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Published in:
Proceedings of IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society, 16-19 Oct. 2023

DOI (link to publication from Publisher):
https://ieeexplore.ieee.org/document/10312676

Publication date:
2023

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Tan, S., Wei, B., Vasquez, J. C., & Guerrero, J. M. (2023). Junction Temperature Estimation Technologies of IGBT Modules in Converter-Based Applications. In *Proceedings of IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society, 16-19 Oct. 2023* (pp. 1-6). IEEE. https://doi.org/https://ieeexplore.ieee.org/document/10312676

Junction Temperature Estimation Technologies of IGBT Modules in Converter-based Applications

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Abstract—**Insulated Gate Bipolar Transistor modules, known as IGBT modules, play a critical and indispensable role in a wide range of power converter applications. However, IGBT modules are not immune to failures, which can have severe consequences such as system faults, downtime, and economic losses for industries relying on their functionality. Accurately estimating the junction temperature of IGBT modules is essential for managing their thermal characteristics, performing condition monitoring and lifetime prediction. Therefore, in this paper, recent IGBT junction temperature estimation methods of are summarized. First, the package, circuit principle and failure mode of IGBT module are introduced, followed by a discussion of various junction temperature estimation methods, including methods based on optical technologies, thermal network and Finite Element Analysis models, and temperature-sensitive electrical parameters (TSEPs). Finally, future research challenges and opportunities for implementing these technologies are presented.**

Index Terms—**IGBT, junction temperature, temperature sensitive electrical parameters**

I. INTRODUCTION

Power electronic converters play a pivotal role in diverse industrial applications, with power semiconductor devices, including IGBT modules, serving as indispensable components. However, these modules are susceptible to failures, which can cause detrimental system faults and sudden breakdowns, leading to substantial economic losses in both the converter system and the overall industrial process [1]. Research findings indicate that a significant portion (31%) of breakdowns in power electronic conversion systems can be attributed to power device failures, with approximately 60% of these failures being thermally induced [2]. Furthermore, it has been observed that the failure rate doubles with every $10°C$ increase in junction temperature. The most common causes of power device failures include thermo-electrical breakdown, local thermal runaway, and thermo-mechanical failure. Therefore, the implementation of condition monitoring for IGBT modules is of utmost importance, as it ensures reliable operation and facilitates cost-saving measures for power converter systems.

Accurate estimation of the junction temperature is essential for effectively managing the thermal characteristics of insulated-gate bipolar transistor modules and their reliability analysis. As a result, various temperature estimation methods have been proposed, which can be categorized into three primary areas: the utilization of contact and non-contact optical technologies such as optic fiber and infrared (IR) cameras, estimation techniques leveraging thermal network and Finite Element Simulation models, and evaluation based on temperature-sensitive electrical parameters [3]. Table I provides the comparison of different methods to estimate the IGBT junction temperature.

In laboratory settings, non-contact measurement methods utilizing optical temperature sensors such as IR sensors and thermal cameras are commonly used to obtain reference values for indirect measurement method verification. However, achieving accurate temperature readings with these optical devices requires a direct line of sight and a homogeneous emissivity of the surface being sensed. In practical industrial installations, it is impractical to have the IGBT die of a power module permanently exposed. Consequently, the use of optical thermal sensors is not suitable for on-line temperature monitoring of IGBT power modules in industrial applications. In recent years, embedded sensor technologies have gained increasing attention in electrical power conversion devices. Among these technologies, Fiber Bragg Grating (FBG) sensing technology emerges as a promising candidate for embedded thermal monitoring of the IGBT junction [4]. FBG sensors offer advantages such as immunity to electrical/EMI interference, inherent robustness, flexibility, long lifetime, multiplexing capability, and compact size [5]. However, studies on the application of FBG sensors within power electronic modules are still in their early stages and remain limited.

Thermal behavior analysis of IGBT power modules is effectively carried out using calculations based on thermal circuits and Finite Element Method (FEM) simulations. Typically, a thermal model is employed to estimate the junction temperature by capturing the dynamic thermal behavior of the IGBT module. Among the commonly used online thermal models

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Funded by the European Union under GA no 101101961 - HECATE. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them. The project is supported by the Clean Aviation Joint Undertaking and its Members.

This work was also supported by VILLUM FONDEN, Denmark under the VILLUM Investigator Grant (no. 25920): Center for Research on Microgrids (CROM), www.crom.et.aau.dk.

TABLE I
COMPARISION OF DIFFERENT IGBT JUNCTION TEMPERATURE ESTIMATION METHODS.

Categories	Methods	Precision	Complexity	Invasive	Online
Direct	Optical sensor, IR, etc. [4], [5]	High	High	High	No
Thermal Model-based	RC Parameter from datasheet [6]	Low	Low	No	No
	RC Parameter estimation [7], [8]	Low	Low	No	No
	FEM simulation [9], [10]	High	High	No	No
TSEP-based	V_{ce} at low current [11]	Low	High	High	Yes
	V_{ce} at high current [12]	Moderate	Low	Low	Yes
	Short circuit current [13]	High	High	High	Yes
	Voltage Rate of change [11]	Moderate	Moderate	Moderate	Yes
	On-off delay time [14]	Low	Moderate	Low	Yes
	Threshold voltage [3]	High	High	High	Yes

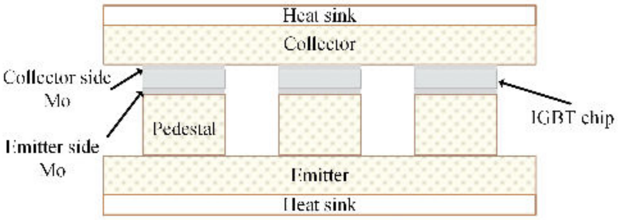
are thermal equivalent circuits, including Foster- or Cauer-type circuits. However, the transient responses of thermal equivalent circuits are not satisfactory in fast-varying loading conditions, which limits their ability to accurately estimate the junction temperature. Furthermore, it is essential to consider the impact of aging on the thermal circuit and FEM model. Failure to account for the internal structure abnormalities can lead to errors in the analysis, particularly due to the increased thermal resistance from the junction to the baseplate.

The TSEPs proposed for evaluating the junction temperature primarily consist of the on-state voltage [11], [12], short circuit current [8], turn-on/off delay time [14] and gate threshold voltage [3]. However, it should be noted that these parameters can also be influenced by the aging process of the IGBT. As a result, the relationship between these parameters and the junction temperature may change over time. Consequently, there are challenges of these electrical parameters for long-term online determination of the junction temperature.

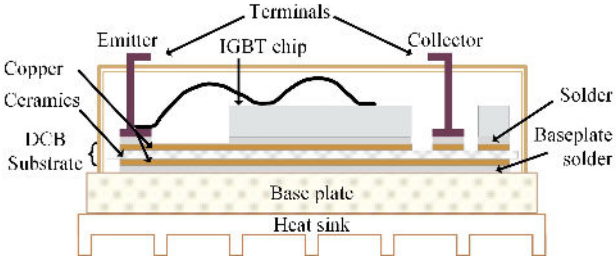
Although these techniques are effective in estimating the junction temperature of IGBTs, inevitably there are some limitations to the application. This paper therefore updates and reviews the junction temperature estimation methods of recent years, and examines their pros and cons along with improvement methods. The primary objectives of this review are to provide a fundamental understanding of technologies in junction temperature estimation on IGBT modules, and to address the challenges and opportunities anticipated for the implementation of these technologies. Specific focus is given to the estimation of temperature using TSEPs, that are regarded as a promising method for conducting online temperature measurements in fully packaged devices.

II. IGBT MODULE TOPOLOGY AND FAILURE MECHANISMS

To better understand the IGBT junction temperature estimation technologies, an introduction to the basic structure of IGBTs, circuit principles, and the corresponding failure mechanisms are presented in this section.



(a) Press-pack module.



(b) Wire-bonded module.

Fig. 1. Structure of IGBT module.

A. Module Package

The structure of IGBT modules can be categorized depending on their packages, i.e. press-pack modules and wire-bonded modules [15]. Fig. 1 illustrates the cross-sectional structures of different IGBT modules.

Compared to the wire-bonded module, due to the substitution of wire and solder connections by a bondless, compact structure, the press-pack module has a lower possibility of fatigue failure and ensures continuous operation in the event of a single chip failure [16]. Moreover, the reliability of the press-pack module is relatively higher due to its better tolerance of thermal cycling. However, this module faces the challenges of a complicated design of the cooling system.

On the other hand, wire-bonded modules use well-established and low cost aluminium wire bonding technology to connect the top die to the output terminals. Thanks to the simplicity of overall module design, wire-bonded module are widely adopted for IGBT packaging. However, due to the vulnerability of connections among the chips, dielectric and base plate, a lower reliability can be observed, which

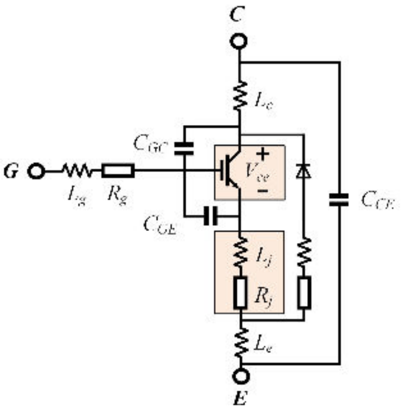


Fig. 2. IGBT module equivalent circuit.

is mainly induced by bond wire fatigue and solder fatigue, as will be explained later in this section. Therefore, the junction temperature estimation method for wire-bonded IGBT modules is the main focus of the paper.

B. IGBT Equivalent Circuit

The terminal characteristics of an IGBT module provide valuable insights into its health status. The key aspect of IGBT health monitoring is identifying the aging precursor. One of the most prominent changes observed in the terminal characteristics during the aging process is the increase in on-state voltage drop and thermal resistance. To analyze the variation pattern of terminal characteristics, an equivalent circuit model that takes into account packaging parameters is used (as illustrated in Fig. 2), where R_j and L_j are the parasitic resistance and inductance of the bond wire respectively; R_g and L_g are the gate parasitic resistance and inductance respectively; L_c and L_e are the collector and emitter parasitic inductance; C_{GC}, C_{GE} and C_{CE} are the parasitic capacitance.

C. Power Module Failure Mechanisms

Power devices commonly experience failure mechanisms attributed to the thermomechanical stress encountered by packaging materials [17]. The disparities in coefficients of thermal expansion (CTE) among the materials used in chip and package construction, coupled with temperature fluctuations induced by the operating environment and mission profile, primarily contribute to these failures [18].

A significant disparity in CTE is observed between the semiconductor chip (silicon) and the bondwires and surface metallization (aluminum) in IGBT modules. This mismatch is particularly pronounced at the end of the bondwire that is directly bonded to the chip's active area. The localized region experiences considerable temperature fluctuations caused by both the power dissipation within the chip and the ohmic self-heating of the bondwire. As a consequence of repeated thermal cycling resulting from these temperature variations, the bondwire is subjected to thermal stress, leading to a prevalent failure mechanism referred to as bondwire fatigue or bandwire liftoff [19].

Thermo-mechanical solder fatigue of alloy layers stands out as an another key failure mechanism in IGBT modules. Among the various interfaces, the solder junction between the ceramic substrate and the base plate, especially when copper base plates are employed, is particularly critical. This interface exhibits the most severe mismatch in coefficients of thermal expansion, experiences the highest temperature swings, and possesses larger lateral dimensions. However, it is essential to acknowledge that fatigue phenomena also occur in the solder connecting the silicon chip and ceramic substrate. Moreover, the presence of process-induced voids further complicates matters by potentially influencing both thermal flow and crack initiation within the solder layer.

It can be observed that the fast power cycling with short durations (tens of seconds) and high temperature swings ($\Delta T > 100°C$) predominantly results in wire bond failure. On the other hand, slow power cycling over several minutes with lower temperature swings ($\Delta T < 80°C$) primarily leads to solder fatigue. It is important to note that solder fatigue alone does not directly cause device destruction. However, the end-of-life failure is often associated with bond-wire damage.

III. JUNCTION TEMPERATURE MONITORING

Accurate estimation of the junction temperature serves as the foundation for health management, lifetime prediction, and reliability assessment of power electronic systems. By precisely monitoring the junction temperature, condition monitoring and overheat protection mechanisms can be implemented, leading to enhanced system reliability [20].

A. Effects of Solder Fatigue

Solder fatigue has a detrimental effect on the thermal resistance of power semiconductor devices and affects the heat dissipation performance, which, therefore, can lead to an increase in the junction temperature, potentially exacerbating other failure modes such as bond wire fatigue [21]. Additionally, the elevated junction temperature can create hot spots and contribute to thermal runaway in specific areas of the module. Consequently, the aging of the solder layer has a significant influence on the thermal behavior and performance of the IGBT module. These effects highlight the importance of addressing solder joint fatigue to maintain the reliability and performance of power semiconductor devices.

B. Electro-thermal Model

The literature offers indirect methods for estimating the junction temperature T_j of IGBTs, which involve using thermal impedance models (such as Cauer/Foster) of the device. One approach is to utilize the lumped RC parameter values provided in the IGBT datasheet for the conventional Foster model. By combining these thermal model parameters with the estimated power loss of the IGBT, it is possible to estimate the junction temperature. Accordingly, the mission/load profile-based thermal analysis and lifetime prediction are accepted as a very popular method for IGBT reliability analysis. However, it should be noted that the model parameters provided in the datasheet are typically calculated for worst-case scenarios and may not be suitable for accurate real-time T_j estimation [6].

In [7], a direct relationship between time constants of the cooling curve of IGBT module and RC parameters of a fourth-order Cauer network is established. This method allows for more precise estimation of the junction temperature without the need to calculate the power losses. However, the degradation of solder layer is not presented. Furthermore, an adaptive thermal model for estimating T_j is established in [8] considering the thermal conductivity, specific heat, and material density of the solder layer, so that the thermal parameters can be updated with device aging. By considering the temperature variations in these parameters, the RC values of the thermal model can be determined, enabling more accurate T_j estimation. However, it relies on two additional thermal sensors to monitor the aging of solder conditions, which may increase the overall cost. Furthermore, the RC parameters of the temperature-dependent thermal model may also be extracted through the use of finite element method simulations [9].

C. Temperature Sensitive Electrical Parameters

Due to the temperature sensitivity of TSEPs, it becomes possible to establish a relationship between the measured electrical parameters and the junction temperature, where experiments or tests need to be carried out to perform this purpose. The TSEPs under research can be divided into static TSEPs (on-state voltage, short circuit current and etc.) and dynamic TSEPs (on-off delay time, voltage rate of change, threshold voltage and etc.). Static parameters refer to the characteristics of a power device when it is either turned off or turned on, while dynamic parameters refer to the characteristics during the transition between these states.

1) On-state Voltage: The on-state voltages V_{ce} of IGBT modules are commonly used as temperature-sensitive electrical parameters in temperature estimation studies. By analyzing the variations in on-state voltages under different thermal conditions, researchers can develop models and algorithms to estimate the junction temperature accurately.

The low current on-state voltage drop method is a well-established technique for monitoring junction temperature. Assuming that the voltage drop across other regions of the IGBT, such as the base region, channel, and metal contact, can be disregarded, the voltage across the IGBT at a small current is nearly equivalent to the forward voltage across the p-n junction. It exhibits a strong linear relationship with the junction temperature when a small current ($< 100mA$) is passed through the device, with sensitivity of approximately $2.3mV/^{\circ}C$. However, although this method has an excellent linear relationship, it requires an uninterrupted injection of current into the IGBTs, which may interfere with the normal device operation. To overcome this limit, additional switches need to be introduced that is capable of interrupting the load current and isolating the device under test during the V_{ce} measurement. Given the above reasons, this method is mostly used in the laboratory junction temperature measurement.

The on-state voltage method at high current is another approach for measuring junction temperature, where the collector current (I_c) itself serves as the heating source, eliminating the need for additional correction currents as in low current method. This simplifies the measurement setup and reduces the reliance on external hardware circuits. However, due to the high currents flowing through the IGBT, there is a measurement error in V_{ce}, due to the presence of a voltage drop across the bond wire. To solve this problem, [3] suggested to calculate the additional voltage drop considering the temperature deviation through the scaling factor and consequently obtain a corrected junction temperature estimation.

2) Short Circuit Current: The short-circuit current I_{sc} and junction temperature demonstrate a negative linear relationship with a temperature sensitivity of around $0.3A/^{\circ}C$. Generally, compared to the fault under load condition, the hard switching short-circuit condition is selected to eliminate the gate voltage variations so that the short-circuit current is only dependent on temperature. However, despite its high accuracy, there are also some drawbacks: a) the measuring of I_{sc} requires the injection of short-circuit pulse currents multiple times, which can result in device losses and present difficulties in implementation; b) I_{sc} is strongly influenced by the gate drive voltage.

3) On-off Delay Time: The on-off delay time T_{don}, T_{doff} method for junction temperature measurement utilizes the parasitic inductance of the device. This method offers good non-invasiveness and integration, as it utilizes internal characteristics of the device with accurate temperature estimation. The temperature sensitivity of the internal gate resistance is also utilized in [22] for temperature monitoring purposes. Furthermore, it has been shown that T_{doff} has a better linearity than the T_{don}.

However, there is a difficulty in real implementation due to the very sensitive measuring parameter, especially in $ns/^{\circ}C$. To accurately extract the time during the switching process, the T_{doff} method requires a complex circuit consisting of a pulse signal sampler, a pulse input signal shaping circuit, and a time interval measurement circuit, which may pose difficulties in terms of complexity and achieving accurate timing [2].

4) Voltage Rate of Change: The rate of change dV_{ce}/dt of collector-emitter voltage at the time of turning-off method offers a linear and non-invasive approach, which demonstrates a strong negative correlation with the junction temperature. As an IGBT module ages, the dV_{ce}/dt value tends to decrease gradually, caused by permanent changes in the parasitic capacitance, which can be an early indication of aging, specifically associated with die solder degradation and failure.

However, the dV_{ce}/dt parameter is susceptible to variations in the bus voltage and load current. Specifically, an increase in bus voltage and load current tends to result in an increase in the dV_{ce}/dt value. Furthermore, it was discovered that using dV_{ce}/dt as a TSEP requires the addition of capacitors in parallel with the IGBT, which may impact the normal operation of the IGBT [23].

5) Other TSEPs: Besides the TSEPs described above, there are other electrical characteristics that can be selected as TSEPs, such as threshold voltage V_{th}, saturation current I_{sat}. The threshold voltage V_{th} exhibits a strong negative relationship to the junction temperature with smooth linearity and sensitivity typically of $-6V/°C$ [11]. However, the measurement of V_{th} is susceptible to noise interference during the sampling process. On the other hand, although I_{sat} can be adopted as a TSEP, its relationship with temperature is not very clear [24]. Furthermore, with high sensitivity and good linearity, V_{GE}(Miller) and t_{GE}(Miller) (time is normally in a fraction of tens of nanoseconds) based on Miller Plateau duration are preferable TSEPs [25]. However, both of these TSEPs require fast capture of a large set of data over a given period (i.e., the length of Miller plateau), after which, the data should be processed through specific software algorithms [26].

IV. TSEP IMPLEMENTATION CHALLENGES AND OPPORTUNITIES

The utilization of temperature-sensitive electrical parameters for temperature measurement systems faces several challenges, including the dependency of electrical parameters on variables, the impact of parasitic and aging effects over the lifetime of a power electronic converter, and the practicality of conducting TSEP measurements without interrupting regular operating cycles. The following paragraphs provide a brief outline of these key issues.

A. Calibration

Prior to employing a TSEP, a preliminary calibration is required to establish the relationship between the TSEP and temperature [27]. During this calibration process, the temperature is controlled using an external system while minimizing self-heating of the device. The measurement of the TSEP needs to be performed quickly within a short time frame. The aging of power modules is a significant factor that affects the use of TSEPs for temperature measurement. Over time, the electrical parameters of a power device, including the voltage drop, tend to change. This natural variation in TSEPs throughout the device's lifetime can significantly impact the accuracy and repeatability of temperature measurements. Therefore, it may require multiple calibration procedures during the module's lifespan or the development of compensation techniques to mitigate these effects.

Furthermore, it should be noted that even when chips within a power module have the same reference and temperature, there can be variations in their TSEP values. For example, when the test is performed with multiple devices connected in parallel, the difference in threshold voltages caused by the different locations of the devices in the chip, due to the production process, can lead to deviations in the associated TSEP. Therefore, a calibration process is necessary for each individual chip within a power module if the TSEP measurement is dependent on the threshold voltage.

B. Complex Characteristics

The dynamic characteristics, such as switching parameters, of power semiconductor devices are particularly sensitive to operating conditions and the presence of parasitic components in a converter setup [28]. Influences on these characteristics include temperature, voltage, current, gate resistance, control strategy, fluctuations in gate driver performance, and parasitic inductances in the circuit. To minimize temperature measurement errors, device calibration should be performed using the same driver as in the final application [29]. The increasing number of variables that affect TSEPs may appear to complicate the development of a reliable temperature measurement strategy for power electronic converters.

In summary, the indicators of aging in IGBT modules are influenced by multiple factors and exhibit nonlinearity and strong coupling effects. Consequently, it is challenging to determine the precise change patterns and identify specific failure levels through direct thermal analysis alone. However, it is valuable to assess whether the indicators are affected by aging failure and observe their changing trends. Therefore, in addition to theoretical analysis, it is essential to conduct accelerated aging tests to evaluate the changing trends and validate the level of failure, which can provide further insights into the aging behavior of IGBT modules and aid in the assessment of their health condition.

C. On-state Voltage Measurement

In a previous study [3], a comprehensive review of hardware-based on-state voltage measurement methods was conducted. The review covered both low-frequency measurement techniques using relay-switches and Zener diodes, as well as high-frequency measurement methods utilizing fast recovery diodes and MOSFETs. These approaches enable the measurement of the voltage drop across the power terminals of a single device. However, despite their potential benefits, these methods also present several practical challenges.

- The main practical challenges associated with these methods are their high complexity and cost. Each switching device requires a dedicated measurement circuit, which significantly increases the overall complexity of the system. Moreover, the need for multiple measurement circuits adds to implementation costs. These factors make the use of these hardware-based on-state voltage measurement methods less feasible in practical applications [30].
- Another challenge of these hardware-based on-state voltage measurement methods is the requirement to connect the power terminals of individual switches. However, in practical converter systems, it may not always be feasible or safe to access and connect to these power terminals, which hinders the widespread application and implementation of these measurement methods.
- A further challenge is the presence of multiple floating grounds, especially when measuring the on-state voltages of all devices in a single-phase or three-phase inverter. With each phase leg having its own middle point as a floating ground, it may introduce additional complexity to the measurement setup, as proper isolation and synchronization techniques are required to accurately measure the voltages across the devices. Failure to address this

issue can result in measurement errors and inaccurate temperature estimation.

To address the above-mentioned challenges, the on-state voltage measurement on converter level is proposed in [31], [32], where the measurement circuit is connected to the middle point of phase legs, with better accessibility and isolation.

V. CONCLUSION

Accurately estimating the junction temperature of IGBT modules allows for the condition monitoring and lifetime prediction of power converter systems, and is therefore crucial for reliable analysis and operation in industrial applications. Various junction estimation technologies focusing on the direct measurement methods, thermal model-based methods and TSEP-based methods have been discussed with advantages and limitations, respectively. However, the development of reliable and cost-effective technologies remains a challenge. Future research should focus on the development of reliable and accurate estimation techniques that take into account dynamic load conditions and aging effects, leading to more effective condition monitoring and proactive maintenance strategies.

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