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Instable mechanisms during unclamped operation of high power IGBT modules

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ABSTRACT

The behaviour in terms of robustness during unclamped operations of power IGBT modules is presented. The experimental characterization is aimed to identify the main instable phenomena during unclamped turn-off in power IGBT modules. Several devices of different generations, current and voltage ratings have been analyzed. Thanks to a non-destructive experimental set-up, it is possible to observe instable phenomena without causing the damage of the device under test. In this paper, it is shown that the destructive conditions during unclamped operations are preceded by precursors on the gate side which indicate instable phenomena taking place inside the device. The dependence of the destructive phenomenon on the driver conditions are widely and exhaustively analyzed.

1. Introduction

Insulated gate bipolar transistors (IGBTs) have received much attention in the last decade for their energy efficiency and rugged performance for a wide range of power applications. These devices are frequently adopted in hard-switching applications, where the device is required to turn-off high currents and voltages under inductive load conditions. Ruggedness of devices used in such applications is a must, and a premium is put on these devices, having a large reverse-bias safe operating area (RBSOA).

Although RBSOA characteristics of the IGBTs do not severely limit the capability of the device in most clamped applications, inductive spikes can lead outside the RBSOA and can cause such devices to avalanche and possibly fail. An understanding of the failure mechanisms of the IGBTs can surely benefit future IGBT designs.

It is commonly shared that RBSOA reduction and IGBT failure occur because harsh dynamic switching conditions can result in current constriction leading to excessive current density in a small region of the device. The excessive current density results in a device failure, characterized by a rapid collapse of the collector blocking voltage [1–4]. For this reason, the high voltage performance of IGBTs is often limited by keeping them widely inside the nominal device RBSOA. The phenomena responsible for the rupture are typically attributed to the presence of an embedded bipolar transistor inside the device structure and are weakly studied in the literature due to the difficulties encountered during their experimental observation [2–4]: during the voltage instable phenomena, typically, the device is destroyed within nanoseconds after the voltage collapse.

The usage of a non-destructive tester may solve these difficulties as it was already demonstrated for the study of second breakdown of power bipolar junction transistors [5]. Moreover, tests have shown a significant impact of the gate drive conditions on the RBSOA capability. In fact, the use of very low gate resistances during turn-off, can cause current unbalance among the chips which sometimes may cause the current filamentation or thermal runaway and the device can result thermally damaged [6–9].

The aim of the present work is to study the occurrence of instable phenomena, as second breakdown, during unclamped turn-off, thanks to the use of a non-destructive circuit. The main goal is to identify precursors and failure mechanisms and to correlate them to the load and driving conditions. In the next paragraphs a wide experimental characterization, executed on several IGBT modules under different load and driver conditions, will be reported.

2. Non-destructive experimental set-up

To make possible the safe investigation of IGBT switching operations outside of the voltage RBSOA limits, a new non-destructive tester has been constructed starting from a preceding version presented in [10] by the same research group. Its electrical scheme has been reported in Fig. 1. Such circuit allows us to characterize the IGBT module under unclamped conditions. Please notice the absence of the freewheeling diode on the inductive load. In fact, in this case, a new diode (D) was inserted in order to obtain the necessary current circulation inside the inductance. With this new arrangement, the device under test (DUT) is subject to the current forced by the inductance during the whole commutation. The behaviour of the apparatus is now presented.

In order to bias the DUT, the test starts with the series switch turned on; the DUT is turned on afterward and the load inductance is magnetized at the desired current value. Before the DUT turn-off,

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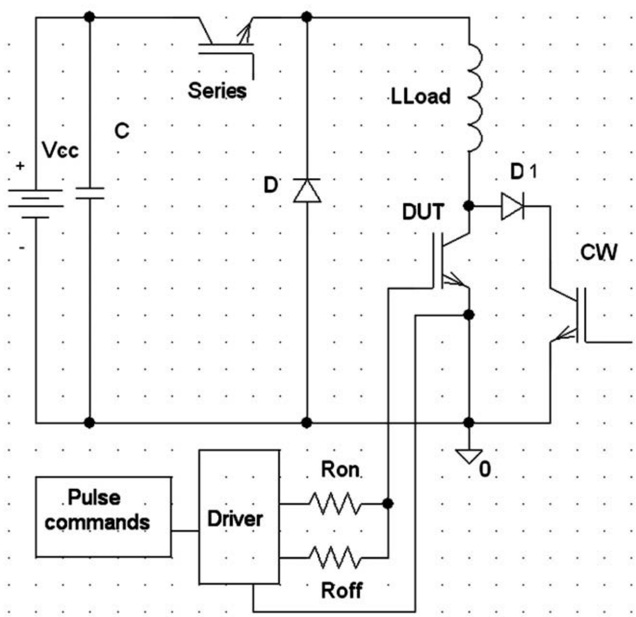

Fig. 1. Electric schematic of experimental set-up.

the series switch is turned off, and the current is forced in the loop D – LLoad – DUT. After few microseconds, the DUT is turned off and the unclamped operation is activated. Thanks to the delayed activation of the crow bar CW switch, it is possible to select the duration of the unclamped phase and to save the DUT in the case of the occurrence of an instable phenomenon involving the device. Moreover, thanks to the driver circuit it is very simple to change the on and off gate parameters, in order to analyze the behaviour during unclamped commutations under different driving conditions. The control circuit is based on a FPGA and is connected to the power circuit by means of optical fibres.

3. Experimental characterization during unclamped operations

In order to identify the occurrence of the instable phenomena during unclamped operations, several IGBT modules of different technology families and power ranges have been experimentally characterized.

As an example, Fig. 2 shows a significant characterization executed on a 1200 V–400 A IGBT module with the activation of the protection switch, CW. The test conditions are: collector current, I_c = 400 A; load inductance, LLoad = 50 μH, gate off resistance, RG_{OFF} = 3.3 Ω. In particular, Fig. 2a shows the collector voltage, the collector current and the gate voltage during the unclamped turn-off; the crow bar switch was activated immediately after the voltage reached its breakdown value. The corresponding switching locus superimposed to the RBSOA is reported in Fig. 2b which shows that the avalanche voltage is about 1350 V, a little bit larger than the maximum operating voltage declared by the manufacturer.

A careful analysis of Fig. 2a, shows a very interesting behaviour. In fact, an abnormal rise-back of the gate voltage V_{ge} takes place at the end of the miller phase (∼2 μs) before the voltage continues going down to the negative bias voltage (−15 V). In this case, the anomalous gate voltage peak is about +4 V. This behaviour is highlighted in Fig. 2c, where the zoom of the interesting area is reported. It is interesting to observe that this increase of the V_{ge} starts to appear when the collector voltage becomes higher than 700 V (dashed box in the same figure). We propose here that this V_{ge} increase can be considered to be the precursor of an instable phenomenon which starts to take place inside the device. During the test of Fig. 2 the device was saved by the protection circuit that was activated at about 2.1 μs. To see if the phenomenon is destructive for the device, the experiment was repeated in the same test conditions with the only difference that the crow bar was intentionally delayed. The results are reported in Fig. 3 which shows that after the increase of V_{ge} at about 1.95 μs the collector voltage reaches a sustaining phase during which a small oscillation takes place followed by a very fast collapse. The phenomenon is very similar to the second breakdown of a BJT and causes the failure of the DUT.

For the sake of comparison the collector and gate waveforms of the previous two experiments are both reported in Fig. 4. The dotted lines refer to the case where the protection circuit saves the device whereas solid ones correspond to the test where the device is destroyed. The two sets of waveforms are practically coincident up to 2 μs when the protection circuit starts its action and saves the DUT. The waveforms in both cases evidence the presence of the precursor on the gate signal that is not affected by the activation of the protection circuit.

3.1. Tests with lower values of the gate resistance

In order to evidence the dependence of the precursor of the instable phenomenon with the driver conditions, a new experimental characterization on 1200 V IGBT module was executed with lower values of the gate resistance.

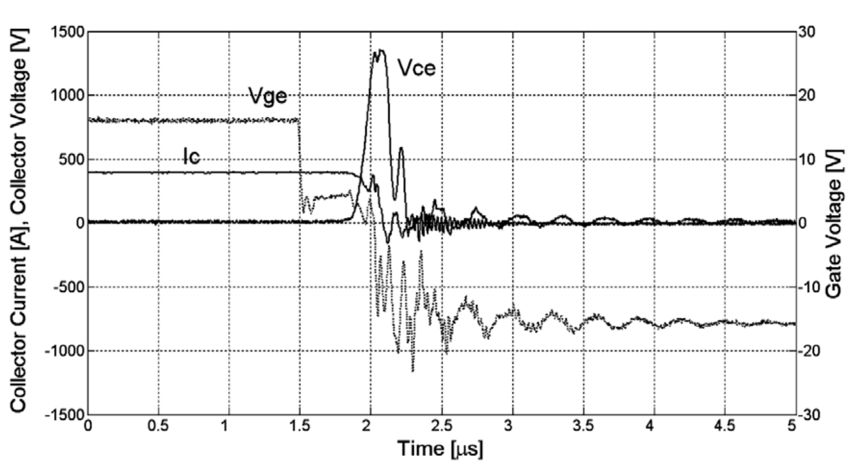

Fig. 2a. Collector and gate waveforms for a 1200 V–400 A IGBT module during unclamped test at I_c = 400 A, RG_{OFF} = 3.3 Ω.