Thermal Breakdown Failure Mechanisms of IGBT Chips

Tang Yong*, Wang Bo and PANG Qiu

College of Mechanical and Electronic Engineering, Wuhan Donghu University, Wuhan 430000, Hubei Province, China

*E-mail address of corresponding author: tangyong_tt@163.com; Tel.13871152506

Abstract. As insulated gate bipolar transistors (IGBTs) become widely used in all kinds of power conversion systems, the demands of power converters to the IGBT’s reliability turn to be more stringent. Thus, investigations of the IGBT’s internal failure mechanism are very important to guarantee the improvements of device reliability and the optimizations of design and applications. Previous researches concentrate on the external factors of the device failures which are the failure modes. However, it lacks thorough studies of the internal mechanism which ultimately causes the device failure. In this paper, the analysis of the internal mechanism of thermal breakdown, has been presented based on the detailed investigations of the IGBT’s structure and operation principles, applying the semiconductor physics theory. In addition, the existing misunderstandings on the IGBT’s failure mechanism in the normal applications have been pointed out. Finally, experiments were designed to rebuild the failure process with the online monitoring through the high speed thermal infrared imager. This further verified the proposed conclusion and ascertained the internal failure mechanism of the IGBT chips.

1. Introduction

The IGBT is a power semiconductor device with an insulated gate input like that of a power MOSFET but with the low on-state resistance of a power bipolar transistor, which has the advantages of easy drive, high power rates, low power consumption, good thermal stability and etc [1]-[2]. Since the invention of IGBTs in 1980’s, there have been great progresses in low power consumption and high controllability which covers the voltage range of 600V~6500V and the current range of 1A~3600A. Furthermore, the IGBT has been used in all kinds of medium and high rates power electronic components and becomes the currently most widely used full control power electronic device [3]-[5]. Because the power electronic device is the most critical part in power electronic systems, its reliability turns to be the most important factor determining the safe operations of the whole system. According to a survey from foreign research institutes based on over 200 products from 80 companies, nearly 40% of power electronic faults are due to the device failures [6]. As the applications of IGBTs become prevailing in AC speed regulation, wind power and high speed electric locomotives, the IGBT’s operation voltage and current rates increase rapidly. More stringent requirements to the IGBT’s reliability have also been put forward due to the increasing abominable working environments and harsher application conditions [7]-[9]. Therefore, investigations of the internal mechanisms of the IGBT failures are required to improve the device reliability and to guarantee the safe operations so that corresponding actions can be taken to implement reasonable plans and optimizations at the design stage.

The present high-power IGBTs use the module package which integrates IGBT chips and reverse parallel diodes in the same module. Bond wires are used to connect the chip with the external pads.
There are multiple layers between the chip and the case bottom plate such as the copper layer, the DCB layer, the base plate and so on, which are welded through solder. The IGBT failures can be categorized into the chip-induced failure and the package-induced failure according to the failure locations. The package-induced failure is the fatigue of the package materials after a long time operation of the device and this failure happens to bond wires and solder layers. This is because of the repeated impact of the thermal gradient and the thermal stress due to different thermal expansion coefficients of the materials. Many researches on the IGBT package failure have been reported and the failure mechanism has been partially ascertained [10]-[14].

The IGBT chip failure can have various causes such as power or load swing, driver or controller faults, heat sink issues and short-circuit, all of which can be ultimately attributed to electronic voltage and thermal breakdown. Fewer researches on the IGBT chip failure has been carried out so far and the previous work only concentrates on the external factors of the failure such as over voltage, over current and short-circuit. It still lacks the studies on the internal mechanisms of failures and the substantial relationship between voltage breakdown and thermal breakdown.

In this paper, the analysis of the basic principle of thermal breakdown for IGBT failures, was supplied and some misunderstandings on chip failures were pointed out. Furthermore, experiments were designed to rebuild the failure process with the on-line monitoring through the high precision digital oscilloscope and the high speed thermal infrared imager. This ascertained the internal mechanisms of the IGBT chip failures and provided a conclusion to guide device applications and reliability analysis [15]-[17].

2. IGBT Structure and Operation

An IGBT chip is built with thousands of parallel connected cells which have common P+ emitters and N- bases while separate gates and P+ collectors. In Figure 1, the part within the dash line shows a PT (Punch Through) or FS (Field Stop) IGBT, and the NPT (Non Punch Through) IGBT has the same structure except the elimination of the N+ buffer layer or the field stop layer.

![Figure 1. IGBT cell structure](image)

As shown in figure 1, every IGBT cells can be considered as the compound structure of PNP transistors and N-channel MOSFETs. The P+ substrate at the bottom is the emitter of the internal BJT which is also connected to the anode of the IGBT. The N- epitaxial layer in the middle is also the N- base of the internal BJT and the drain of the MOSFET. The P+ body at the top is the collector of the internal BJT, above which is the N+ source of the MOSFET. When the gate-cathode (or gate-source of the internal MOSFET) voltage is larger than the threshold, an inversion layer will occur on the surface of the P+ collector under the gate. This also forms the N-channel of the MOSFET through which the electrons flow from the N+ source to the N- base. If the IGBT is forward biased which has a positive voltage across the anode-cathode, the holes will be injected from the P+ emitter to the N- base and finally the injected electrons and holes will form a stable distribution in the base. Then the IGBT enters the forward conducting state in which both the P+ emitter/N+ junction (J1) and the P+ collector/N+ junction (J3) are forward biased while the N-/P+ collector junction (J2) is reverse biased.
The reverse biased J2 junction then generates a depletion region with the width increasing as the applied junction voltage rises. The voltage breakdown and thermal breakdown will happen when the applied voltage and the leakage current over the reverse biased PN junction exceed the limitation, according to the semiconductor physics theory[18]-[19]. Therefore, the IGBT failure has very tight correspondence with the operation states of J2 junction.

3. Thermal Breakdown Failure Mechanism

During the operation of the IGBT, the generated power is dissipated through the heat sink, leading to the rise of the chip temperature. Failures will then occur after the temperature exceeds the limit. Therefore, the device manuals specify the limitations of the junction temperature during operation, such as 125℃, 150℃ and etc. Those limitations actually restrict the application ranges of operation current, voltage and duty cycle, and further put forward detailed requirements to the external heat dissipation conditions.

The IGBT module used in this paper is a GD50HFL120C1S with 125℃ the maximum allowable junction temperature. A thermostatic container is used to control the junction temperature. The dual-pulse operation mode is implemented and figure 2 (a) and figure 2 (b) show the measured waveforms of the turn-off voltage and current under different temperatures.

As shown in figure 2, the IGBT can still switch normally even when the temperature reaches 215℃ which is much higher than the allowable value in the manual, and no failures occur although the turn-off becomes slower. This indicates that the maximum junction temperature in the manual is a conservative safety range or an industrial standard while not necessarily the failure temperature. In addition, the melting point and intrinsic temperature of the silicon-fabricated IGBT chip are much higher than this rated temperature. In fact, the maximum operation temperature of the IGBT chip is determined by the leakage of the reverse biased PN junction and the thermal breakdown failure.

During the normal operation of IGBTs, only J2 junction is reverse biased and thus the leakage current mainly consists of the reverse current of J2 junction, which means the thermal breakdown theory of PN junction is still applicable to the IGBT. Because of the heavy and lightly doping in P+ collector and N- base respectively, J2 junction belongs to P+N type in which the reverse leakage current $I_R$ can be described by (1) [20].

$$I_R = \frac{qn_i^2 A_s \sqrt{D_p}}{N_D \sqrt{\tau_p}} + \frac{qn_i A W}{\tau_w}$$

(1)

Where $q$ is the electron charge constant, $n_i$ is the intrinsic electron concentration, $N_p$ is the doping concentration of N- base, $D_p$ and $\tau_p$ are the diffusion coefficient for holes and the hole lifetime

![Figure 2. IGBT turn-off wave under different temperature](image-url)
respectively, $\tau_{sc}$ is the lifetime of the extra carriers in the space charge region, $W$ is the width of the space charge region and $A$ is the chip conduction area.

Because $n_i$ increases exponentially with the temperature rise, $I_R$ also increases as temperature rises, especially at high temperatures during which abrupt changes happen. From the experiment results, the leakage current of an IGBT can increase from 100uA at ambient temperature to 200mA at 200°C, which is a thousand times larger. This abrupt change of the leakage current at high temperature leads to the increase of power loss during turn-off, especially for the high-power IGBT in which only several hundred mA of leakage current can generate noticeable power loss because of the high voltage drop at off-state. Except for the loss due to the leakage current, the switching loss and conduction loss also increase as temperature rises but are less significant than the leakage loss. There exists a positive feedback between the total power loss and the temperature, resulting in the thermal breakdown of the PN junction as temperature rises to a certain value under a given heat sink condition, as shown in figure 3.

![Figure 3. Schematic of IGBT thermal balance](image)

In figure 3, the $P_{heat}$ curve (heat generating curve) is also the power consumption curve of the IGBT which includes the switching loss, the conduction loss and the leakage-induced turn-off loss, presenting a positive exponential relationship with the temperature rise. The increase of $P_{heat}$ will lead to the rise of $T_J$, which further increases $P_{heat}$. Therefore, there exists a positive feedback between $P_{heat}$ and $T_J$, and they will keep increasing until reaching the thermal balance. The $P_{cool}$ curve (heat dissipation curve) shows the power dissipated by the external heat sink and can be described by (2).

$$P_{cool} = \frac{T_J - T_C}{R_{thJC}} = \frac{1}{R_{thJC}} T_J - \frac{T_C}{R_{thJC}}$$ (2)

Where $T_J$ is the junction temperature, $T_C$ is the case temperature, $R_{thJC}$ is the thermal impedance between the junction and the case. $P_{cool}$ is linearly proportional to $T_J$ and shifts to the positive direction of $T_J$ as $T_C$ increases, generating three cases: crossing over $P_{heat}$, being tangential with $P_{heat}$, and apart from $P_{heat}$. If $P_{heat}$ and $P_{cool}$ intersect at point A and B, then $P_{heat} > P_{cool}$ below point A, which means the generated power is larger than the dissipated power and $T_J$ keeps increasing. When $T_J$ reaches point A, $P_{heat} = P_{cool}$ and the chip reaches the thermal balance, maintaining a stable temperature. For the section between A and B, $P_{cool} > P_{heat}$, and $T_J$ will then drop back to balance point A. For the section above point B, $P_{heat} > P_{cool}$, $T_J$ will rise and can no longer achieve the thermal balance. After that, $T_J$ and the power consumption enter a positive feedback cycle as described above, leading to the thermal breakdown of the PN junction ultimately. Finally, the chip temperature rises quickly to the intrinsic value and short-circuit occurs. Therefore, point B can be
called the unstable point, that is, the maximum operation temperature of IGBTs corresponding to a certain case temperature (heat dissipation). In another case, when shifting $P_{\text{cool}}$ curve to the positive direction of $T_j$ axis, points A and B and C will overlap once $P_{\text{cool}}$ is tangential with $P_{\text{heat}}$, generating the maximum stable temperature under the worst heat dissipation condition. Figure 4 summarized the different critical operation temperatures of the IGBT.

![Figure 4. The key point of IGBT work temperature](image)

As shown in figure 4, $t_1$ is the melting point of semiconductor chips which is around 1360°C for silicon. $t_2$ is the intrinsic temperature of the silicon material above which the chip temperature will rise quickly until reaching $t_1$ because of the short-circuit of PN junction due to the low impedance plasmas in the chip. $t_2$ rises as the doping concentration increases and it normally ranges from 300°C to 700°C. $t_3$ is the thermal unstable operation point of the chip, correlating with the chip power consumption, thermal impedance and heat dissipation conditions while being determined by the thermal breakdown temperature.

4. Thermal Breakdown Experiments

In this paper, the above thermal balance and thermal breakdown failure mechanism of the IGBT are verified by means of leakage current experiments. After being heated for 15~20 minutes by the thermostatic container, the junction temperature and the case temperature of the IGBT module can be considered the same as the preset temperature. In the testing module, the gate was shorted and the off-state voltage was applied across the anode-cathode. The leakage current was measured by the series connected digital multimeter from Agilent. The case temperature was measured through the thermocouple below the base plate. An air switch was used to control the on/off of the loop which also adopted a series connected protection and a resistor load to limit the short-circuit current. After the bus capacitors were fully charged, the charge loop was then opened and the breakdown energy was controlled only by the charged capacitors with a preset off-state voltage of 800V. Since the reverse parallel diodes also generate leakage current, the bond wires of those diodes were cut off during the measurements (the thermal breakdown mechanism of diodes is simple). The first step is to measure the leakage power: increasing the temperature by 10°C/step from the room temperature, closing the switch immediately after the temperature was stable and then recording the leakage current value, then cutting off the switch quickly after the recording to avoid the self-heating of the leakage current. The second step is to test the thermal balance: increasing the case temperature from 100°C with 10°C/step, and then closing the switch for a long time at each step point, observing the change of the leakage and case temperature. The junction and case temperature will rise due to the chip self-heating effect by the influence of the leakage power, which further leads to the increase of the leakage current. The generated power and the dissipated heat can reach thermal balance in the beginning, showing that both the leakage current and the case temperature stabilize gradually after reaching a certain value. However, with the initial temperature being 215°C, the leakage current increases...
abruptly until the thermal breakdown happens after the switch is closed for a long time. The chip temperature rise to the intrinsic temperature afterward which results in short-circuit of the PN junction and the abrupt rising of the current, melting the fuse and discharging all the capacitors. Figure 5 shows the chip photo after the thermal breakdown happened.

As shown in figure 5, there is an obvious burning track which is small in the IGBT chip because the total power has been limited by the capacitors. It is measured that the voltage across the anode-cathode was two forward diode voltage drops due to the low impedance of the breakdown of J2 junction, and the anode-cathode was reverse blocked (no failures happened to the collector and emitter diodes). In normal applications, the circuit short in the same bridge will lead huge short current, which melts the chip and bond wires very quickly, resulting in the open-circuit of the external ports.

The P-T curve of $P_{\text{leak}}$ is obtained by multiplying the leakage current with the off-state voltage at different temperatures. The P-T curve of $P_{\text{cool}}$ is calculated using the case temperature and the case-to-junction thermal impedance. Figure 6 shows the thermal balance relationship between $P_{\text{leak}}$ and $P_{\text{cool}}$ curves.

As shown in figure 6, $P_{\text{cool}}$ curve shifts to the positive direction of the T axis as the initial case temperature rises. $P_{\text{cool}}$ and $P_{\text{leak}}$ always intersect from the beginning which means the leakage power and the dissipated power can reach thermal balance at the intersection point. As the case temperature keeps rising, $P_{\text{cool}}$ will be tangent to $P_{\text{leak}}$, reaching the maximum balance temperature at the tangential point. The calculated case temperature at the tangential point is 209°C which is around 6°C lower than the measured value. This difference is mainly caused by the inevitable self-heating of the junction due to the leakage current even with a very short closing time of the switch during the testing. The self-heating then causes the rise of the chip temperature which leads to the increase of the leakage current, resulting in a higher case temperature at thermal balance. During the continuous operation, the on-state voltage and the switching power increase as temperature rises but not as abrupt as the leakage current. In fact, their effect to the total power is to lift up $P_{\text{heat}}$ curve which reduces the thermal breakdown temperature. As shown in figure 5, the case temperature corresponding to the tangent curve of $P_{\text{heat}}$ is 139°C, obtaining that the leakage current dominates during the abrupt change of the power.

5. Conclusion
In this paper, the internal mechanisms of the IGBT failures were ascertained, and conclusions were obtained about the thermal breakdown of the IGBT. This further provides practical instructions to the reliability and application designs of the IGBT.

1) Thermal breakdown exists in the PN junction of the IGBT. A positive feedback exists between the leakage current and the temperature in which an abrupt increase of the current will occur once the
temperature reaches the thermal unbalance point, resulting in the intrinsic short-circuit and the burn-out of the chip.

2) The maximum operation temperature of IGBTs is restricted by the balance between the total chip power and the heat dissipation instead of a single provided temperature. In addition, the maximum temperature is also related to the IGBT’s electrical characteristics (leakage current, on-state voltage drop, switching frequency), heat transfer characteristics (heat impedance), and external heat sink characteristics (case temperature).

References

[1] Majumdar G, Minato T. Recent and future IGBT evolution[C] Power Conversion Conference, Nagoya, Japan ,2007:355-359.
[2] Zhou WenDing, Kang BaoWei. The Summary on Continuous Development of IGBT Technology[J].Power Electronics, 2008, 41(9):115-118.
[3] Xiao Huafeng, Xie shaqian. A ZCS PWM current-fed half-bridge converter with reverse block IGBT[J].Proceeding of the CSEE, 2007, 27(31):110-114(in Chinese).
[4] Cai Hui, Zhao Rongxiang, Chen Huiming, et al. Study on multiple-frequency IGBT high frequency power supply for induction heating[J].Proceeding of the CSEE, 2006, 26 (2): 154-158(in Chinese).
[5] Tang Yong, Chen Ming, Wang Bo. Switching Transient Model of Field-Stop IGBT[J]. Proceedings of the CSEE, 2011 , 31 (30): 54-60.
[6] Shaoyong Yang, Dawei Xiang, Philip Mawby, et al. Condition Monitoring for Device Reliability in Power Electronic Converters: A Review[J]. IEEE Trans. on power electronics, 25(11):2734-2752.
[7] Lixiang Wei, Richard A Lukaszewski, Thomas A Lipo. Analysis of Power Cycling Capability of IGBT Modules in a Conventional Matrix Converter[J]. IEEE Transactions on industry applications, 2009, 45(4): 1443-1451.
[8] M. Ciappa, F. Carbognani, W. Fichtner. Lifetime prediction and design of reliability tests for high-power devices in automotive applications[J].IEEE Trans. on Device Mater, 2003, 3(4): 191-196.
[9] D. Hirschmann, D. Tissen, S. Schröder, et al. Reliability prediction for inverters in hybrid electrical vehicles[C]/ In Proc. IEEE PESC, Jeju, Korea, 2006 :1–6.
[10] S. Ramringer, G. Wachutka.Predicting the crack progression in PbSnAg-solder under cyclic loading[C]/In Proc. CIPS, Naples, Italy, 2006: 75–80.
[11] Onuki J, Masahiro Koizumi, Masateru Suwa. Reliability of thick Al wire bonds in IGBT modules for traction motor drives[J]. IEEE Trans. on Advanced Packaging, 2000,23(1) : 108-112.
[12] Akira Morozumi, Katsumi Yamada, Tadashi Miyasaka, et al. Reliability of power cycling for IGBT power semiconductor modules[J]. IEEE Trans. on industry applications, 2003, 39(3):665-671.
[13] A.Hamidi,N.Beck,K.Thomas, et al. Reliability and lifetime evaluation of different wire bonding technologies for high power IGBT modules[J].Microelectronics Reliability, 1999, 39(1999): 1153-1158.
[14] J. Lehmann, M. Netzel, R. Herzer, et al. Method for electrical detection of bond wire lift-off for power semiconductor[J]. In Proc. Int. Symp. Power Semiconductor Devices IC’s, 2003:333-336.
[15] G E Leyh. A critical analysis of IGBT geometries, with the intention of mitigating undesirable destruction caused by fault scenarios of an adverse nature[C]/ In Proc. Pulsed Power Conf., 2003:366–368.
[16] Michael J. Barnes, Ewart Blackmore, Gary D. Wait. Analysis of High-Power IGBT Short Circuit Failures[J]. IEEE Transactions on plasma science, 2005,33(4):1252-1261.
[17] Musumeci, S. Pagano, R. Raciti, A. A new gate circuit performing fault protections of IGBTs during short circuit transients[C] 37th IAS Annual Meeting. Conference , 2002:2614 – 2621.
[18] R.M.Warner, B.L.Grung.Semiconductor device electronics[M]. Beijing: Publishing House of Electronics Industry, 2005:219-232.
[19] Vitezslav Benda, John Gowar, Duncan A.Grant. Power Semiconductor devices:Theory and Applications[M]. Beijing: Chemical Industry Press, 2005:39-44(in Chinese).
[20] Chen Zhihong, Li Shouzhi. Wide Enegy Bandgap Semiconductor Power Electronics Devices [M]. Beijing: China Machine Press, 2009:43-51.