MOSFET Characteristics at Cryogenic Temperature

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Abstract—Efficiency is a large concern in power electronics but size and weight must be taken into consideration as well. Power devices in need of thermal sinks for appropriate performance will affect both size and weight. MOSFET devices are the main components in the power electronics world because of their comparatively promising characteristics in power loss and switching performance. The objective of this research is to obtain results as to how the MOSFET device will perform in various temperatures that go as low as liquid nitrogen temperatures. More than one device was tested and compared in order to get the best performing. It is believed Cryogenic operation of MOSFET devices results in improved performance and efficiency. The switching performance of the devices will be analyzed using the Double Pulse Test (DPT). Ultimately, the objective of this research is to design a DC–AC inverter for Boeing & NASA aircraft using the best performing MOSFET device.

Index Terms—Double Pulse Test, Power Inverter, Cryogenic Temperature

I. INTRODUCTION

It is essential to understand the structure of MOSFET devices and the Double Pulse Test process that is used to analyze them. There are four main characteristics that are being observed for each device. Each defines the device’s efficiency and performance. On-state resistance, switching loss, body diode, and breakdown voltage are the four characteristics that will be affected by the change in temperature and determine the device performance gains. Different techniques are used to obtain each one and will be discussed further on.

The purpose of the Double Pulse Test is to obtain data reflecting the switching characterization of power devices in a simplified printed circuit board (PCB). This board allows to evaluate their switching behaviors as if in an actual power converter. The Double Pulse Test consists of manually triggering two pulse as an input to the gate of the device. Each pulse has its purpose and effect to the device. The length of the first pulse, in time, builds up a desired current through the inductor load. The switching transient consists of the turn off and turn on of the device. The falling edge of the first pulse corresponds to the turn off transient while the rising edge of the second pulse corresponds to the turn off.

The components required for this set up are the following:

- Device Under Test (DUT)
- Inductive Load
- Auxiliary DC Power Supply

Lab procedures for testing devices have to be taken into consideration for accurate results. Initially, probe compensation and de-skew correction are necessary for voltage-current alignment. The yellow scope must compensate for the input at the gate of the MOSFET while the blue scope compensates for the drain source voltage. As it is usually assumed, the channel 1 with yellow waveforms is used as gate-source voltage measurement, the channel 2 with blue waveforms is used as drain-source voltage measurement, the channel 3 with purple waveforms is used as drain-current measurement, and the channel 4 with green waveforms is used as load-current measurement. The purple current probe is de-skewed and the propagation delay for all are minimized as much as possible. The probes have different purposes such as the probes being used in channels 1 and 2 for voltage measurement. The difference in those two channels are the voltage levels: 1 for ≤ 600V; 2 for 600V ~ 1200V. Different probes will have different parasitic, which will cause the error of the measurement, in order to avoid that, the de-skew process was conducted. Meanwhile, when the 600V-level test was conducted, same type of probes was used for both channel 1 and 2, the de-skew process was not necessary in this case.

Before any testing is done to the devices, the circuit board must have exposed, conductive parts covered. Icing at lower temperatures can cause problems such as shorts in the circuit leading to damaging equipment. The lowest temperature, for the chamber, allowed is 93 K (-180°C) and the highest temperature tested is 23 K (room temperature). Once the board is ready, it is placed inside the chamber even for room temperature testing. The room temperature testing is done after the chamber has been heated up for moisture dissipation. This procedure mitigates humidity in the inner chamber and reduces the possibility of short-circuiting due to icing at cryogenic temperature.
The circuit board consists of several parts having voltage supplied to it. The gate driver has a 25 V DC supplied to it and the 250 V DC auxiliary power is the main supply for the circuit. The device rated at 500 V is supplied with 250 V from the auxiliary power. Other devices rated at higher voltages such as 800, 900 and 1200 V are supplied with up to 500 V from the bus voltage. The last input for the test would be using the Tektronix program to generate a double pulse gate signal. For more accurate results, the Auxiliary power supply for gate the drive does not function properly at cryogenic temperature; therefore, placed outside the chamber. The first pulse is varied in time which increases the current induced in the device. This changes the switching characteristics, which is what is being analyzed. The falling edge of the first pulse is the turn off region while the rising edge of the second pulse is the turn on. This switching transient region is analyzed for the device’s switching characteristics.

Scaling and positioning may have to be adjusted on the oscilloscope when showing results. Every value of the transient switching time must be shown on the display. Overshooting and ringing are the main causes of displaying problems, which add difficulty of MATLAB calculations of the switching characteristics: energy loss, switching time, delay time, etc. After adjusting, the double pulses are inputted again and repeated until the right scaling and positioning is acquired. The saving process includes the time periods and values of the switching transient, which are then implemented in a MATLAB code. Values for time delays of the drain source voltage, gate voltage, and current are obtained using code.

The four characteristics are broken down and explained in the following sections. Each concluding with results from experimentation and graphs using the data obtained. The experiment consists of more than one device from different manufacturers: Microsemi, Infineon, IXYS

II. ON-STATE RESISTANCE

The University of Birmingham tested the SPP20N60C3 power MOSFET for a 500 V converter and obtained its characteristics. These higher voltage devices result in a larger reduction of on-state resistance at cryogenic temperatures [1]. The on-state resistance consists of more than one component; the drift region resistance of MOSFET devices dominate the on-state resistance when devices are rated above 150 V [4]. This is due to its temperature sensitivity [1].

Components of the MOSFET resistance [2]:
\[
R_{DS(ON)} = R_{source} + R_{ch} + R_{A} + R_{J} + R_{D} + R_{sub}
\]
- Source diffusion resistance
- channel resistance
- accumulation resistance
- JFET component-resistance
- drift region
- substrate

The following shows the basic components of a power MOSFET which include major contributors to the device’s resistance [4].

The Lab procedure consists of using a high power curve tracer which plots the devices characteristic curve. The plot is labeled as the following: (V_{DS}) drain-source voltage on horizontal axis and (I_{D}) drain current on the vertical axis. (V_{GS}) Gate-source voltage is a constant input for each individual curve, normalized throughout 10 V to 20 V.
The resulting curves will allow to find the drain-source voltage that corresponds to the rated drain current recommended in the device’s datasheet at various temperatures. The two values can then be used to calculate the on-state resistance for each individual device at a certain temperature. The experiment began at room temperature and decreased to -180 degrees Celsius in intervals of 50 degrees, resulting in 6 plots for each device.

In closing, the $R_{DS-ON}$ significantly reduces as temperature drops. Due to the improvement of carrier mobility in the drift region, conduction loss during operation is reduced [1]. Plot of on-state resistance using curve tracer results:

As earlier stated, the procedure used is called the double pulse test and allows for the observation of delays and propagations in the switching transient. The double pulse test consists of two pulses that are inputted into the gate; the first falling edge of the first pulse is the turn off transient while the rising edge of the second pulse is the turn on transient. Before testing the devices, the probes being used must be well calibrated and the V-I alignment must be done. Within the probes being used, the voltage and current probes are ones that have different characteristic propagation delay and are de-skew corrected for accuracy enhancement. This process is done for each individual test.
MOSFET devices have internal parasitic that effect the behavior in the switching transient. Parasitic inductances will cause ringing and overshooting; parasitic capacitance determines a time constant for the circuit and increases delay. The results in the oscilloscope show the following: \( V_{GS} \), \( V_{DS} \), \( I_{D} \) and inductor current.

The ringing due to parasitics is shown in a turn on transient response [5]:

![Figure 7: DPT Switching Characteristics](image)

These results lead to the calculation of \( T_{ON\_DELAY} \), \( T_{ON} \), \( T_{OFF\_DELAY} \), \( T_{OFF} \), \( E_{OFF} \) and \( E_{ON} \) via MATLAB code. The code calculates average values over a certain period of time and value of energy loss. The delay times relate to the amount of time difference between the current and voltage at an off or on transient. On and off time corresponds to just the current. It is the amount of time it takes the current to change within 10% to 90% of its value.

The MOSFET switching performance improves at lower temperatures, resulting in changes of the calculated values. The energy loss and the \( T_{ON} \) for the on period is significantly reduced while the \( E_{OFF} \) and \( T_{OFF} \) are only slightly reduced. The delay times both roughly remained the same value as temperature decreased. The turning on switching transient shows the most improvement in the device’s testing at lower temperatures.

As the device is in the off mode/cut off region, the reverse drain current is now passing through the body diode which shorts the source and drain [2]. This creates a high current path for the device, rather than the drain-source conducting channel [2]. Reverse recovery characteristics of the body diode play a significant role in the switching characteristics of the device. During switching transients, the reverse recovery is divided into time periods as seen below. The reverse recovery time is an important factor of losses and defines the time it takes for drain current to reach a constant value of zero amperes.

![Figure 8: Reverse Recovery behavior](image)

In order to decrease switching and conduction losses, the input from oscilloscope now includes a dead time. Dead time is an input that is between two other pulses in which the inductor current is taking the body diode path.

**IV. BREAKDOWN VOLTAGE & BODY DIODE**

The power MOSFETs can be operating in three different stages: cut-off, saturation, and breakdown region. The breakdown region limits the drain-source voltage amplitude of the device and is located to the far right of the MOSFET characteristic curve. The breakdown region varies while it depends on the gate-source input and temperature. When the device receives too much voltage across the drain-source terminals, it reaches the point where the device cannot resist current and breaks down. This allows a large amount of current to flow through the device and drastically increases. Due to a correlation with temperature, on-state resistance shows a non-linear relationship with the breakdown voltage when plotted.
The breakdown voltage configuration allows the measurement of current when the device is reaching its rated voltage. Initially, the current is so small it is considered to be zero and 1 mA when at its breakdown. The devices under testing had a smaller breakdown voltage than the voltage they were rated at, when operating at lower temperatures.

The configuration shows the device is set up in series with a large resistance of 100 kOhms that will limit the current. While the gate and source are short circuited, voltage is applied to see how much is needed in order for the ammeter to read current. The breakdown voltage is set as to when the leakage current reaches 1 mA. The diode forward voltage is the amount of voltage drop across the diode when the source has a specified value of current. The usual current used is the rated current from the device’s datasheet.

The following figure shows the configuration when using the curve tracer for on-state resistance and body diode testing:

V. 77K LIQUID NITROGEN POURING TEST

The lowest temperature used on the devices under testing was the liquid nitrogen temperature of about 77 K. Having a minimum temperature operation of about 93 K, the cooling chamber Delta 9023 model was not functional for the lowest temperature. Using a Styrofoam container and a larger plastic container, each device was directly inserted into the liquid nitrogen while under testing. The previous schematics for the tests still apply for the 77 K testing; therefore, same procedures apply.

The time for this is quite limited because the liquid nitrogen will last about 30 minutes in its liquid state and will evaporate. This evaporation will cause the temperature to start to increase again. In order to keep the temperature constant at around 77 K, liquid nitrogen is constantly being poured in small amounts into the Styrofoam container. The larger plastic container is uses as an outer shell in case of leaks or spills.

The image below shows the set up for the lowest temperature testing:
VI. CONCLUSION

This research demonstrates a way to reduce the losses in power MOSFETs. This allows for more efficient power devices with many advantages when operating at cryogenic temperature. MOSFET devices have switching characteristics that will have losses at high frequencies. Under low temperatures, the devices have slightly faster switching with less ringing, which is caused by internal parasitic as earlier stated. On-state resistance drastically decreased due to the increase of carrier mobilities in the MOSFET’s main resistive components. These factors allow the efficiency of the device to increase and enhance its performance at cryogenic temperatures.

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