Yrkes Akademin

Vi hjälper dig att lyckas!

Introduction

Electrical & Electronic Circuits and Elements

Embedded Systems & Embedded Programming

Fundamentals of Electronic Circuits (Field Effect Transistors)

- Field Effect Transistor (**FET**)
  - Has three terminals (**Source**, **Gate** and **Drain**)
  - Can be used as switch, amplifire, resistor, capacitor and etc.
  - Is high efficiency and robust and can be used in most applications to replace **BJT**s
  - Is a unipolar semiconductor device (charge carriers are electrons **or** holes)
  - Unlike **Bipolar Junction Transistor,** it is controlled by an electric field (**Gate Voltage**)
  - Two basic classifications: the **N-channel FET** and the **P-channel FET**
  - Has a very high input impedance (more than $10^9\Omega$)
    - Very sensitive to input voltage signal and can be easily damaged by static electricity
    - Lower power consumption and smaller than an equivalent BJT transistor
    - Very low gate leakage current (less than 10^{-9}A)
  - Types of FETs: **JFET**, **MOSFET**, MESFET, FinFET and etc.

[Field Effect Transistors]

Fundamentals of Electronic Circuits (Field Effect Transistors)

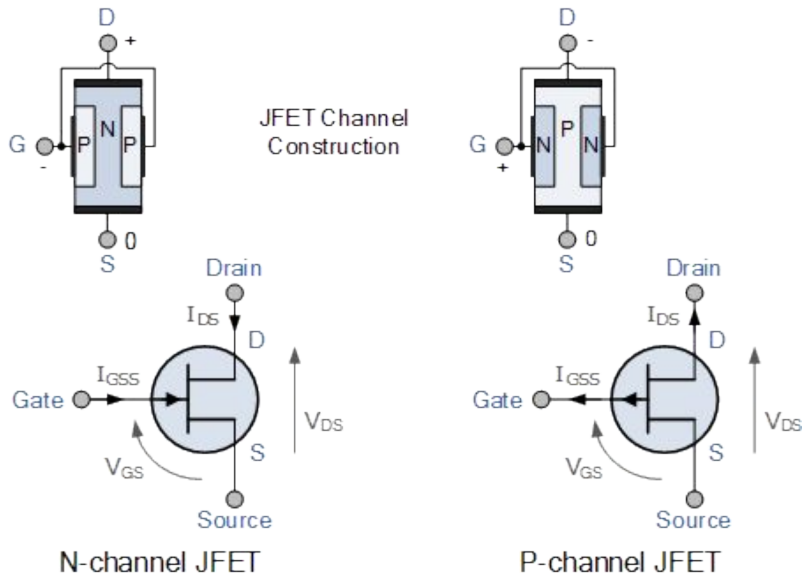
- Field Effect Transistor (**FET**)
  - It has a high power gain and It can deliver more power than BJT
  - It is less noisy and has a higher frequency response in compare with BJT
  - Has a very low "ON" resistance and have a high "OFF" resistance
  - It can dissipate large amounts of power while switching
  - It provides more thermal stability
  - Applications
    - FETs are widely used in analog and digital circuits
    - Power converters and suppliers, RF power amplifiers and etc.
    - Integrated circuits like processors such as the **CMOS** range of digital logic chips
    - Sensors; like pressure and image sensors
    - Volatile and non-volatile memories

Field Effect Transistor Types & Technology

Fundamentals of Electronic Circuits (JFET)

❖ Junction Field Effect Transistors (**JFET**s)

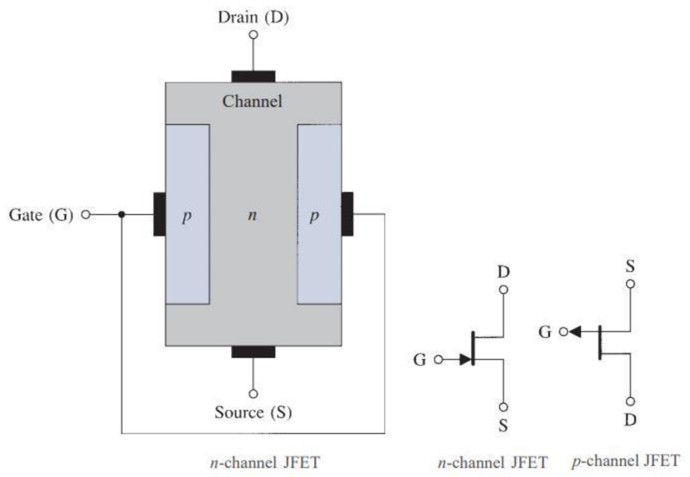
- ➢ Two types: P-channel and N-channel
- ➢ They are depletion type transistors only
- ➢ They typically offer about 10^9 Ω of input impedance
- ➢ The gate-channel junctions are reverse-biased
  - ■ Otherwise whole the current from source will flow to the gate and the device gets damaged
- ➢ Can operate in four regions
  - ■ Cut-off or pinch-off region
  - ■ Ohmic or triode region
  - ■ Saturation or active region
  - ■ Breakdown region

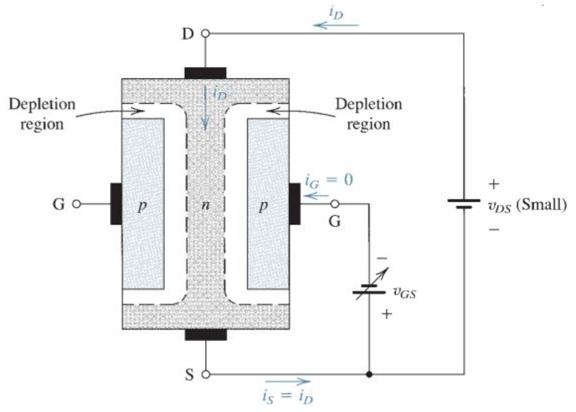


[Junction Field Effect Transistor]

Fundamentals of Electronic Circuits (JFET)

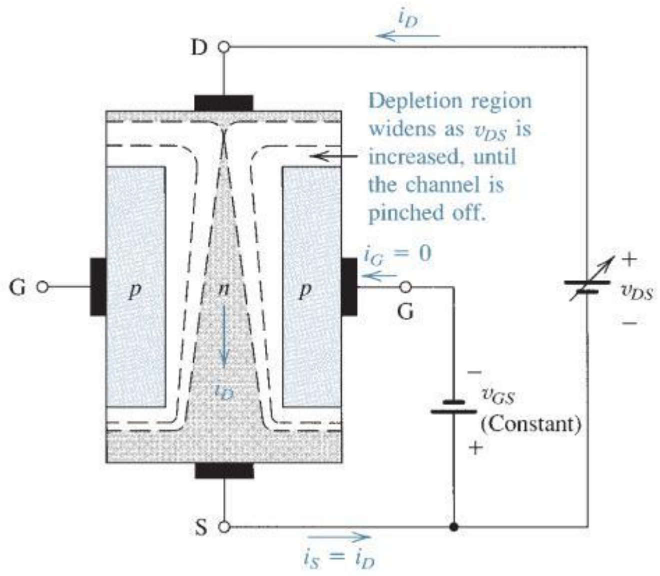
- JFETs are specified in term of $\mathbf{I_{DSS}}$ and $\mathbf{V_P}$; i.e $\mathbf{V_{GS(\mathit{off})}}$
  - Pinch-off voltage ($\mathbf{V_P}$) is the voltage at which the channel is closed
  - Drain to source saturation current ($\mathbf{I_{DSS}}$) when $\mathbf{V_{GS} = 0}$
  - $\mathbf{V_P}$ for N-channel is negative and for P-channel is positive
- Biasing of an N-channel JFET
  - With $V_{GS} = 0$ and small V_{DS}
    - Maximum saturation current (I_{DSS}) will flow through the channel from the drain to the source restricted only by the small depletion region around the junctions and $R_{DS(on)}$ is about 0.05 Ω
  - By decreasing the V_{GS}, the width of the depletion region is increased which in turn reduces the conduction of the channel
  - When the $V_{GS} \leq V_P$, the channel will be closed and no more current flows between the drain and the source ($I_D = 0$)





Fundamentals of Electronic Circuits (JFET)

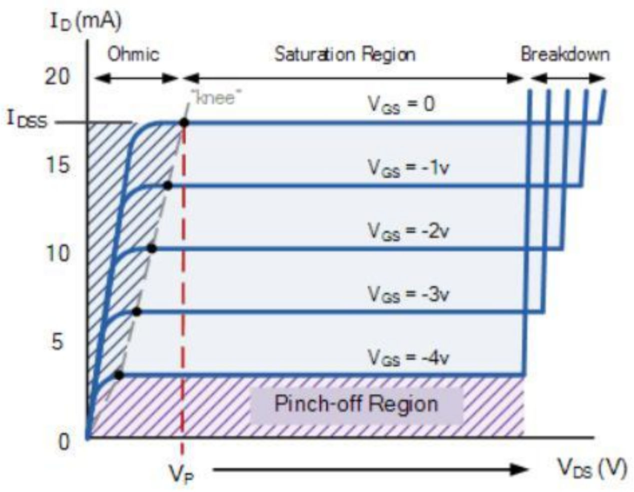
- Biasing of an N-channel JFET
  - With $V_P \leq V_{GS} \leq 0$ and increasing the V_{DS} from Zero
    - The most-depleted portion of the depletion region is in between the gate and the drain, while the least-depleted area is between the gate and the source
    - The depleted portion of the depletion region between gate and drain increases and therefore the conduction of the channel reduces
    - When $V_{DS} \geq V_{GS} - V_P$, then the channel gets saturated and
      - The drain current I_D no longer increases with increasing of V_{DS}
      - The drain current I_D remains fairly constant
    - If V_{DS} is continuously increased, the junctions are broken and the JFET may be destroyed

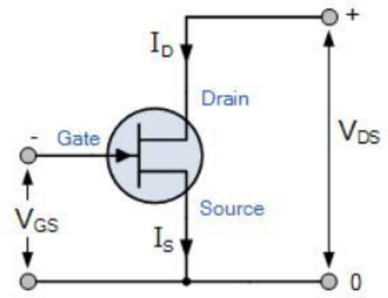


[Characteristics of JFETS]

Fundamentals of Electronic Circuits (N-channel JFET)

- Four different regions of operation for a JFET
  - Cut-off ($V_{GS} \leq V_P$)
    - Where V_{GS} is sufficient to cause the JFET to act as an open circuit as the channel resistance is at maximum ($I_D = 0$)
  - Ohmic or triode ($V_P < V_{GS} \leq 0$ and $V_{DS} \leq V_{GS} - V_P$)
    - The depletion layer of the channel is small and the JFET acts like a voltage controlled resistor
  - Saturation or active ($V_P < V_{GS} \leq 0$ and $V_{DS} > V_{GS} - V_P$)
    - It becomes a good conductor controlled by V_{GS}
    - V_{DS} has little or no effect and the device is used as an amplifier
  - Breakdown
    - V_{DS} is high enough to causes the channel to break down and pass uncontrolled maximum current





KVL: $V_{DS} = V_{DG} + V_{GS}$, KCL: $I_G = 0$, $I_D = I_S$

Fundamentals of Electronic Circuits (N-channel JFET)

❖ The drain-source current in ohmic region is

$$i_D = I_{DSS}\left[2\left(1-\frac{V_{GS}}{V_P}\right)\left(\frac{V_{DS}}{-V_P}\right)-\left(\frac{V_{DS}}{V_P}\right)^2\right]$$

❖ The drain-source current in saturation region is

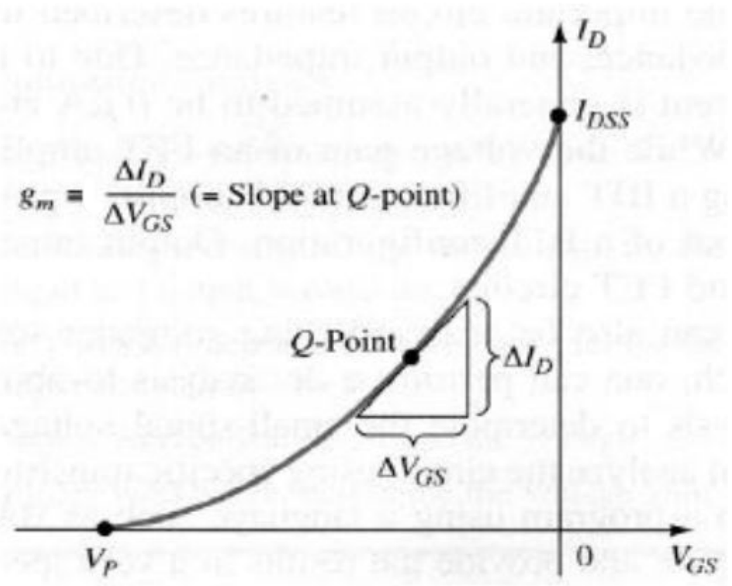
$$i_D = I_{DSS}\left(1-\frac{V_{GS}}{V_P}\right)^2$$

❖ Transconductance gain of the JFET in active mode is

$$g_m = \left(\frac{2I_{DSS}}{|V_P|}\right)\left(1-\frac{V_{GS}}{V_P}\right)$$

➢ Where **g_m** is the ratio of change in drain current, **ΔI_D**, to the change in gate-source voltage, **ΔV_{GS}**.

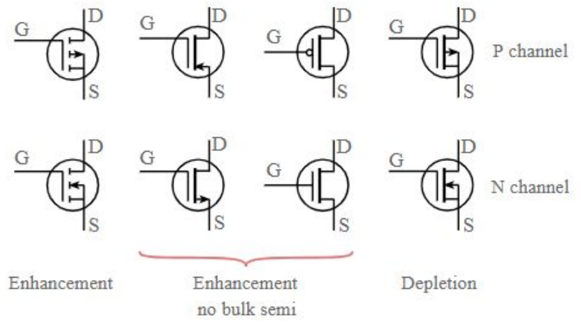
➢ Its unit is 1/Ω (mho or Siemens)

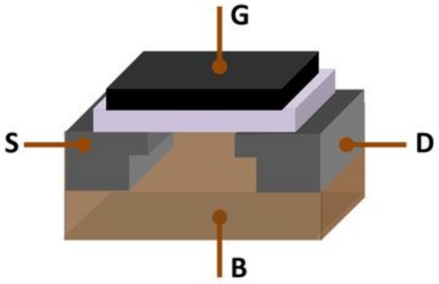


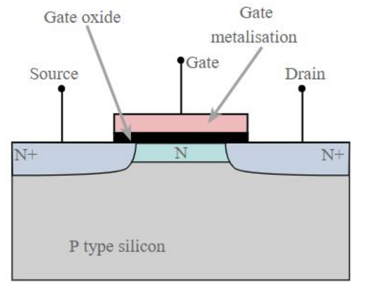
[How FETs Function - The Learning Circuit]

Fundamentals of Electronic Circuits (MOSFET)

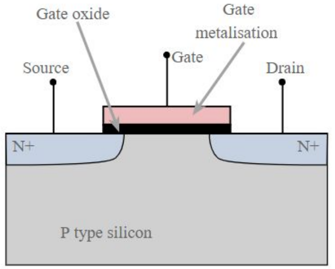
- Metal Oxide Semiconductor Field Effect Transistor (MOSFET)
  - The gate is physically insulated from the channel by an oxide layer (SiO_2)
  - Voltage applied to the gate controls the conductivity of the channel   Working of Transistors | MOSFET
    - As a result of the electric field induced capacitively across the insulating dielectric layer
  - Both N-channel (NMOS) and P-channel (PMOS) variants are available
  - Both enhancement and depletion types are available
  - Typically offers more than 10^{14} Ω of input impedance
  - Is the most manufactured device in history
    - 1.3×10^{22} MOSFETs between 1960 and 2018
  - Three terminals
    - Gate, Drain, Source
    - Bulk/Body is connected to source or has no effect (in no bulk E-MOSFET)







N channel depletion mode MOSFET structure



N channel enhancement mode MOSFET structure

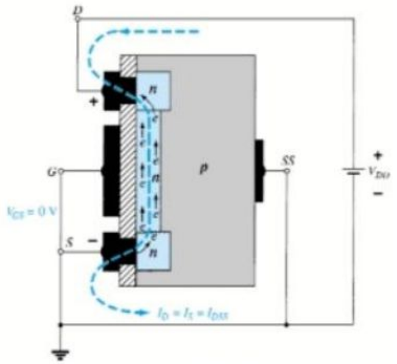
Fundamentals of Electronic Circuits (MOSFET)

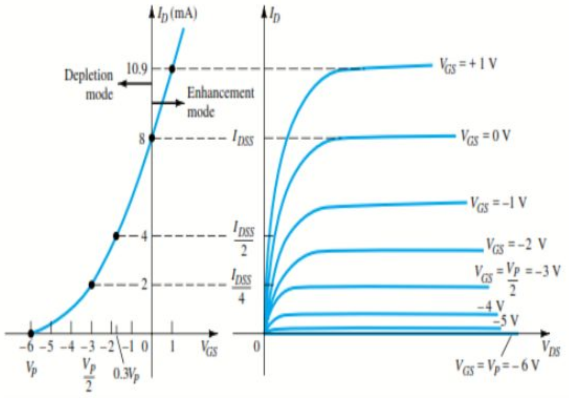
❖ Depletion MOSFET

- ➢ it consists of a channel diffused between the drain to source terminal
- ➢ It requires the Gate-Source voltage, (VGS) to switch the device “OFF”
- ➢ It is equivalent to a “Normally Closed” switch

[Depletion Type MOSFET: What is it?]

- ➢ Its behaviour is almost like a JFET but because of the insulated gate
  - ■ it is possible to bias its gate in either polarity, positive or negative
  - ■ For example in a N-channel MOSFET
    - ● More +V_{GS} means more current
    - ● While more -V_{GS} means less current
- ➢ Operate within three different regions
  - ■ Cut-off, Linear (Ohmic) and Saturation
- ➢ Is less common than the enhancement mode types
- ➢ Like a JFET, it is specified in term of **I_{DSS}** and **V_P**



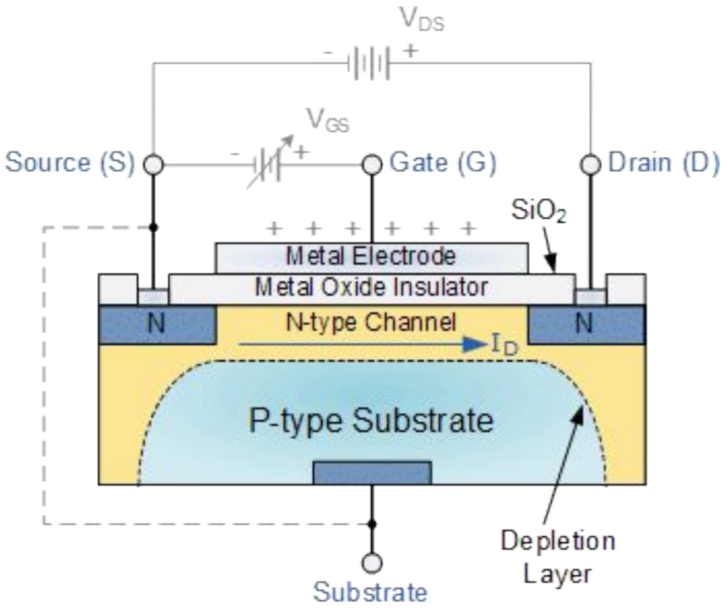


$$i_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

Fundamentals of Electronic Circuits (MOSFET)

❖ Enhancement MOSFET (eMOSFET)

- ➢ The conducting channel is lightly doped or even undoped
- ➢ The device is normally "OFF" when V_{GS} is 0V
- ➢ It requires a Gate-Source voltage to switch the device "ON"
- ➢ It is equivalent to a "Normally Open" switch
- ➢ For an n-channel eMOSFET
  - ■ + V_{GS} turns it "ON", while a zero or - V_{GS} turns it "OFF"
  - ■ Increasing the + VGS will decrease the channel resistance

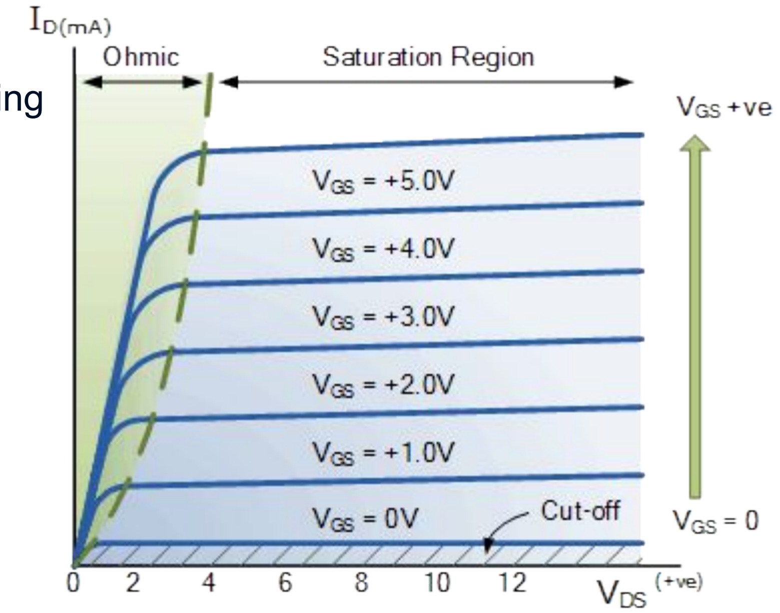


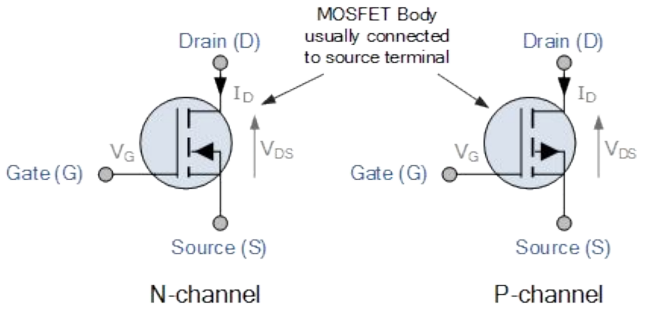
- ➢ A drain current will only flow when **V_{GS}** greater than the threshold voltage (**V_{TH}**)
- ➢ It is an excellent electronics switch due to its
  - ■ Infinitely high input impedance
  - ■ Low "ON" and extremely high "OFF" output impedances
- ➢ eMOSFETs are used in ICs to produce CMOS type Logic Gates and power switching circuits

[MOSFET Transistor Basics & Working Principle]

Fundamentals of Electronic Circuits (MOSFET)

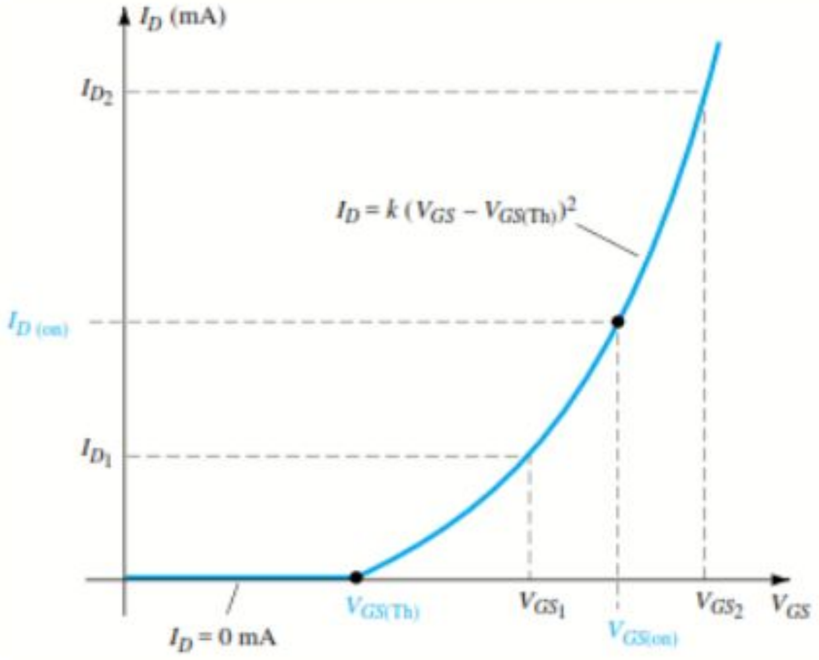
- An eMOSFET is specified in term of (**V_{th}**) and **K_n**
  - **V_{th}** (threshold) is the minimum required **V_{GS}** to make the device conducting
  - **K_n** is the conductance coefficient and it can be calculated form
    - **$I_{D(on)}$** and **$V_{GS(on)}$** form its datasheet
- eMOSFET operation modes
  - Cut-off Region (**$V_{GS} \leq V_{th}$**):
    - It is "fully-OFF" thus, **I_D** = 0
    - It acts like an open switch regardless of the value of **V_{DS}**
  - Ohmic Region (**$V_{GS} > V_{th}$** and **$V_{DS} \leq V_{GS} - V_{th}$**):
    - It acts like a voltage-controlled resistance
  - Saturation Region (**$V_{GS} > V_{th}$** and **$V_{DS} > V_{GS} - V_{th}$**):
    - It is "fully-ON" and the drain current is maximum
    - It acts like a closed switch





Fundamentals of Electronic Circuits (MOSFET)

- The conductance coefficient is $k_n = \mu_n C_{ox} \frac{W}{L}$
  - **μ_n** is the charge-carrier effective mobility, **C_{ox}** is the gate oxide capacitance per unit area
  - **W** is the gate width and **L** is the gate length
- The drain current in ohmic mode is
  - **$I_D = K_n(V_{GS} - V_{th} - 0.5V_{DS})V_{DS}$**
- The drain current in saturation mode is
  - **$I_D = 0.5 \times K_n(V_{GS} - V_{th})^2$**
- The gain of an eMOSFET in saturation mode is
  - **$g_m = 2 \times K_n \times (V_{GS} - V_{th})$**

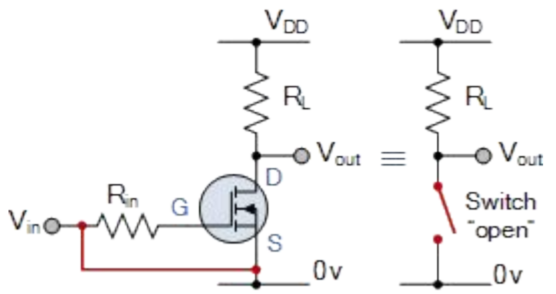


[MOSFETs and How to Use Them | AddOhms]

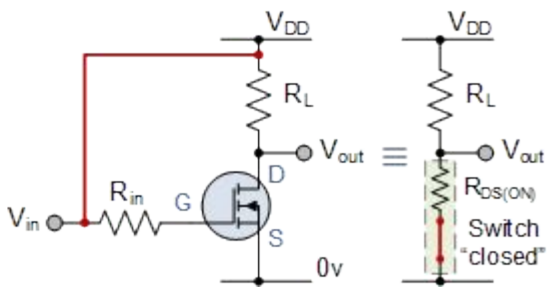
[Power Electronics - MOSFET Power Losses]

Fundamentals of Electronic Circuits (MOSFET)

- MOSFET as a switch
  - OFF State
    - $V_{GS} = 0V$ and $V_{GS} < V_{TH}$
    - MOSFET is “OFF” and $I_D = 0A$
    - MOSFET operates as an “open switch”
    - $V_{OUT} = V_{DS} = V_{DD}$ == HIGH
  - ON State
    - $V_{GS} = V_{DD}$ and $V_{GS} > V_{TH}$
    - MOSFET is “ON” and $I_D = V_{DD} / R_L$
    - $V_{DS} = 0V$ (ideal saturation) and channel resistance $R_{DS(on)} < 0.1\Omega$
    - MOSFET operates as a low resistance “closed switch”
    - $V_{OUT} = V_{DS} \cong 0.2V$ due to $R_{DS(on)}$



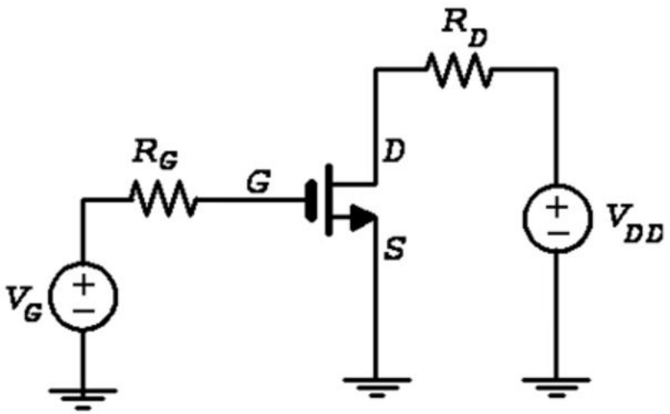
The MOSFET is in the cut-off mode



The MOSFET is in saturation mode

Fundamentals of Electronic Circuits (MOSFET)

- Example: Calculate V_{GS}, V_{DS} and I_D
- Known values
  - V_{GG} = 1.5V, V_{DD} = 7V, V_{th} = 1V, K_n = 1.2mA/V^2 and R_D = 7 kΩ
- Answer
  - $I_G = 0$, $V_{GS} = V_{GG} = V_G - V_S = 1.5V$
  - $V_{GS} > V_{th}$, we assume that the MOSFET is in saturation mode
  - I_D = 150 μA and V_{DS} = 5.95V
  - $V_{DS} > V_{GS} - V_{th}$ => 5.95 > 1.5 - 1 ✅ so the transistor is in the saturation mode

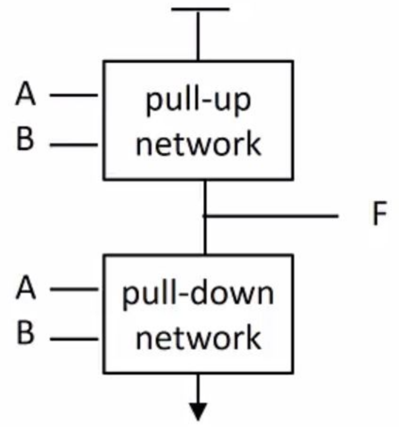


[The MOSFET]

[MOSFET as a Switch]

Fundamentals of Electronic Circuits (CMOS)

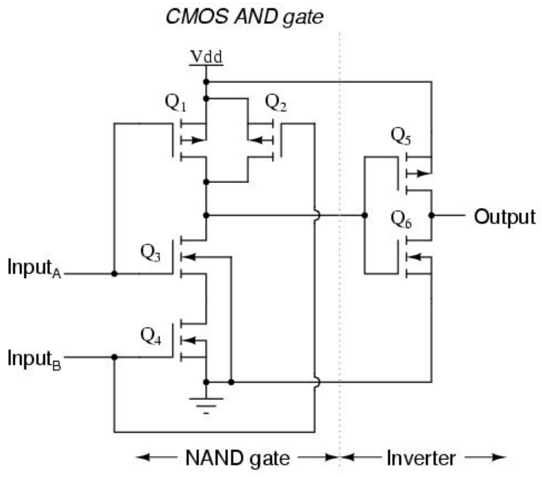
- CMOS (Complementary MOS)
  - Is a type of MOSFET fabrication process
  - Uses complementary and symmetrical pairs of NMOS and PMOS for logic function
- Features
  - Dissipates low power
    - At 1 MHz and 50 pF load, the power dissipation is typically 10 nW per gate
    - Power consumption increases with higher clock speeds
  - Short propagation delays (around 25 ns)
  - Good noise immunity (50% or 45% of the full logic)
    - $NM_H = NM_L = 3(V_{DD} + 2V_{th}/3)/8$
  - Levels of the logic signal will be equal to V_{DD} since the input impedance is so high.
  - Voltage levels range from 0 to V_{DD}
  - A low level is between 0 and 1/3 V_{DD} while a high level is between 2/3 V_{DD} and V_{DD}

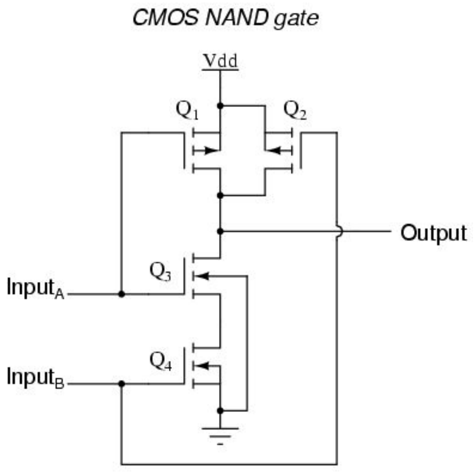


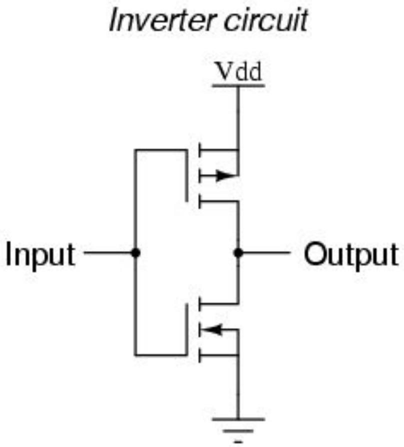
Pull-up: PMOS only
Pull-down: NMOS only

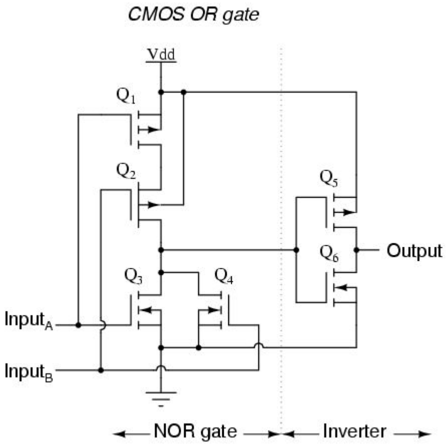
Fundamentals of Electronic Circuits (CMOS)

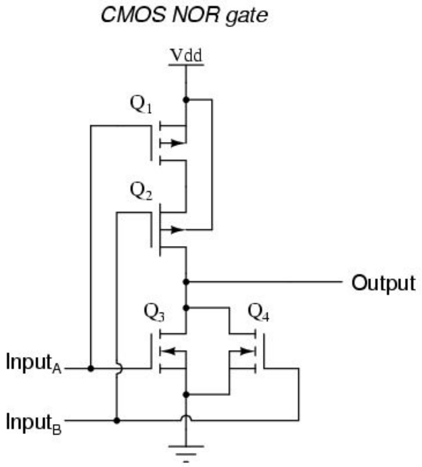
- Basic Logic Gates
- Useful links
  - [CMOS Gate Circuitry]()
  - [CMOS Logic Gates]()
  - [CMOS Transistors]()
  - [CMOS Introduction]()











Fundamentals of Electronic Circuits

- Some useful links
  - MOSFET BJT or IGBT - Brief comparison Basic components
  - The FET (field effect transistor)
  - How FETs Function - The Learning Circuit
  - What is Field Effect Transistor - FET - JFET - MOSFET - Applications of MOSFET
  - The MOSFET (part 1, part 2 and part 3)
  - MOSFET
  - Field Effect Transistor (FET)
  - Depletion MOSFETs
  - Understanding The FinFet Semiconductor Process
  - Investing in FinFET Technology Leadership Presented by ARM
  - Samsung Foundry's New Transistor Structure
  - Using Power MOSFETS with Arduino