CHARACTERIZATION OF GaN POWER SEMICONDUCTORS

OSCAR MAURICIO MEJIA SUAREZ

UNIVERSIDAD PONTIFICIA BOLIVARIANA

ELECTRONIC ENGINEERING FACULTY

BUCARAMANGA

2013

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OSCAR MAURICIO MEJIA SUAREZ

Company

ROBERT BOSCH GmbH

Supervisor

FABIO ALONSO GUZMAN SERNA

Electronic Engineer

UNIVERSIDAD PONTIFICIA BOLIVARIANA

ELECTRONIC ENGINEERING FACULTY

BUCARAMANGA

2013

GRADE OF ACCEPTANCE

Juror`s Signature

Juror`s Signature

Bucaramanga, September 2013.

ACKNOWLEDGEMENT

To God for being a big support and enlighten me in all the steps that I have done in the course of my existence.

To my parents for their unconditional support in all the moments and decisions of my life, being my motor for getting goals.

To my siblings Wilber and Marcela for their advices and being an example of responsibility and perseverance to follow. For showing me that the self-confidence is one of the keys to success.

To the Universidad Pontificia Bolivariana for giving me the tools to be trained as an engineer.

To the Engineer Fabio Alonso Guzman Serna for his suggestions and assisting me as a supervisor during the internship.

To those people close to me that somehow contributed in the finalization of my career.

GLOSSARY

Hot plate: Platform or base where the power devices are placed for testing them at high temperatures. This Setup is heated up through a heater.

On –Resistance: Resistance between Drain and Source terminals of a MOSFET and It appears when the device is on (current flow). The amount of this resistance determines how much power the device can dissipate.

Ohmic Region: Operation region of the MOSFET where the device behaves as a resistance controlled by gate voltage.

Four point measurement: Electrical Technique used for measuring impedance by using four sensing wires of which a pair give the current to the load and the other pair measure the voltage on terminals of the device, allowing more accurate measurements than traditional two terminal sensing.

Band gap: Energy difference between valence band and the conduction band in semiconductors. The band gap is the energy required for an electron to move from the valence band to the conduction band and becoming in a mobile charge carrier.

Semiconductors: Material that has an electrical conductivity between a metal such as copper and an insulator such as glass.

Positive temperature coefficient: Occurs when the resistance increases its value when increasing the temperature.

Negative temperature coefficient: Occurs when the resistance decreases its value when increasing the temperature.

Holes: A hole is the space that an electron leaves when moving from one place to another.

Traps: Sort of holes that come from the fabrication process or type of material of electronic devices and the electrons are trapped inside them.

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RESUMEN GENERAL

TITULO: CARACTERIZACIÓN DE SEMICONDUCTORES DE POTENCIA A BASE DE NITRURO DE GALIO (GaN).

AUTOR: OSCAR MAURICIO MEJIA SUAREZ

FACULTAD: Ingeniería Electrónica

DIRECTOR: Ing. Fabio Alonso Guzmán Serna

RESUMEN

Este proyecto consiste en la caracterización de dispositivos de potencia a base de semiconductores como Nitruro de Galio (GaN), Carburo de Silicio (SiC) y Silicio (Si), analizando sus propiedades, comportamientos y rendimientos a diferentes pruebas de voltajes, corrientes y temperaturas, llevados acabo mediante una placa caliente implementada y el uso de un software llamado ARYLAB.

PALABRAS CLAVE: PLACA CALIENTE, ARYLAB, SEMICONDUCTORES DE POTENCIA DE BANDA PROHIBIDA ANCHA, DISPOSITIVOS DE POTENCIA, RESISTENCIA DE ACTIVACIÓN ($R_{DS}ON$).

GENERAL ABSTRACT

TITLE: CHARACTERIZATION OF GaN POWER SEMICONDUCTORS

AUTHOR: OSCAR MAURICIO MEJIA SUAREZ

FACULTY: ELECTRONIC ENGINEERING

DIRECTOR: Ing. FABIO ALONSO GUZMAN SERNA

ABSTRACT

This project involves the characterization of power semiconductor devices based on materials such as Gallium Nitrite (GaN), Silicon Carbide (SiC) and Silicon (Si) by analyzing their properties, performance and behavior through various tests with voltages, currents and temperatures carried out with a suitable hotplate setup and using the software ARYLAB.

KEYWORDS: HOTPLATE, ARYLAB, WIDE BAND- GAP SEMICONDUCTORS, POWER DEVICES, DRAIN-SOURCE RESISTANCE.

1. INTRODUCTION

The semiconductors have had a big effect in our daily life. They have been playing a big role in the technology development and it could be said that almost in all electronic devices there is at least one component made of semiconductor material. Silicon is the most common semiconductor material and it can be found in big quantities on the earth surface. Transistors made of silicon offer good electrical characteristics and have been used along the history but the quick technology development also requires faster, cheaper and better devices that fit to this fast changing world.

Currently, it is intended to improve the efficiency, conductivity and speed of the power MOSFETs devices. New alloys and material shave been investigated and they promise better results of switching and blocking voltage due to their wide band gap.

In the frame of this internship it was intended to compare and analyze the electrical behavior of Power semiconductor devices made of Silicon, Silicon Carbide and Gallium Nitride under various high temperatures.

After some laboratory tests it could be seen in devices made of Silicon Carbide and Gallium Nitride, exceptional physical properties that promise them a brilliant future in the semiconductor technology particularly in the field of high-frequency electronic applications and high power applications.

2. COMPANY OVERVIEW

2.1. Company Name:

ROBERT BOSCH GmbH

2.2. Economic Activity/ Products and Services:

The Bosch Group is a leading global supplier of technology and services. In 2012, its roughly 306,000 associates generated sales of 52.5 billion Euros. Since the beginning of 2013, its operations have been divided into four business sectors: Automotive Technology, Industrial Technology, Consumer Goods, and Energy and Building Technology.

The Bosch Group comprises Robert Bosch GmbH and its more than 350 subsidiaries and regional companies in some 60 countries. If its sales and service partners are included, then Bosch is represented in roughly 150 countries. This worldwide development, manufacturing, and sales network are the foundation for further growth. Bosch spent some 4.5 billion Euros for research and development in 2012, and applied for over 4,700 patents worldwide. The Bosch Group's products and services are designed to fascinate, and to improve the quality of life by providing solutions which are both innovative and beneficial. In this way, the company offers technology worldwide that is "Invented for life."

2.3. Products and Services

Mobility

- Bosch service
- Car parts and accessories
- Automotive and technology
- Mobility solutions
- Bike Systems

Home Industry

- Power Tools for DIY enthusiasts
- Garden tools
- Household appliances
- Heating and hot water

Industry and trade

- Commutation center
- Power tools for professionals
- Sensors (MEMS) for consumer electronics
- Security Systems
- Packaging Technology
- Photovoltaic

Software Solutions

- Business rules management
- Business process management
- Industry solutions [1]

The Bosch Company is a leader in production and optimization of technological products in different kinds of areas, such as Automotive Technology, Industrial Technology, Consumer Goods, and Energy and Building Technology.

This company counts with different industrial development departments, where there are work groups formed by people such as physicals, chemicals, Electric, Electronic, Mechatronic among others, some of them with doctorates titles, PhD candidates and university students doing their internship. They all are responsible to innovate and improve various products for consumer's needs.

2.4. Specific Description of working area.

The internship was held in the CR/ARY(**C**orporate **R**esearch / **A**dvance **R**esearch Micros**y**stems) department, where a group of researchers are working on power semiconductors area, testing and analyzing behaviors, characteristics and viability of new types of material semiconductors to be applied in the future in the industry sector.

During the project some of the aims are to take measurements and make characterizations of two types of power semiconductors such as GaN and SiC to analyze the advantages and disadvantages of their use and to be able to implement them in the future in electronic products, so that, we can improve the performance of this products.

The semiconductor GaN belongs, likeSiC, to the group of wide band gap semiconductors which promise higher breakdown voltages as corresponding Si devices. In the research project “Scouting GaN as a material for power semiconductors”, GaN device of different companies are purchased and will be benchmarked against Si and SiC devices. Existing Measurement setup characterization will be extended to allow measurements of examples given $R_{DS\ on,\ IDsleak}$ at elevated temperatures. The acquired knowledge about the devices will help to validate the potential of GaN as a material for power semiconductors.

2.5. History

In 1886, Robert Bosch founded the “Workshop for Precision Mechanics and Electrical Engineering” in Stuttgart (Germany). This was the birth of today's globally active Robert Bosch GmbH.

On November 15, 1886, Robert Bosch received official approval to open a “Workshop for Precision Mechanics and Electrical Engineering” at 75B

Rotebühlstrasse in Stuttgart. He opened the workshop together with a mechanic and an errand boy. The rented premises comprised an office, one larger and one smaller workshop, and a room in which a small forge was housed.

The first high-voltage magneto ignition system with Bosch spark plugs was delivered to Daimler-Motoren-Gesellschaft in 1902. The previous year, Robert Bosch had asked his development engineer Gottlob Honold to improve the design of the low-voltage magneto ignition device so that it could do without its break-spark rodding, a high-maintenance component prone to breakdowns. Robert Bosch was very impressed when, in the same year, Gottlob Honold presented his first prototypes with spark plugs in place of break-spark rodding.

At the Leipzig trade fair in 1932, Bosch unveiled its new hammer drill. Bosch had succeeded in series-producing the first electric drill that could strike and rotate at the same time. The tool made work at construction sites much easier, and quite literally stuck by its users "through thick and thin."

In 1953, with the slogan "Bosch hydraulics – instead of muscle power," the company advertised its first product in the hydraulic segment, a mobile hydraulic lift that used the power of a tractor engine to lift and lower the plow.

Bosch had already played a pioneering role in the 1970s with ALI, its driver guidance and navigation system. The next prototype, presented in 1983, was EVA, an "electronic pilot for drivers" that used an electronic map to guide drivers from one destination to the next. Travel Pilot IDS followed in 1989, but the breakthrough was not to come until 1995 with the introduction of the Travel Pilot with satellite navigation, route guidance, and speech output.

In 2000, Bosch returned to gasoline direct injection, an idea that had caused a stir in 1954 when it featured in the Mercedes 300 SL. What was innovative about DI Moronic was the "stratified charge basis," which burned a localized cloud of the air-fuel mix generated by the direct injection, thus lowering fuel consumption by up to 10 percent.

The individual components of the Bosch bike system have been carefully matched to one another. The drive unit and its power electronics, the battery pack and its charging unit and the HMI that is mounted on the handlebars together constitute a high-performance, lightweight drive system that is both powerful and robust, with a high degree of ride stability thanks to its central, low-slung center of gravity.[2]

3. OBJECTIVES

3.1. General Objective

Analyze the characteristics and electrical behaviors of power devices based on Gallium Nitride (GaN), Silicon (Si) and Silicon Carbide (SiC) under different temperatures, Currents, Voltages. The results will be compared to each other to validate the potential of the GaN as a material for power semiconductor.

3.2. Specific Objectives

- To know the safety rules used in each laboratory where measurement processes of power semiconductor devices are performed.

- To know and understand the functioning and characteristics of different types of power semiconductors, their composition and how they are used in the industry.

- To learn how to operate high-power sources used for measurement and testing of power semiconductor devices.

- To understand the MOSFET testing processes and tools used to carry out their measurements

4. WORK PLAN

The development of this internship was structured in 3 main parts as follows: The first part involved mainly the introduction to the company, to work area including the safety rules in the laboratories and colleagues. The Second part referred to the familiarization with the Semiconductors devices fabrication and training of instruments used in the projects and the third part was the active participation in the project. In this part following activities were realized or supported:

- Validation and improvement, especially by implementing a controlled hotplate, of existing measurement setups for the characterization of packaged power semiconductors.

- Photolithography process support of test structures on SiC wafers in clean room.

- Benchmarking various GaN, SiC and Si devices against each other.

- Documentation of the results.

5. THEORETICAL FRAMEWORK

5.1. Silicon Carbide

Silicon Carbide (SiC) is a synthetic mineral most commonly produced in electrical resistance furnaces, by the Acheson process, named after the American E.G. Acheson who invented it in 1891.

In an Acheson furnace, a mixture of carbon material (usually petroleum coke) and a silica or quartz sand is reacted chemically at high temperatures in the range of 1700 – 2500°C resulting in the formation of α-SiC.The energy for the reaction is provided by the resistive heating of a graphite core done by connecting this core to two electrodes at both ends of the furnace.

SiC develops as a solid cylindrical ingot around the core, with radial layers ranging from graphite in the inside, to α-SiC (the highest grade material with coarse crystalline structure), β-SiC, metallurgical grade and finally un-reacted material on the outside. SiC can be produced as either black or green, depending on the quality of the raw materials.

After a cooling period, the SiC ingot is sorted accurately and further processed for different applications. The SiC crude material is carefully crushed, classified, sometimes milled again, and optionally chemically treated in order to obtain the specific properties for which it will be applied. These subsequent processing steps actually account for the bulk of our know-how and of the value we add to our products.

5.1.1. Properties of Silicon Carbide

SiC is a ceramic material with an outstanding hardness, only surpassed by diamond, cubic boron nitride and boron carbide. The material is highly wear resistant and chemically inert to all alkalises and acids. It is also highly heat resistant. These properties make Silicon Carbide an outstanding abrasive and ceramic material to be used under extreme operating conditions.

- Density: 3.21 g/cm3
- Vickers hardness: 29 GPA

- Coefficient of Thermal expansion: 5·10-6/K
- Thermal conductivity: 50 to 100 W/m K
- Typical temperature resistance: 1500°C in air, 2400°C in inert atmosphere
- Specific heat: 750 J/kg K [4]

5.2. Gallium Nitride

Gallium Nitride (GaN) is a binary III-V direct band gap semiconductor. The material used to create working transistors is actually a crystal, and these crystals are grown layer-by-microscopic layer, using a precise mixture of different gases, flowing into a reaction chamber. The electrical properties of GaN make it an ideal choice of material for optoelectronic, high-power and high frequency devices. Because GaN offers very high breakdown voltage, high electron mobility and saturation velocity, it is also an ideal candidate for high-power and high-temperature microwave applications like RF power amplifiers at microwave and mm frequencies, and high-voltage switching devices

The entire GaN semiconductor is grown into a crystal lattice structure material that has a very high threshold for electron mobility and has excellent thermal conductivity properties, allowing high temperature operation and effective heat transfer. Therefore the devices using GaN can operate at very high temperatures (up to 350 °C) and can dissipate all the heat generated by these devices at very high temperatures.

Obviously, the best match is to grow GaN transistors on GaN substrates, because they have an identical crystal lattice structure; however this is slow growing and hence expensive process. Recently non-lattice matched substrate materials have been developed and now are commonly used. Among them, silicon carbide is the current favorite because of the low cost/high performance combination. Therefore due to these technological advancements and refinements of the processes and use of composite materials, GaN devices can be produced in large volumes relatively cost effective. [5]

5.3. Manufacturing Processes of Semiconductor Devices.

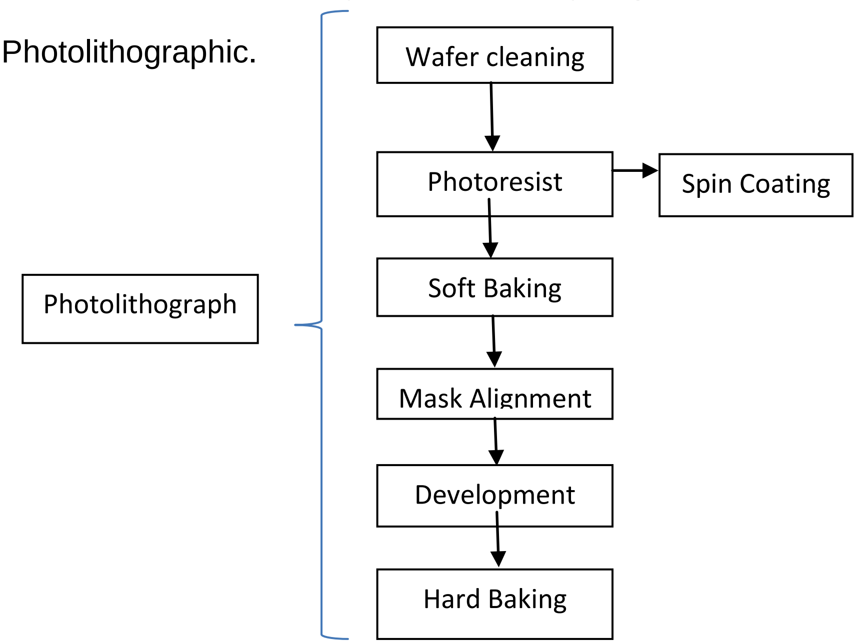
A quickly overview into the fabrication processes of semiconductor devices begin with obtaining the raw material, for example Silicon, Silicon Carbide and Gallium Nitride, passing by the generation and cutting of ingots to create the wafers, cleaning process to eliminate impurities on the wafer, Photolithography, layer deposition and etching process, wiring and encapsulated of the semiconductor device.

The Photolithography is a process used in the semiconductor device fabrication, which by using UV light can impregnate patterns on a semiconductor wafer for creating small scale features of integrated circuits.

The photolithography process is formed by several steps in sequences which are realized in modern clean rooms where the processes are coordinated by using robotic wafer track system.

The process is described basically in the following steps.

Figure 1.Photolithographic.



5.4. Brief description of main Power Semiconductor Devices

Devices made by semiconductor materials are used in Power Electronics and are classified in three groups according to their control way:

1. Uncontrolled Devices: In this group, one can find the Diodes, which are open or close depending on the power circuit.

2. Semi controlled Devices: In this group are found the tiristors such as SCR (Silicon Controlled Rectifier) and TRIACS (Triode of Alternating Current). These Devices have a control from Off state to on state through a signal which is applied in one of the terminals of the device, mostly in the gate terminal.

3. Controlled Devices: In this group, we find transistors such as BJT (Bipolar Junction Transistor), MOSFET (Metal Oxide Semiconductor Field Effect Transistor), and IGBT (Insulated Gate Bipolar Transistor) inter alia.

MOSFETs, BJTs, IGBTs, JFETs, in Power Electronics, are used to switch electronic signals as switches, however MOSFETs have the advantage of the bipolar transistors to operate at high frequencies. MOSFETs,IGBTs,JFETs transistors have to control current into drain-source terminals from a gate terminal voltage, that is why it is said they can work as voltage controlled resistors (VGS).

5.4.1. IGBT

The insulated gate bipolar transistor or IGBT is a three-terminal power semiconductor device, noted for high efficiency and fast switching. It switches electric power in many modern appliances: electric cars, trains, variable speed refrigerators, air-conditioners and even stereo systems with switching amplifiers. Since it is designed to rapidly turn on and off, amplifiers that use it often synthesize complex waveforms with pulse width modulation and low-pass filters.

The IGBT combines the simple gate-drive characteristics of the MOSFETs the high-current and low–saturation-voltage capability of bipolar transistors by combining an isolated gate FET for the control input, and a bipolar power transistor as a switch, in a single device.

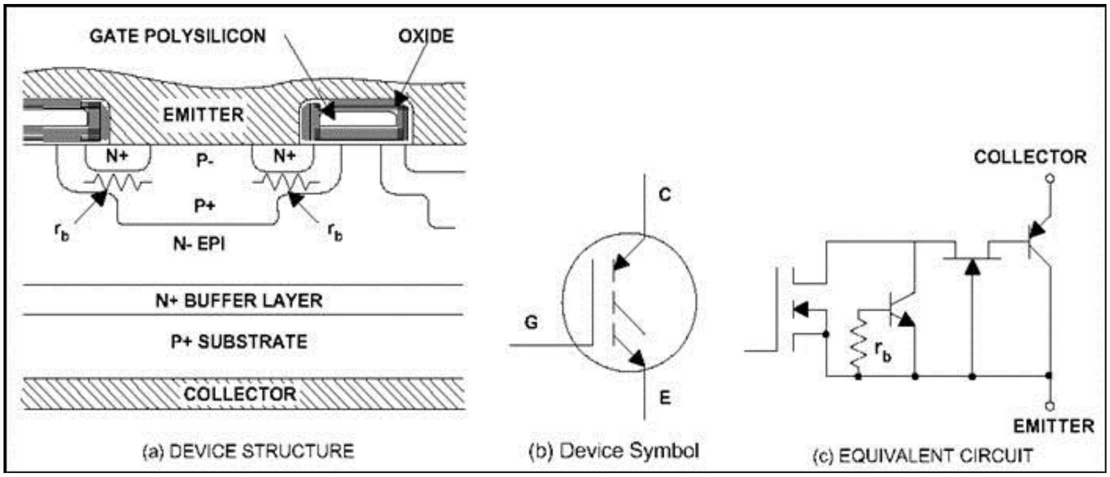


Figure 2.IGBT: cross-section, symbol and equivalent. [6]

The IGBT is used in medium- to high-power applications such as switched-mode power supply, traction motor control and induction heating. Large IGBT modules typically consist of many devices in parallel and can have very high current handling capabilities in the order of hundreds of amperes with blocking voltages of 6000 V. [7]

5.4.2. JFET

The single channel junction field-effect transistor (JFET) is probably the simplest transistor available. As shown in the schematics below for the n-channel JFET (left) and the p-channel JFET (right), these devices are simply an area of doped silicon with two diffusions of the opposite doping.

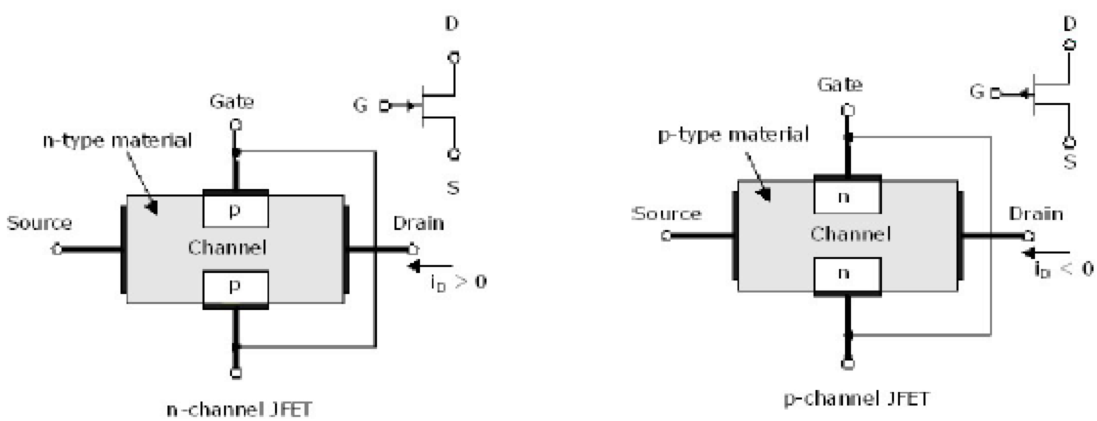


Figure3. JFET transistor

Like the BJT, the JFET is a three terminal device. Although there are physically two gate diffusions, they are tied together and act as a single gate terminal. The other two contacts, the drain and source, are placed at either end of the channel region.

The operation of the JFET is based on controlling the bias on the pn junction between gate and channel. If a voltage is applied between the drain and source, current will flow. The device is therefore in a normally on state. To turn it off, we must apply an appropriate voltage to the gate and use the depletion region created at the junction to control the channel width. [8]

5.4.3.HEMTs

The High Electron Mobility Transistor (HEMT) is a heterostructure field-effect transistor (FET).Its principle is based on a heterojunction which consists of at least two different semiconducting materials brought into intimate contact. Because of the different band gaps and their relative alignment to each other, band discontinuities occur at the interface between the two semiconducting materials.

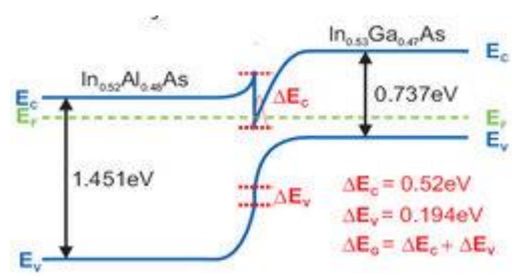


Figure 4.Semiconductors in contact at the equilibrium. A 2DEG is formed at the interface. [9]

These discontinuities are referred to as the conduction and valence band offsets ΔEc and ΔEv. By choosing proper materials and compositions thereof, the conduction band offset can form a triangular shaped potential well confining electrons in the horizontal direction. Within the well the electrons can only move in a two-dimensional plane parallel to the heterointerface and are therefore referred to as a two-dimensional electron gas (2DEG).

To determine the exact shape of the conduction and valence bands, the Schrödinger and Poisson equations must be solved self-consistently. [9]

5.4.4.MOSFET

The MOSFETs (Metal Oxide Semiconductor Field Effect Transistor), are very similar to the JFET transistors, but the difference is that in the MOSFET gate is insulated from the channel, therefore there is not current flowing at the terminal. [10]

MOSFETs are manufactured according to its internal structure in two types: the depletion and enhancement mode.

The depletion type has a channel formed between the terminals Drain – Source, therefore is already activated and the current can flow through the channel even if VGS is zero. To control the flow of the current, VGS has to be lower than the Threshold Voltage in order to decrease the channel size and the current as well (VGS< VTH). In this depletion type MOSFET, the Threshold Voltage is negative (VTH<0). The depletion MOSFET are applied in weak signal amplification at high frequencies and radio frequencies, and these may also have the same function of the enhancement mode MOSFET, since for VGS> 0 volts the current IDS increases.

In other hand, the Enhancement type MOSFET owns a positive Threshold Voltage (VTH>0) and a channel is developed only when VGS> VTH. Enhancement type is normally off (there is not channel active) and it is used more than the depletion type, usually in power electronics, due to the mobility of electrons is much higher than that of the holes.

Threshold voltage VTH is the major difference between these types of MOSFET structures. This Voltage (VTH) is defined as the VGS voltage necessary to create the channel in enhancement MOSFET or to reduce the formed channel in depletion MOSFET. Figure 5 shows the basic structure of depletion MOSFET (N channel). [10]

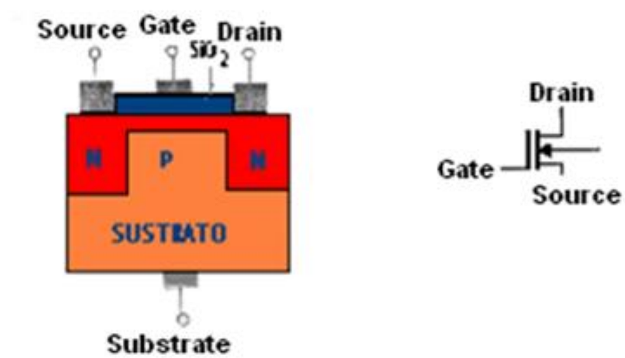


Figure 5. Depletion type MOSFET. [11]

5.4.4.1. Types of MOSFET

The internal composition of the MOSFET is based on semiconductor P-type or N-type substrate according to the doping material and two additional N-type semiconductor materials or P-type depending on the impurities that the material has. One of the most important internal structure arguably is the isolation of the gate terminal (gate) with the substrate, which is carried out by adding a layer of silicon dioxide SiO2 between the gate terminal (in many cases polysilicon) and the base substrate creating a capacitor in the area, where the current IG is very negligible.

Besides of their structure, MOSFETs are classified by the type of substrate; when the base material (substrate) is made of P-type doping, Drain and Source terminals must be placed on dopant diffusion region such as N-type. In the other hand, if the base substrate is made of N-type doping, Drain-Source terminals must be placed therefore on a dopant diffusion region P-type, these types of doping materials cause many differences respect to channel creation between terminals Drain and Source.

When the MOSFET is NMOS (substrate P-type), a channel is formed between terminals (Drain-Source) by accumulation of electrons, nevertheless the PMOS MOSFET (substrate N-type), a channel is also formed between Drain-Source terminals, but based on accumulation of holes (positive Charges).

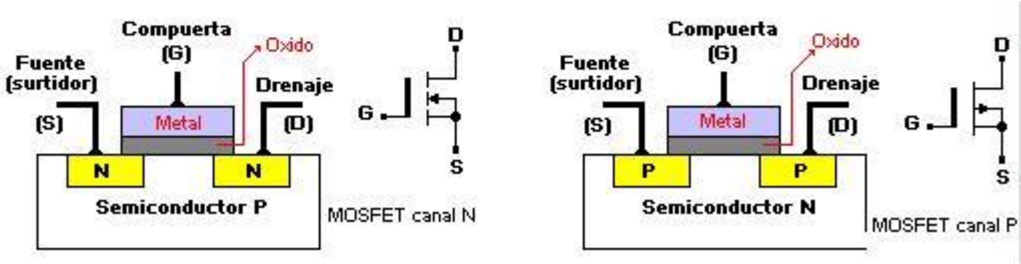


Figure6.Types of MOSFET [11].

5.4.4.2.Operation

The MOSFET starts to work when applying a Bias Gate Voltage (VGS) as well as Bias Drain-Source Voltage. The Gate Voltage has to be higher than the Threshold Voltage in order to create a channel between the Drain-Source terminals, which lets the Drain Current flows through it.

Depending on the type of MOSFET(N-MOS or P-MOS), the Bias Gate Voltage may be positive for NMOS or Negative for PMOS.This Gate Voltage varies according to the dopant regions at the terminals and the base substrate.

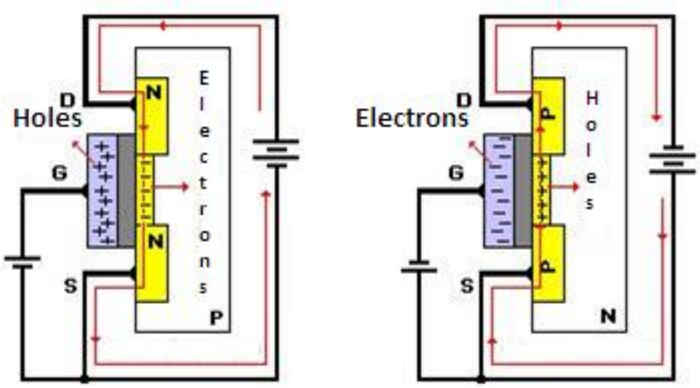


Figure 7. Operation mode of MOSFET P-Type and N-type. [12]

PMOS MOSFETs when a Negative Gate Voltage is applied, positive charges (holes) are accumulated creating a P-channel allowing current flows in it. N-MOS MOSFETs create an N-channel formed by negative charges (electrons) which are attracted by applying a positive Gate-Voltage, it is important to make clear that there will be current flow as long as an electric field is applied between Drain and Source terminals.

5.5. POWER MOSFETs

Unlike the lateral MOSFETs aforementioned, power MOSFETs have a vertical structure and are designed for switching applications, while the lateral or planar MOSFETs are better in behavior in the saturated than the vertical MOSFETs as well as they are mainly used in high-end audio amplifiers.

They are manufactured with the need to handle high voltages and high currents thus higher power. Due to their High frequencies, these the Power MOSFETs have overcome BJT and other types of power semiconductors. Power MOSFETs are improvement of CMOS technology, which is used in manufacturing integrated circuits. Power MOSFETs are commonly used in power devices due to their low gate drive power and fast switching speed. Most Power MOSFETs feature a vertical structure with Source and Drain on opposite sides of wafer in order to support higher current and voltage. [13]

The DMOS MOSFET, is one of the types used frequently in Power ICs and power semiconductors circuits, however due to their large N^- region on the surface of the semiconductor, they handle low current-load capacity. For solving this inconvenience and controlling real power, Vertical MOSFETs were realized by arranging the area for the electric field vertically. The figure 8shows a DMOS MOSFET (Double Diffused), which is used for voltages higher than 10 volts. [13]

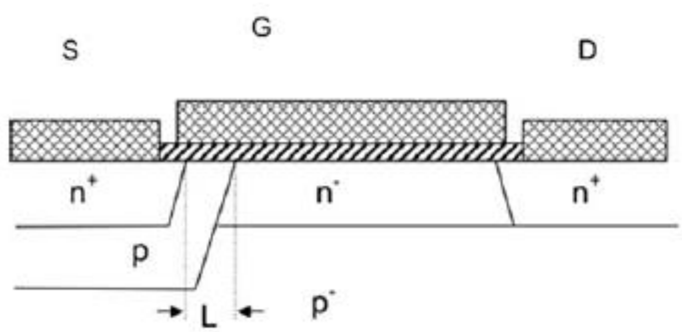


Figure 8. Lateral DMOS. [14]

The Vertical MOSFETs use the surface for the formation of the individual cells and the volume of the semiconductor for laying the source and drain on opposite sides in order to bear higher current and voltage. These Vertical MOSFETs work in the same way that the planar MOSFETs, namely , if a bias gate voltage(VGS) is higher than the gate threshold voltage, there will be an n-type inversion channel underneath the gate oxide, which connects the source and drain and enabling the current to flow.

Power MOSFETs have an intrinsic body diode in the junction connected between drain and source, and a parasitic BJT which its base is located in P-body region, source is the emitter and drain is the collector. This BJT has to be off all times otherwise if it is on, could lead the device into the latchup condition, making the MOSFET uncontrollable and would destroy the device. [15]

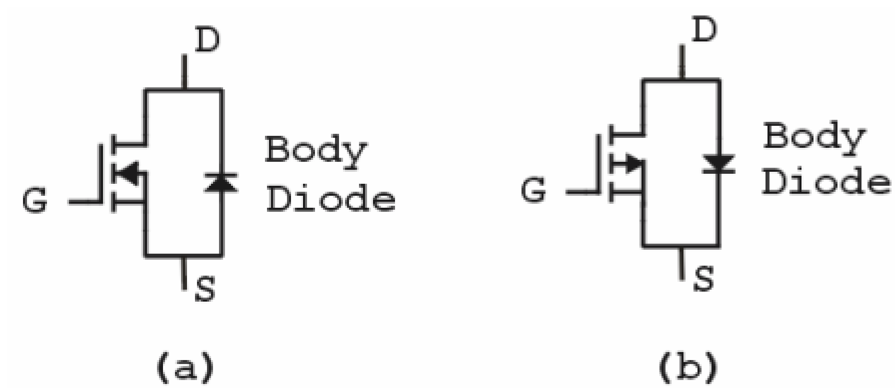


Figure 9. (a)N-Channel (b) P-Channel enhancement-mode Power MOSFET. [15]

The body diode is necessary in circuits as converters, motor control applications where a path for reverse drain current is convenient. [15]

Vertical MOSFETs the cells formed on the surface of the semiconductor consist of p-wells and diffused N^+ source areas, as the figure 11 shows. These p-wells are connected to the source metallization avoiding the formation of the npn- transistor (BJT), in other hand, the doping is increased by an additional p+-implantation, followed by a diffusion which refers to the double diffusion process to get the p and n regions. At the edges of the well is the channel, which is covered with the thin gate oxide [14]

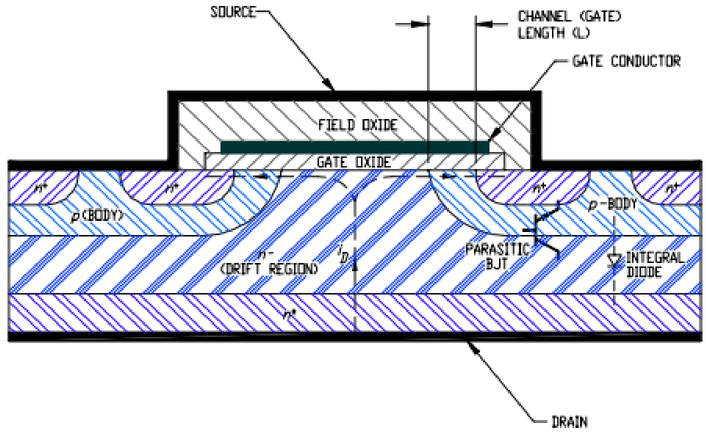


Figure 10. Vertical MOSFET VDMOS. [15]

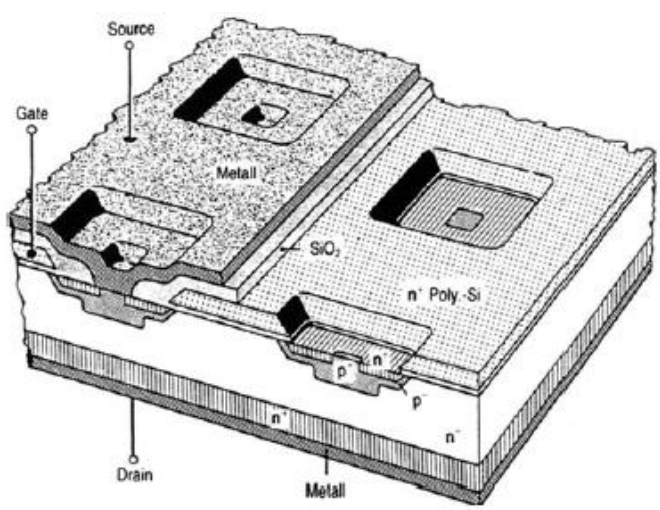


Figure 11.Cell structure of a vertical VDMOS. [14]

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Power MOSFETS have advantages as high input impedance, efficiency at low voltages, constant transconductance, positive temperature coefficient and are used mainly as switches due to high switching velocity as well as energy sources, motor controls and converters DC-DC.[16]

5.5.1.Static Behavior

Defined by transconductance, the output characteristics and on-resistance.

In an n-channel enhancement-mode power MOSFET, the output characteristics consist of drain current (ids) as a function of drain-source voltage (V_{DS}) and the bias gate voltage (V_{GS}) as a parameter.

The figure 12 shows, how the drain-current varies depending on the bias gate voltage (V_{GS}) and the drain-voltage. There are three regions in the output characteristics where the device is able to operate; ohmic region, saturated region and cut-off region.

In ohmic region, the device behaves as a resistor which is defined by Rdson= V_{DS} / I_{DS}. The saturated region is reached when V_{DS}> (V_{GS}-V_{TH}),and the current depends on the gate voltage, in this point the devices behaves such a current source. The cut-off region is when the gate voltage (V_{GS}) is lower than threshold voltage and the device behaves as open circuit, so it is in off-state.

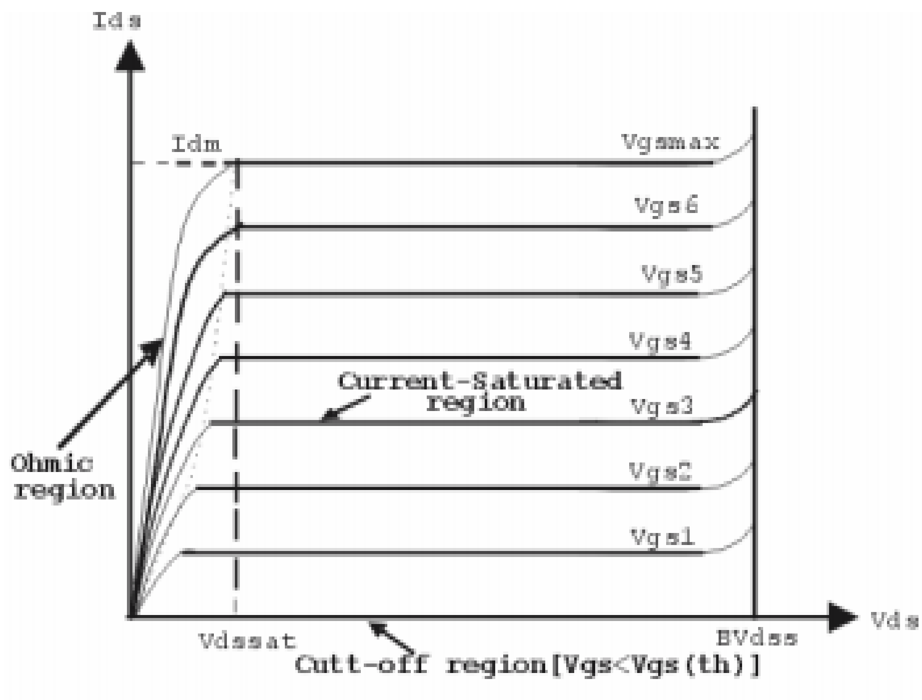


Figure12.Drain- Current Vs Drain-Voltage Characteristics of MOSFET. [15]

5.6.Tools and Instruments Used

5.6.1.High Power Source Measurement Unit (SMU) model 2657 A.

Model 2657A is a SMU of high voltage which provides unprecedented accuracy, speed, flexibility and ease of use to improve productivity in R & D, testing production and reliability environments. The model 2657A was designed to characterize and test high voltage and high power electronics; this source handles a dynamic range of 3000 volts, 120 mA, 1fA, which can be used in measurements of power semiconductor for determining the blocking voltage limit and other parameters such as accurate voltage measurements. By using TSP-Link interface and embedded plug and play web software, the model 2657A can be combined with other source meters to create high power test systems capable of 3000v and 100 A. [17]

5.6.2.High Power Source Measurement Unit (SMU) model 2651A

Model 2651A is a SMU design specifically for characterizing and testing high power and high current devices. This source handles a wide dynamic range of 50A, 40V, 100fA, which can contribute to enhance productivity in applications across reliability, R&D and production spectrums. By using TSP-Link interface and embedded plug and play web software, the model 2651A can be combined with the source model 2657A to create high power test systems capable of 3000V and 100A.[18]

Figure 13. High Power system source meter SMU 2651A. [18]

The high Power system sources SMU models 2657A and 2651A are able to work with the following applications:

- Power Semiconductor and optical device characterization and testing.
- Solar cell characterization and testing.
- Characterization of GaN, SiC and other compound materials.
- High precision, speed digitization.
- High current, high power device testing.

Furthermore this High Power sources have other features such as:

- Voltage or current generator of waveform.
- Voltage or current generator of pulses.
- Accurate supply of voltage and current measurement.
- Digital Multimeter
- Accurate electronics[18]

5.6.3.High Power Device Test Fixture model 8010.

The Model 8010 has full interlock capability for up to six Source Meter instruments. The Model 8010 has integrated protection circuits that protect the low voltage Source Meter instruments from high voltages the Model 2657A can output should a device fault occur. The Model 8010 includes both a high current (100A) and a high voltage (3000V) test socket. Various replacement test socket modules are available, including TO-247, TO-220, axial lead, and a blank socket module that allows building a custom socket. In addition to standard banana jumpers, the Model 8010 has rear-panel scope and thermal probe ports to simplify system integration.

The Model 8010 provides simultaneous connections for:

- High voltage Source Meter instrument (Model 2657A)
- One or two high current Source Meter instruments (Model 2651A)
- Three low power Source Meter instruments (other Series 2600A or Model 4200-SCS source measurement unit (SMU) instruments)

This allows devices with two terminals (diodes) or three terminals (transistors) or even four or five terminals to be characterized safely and accurately. [18]

Figura14. High Power Test Fixture. [18]

5.6.4. ARYLAB Software

This software was made by the company in order to facilitate the measurements on test power semiconductor devices developing for the company. Due to it was made with same program language established by the SMU, it is able to work with any of them by changing the settings according to the measurement needed , so when a computer is connected to any of source meters, the software ARYLAB detects the SMU then is possible to set the configuration thus the measurement.

This software is capable to realize measurements of voltage, current, resistance, capacitance, leakage currents and others.

5.6.5. Devices Communication

The GPIB system is a parallel communication system, which can communicate with several devices through the same interface port. The devices that are connected to this bus fall into three categories: controller, listener and talker, all of which are connected through the IEEE-488 connector.

The USB-3488A GPIB interface provides a direct connection between the USB port on a desktop or laptop computer to GPIB instrumentation. With the USB-3488A GPIB interface and its USB Plug and Play feature, GPIB instruments can be connected and disconnected without having to shut down the computer. No external power supplies are necessary. The USB-3488A GPIB interface is equipped with a 2 meter USB cable that is USB 2.0 compliant. [19]

Figure 15. Laptop and source connected by using GPIB.

6. WORK PLAN DEVELOPMENT

Once the internship started, it was important to know the work area and the department where the semiconductors projects are carried out. The safety work standards in the company -especially in the laboratories where the semiconductors materials are processed for the development of electronic devices- were also explained by the security personnel.

The laboratories are known as Clean Rooms, and are specially characterized by having very low contamination levels, and parameters like temperature, humidity and air flow are also well monitored. Additionally, the working personnel need to wear special dress to avoid contamination of the room.

Figure16.Clean Room. [20]

The Figure 16 shows, that some clean rooms are lighted with a white light. The purpose of this type of light is to avoid unwanted exposure or alteration of photoresist material to wavelengths of the normal light.

After becoming familiar with the safety rules, readings about composition and operation of power semiconductors with emphasis in power MOSFETs were conducted in order to get a clear idea about the project itself. These readings were very useful in understanding the types of MOSFETs, their structure, characteristics and properties and the way how they work depending on the semiconductor material from which they are made.

The company has laboratories especially for testing power semiconductor devices (package devices, wafers and chips). These laboratories have the appropriate equipment to measure various types of parameters on the power devices. Some parameters that could be measured here are: gate leakage current, Drain leakage current, high blocking voltage, contact resistances, etc.

A reading of the equipment used to test power semiconductors- which also included the high voltage sources and high current sources well known as Source Meter Unit (SMU) was also conducted. In order to make an accurate test, these sources also have the function to measure the voltage being supplied directly on the device, considering the voltage loses on the connection wires. For security reasons, these measurements are always carried out inside of a safety box.

The SMU and safety box are manufactured by KEITHLEY and some of the equipment used in the measurements of power semiconductor devices were:

- High Voltage Source Meter Unit model 2657A.
- High Current Source Meter Unit model 2651.
- High power test fixture model 8010.

These SMU supply voltage/current have the ability to measure simultaneously the applied variable in the load, and auto-regulate in case the load does not have the exact voltage, or the current flowing through it is not the desired one. Because of this, the results are very reliable.

Voltage and current measurements have been conducted with various types of MOSFETs to observe the behavior and characteristics they present according to their type of material. These measurements have been realized on SoC MOSFETs made by Silicon(Si) , Silicon carbide (SiC) and Gallium Nitride (GaN), using SMU supply voltage to get high accuracy results. The Software to operate the SMU depends on type of measurement to be executed and a safety box to perform the measurement was also used to avoid any accident.

The process of measurement on these power devices can be seen in the following steps:

- Connection of sources (SMU) with the computer by using USB- GPIB (General Purpose Interface Bus).
- Configuration of the ARYLAB software to operate the SMU.
- Selection of the type of measurement to execute (E.g.: Leakage current, blocking voltage, etc.).
- Connection of sources (SMU) with the High power test fixture (safety box).
- Positioning of the power device (SoC) in a socket inside of the High Power Test Fixture (safety box).
- Connection of the device (MOSFET) with the SMU inside the safety box.
- Execution of the measurement.

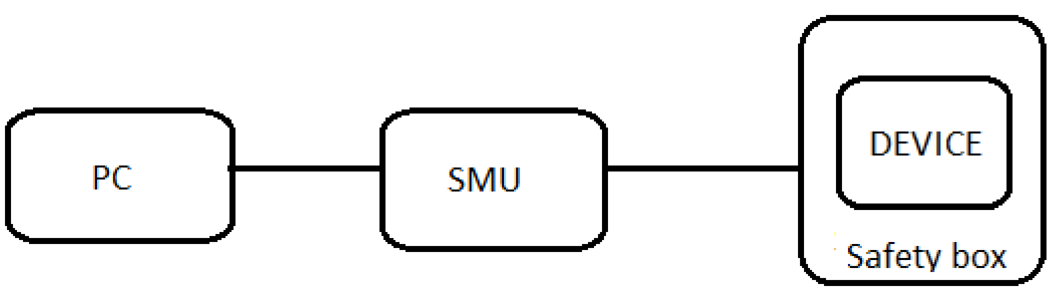


Figure 17.Sketch of the connection equipment.

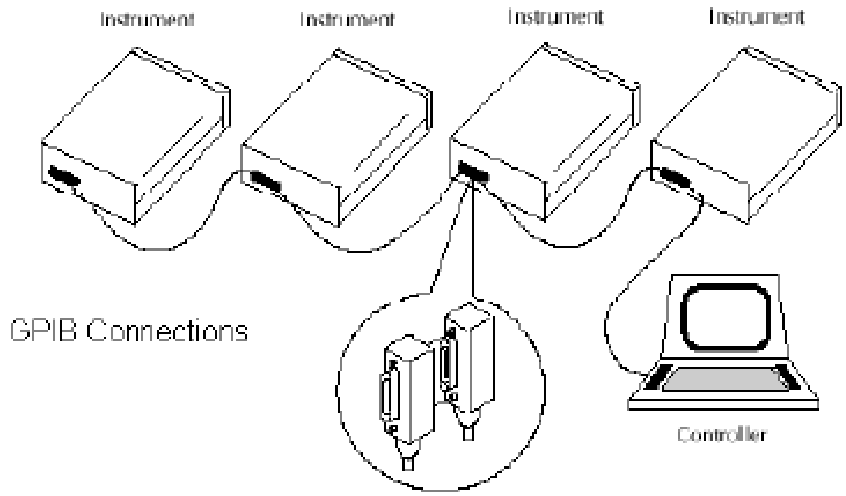


Figure 18. GPIB connections. [21]

The cabling configuration used to connect these power devices depends on the datasheet of each device because not all of the SoC devices have the same pinning configuration. This means that the cabling for polarizing must be configured to avoid wrong polarization and the device damage. In order to achieve good accuracy within the measurements, the four point measurement technique is implemented. The figure 19 shows the configuration for polarizing the MOSFETs using a four point measurement both in the drain terminal and gate terminal.

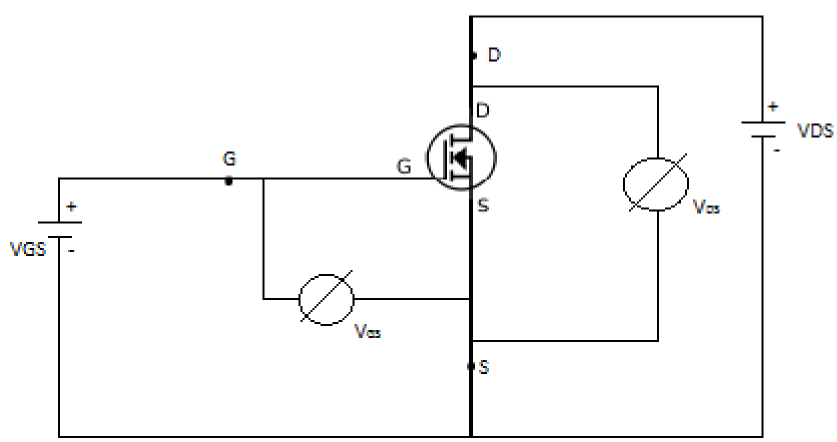


Figure 19.Four point measurement on a MOSFET.

6.1. Measurement Settings

As mentioned before, the software ARYLAB is able to configure the sources depending on the type of measurement. To make a measurement on power devices, it is first necessary to check its datasheet in order to know the working parameters of the device and its operation limits. One of these parameters is the drain current, which has to be lower than the maximum continuous value shown in the datasheet. However, this current depends of the temperature of the device because as the heat increases, the resistance and the current drop to a lower value.

As it is shown in figure 20, there are three time based parameters that are covered in a current width pulse. These parameters of measurement are the stabilization time, the Number of Power Line Cycles -NPLC- and buffer time, which need to be configured in the ARYLAB software before running the measurement.

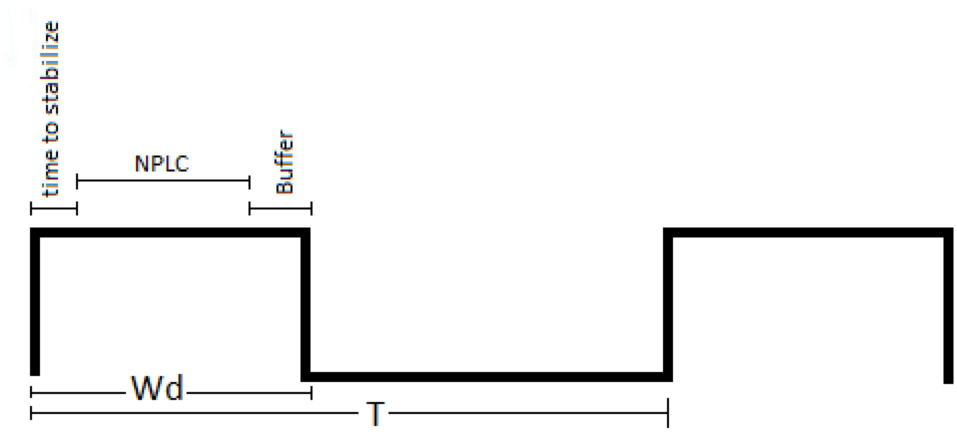


Figure 20. Current Pulse for testing power devices. [22]

NPLC indicates how long an input signal is integrated to obtain a single measurement. This parameter allows the source to adjust the tradeoff between accuracy and speed. Generally speaking, the longer a signal is integrated by the A/D converter, the more accurate the result is. For 50Hz power and 1 NPLC, a new value can be reported no faster than at 20 msec intervals.

Buffer time at the end of the pulse width is needed for storing data after the measurement. The time of stabilization is Wd (width) – (NPLC+Buffer), which the time where the current starts increasing

Other parameters that need to be adjusted in the software before measuring are the ranges of voltage that the device can withstand, such as gate voltage, drain voltage, drain current limit, gate current limit and also other values depending on the type of measurement implemented.

6.2. Measurement Startup

The power devices like MOSFETs, JFETs, and HEMTs are controlled by VGS voltage which allows that the current ID increases as long as VGS increases. The output characteristics obtained in these measurements come from applied voltages at the drain from -10v to 10v , and applied gate voltages which depend on the datasheet of each device and are important because they determine when the device gets in the active zone (ohmic zone where it starts to conduct current) or when it gets in the blocking zone (open circuit, VG <VTH). On the other hand, the drain voltage needs to be low in these measurements (between -10 [v] to10 [v]) in order to avoid the saturation zone (VDS ≥VGS-VTH), where much more power is dissipated.

To get the output characteristics of a Power Semiconductor Device, a sweep voltage at the gate and Drain is established by using of ARYLAB.

The figure 21, is a graphic created by the software ARYLAB and it shows the results of the output characteristics of GaN power MOSFET. In this measurement the parameters VGS and VDS were configured as follows: VGS = -10 [v] to 1[v] and VDS = -4 [v] to 4[v]. This type of GaN transistor has the behavior of decreasing the current that flows through the channel (drain-source) by applying a bias negative gate voltage and increases the current flow when gate voltage exceeds zero volts and continues rising, in other words; this transistor works in the same way as the depletion MOSFETS.

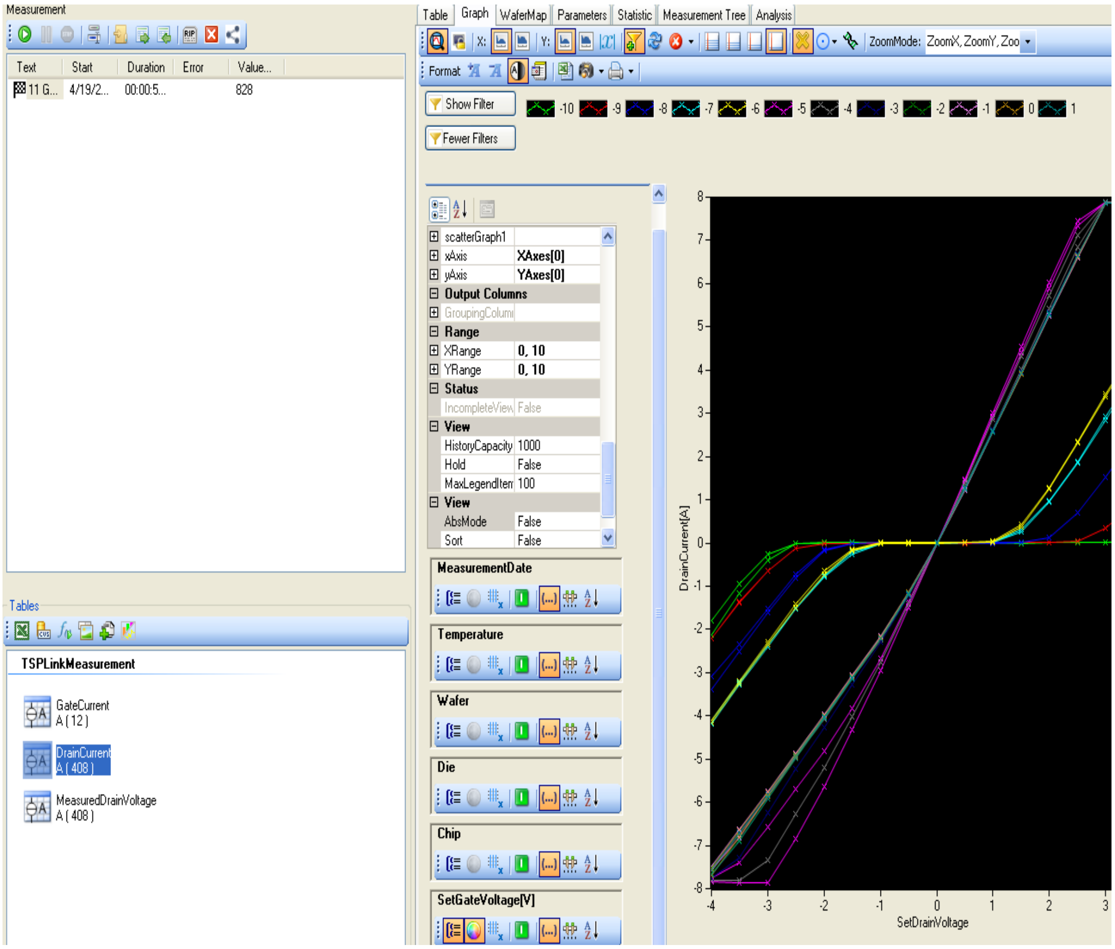


Figure 21 .Results of measurement of GaN transistor using ARYLAB.

The Y-axis in the figure 21 indicates the drain current at different values of gate voltage and the X-axis indicates the sweep Drain Voltage.

This interface shows the different options after the measurement, for example, it is possible to get a table with all the data collected during the measurement, as well as to export the data to an Excel file. This interface allows the gate current to be checked by changing the icon on the left side at the bottom; this can be done in different measurements according to the settings established.

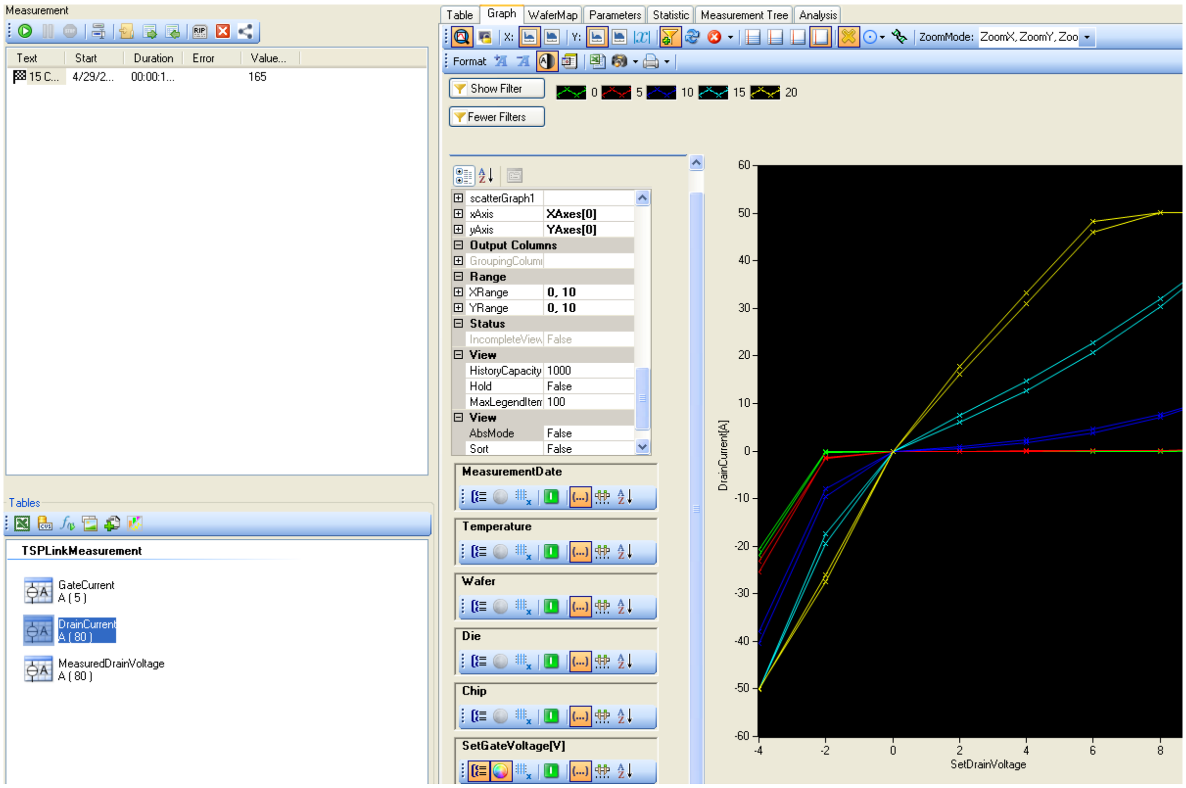


Figure 22 .Results of measurement of SiC transistor by using ARYLAB.

The figure22 shows the results of an output characteristics of Sic power device. VDS = 0 [v] to 10 [v] and VGS= 0 [v] to 20[v] were the parameters of this measurement. According to the graphic; this type of SiC transistor behaves as a MOSFET improved, which increases its current by applying positive bias gate voltage.

Instead of SoC Power Transistors, chip transistors on wafers made by Silicon Carbide (SiC) and Silicon (Si) were measured using a probe-station. The probe-station is formed by a hot plate where wafers are placed, test needles located on the top of the hot-plate, source- meters (SMU) and a high scale microscope. The connection of the sources (SMU) to the back side of the needles is possible by coaxial cables, hence they are able to supply voltage and current to the wafers.

The microscope is used for visualizing when the test needles are placed on the wafer. The movements of the hot plate setup are controlled by a joystick.

This microscope has a camera inside that aids in positioning between the needles and the wafer to be measured.

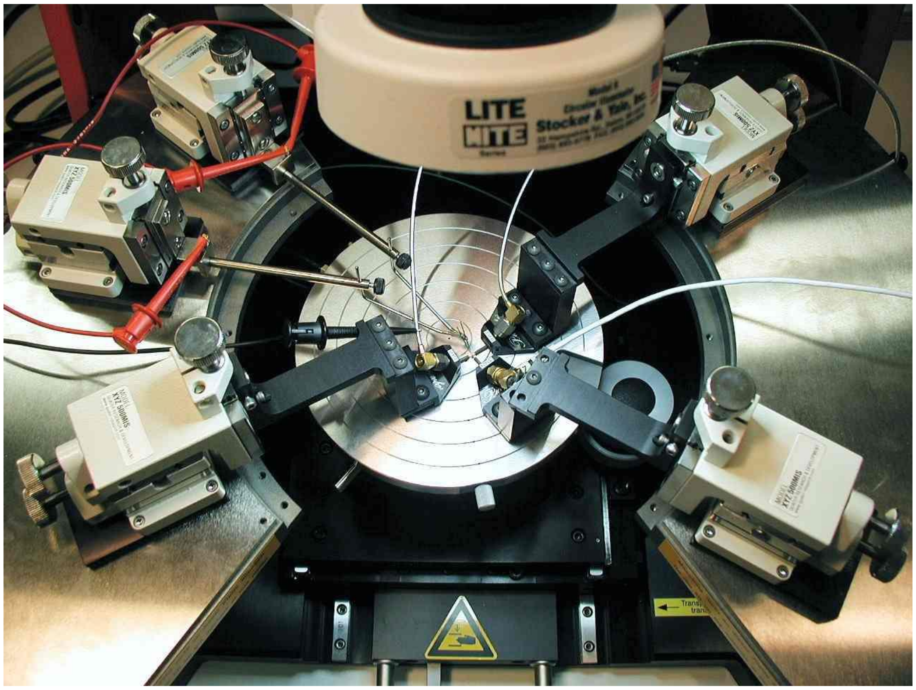


Figure 23. Probe station with a wafer on it and the test needles. [23]

One of the important aspects in this type of measurements is the high accuracy needed for placing the needles on the wafer, otherwise it could lead to wrong results.

By using the four point measurement on the wafers (chips) it is possible to observe the important characteristics and behavior of the chip structure, such as drain current ,the ON resistance of the device, and the leakage current between drain and source, which must be small for a good operation and large lifetime in the MOSFET.

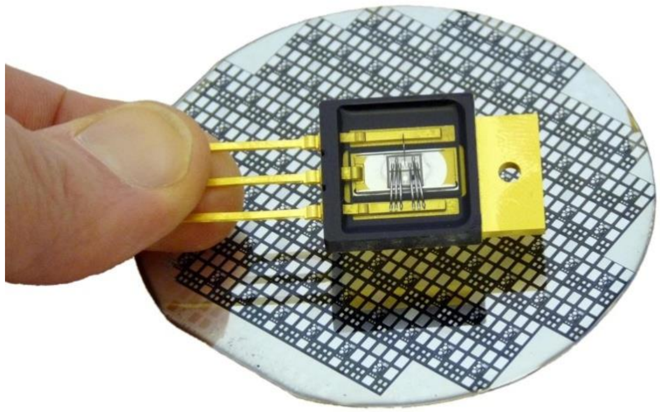


Figure 24. Power Device and wafer with chips on it. [24]

One of the additional features of this probe station is the capability of conducting tests on wafers at different temperatures in order to know how the chip is affected by the temperature change. It also has the ability to measure various chips (on the same wafer) by moving the hotplate setup using the joystick.

6.3. Hotplate Setup

The hot plate was designed to perform current-voltage tests over transistors with various high temperatures. Because all of these tests are conducted with high current and high voltages; the whole system was designed to be inside of a safety box to prevent any risk or harm to the user.

Figure 25. High power devices test box. [18]

The components coupled with the hotplate that form the temperature system are:

- Heater Cartridge
- Base structure of hotplate
- Temperature Sensor
- Controller EUROTHERM 2604

The design of the hot-plate consists of 2 brass blocks, which is an alloy that has good thermal conductivity and does not rust as easily as copper. The bottom block has a hole of circa 6 mm diameter, where the heater cartridge is inserted. The top block has a 1 mm hole to insert the temperature sensor.

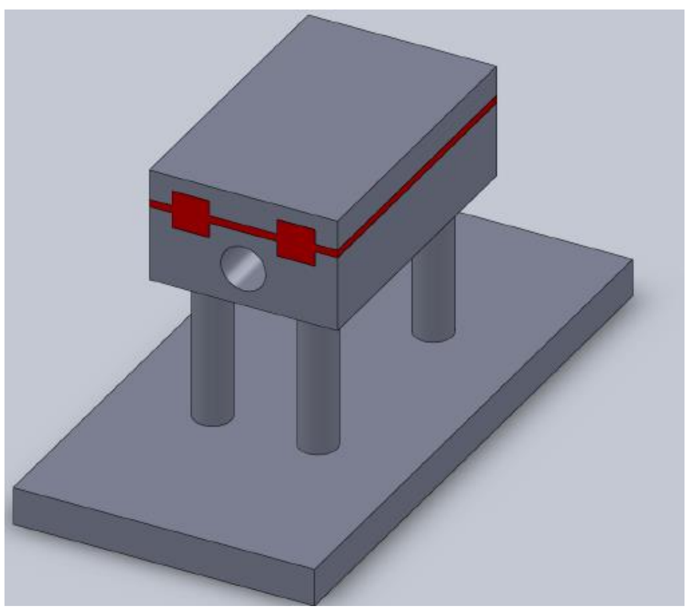


Figure 26.General diagram of the hot-plate model (external view).

Both blocks are separated by a calcium silicate layer (figure 27) with the goal of preventing any kind of electric interference (e.g. magnetic fields) with the measurement on the device.

The chip or SoC device to be tested is placed on the surface of the top block. The temperature is sensed by a thermocouple which is introduced into a small hole in the upper block, 5 mm under the device.

Figure 27.Calcium silicate layer. [25]

Once the design of the setup was ready, the hotplate, the cartridge heater, the controller and the temperature sensor were placed inside the high power security box.

In order to heat the system uniformly, the heater cartridge is place into a hole in the first block. This cartridge has 3 cm length and 6mm diameter and it can work with voltages until 240V AC and maximum temperature of 593°C Fiberglass is the type of temperature sensor used in this system and its physical measurements are 1 mm diameter and it can measure temperatures until 400°C.

The heater cartridge was chosen because of the high temperatures it can handle and also because of the amount of power per square centimeter it can supply.

Figure 28. Heater Cartridge

Figure 29. Temperature Sensor

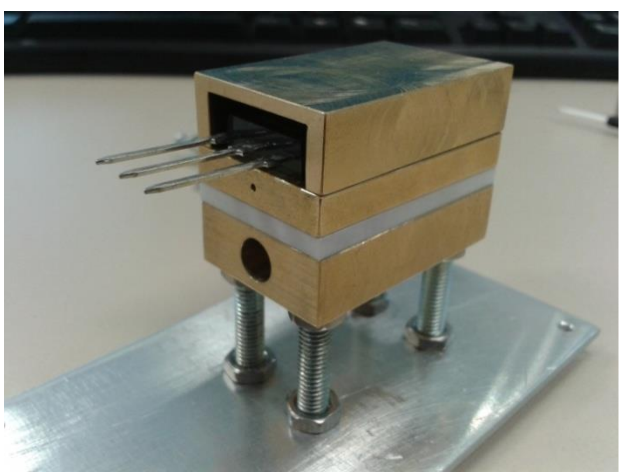


Figure 30. Complete Hot-plate system with a MOSFET inside.

Figure 30 shows the prototype obtained before it was introduced in the security box. In the image, it can be observed that the metal blocks are fixed to the aluminum base through screws. A second aluminum layer was added in parallel to the base in order to better dissipate the temperature in this part and to avoid possible problems inside the security box.

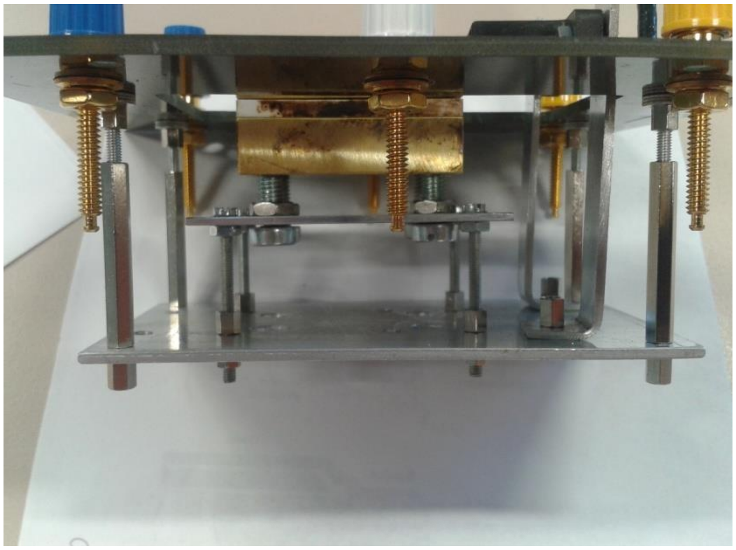


Figure 31. Hot-plate system with double aluminum base and adaptation layer for the box

The security box was adapted with temperature sensors located in different positions in order to establish the heat distribution along the hot-plate system. The measurements were done with and without the brass cover in order to analyze the influence of the cover on the temperature of the device.

The graphic number 32 shows a general sketch of the system inside the box.

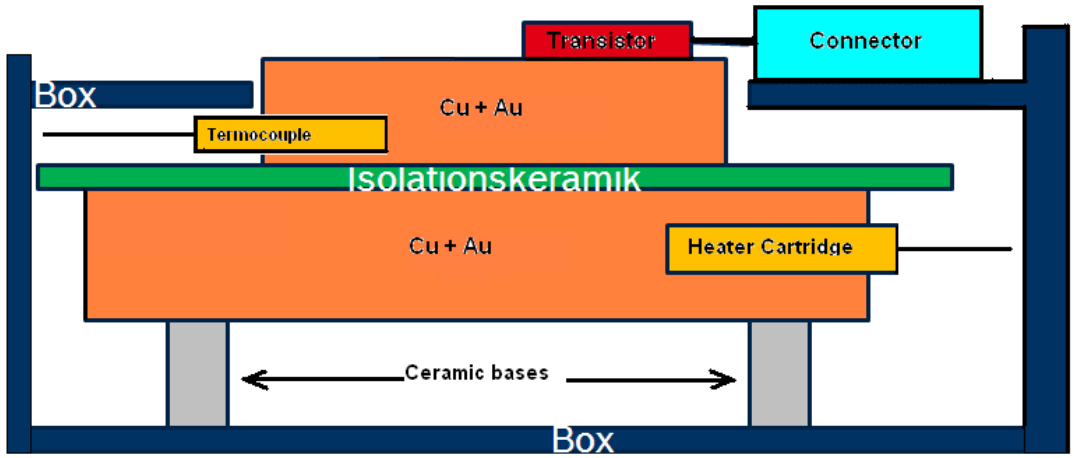
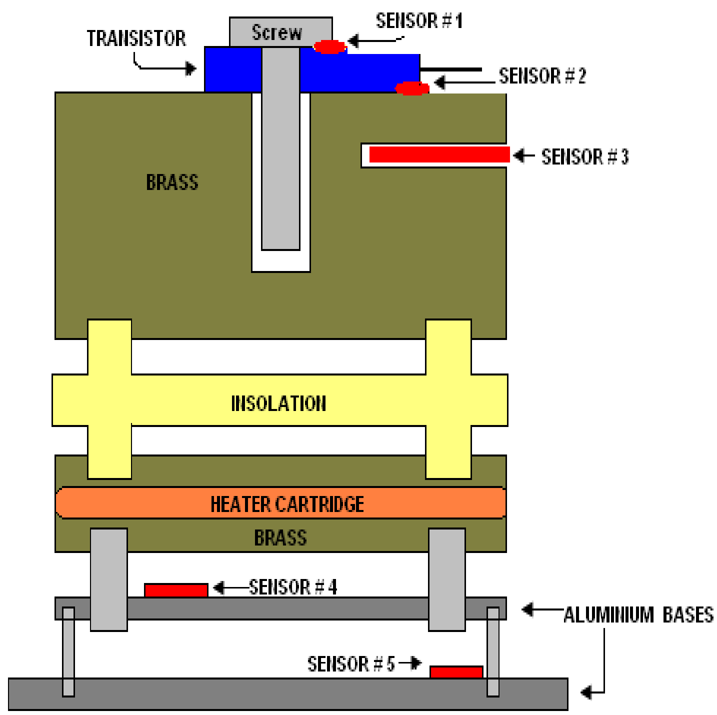


Figure 32.General sketch of the hot-plate test system.



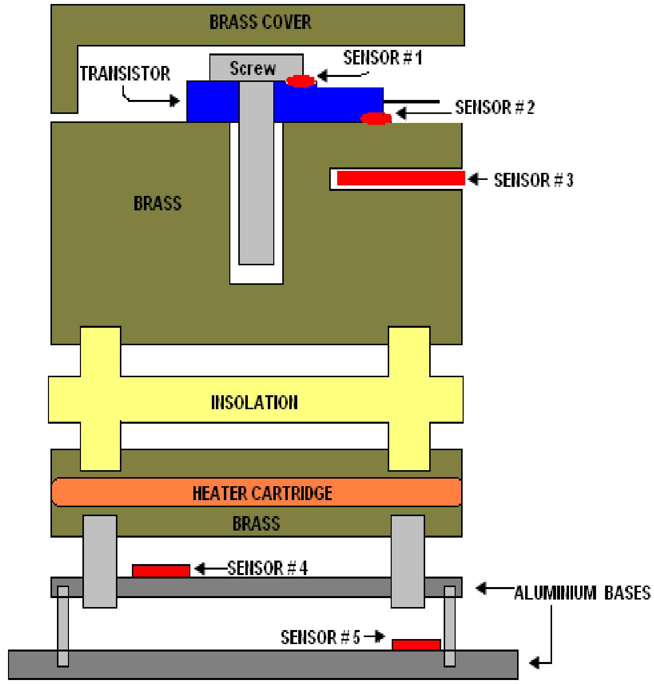


Figure 33.Sketch of the location of the sensors to measure the temperature in a system with and without brass cover.

Sensor	Set Point(°C)	Temperature	
		With brass cover (°C)	With out brass cover (°C)
Sensor # 1	250	227.4	182.3
Sensor # 2	250	242.4	231.3
Sensor # 3	250	250	250
Sensor # 4	250	141.9	141.9
Sensor # 5	250	59.9	59.9

Table1. Temperature chart of the different sensors located in the hot-plate system.

The module EUROTHERM 2604 was tested together with the hot-plate system. During this test, the behavior of the system, the rise time and settling time were analyzed. The overall temperature in the whole system is acceptable. However, there are some temperatures loses on the surfaces where the MOSFET is analyzed.

The controller has two basic modes of operation; Automatic and Manual Mode. The Automatic Mode the output is automatically adjusted to maintain the process value at the set point. In the Manual Mode the output can be adjusted independently of the set point.

The controller is mounted in an external box which is connected to the hot-plate system including the temperature sensors and the heater cartridge through connectors.

The module EUROTHERM 2604 controls the amount of current supplied to the heater cartridge. The controller switches a TRIAC, allowing the current flow through the cartridge until the main sensor reaches the set point value. Once the temperature set point is reached, the TRIAC is switched off and the hot-plate system start to cool down.

To calculate the Tuning values, a open loop test was done and the delay time L and the time constant T were measured by drawing a tangent to the step response at its point of inflection and noting its intersections with the time axis and the steady state value. Then the control parameters were obtained based on according to the table 2.

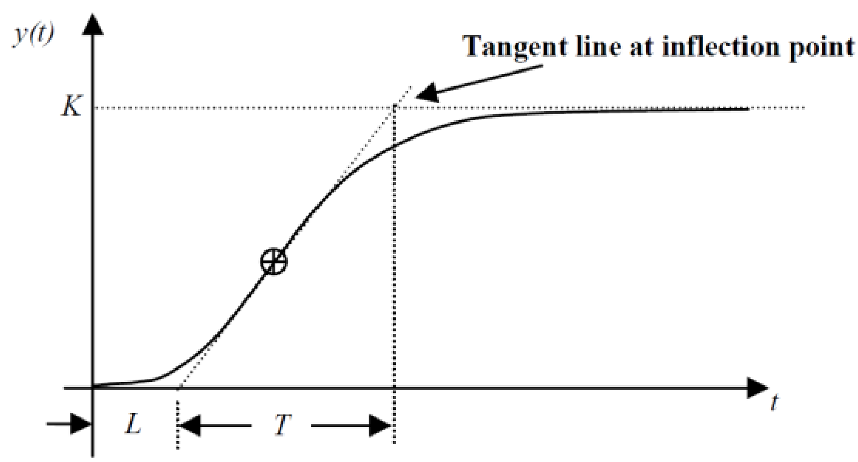


Figure 34. Response Curve for Ziegler-Nichols [26]

However, this control is not very precise and after testing the controller with the new parameters, a big overshoot was seen with the step response leading to a slight modification of the parameters using trial and error technique.

PID Type	*Kp*	*Ti*	*Td*
P	T/L	∞	0
PI	0.9(T/L)	L/0.3	0
PID	1.2(T/L)	2L	0.5L

Table 2. Ziegler-Nichols Parameters [26]

After the controller was configured and using the ARYLAB Software, SiC and Si, GaN based MOSFETs were put on the hot-plate system and their terminals were connected to the high current source. Current and voltage tests were done while varying the temperature and the change in current behavior according to the temperature was observed.

Figure 35 and 36 show some of the obtained results of a SiC MOSFET. As the temperature in the hot-plate was increasing, the current through the drain was decreasing which means that the Drain-Source resistance was increasing.

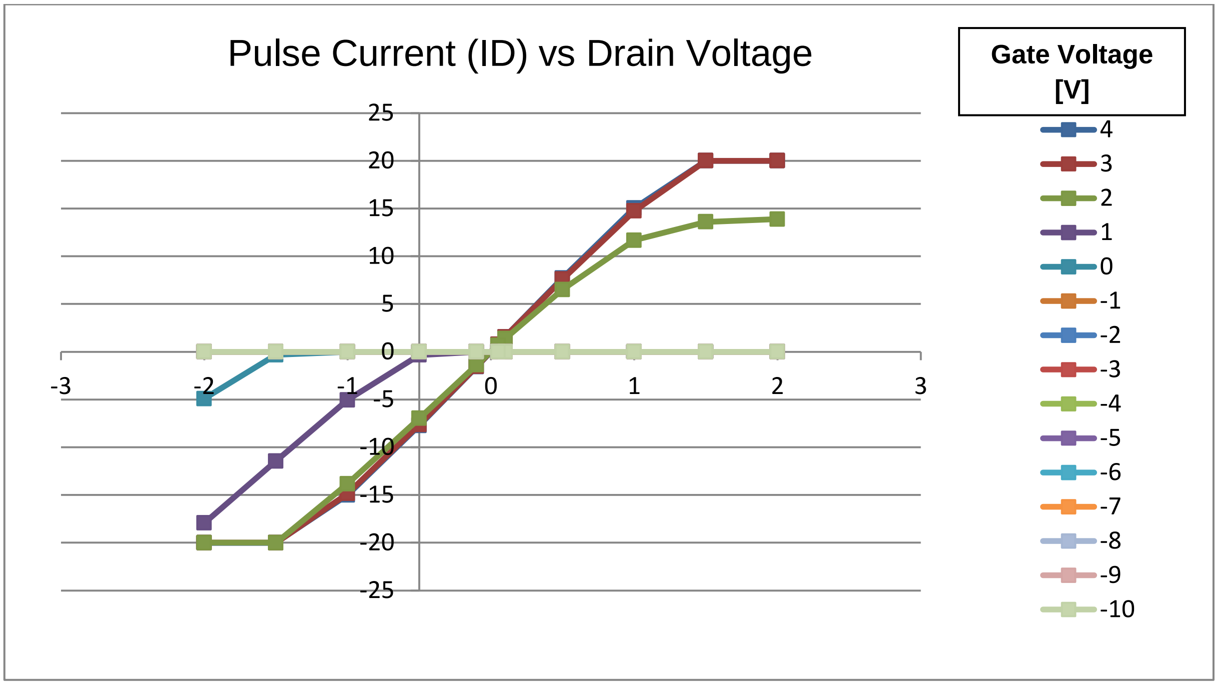


Figure 35. Drain Current vs. Drain Voltage with different gate voltages at 25°C.

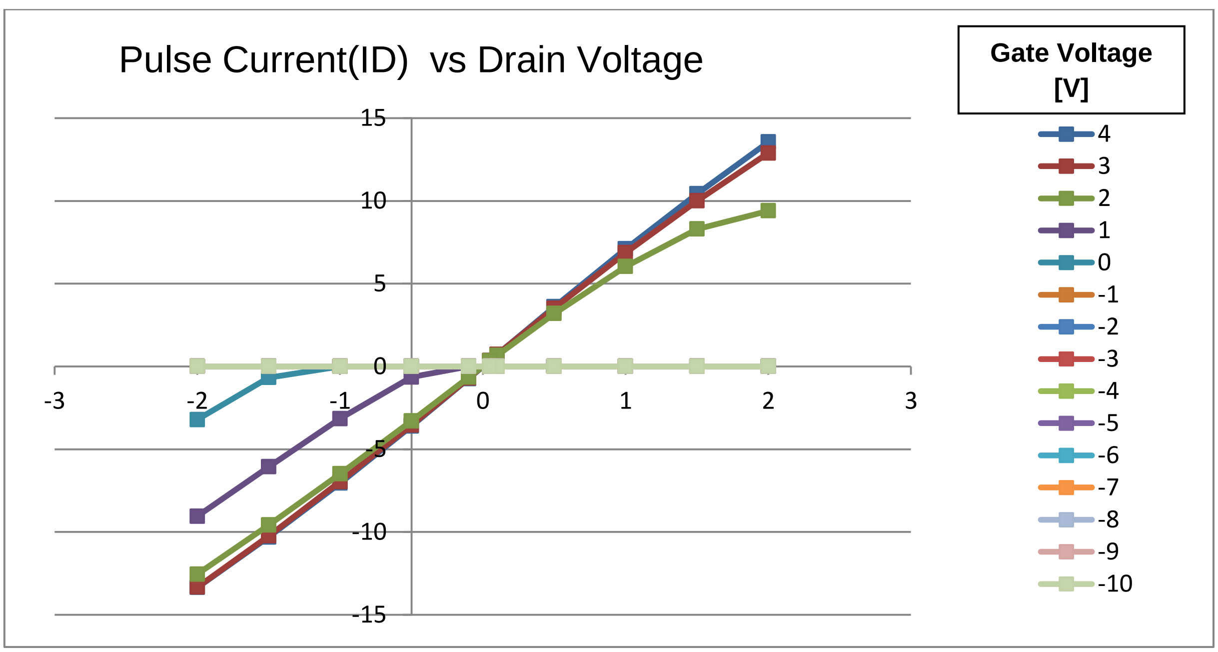


Figure 36. Drain Current vs. Drain Voltage with different gate voltages at 200°C.

7. RECOMMENDATIONS TO THE COMPANY

The following recommendations are just possible improvements that could be implemented to lead for a better development of the tasks.

- Organization in the laboratory of the measurement equipment of power semiconductors devices in order to get a suitable work space for performing the measurements.

- Implementation of a second safety box for testing semiconductors devices in order to get easy disposition of the equipment when a measurement is needed.

8. ANALYSIS OF RESULTS AND CONCLUSIONS.

Power Semiconductor devices were compared by performing measurements at different temperatures and determining how the resistance (RON) changes at high temperatures and how it influences the behavior of the device.

RON resistance of a MOSFET transistor varies by temperature and can get a positive or negative temperature coefficient according to the value of VGS voltage applied.

The following chart shows the transfer characteristics of a MOSFET-based on silicon carbide at different temperatures with a constant drain voltage of 100mV.

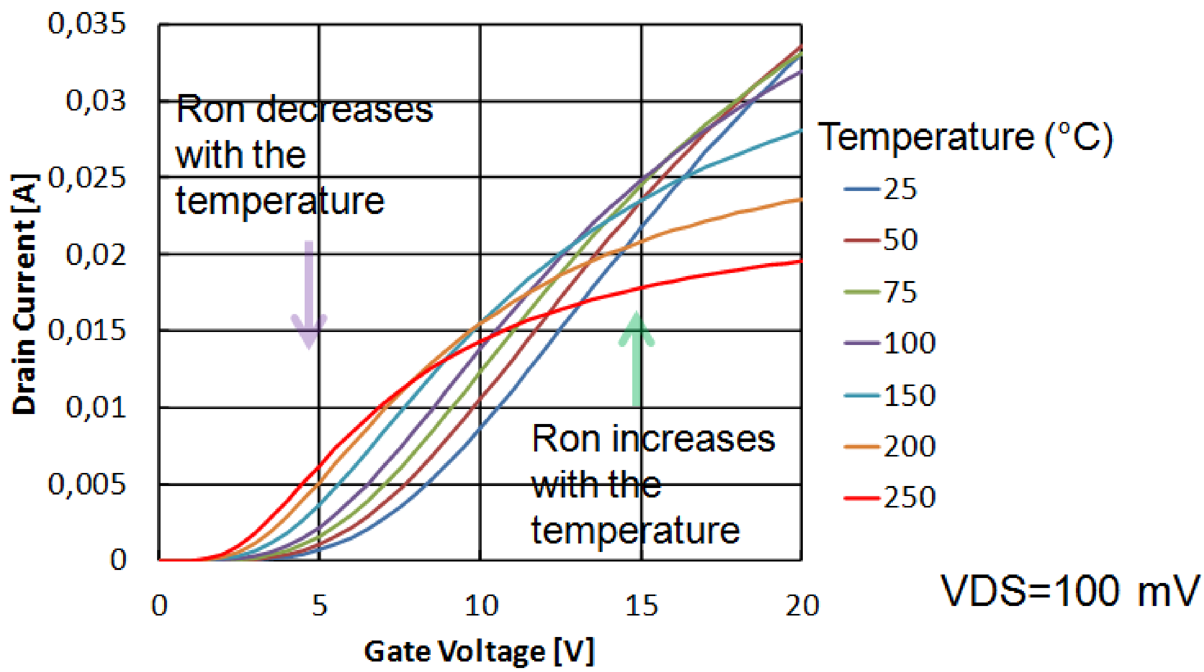


Figure 37. Transfer curve SiC –MOSFET

As the figure37 shows, the temperature coefficient in RDS changes from negative to positive when VGS increases. When the voltage at the gate is low the concentration of electrons in the channel is minor (majority of electrons will be in the traps) so the current is also low. When the temperature increases; the electrons in the traps are crashed by photons and they jump from the traps to the conductive band; which means that the current increases due to the temperature increasing (negative coefficient).

If the gate voltage is increased, the amount of electrons in the channel is also increased, allowing more flow of current through the channel. When the temperature is increased the current goes down due to the scattering effect, which occurs when the electrons are forced to divert its trajectory due to the impacts received by photons.

After measuring and collecting the data of output characteristics from the power devices, it was necessary to compare how the on-resistance (RON) changed in each device at different temperatures and how the behavior of current performed for the devices that were tested.

The following figures show the highest Drain current versus Drain voltage according to Maximum gate voltage (VGS) for each measurement on the power semiconductor device at different temperatures.

The figures 38-40 show the slope of the drain current for different transistors giving the possibility to determine how the on-resistance (Ron) behaves depending on the material of the devices.

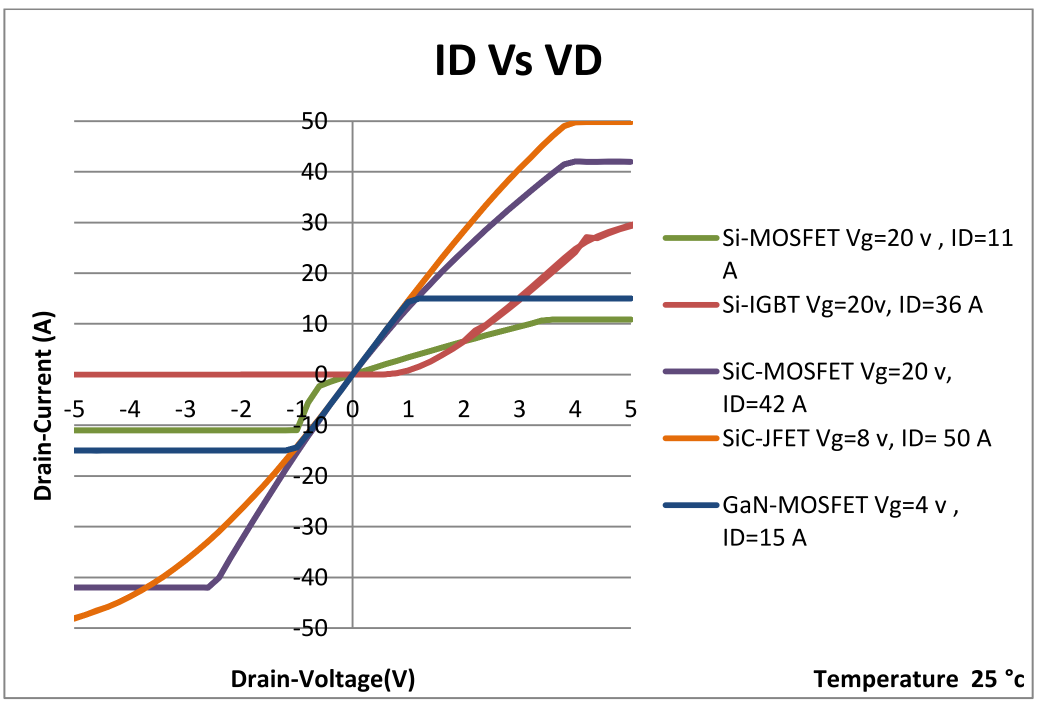


Figure 38. Output Characteristics of Different Power Devices at Room Temperature.

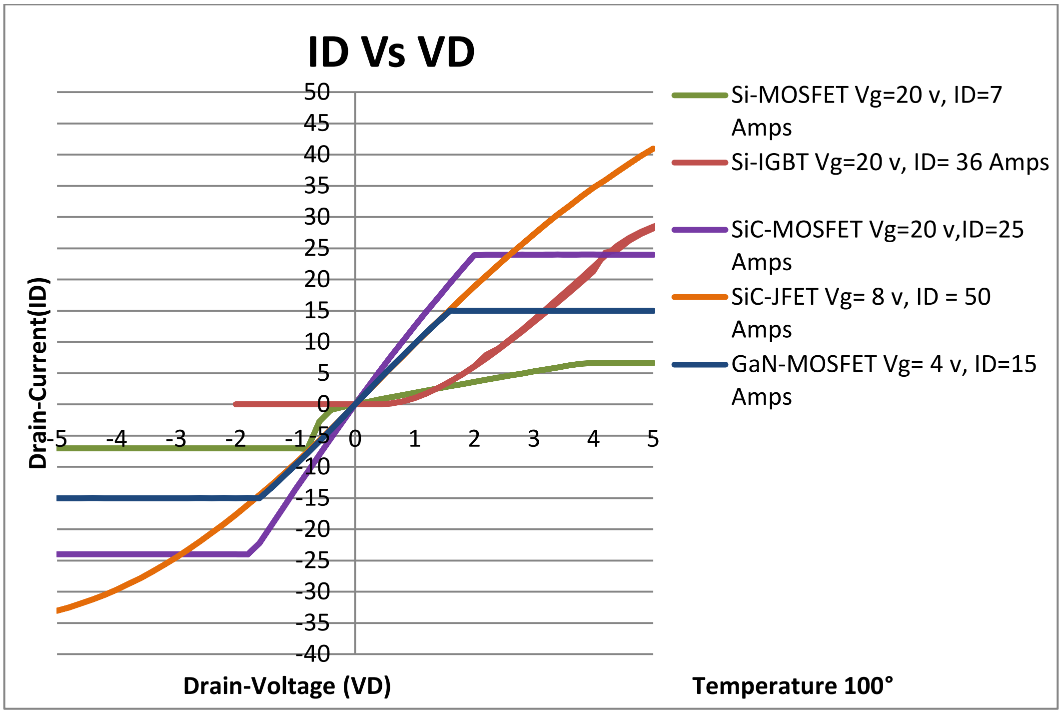


Figure 39. Output Characteristics of Different Power Devices at 100˚C.

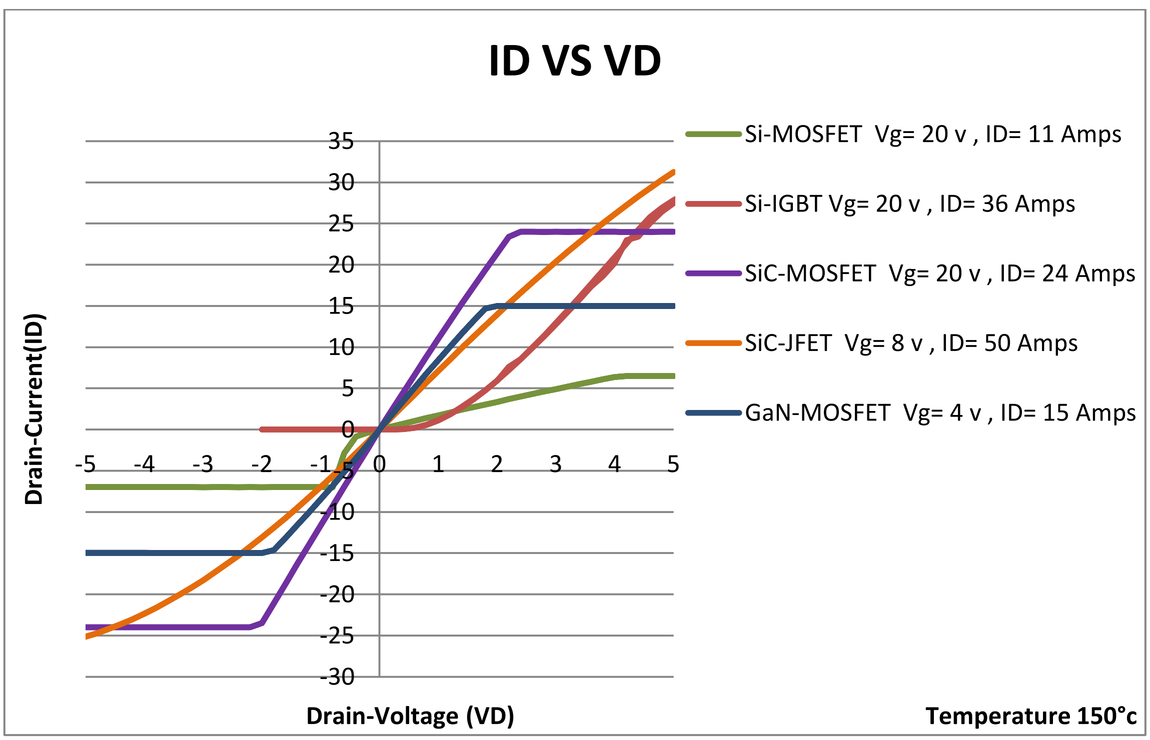


Figure 40. Output Characteristics of Different Power Devices at 150 ˚c.

The Drain- Source Resistance (Ron) was determined by taking a Drain Voltage of 1 [V] divided by the current for the highest gate-voltage (VGS) applied.

The following graphic shows the change in percentage of the resistance (RON) against the temperature.

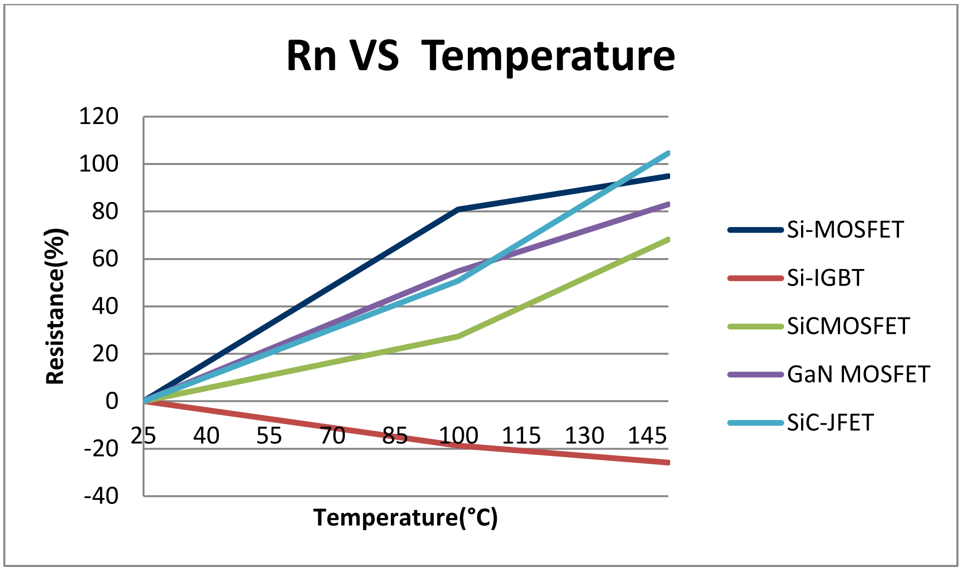


Figure 41.Dependence of activation resistance (Ron) with temperature.

The figure41shows different behaviors of the resistance(RDSON) of power devices as a SiC-JFET, GaN MOSFET, Si-IGBT, SiC- MOSFET and Si-MOSFET. Considering a constant flow current, if the resistance RDSON increases because of temperature; the power losses will also increase.

Device	RON at 25 ˚C. [mΩ]	RON at 100 ˚ C. [mΩ]	RON at 150 ˚ C. [mΩ]
Si-MOSFET	296,919	537,089	578,597
Si-IGBT	1219,46	991,69	903,75
SiC-MOSFET	89,56	113,991	150,632
GaN-MOSFET	140,605	217,633	257,376
SiC-JFET	68,74	103,66	140,61

Table 3.ON-Resistance (RON) of different power semiconductor devices.

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