# To Investigate the use of SI Carbide MOSFETs in an H-Bridge

by

**Talha Tallat | D18124645**

This report is submitted in partial fulfilment of the requirements of the Honours Degree in Electrical and Electronic Engineering (DT021A) of the Technological University Dublin (TU Dublin).

May 23rd, 2022

Supervisor: **Colm Murray**

## DECLARATION

I, the undersigned, declare that this report is entirely my own work, except where otherwise accredited, and that it has not been submitted for a degree or other award to any other university or institution.

Signed: **Talha Tallat**

Date: 1st May 2022

Project “To-investigate-the-use-of-SiCarbide-MOSFETs-in-a-H-Bridge” resources of this thesis are available on the GitHub page. QR link to the resources is provided below.

### GitHub Account

SCAN ME

## Acknowledgments

This project would not have been possible without the support, guidance, equipment, and software support provided by the staff of the Technological University of Dublin.

I would love to thank my project supervisor of this thesis "Dr. Colm Murry" for providing professional guidance and insight throughout the duration of this project and for his flexibility and efforts during this pandemic. I would like to thank Dr. Murry for helping me to test the device multiple times with a high-power supply.

I would like to acknowledge the technician of Technology university of Dublin on Grangegorman central quad campus Martin Sorohan & Finbarr for providing me with the tools, equipment, and parts required to carry out this project. Thanks to Finbarr for setting up a safe work environment to carry out testing in the machine lab.

I would also like to thank the Technological University of Dublin for providing students with the facilities and expensive equipment and tools.

# Table of Contents

# Table of Figures

# List of Tables

# 1 Introduction

This project is an investigation that observes the behaviour of Silicon Carbide (**SIC**) **MOSFET** when switching the high-power electronics load at relatively high speeds using SIC MOSFET, where MOSFET stands for Metal Oxide Semiconductor Field Effect Transistor. SIC MOSFET are produced using semiconductor compound composed of silicon and carbide as discussed in research section below. The investigation also takes in account of the key problems that arise while testing the SIC MOSFET at range of various frequencies which can potentially damage the SIC MOSFET.

To be able to drive the SIC MOSFET, it requires a **Gate Driver** to perform on/off operations at the desired frequency. The gate driver is a power amplifier that requires a low-power input signal from a **Microcontroller** and produces a high-current drive output at the gate to be able to control the SIC MOSFET. Therefore, the construction of the gate driver, microcontroller was also designed, built, and tested.

Microcontroller is a control device that contains a microprocessor which was programmed to produce Pulse Width Modulation (**PWM**) to control the gate driver at various set frequencies, which amplifies the current in order to control the SIC MOSFET as the same frequency set by the microcontroller.

Specific attention is drawn to the behaviour and performance of the SIC MOSFET to visualize the effects and efficiency when comparing it to the normal silicon MOSFET and other types available in the market.

## *1.1 Objectives*

This aim of this project is to investigates the use of Silicon Carbide type of MOSFETs, involving a construction of a high-power electronic switching approximately up to 5 Kilo Watts (KW) power operating at relatively high frequencies up to 100 Kilo Hertz (KHz) using SIC MOSFET.

In order to successfully accomplish the desired outcome of this project, the appropriate safety was applied while carrying out testing in the machine lab and list of components used were supplied to complete the project and following list of tasks were carried out to be able to implement the design to investigate the behaviour of the SIC MOSFET.

### 1.1.1 List of Objectives

1. Design & programme a microcontroller circuit
    a. Produce a **PWM signal** at a **set frequency** and which allows a potentiometer to vary the **duty cycle** of that PWM signal.
    b. Test & debug the program to observe the output of the microcontroller.
2. Construct a **Gate Driver** circuit
    a. Build & manage power consumption of gate driver circuit
    b. Test and observe the output of the gate driver when applying PWM
3. Design a **SIC MOSFET** circuit
    a. Construction of a SIC MOSFET
    b. Build & mange power consumption of the SIC MOSFET circuit.
    c. Use Heat sink to dissipate heat
    d. Design a safety for protection before testing.
    e. Test with **1kHz** frequencies and then higher frequencies up to **100KHz** while switching **+30** volts to **+240V** DC.
    f. Analyse the effects of switching at high frequencies and record the results.
4. Investigate the behaviour of the power SiC MOSFETs using driver circuit to test over a range of frequencies, voltages, and currents.
5. Instrumentation setup to test the system to measure the performance of MOSFET bridge into the resistor as a function of a load, voltage, current and switching frequency.

## 1.2 *Ethics*

### 1.2.1 Engineering Safety Ethics

Safety is the number one priority, especially when dealing with high power supply units, whether in the university laboratory or anywhere else. If a positive or negative spike gets onto the drain of the power MOSFET via gate capacitance, the MOSFET can explode in a cloud of flame and black smoke. However, it is important to follow the engineering ethical standard because otherwise, it can cost someone's life and these small mistakes might be the very thing that causes a disaster. Since modern societies are heading towards an era of technology, where all members of society will be affected, electrical engineers need to follow a code of engineering ethics.

### 1.2.2 Power Design Awareness

The poor designs of the power circuits can cost a lot of money, inefficiency, non-functional and dangerous circuitry can harm the environment and can destroy other technology due to the excess temperature, currents, or voltages. It is important to read the datasheet for each component used in the circuit design to be aware of the ratings and limitations to avoid any casualties. Unknown information's must be not implemented in the designs and development of the project.

### 1.2.3 Researching effectively

There are bibliography meatheads available to reference someone else's work that is published but utilizing reliable academic resources while researching to avoid plagiarism and stealing someone else idea is unacceptable.

### 1.2.4 Climate

Climate change ethical problem's biggest victims are people and change impacts are potentially catastrophic around the world. Modern technologies are emitting large amounts of carbon dioxide, causing global warming. are operated by fossil fuel. fewer natural resources, including energy, producing less a negative impact to the environment. Modern technology like Silicon Carbide materials is used in many driver and semiconductor applications which will allow us to capture naturally energy and convert it into electricity or useful heat through devices such as solar panels, wind, and water turbines, which reflects a highly positive impact of technology on the environment.

Provide a discussion on relevant ethical considerations in the context of your project. It may be useful to review Engineers Ireland’s code of Ethics.

Climate >> drivering electricity systems >> industrial sectors

# 2 Research

The aim is to carry out research to be able to investigate the behaviour of SIC MOSFET. In order to do that, research was broken down into categories to understand pieces of the puzzles involved with this project.

## *2.1 Silicon Carbide SiC*

Silicon Carbide (**SiC**) is a compound semiconductor composed of silicon and carbide (Si+C = SiC), which provides significant benefits when compared to traditional silicon (Si) technology as they are known for their hardest synthetic material and high thermal conductivity with its high-temperature strength makes a great substitute for traditional Silicon (Si) semiconductors and offers better overall performance. However, three times more energy is required for an electron to move freely within the material. This wider **bandgap** provides the materials with qualities such as faster switching and higher power density.

### 2.1.1 Bandgap

The band gap is the gap between the valence and conduction band. When material gap increases, more energy is required to transfer the electrons from the valence band to the conduction band. Valence band is formed due to the low energy orbitals combined, and the higher energy orbitals combine forms a conduction band.

Conductor materials such as metals have conduction and valence bands that have a very small bandgap, while insulators have an extremely wide gap as shown in figure below.

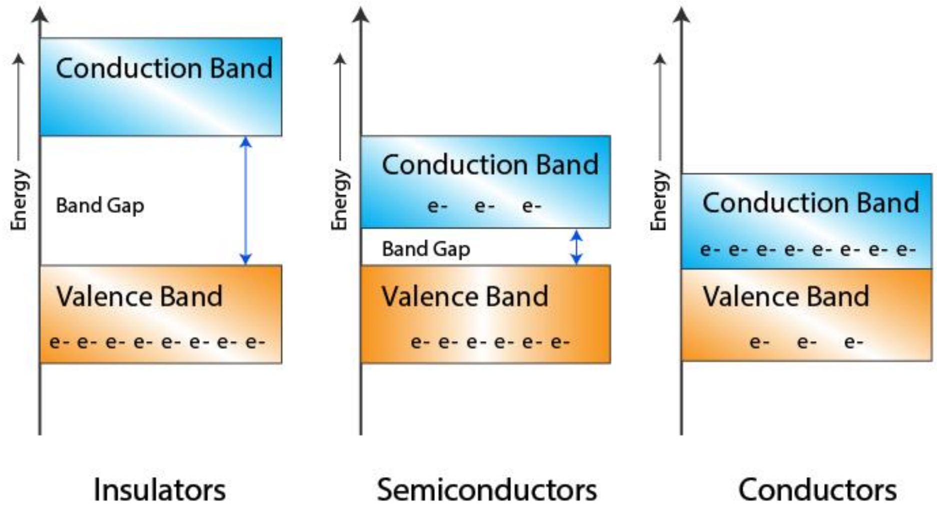



*Figure 1 - bandgap of the insulators, semiconductors, and conductors [1]*

The bandgap refers to energy which is measured in electron volts (eV, a unit of energy equal to approximately 1.602×10−19 J). The bandgap of SiC is 3.26 eV, compared to that of Si at 1.12 eV or Gallium Arsenide (GaAs) at 1.42 eV. SiC, therefore, is referred to as having a **wide bandgap** [2].

### 2.1.2 Wide Bandgap

SiC has a wideband than traditional silicon meaning that heat can transfer more effectively in SiC due to the wide bandgap and is capable of operating in higher temperatures up to 400 degrees Celsius.

However, SiC is widely used in electronics circuit elements, power electronics devices, automobile parts, Automotive etc. The below-highlighted use cases where SiC devices deliver a significant benefit.

## *2.2 SiC in Automotive*

In the SiC field, there is a lot of hype going on about the SiC within the leading electric vehicle companies and new vehicle manufacturers. As the Electic vehicles is big thing now and according to the IEA, the global electric car market is growing exponentially. Worldwide sales of electric cars hit 6.6 million in 2021, almost doubling from the previous year [3][4]. As of 2017, 1.9 million cars or about 0.2% were electric. The proportion is expected to grow to 50% by 2040 [5].

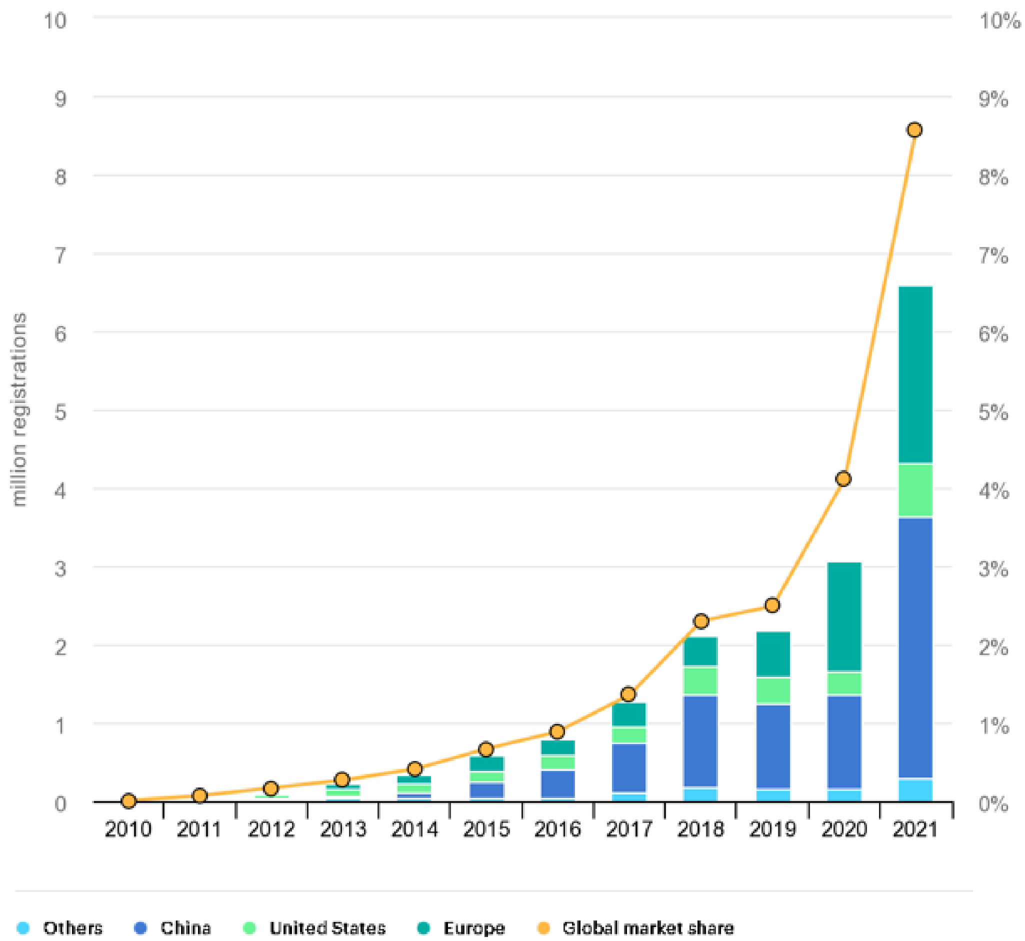



*Figure 2 - Global sales and sales market share of electric cars, 2010-2021 [4]*

As the demand for Electric Vehicles (**EV**) is raising the EV manufacturing campiness are looking for ways to minimize wasted power and achieve higher efficiency and that's where the development of new materials like silicon carbide (SiC), promise superior performance comes in to play.

Electric Vehicles typically have a main motor that powers the wheels. Six power transistors and diodes are deployed to turn the motor [5]. Each transistor blocks 700V and switching a few hundred amps. Most power switches use pulse width modulation (PWM) techniques, which means they are turned on and off thousands of times each second. When a transistor is switched on and off, there is a transition delay between the states as shown in Figure 3.

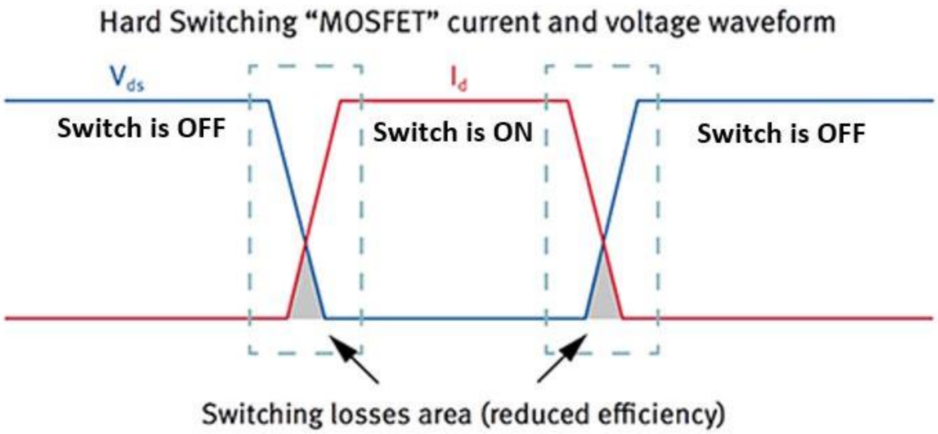



*Figure 3 - Power losses occur during voltages/currents overlap when the MOSFET switches [5]*

The combination of better switching performance, low $l_{on}$ resistance and high breakdown voltage make SiC devices ideal alternatives to traditional Si power MOSFETs, DC-DC converters, uninterruptible power systems and motor applications as shown in figure 4 [5].

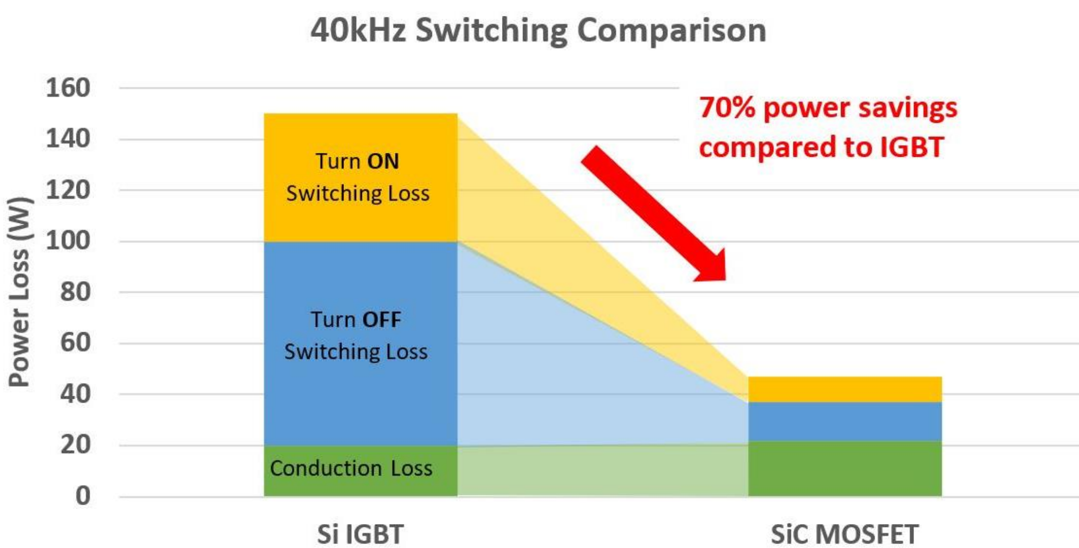



*Figure 4 - performance advantages of SiC MOSFET versus IGBTs [5]*

SiC MOSFETs can help drive the electric vehicle's motor with less power. Higher switching frequency leads to higher power density and smaller, lighter motors, which reduces wasted heat allows smaller and lighter heatsinks to be used, further optimizing weight and range.

### 2.2.1 EV campiness battling for SiC

- **Renault Group** and **STMicroelectronics** reached a cooperative agreement on the supply of SiC (silicon carbide) and GaN (gallium nitride) products for new-energy vehicles from 2026 to 2030 [6].
- **Vitesco Technologies** (Germany) received an order for 800V SiC inverters from the Hyundai Motor Company for hundreds of millions of Euros earlier in 2021 [6].
- **JAC Motors** and **Bosch** signed a strategic agreement for cooperation in the field of SiC inverters [6].
- **Tesla**, who released a new model Model S Plaid uses a SiC inverter [6].
- **BYD** Company launched the "BYD Han," its first model with SiC technology, announced that by 2023 it will achieve full replacement of silicon (Si)-based IGBTs with SiC automotive power semiconductor devices [6].
- **NIO** has also expressed that it will adopt an electric drive system based on SiC technology on its new ET7 models for 2022 [6].

When considering the cost of the electric drive inverter in an electric vehicle, if SiC power devices are used to replace mature Si-based IGBTs, the cost of a single vehicle will increase by US$200 to 300, yet people are willing to spend more money to adopt this more expensive plan due to the **characteristics** of the SiC device itself [6].

### 2.2.2 Characteristics of SiC

SIC materials have increasingly demanding power requirements, ranging from 650 Volts to 3.3 Kilo Volts (KV) capable switching at relatively high levels of switching speeds and it associate all new problems that arise, such as difficult accurate testing & measurements and circuit parasitic capacitance that create excessive voltage spikes, etc. These types of challenges are mentioned in the research chapter along with a few best practices that, when properly incorporated, can clear these barriers, and untie the unquantified benefits of SiC's high switching speeds. There are unparalleled advantages that a SIC offers in semiconductor devices are mentioned in the research chapter below.

However, SiC is next generation technology used in semiconductor electronics devices that operate at high temperatures, high voltages and higher speeds which are ideal for power electronics and these materials are used in semiconductors especially in **MOSFETs**.

## 2.3 MOSFET

MOSFET stands for Metal Oxide Semiconductor Field Effect Transistor, which is a well-known semiconductor device that is used in amplifier circuits, digital switches, and power applications to achieve faster switching speeds and amplification. It is a form of a field-effect transistor (FET) in which there is a thin layer of silicon oxide between the gate and the channel. and is a voltage-controlled device, where currents in the FET depends upon the electric field. The MOSFET usually has three terminals: gate, drain, and source as shown in figure 5 and 6.

MOSFETS are classified into 2 types depending upon the channel (n type & p type) or majority carries present in it.

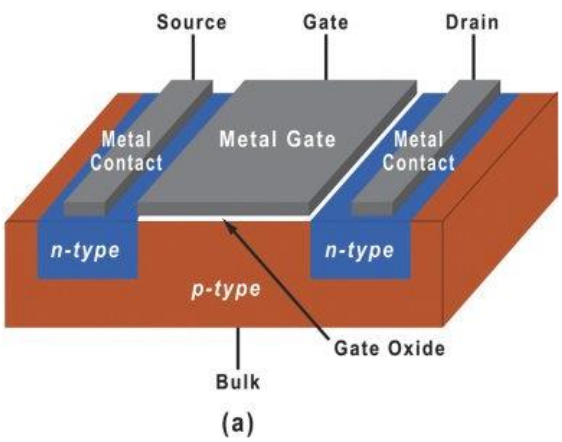



*Figure 5 P-type (a) MOSFETS [7]*

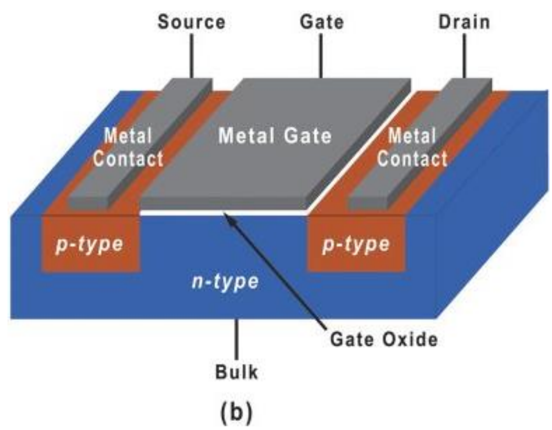



*Figure 6 N-type (b) MOSFETS [7]*

- In NMOSFET, the substrate is p-type and depending upon the gate voltage applied the channel present between source and drain is converted into n-type. The minimum gate voltage to be applied to make it conduct is known as the threshold voltage. It can be positive or negative depending upon the mode of operation of MOSFET, i.e enhancement or depletion mode.
- The substrate is n-type in PMOSFET, and the channel is of p-type.

Classification depending on modes of operation or channel formation is of 2 types.

**Enhancement mode**:

Here channel is not formed initially but on the application of appropriate gate voltage, the channel is formed. For n-channel type, positive gate voltage should be applied for channel formation whereas for p channel MOSFET, the negative voltage should be applied.

**Depletion mode**:

Channel is already present, and it conducts even if no gate voltage is applied. It can be operated both in enhancement and depletion modes.

MOSFETs have a **higher power density**, which is a definite advantage. When compared to other types of transistors, for example, BJTs (Bipolar Junction Transistors), MOSFETs require a **minimal amount of input current** to control the load current.

## *2.4 IGBT*

IGBTs stands for Insulated-Gate Bipolar Transistor which is a power transistor that combines an input MOS and are voltage control device, has higher switching frequency, low switching loss, low on-stage power dissipation, low gate drive requirements and does not have secondary breakdown problems because it has high voltage capacity.

IGBT is a voltage-controlled device which requires a small voltage on the Gate to maintain conduction through the device unlike BJT’s which require that the Base current is continuously supplied in a sufficient enough quantity to maintain saturation.

## 2.4.1 IGBT Characteristics

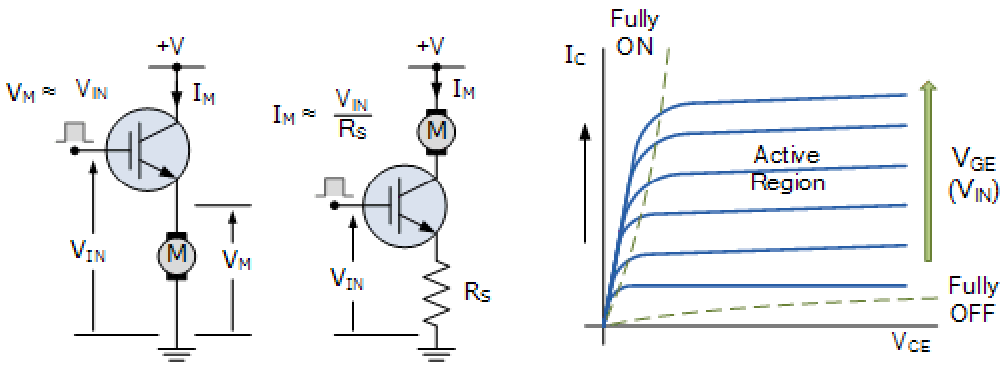



*Figure 7 - IGBT Characteristics & simple testing circuit diagram [8]*

IGBT is a unidirectional device, meaning it can only switch current in the "forward direction", that is from Collector to Emitter unlike MOSFET's which have bi-directional current switching capabilities (controlled in the forward direction and uncontrolled in the reverse direction) [8].

*Table 1 - IGBT Comparison Table [8]*

| Device Characteristic | Power Bipolar | Power MOSFET | IGBT |
|---|---|---|---|
| **Voltage Rating** | High <1kV | High <1kV | Very High >1kV |
| **Current Rating** | High <500A | Low <200A | High >500A |
| **Input Drive** | Current, $h_{FE}$ 20-200 | Voltage, $V_{GS}$ 3-10V | Voltage, $V_{GE}$ 4-8V |
| **Input Impedance** | Low | High | High |
| **Output Impedance** | Low | Medium | Low |
| **Switching Speed** | Slow (uS) | Fast (nS) | Medium |
| **Cost** | Low | Medium | High |

## 2.5 SiC MOSFET

The use of SiC MOSFETs has been immensely increased in modern industrial applications especially in modern electric vehicle industries due to their fast-switching speeds at higher frequencies and SIC offers lighter systems that makes them more efficient and often less expensive.

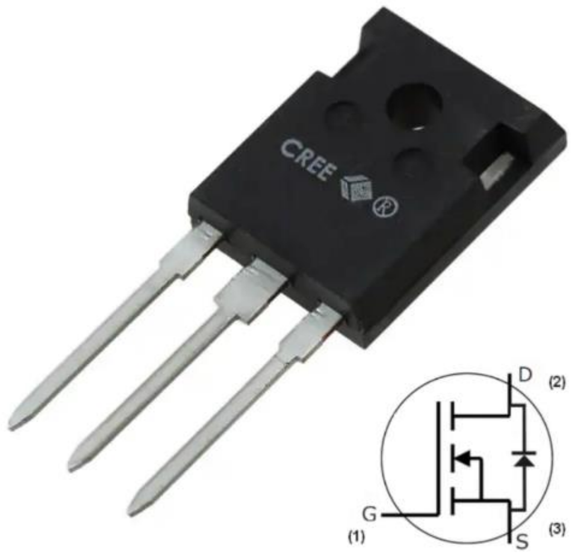


*Figure 8 - Silicon Carbide Power MOSFET [12]*

Silicon Carbide (SiC) has a wide-bandgap semiconductor material that has several promising properties for use in power electronics applications. [9] It enables higher switching frequencies and reduces the size of components like inductors, capacitors, filters & transformers. It replaces silicon devices to enable lower switching and conduction losses with higher blocking voltages and avalanche capability, where “avalanche capability” is how much energy loss can resist at a time. the VDSS is exceeded, current will flow despite the MOSFET being in the OFF state, so this generates high loss and can damage the MOSFET. [9] The SiC device compares favourably to the Si device tested as well as other Si devices available on the market for a similar voltage range.

Silicon carbide (SiC) is a wide-bandgap semiconductor material with a bandgap energy of 3.3 eV compared to 1.1 eV for silicon (Si). SiC has a single silicon-carbon bond that gives it that higher bandgap energy as well as several other (W/cmK) useful properties. These properties allow higher voltage blocking, lower switching losses, and improved high-temperature performance compared to Si, making the material very attractive for power electronics applications [10].

*Table 2 - Properties Comparison of SiC & Si*

| No. | Properties | Si Carbide | Si |
|---|---|---|---|
| 1 | Bandgap, Eg (eV) | 3.3 | 1.1 |
| 2 | Critical field, Ec $\left(\frac{MV}{cm}\right)$ | 2.2 | 0.25 |
| 3 | Electron Saturation velocity, $V_{\text{sat}}$ $\left(\frac{10^7 V}{cm}\right)$ | 2 | 1 |
| 4 | Electron mobility, Mn $\left(\frac{cm^2}{Vs}\right)$ | 947 | 1350 |
| 5 | Hole mobility Mp $\left(\frac{cm^2}{Vs}\right)$ | 120 | 480 |
| 6 | Dielectric constant (Er) | 9.7 | 11.8 |
| 7 | Melting point (°C) | 2820 | 1420 |

### 2.5.1 Advantages of SiC over Si

Silicon Carbide has a good few advantages over Si when used in semiconductor technology, which includes the following:

- A higher critical breakdown field, meaning a voltage rating can be maintained while still reducing the thickness of the device. [11]
- A wider bandgap, leading to lower leakage current at relatively high temperatures [11].
- A higher thermal conductivity, which supports a higher current density [11].
- An overall reduction in energy losses [11].
- Reduced switching losses, which impact losses that occur when the MOSFET is transitioning from blocking to conducting (and vice versa) [11].
- Higher switching frequencies, which means smaller peripheral components (e.g., filters, inductors, capacitors, transformers) can be used [11].
- Increased critical breakdown strength, about 10x what is achievable with Si [11].
- Higher temperature operation, which means simplified cooling mechanisms (e.g., heat sinks) [11].

When compared to their Si counterparts, SiC MOSFETs offer better overall performance, higher efficiency, higher switching frequencies, and more compact components. More and more engineers are turning to SiC MOSFETs and taking advantage of the superior properties that they offer.

## 2.6 SI Carbide module driver

Gate Driver is required to perform on/off operations at the desired frequency. The gate driver is a power amplifier that requires a low-power input signal from a **Microcontroller** and produces a high-current drive output at the gate to be able to control the SIC MOSFET. Therefore, the **SIC MOSFET Driver** or **BJT** with high switching speeds can be used to perform high current amplification.

### 2.6.1 SIC MOSFET Driver

MOSFET Gate Driver is a specialized circuit used to drive the gate power MOSFETs effectively and efficiently in high-speed switching applications.

*Figure 9 - Silicon Carbide MOSFET Driver [13]*

#### 2.6.1.1 SIC MOSFET Driver Features [13]:

- Designed for driving CREE CAS300M12BM2 SIC MOSFETS modules
- Low jitter: typical 1ns
- +20V/-6V gate driving, output currents up to +/- 20A and Switching frequencies up to 125kHz
- Over-current protected and under & over voltage lock out
- Adjustable dead and blanking time
- Dead-time generator and no optocouplers
- High dV/dt immunity
- Large power supply range, from 15V up to 24V

SIC MOSFET uses **RS422** Input Interfacing which is a high speed and/or long-distance data transmission. Each signal is carried by a pair of wires and is thus a differential data transmission system [14].

### 2.6.2 BJT

BJT stands for Bipolar Junction Transistor which is a type of semiconductor that uses both electron and hole charge carriers. They are used to amplify electric current which are ideal for this project.

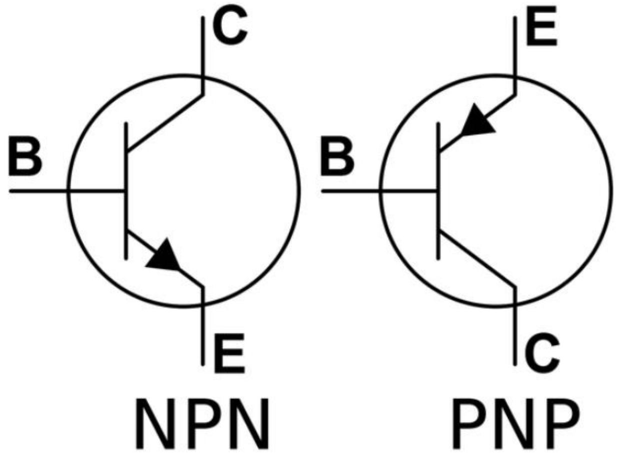



*Figure 10 - NPN vs PNP BJT circuit symbols [16]*

BJTs are available both alone and packaged into integrated circuits (ICs). BJTs are widely used in amplifiers for a large amount of everyday electronic equipment.

NPN transistor is used in this project which consist of a layer of P-doped semiconductor between two layers of N-doped material, where electrons are passed from the emitter to the collector. The emitter then “emits” electrons into the base, with the base controlling the number of electrons the emitter emits. The emitted electrons are finally collected by the collector and sent to the following part of a circuit load.

## *2.7 Microcontroller*

Microcontroller is a control device that contains a microprocessor which is programable to produce Pulse Width Modulation (**PWM**) to control the gate driver at various set frequencies. Simply **Arduino Uno** is useable to produce PWM at set frequency.

### 2.7.1 Arduino Uno

Arduino Uno is easy to use programable open-source board based on the ATmega328P microcontroller developed by Arduino.cc that can be integrated into variety of projects. It has 14 digital input/output pins in total and of which 6 can be used as PWM outputs, 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header and a reset button.

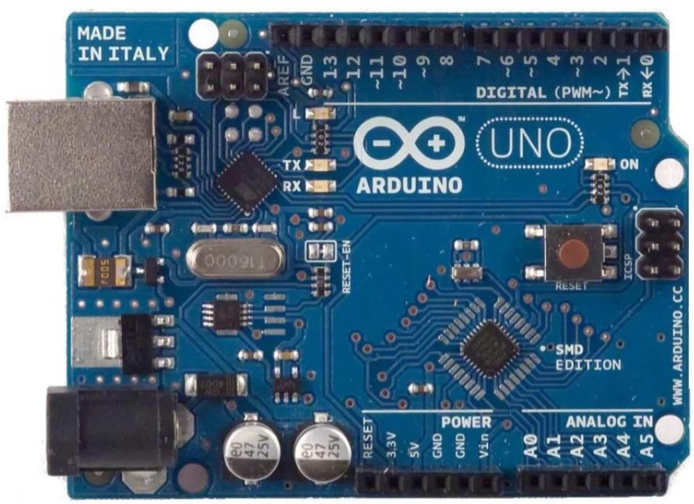



*Figure 11 - Arduino Uno microcontroller supplies PWM (0-5v) [15]*

Arduino Uno produces 5 volts at output of digital pin at 20mA which is not enough to drive the SIC MOSFET therefore, gate driver is required.

Constructing the design of the project when research was carried out.

# 3 Implementation

The complete research was carried out involving clear understanding of the **components** required to construct this project and **datasheets** were used to read and understand the maximum power ratings to make sure no components or equipment's is damaged during implantation and also, clear understanding of the **safety** guidelines was placed in the power lab before carrying out any testing and supervision is must in the power lab to be able to protect the safety of ourselves, others and expensive equipment's that are required for the implementation.

Project construction is divided into parts to make it easier for the users to benefit from this investigation.

1. **Requirements**
2. **Installation**

## *3.1 Project Requirements*

The requirement details of the project are listed below consist of list of components, equipment's and tools used during the experiment.

### 3.1.1 List of Components

*Table 3 - List of Components used in the project*

| No. | Qty | Value | Unit | Components |
|---|---|---|---|---|
| **1.** | 1 | - | - | Arduino Uno board |
| **2.** | 2 | 100 K | Ohms | Potentiometers |
| **3.** | 2 | 47 | Ohms | Resistors (1W) |
| **4.** | 1 | - | - | Gate driver (BJT \| PT62SCMD17 SiC MOSFET Driver) |
| **5.** | 4 | - | - | SIC MOSFET |

### 3.1.2 List of Equipment

*Table 4 - List of Equipment used in the project*

| No. | Qty | Equipment's |
|---|---|---|

| | | |
|---|---|---|
| **1.** | 2 | Instantaneous voltages and currents supply |
| **2.** | 1 | Multimeter, Voltmeter & Ammeter |
| **3.** | 1 | Oscilloscope |
| **4.** | 1 | Breadboard |
| **5.** | 10 | Jumper wires & long wires |
| **6.** | 1 | Soldering Iron |
| **7.** | 1 | **Hand tools**: Wire Stripper, Cutter, screwdriver & |

## *3.2 Project Installation*

### 3.2.1 Microcontroller Setup

**Arduino Uno** board was used in this project which contains a microprocessor ATmega328P which was programmed to produce Pulse Width Modulation (**PWM**) to control the gate driver at various set frequencies and using potentiometer to vary the duty cycle of that PWM signal. PWM frequency for digital pin 3, 9, 10, 11 are set to 490.20 Hz by default. PWM frequency for digital pins 5& 6 are set to 976.56 Hz by default.

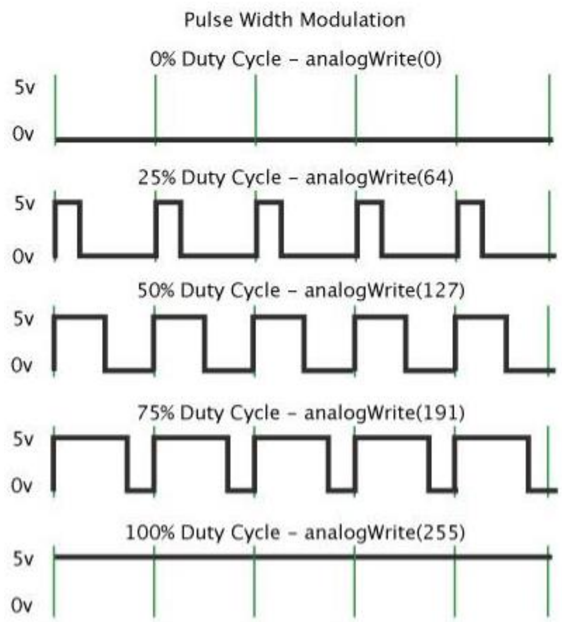



*Figure 12 Ardino Uno microcontroller produces PWM (0-5v) [15]*

### 3.2.1.1 Arduino Uno Setup

The Arduino UNO was connected to the computer which powers the Arduino board via USB cable and lunched Arduino IDE software to be able to communicate with the board.

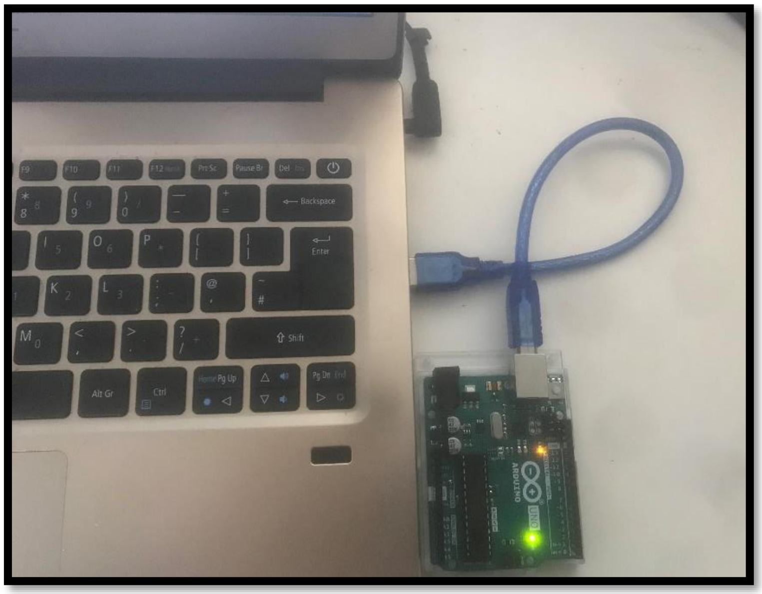


*Figure 13 - Connected an Arduino UNO to the computer*

The Arduino Uno board was selected in the “Tools” drop down menu and ones the “COM 5” port was selected, the Arduino Uno was ready to communicate.

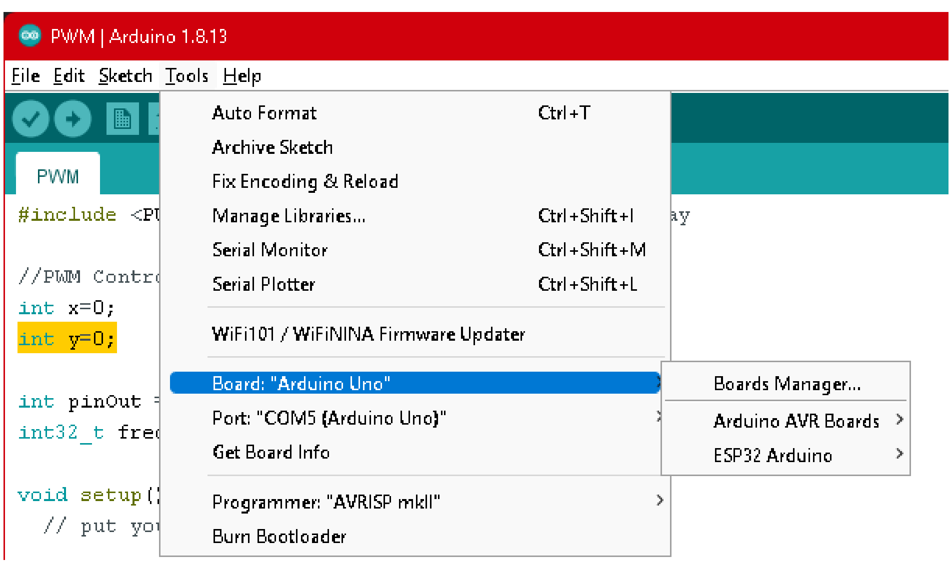



*Figure 14 - Arduino Uno board was selected from the Tools drop-down menu in Arduino Ide*

### 3.2.1.2 Programming Arduino Uno to produce PWM

```
int pot = A0;

// Assigning "pot" variable to the analog input pin A0 with type integer

int pinOut = 9;

// Assigning "pinOut" variable to the digital output 9 with type integer

void setup() {  // setup code run once:

  Serial.begin(9600); // starts the seriral monitor at 9600 bot rate

  pinMode(pinOut, OUTPUT);// pin 9 is declared as a ouput

  pinMode(A0, INPUT);//pot

}

void loop() { //run continousily

 int readPotValues = analogRead(pot);

 /*reads the pot 10-bit values and stores it to the "readPotValues" variable*/

int dutyCycle = (255./1023.) * readPotValues;

/* conversion from reading analog 10-bit (0-1023) to 8-bit (0-255) scale*/

 analogWrite (pinOut, dutyCycle);

/* write a 8-bit stored values in "dutyCycle" to the output pin 9 */

 Serial.print("Analog Value to the Output");

/* print "Analog Value to the Output" in serial monitor*/

 Serial.print (x); // prints the output to the serial monitor

 delay (500); // addes half a minute delay

}
```

### 3.2.1.3 Circuit Design

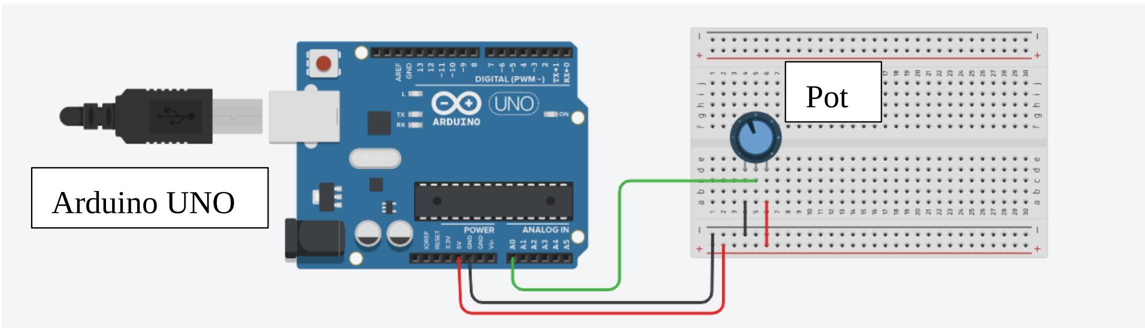



*Figure 15 - Circuit Diagram of the Arduino producing controllable PWM on Thinker CAD*

Arduino digital pin 9 was programmed to produce PWM signal and reads potentiometer analogue values form the analogue input A0 which then controls the duty cycle of the PWM signal.

PWM frequency for digital pin 9 are set to 490.20 Hz by default in following register according to the ATMEGA328P datasheet TCCR1B = TCCR1B & B11111000 | B00000011 [17].

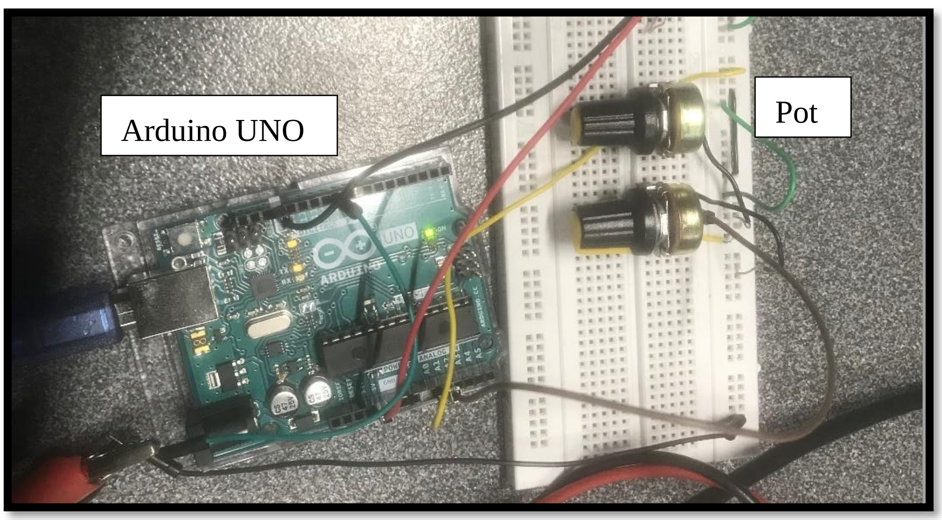



*Figure 16 - Circuit diagram of the microcontroller build*

The frequency later is increased by forcing the register to test the SIC MOSFET at higher frequencies.

### 3.2.2 Gate Driver Setup

Gate Driver is designed using the BJT to drive the SIC MOSFET, which requires to perform on/off operations at the desired frequency by the microcontroller. The gate driver is a power amplifier that takes PWM signal with amplitude of 0-5 Volts at 20 milli amps from an Arduino Uno digital pin 9 and produces a high-current drive output at the gate to be able to control the SIC MOSFET.

#### 3.2.2.1 Calculated the current flow

Supplying 10 volts to the collector of the BJT to be able to control the gate of SiC MOSFET.

$$V = 10v$$

$$R = 47 \ ohms$$

$$I = V/R = 10/47 = 212mA$$

After checking the datasheet [18], the 212 mA is enough to drive the gate.

#### 3.2.2.2 Power dissipating in the Resistor

As the current values were calculated along with appropriate resistor values.

$$P = I^2 R$$

$$P = (212 * 10^{-3})^2 (47)$$

$$P = 2.11 \, W$$

47 ohms and 2.11 of a watt resister is required.

### 3.2.2.3 Gate Driver Circuit Design

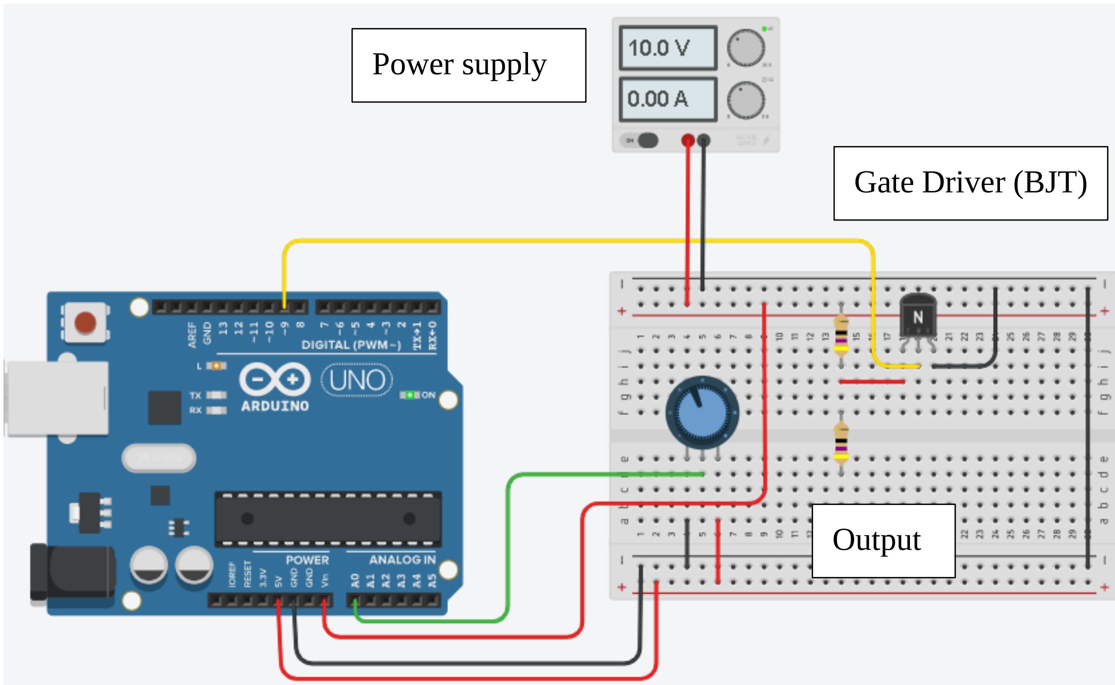



*Figure 17 - Circuit design of the Gate Driver using BJT*

When the Arduino PWM signal is high (5V) then BJT is high then current flows to the ground which turn off the output controlling the SiC MOSFET. When the Arduino PWM signal is low (0V) then BJT is low meaning then current does not flow to the ground which turn on the output controlling the SiC MOSFET.

The output of the gate driver produces the PWM signal which is inverted that goes to the gate of the SIC MOSFET.

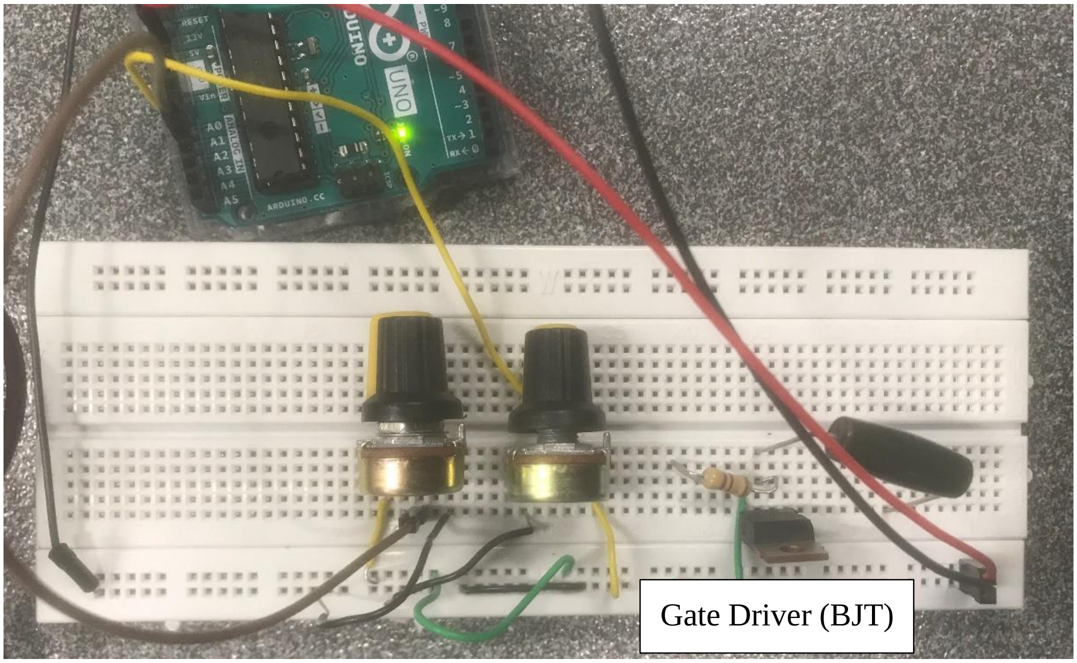



*Figure 18 - Built Circuit design of the gate driver without connected to any source*

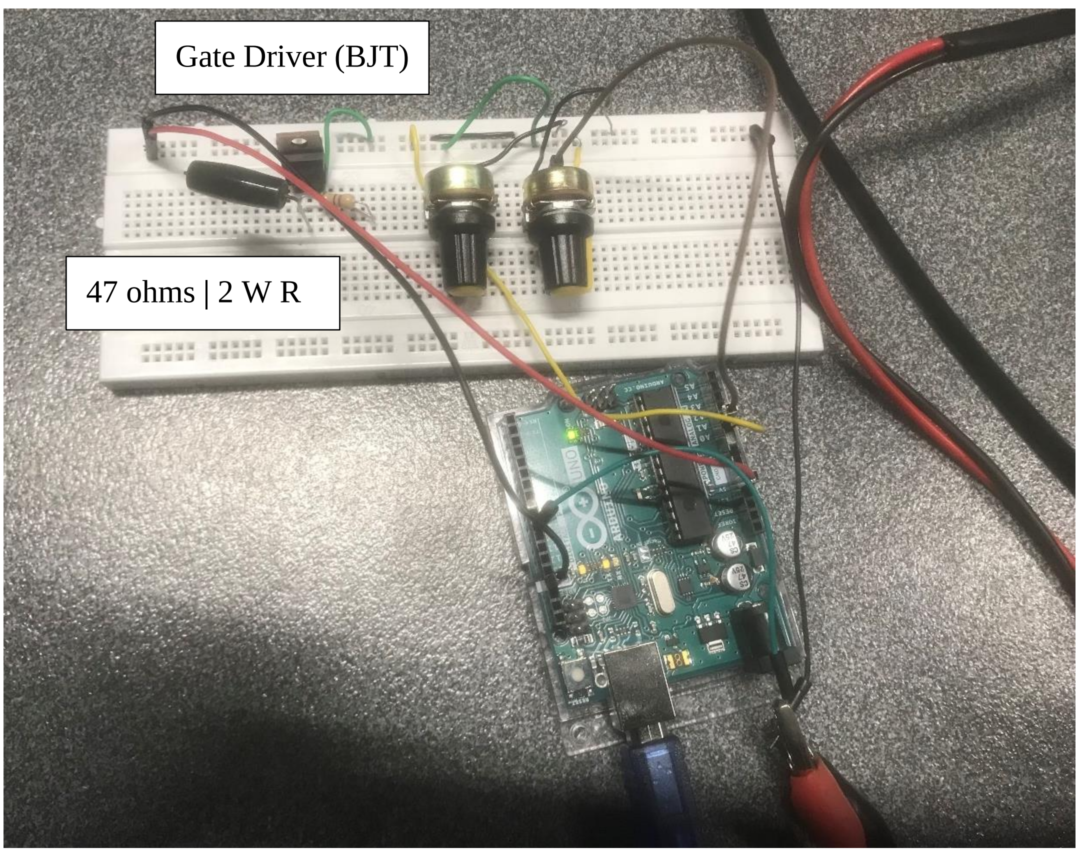



*Figure 19 – Built Circuit design of the gate driver*

## 3.2.3 SIC MOSFET Setup

### 3.2.3.1 SiC Circuit Design

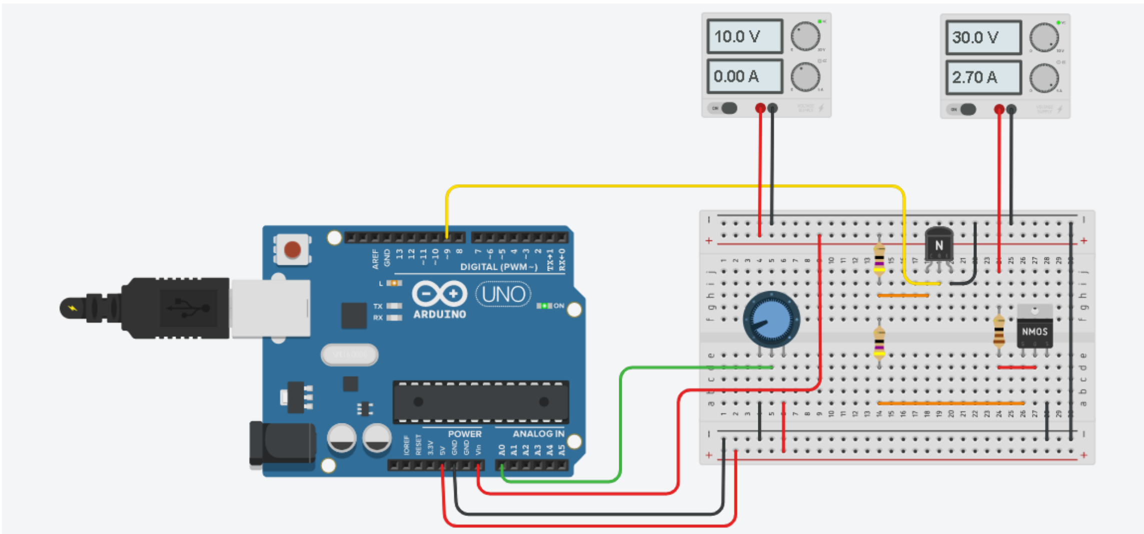



*Figure 20 - Full circuit design of the SiC MOSFET*

### 3.2.3.2 safety for protection before testing.

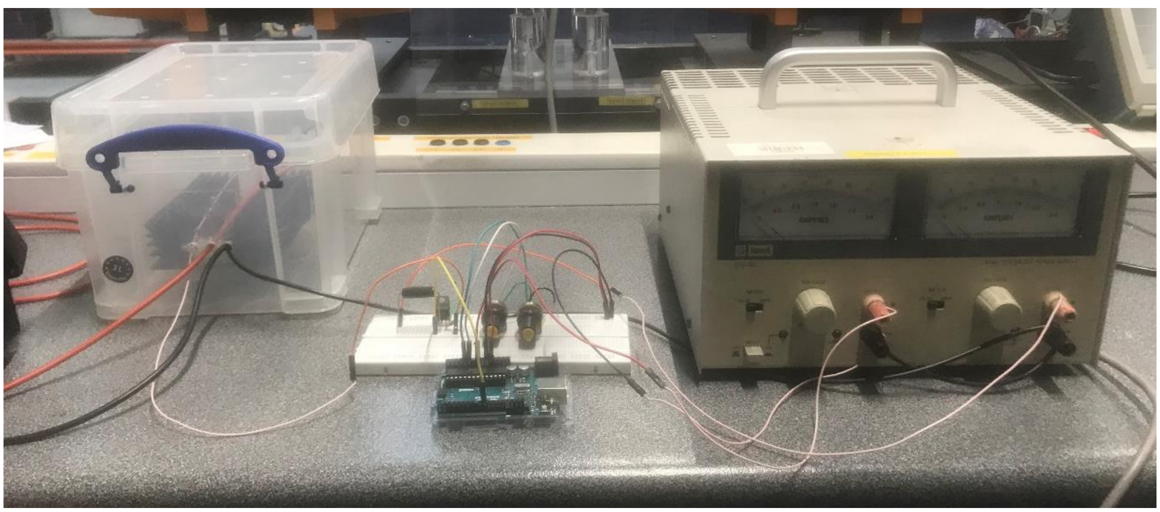


*Figure 21 - safety box designed to place the MOSFET*

### 3.2.4 Full setup

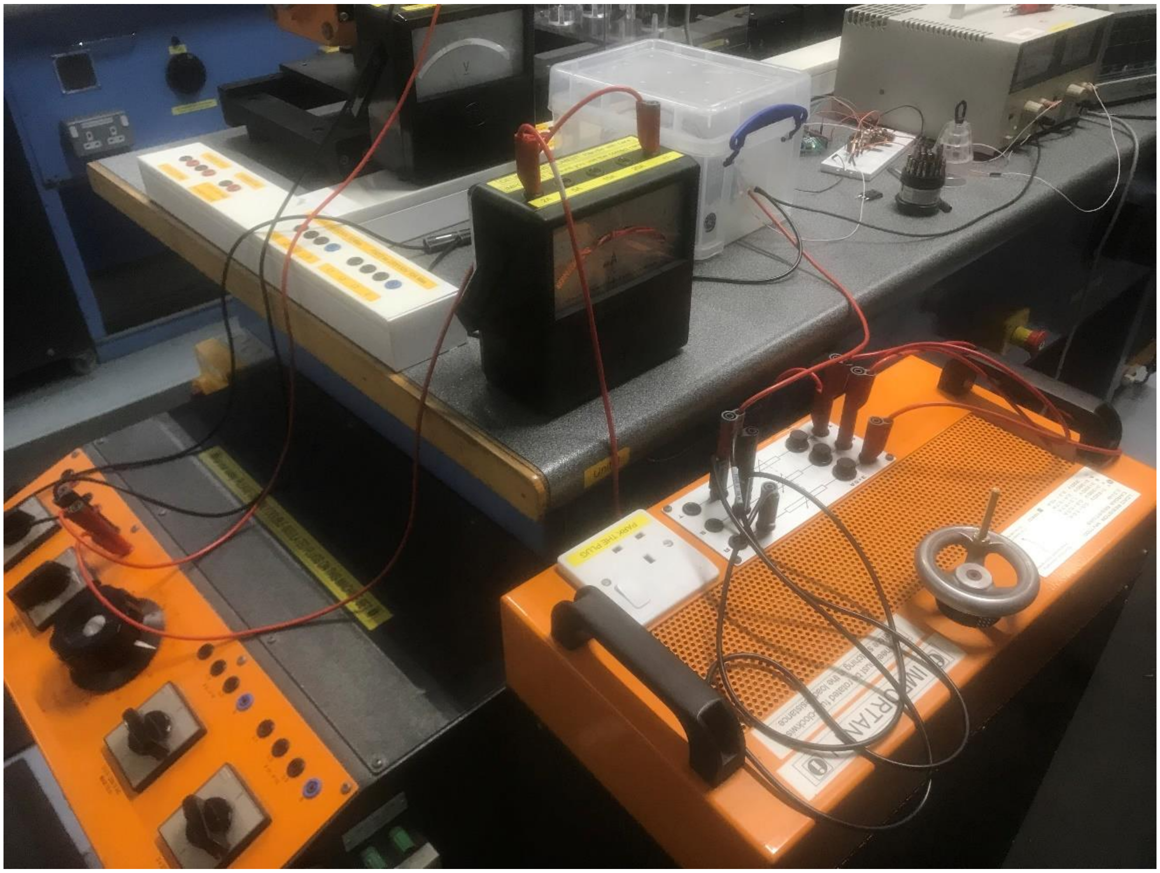


*Figure 22 - Setup*

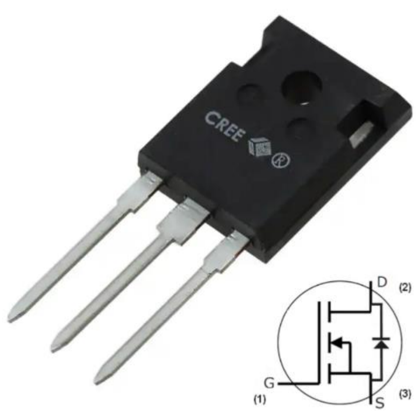
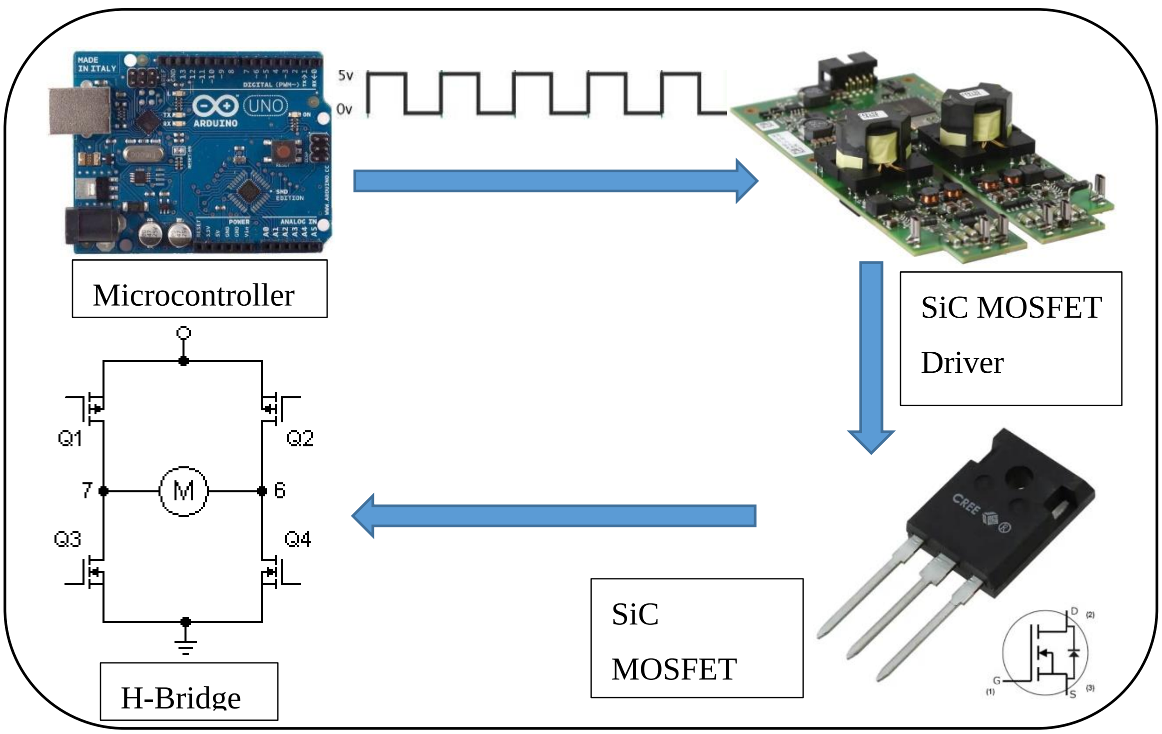



*Figure 24 C3M0065090D Silicon Carbide Power MOSFET [1][2]*

*Figure 23 PT62SCMD17 Silicon MOSFET Driver [3]*

C3M0065090 SiC Power MOSFET will be used along with PT62SCMD17 silicon MOSFET Driver. The gate driver is a power amplifier that will require a low-power input from a controller (Arduino) and produces a high-current drive input for the gate of a high-power MOSFET. MOSFET requires higher voltage than the rated gate threshold voltage (Vth) to turn on. The MOSFET gate drive consumes no power, when in a steady on or off state. The gate-source capacitance of a MOSFET seen by the driver output varies with its internal state. MOSFET operation & features are describes in the research section.
The microcontroller will be used to supply Pulse with modulation (PWM) varying from 0 to 5v into the gate of the driver.

### 3.2.5 Circuit Diagram



# 4 Testing

## 4.1 Results of the Gate driver at high frequency

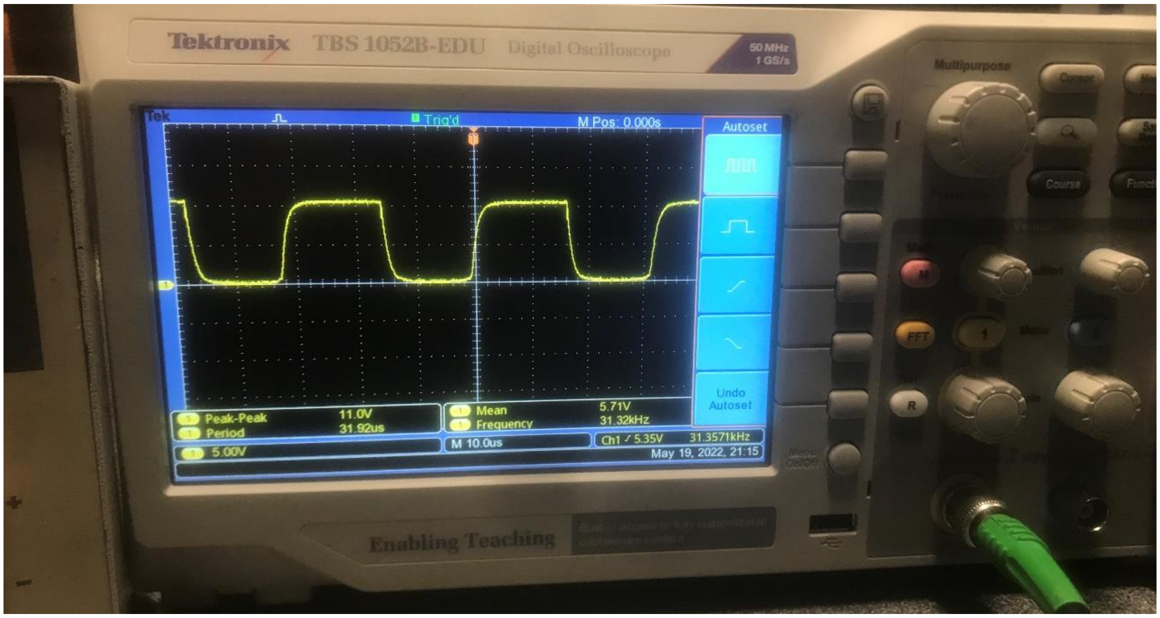



*Figure 25 - Output of the gate driver BJT at high frequency*

## 4.2 Results of the SiC MOSFET at high frequency

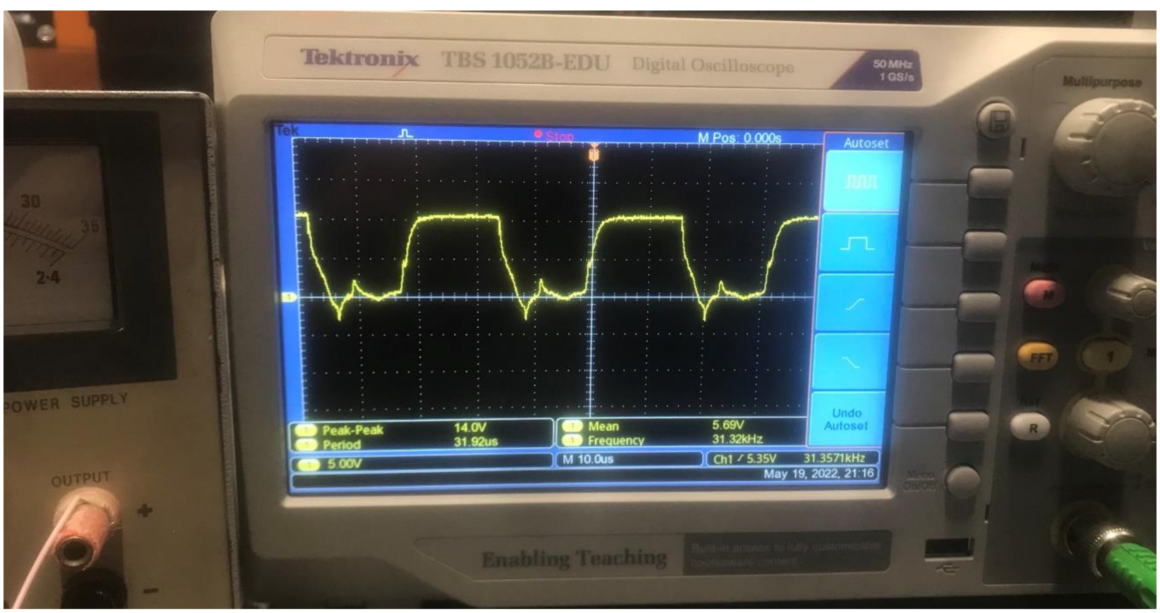



*Figure 26 - Output of the SIC MOSFET at high frequencies*

### 4.2.1 Results of the max voltage applied to SiC MOSFET at high frequency until the MOSFET blew up dur to the ringing effects

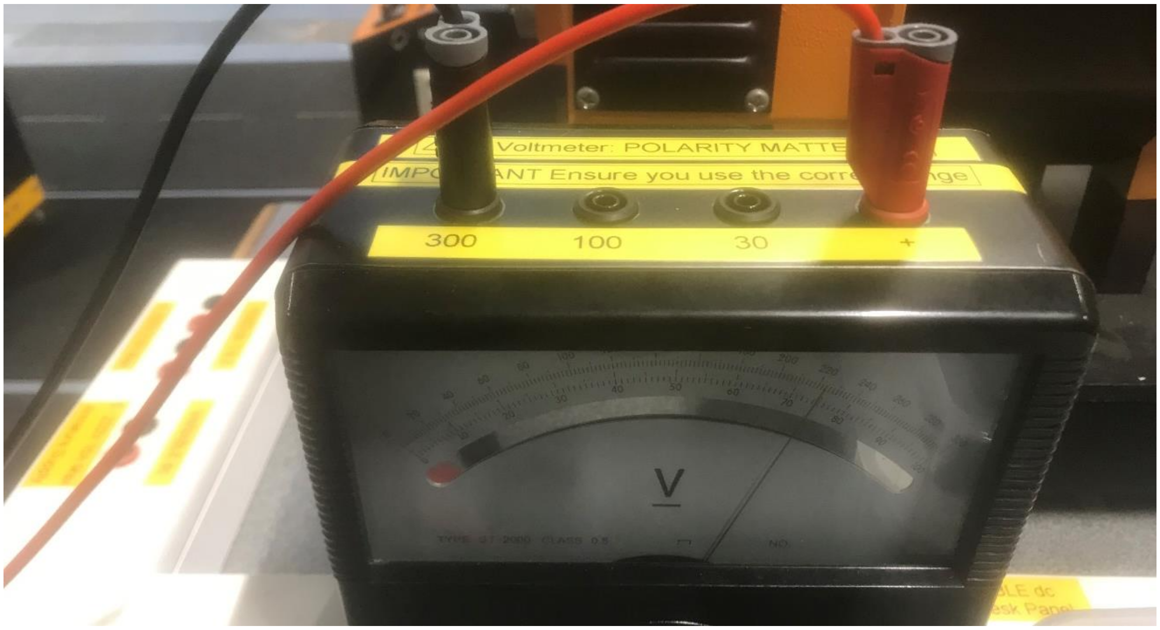



*Figure 27 - Maximum voltage applied to the SiC MOSFET*

## 4.3 Results of the SiC MOSFET at high frequency

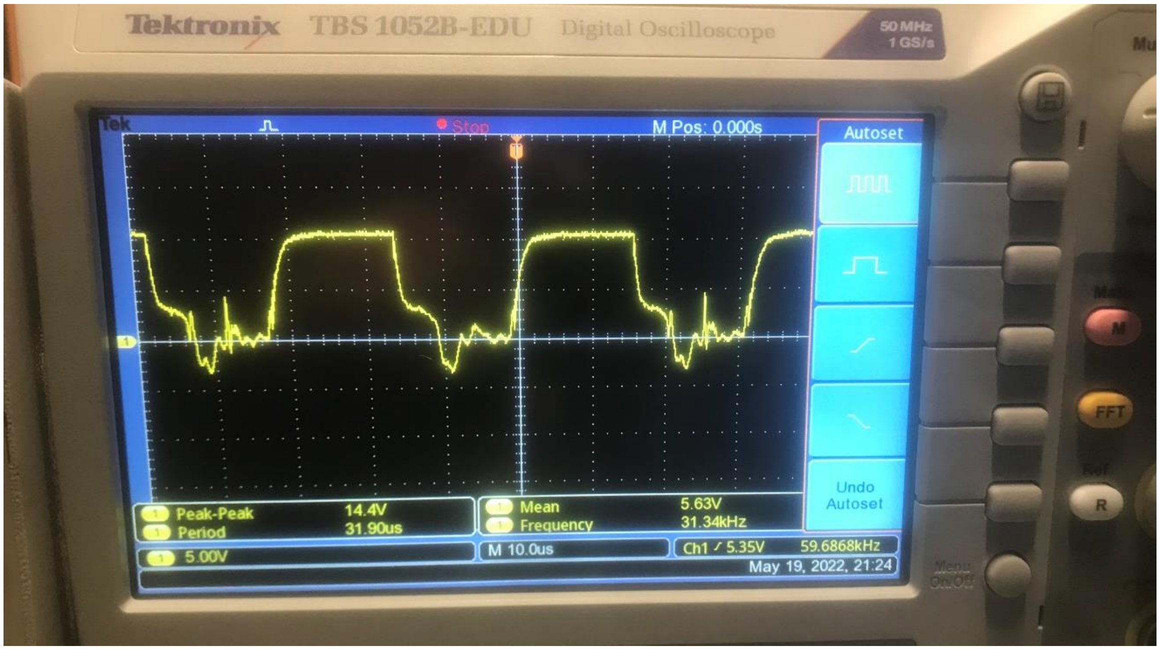



*Figure 28 - Ringing can be noticed at frequencies*

# 5 Conclusions

## 5.1 PWM frequency: ~500 Hz

Tested the SIC MOSFET at 60V while driving it with 500 Hz at the gate of the SIC MOSFET with the peak amplitude of 10V DC. The BJT produces 10V DC at the Source as it was derived using the Arduino UNO supplying 5V DC at approximately 500Hz at the base of the BJT.

BJT driver was used to power the SIC MOSFET as the Arduino UNO does not produce enough current, only produces 20mA at the output of the digital pin. Therefore, BJT was powered by external power supply to have enough current to drive the base of the BJT.

## 5.2 PWM frequency: ~31K Hz

The test was carried out to see how well the SIC MOSFET performs at high frequencies and high power.

Have destroyed two MOSFETS while testing the device and it turns out the Oscilloscope common ground effects the common ground of the Circuit design. Therefore, took out the common, and ran the test. This would have been resolved if used the SIC MOSFET Driver which uses transformers which isolates this completely due to the primary and second coil are separate.

The SIC MOSFET was tested up to 240VDC while driving it with ~31KHz at the gate of SIC MOSFET with the peak amplitude of 10V DC.

and resistance of the load was 11 ohms therefore the current was too high, $I = V/R$, $I = 240/11 = 21.8$ A. The wire was only rated up to 16A MAX therefore it got on fire and burned.

The Ammeter was not measuring correct current values because the Ammeter is rated for 50 Hz AC and can't handle high frequencies therefore the ammeter readings were not trusted.

# 6 Bibliography

[1] "Energy Bands - Definition and Classification of Energy Bands | Band Theory", BYJUS, 2022. [Online]. Available: https://byjus.com/physics/what-are-energy-bands/. [Accessed: 09- May- 2022]

[2] "The Importance of Silicon Carbide's Wide Bandgap", Wolfspeed.com, 2022. [Online]. Available: https://www.wolfspeed.com/knowledge-center/article/importance-of-silicon-carbide-wide-bandgap/#:~:text=The%20bandgap%20represents%20energy%20and,as%20having%20a%20wide%20bandgap. [Accessed: 12- May- 2022]

[3] J. Wood, "More electric cars are now sold every week than in the whole of 2012", World Economic Forum, 2022. [Online]. Available: https://www.weforum.org/agenda/2022/02/electric-cars-sales-evs/. [Accessed: 07- May- 2022]

[4] L. Paoli and T. Gül, "Electric cars fend off supply challenges to more than double global sales – Analysis - IEA", IEA, 2022. [Online]. Available: https://www.iea.org/commentaries/electric-cars-fend-off-supply-challenges-to-more-than-double-global-sales. [Accessed: 10- May- 2022]

[5] L. Vaughan-Edmunds, "Silicon Carbide—The Superhero of Silicon | Applied Materials Blog", Blog.appliedmaterials.com, 2022. [Online]. Available: https://blog.appliedmaterials.com/silicon-carbide-superhero-silicon. [Accessed: 09- May- 2022]

[6] "Avnet: Quality Electronic Components & Services", Avnet.com, 2022. [Online]. Available: https://www.avnet.com/wps/portal/apac/resources/article/electric-cars-are-all-vying-for-sic/. [Accessed: 14- May- 2022]

[7] "MOSFET Physics", Mksinst.com, 2022. [Online]. Available: https://www.mksinst.com/n/mosfet-physics. [Accessed: 03- Feb- 2022]

[8] "Insulated Gate Bipolar Transistor", electronics-tutorials.ws, 2022. [Online]. Available: https://www.electronics-tutorials.ws/power/insulated-gate-bipolar-transistor.html. [Accessed: 09- May- 2022]

[9] A. Ong, J. Carr, J. Balda and A. Mantooth, "A Comparison of Silicon and Silicon Carbide MOSFET Switching Characteristics", Ieeexplore.ieee.org, 2022. [Online]. Available: https://ieeexplore.ieee.org/document/4380318. [Accessed: 01- Feb-2022]

[10] A. Ong, A. Mantooth, J. Carr and J. Balda, A Comparison of Silicon and Silicon Carbide MOSFET Switching Characteristics, 5th ed. Fayetteville, AR, USA, 2007, p. Range of pages.

[11] "Comparing Silicon Carbide MOSFETs to Si MOSFETs", Wolfspeed.com, 2022. [Online]. Available: https://www.wolfspeed.com/knowledge-center/article/basics-of-sic-seriescomparing-sic-mosfets-to-si-mosfets. [Accessed: 02- Feb- 2022]

[12] "C3M0065090D Silicon Carbide MOSFET", Assets.wolfspeed.com, 2022. [Online]. Available: https://assets.wolfspeed.com/uploads/2020/12/C3M0065090D.pdf. [Accessed: 02-Feb- 2022]

[13] "Cree Dual 1700-V SIC MOSFET Driver", Mouser.com, 2022. [Online]. Available: https://www.mouser.com/datasheet/2/90/PT62SCMD17-519444.pdf. [Accessed: 02- Feb2022]

[14] "What is the difference between RS422 communication and RS485 communication? | Brainboxes", Brainboxes.com, 2022. [Online]. Available: https://www.brainboxes.com/faq/what-is-the-difference-between-rs422-communication-and-rs485-com#:~:text=RS422%20is%20a%20high%20speed,receiving%20end%20of%20the%20line. [Accessed: 09- Apr- 2022]

[15] S. Boral, "What Is PWM in Arduino - IoT Tech Trends", IoT Tech Trends, 2022. [Online]. Available: https://www.iottechtrends.com/what-is-pwm-arduino/. [Accessed: 03- Feb2022]

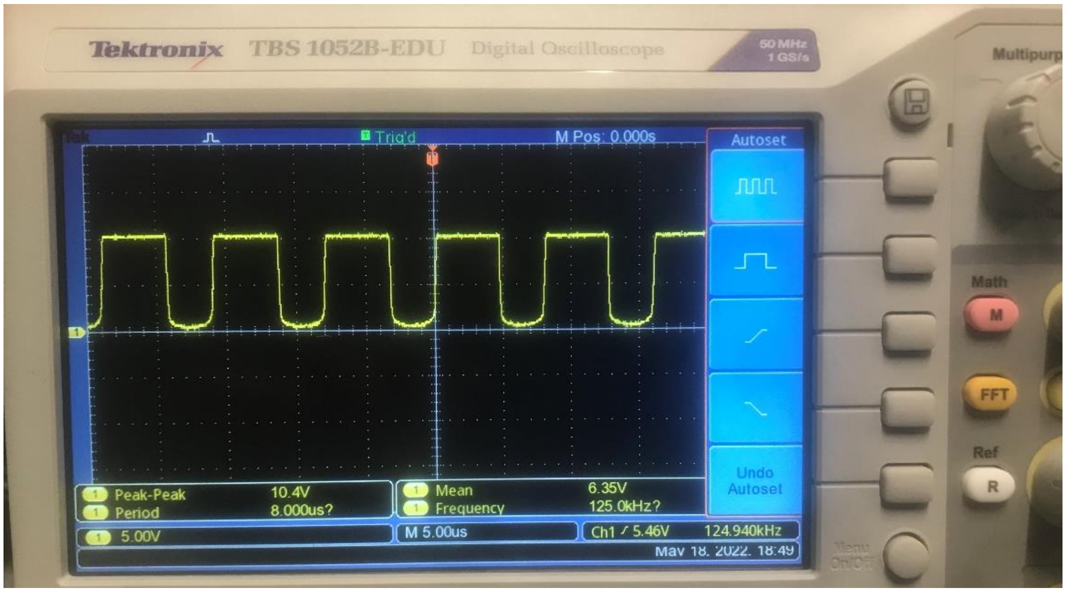
[16] "What is a Transistor? Types, Uses, Working Principle - Latest Open Tech From Seeed", Latest Open Tech From Seeed, 2022. [Online]. Available: https://www.seeedstudio.com/blog/2020/03/11/what-is-a-transistor-types-uses-working-principle/. [Accessed: 07- Apr- 2022]

[17] "ATmega328P Datasheet", Ww1.microchip.com, 2022. [Online]. Available: https://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-7810-Automotive-Microcontrollers-ATmega328P_Datasheet.pdf. [Accessed: 18- May- 2022]

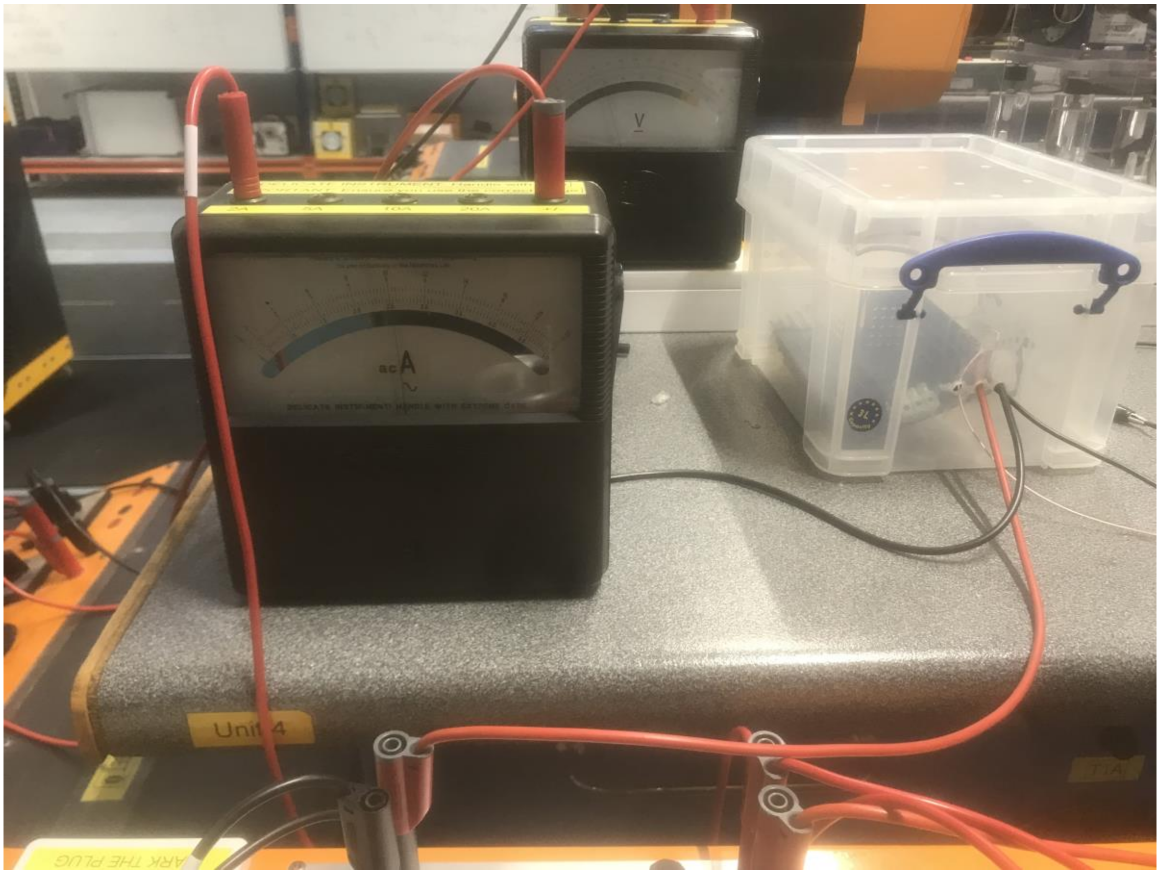
[18] "BUV46 Datasheet", St.com, 2022. [Online]. Available: https://www.st.com/resource/en/datasheet/cd00001297.pdf. [Accessed: 20- May-2022]

# 7 Appendix

## Appendix A. Output PWM signal of the gate Driver at 125 KHz




## Appendix B. Ammeter


V
A