Experiment 1

Bipolar Junction Transistor. Output characteristics.

Main objectives:
1. Understanding the BJT operation and configurations.
2. Measuring the BJT output characteristics.
3. Determining the BJT parameters.

Background

A bipolar junction transistor is composed of two back-to-back p-n junctions. Depending on the polarities, two types of BJTs can be constructed: n-p-n and p-n-p. These three BJT regions are called emitter, base and collector. In simplified theory, the transistor structure is symmetric and exchanging emitter and collector regions should not change its properties, however, in real devices emitter is made more heavily doped compared to the collector region.

Let us consider the n-p-n transistor. In a typical regime of n-p-n BJT operation, one of the p-n junctions is forward-biased, while another one is reverse-biased. The forward-biased is the emitter-base junction, and the collector-base junction is reverse-biased.

As in a p-n junction diode, the electrons from the emitter enter the base region. The base region is purposefully made thin, so that most of the electrons injected into the base region reach the collector region. Only a small fraction of electrons recombine in the base region. The collector-base junction is reverse-biased, thus no electrons are injected into the base from the collector region. Meanwhile, electrons that are injected into the base and diffuse towards the collector are swept into it by the electric field in the collector-base junction. The portion of electrons able to cross the base and reach the collector is a measure of the BJT efficiency. The heavy doping of the emitter region and light doping of the base region cause many more electrons to be injected from the emitter into the base than holes to be injected from the base into the emitter. The base current is the sum of the holes injected into the emitter and the electrons that recombine in the base. Both these current components are small compared to the emitter-to-collector current.

A BJT can be operated as an amplifier. Since a BJT is a three terminal device, one of the terminals must be shared between input and output loops. Each terminal can be used as the shared one, and thus, there are three possible configurations of BJT: the common base, common emitter and common collector configurations (Fig. 1).
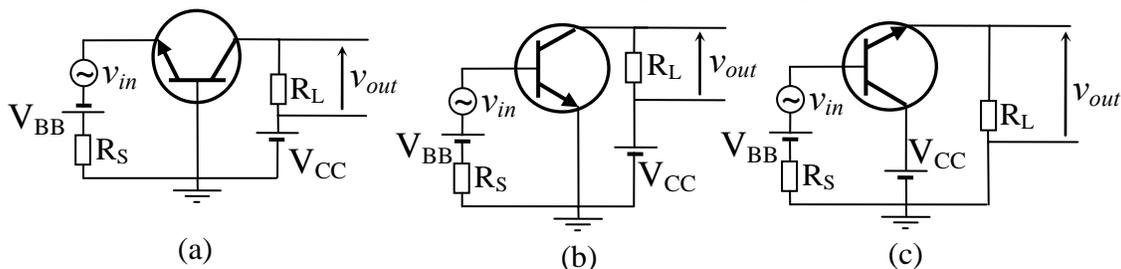

Fig. 1. Three possible configurations of BJT: common base (a), common emitter (b) and common collector (c).
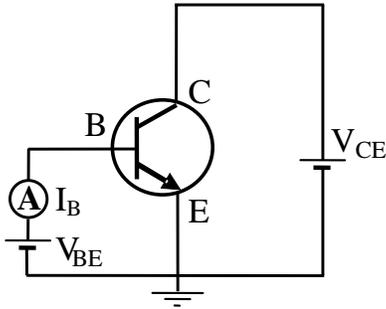
Fig. 2. The circuit used in the experiments.

Each of the three configurations has its own advantages and use. The common collector configuration is often used as a resistance-matching device, since its input resistance is much higher than its output resistance. It has a large current gain and close to unity voltage gain, and can be used as a voltage buffer.

The common base configuration is used for high frequency applications, because the base separates the input and output, minimizing oscillations at high frequency. It has a high voltage gain, but the current gain in this configuration is smaller than unity.

The common emitter configuration provides good current, voltage and power gain. It is the most commonly used configuration of BJT.

More details on BJTs operation can be found in refs. [1,2].

Tasks

1. Measure the output characteristics of BJT in common emitter mode.
2. Determine the Early voltage and current gain at several base current values.

Experiment

The output characteristics of BJT are measured by using the circuit schematically shown in Fig. 2.

The base-emitter voltage is kept constant to set a certain value of base current, I_B. The collector current, I_C, is measured versus the collector-emitter voltage, V_{CE}. The output characteristics of the BJT are the linear plot of I_C vs. V_{CE} at several different values of I_B.

The experimental parameters to be entered in the Source Setup pop-up panel include the start, stop, and number of steps for the collector-emitter voltage, also the start, step size and number of steps for the base current. You may also set the *compliance current* for protection. The base current, I_B, should not be set too high.

Determination of BJT parameters

The typical output characteristics of the common emitter BJT are shown in Fig. 3. For the ideal transistor the I_C-V_{CE} curves in the active region should be flat. However, in real devices they are slightly going upwards. This increase is more noticeable at higher
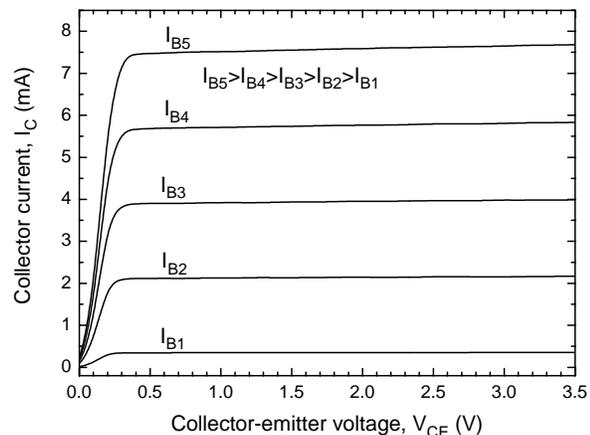

Fig. 3. The typical output characteristics of the BJT in common emitter mode.

base current values. Such effect is called the Early effect, and is described by the Early voltage. The Early effect is caused by the reduction of the base width due to the widening of the base-collector junction with increasing base-collector voltage.

The Early voltage is an important transistor parameter. It can be determined from the slopes of the I_C curves. The collector current, I_C, dependence on the collector-emitter voltage, V_{CE}, in the linear region can be described by the following equation:

$$I_C = I_{C0}\left(1+\frac{V_{CE}}{V_A}\right),\tag{1}$$

where I_{C0} is the collector current without including Early effect, and V_A – is the Early voltage. The collector current, I_C, becomes zero for $V_{CE} = -V_A$. Thus, Early voltage can be extracted by extrapolating the linear fit until it intersects with the x-axis.

Extracting V_A at several values of base current reveals the dependence of the Early voltage on the base current.

The current gain can be determined by using the relationship:

$$\beta = \frac{I_C}{I_B}.\tag{2}$$

The current gain, β, is usually plotted versus the collector current, I_C, which gives additional information about gain limitations in the transistor.

How to run the Experiment

To run an experiment, open the client window and connect to the Remote Lab server. To open the client window, go to the website **nina.ecse.rpi.edu/shur/remote**, and click the button *Connect to the measurement setup*. You should see the greeting message from the server displaying in the text field. If you want to see the instructions now or at any time later, you may activate the menu item *Show instructions* in the *Help* menu, and a dialog window will pop-up displaying the instructions. The opening of the client window as well as the connection to the server needs to be done just once for each session.

To start the experiment, click the button *Start Experiment* and the *Experiment Selection Dialog* will pop up. You may select the experiment by clicking on it, and clicking the *OK* button.

On the *Source Setup* pop-up panel, select the experiment parameters. You can also use the default settings. When the setting is finished, you may click the button *Send experiment to server*, which will send the commands generated according to your settings to the HPIB server. If the parameters you set exceed the safety voltage limit, or any other trivial mistakes happen, a warning message will appear in the *Message* text field. Then you have to correct the experiment settings. You may cancel the experiment at any time before your experiment configuration is sent for execution.

After the experiment is finished, the measurement results are sent back to your page (through the client window). The client page uses one single display area for all the experimental data, and the plot area behaves like a multi-page display. The user can go to any "page" to view the plot of the experiment on that page by clicking on the "next page" and "previous page" buttons. When all the experiments are finished, click the button *Quit*. After clicking *Quit*, both the connection and the client window are closed.

The data in the text field can be saved using "copy and paste" functions of Windows and UNIX systems. To save the plotted graph, you can use screen hard copy methods, such as pressing "Alt-Print Screen" on a PC keyboard and then paste as usually in any document.

References

[1] M.Shur, *Introduction to electronic devices,* Wiley, New York, 1995, pp. 297-362.
[2] A.Sedra and K.Smith, *Microelectronic circuits, 4th edition,* Oxford University Press, USA, 1997, pp. 221-352.

Experiment 2

Bipolar junction transistor. Gummel Plot

Main objectives:

1. Understanding the principles of the bipolar junction transistors operation.
2. Measuring the BJT transfer characteristics.
3. Determining the BJT parameters.

Background

A bipolar junction transistor (BJT) is composed of two back-to-back p-n junctions. The three regions are called emitter, base and collector. Depending on the polarities of the regions, two types of bipolar junction transistors can be constructed: n-p-n and p-n-p. Let us consider an n-p-n transistor, a schematic diagram of which is shown in Fig. 1. In a typical regime of n-p-n BJT operation, the emitter-base junction is forward-biased, while the collector-base junction is reverse-biased. In theory, the transistor structure is symmetric and

Fig. 1. Amplification of electrical signal by using n-p-n transistor. Emitter, base and collector regions are shown by E, B and C, respectively.

exchanging emitter and collector regions should not change its properties, however, in real devices emitter is made more heavily doped compared to the collector region.

As in a p-n junction diode, the electrons from the emitter enter the base region. The base region is specially made very short, so that most of the electrons reach the collector region. Only a small fraction of electrons recombine in the base region. Since the collector-base junction is reverse-biased, no electrons are injected into the base from the collector region. However, electrons that diffuse towards the collector are swept into it by the electric field in the collector-base junction. The portion of electrons able to cross the base and reach the collector is a measure of the BJT efficiency. The heavy doping of the emitter region and light doping of the base region cause many more electrons to be injected from the emitter into the base than holes to be injected from the base into the emitter. The base current is the sum of the holes injected into the emitter and the electrons that recombine in the base. Both these base current constituents are small compared with the emitter and collector currents. Thus, emitter and collector currents can be approximated to be nearly equal: $I_C \approx I_E$.

A BJT can be used as an amplifier. The amplification of the signals can be explained by using circuit shown in Fig. 1 for the BJT common-base configuration. The DC sources set the BJT in a forward active regime, by making emitter-base junction forward-biased
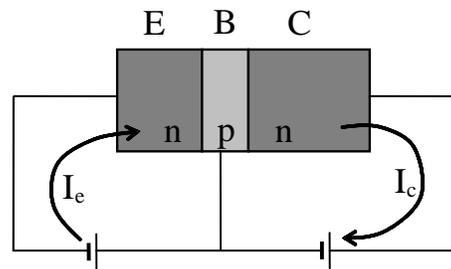
and collector-base junction reverse-biased. The signal is applied by an additional AC source. By using Kirchhoff laws for emitter and collector circuits, we can write:

$$V_E = I_E R_E, \qquad V_C = I_C R_C,$$ (1)

where R_E and R_C are effective resistances of emitter and collector regions. Since the emitter and collector current are nearly equal, we get the following relationship:

$$V_C = V_E \frac{R_C}{R_E}.$$ (2)

Since the emitter-base junction is forward-biased, electrons can easily flow through it and emitter resistance is small. The collector-base region is reverse-biased, and collector resistance is high. Thus, $R_C \gg R_E$, and V_C is equal to the amplified V_E signal.

More details on BJTs operation can be found in refs. [1,2]

Tasks

1. Measure the collector and base current dependence on base-emitter voltage.
2. Determine the base and collector ideality factors, and common-emitter current gain.

Experiment

The measurements of the base and collector current dependencies on base-emitter voltage are performed by using the circuit schematically shown in Fig. 2.

The collector-emitter voltage, V_{CE}, is kept at a constant bias. The collector current, I_C, and base current, I_B, versus the base-emitter voltage, V_{BE}, are measured. The Gummel plot is a semilog plot of I_C and I_B (logarithmic scale) vs. V_{BE} (linear scale).

The experimental parameters to be entered in the Source Setup pop-up panel include the collector-emitter voltage and start, stop, and number of steps for the base-emitter voltage. You may also set the *compliance current* for protection. The collector-emitter voltage, V_{CE}, should not be set too high to reach the breakdown voltage.
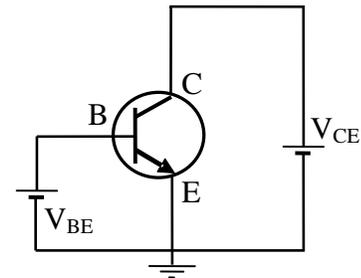

Fig. 2. The circuit used in the experiments.

Determination of BJT parameters

The BJT Gummel plot is the common-emitter transfer characteristics of the BJT in the forward active regime. In it, the I_C and I_B are simultaneously plotted versus base-emitter voltage, V_{BE}, on semi logarithmic scale. Certain parameters can be determined from the Gummel plot, such as collector and base ideality factors and current gain.

For determination of ideality factors, we have to remember that the emitter-base junction can be approximately described by the diode equation:

$$I_B = I_{SB} \exp\left(\frac{eV_{BE}}{\eta_B k_B T}\right),$$ (3)

and similarly for collector-base junction:

$$I_C = I_{SC} \exp\left(\frac{eV_{BE}}{\eta_C k_B T}\right).$$

(4)

Here, I_{SB} and I_{SC} are the effective saturation base and collector currents, respectively, η_B and η_C – base and collector ideality factors, respectively.

The ideality factors are obtained from the slope of the I-versus-V semi-log plot, as from the diode equations (3) or (4) we can get the following relation:

$$\frac{eV}{\eta k_B T} = \ln I - \ln I_S,$$

(5)

which shows that the slope is equal to $e / \eta k_B T$.

The common-emitter current gain is the ratio between output (collector) and input (base) currents:

$$\beta = \frac{I_C}{I_B}.$$

(6)

The current gain, β, is usually plotted versus the collector current, I_C, which gives additional information about gain limitations in the transistor.

How to run the Experiment

To run an experiment, open the client window and connect to the Remote Lab server. To open the client window, go to the website **nina.ecse.rpi.edu/shur/remote**, and click the button *Connect to the measurement setup*. You should see the greeting message from the server displaying in the text field. If you want to see the instructions now or at any time later, you may activate the menu item *Show instructions* in the *Help* menu, and a dialog window will pop-up displaying the instructions. The opening of the client window as well as the connection to the server needs to be done just once for each session.

To start the experiment, click the button *Start Experiment* and the *Experiment Selection Dialog* will pop up. You may select the experiment by clicking on it, and clicking the *OK* button.

On the *Source Setup* pop-up panel, select the experiment parameters. You can also use the default settings. When the setting is finished, you may click the button *Send experiment to server*, which will send the commands generated according to your settings to the HPIB server. If the parameters you set exceed the safety voltage limit, or any other trivial mistakes happen, a warning message will appear in the *Message* text field. Then you have to correct the experiment settings. You may cancel the experiment at any time before your experiment configuration is sent for execution.

After the experiment is finished, the measurement results are sent back to your page (through the client window). The client page uses one single display area for all the experimental data, and the plot area behaves like a multi-page display. The user can go to any "page" to view the plot of the experiment on that page by clicking on the "next page" and "previous page" buttons. When all the experiments are finished, click the button *Quit*. After clicking *Quit*, both the connection and the client window are closed.

The data in the text field can be saved using "copy and paste" functions of Windows and UNIX systems. To save the plotted graph, you can use screen hard copy methods,

such as pressing "Alt-Print Screen" on a PC keyboard and then paste as usually in any document.

References

[1] M.Shur, *Introduction to electronic devices,* Wiley, New York, 1995, pp. 297-362.
[2] A.Sedra and K.Smith, *Microelectronic circuits, 4th edition,* Oxford University Press, USA, 1997, pp. 221-352.

Experiment 3

Light emitting diodes. I-V characteristics

Main objectives:

1. Understanding the principles of LEDs operation and their I-V characteristics.
2. Measuring the LED I-V curves.
3. Determining the diode parameters.

Background

A semiconductor diode consists of a chip of semiconductor material doped with impurities to create a structure called a p-n junction. It can be thought of as a border region between n-type and p-type blocks.

In p-n junction, holes tend to diffuse from p-type region, where their concentration is high, to n-type region, where their concentration is low. Since holes are charged positively, they leave behind a layer of negatively charged acceptors. In similar way, electrons tend to diffuse from n-type region to p-type region, and leave a layer of positively charged donors. These charges create a potential barrier and prevent more electrons from going to p-type region, and holes from going to n-type region. Between these two layers, the so-called depletion region occurs, as there are much less electrons and holes, compared to the n-type and p-type regions, respectively.

Under reverse bias, the negative voltage is applied to the p-region, and positive to the n-region. The holes and electrons are pulled away from the junction, the depletion region width and the potential barrier increase. Due to the high potential barrier, the current through the junction will be minimal, usually caused by the thermal generation of carriers in the depletion region.

Under forward bias, the positive voltage is applied to the p-region, and negative to the n-region. The holes and electrons are pushed towards the junction, the depletion region width and the potential barrier decrease. Increasing the applied voltage causes decreasing of the potential barrier height and makes it easier for electrons and holes to diffuse, thus, causing the increase of the current.

Thus, such structure allows the current to flow in one direction, but not in the opposite.

If a diode is formed from the direct-gap semiconductor, the carriers that cross the junction recombine with the majority carriers on the other side and emit photons. Such diodes are called light-emitting diodes (LEDs). Depending on the band gap, different wavelength light may be produced. The spectra of the available LEDs cover the entire range from infrared to ultraviolet.

More information on semiconductor diodes and LEDs can be found in references [1,2].

Tasks

1. Measure the I-V curves for three different LEDs.
2. Determine the ideality factors and series resistances of the diodes.

Experiment

The I-V measurements for different diodes are performed by selecting different experiments in the experiment selection menu. The experiments with blue, green and yellow LEDs are used in this lab work.

The schematics of the experiments are shown in Fig. 1. The diode I-V characteristics are measured by applying a staircase sweep voltage to the diode and monitoring the current.

The experimental parameters to be entered in the Source Setup pop-up panel include the start, stop, and number of steps for the sweep. You may also select the *compliance current* for protection. The diode voltage is limited to (-5 V, 5 V) for green and yellow LEDs and (-10 V, 10 V) for blue LED.
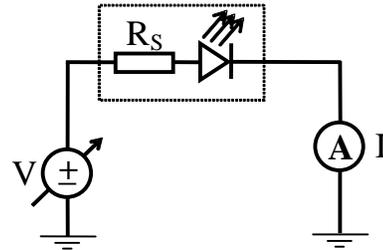

Fig. 1. The circuit used in the experiments.

Determination of diode parameters

The typical semiconductor diode's current-voltage (I-V) characteristic curve is shown in Fig. 2.

The current-voltage relation of the ideal diode is described by the Shockley equation:

$$I = I_S \left[\exp\left(\frac{eV}{k_B T} \right) - 1 \right], \tag{1}$$

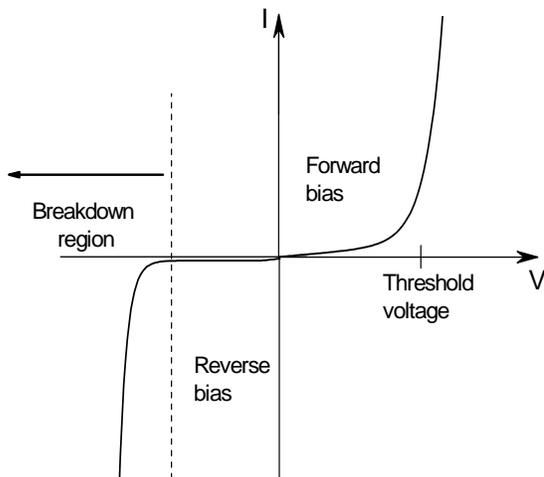where I_S is the saturation current. Under typical forward bias conditions, the diode voltage is $V \gg k_B T / e$, and second term in Eq. (1) can be neglected. The influence of semiconductor material parameters, such as band gap, is not explicit in this relation and is hidden in the saturation current. To explicitly show dependence on the material band gap, the Shockley equation can be rewritten, for the forward bias conditions, as:

$$I = I_{Seff} \exp\left(\frac{e(V - V_{th})}{k_B T} \right). \tag{2}$$

Fig. 2. I-V characteristics of a p-n junction diode (not to scale).

Here I_{Seff} is the effective saturation current, and V_{th} is the threshold voltage. The threshold voltage is the voltage at which the diode current starts strongly increasing, and can be approximately related to the diode material band gap energy: $V_{th} \approx E_g / e$.

In real devices, additional generation and recombination currents exist, which are not taken into account in the Shockley equation, and the following empirical equation is often used instead of Eq. (1) to describe experimentally measured characteristics:

$$I = I_S \left[\exp\left(\frac{eV}{\eta k_B T} \right) - 1 \right], \tag{3}$$

where η is called the ideality factor. The deviation of η from unity may be considered as a measure of the importance of the recombination current.

Additionally, a diode has the parasitic series resistance, R_S, of the device contacts and the semiconductor neutral regions. This resistance might play an important role, and Eq. (3) has to be modified to include the voltage drop across the series resistance:

$$I = I_S \left[\exp\left(\frac{e(V - IR_S)}{\eta k_B T} \right) - 1 \right]. \tag{4}$$

The ideality factor and series resistance value are important parameters of the LED. Both of them can be obtained from the I-V curve of the device.

The ideality factor η can be determined from the slope of the I-V curve. At forward bias, the second term on the right side in Eq. (4) is neglected. We also neglect the series resistance, as it plays an important role only at high forward bias, and from Eq. (4) we get:

$$\frac{eV}{\eta k_B T} = \ln I - \ln I_S. \tag{5}$$

The slope of the I-V curve in semi-log scale is equal to $e / \eta k_B T$.

To determine the series resistance, we analyze the I-V curve for $V \gg k_B T$, where the series resistance starts to influence the current. We solve the Eq. (4) for V, differentiate both sides with respect to V and multiply by I; we get the following equation:

$$I \frac{dV}{dI} = IR_S + \frac{\eta k_B T}{e}. \tag{6}$$

The series resistance is determined from the slope of a (IdV/dI)-versus-I plot.

How to run the Experiment

To run an experiment, open the client window and connect to the Remote Lab server. To open the client window, go to the website **nina.ecse.rpi.edu/shur/remote**, and click the button $\boxed{Connect\ to\ the\ measurement\ setup}$. You should see the greeting message from the server displaying in the text field. If you want to see the instructions now or at any time later, you may activate the menu item $\boxed{Show\ instructions}$ in the $\boxed{Help}$ menu, and a

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To start the experiment, click the button *Start Experiment* and the *Experiment Selection Dialog* will pop up. You may select the experiment by clicking on it, and clicking the *OK* button.

On the *Source Setup* pop-up panel, select the experiment parameters. You can also use the default settings. When the setting is finished, you may click the button *Send experiment to server*, which will send the commands generated according to your settings to the HPIB server. If the parameters you set exceed the safety voltage limit, or any other trivial mistakes happen, a warning message will appear in the *Message* text field. Then you have to correct the experiment settings. You may cancel the experiment at any time before your experiment configuration is sent for execution.

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References

[1] M.Shur, *Introduction to electronic devices,* Wiley, New York, 1995, pp. 188-296.
[2] E.F.Schubert, *Light-Emitting Diodes,* Cambridge University Press, UK, 2003, pp. 58-66.

Experiment 4

NMOS. Output characteristics

Main objectives:

1. Understanding the operation of field-effect transistor.
2. Measuring the NMOS characteristics.
3. Determining the NMOS parameters.

Background

The field-effect transistor (FET) is a type of transistor that relies on an electric field to control the shape and the conductivity in a semiconductor material. Fig. 1 shows the physical structure of the n-channel enhancement type metal-oxide-semiconductor FET (MOSFET). The n-type MOSFET (NMOS) is fabricated on a p-type substrate. Two heavily doped n-type regions, indicated in the figure as the n^+ source and the n^+ drain regions, are created in the substrate. A thin

Fig. 1. Physical structure of the enhancement type NMOS transistor.

layer of insulating SiO_2 is grown on the surface of the substrate and covers the area between the source and drain regions. Metal is deposited on top of the oxide layer to form the gate electrode of the device. Metal contacts are also made to the source region, the drain region, and the substrate, also known as the body. Thus, four terminals are brought out: the gate (G), the source (S), the drain (D) and the substrate or body (B). Usually, the body terminal is connected to the source. Unlike the bipolar junction transistor, the MOSFET is normally constructed as a symmetrical device, and its source and drain can be interchanged with no change in device characteristics.

With no bias voltage applied to the gate, two back-to-back diodes exist in series between drain and source. One diode is formed by the p-n junction between the drain and substrate, and another diode is between source and substrate. These diodes prevent current conduction from drain to source when a voltage V_{DS} is applied.

Consider next the situation depicted in Fig. 2. Here, the source and the drain are grounded and a positive voltage is applied to the gate. The positive voltage on the gate causes the
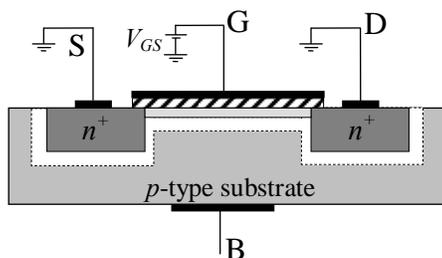

Fig. 2. NMOS transistor with a positive voltage applied to the gate.

free holes to be repelled from the region under the gate. The holes are pushed downward into the substrate. As well, the positive gate voltage attracts electrons from the source and drain regions into the channel region. When a sufficient number of electrons accumulate near the surface of the substrate under the gate, an n region is actually created, connecting the source and drain regions. Now, if a voltage is applied between drain and source, the current of

mobile electrons flows through this induced n region. The induced *n* region thus forms a channel for current flow from drain to source. Correspondingly, such MOSFET is called an *n*-channel MOSFET or, alternatively, an NMOS transistor.

The MOSFET could also be fabricated on an *n*-type substrate with *p+* regions for the drain and source. Such transistor would have holes as charge carriers, and the induced region would be *p*-type. Such MOSFET is called a *p*-channel MOSFET (PMOS). The device operates in the same manner as the *n*-channel device except that negative voltages are applied to the gate and drain instead of positive.

More information on FETs could be found in Refs. 1 and 2.

Tasks

1. To measure the input and output characteristics of NMOS.
2. To determine the parameters of NMOS.

Experiment

The measurements are performed by selecting two different experiments in the experiment selection menu: "*NMOS I_d-V_d characteristics*" and "*NMOS I_d-V_g characteristics*".

The NMOS I_d-V_d characteristics are measured by using the circuit schematically shown in Fig. 3. A staircase sweep voltage is applied to the drain (V_d) of the NMOS and drain current is monitored. A constant voltage is applied to the gate (V_g) during each sweep, and

Fig. 3. The circuit used in the experiments.

a group of I_d-V_d data curves are acquired by varying the gate voltage between sweeps. The substrate can also be applied with bias voltage (V_b). The source is grounded.

The I_d-V_g characteristics are measured by using the same circuit, only now the staircase sweep voltage is applied to the gate (V_g) and constant voltage is applied to the drain (V_d) during each sweep.

The experimental parameters are entered using two Source Setup pop-up panels, one for each of the two experiments. The parameters to be entered in the [Source Setup] pop-up panel include the start, stop, step voltages for the sweep, the start voltage, the step voltage and the number of steps for the gate voltages as well as the bias voltage of the substrate. You may also set the *compliance current* for protection. Both the drain and gate voltages are limited within a range from -5.0 V to 5.0 V, and the substrate bias is limited between -0.3 V, and 3.0 V.
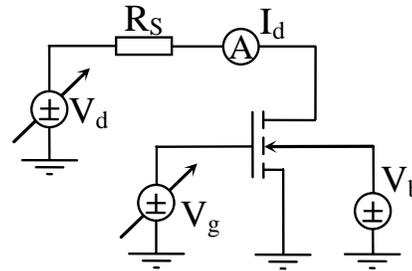
Determination of NMOS parameters

Fig. 4. The typical output characteristics of NMOS.

The typical output characteristics of the NMOS are shown in Fig. 4. The curves indicate that there are three distinct regions of operation: the cutoff region, the triode region, and the saturation region. The device is cut off, when V_{gs} is below threshold voltage V_T, since the gate voltage is too small to create a channel and no current flows from drain to source.
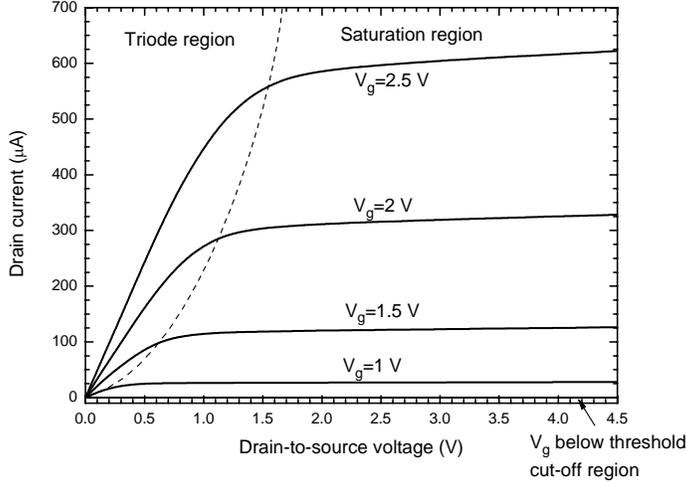
The threshold voltage is an important parameter of the MOSFET, it can be determined from the transfer characteristics. The transfer characteristics plot the I_{ds} versus. V_{gs} at several values of V_{ds}. The threshold voltage is the gate voltage at which the current starts to flow.

When $V_{gs}>V_T$ and V_{ds} is small enough, the MOSFET operates in the triode region. The I_d-V_{ds} characteristics can be described by the relation:

$$I_D = k_n' \frac{W}{L}\left[\left(V_{GS} - V_T\right)V_{DS} - \frac{1}{2}V_{DS}^2\right], \tag{1}$$

where k_n' is the transconductance parameter of the process, W is the channel width and L is the channel length. If V_{ds} is sufficiently small, we can neglect the quadratic term in Eq. (1) and obtain the following relationship near the origin:

$$I_D \square \ k_n' \frac{W}{L}\left(V_{GS} - V_T\right)V_{DS}. \tag{2}$$

The linear part of the I_d-V_{ds} curves allows determining the process transconductance parameter k_n', if the channel width and length are known.

Further increasing the V_{ds} value, the MOSFET starts to operate in the saturation region. For the ideal transistor, the I_d-V_d curves should be flat in the saturation region, however in real devices they are slightly going upwards. Such behavior is related to the effect of V_{ds} on the channel shape. In the saturation region, with the increase of the voltage V_{ds}, the effective channel length is reduced, and I_d is inversely proportional to the channel length. This effect is taken into account by introducing additional factor:

$$I_D = \frac{1}{2}k_n' \frac{W}{L}\left(V_{GS} - V_T\right)^2\left(1 + \lambda V_{DS}\right), \tag{3}$$

where the positive constant λ is a MOSFET parameter. The inverse parameter $V_A = 1/\lambda$ is similar to the Early voltage in a BJT, and is usually referred also as the Early voltage. It can be extracted by extrapolating the linear fit until it intersects with the x-axis.

How to run the Experiment

To run an experiment, open the client window and connect to the Remote Lab server. To open the client window, go to the website **nina.ecse.rpi.edu/shur/remote**, and click the button $\boxed{\textit{Connect to the measurement setup}}$. You should see the greeting message from the server displaying in the text field. If you want to see the instructions now or at any time later, you may activate the menu item $\boxed{\textit{Show instructions}}$ in the $\boxed{\textit{Help}}$ menu, and a dialog window will pop-up displaying the instructions. The opening of the client window as well as the connection to the server needs to be done just once for each session.

To start the experiment, click the button $\boxed{\textit{Start Experiment}}$ and the $\boxed{\textit{Experiment Selection Dialog}}$ will pop up. You may select the experiment by clicking on it, and clicking the $\boxed{\textit{OK}}$ button.

On the $\boxed{\textit{Source Setup}}$ pop-up panel, select the experiment parameters. You can also use the default settings. When the setting is finished, you may click the button $\boxed{\textit{Send experiment to server}}$, which will send the commands generated according to your settings to the HPIB server. If the parameters you set exceed the safety voltage limit, or any other trivial mistakes happen, a warning message will appear in the $\boxed{\textit{Message}}$ text field. Then you have to correct the experiment settings. You may cancel the experiment at any time before your experiment configuration is sent for execution.

After the experiment is finished, the measurement results are sent back to your page (through the client window). The client page uses one single display area for all the experimental data, and the plot area behaves like a multi-page display. The user can go to any "page" to view the plot of the experiment on that page by clicking on the "next page" and "previous page" buttons. When all the experiments are finished, click the button $\boxed{\textit{Quit}}$. After clicking $\boxed{\textit{Quit}}$, both the connection and the client window are closed.

The data in the text field can be saved using "copy and paste" functions of Windows and UNIX systems. To save the plotted graph, you can use screen hard copy methods, such as pressing "Alt-Print Screen" on a PC keyboard and then paste as usually in any document.

References

[1] M.Shur, *Introduction to electronic devices,* Wiley, New York, 1995, pp. 297-362.
[2] A.Sedra and K.Smith, *Microelectronic circuits, 4th edition,* Oxford University Press, USA, 1997, pp. 353-380.

Experiment 5

CMOS. Transfer characteristics.

Main objectives:

1. Understanding the operation of field-effect transistor.
2. Measuring the CMOS characteristics.
3. Determining the CMOS parameters.

Background

The field-effect transistor (FET) is a type of transistor that relies on an electric field to control the shape and the conductivity in a semiconductor material. Fig. 1 shows the physical structure of the n-channel enhancement type metal-oxide-semiconductor FET (MOSFET). The n-type MOSFET (NMOS) is fabricated on a p-type substrate. Two heavily doped n-type regions, indicated in the figure as the n^+ source and the n^+ drain regions, are created in the substrate. A thin

Fig. 1. Physical structure of the enhancement type NMOS transistor.

layer of insulating SiO_2 is grown on the surface of the substrate and covers the area between the source and drain regions. Metal is deposited on top of the oxide layer to form the gate electrode of the device. Metal contacts are also made to the source region, the drain region, and the substrate, also known as the body. Thus, four terminals are brought out: the gate (G), the source (S), the drain (D) and the substrate or body (B). Usually, the body terminal is connected to the source. Unlike the bipolar junction transistor, the MOSFET is normally constructed as a symmetrical device, and its source and drain can be interchanged with no change in device characteristics.

With no bias voltage applied to the gate, two back-to-back diodes exist in series between drain and source. One diode is formed by the p-n junction between the drain and substrate, and another diode is between source and substrate. These diodes prevent current conduction from drain to source when a voltage V_{DS} is applied.

Consider next the situation depicted in Fig. 2. Here, the source and the drain are grounded and a positive voltage is applied to the gate. The positive voltage on the gate causes the

Fig. 2. NMOS transistor with a positive voltage applied to the gate.

free holes to be repelled from the region under the gate. The holes are pushed downward into the substrate. As well, the positive gate voltage attracts electrons from the source and drain regions into the channel region. When a sufficient number of electrons accumulate near the surface of the substrate under the gate, an n region is actually created, connecting the source and drain regions. Now, if a voltage is applied between drain and source, the mobile
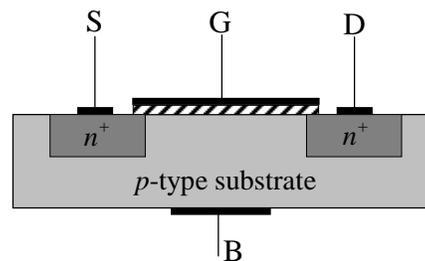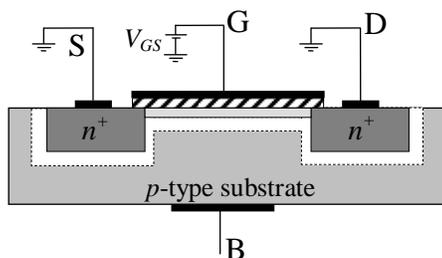
electrons current flows through this induced n region. The induced *n* region thus forms a channel for current flow from drain to source. Correspondingly, such MOSFET is called an *n*-channel MOSFET or, alternatively, an NMOS transistor.

The MOSFET could also be fabricated on an *n*-type substrate with *p+* regions for the drain and source. Such transistor would have holes as charge carriers, and the induced region would be *p*-type. Such MOSFET is called a *p*-channel MOSFET (PMOS). The device operates in the same manner as the *n*-channel device except that negative voltages are applied to the gate and drain instead of positive.

Both PMOS and NMOS transistors are utilized in complementary MOS or CMOS circuits as shown in Fig. 3. Although CMOS circuits are somewhat more difficult to fabricate than NMOS, the availability of

Fig. 3. Cross section of a CMOS integrated circuit.

complementary devices makes possible many powerful circuit-design possibilities. CMOS technology is used in chips such as microprocessors, microcontrollers, static RAM, and other digital logic circuits.

More information on FETs could be found in References 1 and 2.

Tasks

1. To measure the transfer characteristics of CMOS.
2. To determine the parameters of CMOS inverter.

Experiment

The CMOS inverter is composed of one NMOS and one PMOS, with their gates connected together as the input, and their drains connected together as the output (see Fig. 4). The transfer I-V characteristics are measured by applying staircase sweep voltage to the input, (V_i) and applying a current source to the output (I_o) while monitoring the output voltage. The source (V_{dd}) and substrate (V_b) of the PMOS are set to a constant positive voltage, and the source and substrate of the NMOS are grounded.
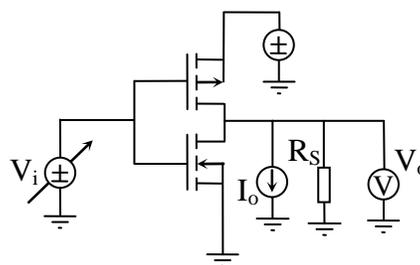

Fig. 4. The circuit used in the experiments.

The experimental parameters to be entered in the *Source Setup* pop-up panel include the start, stop, and step voltages for the input sweep voltage. You may also select the compliance current for protection. The input voltage is limited in the range from 0 to 5V.

CMOS inverter parameters

The voltage transfer characteristics of a CMOS inverter can be characterized by several specific points. The first two points are the output high level, V_{OH}, and the output low level, V_{OL}. The V_{OH} is the output voltage at low input voltage, while V_{OL} is the output at high input voltage.

In an ideal inverter, the V_{OH} should be equal to the dc supply voltage and should not change until input voltage reaches the transition voltage of the inverter. Once the transition voltage is reached, the output should change to V_{OL}, which is equal to zero in an ideal case. In real inverters, however, the curves are not flat, and the transition voltage has no fixed value, but rather corresponds to a range of voltages.

The transition region of an inverter is described by two additional parameters: V_{IL} and V_{IH}. The V_{IL} is the maximum value that input voltage can have while being interpreted by the inverter as representing a logic 0. Meanwhile, the V_{IH} is the minimum value that input voltage can have while being interpreted by the inverter as representing a logic 1. These two points are defined as the points on the transfer curve at which the incremental gain is unity (i.e. the slope is -1V/V).

The four parameters mentioned above define the voltage transfer characteristics of an inverter and determine its noise margins, which measure the ability of the inverter to tolerate the variations in the input signal levels.

The noise margin for low input, NM_L, is $NM_L = V_{IL} - V_{OL}$, and the noise margin for high input, NM_H, is $NM_H = V_{OH} - V_{IH}$.

How to run the Experiment

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To start the experiment, click the button *Start Experiment* and the *Experiment Selection Dialog* will pop up. You may select the experiment by clicking on it, and clicking the *OK* button.

On the *Source Setup* pop-up panel, select the experiment parameters. You can also use the default settings. When the setting is finished, you may click the button *Send experiment to server*, which will send the commands generated according to your settings to the HPIB server. If the parameters you set exceed the safety voltage limit, or any other trivial mistakes happen, a warning message will appear in the *Message* text field. Then you have to correct the experiment settings. You may cancel the experiment at any time before your experiment configuration is sent for execution.

After the experiment is finished, the measurement results are sent back to your page (through the client window). The client page uses one single display area for all the experimental data, and the plot area behaves like a multi-page display. The user can go to any "page" to view the plot of the experiment on that page by clicking on the "next page" and "previous page" buttons. When all the experiments are finished, click the button Quit. After clicking Quit, both the connection and the client window are closed.

The data in the text field can be saved using "copy and paste" functions of Windows and UNIX systems. To save the plotted graph, you can use screen hard copy methods, such as pressing "Alt-Print Screen" on a PC keyboard and then paste as usually in any document.

References

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[2] A.Sedra and K.Smith, *Microelectronic circuits, 4th edition,* Oxford University Press, USA, 1997, pp. 425-436.