect [3]. Specimen Mod-2 performs quite well at first, however a sudden jump in chip temperature after five weeks in the test gives a clear hint that the material suffers and looses its thermal capabilities. Mod-1 shows the constant behaviour as it is expected from TIM in power electronics, however the general purpose component is outperformed by the dedicated material labeled IFX-Solution.

4 Lifetime Considerations

Designers need to predict the lifetime of their devices based on the information available on the thermal capabilities of the material involved. Properties that change over time lead to uncertainties that need to be taken into account.
Based on the findings documented in figure 2 it becomes obvious, that uncertainties in thermal models used for the calculations lead to unpredicted thermal results and therefore to wrong assumptions regarding the predicted lifetime.
A predestined example is found in material 4 displayed in figure 2. Calculating the thermal conditions purely based on datasheet values would have lead to the lowest junction temperature corresponding to the lowest stress and the most optimistic lifetime prediction. Contradictory, the experimental results show, that the measured result were the worst among all candidates. The consequences for the final design would have been fatal. The additional temperature swing turns out to be of a massively detrimental influence which can best be explained looking at the graph in figure 4 [5].

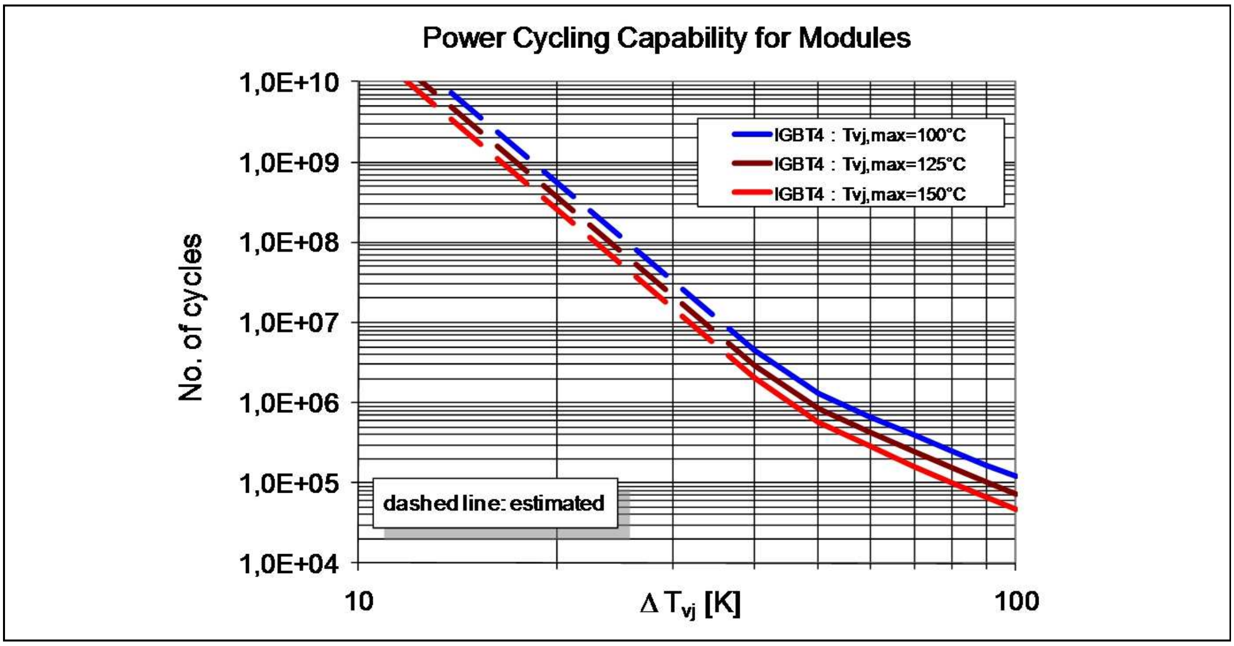

Figure 4: Power Cycling curve for industrial modules based on IGBT4

At an ambient temperature of 25^oC, the temperature swing ΔT_{vj} using material 4 is measured to be about $107K$. According to the graph for $T_{vj,max} = 125^oC$, this resembles a power cycling capability of about $7 \cdot 10^4$ cycles. Upgrading the experiment with the best material in the test, a reduction of the chip temperature of $18K$ can be achieved. This correlates to an improvement in power cycling capability to $1,5 \cdot 10^5$ cycles even if the reference remains the line for $T_{vj,max} = 125^oC$; twice the cycling capability as a consequence of thermal interface materials. As the juntion temperature drops below 125^oC, this estimation is conservative.

Conclusion

Proper thermal managenemt is a key factor in designing power electronic devices. Despite the efforts done to improve the thermal capabilities of every single component, special care has to be taken in building an adequate thermal interface connecting the power electronic components to their heat sink. Dedicated materials, especially designed for these applications can dramatically improve the thermal situation leading to massive improvements regarding the device's lifetime.

References

[1] Karsten Guth et al.
New assembly and interconnects beyond sintering methods
PCIM 2010 Nuremberg, Germany in May 2010

[2] Martin Schulz,
The Challenging Task of Thermal Management
PCIM 2011 Nuremberg, Germany in May 2011

[3] Ijeoma M. Nebe and Claudius Feger
Drainage-Induced Dry-Out of Thermal Grease
IEEE Transaction on advanced packaging, VOL31, No3, August 2008

[4] R. Ott et al.
New superior assembly technologies for modules with highest power densities,
PCIM, Nuremberg, May 2010

[5] Infineon Technologies
Power Cycling Capabilities of IGBT4,
see also www.infineon.com