Observer based Dynamic Adaptive Cooling System for Power modules

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Abstract

This paper presents an advanced dynamic cooling strategy for multi-layer structured power electronic modules. A observer based feedback controller is proposed to reduce a power device or module's thermal cycle amplitude during operation, with the aim of improving reliability and lifetime. The full-state observer design is based on a developed Cauer type thermal model. The observer enables estimation and control of the temperature at reliability critical locations only measuring one accessible location. This makes the method particularly powerful and suitable for application in power systems. The designed strategy is confirmed experimentally. Although the experiment is developed for a specific application scenario, the proposed strategy is of general validity.

Keywords: Cooling, Reliability, Temperature Control, Thermal Stress, Thermal Cycle, Lifetime

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1. Introduction

In power electronics, the failure mechanisms generally can be grouped by random and wear-out failures [1, 2, 3]. Wear-out mechanism failures make up the majority of failures in power electronic modules [4]. In wear-out mechanism, thermo-mechanical stress plays a very important role in affecting power electronic devices/modules reliability [1, 5], such as the fractures propagation and degradations in solder layers [6], wire-bond lift-off [7] and emitter metallization [8]. The failure mechanisms are influenced by both environmental and load conditions [9, 10]. To address this issue, research has addressed different aspects, for example, new semiconductor and materials technologies [11, 12], package architecture [13], interconnection [14], control of power electronic modules [15] and advanced cooling technologies [5, 16].

Fig. 1 describes a summary of the results of extensive reliability tests on IGBT power modules [17]. These results clearly indicated that, over the considered temperature range, a power module operational lifetime depends mainly on two parameters: 1) the amplitude of the thermal cycles, ΔT, that the module experiences; 2) the average operational temperature, Tm. Fig. 1 clearly shows that if ΔT is reduced by even the same amount that Tm is increased, a much higher number of cycles to failure can be achieved. For instance, moving from point 1 to point 2, as ΔT is fixed at 50K, increasing Tm by 20K from 80°C (353.15K) to 100°C (373.15K), the cycles to failure will be reduced 3×10^5 cycles from point 1 (5×10^5 cycles) to point 2 (2×10^5 cycles). However, moving from point 2 to point 3, keeping the same Tm, a reduction of 20K in ΔT increases the number of cycles to failure to 2×10^6, that is, even better than the starting point 1. In other words, quantitatively

ΔT has a much more significant effect on the reliability of power modules than Tm.

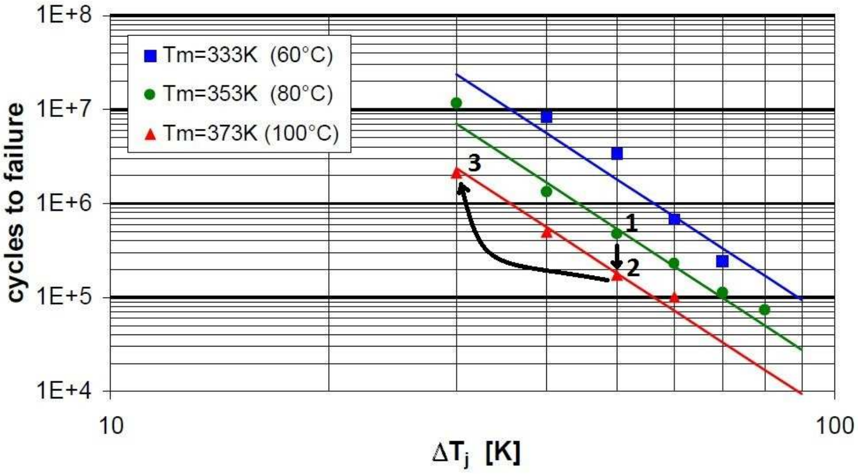

Figure 1: Reliability of power modules as a function of thermal cycle amplitude for different values of average temperature [17]

Presently, typical power device thermal management only aims at ensuring that the maximum operating temperature is kept below a safety critical value at full-load or worst-case conditions and the cooling device is based on fixed designed parameters. In view of the close considerations, from a reliability point of view, this is clearly not optimum. Some temperature regulated thermal management strategies have been proposed with consideration of maintaining device operation temperature variation as small as possible [18, 19, 20]. A temperature control system is presented in [18], where the device under test (DUT) is sandwiched with a heat sink and heater. By electrically controlling the heater power, heat flow to/from the electronic device is quickly adjusted; and that in turn regulates the device temperature. This strategy is actually a heating strategy instead of a cooling strategy and it costs extra power for heating the device to a certain temperature value. The patent in [19] demonstrates a temperature controlled cooling method. In this method, the DUT is cooled by mechanically swing the cooling fluid direction (e.g. the cooling fan facing direction) towards the heat dissipation element to regulate the temperature to a target value. However, this method requires several parallel mounted cooling fans and each fan needs a motor for swing functions, which increases the complexity of the cooling system and limits its thermal response time. In [20], a method to control the fan speed used in cooling integrated circuits is presented. In this method, a thermal diode is used to monitor device temperature, and the fan speed is adjusted by looking up a pre-defined temperature-speed table. There are two main shortages for this method: 1) a temperature sensor must be mounted inside the device; 2) controlling cooling fan by look-up table is an open loop control thus it is sensitive to system variations and easy to have temperature errors. Therefore, considering the reliability and temperature control issues, an observer-based adaptive cooling strategy with multi-variable feedback control technique is proposed here.

As shown in Fig. 2, the temperature with constant cooling power will vary as load changes. In order to decrease ΔT, the cooling power can be adjusted according to the load variations and this can be achieved simply by reducing the cooling power.

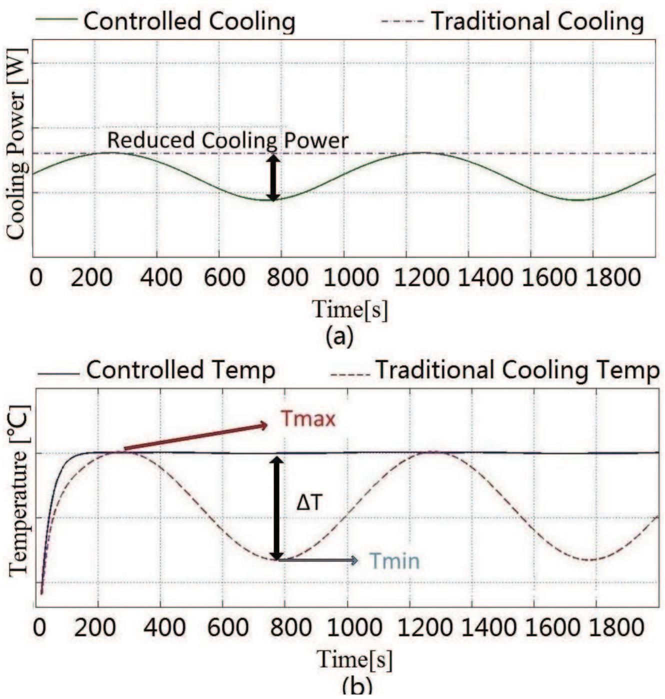

Figure 2: Change in thermal cycling with traditional cooling approach and with the proposed cooling strategy: (a) Cooling power (b) Temperature

This paper presents an advanced dynamic cooling strategy for multi-layer structured power electronic modules. An observer based feedback controller is proposed to reduce a power device or module's thermal cycle amplitude during operation, with the aim of improving reliability and lifetime. The proposed methodology is schematically illustrated in Fig. 3:

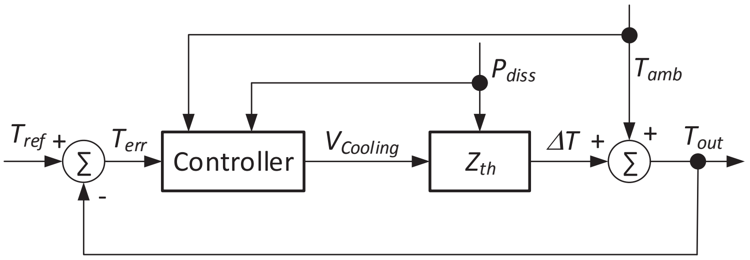

Figure 3: Block diagram for the control design

the temperature at a reliability critical location of the power assembly is controlled against variations in the actual load and power losses P_{diss} (i.e., power dissipation) and boundary condition T_{amb} (i.e., ambient temperature). The feedback control loop monitors the temperature of the desired location T_{out} and intervenes on the cooling parameter $V_{cooling}$ to eliminate temperature errors T_{err} to control the temperature output and decrease temperature variations. The control parameter $V_{cooling}$ is the controller output signal used to control the cooling devices. It can be the bias voltage applied on the fan for a forced air convection cooling, or the voltage on the pump in a liquid cooling system. By controlling the cooling device, the thermal impedance of the system, Z_{th}, is adjusted to meet the temperature regulation. A observer based feedback controller is proposed to reduce a power device or modules thermal cycle amplitude during operation, with the aim of improving reliability and lifetime. The full-state observer design is based on a developed *Cauer* type thermal model. To ensure the accuracy of the developed model, FEA (Finite Element Analysis) method is applied to deriving a Cauer type thermal network where the observer is modelled on. The observer enables estimation and control of the temperature at reliability critical locations only measuring one accessible location. This makes the method particularly powerful and suitable for application in power systems. The designed strategy is confirmed experimentally. Although the case-study experiment is developed for a specific application scenario, the proposed strategy is of general validity.

2. Temperature Estimation

A common way to estimate junction temperature is building a real-time thermal model and match the model to experiment data to get a reference look-up table for temperature estimation [21]. This requires high accuracy physical parameters, proper initial conditions to ensure the precision of modelling, high initial efforts to build up the look-up table and basically only for junction temperature estimation. Here, the proposed temperature full-order observer is a system that provides an estimation of the internal states (temperatures) of a given real system (power module). The state-space thermal model is based on module's physical structure and material properties, thus with knowing the system's inputs P_{diss} (i.e., power dissipation), T_{amb} (i.e., ambient temperature) and output (i.e., the temperature at any certain layer location inside the module), the observer will be able to calculate the junction temperature and temperatures at other layers inside the module. This enables that many modules have inbuilt temperature sensors [22] can be used with the proposed observing method. The system states are necessary to solve many control theory problems so that the state observer can be used in investigating the critical temperature location (e.g. junction temperature or solder layer temperature) in active temperature control applications. Because the temperatures are treated as internal states in the observer, the temperature information at all physical layers can be achieved at same time.

For validation purposes a simple test assembly was produced as shown in Fig. 4, and the validation process and results are discussed in detail in early works [23]. This consists of an IGBT to be used as the heating element and a diode to be used as temperature sensor; the top surface of the IGBT (source terminal) was contacted with hollow copper bumps, into which a thermocouple (here, a K-type thermocouple was used) was inserted to provide a second temperature measurement point, much closer to the actual heat source (i.e., the IGBT chip). The IGBT is driven in the on-state with a constant gate-emitter voltage; a variable DC voltage source is connected to collector and emitter to generate variable power dissipation; the diode, previously duly calibrated, is biased with constant current ($500mA$) to monitor variations of its forward voltage drop with temperature.

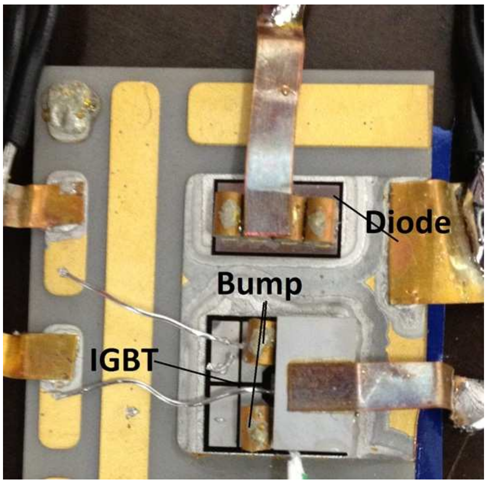

Figure 4: Tested IGBT assembly

The *Cauer* type thermal network is built because it can represent a real physical heat-flow path. To ensure the accuracy of the thermal model, the thermal resistance and thermal capacitance values in *Cauer* network are derived from FEA simulation results [24]. The test model is built in 3-D with FEA software, Abaqus. In FEA simulation, assuming a $100W$ power is dissipated and the top 1/3 part of the silicon layer of IGBT is set to the heat source. Adiabatic boundary conditions are applied to the top and lateral surfaces and convective boundary conditions are applied to the bottom surface only (heat-sink). As mentioned above, for most cooling conditions and assembly structures, heat conduction can be assumed to take place essentially in the vertical direction, from the chips towards the heat-sink, enabling for an essentially 1-D treatment of the problem. This allows derivation of the associated thermal resistance R_i, and thermal capacitance, C_i, of each layer. Therefore, the temperature measuring locations are set to the elements beneath the centre of the IGBT gate chip, and in the center of each material layer. To verify the extracted parameters, a Cauer type thermal model is simulated in Simulink with the same load parameters in Abaqus, and the simulated temperature results are compared with the original FEA results.

Based on the derived *Cauer* network, the thermal model can be formalised in the framework of state-space description. Based on this state-space model, a full-order state observer can be built in the form of Fig. 5 [23]:

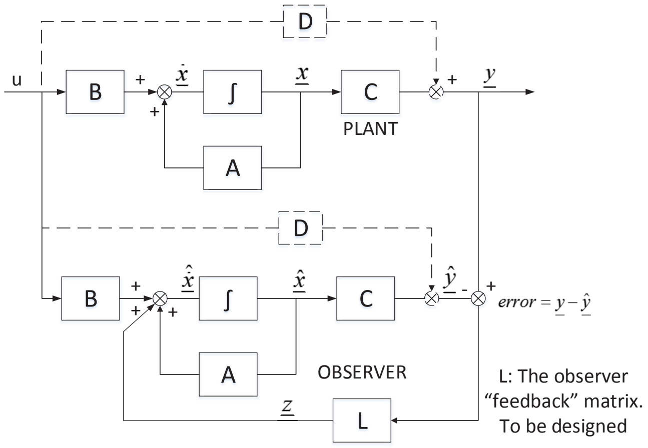

Figure 5: Full-state observer scheme

3. Temperature Control System Design

Based on the proposed thermal modelling method and the temperature observer, the adaptive cooling system controller can be designed. Usually, the equations of the thermal model involving the controllable thermal impedance Z_{th} (or using thermal resistance $R_{cooling}$ for simplicity) and the cooling parameter $V_{cooling}$ are non-linear. However, modern control system design is mainly based on linear system design: analysis methods are much easier for linear models than for non-linear models. Therefore, the developed thermal model must be linearised so to allow control methods to be applied and achieve the expected thermal performance.

The thermal system used in the experiment is modelled based on an $Cauer$-type electrical equivalent circuit for the assembly including the cooling device. In the circuit structure shown in Fig. 6, each node of the network corresponds to an actual physical location of the assembly: voltage corresponds to temperature and current to heat-flow.

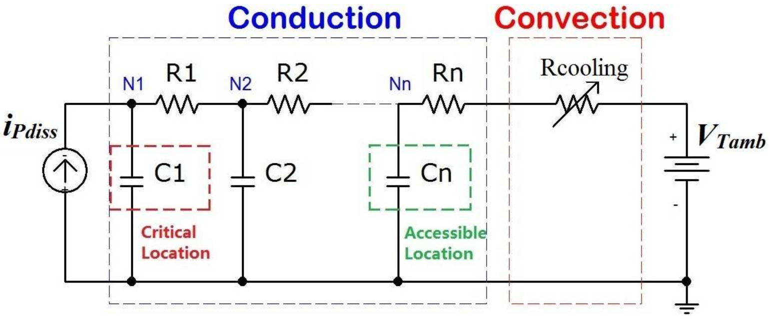

Figure 6: Thermal-Electrical equivalent circuit of a typical assembly

Here, the convective boundary conditions are emulated by means of a variable thermal resistance, $R_{cooling}$, which corresponds to the heat-sink as well as the convection part. The action of the convection cooling is modelled by Equation (1), where the cooler's thermal resistance, $R_{cooling}$, is a function of control parameters (e.g., the bias voltage of a fan or that of a liquid cooler's pump). Here, $R_{cooling}$ becomes the control variable and it will be adjusted during the operation.

$$\Phi = \frac{T_n - T_{amb}}{R_n + R_{cooling}} \tag{1}$$

Based on the derived equivalent thermal model, the state-space model used for the temperature controller design can be built, and the detailed procedure is described in [25, 26] . Note that due to the non-linearity of $R_{cooling}$ and $V_{cooling}$, the state-space system must be linearised before designing controller with it.

In the state-space system, among the inputs, only $V_{cooling}$ is the controllable signal, and both P_{diss} and T_{amb} are decided by the loading and the external environment so that they can be treated as system disturbances. To control the output temperature at the desired value accurately, the system output temperature must present zero steady-state error to a step command. However, using the multivariable state feedback control on its own, any change in the model parameters will cause the error to be non-zero. Therefore, integral control is introduced. Then, the open-loop system eigenvalues (poles) of the augmented system can be calculated and the closed-loop poles can be placed according to the desired dynamic response performance by the feedback law. A detailed feedback controller design and validation on a preliminary assembly was published earlier in [25].

4. Reliability Testing: Proof of Concept Demonstration

A photograph of the test vehicle is shown in Fig. 8: it is a commercial IGBT module mounted on a fanned heat-sink.

Figure 7: Tested IGBT module on heat-sink

It was subjected to 3000 temperature and power cycles derived from a realistic mission profile for wind applications, shown in Fig. 8. The temperature at baseplate was measured during operation, a certain part of two cycles is shown in Fig. 9. With the collected baseplate temperature and the proposed observer, the reference temperature at the solder layer beneath the substrate is set to 80 °C, which is the peak solder layer temperature with fixed cooling. However, during the steady state, the thermal chamber used in this experiment shifts its temperature somewhat so that the temperature with fixed cooling shifts as well. But, the controlled one can still reach its reference temperature by adjusting its cooling power, therefore a peak temperature difference T_{diff} is generated as shown in Fig. 9. From the measured baseplate temperature profile we can clearly see that although the controller cannot keep temperature constant during the whole cycling due to the harsh ambient temperature change, it still can reduce almost 45°C in ΔT with only increasing 20°C in its average temperature. This 25°C temperature difference can improve the device reliability a lot.

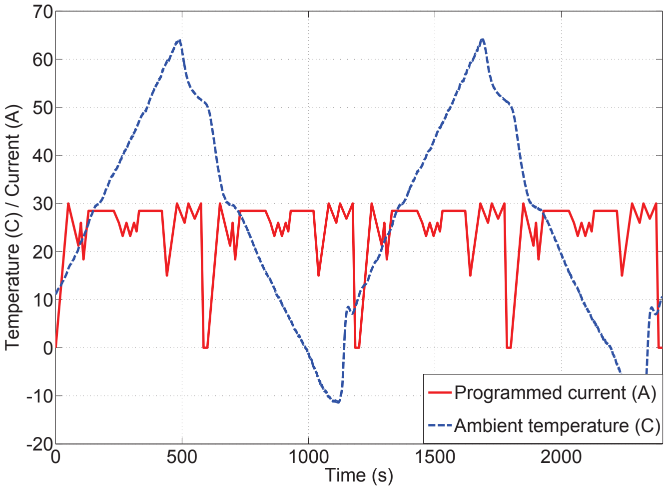

Figure 8: Long-term degradation test conditions for active and passive thermal cycling

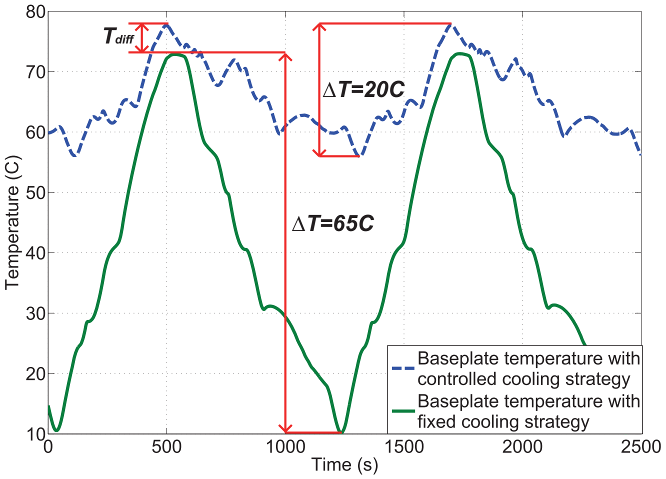

Figure 9: Measured temperature variation at the baseplate for the test conditions of Fig. 8, with and without the proposed regulated cooling strategy, respectively

The proofs of reliability and lifetime improvement are demonstrated by checking the tested IGBT module solder layers, which are scanned before and after the test for both of the adaptive cooling and fixed cooling solutions. The SAM (Scanning Acoustic Microscope) scanned pictures are shown in Fig. 10 and Fig. 11.

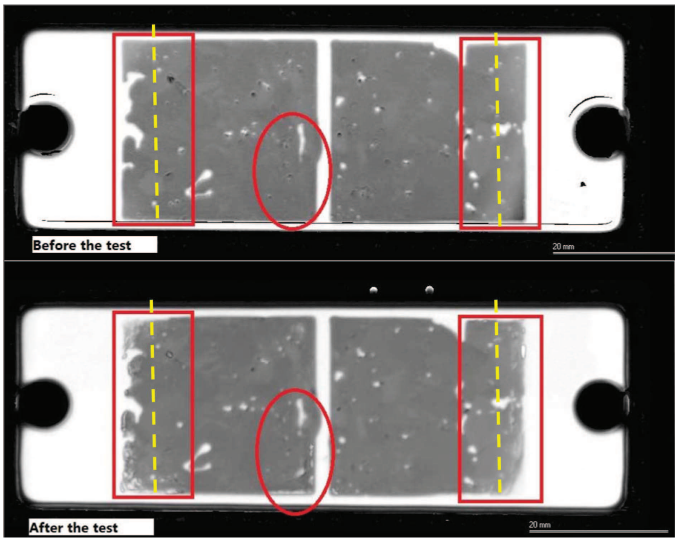

Figure 10: Fixed cooling: Tested IGBT module baseplate solder layer SAM scan results after 3000 temperature cycles.

Fig. 10 shows the tested IGBT module baseplate solder layer SAM scan results with fixed traditional cooling strategy after 3000 temperature cycles: the comparison of results before and after the test shows that degradation and solder delamination happened around the solder layer corner first under the test (indicated in the red areas).

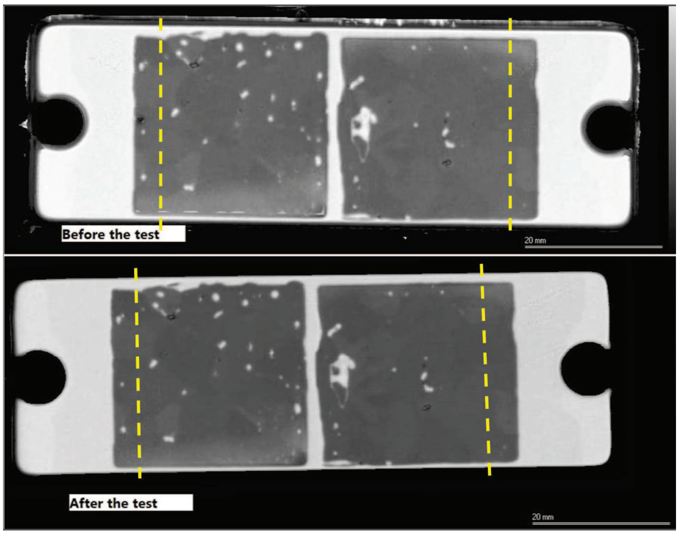

Figure 11: Adaptive controlled cooling: Tested IGBT module baseplate solder layer SAM scan results after 3000 temperature cycles.

Fig. 11 shows the tested solder layer SAM scan results with the proposed adaptive cooling strategy after 3000 temperature cycles: the comparison of results before and after the test shows that by regulating the temperature variation amplitude during cycling, there is no obvious degradation. These results prove that the proposed adaptive cooling improves solder layer reliability , as indicated in the red area along the edge side.

To have a more detailed observation of the tested device, cross-section examination of the devices near solder layer edge (the location as the yellow dashed lines in Fig. 10) are scanned by SEM (Scanning Electron Microscope), as shown in Fig. 12 and Fig. 13.

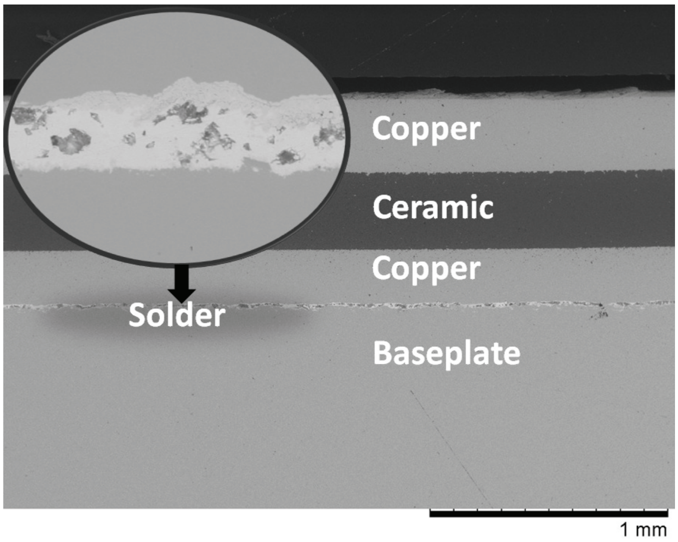

Figure 12: SEM cross-section scanning for fixed cooling solution

In the case of traditional fixed cooling, shown in Fig. 12, the baseplate solder layer has cracks and voids generated by the cycling test and the solder layer becomes thinner along its edge due to the warpage of the device during thermal cycling [27].

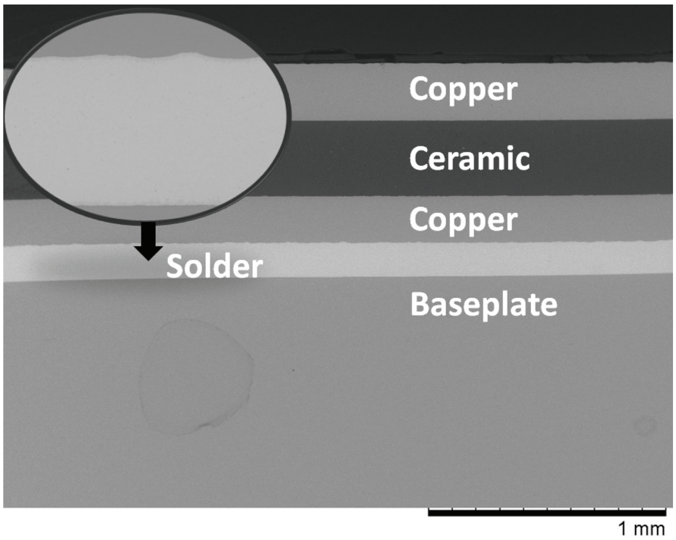

Figure 13: SEM cross-section scanning for adaptive cooling solution

In the case of adaptive cooling, shown in Fig. 13, due to the controller reduces the ΔT so that the thermal-mechanical stress is reduced, there is no obvious void or crack is observed, and the solder layer thickness is kept as its original value. By comparing Fig. 12 and Fig. 13, it can be observed that the copper-ceramic interface in the substrate becomes more rough in fixed cooling than adaptive cooling. A compare of more zoomed-in scanning pictures on this interface are presented as in Fig. 14 and Fig. 15.

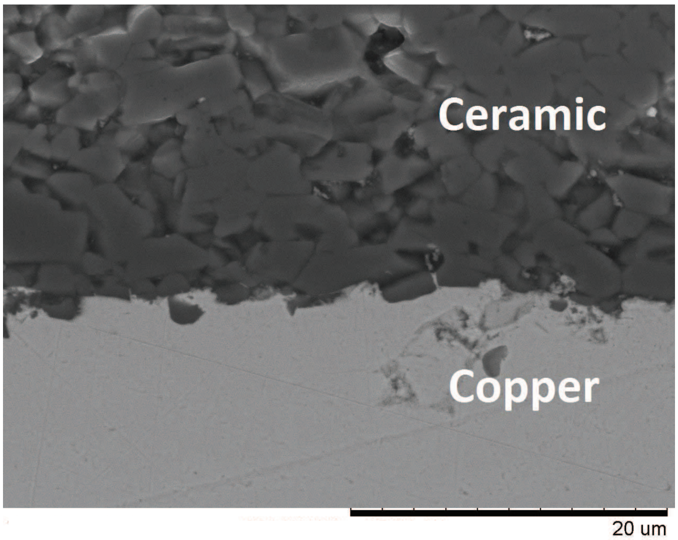

Figure 14: SEM cross-section scanning on substrate for fixed cooling solution

In Fig. 14, it can be seen that the thermal cycling test develops coarse ceramic grains in substrate when fixed cooling strategy is applied.

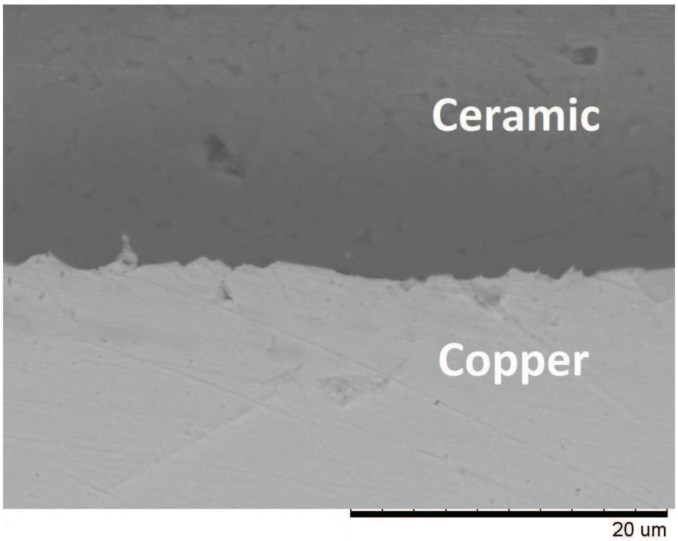

Figure 15: SEM cross-section scanning on substrate for adaptive cooling solution

While for adaptive cooling in Fig. 15, the ceramic grains in substrate are still smoothly arranged and the copper-ceramic interface is much more smooth than the fixed cooling one. Therefore, it can be summarised that the module with adaptive cooling solution has better performance in preventing voids generation and cracks propagation in solder layer, and even reduce copper-ceramic thermal-mechanical stress. The results clearly show that the proposed adaptive cooling can improve solder layer reliability and elongate device lifetime.

5. Conclusion

In this paper, an observer based dynamic adaptive cooling strategy has been proposed and validated. Considering the effect of temperature variation ΔT and average temperature T_m on device reliability, the proposed cooling strategy uses multi-variable feedback control to regulate the device temperature against loads variations (e.g. power and ambient temperature change). With the developed feedback controller, a higher temperature reduction in ΔT is achieved than the increase in T_m. This regulated temperature result leads to an extended device lifetime. It can be observed from the experimental results that the proposed dynamic cooling strategy improves device lifetime beyond the existing fixed cooling method by adaptively adjust its cooling power to the loads. Due to the cooling power being controlled within its maximum value, the adaptive cooler does not require more power than the traditional fixed cooling.

Another original contribution of this work is the use of a temperature observer. Considering the difficulties in measuring temperatures at certain desired locations inside a commercialised module during operation, a temperature observer is proposed and validated. The proposed observer is able to estimate the internal module temperature (e.g. junction temperature or solder-layer temperature) in real-time without opening its package by just measuring the temperature at one accessible location (e.g. baseplate, heat sink). As the temperature dynamics information is reflected by the power dissipation and the ambient temperature signals, the observer doesn't rely on the dynamics of the temperature sensor. Therefore, the observer is especially suitable for power electronics temperature monitoring applications.

To verify the proposed cooling strategy, the observer and feedback controller were validated separately and then tested combined together on a commercial IGBT module (case-study). The test condition are scaled from domestic wind-turbine inverter applications, but the idea is very general and can be applied to a broad variety of power electronics applications (e.g. automotive, ship). During this case-study implementation, the power and temperature cycling were ran simultaneously for 3000 cycles. Temperature at the IGBT baseplate were compared and a reduction of 45°C in ΔT is achieved. The solder layer degradation were compared between the proposed adaptive cooling and the fixed cooling method by SAM and SEM scanning. The results demonstrate good result in improving device reliability and lifetime with the proposed adaptive cooling strategy.

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