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Assessment of the Trench IGBT reliability: low temperature experimental characterization

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Abstract

The purpose of this study is an assessment of the Trench IGBT reliability at low temperature under static and dynamic operations by the aim of intensive measurements. The analysis of the Trench IGBT behaviour in these conditions is dedicated to the HEV applications. One question can be raised in case of the use of HEV in countries where during winter the temperature drops down -50°C or less: are Trench IGBT strongly affected by the low temperature environment? In this paper, we present experimental results under various test conditions (temperature, gate resistance, voltage and current) to give an understanding of the device behaviour by focusing on the device current and voltage waveforms and the power losses.

1. Introduction

Technical progress in power electronics depends on the development in the fields of power circuit topologies, power devices technologies and control techniques. Since the 80's, significant new developments have been made in the area of power electronics devices, more precisely for the Insulated Gate Bipolar Transistor (IGBT) [1-2]. Widely used for the medium voltage and medium current application ranges (300-1500V/50-300A), for instance motors drives, DC/DC converters, it allows a good trade-off between the switching speed, the on-state voltage drop and the ruggedness [3].

Nowadays, Hybrid Electric Vehicles like PRIUS started becoming very popular in Japan and US. However, for some countries such as Canada, Russia and even from north Europe such kind of cars will be submitted to low temperature environment during

winter. Using devices such as IGBT for the motor drive part, the transistor is submitted to this low temperature only for several switching transients, after the temperature will rise and reaches the steady state temperature within the crystal. It is well known that temperature swing is stressful for the power hybrid assembly. Obviously, the switched power becomes higher and higher and IGBTs used in converters are submitted to high temperature changes, which disturb physical parameters of silicon, and change their behaviour. In another way, we can wonder what can be the behaviour of IGBT submitted to this initial low temperature such as -50°C ?

In the literature, it is possible to find some data related to cryogenic operations (down to 77°K) on power semiconductor devices and more precisely for IGBT for space applications [4-5-6-7], but it needs very specific and quiet expensive equipment.

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Furthermore, only very few data are available regarding the low temperature operations of Trench-IGBT (T-IGBT) [8].

In this paper, we propose to investigate the static and dynamic behaviour of T-IGBT at low temperatures from 25°C down to -50°C. Using conventional equipments for both operating modes, it is possible to see the influence of the temperature for static operation as well as the influence of external parameters (temperature, gate resistance, voltage and load current) for dynamic operation.

2. Device structure

Using a punch-through structure (Fig. 1), the gate oxide and the conductive poly-silicon gate electrode of the T-IGBT are formed in a deep narrow trench below the chip surface. This structure allows a reduction of the on-state voltage drop by suppressing the JFET resistance, which results from the constriction of the current flow in the region between adjacent cells in the planar structure. Furthermore, the vertical channel requires less chip area and permits an increase in cell density. A local lifetime control, using heavy ion irradiation process, allows to keep a low on-state voltage drop as well as to improve the control of the storage charges in the drift region.

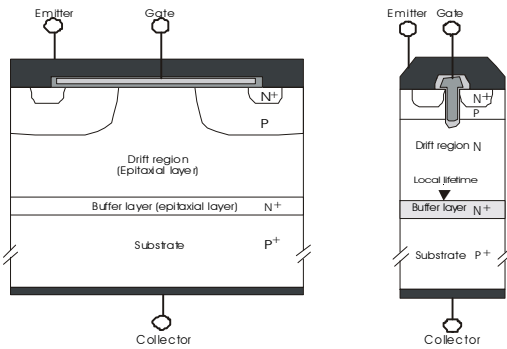


Fig.1 – Structure of the Planar and Trench punch through IGBTs

3. Experimental test bench

3.1. Temperature set up equipment

The temperature is controlled by a climatic chamber which allows to set up easily a temperature down to -50°C. Thermocouples are used to check the temperature of the device. To be sure that the temperature is well established, the module has to overcome the fixed temperature for about 45min before performing the test in a specific operating mode.

3.1. Static mode

The main part of the static operating mode is based on the use of the curve tracer TEKTRONIX 371A and the design of a specific cable. This cable has been validated and allows to insert the device connector inside the climatic chamber. Thanks to this equipment, the measure of I_c - V_{ce} , $V_{ce,sat}$, I_c - V_{ge} and breakdown voltage characteristics are possible.

3.1. Dynamic mode

More detail about the test circuit (figure 2) can be found in [9], some explanations are reminded in this paper.

The guiding principle of this circuit is to suppress the influence of the diode reverse recovery by keeping the diode D_F on during the switching and the on-state times of the IGBT₂, which is the Device Under Test (DUT). Consequently, it is possible to obtain the own current and voltage waveforms of the DUT.

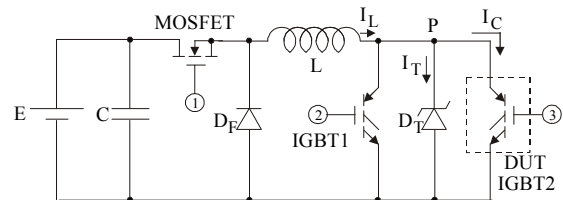


Fig.2 – Hard-switching test circuit [8]

First, the MOSFET and the IGBT₁ are turned on, so the current I_L increases linearly. These two switches are turned off after a while to ensure enough energy storage in the inductance. Then, the current I_L flows through D_F all the remaining time. During the IGBT₁ turn-off, the voltage in P increases until it exceeds the breakdown voltage of the Transient Voltage Suppressor component D_T . Then, the current runs through D_T which keeps the voltage at point P constant. Thus, the IGBT₂ can be turned on and turned off during the selected time without the influence of any diode reverse recovery operation.

The use of single-shot operating mode limits the power source consumption, does not risk to damage the device, and does not affect the temperature of the device during fast single shot event.

The experimental collector-emitter voltage and collector current waveforms of the DUT have been measured with the high voltage probe TEKTRONIX 2.5kV and the current probe TEKTRONIX TCP220. For the switching power loss measurements, the use of the TEKTRONIX oscilloscope model TDS5054

allows to compensate the delay between the voltage and the current probes using a calibration source.

4. Experimental test conditions

4.1. Static mode

The temperature was the only changeable parameter and experiments have been performed for the temperature values: +25°C and from 0°C down to -50°C by -10°C step.

4.2. Dynamic mode

Several parameters have to be taken into account for the switching operations. Table 1 gives a sum up of the chosen values for the experiments

Table.1 – Experimental conditions

Temp.	Gate Resistance	Current	Voltage
25°C, 0°C, -25°C, -50°C	4.7Ω, 10Ω, 22Ω	10A, 20A	200V, 450V, 650V

5. Results and discussion

5.1. Static mode

As it can be observed in figure 3, the dynamic breakdown voltage of the T-IGBT decreases from 1400V down to 1280V, when the temperature decreases due to the reduction of the impact ionization rate.

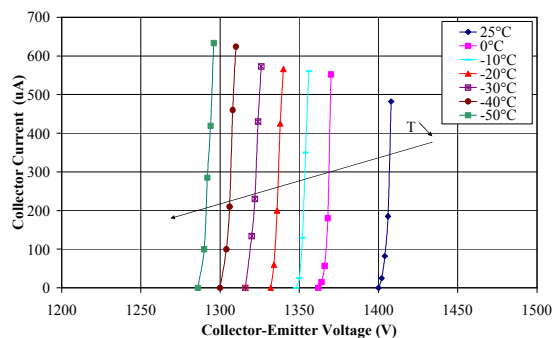


Fig.3 – Breakdown voltage for 25°C down to -50°C

Furthermore, and it can not be possible to see it on this curve, the leakage current also decreases with decreasing temperature linked to the reduction of the intrinsic carrier concentration [6].

The following characteristics, as depicted in figure 4, are the I_c - V_{ge} curves. It is important to see that low temperature induces an increase of the threshold voltage as reminded in [8]. This is directly

in relation with the reduction of the intrinsic carrier concentration when the temperature decreases.

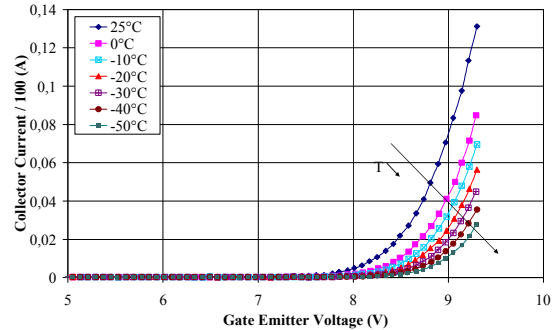


Fig.4 – I_c - V_{ge} characteristics for 25°C down to -50°C

One of the most important effects of the temperature reduction can be analyzed in figure 5 where the gate voltage is set up to about 10V. Below a collector current value equal to about 35A, the studied T-IGBT presents a positive temperature coefficient (for a same V_{ce} , the collector current decreases when the temperature decreases). Upper this current value, the temperature coefficient becomes negative (for a same V_{ce} , the collector current rises when the temperature decreases).

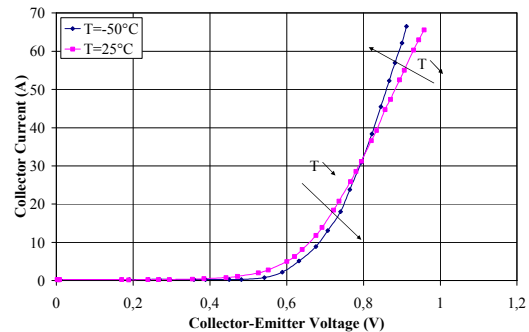


Fig.5 – I_c - V_{ce} characteristics and on-state voltage for 25°C and -50°C ($V_{ge} = 10V$)

Furthermore, below 35A, the temperature decrease induces an increase of the on-state voltage. Upper 35A and for higher collector-emitter voltage, the saturation current level gets up due to the rise of the carrier mobility with the decrease of the temperature.

5.2. Dynamic mode

Since the saturation velocity of carriers and their mobility are increased with the reduction of the temperature, the switching behavior of the IGBT will

be changed.

Figures 6 (a), (c) and (e) illustrate the turn-on switching whereas figures 6 (b), (d) and (f) depict the turn-off switching for various temperature values (25°C, 0°C and -50°C) for a collector-emitter voltage of 650V and a collector current of 20A.

For the turn-on, as well as the collector-emitter voltage, the collector current is not strongly affected by the temperature decrease. In fact, as the turn-on phase mainly depends on the MOSFET part of the T-IGBT which is not influenced so much by the temperature variation, then the T-IGBT turn-on slightly changes. Additionally to the fact that stray inductances disturb the device waveforms, some ringing appearing at 25°C, which do not appear for 0°C and -50°C, may suppose that the physical behavior of the T-IGBT has an effect on the waveforms which may be investigated by the help of a 2D physically-based device simulator. Whereas the turn-on waveforms seem to be similar whatever the temperature value, figure 7 (a) shows that the power losses during turn-on increases slightly when the temperature decreases. This can be explained by figure 8 (a) and 9(a) illustrating the current and voltage rise and fall times. When the temperature is reduced, the current rise time increases slightly and the voltage fall time also increases. Higher rise or fall times induce longer overlap between the current and voltage waveforms. The effect of the gate resistance on the turn-on switching for a temperature equal to -50°C is illustrated in figure 7 (b). The gate resistance increases the power losses due to the effect on the dv/dt . Figures 8 (b) and 9 (b) illustrates the increase of the collector current rise time linked to the increase of the voltage fall time when the gate resistance rises.

For the turn-off, the most important feature of the T-IGBT is the current tail, due to minority carriers responsible for a stored charge in the drift region. When the temperature decreases, it is obvious to notice that the tail is not so much influenced by the temperature variation for the chosen load current (figures 6 (b), (d) and (f)). The effect of the temperature is higher when the temperature rises, since the bipolar part is strongly sensitive to high temperature value. In fact, figure 7 (a) indicates that the temperature reduction induces a decrease of the turn-off power losses. This tendency is also confirmed by figures 8 (a) and 9 (a) depicting the reduction of the voltage rise as well as the reduction of the current fall time with the temperature rise. The decreases in turn-off time with decreasing temperature is a result

of both decreasing the current gain of the PNP bipolar part and the decreasing carrier lifetime [10]. The effect of the gate resistance on the turn-off switching for a temperature equal to -50°C is illustrated in figure 7 (b). As for the turn-on, the gate resistance has a strong effect on the power losses due to the effect on the dv/dt . It has to be noticed that for the experimental turn-on losses are higher than the turn-off losses. This is mainly due to the high input capacitance of the T-IGBT as reported in [11]. Figures 8 (b) and 9 (b) illustrates the increase of the collector current fall time linked to the increase of the voltage fall time during turn-off when the gate resistance rises.

6. Conclusion

The Trench IGBT characterization at low temperatures has been investigated with the help of intensive measurements under static and dynamic operating modes. It has been shown that the low temperature improves the T-IGBT performances by reducing the power losses and the current tail influence, which have certainly a strong influence on the device reliability for hard-switching operations.

More investigations are in progress to consider the device structure at low temperature by the help of the physically-based bi-dimensional device structure simulator and also under severe test conditions.

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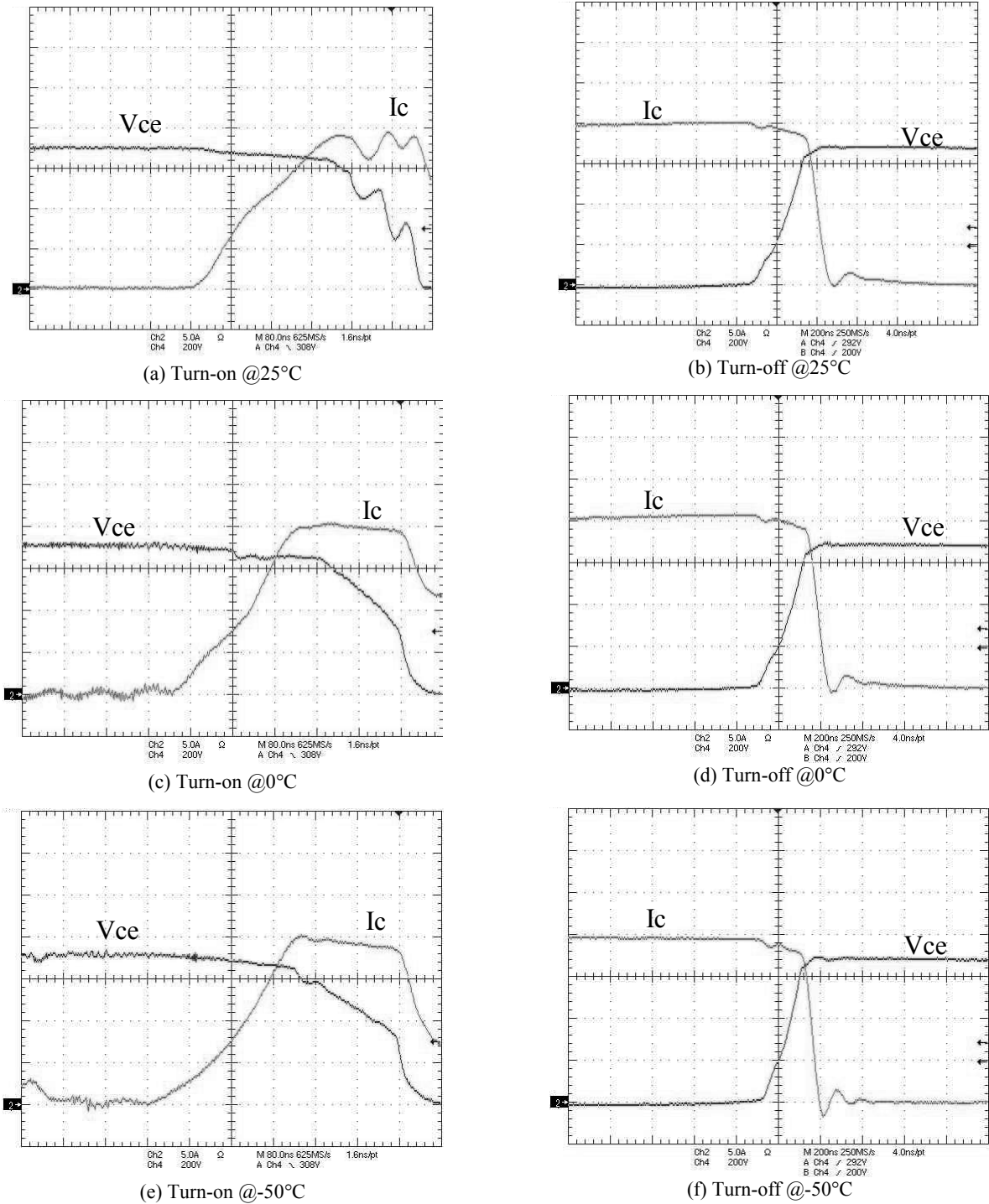
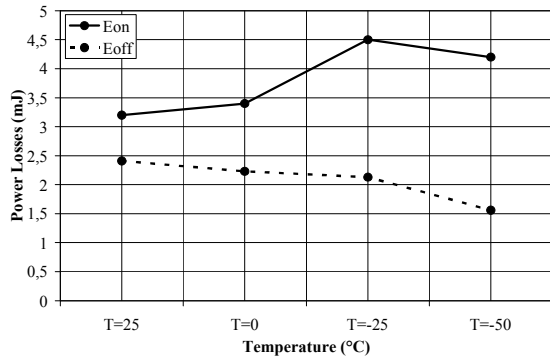
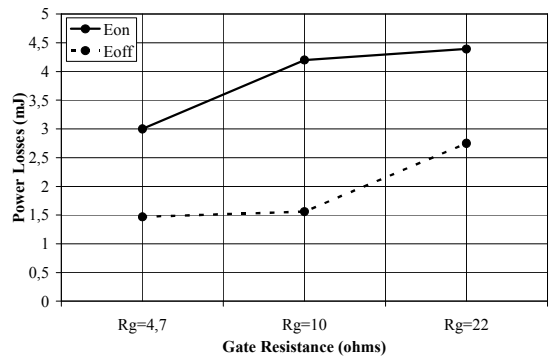


Fig.6 – Turn-on and turn-off switching waveforms for $V_{ce}=650V@R_g=10\text{ohms}@I_c=20A$ at various

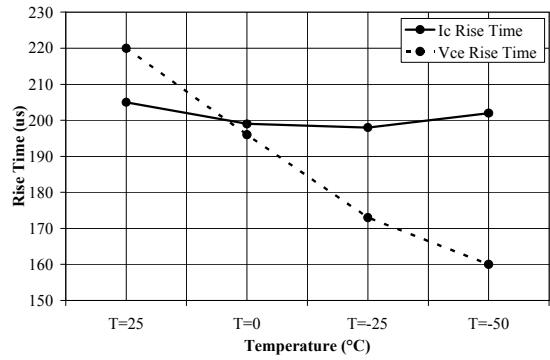


(a) Temperature from 25°C down to -50°C
(Vce=650V@Rg=10ohms@Ic=20A)

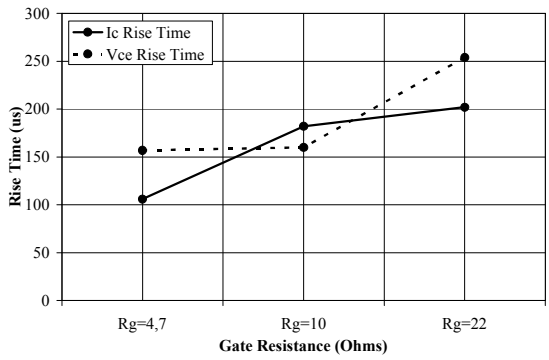


(b) Gate resistance from 4.7ohms up to 22ohms
(Vce=650V@T=-50°C@Ic=20A)

Fig.7 – Power losses for turn-on and turn-off

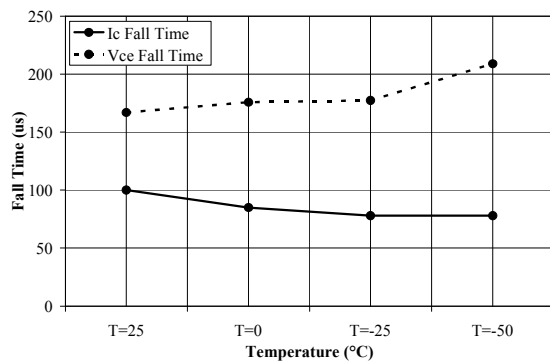


(a) Temperature from 25°C down to -50°C
(Vce=650V@Rg=10ohms@Ic=20A)

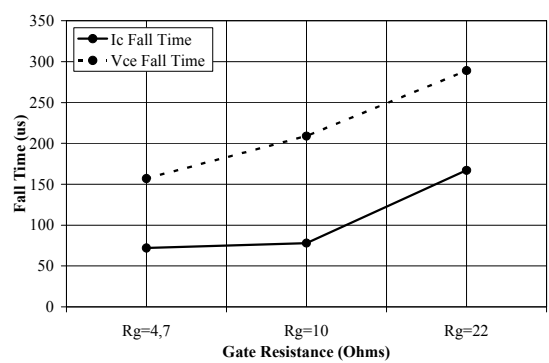


(b) Gate resistance from 4.7ohms up to 22ohms
(Vce=650V@T=-50°C@Ic=20A)

Fig.8 – Current and voltage rise times for turn-on and turn-off



(a) Temperature from 25°C down to -50°C
(Vce=650V@Rg=10ohms@Ic=20A)



(b) Gate resistance from 4.7ohms up to 22ohms
(Vce=650V@T=-50°C@Ic=20A)

Fig.9 – Current and voltage fall times for turn-on and turn-off