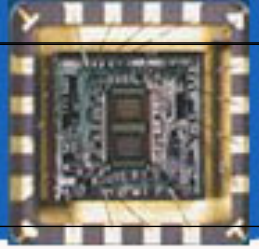


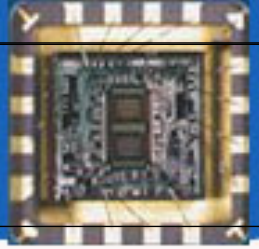
The MOSFET as an Amplifier

Operation and small signal model

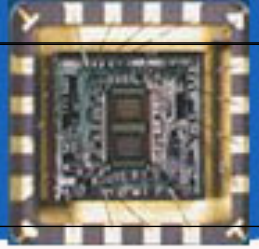
Dr. Alaa El-Din Hussein

March 21, 2008

Outline

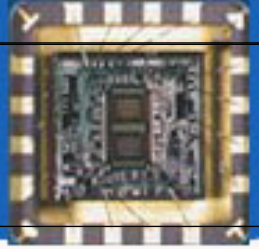


Outline



The Transistor as An Amplifier

How it works?



Basic Idea

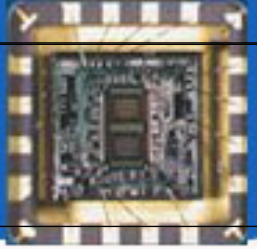
- Step 1: Set the transistor at a certain DC level (BIASING)
- Step 2: Inject a small signal to the input and get a bigger output (COUPLING)

Important

- Biasing point will determine AC Gain, I/P Impedance, O/P Impedance, and Maximum Output Swing

The Transistor as An Amplifier

How it works?



Basic Idea

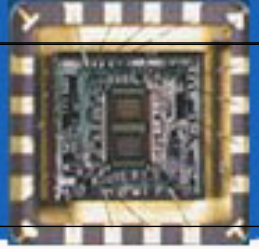
- Step 1: Set the transistor at a certain DC level (BIASING)
- Step 2: Inject a small signal to the input and get a bigger output (COUPLING)

Important

- Biasing point will determine AC Gain, I/P Impedance, O/P Impedance, and Maximum Output Swing

The Transistor as An Amplifier

How it works?



Basic Idea

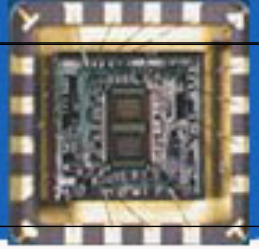
- Step 1: Set the transistor at a certain DC level (BIASING)
- Step 2: Inject a small signal to the input and get a bigger output (COUPLING)

Important

- Biasing point will determine AC Gain, I/P Impedance, O/P Impedance, and Maximum Output Swing

The Transistor as An Amplifier

How it works?



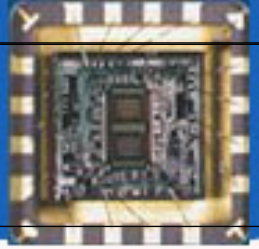
Basic Idea

- Step 1: Set the transistor at a certain DC level (BIASING)
- Step 2: Inject a small signal to the input and get a bigger output (COUPLING)

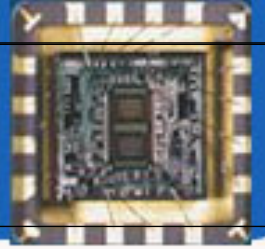
Important

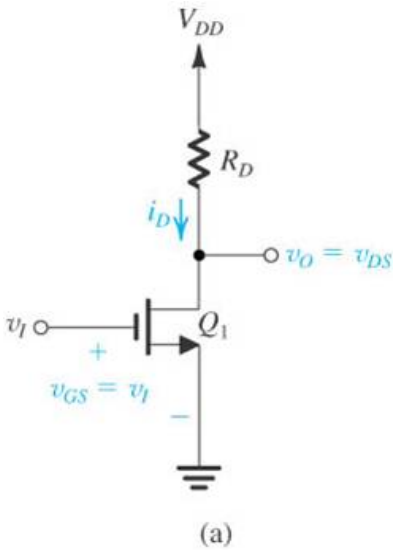
- Biasing point will determine AC Gain, I/P Impedance, O/P Impedance, and Maximum Output Swing

Outline

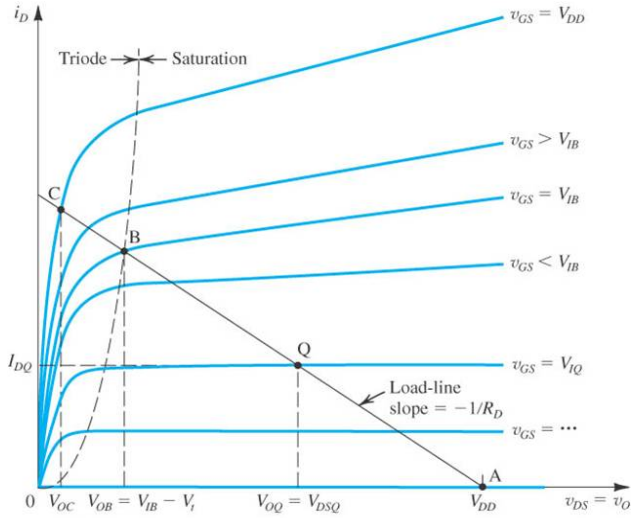


Large Signal Operation





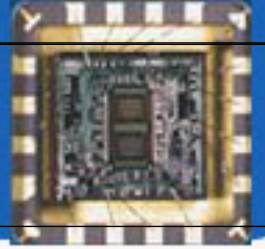
(a)

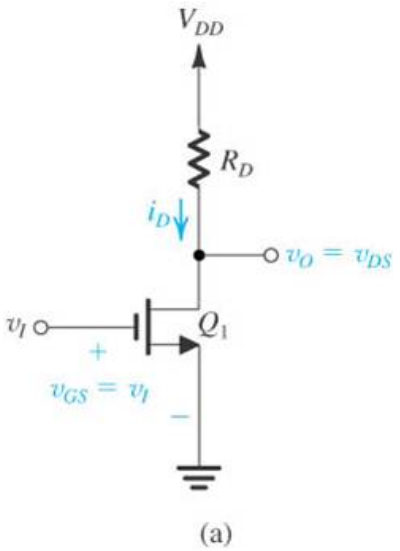


(b)

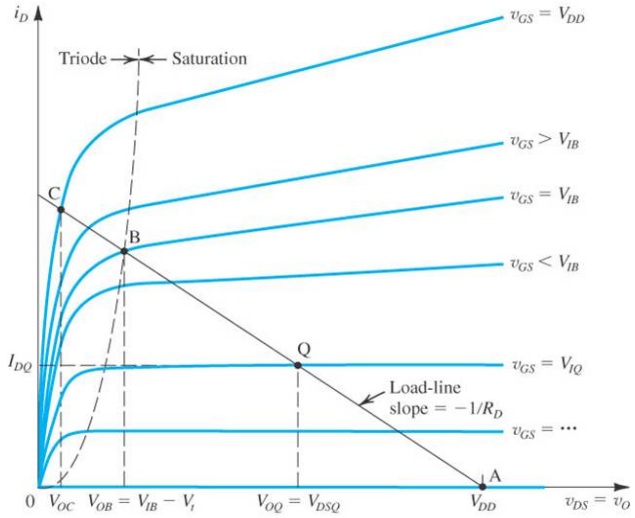
- If $v_I < V_t$, the transistor is OFF and we are at point A
- If v_I increased the transistor will be in saturation region A-B
- $v_o = v_{DS} = V_{DD} – R_D.i_D$ as $v_I \uparrow \rightarrow v_o \downarrow$
- If v_I increased beyond point B, the transistor enters triode region B-C

Large Signal Operation





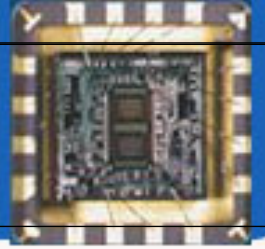
(a)

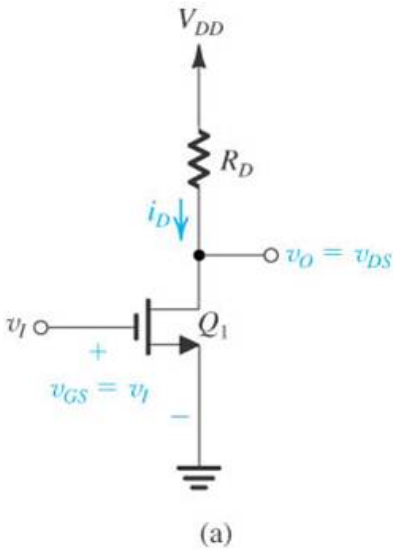


(b)

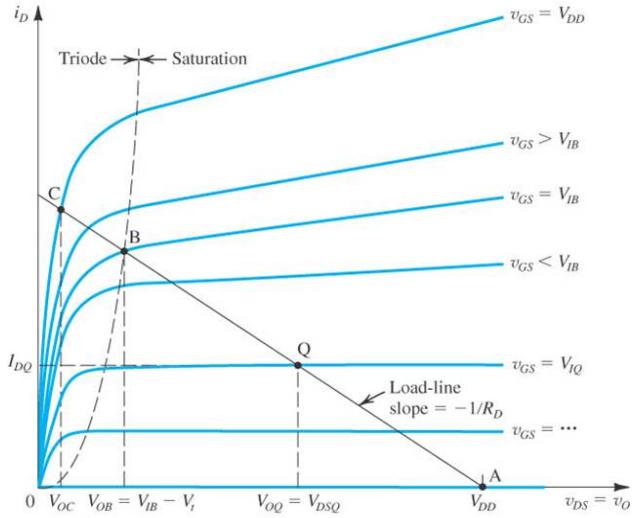
- If $v_I < V_t$, the transistor is OFF and we are at point A
- If v_I increased the transistor will be in saturation region A-B
- $v_o = v_{DS} = V_{DD} – R_D.i_D$ as $v_I \uparrow \rightarrow v_o \downarrow$
- If v_I increased beyond point B, the transistor enters triode region B-C

Large Signal Operation





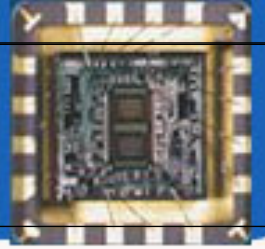
(a)

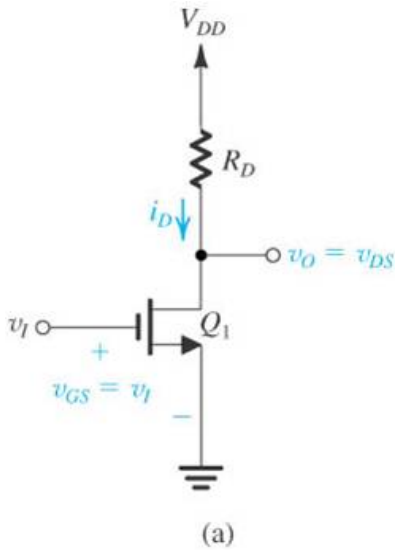


(b)

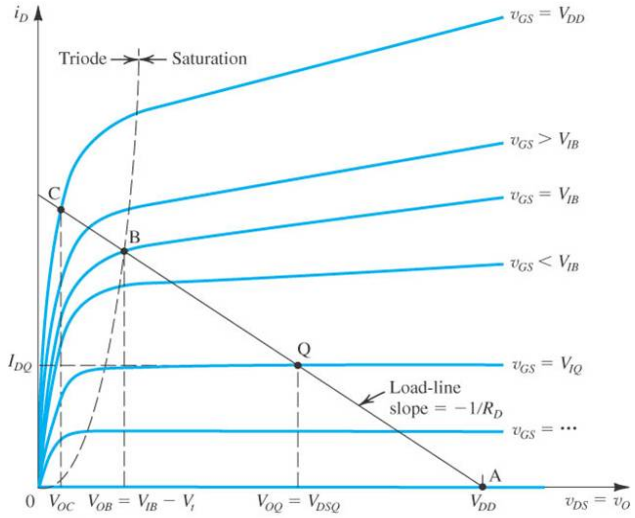
- If $v_I < V_t$, the transistor is OFF and we are at point A
- If v_I increased the transistor will be in saturation region A-B
- $v_o = v_{DS} = V_{DD} - R_D.i_D$ as $v_I \uparrow \rightarrow v_o \downarrow$
- If v_I increased beyond point B, the transistor enters triode region B-C

Large Signal Operation





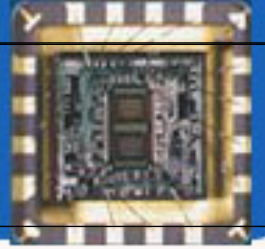
(a)

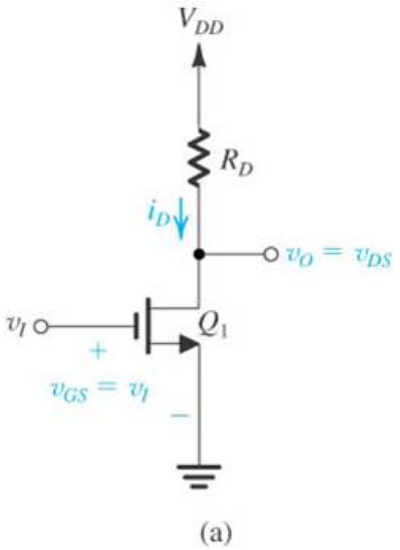


(b)

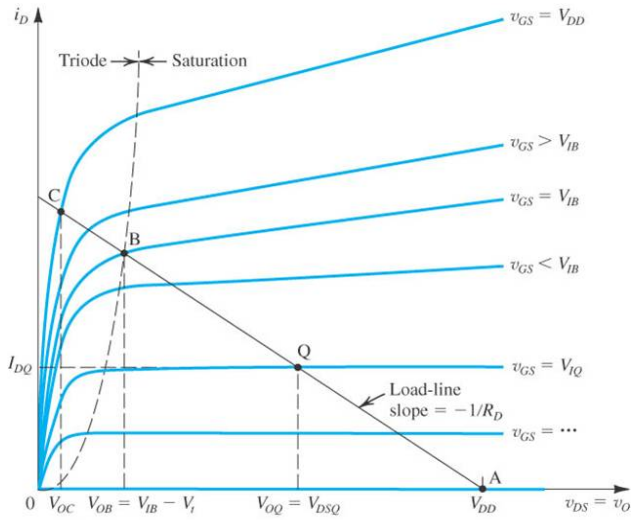
- If $v_I < V_t$, the transistor is OFF and we are at point A
- If v_I increased the transistor will be in saturation region A-B
- $v_o = v_{DS} = V_{DD} - R_D.i_D$ as $v_I \uparrow \rightarrow v_o \downarrow$
- If v_I increased beyond point B, the transistor enters triode region B-C

Large Signal Operation





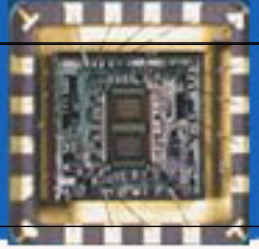
(a)

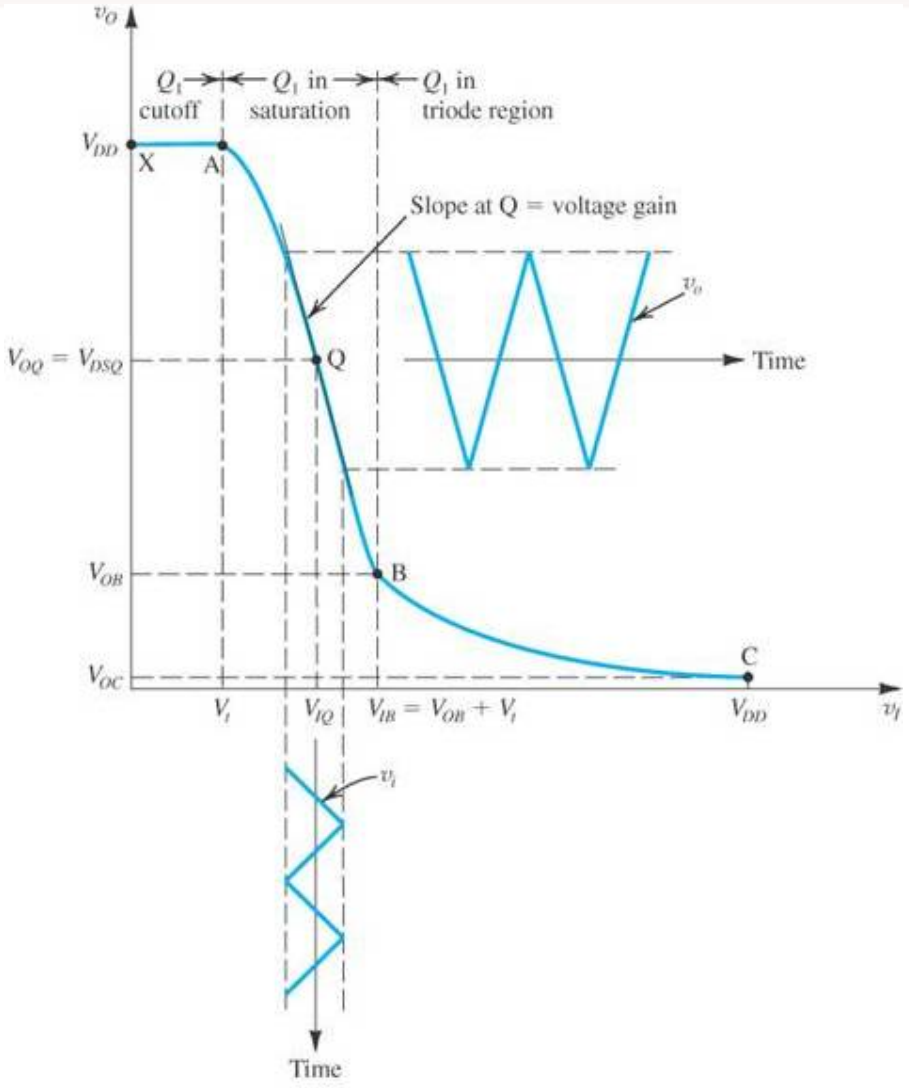


(b)

- If $v_I < V_t$, the transistor is OFF and we are at point A
- If v_I increased the transistor will be in saturation region A-B
- $v_o = v_{DS} = V_{DD} - R_D.i_D$ as $v_I \uparrow \rightarrow v_o \downarrow$
- If v_I increased beyond point B, the transistor enters triode region B-C

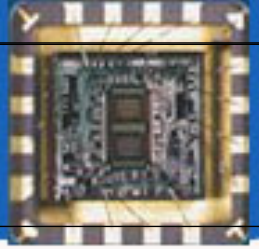
Large Signal Operation

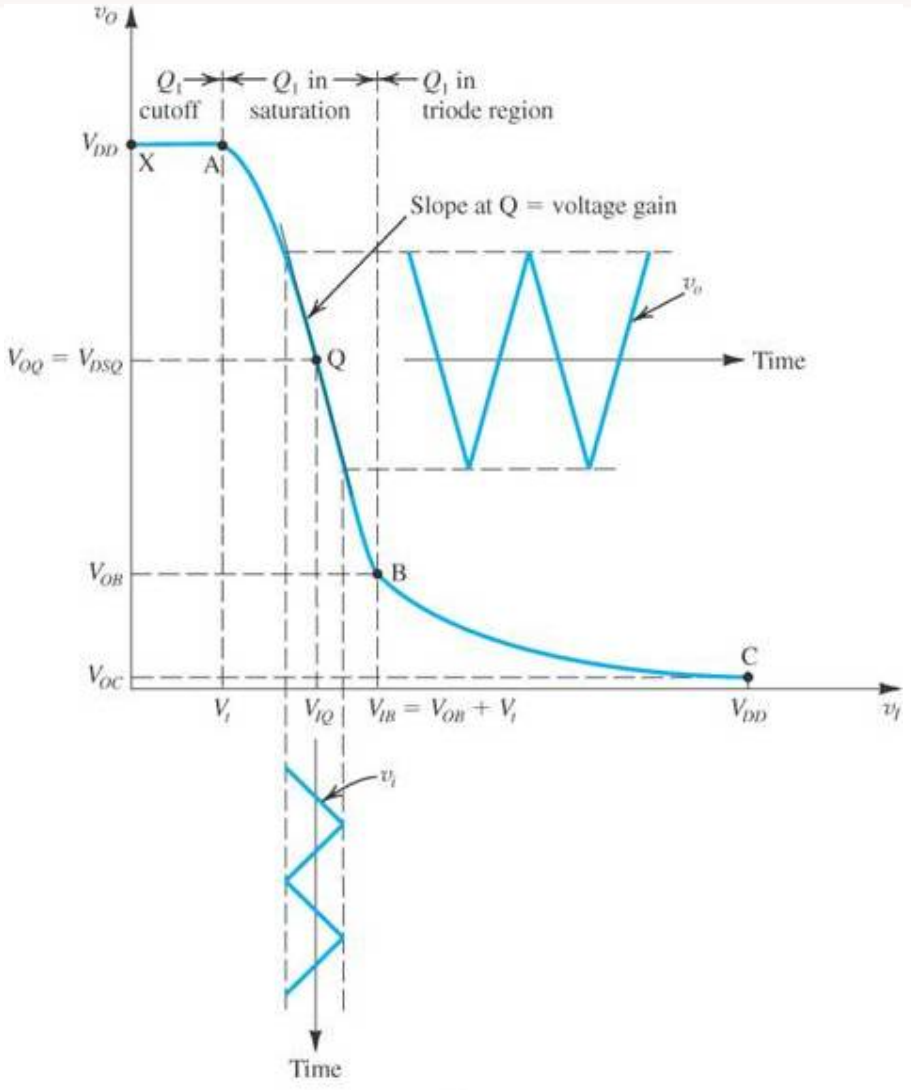




- For small signal the amplification will be linear
- To work as a switch the transistor will work either at points A, or point C (will be studied later)

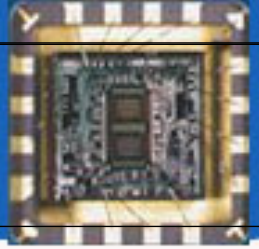
Large Signal Operation

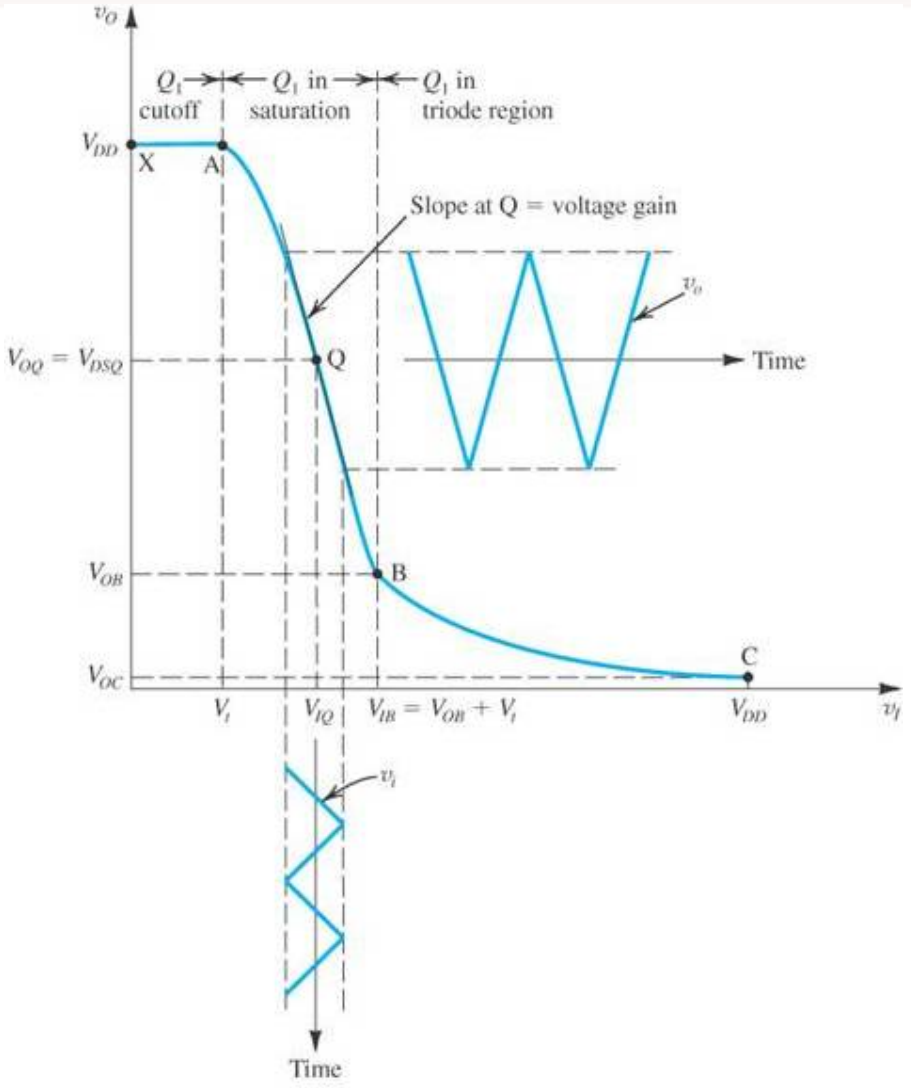




- For small signal the amplification will be linear
- To work as a switch the transistor will work either at points A, or point C (will be studied later)

Large Signal Operation

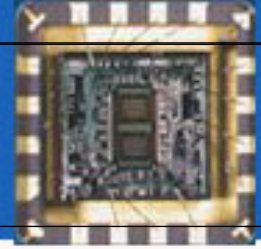


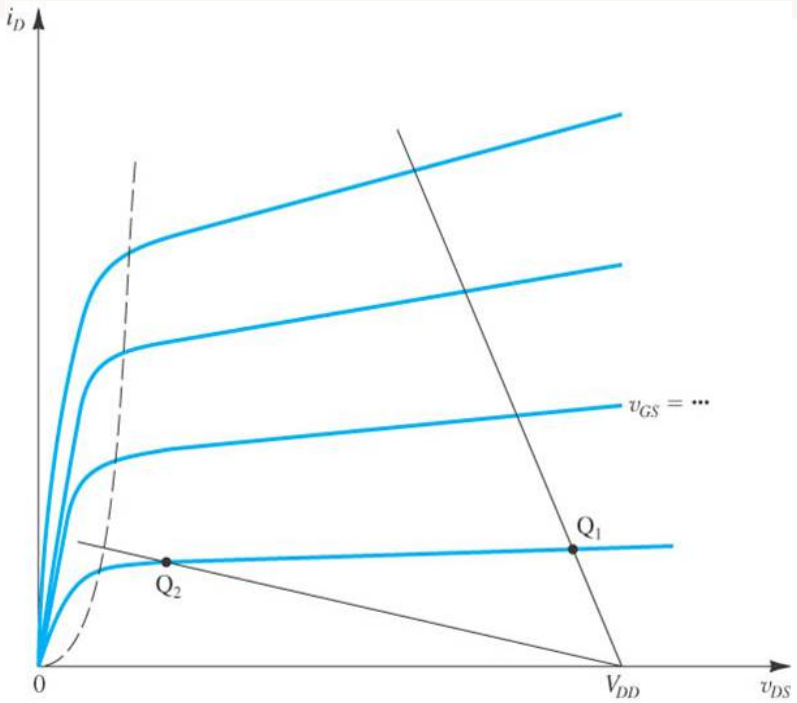


- For small signal the amplification will be linear
- To work as a switch the transistor will work either at points A, or point C (will be studied later)

Large Signal Operation

Maximum Symmetrical Swing



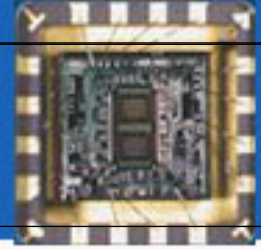


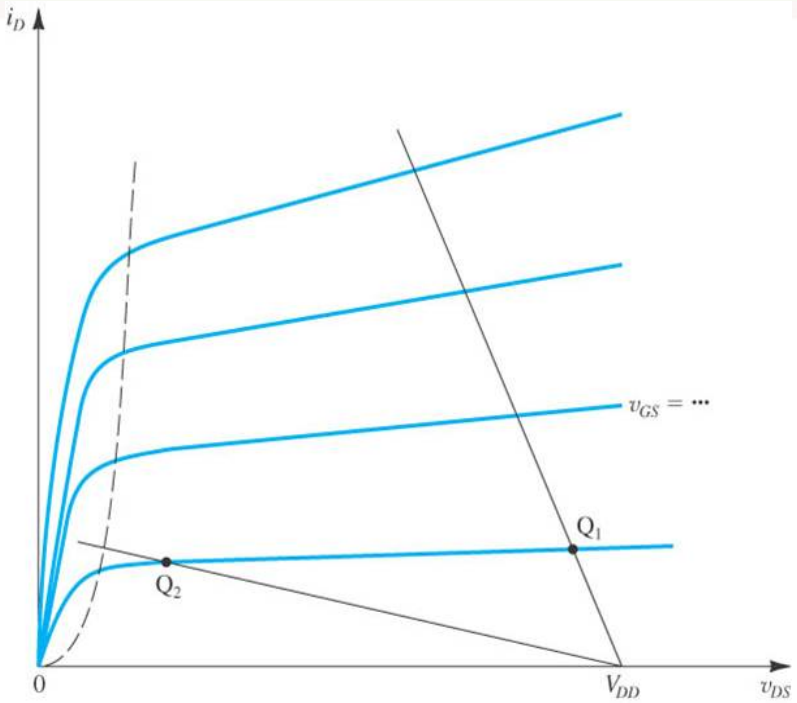
Notes

- Please note the shown two load lines and corresponding bias points.
- Bias point Q_1 does not leave sufficient room for positive signal swing at the drain (too close to V_{DD}).
- Bias point Q_2 is too close to the boundary of the triode region and might not allow for sufficient negative signal swing.

Large Signal Operation

Maximum Symmetrical Swing



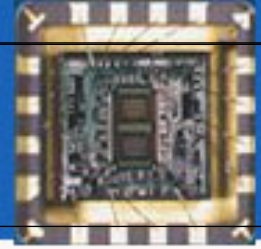


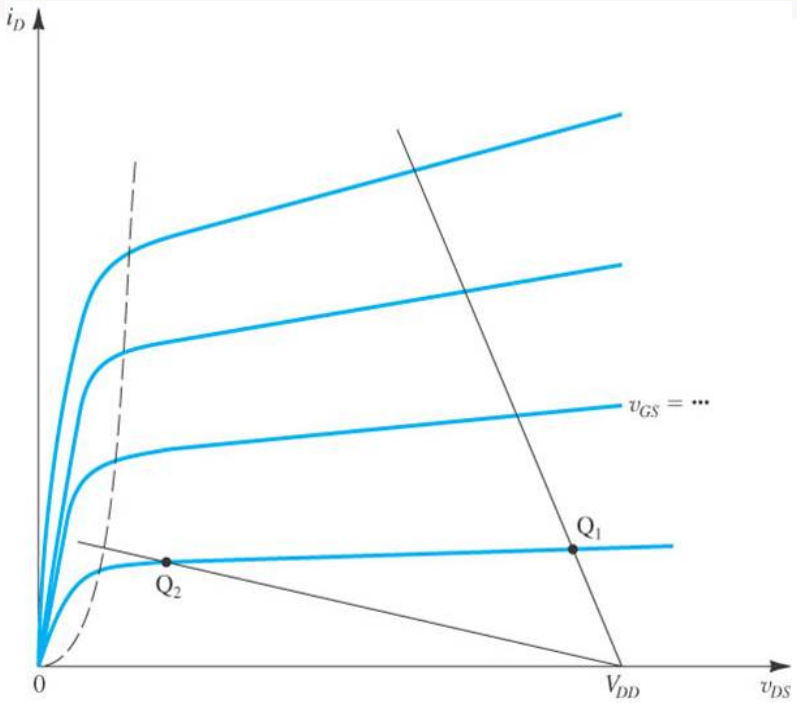
Notes

- Please note the shown two load lines and corresponding bias points.
- Bias point Q_1 does not leave sufficient room for positive signal swing at the drain (too close to V_{DD}).
- Bias point Q_2 is too close to the boundary of the triode region and might not allow for sufficient negative signal swing.

Large Signal Operation

Maximum Symmetrical Swing



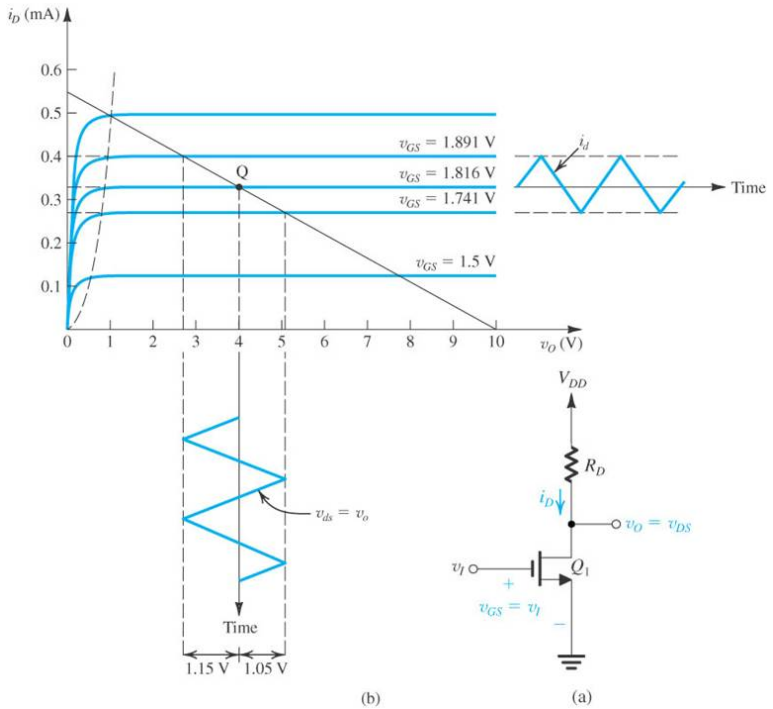


Notes

- Please note the shown two load lines and corresponding bias points.
- Bias point Q_1 does not leave sufficient room for positive signal swing at the drain (too close to V_{DD}).
- Bias point Q_2 is too close to the boundary of the triode region and might not allow for sufficient negative signal swing.

Large Signal Operation

Example

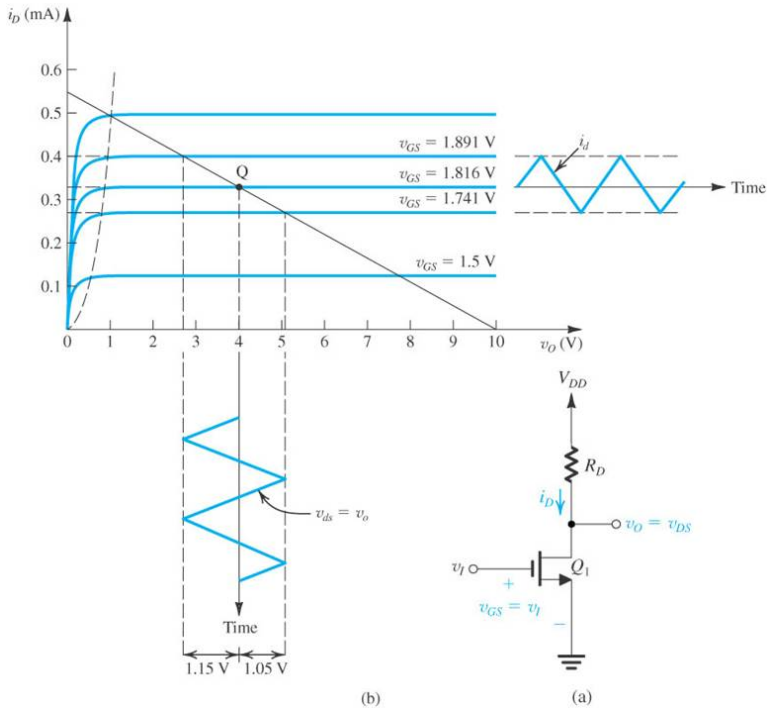


Notes

- The input is a triangular signal with $V_{PP} = 150\text{mV}$.
- From the shown figure: $Gain = \frac{\Delta v_O}{\Delta v_I} = -\frac{2.2}{0.15} = -14.7 V/V$

Large Signal Operation

Example

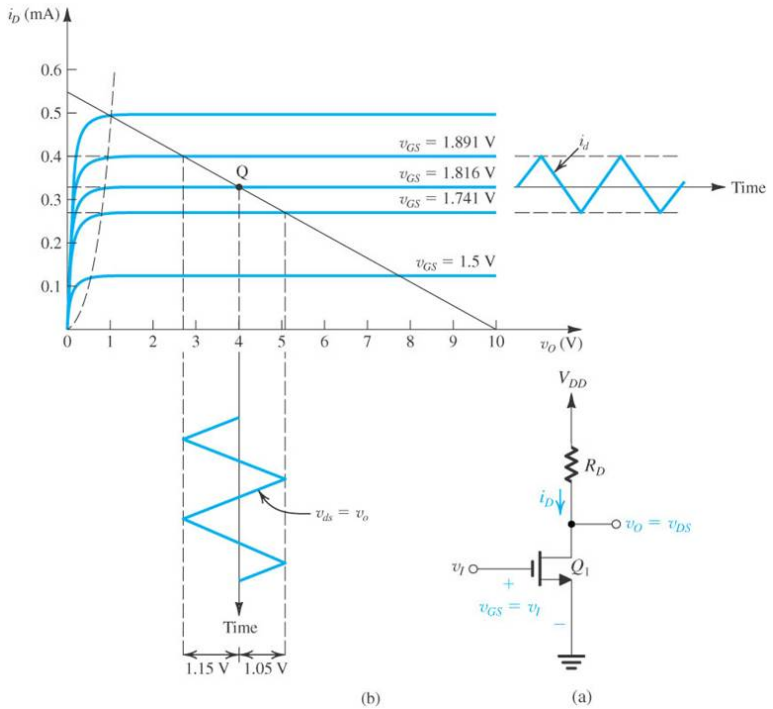


Notes

- The input is a triangular signal with $V_{PP} = 150\text{mV}$.
- From the shown figure: $Gain = \frac{\Delta v_O}{\Delta v_I} = -\frac{2.2}{0.15} = -14.7 V/V$

Large Signal Operation

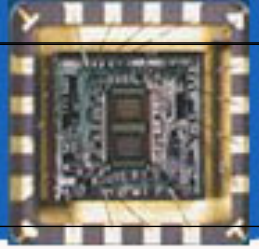
Example



Notes

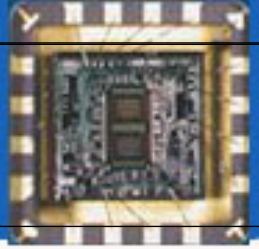
- The input is a triangular signal with $V_{PP} = 150\text{mV}$.
- From the shown figure: $Gain = \frac{\Delta v_O}{\Delta v_I} = -\frac{2.2}{0.15} = -14.7 V/V$

Outline



MOSFET Amplifier Biasing

Biasing Methods



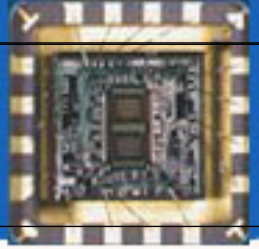
Several Biasing schemes are available for MOSFET amplifiers. Each of them will have its cons and pros. The mostly common schemes are:

Biasing Schemes

- Fixed V_{GS} Biasing.
- Source Resistance Feedback Biasing.
- Drain Feedback Biasing.
- Constant Current Biasing.

MOSFET Amplifier Biasing

Biasing Methods



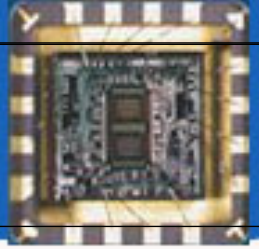
Several Biasing schemes are available for MOSFET amplifiers. Each of them will have its cons and pros. The mostly common schemes are:

Biasing Schemes

- Fixed V_{GS} Biasing.
- Source Resistance Feedback Biasing.
- Drain Feedback Biasing.
- Constant Current Biasing.

MOSFET Amplifier Biasing

Biasing Methods



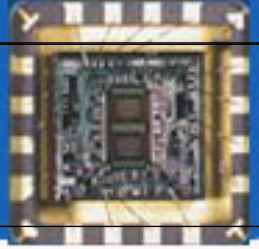
Several Biasing schemes are available for MOSFET amplifiers. Each of them will have its cons and pros. The mostly common schemes are:

Biasing Schemes

- Fixed V_{GS} Biasing.
- Source Resistance Feedback Biasing.
- Drain Feedback Biasing.
- Constant Current Biasing.

MOSFET Amplifier Biasing

Biasing Methods



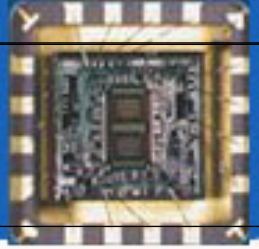
Several Biasing schemes are available for MOSFET amplifiers. Each of them will have its cons and pros. The mostly common schemes are:

Biasing Schemes

- Fixed V_{GS} Biasing.
- Source Resistance Feedback Biasing.
- Drain Feedback Biasing.
- Constant Current Biasing.

MOSFET Amplifier Biasing

Biasing Methods



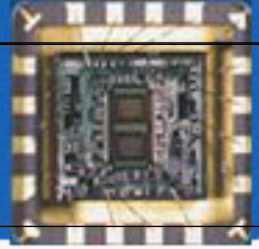
Several Biasing schemes are available for MOSFET amplifiers. Each of them will have its cons and pros. The mostly common schemes are:

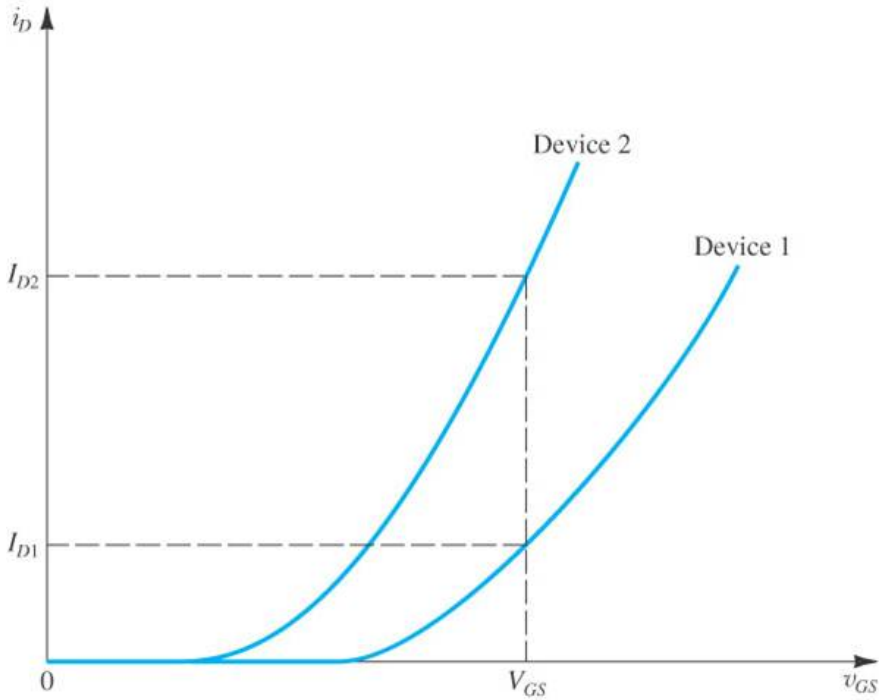
Biasing Schemes

- Fixed V_{GS} Biasing.
- Source Resistance Feedback Biasing.
- Drain Feedback Biasing.
- Constant Current Biasing.

MOSFET Amplifier Biasing

Fixed V_{GS} Biasing



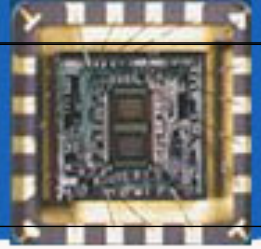


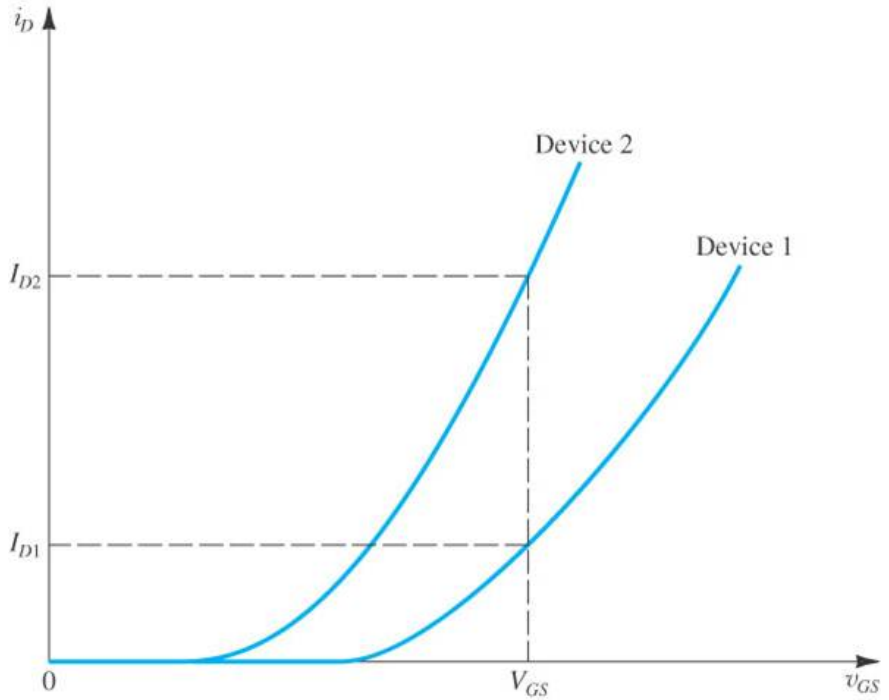
Notes

- Please note that changing the device may result in a large change in the drain current and hence the operating point and the amplifier performance.

MOSFET Amplifier Biasing

Fixed V_{GS} Biasing



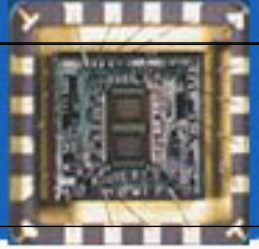


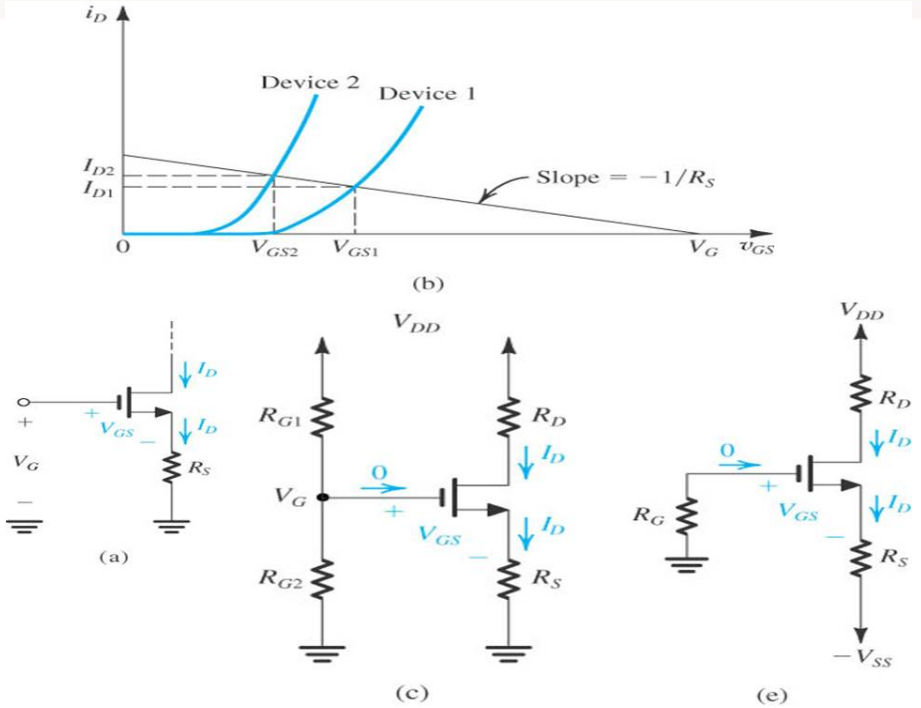
Notes

- Please note that changing the device may result in a large change in the drain current and hence the operating point and the amplifier performance.

MOSFET Amplifier Biasing

Source Resistance Feedback Biasing



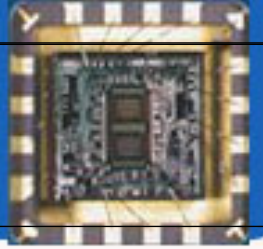


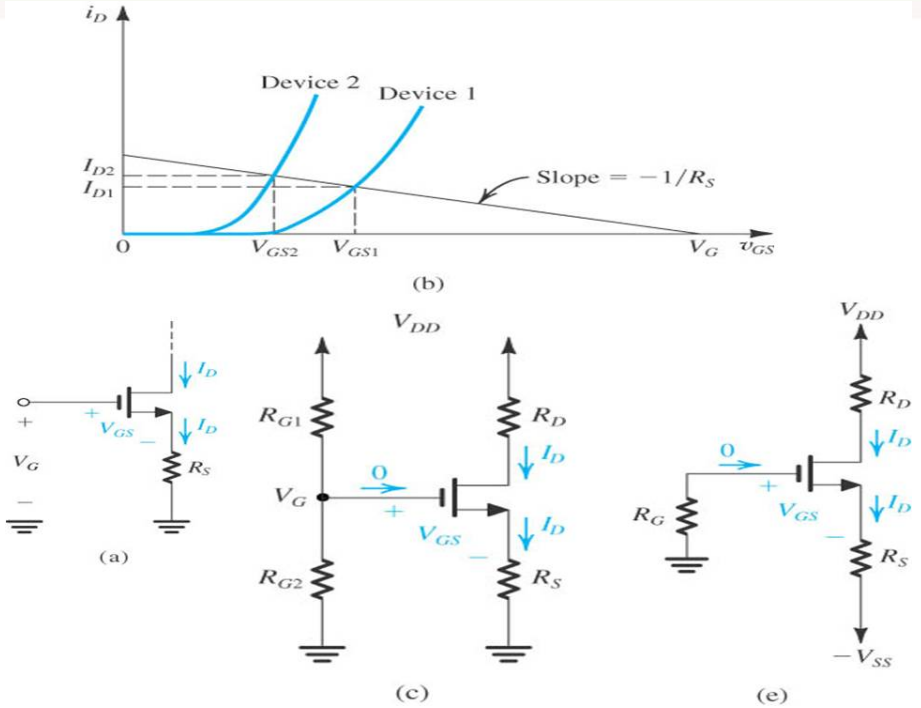
Notes

- Please note that changing the device will result in a reduced change in the drain current compared to the fixed V_GS.
- If I_D is increased (e.g. by temperature) V_S will increase and V_{GS} will decrease stabilizing I_D
- It could utilize single supply as in (c) or dual supplies as in (e).

MOSFET Amplifier Biasing

Source Resistance Feedback Biasing



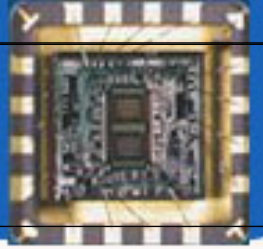


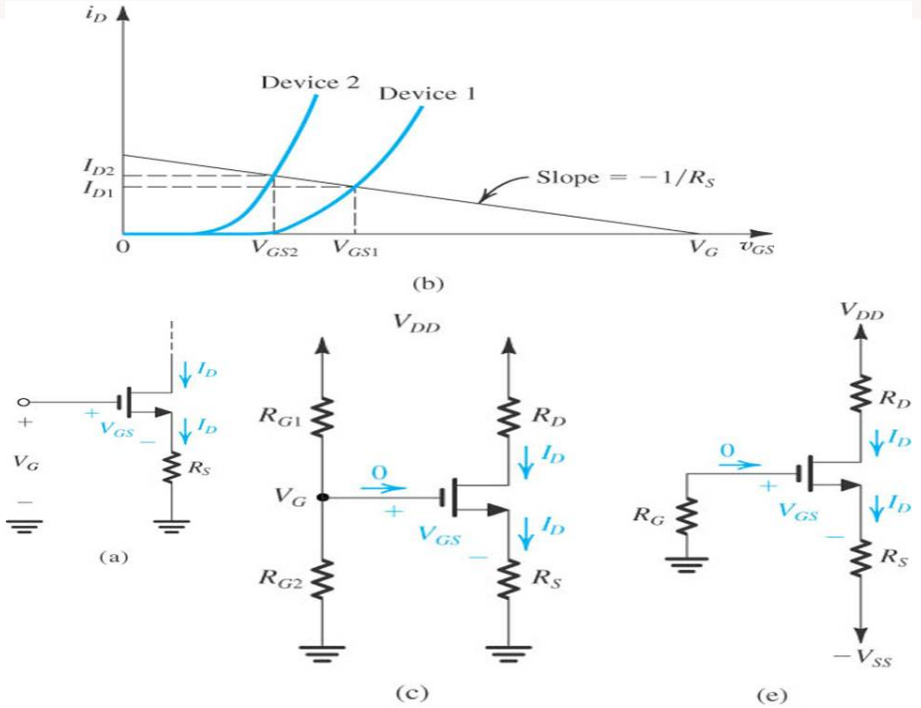
Notes

- Please note that changing the device will result in a reduced change in the drain current compared to the fixed V_GS.
- If I_D is increased (e.g. by temperature) V_S will increase and V_{GS} will decrease stabilizing I_D
- It could utilize single supply as in (c) or dual supplies as in (e).

MOSFET Amplifier Biasing

Source Resistance Feedback Biasing



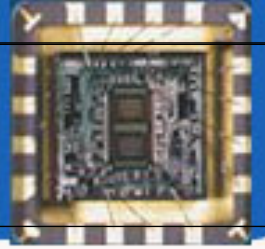


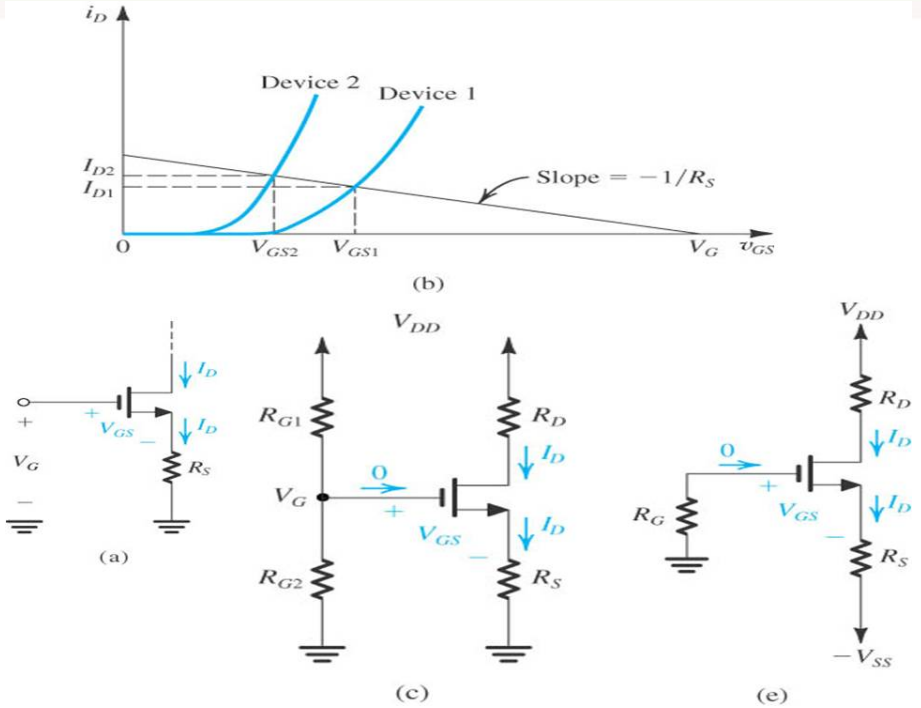
Notes

- Please note that changing the device will result in a reduced change in the drain current compared to the fixed V_GS.
- If I_D is increased (e.g. by temperature) V_S will increase and V_{GS} will decrease stabilizing I_D
- It could utilize single supply as in (c) or dual supplies as in (e).

MOSFET Amplifier Biasing

Source Resistance Feedback Biasing



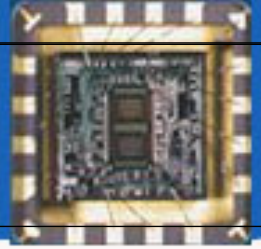


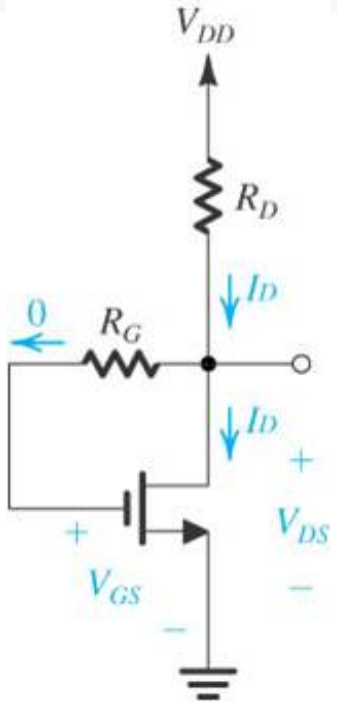
Notes

- Please note that changing the device will result in a reduced change in the drain current compared to the fixed V_GS.
- If I_D is increased (e.g. by temperature) V_S will increase and V_{GS} will decrease stabilizing I_D
- It could utilize single supply as in (c) or dual supplies as in (e).

MOSFET Amplifier Biasing

Drain Feedback Biasing



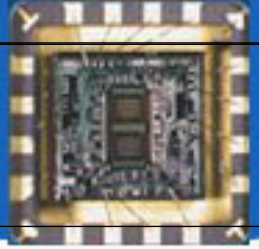


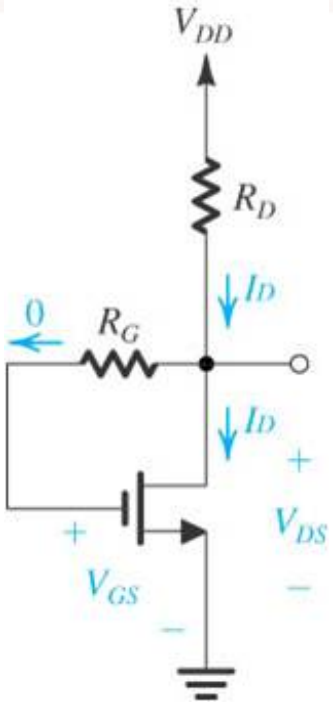
Notes

- Please note that the transistor is always in saturation as $V_{GS} = V_{DS}$
- If I_D is increased (e.g. by temperature) V_S will increase and V_{GS} will decrease stabilizing I_D
- It could utilize single/dual supply.

MOSFET Amplifier Biasing

Drain Feedback Biasing



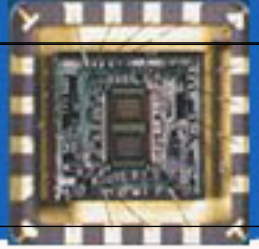


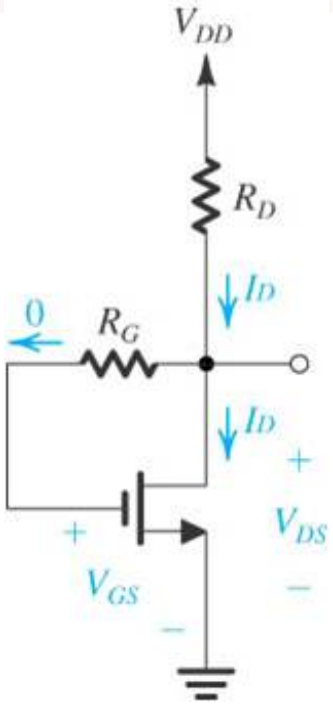
Notes

- Please note that the transistor is always in saturation as $V_{GS} = V_{DS}$
- If I_D is increased (e.g. by temperature) V_S will increase and V_{GS} will decrease stabilizing I_D
- It could utilize single/dual supply.

MOSFET Amplifier Biasing

Drain Feedback Biasing



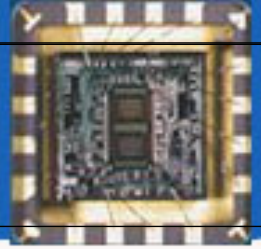


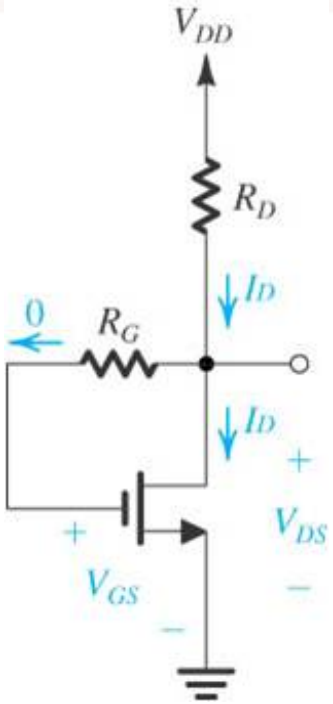
Notes

- Please note that the transistor is always in saturation as $V_{GS} = V_{DS}$
- If I_D is increased (e.g. by temperature) V_S will increase and V_{GS} will decrease stabilizing I_D
- It could utilize single/dual supply.

MOSFET Amplifier Biasing

Drain Feedback Biasing



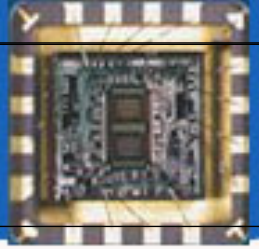


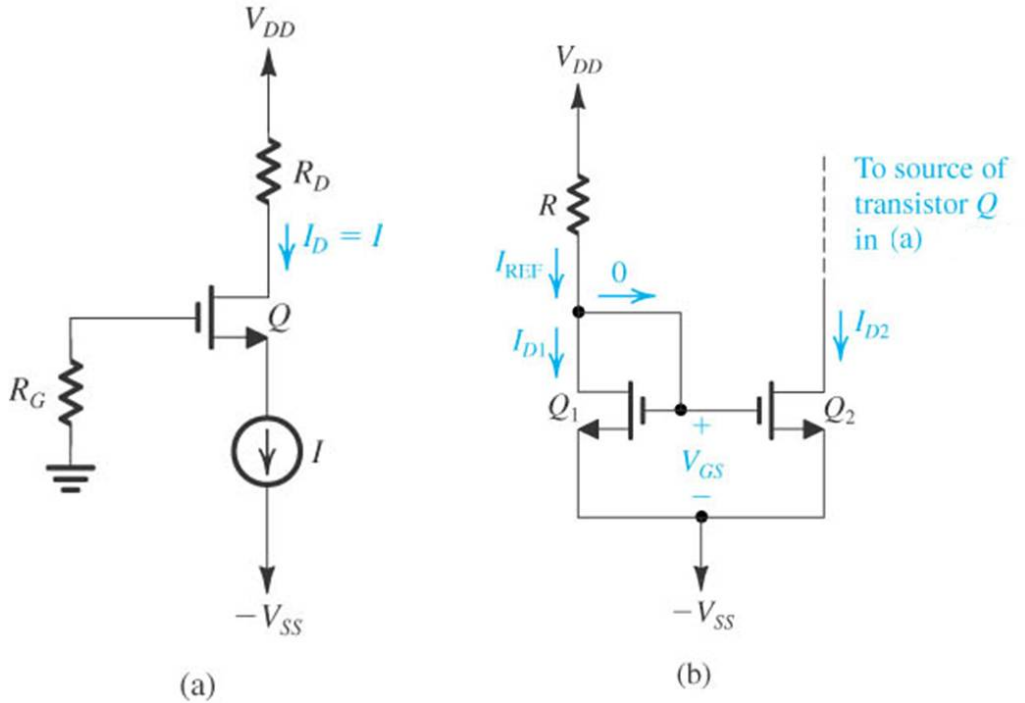
Notes

- Please note that the transistor is always in saturation as $V_{GS} = V_{DS}$
- If I_D is increased (e.g. by temperature) V_S will increase and V_{GS} will decrease stabilizing I_D
- It could utilize single/dual supply.

MOSFET Amplifier Biasing

Constant Current Biasing



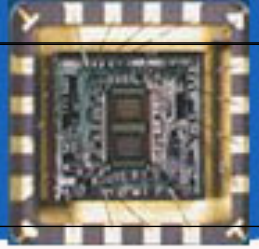


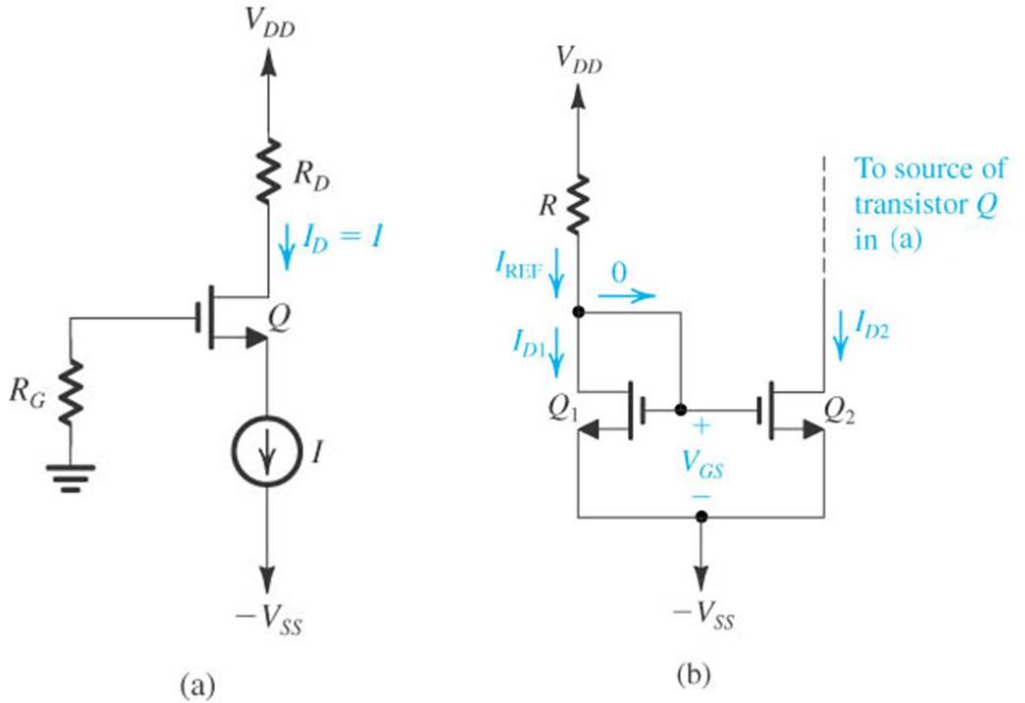
Notes

- Please note that the drain current will be independent of the amplifier transistor.
- the current source is constructed of a current mirror as shown in (b)
- Dual supplies are usually needed.

MOSFET Amplifier Biasing

Constant Current Biasing



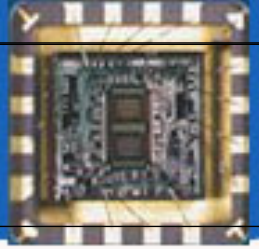


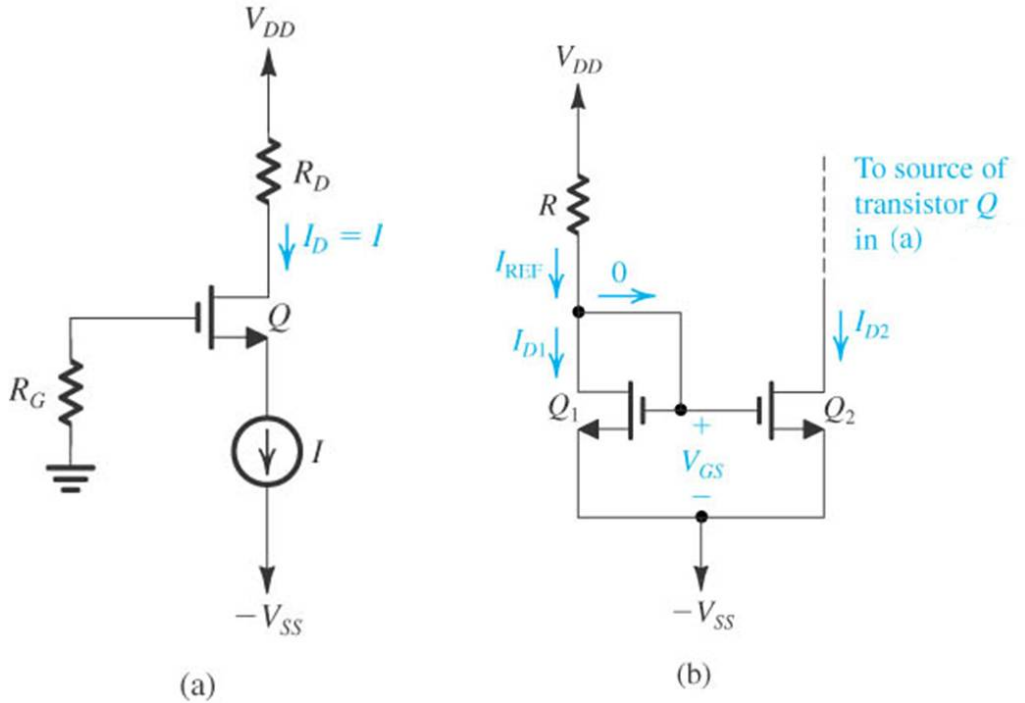
Notes

- Please note that the drain current will be independent of the amplifier transistor.
- the current source is constructed of a current mirror as shown in (b)
- Dual supplies are usually needed.

MOSFET Amplifier Biasing

Constant Current Biasing



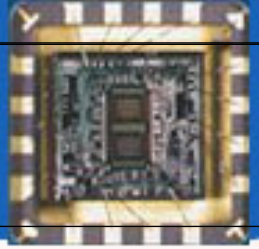


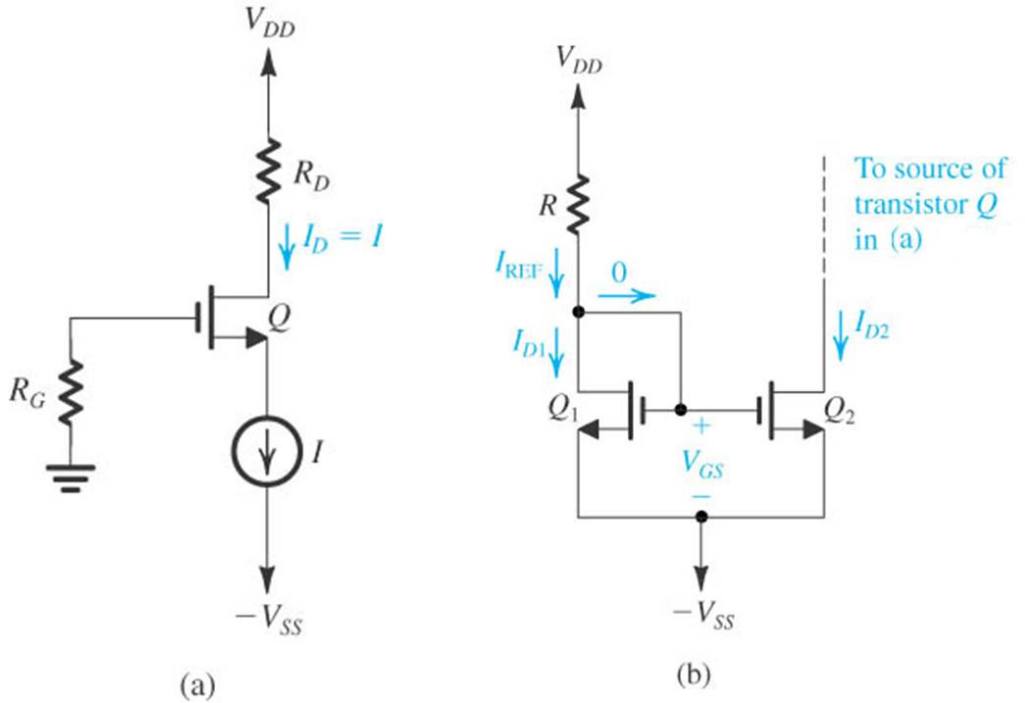
Notes

- Please note that the drain current will be independent of the amplifier transistor.
- the current source is constructed of a current mirror as shown in (b)
- Dual supplies are usually needed.

MOSFET Amplifier Biasing

Constant Current Biasing

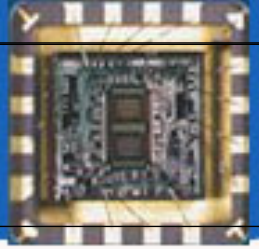




Notes

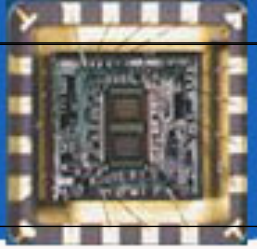
- Please note that the drain current will be independent of the amplifier transistor.
- the current source is constructed of a current mirror as shown in (b)
- Dual supplies are usually needed.

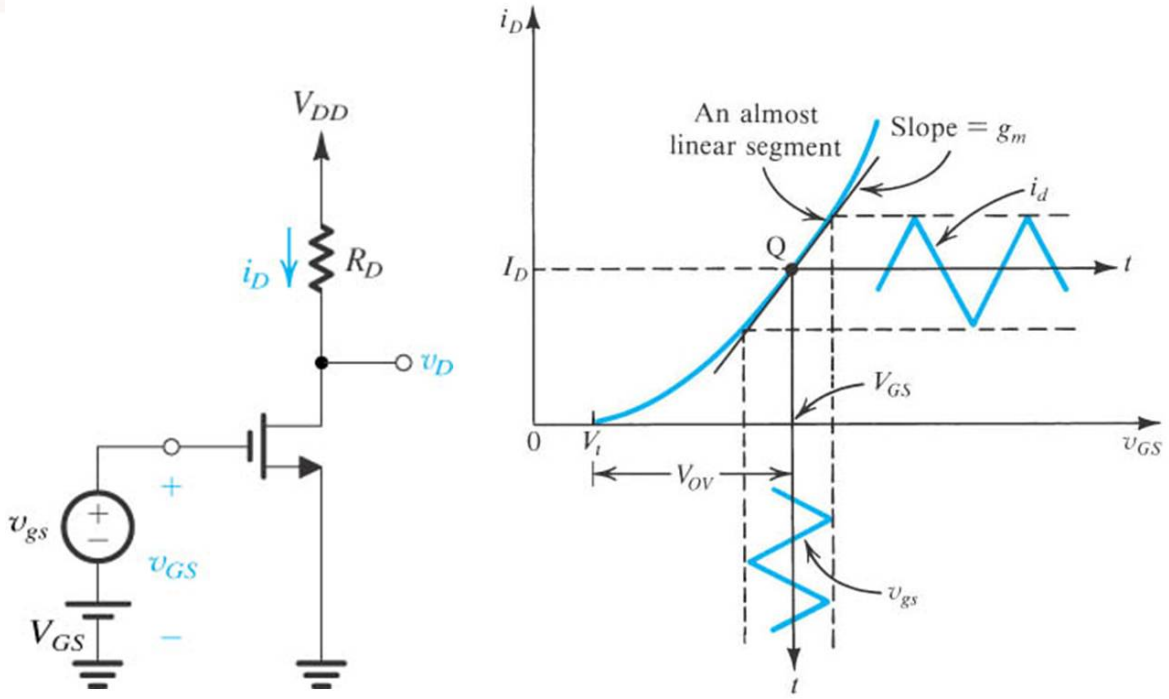
Outline



MOSFET Small Signal Operation

Basic Operation



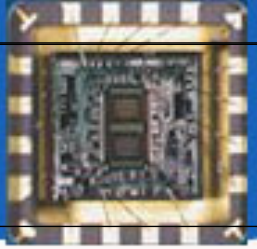


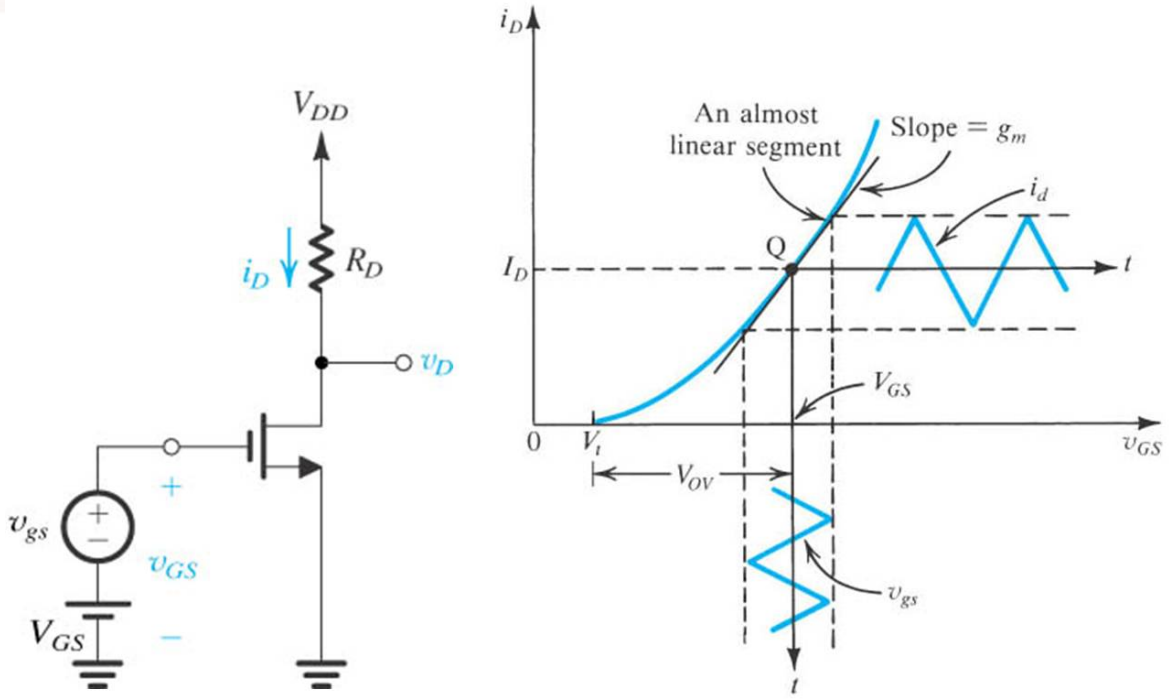
Notes

- v_{GS} represents the total voltage (D.C+A.C), V_{GS} represents the D.C only (Q-Point), and v_{gs} represents the A.C only (small signal).
- For small signal the characteristic is linear.
- The DC biasing is important to set the small signal parameters (e.g. g_m)
- Can you think what will happen if the DC is removed?

MOSFET Small Signal Operation

Basic Operation



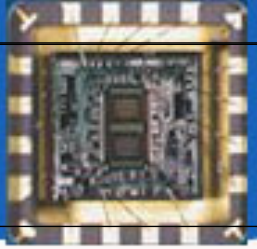


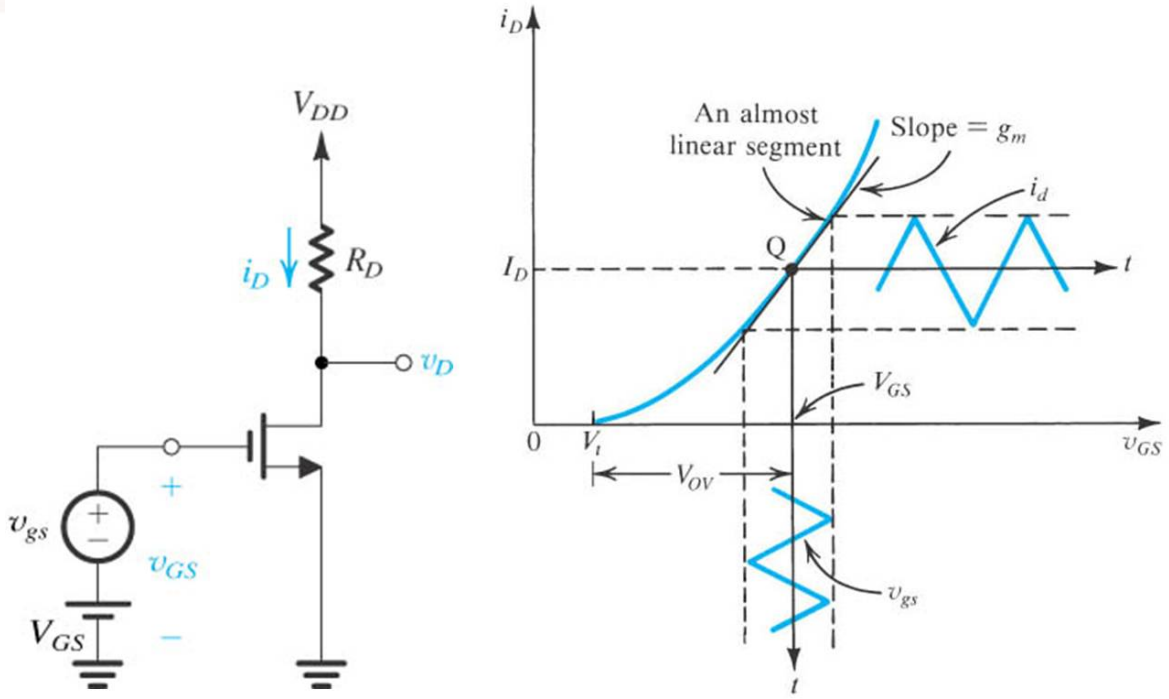
Notes

- v_{GS} represents the total voltage (D.C+A.C), V_{GS} represents the D.C only (Q-Point), and v_{gs} represents the A.C only (small signal).
- For small signal the characteristic is linear.
- The DC biasing is important to set the small signal parameters (e.g. g_m)
- Can you think what will happen if the DC is removed?

MOSFET Small Signal Operation

Basic Operation



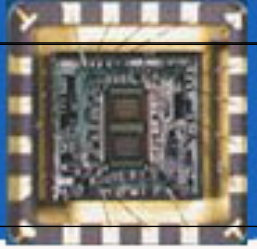


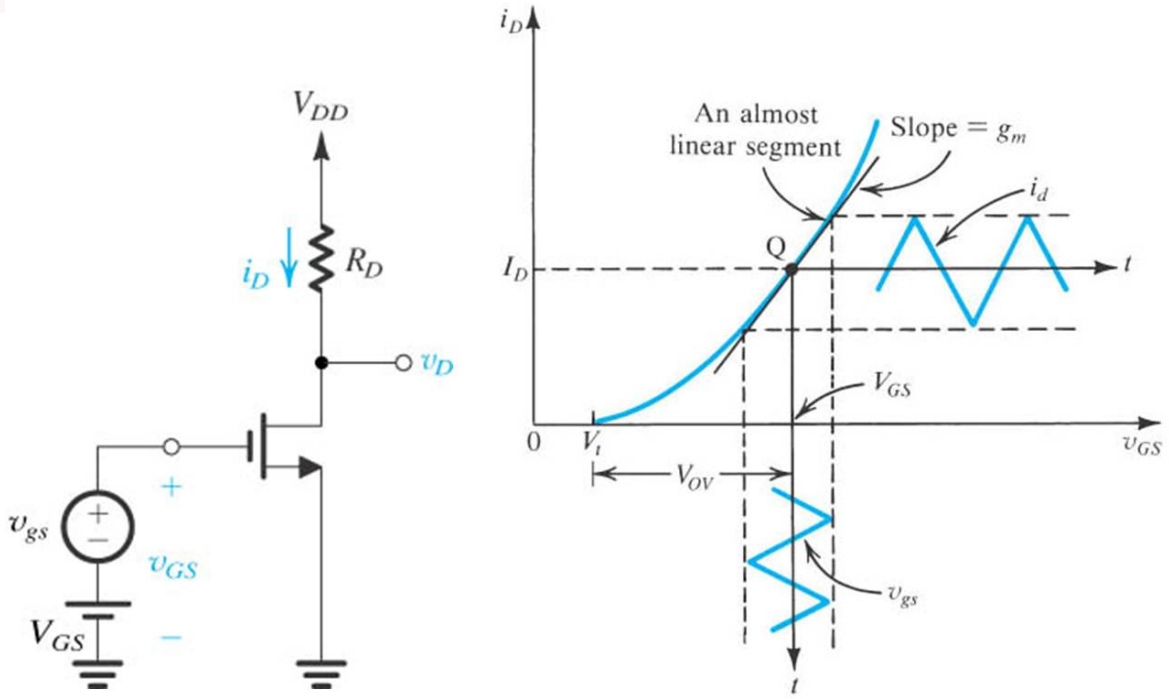
Notes

- v_{GS} represents the total voltage (D.C+A.C), V_{GS} represents the D.C only (Q-Point), and v_{gs} represents the A.C only (small signal).
- For small signal the characteristic is linear.
- The DC biasing is important to set the small signal parameters (e.g. g_m)
- Can you think what will happen if the DC is removed?

MOSFET Small Signal Operation

Basic Operation



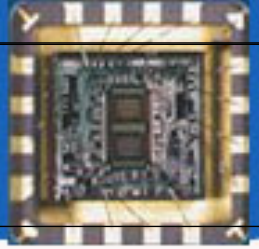


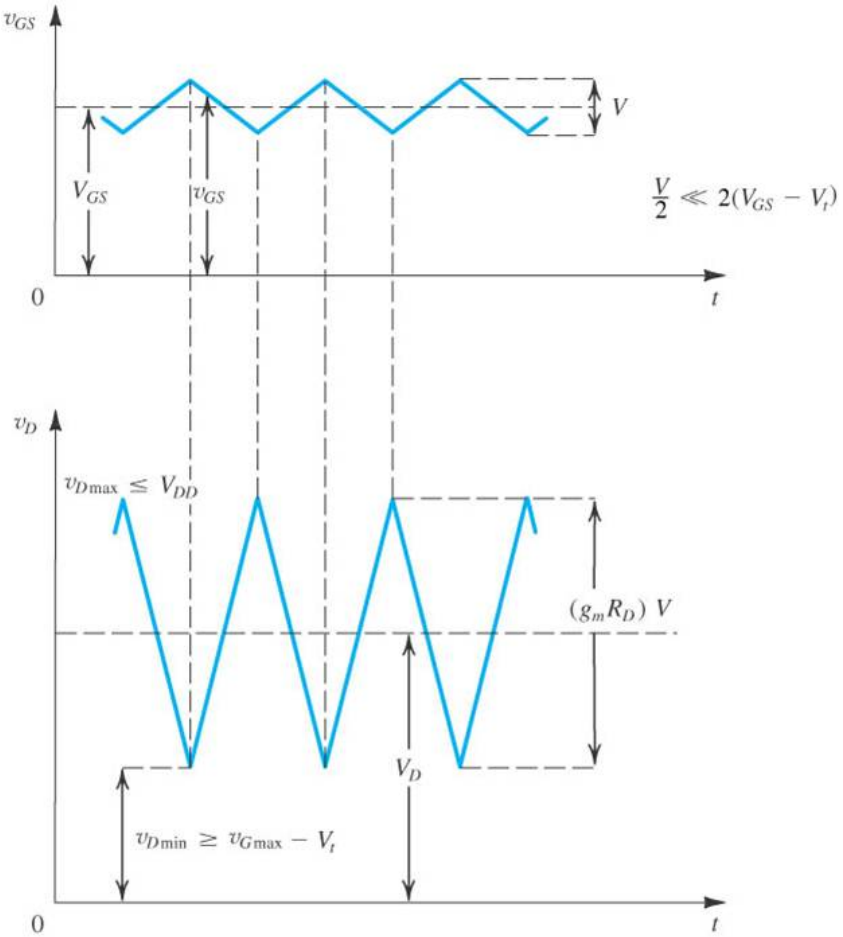
Notes

- v_{GS} represents the total voltage (D.C+A.C), V_{GS} represents the D.C only (Q-Point), and v_{gs} represents the A.C only (small signal).
- For small signal the characteristic is linear.
- The DC biasing is important to set the small signal parameters (e.g. g_m)
- Can you think what will happen if the DC is removed?.

MOSFET Small Signal Operation

Example



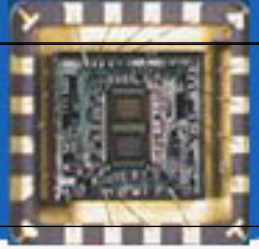


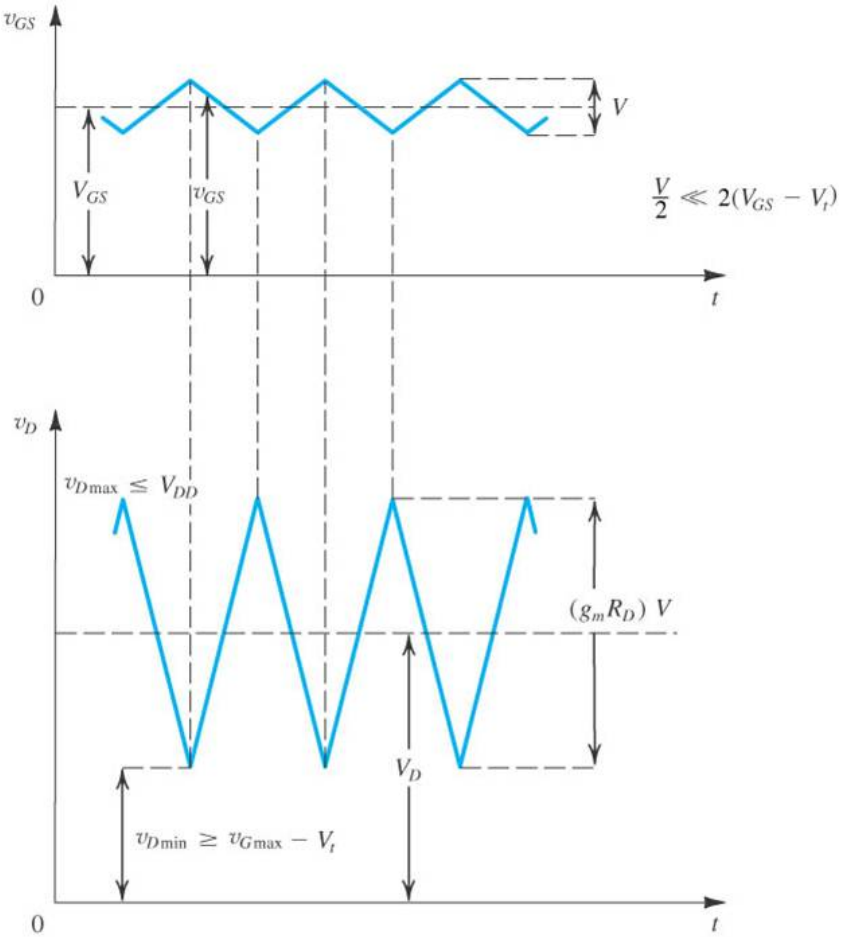
Notes

- From the figure, the gain equals $g_m.R_D$
- $v_{Dmax} = V_{DD}$
- $v_{Dmin} = V_{Gmax} - V_t$ to ensure saturation operation.

MOSFET Small Signal Operation

Example



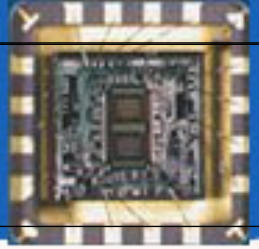


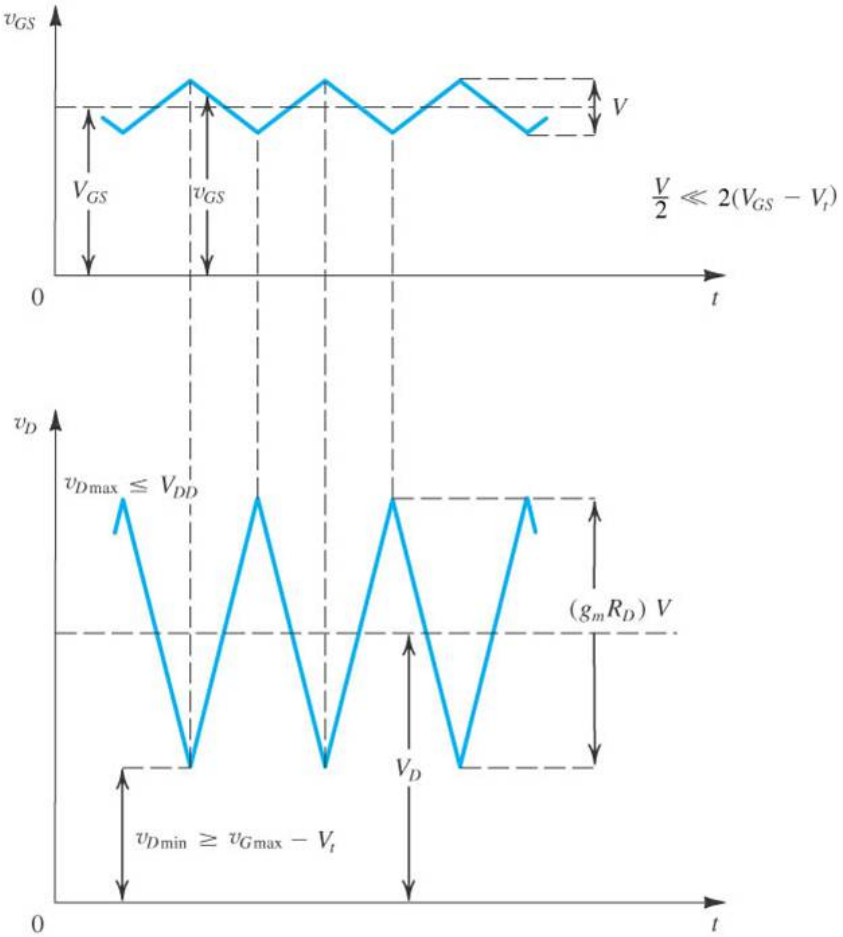
Notes

- From the figure, the gain equals $g_m.R_D$
- $v_{Dmax} = V_{DD}$
- $v_{Dmin} = V_{Gmax} - V_t$ to ensure saturation operation.

MOSFET Small Signal Operation

Example



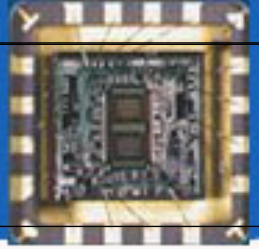


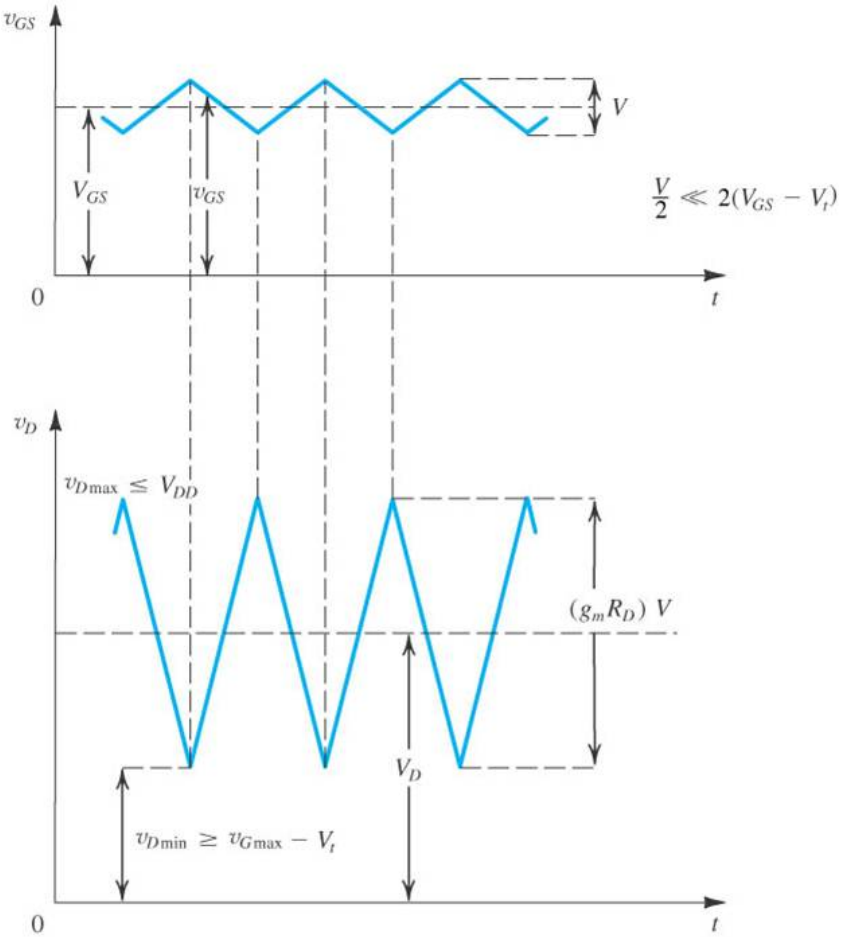
Notes

- From the figure, the gain equals $g_m.R_D$
- $v_{Dmax} = V_{DD}$
- $v_{Dmin} = V_{Gmax} - V_t$ to ensure saturation operation.

MOSFET Small Signal Operation

Example

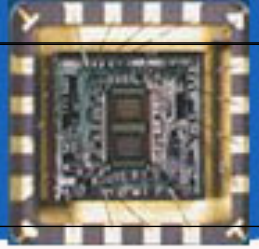




Notes

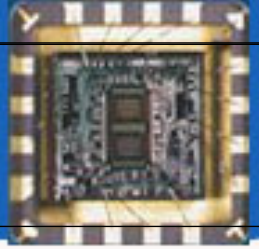
- From the figure, the gain equals $g_m.R_D$
- $v_{Dmax} = V_{DD}$
- $v_{Dmin} = V_{Gmax} - V_t$ to ensure saturation operation.

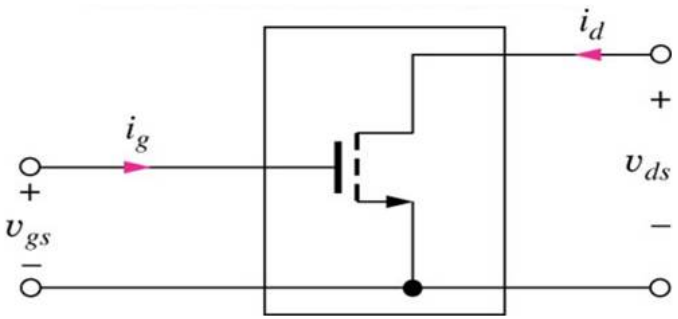
Outline



MOSFET Small Signal Model

y-parameters





Using 2-port y-parameter network,

$$i_g = y_{11} v_{gs} + y_{12} v_{ds}$$
$$i_d = y_{21} v_{gs} + y_{22} v_{ds}$$

The port variables can represent either time-varying part of total voltages and currents or small changes in them away from Q-point values.

$$y_{11} = \left.\frac{i_g}{v_{gs}}\right|_{v_{ds}=0} = \left.\frac{\partial i_G}{\partial v_{GS}}\right|_{Q-point} = 0$$

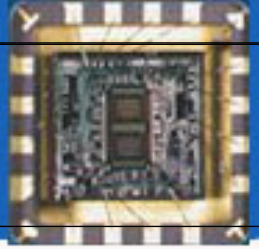
$$y_{12} = \left.\frac{i_g}{v_{ds}}\right|_{v_{gs}=0} = \left.\frac{\partial i_G}{\partial v_{DS}}\right|_{Q-point} = 0$$

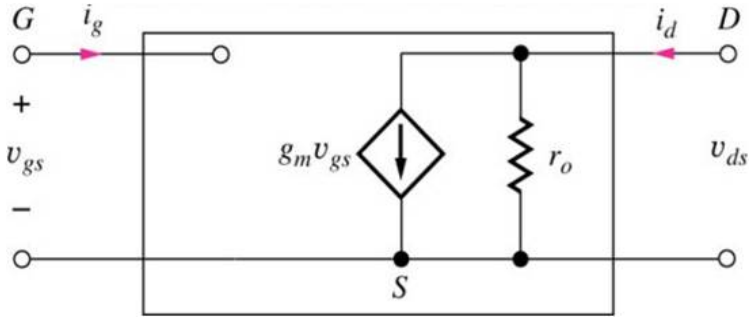
$$y_{21} = \left.\frac{i_d}{v_{gs}}\right|_{v_{ds}=0} = \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{Q-point} = \frac{2I_D}{V_{GS} - V_{TN}}$$

$$y_{22} = \left.\frac{i_d}{v_{ds}}\right|_{v_{gs}=0} = \left.\frac{\partial i_D}{\partial v_{DS}}\right|_{Q-point} = \frac{I_D}{\frac{1}{\lambda} + V_{DS}}$$

MOSFET Small Signal Model

Small Signal Parameters





- Since the gate is insulated from the channel by gate-oxide, the input resistance of the transistor is infinite.
- Small-signal parameters are controlled by the Q-point.

Transconductance:

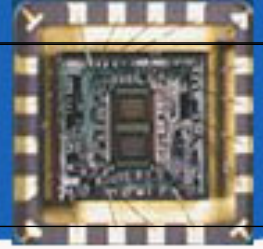
$$g_m = y_{21} = \frac{I_D}{\frac{V_{GS}-V_{TN}}{2}} = \sqrt{2K_n I_D}$$

Output resistance:

$$r_o = \frac{1}{y_{22}} = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} \cong \frac{1}{\lambda I_D}$$

MOSFET Small Signal Model

Small Signal Condition



The drain current in the saturation region is given by:

$$i_D = \frac{K_n}{2}\left(v_{GS} - V_{TN}\right)^2$$

$$\therefore i_D = I_D + i_d = \frac{K_n}{2}\left[\left(V_{GS} - V_{TN}\right)^2 + 2v_{gs}\left(V_{GS} - V_{TN}\right) + v_{gs}^2\right]$$

$$\therefore i_d = \frac{K_n}{2}\left[2v_{gs}\left(V_{GS} - V_{TN}\right) + v_{gs}^2\right]$$

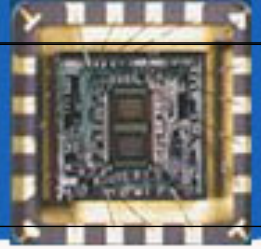
For linearity, i_d should be proportional to v_{gs}, that means
$v_{gs} << 2\left(V_{GS} - V_{TN}\right)$
Change in drain current that corresponds to small-signal operation is:

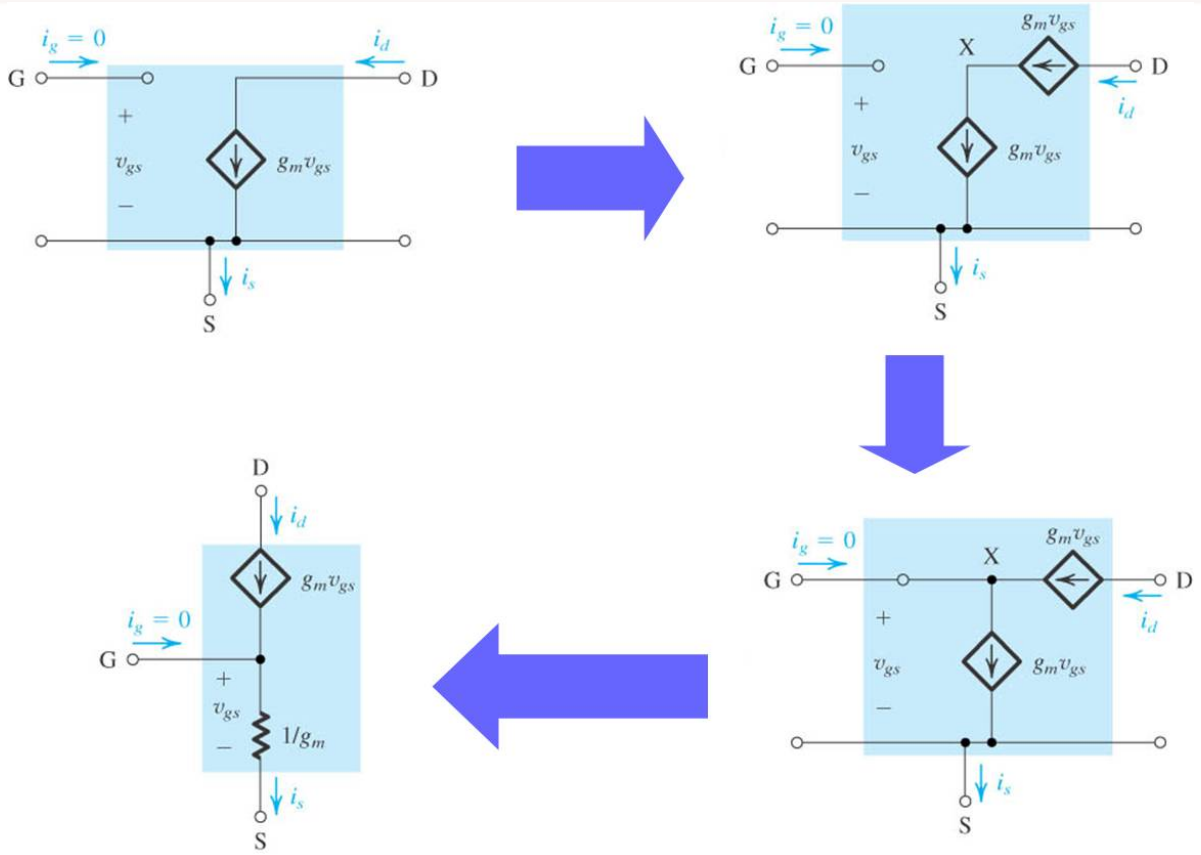
$$\frac{i_d}{I_D} = \frac{g_m}{I_D} v_{gs} = \frac{2v_{gs}}{V_{GS} - V_{TN}} << 4$$

If we considered $\ll$ means 0.1 then $i_d/I_D/0.4$

MOSFET Small Signal Model

T-Equivalent Small Small Signal Model

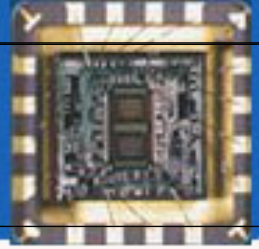


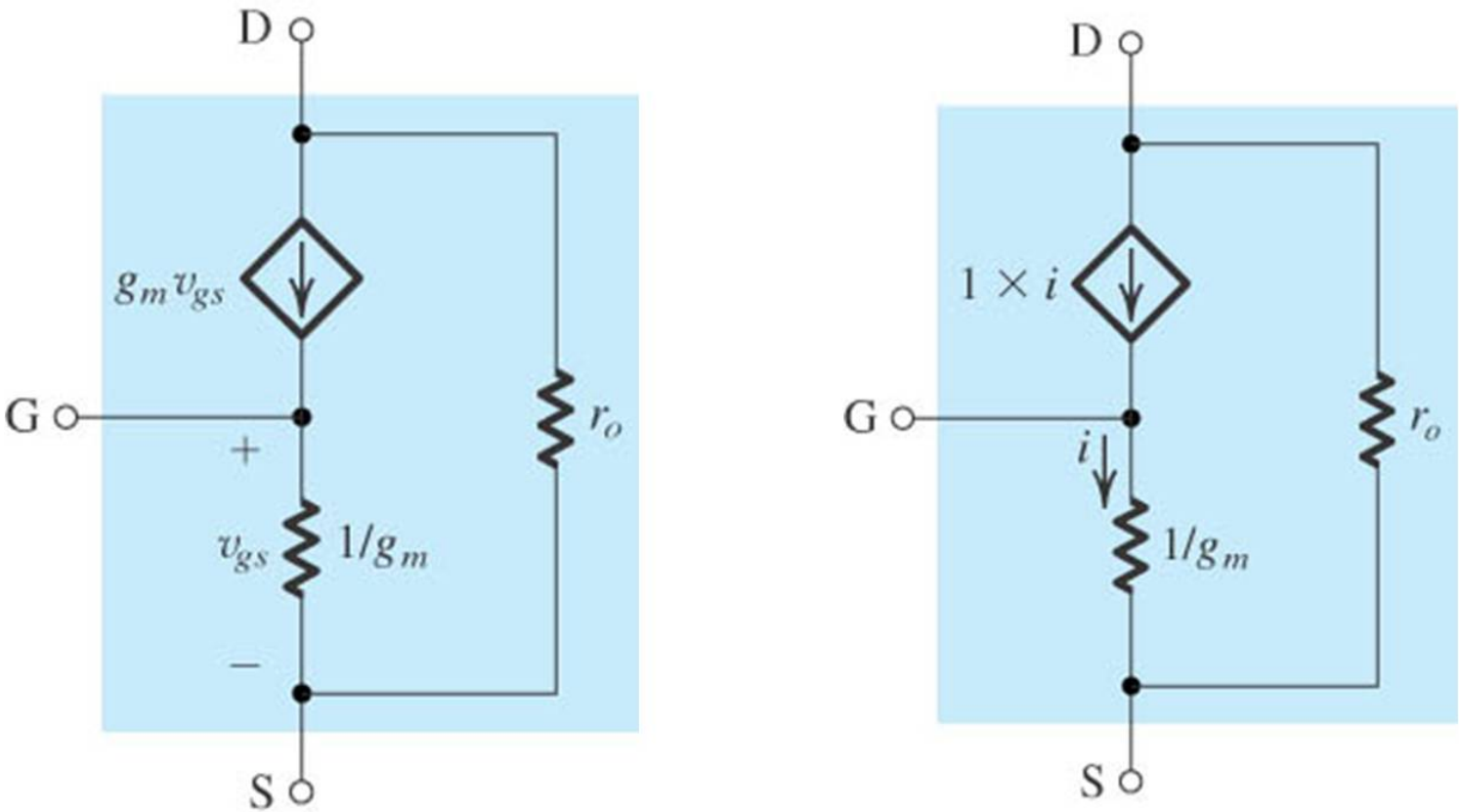


- The T-model may be obtained as shown
- It may ease the analysis if source resistance is exist

MOSFET Small Signal Model

T-Equivalent Small Signal Model with r_o





- r_o may be added as shown