Cryoelectronics – An experimental examination of the behaviour of power electronic devices at low temperatures

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ABSTRACT

The operating characteristics of power electronic devices vary greatly with the operating temperature at which the device is used. The characteristics for devices operating at room temperature or above are well documented. However, only limited data is available for operation at cryogenic temperatures, especially for recently released devices. Operation of power electronic devices at cryogenic temperatures is known as cryoelectronics and operation in this temperature region can be beneficial as the operating characteristics of some devices can improve markedly. The potential use of cryoelectronics is quite broad, but it is particularly relevant in applications where a cryogenic environment exists such as spacecraft design and superconducting technologies.

INTRODUCTION

This study examines the two main semiconductor-switching technologies, Metal Oxide Silicon Field Effect Transistors (MOSFETs) and Insulated Gate Bipolar Transistors (IGBTs). It has already been demonstrated that when operating at 77K, MOSFETs show a large drop in on-resistance ($R_{ds(on)}$) [1] but also a proportional drop in breakdown voltage (V_{BD}) [2]. This might suggest that at cryogenic temperatures MOSFETs are only suitable for low voltage applications, however devices that exhibit very high V_{BD} and current carrying (I_{ce}) ratings have recently become available. If the reduction in breakdown voltage is within an acceptable level then paralleling such devices may be a viable solution for high power applications. IGBTs are specifically designed for high power applications, and whereas MOSFETs would need to be paralleled to satisfy the current rating, a single IGBT device would be required.

Past work on cooling IGBTs to cryogenic temperatures showed that some devices did exhibit reduced losses whilst others would not work below certain temperatures – typically 120K [3]. Development of the Non Punch Through (NPT) technology in IGBTs has produced devices that are capable of operating at cryogenic temperatures down to 5K [3]. Whether or not the cooling of these devices results in a substantial drop in power loss is yet to be determined.

In this paper, operating characteristics including V_{BD}, $R_{ds(on)}$ and forward collector-emitter voltage (V_{ce}) of various MOSFETs and IGBTs operating at cryogenic temperatures will be presented and discussed.

EXPERIMENTAL SET-UP

Devices Under Testing (DUTs)

The DUTs used in the experiments were selected with the following three objectives in mind. 1) To confirm the decline in $R_{ds(on)}$ in MOSFETs and investigate the resulting reduction in V_{BD} in highly rated devices. 2) To confirm that Punch Through (PT) IGBTs are unable to operate below certain temperatures and quantify the operating characteristics within their temperature limitation. 3) To investigate the claims of consistent positive temperature coefficients of NPT IGBTs by some manufacturers and confirm that these devices do not cease to conduct at any cryogenic temperature.

Using the three objectives as a guide, six DUTs were selected for experimentation; the specifications for these devices are shown in Table 1.

Table 1 Device Characteristics as Specified by Manufacturer (Ambient Temperature Operation)

Brand	Type	Device No.	V_{BD}	I_{CEmax}	Package
STM	MOSFET	STY15NA100	1000	10	TO-247
IXYS	MOSFET	IXTH13N80	800	13	TO-247
Fairchild	PT	SGL40N150DTU	1500	40	TO-264
IRF	PT	IRG4PH50S	1200	57	TO-247
Infineon	NPT	BUP314	1200	52	TO-218
Infineon	NPT	SKW25N120	1200	46	TO-247

It should be noted that these devices were selected due to the package type. This was for two reasons; firstly the physical size of the cold head used for the V_{ce} experiments was quite small and secondly, previous experiments with large package devices revealed that the devices were destroyed due to the thermal shock when immersed in liquid nitrogen (LN2).

V_{ce} and $R_{ds(on)}$ Test Rig

To determine the increase or decrease in power losses by a device operating at cryogenic temperatures, accurate measurements of the V_{ce} of the IGBTs and the $R_{ds(on)}$ of the MOSFETs are needed. The experimental rig was the same for both measurements and a schematic of the set-up is shown in Figure 1.

The DUTs were placed on a cold head cooled by a gaseous helium CTI Cryogenics Model 8300 cryocompressor. The chamber around the DUT was evacuated to 2 Pa, enabling the device to be operated in an environment ranging from 300K to 30K. The gate of the devices remained open as a single 20A pulse of current was applied across the collector-emitter and the resulting V_{ce} measured by a Lecroy 9304AM 4 channel CRO. For the $R_{ds(on)}$ measurements, a 10A pulse was used and a current transformer monitored the current waveform enabling resistance of the device can be accurately determined. For each of the DUTs, the value was then confirmed by re-measuring it in LN2.

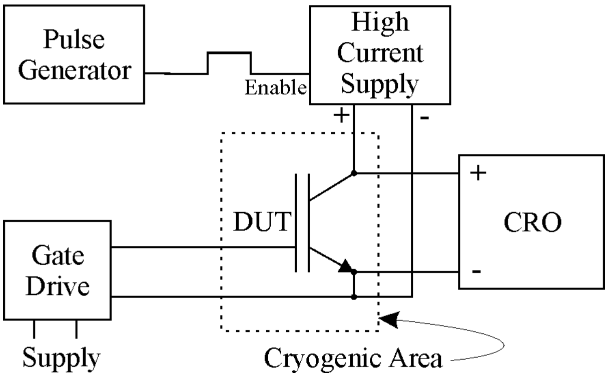

Figure 1 Experiment set-up for V_{ce} and $R_{ds(on)}$ measurement

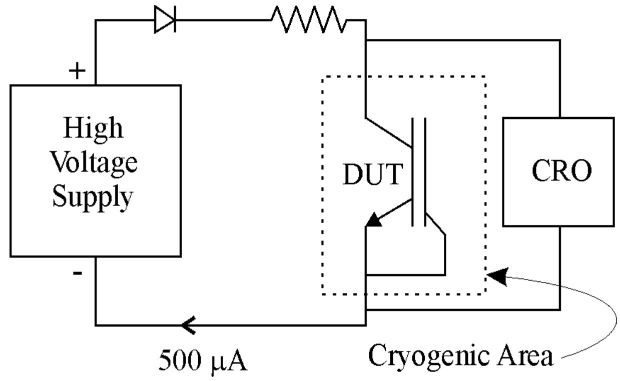

Figure 2 Experiment set-up for V_{BD} measurement

<u>V_{BD} Test Rig</u>

Operating semiconductor devices at cryogenic temperatures causes an increase in the carrier mobility, leading to an increase in the ionization impact rate and hence a decreased V_{BD} rating [4, 5]. To effectively use these semiconductors at cryogenic temperatures it is important to determine how much each device is de-rated.

To determine the V_{BD} for each device, the experimental set-up shown in Figure 2 was used. Due to the destructive nature of the tests, the V_{BD} value for each DUT was measured at two temperatures. LN2 provides an easily available and stable cryogenic environment at 77K and hence this was the temperature chosen as a comparison to room temperature.

The high voltage supply was applied across each of the DUTs and the voltage increased until avalanche occurred. At this point, the V_{BD} was measured.

RESULTS

<u>V_{ce} and $R_{ds(on)}$ Test Results</u>

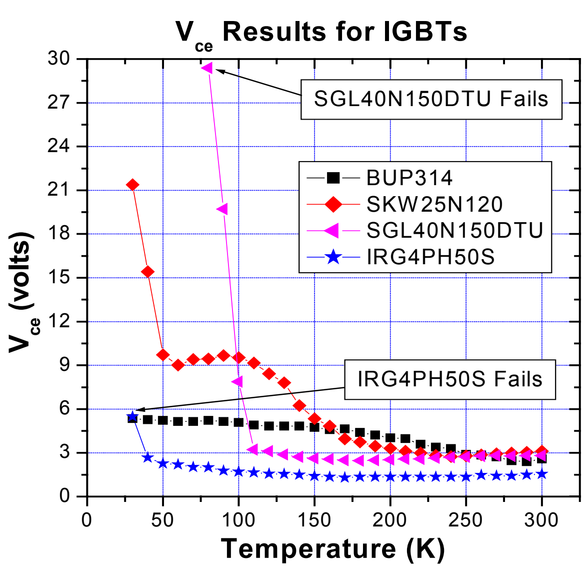

Figure 3 Graph of V_{ce} results for the IGBTs

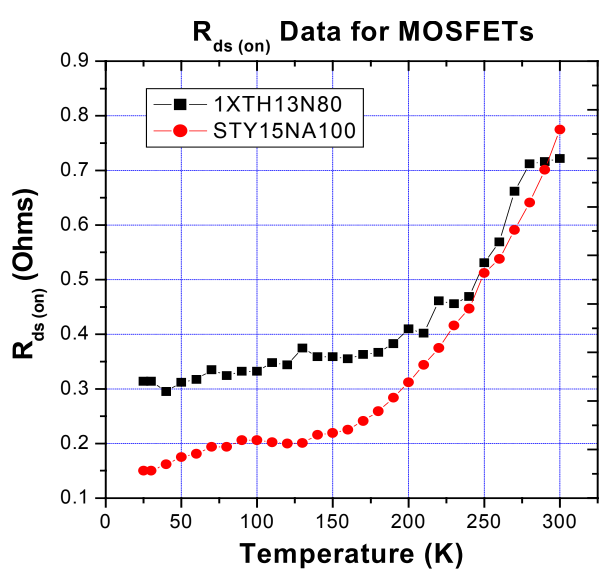

Figure 4 Graph of $R_{ds(on)}$ results for MOSFETs

Each of the devices were tested from 300K to 30K in increments of 10K. To ensure repeatability of the data, measurements on the samples were repeated as the devices warmed to ambient temperature. The V_{ce} results for the NPT and PT IGBTs are given in Figure 3 and the $R_{ds(on)}$ measurements for the MOSFETs in Figure 4.

V_{BD} Test Results

The measured V_{BD} at ambient temperature and at LN2 temperatures is recorded in Table 2 for each device.

Table 2 V_{BD} Results at 300K and 77K

Device	V_{BD} 77K (V)	V_{BD} 300K (V)	V_{BD77}/V_{BD300} (%)
STY15NA100	-	1182	-
IXTH13N80	723	960	75.3
SGL40N150D	1286	1612	79.7
IRGPH50S	1067	1332	80.1
BUP314	1105	1433	77.1
SKW25N120	1098	1307	74.9

Note there was no value recorded for STY15NA100 as the package design was not able to withstand the thermal shock associated with immersion in an LN2 bath. It was also observed that the V_{BD} measured at ambient room temperature was consistently higher than that specified by the manufacturers.

CONCLUSIONS

From the results presented, the following conclusions can be drawn; 1) NPT IGBTs are able to operate at cryogenic temperatures down to 30K, however do so at an increase in continuos power losses and a reduction in V_{BD}. 2) PT IGBTs show stable operation in regard to temperature and show a slight reduction in power loss at some temperatures; however they have an intrinsic cut-off temperature below which they will not function. 3) MOSFETs are the most suitable device for cryogenic operation. In this sample, some showed a reduction in $R_{ds(on)}$ of greater than five times. A reduction in V_{BD} was apparent but was no more than other types of semiconductors. The advent of high V_{BD} MOSFETs means this is not as significant a problem.

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