Letters

Evaluation of V_{ce} at Inflection Point for Monitoring Bond Wire Degradation in Discrete Packaged IGBTs

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***Abstract*—A novel scheme is proposed for online condition monitoring of bond wires present in insulated gate bipolar transistor (IGBT) package. The proposed method detects bond wire degradation using on-state collector emitter voltage at the inflection point. Previously reported condition monitoring methods based on on-state collector-emitter voltage as a precursor of aging require an accurate knowledge of junction temperature which is difficult to measure online during an inverter operation. The key advantage of the proposed scheme is that it monitors the bond wire degradation irrespective of the junction temperature. Therefore, this technique is not affected by increase in junction temperature due to die attach degradation or change in ambient temperature. The proposed scheme is verified experimentally under realistic operating conditions.**

***Index Terms*—Bond wire degradation, insulated gate bipolar transistor (IGBT), online condition monitoring (CM).**

I. INTRODUCTION

IN THE past few decades, role of power electronic circuits for renewable energy applications, such as solar photovoltaic (PV) systems and wind turbines, is of increasing interest. In addition to efficiency, power density, and cost, reliability is now one of the major factors taken into consideration while designing inverters for any application. Power semiconductor devices form an integral part of inverter and are critical for reliable operation of the entire system.

Earlier, military handbook techniques were used for determining the reliability of power semiconductor devices [1]. However, military handbook techniques are based on statistical data gathered from identical products. This may lead to erroneous results. This called for a paradigm shift to the "Physics-of-Failure"-based analysis to determine the reliability of power semiconductor devices [2]. Power semiconductor devices may fail due to either chip related failures (latch up, device burnout, dielectric breakdown, etc.) or due to package related failure (bond wire degradation, solder fatigue, etc.). With aging, the device become more prone to failures due to package related issues [3]. The internal structure of an insulated gate bipolar transistor (IGBT) package, consisting of different layers, is shown in Fig. 1. During an inverter/converter operation, the junction temperature of the power semiconductor device varies due to various factors like sinusoidal loading, change in load current, change in ambient temperature, etc. Due to a difference in the coefficient of thermal expansion (CTE) between the chip and the bond wires, shear stresses are induced between them which degrades the wire joints (bond-wire degradation). In addition to it, the difference in CTE between the chip and the copper tab leads to a fatigue in the solder layer (die attach degradation) [4]. Condition Monitoring (CM) provides an intelligent approach for improving the availability of the system by anticipating the failure of devices and planning a scheduled maintenance [5]. This letter focuses on the CM of bond wire degradation. Various methods for CM of bond wire are suggested in literature.

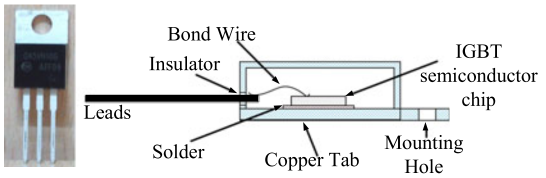

Fig. 1. Cross-sectional view of TO-220 Package of IGBT.

In [6], it is shown that the on-state collecter-emitter voltage of an IGBT increases with ageing. The ageing causes bond wire degradation resulting in an increase in on-state resistance, and consequently, the collecter-emitter voltage. However, the on-state collecter–emitter voltage drop depends not only on ageing but also on the junction temperature and current through the device. Therefore, it is not accurate to determine the health of bond wire by monitoring only the on-state collecter-emitter voltage drop.

In [7], a health monitoring algorithm is proposed in which the on-state resistance of a metal-oxide field-effect transistor (MOSFET) and voltage drop across the *pn* junction and drift region are extracted. Considering inverter operation, the current flowing through the device is not constant and varies with the fundamental frequency. This leads to variation in junction temperature. In case the on-state resistance is measured using two different values of collecter current and their corresponding collecter-emitter voltages, the calculation of on-state resistance

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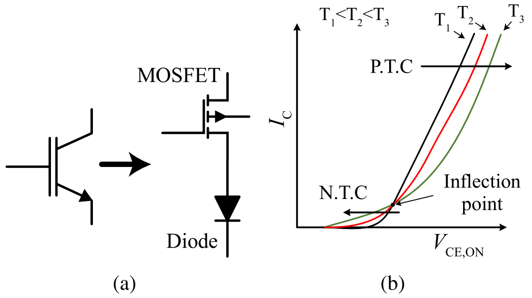


Fig. 2. (a) Representative model of an IGBT. (b) Inflection point.

could lead to inaccurate results due to difference in junction temperature at these two instants.

In [4], the on-state collecter–emitter voltage is measured by injecting currents of different magnitude. The high magnitude current is used for determining bond wire degradation and the low magnitude current is used to estimate the junction temperature, when the converter is idle. However, this method may not be applicable for online monitoring in various other applications, due to requirement of idle period and controlled injection of small and large current pulses.

In summary, without an accurate knowledge of junction temperature, an increase in the on-state collector–emitter voltage cannot be attributed to bond wire degradation. Accurate estimation or measurement of on-line junction temperature leads to an increase in cost and complexity. In this letter, a novel method is proposed to monitor the changes in on-state collecter–emitter voltage at the inflection point to account for bond wire degradation. This method does not require a junction temperature estimation. Further, it separates other effects of degradation due to aging and thus, accurately estimates the health of the bond wire contacts.

II. PROPOSED SCHEME

In order to determine the health of bond wires inside the IGBT, a method involving the measurement of on-state collector–emitter voltage at the inflection point is proposed.

The IGBT is modeled as a diode and MOSFET in series as shown in Fig. 2(a) [4]. The total voltage drop across the IGBT during on-state is given by

$$V_{\mathrm{CE,ON}} = V_{\mathrm{Diode}} + V_{\mathrm{MOSFET}} \tag{1}$$

where, $V_{\mathrm{CE,ON}}$ is the on-state collector–emitter voltage, V_{Diode}, and V_{MOSFET} are the voltages across the modeled diode and MOSFET, respectively. The diode has negative temperature coefficient (NTC) while the MOSFET has a positive temperature coefficient (PTC). Hence, the on-state collector emitter voltage of an IGBT as a function of junction temperature T_{j} and collector current, I_{CE} is given as [4]

$$\begin{aligned} V_{CE}(T_{\mathrm{j}}, I_{\mathrm{CE}}) = &\ [V_{\mathrm{D0}} - \alpha(T_{\mathrm{j}} - T_{\mathrm{j0}})] \\ &+ [R_{\mathrm{on0}} + \beta(T_{\mathrm{j}} - T_{\mathrm{j0}})] \times I_{\mathrm{CE}} \end{aligned} \tag{2}$$

where, α and β are the temperature coefficient of the diode and the MOSFET, respectively. V_{D0} and R_{on0} are the voltage drop across the diode and the resistance of the MOSFET at the reference temperature T_{j0}, respectively.

At low current, the temperature coefficient of the IGBT is governed by the characteristics of the diode voltage drop. As current level increases, the voltage drop across MOSFET becomes predominant. This causes the IGBT characteristics to shift from NTC to PTC, as shown in Fig. 2(b). The current at which the characteristics of IGBT shifts from negative to positive temperature coefficient is called as the inflection point. Therefore, the on-state collecter–emitter voltage drop across IGBT at the inflection point is independent of junction temperature.

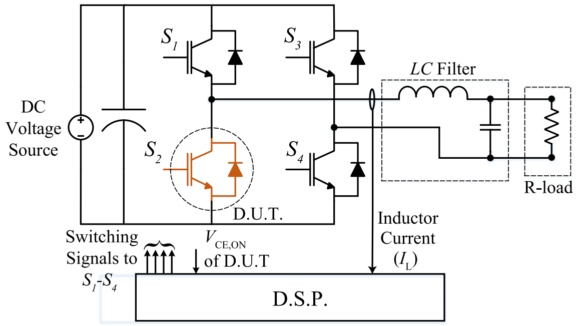


Fig. 3. FB inverter with D.U.T. along with measurement scheme.

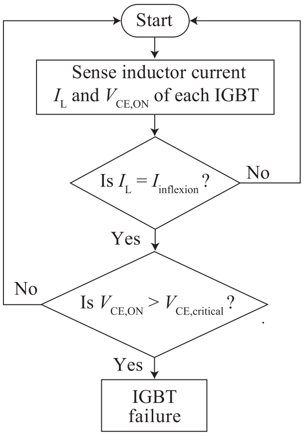
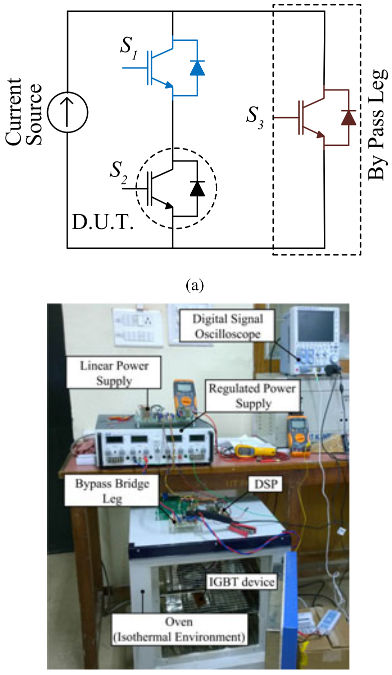


Fig. 4. Flowchart of bond wire degradation CM method.

In the proposed method, the on-state collector emitter voltage is measured at the inflection point. Any increase in the on-state collector–emitter voltage is attributed to bond wire degradation.

A circuit of the full-bridge (FB) inverter is shown in Fig. 3. Switch S_2 is used as device under test (DUT). However, the proposed scheme is applicable for all four devices in the inverter. The flowchart of the proposed scheme when used along with the FB inverter is shown in Fig. 4. The inductor current is continuously monitored by the controller. Whenever this current equals the inflection current, the on-state voltage of IGBT is measured. This voltage is compared with its critical value to determine the health of IGBT.

The current at which inflection point occurs in the IGBT's characteristics depends on the gate voltage and silicon die characteristics. It does not depends on the die temperature, solder fatigue, and bond wire degradation. In case of accelerated aging (thermal and power cycling), different coefficients of expansion leads to development of thermomechanical stress, which causes solder fatigue or bond wire degradation. However, these phenomena do not affect the silicon die characteristics. Hence, it can be said that the power semiconductor switch fails due to thermomechanical stress and these degradation processes do not affect the current at which inflection point occurs and this point (inflection point current) remains constant with accelerated aging. The key advantage of this method is that the current at



(a)

(b)

Fig. 5. (a) Circuit for characterization of an IGBT. (b) Experimental Setup.

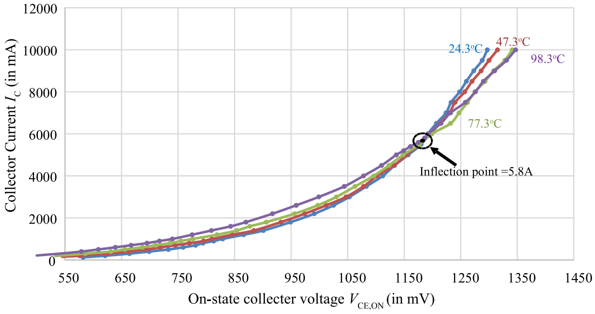


Fig. 6. Inflection point in IGBT characteristics.

which the voltage across the IGBT is measured is independent of its junction temperature. In the previous CM methods based on online on-state collector–emitter voltage measurements, this dependency of junction temperature on monitoring the health of bond wires serves as a major drawback. It is difficult to accurately determine the cause of change in the on-state collector–emitter voltage, which can be either due to ageing or changes in loading or ambient temperature. Further, since the proposed method is independent of the junction temperature, die-attach degradation does not affect the prediction of bond wire health.

III. EXPERIMENTAL RESULTS AND ANALYSIS

The proposed scheme requires the knowledge of inflection point, which is determined by the characterization of a healthy IGBT. For the validation of proposed scheme experimentally, the DUT is included in the inverter and the $V_{\mathrm{CE,ON}}$ at inflection point is monitored. For accelerated ageing of DUT, a dc power cycling method is used. STMicroelectronics made STGP40V60F discrete IGBT is used for experimentation.

A. Characterization of IGBT for Determining the Inflection Point

For characterization of the IGBT, the DUT [shown in Fig. 5(a)] is kept in the thermal chamber and a fixed value of dc current is set on the dc current source. The DUT is continuous provided with a high gate signal. S_3 is kept ON from the beginning and S_1 is kept OFF. For a short duration, S_3 is turned OFF and S_1 is turned ON to allow the flow of current from the DUT. Voltage across the DUT is measured during this short period, after which S_1 is again turned OFF and S_3 is turned ON. The dc current source is allowed to maintain its set current value without any change. During transition (turning ON/OFF of the devices S_1 and S_3), it is ensured that at least one of these two devices is always ON by providing an overlap in their gate signals. This provides a continuous path for the dc source current. Further, devices S_1, S_2, and S_3 are placed as close as possible to minimize loop inductance, thereby avoiding overvoltage conditions during transients. The experimental setup is shown in Fig. 5(b). During the characterization procedure, it is ensured that the DUT does not self-heat. Hence, current is allowed to flow only for a short period of 500 μs through it. The above process is repeated for various value of currents (set in the dc current source) to determine the variation of $V_{\mathrm{CE,ON}}$ with the collector current. This experiment is repeated for different temperatures (in the thermal chamber) to generate $V_{\mathrm{CE,ON}}$ versus I_{CE} curves for various temperatures, as shown in Fig. 6.

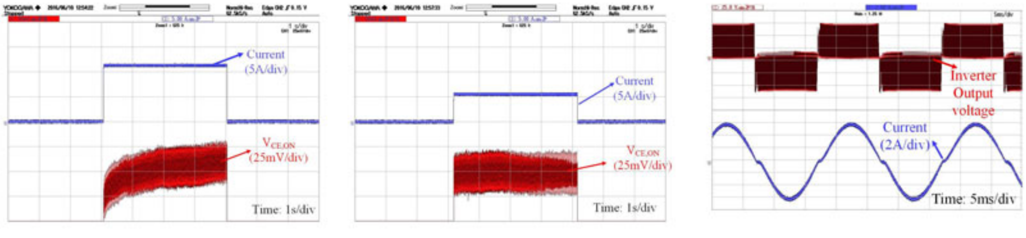
The inflection point is found to be at 5.8 A for a gate voltage of 15 V. Even a tolerance of $\pm$ 5% in the inflection point (current), due to fabrication process, would lead to variation of about 5 mV (maximum) as temperature varies from 24.7 to 98.3 °C, as observed from Fig. 6. Due to small variations of $V_{\mathrm{CE,ON}}$, characterization of single IGBT is sufficient, provided that all the IGBTs used in inverter are made by same manufacturer, are of same rating and manufactured in the same batch.

B. Accelerated Ageing of IGBT

Fig. 5(a) is also used as a dc power cycling setup for the accelerated aging of the IGBT. A constant dc current of 11 A is fed in to the DUT for 4 s, by keeping switch S_1 ON. This leads to an increase in the junction temperature due to the conduction loss in the switch. Switch S_1 is then turned OFF for 6 s, which allows the device to cool down to its initial temperature. During this period switch S_3 conducts, allowing path for the dc source current. The on-state voltage of DUT is measured just after S_1 is turned ON and just before it is turned OFF. Fig. 7(a) and (b) shows the increase and decrease in $V_{\mathrm{CE,ON}}$ when injected current is greater and equal to inflection point current magnitude, respectively.

C. Real Time Monitoring of $V_{\mathrm{CE,ON}}$

In order to measure the on-state collecter–emitter voltage drop of the IGBT during inverter operation, a measurement circuit is integrated with the IGBT gate driver card. Operation of the circuit is discussed in [8]. Fig. 8 shows the block diagram of the smart gate driver. This smart gate drive includes normal gate driver functions, such as gate signal isolation, current amplification, and desaturation protection. In addition, it is capable of measuring $V_{\mathrm{CE,ON}}$. Further, isolation error amplifier, ADuM3190 is used to provide isolation between the output of measurement circuit and the analog to digital converter of digital signal processor.



(a) (b) (c)

Fig. 7. Experimental results: (a) Variation in $V_{CE,ON}$ (25 mV/div) 11 A (current greater than inflection point current), time: 1s/div (b) Variation in $V_{CE,ON}$ (25 mV/div) at 5.8 A (inflection point), time: 1 s/div (c) Inverter voltage (25 V/div) and inductor current(5 A/div); time: 5 ms/div.

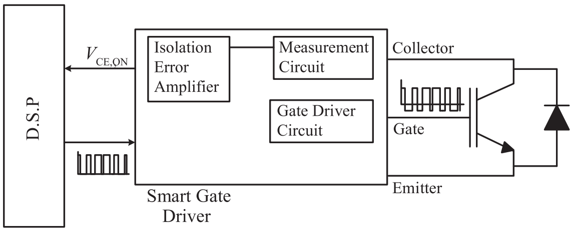


Fig. 8. Measurement of on-state voltage.

TABLE I
PARAMETERS OF INVERTER

Inverter Parameters	*Values*
DC link voltage	70 V
DC link capacitor	470 μF
Peak current	6.5 A
Inductor (Filter)	1.5 mH
Capacitor (Filter)	10 μF
Modulation Scheme	Unipolar Modulation

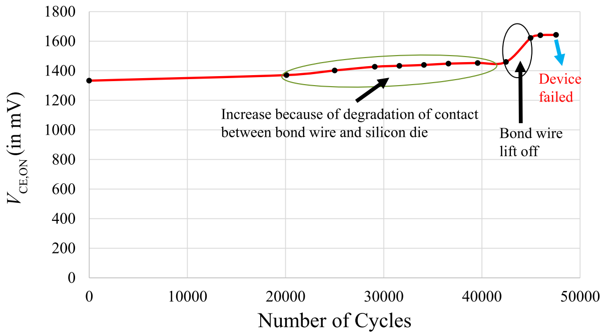


Fig. 9. Evolution of $V_{CE,ON}$ with ageing.

D. Validation of Proposed Scheme

To experimentally validate the proposed scheme, a FB inverter laboratory prototype is developed. It uses one STMicroelectronics made STGP40V60F discrete IGBT as DUT and remaining three switches from an IGBT module (FSBB20CH60C) as shown in Fig. 3. The parameters of the inverter are given in Table I. Fig. 7(c) shows the output voltage of inverter and inductor current.

Due to operation of the inverter, the current through DUT varies. The $V_{CE,ON}$ is measured at the instant when inductor current is equal to its value at inflection point (5.8 A). The plot of $V_{CE,ON}$ at inflection point and operational cycles (accelerated aging) is shown in Fig. 9. Initially, $V_{CE,ON}$ increases gradually with the number of power cycles. At about 45 000 cycles, bond wire lifts off and this is observed by a sudden jump in the $V_{CE,ON}$. This leads to an increase in $V_{CE,ON}$ by 20% as compared to its starting value. After this point, the on-state resistance of the device increases, due to less number of bond wires available for the current flow. This results in increase in junction temperature, which leads to catastrophic failure of the device due to thermal runaway at 49 000 cycles.

IV. CONCLUSION

This letter proposes a method to monitor the bond wire degradation by measuring the on-state collector–emitter voltage at the inflection point. An increase in this voltage is attributed to degradation of the contacts between the bond wire and silicon die junction. The key advantage of the proposed scheme is that it does not require additional temperature sensors. However, this method can only be used for semiconductor device, which offer both NTC and PTC within operating characteristics , such as IGBT. This method is not applicable for diodes or MOSFETs. In order to validate the proposed scheme, an experimental setup is made. In the experimental setup, the IGBT is aged and it is observed that the on-state collector–emitter voltage at inflection point increases as the IGBT ages due to the bond wire degradation. Bond wire lift off is observed at 45 000 cycles. Based on this, an increase of $V_{CE,ON}$ by 20% is set as the critical value for determining health of the DUT.

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