Lecture 10: Semiconductors

- **Announcements**:
- HW#4 online and due Friday via Gradescope
- Lab#2 continues into next week
    - Prelab is due at the beginning of lab
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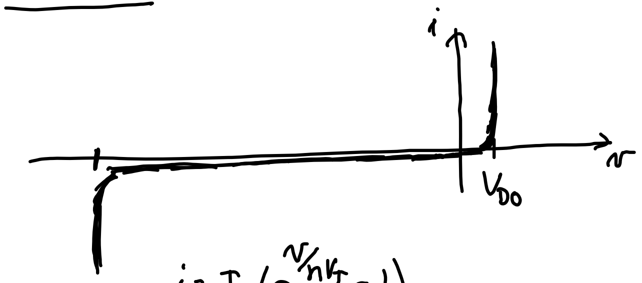
- Lecture Topics:
    - Conductors
    - Insulators
    - Semiconductors
    - Doping
    - Semiconductor Currents
- ------------------------------------
- **Last Time**:
- Specified iv curves and equations for a diode
- Now, go into the physics of how a diode works …

C. Actual Diode –



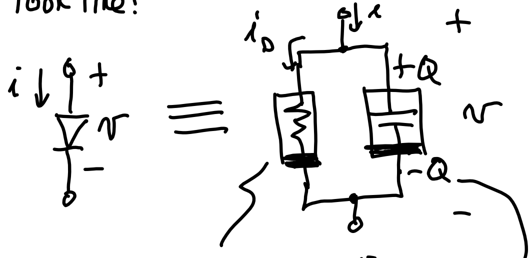
$i = I_s(e^{v/nV_T} - 1)$

$I_s \triangleq$ saturation current

$V_T = 25mV = \frac{kT}{q} \triangleq$ thermal voltage

$n = 1$ a 2 ↖ discrete diodes
↑
IC diodes

Diode → not only a nonlinear resistr
→ also includes nonlinear capacitance
→ a more exact model for a diode would look like:



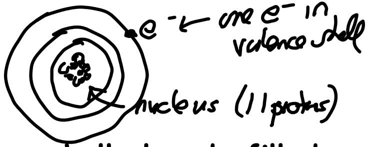
$i_D = f'(v) = I_S(e^{v/nV_T} - 1)$

$Q = f''(v) = q\left(\frac{N_A N_D}{N_A + N_D}\right) A W_{d0} \sqrt{1 + \frac{v_R}{\phi_j}}$
$[v_R = -v]$

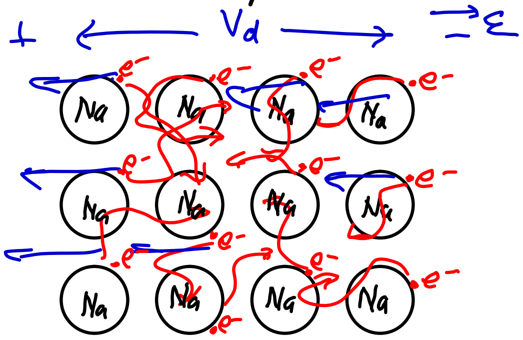
- **Semiconductors**:
- To better understand the physical operation of diodes (and later, transistors), need to understand semiconductors
- Best to describe them in the context of other materials, like conductors and insulators
- **Materials**:
  - Made up of atoms
  - In solids, the atoms often bond together in a regular lattice
  - The atoms in the lattice happiest in a lowest energy state, i.e., with filled orbitals
  - Go to periodic table supplement

1. **Conductors**:

- Close-packed atoms in a cloud of electrons
- Ex. Na (sodium) – a metal
  - Alkali metal w/ one valence e^-

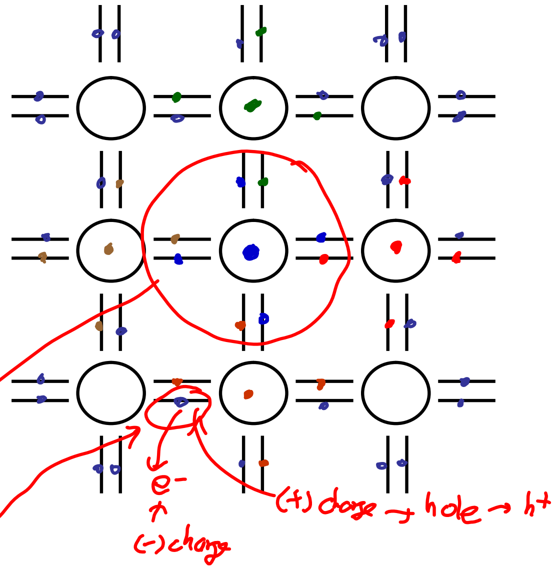


  - Orbital below valence shell already filled, so e^- can leave and be shared by all atoms in the solid



2. **Insulators**:

- Held together very strongly in a regular lattice by strong covalent bonds
- Lowest energy state when the valence shells of each atom are filled



- Atom happy w/ an effectively filled valence band, so e^-'s not free to move about
- An increase in energy can allow an e^- to break free into a higher energy free state in which an electric field can move the e^-
- For example, high enough temperature generates a free e^- and h^+ pair, each of which is free to move under an applied electric field

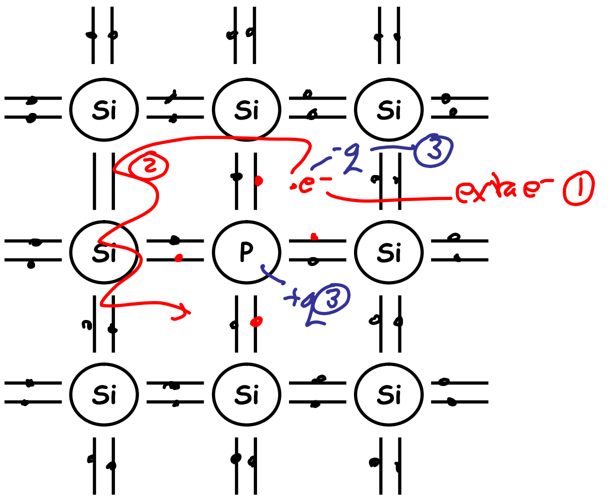
3. **Semiconductors**:

- Basically the same as insulators, except they require smaller temperatures to free e^-s
- For most purposes, they are just like insulators … until they are doped, at which point they become like metals

- **Doping**:
- A semiconductor converts to a conductor when one adds certain impurities that substitute for Si atoms
- Type types of substitutional impurities
    - Donors
    - Acceptors

1. **Donors**:

- Elements with 5 valence e^-'s, e.g., phosphorous (P) and Arsenic (As)



① – 4 e^-'s from P contribute to covalent bonds, leaving one extra e^-

② – extra e^- can now move around

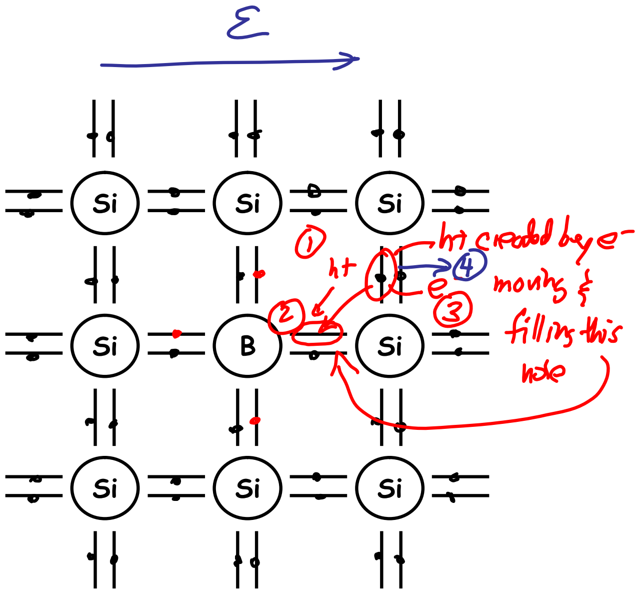
③ – When e^- moves away from the donor atom (in this case, P), the donor atom effectively represents a (+) static charge

- The larger the concentration of donors N_D, the greater the number of e^-'s available to generate the e^- cloud, i.e., the better the conductor

$n = \#$ of free e^-'s $\sim N_D$ $[cm^{-3}]$

2. **Acceptors**:

- Elements w/ 3 valence e^-'s, e.g., Boron (B)



① – 3 e^-'s from B not enough to complete the valence shell → leaves a hole, h^+

② – h^+=absence of e^- = hole

③ – e^- can move into this h^+, creating another h^+

④ – h^+'s propogate this way under an applied electric field, generating current

- The larger the concentration of acceptors N_A, the greater the number of h^+'s available for current, i.e., the better the conductor

$$p = \#\text{free } h^+ \sim N_A \ [cm^{-3}]$$

- Thus, we can convert a semiconductor to a conductor by doping w/ donors (which generate an e^- cloud) or doping w/ acceptors (which generate a h^+ cloud)

- n_i = concentration of free e^-'s in intrinsic (undoped) Si = 1.45×10^{10} cm^{-3} ← at room temperature
- $p = n = n_i$ in intrinsic silicon
- As a rule of thumb, at any given location at equilibrium, $\underline{pn = n_i^2 = (1.45\times10^{10})^2}$
- If a region is doped predominantly one type (p or n), then the carrier concentrations are as follows:

<u>Predominantly n-type ($N_D \gg N_A$)</u>: $n \cong N_D \rightarrow p = \frac{n_i^2}{N_D}$

<u>Predominantly p-type ($N_A \gg N_D$)</u>: $p \cong N_A \rightarrow n = \frac{n_i^2}{N_A}$

Types of Currents in Semiconductors

⇒ two possible current components:

① <u>Drift Current</u> –