Name of the Experiment: Double Pulse Test Based Switching Characterization of SiC MOSFET.

Aim:

i) Analyze the switching waveforms (Gate to Source Voltage (V_{GS}) , Drain to Source Voltage (V_{DS}) and Drain to Source Current (I_{DS})) of the device under test.

ii) Calculation of Switching Times (Delay Time (t_d) , Rise Time (t_r) & Fall Time (t_f)) and the Switching Losses.

Theory:

Double-pulse test is a method widely used to evaluate the characteristics of power switching elements such as MOSFETs and IGBTs. In these tests, apart from the switching characteristics of the tested element, it is also possible to evaluate the recovery characteristics of the body diode and fast recovery diodes (FRDs) which are often used together with IGBTs. Hence these tests are extremely useful for evaluations that assume a circuit in which losses occur due to recovery characteristics during driven-side element turn-on. The basic circuit diagram for double-pulse tests is shown below.

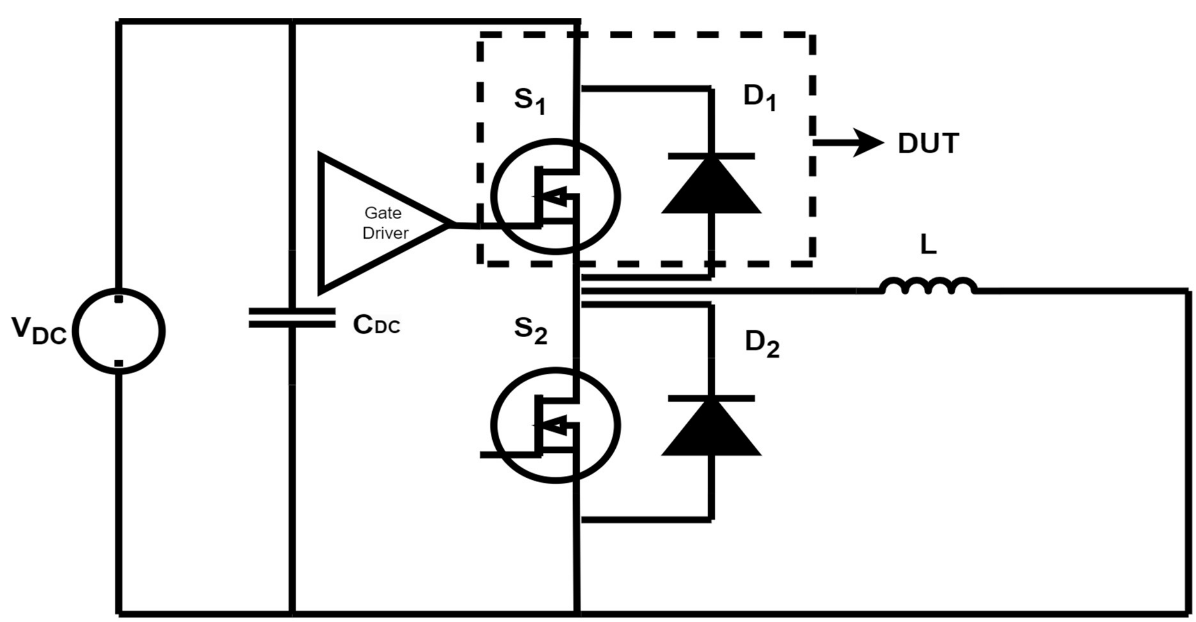
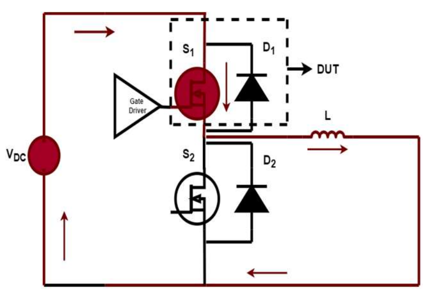
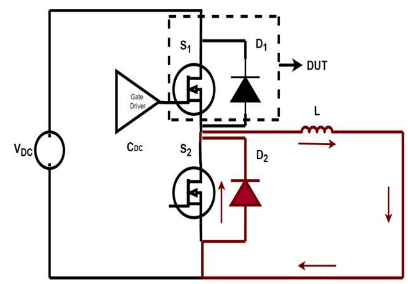
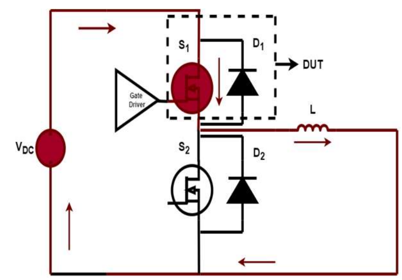
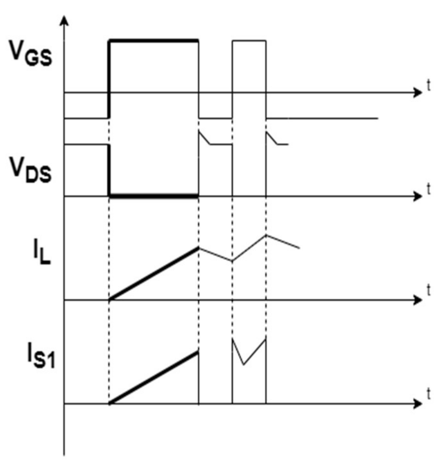
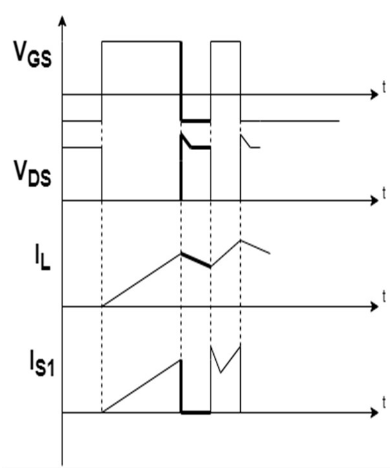
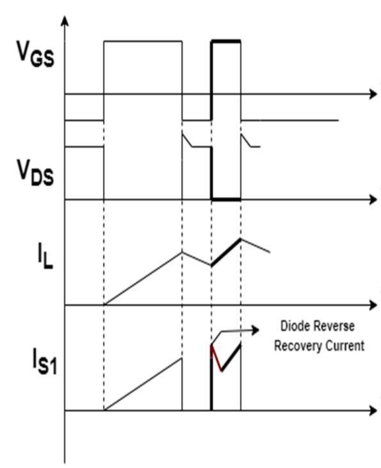
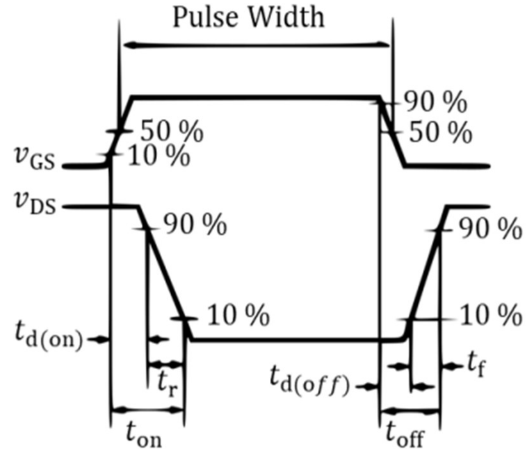


Fig. 1

The table shown below indicates the basic operation of double-pulse test. The operation can be mainly categorized as three modes ①, ②, and ③. Current paths, and waveforms in each of these modes are shown below.

MODE 1	**MODE 2**	**MODE 3**
• $S_1$is in on state. • Current path is **Power Supply–S_1–L–Power Supply.** • Inductor stores energy during this interval.	• S_1 is turned off. • As S_1 is turned off inductor current makes a closed path through the body diode D_2.	• S_1 is turned on. • Current path is **Power Supply–S_1–L–Power Supply.** • Diode reverse recovery current gets superposed on inductor current during turn on.
		
		

Switching Times:

$t_{d(on)}$: Turn-on delay time is the time interval between 10% of the rising V_{GS} and 90% of the dropping V_{DS}. **t_r :** Rise time (due to the rising current) is the time interval between 10% and 90% of the V_{DS}. **$t_{d(off)}$:** Turn-off delay time is the time interval between 90% of the droppingV_{GS} and 90% of the rising V_{DS}. **t_f :** Fall time (due to the falling current) is the time interval between 10% and 90% of V_{DS}.	

Calculation of Pulse Duration:

For the double pulse test, the necessary pulse sequence is calculated beforehand. The phases are as following: first pulse with the duration τ_1 , the pulse break with a duration τ_{break} , the second pulse with duration τ_2.

The first pulse turns on the DUT and thus, a closed loop circuit consisting of the capacitor bank, load inductance and parasitic series resistance (R_s) is formed. The pulse length is chosen such that the desired load current (test current) is reached. The duration of the first pulse is defined according to the equation for the inductance,

$$v_{\mathrm{load}} = L_{\mathrm{load}} \cdot \frac{\mathrm{d}i_{\mathrm{load}}}{\mathrm{d}t}$$

…………….(1)

After integrating the above equation, substituting i_{Load} with the desired test current I_{Test} & $V_{\mathrm{Load}}=V_{\mathrm{DC}}$ leads to the pulse duration (τ_1) for the first pulse (the parasitic series resistance R_s is neglected):

$$\tau_1 = L_{\mathrm{load}} \cdot \frac{I_{\mathrm{Test}}}{V_{\mathrm{DC}}} \cdot$$

...................(2)

During the pulse break τ_{Break} , the DUT is turned off and the current flows through the freewheeling diode. Due to the parasitic series resistances R_s , the inductor current drops slightly. By applying Kirchhoff's voltage law to the closed loop circuit, we get:

$$v_{\mathrm{f}} = -(R_{\mathrm{S}} \cdot i_{\mathrm{load}} + L_{\mathrm{load}} \cdot \frac{\mathrm{d}i_{\mathrm{load}}}{\mathrm{d}t})$$

..................(3)

where v_{f} is the forward voltage of the diode, which can be obtained from the data sheet.The drop in current during this period can be taken as 1 to 5 % of the rated load current.

With the second pulse (τ_2), the DUT is turned on again, and energy is transferred to the load inductor. As a result, the voltage drops and the current continues to rise. The duration of the second pulse should be chosen so that the current through the DUT does not reach an impermissibly high value. The peak overshoot in the current observed, is caused by the reverse recovery of freewheeling diode. Here, the stored charges of the diode add an additional current component which has to be taken by the switch. τ_2 can be calculated using the equation (1).

Voltage and Current Measurements :

For the estimation of all the devices' switching characteristics, both voltages and currents have to be measured. The first challenge of the double pulse test setup is to obtain comparably large values with a large rate of change (v_{DS} and i_D). To tackle this, it is of importance that the applied probes have adequate bandwidth and a wide range of linearity to record the rising and falling edges of the switching waveforms. The second challenge is that comparably small voltages have to be measured in the presence of large common mode voltages (v_{GS} vs. v_{DS}). Therefore, a large common mode rejection ratio over a wide bandwidth is required.

Voltage Measurement :

There are basically two categories of voltage probes, **active differential probes** and **passive probes**.

Active differential voltage probes allow voltage measurement to be carried out independent of the oscilloscope's ground. Therefore, it can be flexibly used in the test setup as long as the maximum input voltage is not exceeded.

Passive probes on the other hand are robust and have no active components and do therefore not require a power supply.High-impedance passive probes generally have maximum voltage limits of about 500 V and are ground referenced—meaning, one side of the probe is connected physically to earth ground through the oscilloscope.

In our case the device under test is the high side device. So while measuring V_{DS} and V_{GS} using passive probe , connecting the ground clip of the passive probe to the switch node i.e to the source terminal of the high side switch would likely result in a pretty bad short circuit. So we will be using high voltage differential probe to measure the V_{DS} and V_{GS} of the high side switch.

Current Measurement :

We will be using **Rogowski coil** to measure the drain current of the DUT. A Rogowski coil has similar operation principle as a current transformer. However, the main difference is that it is wound on an air core (non-magnetic) instead of an iron core. A Rogowski coil encloses the current carrying conductor of which the current is to be measured. This method is based on the principle that the voltage induced in the Rogowski coil is proportional to the rate of change of current in the conductor. The voltage that is induced in the coil must be integrated in order to get the output voltage that is proportional to current in the conductor and in most cases magnified to meet oscilloscopes sensitivity requirements. This coil has a linear behavior as there is no saturation effect due to the absence of magnetic material.

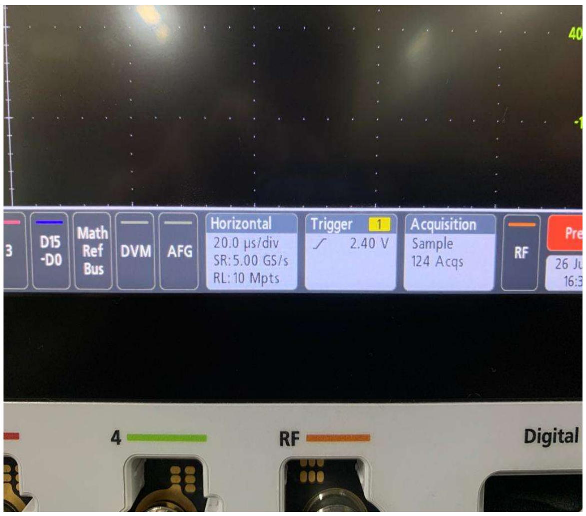
Coaxial Shunts can also be used for the purpose of measuring i_{D}. This method uses low ohmic resistances in the circuit where the current is to be measured and relies on the Ohm's law. For an ideal resistance, the current is proportional to the measured voltage. Therefore, measurement results can be obtained with the help of the voltage drop across these resistors. A limiting factor for measurement of current with coaxial shunt is the parasitic inductance L_{Shunt} of the measurement setup.

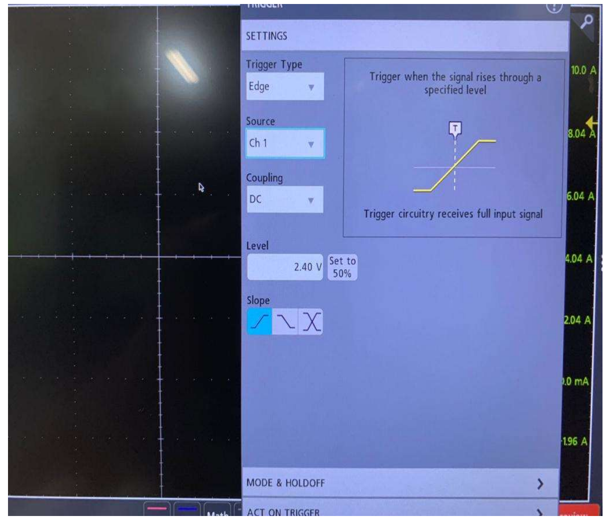
Triggering Concept of Oscilloscope:

The trigger event establishes the time-zero point in the waveform record. All waveform record data are located in time with respect to that point. The instrument continuously acquires and retains enough sample points to fill the pre-trigger portion of the waveform record (that part of the waveform that is displayed before, or to the left of, the triggering event on screen). When a trigger event occurs, the instrument starts acquiring samples to build the post-trigger portion of the waveform record (displayed after, or to the right of, the trigger event). Once a trigger is recognized, the instrument will not accept another trigger until the acquisition is complete and the holdoff time has expired.

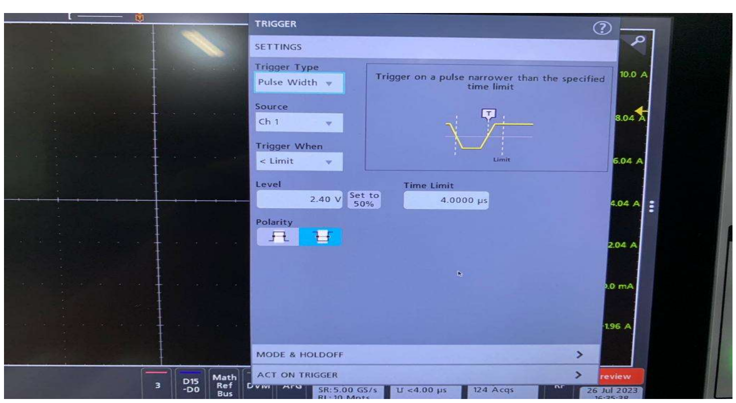
Triggering Procedure:

Step1: Select the trigger source. Analog input channels are the most commonly used trigger sources. You can select any of the input channels. The channel that you select as a trigger source will function whether it is displayed or not.





Step2: Select a trigger type. Since the purpose of this experiment is to observe the switching behaviour of the devices, so we need to zoom into the proper rising/falling edges of the switching waveforms. To observe the turn-on transient ,we need to zoom into the rising edge of the second pulse while to observe the turn-off transient, we need to zoom into the falling edge of the first pulse. So outof the various triggering type you need to choose the **"Pulse Width Trigger"**.A pulse width trigger occurs when the instrument detects a pulse that is less than, greater than, equal to, or not equal to a specified time. Additionally, you can trigger when a pulse width is within or outside a range of two different specified times. The instrument can trigger on positive or negative width pulses.



Test Procedure:

1) Before applying the pulse signal to the evaluation board from the microcontroller launchpad, it is essential to verify the pulse width using an oscilloscope to ensure it meets the desired specifications. Follow these steps:

i) Connect the output of the microcontroller launchpad to the oscilloscope's input channel.
ii) Configure the oscilloscope to display the waveform accurately, adjusting settings such as horizontal scale , vertical scale , trigger type. Also put the oscilloscope in single shot mode
iii) Apply the pulse signal from the microcontroller to the oscilloscope and observe the waveform on the oscilloscope screen.
iv) Check whether the measured pulse width matches your calculated pulse width. Ensure that it falls within the acceptable range as per your requirements.

2) Now Connect high voltage differential probes to the switch terminals. Use one probe to measure the gate-to-source voltage and the other probe to measure the drain-to-source voltage of the high-side device. Additionally, attach a Rogowski coil to the drain terminal to capture the drain current.

3) Turn on the 32V DC power supply and adjust it to provide 15V to the gate driver circuit, ensuring the proper voltage level for driving the high-side device.

4) Configure the oscilloscope to display the waveform accurately, adjusting settings such as horizontal scale , vertical scale , trigger type.

5) Again configure the oscilloscope to display the waveform accurately, adjusting settings such as horizontal scale , vertical scale , trigger type.Set the oscilloscope to single-shot mode and run the code from your PC to apply the pulse signal.

Pre-lab work:

a) Write a code in CCS to generate the double pulse for DPT.

b) Write the analytical equations for switching energy loss in the MOSFET. Assume the MOSFET is turned off with a negative gate bias. Also, show the necessary switching waveforms.

(Take $R_{g,on\,,external} = 80\ ohm\,, R_{g,off,external} = 80\ ohm\,, L = 650$ µH).

Use the GPIO 0 pin to generate a pulse for the control switch.

Groups	Voltage	Current
1	V=100,400 V	I=2,4 A
2	V=200,300 V	I=2,4 A
3	V=150,350 V	I=2,4 A
4	V=250,300 V	I=2,4 A
5	V=100,400 V	I=6,8 A
6	V=200,300 V	I=6,8 A
7	V=150,350 V	I=6,8 A
8	V=250,300 V	I=6,8 A

Lab Work:

Steps:

1. Calculate the time period required to increase the inductor current to a required value.
2. Generate the double pulse for DPT setup using the time period calculated above.
3. Deskew the waveform (Vds, Ids and Vgs) to get the accurate results.
4. Use math function to integrate the Vds*Ids.
5. Calculate the on and off switching energy loss at required voltage and current.

Post lab work:

a) Compare and comment on the measured and calculated switching energy loss. (Take at least four measurements in the lab for comparison).

References:

[1] Z. Zhang, B. Guo, F. F. Wang, E. A. Jones, L. M. Tolbert and B. J. Blalock, "Methodology for Wide Band-Gap Device Dynamic Characterization," in IEEE Transactions on Power Electronics, vol. 32, no. 12, pp. 9307-9318, Dec. 2017, doi: 10.1109/TPEL.2017.2655491.

[2] Baliga, B.J. (1996). Power Semiconductor Devices, 407. Boston, MA: PWS Publishing Company.(Fundamentals of Power Semiconductor Devices)

Data sheet of the switch used: C3M0060065K