THE FAILURE OF PUNCH-THROUGH IGBTs TO REACH FORWARD CONDUCTION MODE AT LOW TEMPERATURES

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***Abstract-* The failure of Punch-Through (PT) IGBTs to reach forward conduction mode at cryogenic temperatures has already been observed in previous work, but no explanation has been given. In this work detailed experimental data collected for PT IGBTs are presented. The forward conduction drops and switching behavior of the IGBTs are examined over a temperature range from 4.2 to 295 K. The phenomenon under analysis is presented. Connections between the failure of PT-IGBTs and other phenomena are highlighted. Physical behavior at low junction temperatures is analyzed and the failure at cryogenic temperatures is discussed and analyzed.**

Keywords: IGBT PT Cryogenic

I. INTRODUCTION

In the recent years, there has been an increasing interest in semiconductor device behavior at low temperatures. While the behavior of power electronics devices down to liquid nitrogen temperature (LNT) has been explored [1], [2], [3], [4], [5], there are just a few studies related to the behavior of power electronics devices at the temperature of liquid helium (LHT) [6], thyristors [7], and very limited data on IGBTs [8], [9]. The interests in the behavior of power electronic devices at cryogenic temperatures lower than LNT originate from the possible application of semiconductor switches in conjunction with superconductor materials operated at a high energy level. Examples of the application of such superconductor technology are SMES (Superconducting Magnetic Energy Storage System) [7], [8], [10] MAGLEV train technology (Japanese solution), more recently, a superconducting transformer developed and installed by ABB in 1997, and superconducting cables installed by Pirelli in 2001 for Detroit Edison that are able to deliver 100 MW. Due to extreme temperatures of the outer planets of the solar system, the USA space program (NASA) is also interested in this particular topic. Being able to switch large amounts of power in a short time, the IGBT seems to be the device of choice for these applications. This work stems from a larger study on IGBT behavior at very low temperature and will address the peculiar behavior of the Punch-Through (PT) IGBT at very low temperatures, highlighting the failure to reach forward conduction mode under certain specific conditions. This behavior was already observed in [8] but an explanation of the phenomenon was not provided. Moreover, this work will show the connection between this failure and the relatively high voltage drop across the collector emitter of the PT IGBT at very low temperature observed and reported in [11].

II. EXPERIMENTAL SETUP

The experimental setup is designed in order to capture the switching behavior of the Device Under Test (DUT). The main goals pursued in designing the test bed are to minimize the overall parasitic inductance, to provide cooling of the DUT only, and to give an easy way to modify the load impedance. Details concerning these issues are addressed in the main work [11].

The structure of the experimental setup includes a set of five capacitors connected in parallel, one isolated dc voltage source, two isolated small voltage sources, one gate drive, one isolated logic double-pulse generator, one cryostat, and one vacuum pump station. The layout of the circuit is shown in Figure 1.

As it is illustrated in Figure 1, the voltages are measured using the four-point probe technique, a requirement imposed by the presence of the stainless steel pipes. Due to the presence of the stainless steel pipes, particular consideration has been dedicated to the grounding of the system and all the instrumentation used.

The temperature was measured by a Lakeshore silicon diode probe that was attached to the package base plate of the DUT. The DUT is cooled slowly over a period of about two days. The refrigerating procedure will be explained in detail in the final document. During the measurements, the thermal system is "open", meaning that the vaporized helium inside the cryostat flows to the outside environment, a condition that allows easier adjustment of the DUT temperature. The tested device is a PT IGBT rated for 600 V and 100 A. The DUT has been tested with a variable bus voltage from 50 V to 250 V, in 50 V steps. A clamped inductive load was used.

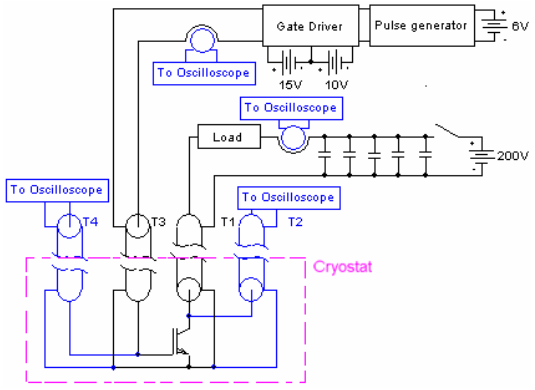


Figure 1: Experimental setup.

. Once the DUT is at liquid helium temperature (LHT), the bank capacitor is charged to 250 V. The DUT is pulsed twice:

first it is turned on for 10 µs, then off for 20 µs, then on again for 10 µs. The collector-emitter voltage is decreased to 200 Vand the measurement is repeated again. Once the DUT is tested with all five different voltages at LHT, the liquid helium flow is cut causing the junction temperature of the DUT to slowly increase. Once the temperature is in the vicinity of 70 K, the DUT is submerged with liquid nitrogen. This ensures that the DUT temperature stays constant at LNT. The testing is then repeated for the five collector-emitter voltage values.

III. RESULTS

This section is devoted to the introduction and discussion of the failure of the PT structure to reach forward conduction mode under certain conditions. Figure 2 shows the collector-emitter voltage waveforms at 78 K, as the device starts to switch into a conduction state but then pulls back into a blocking mode at various dc bus voltages. Figure 4 shows similar waveforms at 4.2 K. The collector-emitter voltages presented in Figure 2 and Figure 4 are normalized to their steady state values to allow an easier comparison of the waveforms. All the data presented in this section are relative to a PT planar-gate device rated for 600 V and 100 A. It must be said that several PT and NPT devices were tested and the same gross behavior was observed in all of the PT devices.

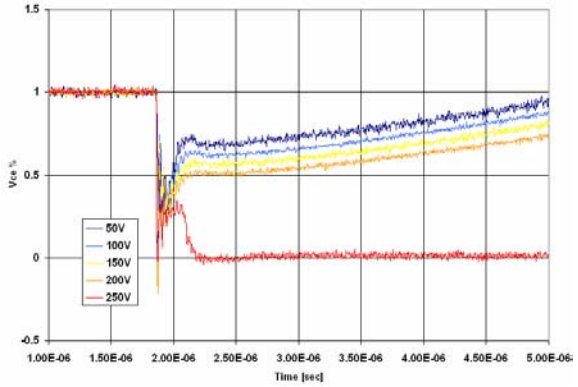


Figure 2: Normalized collector-emitter voltage Vce waveforms for different bus voltages at 78 K, showing failure to reach forward conduction mode.

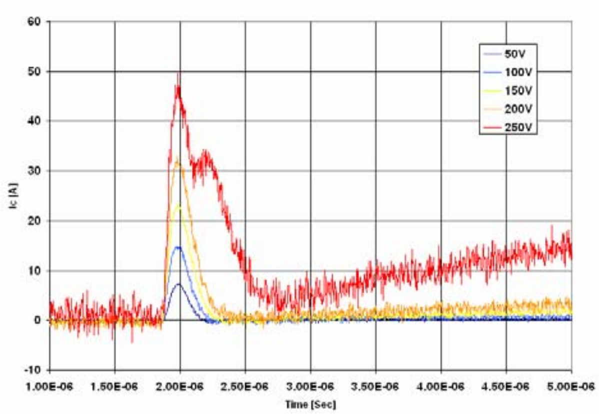


Figure 3: Collector current Ic waveforms for different bus voltages at 78 K, showing failure to reach forward conduction mode.

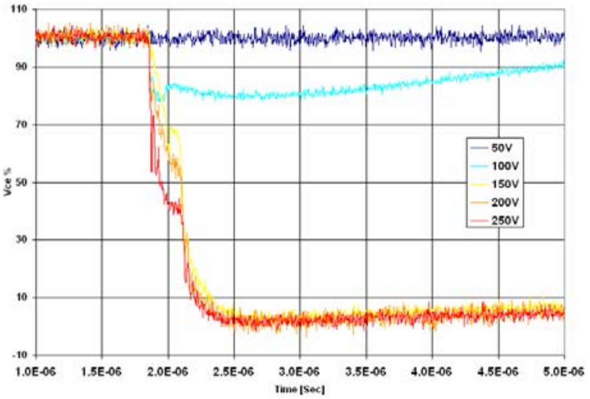


Figure 4: Normalized collector-emitter voltage Vce waveforms for different bus voltages at 4.2 K, showing, failure to reach forward conduction mode.

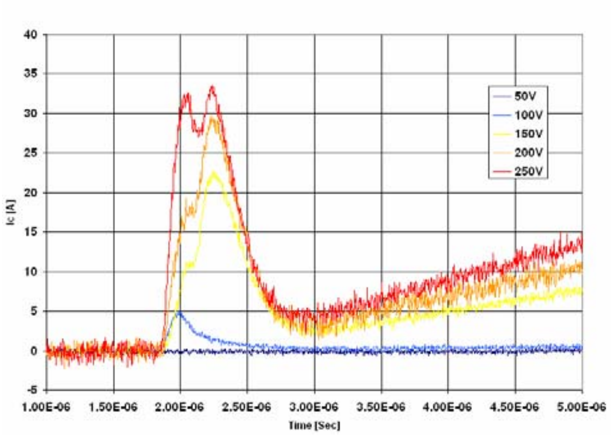
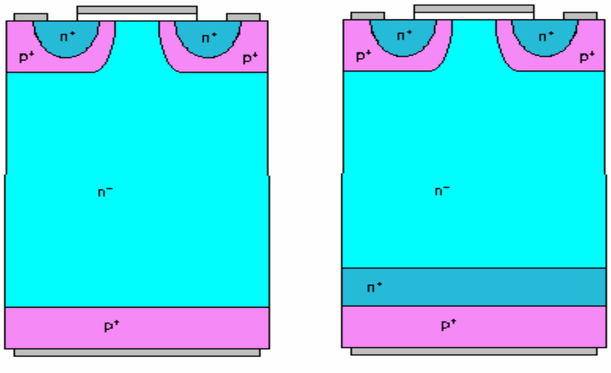


Figure 5: Collector current Ic waveforms for different bus voltages at 4.2 K, showing failure to reach forward conduction mode.

Since the failure to reach the forward conduction mode under extreme temperatures is observed only in PT-IGBTs, the reason must be connected with the buffer layer. Figure 6 (a) and (b) show the two different structures for planar and trench gate IGBTs; NPT and PT respectively.



(a) (b)

Figure 6: (a) NPT structure (b) PT structure

Figure 2 and Figure 4 show the behavior of the collector-emitter voltage Vce for different values of bus voltage at 78 K and 4.2 K respectively. It must be noted that while the threshold value of the bus voltage at 78 K is between 200 and 250 V, the threshold value at 4.2 K is between 100 and 150 V. Therefore the phenomenon is less pronounced at very low temperatures, while it is more pronounced at temperatures near LNT.

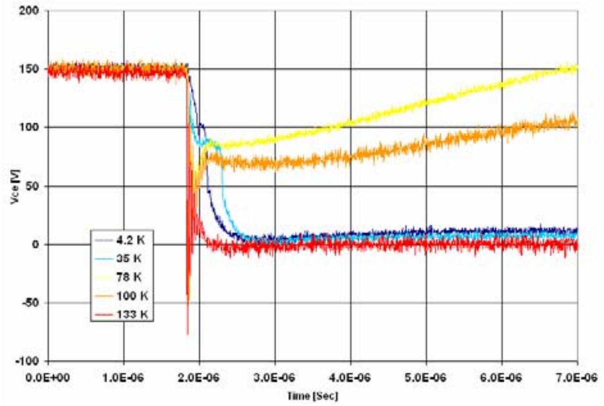


Figure 7: Collector-emitter Vce switching waveforms for a bus voltage of 150 V at various temperatures from 4.2 to 133 K.

Figure 7 shows the collector-emitter voltage Vce across the IGBT for various temperature values for a bus voltage of 150 V. The waveforms shown confirm that the phenomenon is more pronounced at temperatures close to liquid nitrogen, while it is less severe at very low temperatures. In the case shown in Figure 7, the threshold collector-emitter voltage is highest when the temperature is around 78 K, then decreases as the temperature moves away (increasing or decreasing) from 78 K. It is important to notice that this is not the first time that a non monotonic phenomenon (as function of temperature) has been observed [12].

IV. DISCUSSION

Below 20 K the density of ionized impurities greatly decreases as is shown in Figure 8 and reported in [9]. At these extreme temperatures, the drift region and buffer layer approach the intrinsic condition. Therefore, the PT structure becomes a NPT structure, with no discernable difference between the drift region and buffer layer. Concurrent with this effective change, is the large increase in carrier mobilities and decrease in carrier recombination lifetimes from their values at 78 K. The net effect is a large decrease in effective diffusion length at 4.2 K as compared to 78 K. At 4.2 K, with the device in a virtual NPT condition, an appropriately large applied voltage (electric field) will cause most of the renamed “effective drift region” to be depleted to the point that electron flow from the channel (drift current) can cause enough hole injection from the collector (p-emitter) to overcome the recombination current and thus switch the device into its forward conduction state. If the applied electric field (collector-emitter voltage) is too low, the undepleted width across the “effective depletion region” is too large as compared to the effective diffusion length and significant recombination occurs such that no net hole injection is possible and the device does not switch on.

At 78 K the percent ionization of impurities is above 90% (see Figure 8) and the PT design retains its integrity. However, the effective diffusion length is still quite small compared to its value at room temperature (lower recombination lifetime at 78 K). Also, the undepleted portion of the buffer layer is relatively insensitive to applied voltage because of the field pinning. Only at the highest values of applied voltage (250 V from Figure 2) is the undepleted width small enough to allow sufficient electron diffusion to the collector, thus resulting in significant hole back injection and turn-on.

The variation of the electron diffusion length as a function of temperature is shown in Figure 9. The curve is calculated using the temperature dependencies of the mobility and carrier lifetime as described in [9]. The diffusion length decreases by almost a factor of three as the temperature decreases from 78 to 4.2 K.

V. CONCLUSIONS

This work has highlighted the relationship between the junction temperature and the collector-emitter voltage applied and the effect this interdependence has on achieving turn-on in PT IGBTs. While the PT IGBT operating at very low temperatures does not completely lose the capability of turning on, it is limited by the presence of a collector-emitter voltage “threshold”.

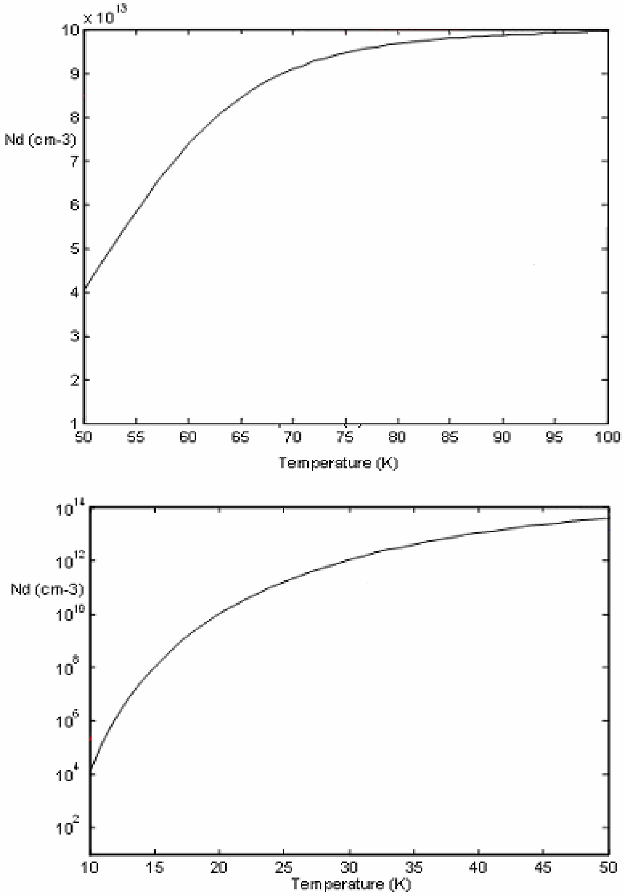


Figure 8: Ionized impurity concentration as a function of temperature.

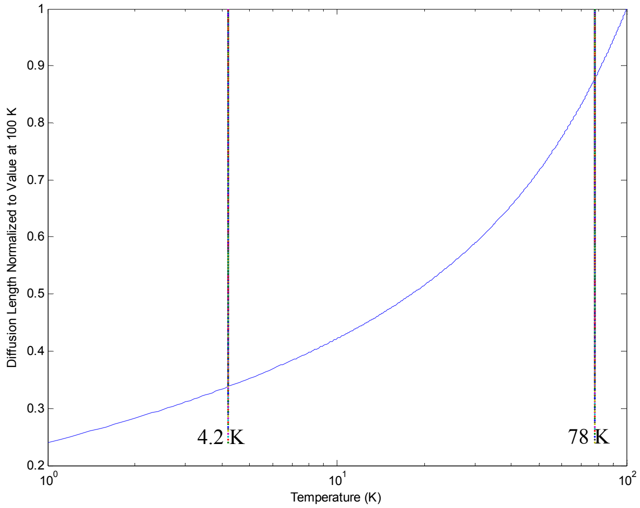


Figure 9: Diffusion length as a function of temperature, normalized to its value at 100 K.

The collector-emitter voltage threshold for turn-on has been shown to be affected by the integrity of the buffer layer. When the temperature decreases below 20 K, ionization of impurity atoms is too low to realize the PT structure and the device becomes solely dependent on the effective undepleted base width and its relative value as compared to the effective carrier diffusion length. Further quantitative analysis of the interplay between the impressed electric field, undepleted base width, ionization level of the buffer layer, and effective diffusion length are needed to describe the details of the qualitative description given in section IV, above.

VI. ACKNOWLEDGMENT

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