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Research on Breakthrough Failure of IGBT Chip

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Research on Breakthrough Failure of IGBT Chip

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Abstract. In large-capacity power electronic devices, fully controlled power electronic devices, such as insulated gate bipolar transistors (IGBT), which are widely used at present, are the core components to realize high-performance power conversion and control. With the increasingly wide application of IGB, its voltage, current level and working junction temperature are getting higher and higher, and its working environment is also getting worse, putting more and more stringent requirements on reliability, and the reliability of power electronic devices has also become the most important factor determining the safe operation of the whole device. Therefore, finding out the internal mechanism of IGBT failure is an important guarantee for improving the reliability of device operation and realizing optimal design and application. The research that has been carried out mainly focuses on various external factors that cause failure, namely various failure modes of IGBT, and lacks in-depth research on the internal mechanism of final failure. On the basis of in-depth analysis of IGBT's structure and working principle, this paper analyzes the internal mechanism of IGBT's breakdown failure with semiconductor physics theory, finds out the fundamental principle of causing failure, and designs experiments to reproduce the occurrence of failure, thus further verifying the conclusion reached in the analysis.

1. Introduction

With the rapid development of the national economy, the use of various power electronic devices to efficiently and reliably transform and control the generation, transmission and use of electric energy has become an indispensable and important link in the fields of electrical applications such as energy conservation and emission reduction, rail transit, and the development of new energy sources. Among these power electronic devices, fully controlled power electronic devices, such as insulated gate bipolar transistor (IGBT), which is widely used at present, are the core components to realize high-performance power conversion and control [1-[3]. With the increasingly wide application of IGBT, its voltage, current level and working junction temperature are getting higher and higher, and its working environment is also getting worse, which puts forward more and more strict requirements for reliability [4]-[5]. After investigating more than 200 products from 80 companies, foreign research institutions found that nearly 40% of power electronic device failures are caused by device failures, so the reliability of power electronic devices has also become the most important factor determining the safe operation of the whole device [6]-[7]. Therefore, in order to ensure the safe and reliable operation of IGBT, it is necessary to master the fundamental principle of its failure, which is of great significance to the study of causing its breakdown.

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 [8]-[11].

In this paper, the analysis of the basic principle of voltage 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 [12]-[14].

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.

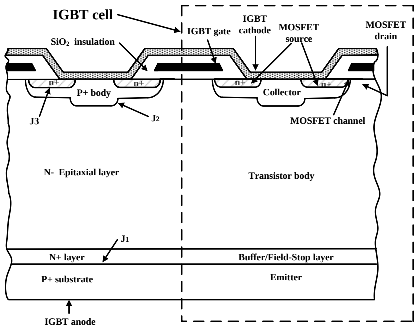


Figure 1. IGBT cell structure

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 [15]-[16]. Therefore, the IGBT failure has very tight correspondence with the operation states of J2 junction.

3. Voltage Breakdown Failure Mechanism

Because of the influences of power grid fluctuations, abrupt changes of the loads, circuit faults and electron migration interferences, and the existence of the stray inductance in circuits and devices, a voltage peak will occur during the IGBT turn-off and this peak voltage will be added to the bus voltage leading to the voltage breakdown once the total voltage exceeds the reverse breakdown voltage of the PN junction. The IGBT is a high-power compound device to which voltage breakdown and thermal breakdown take effects simultaneously. However, many misunderstandings on the voltage breakdown of IGBTs exist in present applications, e.g., the rated voltage is the breakdown voltage, voltage breakdown causes IGBT failures, and the voltage breakdown and thermal breakdown are independent to each other.

During the IGBT's normal operation, only N-/P+ collector junction which is the J2 junction, is reverse biased and almost the whole blocking voltage is applied across J2 at the forward blocking state. Therefore, the electrical breakdown theory of PN junction still adapts to the IGBT. The electrical breakdown of PN junction mainly consists of two types: the Zener breakdown and the avalanche breakdown. The former most happens to the devices with voltage capacity smaller than 7V while the voltage breakdown is typically sorted to the latter. As the reverse biased voltage across J2 increases, the depletion region of J2 will extend to P+ emitter and the electrical field of the depletion region will become stronger. Under this strong electrical field, the carriers gain enough energy by the acceleration through the twice collisions, which excite the electrons from the valence band to the conduction band, generating the second electron-hole pairs. The newly generated carriers are accelerated by the electrical field again and produce more electron-hole pairs. The above repeated process is named impact ionization. Once the reverse biased voltage of the PN junction is close to or reaches the breakdown voltage, the number of carriers increases abruptly which is called the avalanche multiplication effect. The equation of the avalanche breakdown voltage can be found in [15]-[16].

Since the avalanche multiplication of carriers leads to the simultaneous multiplication of the reverse biased current, that is, the leakage current, of the PN junction, the dominating characteristic of the electrical breakdown will be the sharp increase of the leakage current. According to the breakdown theory of PN junction, the PN junction under voltage breakdown can still recover to its normal operation after the breakdown voltage is removed, as long as the temperature rise due to the leakage current is not high enough to excite the second breakdown. Therefore, the voltage breakdown is a reversible process if only the thermal breakdown can be avoided, which guarantees that no irreversible failures will happen to the PN junction. In this paper, experiments were designed to reproduce the voltage breakdown process with the on-line monitoring in order to verify the validation of the breakdown theory in IGBTs.

4. Voltage Breakdown Experiments

A IGBT module of GD50HFL120C1S is used in which two IGBTs are in series connection with each one being paralleled by a reverse diode. The rated voltage in the manual is 1200V. The J2 junctions in the IGBTs are in parallel connection with those two reverse diodes at the same direction, meaning that the one with lower breakdown voltage will break first. In the experiment, the bond wires of the reverse biased diodes were cut off so that only the breakdown process of the IGBT was in test. The bus voltage and load impedance were adjusted to reproduce the avalanche breakdown in the off-state of the IGBT with the breakdown voltage being the sum of the bus voltage and the peak voltage which is due to the stray inductance in the loop. Therefore, the breakdown duration can be controlled by means of adjusting the conduction current and the stray inductance. In addition, the accumulated energy can be enhanced by increasing the pulse cycles until the chip is burned out. The external power supply was disconnected during the test so that the total energy during breakdown could be controlled only by the discharge of the capacitors. The voltage and current during the voltage breakdown and the breakdown process were on-line monitored by a high accuracy oscilloscope Lecoy wavepro7000 and a high speed thermal infrared imager Xenics320. Figure 2 shows the measured voltage and current waveforms during the voltage breakdown of this IGBT module.

It is shown in figure 2 that the voltage breakdown happens when the superposed voltage of the peak voltage and the bus line voltage exceed the IGBT breakdown value. After that, the voltage is locked to the avalanche breakdown value of 1380V for this chip which is 180V higher than the rated value. Meanwhile, the leakage current increases and the gate lost its control, resulting in the slow turn-off of the IGBT. The current then reduces gradually until the breakdown process is over, and the voltage returns to the bus line voltage after an oscillation. Another observation from figure 2 is that the IGBT can still turn on/off in the following pulse after the breakdown is over, indicating that the voltage breakdown does not mean the failure. However, the IGBT failure will happen if the pulse cycle keeps increasing, as shown in figure 3.

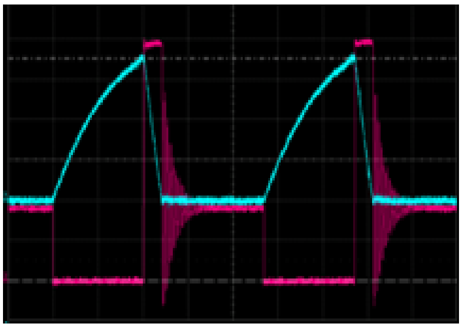


Figure 2. Wave of voltage breakdown

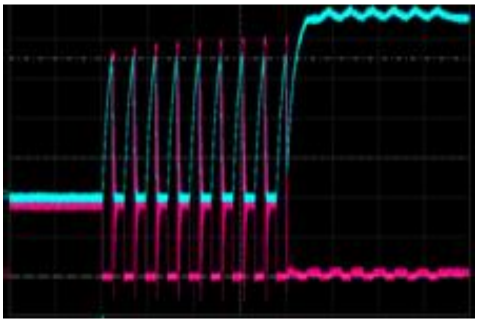
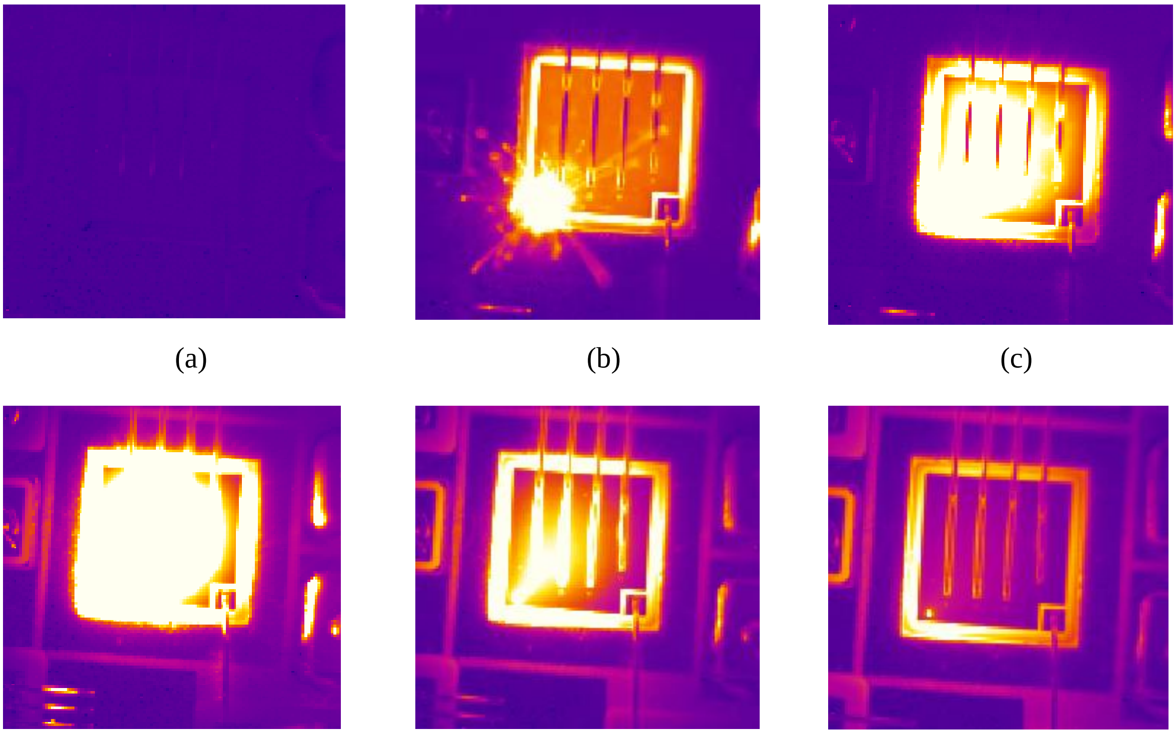


Figure 3. IGBT voltage breakdown and failure

Figure 3 shows that the IGBT failure happens after the 9th breakdown (the 9th pulse cycle), releasing all the energy stored in the capacitors due to short-circuit of the testing loop. This illustrates that the voltage breakdown does not cause the IGBT failure immediately because of its reversible process. However, the temperature rises as the energy in breakdown accumulates after several pulses, leading to the increase of the leakage current, this further increases the temperature due to its positive feedback relationship with the leakage current. Finally, the thermal breakdown happens when the temperature reaches the unbalance value. This results in an abrupt temperature rise till to the intrinsic value, causing short-circuit of the chip. The current at this moment will stop decreasing and then begin to increase to the short-circuit value which is determined by the bus line capacitors and the loop impedance, until the stored energy is fully released and the chip is finally burned out. Furthermore, it is observed that the reverse biased J2 junction in the IGBT was punctuated after the failure happened, and the forward direction shows the case of two series connected diodes while the IGBT is reverse blocked. The above phenomenon is the same as that in the thermal breakdown in the leakage current experiment, which illustrates that the voltage breakdown will induce the thermal breakdown after the former accumulates enough energy. It is also obtained from figure 3 that the breakdown voltage increased gradually from the first pulse to the 9th pulse with totally around 100V higher. Figure 4 shows the pictures of the voltage breakdown failure process of the IGBT taken by the high speed thermal infrared imager.

As shown in figure 4, the breakdown is only a needle-like spot near the chip edge. Because the discharging energy of the capacitor was under control, the breakdown process was clearly observed as follows: a fireball erupted from the spot in the beginning, and then it became smaller as the stored energy dissipated until being a thermal spot and cooling down in the end. In the experiments, the burn-out area was very small because the breakdown energy was limited by the capacitors. However, the burn-out spot will spread to the whole chip in normal applications with large energy being released instantaneously, and the same time the heat generated by the short-circuit current will melt the bond wires, resulting in the open-circuit to the ports of the IGBT module.



(a) (b) (c)

(d) (e) (f)

Figure 4. IGBT voltage breakdown process

5. Conclusion

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

1) The breakdown voltage of IGBTs is typically higher than the rated voltage and the breakdown itself is an non-destructive reversible process. Only when the accumulated energy of the voltage breakdown excites the thermal breakdown will the unrecoverable failure happen.

2) The voltage breakdown of IGBTs normally happens at the weakest spot near the chip edge. The accumulated breakdown energy will further cause thermal breakdown and short-circuit, which result in the temperature rise and the chip melting, spreading from a spot to the whole chip and burning it in the end.

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