# SEMICONDUCTORS

## Transistors

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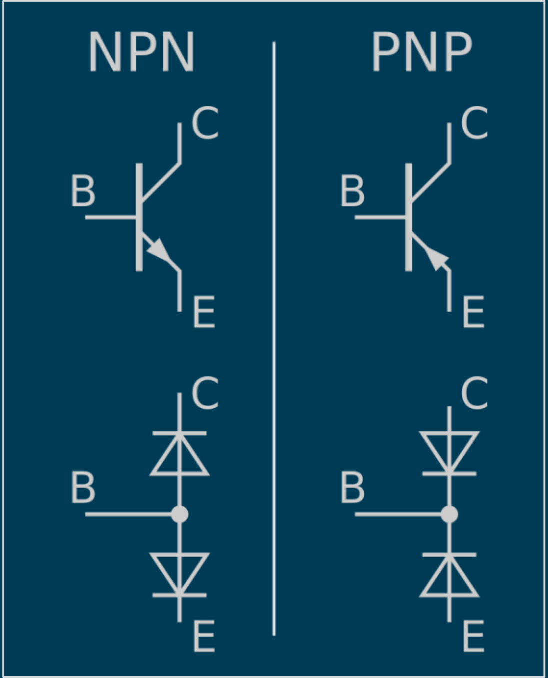
# BJTs

# BJT – Bipolar Junction Transistor

- A BJT is a type of transistor that uses both electron and hole charge carriers.
- They come in two types:
  - NPN
  - PNP
- Emitter always has arrow
  - NPN – not pointing in
  - PNP – pointing in proudly



# BJT Functionality

- BJTs work as current-controlled current regulators.
- In other words, BJTs restrict the amount of current passed according to a smaller, controlling current.
- BJTs can be used both as amplifiers and as switches.
- They have 3 terminals:
  - Collector
  - Base
  - Emitter
- Uses both hole and electron charge carriers.

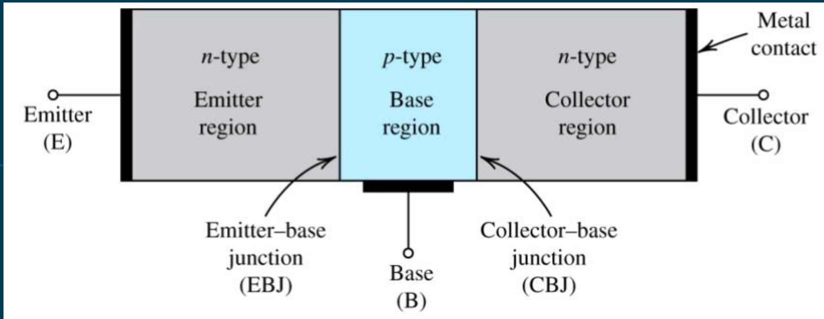
# BJT: 3 Operating Modes

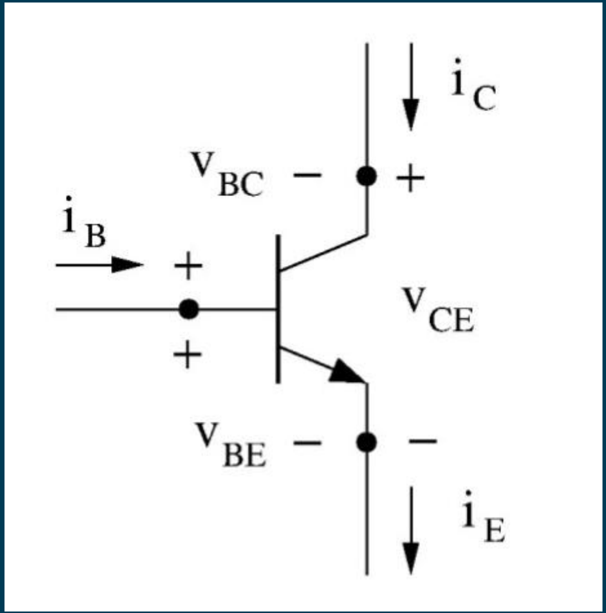
- Cut-off – the transistor is fully “off” operating as a switch and $I_c = 0$
- Active Region – the transistor operates as an amplifier and $I_c = \beta * I_b$
- Saturation – the transistor is fully “on” operating as a switch and $I_c = I_{saturation}$

# NPN

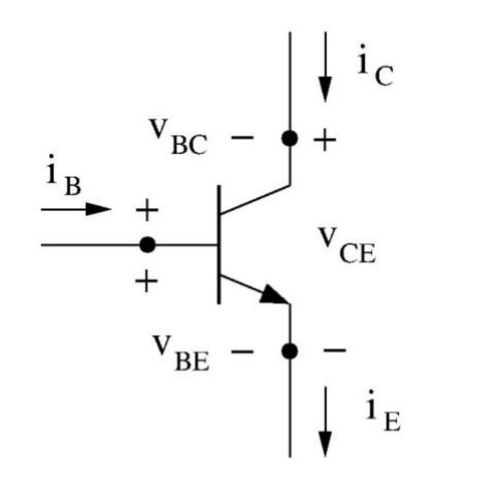
- A small current entering the base is amplified to output a large emitter current.
- Only when the base voltage is high relative to the emitter voltage. i.e. $V_{BE} = 0.7$ V

- KCL: $I_E = I_C + I_B$
- KVL: $V_{BC} = V_{BE} - V_{CE}$
- Note: $V_{CE} = V_C - V_E$



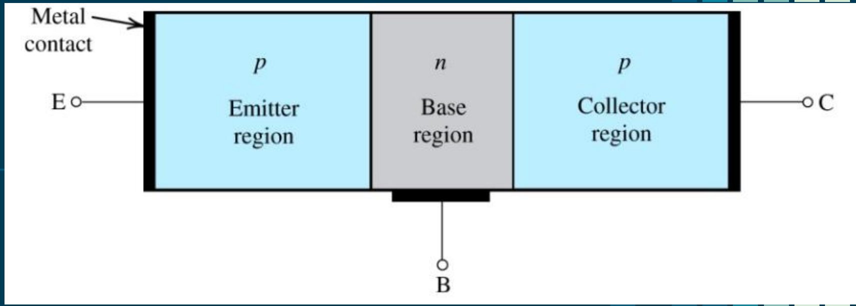



# 3 Operating Regions of NPN

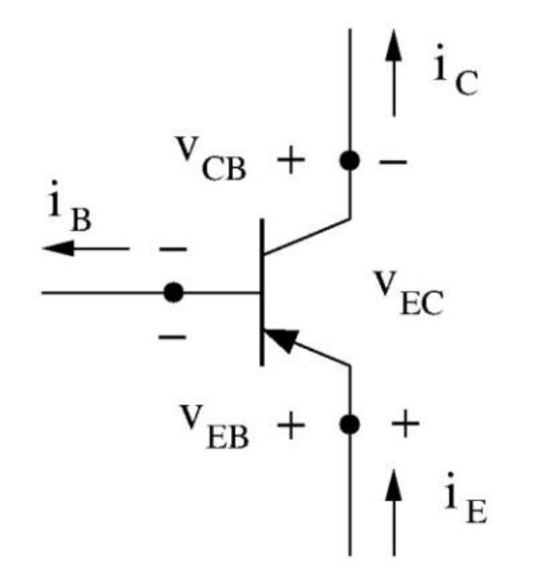



- Cut-off: Logic "off"
  - $V_{BE} < 0.7$ V (BE is reverse biased)
  - $I_C = 0$, $I_B = 0$
- Active: Partially "on"
  - $V_{BE} = 0.7$ V (BE is forward biased)
  - $V_{CE} \geq 0.7$ V (BC is reverse biased)
  - $I_C = \beta I_B$, $I_B > 0$; $\beta$ is given characteristic
- Saturation: Logic "on"
  - $V_{BE} = 0.7$ V (BE is forward biased)
  - $V_{CE} = 0.2$ V (BC is forward biased) – saturation voltage
  - $I_C < \beta I_B$, $I_B \geq 0$

# PNP

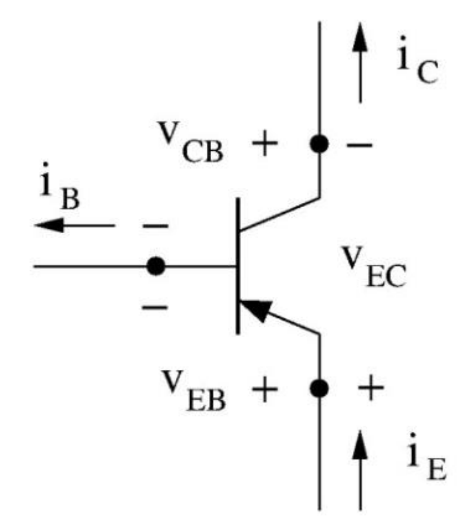



- A small current leaving the base is amplified to output a large collector current.
- Only when the base voltage is high relative to the emitter voltage. i.e. $V_{EB}$ = 0.7 V




- KCL: $I_E = I_C + I_B$
- KVL: $V_{CB} = V_{EB} - V_{EC}$
- Note: $V_{EC} = V_E - V_C$

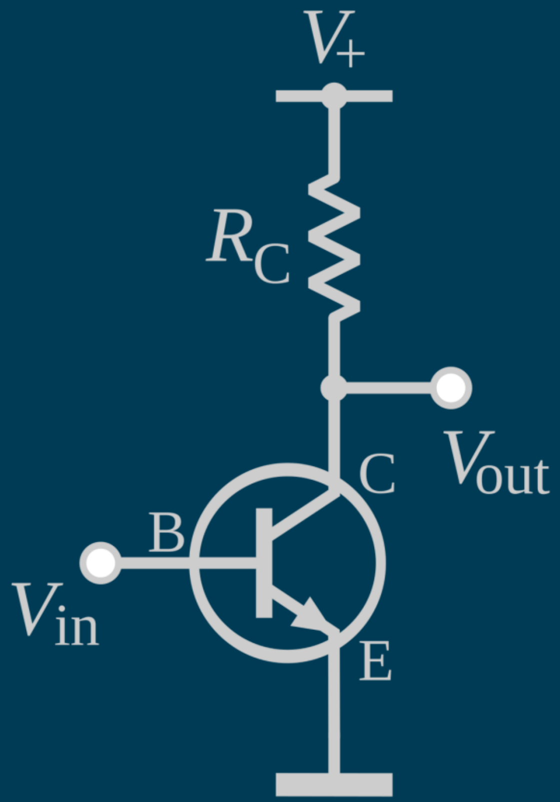
# 3 Operating Regions of PNP




- Cut-off: Logic "off"
  - $V_{EB} < 0.7$ V (EB is reverse biased)
  - $I_C = 0$, $I_B = 0$
- Active: Partially "on"
  - $V_{EB} = 0.7$ V (EB is forward biased)
  - $V_{EC} \geq 0.7$ V (CB is reverse biased)
  - $I_C = \beta I_B$, $I_B > 0$; $\beta$ is given characteristic
- Saturation: Logic "on"
  - $V_{EB} = 0.7$ V (EB is forward biased)
  - $V_{EC} = 0.2$ V (CB is forward biased) – saturation voltage
  - $I_C < \beta I_B$, $I_B \geq 0$

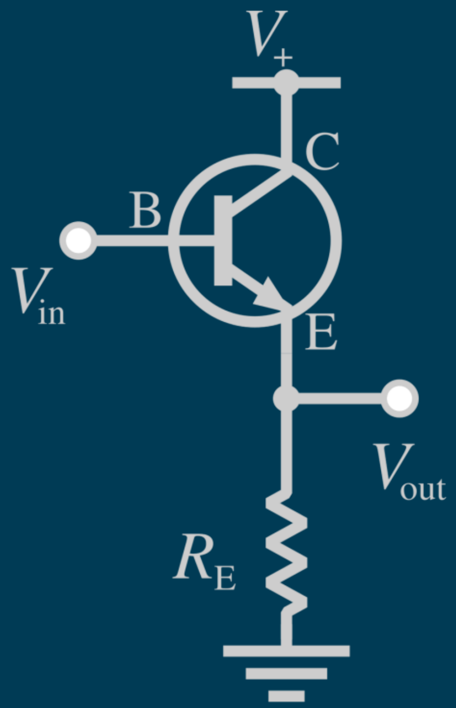
# Common Emitter Amplifier

- Voltage amplifier
- Boosts Vin at Vout



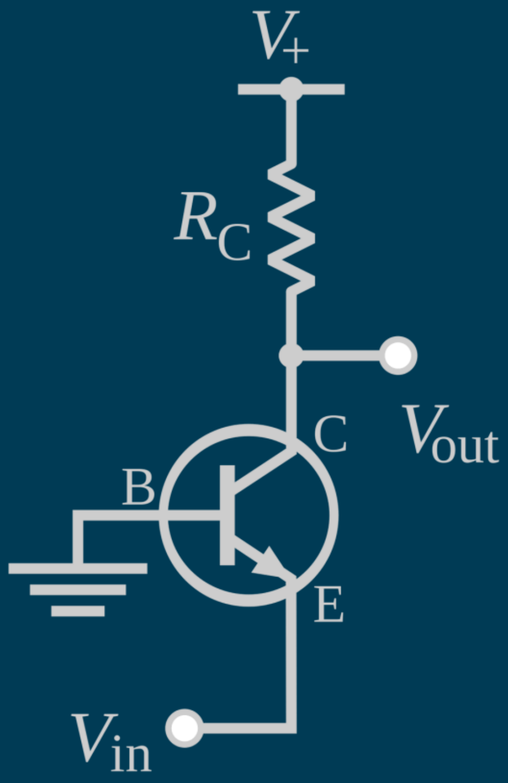
# Common Collector Amplifier

- AKA Emitter Follower
- Voltage buffer
- If no more available current for Vin, use voltage buffer to draw current from V+

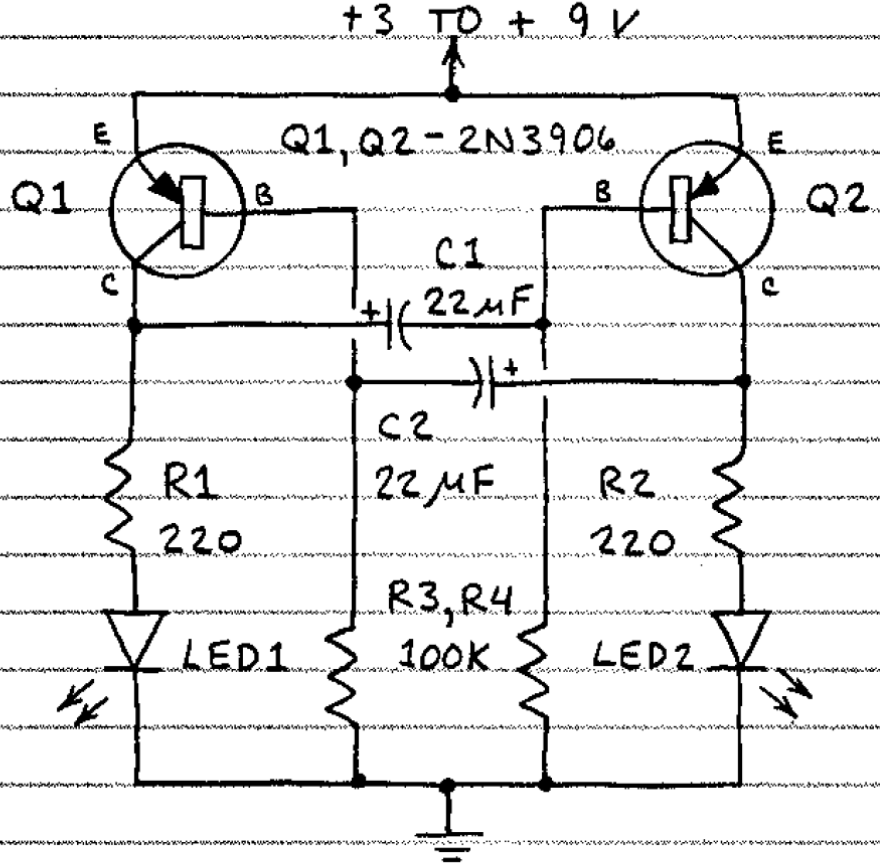


# Common Base Amplifier

- Current buffer or voltage amplifier
- Current is sunk from the emitter, providing voltage difference causing the transistor to conduct.
- The current conducted via the collector is proportional to the voltage across the base–emitter junction.



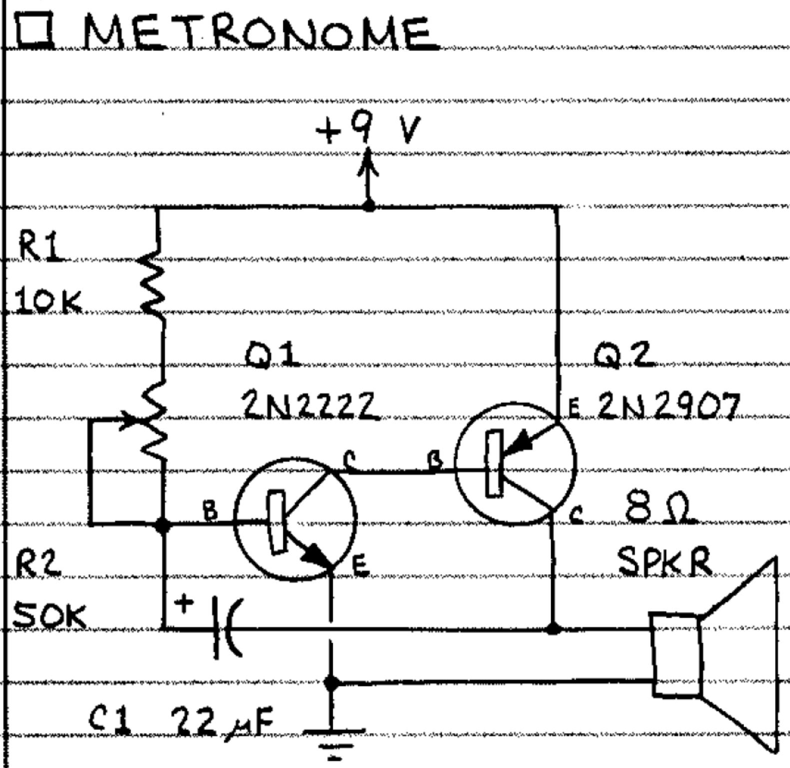
# DUAL LED FLASHER




THIS CIRCUIT IS CALLED A FREE-RUNNING MULTIVIBRATOR. IT'S IDENTICAL TO A FLIP-FLOP THAT TRIGGERS ITSELF REPEATEDLY. Q1 AND Q2 ARE GENERAL PURPOSE PNP TRANSISTORS (2N3906, 2N2907, ETC.). R1 AND R2 LIMIT THE CURRENT TO THE LEDs (WHICH FLASH ALTERNATELY). INCREASING THE VALUES OF C1 AND C2 WILL SLOW THE FLASH RATE.

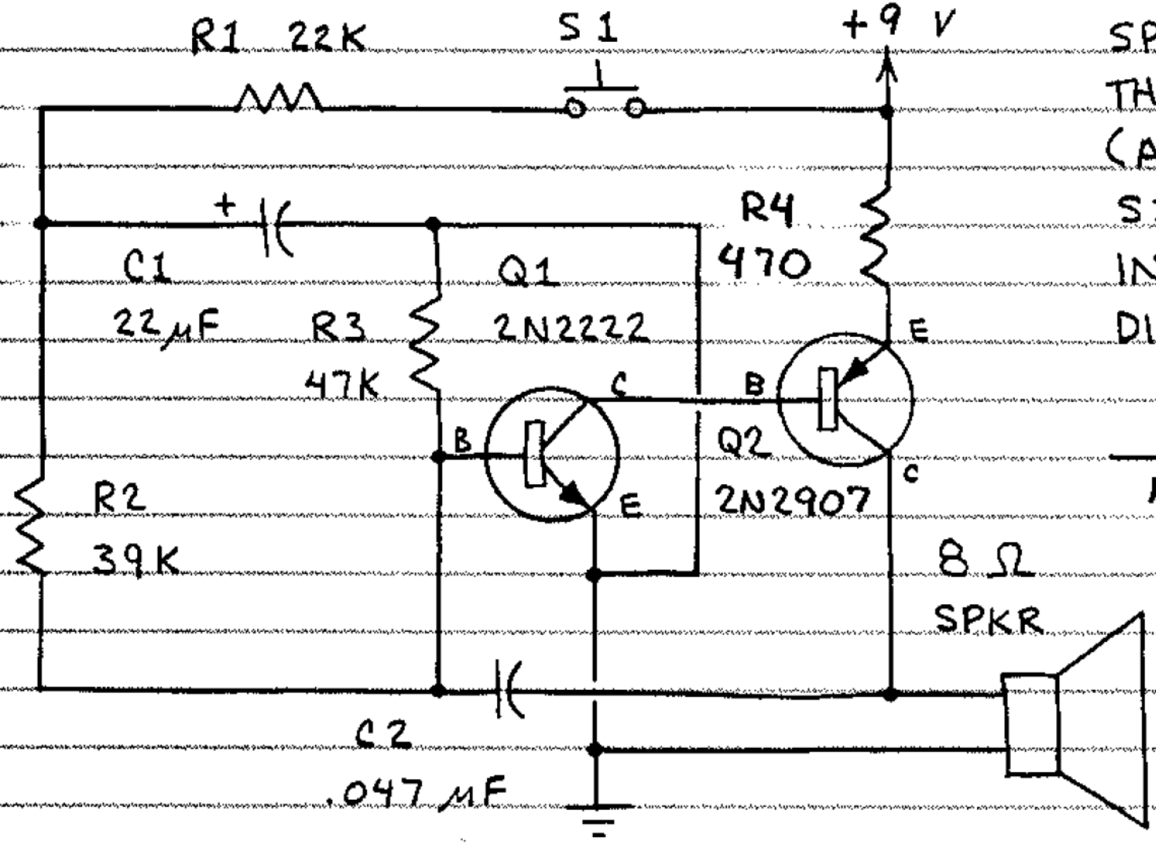
# Activity: Metronome

- Pg. 104




A METRONOME MARKS TIME BY PRODUCING A REGULAR SEQUENCE OF "CLICKS" OR "POCKS." ADJUST THE CLICK RATE BY ADJUSTING R2 OR CHANGING C1'S VALUE.

## ☐ SIREN




CLOSE S1 AND THE SPEAKER EMITS A TONE THAT RISES IN FREQUENCY (AS C1 CHARGES). OPEN S1 AND THE TONE FALLS IN FREQUENCY (AS C1 DISCHARGES). LIKE THIS:


HINT: CHANGE R1 TO CHANGE UP-DOWN TIME.

# MOSFETs

# Intro to FETs

- BJTs seem simple. They are just 2 diodes put together, but the math quickly got difficult.
- FETs, or field effect transistors, are much simpler!
- Their construction is more complex than BJTs, but they operate much more like a true switch.
- A FET is  an electronic device which uses an electric field to control the flow of current.
- This means they are much easier to turn on and turn on much faster!

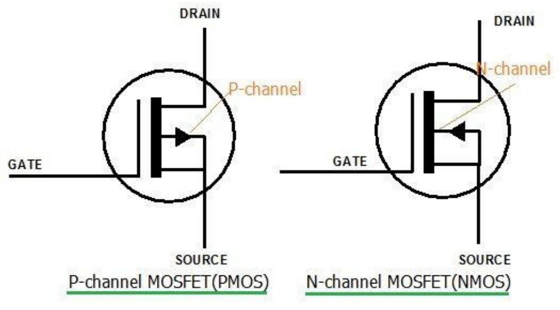
# MOSFETs

- We will focus on one type of FET, a MOSFET.
- MOSFET – Metal-Oxide Semiconductor FET
- MOSFET – a type of FET most commonly fabricated by the controlled oxidation of silicon.
- They are voltage-controller and require virtually no current to turn on as compared to BJTs.
- They come in pMOS and nMOS.
- Millions of them in phones and computers!

# BJTs vs. MOSFETs

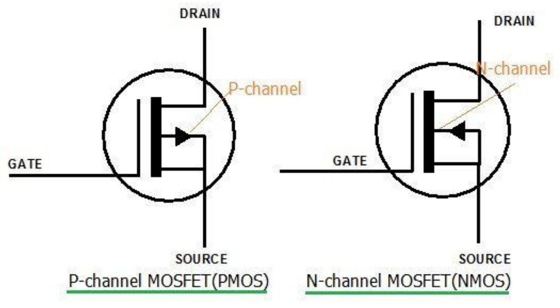
| | BJTs | MOSFETs |
|---|---|---|
| **How it operates** | BJTs are current-controlled. They require a biasing current to the base terminal for operation. | FETs are voltage-controlled. They only require voltage applied to the gate to turn the FET either on or off. They do not require a biasing current for operation. |
| **Input Impedance** | BJTs offer smaller input impedances, meaning they draw more current from the power circuit feeding it, which can cause loading of the circuit. | FETs offer greater input impedance than BJTs. This means that they practically draw no current and therefore do not load down the power circuit that's feeding it. |
| **Gain** | BJTs offer greater gain at the output than FETs. | The gain of FETs are smaller than for BJTs. |
| **Size** | BJTs are larger in size and therefore take up more physical space than  FETs normally. | FETs can be manufactured much smaller than BJTs. This is especially important for integrated circuits that are composed up of many transistors. |
| **Popularity** | BJTs are less popular and less widely used | FETS are definitely more popular and widely used in commercial circuits today than BJTs |
| **Cost** | BJTs are cheaper to manufacture | MOSFETs are more expensive to manufacture |

# How a MOSFET works




- A MOSFET is acts just like a switch.
- It either connects the drain to the source (short) or disconnects the drain from the source (open).
- It does this based on the gate voltage $V_{GS}$, which is the voltage difference between the gate and source.
- Every MOSFET has a $V_{GS,threshold}$ characteristic.
- Once $V_{GS}$ exceeds $V_{GS,threshold}$, the MOSFET will connect drain to source.

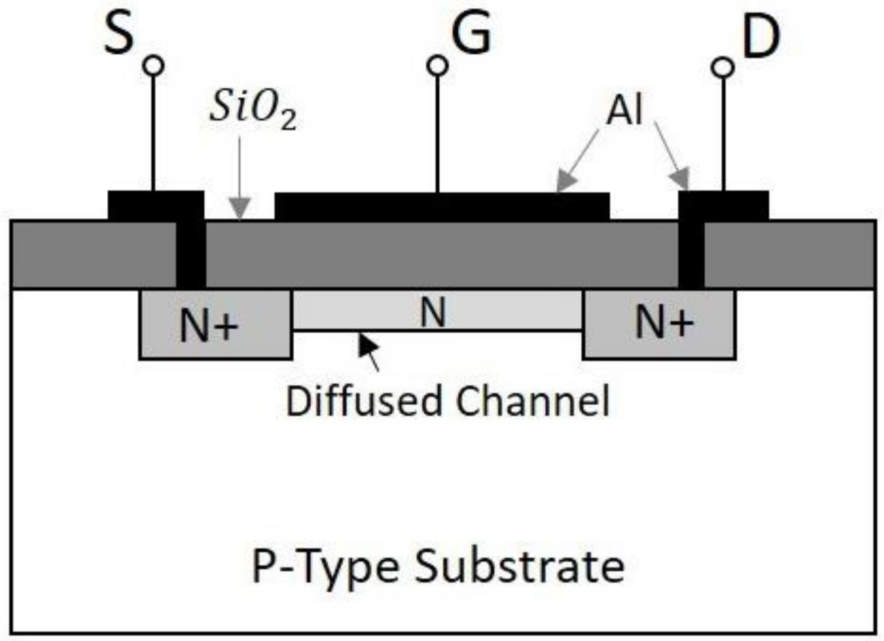
# MOSFET Characteristics



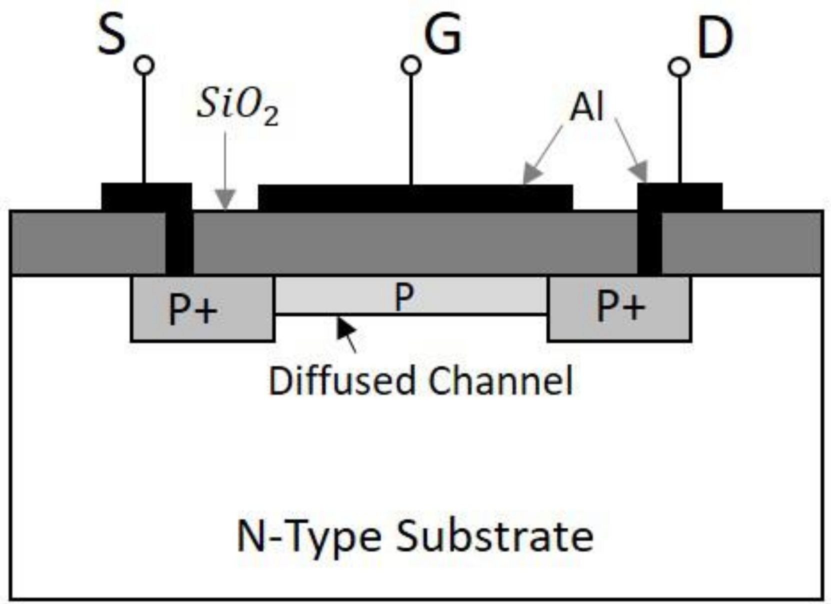

- MOSFET $V_{GS}$ Thresholds
  - nMOS have a positive threshold voltages
  - pMOS have a negative threshold voltages
- The threshold voltages depend on the specific MOSFET, but most are between 2.5 and 10V for nMOS or -2.5 and -10V for pMOS.

| MOSFET Type | $V_{GS} \ll 0$ | $V_{GS} = 0$ | $V_{GS} \gg 0$ |
|---|---|---|---|
| **nMOSFET** | OFF | OFF | ON |
| **pMOSFET** | ON | OFF | OFF |

# PMOS & NMOS Construction

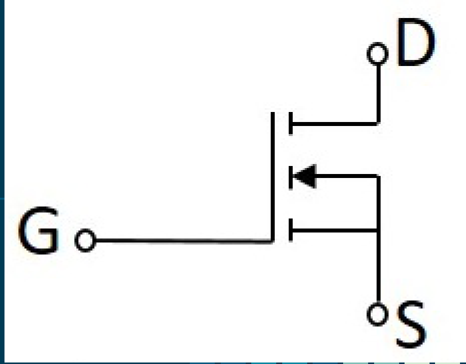



Structure of N-channel MOSFET



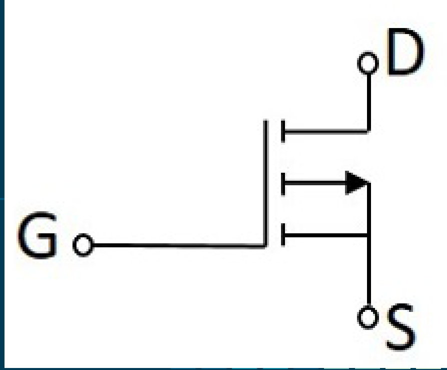

Structure of P-channel MOSFET

# nMOS




- $V_{DS}$ is positive.
  - Drain to Source voltage.
  - This means that if you're switching on a positive voltage source, it should be connected to Drain.
- $V_{GS,threshold}$ is positive.
  - Source should be tied to ground.
  - That way you can easily turn on the nMOS by applying a voltage to Gate.

# pMOS




- $V_{DS}$ is negative.
  - Drain to Source voltage.
  - This means that if you're switching on a positive voltage source, it should be connected to Source.
- $V_{GS,threshold}$ is negative.
  - If there is a positive voltage at the Source, you can likely drive Gate to ground to turn on pMOS.
  - To turn off pMOS, the Gate voltage will have to be the same or higher than the Source voltage.

# MOSFET Uses

- Used in processors for computers, phones, etc. because it is a quick, low-power switching device
  - Computational logic
  - Storage
- Used in many different integrated circuits (ICs)
- Power supplies
- Variable frequency motor drivers

# Moore's Law

- Moore's law is the observation that the number of transistors in a dense integrated circuit doubles about every two years. Projected in 1965.
- Moore's law is an observation and projection of a historical trend and not a physical or natural law.
- Although the rate held steady from 1975 until around 2012, the rate was faster during the first decade.
- End of Moore's Law?

# MOSFET Simulations

- LTspice

# Activity: Use nMOS to drive a motor

# Activity: Reverse Polarity Protection

- Design a circuit that provides reverse polarity protection using a PMOS.