CMOS ANALOG CIRCUIT DESIGN
UE18EC203

Course Content

1.PhysicsofMOSTransistors:

Structure of MOSFET, Operation of MOSFET, MOS device Models, PMOS transistor, CMOS technology.

2.Single Stage Amplifier:

Basic Concepts, Common Source stage, Source follower, Common gate stage, Cascode stage

3.Passive and active current mirrors:

Basic current mirror, Cascode current mirrors, Large signal analysis of active current mirror, small signal analysis of active current mirror

4.Differential amplifier:

Single Ended and Differential operation, Basic differential pair, Common Mode response, Differential Pair with MOS loads

5.Frequency Response:

Miller Effect, Common source stage; Feedback: General Consideration, Properties of negative feedback, Feedback Topologies, Effect of Loading.

ReferenceBooks:

1. Behzad Razavi, “Fundamentals of Microelectronics”,First Edition, Wiley, 2013
2. Behzad Razavi, “Design of Analog CMOS Integrated Circuits”, First Edition, McGraw-Hill, 2002
3. A.S.Sedra,K.C.SmithandA.N.Chandorkar, “Microelectronic Circuits:Theory And Applications”,7thEdition,OxfordUniversityPress,2017
4. D.A.JohnsandK.Martin,“Analogintegratedcircuitsdesign”,JohnWiley&Sons, New York,1997
5. P.R.Grayand R.G.Meyer,“AnalysisandDesignofAnalogIntegratedCircuits”,4th edition, Wiley,2001.
6. MuhammadHRashid,“MicroelectronicCircuits:AnalysisandDesign”,2nd Edition,

Marks split-up theory ISA

- Theory ISA

#	Components	Marks
1	ISA 1	15
2	ISA 2	15
3	Assignment	10
	Total	**40**

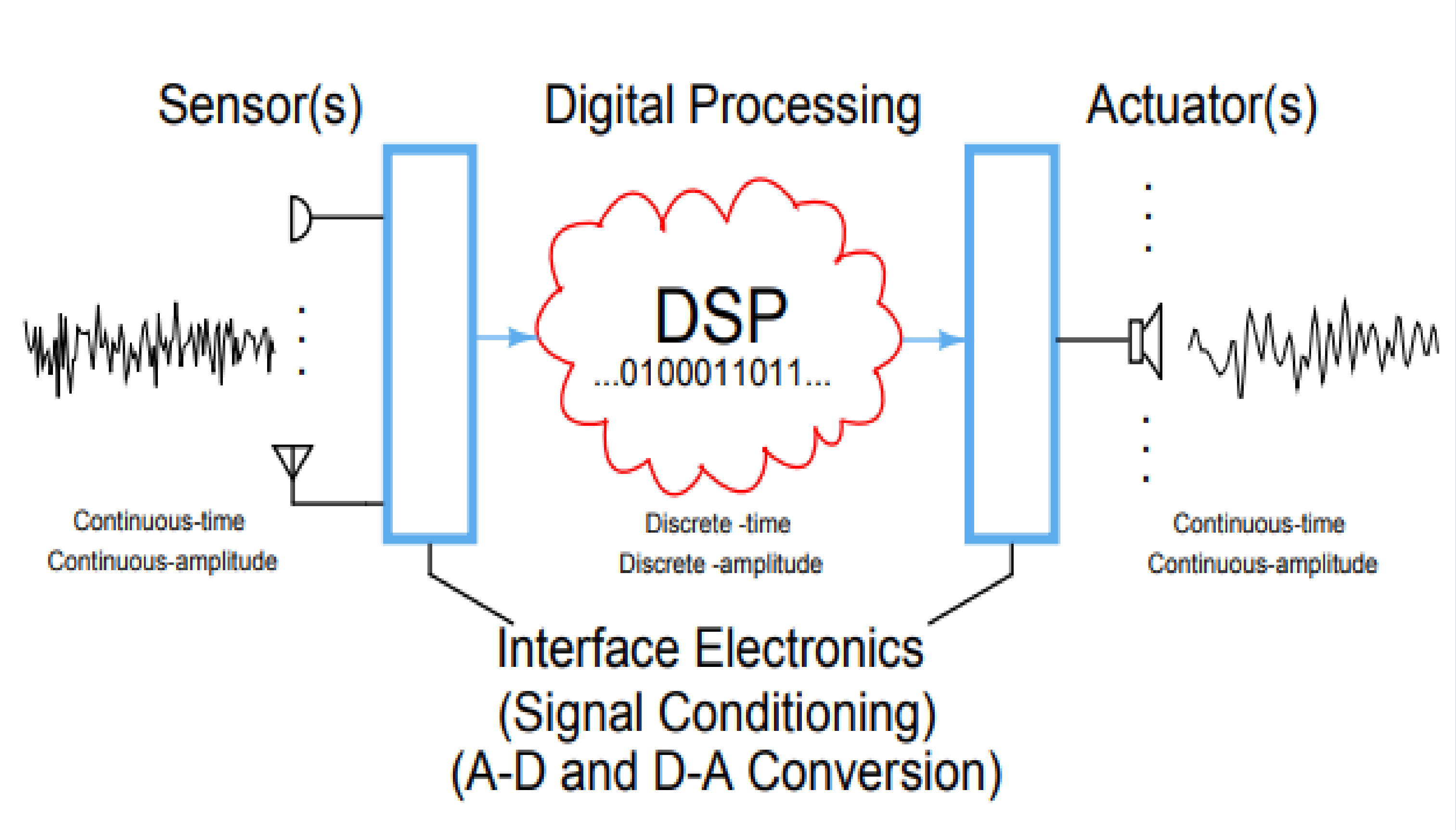
- LAB ISA

#	Components	Marks
1	Lab Assignments	16
2	Observation	04
3	Two intermediate progressive Evaluation	20 each
	Total	**60**

Why Analog?

- Most of the physical signals are analog in nature!
- Although digital is great we need an analog interface to convert physical signals from analog to digital
- Also, in some application after processing the signals in digital domain, we need to convert them back to analog.
- Thus in many applications analog and mixed-signal circuits are the performance bottlenecks.
- Also with constant process improvements the boundary of between high-speed digital and analog circuits becomes more and more fuzzy!
- That is why analog and mixed-signal designers are still and hopefully will be in demand for the foreseeable future.

Modern Signal Processing System



Analog circuits in modern systems on VLSI chips

- Analog to digital conversion
- Digital to analog conversion
- Amplification Signal processing circuits at high frequencies
- **Power management-voltage references, voltage regulators**
- **Oscillators, Phase locked loops**

The last two are found even on many “digital” ICs

Physics of MOS Transistors

Chapter 6 from Behzad Razavi, “Fundamentals of Microelectronics”

- 6.1 Structure of MOSFET
- 6.2 Operation of MOSFET
- 6.3 MOS Device Models
- 6.4 PMOS Transistor
- 6.5 CMOS Technology

Chapter Outline

Operation of MOSFET
- MOS structure
- Operation in Triode region
- Operation in Saturation
- I/V Characteristics

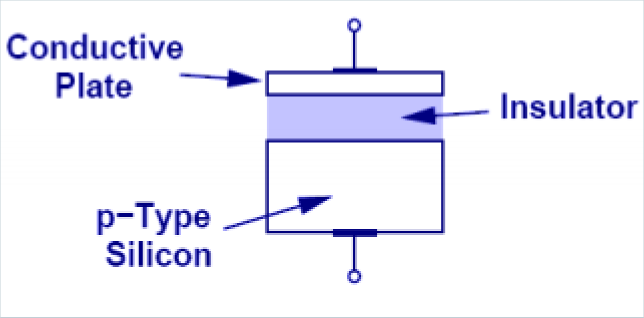
MOS Device Models
- Large-Signal Model
- Small-Signal Model

PMOS Devices
- Structure
- Models

Structure of MOSFET

Metal-Oxide-Semiconductor (MOS) Capacitor

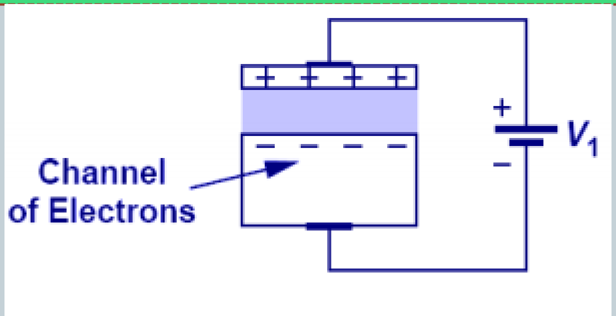
- To arrive the structure of MOSFET, begin with a simple geometry consisting of a conductive (metal) plate, an insulator (dielectric) and a doped piece of silicon.



The MOS structure can be thought of as a parallel-plate capacitor, with the top plate being the positive plate, oxide being the dielectric, and Si substrate being the negative plate. (We are assuming P-substrate.)

Structure of MOSFET

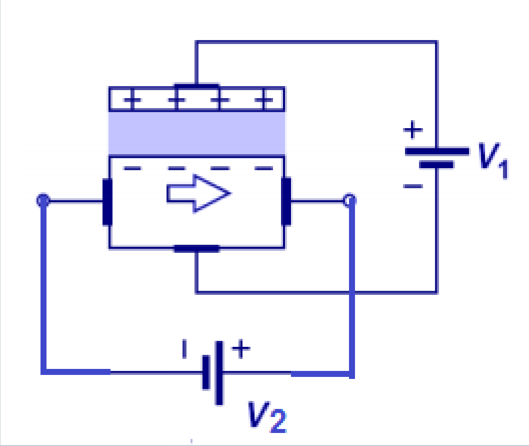
What happens if a potential difference is applied ?



- A "**channel**" of ***free*** electrons may be created at the interface between the insulator and the piece of silicon, potentially serving as a good conductive path if the electron density is sufficiently high.
- The density of electrons in the channel ***varies*** with V_1, $Q = CV_1$
  - Where C denotes the capacitance between the two plates.

Structure of MOSFET

- The electron density in the channel depends on V1.
- Now if V2 is connected as shown in the fig below



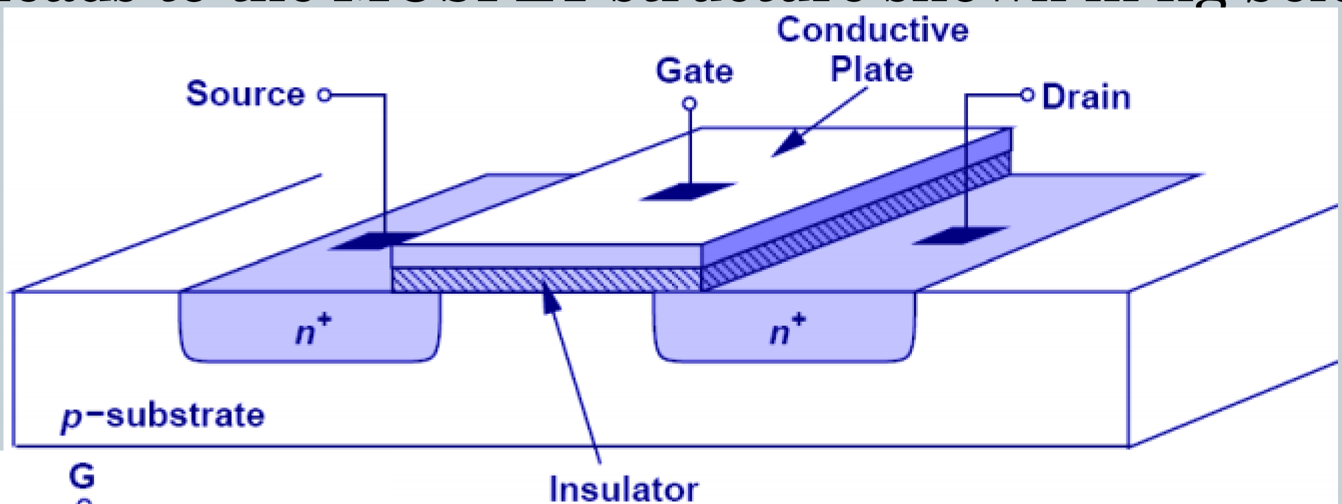
- Current flows from left to right through the silicon material.
- V1 can control the current by adjusting the resistivity of the channel.
- This will serve the objective of building a Voltage-controlled current source.

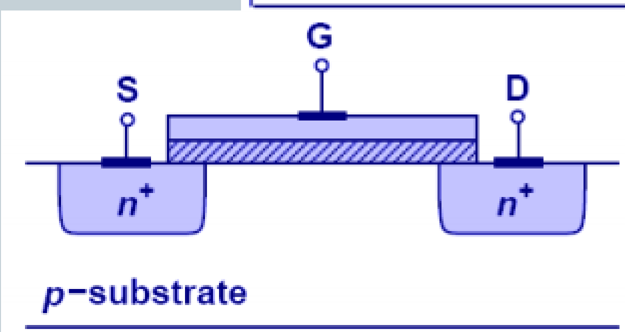
Structure of MOSFET

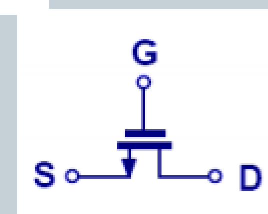
- Q = CV suggest that, to achieve a strong control of Q by V, the value of C must be maximized, for example, by reducing the thickness of the dielectric layer separating the two plates.
- The ability of silicon fabrication technology to produce extremely thin but uniform dielectric layers has proven essential to the rapid advancement of microelectronic devices.
  - (with thickness below 20 Å today).

Structure and Symbol of MOSFET

- This leads to the MOSFET structure shown in fig below



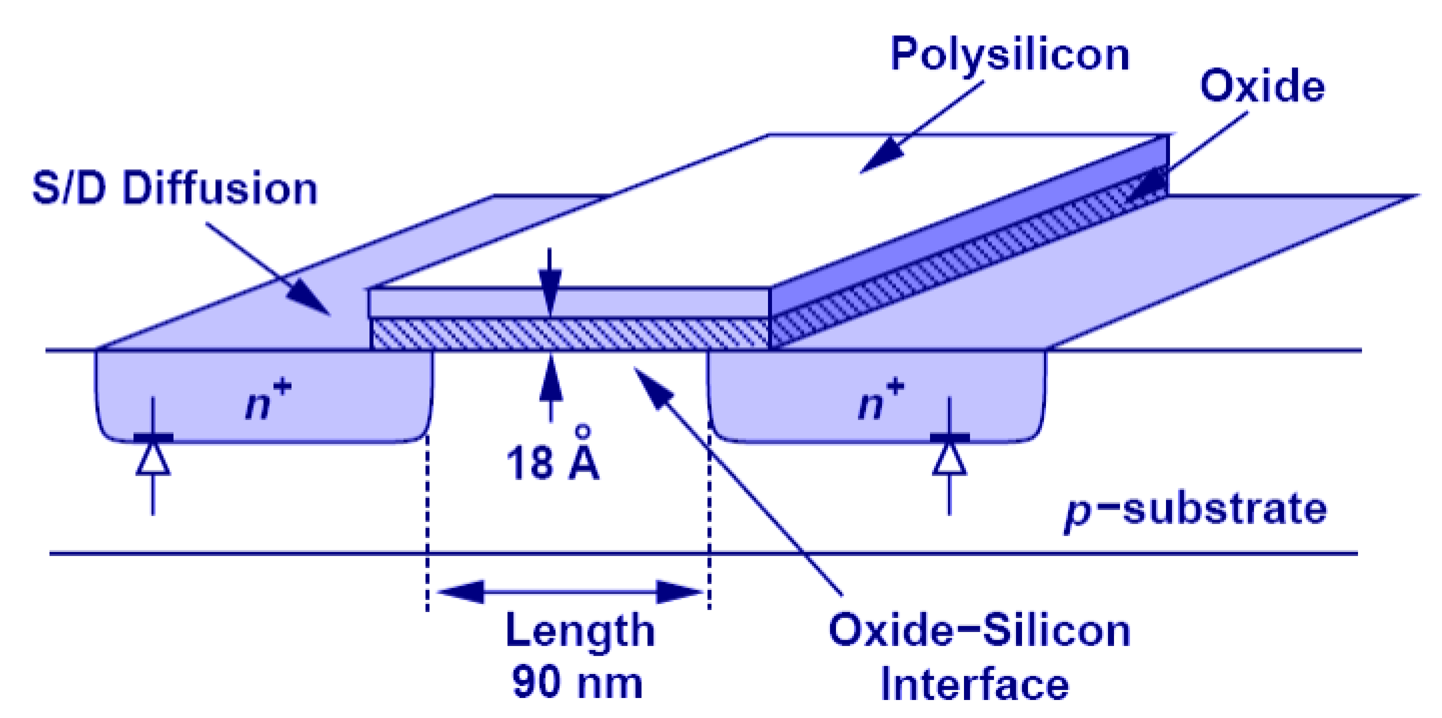




- This device is symmetric, so either of the n+ regions can be source or drain.

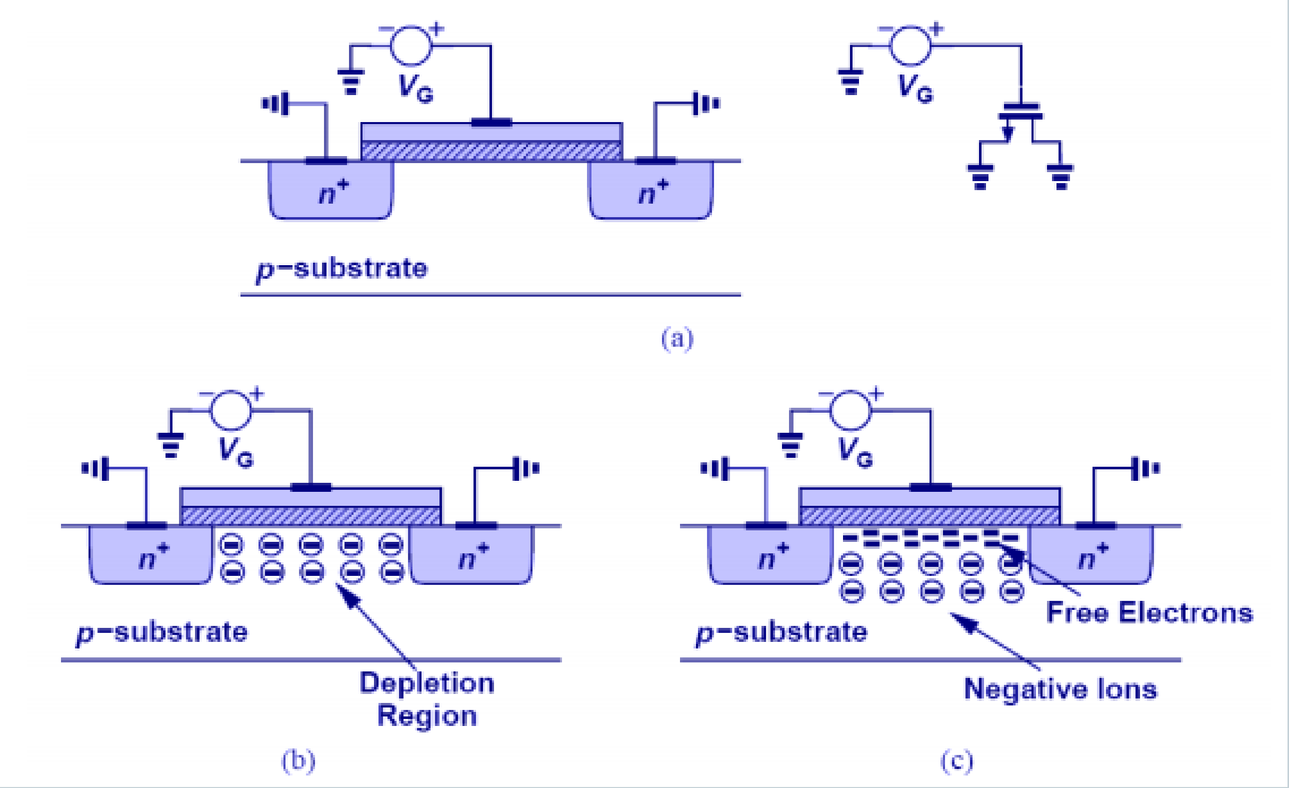
- “Gate” (G), the top conductive plate resides on a thin dielectric layer, which itself is deposited on the underlying p-type silicon “substrate”.
- To allow current flow through the silicon material, two contacts are attached to the substrate through two heavily doped n-type regions.
- Because direct connection of metal to the substrate would not provide good “ohmic” contact.
- These two terminals are called “source”(S) and “drain” (D).
- This transistor operates with electrons rather than holes and is therefore called n-type MOS (NMOS) device.

Typical dimensions of today's state-of-the-art MOSFETs



Operation of MOSFET

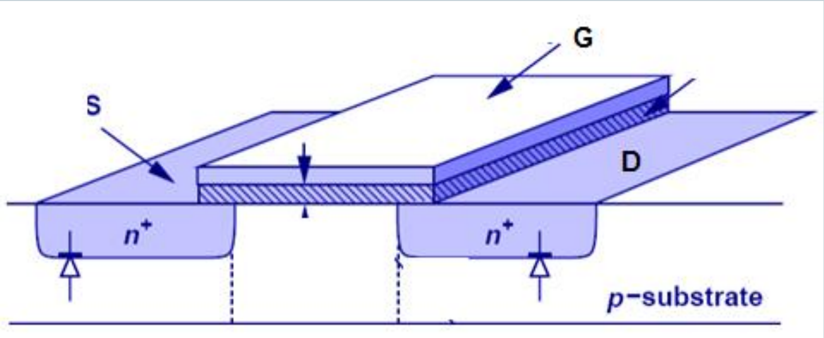
- $I_g = 0$,
- What happens as Vg increases ?



First, the holes are repelled by the positive gate voltage, leaving behind negative ions and forming a depletion region. Next, electrons are attracted to the interface, creating a channel ("*Inversion Layer*"). P-type channel is inverted to n-type

Operation of MOSFET

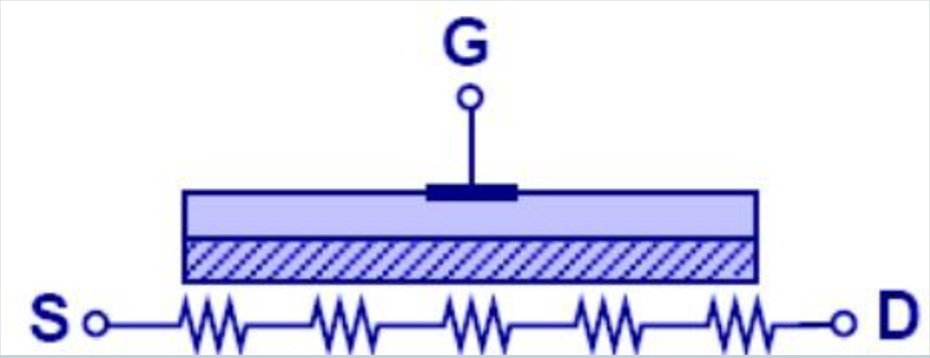
- Threshold Voltage (V_{th}): the gate potential at which the channel begins to appear is called V_{th}(range .3V - .5V)
- Can the source-substrate and drain-substrate junctions carry current in the mode?



- It is interesting to recognize that the gate terminal of MOSFET draws no current.
- Resting on top of the oxide, the gate remains insulated from other terminals and simply operates as plate of a capacitor.

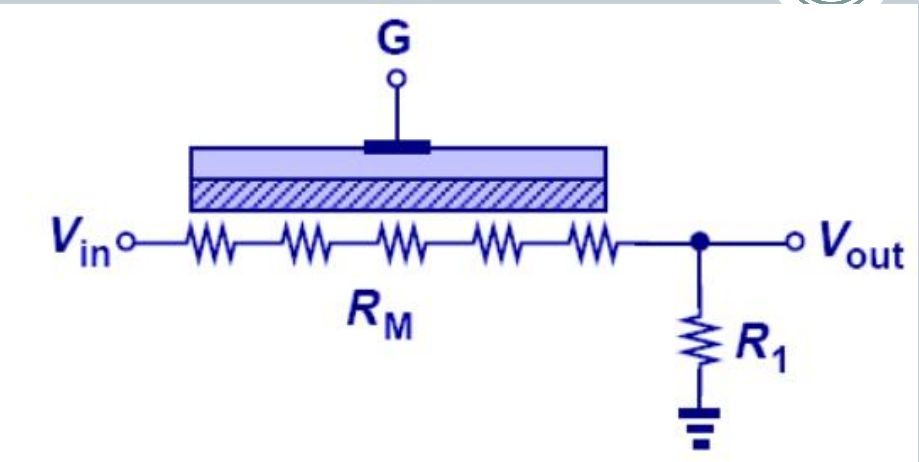
Voltage-Dependent Resistor

MOSFET as a Variable Resistor.



- The inversion channel of a MOSFET can be seen as a resistor.
- Since the charge density inside the channel depends on the gate voltage, this resistance is also voltage-dependent
- Such a voltage-dependent resistor proves extremely useful in analog and digital circuits.

Voltage-Controlled Attenuator



- As the gate voltage decreases, the output drops because the channel resistance increases.

$$\frac{v_{out}}{v_{in}} = \frac{R_1}{R_M + R_1}$$

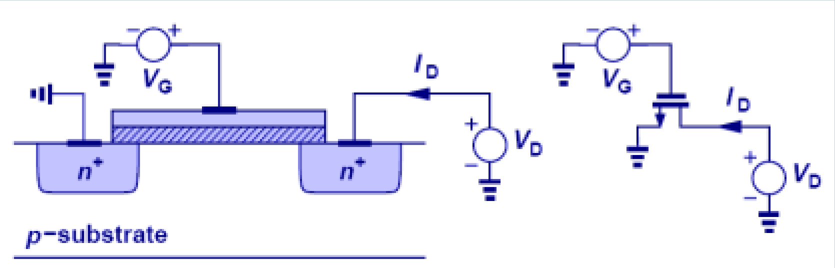
In the vicinity of a wireless base station, the signal received by a cell-phone may become very strong, possibly "saturating" the circuits and prohibiting proper operation. Devise a variable-gain circuit that lowers the signal level as the cell-phone approaches the base station.

rent methods.
hile an amplifier

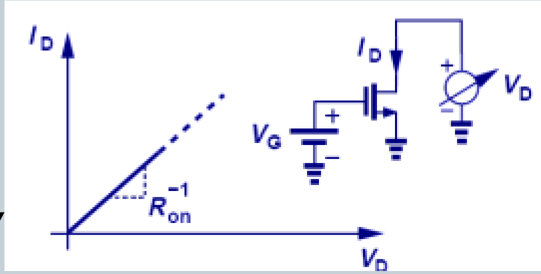
- This type of gain control finds application in cell phones to avoid saturation near base stations

MOSFET Characteristics

- If Vg < Vth,
  - No channel exists,
  - The device is off
  - The drain current $I_D = 0$
  - Regardless of the Value of V_D

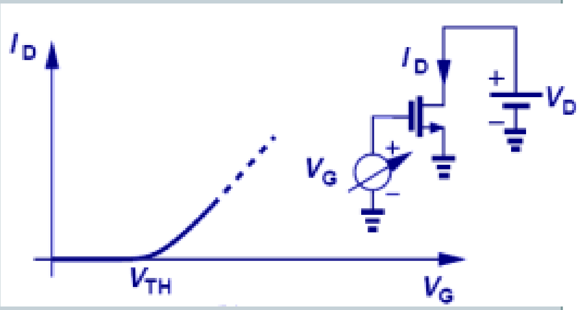


- If Vg > Vth,
  - Channel exists,
  - The device is ON
  - The drain current I_D, dependence on both V_g and V_D
  - The source – drain path may act as simple resistor, yielding the ID – VD characteristics
  - The slop of the characteristics is equal to 1/Ron, where Ron denotes the "on-resistance" of the transistor

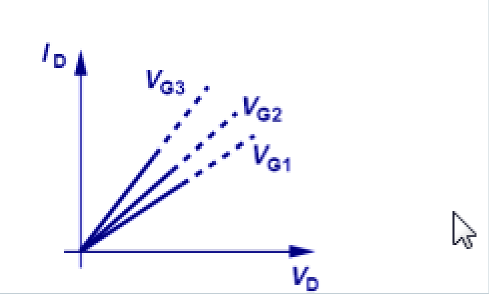


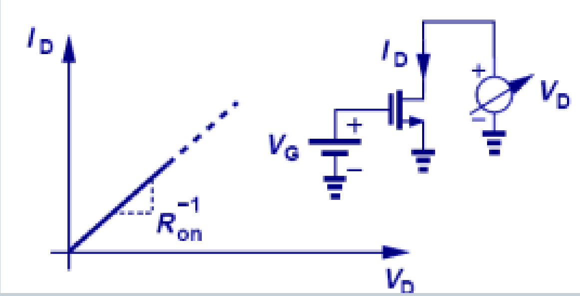
MOSFET Characteristics

- When V_G is increased, V_D remains constant
  - The higher the density of electrons in the channel lowers the on-resistance,
  - Yielding a greater slope.
  - Resulting characteristics strengthen the notion of voltage-dependent resistance
  - The voltage source tied to the drain creates an electric field along the channel, the results from the drift of charge.



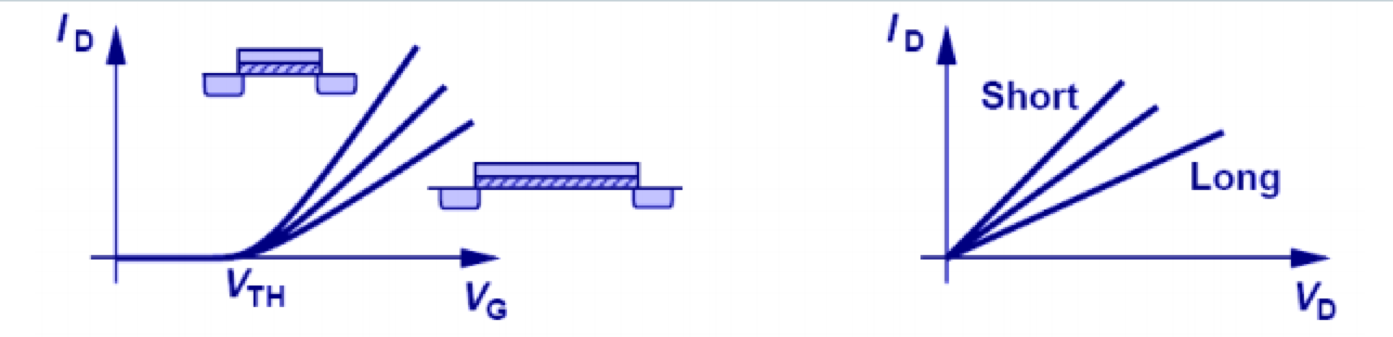
This shows the voltage dependence of channel resistance





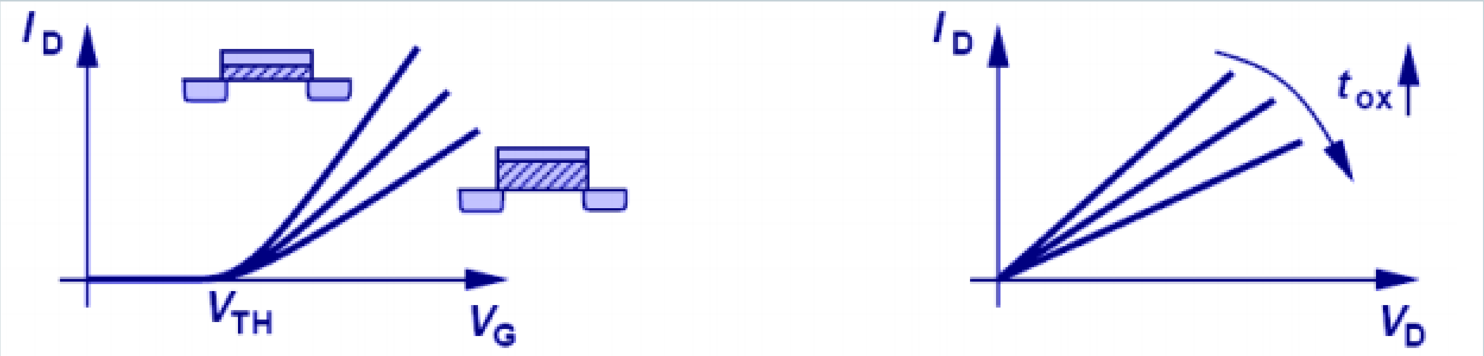
Channel length (L) and Oxide thickness (tox)Dependence

- Channel Length increases:
  - The drain current begins with lesser values as the channel length increases
  - I_D exhibits a smaller slope as a function of V_D
  - Therefore desirable to minimize the channel length sa as to achieve large drain currents – an important trend in the MOS technology development.



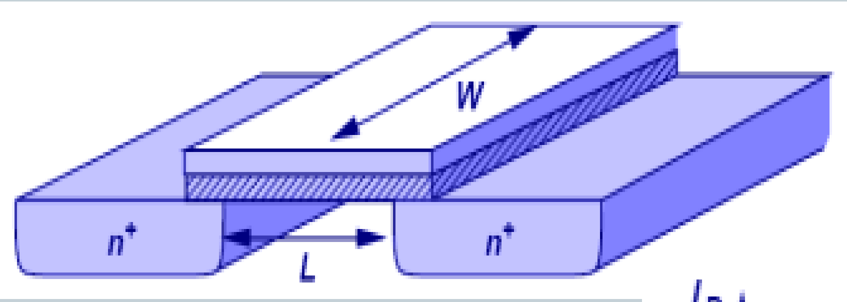
Channel length (L) and Oxide thickness (tox)Dependence

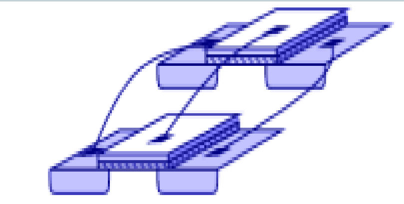
- Oxide thickness increases:
  - The capacitance between G and silicon decreases
  - Q = CV, hence charge density decreases
  - Hence, device will have higher on-resistance
  - Which decreases the drain current for given drain voltage or gate voltage.

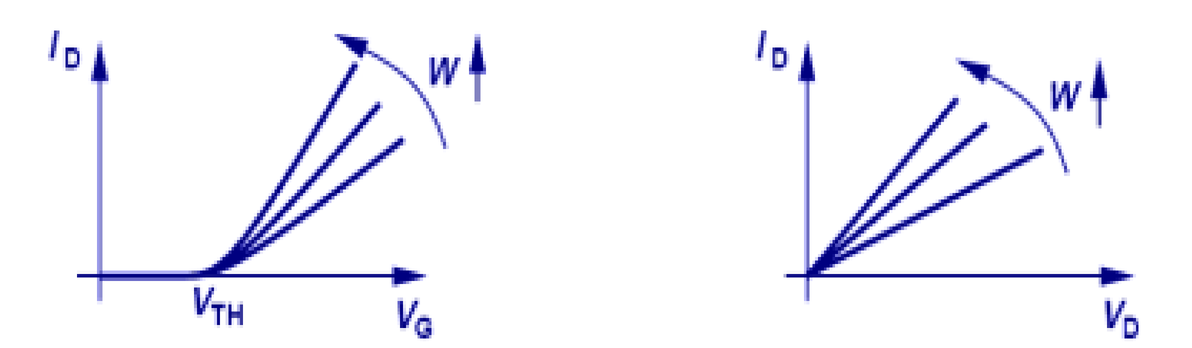


Small gate length and oxide thickness yield low channel resistance, which will increase the drain current.

Effect of W





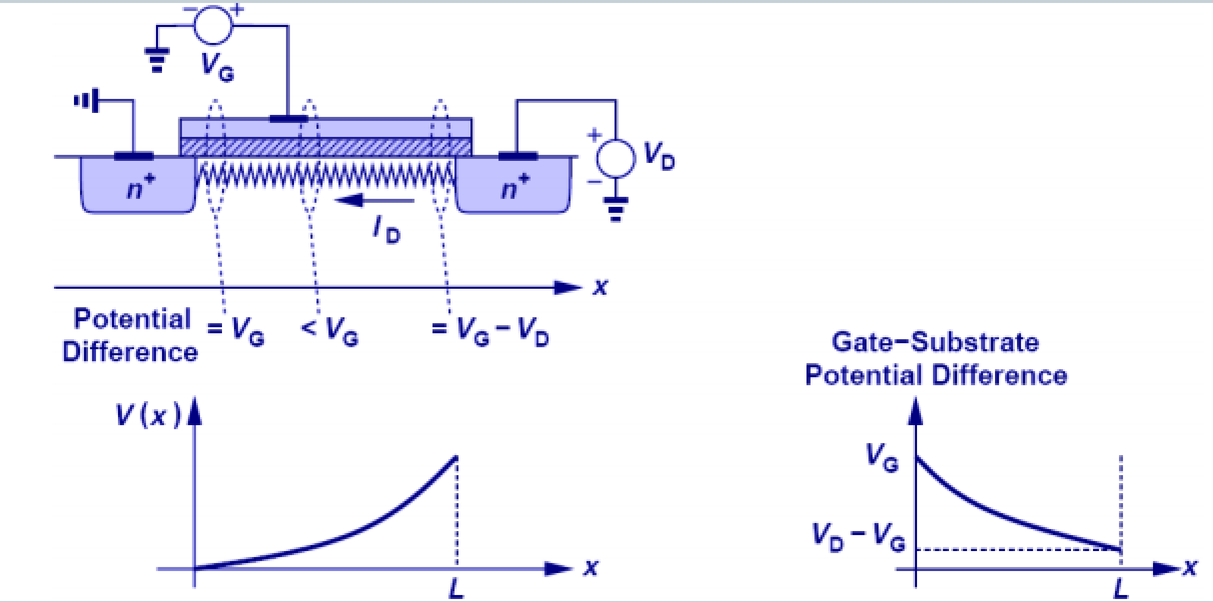


- As the gate width increases, the current increases due to a decrease in resistance. However, gate capacitance also increases thus, limiting the speed of the circuit.
- An increase in W can be seen as two devices in parallel.

Channel Potential Variation

- In reality, the transistor operates as a current source if the drain voltage is sufficiently positive.

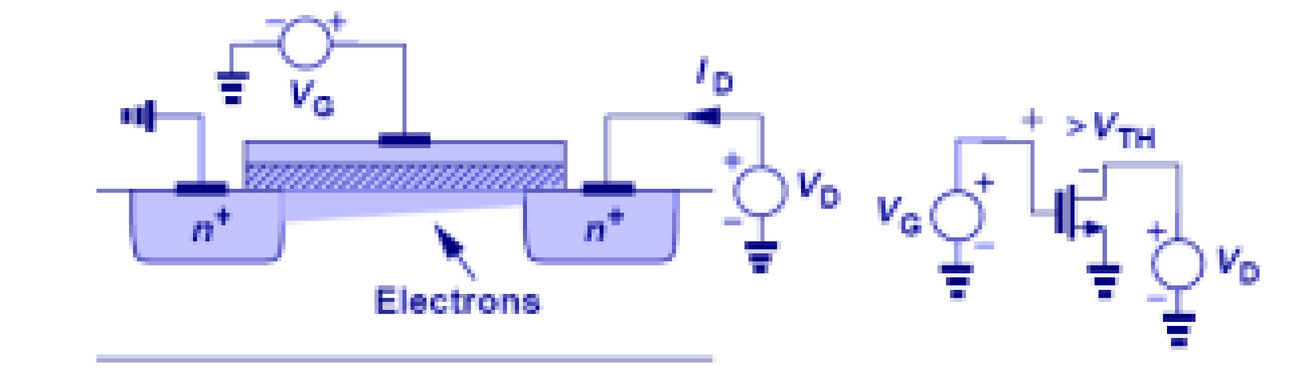
1. To form a channel, Vg > Vth
2. If the drain voltage remains higher than the source voltage, then the voltage at each point along the channel with respect to ground increases as we go from the source towards the drain

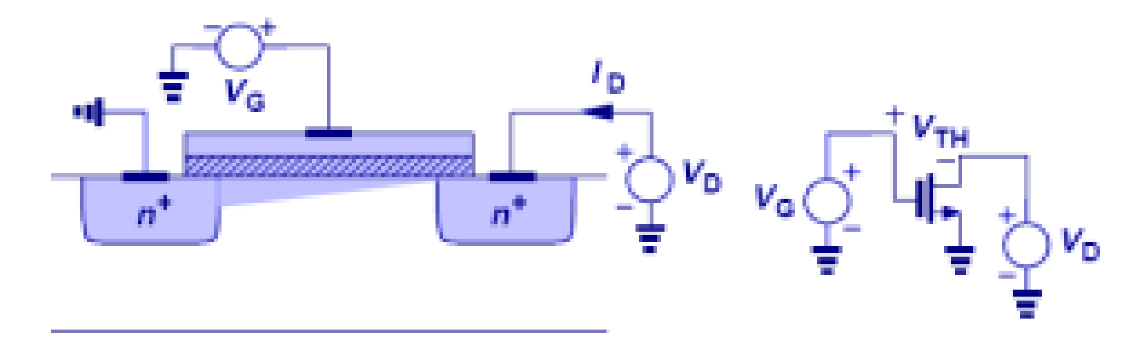


- Since there's a channel resistance between drain and source, and if drain is biased higher than the source, channel potential increases from source to drain, and the potential between gate and channel will decrease from source to drain.

Channel Pinch-Off

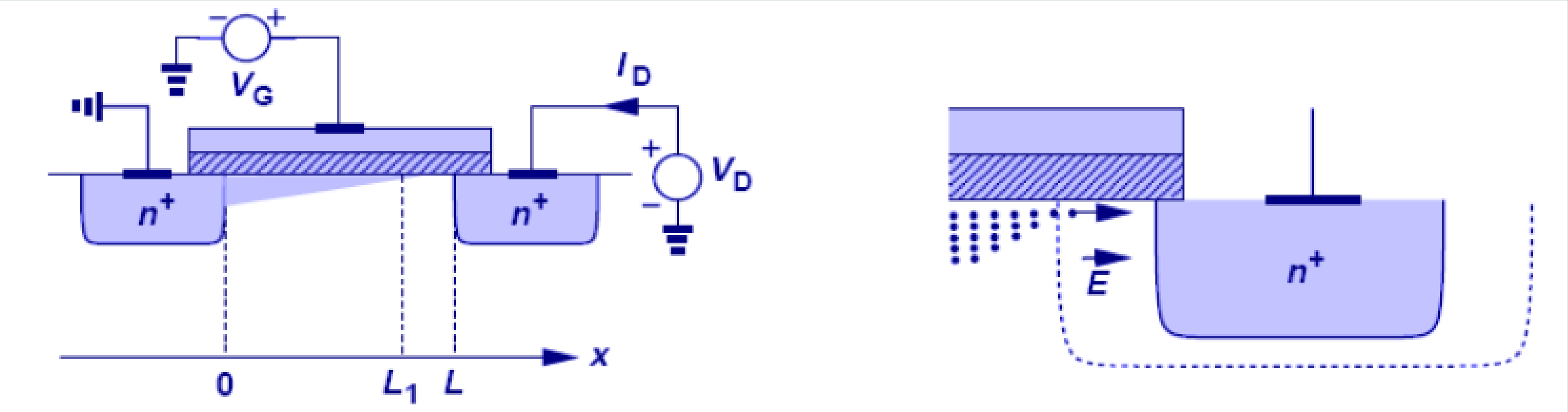
- $V_D < V_G - V_{th}$





Channel Pinch-Off

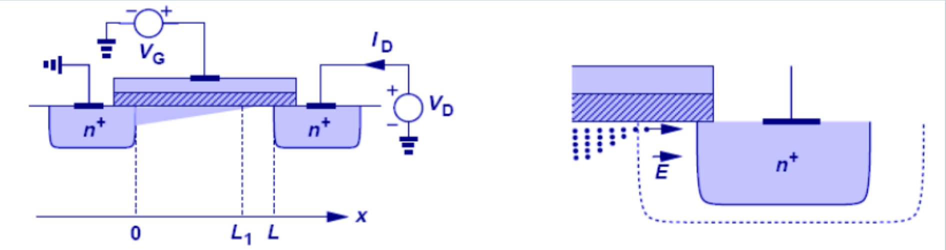
- $V_D > V_G - V_{th}$



- As the potential difference between drain and gate becomes more positive, the inversion layer beneath the interface starts to pinch off around drain.
- When VD – VG = Vth, the channel at drain totally pinches off, and when VD – VG> Vth, the channel length starts to decrease.

Channel Pinch-Off

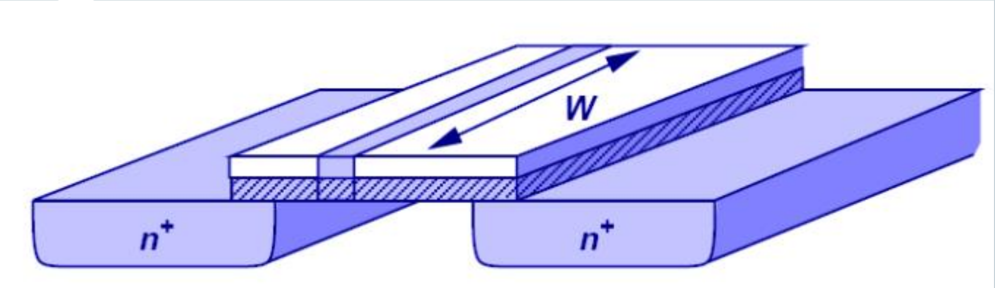
- The device therefore contains no channel between L1 and L.
  - Means does transistor conducts?



- Once the electrons reach the end of the channel, they experience the high electric field in the depletion region surrounding the drain junctions and are rapidly swept to the drain terminal.
- Drain voltage no longer affects the current significantly, and the MOSFET acts as a constant current source.

Derivation of I-V Characteristics (Qualitative study)

Channel charge density



- Q = CV
  - If C is the gate capacitance per unit length and
  - V the voltage difference between the gate and the channel
  - The gate capacitance per unit area is denoted by Cox

    C = W Cox (width of the transistor is taken into account)

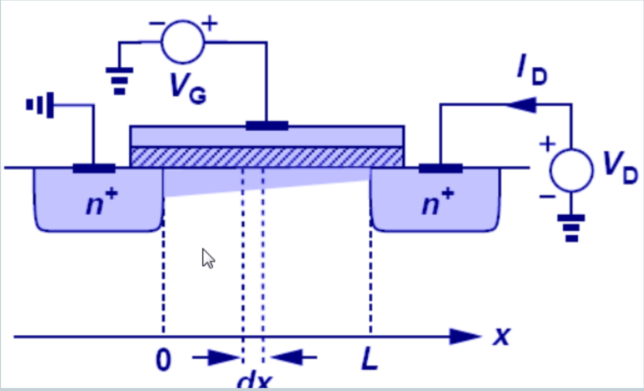
    $V = V_{GS} - V_{TH}$
  - Hence, $Q = W\,Cox\,(V_{GS} - V_{TH})$
  - Q is expressed in coulomb/meter

The channel charge density is equal to the gate capacitance times the gate voltage in excess of the threshold voltage.

Derivation of I-V Characteristics (Qualitative study)

- The equation $Q = W\,C_{ox}\,(V_{GS} - V_{TH})$ is valid only near the source terminal there channel potential close to zero.
- Since, channel potential is V(x) at x
- Hence, charge density at a point

$Q(x) = W\,C_{ox}\,(V_{GS} - V(x) - V_{TH})$



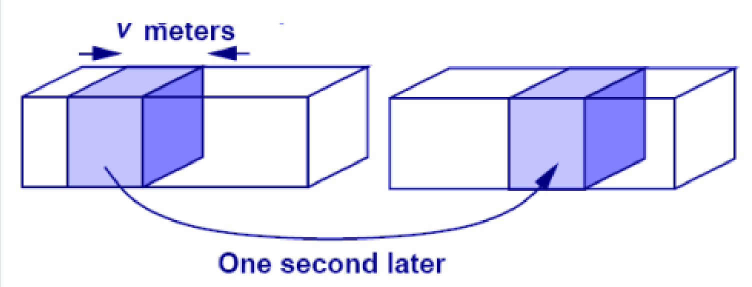
- Let x be a point along the channel from source to drain, and V(x) its potential; the expression above gives the charge density (per unit length).

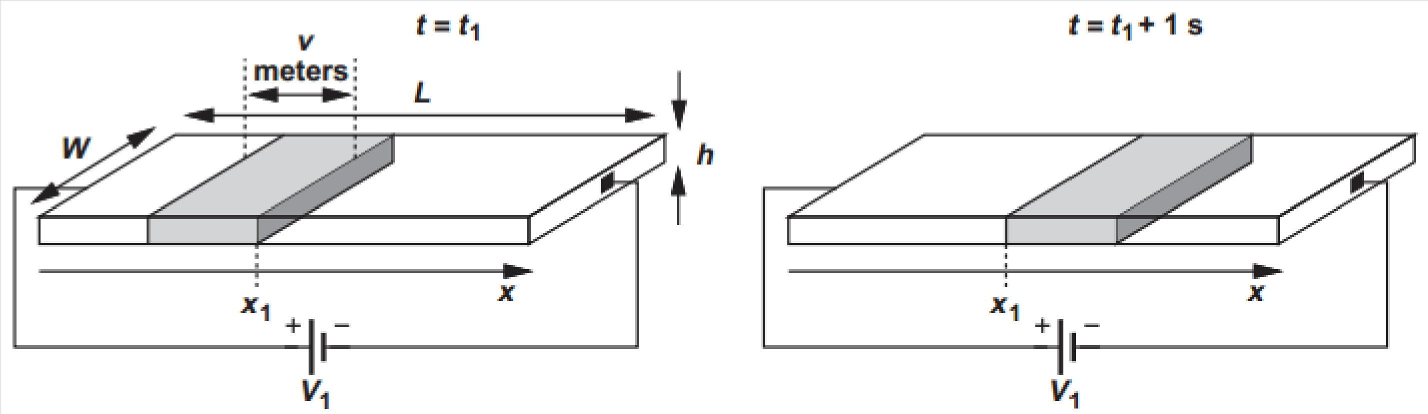
V(x) goes from zero to V_D if the channel is not pinched off.

Derivation of I-V Characteristics (Qualitative study)

- I is given by the total charge that passes through the cross section of the channel in one second with a velocity of v m/s.

$$I = Q.v$$





Relationship between charge velocity and current.

Derivation of I-V Characteristics (Qualitative study)

- The current that flows in the channel is related to the charge density in the channel by the charge velocity.
- Where

$$v = +\mu_n \frac{dV}{dx}$$

$$I_D = WC_{ox}[V_{GS} - V(x) - V_{TH}]\mu_n \frac{dV(x)}{dx}$$

$$\int_{x=0}^{x=L} I_D\, dx = \int_{V(x)=0}^{V(x)=V_{DS}} \mu_n C_{ox} W[V_{GS} - V(x) - V_{TH}]\, dV.$$

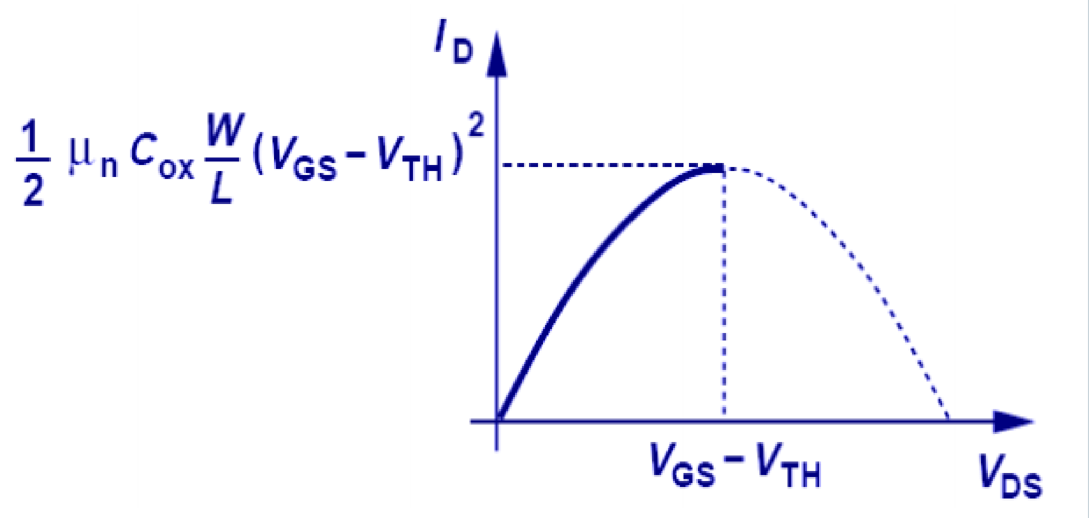
$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}[2(V_{GS} - V_{TH})V_{DS} - V_{DS}^2].$$

- Linear dependence of ID
  - µn , Cox, and (W/L)
  - (W/L) is called aspect ratio

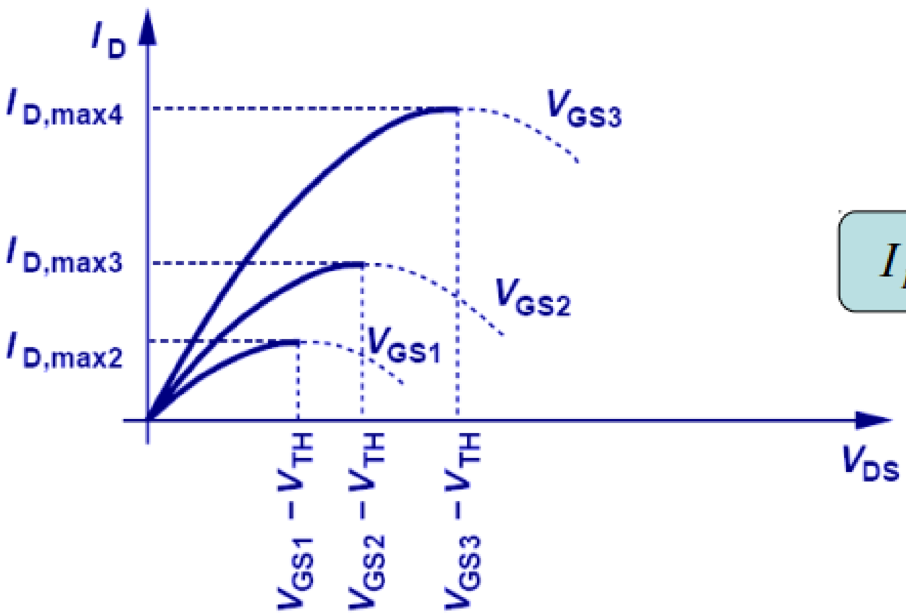
Note: individual values of W and L also become critical in most cases. For example, if both W and L are doubled, the ratio remains unchanged but the gate capacitance increases.

Parabolic I_D-V_{DS} Relationship

- for a constant V_{GS}, I_D varies parabolically with V_{DS} reaching a maximum of $I_{D,max} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2$
- By keeping V_G constant and varying V_{DS}, we obtain a parabolic relationship.
- The maximum current occurs when V_{DS} equals to V_{GS}- V_{TH}.



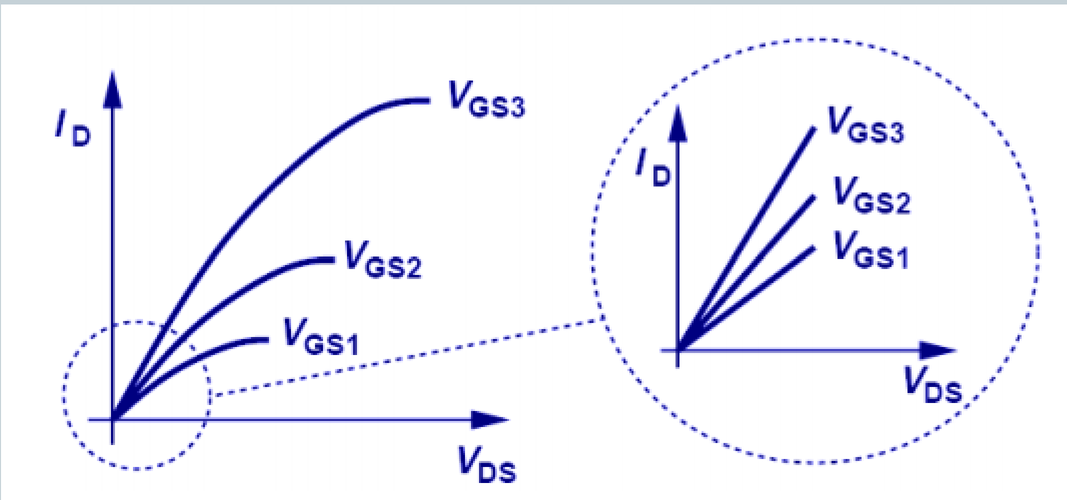
I_D -V_{DS} for Different Values of V_{GS}



$$I_{D,\max} \propto (V_{GS} - V_{TH})^2$$

Linear Resistance

- If $V_{DS} << 2(V_{GS} - V_{TH})$



By neglecting Vds²

$$ID \approx \mu_n C_{ox} (W/L)(V_{GS} - V_{TH}) V_{DS}$$

- At small V_{DS}, the transistor can be viewed as a resistor, with the resistance depending on the gate voltage .

$$\textbf{Ron} = \frac{V_{DS}}{I_D}$$

$$R_{on} = \frac{1}{\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{TH})}$$

- It finds application as an electronic switch.

Application of Electronic Switches

$$R_{on} = \frac{1}{\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{TH})}$$

- Ron can be controlled by Vgs.
- For Vgs = Vth, Ron = ∞
- Hence, the device can be operate as an electronic switch.
- In a cordless telephone system in which a single antenna is used for both transmission and reception
  - The system is designed so that the phone receives for half of the time and transmits for the other half.
  - Thus, the antenna is alternately connected to the receiver and the transmitter in regular intervals, e.g., every 20 ms).
  - An electronic antenna switch is therefore necessary here.
  - a switch is used to connect either the receiver or transmitter to the antenna.

Application of Electronic Switches

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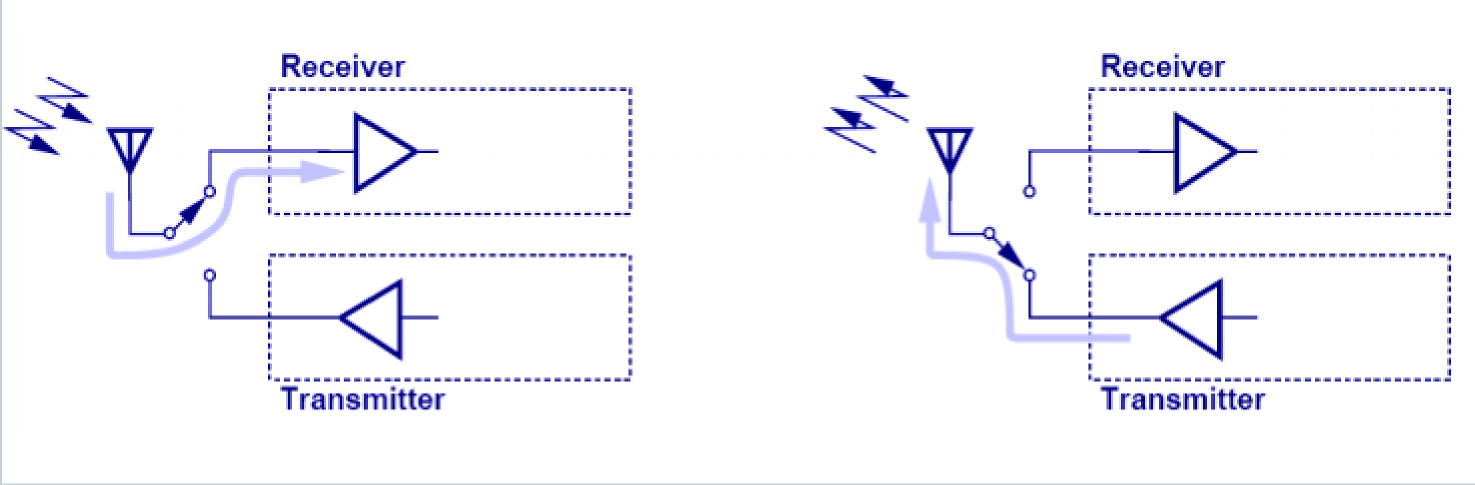
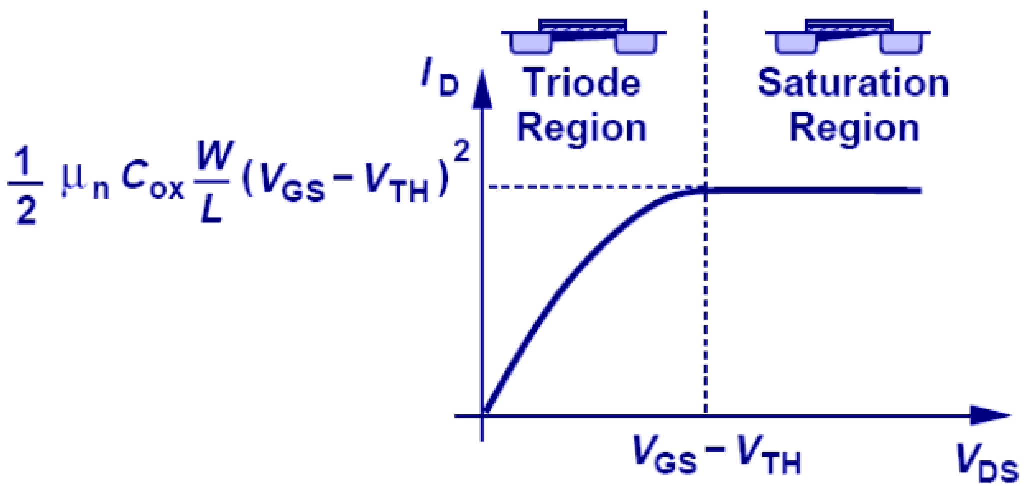


Different Regions of Operation

Cutoff Region	Linear / Triode region	Saturated Region
$V_{gsn} < V_{tn}$	$V_{gsn} > V_{tn}$ $V_{dsn} < V_{gsn} - V_{tn}$	$V_{gsn} > V_{tn}$ $V_{dsn} > V_{gsn} - V_{tn}$

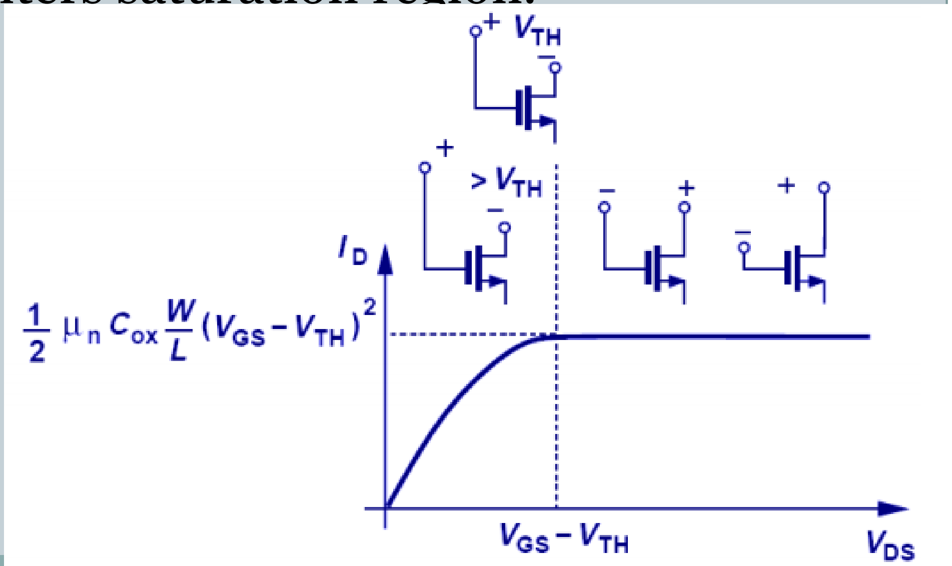
if Vds<< 2(Vgs - Vth), then it will be deep triode region. where the transistor operates as resistor



How to Determine 'Region of Operation'

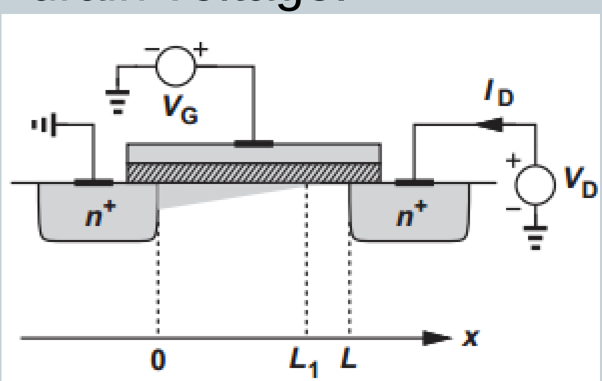
 # In saturation region, Ids is independent of Vds
 # (Vgs - Vth) called overdrive voltage plays a key role in MOS circuits
#MOSFET's sometimes called "square law"device to emphasize the relationship between Id and the overdrive.

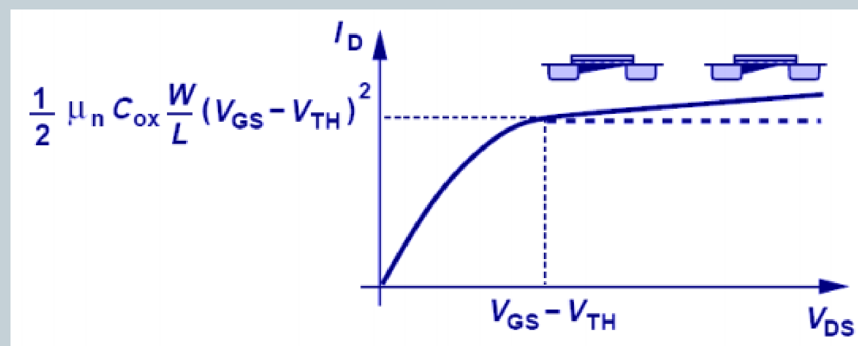
- When the potential difference between gate and drain is greater than VTH, the MOSFET is in triode region.
- When the potential difference between gate and drain becomes equal to or less than VTH , the MOSFET enters saturation region.



Channel-Length Modulation

- The original observation that the current is constant in the saturation region is not quite correct.
- the value of L1 varies with V_{DS} to some extent. Called “channel-length modulation” and this phenomenon yields a larger drain current as V_{DS} increases because $I_D \propto 1/L$
- The end point of the channel actually moves toward the source as V_D increases, increasing I_D .
- Therefore, the current in the saturation region is a weak function of the drain voltage.

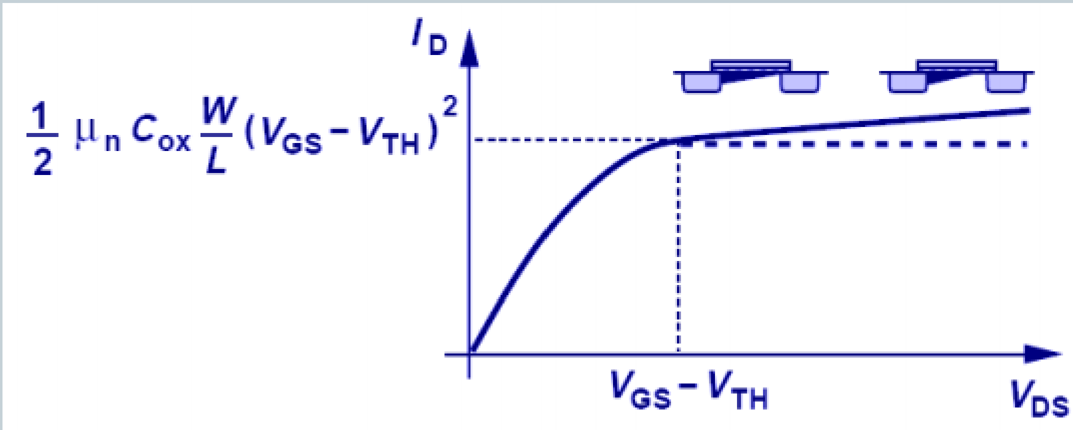




$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})$$

Channel-Length Modulation

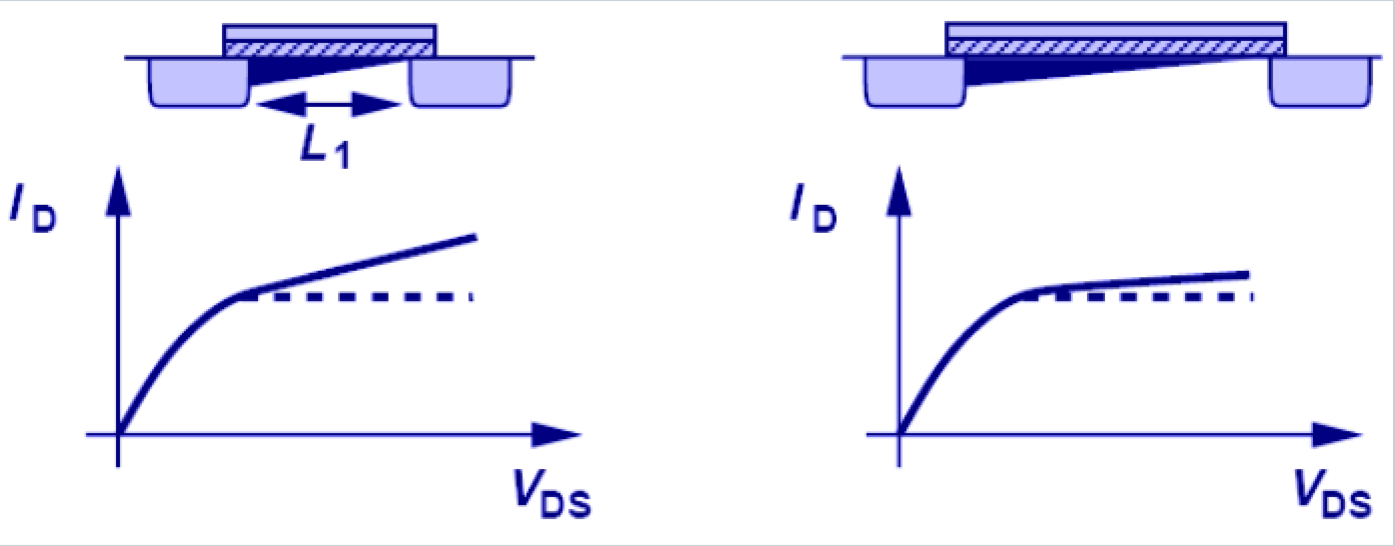
- The original observation that the current is constant in the saturation region is not quite correct.
- The end point of the channel actually moves toward the source as V_D increases, increasing I_D .
- Therefore, the current in the saturation region is a weak function of the drain voltage.



$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})$$

λ and L

- Unlike the Early voltage in BJT, the channel- length modulation factor can be controlled by the circuit designer.
- This is because λ is inversely proportional to L: for a longer channel, the relative change in L (and hence in I_D) for a given change in V_{DS} is smaller
- For long L, the channel-length modulation effect is less than that of short L.



MOS Transconductance

- As a voltage-controlled current source, a MOS transistor can be characterized by its transconductance

$$g_m = \frac{\partial I_D}{\partial V_{GS}}.$$

- This quantity serves as a measure of the "strength" of the device: a higher value corresponds to a greater change in the drain current for a given change in V_{GS}.

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2$$

$$g_m = \mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})$$

- Or

$$g_m = \sqrt{2\mu_n C_{ox}\frac{W}{L}I_D}.$$

Transconductance

- Transconductance is a measure of how strong the drain current changes when the gate voltage changes.
- It has three different expressions.

$$g_m = \mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{TH}) \qquad g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D} \qquad g_m = \frac{2I_D}{V_{GS} - V_{TH}}$$

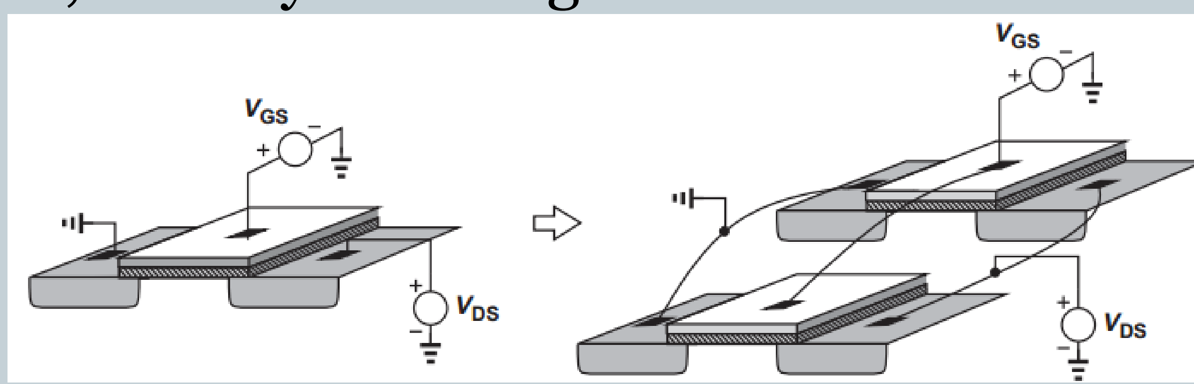
$\frac{W}{L}$ Constant $V_{GS} - V_{TH}$ Variable	$\frac{W}{L}$ Variable $V_{GS} - V_{TH}$ Constant	$\frac{W}{L}$ Variable I_D Constant
$g_m \propto \sqrt{I_D}$ $g_m \propto V_{GS} - V_{TH}$	$g_m \propto I_D$ $g_m \propto \frac{W}{L}$	$g_m \propto \sqrt{\frac{W}{L}}$ $g_m \propto \frac{1}{V_{GS} - V_{TH}}$

Transconductance

- For a MOSFET operating in saturation, how do g_m and $V_{GS}-V_{TH}$ change if both W/L and I_D are doubled?

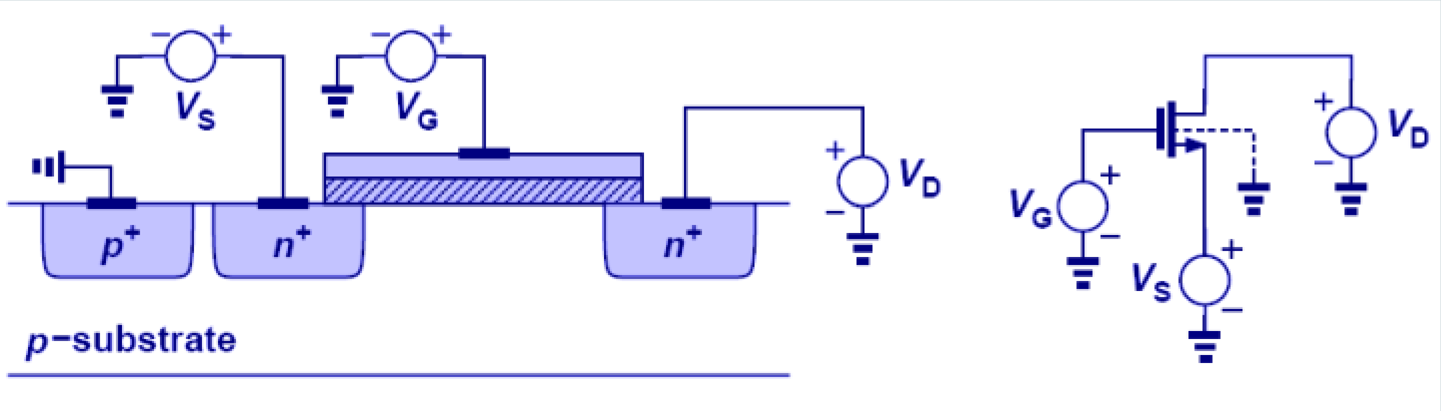
$$g_m = \sqrt{2\mu_n C_{ox}\frac{W}{L}I_D}.$$ ——— indicates that gm is also doubled

- If V_{GS} remains constant and the width of the device is doubled, it is as if two transistors carrying equal currents are placed in parallel, thereby doubling the transconductance.



Body Effect

- As the source potential departs from the bulk potential, the threshold voltage changes.



$$V_{TH} = V_{TH0} + \rho\left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F}\right)$$

Subthreshold Conduction

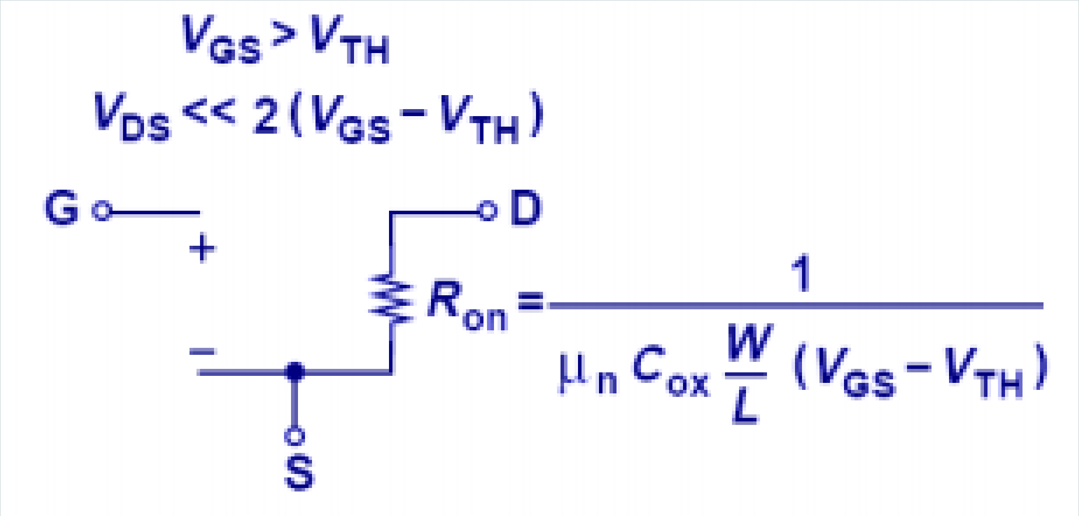
- The derivation of the MOS I-V characteristic has assumed that the transistor abruptly turns on as V_{GS} reaches V_{TH}.
- In reality, formation of the channel is a gradual effect, and the device conducts a small current even for $V_{GS}<V_{TH}$. Called "subthreshold conduction"
- this effect has become a critical issue in modern MOS devices

MOS DEVICE MODELS

Large-Signal Model

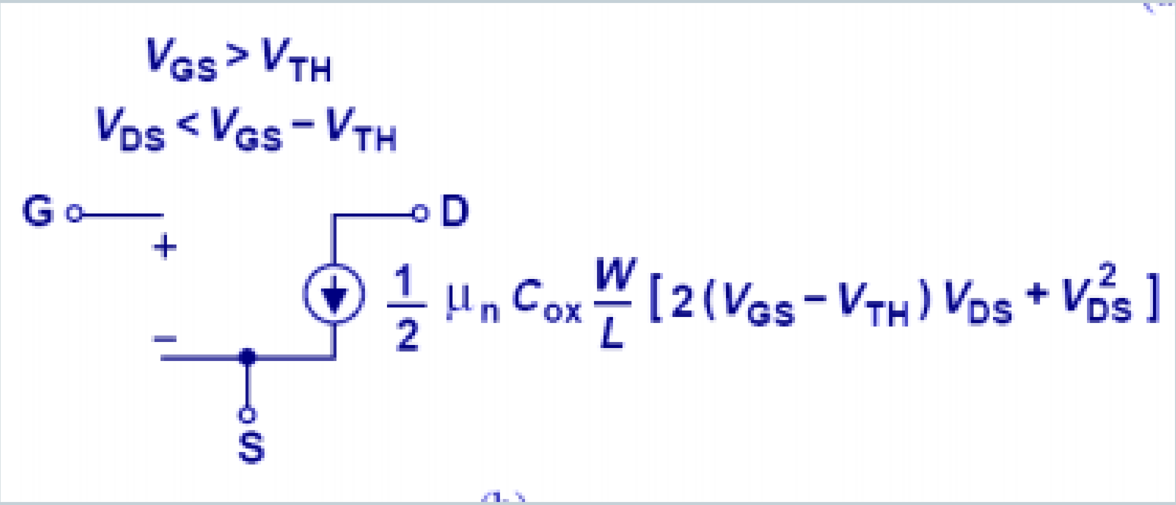
Based on the value of V_{DS}, MOSFET can be represented with different large-signal models.

In deep triode region, it acts as Voltage controlled Resistor



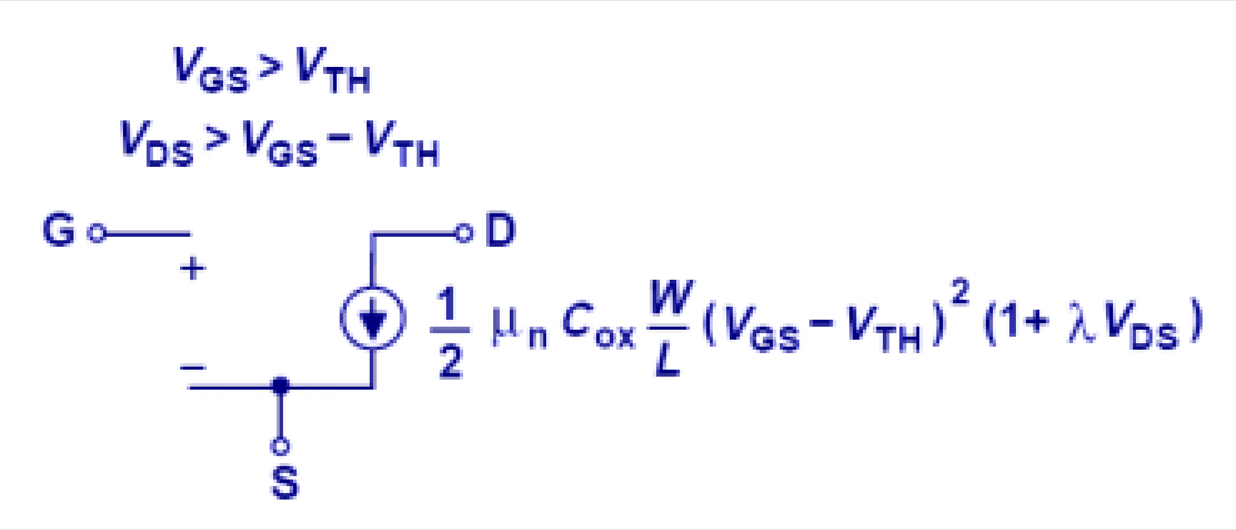
MOS DEVICE MODELS
Large-Signal Model

In Triode / linear region, but it still incorporate a voltage controlled current source.



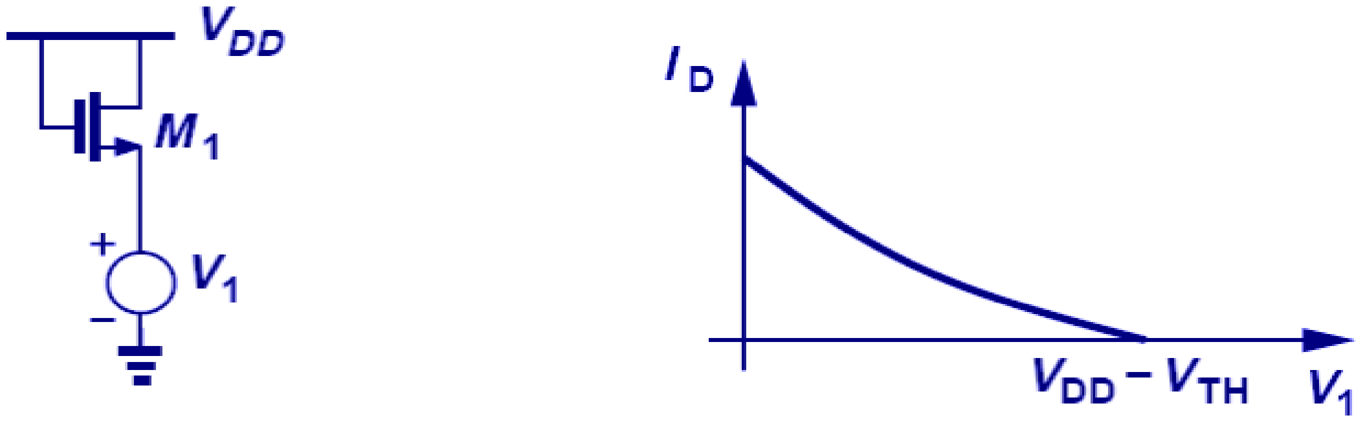
MOS DEVICE MODELS
Large-Signal Model

In saturation region ---- transistor acts as a voltage controlled current source, lending itself to the model



Large-Signal Model

Example: Behavior of I_D with V_1 as a Function



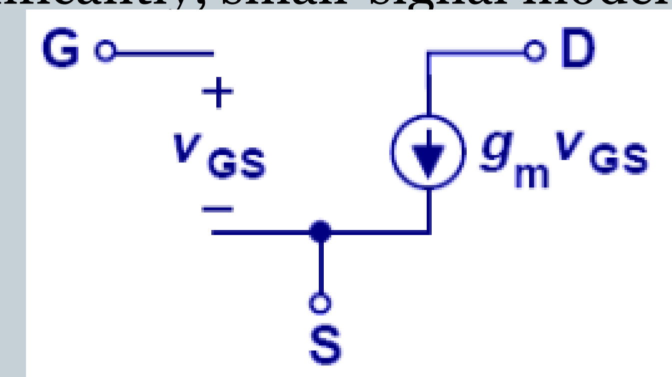
(a) (b)

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{DD} - V_1 - V_{TH}\right)^2$$

- Since V_1 is connected at the source, as it increases, the current drops.

Small-Signal Model

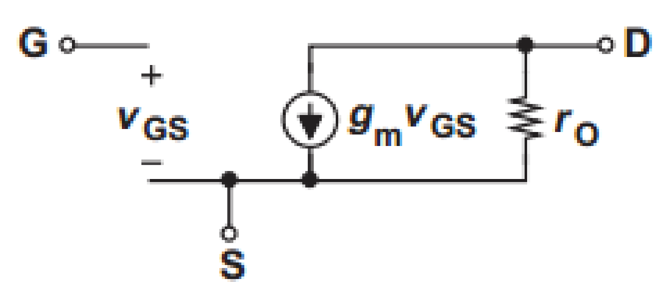
- If the bias currents and voltages of a MOSFET are only slightly disturbed by signals, the nonlinear, large- signal models can be reduced to linear, small-signal representations.
- When the bias point is not perturbed significantly, small-signal model can be used to facilitate calculations.



- To represent channel-length modulation,

i.e., variation of i_d with v_{ds},

we add a resistor



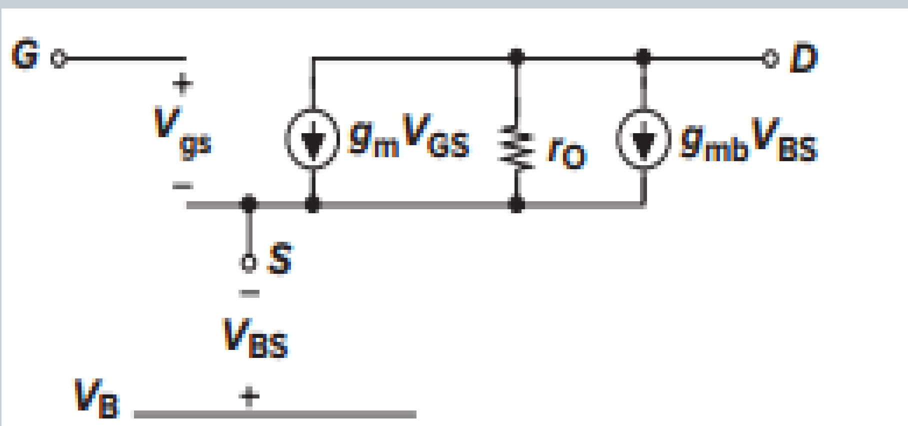
$$r_O = \left(\frac{\partial I_D}{\partial V_{DS}}\right)^{-1}$$

$$= \frac{1}{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2 \cdot \lambda}$$

$$r_O \approx \frac{1}{\lambda I_D}$$

MOS DEVICE MODELS
Small-Signal Model

- the bulk potential influences the threshold voltage and hence the gate-source overdrive.
- , with all other terminals held at a constant voltage, the drain current is a function of the bulk voltage.
- That is, the bulk behaves as a second gate. Modeling this dependence by a current source connected between D and S



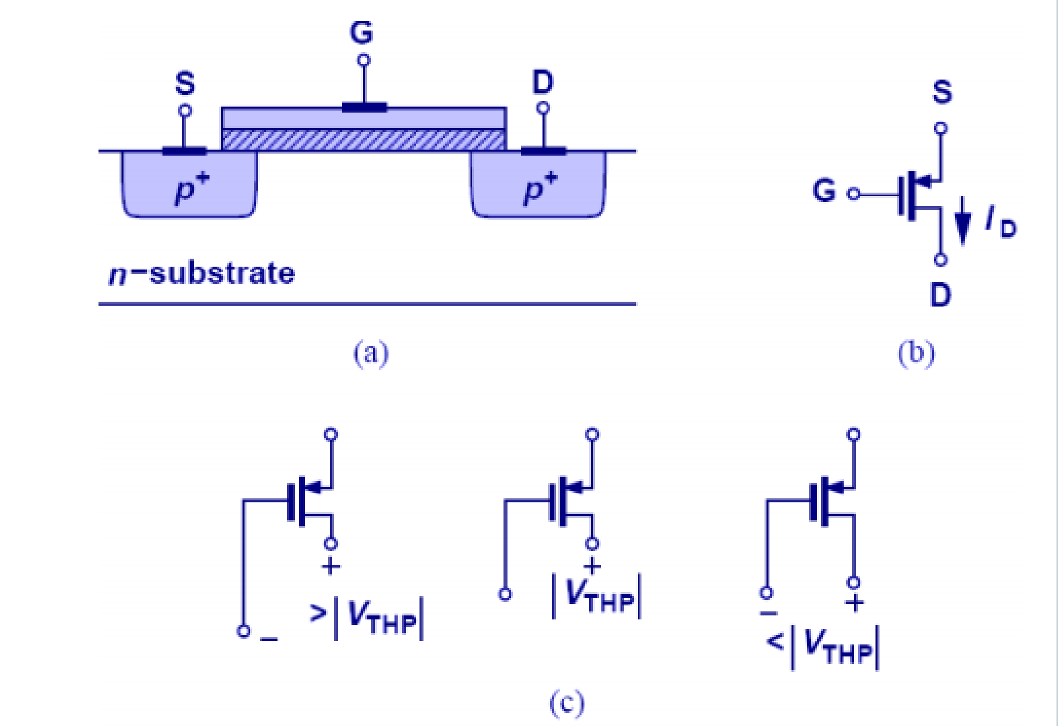
$$g_{mb} = \frac{\partial I_D}{\partial V_{BS}}$$
$$= \mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{TH}) \left(-\frac{\partial V_{TH}}{\partial V_{BS}}\right)$$

$$\frac{\partial V_{TH}}{\partial V_{BS}} = -\frac{\partial V_{TH}}{\partial V_{SB}}$$
$$= -\frac{\gamma}{2}(2\Phi_F + V_{SB})^{-1/2}$$

$$g_{mb} = g_m \frac{\gamma}{2\sqrt{2\Phi_F + V_{SB}}}$$
$$= \eta g_m$$

PMOS Transistor

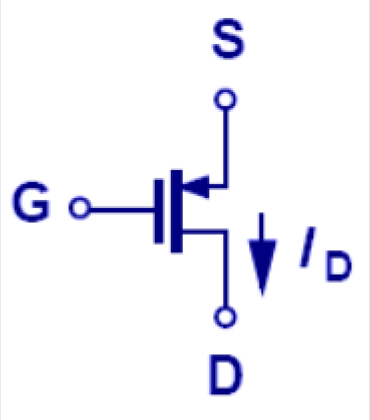
- Just like the PNP transistor in bipolar technology, it is possible to create a MOS device where holes are the dominant carriers. It is called the PMOS transistor.
- It behaves like an NMOS device with all the polarities reversed.



PMOS Equations

pMOS Operation

Cutoff	Linear / Triode	Saturated
$V_{gsp} > V_{tp}$	$V_{gsp} < V_{tp}$ $V_{dsp} > V_{gsp} - V_{tp}$	$V_{gsp} < V_{tp}$ $V_{dsp} < V_{gsp} - V_{tp}$



$$I_{D,tri} = \frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left[2(V_{GS} - V_{TH})V_{DS} - V_{DS}^2\right]$$

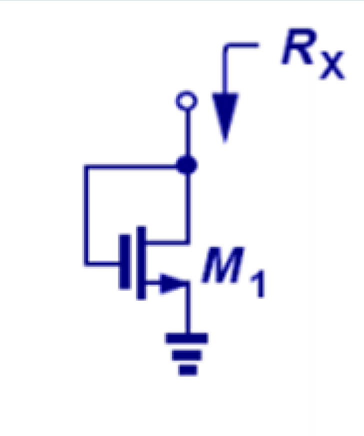
$$I_{D,tri} = \frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left[2(|V_{GS}| - |V_{TH}|)|V_{DS}| - V_{DS}^2\right]$$

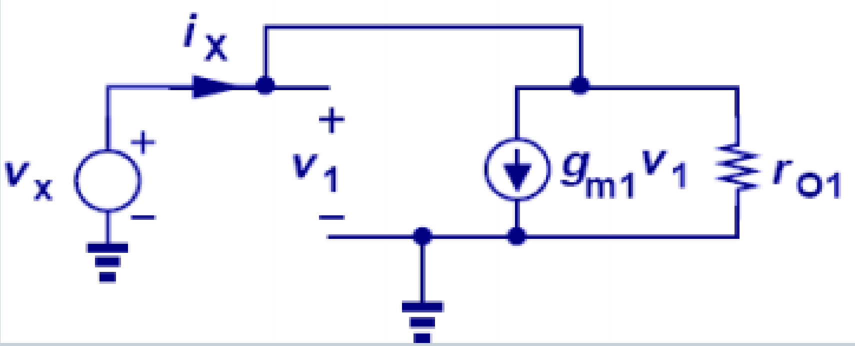
$$I_{D,sat} = \frac{1}{2}\mu_p C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2(1 - \lambda V_{DS})$$

$$I_{D,sat} = \frac{1}{2}\mu_p C_{ox}\frac{W}{L}(|V_{GS}| - |V_{TH}|)^2(1 + \lambda|V_{DS}|)$$

pMOS and nMOS as diode

- nMOS as Diode





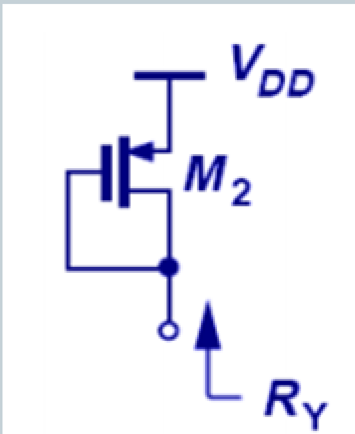
$$R_X = \frac{v_X}{i_X}$$

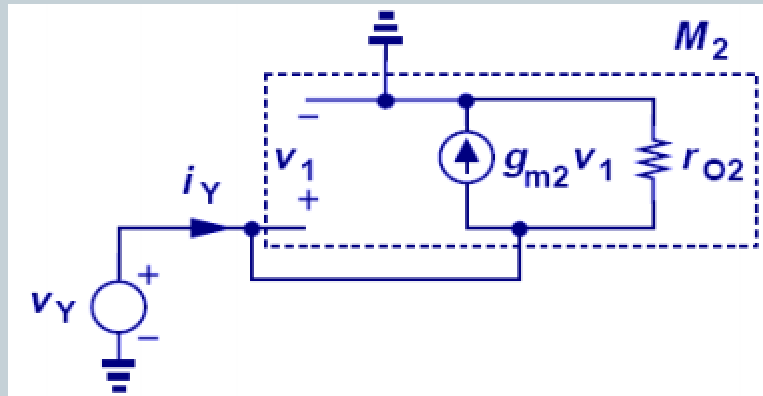
$$= \left(g_{m1}v_X + \frac{v_X}{r_{O1}}\right)\frac{1}{i_X}$$

$$= \frac{1}{g_{m1}} || r_{O1}.$$

pMOS and nMOS as diode

- pMOS as Diode



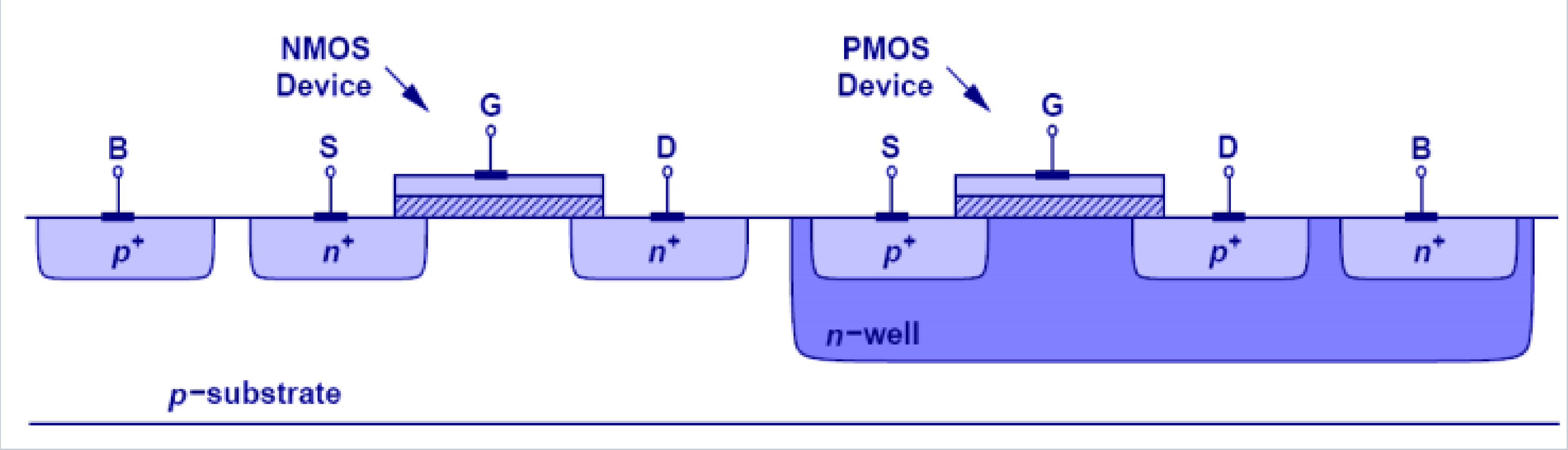


$$
\begin{aligned}
R_Y &= \frac{v_Y}{i_Y} \\
&= \left(g_{m2}v_Y + \frac{v_Y}{r_{O1}}\right)\frac{1}{i_Y} \\
&= \frac{1}{g_{m2}} || r_{O2}.
\end{aligned}
$$

- The small-signal model of PMOS device is identical to that of NMOS transistor; therefore, RX equals RY and hence (1/gm)||ro

CMOS Technology

- It possible to grow an n-well inside a p-substrate to create a technology where both NMOS and PMOS can coexist.
- It is known as CMOS, or “Complementary MOS”.



Comparison of Bipolar and MOS Transistors

- Bipolar devices have a higher gm than MOSFETs for a given bias current due to its exponential IV characteristics.

Bipolar Transistor	MOSFET
Exponential Characteristic	Quadratic Characteristic
Active: $V_{CB} > 0$	Saturation: $V_{DS} > V_{GS} - V_{TH}$
Saturation: $V_{CB} < 0$	Triode: $V_{DS} < V_{GS} - V_{TH}$
Finite Base Current	Zero Gate Current
Early Effect	Channel-Length Modulation
Diffusion Current	Drift Current
–	Voltage-Dependent Resistor