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Observer based temperature control for reduced thermal cycling in power electronic cooling

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HIGHLIGHTS

- An observer based temperature control strategy is proposed.
- This strategy aims at improving power module's reliability and lifetime.
- Reduce temperature change under various power dissipations and ambient temperatures.
- The observer can estimate temperature without direct sensing.

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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.

1. Introduction

A typical packaged semiconductor power switch or module has multilayer structure, and the schematic is shown in Fig. 1. The different materials used in this multilayer structure provide different thermal expansion coefficients for each layer [1]. During operation, temperature cycles lead to different thermo-mechanical stresses between adjacent layers, which leads to degradation or even failure of the module.

The failure mechanisms generally can be grouped by random and wear-out failures [2–4]. Wear-out mechanism failures make up the majority of failures in power electronic modules [5]. In wear-out mechanism, thermo-mechanical stress plays a very important role in affecting power electronic devices/modules reliability [2,6], such as the fractures propagation and degradations in solder layers [7], wire-bond lift-off [8] and emitter metallization [9]. Fig. 2(a) shows an acoustic microscope image of the baseplate of a power module, revealing solder layer delamination below the substrates; Fig. 2(b) shows an example of wire-bond lift-off after power cycling of a module.

The failure mechanisms are influenced by both environmental and load conditions [10,11]. To address this issue, research has addressed different aspects, for example, new semiconductor and materials technologies [12,13], package architecture [14], interconnection [15], control of power electronic modules [16] and advanced cooling technologies [6,17]. The motivation for this work is based on a more detailed analysis of Fig. 3 showing a summary of the results of extensive reliability tests on IGBT power modules [18]. These results clearly indicated that a power module's operational lifetime depends mainly on the average operational temperature, T_m, and the amplitude of the thermal cycles, ΔT, that the module experiences [2,18]. From Fig. 3 one can see that if ΔT is reduced by even the same amount that T_m is increased, a much

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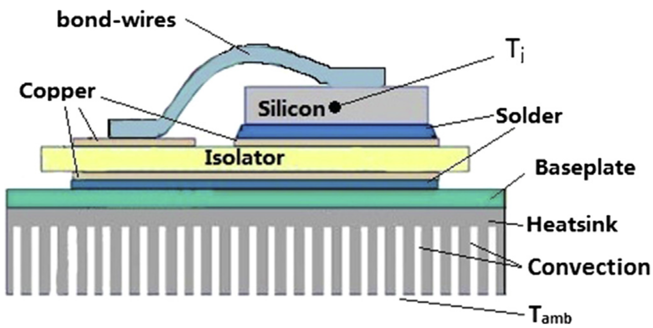

Fig. 1. Semiconductor power module structure.

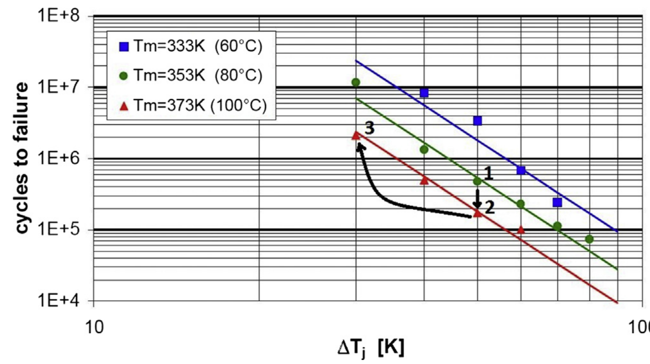

Fig. 3. Reliability of power modules as a function of thermal cycle amplitude for different values of the average temperature [18].

higher number of cycles to failure can be achieved. For instance, moving from point 1 to point 2, As ΔT is fixed at 50 K, increasing Tm by 20 K from 80 °C to 100 °C, the cycles to failure will be reduced 3×10^5 cycles from point 1 (2×10^5 cycles) to point 2 (5×10^5 cycles). However, moving from point 2 to point 3, keeping the same Tm, a reduction of 20 K in ΔT increases the number of cycles to failure back to 2×10^6, that is, even better than the starting point 1.

However, typical power device thermal management design only aims to ensure 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. This is not optimum for thermal stresses consideration nor energy saving. Therefore, considering lifetime and energy efficiency, the adaptive cooling strategy is proposed here. As shown in Fig. 4, 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.

In power electronics, thermal stresses are mainly lead by active and passive thermal cycling. Active thermal cycling is a result of power dissipation in the semiconductor devices. Therefore it is characterised by relatively high frequency components (typically a superposition of PWM (pulse-width modulation) and load characteristic frequencies) and affects wire-bond lifetime. Passive thermal cycling is due to variations in ambient temperature and cooling conditions, and it usually takes place on large time-scales. Passive cycling mainly affects solder layers and baseplate reliability. However, active cycling has never been detected without passive cycling and passive cycling is also quite critical in many applications (e.g., large power systems). In reality, power devices, like converters used in traction or wind turbines, usually suffer both cycling modes and this results in different levels of temperature swings, as well as frequency [9].

In this work, a dynamic active cooling controller is proposed, which is shown as in Fig. 5, where the temperature at the reliability critical location of the power assembly is controlled according to the actual load 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 can be adjusted to meet the temperature regulation. In particular, in view of typical practical difficulties in introducing temperature sensors in the assembly of a packaged power device or module, the design has been formalised in the framework of a full-order observer state-space thermal model, so as to enable estimation and control of the temperature at reliability critical locations (e.g., substrate solder layer in a power module) based only on the actual temperature measurement at a different, more accessible location in the assembly (e.g., the top of the heat-sink).

Considering that both the control signal, $V_{cooling}$, and the disturbances, P_{diss} and T_{amb}, have impacts on the system, the State Feedback Control method is applied in a MIMO (Multiple Input Multiple Output) system. The developed design was tested in simulation and implemented experimentally in an DSP (Digital Signal Processor) platform. The results clearly show that temperature control can greatly reduce the amplitude of temperature

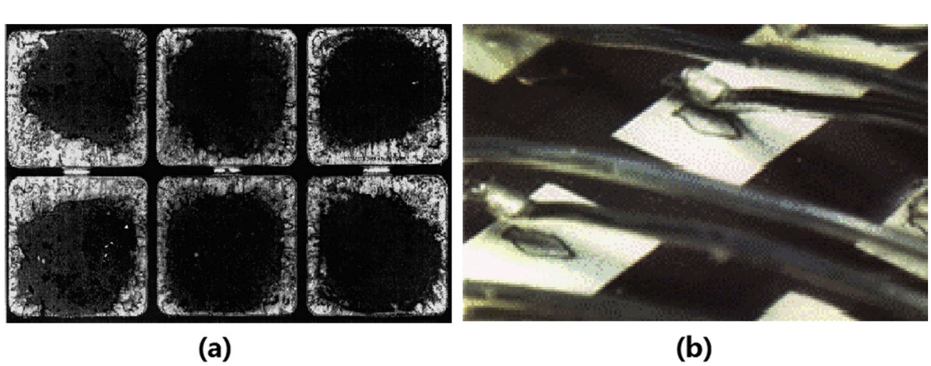

Fig. 2. Typical failure mechanisms of semiconductor power electronic modules: (a) solder layer delamination; (b) bond-wire lift-off.