Abstract—Detailed experimental data taken for Punch Through (PT) and Non Punch Through (NPT) IGBTs are presented. The test program covered IGBT devices rated for 100–600 A and 600-1200 V from different manufacturers. The forward conduction drops and switching behavior of the IGBTs are examined over a temperature range of 4.2 to 295 K. Physical behavior at low junction temperatures is analyzed. Different behavior of the two structures at cryogenic temperatures is highlighted and the better performances of the NPT technology are shown.

Keywords: IGBT NPT 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 at 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 paper will address the behavior of the Punch-Through (PT) and the Non-Punch-Through (NPT) IGBTs at very low temperatures and specifically highlight the substantial differences in their behaviors under this extreme condition.

II. EXPERIMENTAL SET-UP

The experimental set up is designed in order to perform and capture the switching behavior of the Device Under Test (DUT). The main goals pursued in designing the test bed are the reduction of the overall parasitic inductance, the cooling of the DUT only, and an easy way to modify the load impedance. The DUT, the only part of the circuit inserted into the cryostat, has been connected to the rest of the experimental set-up by stainless steel pipes, a material presenting very poor thermal conductivity and acceptable electrical conductivity. The stainless steel pipes have been arranged in a coaxial structure: it allows a reduction of parasitic inductance and it reduces the cryostat opening necessary to fit all connections. Figure 1 illustrates the connections of the stainless steel pipes with the DUT, and the space occupied by them.

Figure 1: Connections

The structure of the experimental set-up 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 2 with a corresponding photograph of the experimental set-up shown in Figure 3.

Figure 2: Experimental Set-up layout
As it is illustrated in Figure 2, 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 system has been grounded at T2 through the oscilloscope connection.

The temperature was measured by a Lakeshore silicon diode probe model DT-470 that was attached to the package base plate of the DUT. Once the DUT has been placed inside the cryostat, the nitrogen shields of the cryostat are filled and the system cools to 90 K approximately over a period of two days. Next liquid helium is introduced inside the cryostat and the DUT reaches 4.2 K over a period of 20 minutes approximately. 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 devices are listed in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Gate</th>
<th>Structure</th>
<th>I_{max} [A]</th>
<th>V_{ces} [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Planar</td>
<td>NPT</td>
<td>600</td>
<td>1200</td>
</tr>
<tr>
<td>b</td>
<td>Trench</td>
<td>PT</td>
<td>600</td>
<td>1200</td>
</tr>
<tr>
<td>c</td>
<td>Trench</td>
<td>PT</td>
<td>600</td>
<td>600</td>
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<tr>
<td>d</td>
<td>Planar</td>
<td>PT</td>
<td>100</td>
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<tr>
<td>e</td>
<td>Planar</td>
<td>PT</td>
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<td>600</td>
</tr>
<tr>
<td>f</td>
<td>Planar</td>
<td>NPT</td>
<td>100</td>
<td>600</td>
</tr>
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</table>

Table 1: Device tested

All DUTs have been tested with 200 V applied across the collector-emitter in forward blocking and switched so that different collector current values were obtained (by changing the load impedance). Once the DUT is at liquid helium temperature (LHT), the bank capacitor is charged to 200 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. Five different tests are performed. Once all five different testing have been performed at LHT the liquid helium flow is cut causing the junction temperature of the DUT to slowly increase. During this process the load is not replaced and measurements are performed at every 5 K increase. The temperature rise is approximately equal to 1 K/min. This rate decreases when the temperature is close to the liquid nitrogen temperature (LNT). Once the temperature reaches 60 K, the load is replaced, the device is cooled down to approximately 4.2 K and measurements are performed again for every 5 K increase in temperature. This procedure is repeated for each load value (controls the switched collector current value).

III. NPT IGBT

The IGBTs have each been tested with three resistive loads of different value, one inductive load, and in order to measure the output characteristic, a second large inductive load.

a. STEADY STATE BEHAVIOR

The general behavior of the IGBT in steady state will be presented and experimental data will be used to illustrate it. This data was obtained to provide a complement to the switching data that would more clearly indicate the temperature dependence of the carrier recombination lifetimes.

i-v characteristics

A set of output characteristics has been measured for each DUT at several temperatures. In order to minimize the self-heating of the DUT, as reported in a previous work [8], these curves have been obtained by pulsed measurements. The recorded set of collector-emitter voltage and the collector current waveforms are averaged, then plotted to obtain the output characteristic. Figure 4 shows all the resultant average waveforms superimposed with the recorded.

Figure 5 shows the output characteristic derived using this technique. In Figure 4 and Figure 5, the part of the waveform associated with the DUT turn-on transition, the region A, is clearly visible. This portion of the characteristic curve is not meaningful therefore it is not shown in the other figures.
Figure 6 and Figure 7 show the output characteristics of a NPT IGBT (namely \(a\)) for temperatures included between room temperature and LHT.

Figure 8 and Figure 9 show the output characteristics of a NPT IGBT \(f\).

The results relative to the NPT-IGBTs rated for 600 V and 100 A (DUT \(f\)) are consistent with the results relative to the NPT-IGBTs rated for 1200 V and 600 A (DUT \(a\)). They both present three different regions as described below.

For temperatures ranging from room temperature down to 60 K the output characteristics present the same features already described in the literature, namely a shift of the curve’s knee toward higher voltages, an increase of the slope, and a move to a more “square” shape characteristic as the temperature decreases. This behavior has been described in literature for both power diodes and IGBTs. It can be related to two different phenomena. There are fewer free carriers and there is an increase in carrier mobility. The mobility can be related to the slope of the output characteristic and therefore to an increasing slope as the temperature decreases.

For temperatures lower than 60 K the output characteristics do not quite follow the same trend. In both cases for temperatures between 45 and 25 K the characteristics lose their steep slope at low currents and present a two-phase transition between low and high currents. The overall curve still moves toward higher voltages as the temperatures are lowered. The behavior can be explained by considering the carrier lifetime and impurity doping. As the junction temperature drops below 35 K, the recombination traps remain filled until a higher value of electric field provides enough energy to cause some improvement in recombination efficiency. In addition, the ionized impurity concentration
begins to very rapidly decline such that the device begins to become more and more intrinsic throughout. This helps explain the reason that the curves for temperatures of 25, 20 and 15 K look similar. The DUT turn-on becomes slower at lower temperatures, thus this transition time becomes comparable to the circuit time constant and makes it difficult to reach steady state during the pulse testing. Allowing a longer turn-on time would cause serious self-heating and would invalidate the approximation for the junction temperature.

Conduction Losses

The conduction losses have been measured for three different resistive loads. It will be shown in the comparison section that as the temperature decreases, the losses decrease until a threshold temperature value is reached, then they increase again.

b. Dynamic Behavior

Turn off time

Figure 10: $I_c$ Turn-off family for DUT a shows a family of collector currents tails for temperatures ranging from room temperature to liquid helium temperature for DUT a.

In Figure 10 the collector current tail is very noticeable when the device is tested at room temperature, and it virtually disappears when the operational temperature is equal to or lower than 60 K. The length of the collector current tail is directly connected to the carrier lifetime of the drift region. A decrease of the operating temperature corresponds to a decrease of the carrier lifetime.

Another phenomenon that can be observed when the temperature is between 70 and 30 K is the incremental slope relative to the part of the collector current associated with the MOSFET turn-off and establishment of the depletion region in the IGBT drift region. To avoid confusion, every time the “slope” is mentioned, it refers to the slope just mentioned. This slope depends, among other parameters, upon the resistance of the drift region. Considering the general expression of the resistivity in silicon:

$$\rho = \frac{1}{q \cdot (n \cdot \mu_n + p \cdot \mu_p)}$$  \hspace{1cm} (1)

It is possible to say that its value depends on the value of the mobilities (electrons and holes). When the operating temperature is decreased, the values of the mobilities increase (from 300 down to about 30 K). This is the range in which the lattice scattering dominates. Below 30 K the scattering due to impurity atoms dominates and the mobilities again decrease causing a slight increase in fall time.

In Figure 11 the turn off time of the different loads merges. It is directly connected with the decrease of the carrier lifetime value.

Energy losses

A good understanding of the relation between the energy lost during turn-off and the device temperature can be gained from Figure 12.

In Figure 10 the collector current tail is very noticeable when the device is tested at room temperature, and
IV. PT IGBT

The PT IGBTs have been tested exactly as the NPT IGBTs such that a final comparison will be consistent. Steady state behavior and dynamic behavior has been investigated.

a. Steady State Behavior

The measurements of the output characteristic of PT-IGBTs with this technique led to some incomplete results. While the technique gave appropriate and correct data from room temperature to LNT, due to the structure and dynamics of the PT-IGBT, it gave unexpected results for lower temperatures. This indicates that this technique is not adequate for output measurements of PT-IGBTs at temperatures below the LNT. Problems in measuring the output characteristic of a PT-IGBT at very low temperatures have already been reported in the literature [8]. The output characteristic of a PT-IGBT at very low temperature in fact has never been reported in any previous work. Nevertheless, data as poor as it is are reported and illustrated.

i-v characteristics

Figure 13 and Figure 14 represent the output characteristics of a PT IGBT rated for 1200 V and 600 A (DUT b).

![Figure 13: i-v characteristic of PT IGBT b](image)

![Figure 14: i-v characteristic of PT IGBT b](image)

Figure 13 shows the voltage drop characteristics from room temperature to LNT. The evolution of the curves confirms the data reported in literature relative to the PT-IGBT [2]. Figure 14 shows the evolution of the voltage drop characteristics from the LNT to the LHT. The data shown in Figure 14 have not been selected intentionally. The curves do not follow a classical shape; they present different regions with different slopes. This phenomenon can be partially attributed to a very slow transition from the off-state to the on-state. Another subject that is related to this phenomenon is the partial failure of PT-IGBT to turn-on. This issue will be separately addressed in another work. When the temperature is very low, the device becomes extremely slow and therefore cannot fully turn on during the measurement timeframe. Although the data shown in Figure 14 do not fully capture the voltage drop characteristics at very low temperatures, they draw attention to the very large value of voltage drop across the device at the lower temperatures. The large voltage drop at extremely low temperatures has been observed during the switching measurements, also. PT-IGBTs with different ratings and from different makers show a similar behavior.

Conduction Losses

The conduction losses have been measured for the PT structure as well. It will be shown in the comparison section that the losses have a behavior similar to the losses presented by the NPT structure: as the temperature decreases, the losses decrease until a threshold temperature value is reached, then they increase again.

b. Dynamic Behavior

Turn off time

Figure 10: Ic Turn-off family for DUT a shows a family of collector currents tails for temperatures ranging from room temperature to liquid helium temperature, and Figure 16 shows the turn off time interval for the DUT a at different loads.

![Figure 15: Ic Turn-off family for DUT b](image)

![Figure 16: Turn-off time interval for resistive switching of DUT b](image)
The behavior of the PT IGBT can be explained with the same motivations introduced to explain the behavior of the NPT-IGBT.

Energy Losses

Figure 17 shows the losses in the DUT b for various loads versus junction temperature. The macro-behavior is similar to the NPT devices. It must be noted that while there is generally a reduction in energy losses due to a reduction of temperature, the difference between the energy losses at room temperature and the lowest values of energy losses is not large.

V. COMPARISON

i-v characteristics

At low temperature PT-IGBTs present a forward voltage drop higher than the one presented by the NPT-IGBTs. Moreover, it has been noted that the PT-IGBTs require a relatively high collector to emitter voltage for turn-on while the NPT-IGBTs do not require any particular collector to emitter voltage value. This behavior was first observed in [8], but was erroneous in stating that the switchability of the device was lost at low temperature. The lower the temperature the higher the activation voltage (applied collector-emitter voltage) must be. This issue will be addressed in another work. The NPT IGBTs switch slower at very low temperatures as well, but not to the extent of the PT devices.

Conduction Losses

Figure 18 shows the power losses using different loads in two DUTs, a and b (NPT and PT respectively), with similar ratings (1200 V and 600 A).

These instantaneous power values have been calculated combining the dynamic switching characteristics and the forward voltage drop data where the collector current measured during the on-condition of the DUT has been multiplied by the value of the forward voltage drop measurement corresponding to the temperature and the collector current value from the previous figures.

Figure 18 shows that there are three main regions: the high temperatures (250-300 K) where the PT device has smaller losses, the intermediate temperatures (70-250 K) where the losses are roughly constant and nearly equal, and the lowest temperatures (less than 70 K) where the losses in both devices increase dramatically. Due to the low resolution of the data used, the minimum of the losses (as a function of temperature) cannot be pinpointed, but it is between 70 and 200 K. The losses, after a small reduction with decreasing temperature, suddenly increase at a threshold temperature between 50 and 70 K. The observed increase is much more significant in the PT IGBT. This phenomenon can be attributed to the much higher forward voltage drop associated with the PT devices at low temperatures. These results are consistent with the forward voltage drop measurements.

Turn off time

Figure 19: Comparison of turn-off time at various loads between the DUT a and b versus temperature
Figure 19 shows that below 100 K the similarly rated PT and NPT devices have turn-off times close in value to each other. This is indicative of the recombination lifetime moving toward a minimal value because all trap levels are empty due to the lack of thermal energy available from the lattice.

Energy Losses

As expected, at room temperature the losses related to the NPT structure are higher than the ones related to the PT structure. The reason of it is found in the much longer collector current tail of the NPT structure than the one of the PT structure. When the temperature is low enough and the corresponding lifetime is small enough, and given the fact that the two devices have comparable sizes, the two curves merge and they present almost the same values of energy losses. In this case too, at very low temperature the PT structure loses its advantage over the NPT structure.

VI. CONCLUSIONS

In this work data have been presented relative mostly to DUT a and b. Data collected from the other four DUTs confirm the behavior observed and presented in this study. It has been shown that, at very low temperatures, the PT structure loses all the advantages over the NPT structure. Moreover, the losses during conduction mode are much greater than those observed for the NPT structure.

Another problem related to the PT devices is the difficulties to turn them on. This particular feature is analyzed in another work.

Concluding it is possible to say that the NPT structure should be the choice if the operating temperature is extremely low.

VII. ACKNOWLEDGMENT

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VIII. REFERENCES