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Measuring Temperature Swing with Optical Fibers during Power Cycling of Power Components

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***Abstract*—Power semiconductor components play an important role in the power electronics field and their reliability and lifetime have been attracting more and more attention recently. The power cycling test method has been widely used to accelerate the degradation of the device and evaluate its reliability and lifetime. This paper presents a power cycling setup based on optical fibers to measure the power module's chip junction temperature during operation under different loading conditions. The setup has been used to conduct both the DC- and AC-power cycling tests, and the junction temperature measured by the optical fibers during the tests can help to evaluate the thermal stress during operation, indicate the health status of the device under test (DUT) and record its degradation process. Experimental results verified that implementing optical fibers is an effective way of measuring the junction temperature while conducting the accelerating test.**

***Index Terms*—junction temperature measurement, accelerated power cycling test, reliability, on-line monitoring, IGBTs, power module, lifetime prediction**

I. INTRODUCTION

Reliability issues of the power semiconductor components have been highly stressed in many applications such as renewable energy and traction. More knowledge about the expected lifetime of the device is demanded, [1]. For designers, to choose the proper power modules applied for realizing the specific mission profiles, relevant reliability investigation is necessary for the early development stage. For device manufacturers, a deep understanding of the power semiconductor component's lifetime and failure modes can help to evaluate and improve in the aspect of packaging materials and designs [2] - [6].

The lifetime prediction methods generally consist of two categories. The first one is based on physics-of-failure (PoF) lifetime models, which are limited due to the lack of detailed information on the materials and geometries of the power modules. Another one is the analytical models, the many use of the rain-flow counting methods, etc, which all need experimental power cycling tests [7] - [8].

Power cycling test in power semiconductor devices generates repetitive thermal-mechanical stresses, which will bring accumulated fatigue and accelerate the aging of the device till the end of life. Among other failure indicators, the junction temperature is one of the most strongly focused. For instance, in the distributed generation applications such as the photovoltaic (PV) system, the knowledge of the junction temperature of the power semiconductor of a converter is of high importance, as the thermal cycling induced failure could impact a lot of the PV energy. These all make the detection of the junction temperature itself is a challenging and necessary research goal [9] - [13].

One of the most critical bottlenecks of the power cycling test is that while the junction temperature can be derived by $V_{ce,on}$ ($V_{ds,on}$) during DC power cycling, the off- time can be used to inject a monitoring current and measure the on-state voltage at low current this way, i.e., making effects of degradation such as bond-wire degradation, negligible. However, in the case of modern AC power cycling, this is not possible as injecting a measurement current requires additional circuitry able to disconnect the IGBT / MOSFET from the circuit, thus introducing measurement artifacts, such as stray inductance and resistance [4]. Besides, in the aspect of junction temperature measurement for IGBT Multichip Power Modules, it's only possible to estimate the average IGBT junction temperature among paralleled chips due to physical limit [14].

Normally, it has been believed that direct access to the

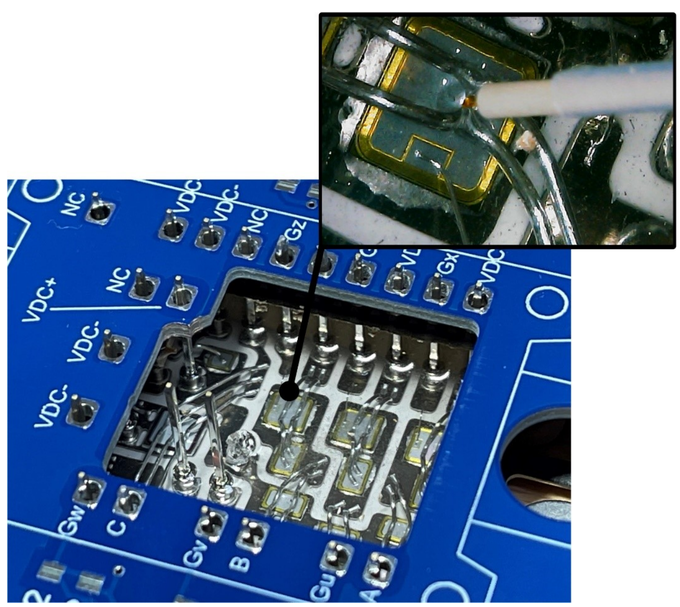
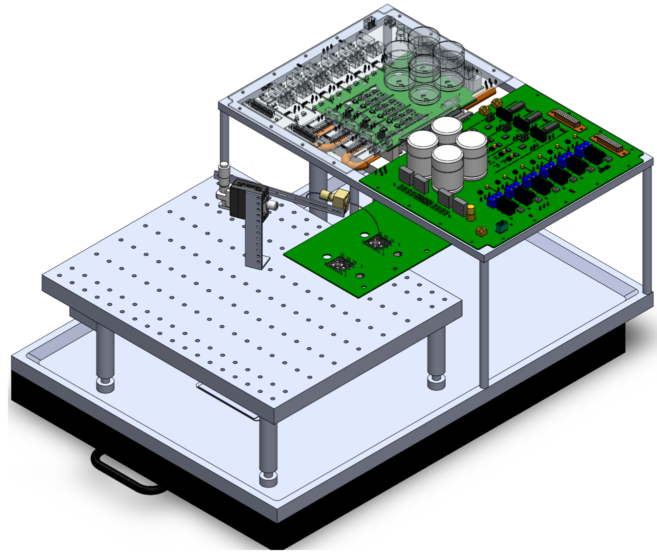


Fig. 1. DUT adapter PCB with optical fiber installed on the power module.

(a) 6-unit, 19" industrial rack array with detailed configuration.



(b) Three-dimensional mechanical layout of the developed test bench.

Fig. 2. Power cycling setup at AAU Energy, Aalborg University.

chips to measure the junction temperature can be difficult due to the limit of the module packaging and the dielectric gel [9], even though the optical fibers can be a valid alternative for measuring the T_j in a non-invasive and isolated manner, especially under the case (AC power cycling) when the traditional TSEP (Temperature Sensitive Electrical Parameter) method is not easy to implement. Not until recently, one innovative optical fiber sensing technology is proposed by the OpSense Solutions©, which enables an online junction temperature measurement during the power cycling test. In this paper, the details of using the optical fibers to measure the junction temperate under both DC- and AC- power cycling tests are explained, also comes with the experimental results and conclusions.

II. Fiber Principle

The implementation of optical fiber sensor OTG-PM makes the direct online junction temperature measurement method

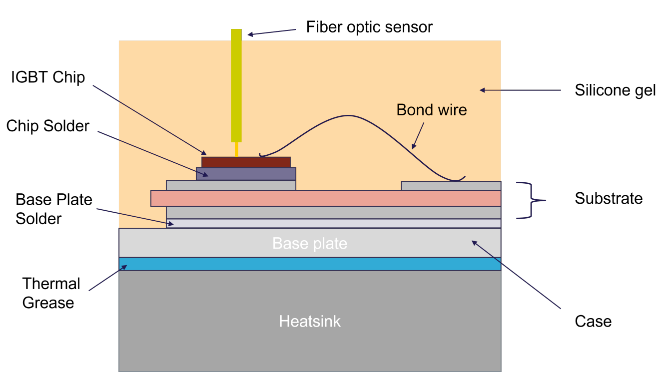


Fig. 3. Scheme of installation of optical fiber in contact with the chip to measure the junction temperature.

possible when conducting AC power cycling test. Details of the junction temperature measurement using an optical fiber sensor are described as follows.

Fig.1 and Fig.3 depict the way of using the isolated optical fiber to measure the junction temperatures of one 650V - 20A IGBT module in real-time. One cutout is made on top of the plastic housing of the power module in order to have the sensor able to reach out to the chip surface. As is essential to keep the packaging's insulation property to assure that the converter can run under rated power, voltage, and normal working conditions, the way of implementing the temperature measurement system can be challenging.

Designed in a way that the miniature sensor head is protected by rigid ceramic tubing, which allows for ease of piercing. Not until the sensor tip is getting close to the chip surface, the miniature tip will be spun out of the tube using one screw. In such a way, the OTG-PM sensor can get in touch with the chip surface without removing the silicone gel. Before getting the sensor tip penetrated through the gel, the sensor is prepositioned with the help of fiber holders, and the target zone is determined to be between the two bonding wires in the active area [15].

Except for its ease of mounting on the gel-filled power module, the sensor's fast response time feature (few ms), wide operating temperature range (-40 °C - 250 °C), immunity to EM and RF interference, etc, all make it well suited for in-situ junction temperature measurement during the power cycling test.

III. Case Study

The test setup shown in Fig.4 is designed to perform power-cycling tests on several kinds of samples and under different conditions, including varied junction temperature swings. As shown in Fig.2, two 3-phase converters are back-to-back

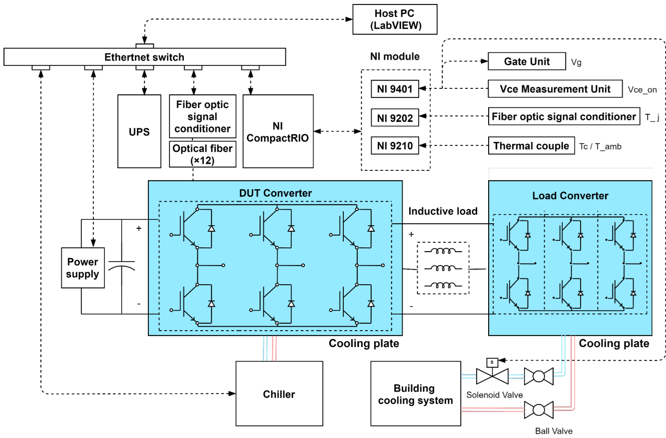


Fig. 4. Schematic of the power cycling setup.

connected in order to circulate power. A load converter is used to regulate the current through the inductor at the wanted amplitude and phase. Large space around the DUT converter is saved for optical fiber holder placement. More details of the setup can be found in [16].

Both DC- and AC- power cycling tests can be conducted on this setup, and the experimental test results are shown below:

A. DC Power Cycling

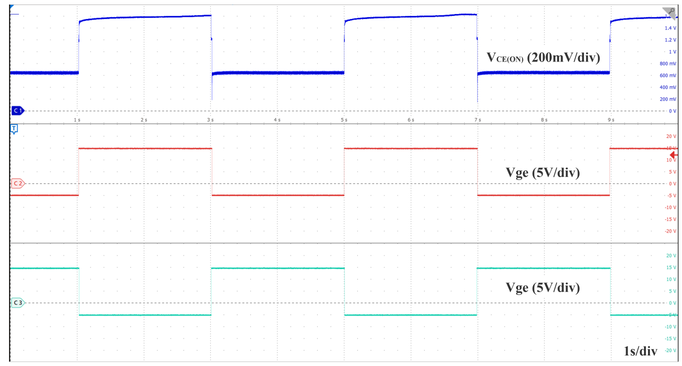
The DC power cycling is conducted with a load current of 20A, 2s on/off time, and the current is commutating between two phases of the power module. A diagram of the on-state voltage and gate voltage measurement results and a diagram of T_j vs time are reported in Fig.5.

B. AC Power Cycling

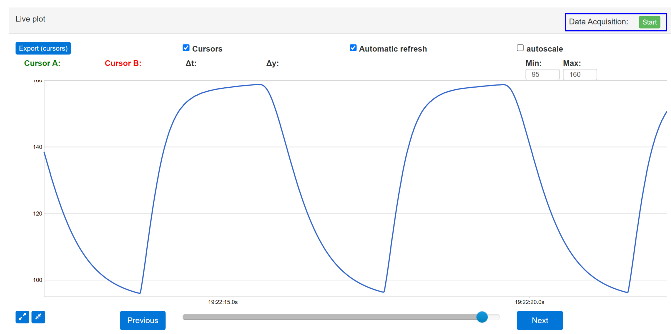
The AC power cycling is conducted with a circulated AC current among phases, of which the fundamental frequency is 0.25 Hz. Correspondingly, for each IGBT chip, it will be actively heated up by the switching losses and conducting losses for 2s and cooled down for another 2s. The corresponding junction temperature measurement result is shown in Fig.6, with a temperature swing of 80°C.

IV. Conclusion

This paper demonstrates that implementing the OpSens optical fiber sensors on the DUT can be one effective and practical way of measuring the junction temperature in power cycling tests (especially for AC-). The results reveal that a stable and accurate measurement result can be achieved without influencing the converter's normal operation. Note: it is possible to further elaborate on the study of the junction temperature swing, however, the chief goal of this paper was to illustrate the concept of using the optical fiber to measure the junction temperature during AC- and DC power cycling, and hence the lifetime estimation of the power semiconductor components is the subject of future work.

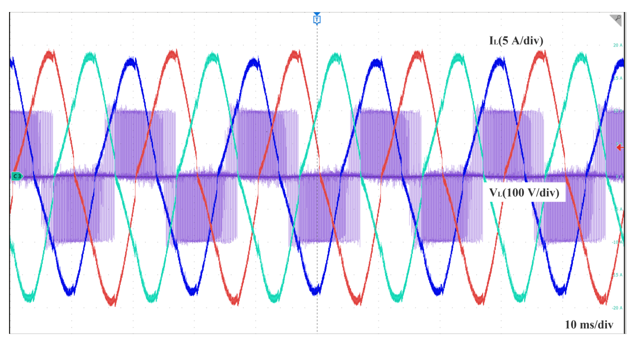


(a) On-state voltage and gate voltage measurement results.

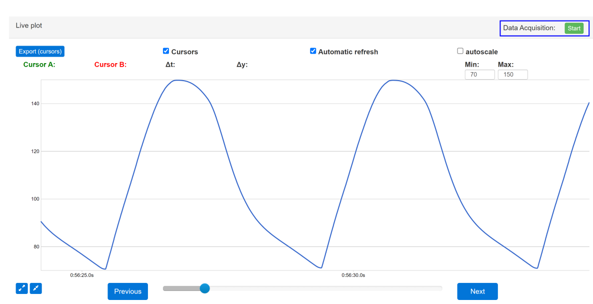


(b) Junction temperature measurement result.

Fig. 5. DC power-cycling test waveform.



(a) Load current and voltage measurement results.



(b) Junction temperature measurement result.

Fig. 6. AC power-cycling test waveform.

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