Simultaneous Interface Application Development for an Electrometer and a Source Meter Using Lab VIEW to Study three terminals Semiconducting Device

Inspiring Excellence

Thesis submitted to

The Department of Electrical and Electronics Engineering, BRAC University in partial fulfillment of the requirements of the award of the degree of Bachelor of Science in Applied Physics and Electronics

By

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Declaration

I do hereby declare that the thesis titled "Simultaneous Interface Application Development for an Electrometer and a Source Meter Using Lab VIEW to Study three terminals Semiconducting Device" is submitted to the Department of Electrical and Electronics Engineering of BRAC University in partial fulfillment of the Bachelor of Science in Electrical and Electronics Engineering. 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.

Date:

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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. A transistor to be used effectively and perform it's full functions as amplifiers and switches, it is important to know its characteristics, electrical properties and operational specifications, it needs to be adaptable to the circuit's current/voltage limits and other operating conditions. There are many types of 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. An electrometer is a device which is a measuring instrument with various applications and can be used to measure the current readings of a transistor subjected to different levels of input 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). As the program is software controlled, it decreases the data acquisition time drastically and eliminates the factor of human error the source meter is used to apply different amount of voltages at the gate terminal of the transistor and the electrometer measures the different drain current values. Such a program, coupled with the electrometer and source-meter, promotes an efficient way of making a voltage sweep and displaying a graph of the input voltage and output current from the data obtained simultaneously. This enables us to characterize the transistors and the data can be used to identify whether the transistor can be used in a particular system or circuit.

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1: Introduction

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. It is composed of semiconductor material usually with at least three terminals for connection to an external circuit. When a voltage or current applied to one pair of the transistor's terminals controls the current through another pair of terminals. A transistor can function as an amplifier or a switch. This is achieved by using a small amount of electricity to control a gate on a much larger supply of electricity.

Now Such conventional transistors are used mainly at higher currents but the electrometer that we have used allows us to measure very low current whose upper current limit is about 10 aA (10×10^{-18} A).that gave us the opportunity to work on the characterize the transistor which works on lower current region. Such transistor is the IRF540N that we considered to characterize. Keithley 6517B allows us higher accuracy and precision for measuring lower ranges of current, thus the amplifying and/or switching operations of each transistor could be monitored. So, my focus was to make a LabVIEW program that can give us a remote access to the Keithley 6517B and keithley 2450. After building the program in order to test its validity we will characterize a MOSFET, in later case which is the IRF540N. The IRF540N has been use because it has a very high resistance, after applying a significant amount of voltage which will result in a very low current. This will allow us to know the transistors behave right at the initial stages where only a little current has started to flow, as contrast to higher current ranges. This process is especially useful since the amplifying and switching actions can be identified from a much earlier stage. This allows us to specify for more sensitive circuits can be made more accurately; which cannot be done using conventional measuring instruments.

There are different types of Transistors such as (JBT, JFET, MOSFET, etc.). They also come with different working conditions and different specifications and methods. So figuring out how every particular transistor carries on under various conditions is basic to distinguish its operational parameters and limits. With that information, one can shrewdly pick which transistors are more appropriate to be components in a particular circuit. This builds circuit's general adequacy in performing errands like exchanging and enhancing signals/input, which are basic in many tasks.

The transistors (IRF540N) used for the study is a MOSFET (Metal-Oxide Semiconductor Field-Effect Transistor) – whose characterization and graphs are shown and explained later on.

1.1 MOSFET

A MOSFET, or Metal-Oxide Semiconductor Field-Effect Transistor, is a kind of transistor utilized for increasing or exchanging electronic signs which has a protected entryway whose voltage decides the conductivity of the component. The MOSFET is viably a four-terminal device, whose terminals are – source (S), gate (G), drain (D), and body (B). The body (or substrate) is regularly associated with the source terminal, making the MOSFET a three-terminal device like other field-effect transistors.

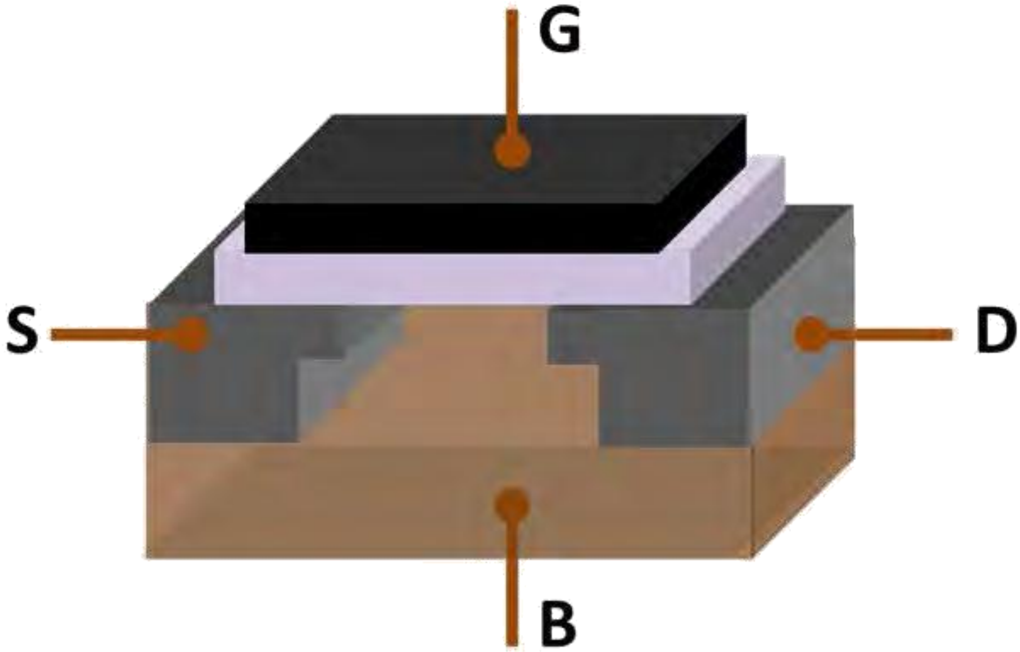


Fig 1.1: Internal structure of a MOSFET

1.1.1 MOSFET FUNCTION

The MOSFET works by electronically varying the width of a channel along which charge carriers flow (electrons or holes). The charge carriers enter the channel at source and exit via the drain. The width of the channel is controlled by the voltage on an electrode is called gate which is located between source and drain. It is insulated from the channel near an extremely thin layer of metal oxide. The MOS capacity present in the device is the main part.

The MOSFET can function in two ways

(1) Depletion Mode

(2) Enhancement Mode

(1) Depletion Mode:

When there is no voltage on the gate, the channel shows its maximum conductance. As the voltage on the gate is either positive or negative, the channel conductivity decreases.

For example

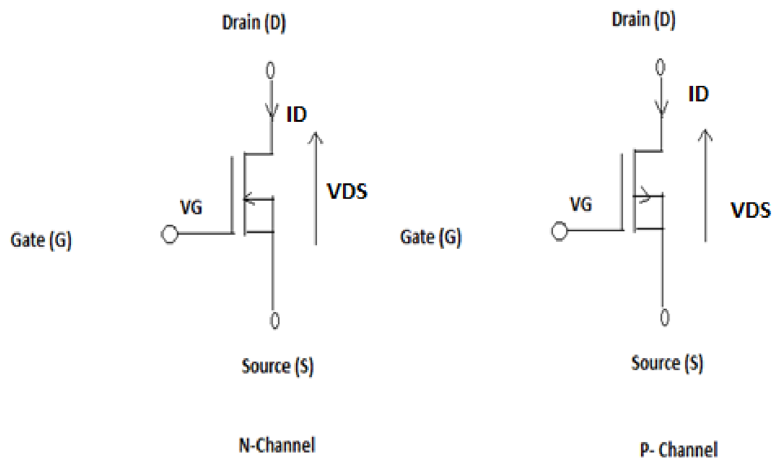


Fig 1.2: Basic construction of p-channel and n-channel MOSFETS for depletion mode

(2) Enhancement mode:

When there is no voltage on the gate the device does not conduct. More is the voltage on the gate, the better the device can conduct.

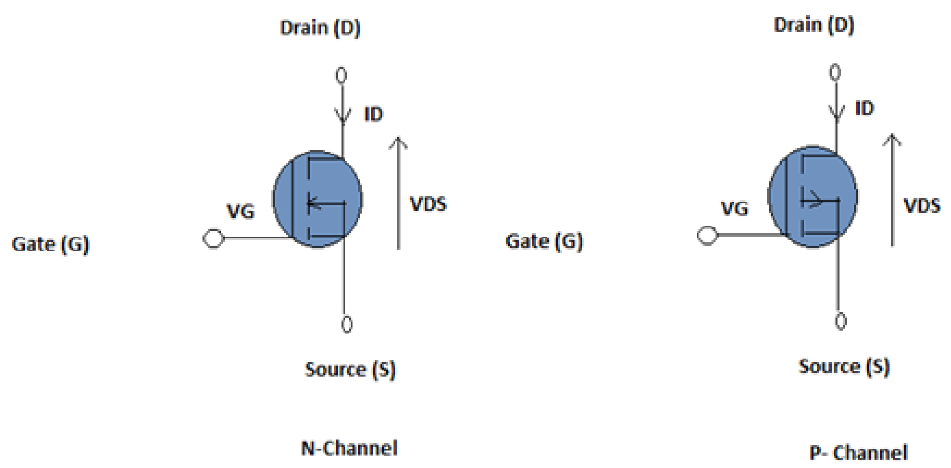


Fig 1.3: Basic construction of p-channel and n-channel MOSFETS for enhancement mode

1.1.2 MOSFET work principle

The point of the MOSFET is to have the capacity to control the voltage and current stream between the sources and deplete. It works nearly as a switch. The working of MOSFET relies on the MOS capacitor. The MOS capacitor is the fundamental piece of MOSFET. It very well may be modified from p-sort to n-type by applying positive or negative entryway voltages separately. When we apply the positive door voltage the openings present under the oxide layer with a horrendous power and gaps are pushed descending with the substrate. The exhaustion district populated by the bound negative accuses which are related of the acceptor particles. The electrons achieve channel is framed. The positive voltage additionally draws in more electrons from the n+ source and depletes locales into the channel. Presently, if a voltage is connected between the depletion region and source, the present streams openly between the source and deplete and the door voltage controls the electrons in the channel. Rather than positive voltage on the off chance that we apply negative voltage, a gap channel will be framed under the oxide layer.

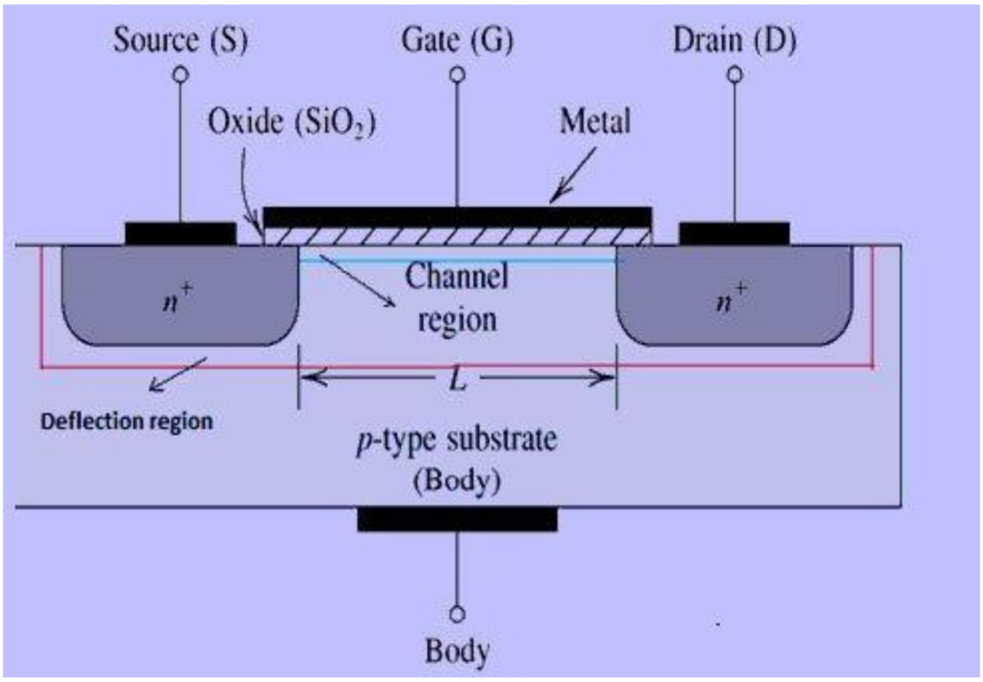


Fig 1.4: Internal structure of a MOSFET extended

P-Channel MOSFET:

The P- Channel MOSFET has a P- Channel region between source and drain. It is a four terminal device such as gate, drain, source, body. The drain and source are heavily doped p+ region and the body or substrate is n-type. The flow of current is positively charged holes. When we apply the negative gate voltage, the electrons present under the oxide layer with are pushed downward into the substrate with a repulsive force. The depletion region is populated by the bound positive charges which are associated with the donor atoms. The negative gate voltage also attracts holes from p+ source and drain region into the channel region.

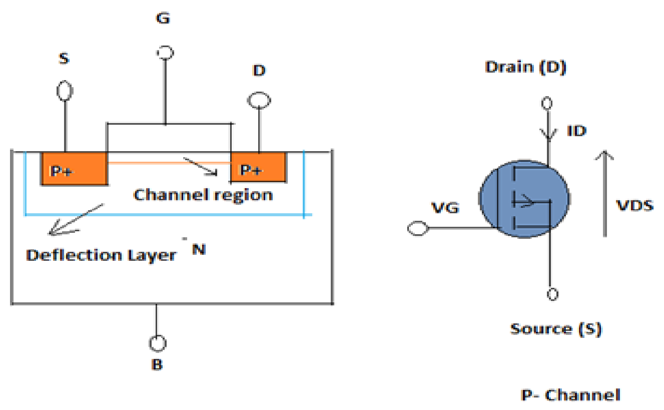


Fig 1.5: Basic construction of p-channel MOSFETS

N- Channel MOSFET:

The N-Channel MOSFET has an N- channel region between source and drain It is a four terminal device such as gate, drain, source, body. This type of MOSFET the drain and source are heavily doped n+ region and the substrate or body is P- type. The current flows due to the negatively charged electrons. When we apply the positive gate voltage the holes present under the oxide layer pushed downward into the substrate with a repulsive force. The depletion region is populated by the bound negative charges which are associated with the acceptor atoms. The electrons reach channel is formed. The positive voltage also attracts electrons from the n+ source electrons reach channel is formed. The positive voltage also attracts electrons from the n+ source and drain regions into the channel. Now, if a voltage is applied between the drain and source, the current flows freely between the source and drain and the gate voltage controls the electrons in the channel. Instead of positive voltage if we apply negative voltage a hole channel will be formed under the oxide layer.

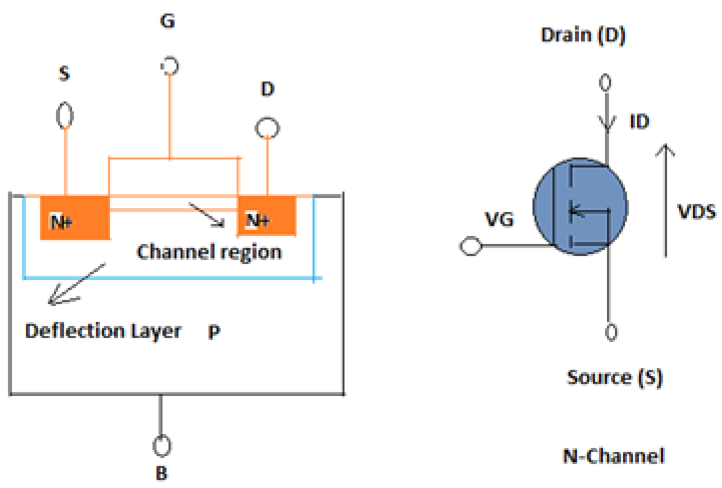


Fig 1.6: Basic construction of n-channel MOSFETS

1.2.1 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.

1.2.2 Source meter

The source measure unit (SMU), or source-measurement unit as it is sometimes called, is an electronic instrument that is capable of both sourcing and measuring at the same time. It can precisely force voltage or current and simultaneously measure precise voltage and/or current. SMUs are used for test applications requiring high accuracy, high resolution and measurement flexibility. Such applications include I-V characterizing and testing semiconductors and other non-linear devices and materials, where sourcing voltage and current source span across both positive and negative values. To accomplish this, SMUs have four-quadrant outputs.[1] For characterization purposes SMUs are bench instruments similar to a curve tracer. They are also commonly used in automatic test equipment and usually are equipped with an interface such as GPIB or USB to enable connection to a computer.

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 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 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.

1.3.1 VIRTUAL INSTRUMENTS

LabVIEW programs are called virtual instruments (VIs) because they often have the look and feel of physical systems or instruments. A VI and its components are analogous to main programs and subroutines from text programming languages like C and Fortran. VIs have both an interactive user interface known as the front panel and the source code represented in graphical form on the block diagram. LabVIEW provides mechanisms that allow data to pass easily between the front panel and the block diagram. The block diagram is a pictorial representation of the program code. The block diagram consists of executable icons (called nodes) connected (or wired) together. We will discuss wiring later in this chapter. The important concept to remember is that in LabVIEW the block diagram is the source code. The art of successful programming in LabVIEW is an exercise in modular programming. After dividing a given task into a series of simpler subtasks (these subtasks are called subVIs), you then construct a virtual instrument to accomplish each subtask.. The resulting subtasks (remember, these are called subVIs) are then assembled on a top-level block diagram to form the complete program. Modularity means that you can execute each subVI independently, thus making debugging and verification easier. Furthermore, if your subVIs are general purpose programs, you can use them in other programs.

1.3.1.1 Front Panel

The front panel of a VI is a combination of controls and indicators. Controls simulate the types of input devices you might find on a conventional instrument, such as knobs and switches, and provide a mechanism to move input from the front panel to the underlying block diagram. On the other hand, indicators provide a mechanism to display data originating in the block diagram back on the front panel. Indicators include various kinds of graphs and charts, as well as numeric, Boolean, and string indicators. Thus, when we use the term controls we mean “inputs,” and when we say indicators we mean “outputs.” You place controls and indicators on the front panel by selecting and “dropping” them from the Controls palette. Once you select a control (or indicator) from the palette and release the mouse button, the cursor will change to a “hand” icon, which you then use to carry the object to the desired location on the front panel and “drop” it by clicking on the mouse button again. Once an object is on the front panel, you can easily adjust its size, shape, and position. If the Controls palette is not visible, right-click on an open area of the front panel window to display the Controls palette.

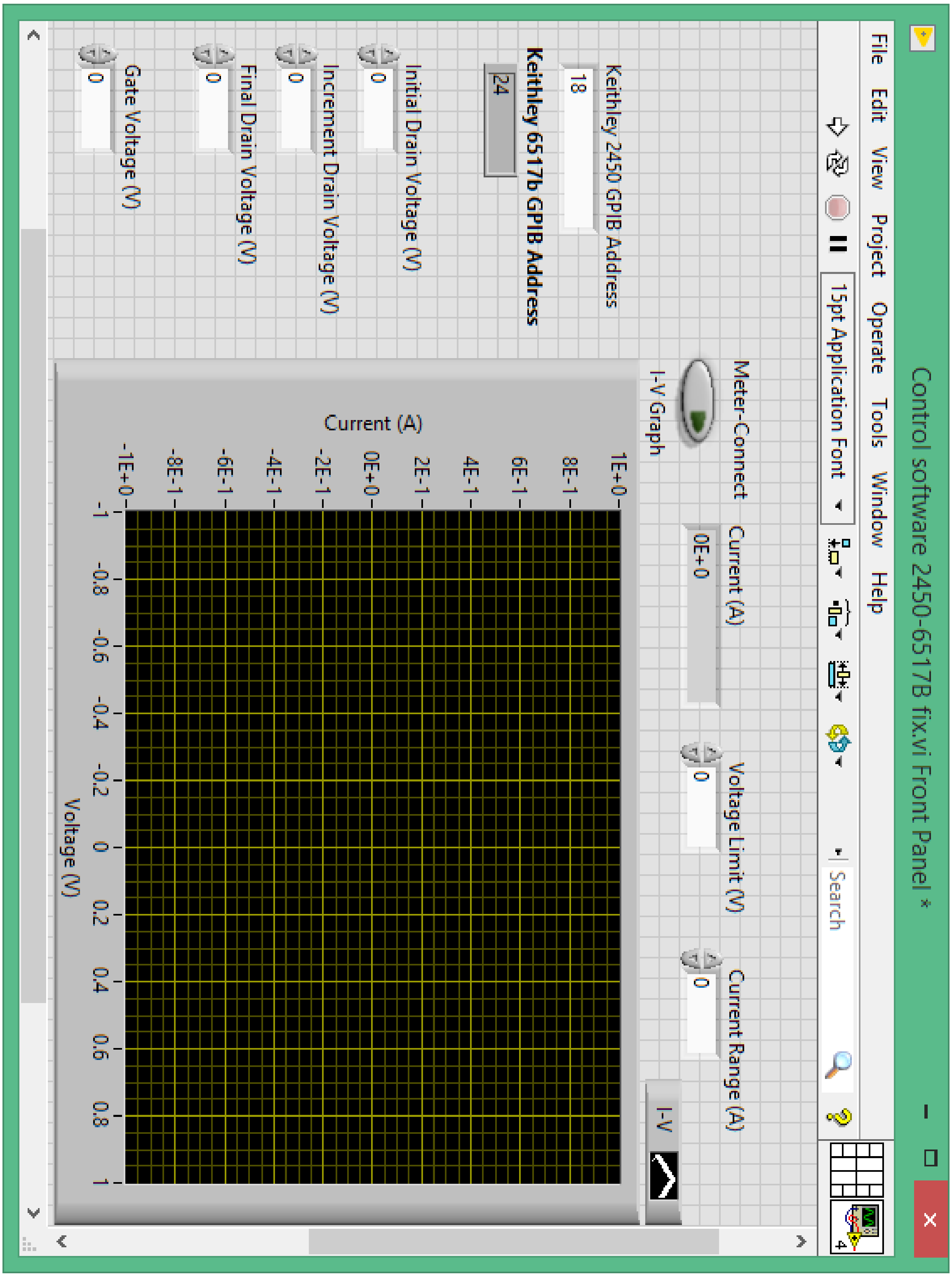


Fig 1.7: Front Panel of Control software VI

1.3.1.1 Block Diagram

The graphical objects comprising the block diagram together make up what is usually called the source code. The block diagram (visually resembling a computer program flowchart) corresponds to the lines of text found in text-based programming languages. In fact, the block diagram is the actual executable code that is compiled while you are programming, allowing instant feedback when you make mistakes, such as wiring incompatible data types. The block diagram is built by wiring together objects that perform specific functions. The components of a block diagram (a VI is depicted) belong to one of three classes of objects:

(i)Nodes: Program execution elements.

(ii)Terminals: Ports through which data passes between the block diagram and the front panel and between nodes of the block diagram.

(iii)Wires: Data paths between terminals.

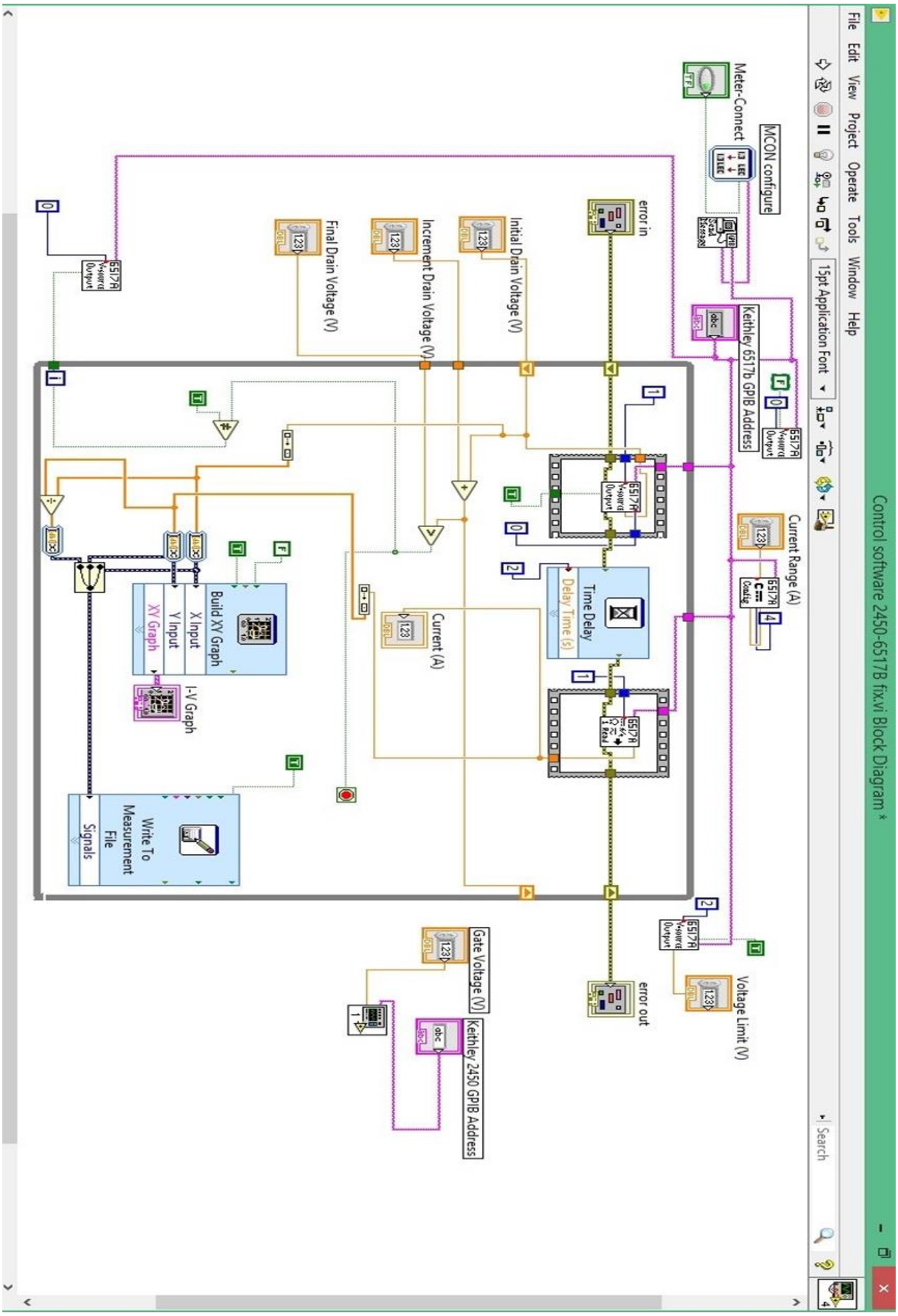


Fig 1.8: Block Diagram of Control software VI

2. DEVICES AND CONNECTIONS

2.1 Kiethley 6517B Electrometer

Fig 2.1: Front panel of Keithley 6517b electrometer

Specifications

Key Features

• Measures resistances up to 1018 Ω

• 10 aA (10×10^{-18} A) current measurement resolution

• <3 fA input bias current

• 6½-digit high accuracy measurement mode

• <20 μV burden voltage on the lowest current ranges

• Voltage measurements up to 200 V with >200 Ω input impedance

• Built-in ±1000 V voltage source

• Unique alternating polarity voltage sourcing and measurement method for high resistance measurements

• Built-in test sequences for four different device characterization tests, surface and volume resistivity, surface insulation resistance, and voltage sweeping

• GPIB and RS-232 interfaces

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.

2.2 Kiethley 2450 Source-meter

Fig 2.2: Front panel of Keithley 2450 source-meter

Key Features

• Capabilities of analyzers, curve tracers, and I-V systems at a fraction of their cost

• Five-inch, high resolution capacitive touchscreen GUI

• 0.012% basic measure accuracy with 6.-digit resolution

• Enhanced sensitivity with new 20mV and 10nA source/measure ranges

• Source and sink (four-quadrant) operation

• Front panel input banana jacks; rear panel input tri-axial connections

• Front panel USB memory port for storing data, programming, instrument configurations, and to upgrade the unit.

• Precision power supply with V and I read back

• True current source

• Trigger controller

2450 Power Envelope

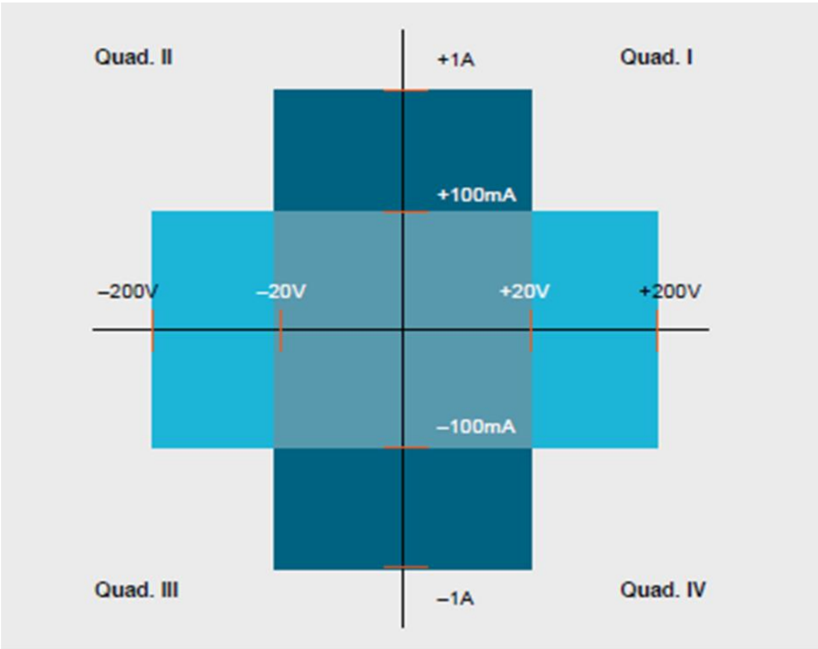


Fig2.3: Power envelop Keithley 2450

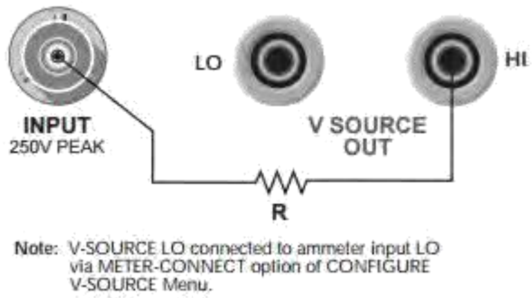
2.3. Basic Connections of Kiethley 6517B

- **Meter-Connect –**

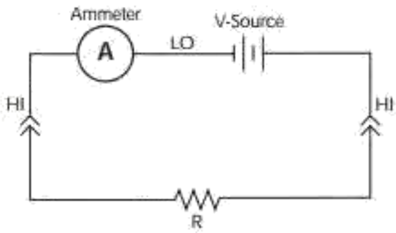
Before making vital associations from the electrometer to the PC for interfacing, a few stages must be taken to ensure appropriate working conditions. It was guaranteed that the electrometer itself was grounded legitimately to avert energize work as an essential wellbeing measure.

There was additionally a meter-interface highlight that demonstrated helpful to me. Since the electrometer has a HI and LO to be associated at each finish of the example to be estimated and a voltage source providing into the circuit, the link setup can get very muddled. To dodge this trouble I arranged the electrometer to empower the meter-associate component. The protection from be estimated is associated with the middle conductor of the info triax connector and the V-Source HI restricting post. This setup permits the V-source LO to be inside associated with ammeter LO.

Subsequently the associations are improved extraordinarily – the ammeter HI is associated with one end of the heap, and the source HI is associated with the opposite end to finish the circuit. The use of the meter-interface and its proportionate circuit is given in the following page:



A. Basic connections



B. Equivalent circuit

Fig 2.4: 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 it 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.

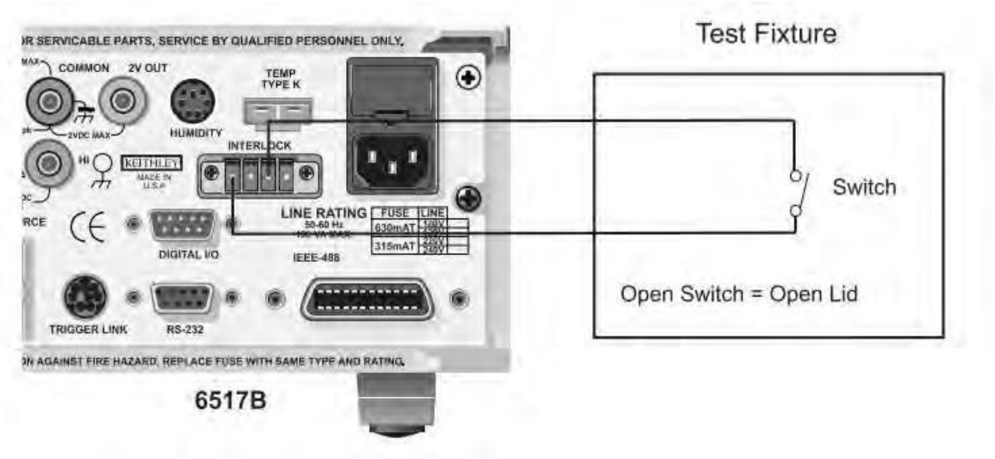


Fig 2.5: Circuit showing test fixture connected to interlock

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 obvious from the circuit chart above, I would need to short sticks 1 and 3 to recreate the circumstance where the test apparatus top is shut and the interlock is associated. Making fundamental associations I could connect with the interlock and permit the voltage source to supply to my circuit.

Fig 2.6: 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.

3. Interfacing and LabVIEW

I was to build up a VI program on LabVIEW to direct a voltage clear for the material to be investigated. The two most fundamental and basic VIs I required for the program comprised of one that can accept voltage to be connected as information (WRITE) from the client and apply said voltage, and an another that can show the electrometer's perusing to a similar client (READ). It was discovered that making these sub-VIs starting with no outside help would be superfluous and tedious, since such fundamental operational VIs are provided by the maker in their site. My whole work on LabVIEW rotated around adjusting the WRITE VI to take different info parameters from the client other than just voltage and issue these directions to the electrometer, and watch the information acquired from the electrometer utilizing the READ VI.

Since the primary target of the program was to direct a voltage clear, it needed to initially educate the electrometer to give incremental voltages at interims over the circuit. At the center of my program I made utilization of a move enlist, which works precisely like those found in computerized circuits. The essential thought was to make a circle inside which we have the sub-VIs (WRITE and READ), and the particular conditions were given for the circle to proceed on. An underlying quality needed to give which was utilized by the WRITE, and the outcome recorded by READ. After each cycle this esteem was expanded by a given sum (increase). At the point when the present esteem achieved a particular given last esteem, the circle would end. Here, the move enroll system enabled this incentive to be moved from one side of the circle to the next, expanding each time. The essential VI made is given beneath:

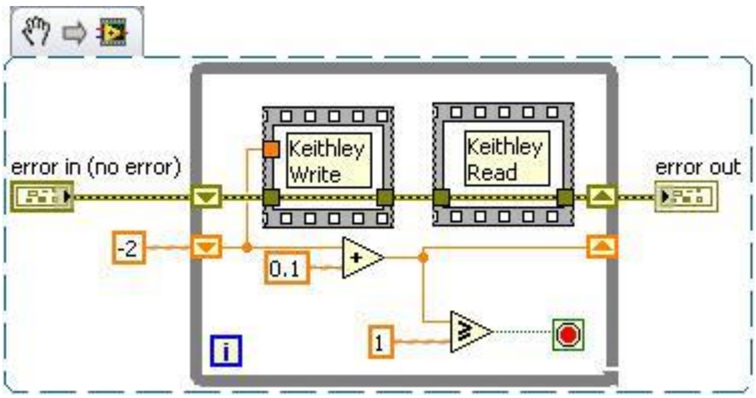


Fig 3.1: A basic looped VI utilizing a shift register (UP and DOWN symbols in orange)

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.

Ultimately, in the last form, I have additionally included a charting framework. This makes investigation of information got simpler and swifter. From the VIs WRITE and READ, I have made associations with the end goal that the present voltage input given (x-pivot) and the present perusing made (y-hub) are sent each one in turn to a dynamic library. This feeds a diagramming apparatus with information each time a circle is finished, which at that point plots the point on a chart that can be seen on the front board. As a result the chart plotting is procedural, implying that the client does not need to sit tight for every one of the information to be put away for the diagram to show up since each point is plotted after every datum WRITE and READ cycle. [6]

Likewise in the last form, I associated the charting apparatus to a document stockpiling framework. This permitted me store every one of the information I required (voltage, current, obstruction) for each perusing anticipating further investigation. This VI depended specifically on the dynamic information library, so its creation is likewise procedural as it stores information in the record one perusing at any given moment as opposed to anticipating the end of the program.

This came about is a program that is instinctive for any new client not associated with its advancement, to be utilized in applications like voltage clear. The front board that the client will see has just been appeared. The back board, containing all my genuine work on the program is appeared in the following part:

4. Transistor Characterization

4.1 Introduction

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.

4.1.1. IRF540N

Advanced HEXFET® Power MOSFETs from International Rectifier utilize advanced processing techniques to achieve extremely low on-resistance per silicon area. This benefit combined with the fast switching speed and ruggedized device design that HEXFET power MOSFETs are well known for, provides the designer with an extremely efficient and reliable device for use in a wide variety of applications.

4.1.2. MOSFET

The enhancement mode MOSFET, or eMOSFET, is the turnaround of the depletion mode composes. Here the directing channel is softly doped or even undoped making it nonconductive. The output in the device is “OFF" (non-leading) when the gate voltage, V_{GS} is equivalent to zero. For the n-channel improvement MOS transistor a deplete current will just stream when an entryway voltage (V_{GS}) is connected to the door terminal more prominent than the limit voltage (V_{TH}) level in which conductance happens making it a trans conductance gadget. The utilization of a positive (+ve) door voltage to a n-type eMOSFET pulls in more electrons towards the oxide layer around the entryway in this way expanding or improving (subsequently its name) the thickness of the channel enabling more present to stream. This is the reason this sort of transistor is called an improvement mode gadget as the utilization of an entryway voltage upgrades the channel. Expanding this positive door voltage will make the channel obstruction diminish additionally causing an expansion in the deplete current, ID through the channel. At the end of the day, for a n-channel improvement mode MOSFET: $+V_{GS}$ turns the transistor "ON", while a zero or - V_{GS} turns the transistor "OFF". At that point, the upgrade mode MOSFET is identical to a "regularly open" switch. A conventional trademark chart of the deplete current (I_D) to the deplete source potential (V_{DS}) is appeared in the page. [9]

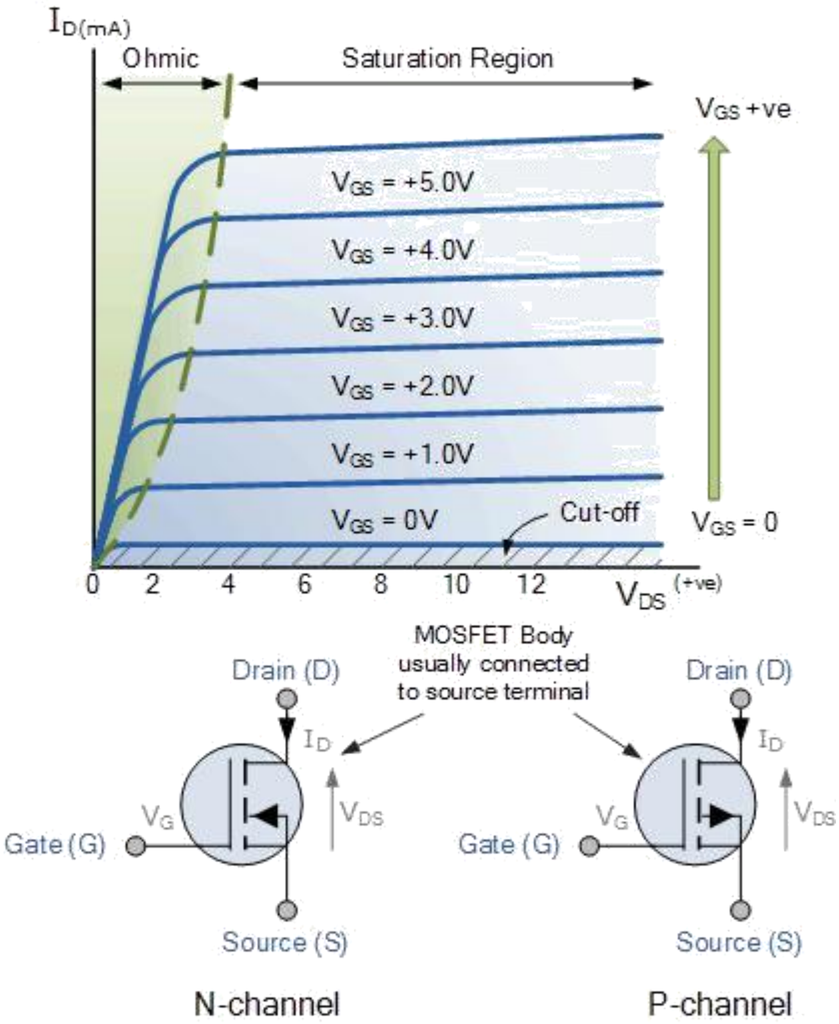


Fig 4.1: eMOSFET characteristic graph with circuit symbols

Taking into account the overall concept and working principle of MOSFETs, I used a model IRF540N 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:

5: Results and Discussions

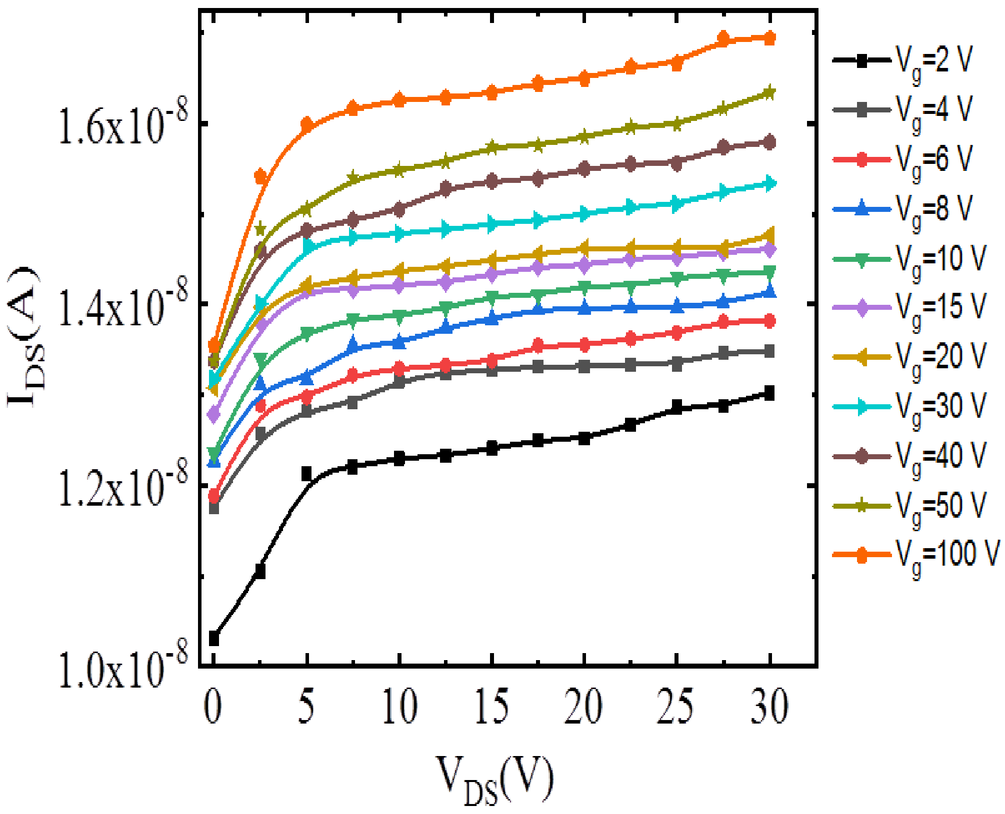


Fig 5.1: ID against VDS of the IRF540N MOSFET

Now as we had taken the data by two segments first we fixed a biasing voltage then changed the drain to source voltage gradually. We increased the drain to source voltage from 0 to 30 with an increment of 2.5V. After that we started to change the biasing voltage and started to take the readings same way as before. So we got a nice set of graphs showing the I-V characteristics of a MOSFET. When we applied a biasing voltage of 2V we got a shoulder sort of image so amplified the section by applying a very small increment od 0.1V. so the got magnified as the one below.

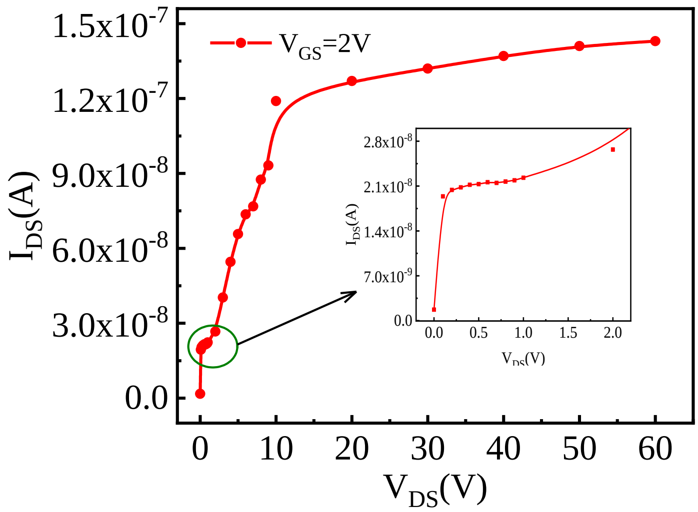


Fig 5.2: ID against V_{DS} for the IRF540N MOSFET (at V_{GS}= 2V)

From 0V to 1V of Drain to source voltage, 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 1V 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 0V-5V or 5V-10V is much greater than that created between 10V-30V. 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.

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.

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}.

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} = 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 3.5V. On the other hand, for V_{GS}> V_{TH}, we can see that the drain current keeps on increasing.

For the V_{GS}=2V 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}<3.5V
- ON – for V_{GS}>3.5V

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, 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

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.

- <u>MOSFET:</u>

As in the case of the PNP BJT, the results obtained for the MOSFET IRF540N was referred to the model-specific datasheet for consistency.

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 25ºC. Increasing the gate voltage, and subsequently VGS, we see an amplification effect on the output current ID. It is also identifiable from the graph that gate voltage of 3V can be considered to be the maximum voltage (threshold voltage) up to 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:

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 reference since 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 up to 10V:

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 VGS which are at or less than 3V gave curves where the drain current ID stopped increasing starting from a relatively low source voltage of about 3.5V. On the other hand, for VGS> VTH, we can see that the drain current keeps on increasing.

- OFF: for V_{GS}< 3.5V
- ON: for 3.5V < V_{GS}< 10V, since amplification is greatly reduced after V_{GS} = 10V

6. Conclusion

So the interface application that had been developed which integrates both the electrometer (Kiethley 6517B) and source meter (Kiethley 2450). The LabVIEW program, runs perfectly without any kind of optimization error. And to verify the programmed runs correct a MOSFET (IRF540N) had been characterized. The characterization graph resembles the graph that we had seen in the data sheet. So we have a glimpse of an idea that the VI is doing as expected. Thus we can reach to a conclusion that the primary focus of the project which was building an interface application was fulfilled.

References

[1] Ma, H. (2005). Fundamentals of electronic circuit design. Retrieved fromhttp://www-mdp.eng.cam.ac.uk/web/library/enginfo/electrical/hong1.pdf

[2] Floyd, Thomas L. (2005). *Electronic devices, 7th Edition*. Pearson Education

[3] Boylestad, Robert L., Nashelsky, Louis. (1999).*Electronic devices and circuit theory, 7th edition.*Prentice Hall

[4] Mini-Coater - high vacuum coating system for thin film deposition. Retrieved fromhttp://www.tectra.de/mico.htm

[5] (2009). Keithley model 6517B reference manual.Retrieved from http://www.keithley.com

[6] LabVIEWtutotials. Retrieved from https://www.labviewmakerhub.com/doku.php?id=learn:tutorials:labview:start

[7] (2015). PNP transistor. Retrieved from http://www.electronicshub.org/pnp-transistor/

[8] Hayt, William H. (2010). *Engineering circuit analysis, 7th edition.*McGraw-Hill

[9] (2014). The MOSFET. Retrieved fromhttp://www.electronics-tutorials.ws/transistor/tran_6.html

[10] nMOSFET (enhancement) characteristic curves. Retrieved from http://www.physics.csbsju.edu/trace/nMOSFET.CC.html

[11] (1997). IRF540N datasheet. Retrieved from http://www.alldatasheet.com/datasheet-pdf/pdf/2842/MOTOROLA/ IRF540N.html