PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 53600
Electronics Techniques for Research

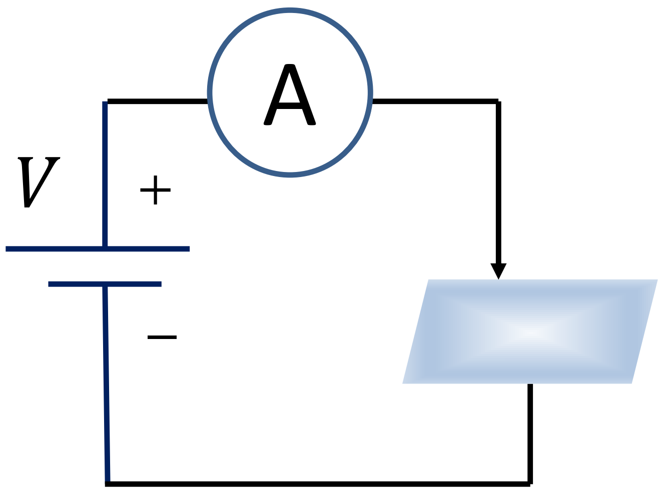
Now in PowerPoint!

Spring 2020 Semester

Prof. Matthew Jones

Semiconductors

- Prior to 1874, it was thought that all materials satisfied Ohm's law
- Ferdinand Braun discovered some minerals violated Ohm's law (eg. lead sulfide)

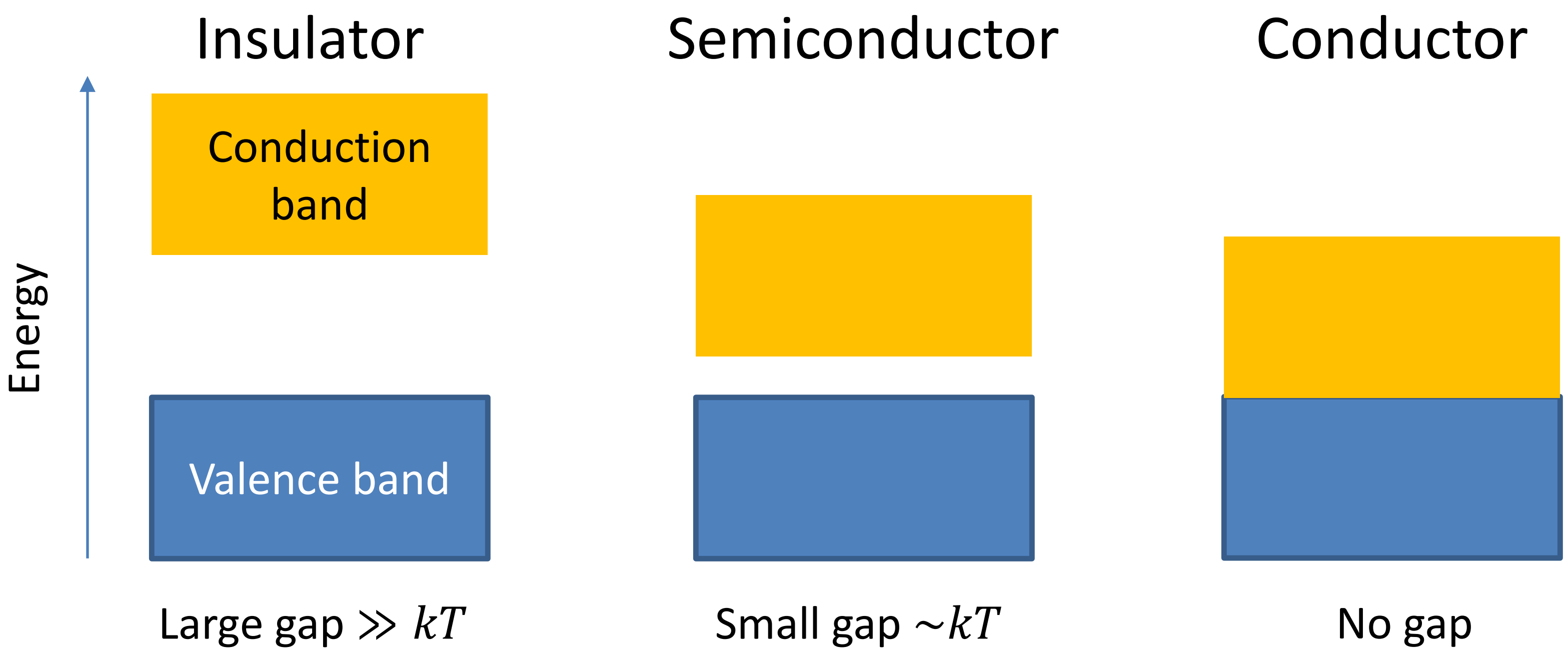


Semiconductors

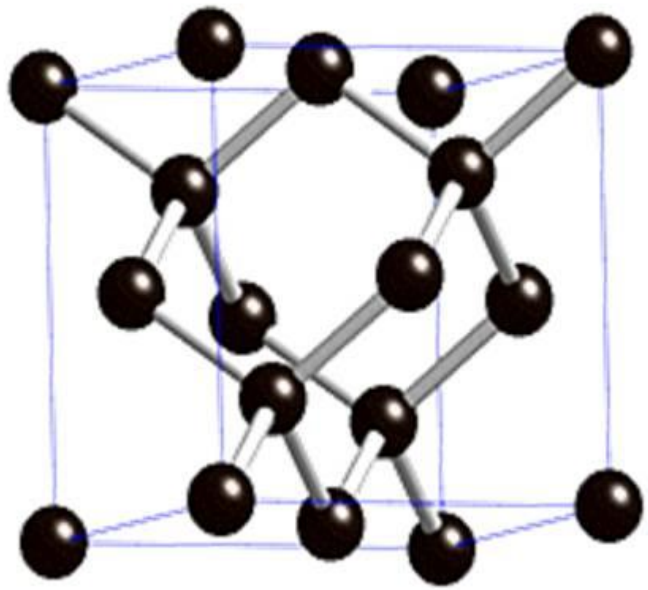
- Observations:
  - Resistance depended on polarity of the voltage source (30% effect)
  - Resistance decreased as current increased
- Hall effect (1879):
  - Magnetic fields deflect charge carriers
  - Most materials had negative charge carriers
  - Some had positive charge carriers

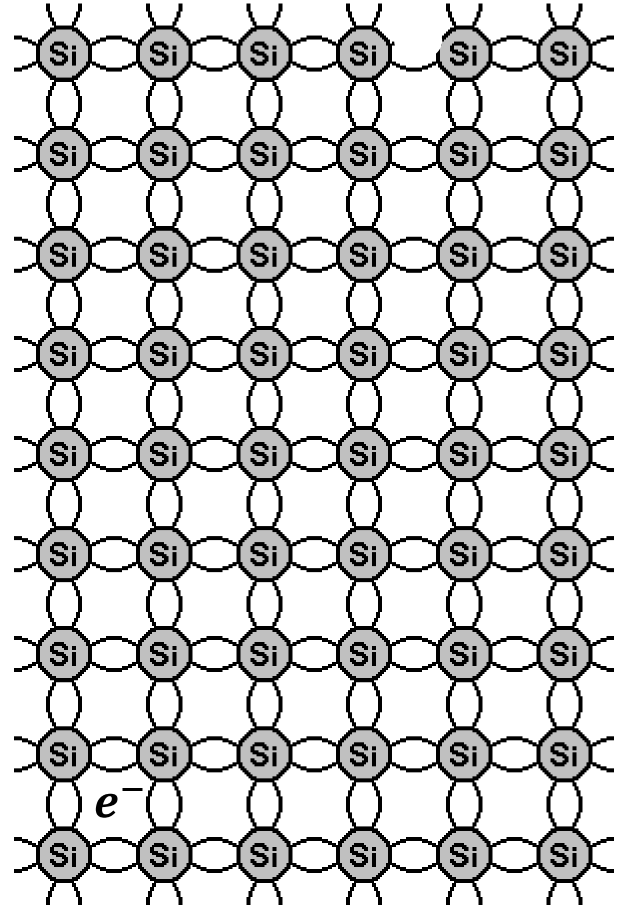
Electron Energy Bands

- A.H. Wilson (1931): electrons exist with discrete energy levels

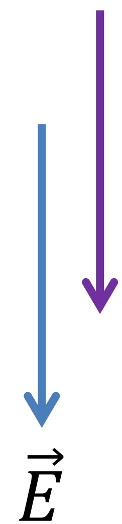


Intrinsic Semiconductors





$$\vec{J} = qn\vec{v}$$



Intrinsic Semiconductors

- Current density:

$$\boldsymbol{J} = \sigma\, \boldsymbol{E}$$
$$= e(n_i \mu_n + p_i \mu_p)\boldsymbol{E}$$

- Charge carrier densities:
  - n_i is the density of electrons (negative)
  - p_i is the density of holes (positive)
- Intrinsic semiconductors:

$$n_i = p_i$$

- Charge carrier mobility:

$$\mu_n > \mu_p$$

Example

- Silicon at room temperature:

$$N_{Si} = 5 \times 10^{28}\ \mathrm{atoms/m^3}$$

$$p_i = n_i = 1.5\ \times 10^{16}\ \mathrm{/m^3}$$

$$\mu_n = 0.135\ \mathrm{m^2/V} \cdot s$$

$$\mu_p = 0.048\ \mathrm{m^2/V} \cdot s$$

- Conductivity:

$$\sigma = 4.4\ \times 10^{-4}\ \Omega^{-1}\mathrm{m}^{-1}$$

- Resistivity: consider 1 mm x 1 mm x 1 cm…

$$R = \frac{L}{\sigma A} = 23\ \mathrm{M\Omega}$$

Doped Semiconductors

- Suppose we added one extra charge carrier per million Si atoms (donors).

$$N_d \sim 10^{22} \gg n_i$$

- Now it is a good conductor:

$$\sigma \sim e\, N_d\, \mu_n \Rightarrow R = 46\ \Omega$$

- Suppose we added extra holes that sucked up free electrons (acceptors).

$$\sigma \sim e\, N_a\, \mu_p \Rightarrow R = 130\ \Omega$$

- Electrical properties are dramatically changed by small concentrations of dopant atoms

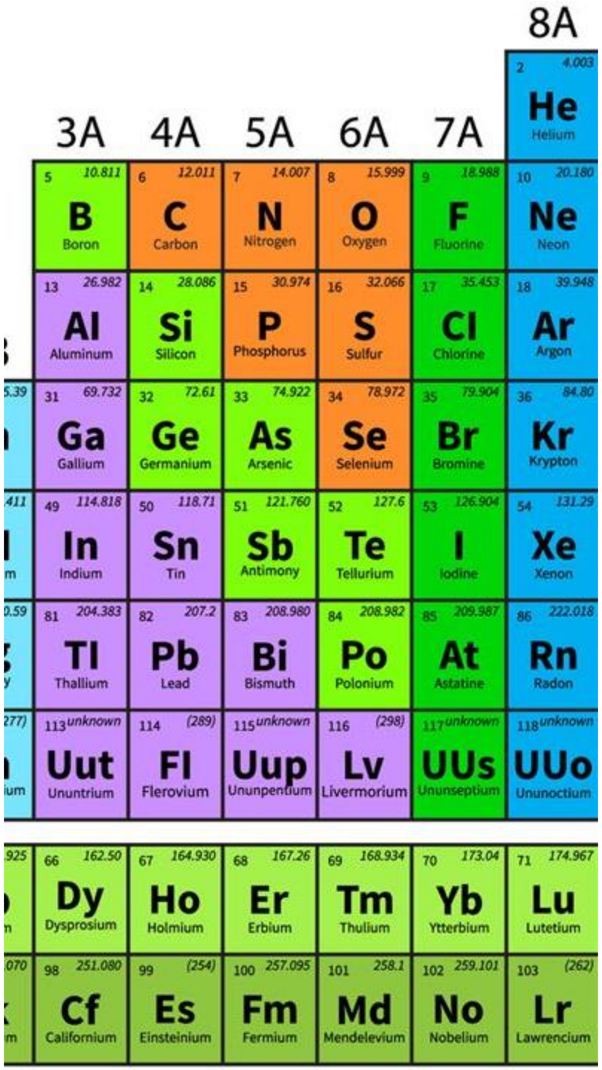
Doped Semiconductors

- Donor impurities:
  - Phosphorus
  - Arsenic
  - Antimony

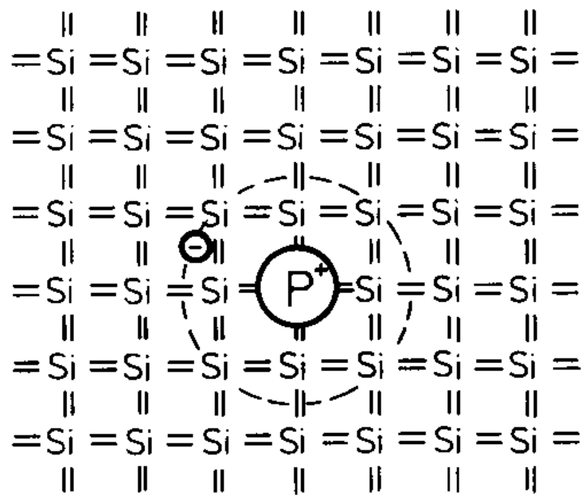
n-type

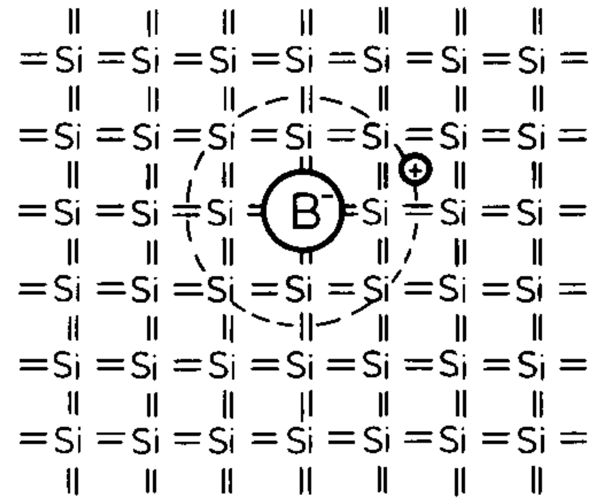
- Acceptor impurities:
  - Boron
  - Gallium
  - Indium

p-type

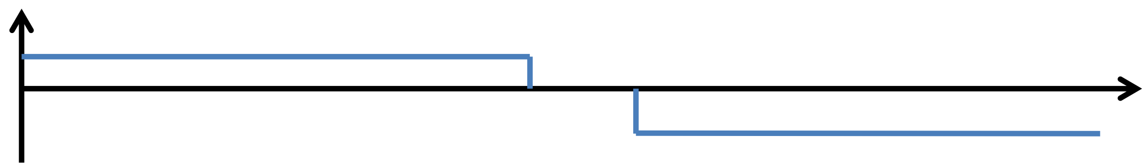


P-N Junction

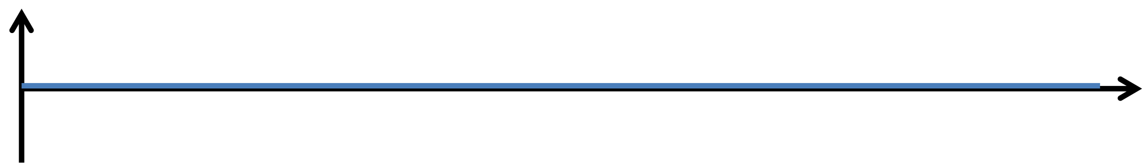




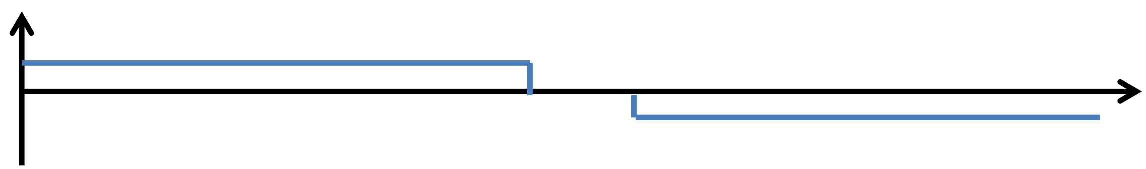
n-type dopant concentration



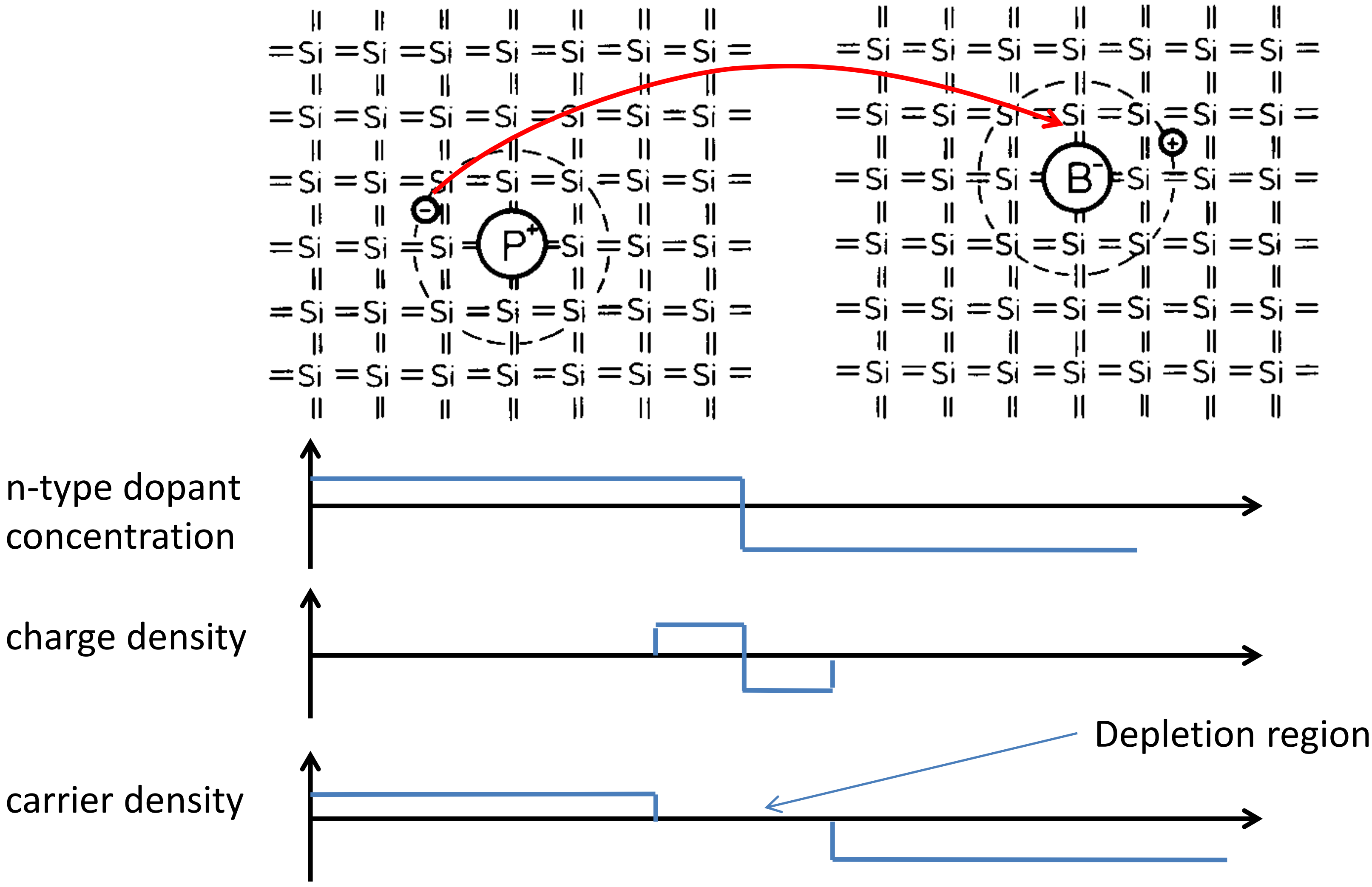
charge density



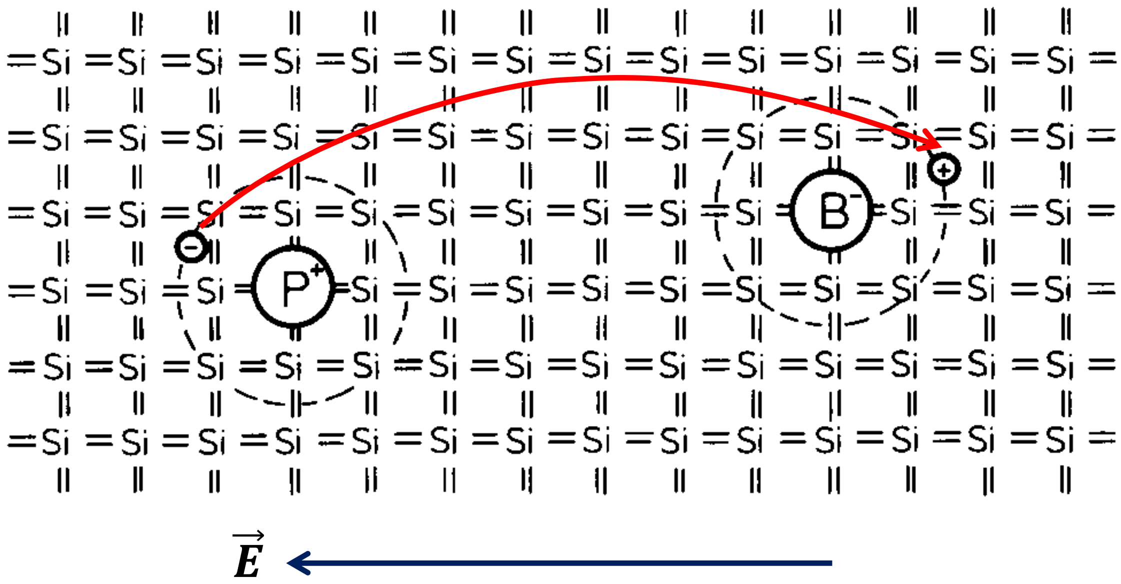
carrier density

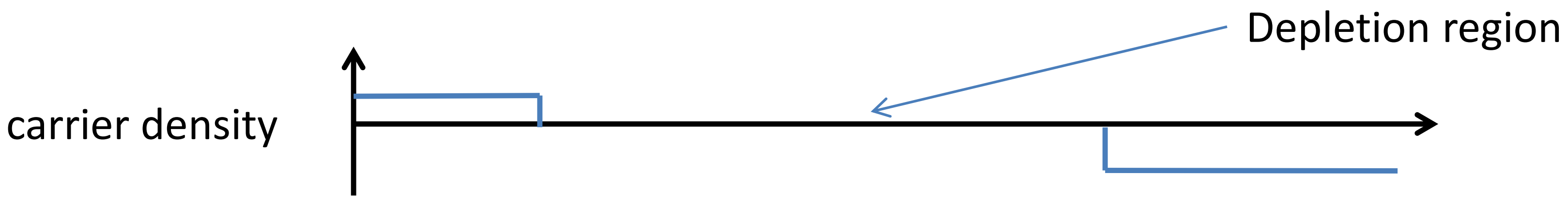


P-N Junction


P+
B-
n-type dopant concentration
charge density
carrier density
Depletion region

P-N Junction





Charge carriers in depletion region created by:

- Thermal excitation
- Ionizing radiation

P-N Junction

- An electron in the n-side needs a finite amount of energy to jump the gap

$$E_0 = e\,V_0$$

- Reverse saturation current:

$$I_0 = Ke^{-eV_0/kT}$$

- Apply a voltage and introduce charge carriers that diffuse across the junction:

$$I_d = Ke^{-e(V_0-V)/kT}$$

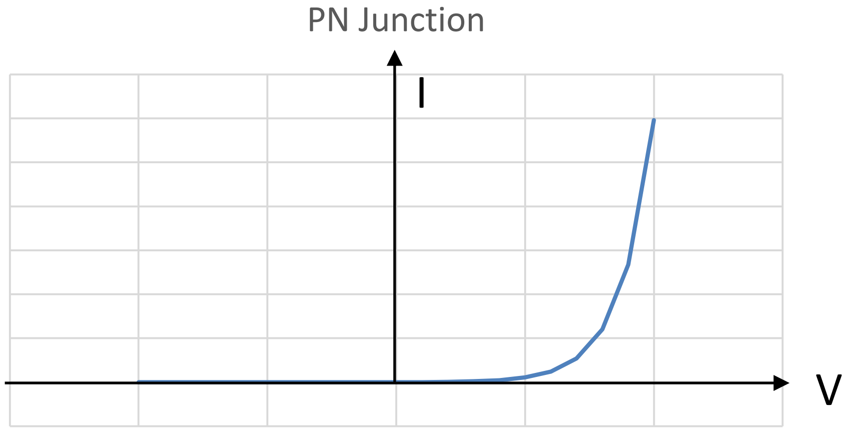
- Total current flow:

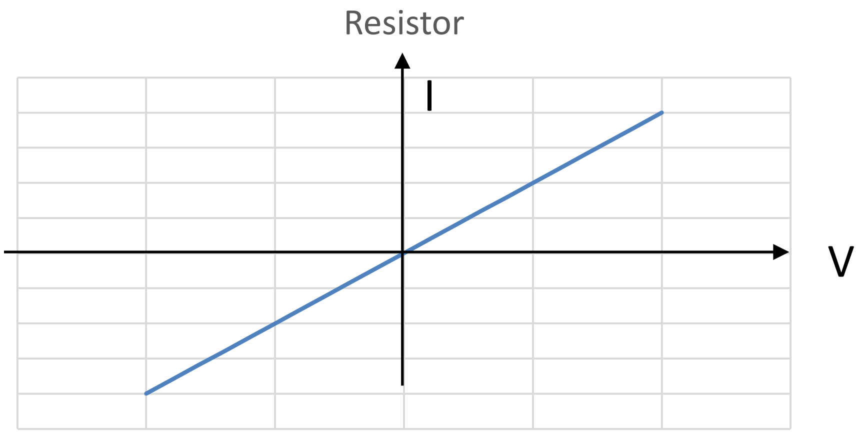
$$I = I_d - I_0 = I_0\left(e^{eV/kT} - 1\right)$$

Shockley equation

- At room temperature, $kT/e \sim 25\ \mathrm{mV}$

P-N Junction

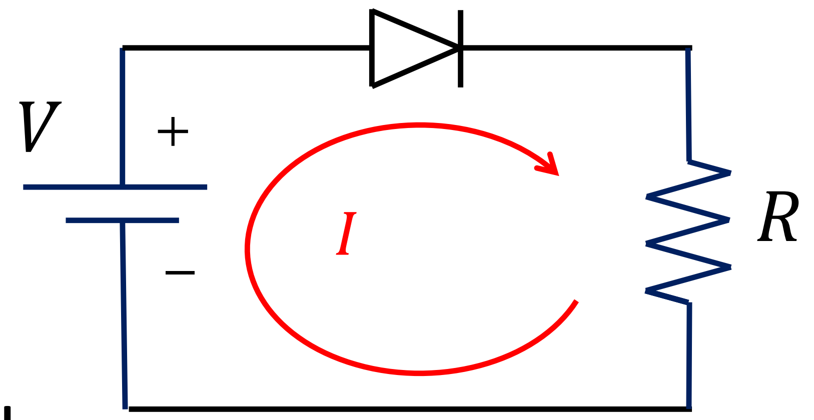




- The PN junction diode conducts significant current in only one direction
- Leakage current in an ideal diode is $\sim 10^{-12}$ A

P-N Junction

- How does a diode behave in a circuit?



- Kirchhoff's rule:

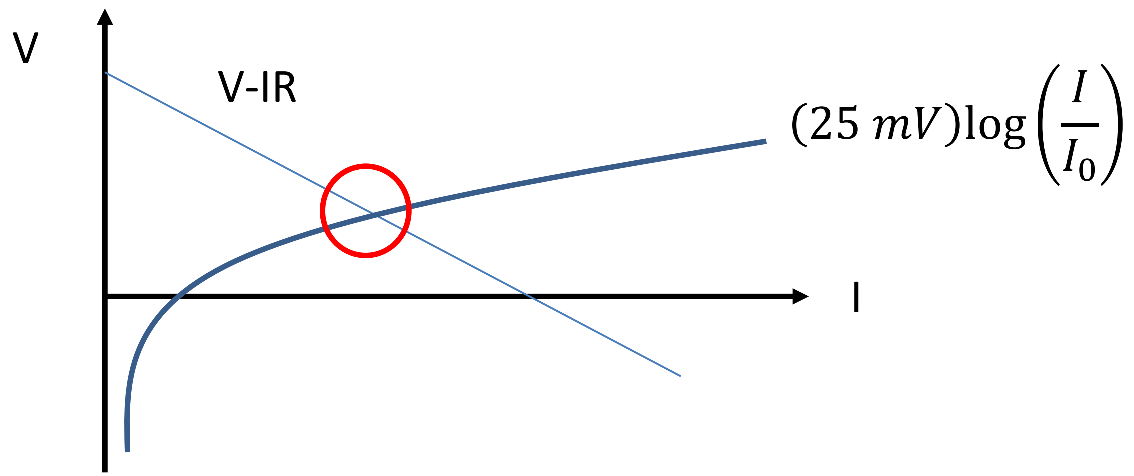
$$V - V_D - IR = 0$$

$$V_D = (25\ mV)\log\left(\frac{I}{I_0}\right)$$

$$V - IR = (25\ mV)\log\left(\frac{I}{I_0}\right)$$

P-N Junction

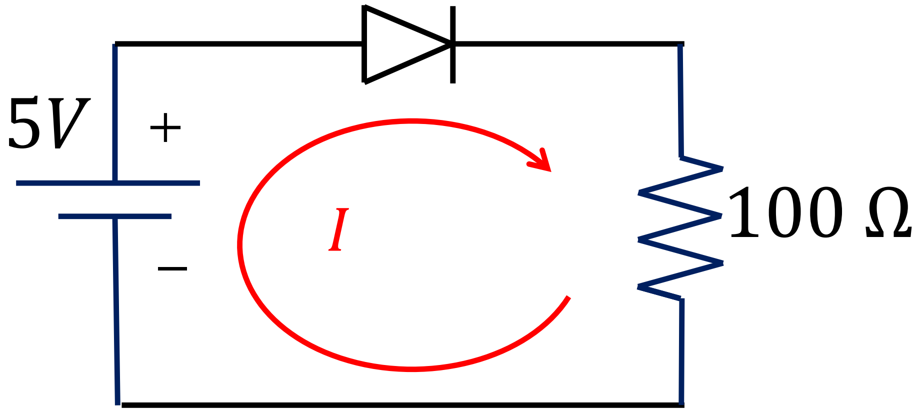
- This is a transcendental equation
  - It can be solved numerically
  - It can be solved graphically



- A solution must exist

P-N Junction

- Suppose that $I_0 = 10^{-12}$ A and that $V_D = 0.727$ V.



- The current in the circuit is

$$I = \frac{5\ \text{V} - 0.727\ \text{V}}{100\ \Omega} = 43\ \text{mA}$$

P-N Junction

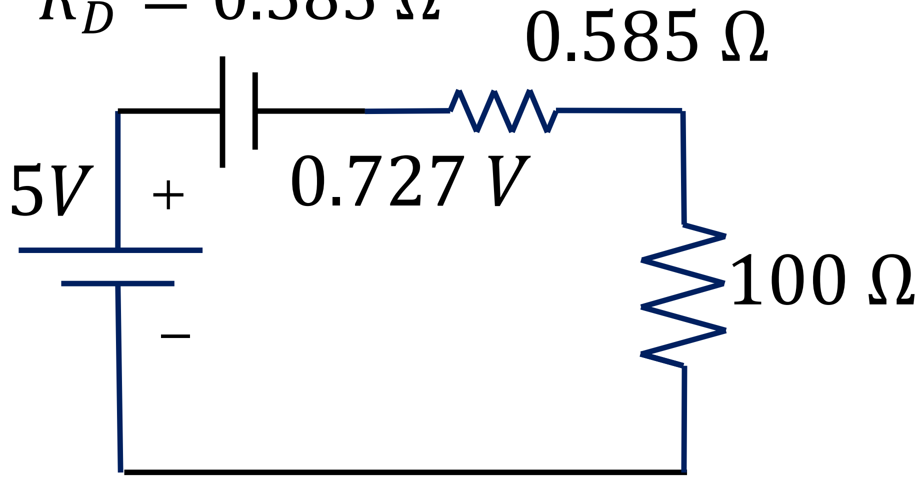
- The "resistance" of the diode is $R_D = dV_D/dI$

$$R_D = \left(\frac{dI}{dV_D}\right)^{-1} = \left(\frac{I_0 e}{kT}\, e^{eV_D/kT}\right)^{-1}$$

- In this case,

$$R_D = 0.585\ \Omega$$

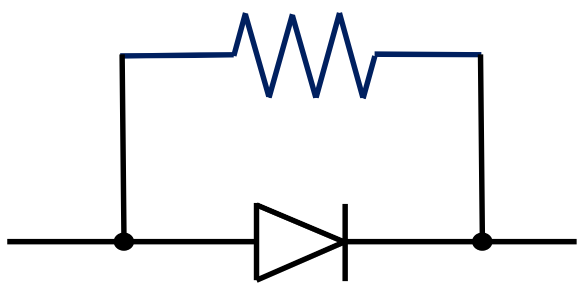
- Equivalent circuit:



- Except for the change in potential across the junction, the diode has a very low resistance.

Non-Ideal Diode Characteristics

- In practice, the reverse saturation current is not quite constant
- A small amount of current that flows past the junction satisfies Ohm's law (large R)



$$R = \frac{1}{G_{min}}$$

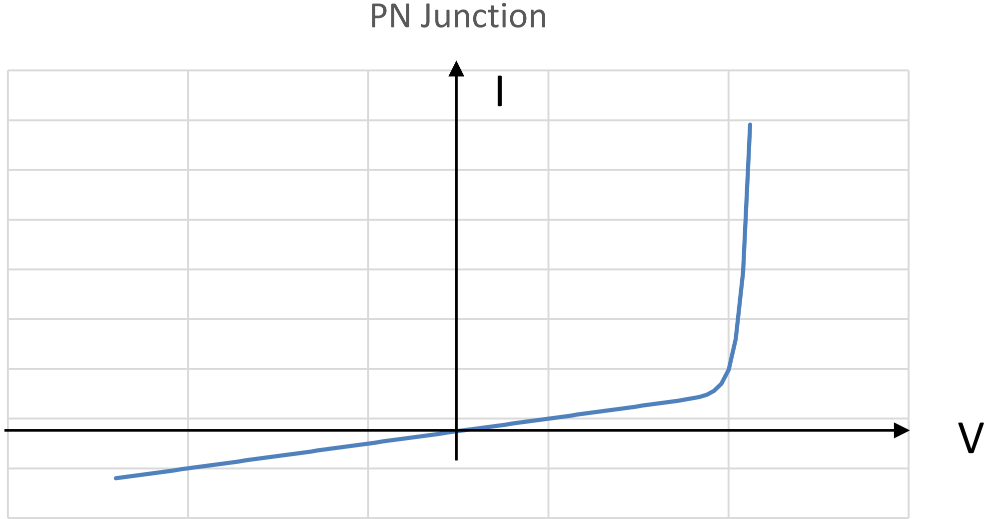
- This is usually specified as a small conductance parameter in diode models
- It also helps with convergence of numerical methods

Non-Ideal Diode Characteristics

- The Shockley equation gets modified slightly…

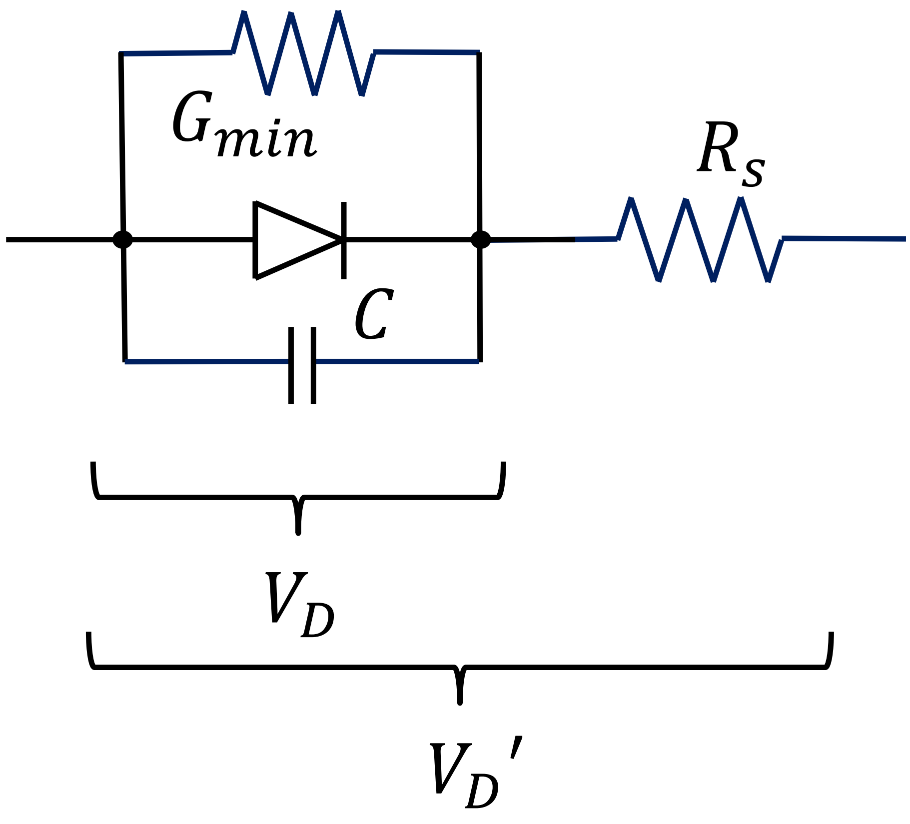
$$I_D = I_0\left(e^{eV/kT} - 1\right) + V_D G_{min}$$

- In the forward biased region this has no effect
- In the reverse biased region there is now a tiny slope:



Non-Ideal Diode Characteristics

- There can also be a small series resistance and capacitance at the junction



Junction Capacitance

- The width of the depletion region increases with reverse bias voltage
- For a parallel plate capacitor,

$$C = \frac{\epsilon_0 A}{d}$$

- The width of the depletion region does not grow linearly with voltage though…

$$C = \frac{C_0}{\sqrt{1 - \frac{V_D}{V_j}}}$$

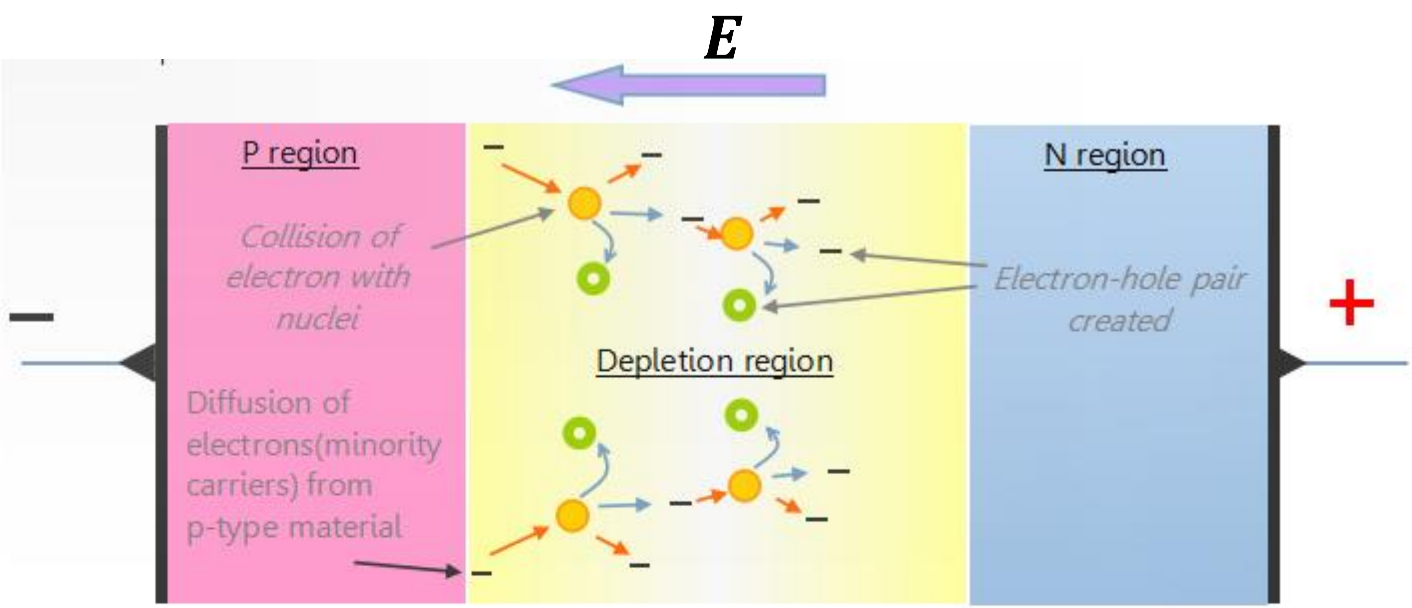
$V_D < 0$ in the reverse biased region.

V_j is the junction potential

Junction Breakdown

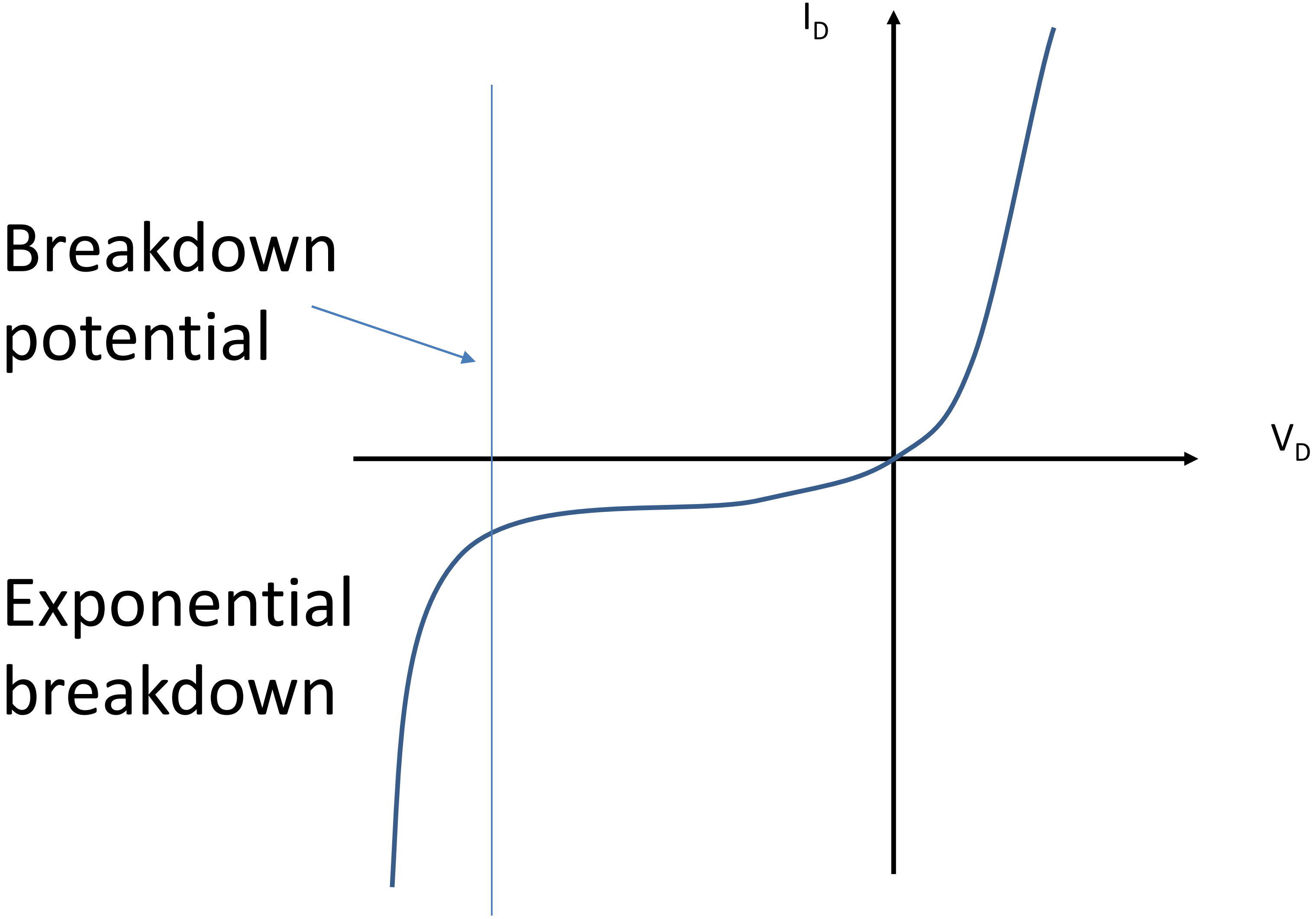
- When the junction is reverse biased with a large potential difference, large electric fields can be present across the junction
- Any charge carriers liberated by thermal excitations will be accelerated
- If they gain enough energy that they can break additional bonds, then an avalanche breakdown occurs

Avalanche Breakdown



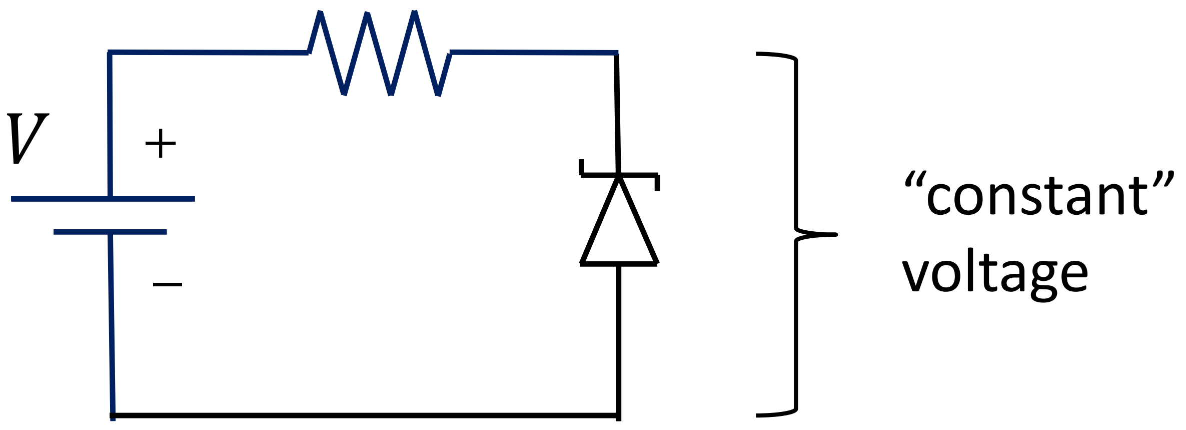
Avalanche breakdown

Avalanche Breakdown



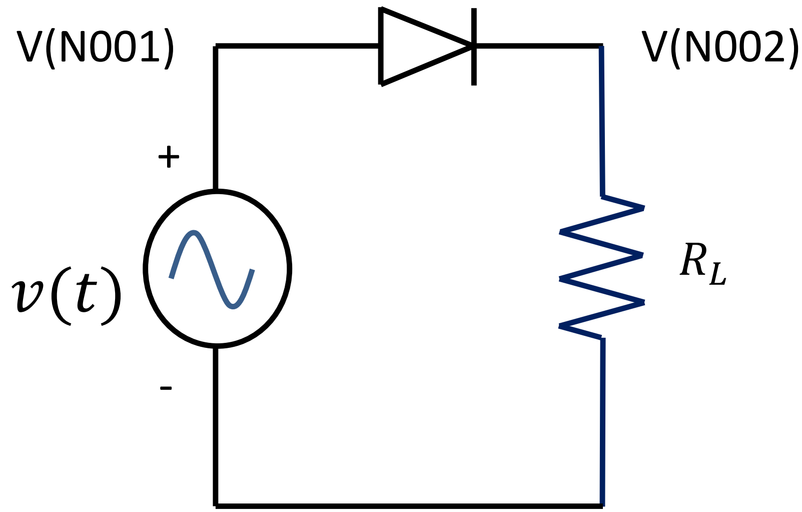
Zener Diodes

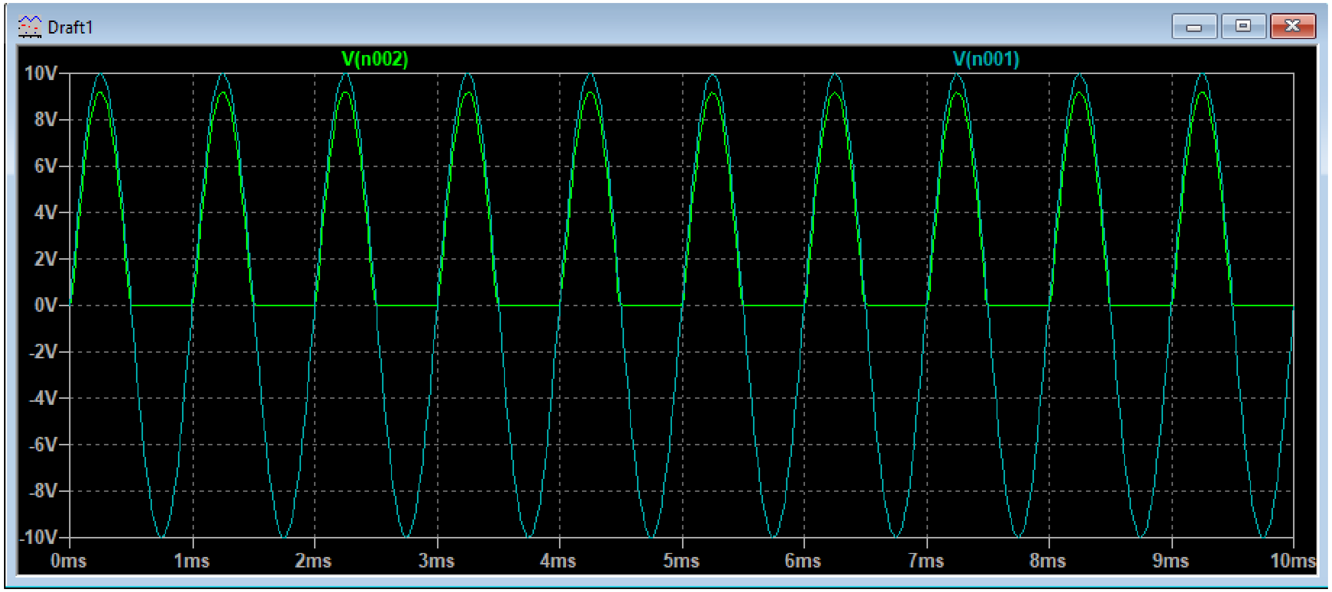
- Zener diodes are designed to break down at a well-controlled reverse bias voltage



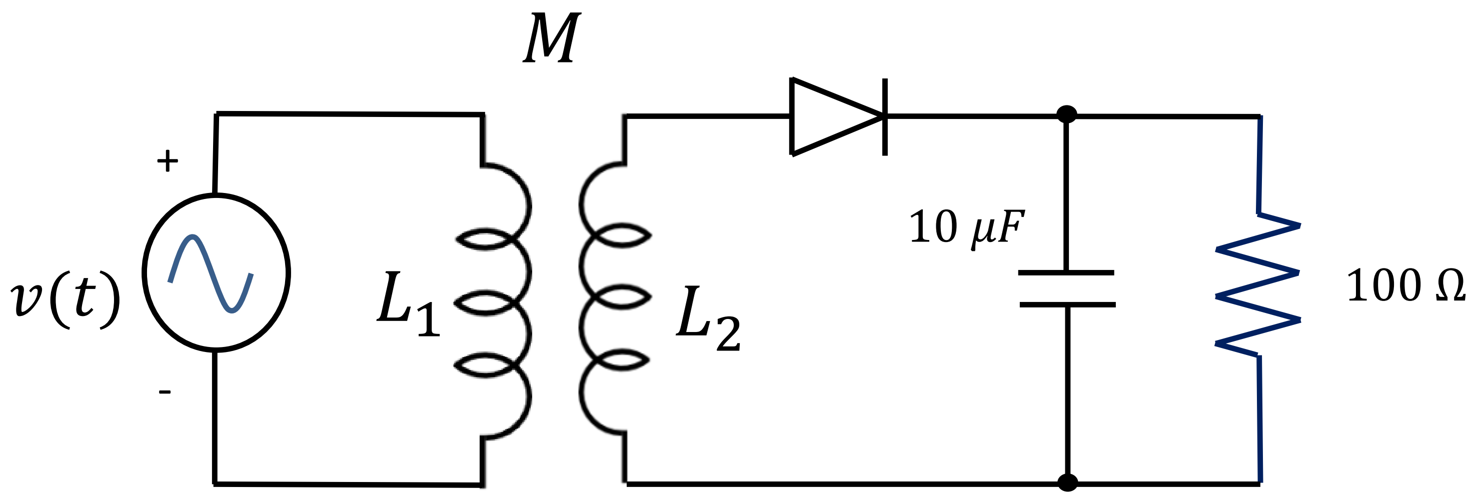
Diode Circuits

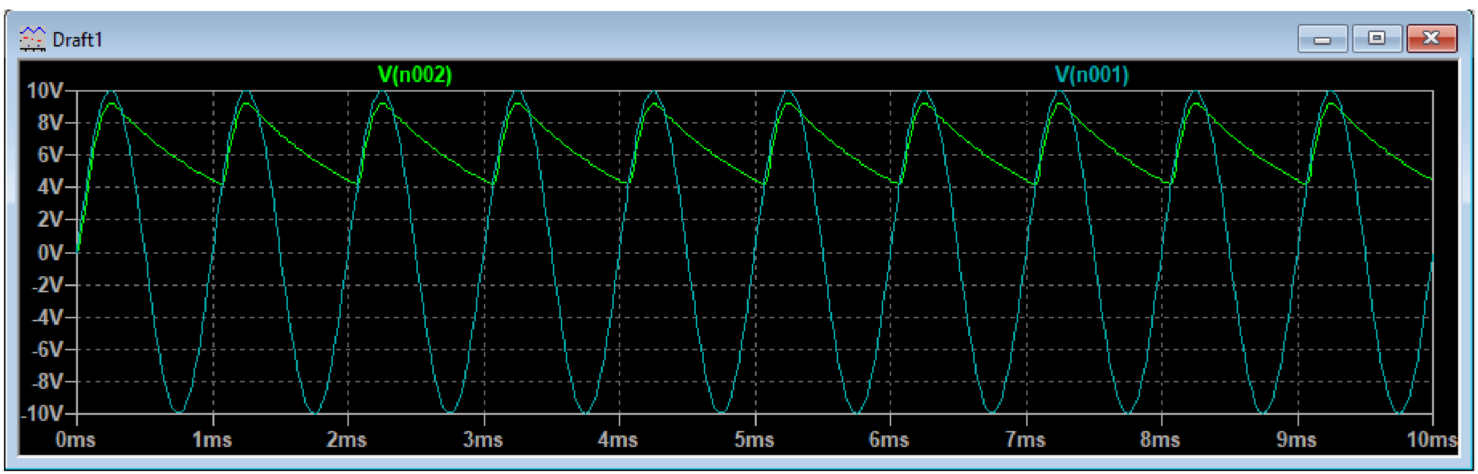
- Rectifiers:



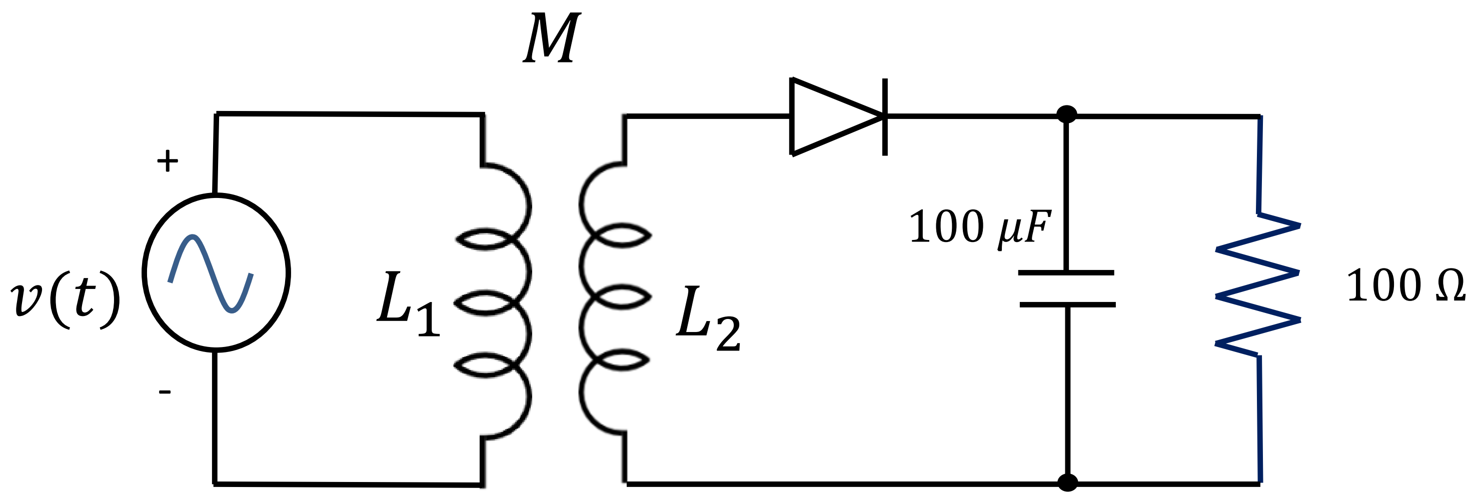


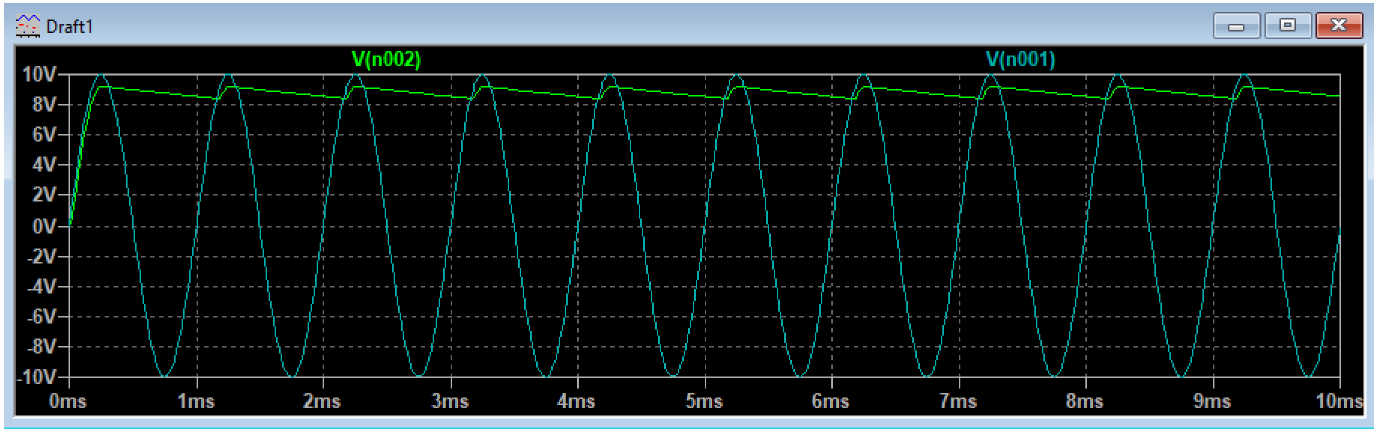
Typical DC Power Supply Circuit



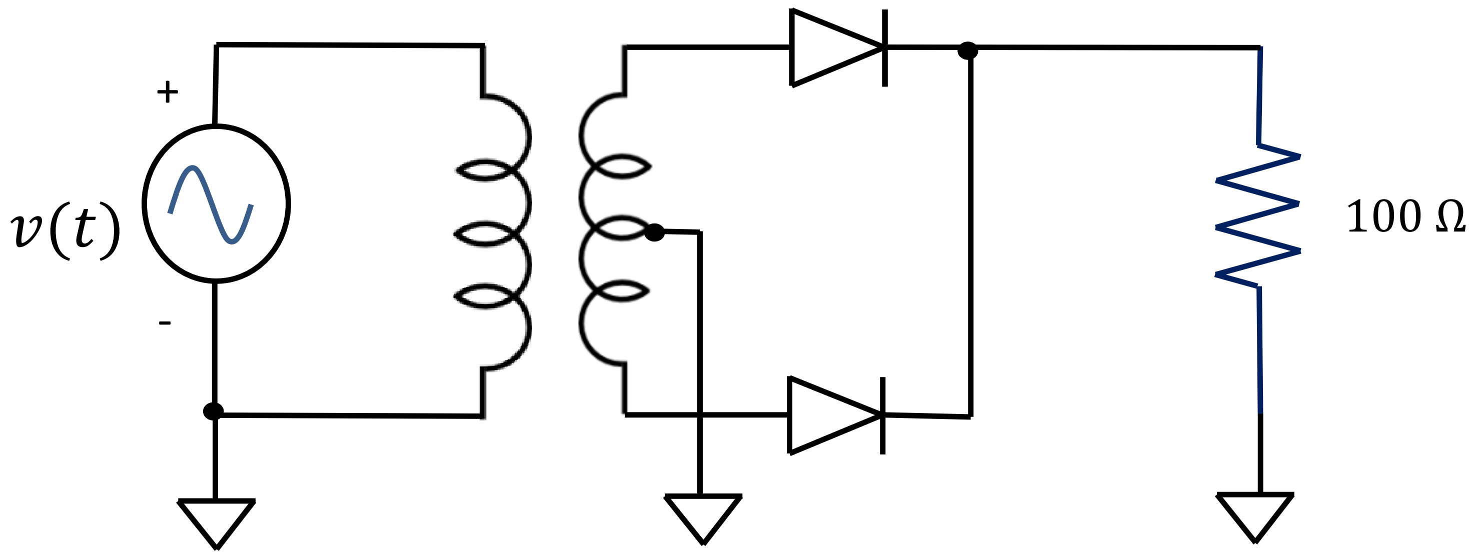


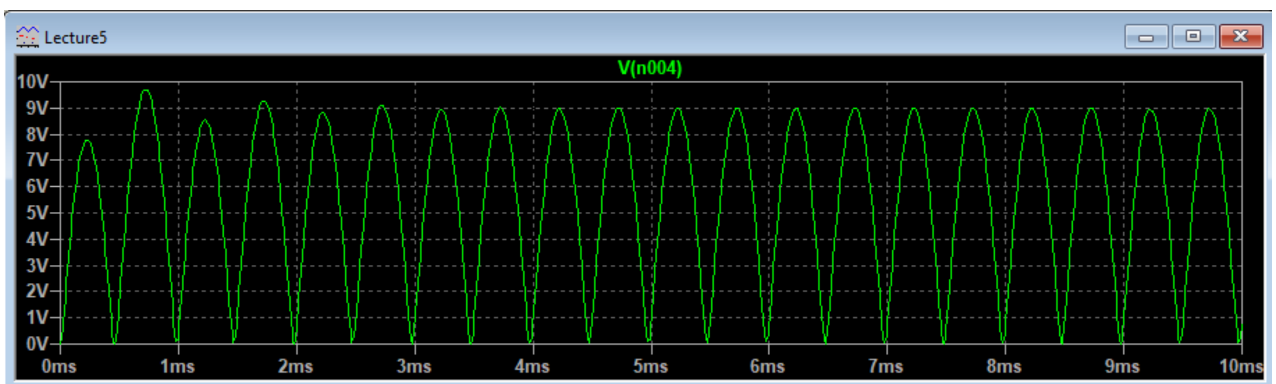
Typical DC Power Supply Circuit



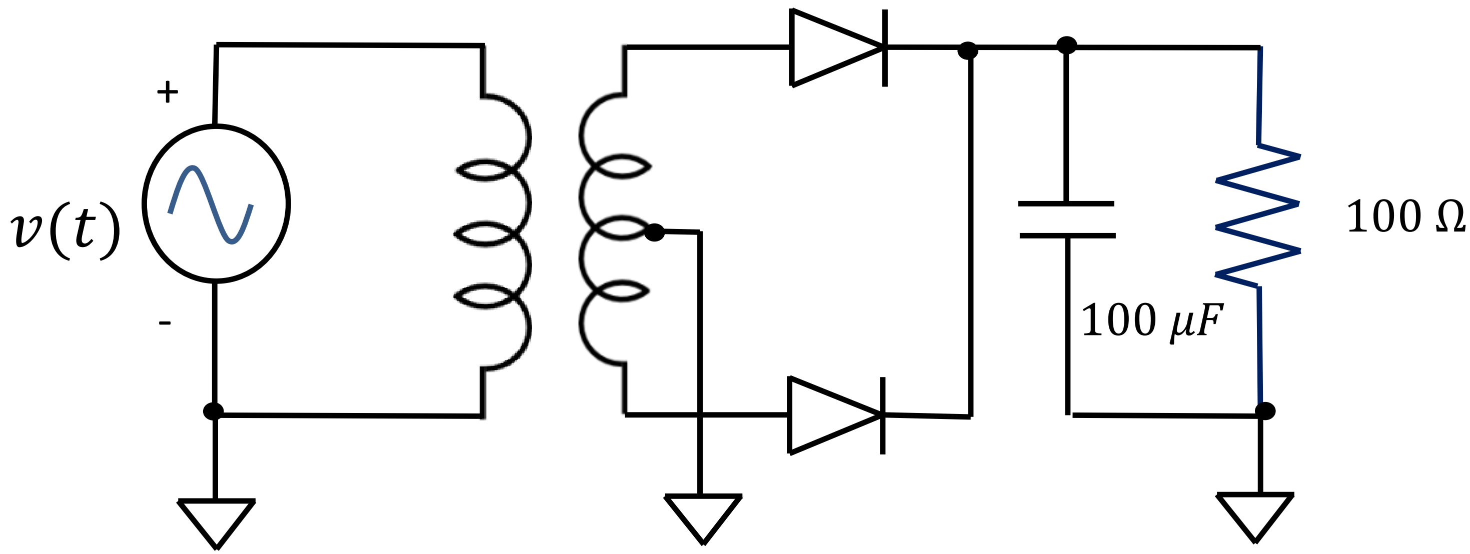


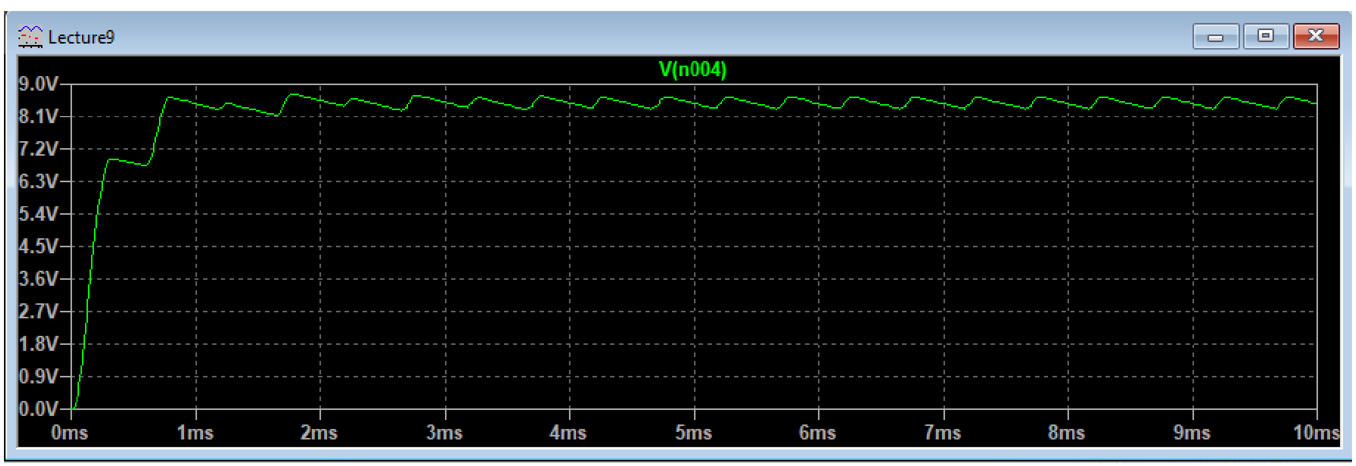
Typical DC Power Supply Circuit





Typical DC Power Supply Circuit





Typical DC Power Supply Circuit