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Published in:
Microelectronics Reliability

DOI (link to publication from Publisher):
10.1016/j.microrel.2013.07.126

Publication date:
2013

Document Version
Accepted author manuscript, peer reviewed version

ARTICLE IN PRESS

Microelectronics Reliability xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Overview of catastrophic failures of freewheeling diodes in power electronic circuits

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ARTICLE INFO

Article history:
Received 24 May 2013
Received in revised form 14 July 2013
Accepted 20 July 2013
Available online xxxx

ABSTRACT

Emerging applications (e.g. electric vehicles, renewable energy systems, more electric aircrafts, etc.) have brought more stringent reliability constrains into power electronic products because of safety requirements and maintenance cost issues. To improve the reliability of power electronics, better understanding of failure modes and failure mechanisms of reliability–critical components in power electronic circuits are needed. Many efforts have been devoted to the reduction of IGBT failures, while the study on the failures of freewheeling diodes is less impressive. It is of importance to investigate the catastrophic failures of freewheeling diodes as they could induce the malfunction of other components and eventually the whole power electronic circuits. This paper presents an overview of those catastrophic failures and gives examples of the corresponding consequences to the circuits.

1. Introduction

Power electronics plays an important role in energy conversion applications, such as motor drives, utility interfaces with renewable energy sources, power transmission (e.g. high voltage direct current systems, and flexible alternating current transmission systems), electric or hybrid electric vehicles. Therefore, the reliability of power electronics becomes more and more vital, and should draw more attention [1]. According to a survey, semiconductor failures and soldering joints failures in power devices take up 34% of power electronic system failures [2]. Another survey shows that around 38% of faults in variable speed ac drives are due to failures of power semiconductor devices [3]. A recent questionnaire on industrial power electronic systems also shows that the responders regard power electronic reliability as an important issue, and 31% of responders selected power semiconductor devices as the most fragile component in their applications [4]. Therefore, it demands a better understanding of failure mechanisms of power semiconductor devices so as to reduce their failure rates.

Diodes and Insulated Gate Bipolar Transistors (IGBTs) are two kinds of reliability–critical power semiconductor devices widely used in power electronic circuits [1]. Power diodes are usually assumed to have outstanding ruggedness performance. However, freewheeling diodes fail under various circumstances, especially during the turn-on transition of IGBTs in high switching frequency applications. The freewheeling diodes slow down the switching speed of the IGBTs due to severe stresses induced by the reverse recovery process. Therefore, it is worth to investigate the failures of freewheeling diodes and exploring the solutions to improve the reliability of both freewheeling diodes and IGBTs.

Diode failures can generally be classified as catastrophic failures and wear out failures. Diode wear out failures are mainly induced by accumulated degradation with time, while catastrophic failures are triggered by single-event overstress, such as overvoltage, overcurrent, overheat. Prognostics and Health Management (PHM) method can monitor the degradation of diodes and estimate wear out failures [5]. However, PHM is not applicable for catastrophic failures, which are more difficult to be predicted.

Several overview papers cover the topic on diode failures. In [6], Rahimo et al. discuss the major reverse recovery failure modes of freewheeling diode in IGBT applications. While it only focuses on snappy recovery and dynamic avalanching, no static failure is mentioned. In [7], Ciappa gives a comprehensive overview on the wear out failure mechanisms of power semiconductor devices, such as bond wire fatigue, aluminum reconstruction, substrate cracking, interconnections corrosion, and solder fatigue and voids. However it mainly focuses on IGBT, and freewheeling diodes catastrophic failures are not discussed. Therefore, a detailed and comprehensive review on diode catastrophic failures is still lack in the prior-art literatures. Moreover, it is also worth to investigate the influence of freewheeling diode failures to IGBT operations in power electronic converters.

The aim of this paper is to provide a review of the key behaviors of diode catastrophic failure due to overstresses and the corresponding influence to IGBTs in power electronic circuits. Section 2 classifies the types of freewheeling diode catastrophic failures. Section 3 summarizes the catastrophic failures of diode in terms of failure mode and failure mechanism. Section 4 investigates the influence of freewheeling diode failures to IGBT operations in

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http://dx.doi.org/10.1016/j.microrel.2013.07.126

power electronic converters, followed by the conclusion in Section 5.

2. Classification of failure modes of freewheeling diodes

The catastrophic failure modes of freewheeling diodes can be classified into open-circuit failures and short-circuit failures. Normally open-circuit failures are considered not fatal to converters, since the converter can operate with lower quality of output [8]. On the contrary, short-circuit failures are more fatal to converters, as the uncontrolled short-circuit current may destroy the active switching devices (e.g. IGBTs) or other components in the circuit. Fig. 1 shows the typical open-circuit failures and short-circuit failures of freewheeling diodes.

2.1. Open-circuit failures

Freewheeling diode open-circuit failures are generally due to mechanical causes. Open-circuit failure mode can happen because of external disconnections due to vibration, or internally by bond wire lift-off or rupture after temperature swings or high short-circuit current.

2.2. Short-circuit failures

Short-circuit is also a common failure mode of freewheeling diodes in power electronic circuits. Failures can happen during reverse blocking state as well as the reverse recovery transition. Fig. 2 shows the definition of reverse and forward voltage for diodes [9]. There are five major failure mechanisms as shown in Fig. 1, which will be discussed in next section.

3. Major failure mechanisms of freewheeling diodes

3.1. Open-circuit mechanisms

Similar to IGBTs, diode open-circuit will not be initially fatal to the converter, but may result in secondary failures of other devices in a power electronic circuit due to interaction among them.

The mechanism is similar to that of IGBTs. Bond wire lift-off failure can happen after short-circuit, caused by high temperature fatigue and the mismatch of Coefficients of Thermal Expansion (CTEs) between Silicon and Aluminum. Crack may also be initiated at the periphery of the bonding interface, and the bond wire finally lifts-off when crack propagates to the weaker central bonding area. Central bond wires normally fail at first, and then the survivor bond wires follow [10]. Bond wire rupture is usually slower than lift-off mechanism and usually observed after long power cycling tests or long time operation.

3.2. Short-circuit mechanisms

The short-circuit failures of freewheeling diode could lead to potential destruction to the relevant IGBTs, and other components, as it induces uncontrolled high current to the circuit. The failure mechanisms can be static high voltage breakdown, leakage current rising, snappy recovery, dynamic avalanche during reverse recovery, as well as high temperature due to the power dissipation and so on.

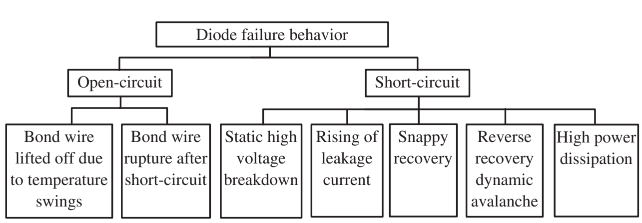

Fig. 1. Overview of freewheeling diodes catastrophic failures.

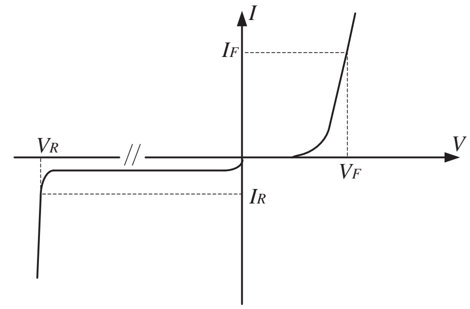

Fig. 2. Definition of reverse and forward voltage of diodes.

3.2.1. Static high voltage breakdown

High reverse voltage can cause diodes static avalanche. With reverse voltage reaching first static avalanche point, the current rises with positive slope, while no permanent failure happens. If the voltage reaches the second avalanche point, there will be a Negative Differential Resistance (NDR), which will lead to the current filament and a quick short-circuit. Detailed numerical simulations are carried for a rated 3.3 kV/1 kA diode, and the results are shown in Fig. 3 [11]. Another research reveals metallization between copper and silicon can also lead to diode electrical breakdown [12]. It is also revealed that the avalanche capability is strongly dependent on the initial breakdown location and the edge termination design by numerical simulation and experiments, and the common failure locations are near the chip's edge and the bond wires [13]. Since operating voltage of freewheeling diodes is normally much lower than rated voltage, static high voltage breakdown is not common in nowadays applications.

3.2.2. Rising of leakage current

The leakage current of power diodes is usually very low, but it increases with voltage and temperature. The value is roughly doubled for every 10 °C raise of temperature. This effect is more obvious for gold-diffusion diodes, which may be thermally destroyed at high temperature [9].

With operating voltage and temperature above the rating parameters, leakage current increases dramatically and the diodes fail into short circuit at the chip's peripheral surface [14,15]. Experiments show that the diodes operation temperature can be increased without risks of failure by improving the junction edge current control, like a junction passivation process [16,17]. A further research reveals the mechanism is junction carrier avalanche multiplication, and the weak spots are near the chips' edge [18]. The leakage current rising can also be due to repetitive electrostatic discharge [19]. Since short-circuit failures during freewheeling diode reverse status can damage IGBT and circuit quickly, it is critical to prevent this event.

3.2.3. Snappy recovery

Freewheeling diodes are prone to fail easily during reverse recovery process because of snappy recovery. The behavior of snappy recovery is shown in Fig. 4, in which a steep decline in the current is observed after the reverse recovery current reaches the peak value. The main reason is the sudden disappearance of the remaining carriers at the end of the recovery process. Due to high *di*/*dt* and stray inductance in the circuit, high voltage spikes can appear and damage the diode.

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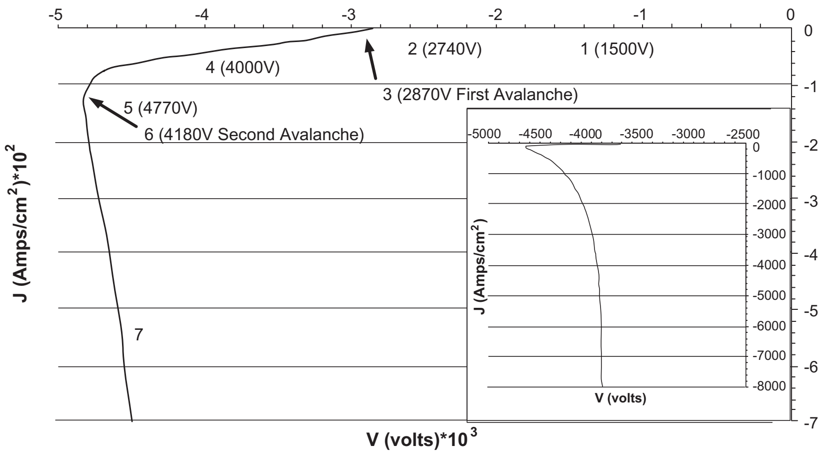

Fig. 3. First and second static avalanche breakdown of a 1700 V rated power diode [11].

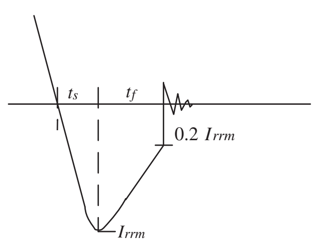

Fig. 4. Current characteristics of snappy reverse recovery behavior [9].

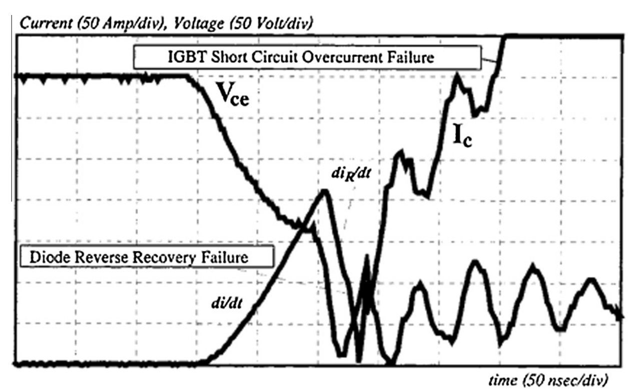

Fig. 5. Freewheeling diode reverse-recovery failure with IGBT short circuit failure [6].

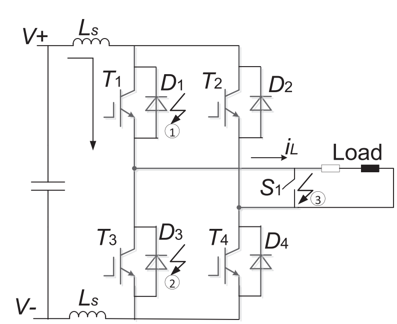

Fig. 6. Operation of a single phase inverter under different failure conditions – ① reverse recovery transition, ② reverse state, ③ load short-circuit.

It has been validated that both reverse recovery charge and time increase with diode effective contact area, and snappy recovery is clearly observed for larger area in numerical simulation and experiments [20]. Thus special attention should be paid to choose the diode size for avoiding diode failures. H+ irradiation has been proposed to obtain trade-off between diodes switching speed and softness, which can avoid snappy recovery, validated by comprehensive experiments and numerical investigations [21–23]. A new design procedure of freewheeling diodes based on measurement and simulation is also proposed to improve the reverse recovery softness [24]. Controlled Injection of Backside Holes (CIBH) diodes are also proposed to increase the soft reverse recovery behavior [25]. However, it is still a critical point to avoid snappy recovery when designing freewheeling diodes.

3.2.4. Reverse recovery dynamic avalanche

Dynamic avalanching occurs at high *di*/*dt* switching speeds, as shown in Fig. 5. Dynamic avalanching can result in the generation of a hot spot in the silicon die itself due to non-uniform current crowding which leads to the destruction of the device. The causes of these hot spots can range from process to material variations in a single diode silicon chip [26].

Impact ionization near N-N+ junction is considered as the main reason for the failure. It leads to the negative differential resistance and current filament, finally a thermal runaway [27–30]. This process called Egawa effect [26] is very similar to the second breakdown in bipolar transistors. Local heating and explosion at the corner of anode is observed even the reverse voltage is lower than static breakdown voltage [31]. A detailed study of dynamical behavior of the plasma layer also explains this reverse recovery failure [32,33]. To avoid the second current bump observed during reverse recovery failure, a merged P-i-N Schottky diode is proposed to replace conventional P-i-N freewheeling diode [34]. It shows deep N+ emitter and wide n-base can improve the dynamic avalanche characteristic in 2*D* simulations [35,36]. It is also proved CIBH diode can prevent the filaments in N-N+ junction by 2D numerical simulations [33]. An improved impact-ionization model is proposed to simulate high electrical fields in diodes [37]. Electro thermal simulations show that thermal-induced filament can lead to destructive thermal runway and it is sensitive to contacts thermal resistance [38]. There could be further work to improve both die structure and thermal performance.

3.2.5. High power dissipation

When the diode forward current is high and temperature is rising, the forward voltage will increase. If the forward voltage

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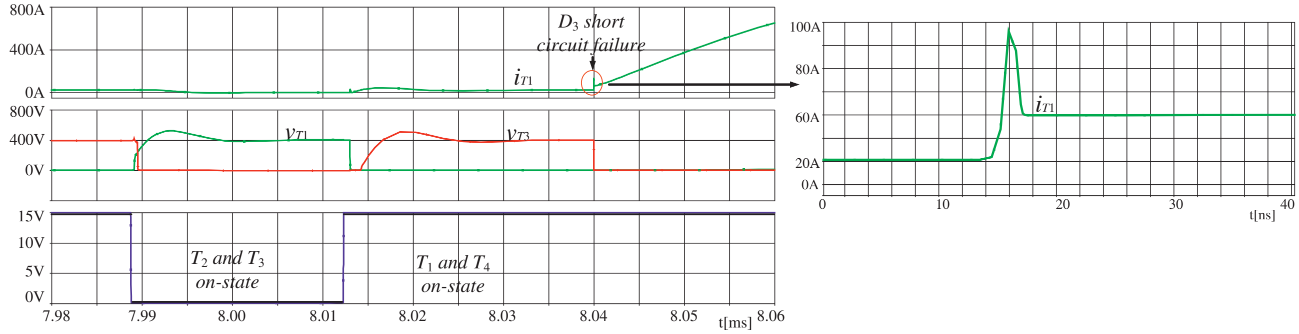

Fig. 7. PSpice simulation waveforms of IGBTs after D_3 short circuit in reverse state.

exceeds a specified limit value, the overload high power dissipation may fatally damage the silicon die [9].

4. Influence of freewheeling diode failures on the operations of IGBTs in power electronic circuits

Fig. 6 shows a single phase inverter consisting of IGBTs (T_1–T_4) diodes (D_1–D_4), and stray inductance L_s (which may lead vital stress to device).

The operation of the inverter is as follows: initially, T_2 and T_3 are on, the current i_L flows through the load, then T_2 and T_3 are turned-off and T_1 and T_4 are switched on after a certain period of dead time. Because the load determines the direction of the current flow, the current will flow through the diodes D_1 and D_4 back to the voltage source. After i_L decreases to zero and to the negative, the current will flow through T_1 and T_4.

There are three typical failure behaviors:

(a) When the current is commutating from diode to IGBT, the freewheeling diode reverse recovery failure may lead to an IGBT short-circuit failure, as shown by ① in Fig. 6.
(b) When IGBTs T_1 and T_4 are on, and the current i_L flows through the load, reverse diode D_3 fails into the short-circuit, the short-circuit current between $V+$ and $V-$ may damage T_1 fast, as shown ② in Fig. 6.
(c) When current is flowing through D_1 and D_4, a load short circuit will cause overstress of the diodes and IGBTs (symbolized as ③ – closing the switch S_1 in Fig. 6). As the current flowing through D_1 and D_4 will be commutated to T_1 and T_4 rapidly, short-circuit current on IGBTs will be larger. During the transient, both the high reverse recovery current and the voltage may produce large energy dissipation and damage the diode. However, the IGBT may also fail first if the peak voltage is over the rated voltage [39].

As an example, Fig. 7 shows the simulation results of the scenario ② in which D_3 is short during the conduction of T_1. It could subsequently induce the failure of T_1 due to its increased current stress as shown in Fig. 7.

5. Conclusions

The typical failure modes and failure mechanisms of freewheeling diodes due to over stresses are overviewed in this paper. Initial short-circuit failures may lead to open-circuit finally. Short-circuit failures can happen at five typical occasions.

The influence of the freewheeling diode failures to IGBT failures is also investigated on the circuit level. The associated behaviors of the IGBTs are also briefly described.

The overview in this paper could be useful for further work in the following areas: correlations between IGBT and diode failures; improvements of diode performance due to failure mechanisms; effective protection circuits dealing with different catastrophic failures; fault tolerant design coping with freewheeling diode catastrophic failures; better models of failure mechanisms; better models and tests of devices beyond the specific rating.

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