BRAC UNIVERSITY

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# CSE251

## Electronic Devices and Circuits

## Spring-24

## Lab Experiment No- 5


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**Section: 03**

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Group No: 04

Experiment-05

# Study of I-V Characteristics of MOSFET, BJT and Implementation of Logic Functions

CSE251 - Electronic Devices and Circuits Lab

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## Objective

1. To observe and understand the I-V characteristics of MOSFET and BJT.
2. To implement a NAND gate and a Logic Function using MOSFETs and BJTs and verify the truth tables.

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## Background Theory

### Introduction to MOSFET

Three-terminal devices are far more useful than two-terminal ones (such as Diodes) because they can be used in a multitude of applications, ranging from signal amplification to digital logic and memory. The basic principle involved is the use of the voltage between two terminals to control the current flowing in the third terminal. In this way a three-terminal device can be used to realize a controlled source.

The control signal can be used to cause the current in the third terminal to change from zero to a large value, thus allowing the device to act as a switch. Switch is the basis for the realization of the logic inverter, which is a basic element of digital circuits.

There are two major types of three-terminal semiconductor devices: (i) MOSFET (Metal-Oxide Semiconductor Field-Effect Transistor) and (ii) BJT (Bipolar Junction Transistor). Although both of them offer unique features and areas of application, MOSFET has become by far the most widely used electronic device, especially in the design of integrated circuits (ICs).

There are two kinds of MOSFET: (i) NMOS and (ii) PMOS. In this experiment, we will study about the I-V characteristics of NMOS and design an NAND gate and a Boolean Logic Function using the NMOS transistor. The figure above shows the IC and the circuit diagram of a MOSFET (NMOS).

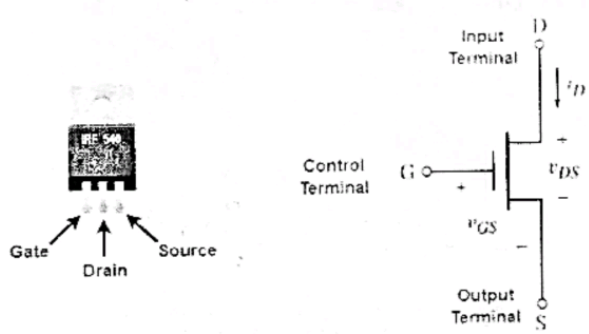



Figure 1: *NMOS IC and Circuit Diagram*

## MOSFET as a Switch

MOSFET is a three-terminal device with a control terminal, an input terminal, and an output terminal. The control terminal of the MOSFET is called its gate G, the input terminal its drain D, and the output terminal its source S. MOSFET can act as a switch depending upon the applied voltage in the input terminal. A simple circuit model known as 'Switch Model' or 'S-Model' is used to model this behavior.

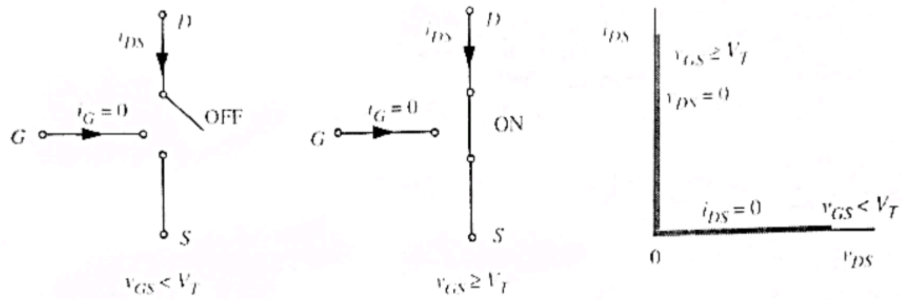



Figure 2: ***S-Model of MOSFET***

We can summarize the S-model of the MOSFET in algebraic form as:

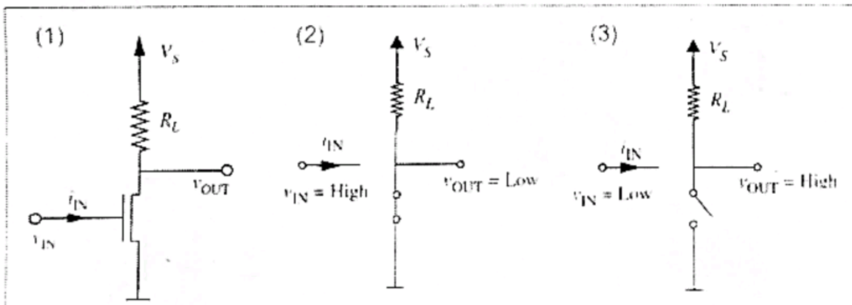
$$\text{when} \longrightarrow v_{GS} < V_T, \quad \text{then} \longrightarrow i_{DS} = 0 \quad \text{and} \quad \text{when} \longrightarrow v_{GS} \geq V_T, \quad \text{then} \longrightarrow v_{DS} = 0$$

## MOSFET Switch Implementation of Logic Gates and Logic Functions

Switches can be used to build logic gates. As we can use MOSFET as a switch, logic gates can be built using MOSFETs. The following subsections discuss two logic gates, NOT gate and NAND gate, which are implemented using MOSFETs. We can also implement various Logic Functions using MOSFETs. To demonstrate this thing, a logic function will be implemented in Task-01.

### NOT Gate/Inverter Using MOSFET

Consider the circuit shown in following figure, which comprises a MOSFET and a load resistor powered by a supply voltage $V_S$. This circuit acts as a NOT Gate/Inverter.




(4)

| $v_{IN}$ | $v_{OUT}$ |
|---|---|
| $High \equiv 1$ | $Low \equiv 0$ |
| $Low \equiv 0$ | $High \equiv 1$ |

Figure 3: ***(1) MOSFET NOT Gate (2) When Input is '1' (3) When Input is '0' (4) Truth Table***

### NAND Gate Using MOSFET

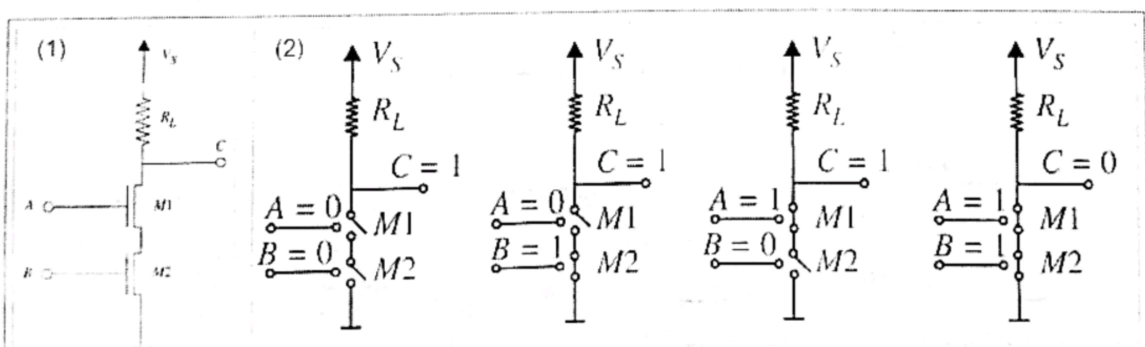



Figure 4: ***(1) MOSFET NAND Gate (2) Equivalent Circuits for Different Inputs***

Consider the circuit shown in the figure above, which comprises a two MOSFETs and a load resistor powered by a supply voltage $V_S$. This circuit acts as a NAND gate. NAND gate is a universal gate that can be used to implement any Logic Function.

### Logic Function Using MOSFET

We can use combinations of MOSFETs to implement various logic funtions. The circuit shown in **Figure-5** implements $f = \overline{xy + z}$.

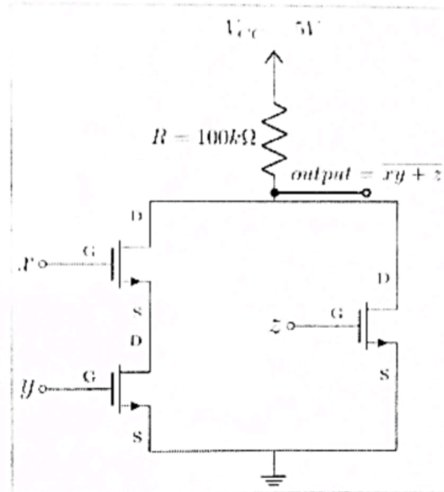



Figure 5: ***Logic Function using MOSFET***

## I-V Characteristics of a MOSFET

The S-model of a MOSFET is a simplification of the actual I-V characteristics of a MOSFET which helps us understand the behavior of a MOSFET as a switch. But the actual I-V characteristics is very different from it.

**Figure-6** represents the actual I-V characteristics of a MOSFET. There are 3 operating regions in the I-V characteristics graph: **Cut-off, Triode, Saturation**. The first two are useful if we want to use MOSFET as a switch. On the other hand, if we want to use MOSFET as an amplifier, we must operate it in the saturation region.

MOSFET's operating region depends on the applied voltages at Gate, Drain, Source terminals which can be seen in the I-V characteristics graph.

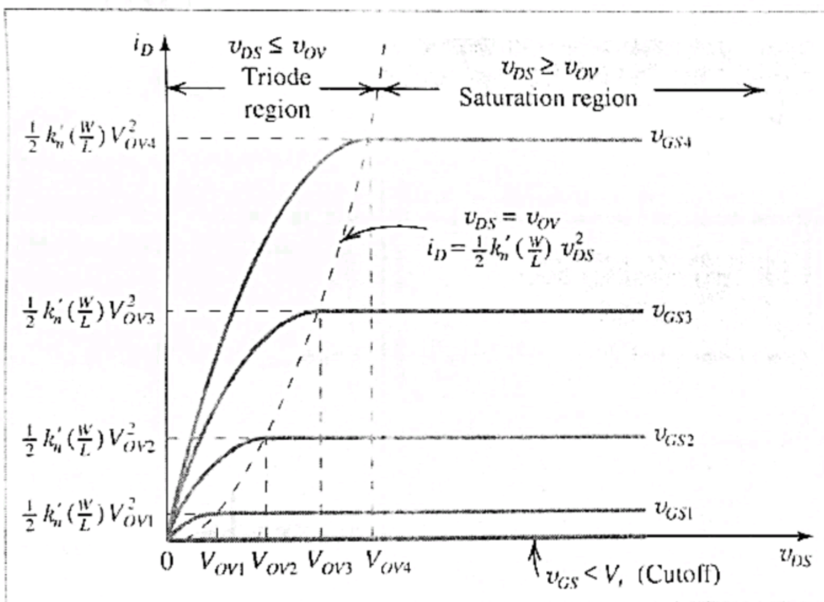



Figure 6: ***I-V Characteristics of a MOSFET***

In this graph

$V_T$ = *Threshold Voltage*

$v_{OV}$ = *Overdrive voltage*

$L$ = *Channel Length*

$W$ = *Channel Width*

$k_n'$ = *Process Transconductance Parameter*

$v_{GS} = v_G - v_S$

$v_{DS} = v_D - v_S$

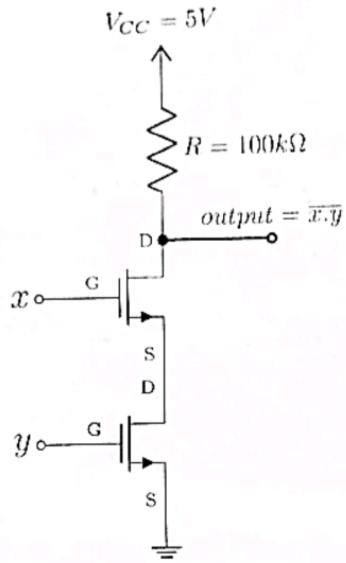
$v_{OV} = v_{GS} - V_T$

We can summarize the operating regions of as MOSFET as:

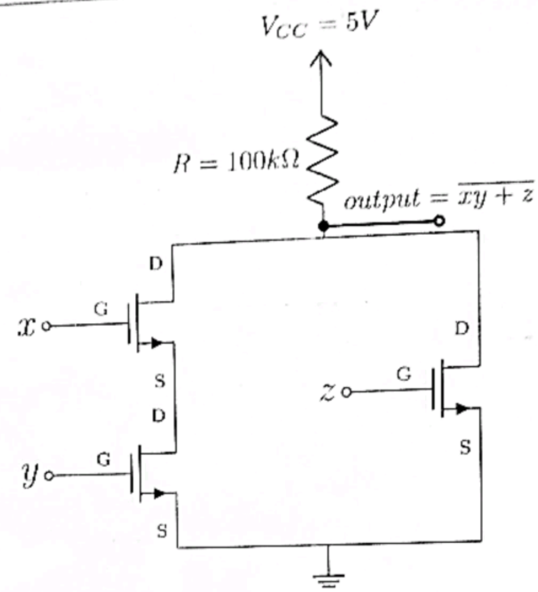
| When | Operating Mode | Equation of Current |
|---|---|---|
| $v_{GS} < V_T$ | Cutoff Mode | $i_D = 0$ |
| $v_{GS} \ge V_T, v_{DS} \le v_{OV}$ | Triode Mode | $i_D = k_n'\,(W/L)\,(v_{OV} - \frac{1}{2}v_{DS})\,v_{DS}$ |
| $v_{GS} \ge V_T, v_{DS} > v_{OV}$ | Saturation Mode | $i_D = \frac{1}{2}k_n'\,(W/L)\,v_{OV}^2$ |

The value of $V_T$ is controlled during device fabrication and typically lies in the range of 0.3 V to 1 V. From the graph, we see that, for the same value of $v_{DS}$, $i_{DS}$ increases if we increase $v_{GS}$. Also, for a lower value of $v_{GS}$, the MOSFET operates in Saturation for a lower value of $v_{DS}$ and for higher value of $v_{GS}$, the MOSFET goes into Saturation for a higher value of $v_{DS}$.

## Task-01: Logic Gate and Logic Function Implementation




*Circuit-1*
*NAND Gate using MOSFET*




*Circuit-2*
*Logic Function, $f = \overline{xy + z}$ using MOSFET*

### Procedure

1. On a trainer board, setup the Circuit 1.
2. Connect the gate terminals (input x and y) to data switches. Those switches provide 5V approximately.
3. Keeping $V_{CC}$ constant at 5V, at first turn off the data switches connected to the gate terminal. This implies you are now applying $V_x$= 0V, $V_y$= 0V. Measure the corresponding output voltage, $V_{out}$ which should be approximately 5V which corresponds to boolean 1.
4. The boolean outputs can also be determined by the state of an LED. Connect $V_{out}$ to one of the LEDs and check it. When the LED is ON, the boolean output is 1. Similarly, when the LED is OFF, the boolean output is 0.
5. Next, use the input voltage combinations of Data Table 1 and observe the state of LED again.
6. Verify the truth table of the NAND gate.
7. Now we will implement a Logic Function, f = $\overline{xy + z}$ using MOSFET. Circuit 2 in the figure shown above represents the Logic Function f = $\overline{xy + z}$. Setup Circuit 2 in a similar way to the procedure followed for Circuit 1.
8. Keeping $V_{DD}$ constant at 5V, observe the state of the LED for different combinations of the inputs $x$, $y$ and $z$ as shown in Data Table 1.
9. Verify the truth table of the Logic Function, f = $\overline{xy + z}$.

### Data Table 1: Verification of the Truth Tables of Logic Gate and Logic Function

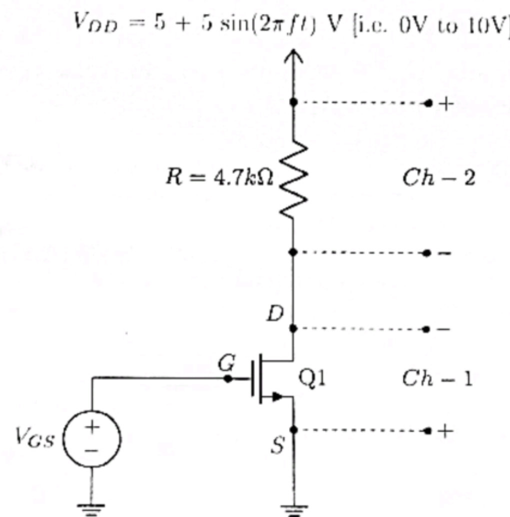
1. NAND Gate

| Input Voltage, $V_x$ (volt) | Input Voltage, $V_y$ (volt) | State of LED (On/Off) | Boolean Output (0 or 1) |
|---|---|---|---|
| 0V | 0V | On | 1 |
| 0V | 5V | On | 1 |
| 5V | 0V | On | 1 |
| 5V | 5V | Off | 0 |

2. Logic Function, $f = \overline{xy + z}$

| Input Voltage, $V_x$ (volt) | Input Voltage, $V_y$ (volt) | Input Voltage, $V_z$ (volt) | State of LED (On/Off) | Boolean Output (0 or 1) |
|---|---|---|---|---|
| 0V | 0V | 0V | ON | 1 |
| 0V | 0V | 5V | OFF | 0 |
| 0V | 5V | 0V | ON | 1 |
| 0V | 5V | 5V | OFF | 0 |
| 5V | 0V | 0V | ON | 1 |
| 5V | 0V | 5V | OFF | 0 |
| 5V | 5V | 0V | OFF | 0 |
| 5V | 5V | 5V | OFF | 0 |

## Task-02: I-V Characteristics of a MOSFET




### Procedure

1. Construct the circuit shown above. Use a data switch and connect it to the Gate of the MOSFET which will provide necessary voltage for $V_{GS}$. Use the function generator for $V_{DD} = 5 + 5\sin(2\pi ft)$ V [i.e. an AC voltage that varies from 0V to 10V] and set $f = 50$ Hz.
2. Set the oscilloscope in X-Y mode. Invert the Channel-1.
3. Observe the plot in the oscilloscope when the data switch is ON and OFF. This plot shows the I-V characteristics of a MOSFET as a switch. Capture the plots using your mobile camera.
4. Now, disconnect the data switch from the gate of the MOSFET and connect the dc power supply to the gate terminal so that we can increase or decrease $V_{GS}$.
5. Rotate the voltage knob of the dc power supply slowly from 0V to 5V. You should observe the change in the I-V characteristics.
6. Use your mobile camera to capture the image of the I-V characteristics graphs for 3 different $V_{GS}$. Measure the values of $V_{GS}$ of the captured images and write them below:

| Values of $V_{GS}$ | |
|---|---|
| 1st Value | 2.3 |
| 2nd Value | 2.2 |
| 3rd Value | 2.1 |

## Introduction to BJT

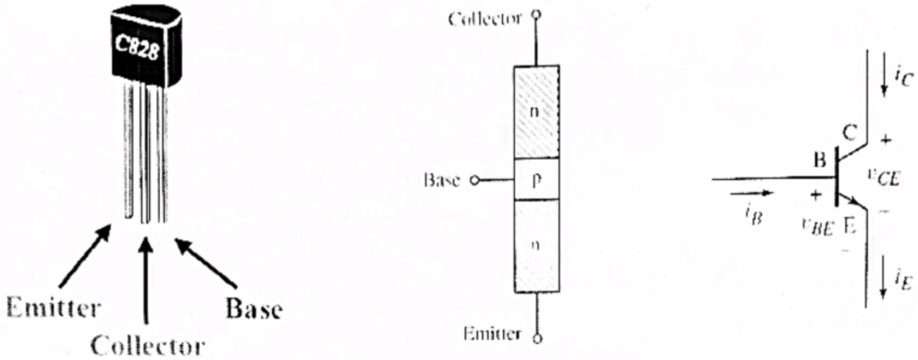



Figure 7: ***IC, Simple Geometry and Circuit Symbol of an npn BJT***

The bipolar junction transistor (BJT) is a type of transistor that is used for electrical amplification and in very-high frequency applications such as radio frequency (RF) circuits for wireless systems and high-speed switching emitter-coupled logic (ECL) gates. BJT is primarily a three terminal device consisting of the following terminals: Base (B), Emitter (E), Collector (C). There are two types of BJTs: (i) npn BJT and (ii) pnp BJT. Our discussion and experiment will be confined to npn BJT.

Figure 7 shows the IC, circuit symbol and simple geometry of an npn BJT. The arrowhead in the circuit symbol is always placed on the emitter terminal, and it indicates the direction of the emitter current. For an npn BJT, this direction is out of the emitter. The npn BJT contains a thin p-region between two n-regions. So the transistor consists of two pn junctions, the emitter–base junction (EBJ) and the collector–base junction (CBJ). Depending on the bias condition (forward or reverse) of each of these junctions, different modes of operation of the BJT are obtained. The operating modes are: Cut-off, Active and Saturation. The following table summarizes the modes of operation.

The active mode is the one used if the transistor is to operate as an amplifier. Switching applications (e.g. logic circuits) utilize both the cutoff mode and the saturation mode. There can be a fourth mode of a BJT called the reverse-active mode which occurs when the EBJ is reversed biased and the CBJ junction is forward biased (not shown in the table).

| BJT Modes of Operation | | |
|---|---|---|
| Mode | **Emitter Base Junction** | **Collector Base Junction** |
| **Cutoff** | Reverse Bias | Reverse Bias |
| **Active** | Forward Bias | Reverse Bias |
| **Saturation** | Forward Bias | Forward Bias |

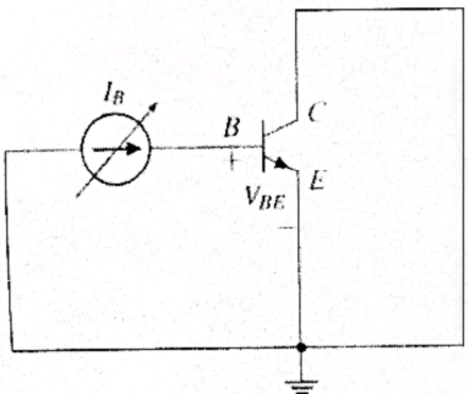
The active mode is the most important mode of the 3 modes of operation of BJT. Because BJT can be used as an amplifier only in this mode. BJT will be in active mode when EBJ is in Forward Bias and CBJ is in Reverse Bias. BJT operates in saturation mode when its collector current is not dependent on the base current and has reached a maximum. This happens when both the EBJ and the CBJ are in Forward Bias. In saturation mode, huge amount of current flows through BJT and it acts like a closed switch. Cut-off mode is the opposite of saturation mode. In cut-off mode, both junctions of BJT remain reverse biased. That is why no current flows through the device (actually, very negligible amount of current flows) and the BJT acts like an open switch.

## Input and Output I-V Characteristics of BJT

The I-V characteristics of a BJT depends on the circuit configuration. There are three basic configurations for connecting the BJT: the common base (CB) configuration, the common emitter (CE) configuration, and the common collector (CC) configuration. Though each configuration has their own applications, the CE is the most widely used configuration and by far the most popular for amplifiers.

In CE configuration, the emitter is the common terminal. Hence, the input is between the base and the emitter while the output is between the collector and the emitter. So, the input I-V characteristics is the variation of the base current $I_B$ with the base-emitter voltage $V_{BE}$, and the output I-V characteristics is the variation of the collector current $I_C$ with the collector-emitter voltage $V_{CE}$.

The following figure shows the input I-V characteristics of an npn BJT for the CE circuit configuration which illustrates the variation in $I_B$ with respect to $V_{BE}$ when $V_{CE}$ is kept constant. In the graph, $I_B$ changes exponentially as $V_{BE}$ changes. This is obvious since the BJT's base-emitter junction is similar to a pn junction diode. So it's current voltage relationship should also be like a pn junction diode.



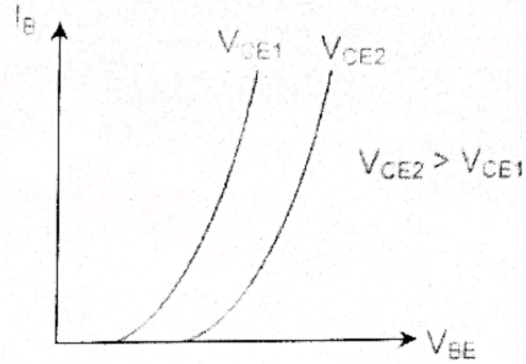
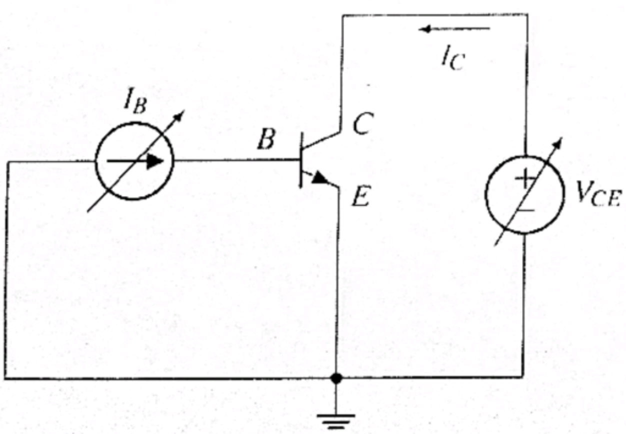




Figure 8: BJT input I-V characteristics Circuit and Graph in CE configuration

The output I-V characteristic of a BJT in CE configuration is also referred to as the collector characteristic. We are mainly interested in this one. The following circuit and graph shows the output I-V characteristics of a BJT in CE configuration. The I-V characteristics shows the variation in $I_C$ with the changes in $V_{CE}$ when $I_B$ is held constant. In the graph we can see a rapid increase in collector current at the beginning. Then the collector current becomes almost constant. This graph can be divided into 3 regions:

1. Active Region (where output current becomes almost constant)
2. Saturation Region (where $I_C$ increases rapidly)
3. Cut-off Region (where the current is zero/almost zero)



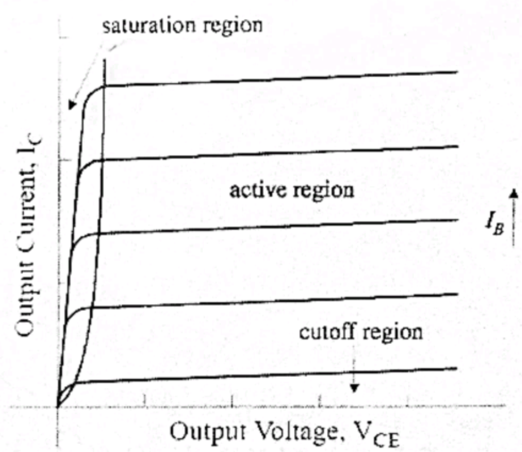
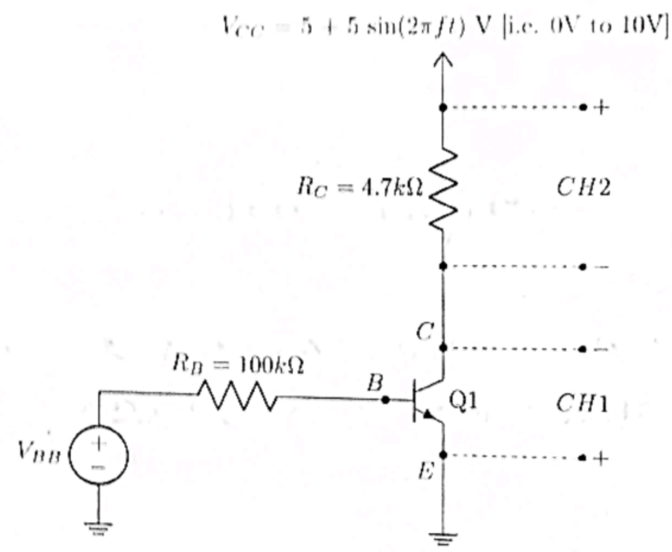




Figure 9: BJT output I-V characteristics Circuit and Graph in CE configuration

From the output I-V characteristics we see that, in the active region, if we keep $V_{CE}$ constant, $I_C$ increases with the increase of $I_B$. This relationship between $I_C$ and $I_B$ in active mode is actually linear in nature which can be represented by the following equation: $I_C = \beta I_B$, where $\beta$ is a constant. Typically, $\beta = 50$ to 200.

## Task-03: I-V Characteristics of a BJT




### Procedure

1. Construct the circuit shown above. Use the function generator for $V_{CC} = 5 + 5\sin(2\pi ft)$ V [i.e. an AC voltage that varies from 0V to 10V]. Set $f = 50$ Hz. Use the dc power supply for $V_{BB}$.
2. Invert the Channel-1. Set the oscilloscope in the X-Y mode.
3. Now, rotate the voltage knob of the dc power supply slowly from 0V to 5V to vary $V_{BB}$. You should observe the change in the I-V characteristics.
4. Use your mobile camera to capture the image of the I-V characteristics graphs for 3 different values of $V_{BB}$. Measure the values of $V_{BB}$ of the captured images and write them below:

| Values of $V_{BB}$ | |
|---|---|
| 1st Value | 0.7 |
| 2nd Value | 1.1 |
| 3rd Value | 1.3 |

Signature of the lab faculty

## Task-04: Report

1. Cover page [include course code, course title, name, student ID, group, semester, date of performance, date of submission]
2. Attach all the captured images and describe them properly using the experimental data [if any].
3. Answer the questions of the Test Your Understanding section.
4. Add a brief Discussion regarding the experiment. For the Discussion part of the lab report, you may include the answers of the following questions in your own words:
   - What did you learn from this experiment?
   - What challenges did you face and how did you overcome the challenges? (if any)
   - What mistakes did you make how did you correct the mistakes? (if any)
   - How will this experiment help you in future experiments of this course?

## Test Your Understanding

Answer the following questions:

1. We can use the MOSFET as a switch. Which operating regions do we need for this purpose and why?

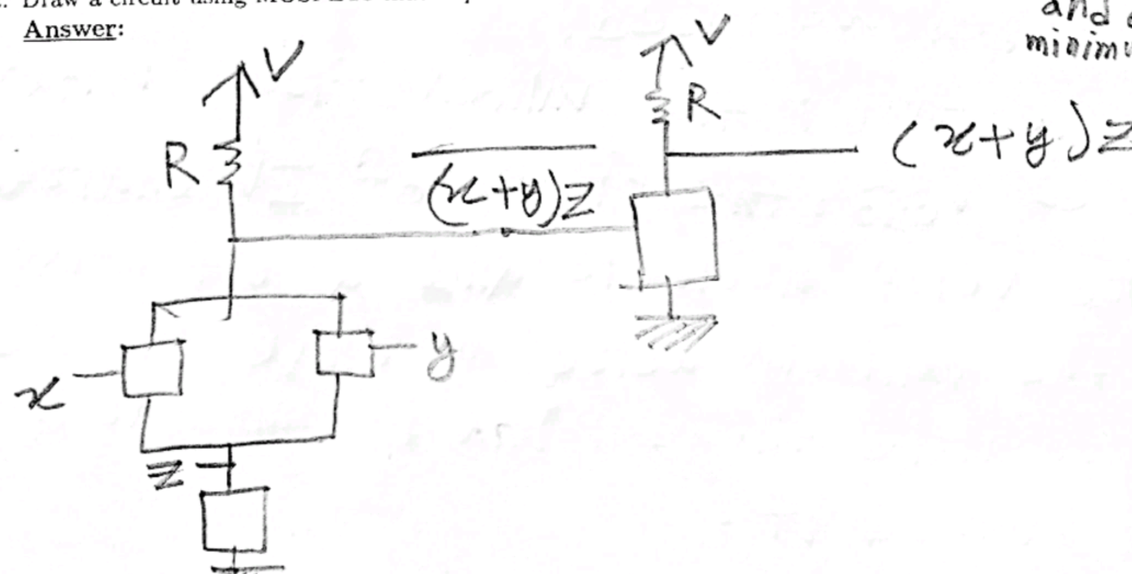
   <u>Answer:</u> → cutoff region

   → Saturation region

Mosfet acts a short ckt or closed switch in the saturation region and open ckt or opened switch in the cutoff region. In cutoff region, $\boxed{V_{GS} < V_{th} \; R_S \text{(high)}}$ minimize leakage current and power consumption the device doesn't conduct. On the other hand, saturation region minimizes power dissipation and ensure minimum Vdrop.

2. Draw a circuit using MOSFETs that implements the following logic function, $f = (x+y)z$

   <u>Answer:</u>




3. We used MOSFET as a switch and implemented various logic funtions. Can we do the same using BJTs? Explain briefly.

   <u>Answer:</u> Yes similar to mosfet, we can use BJT as a switch and implement various logic functions.

→ cutoff and saturation mode

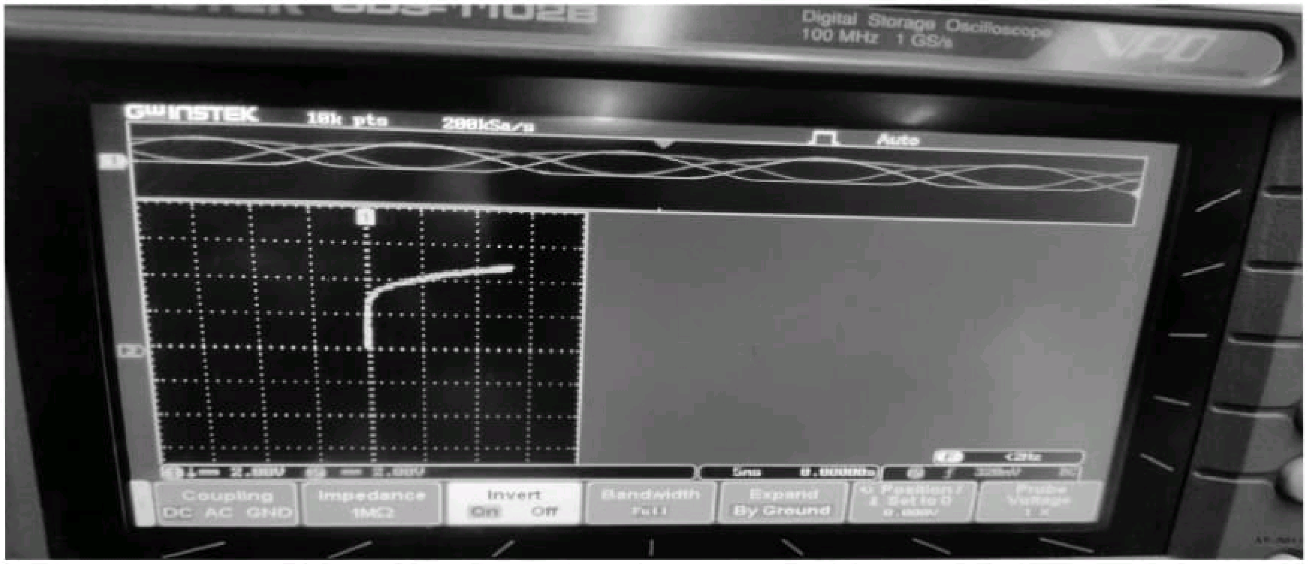
(open switch) (closed switch)

$I_{CE}$ (negligible) $I_{CE}$ (exists)

→ NOT, AND, OR, NAND, XOR, NOR gates can be implemented via this switch combining various config

Discussion:
From the following experiment, after conducting task 1, 2, 3 I learned.
- The practical implementation of Mosfet and BJT.
- How these swiches work as a logic gate by implying inputs and configuring the outputs as well.
challenges we faced:
- while taking the values from voltage regulator Vgs & VBB, the graph of IV characteristics were very unclear and a bit noisy. Also all the outputs were so close. so we tend to regulate those points in minimalistic way and solved it.
- Jumper wires were connected to the trainer board (loose connection) & showcased adverse output and to prevent this we took assistance further.
Overall this experiment will assist me to solve the complex logic gates problem in the future.

**MOSFET**

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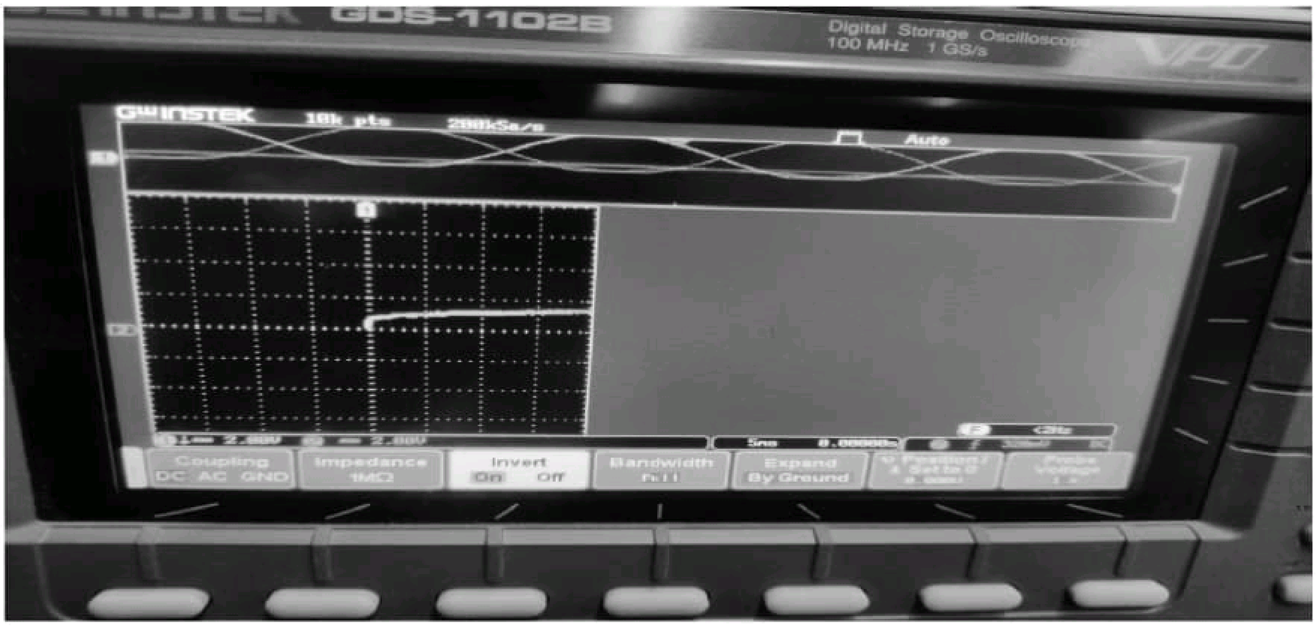


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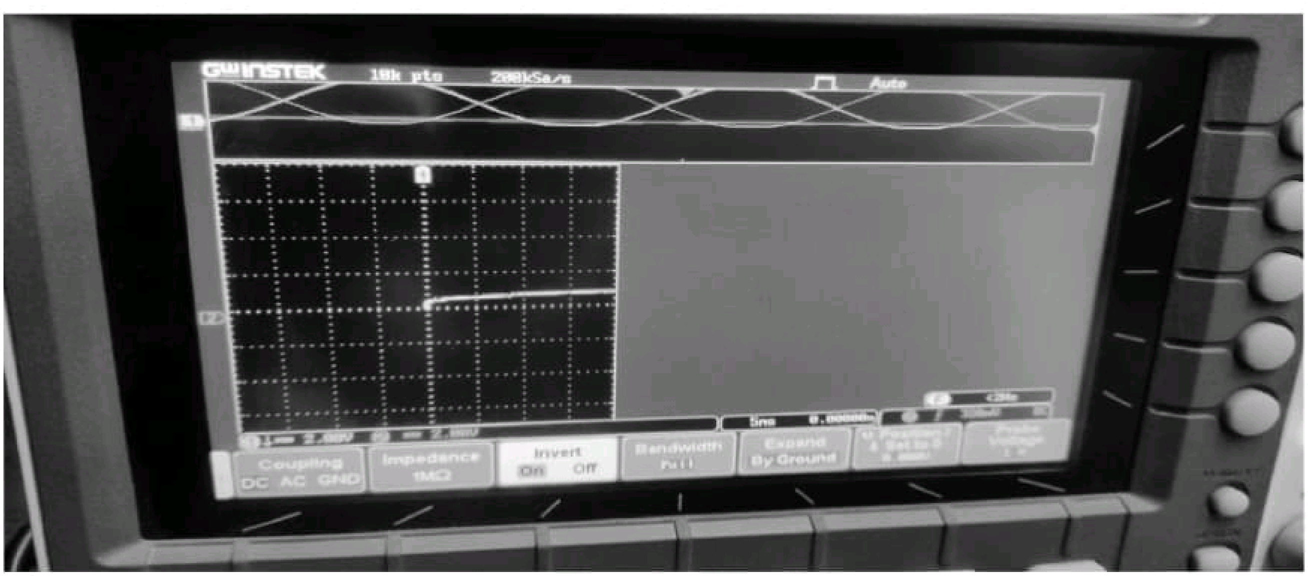
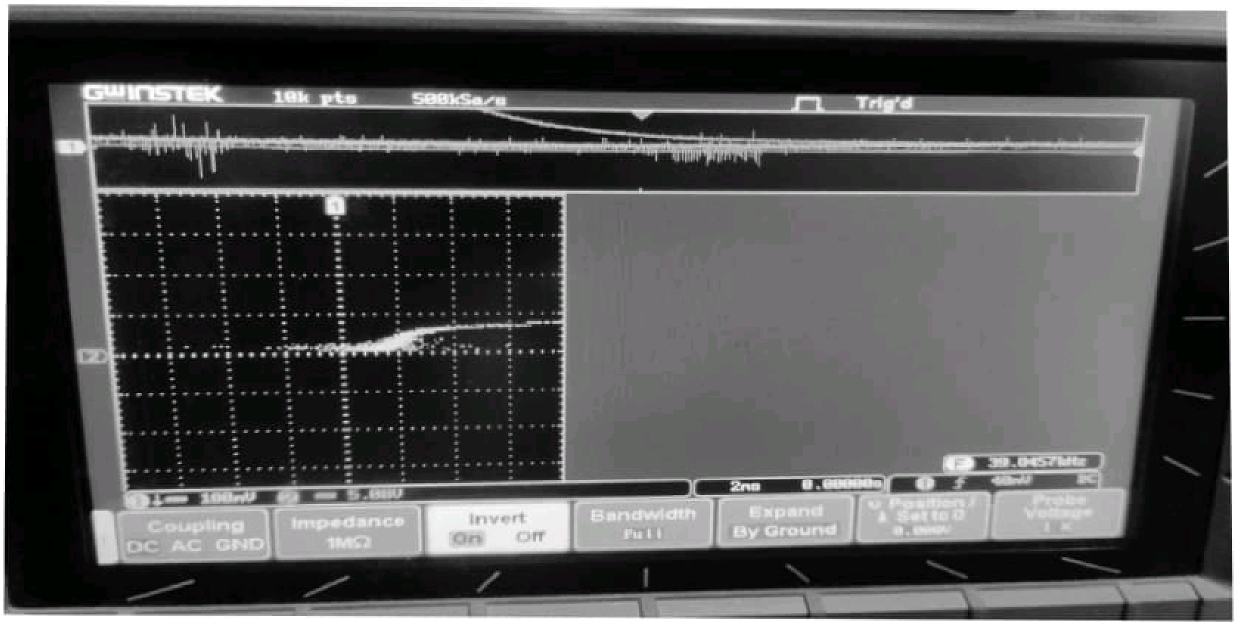



2.1

**BJT**


GW INSTEK
10k pts
500kSa/s
Trig'd
Coupling
DC AC GND
Impedance
1MΩ
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On Off
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Expand
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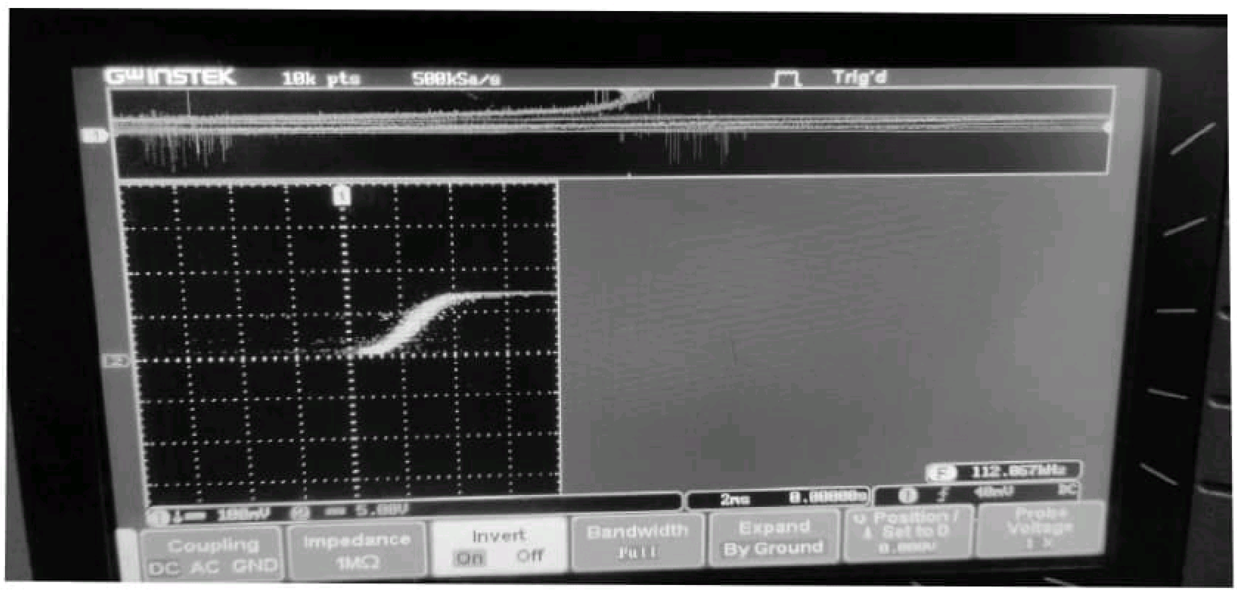
Probe
Voltage

**0.9**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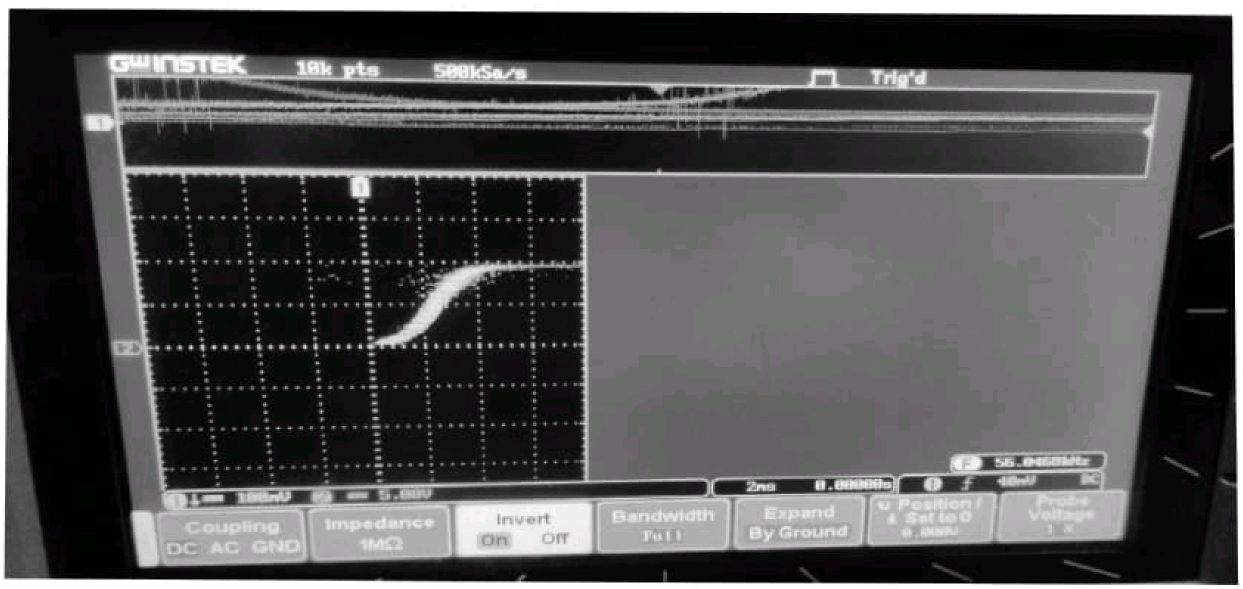
**1.1**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**1.3**