PHY405-L07

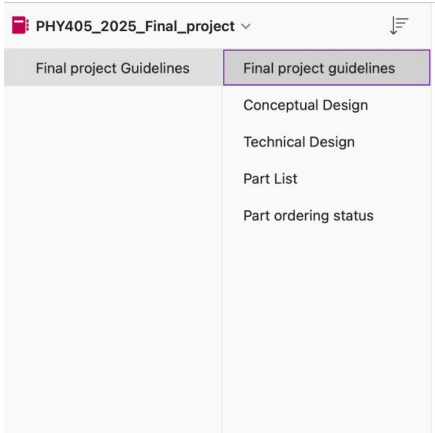
Currents and amplifiers: Transistors

Logistics -- Final project

- 3 more regular labs to go, final project afterwards.
  - See the project guidelines for more information.
- Coordinate with this OneNote page
- We'll follow the steps of
  1. Conceptual design -- due Mar. 6th
     a. Please discuss and come up with a project
  2. Technical design -- due Mar 13th
     a. Try to use in-house components as much as possible
     b. Part list finalized by the end of this day
     c. Order will go out on Friday. Usually takes a week to get back
  3. Realization -- the two weeks following

Project coordination

- New section with your name
- Add pages of
  - Conceptual design
  - Technical design
  - Part list
  - Etc.
- I'll collect part list by the end of Mar. 13



Final project guidelines

Tuesday, February 28, 2023 4:31 PM

https://www.physics.utoronto.ca/apl/405/ProjectGuidelines.html

We'll attempt to use this OneNote to coordinate the projects, especially the part lists in case new components need to be purchased.

Please create a new section with your names

Create pages like "conceptual design", "technical design", "part list", etc.

Timeline:

Mar. 6, Thursday : Conceptual design posted. Discussions and refinement is allowed in the week following.
Investigation of new parts needed, vs can we build the project with in-house components.
Mar. 13, Thursday: Technical design posted. Part list needs to be finalized by the end of the day.
Mar. 14, Friday: Purchase order sent out for parts required.
Mar. 21/24: Building final project

Breadboard housekeeping

- From this lab, we will enforce stricter breadboard housekeeping rules

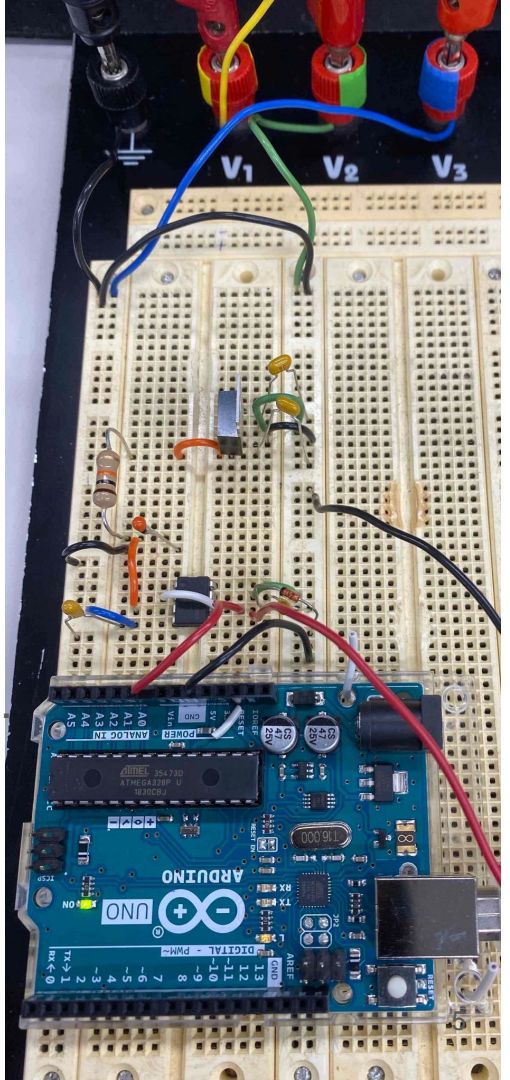
Exercises

You will be asked for photos of some of your circuits.

- **You will lose points if your hook-up wire colours do not follow a clearly specified sensible convention**, e.g. as described in the previous lab.

Reminder: Breadboard Organization

- Use consistent colour wires. For example:
  - Black wires→Common.
  - Yellow wires→DC Power Supply Output 1.
  - Green wires→DC Power Supply Output 2 (V+supply)
  - Blue wires→DC Power Supply Output 3 (V-supply).
  - White or Orange wires→internal connections.
  - Red wires are Input or Output
  - Use power rails columns for V+supply and V-supply.
  - Create Common rows or columns to provide easy access.
    - In general best to only have a single Common connection for any circuit.
- Some short white wires hold Arduino on the board.



Voltage vs Current Sources

- The simplest power supplies are voltage, not current, sources
  - Batteries have voltages determined by chemical potentials
  - Electrical generators have an EMF voltage determined by

$$\varepsilon = -N\frac{d\phi_B}{dt}$$

- Output currents are determined by the total impedance

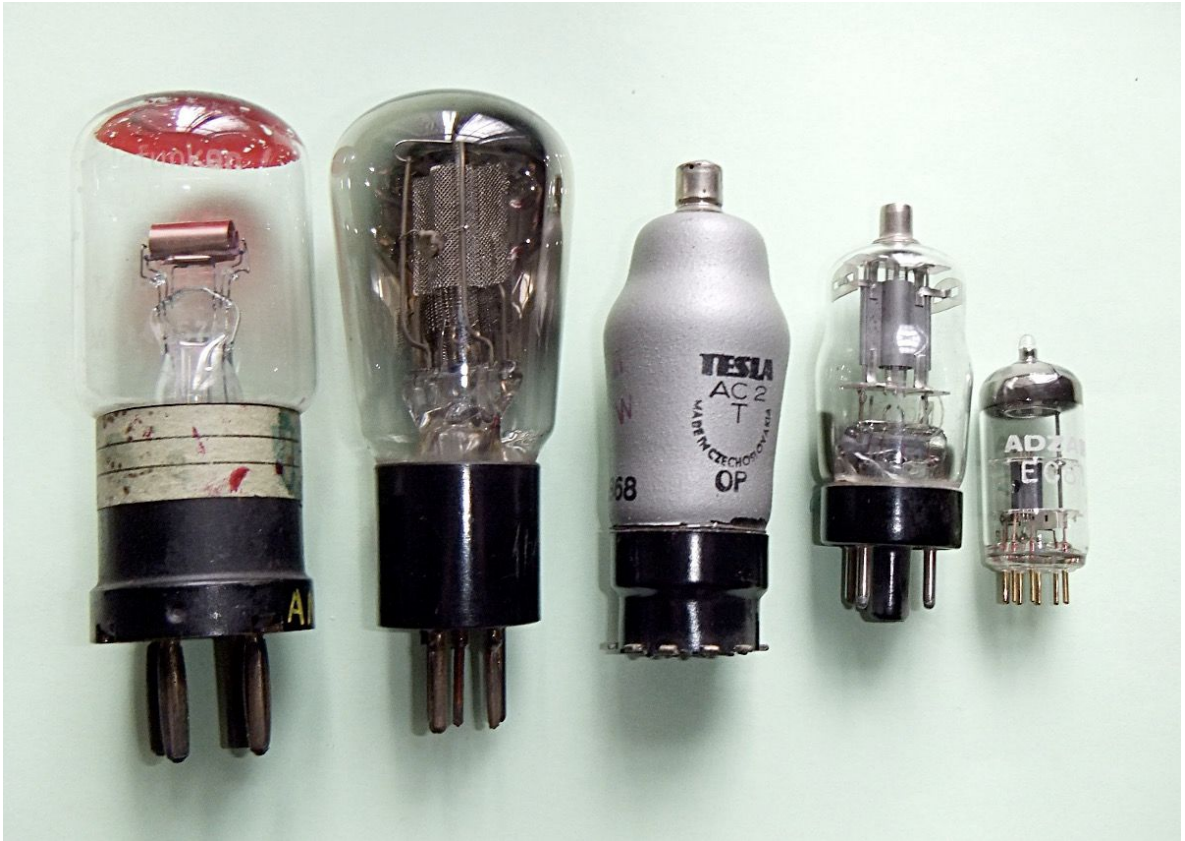
$$I = \frac{V}{Z_{load} + R_{internal}}$$

- So unless power supply internal resistance is huge - which makes it hard to provide much current - the output current will vary with the load impedance.
- If we want a controlled output current, we use active devices with feedback.

Real Triodes

Vacuum tubes

(source: wikipedia)



Ideal Triodes

- Heater bake cathode to get electrons popping out
- Apply a high voltage between cathode and anode
- A voltage on the grid controls whether electrons get accelerated to anode

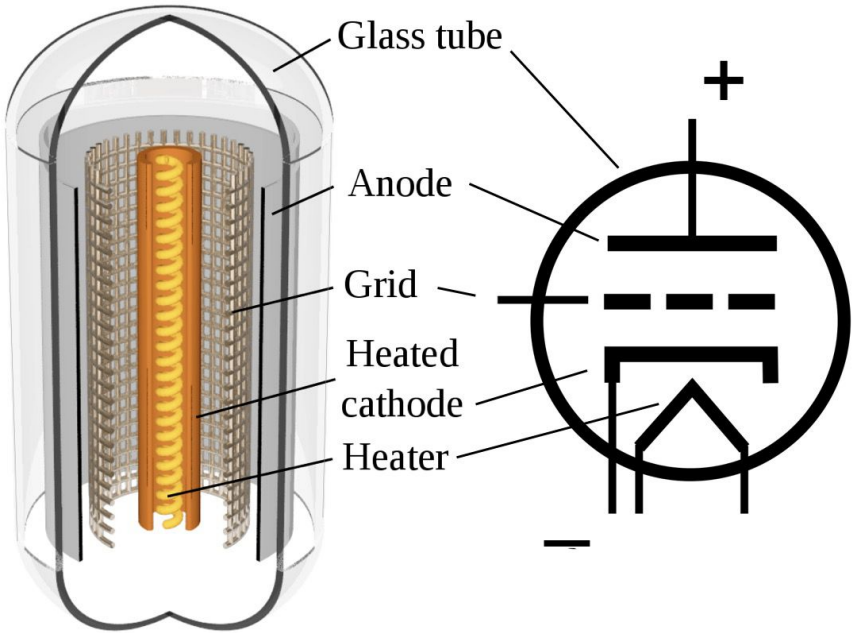


Illustration and symbol for triode with indirectly heated filament (source: wikipedia)

Vacuum tubes are still used nowadays

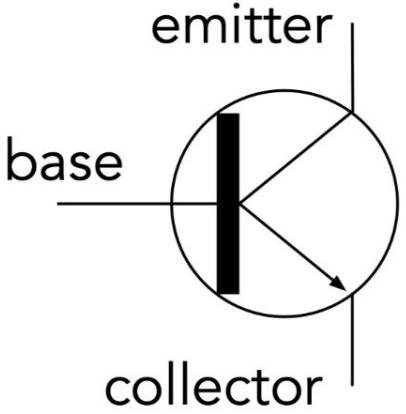
Eg. Headphone audio amplifier

https://a.co/d/9HqKmHB
^^ A reference, not a commercial ad..

Transistors

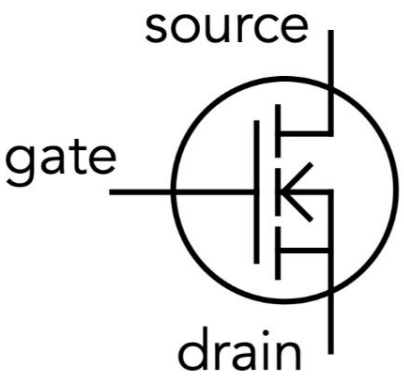
- The simplest semiconductor active components that can act as amplifiers or switches.

BJT

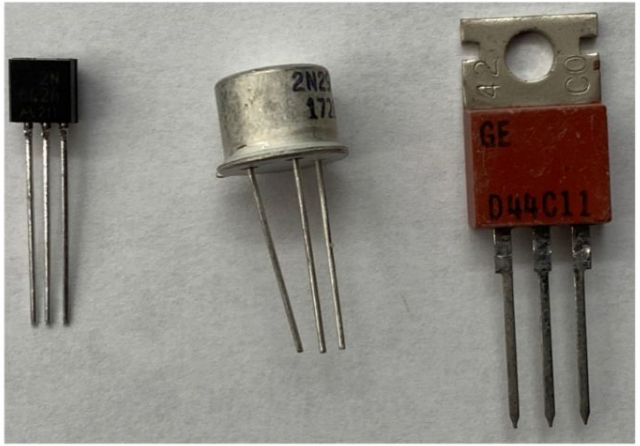


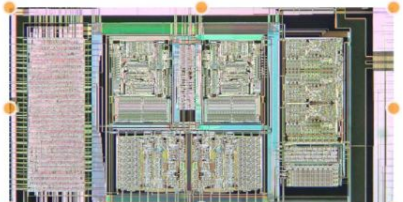
Current controlled

MOSFET

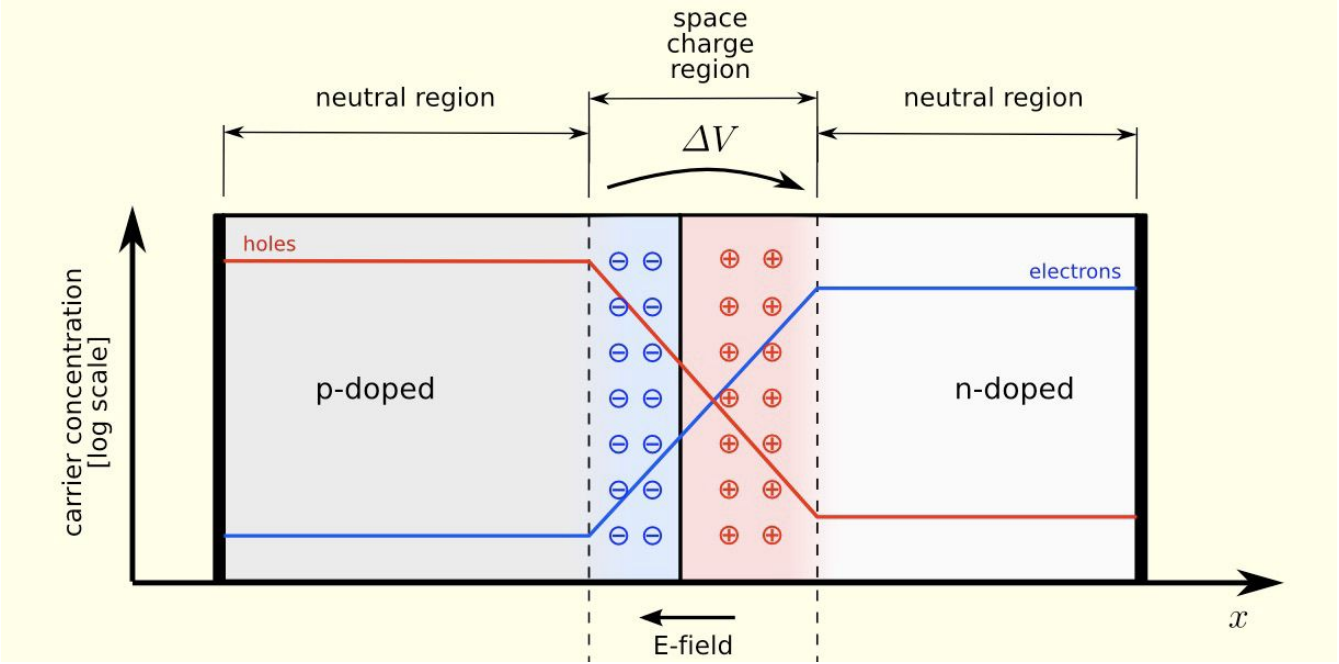


Voltage controlled



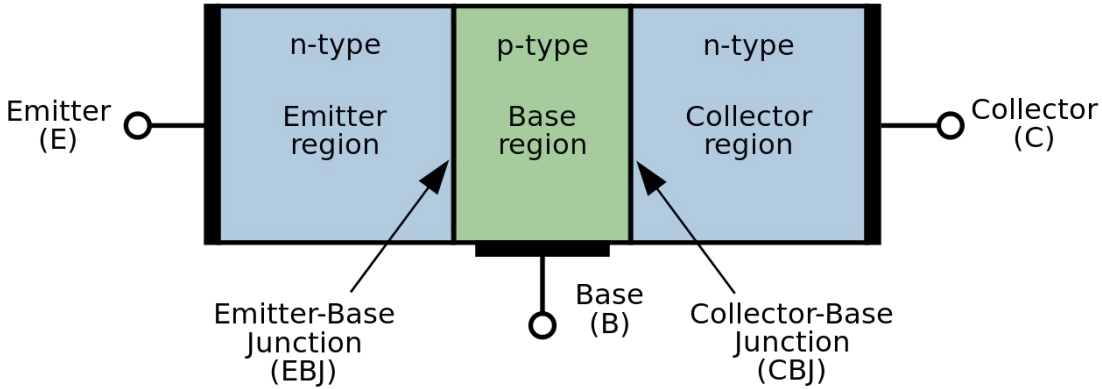


Reminder: PN junction and Diode



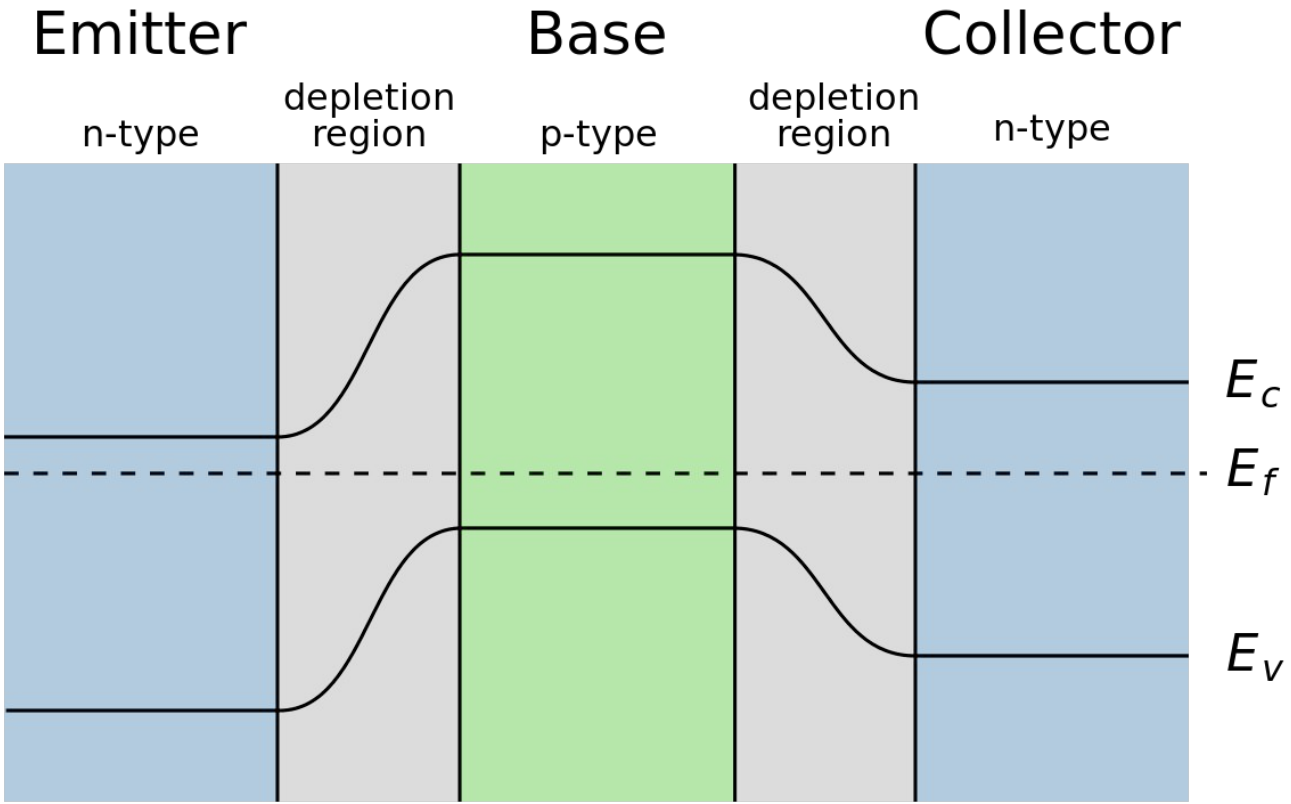
(credit: Wikipedia)

Bipolar Junction Transistor (BJT)



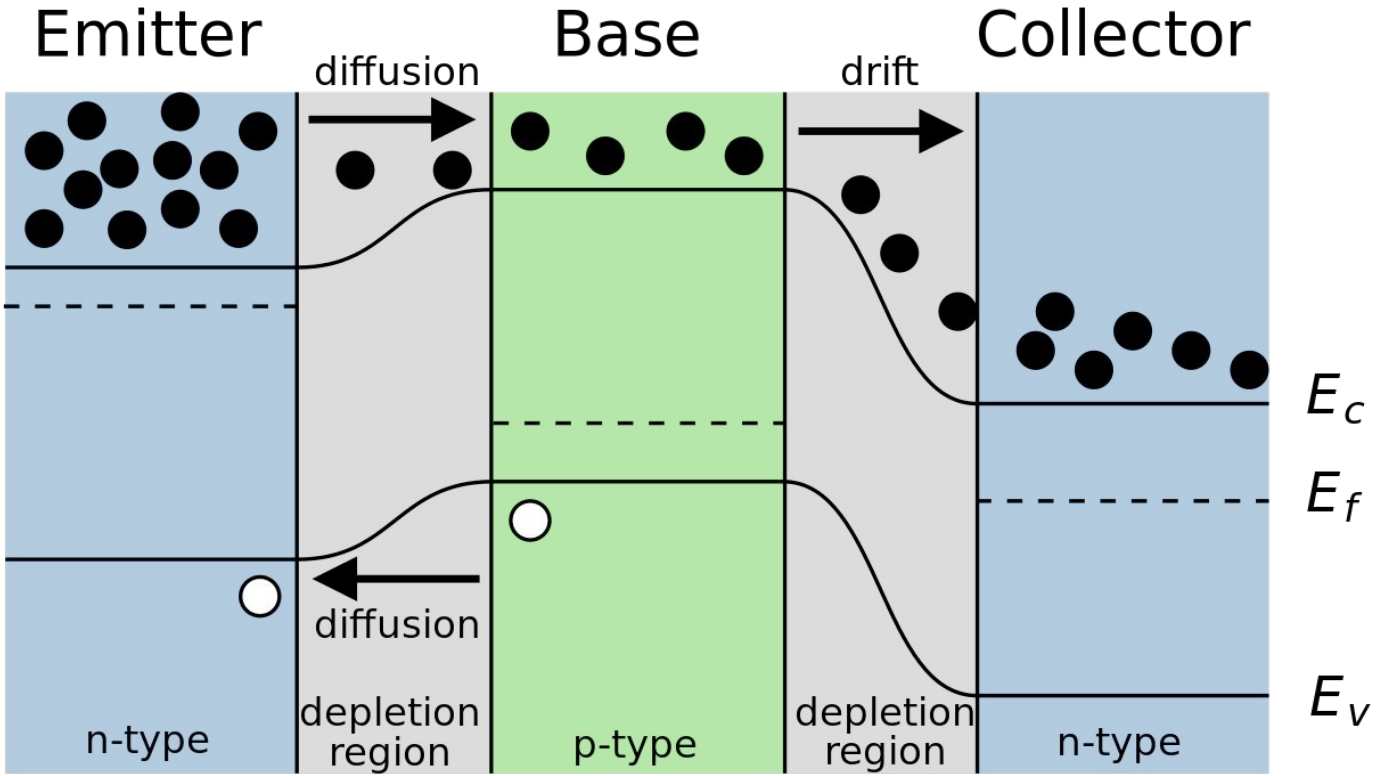
- Ideal npn Bipolar Junction Transistor (from wikipedia).
  - This is not to scale.
  - The base region is usually ~ 0.1 μm thick, at least an order-of-magnitude less than the electron diffusion length (the average distance an electron can travel in the p-type material before recombining with a hole).
- Emitter is heavily doped, Base is lightly doped, Collector is in between.

npn BJT



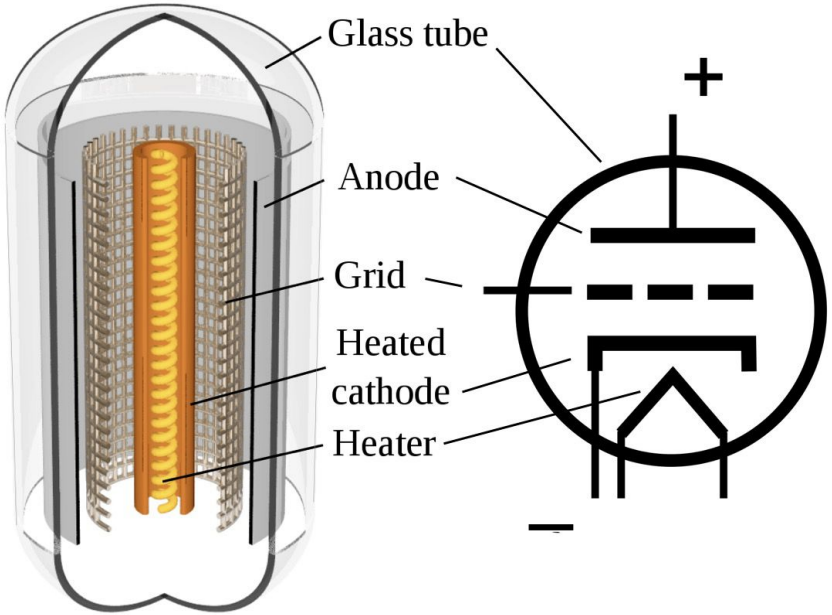
npn BJT energy bands with no applied voltage (from wikipedia)

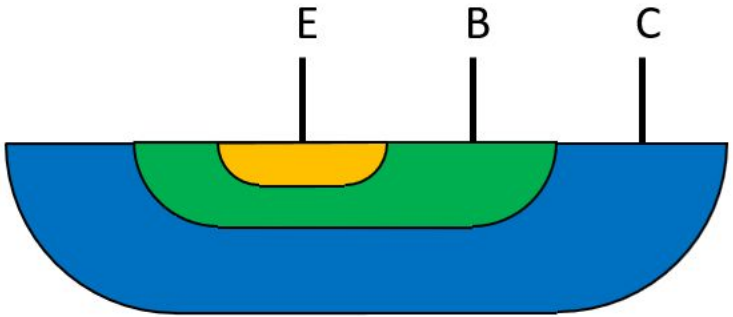
npn BJT with voltage

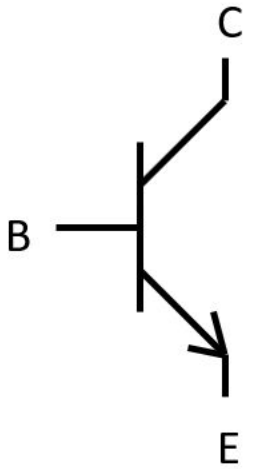


npn BJT energy bands with applied voltage (from wikipedia)

Vacuum tube vs BJT





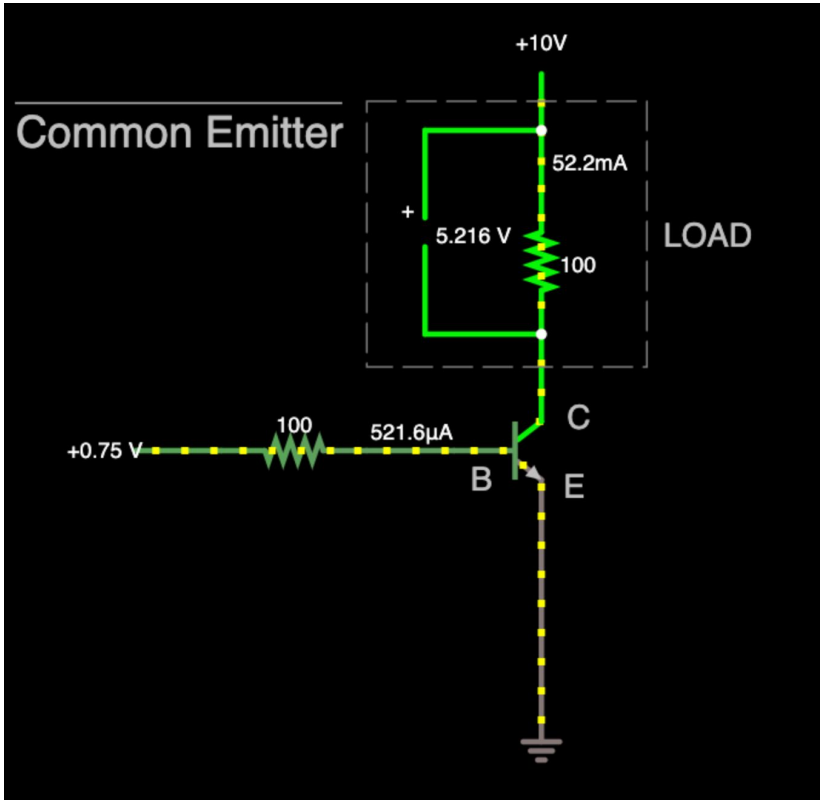


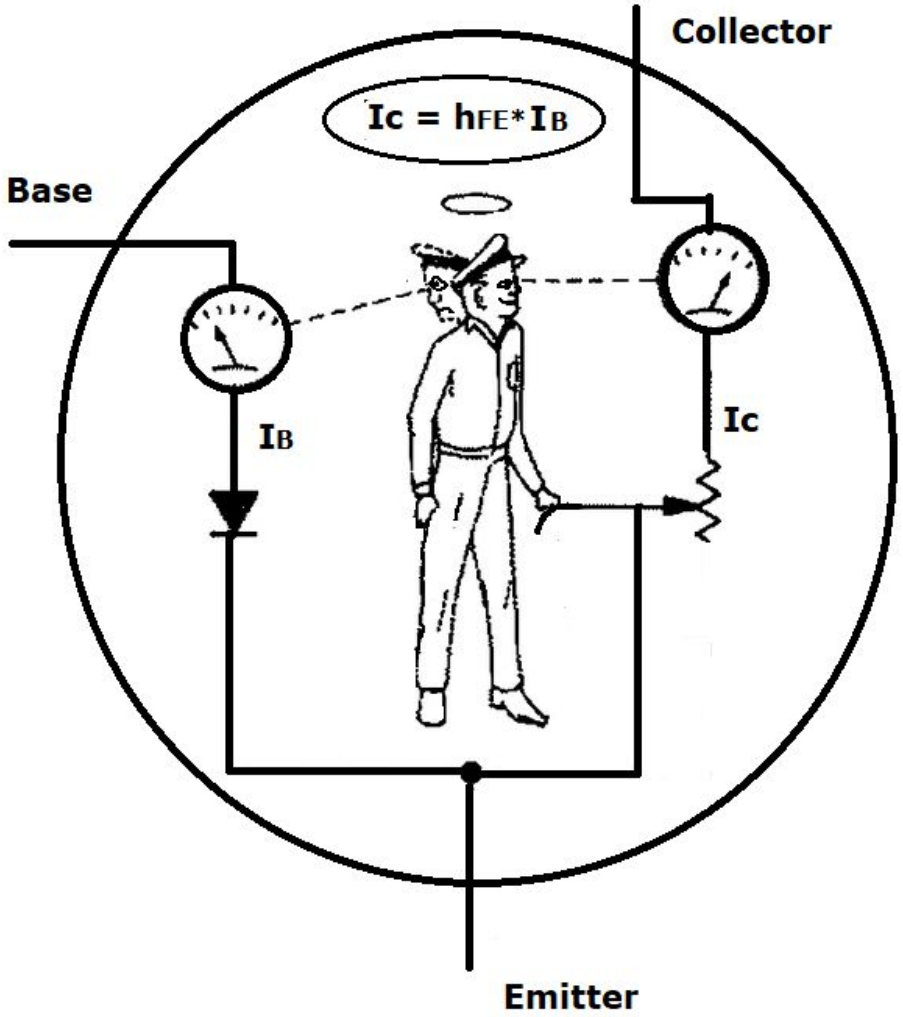
Transistor gain

- Gain parameter for a bipolar transistor:

$$\beta = \frac{I_{\text{Collector}}}{I_{\text{Base}}}$$

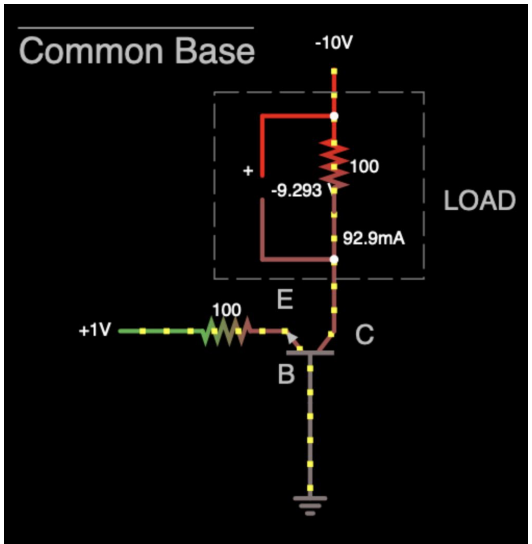
- This is measured in the Common Emitter mode.
- β is also known as the hybrid forward transfer characteristic h_{fe}
- Usually β ~ 100

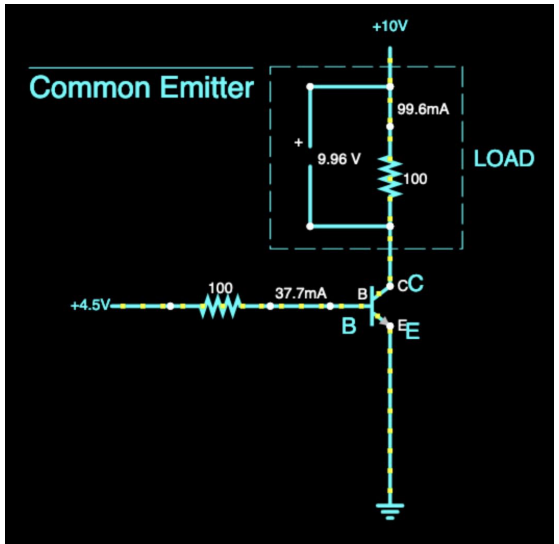


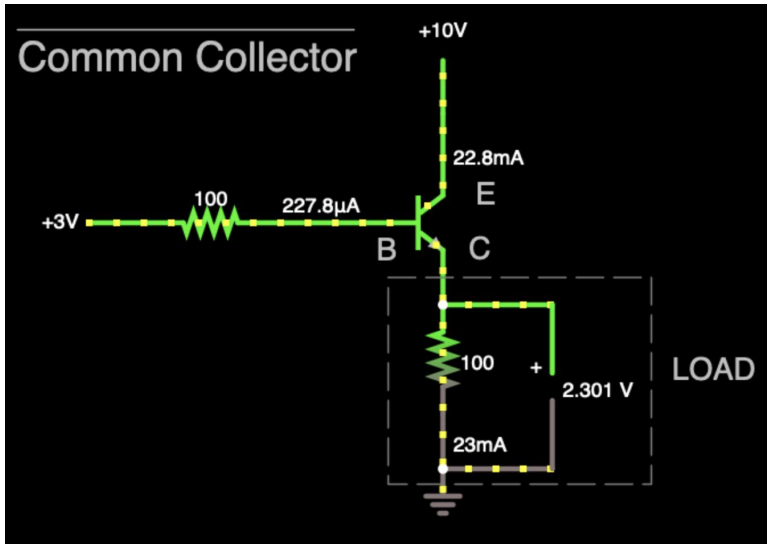

Collector
Ic = hFE*IB
Base
IB
Ic
Emitter

Transistor connections

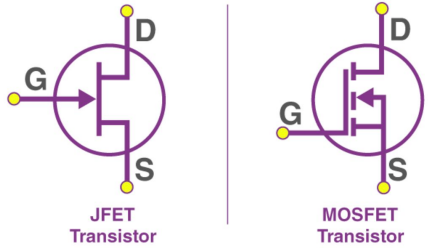
Common	Gain
Base	V
Emitter	V & I
Collector	I





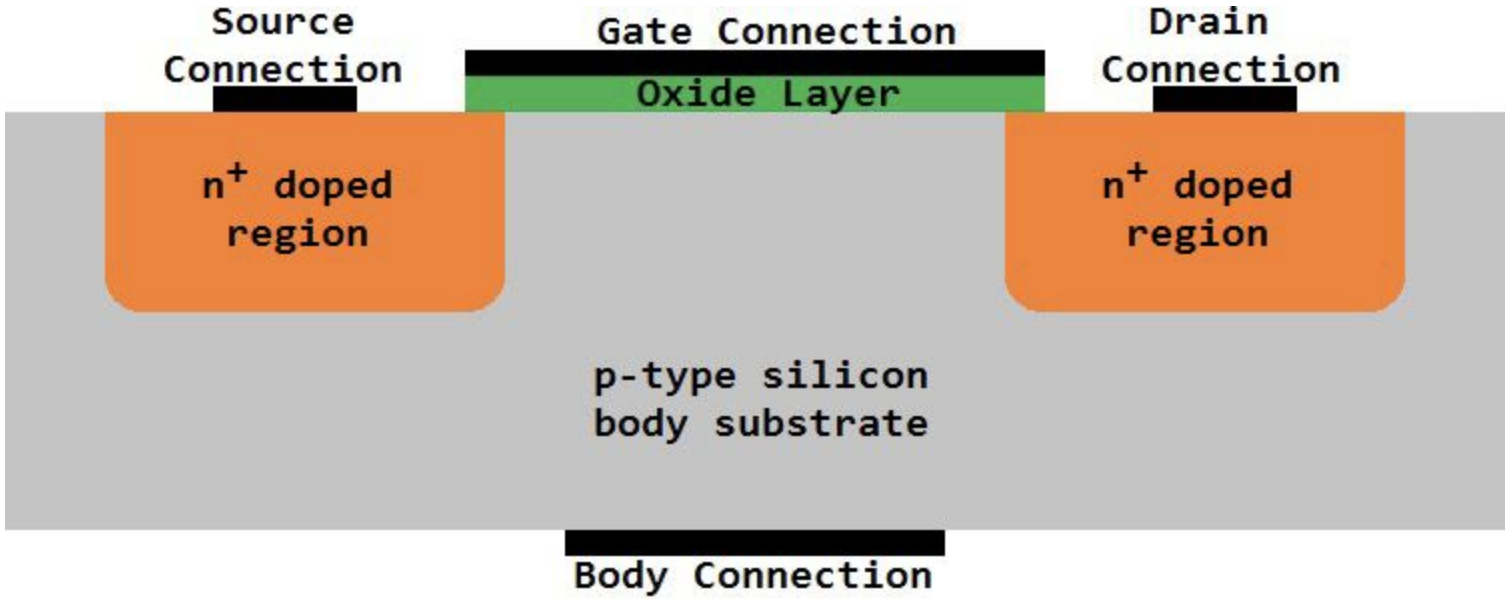


Field Effect Transistor (FET)



- Field Effect Transistor control currents using voltage
- The common types are
  - MOSFET (Metal Oxide Semiconductor Field-Effect Transistor)
    - typical input impedance ~ $10^{14}\Omega$
    - depletion and enhancement types
    - lowest power requirements, so can be more densely packed
    - also known as "Magically Obliterated, Smoke and Fire Emitting Transistor"
  - JFET (Junction Field-Effect Transistor)
    - typical input impedance ~ $10^{9}\ \Omega$
    - depletion type only
    - cheaper and more robust

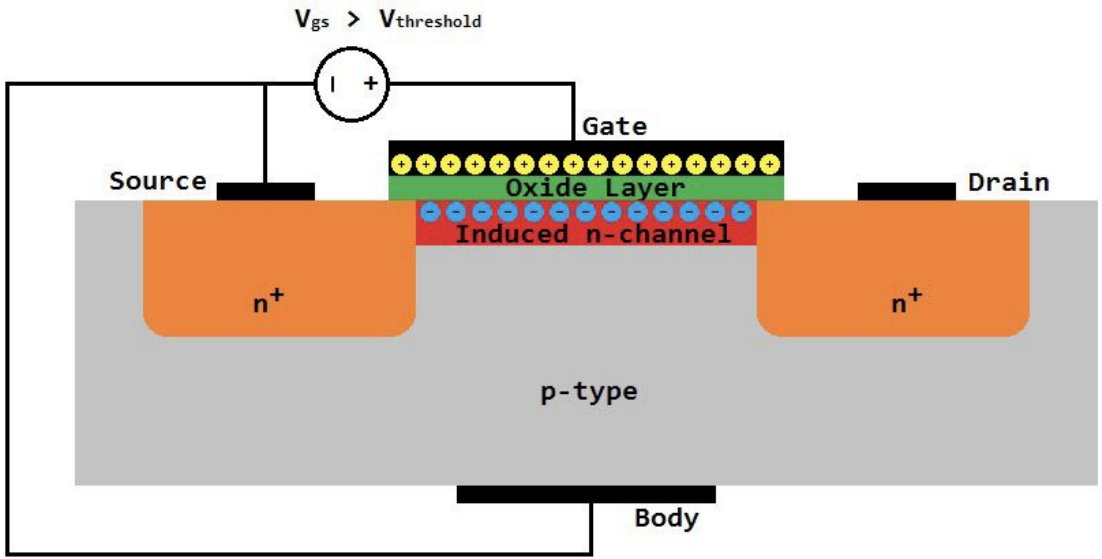
Enhancement-mode MOSFET



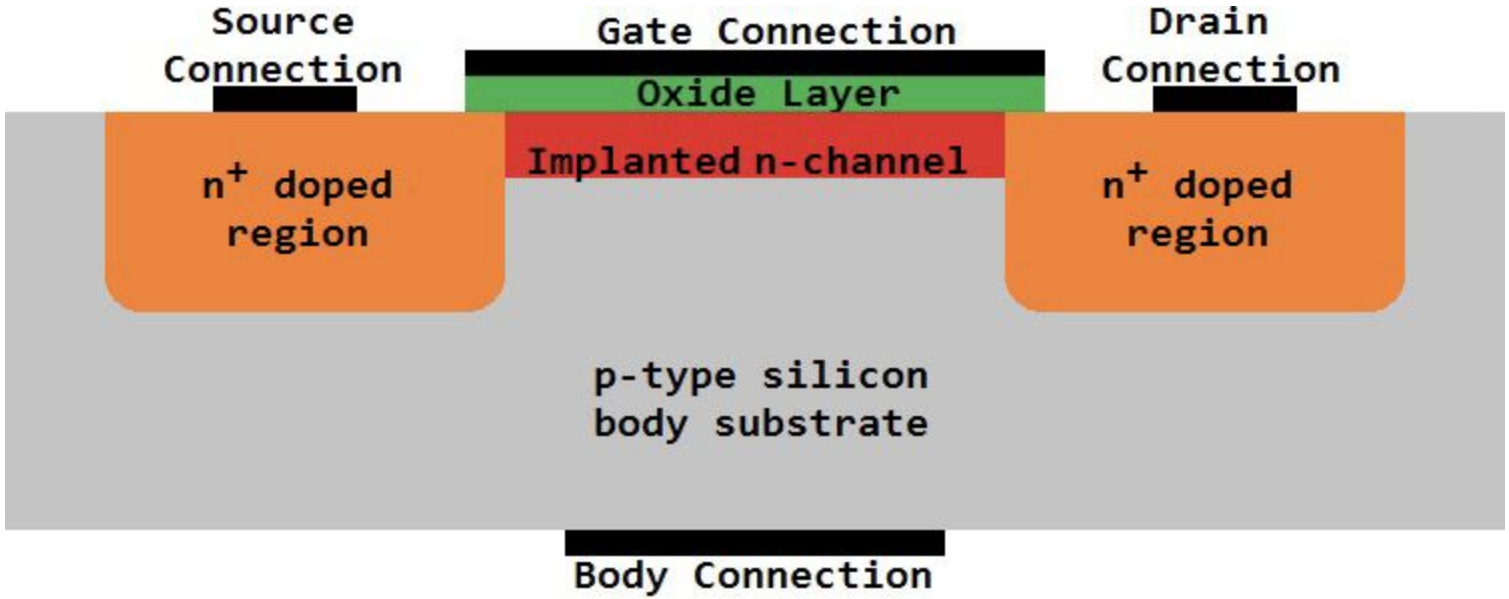
n-channel enhancement-mode MOSFET (source: DigiKey).

Enhancement MOSFET Current Flow

- Current only flows when positive voltage applied to gate
  - Attracts electrons and creates an effective n-type conductive channel between the Source and Drain.
  - The oxide layer is very thin and can easily be ruptured by voltage surges. (source: DigiKey).

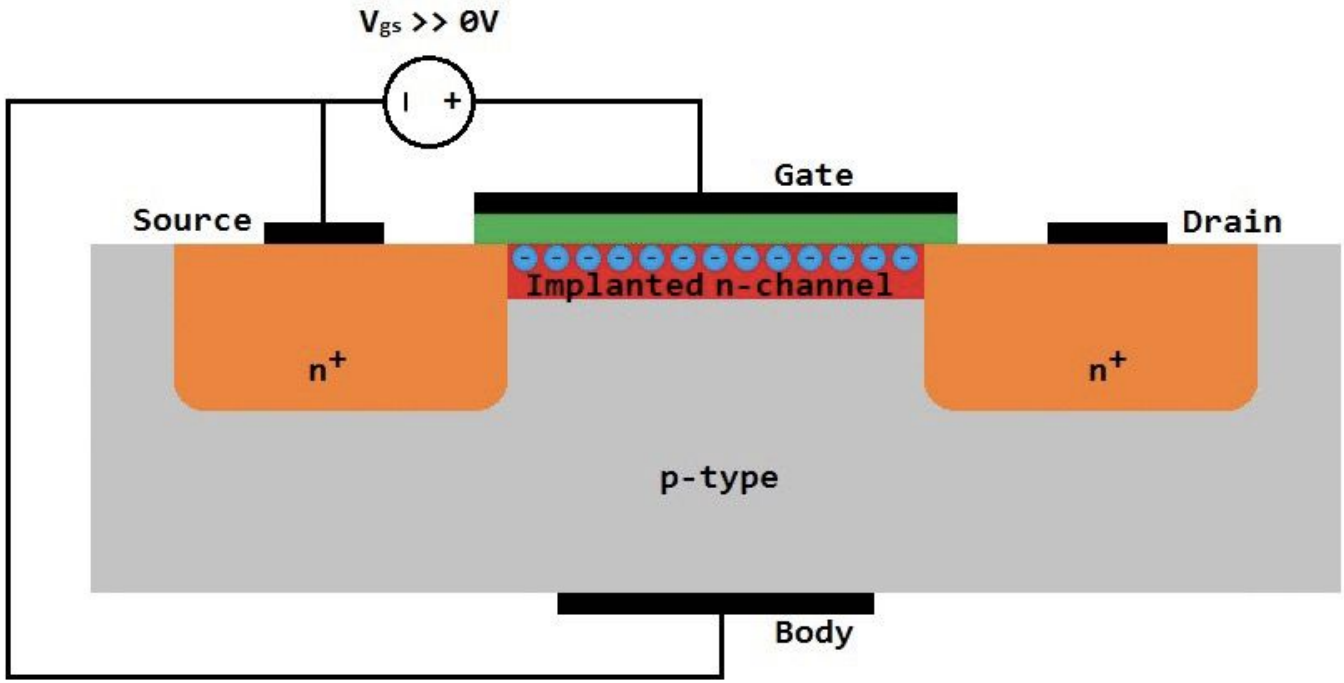


Depletion-mode MOSFET



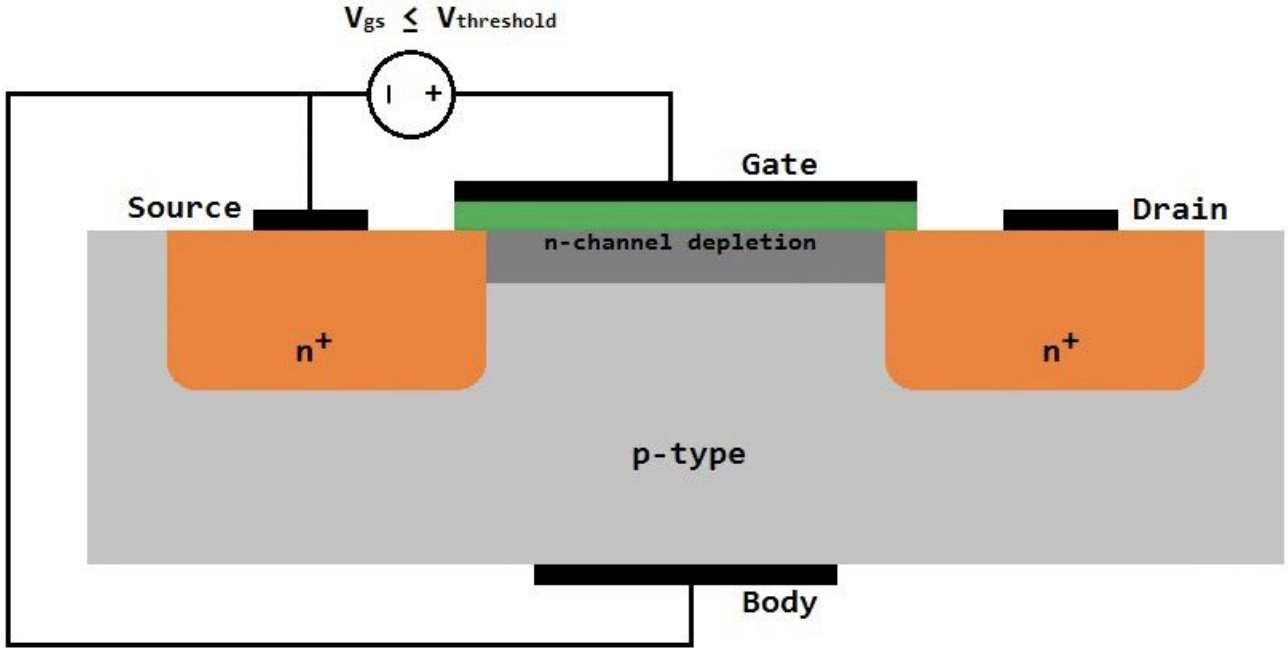
n-channel depletion-mode MOSFET. Current can normally flow through the n-type connection between Source and Drain. (source: DigiKey).

Depletion MOSFET Current Flow



Current increases when positive gate voltage attracts electrons and enhances the conduction channel. (source: DigiKey).

Depletion MOSFET Current Blocked



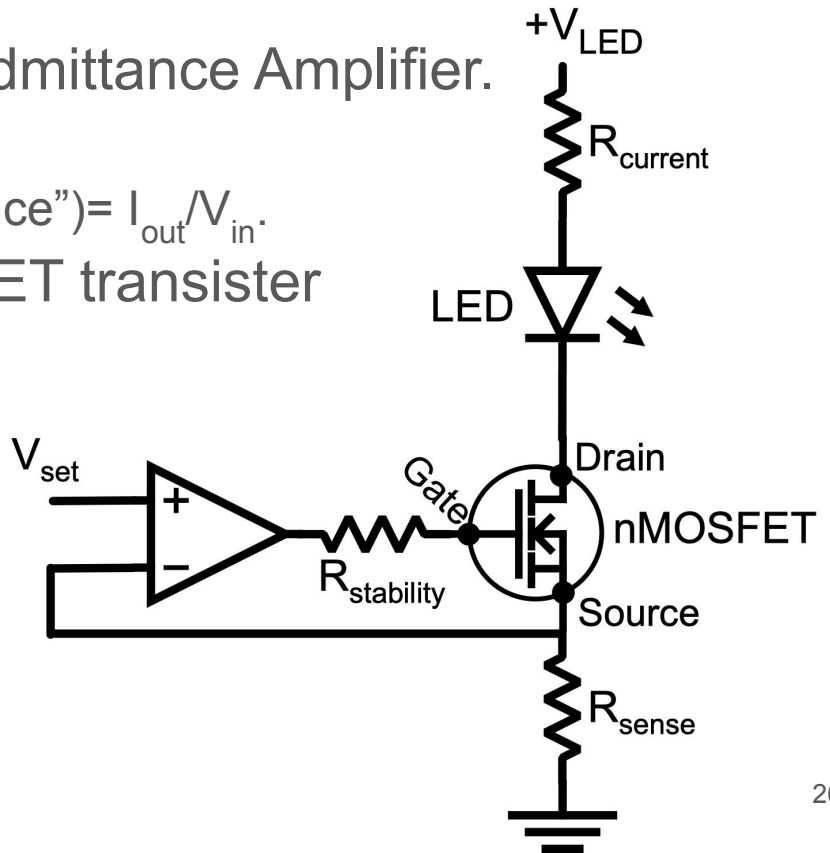
Current is blocked when a negative Gate voltage repels electrons from the connection, turning it effectively into p-type. (source: DigiKey).

Bipolar Junction Transistor (BJT) vs Field Effect Transistor (FET)

	Bipolar Junction	Field Effect
Carriers	bipolar (*e* and *h*)	unipolar (*e* or *h*)
Controlled by	current	voltage
Terminals	**E**mitter, **B**ase, **C**ollector	**S**ource, **G**ate, **D**rain
Input Impedance	~kΩ - MΩ	Extremely high (10^9 – $>10^{14}$ Ω)
Strengths	Highest I, V; robust	Faster, Higher gain, I_{switch}=0, Small

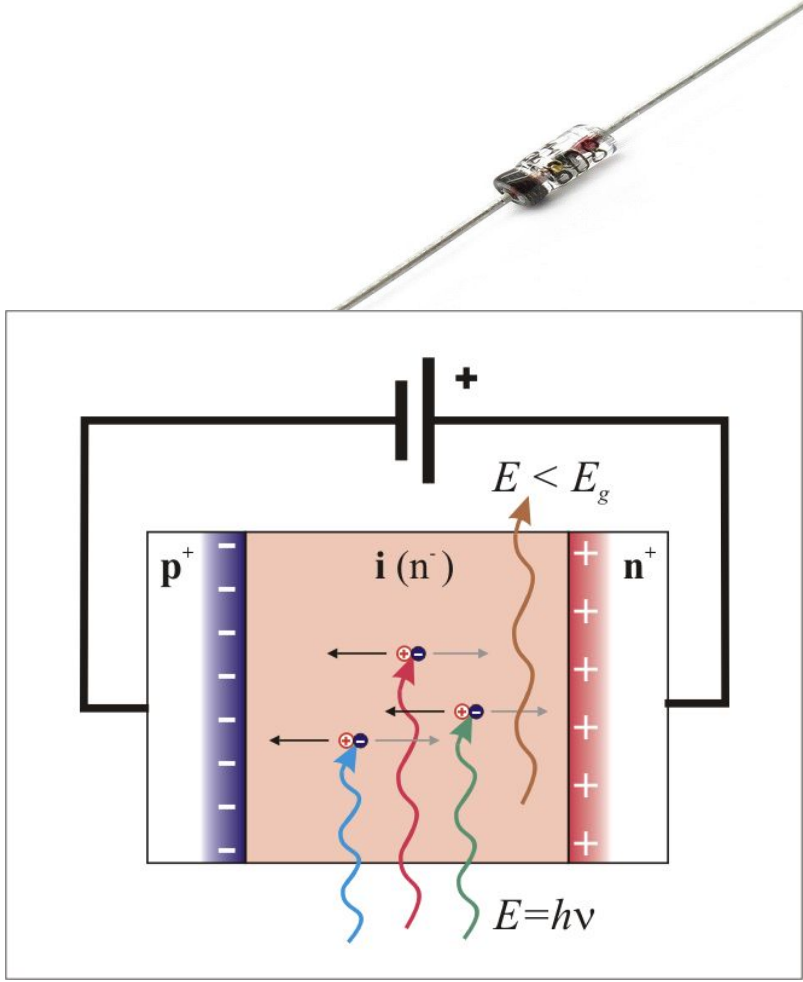
Voltage Controlled Current Source (VCCS)

- Occasionally known as a Transadmittance Amplifier.
  - Admittance is 1/impedance.
  - Transadmittance ("transfer admittance")= I_{out}/V_{in}.
- Uses an op-amp and an nMOSFET transister to drive a current
- $I_{LED}=V_{set}/R_{sense}$ through an LED
- The optional series resistor, $R_{stability}$, improves the stability of the feedback loop.



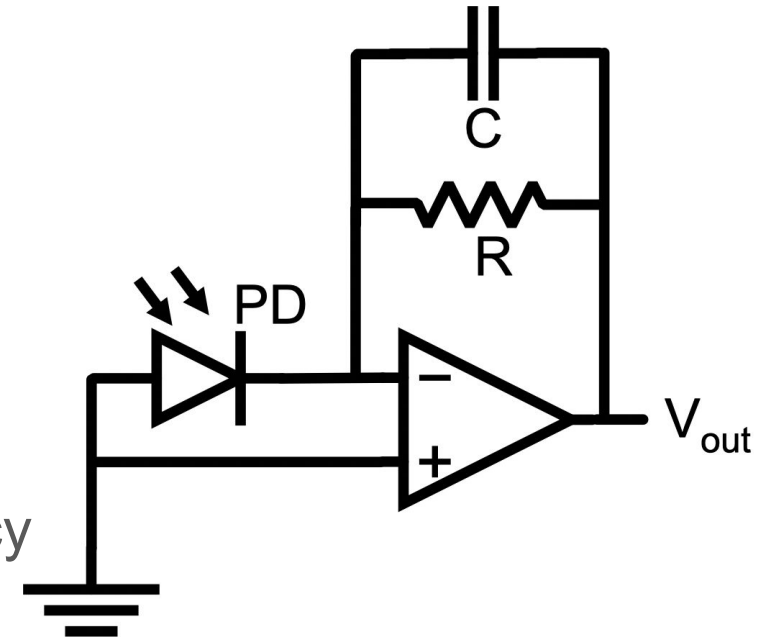
PIN Photodiode

- PIN (p-type – intrinsic – n type) photodiode.
- When light produces electron hole pairs in the intrinsic region, a current flows. (source: Wikipedia).
- Often used as a photon detector

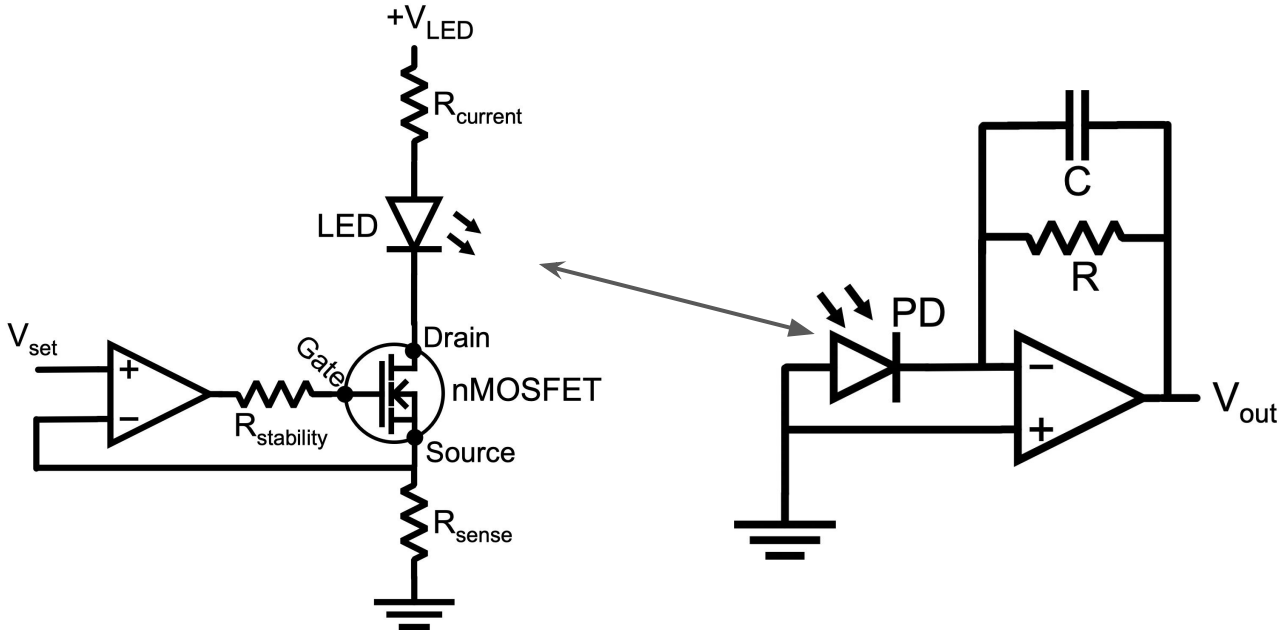


Current Controlled Voltage Source

- Also referred to as transimpedance amplifier
  - Transimpedance is short for transfer impedance, which is the ratio of the output voltage of a circuit to its input current.
- A transimpedance amplifier uses an op-amp, with a feedback resistor (R~1-10 MΩ) and a feedback capacitor (C~10-100 pF).
- $V_{out} = R * I_{PD}$
- Capacitor shorts out high frequency noise



Arduino Controlled Light Communication



Control V_{set} with Arduino digital pin, detect LED output with photodiode, observe signal on scope

Questions?