A condition monitoring method for solder layer degradation of liquid-cooled power semiconductors

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Abstract

This paper presents a new method for condition monitoring of solder layer degradation of liquid-cooled power semiconductors. Solder layer degradation is detected by an increased thermal impedance, which has the effect that more heat is dissipated to the air instead to the cooling liquid. The proposed condition monitoring method is based on detecting the share of heat dissipated to the liquid and to the air. Experimental validation in a down-scaled laboratory setup is presented, with the focus on an application in an industrial converter.

1 Introduction

Condition monitoring of bond wires and solder layers in power semiconductor devices is crucial for optimised maintenance scheduling [1]. A common condition monitoring method is based on monitoring the junction temperature. In most cases this temperature cannot be measured directly. It is possible to estimate the junction temperature by using the provided thermal model from the semiconductor manufacturer, case temperature and power dissipation. Still, solder layer delamination changes the thermal impedance, which must be taken into account for modeling the thermal network over time. Direct attachment of temperature sensors close to the dies has been shown as a method to measure the junction temperature [2], [3]. However, this necessitates complicated manufacturing due to space limitations. For this reason the junction temperature is estimated using temperature sensitive electrical parameters (TSEPs) [4]. However, TSEPs are also affected by degradation, thus necessitating re-calibration [5]. The degraded solder layer also affects the temperature distribution under the base plate. This can be detected by applying several temperature sensors under the base plate to monitor the heat spread [6]. Nevertheless, it is not practically feasible to place a large number of temperature sensors under each semiconductor device.

This paper proposes a condition monitoring scheme for detecting solder delamination in liquid-cooled power semiconductors, without the need for junction temperature estimation. As solder delamination progresses, an increased amount of heat dissipation to the air instead through the base plate will occur. Thus, by monitoring the heat dissipated to the liquid and having the thermal network pre-characterized, solder layer degradation can be estimated. The paper is organized as follows. Section 2 presents the proposed conditioning monitoring principle by analyzing all the power paths and the construction of the thermal network. In Section 3 the method gets experimentally validated with a down-scaled test setup. Then in Section 4 the feasibility of the new method is discussed. Finally, the conclusion follows in Section 5.

2 Proposed Condition Monitoring Scheme

An illustration of a liquid-cooled semiconductor is depicted in Fig. 1.

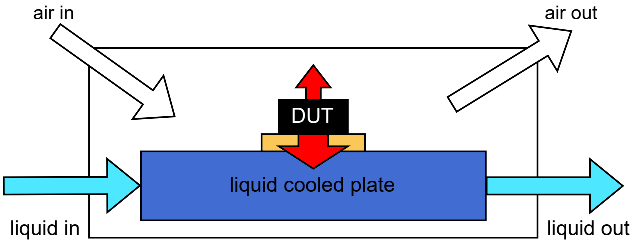

Fig. 1: Principle of liquid-cooled semiconductor

In this figure, the big box around represents the converter cabinet. The semiconductor device, here called Device Under Test (DUT) is mounted with a thermal interface material (orange) on the liquid-cooled plate. The idea is to extract most of the dissipated power due to losses with the cooling liquid (big red arrow). Nevertheless, a fraction of this power will be dissipated through the DUT's plastic encapsulation (i.e., packaging) into the air due to convection and thermal radiation (small red arrow). The power to the air is defined as the remaining power of the DUT which is not removed by the liquid. However, heat exchange between the cooling plate and air is also possible. In a practical converter, the air is often forced (white arrows) due to the cooling requirements of auxiliary circuits, such as gate driver boards, control circuits etc. The proposed method estimates the State Of Health (SOH) of the solder layers by comparing the losses of the DUT with the measured power in the liquid (see Eq. (1))

$$Powershare = \frac{P_{liquid}}{P_{DUT}} \tag{1}$$

To estimate the SOH from the power share, the thermal network of the power semiconductor packaging and cooling plate is needed.

2.1 Dynamics of the thermal model

In the current model, only the thermal resistances are analyzed, which means that only the thermal steady state condition is considered. This steady state describes the condition when the power dissipation is constant and all temperatures have reached a steady level. In many converter applications, a thermal steady state is never reached due to the varying load requirements. The dynamic behaviour is described by the thermal capacitance. The system complexity will be significantly increased by using a dynamic model. To avoid the need for a dynamic model, it is sufficient to apply a moving average filter to all measured signals. The idea is to get signals that emulate the steady-state operation. That is correct because thermal networks can only have a low pass characteristic and all thermal energy needs to pass through this network. It is required that the thermal network behaves linearly. That means the thermal impedances need to be independent on temperature. The linearity can be checked by performing a step-response thermal test. Non-linearity becomes visible when temperatures reach a maximum level which exceeds the steady-state value. The step-response test is additionally required to design the moving average filters. The averaging duration corresponds to the time for reaching the steady state. The implementation of the condition monitoring system including these filters is visualized in Fig. 2.

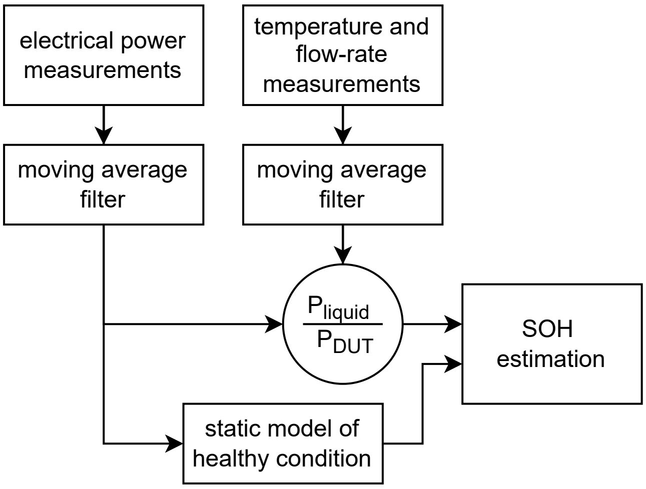

Fig. 2: Condition monitoring principle and filtering

The estimation of the SOH is realised by comparing the measured power share P_{liquid}/P_{DUT} with the calculated share for the healthy condition. With the liquid temperatures and flow rate, the power into the liquid is calculated (explained in 2.4). The information about the losses (electrical power measurements) is required to calculate the actual power share and to estimate the share for the healthy case.

2.2 Thermal network analysis

To estimate the effect of a degraded solder layer on the power share, all possible thermal paths shall be analysed. With this, a thermal network will be reconstructed. The basic thermal network has a triangular form as shown in Fig. 3. The measured parameters on which the method is based on, are blue-marked in this figure.

In this thermal network, the junction temperature, T_{DUT}, temperature of the in-flowing liquid, $T_{liquid-in}$, and temperature of the incoming air, T_{air-in}, are coupled by thermal resistors. This network describes correctly the behaviour of the entire system but does not directly represent the physical structure. An alternative way to describe this network is the star form (using star-delta transformation). The values of the thermal resistors depend on the cooling plate design, the semiconductor packaging and on the flow rate of the air and liquid.

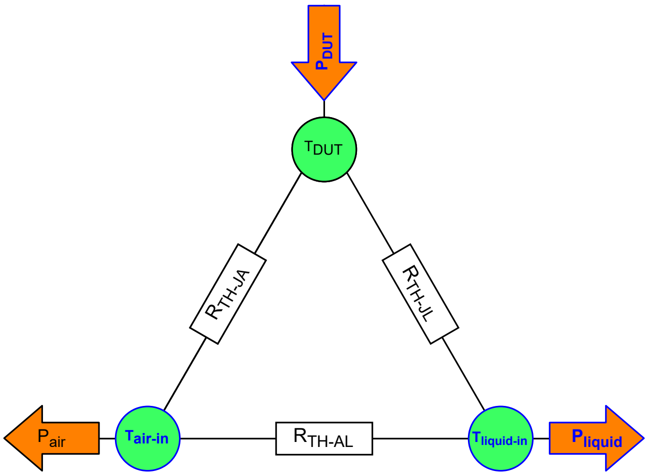

Fig. 3: Basic thermal network triangular representation

Solder layer degradation causes an increased internal junction-case thermal resistance R_{TH-JC}. This internal thermal resistance is mainly part of the junction-liquid thermal resistance, R_{TH-JL}, together with the thermal resistance of the thermal connection (insulation pad), R_{TH-CH} and the heat sink, R_{TH-HL} according to Fig. 4.

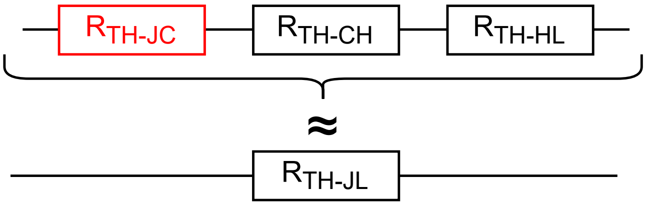

Fig. 4: Detail view of thermal network

An increase of R_{TH-JL} will cause an increase of the junction temperature, with the effect of an increased thermal flow to the air. Therefore, the share of the power dissipated into the water will indicate the state-of-health of the solder layer. This method eliminates the need for measuring or estimating the junction temperature.

2.3 Power flow paths

The thermal resistance defines the power flow depending on the temperature difference according to $R_{th} = \Delta T/P$. Finally, a detailed thermal network, to reconstruct the solder layer thermal resistance from the measured power share is required. For the construction of this thermal network, all relevant power flow paths need to be analyzed. Additionally to the desired thermal flow which is visualised with red arrows in Fig. 5, a number of other possible thermal flows have to be considered, as analyzed below.

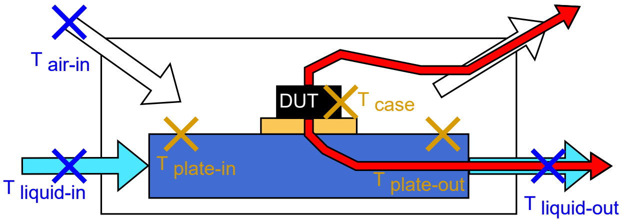

Fig. 5: Main thermal flows

In Fig. 5, crosses indicate the place of described temperatures. Temperature sensors are only installed at the blue crosses. The heat transmission into the cooling plate will also increase the plate surface temperature. Therefore, a further flow through the base plate of the semiconductor into the cooling plate and back to the air occurs as shown in Fig. 6.

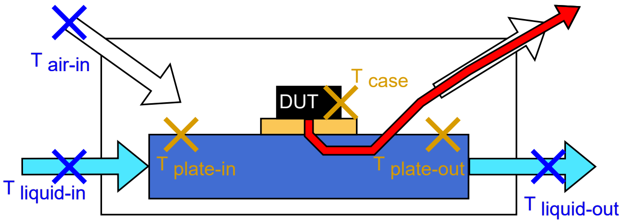

Fig. 6: Indirect thermal flow into the air

If intake air temperature T_{air-in} and intake liquid temperature $T_{liquid-in}$ are unequal, heat is transmitted between liquid and air. The transmission paths are marked for both cases in Fig. 7 with red arrows.

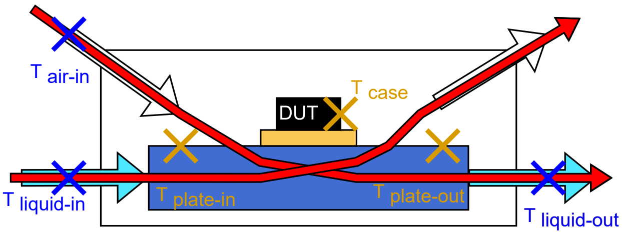

Fig. 7: Cross-flow between liquid and air

It must be noted that this cross-flow appears even without power dissipation at the semiconductor and disappears if T_{air-in} is equal to $T_{liquid-in}$. Significant main heat flows according to Fig. 5 and minor additional thermal flows according to Fig. 5 and Fig. 6 make the proposed condition monitoring method more feasible. That means the method works better when only a small area of the cooling plate without mounted semiconductors is in contact with forced air. The effect of the cross-flows (according to Fig. 7) can be measured by applying different water and air temperature without power

dissipation at the semiconductor device. The indirect flow to the air (according to Fig. 6) is more challenging to estimate. It can be estimated by measuring the heat transfer from liquid to the air (no power at the semiconductor) when the cooler surface ($T_{plate-in}$ and $T_{plate-out}$) is heated with the cooling liquid to the same temperature.
The analysis of all these thermal paths allows the construction of a more detailed thermal model. The resulting model is depicted in Fig. 8.

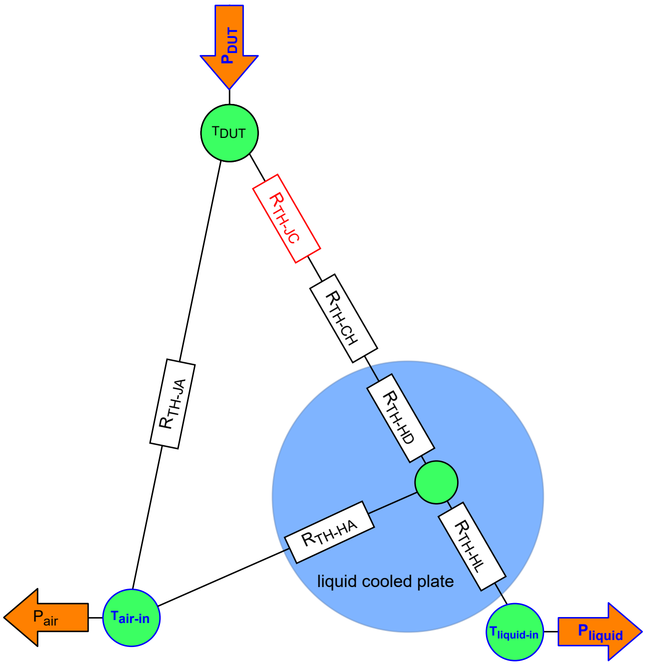

Fig. 8: Possible detailed thermal network

The liquid-cooled plate is now modelled as a three-terminal thermal network in a star configuration (see blue circle in Fig. 8). It consists of the thermal resistance where the semiconductor is mounted R_{TH-HD}, one into the liquid R_{TH-HL} and an additional into the air R_{TH-HA}. This model allows explaining all the considered thermal flows.

2.4 Measuring power to the liquid

The power of the liquid is defined by the thermal capacitance s of the medium, flow-rate $\dot{v}$, inlet $T_{liquid-in}$ and outlet temperature $T_{liquid-out}$ according to Eq. (2).

$$P_{\text{liquid}} = (T_{liquid-out} - T_{liquid-in}) \cdot s \cdot \dot{v} \qquad (2)$$

Measuring the power in the liquid with high accuracy in order to detect the slight change of the power share is challenging. According to Eq. (2) errors in the temperature difference and flow rate have a linear impact on the liquid power measurement. The interest is on the temperature difference which means that constant offsets on both temperature sensors have no impact. Alternatively, sensors which measure the temperature difference directly like differential thermocouple, could minimize the impact of such errors. Noise on the sensing signals will be less critical because of the applied moving average filters. In total, three sensors (flow-rate $\dot{v}$, inlet $T_{liquid-in}$ and outlet temperature $T_{liquid-out}$) are required to measure the power in the liquid. In the case of a constant flow rate, no built-in flow meter is required. Moreover, the flow rate needs to be constant for this condition monitoring method, because the thermal model depends on the flow rate. If the inlet temperature also remains constant in the system only the liquid outlet temperature needs to be measured.

2.5 Power loss at the semiconductor

The proposed monitoring method requires the total power losses occurring in the semiconductor. The dominant part of these losses are the conduction and switching losses, while losses on the gate driver count as a minor contribution. Depending on the converter type and operation, the power loss information can also be estimated. It should be noted that the estimation needs to deliver correct information on the total losses even in the case of degraded semiconductors. Therefore, a pre-characterization of the power semiconductors' loss performance as a function of operating conditions and lifetime must be developed.

3 Experimental validation

The proposed condition monitoring method has been validated experimentally on a down-scaled experimental setup. The focus is to detect a changed power share (Eq. (1)) in the case of a degraded solder layer. The test is conducted at thermal steady state condition. That means the dissipated power at the DUT remains constant and no moving average filters (Fig. 2) are employed.

3.1 Test setup

The experimental setup is shown in Fig. 9. A plastic cabinet (see Fig. 10) with a water cooled plate where the semiconductor is mounted represents the situation of a real converter. The setup also incorporates a fan that is used for forced air cooling. With a heat exchanger the cooling water is conditioned to a desired temperature and flow-rate. Voltage and current measurement probes, different temperature sensors and a flow meter are connected to a data-logger.

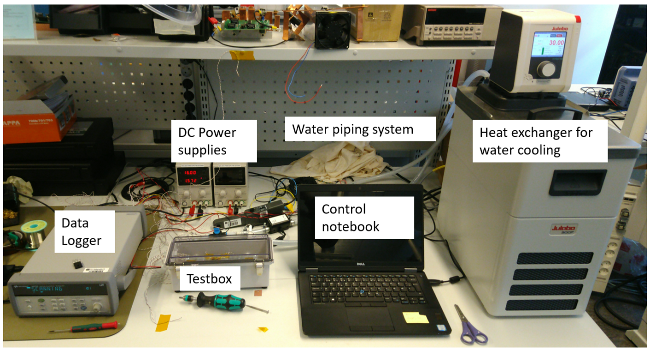

Fig. 9: Laboratory build-up overview

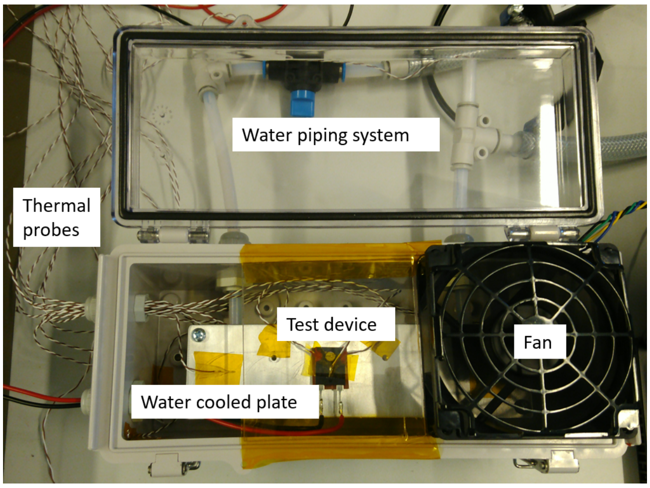

Fig. 10: Laboratory build-up cabinet

The main temperatures are measured using PT1000 thermistors in order to ensure a high accuracy. These are the intake air, intake water and water outlet temperatures on which the suggested condition monitoring method is based. For a better understanding of the behaviour, less accurate thermocouples of type T are also employed to measure the temperatures at the cooling plate and on the case of the DUT. On the DUT case, a thermocouple is directly soldered to the base plate.
For the presented measurements, the DUTs are resistors encapsulated in TO-247 package instead of power semiconductors. This approach emulates the practical case, because only the power dissipation is relevant for the verification of the method. The increased thermal impedance is realised by applying one or two phase-change thermal pads under the case. In table 1 the thermal impedance for both cases are listed. The threshold for a degraded solder layer is usually defined by an increase of R_{TH-JC} by 20% [7]. The difference between one or two thermal pads represents the situation quite well.

R_{TH-JC}	0.9 K/W
R_{TH-CH} "fresh"	0.325 K/W
R_{TH-CH} "degraded"	0.65 K/W
Flow rate	2 ml/s
Power dissipation	70 W

Tab. 1: Build up parameters

The system is operating without load at the DUT until all temperatures reach steady state. That represents the non load condition. Then the power at DUT is activated with nominal load until a thermal steady state is reached again. A steady state reaching time of 20 min is used for the experiment. To avoid noise the results are based on the average values of the last 10 samples.

3.2 Test results

Because of the thermal coupling effects, two test conditions are analysed. First, the cooling water is conditioned to the same value as the intake air temperature. This is done to avoid cross-flows according to Fig. 7. A second test condition including such flows, is realised by setting the cooling water temperature above the air temperature.

3.2.1 Equal air and water temperature

The test results in the case of equal water and air inlet temperatures and where no power is exchanged are presented in Fig. 11.

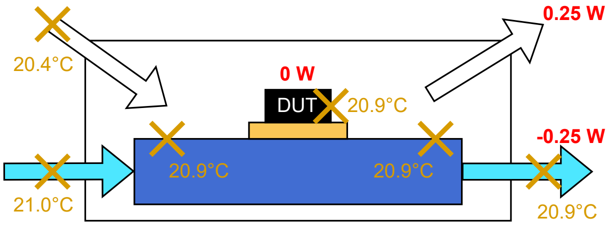

Fig. 11: Heat transmission zero power at DUT at equal air and water temperatures

It is expected that all temperatures are equal without any heat transfer. Nevertheless, due to problems in conditioning the cooling water exactly to the air temperature and errors in temperature measurement, a small heat transfer of 0.25W is measured. After this test, the power at DUT is set to 70W. The results after reaching steady state are presented in Fig. 12.

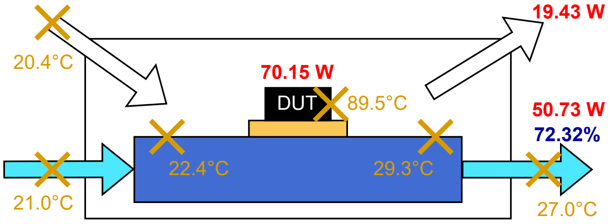

Fig. 12: Heat transmission 70W at healthy DUT at equal air and water temperatures

The power is mainly dissipated into the water (72.32%), but also a fraction of the total power is dissipated directly into the forced air (remaining part). The surface temperature of the cooling plate has also increased compared to Fig. 11. Due to the increased surface temperature a thermal flow from the cooling plate into the air will develop as depicted in Fig. 6.

The results of the degraded situation (here realised with two phase change thermal pads for increasing the thermal resistance) are presented in Fig. 13.

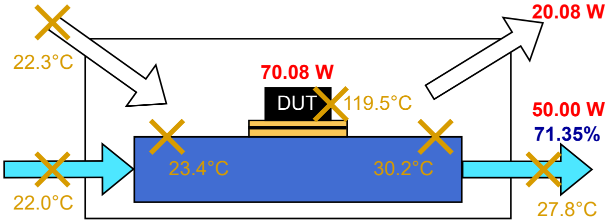

Fig. 13: Heat transmission 70W at degraded DUT equal air and water temperatures

The desired effect of the decreased percentage of the power that is dissipated into the water (71.35%) in the degraded case becomes visible. Here also the case temperature increases, but that is only because of the different realisation of the increased thermal impedance. In the case of a degraded solder layer R_{TH-JC} instead of changing the thermal interface material R_{TH-CH} (like it is done here) no rise of the case temperature would be measurable, because only the junction temperature will rise in that case. The effect on the total thermal impedance will remain the same.

3.2.2 Different air and water temperature

In the more realistic case, the cooling liquid will have a different temperature than the forced air. Therefore, the cooling water was conditioned to 30℃. To analyse which amount of heat is transmitted between water and air, first a test without power at the DUT is performed (see Fig. 14).

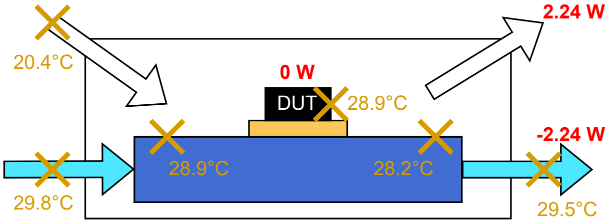

Fig. 14: Heat transmission zero power at DUT water 30℃

A heat flow from the water of 2.24 W into the air is detected. This heat flow will be superimposed to the thermal flow from the DUT. The same test as in the case of equal temperature is repeated. The results are presented in Fig. 15 for the healthy case and in Fig. 16 for the degraded case.

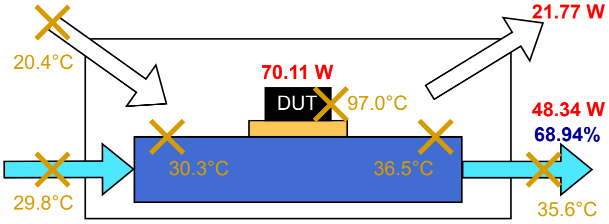

Fig. 15: Heat transmission 70W power at DUT water 30℃ healthy

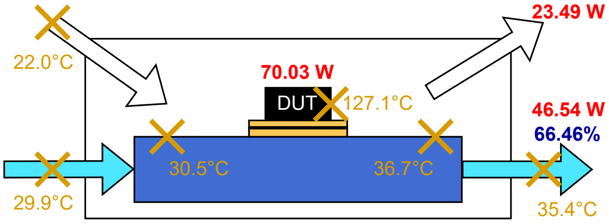

Fig. 16: Heat transmission 70W power at DUT water 30℃ degraded

The situation is quite similar to the case when water and air temperatures are equal. In the degraded case, a decreased amount of power is dissipated into the water. Here the change from 68.94% (healthy) to 66.46% (degraded) which is dissipated to the water seems to be more significant. Note, that the result represents a superposition of the thermal flow through the solder layer with both other flows.

3.3 Test discussion

The experiment has shown that an increased thermal impedance can be detected by a reduced share of the power that is dissipated into the cooling liquid. Therefore, this is a proof of the validity of the proposed condition monitoring principle. In the case with equal temperature for water and air, the increase of the thermal impedance by $0.325 K/W$ which represents an increase of 36.1% has an effect of 1% on the share to the water. That means the resulting error of all measurements needs to be very low. Here, it should be noted that these calculated values are only valid for this test setup.

4 Feasibility discussion

The presented method enables condition monitoring for the solder layer without the need of measuring or estimating the junction temperature. This is very useful because such measurements or estimations are challenging, especially in the case of degraded semiconductors. The experimental test has shown that the increased thermal impedance has the effect that a lower percentage of the power is dissipated into the cooling liquid. Therefore, the condition monitoring principle works. The feasibility finally depends on the ability to measure this change accurately enough. Additionally, the sensing performance depends on the design of the cooling plate and the semiconductors package as well. A low direct heat transfer between the cooling plate and air makes the principle more feasible. This can be reached by covering areas on the cooling plate without semiconductors with thermal insulation material.

4.1 Required sensors

The proposed method requires two temperature (T_{air-in}, $T_{liquid-in}$) and two power (P_{DUT}, P_{liquid}) signals. For the temperatures, the signal comes directly form temperature sensors, but the power signals are based on several sensors as it is presented in table 2.

Signal	Required sensors
T_{air-in}	T_{air-in}
$T_{liquid-in}$	$T_{liquid-in}$
P_{liquid}	$T_{liquid-out}$, $T_{liquid-in}$, $flowrate$
P_{DUT}	e.g. V_{DUT}, I_{DUT}

Tab. 2: Required sensors

P_{DUT} can also be estimated by simulations instead of the current and voltage drop of DUT (see section 2.5.) In the case of constant inlet temperatures and flow rate, these sensors can be eliminated (see section 2.4). If a reduction of required sensors is feasible, this depends on the application requirements and design principles.

4.2 Degraded semiconductors vs resistor tests

The experimental validation was performed with resistors instead of semiconductors. The electrical function of the semiconductor is not relevant for this verification test, but the configuration inside the semiconductor package will be. It is possible that the increased inner thermal resistance R_{TH-JC} (due to degradation) will have a slightly different effect compared with the increased thermal impedance of the thermal interface material R_{TH-CH}. It is possible that a fraction of the heat from the die dissipates through the solder layer into the base plate and then through the plastic case into the air. To analyse this, additional experiments are required.

4.3 Several semiconductors on one cooling plate

In most cases, several semiconductors are mounted on the same cooling plate. In this case, the condition monitoring method is applicable too. Here an overall power share can be analysed. That means the power loss of all semiconductors on the cooling plate is set in relation to the total power measured in the liquid. In this case, it is not directly detectable which semiconductors have solder layer degradation problems. It needs to be investigated if it can be detected due to different delays in the thermal response.

4.4 Extended potential for condition monitoring

In addition to the explained method for detecting the solder layer degradation, analysing the power which is dissipated into the cooling liquid has further potential for condition monitoring. Degraded components have increased losses. That will be detectable in the liquid even when the share of the power in the liquid decreases. With this alternative condition monitoring method, the reference power loss (represents the healthy condition) can be calculated straight forward. Therefore, measurements of the power loss can be avoided. Moreover, it can be combined with the explained method of this paper with the potential of distinguishing between solder layer degradation and bond wire degradation - the two main weak points of semiconductors. The potential of this alternative or combined method will be investigated further.

5 Conclusion

This work presents a new condition monitoring method for detecting solder layer delamination of liquid-cooled semiconductors. In contrast to alternative methods, this approach has no need for measuring or estimating the junction temperature. The proposed method is based on measuring the electrical losses and the thermal power in the cooling liquid. From the experimental validation, it is revealed that a 36.1% increase of the solder layer thermal impedance changes the power share to the liquid by 1%. Therefore, accurate measurements of the power in the liquid are required. A moving average filtering approach eliminates the need for a dynamic thermal model and increases noise tolerance. Further potential for condition monitoring is expected in measuring the thermal power in the cooling liquid due to degraded semiconductors causing increased losses.

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