



Interface Application Development of an Electrometer using LabVIEW Programming to Study Current-Voltage Characteristics of Semiconductor Devices

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By

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Declaration

I do hereby declare that the thesis titled “Interface Application Development of an Electrometer using LabVIEW Programming to Study Current-Voltage Characteristics of Semiconductor Devices” is submitted to the Department of Mathematics and Natural Sciences of BRAC University in partial fulfilment of the Bachelor of Science in Applied Physics and Electronics. This is my original work and has not been submitted elsewhere for the award of any other degree or any other publication. Every work that has been used as reference for this work has been cited properly.

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Abstract

A transistor is an electrical device made of semiconductor material that is used for operations such as amplification and switching of electronic signals and electrical power. Transistors, such as Bipolar Junction Transistor (BJT) and Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET), are used extensively in electrical circuits in applications for a diverse range of electrical devices and systems from mobile phones to computers. In order for a transistor to be used effectively and perform functions as amplifiers and switches, it is important to know its electrical properties and operational specifications as it needs to be adaptable to the circuit's current/voltage limits and other operating conditions. An electrometer, which is in fact a specialized measuring instrument with numerous applications, can be used to measure the current readings of a transistor subjected to different levels of voltages. For the electrometer to function most efficiently, an application is made using LabVIEW software which allows for its remote access to accomplish functions such as conducting a voltage sweep (applying incremental voltages after short delays and recording the current). This simultaneously decreases the data acquisition time drastically and eliminates the factor of human error completely while taking readings, as the electrometer is software-controlled. Such an application, coupled with the electrometer itself, promotes an efficient way of making a voltage sweep and displaying a graph of the input and output from the data obtained simultaneously. This enables the characterization of the transistors and the data can be used to identify whether the transistor, with its own specifications and boundaries, can be used in a particular system or circuit.

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Chapter-1: Introduction

A transistor is a semiconductor device used to amplify or switch electronic signals and electrical power, as stated previously. It is composed of semiconductor material usually with at least three terminals for connection to an external circuit. A voltage or current applied to one pair of the transistor's terminals controls the current through another pair of terminals. Because the controlled (output) power can be higher than the controlling (input) power, a transistor can amplify a signal.

Such transistors are used mainly at higher currents than the electrometer I used for taking measurements allows, whose upper current limit is about 10-11 mA. Thus I focused on identifying transistor properties at lower currents. This allowed for higher accuracy and precision for lower ranges of current, and so the amplifying and/or switching operations of each transistor could be monitored more thoroughly just as the transistor is switched to the “ON” state. So, my work was focused on how the transistors behave right at the initial stages where only a little current has started to flow, as opposed to higher current ranges. This proved to be especially useful since the amplifying and switching actions can be identified from a much earlier stage, so specifications for more sensitive circuits can be made more accurately; which cannot be made as effectively for low-current circuits using conventional measuring instruments.

Transistors of different types (JBT, JFET, MOSFET, etc.) come with different specifications and different working conditions and methods. So learning how each specific transistor behaves under different conditions is critical to identify its operational parameters and boundaries. With that knowledge, one can wisely choose which transistors are more suitable to be elements in a specific circuit. This increases that circuit's overall effectiveness in performing tasks like switching and amplifying signals/input, which are critical in most operations.

The transistors used for my study are PNP BJT (Bipolar Junction Transistor), and MOSFET (Metal-Oxide Semiconductor Field-Effect Transistor) – whose characterization and graphs are shown and explained further on.

1.1 PNP

PNP is one of two forms of BJT (Bipolar Junction Transistor), the other being NPN. BJTs are special in that conduction occurs through both majority and minority carriers. A PNP transistor is formed by placing a n-type semiconductor in between two p-type semiconductors, thus forming a p-n-p junction. This construction produces two p-n junctions: a base-emitter junction and a base-collector junction, separated by a thin region of semiconductor known as the base region.

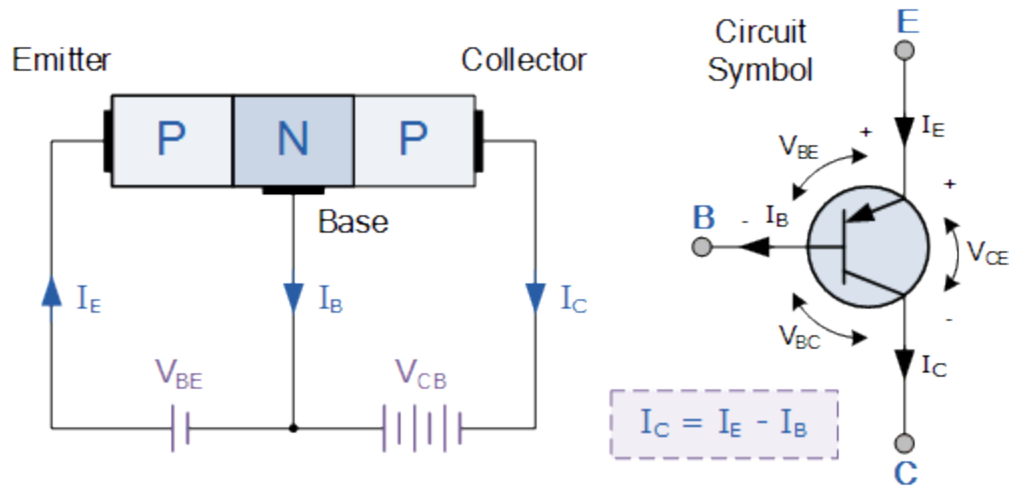


Fig 1.1: PNP symbol and structure

BJTs have three terminals, corresponding to the three layers of semiconductor—an emitter, a base, and a collector. They are useful in amplifiers because the currents at the emitter and collector are controllable by a relatively small base current. This is essentially the basis of my work in the characterization of such semiconductor devices – to find the change in output current due to input voltage, for certain incremental levels of base current/voltage supplied. Following the figure above, connections were made to the collector and emitter with the electrometer’s combined source-meter (reading current and supplying voltage simultaneously). The base voltage was controlled using a simple DC voltage source. Also from the figure, we can see that change in the base current has a direct effect on the output current to be measured. This base current is dependent on the base voltage applied across it, as well as the barrier voltage (V_{BE}) required to allow current to flow through the base terminal. The barrier voltage is the amount of electromotive force required to start current through the p-n junction. This barrier voltage can be obtained from a device’s specific datasheet, or can be assumed to be 0.7V in the case of silicon. This suggests that the collector current (I_C) can only pass through if a

base voltage is provided that is greater than 0.7V. Essentially, the base-emitter acts as a basic silicon diode. This was further proved experimentally, as the I-V curves for base voltages below 0.7V showed close to zero current at all source voltages (V_{CC}). [1]

The data obtained from the electrometer through the software developed would shed light on the characteristics of a given semiconductor device by analyzing its I-V graph for different applied base voltage/current. Essentially, it should give an idea as to whether a given device can be used as an effective amplifier or switch, if its operation is adjustable with a very small base current.

1.2 MOSFET

A MOSFET, or Metal-Oxide Semiconductor Field-Effect Transistor, is a type of transistor used for amplifying or switching electronic signals which has an insulated gate whose voltage determines the conductivity of the device. The MOSFET is effectively a four-terminal device, whose terminals are – source (S), gate (G), drain (D), and body (B). The body (or substrate) is often connected to the source terminal, making the MOSFET a three-terminal device similar to other field-effect transistors.

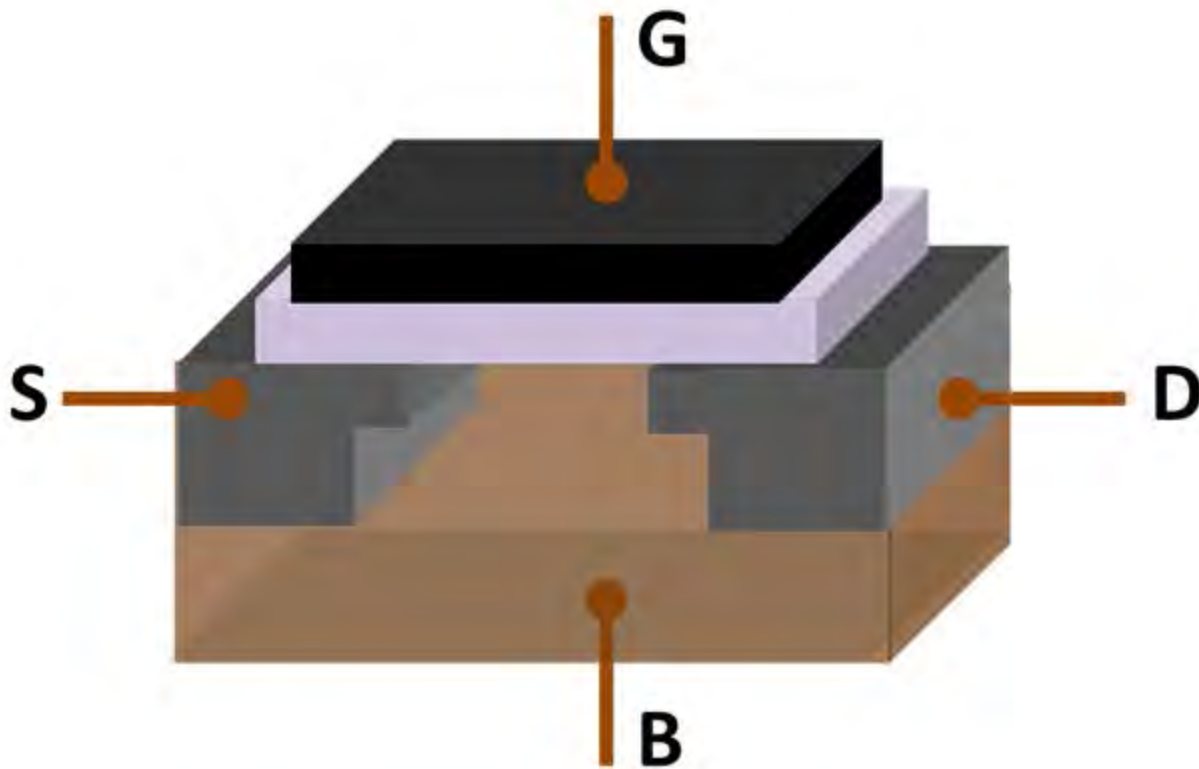


Fig 1.2: Internal structure of a MOSFET

MOSFETs are unipolar transistors, and act as voltage-controlled current devices. The electrode gate, as can be seen from the figure above, has a thin metal-oxide layer sandwiched between a semiconductor and a metal. When a gate voltage is applied, an electric field is created which in turn controls the amount of current that can pass through the drain to source. The gate input is electrically insulated from the main current-carrying channel. In other words, this metal-oxide gate electrode is insulated from the main semiconductor n-channel or p-channel by a thin layer of insulating material, most commonly silicon dioxide (or glass). This is the main difference between a MOSFET and a junction FET (JFET). [2]

This thin insulated metal gate electrode can be thought of as one plate of a capacitor. The isolation of the controlling Gate makes the input resistance of the MOSFET extremely high way up in the Mega-ohms ($M\Omega$) region thereby making it almost infinite.

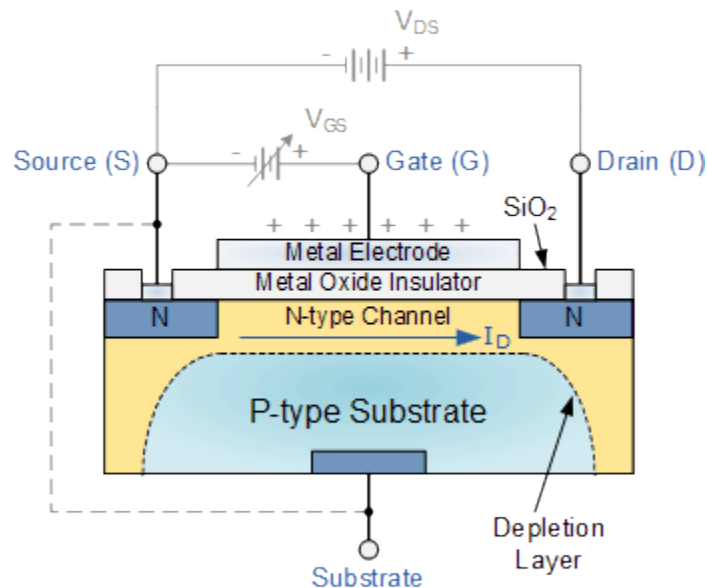


Fig 1.3: Electrical connections and structure of a MOSFET

As the gate terminal is isolated from the main current carrying channel no current flows into the gate and just like the JFET, the MOSFET also acts like a voltage controlled resistor where the current flowing through the main channel between the drain and source is proportional to the input voltage.

As mentioned previously, the “field-effect” in the name refers to the fact that the electric field created at the gate affects the passage of current through the drain-to-source (D-S) channel. Other than amplifying this channel current (I_D), the field also dictates whether any current can

pass through or not; effectively making the MOSFET act as a switch. In terms of how this switching works, MOSFETS are of two types:

- Depletion Type – the transistor requires the Gate-Source voltage, (V_{GS}) to switch the device “OFF”. The depletion mode MOSFET is equivalent to a “Normally Closed” switch.
- Enhancement Type – the transistor requires a Gate-Source voltage, (V_{GS}) to switch the device “ON”. The enhancement mode MOSFET is equivalent to a “Normally Open” switch.

The symbols and basic construction for both configurations of MOSFETs are shown below:

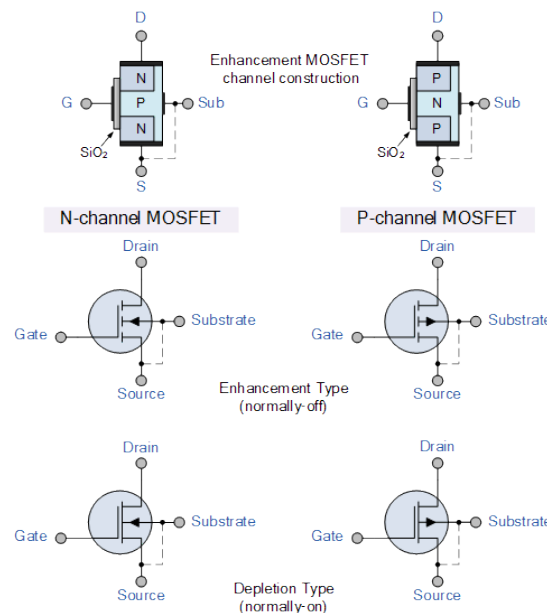


Fig 1.4: Basic construction of n-channel and p-channel MOSFETS for both enhancement and depletion mode

For my particular study I chose an n-channel enhancement mode MOSFET, whose properties are going to be further described. [3]

Both the Depletion and Enhancement type MOSFETs use an electrical field produced by a gate voltage to alter the flow of charge carriers, electrons for n-channel or holes for p-channel, through the semiconductive drain-source channel. The gate electrode is placed on top of a very thin insulating layer and there are a pair of small n-type regions just under the drain and source electrodes.

1.3.1 Electrometer

An electrometer was quite necessary for the work at hand, specifically for the characterization and identification of the electrical properties of a given sample of material, or a specific type of transistor. The electrometer I made use of was the Keithley 6517b high-resistance source-meter. In its basic application, it works similar to a conventional multi-meter. By making proper connections it can measure current, voltage, resistance, charge, etc. from a closed circuit. However it sets itself apart from other simpler measuring instruments due to its complexity. This specific model allowed me to measure very low currents for a given voltage through a highly resistive material. In fact it can measure currents as low as 10^{-12} A, or 1 pico-ampere. This sensitivity to detect low currents precisely was essentially the reason due to which

an electrometer was an essential part to the overall setup of my work. It is also important to note that the electrometer has its own built-in voltage source for measurement purposes, eliminating the need for an external supply.

Other than being a highly sensitive and precise measuring tool, the electrometer is able to scan a multiple number of readings it has made and store it for further inspection. It was due to this, and the fact that the electrometer is programmable through a computer interface, that I worked on creating a PC software. This software would allow me to give specific instructions to the electrometer to apply different voltages and measure the current subsequently, effectively performing a voltage sweep, and then recording all the data regarding the voltage, current, and resistance. Depending on the material or device being studied, this data provides an insight into its electrical properties. Understanding these properties are vital to know exactly the kind of applications it can be utilized. A detailed work behind the software development will be discussed later on.

1.3.2 LabVIEW

LabVIEW, short for Laboratory Virtual Instrument Engineering Workbench, is a development platform that creates an environment to accomplish tasks such as data acquisition, instrument control, industrial control and automation. There are two main ways of creating a

program in LabView – dataflow programming, and graphical programming. The former involves the use of the programming language named “G”. Execution is determined by the structure of a graphical block diagram (the LabVIEW-source code) on which the programmer connects different function-nodes by drawing wires. These wires propagate variables and any node can execute as soon as all its input data become available. The graphical programming aspect of the software is related to the creation of user interfaces (front panels) into the development cycle.

The front panel is essentially what the end-user interacts with to give commands to the connected instruments, once the program is completed. It houses all the buttons, numeric boxes, graphs, etc. that anyone other than the developer can use and understand. Each of the front panel’s elements either takes data to be processed for giving instructions to the electrometer, or to display obtained data from the instrument to the user. Thus, the front panel is merely a user-friendly interface for users, and the actual functions and operations of the program are created on the back panel.

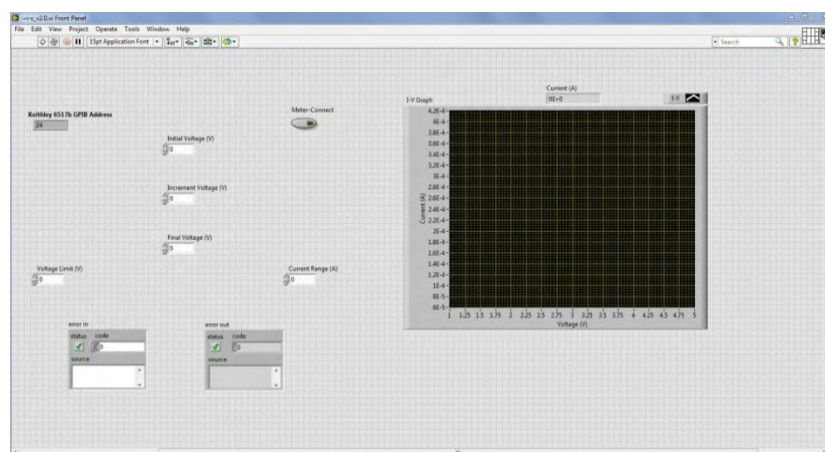


Fig 1.5: Front panel of my LabVIEW program

All of the objects placed on the front panel will appear on the back panel as terminals. The back panel also contains structures and functions which perform operations on controls and supply data to indicators. All these elements have to be created on the back panel and then calibrated, and then the corresponding element will appear on the front panel in the forms shown in the figure above. Each of these structures has to be connected to each other in a logical manner for a specific task to be performed. Irrespective of size, each of these programs is called a VI, and a larger VI may be composed of multiple smaller VIs, also called sub-VIs.

Chapter-2: Experimental Design

The first stage of the studies was utilized on setting up the experiment and the relevant apparatus for it. This included careful understanding of the mini-coater and then using it to fabricate a layer of thin metal film on the glass slide. This fabricated slide with its electrodes would later be used to characterize the electronic properties of a sample material. Application of silver solder paste on the slide had to be done meticulously in order to make direct connection of a wire to the slide's electrodes, making sure that the process does not allow the film on the slide to be scraped off. These wires, which are fixed to each of the slide's electrodes, are then connected to the electrometer to allow measurements to be taken. The electrometer was a feature of the studies that took the bulk of the time; as setting it up to take measurements, preparing it to allow computer interfacing, and then directly controlling the components via software created specifically for the purpose at hand proved to be challenging and time-consuming. The details will be discussed below.

2.1 Introduction to Micro-device Fabrication

2.1.1 Base Medium Selection: Silicon

For the purposes of the experiment, a thin slide of very high resistance was required which would serve as the base on which the electrode films were to be placed. At first, I started work on thin shiny silicon wafers. It would have been more convenient to use silicon slides rather than anything else, since the deposition of metal on it can be carried out more easily and without much difficulties. However, upon further testing and current-voltage measurement analysis, the silicon wafers were deemed to not have the levels of resistance that was necessary for me. Data was recorded for two sample silicon wafers, taking note of its mass, dimensions and resistance values for low voltages:

	Wafer-1	Wafer-2
Mass	0.96 g	0.81 g
Length	5.5 cm	4.8 cm
Width	4 cm	4 cm
Thickness	206 μm	200 μm
Resistance	2.2 kΩ	3.5 kΩ

Fig 2.1: Obtained data for two silicon wafers, emphasizing their resistance values

My supervisor recommended the resistance of the base should be about 1 G Ω . But as we can see the resistance is not appreciable enough for the voltage levels that we are going to operate with.

A workaround for this would be if the silicon slides could be oxidized, as silicon dioxide is the main constituent of glass and possess significantly more resistance compared to silicon. Many trials were done comprising of putting the silicon slides in a rapid thermal annealing (RTA) furnace to achieve oxidization. In the RTA process, the sample is heated to a high temperature and then cooled rapidly. Factors like heating duration, peak temperature, and pressure were tweaked in order to find the suitable conditions for oxidization of the silicon wafers. A suitable condition was found to be around a temperature of 850°C and a heating duration of about 2 hours. But the trials proved to be unsuccessful as the data obtained gave mixed results, with resistance from different slides varying drastically. A possible reasoning behind this was thought to be impurities in the vacuum chamber of the furnace diffusing into the silicon wafer to create regions of varying resistances. The data showing the change in resistance before after heating in furnace is given below:

	Wafer-1	Wafer-2
Before heating	2.2 k Ω	3.5 k Ω
After heating	2.1 k Ω	1.8 k Ω

Fig 2.2: Resistance values of the silicon wafers before and after heating in the furnace

2.1.2 Base Medium Selection: Glass

Since the silicon slides could not serve the purpose, I moved on to thin microscope glass slides. It was chosen owing to its convenience in availability and having negligible electrical conductance. Another factor to take into account for the base was its thickness. For the gate voltage to be supplied to the underside of the slide, its thickness would have to be appreciable thin. A mechanical thickness meter was used to measure the thickness at different points and an average was obtained, whose data are given below:

Middle	Left end	Right end	Average
988 μm	989 μm	985 μm	987.33 μm

Fig 2.3: Microscope glass slide thickness at various points

Having consulted with my supervisor, it was decided that I would have to use a much thinner specimen compared to the microscope slides. After carefully looking at the alternatives, I decided on making use of cover slips. These are slides of glass much thinner than microscope slides, and are usually placed over an object to be viewed by a microscope. These slides had to be handled even more carefully owing to their significantly minuscule thickness. Before deposition of the metal film on it could be started, measurements of its thickness were taken for future reference:

Middle	Left end	Right end	Average
148 μm	149 μm	148 μm	148.33 μm

Fig 2.4: Cover slip thickness at various points

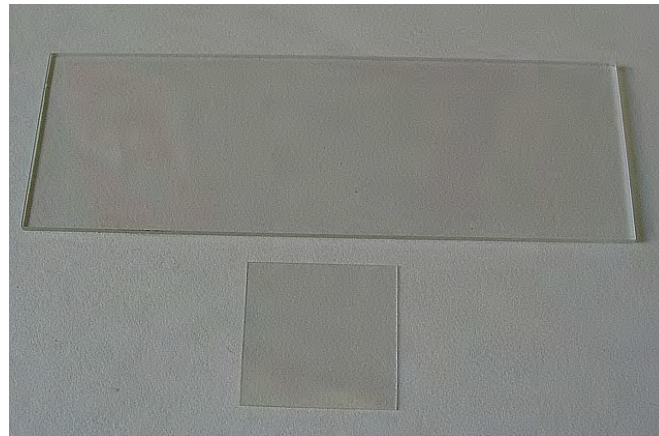


Fig 2.5: Comparison between the sizes of a microscope slide (top) and a cover slip (bottom)

2.1.3 Deposition Masking

After having selected cover slips to serve as the base of our transistor, I proceeded to work on the mask that would be placed over the slides, to create the desired metal pattern on it after evaporation. It was important to cover the sides of the cover slips since its opposite surfaces would have to be kept separate to prevent electrical connectivity between them. This was done using folded aluminium foil, which would prevent the deposition of metal along the sides.

For the purpose at hand, it was also required for the actual metal deposition on the slide to act as electrodes. This is done by attaching two thin wires separated by a substantial distance to the aluminium foil. The purpose behind this was to allow the metal to be deposited all over the slide except for the sides (due to aluminium foil) and two thin regions due to being covered by the thin wires. With the preparation made, the metal film that would be produced on the slide would look like three electrodes separated by narrow straight gaps. A fully prepared cover slip after the heating process in the mini-coater is shown below:



Fig 2.6: Cover slips prepared with mask of aluminum foil and copper wire

The specimen, whose electrical characteristics are required for analysis, is to be placed in these spacings. By making connections to the electrodes on either side of the spacing and then applying the specimen over the aforementioned spacing, an electrical circuit is formed where the load is the specimen itself. This is how the specimen itself can be analyzed for its electrical characteristics; by measuring the current through this circuit for different voltage levels applied, and therefore computing the resistance in each instance. This resistance is directly related to the specimen's impedance, neglecting certain errors, which helps in identifying the electrical nature and properties of said specimen.

When the material to be studied is placed in between two of the deposited electrodes, which in turn are connected to a voltage source, an electrical circuit is created. Depending on the polarity of the connections to the voltage source, one of the electrodes will behave as the source and the other as the drain of a field-effect transistor (FET). By placing a metal surface under the cover slip and connecting it to another source, a gate is formed with its own fixed gate voltage. The details are covered more thoroughly in Chapter-1. Implementing the gate will be covered later on, as we can first move on to creating the source and drain for the circuit using the mini-coater to deposit aluminium on the cover slip.

2.2 Mini-Coater

2.2.1 Introduction

The exact model used for our procedure was the Tectra Mini-Coater high vacuum coating system. It is essentially a system of modular components working together to create the necessary conditions required for a given sample of metal to be evaporated onto a surface placed above it. This can be done through various processes other than thermal evaporation. An e-beam gun can be fitted to directly shoot electrons to a given target and allow deposition; magnetron sputtering and plasma decomposition (RF, microwave, DC) can be demonstrated using the relevant components of the system. I preferred to use the more straight-forward path of thermal evaporation. Before work could begin, however, a thorough understanding behind the working principle of the system was essential to get the desired results. A labeled diagram of the coating system is given in the next page:

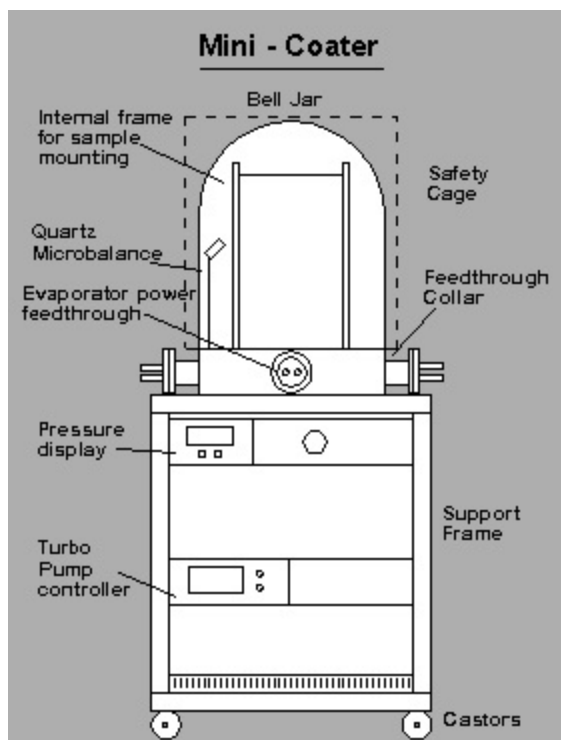


Fig 2.7: Labeled diagram of the Tectra mini-coater

2.2.2 Specifications

The specifications of the mini-coater are given below:

- Corning Pyrex bell jar
- Feedthrough collar with four NW35CF (2.75" OD) ports.
- Recipient size: diameter 300 mm, height 450 mm
- Bell jar safety-guard

- Bell jar base-plate
- Internal frame for sample mounting
- Quartz microbalance (water-cooled)
- Boat evaporator (thermal evaporation) mounted on high current feedthrough
- Evaporator power supply. 1.5 kW (manual control)
- User selectable transformer taps
- 70 l/s turbo pump with automatic venting valve
- Membrane roughing pump
- Balzers Compact full range pressure gauge and display
- Automatic current shutoff to evaporators and filaments
- User-definable pressure set-points
- System fully contained in and on a 19" rack cabinet [4]

2.2.3 Components

The most essential part of the coating system is the turbo pump. This allows the air to be evacuated from the vacuum chamber rapidly once the bell jar has been sealed shut. The evacuation process can be initiated using the controller located on the front panel of the support frame. Starting from atmospheric pressure (about 1 bar), vacuum is created to a high degree as the pressure falls to about 10^{-8} bar at its minimum point. The current pressure reading can also be accessed from the front panel's display. As long as the pressure does not reach the minimum level, the overpressure indicator remains lit to indicate that thermal evaporation cannot be allowed to be initiated. Only when this level of vacuum is reached can the next step finally commence.

It was also necessary to modify and improve the water cooling system for the mini-coater. Such a cooling system was essential especially for regulating the temperature of the system during high activity (evaporation process) by letting in cool water and letting out warmed water, taking the heat away gradually. In order to maintain this workable temperature the chiller had to be improved by fitting a larger fan to supply cooler water into the mini-coater.



Fig 2.8: The mini-coater cooling system after necessary modifications

The vacuum chamber needs to be covered by a bell jar meeting the specifications, to keep the chamber isolated during the degassing process. This jar sits on top of the feedthrough collar, as it was seen in the labelled diagram previously. The chamber within contains other components that warrant further explanation for the mini-coater's overall performance. A photo is given below, showing the jar closely:



Fig 2.9: Zoomed-in photo showing the bell jar

The internal frame has a connected platform where the cover slips that I chose would be mounted. The angle of the mounted slide needs to be adjusted such that it is vertically above the base of the chamber, specifically the evaporator feedthrough, to maximize exposure to the evaporating atoms of which the thin film is to be made of.

The feedthrough mentioned above is composed of a small curved surface on which powdered metal has to be placed. After evaluating the merits of which metal to use, it was decided that the film should be of aluminium instead of copper. The clearest reasoning behind this is the fact that upon deposition, aluminium takes much longer to be oxidized compared to copper when exposed to air. This allowed for a larger window of time for me to use each batch

of fabricated slide in my studies. A photo showing the support frame, feedthrough collar and bell jar is given below:



Fig 2.10: The Tectra mini-coater in full display

The front panel, mentioned previously, also contains controls for adjusting and monitoring several aspects of the whole process. This includes display of current chamber pressure, overpressure status and, most importantly, regulation of voltage for the evaporator power supply. The latter is adjusted by increasing the current percentage voltage compared to the

maximum possible, and stopping only when the powdered metal in the feedthrough starts to glow brightly.

2.2.4 Operation and Working Principle

With all things considered, the first batch of slides was mounted for deposition of metal on it and adjustments and improvements were made upon further trials. Judging by the size of the holder we used to clasp the slides in place, I could use 3 slides for every batch. The mask which consists of aluminium foil (for the sides) and the 2 thin wires (for creating space between electrode-shaped metal films) was connected to the slide, and the whole thing to the holder, using medical tape. It was observed that the bulk of the time taken was due to the creation of vacuum inside the chamber, which sometimes took upwards of 3 hours. But once vacuum was established at a pressure of about 10^{-8} bar, the evaporation of the metal to be deposited took considerably less time (about a minute) for each cycle. At this point, the powdered aluminium was ready to be heated in the feedthrough. The evaporation process was initiated using the buttons on the front panel, which turns on the evaporator power supply. After that, the voltage level is adjusted as mentioned previously. It was seen that the powdered sample of aluminium started glowing brightly at about 50% of maximum voltage. This signals the metal being heated to the point where aluminium atoms begin to escape and radiate. This deposition of one atom at a time through thermal evaporation lack directionality as it spreads in all directions; this makes it important for the slide to be positioned close and at the correct angle to the feedthrough.

Evaporation of powdered metal inside the chamber, in turn, increases the internal pressure. So the actual heating of the metal to release its atoms cannot occur for too long before the overpressure indicator is lit again. Once this happens, the feedthrough heating dissipates as the turbo pump begins to work again to reestablish the vacuum inside the chamber, at which point the feedthrough heating to allow deposition can resume. This is, in general, how I have found the mini-coater to work in practice. The entire process consists of long periods of vacuum generation; and in between these times we have the necessary conditions to heat the feedthrough such that the aluminium melts and then glows brightly. At such a high temperature and low pressure the aluminium atoms are deposited on the slide placed over it through evaporation, making a largely even metal coating on it. This cycle was repeated twice or thrice before we could assume that the coating on the slide was substantial. Once I made sure, the evaporator power supply was cut out and the turbo pump switched off. This allowed air to rush back into the chamber and slowly raised the chamber pressure up to 1 bar (atmospheric pressure), as indicated the front display. Once pressure is high enough, the bell jar can finally be lifted and the holder containing the slides can be taken out very carefully. The slides are then cautiously pulled out of the holder by undoing the tape and placed in a sealed box until it is used in the experiment, in order to prevent dust and/or moisture build-up over its surface. A batch of prepared slides still clamped to the holder after evaporation is shown in the next page:



Fig 2.11: Cover slips after deposition of aluminium using mini-coater

With the device created, having the electrode-shaped pattern on it, work was done on trying to figure out how to take accurate measurements from the device efficiently once the sample material was used with it. It was decided beforehand that the Keithley 6517b electrometer was to be used to take necessary measurements. Due to its interfacing capabilities it would be convenient to develop software that can communicate with the electrometer to conduct its different operations that only needs to be initiated once, as opposed to manually controlling the electrometer using its buttons every time a measurement needs to be taken. This would save time and reduce human error while measurements are taken, making it the convenient choice when it comes to reading and analyzing a large number of data. The work done with the software and the electrometer itself is going to be further described in the next section.

2.3 Electrometer

2.3.1 Specifications

The Model 6517B is a 6½-digit electrometer/high-resistance test and measurement system with the following measurement capabilities:

- DC voltage measurements from 1μV to 210V.
- DC current measurements from 10aA to 21mA.
- Charge measurements from 10fC to 2.1μC.
- Resistance measurements from 10Ω to 210PΩ.
- Surface resistivity measurements.
- Volume resistivity measurements.
- External temperature measurements from -25°C to 150°C using the supplied Model 6517-TP thermocouple.
- Relative humidity measurements (0 to 100%) using the optional Model 6517-RH probe.

Some additional capabilities of the Model 6517B include:

- Built-in V-Source. The 100V range provides up to ±100V at 10mA, while the 1000V range

provides up to $\pm 1000\text{V}$ at 1mA .

- Data storage (50,000 points).
- Single button zeroing (REL).
- Built-in math functions.
- Filtering, averaging, and median.
- Built-in test sequences.
- Remote operation using the IEEE-488 (GPIB) bus or the RS-232 interface.
- Scan (measure) channels of an external scanner.
- Scan (measure) channels of an internal scanner card

As mentioned before that the most important aspect of this instrument is that it can be controlled remotely. For this purpose either IEEE-488 GPIB interface or RS-232 interface can be used. I used IEEE-488 GPIB for interfacing. The IEEE-488 GPIB (General Purpose Interface Bus) connects the 6517B electrometer to the computer using standard IEEE-488 connectors.



Fig 2.12: Front panel of Keithley 6517b electrometer

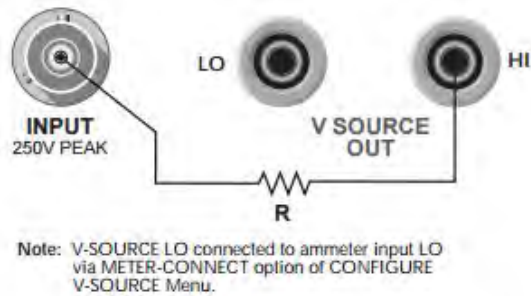
2.3.2 Basic Connections

- **Meter-Connect –**

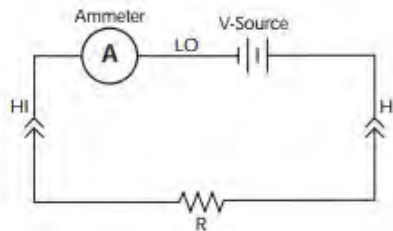
Before making necessary connections from the electrometer to the PC for interfacing, some steps had to be taken to make sure of proper working conditions. It was ensured that the electrometer itself was grounded properly to prevent charge build-up as a basic safety measure.

There was also a meter-connect feature that proved useful to me. Since the electrometer has a HI and LO to be connected at each end of the specimen to be measured and a voltage source supplying into the circuit, the cable configuration can get quite complicated. To circumvent this difficulty I configured the electrometer to enable the meter-connect feature. The resistance to be measured is connected to the center conductor of the input triax connector and the V-Source HI binding post. This configuration allows the V-source LO to be internally connected to ammeter LO.

As a result the connections are simplified greatly – the ammeter HI is connected to one end of the load, and the source HI is connected to the other end to complete the circuit. The application of the meter-connect and its equivalent circuit is given in the next page:



A. Basic connections



B. Equivalent circuit

Fig 2.13: Basic connection (top) and equivalent circuit (bottom) created due to meter-connect feature

In the diagram above, the “R” represents the load of the specimen to be measured for its electrical properties.

- **Interlock –**

The electrometer has a safety interlocking feature. Essentially, it prevents damaging the user due to high levels of voltage supply. Keithley 6517b is best used with a test fixture added to its apparatus. The test fixture is basically a protective box that shields sensitive

parts of the circuit, like the load, from being affected due to external influences by having those elements to be placed inside it and closed with a lid. The electrometer's interlock feature is designed such that the internal voltage source will not supply unless the lid is fixed shut. It was impossible to apply any voltage to a given circuit in that particular configuration, and an error message was displayed on the front panel signifying the interlock violation.

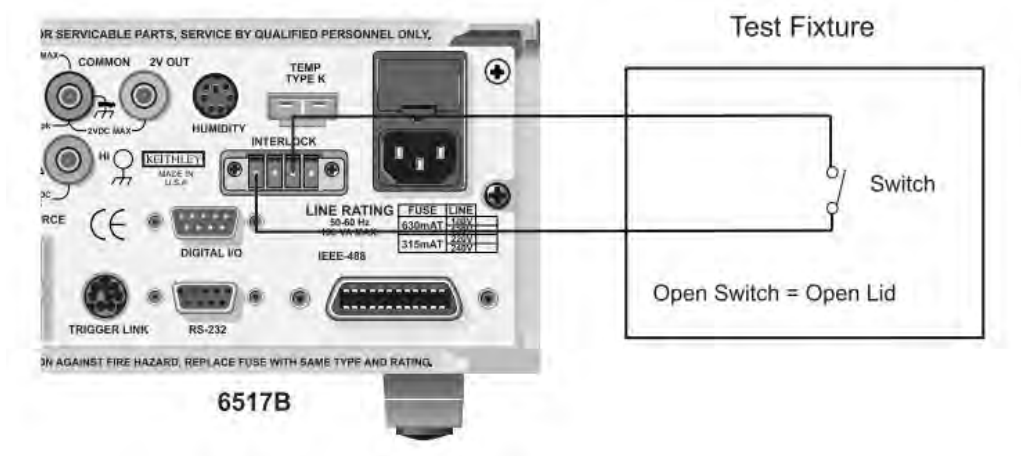


Fig 2.14: Circuit showing test fixture connected to interlock

Since I did not have a test fixture in my setup, I had to prevent the interlocking featuring from interfering with my method. To achieve this I was to make appropriate connections in the interlock section of the back panel, which has four pins:

- Pin 1: Interlock safe
- Pin 2: Ground
- Pin 3: +5 VDC output
- Pin 4: Surface/volume select[5]

As is clear from the circuit diagram above, I would have to short pins 1 and 3 to replicate the situation where the test fixture lid is closed and the interlock is connected. Making necessary connections I was able to engage the interlock and allow the voltage source to supply to my circuit.



Fig 2.15: Interlock connector with pins 1 and 3 shorted (left)
and the back panel showing interlock section (right)

Lastly, I was to establish direct connectivity from the electrometer to a computer. The interface used as industry standards is the IEEE-488, commonly known as GPIB. I managed to procure a GPIB-USB connector for remote access through PC, without needing adaptors or other ports.

2.3.3 Interfacing and LabVIEW

Through the GPIB interface, the electrometer was finally linked to a computer. The software required to access and control the electrometer through GPIB is created by National Instruments. Some basic software was required to check the link status and the basic specifications of the electrometer. Once the connection was firmly established, I started work on learning and understanding the mechanics of LabVIEW software, also created by National Instruments. With this program, it is possible to create an application that can control the electrometer remotely and be utilized to give it specific instructions.

I was to develop a VI program on LabVIEW to conduct a voltage sweep for the material to be analyzed. The two most basic and essential VIs I needed for the program consisted of one that can take voltage to be applied as input (WRITE) from the user and apply said voltage, and another that can display the electrometer's reading to the same user (READ). It was found that creating these sub-VIs from scratch would be unnecessary and time-consuming, since such basic operational VIs are supplied by the manufacturer in their website. My entire work on LabVIEW revolved around calibrating the WRITE VI to take various input parameters from the user other than just voltage and issue these commands to the electrometer, and observe the data obtained from the electrometer using the READ VI.

Since the main objective of the program was to conduct a voltage sweep, it had to first instruct the electrometer to provide incremental voltages at intervals across the circuit. At the

core of my program I made use of a shift register, which functions exactly like those found in digital circuits. The basic idea was to create a loop inside which we have the sub-VIs (WRITE and READ), and the specific conditions were given for the loop to continue on. An initial value had to be provided which was used by the WRITE, and the result recorded by READ. After each cycle this value was increased by a given amount (increment). When the current value reached a specific given final value, the loop would end. Here, the shift register technique allowed this value to be moved from one side of the loop to the other, increasing each time. The basic VI created is given below:

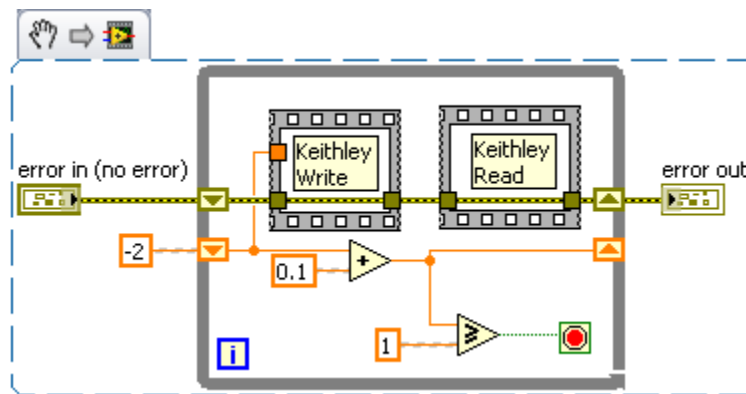


Fig 2.16: A basic looped VI utilizing a shift register (UP and DOWN symbols in orange)

As we can see from the figure, an input of -2 is given into the loop which is used by the WRITE and the result from electrometer displayed on the front panel by READ. The input is then added by +0.1 each time a loop is finished. This value then goes back to the start of the loop, and this cycle continues until the input is equal to or greater than 1. This is connected to the red circle that activates the end of the loop, and the program terminates.

With the backbone of the program having made, I proceeded on improving it. As mentioned previously, the back panel is a schematic block diagram for development purpose and the front panel of the software is what the user is meant to use. So I had to create connections to allow for data input to be made from the front panel in numerical boxes, providing a user-friendly environment to users not directly connected in the development. In the earlier versions of my program only basic input could be made. This included initial, incremental, and final voltage. But with subsequent versions I made several changes and additions to the back panel block diagram to make the program as intuitive as possible. Options were added to change directly the voltage limit of the source, current range of the meter, and a universal GPIB address input to call each VI on command all at once such that the electrometer address for each VI to function does not have to be specified one at a time for each of them.

As mentioned previously, I exploited the meter-connect feature to make physical connections to the circuit more manageable. This feature is no longer activated manually as I have added a switch in my program which, when turned on, engages a VI to control the electrometer hardware guided by a few lines of code.

Lastly, in the final version, I have also added a graphing system. This makes analysis of data obtained easier and swifter. From the VIs WRITE and READ, I have made connections such that the current voltage input given (x-axis) and the current reading made (y-axis) are sent one at a time to a dynamic library. This feeds a graphing tool with data each time a loop is completed, which then plots the point on a graph that can be viewed on the front panel. As a

result the graph plotting is procedural, meaning that the user does not have to wait for all the data to be stored for the graph to appear since each point is plotted following each data WRITE and READ cycle. [6]

Also in the final version, I connected the graphing tool to a file storage system. This allowed me store all the data I needed (voltage, current, resistance) for each reading awaiting further analysis. This VI depended directly on the dynamic data library, so its creation is also procedural as it stores data in the file one reading at a time instead of awaiting the termination of the program.

This resulted is a program that is intuitive for any new user not involved in its development, to be used in applications like voltage sweep. The front panel that the user will see has already been shown. The back panel, containing all my actual work on the program is shown in the next page:

2.4 Transistor Characterization

2.4.1 Introduction

Having completed my work on making the micro-device using the evaporator, and the software to be used to remotely control the electrometer, the next logical step was to use a material with the micro-device for analysis by looking into its electrical characteristics. A conducting polymer was seen to be ideal for characterization, but it was not possible to procure a sample within due time. So it was decided by my supervisor that it would be more beneficial to use the complete set-up I have designed to characterize different transistors. It was especially important to characterize a MOSFET, since the device I was trying to create was basically supposed to work as one. The device had two electrodes which can be considered as the drain and source, with the insulating layer of glass underneath being the gate. The material was required to serve as the body, placed in between the drain and source, for electrical characterization with changing gate voltage. Since this is quite similar to the operation of a MOSFET, it seemed to be the most suitable option moving forward.

2.4.2 PNP

The model A1015 was chosen for the PNP BJT. After the appropriate connections were made, the data was collected in a separate file as part of the software's functionality. As is mentioned previously, the common-emitter configuration was chosen. Resistors were chosen carefully to make sure that the data could be easily analyzed and also due to the limitations of the electrometer. The selected resistors are – $R_B=17.3\text{M}\Omega$ and $R_L=2.66\text{ k}\Omega$. The circuit used following the common-emitter configuration is shown below: [7]

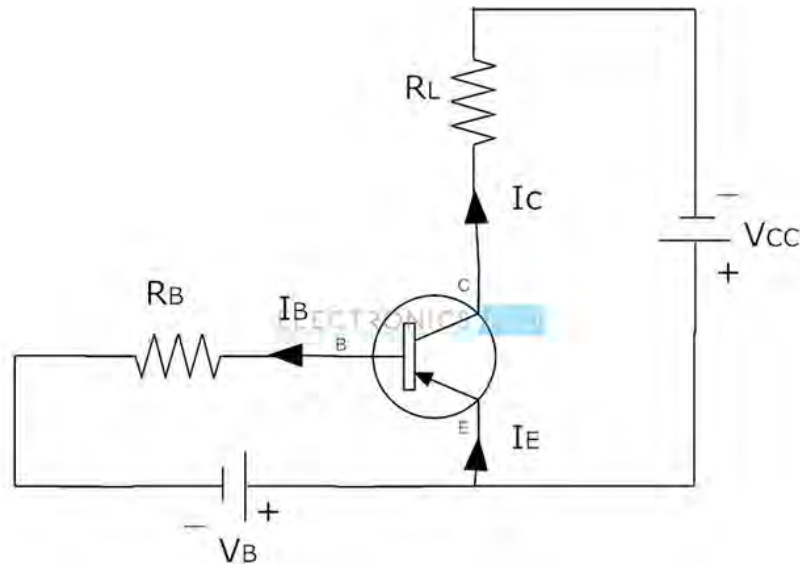


Fig 2.18: Common-emitter configuration circuit for a PNP BJT

The obtained data was used to plot the following graphs, and analyzed ahead. It is important to note that I have reversed the signs of all input and output data by reversing the polarity of each circuit element, as PNP BJTs are usually operated at negative currents. This way

we can work with absolute values of the current and voltage at each stage, which is more convenient for graphical data analysis.

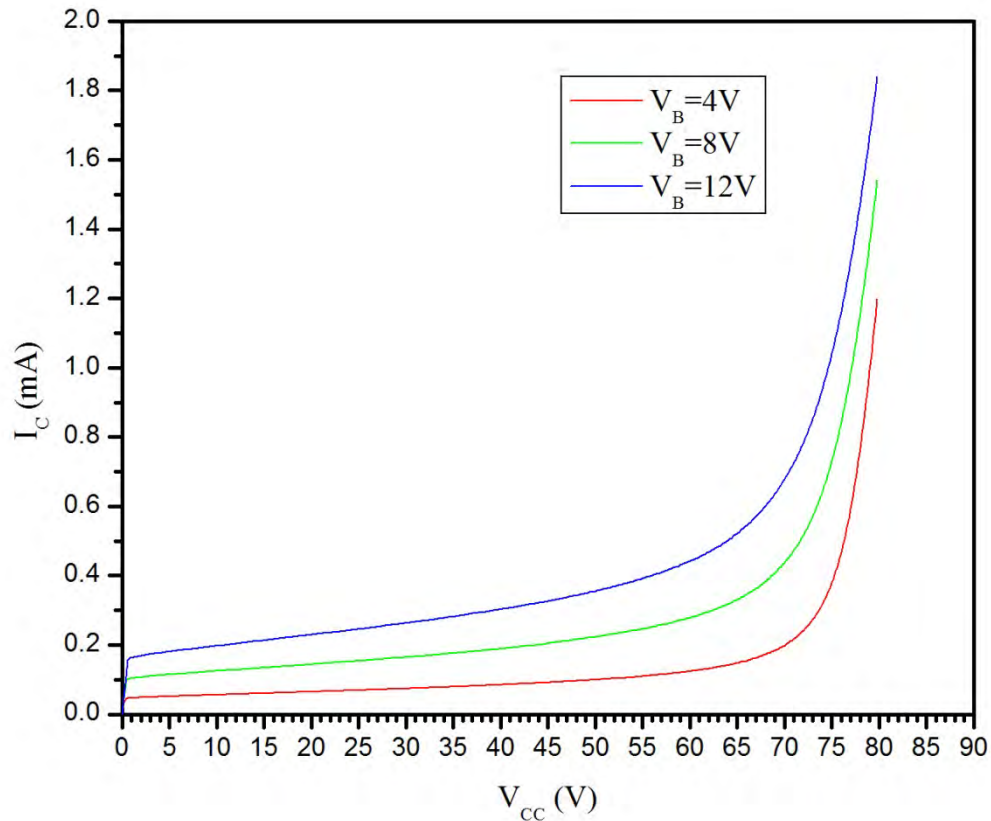


Fig 2.19: I_C against V_{CC} graph of A1015 (PNP)

As we can see from the figure above, regulating the base voltage (V_B) has an immediate effect on the collector current (I_C) for different levels of source voltage applied (V_{CC}). After an immediate “jump” as the source voltage from electrometer is applied, the curves follow a similar trajectory as expected. It can be seen that the magnitude of this initial “jump” for the collector current is largely dependent on the base voltage, with higher base voltages promoting the current

to rise even higher in the lower ends of 1V-2V. For reference, base voltages less than 1V was also selected for data acquisition. However that promoted hardly any current to pass through as the barrier voltage had to be overcome ($V_{BE}=0.7V$ for Si). So instead of a curve, the graph was essentially a straight line travelling on and parallel to the horizontal axis, due to no change in current. For base voltages shown, the curves proceeded to rise after the initial jump. The curve for $V_B=12V$ is seen to rise at a higher rate compared to that of 8V or 4V, meaning the change in gradient of this region is also depending on the base voltage applied. This is the amplification of input current for changing base voltages, a property that is used extensively in electrical circuits.

The currents for the different V_B were seen to peak off at around 70V-80V for this particular circuit. After this stage, the current levels reached higher than that allowed by the electrometer, so the limit up to which data could be taken was reached.

Since we are working with lower current at around mA to μA range, we can also see the switching operation of the PNP BJT. For the specific circuit that I designed, the transistor theoretically remained in the “OFF” state till the curves began to rise drastically around 70V, before that very little current was allowed to pass through. We can also see that this rise is also dependent on the base voltage, since higher values promoted the sudden rise to occur at lower source voltages V_{CC} . So this transistor, other than being an amplifier, can also be used as a switch that will let substantial current pass through only after a certain critical voltage is applied, and that specific critical voltage can also be regulated using varying base voltages.

For clarity, a closer look at the PNP curves at lower voltages is given below:

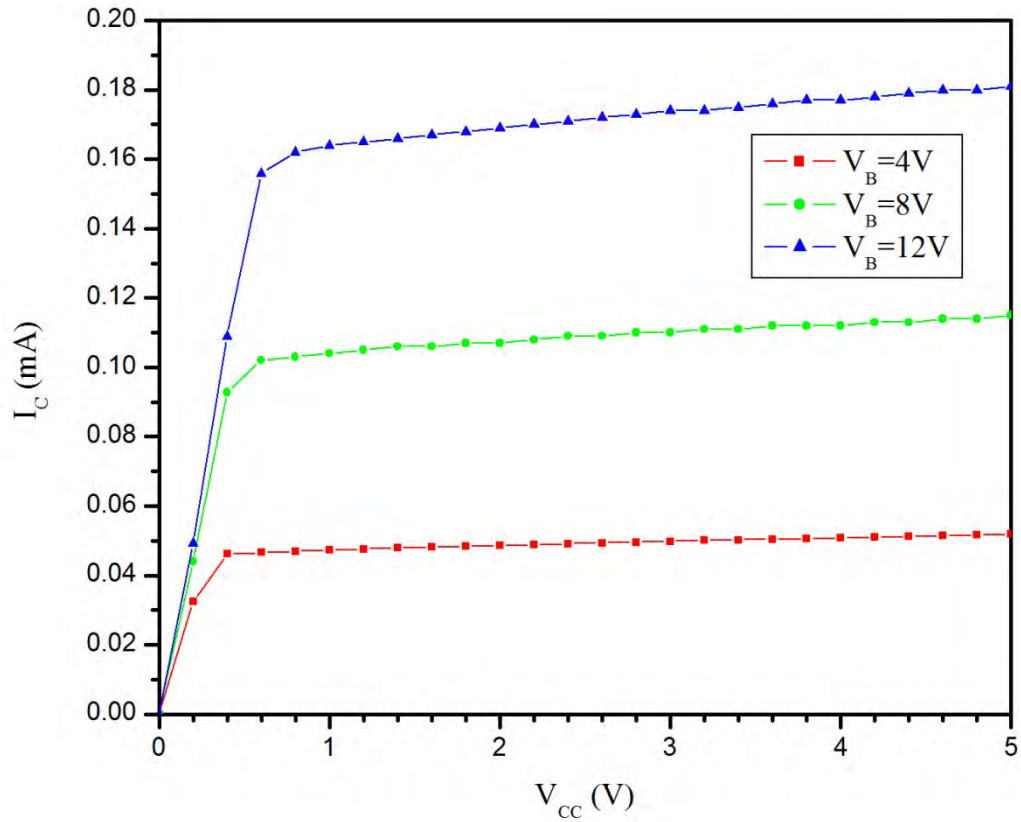


Fig 2.20: I_C against V_{CC} graph of A1015 (PNP) for lower source voltage

From this figure, the rapid rise in current initially can be easily seen. Before applied voltage 1V is reached, the curve stops rising as rapidly and increases at rates depending on its corresponding base voltage used.

In order to make the characterization more comprehensive, it was important to compare the I_C graphs obtained for different base voltages to the junction voltage (V_{CE}). This potential largely depends on collector current I_C for different base voltage V_B , as this V_{CE} is equal to the applied voltage V_{CC} minus the drop at the load resistor R_L . [8]

$$V_{CE} = V_{CC} - (I_C * R_L)$$

Using the above equation, data was obtained for junction voltage and graph of collector current I_C against junction voltage V_{CE} was plotted:

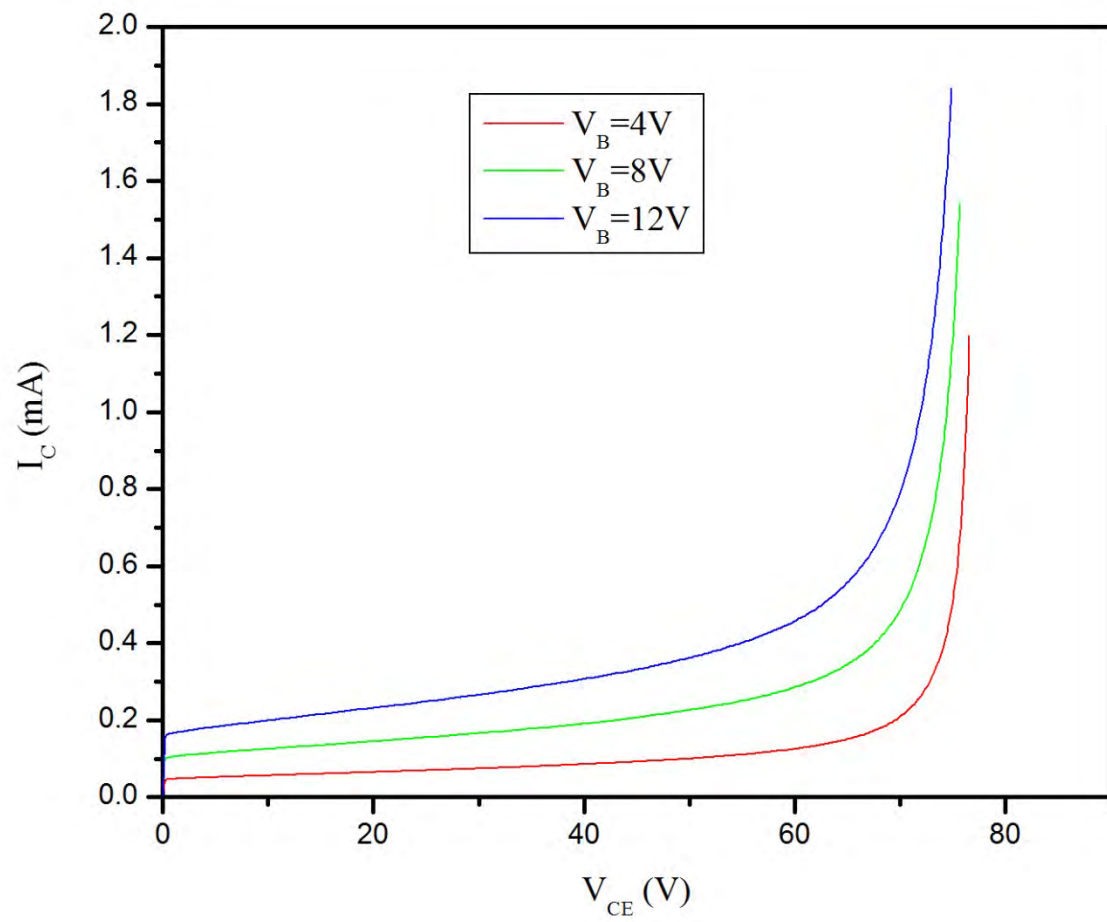


Fig 2.21: I_C against V_{CE} graph for A1015 PNP

2.4.3 MOSFET

The enhancement-mode MOSFET, or eMOSFET, is the reverse of the depletion-mode type. Here the conducting channel is lightly doped or even undoped making it non-conductive. This results in the device being normally “OFF” (non-conducting) when the gate bias voltage, V_{GS} is equal to zero. For the n-channel enhancement MOS transistor a drain current will only flow when a gate voltage (V_{GS}) is applied to the gate terminal greater than the threshold voltage (V_{TH}) level in which conductance takes place making it a transconductance device. The application of a positive (+ve) gate voltage to a n-type eMOSFET attracts more electrons towards the oxide layer around the gate thereby increasing or enhancing (hence its name) the thickness of the channel allowing more current to flow. This is why this kind of transistor is called an enhancement mode device as the application of a gate voltage enhances the channel. Increasing this positive gate voltage will cause the channel resistance to decrease further causing an increase in the drain current, I_D through the channel. In other words, for an n-channel enhancement mode MOSFET: $+V_{GS}$ turns the transistor “ON”, while a zero or $-V_{GS}$ turns the transistor “OFF”. Then, the enhancement-mode MOSFET is equivalent to a “normally-open” switch. A generic characteristic graph of the drain current (I_D) to the drain-source potential (V_{DS}) is shown in the next page. [9]

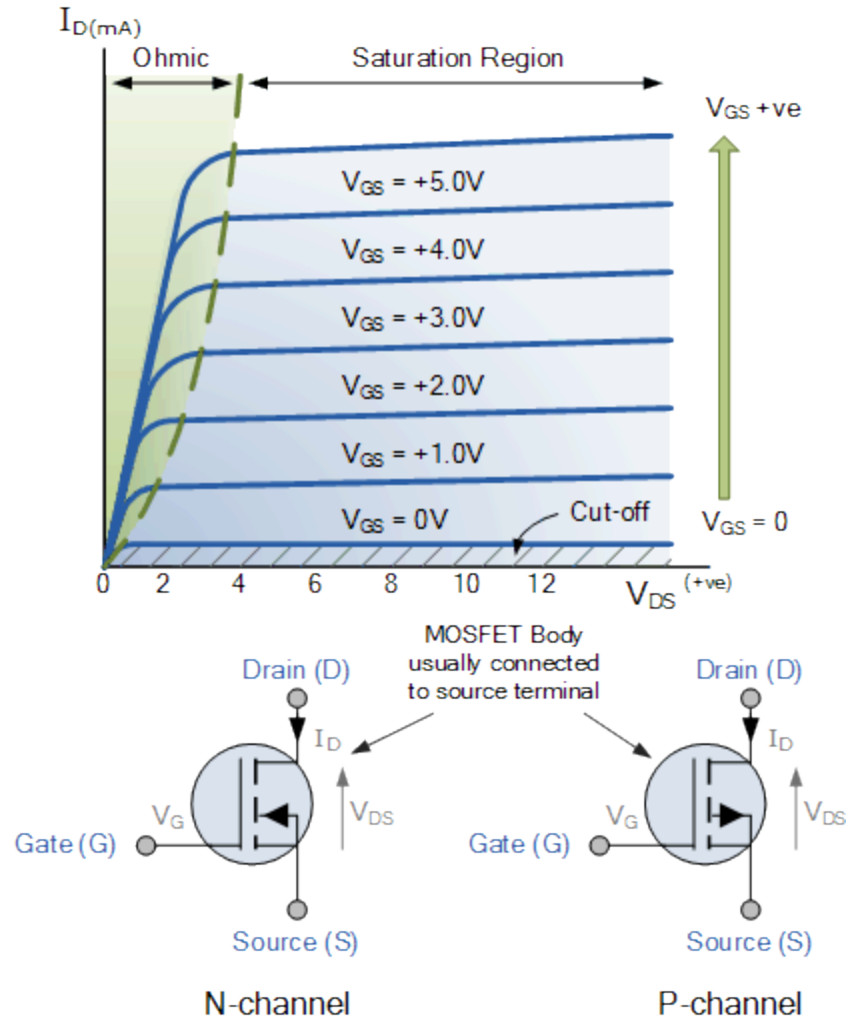


Fig 2.22: eMOSFET characteristic graph with circuit symbols

Taking into account the overall concept and working principle of MOSFETs, I used a model 2N7000 n-channel eMOSFET and recorded the drain currents at increasing source voltages, for particular gate voltage applied. The results are given in the next page:

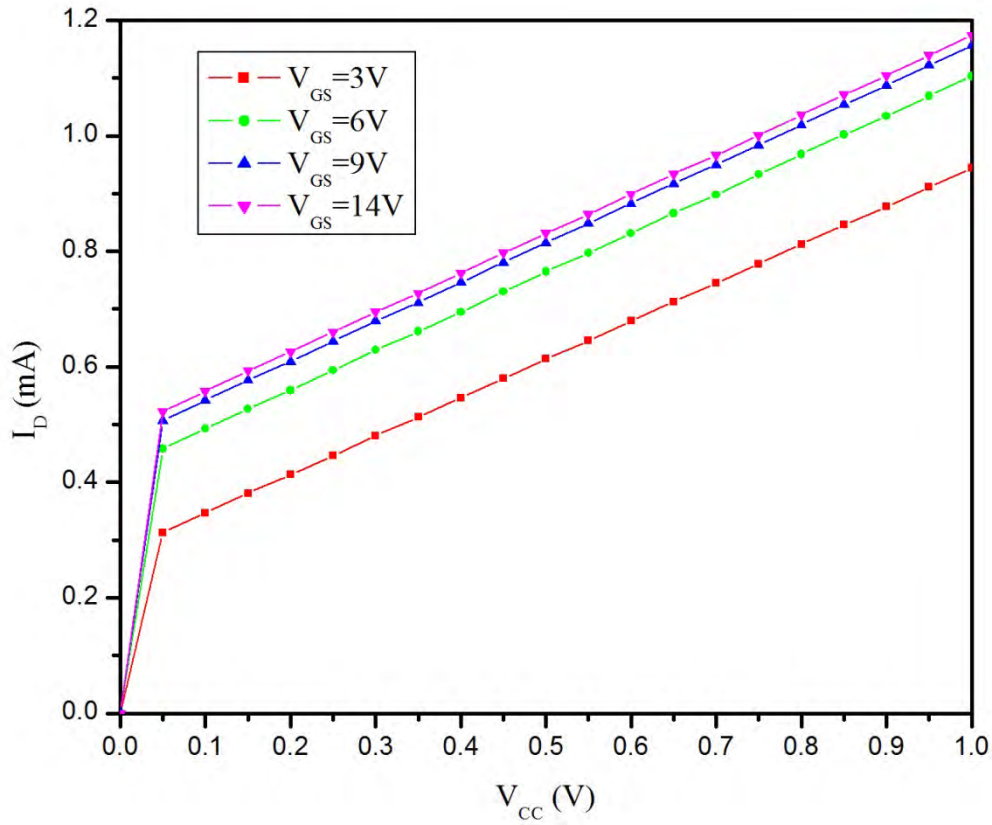


Fig 2.23: I_D against V_{CC} for lower voltages of the 2N7000 MOSFET

To check the overall consistency of the data obtained, the 2N7000 MOSFET's datasheet was consulted extensively. Like the PNP data in the previous section, this analysis is restricted to currents lower than 10mA due to the electrometer's limitation. However, adjustments made to the resistors at the gate and main channel were sufficient to make the data analyzable even at lower currents than the device is supposed to operate at usually. This meant that low-current analysis of the transistor device operation was possible, just like in the case for the PNP BJT.

From 0V to 1V of V_{CC} , we can see that the device is operating as expected. With increasing gate voltage, the curve is rising significantly. This is the amplification process mentioned previously, as a relatively low current from the gate is amplifying the drain current I_D to a larger degree. After an early jump from 0V to 0.05V of source voltage V_{CC} , the current increases at a reduced rate. Also from this graph, we can see that the change in the curve height between gate voltage of 3V-6V or 6V-9V is much greater than that created between 9V-14V. This is because the device is limited to have a maximum gate-source potential V_{GS} of about 10V, as increasing this further would create very little effect on the drain current. Due to this, the curves for 9V and 14V are quite similar. This is a direct consequence of the n-channel itself.

With increasing gate voltage, more and more electrons are being attracted towards the oxide layer around the gate, increasing the thickness of the n-channel. This makes the n-channel wider with increasing gate voltage such that more current is allowed to pass through. In this way, we can amplify the output current of the n-channel simply by regulating the gate voltage, which directly affects the rate at which charge carriers can pass through. This is highlighted in the way the curves are raised higher for higher gate voltages.

It can also be seen that the curves for 9V is very similar compared to that for 14V of gate voltage V_{GS} . After further inspection, it was apparent that the maximum gate voltage allowed for the specific MOSFET was around 10V. From this stage, increasing the gate voltage causes comparatively few electrons to move towards the oxide layer of the gate. This means that at $V_{GS}=10V$, the n-channel is as thick as it can possibly be, so there is little to no change in the I-V

graph for increasing the gate voltage any further. This clearly means that the transistor operates most effectively and efficiently from 0V to 10V of gate voltage V_{GS} .

Next, I took data of drain current I_D for further increase in source voltage.

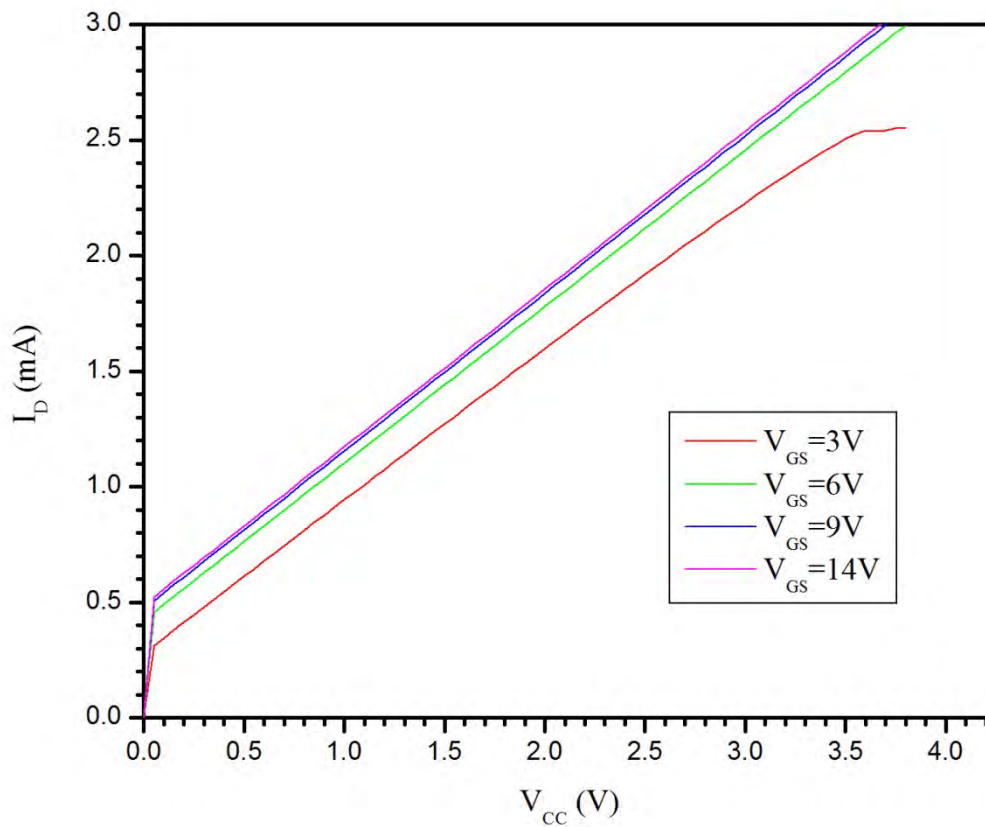


Fig 2.24: I_D against V_{CC} for the 2N7000 MOSFET

Upon further increase of input voltage for varying gate voltage, we can see the trends for the different curves. After about 3.5V of input voltage, we can see that the curve for $V_{GS}=3V$ begins

to flatline, while the other curves continued onwards. From the expected data from the datasheet, we can categorize the different regions of the graph. The three main regions are:

- 1. Cut-off Region – with $V_{GS} < V_{TH}$ the gate-source voltage is lower than the threshold voltage so the MOSFET transistor is switched “fully-OFF” and $I_{DS} = 0$, the transistor acts as an open circuit
- 2. Linear (Ohmic) Region – with $V_{GS} > V_{TH}$ and $V_{DS} < V_{GS}$ the transistor is in its constant resistance region and behaves as a voltage-controlled resistor whose resistive value is determined by the gate voltage, V_{GS}
- 3. Saturation Region – with $V_{GS} > V_{TH}$ the transistor is in its constant current region and is switched “fully-ON”. The current $I_{DS} = \text{maximum}$ as the transistor acts as a closed circuit [10]

Comparing the data obtained to the datasheet, I was able to separate the regions. According to the datasheet, the MOSFET has a maximum threshold voltage of about 3V. This falls in line with the data obtained, as the applied V_{GS} which are at or less than 3V gave curves where the drain current I_D stopped increasing starting from a relatively low source voltage of about 3.5V. So we can accurately deduce that the threshold voltage V_{TH} is somewhere about 3V. On the other hand, for $V_{GS} > V_{TH}$, we can see that the drain current keeps on increasing.

For the $V_{GS}=3V$ we can see that the curve is at the end of its ohmic region at about 3.5V of V_{CC} , and entering the saturation region where we have the flatline. For the region below this

curve, it is referred to as the cut-off region. In this region, we have relatively small I_D as the switch that the transistor is operating as is technically “OFF”. We can clearly see how such a MOSFET can be used as a switch, as a small increase in current at the gate can promote a comparatively large increase in the drain current. For this specific transistor, the switch works as follows:

- OFF – for $V_{GS} < 3V$
- ON – for $V_{GS} > 3V$

The curves for $V_{GS} > 3V$ extends onwards as the current keeps on rising in the ohmic region. Those curves will reach their own saturation region when the drain current will stop increasing at currents much higher than 10mA, due to which I was only able to focus on the lower-current high-resistance region. Also given below are the characteristic curves of drain current I_D against the drain-source voltage (V_{DS}). The data for the V_{DS} for its respective I_D values were obtained similar to the PNP, using the equation below:

$$V_{DS} = V_{CC} - (I_D * R_L)$$

With the obtained dataset, a graph of I_D against V_{DS} was plotted showing similar trends to that for the input voltage V_{CC} .

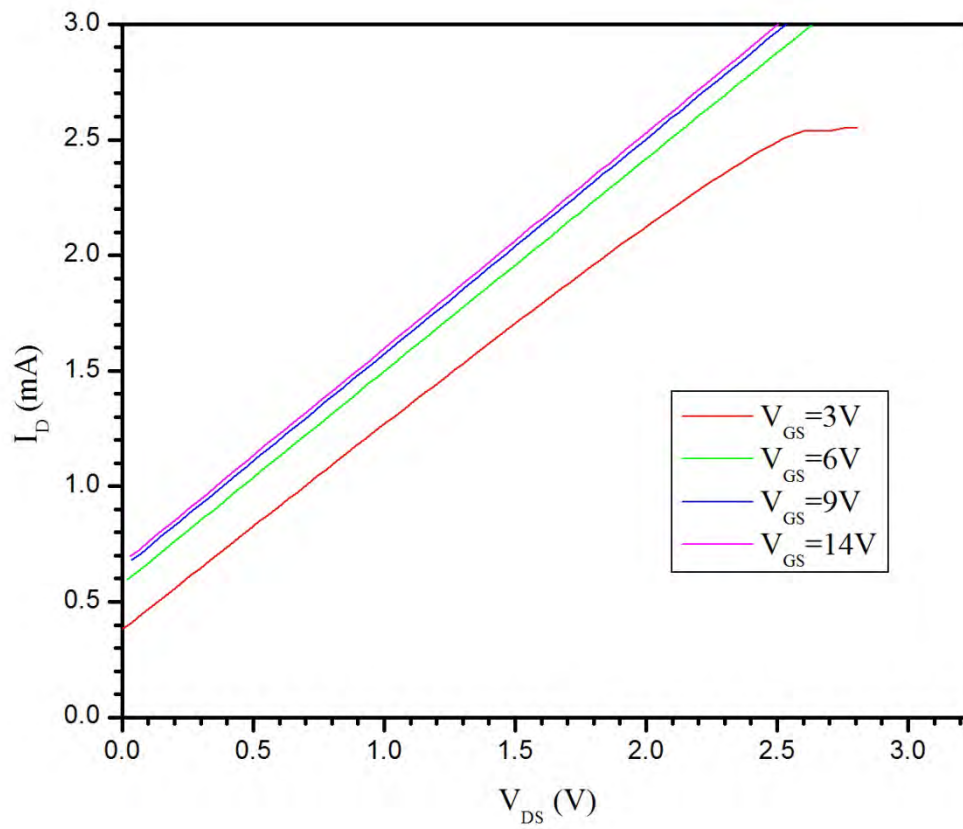


Fig 2.25: I_D against V_{DS} for the 2N7000 eMOSFET

Chapter-3: Results and Discussions

With the data for the two transistors obtained and analyzed, I was able to come up with the results of my work dealing with the transistors' individual characteristics and electrical properties. The results should enable the proper operation of such transistors in circuits pertaining to different electrical applications.

First of all, I made sure that the application that I made using LabVIEW was functioning correctly using simple silicon diodes and resistors and plotting current-voltage graphs for each case. After making necessary adjustments and enhancements to the application, I went ahead to prepare circuits using the transistors which were to be analyzed graphically.

- PNP:

As stated previously it was more convenient to work with reversed polarity for all circuit elements to obtain the absolute value of the input and output data. The results obtained were first analyzed for critical values and trends, and then compared to expected data using the model A1015 PNP datasheet. [11]

Comparing my data to the reference graphs in the datasheet, increasing the base voltage (and subsequently the base current) we see amplification in the output current I_C for the same source voltage V_{CC} or same junction voltage V_{CE} . Differing from this graph is the fact that it has

been plotted for relatively higher current ranges, and thus the saturation region where the curve flatlines can be seen. However it was possible to determine amplification and switching actions from a very low current range, making the data ideal for low-current circuits.

From the data obtained for low voltage range, we can also see that the results matches for those outlined in the datasheet. The base voltages (V_B) are replaced with its corresponding base currents (I_B), which is required for determining transistor parameters.

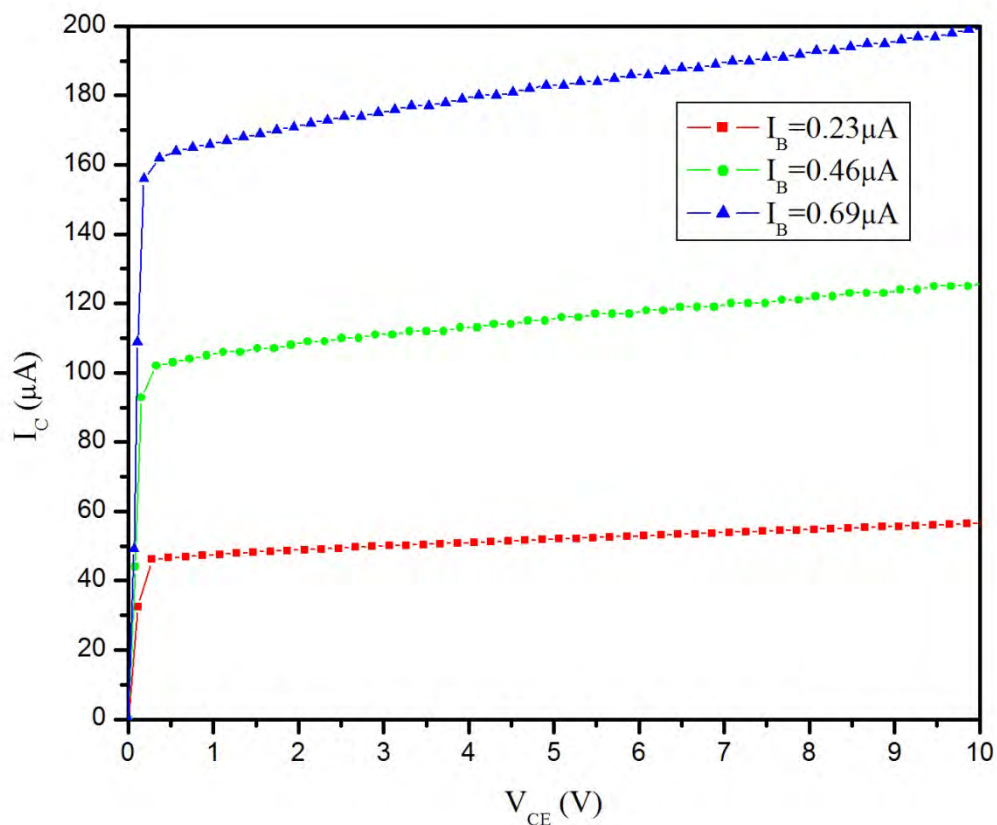


Fig 3.1: I_C against V_{CE} for A1015 PNP

From the graph, we see that base-emitter saturation begins at around 0.3V. Also, it was found that base voltages at or below 1V did not promote any collector current I_C irrespective of source voltage. This matches the reference value from the datasheet, as well as the theoretical value for the barrier voltage for silicon (0.7V). The values from the datasheet are given below for reference.

DC Current Gain $V_{CE} = -6.0V, I_C = -2.0mA$	h_{FE1}	70	-	400	-
Collector-Emitter Saturation Voltage $I_C = -100mA, I_B = -10mA$	$V_{CE(sat)}$	-	-	-0.3	V
Base-Emitter Voltage $I_C = -100mA, I_B = -10mA$	$V_{BE(sat)}$	-	-	-1.1	V

Fig 3.2: Reference data taken from A1015 datasheet

I could also compare transistor parameters from my data to that given in the reference sheet. The datasheet provides the DC current gain h_{FE} (or β) value for $V_{CE} = -6V$ at room temperature of $25^\circ C$. The ideal value of β is somewhere around 250 according to the reference datasheet.

This gain β is the ratio of collector current I_C to the base current I_B . Another parameter worth taking into account is α , which is the ratio between collector current I_C and emitter current I_E . Since $I_E = I_C + I_B$, and $I_B \ll I_C$, the ratio α is usually close to, and less than, unity. Again, we compare the current values at $V_{CE} = 6V$ (reversed). Using the following equations, it is possible to find the experimental value of β and α :

$$\beta = I_C / I_B$$

$$\alpha = I_C / I_E$$

The following values for the ratio are obtained using the equation for $V_{CE} = 6V$:

	I_C (μA)	I_B (μA)	I_E (μA)	h_{FE} / β	α
$V_B = 4V$	53	0.23	53.23	230	0.9957
$V_B = 8V$	118	0.46	118.46	256	0.9961
$V_B = 12V$	186	0.69	186.69	269	0.9963

Fig 3.3: I_C , I_B , I_E , β , α for A1015 PNP at $V_{CE} = 6V$

This gives us estimated values(averaged) for α and β at $V_{CE} = 6$:

$$\alpha = 0.99603$$

$$\beta = 252$$

- MOSFET:

As in the case of the PNP BJT, the results obtained for the MOSFET 2N7000 was referred to the model-specific datasheet for consistency. [12]

The graph provided is mostly for high-current circuits, so the data from my work is able to distinguish the transition from “OFF” to “ON” state to a finer degree at lower currents. Comparing this to the graph I made from the data obtained, we can see similar trends assuming operation at room temperature of 25°C. Increasing the gate voltage, and subsequently V_{GS} , we see an amplification effect on the output current I_D . It is also identifiable from the graph that gate voltage of 3V can be considered to be the maximum voltage (threshold voltage) upto which the MOSFET can be considered to be in the “OFF” state as barely any current is allowed to flow through the drain-source n-channel. This aligns greatly to my findings, giving us a result for the maximum threshold voltage for the MOSFET:

$$V_{TH(max)} = 3V$$

Comparing the graph I obtained to the reference graph, we also see that the limiting gate voltage is at $V_{GS} = 10V$, since there is hardly any change to the curve for 9V compared to that for 14V. This also falls in line to the MOSFET’s expected characteristics from referencesince at $V_{GS} = 10V$, the n-channel is almost as thick as it can be and there is little to no increase in output current for increasing the gate voltage any further. So using the system employed here, we can safely estimate the proper working parameters of such specific transistor devices in terms of efficiency and effectiveness. Summarizing all the data, we find that the MOSFET is turned “ON” after 3V, and amplification occurs by increasing the gate voltage upto 10V:

- OFF: for $V_{GS} < 3V$ (maximum threshold voltage)
- ON: for $3V < V_{GS} < 10V$, since amplification is greatly reduced after $V_{GS} = 10V$

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