ECE 105: Introduction to Electrical Engineering

Lecture 5

Device 1

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How can we create tunable resistors?

- $R = \rho L/A$
- We have three options, change length, change area, or change resistivity
- Semiconductors allow us to electromagnetically and chemically control resistivity

How do semiconductors allow us to tune the resistivity?

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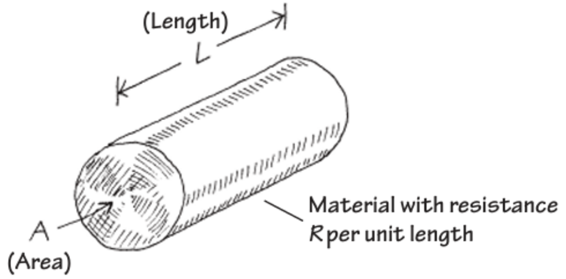
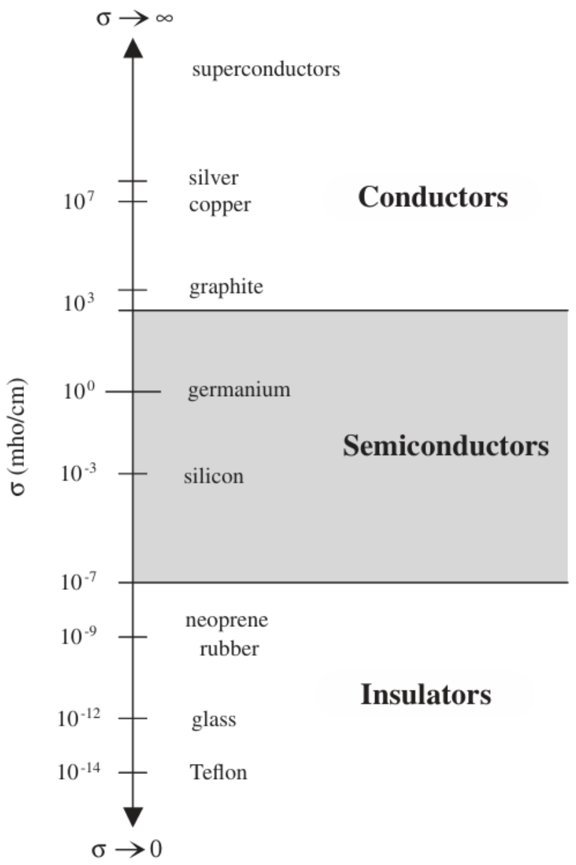
- By allowing us to tune the density of charge carriers!
- In metals, the density of charge carriers is ~ 10^{22} -10^{23}/cm^3
- In insulators, the charge density is ~10^{-57}/cm^3
- In semiconductors, the charge density can be controlled from ~10^{10}/cm^3 – 10^{20}/cm^3



$\rho = R\,\frac{A}{L}$ (Resistivity ohm·cm)

$\sigma = \frac{1}{\rho}$ (Conductivity mho/cm)

mho = $\frac{1}{ohm} = \frac{1}{\Omega}$ = ℧



What can we do with an element that has tunable or non-linear resistance?

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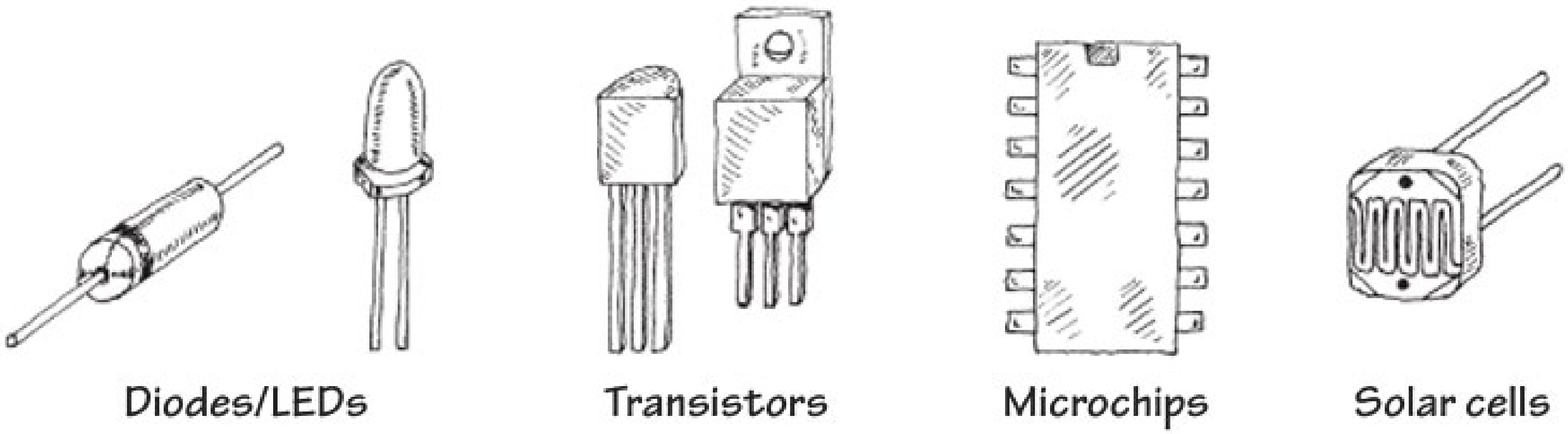
- Create a switch
  - Digital logic
- Amplify a signal
  - Analog circuits
- Rectify an AC voltage
  - Power circuits
- Sensing, power generation, light, etc etc

Why does changing the carrier density change the resistivity?

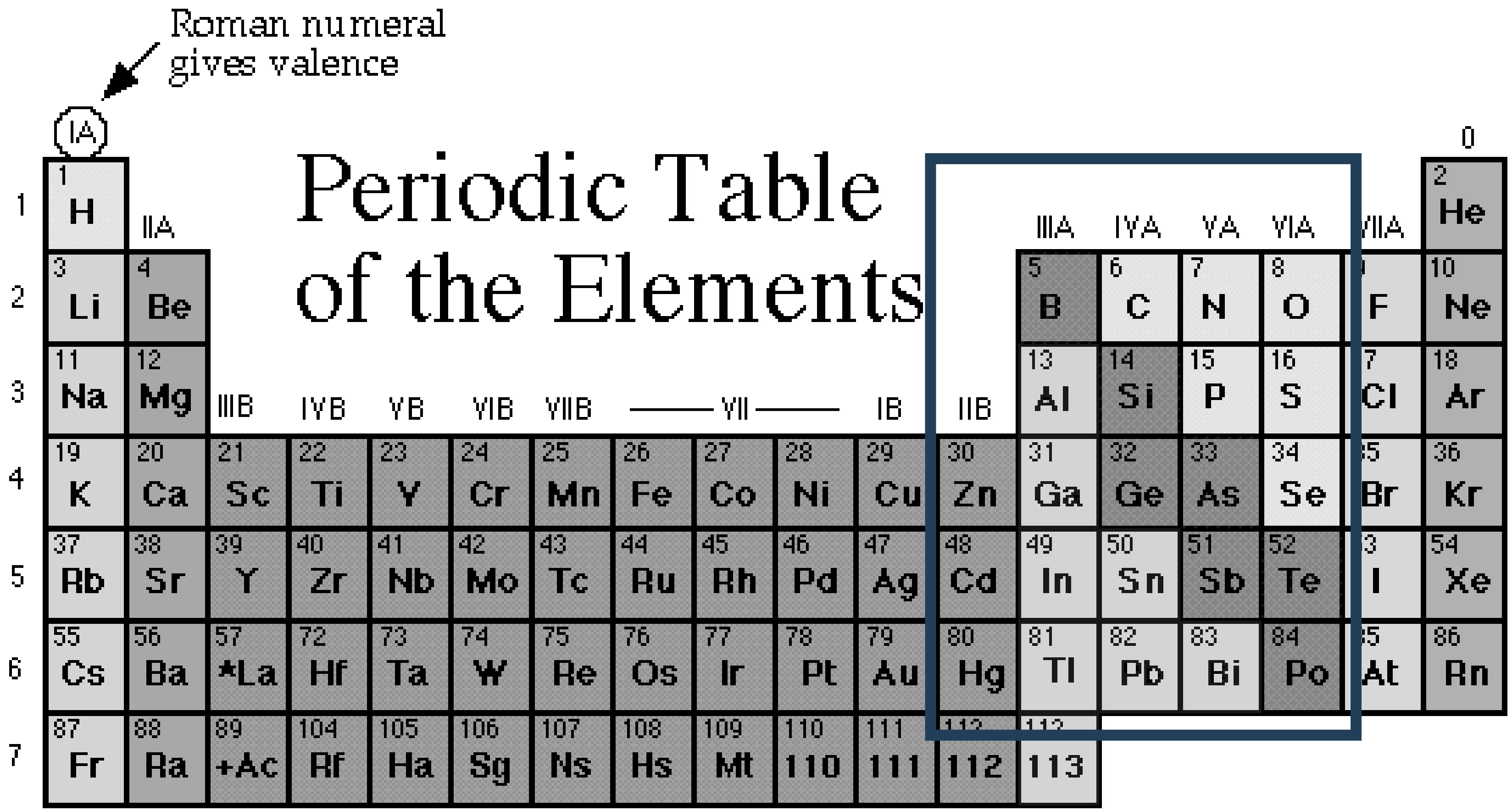
- Let's revisit $R = \rho L/A$
- If I take a material and magically stuff additional mobile electrons into it, then the resistivity would decrease.
- If I remove additional mobile electrons from it, then the resistivity would increase.
- So if I had a material which allows me to change the mobile charge density, then I can tune the resistivity of that material

What's after resistors, capacitors, and inductors



- Each device and circuit allows us to carry out specific functionalities

What are semiconductors

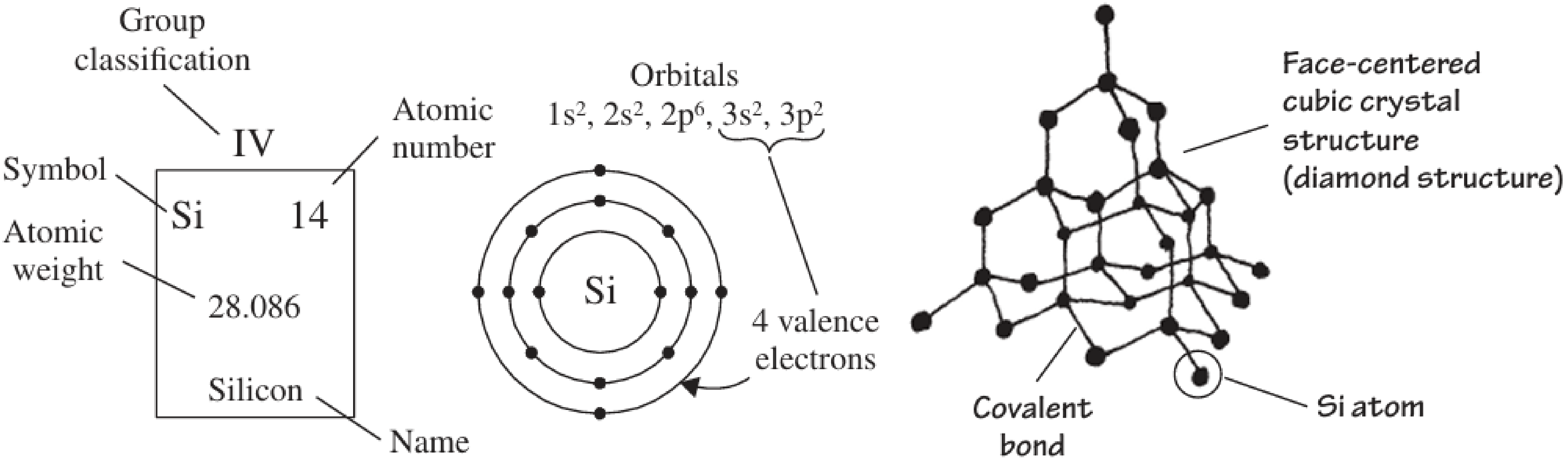


Elements: Si, Ge, C

Binary: GaAs, InSb, SiC, CdSe, etc.

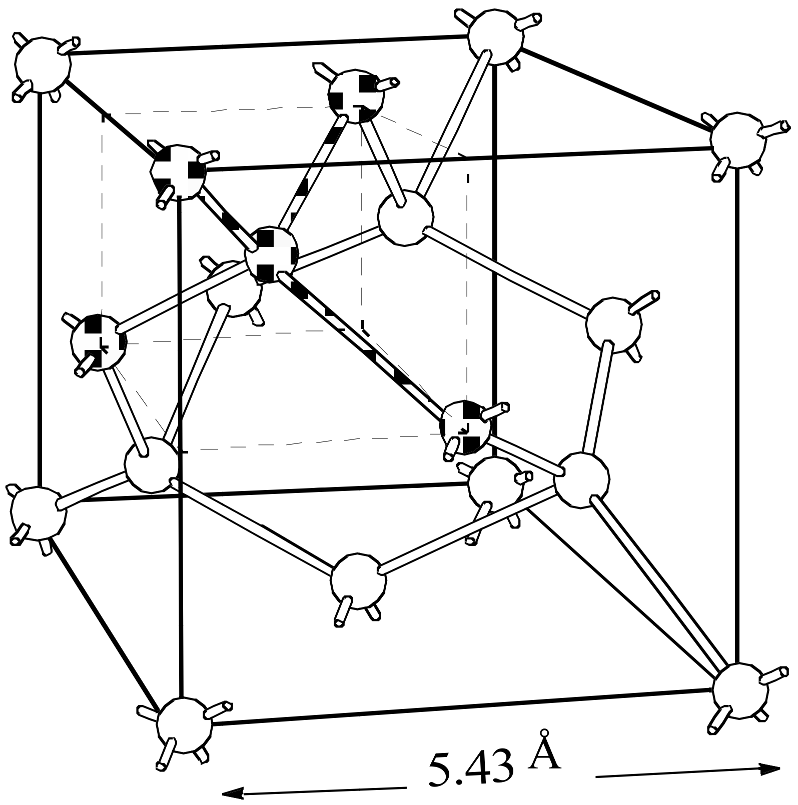
Ternary+: AlGaAs, InGaAs, etc.

Silicon – the workhorse of electronics

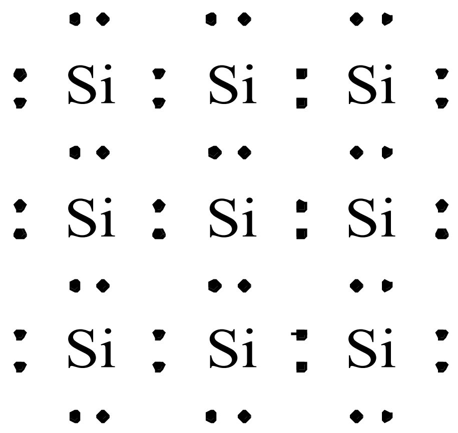


Silicon Crystal Structure

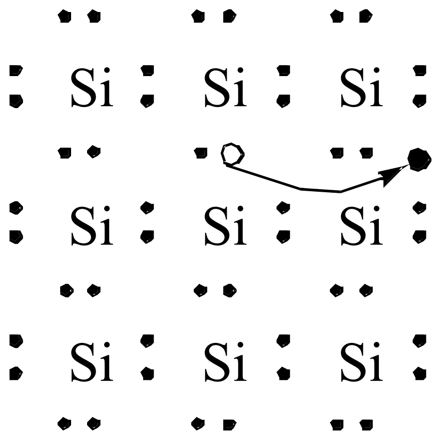
- ***Unit cell*** of silicon crystal is cubic.
- ***Each Si atom has 4 nearest neighbors.***

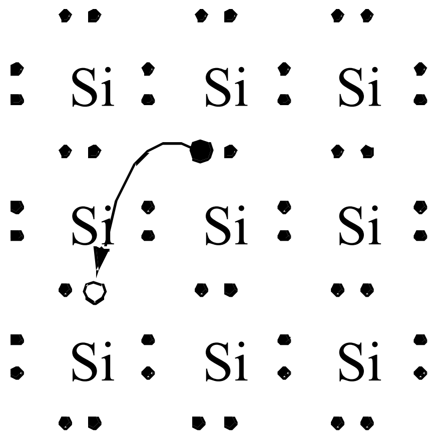


Bond Model of Electrons and Holes (Intrinsic Si)



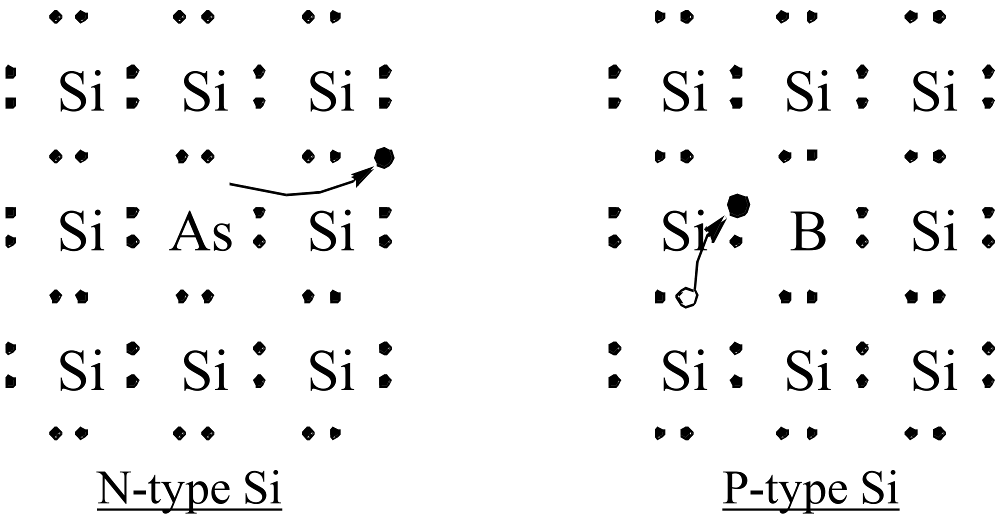
- Silicon crystal in a two-dimensional representation.





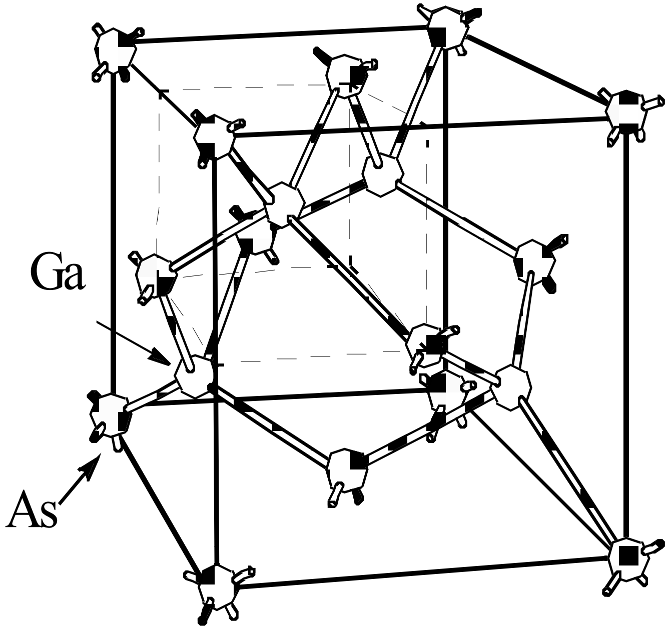
- When an electron breaks loose and becomes a ***conduction electron***, a ***hole*** is also created.

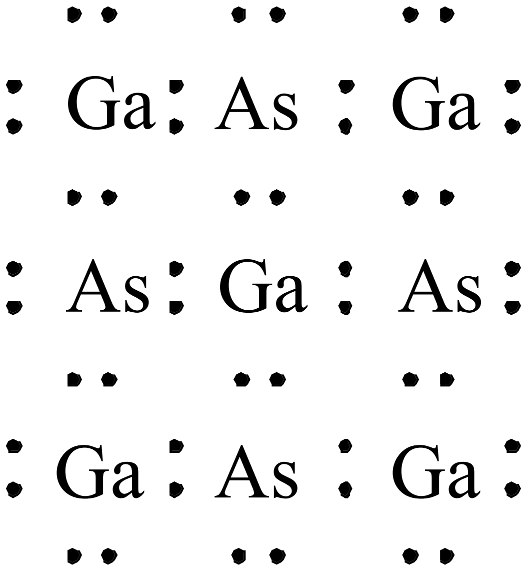
Dopants in Silicon



- As (Arsenic), a Group V element, introduces conduction electrons and creates ***N-type silicon,*** and is called a ***donor.***
- B (Boron), a Group III element, introduces holes and creates ***P-type silicon***, and is called an ***acceptor***.
- Donors and acceptors are known as dopants.

GaAs, III-V Compound Semiconductors, and Their Dopants





- GaAs has the same crystal structure as Si.
- GaAs, GaP, GaN are III-V compound semiconductors, important for optoelectronics.
- Which group of elements are candidates for donors? acceptors?

Energy Band Diagram

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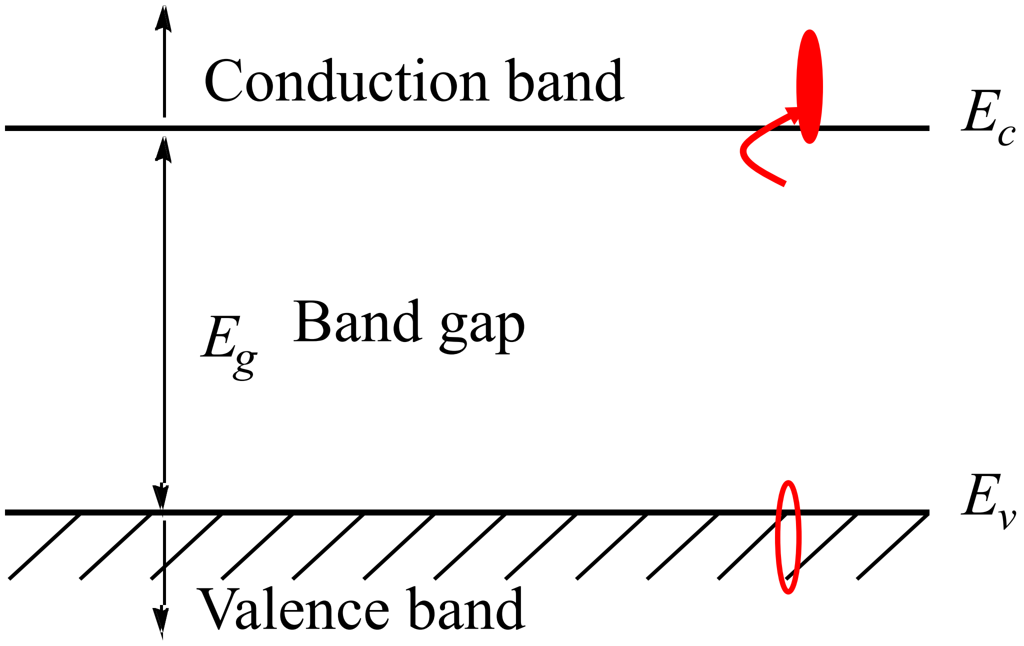

- ***Energy band diagram*** shows the bottom edge of conduction band, E_c , and top edge of valence band, E_v .
- E_c and E_v are separated by the ***band gap energy, E_g*** .

Measuring the Band Gap Energy by Light Absorption

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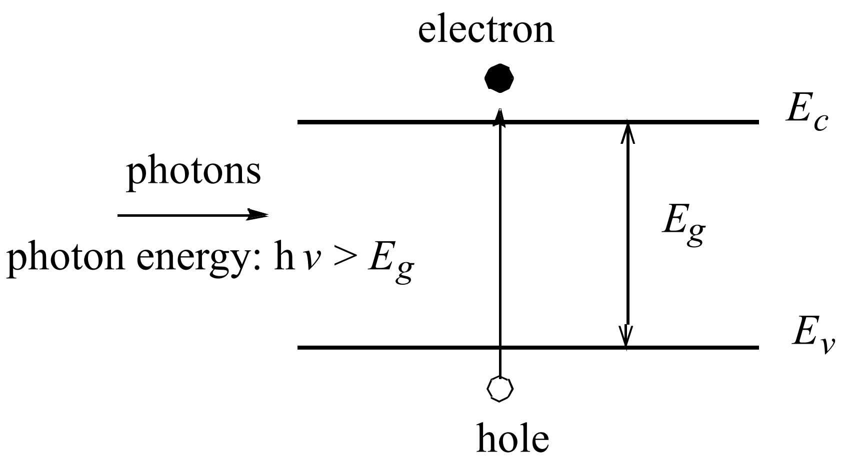
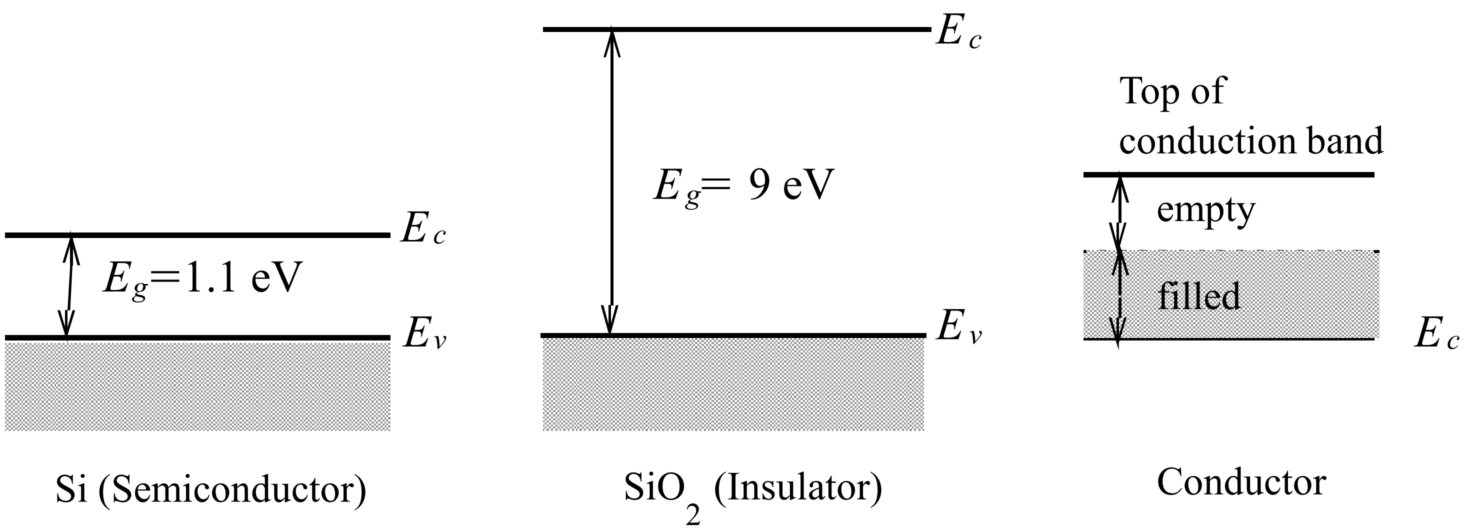


• E_g can be determined from the minimum energy ($h\nu$) of photons that are absorbed by the semiconductor.

Bandgap energies of selected semiconductors

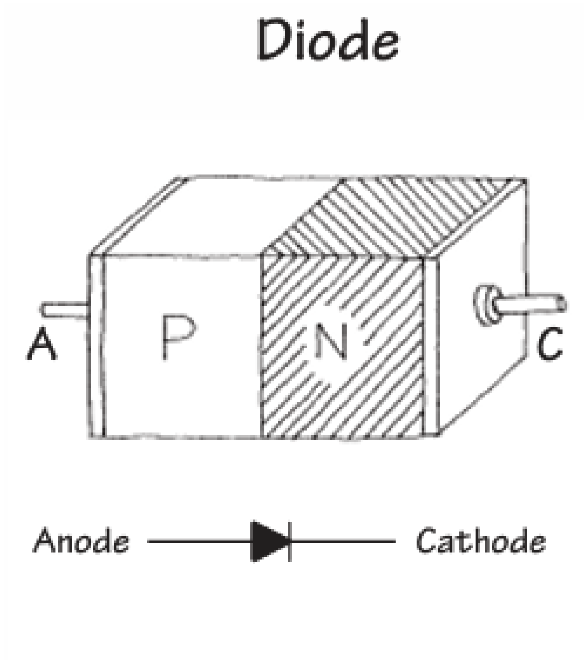
Material	PbTe	Ge	Si	GaAs	GaP	Diamond
E_g (eV)	0.31	0.67	1.12	1.42	2.25	6.0

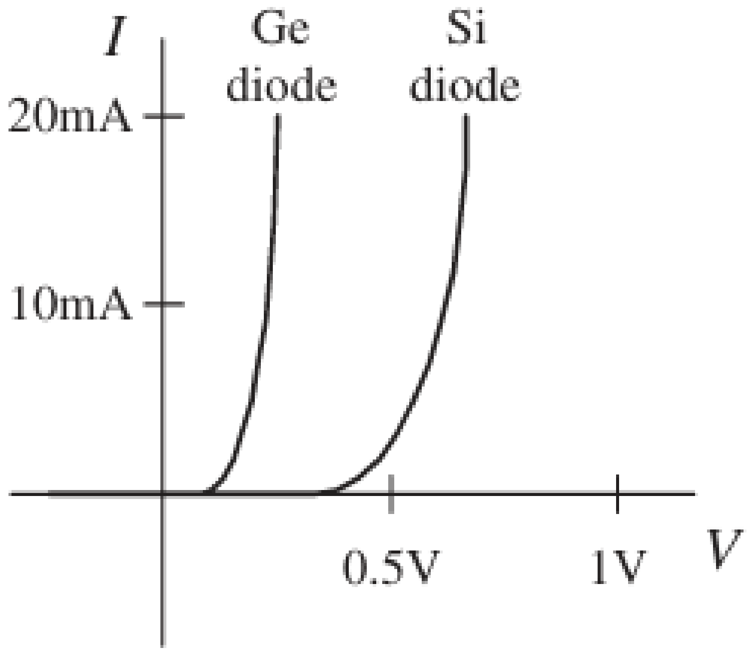
Semiconductors, Insulators, and Conductors



- Totally filled bands and totally empty bands do not allow current flow. (Just as there is no motion of liquid in a totally filled or totally empty bottle.)
- Metal conduction band is half-filled.
- Semiconductors have lower E_g's than insulators and can be doped.

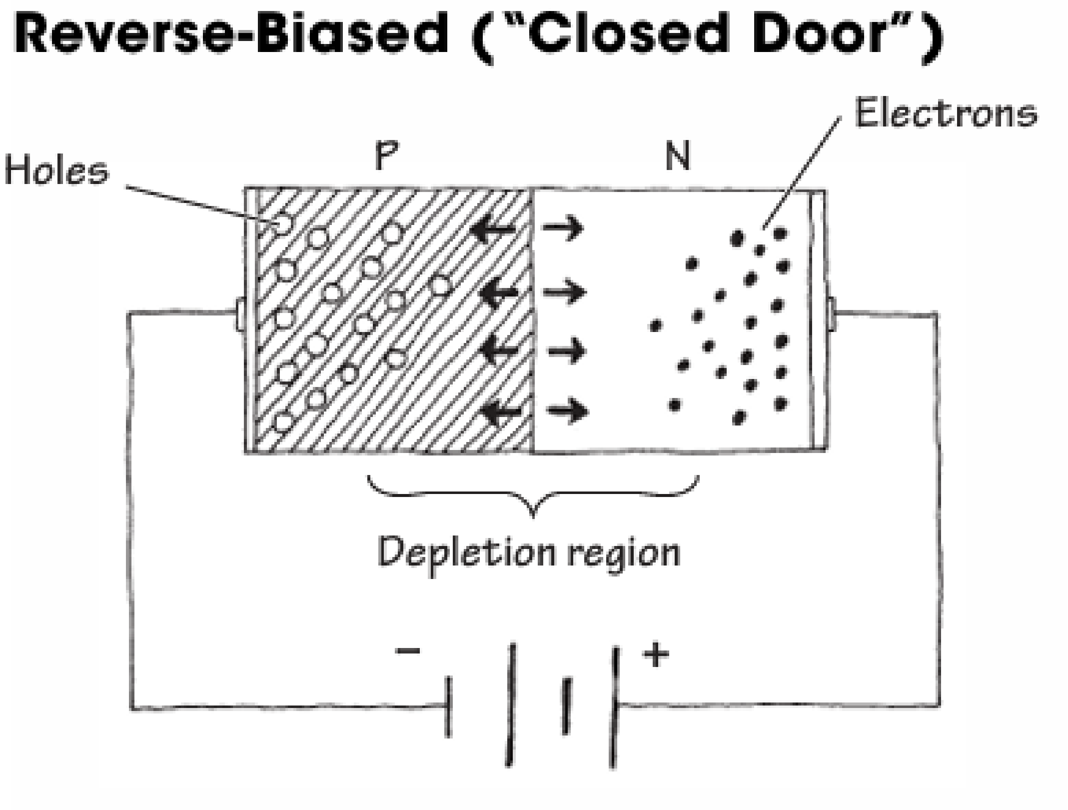
What is a diode

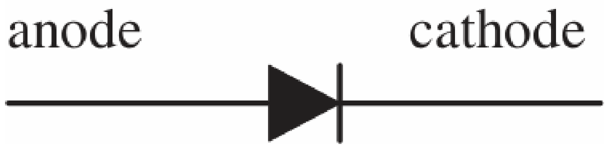




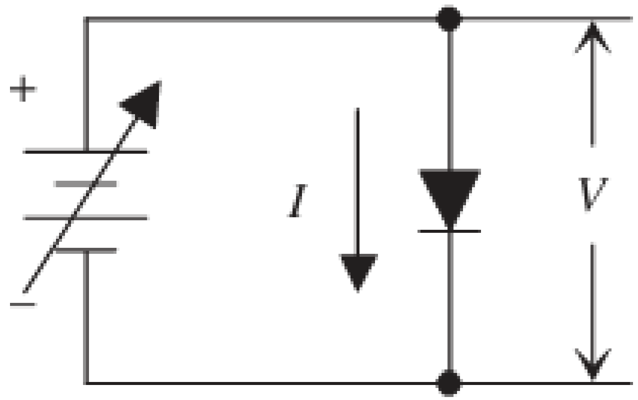
- A diode is a device that exhibits ‘rectifying’ behavior
- Can be made from a physical junction between an n-type semiconductor and a p-type semiconductor
- Can also be made from a physical junction between a metal and semiconductor (not discussed here)

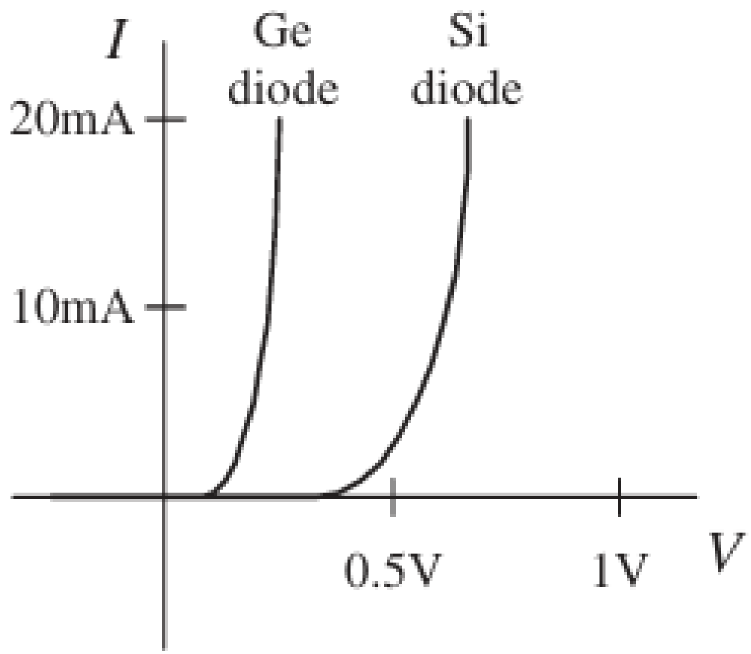
Reverse biasing a diode



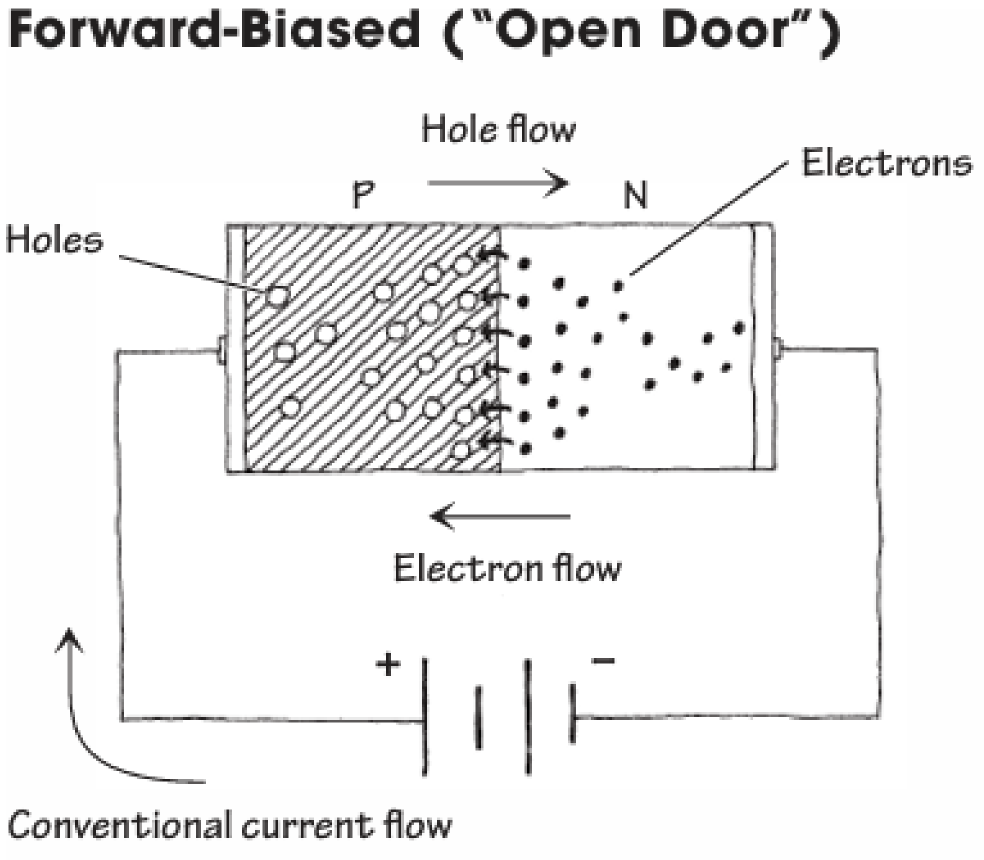


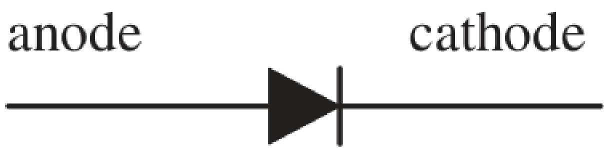
Diode characterization



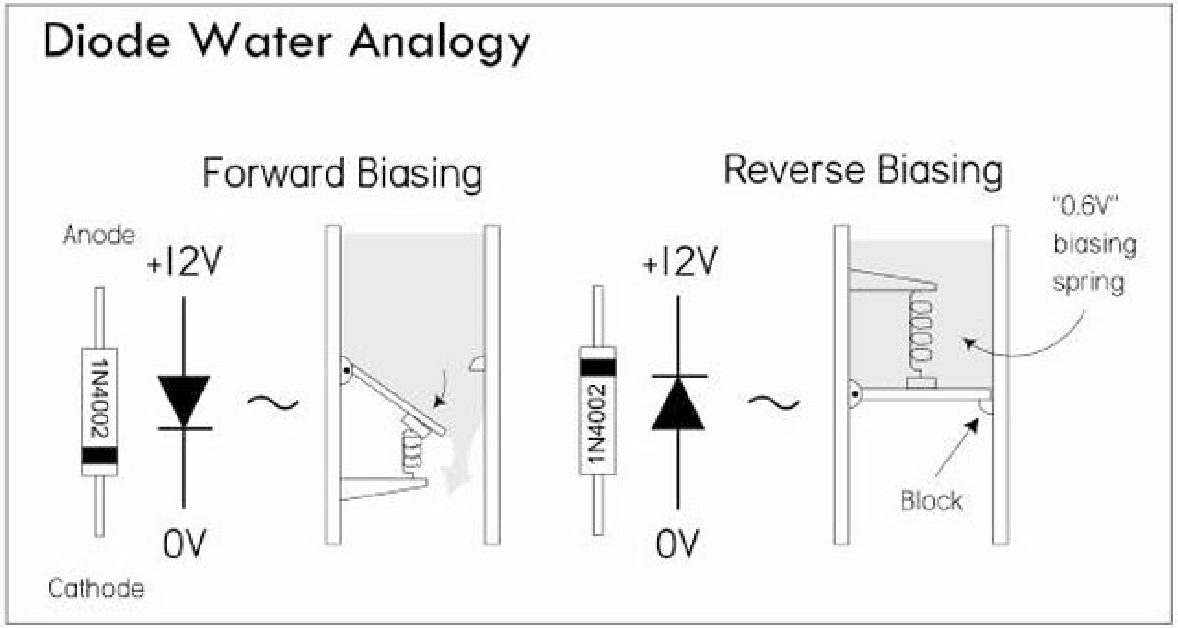


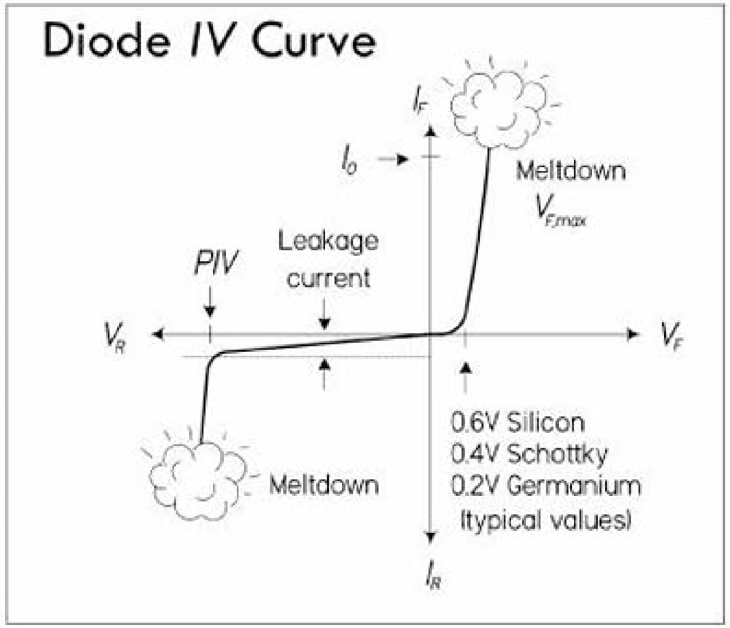
Forward biasing a diode





Water analogy





How do we figure out the behavior?

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Define the physical system	Write the differential equations	Solve the differential equations	Simplify the results for relevant conditions
Materials Science, Chemistry, Physics, etc	Physics, Chemistry	Math, Computing	Engineering

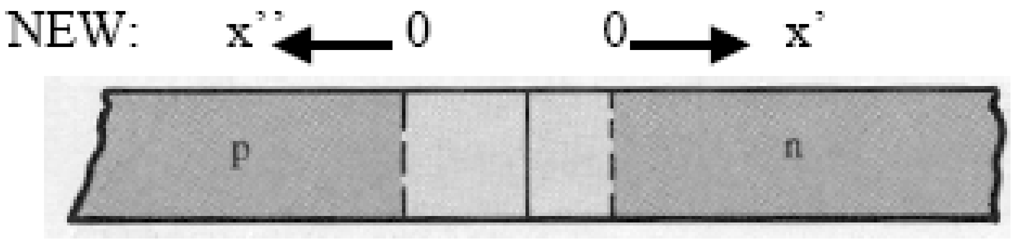
Solving for diode current equations

- From the minority carrier diffusion equation: $\frac{d^2\Delta p_n}{dx^2} = \frac{\Delta p_n}{D_p\tau_p} = \frac{\Delta p_n}{L_p^2}$

- We have the following boundary conditions:

$$\Delta p_n(x_n) = p_{no}(e^{qV_A/kT} - 1) \qquad \Delta p_n(\infty) \to 0$$

- For simplicity, we will develop a new coordinate system:



- Then, the solution is of the form:

$$\Delta p_n(x') = A_1 e^{x'/L_p} + A_2 e^{-x'/L_p}$$

Solving for diode current equations

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$$\Delta p_n(x') = A_1 e^{x'/L_p} + A_2 e^{-x'/L_p}$$

From the $x = \infty$ boundary condition, $A_1 = 0$.

From the $x = x_n$ boundary condition, $A_2 = p_{no}(e^{qV_A/kT} - 1)$

Therefore, $\Delta p_n(x') = p_{no}(e^{qV_A/kT} - 1)e^{-x'/L_p}, \; x' > 0$

Similarly, we can derive

$$\Delta n_p(x'') = n_{po}(e^{qV_A/kT} - 1)e^{-x''/L_n}, \; x'' > 0$$

Solving for diode current equations

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- Current density $J = J_n(x) + J_p(x)$

$$J_n(x) = q\mu_n n\mathcal{E} + qD_n \frac{dn}{dx} = q\mu_n n\mathcal{E} + qD_n \frac{d(\Delta n)}{dx}$$

$$J_p(x) = q\mu_p p\mathcal{E} - qD_p \frac{dp}{dx} = q\mu_p p\mathcal{E} - qD_p \frac{d(\Delta p)}{dx}$$

- J is constant throughout the diode, but $J_n(x)$ and $J_p(x)$ vary with position

Solving for diode current equations

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p-side: $J_n = -qD_n \frac{d\Delta n_p(x'')}{dx''} = q\frac{D_n}{L_n} n_{p0}(e^{qV_A/kT} - 1)e^{-x''/L_n}$

n-side: $J_p = -qD_p \frac{d\Delta p_n(x')}{dx'} = q\frac{D_p}{L_p} p_{n0}(e^{qV_A/kT} - 1)e^{-x'/L_p}$

$$J = J_n\big|_{x=-x_p} + J_p\big|_{x=x_n} = J_n\big|_{x''=0} + J_p\big|_{x'=0}$$

$$J = qn_i^2\left[\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right](e^{qV_A/kT} - 1)$$

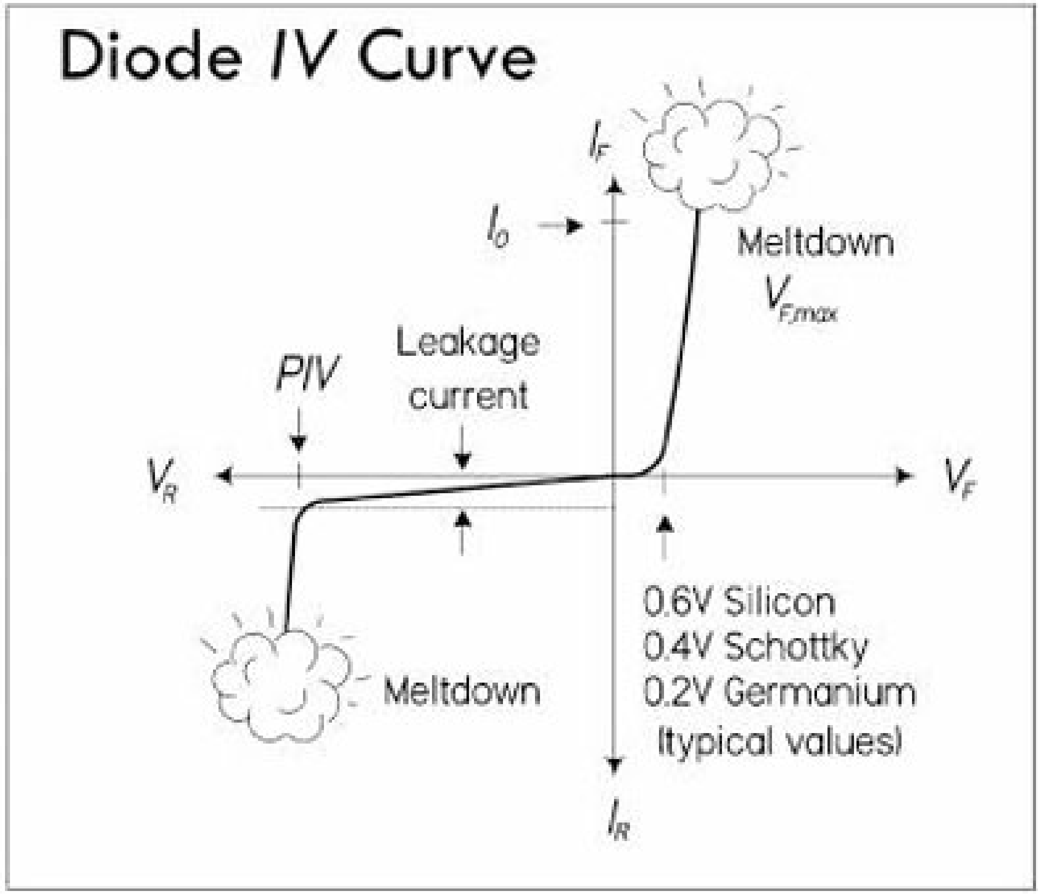
Ideal Diode Current Equation

$$J = qn_i^2\left[\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right](e^{qV_A/kT} - 1) \longrightarrow I = I_0(e^{\frac{qV}{kT}} - 1)$$

- This equation describes the behavior of an ideal diode

Non-Ideal Diode Current Equation

$$I = I_0\left(e^{\frac{qV}{nkT}} - 1\right)$$



- This equation partially describes the behavior of a non-ideal diode