ESE370: Circuit-Level Modeling, Design, and Optimization for Digital Systems

Lec 6: September 17, 2021

MOS Model

You are Here: Transistor Edition

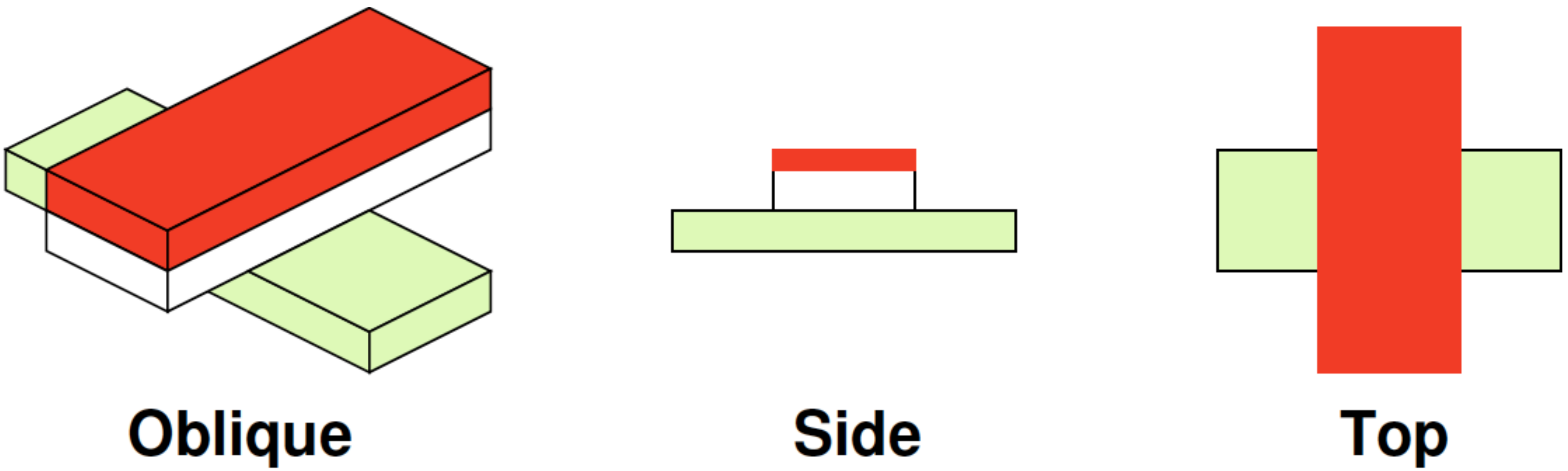
- Previously: simple models (0^{th} and 1^{st} order)
  - Comfortable with basic functions and circuits
- This lecture and next week(4 lectures)
  - Detailed semiconductor discussion
  - MOSFET phenomenology
  - Don’t Blink!
- Rest of term
  - Implications of the MOS device

Today

- MOS Structure
- Basic Fabrication
- Semiconductor Physics
  - Metals, insulators
  - Silicon lattice
  - Band gaps
  - Doping
  - Field Effects

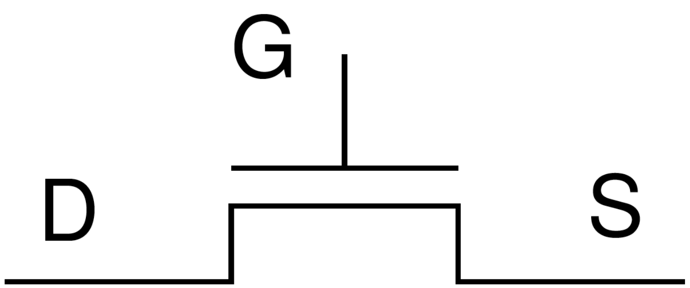
MOS

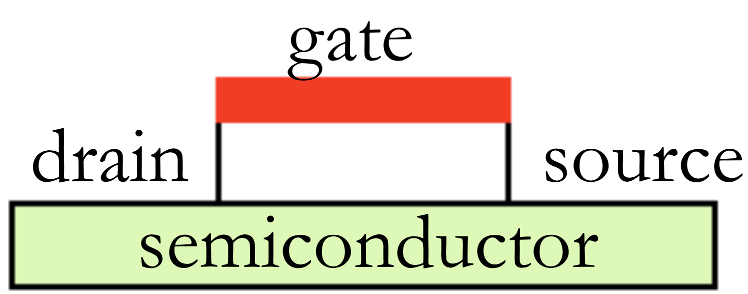
- Metal Oxide Semiconductor



MOS

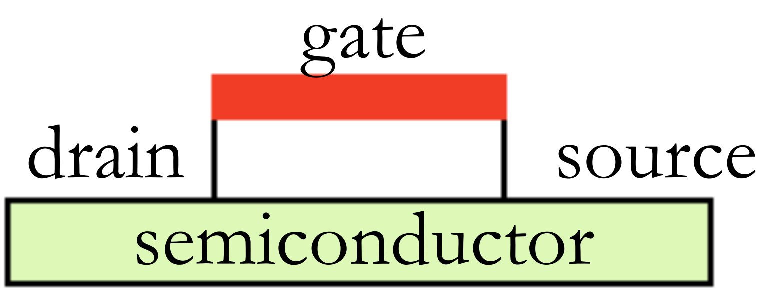
- **M**etal – gate
- **O**xide – insulator separating gate from semiconductor
  - Ideally: no conduction from gate to semiconductor
- **S**emiconductor – between source and drain
- See why gate input is capacitive?

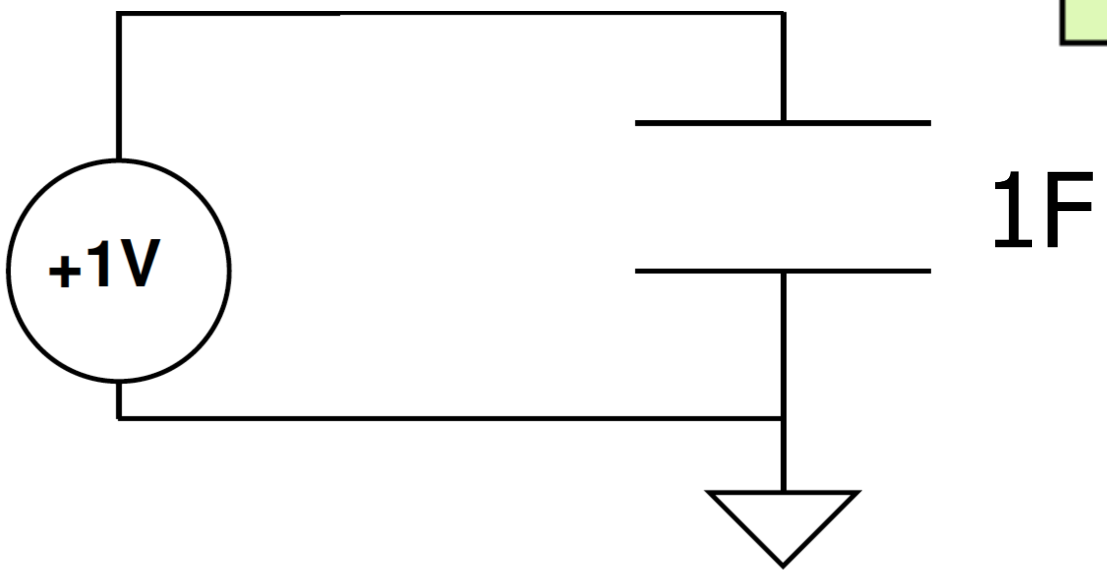




(MOS) Capacitor (preclass 1)

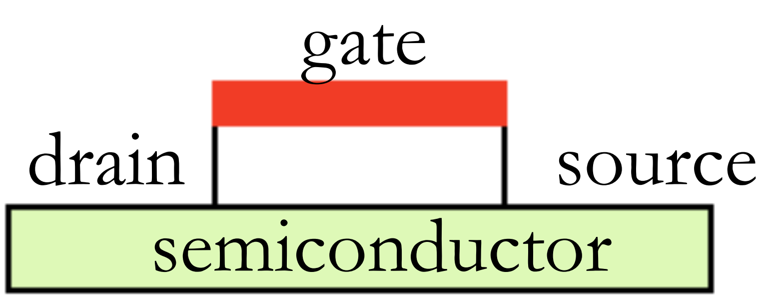
- Charge distribution and field?
- How much charge on plates?





Idea

- Semiconductor – can behave as metal or insulator
- Voltage on gate induces an electrical field
- Induced field attracts (repels) charge in semiconductor to form a channel
  - Semiconductor can be switched between conducting and not conducting
  - Hence "Field-Effect" Transistor



Source/Drain Contacts

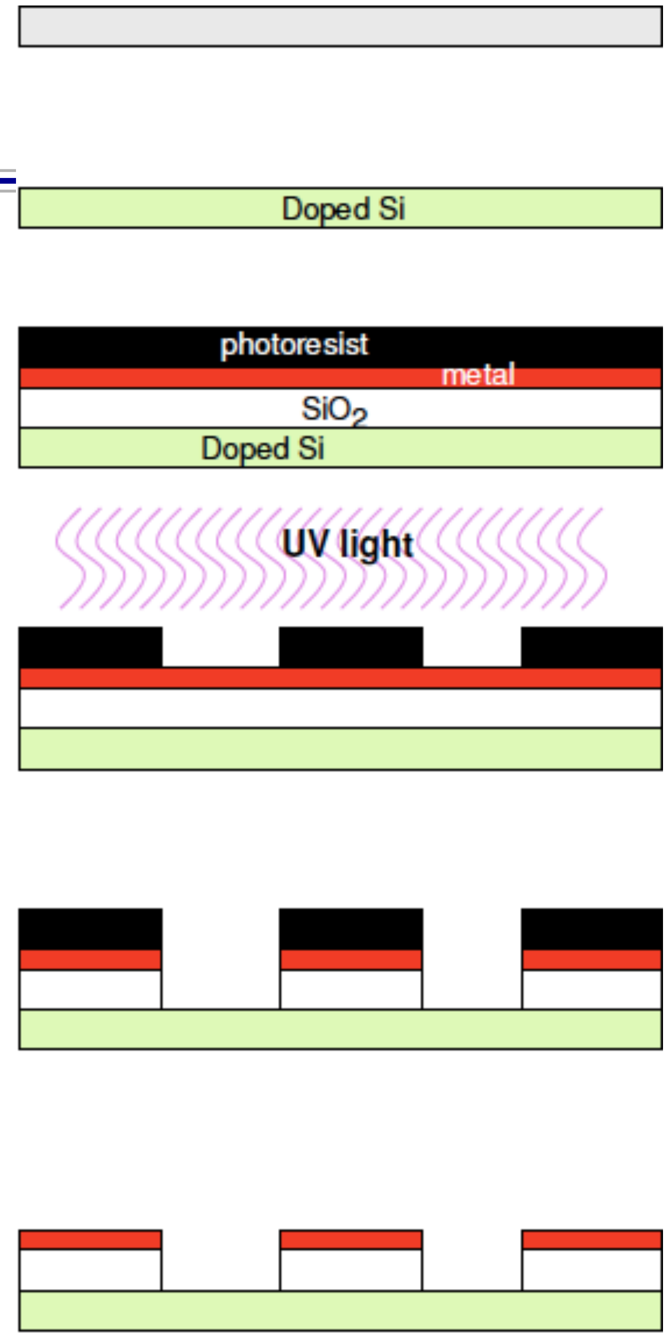
- Contacts: Conductors → metallic
  - Connect to metal wires that connect transistors

Fabrication

- Start with Silicon wafer
- Dope silicon
- Grow Oxide (SiO_2)
- Deposit Metal
- Photoresist mask and etch to define where features go

https://youtu.be/35jWSQXku74?t=119

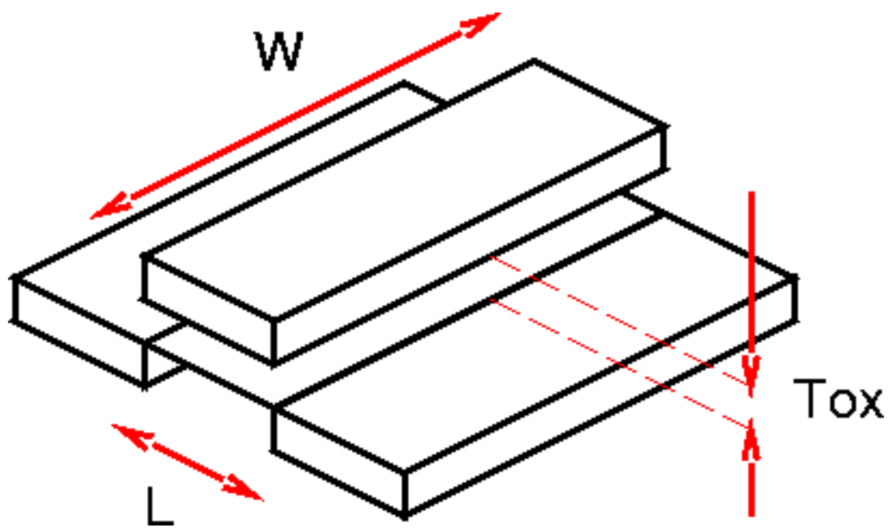
Time Code: 2:00-4:30



Dimensions

- Channel Length (L)
- Channel Width (W)
- Oxide Thickness (T_{ox})

- Process named by minimum length
  - 22nm → L=22nm

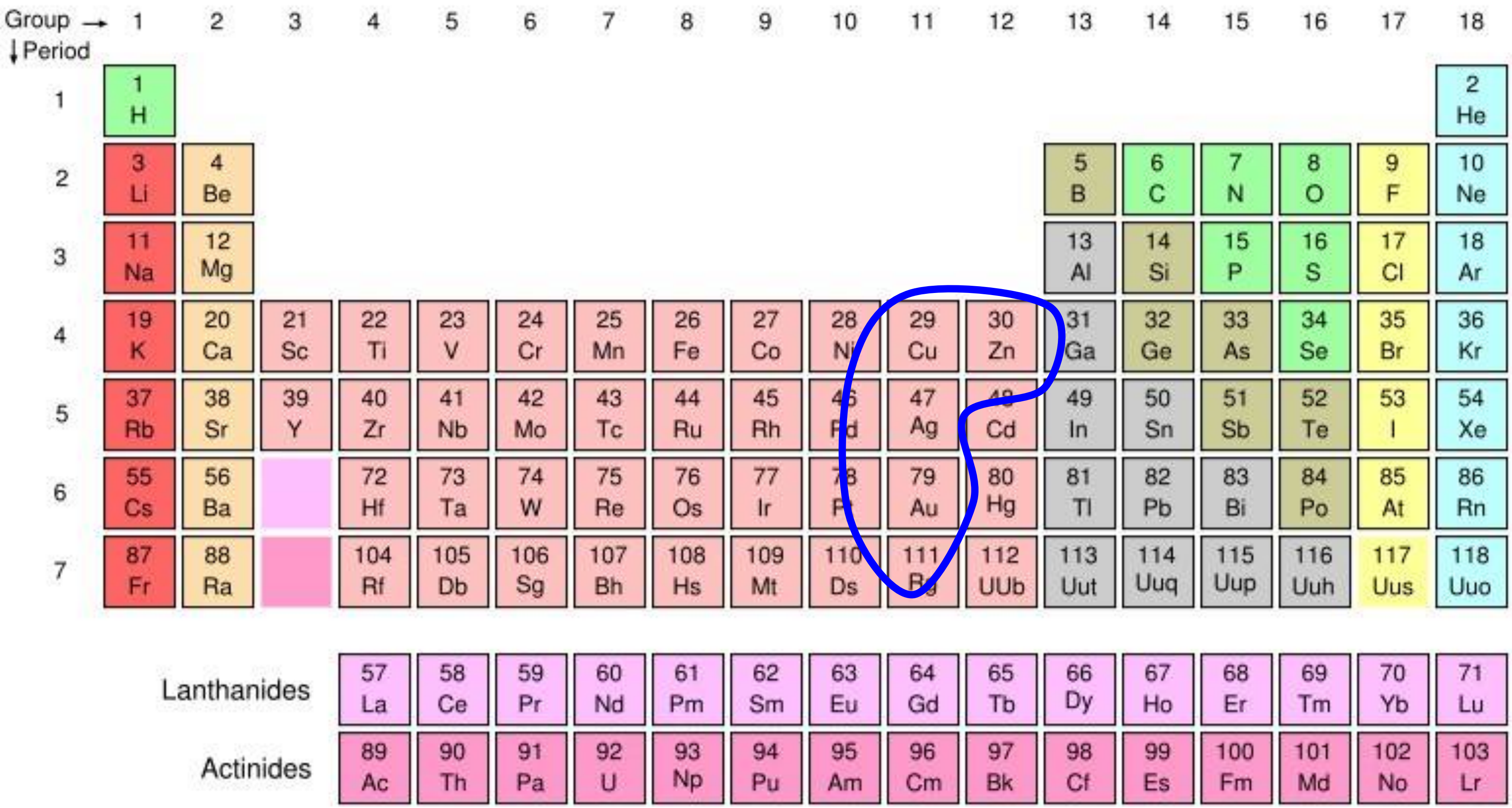


Semiconductor Physics

Conduction

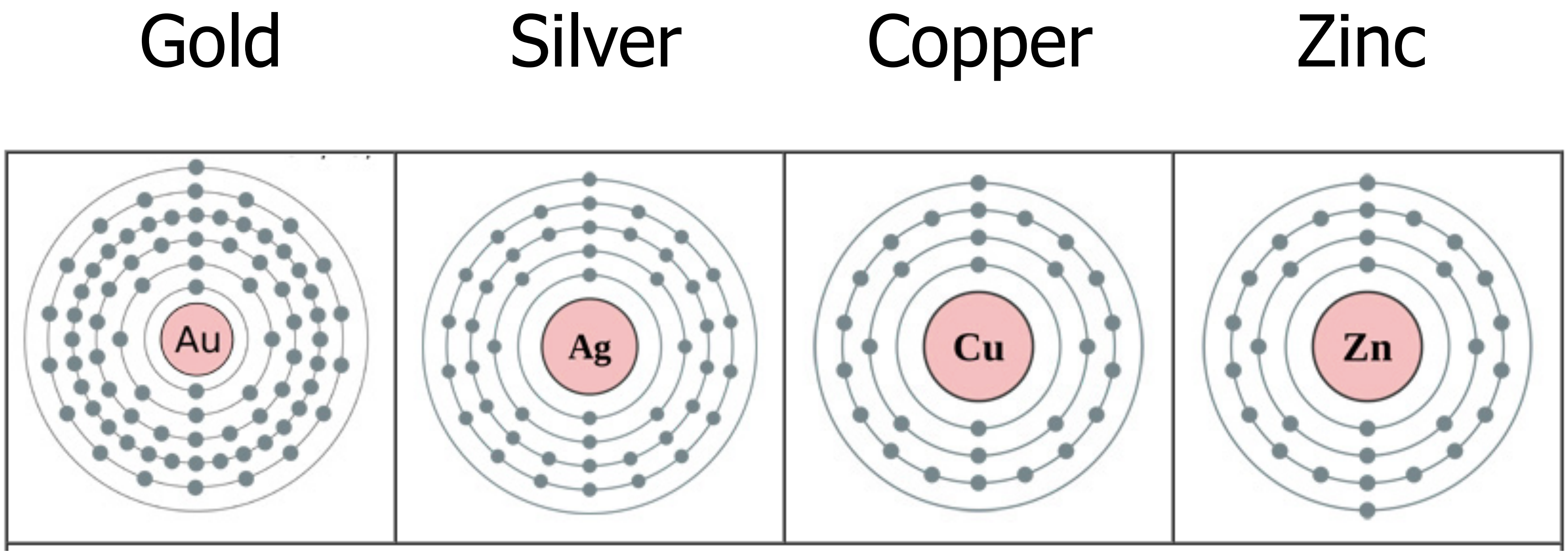
- Metal – conducts
- Insulator – does not conduct
- Semiconductor – can act as either

Why does metal conduct? (preclass 2)



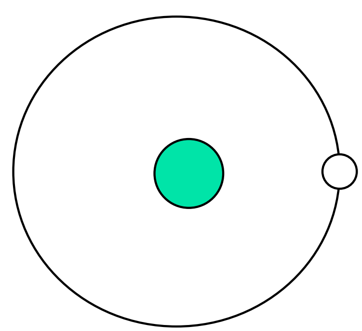
http://chemistry.about.com/od/imagesclipartstructures/ig/Science-Pictures/Periodic-Table-of-the-Elements.htm

Why does metal conduct? (preclass 2)



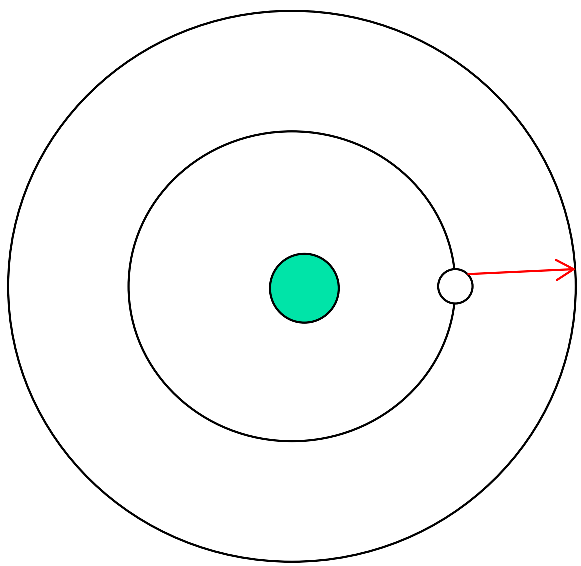
Conduction

- Electrons move
- Must be able to “remove” electron from atom or molecule



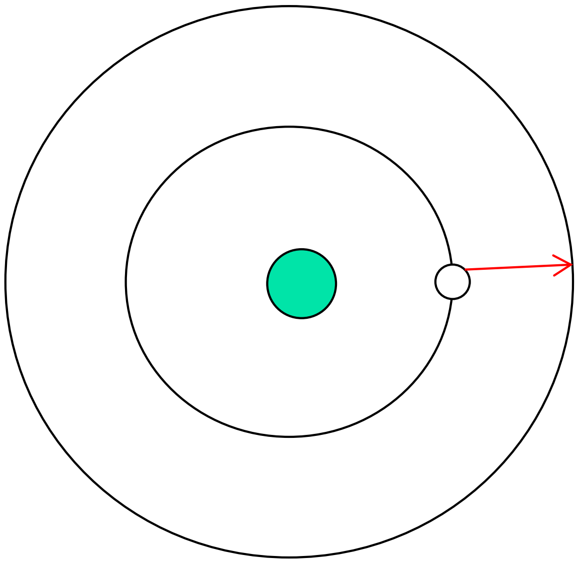
Atomic States

- Quantized Energy Levels (bands)
  - Valence and Conduction Bands
- Must have enough energy to change level (state)



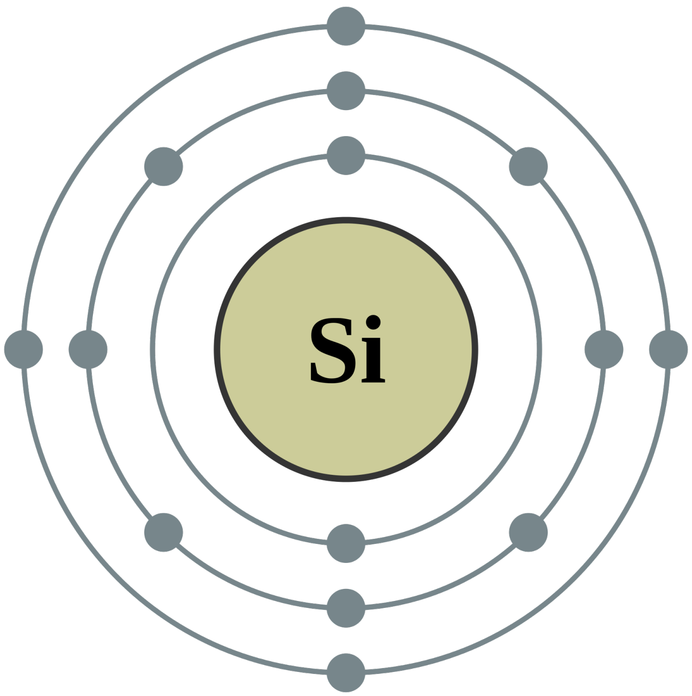
Thermal Energy

- Except at absolute 0
  - There is always free energy
  - Causes electrons to hop around
    - ….when there is enough energy to change states
  - Energy gap between states determines energy required



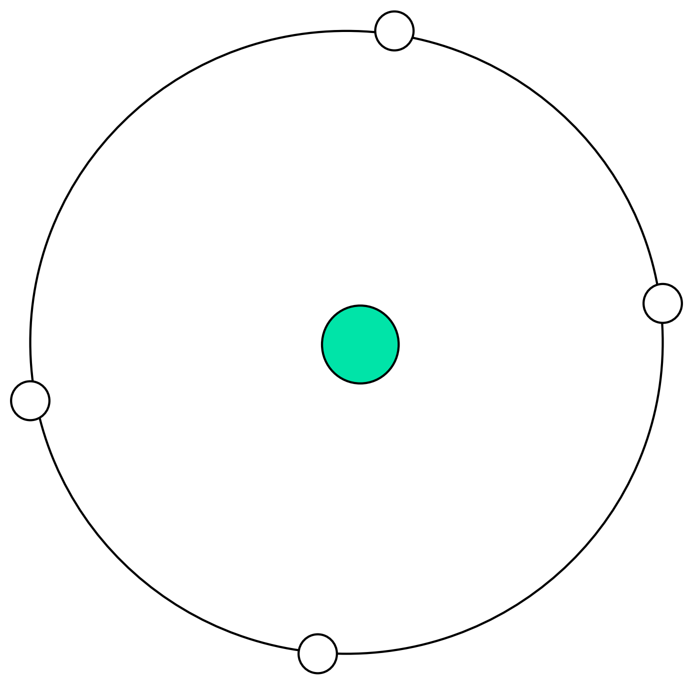
Silicon Atom (preclass 3)

- How many valence electrons?



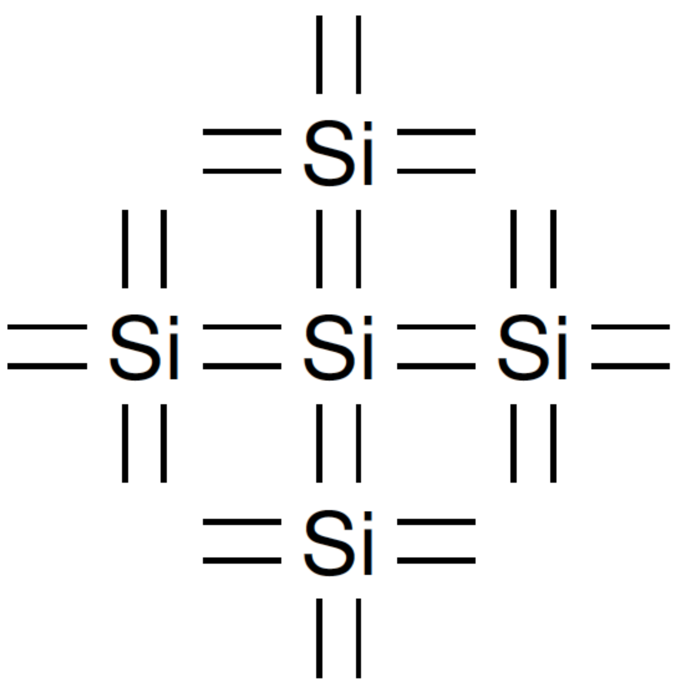
Silicon

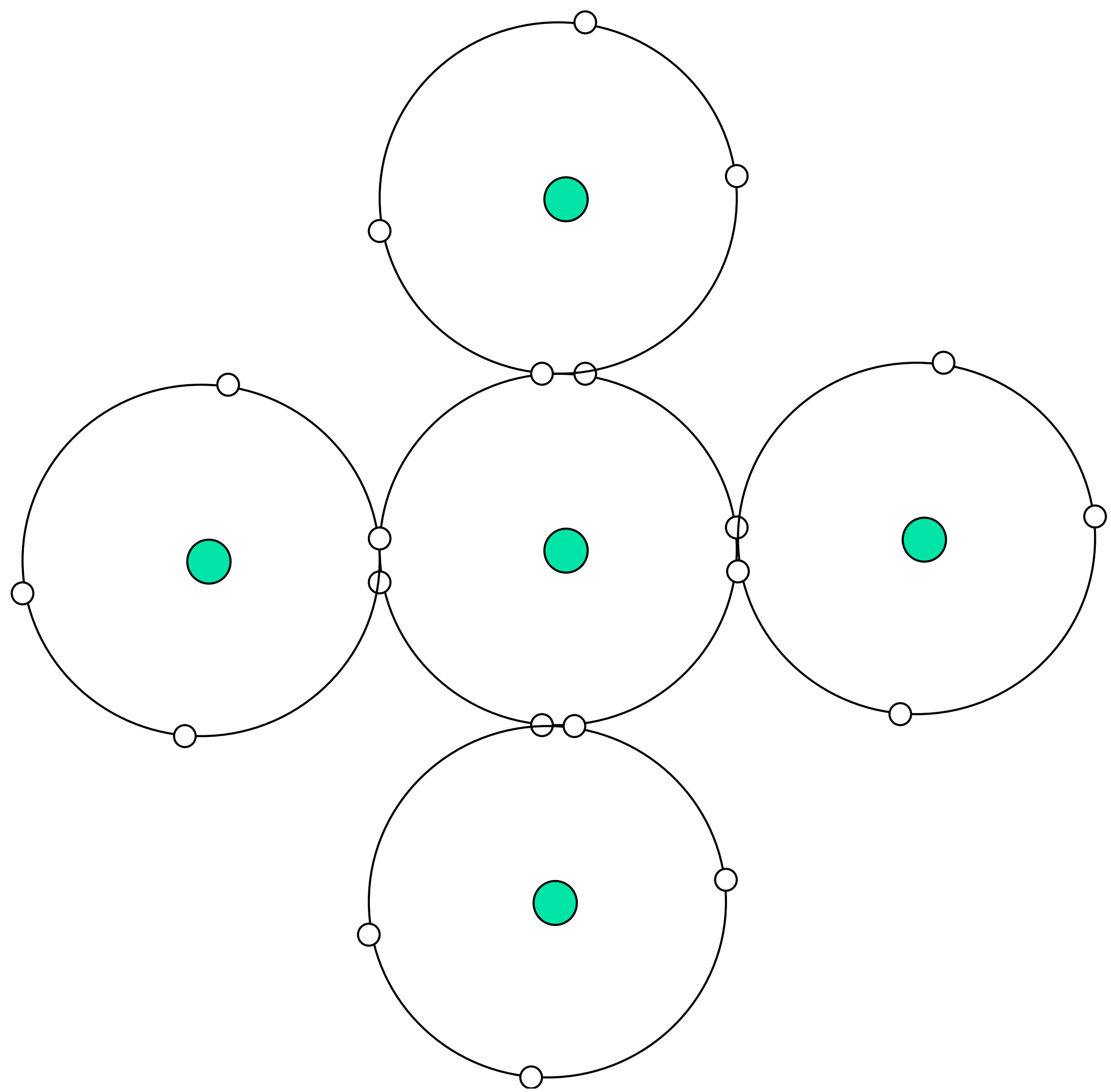
- 4 valence electrons
  - Inner shells filled
  - Only outer shells contribute to chemical interactions



Silicon-Silicon Bonding

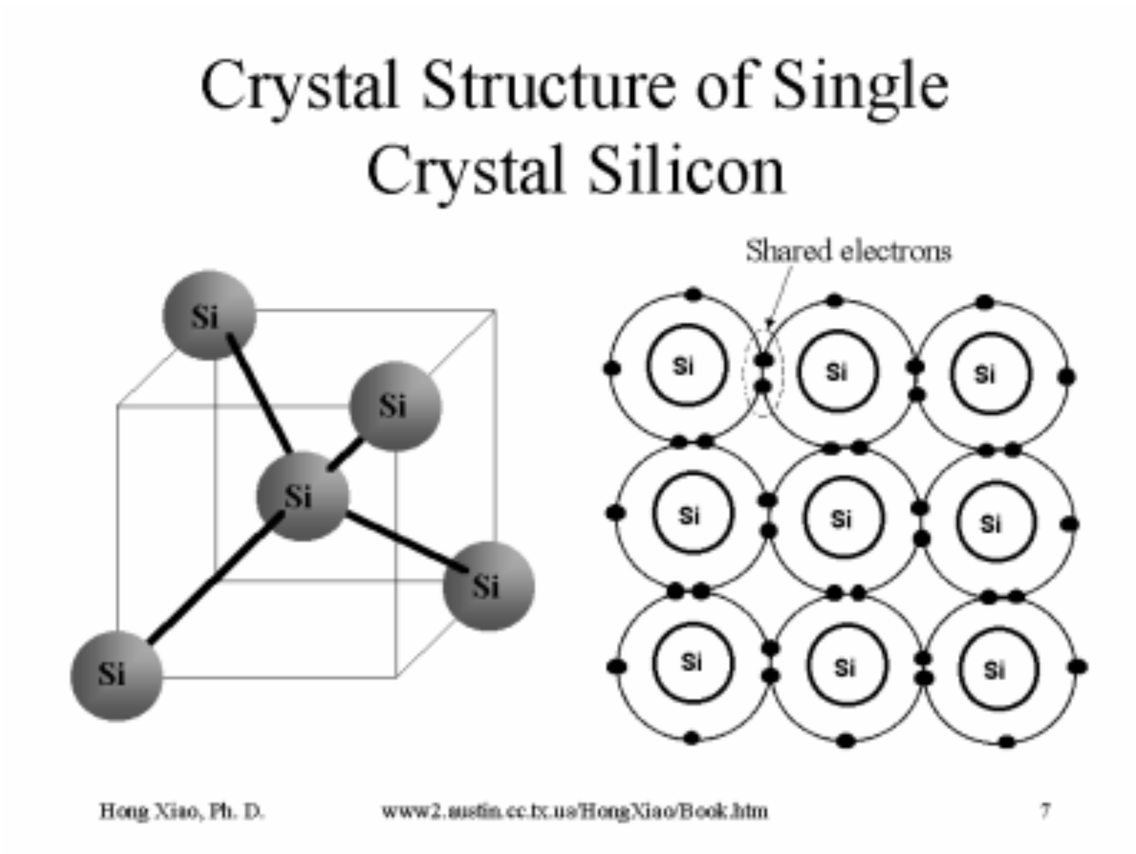
- Can form covalent bonds with 4 other silicon atoms

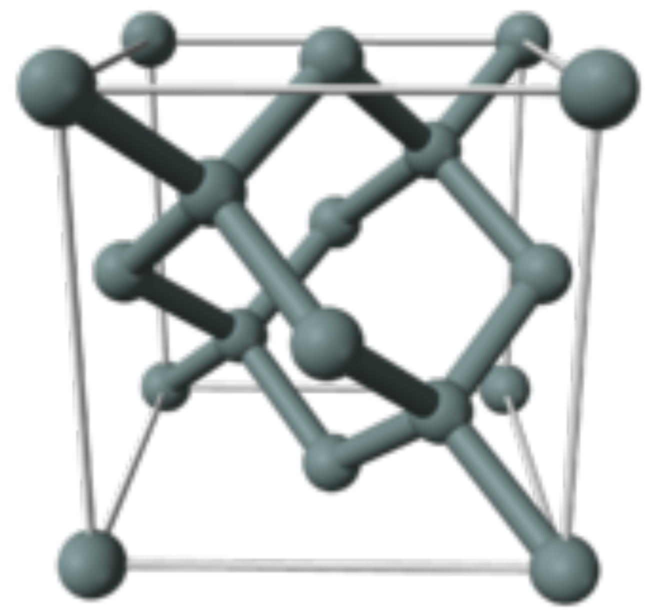




Silicon Lattice

- Forms into crystal lattice



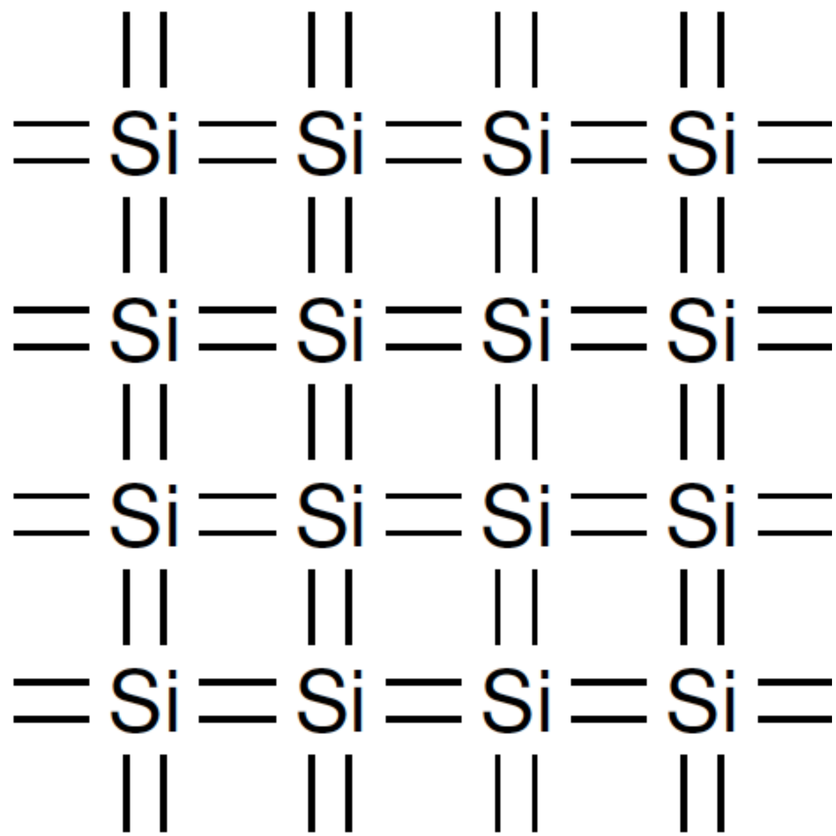


Silicon Ingot

1 impurity atom
per 10 billion
silicon atoms

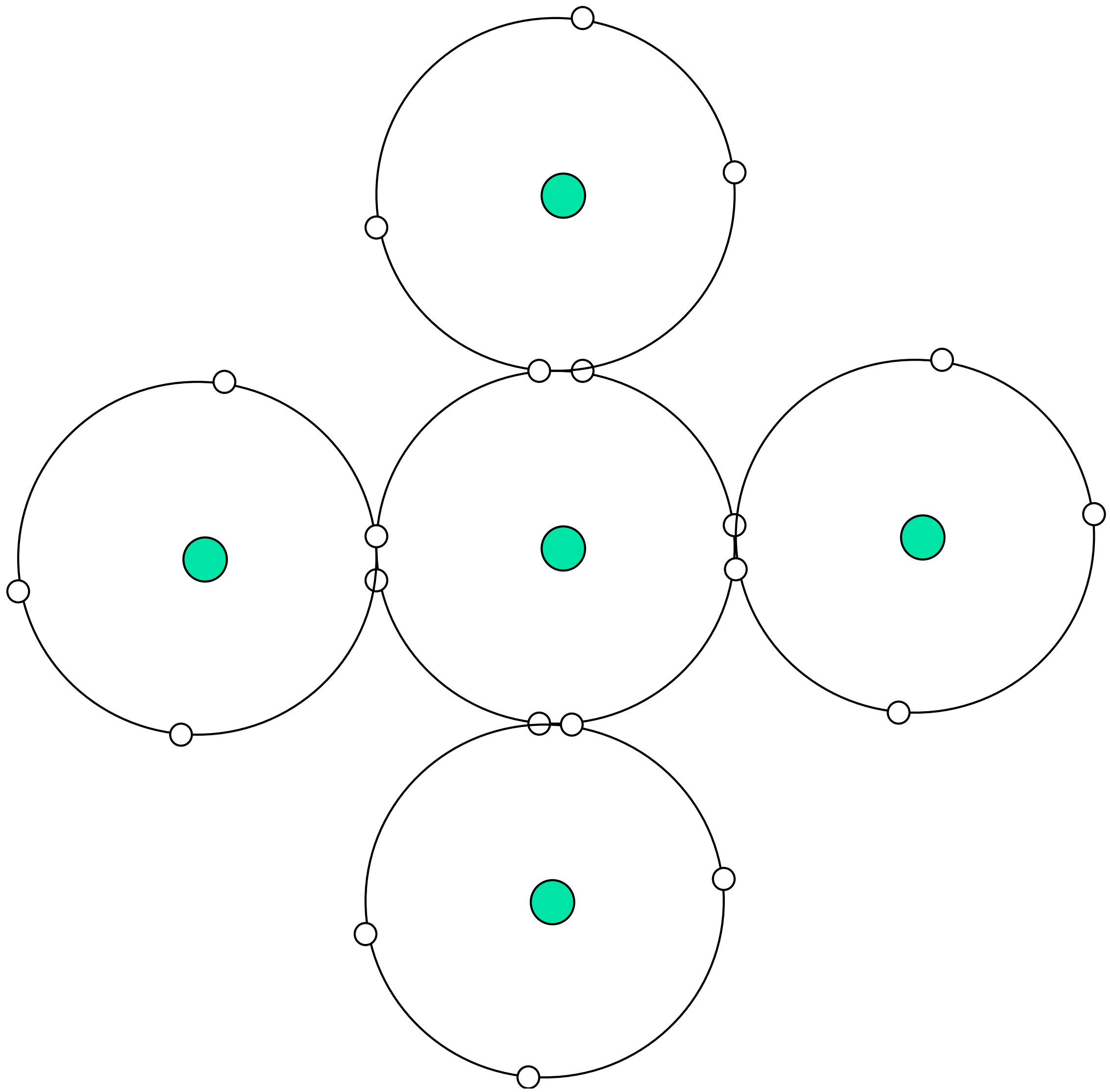
Silicon Lattice

- Cartoon two-dimensional view



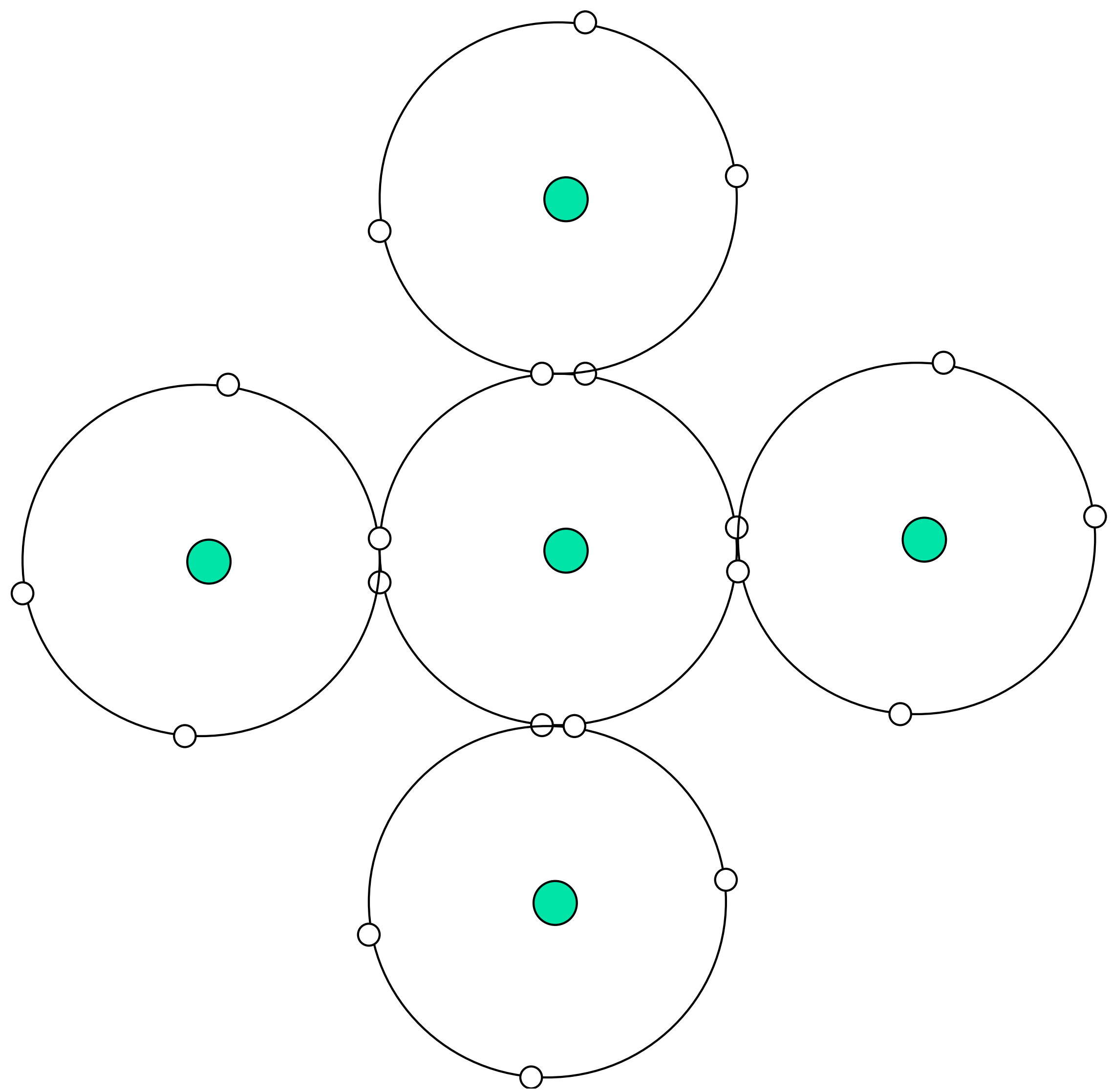
Outer Orbital?

- What happens to outer shell in Silicon lattice?



Energy?

- What does this say about energy to move electron?



Energy State View

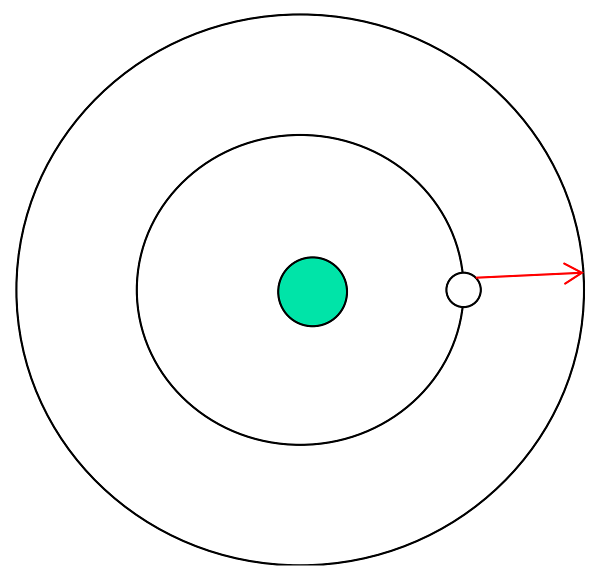
Valance Band – all states filled

Energy State View

Conduction Band– all states empty

Energy

Valance Band – all states filled



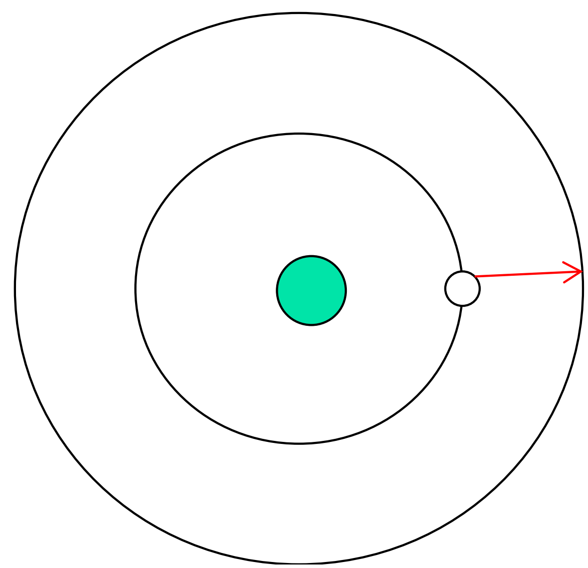
Energy State View

Conduction Band– all states empty

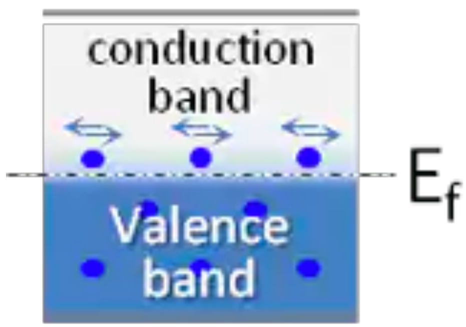
Energy

Band Gap

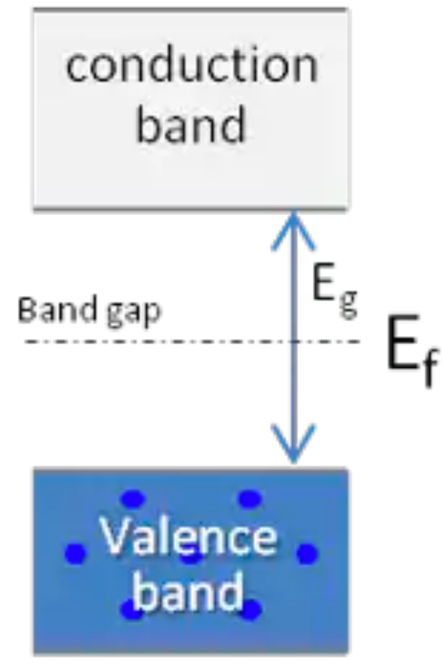
Valance Band – all states filled



Band Gap and Conduction

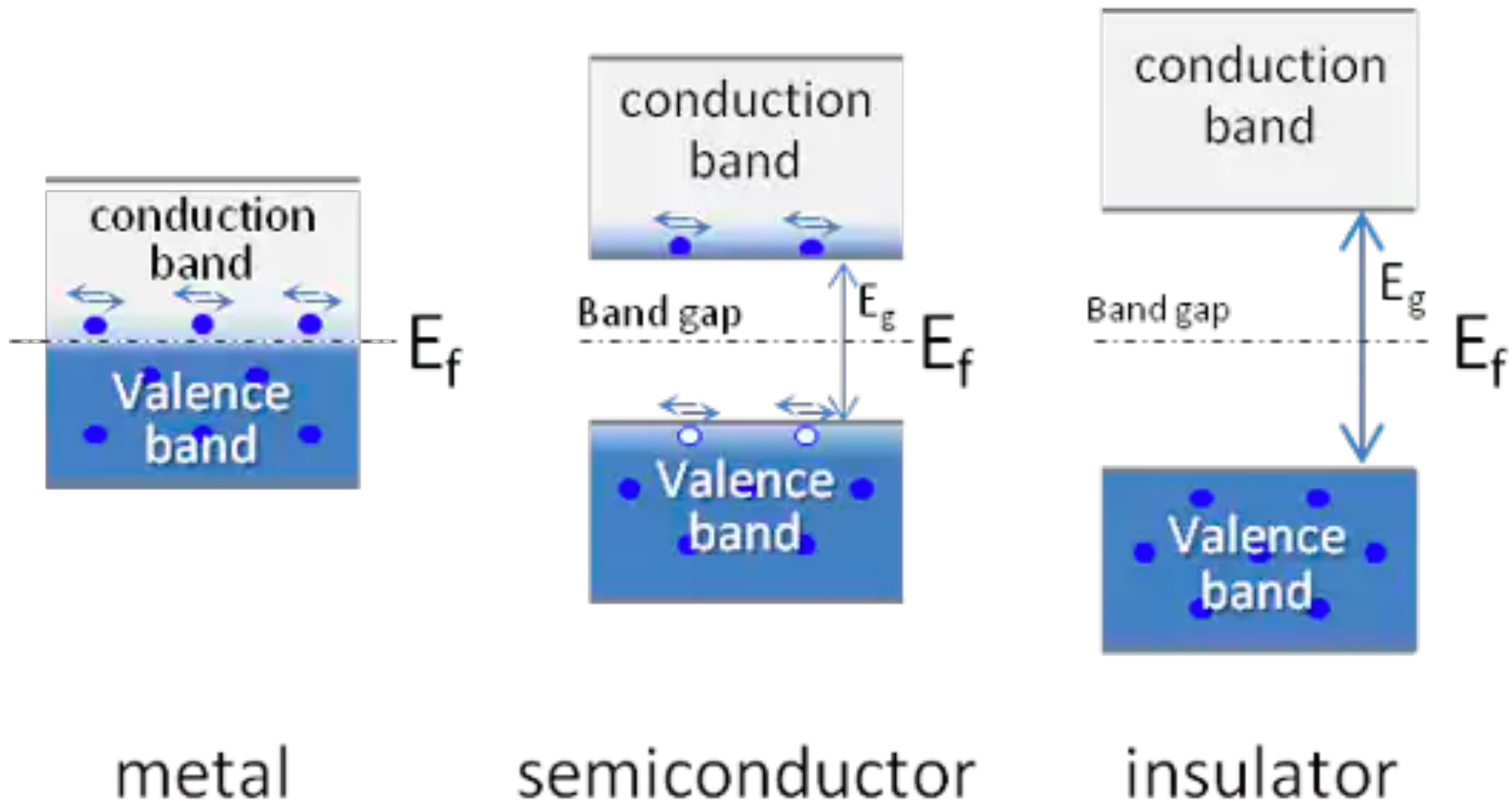


metal



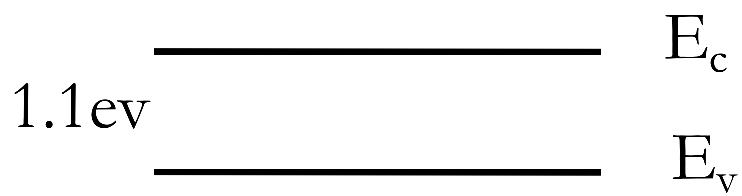
insulator

Band Gap and Conduction



Band Gap and Conduction

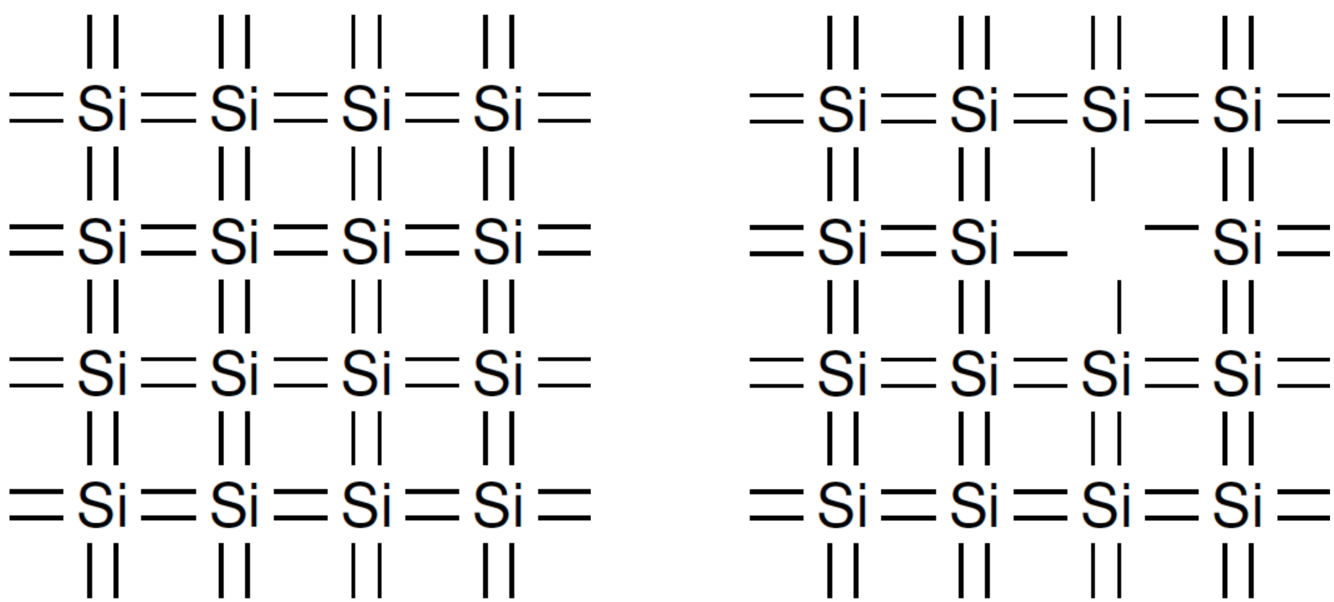
Semiconductor



1eV = 160 zeptojoules (10^{-21} J)

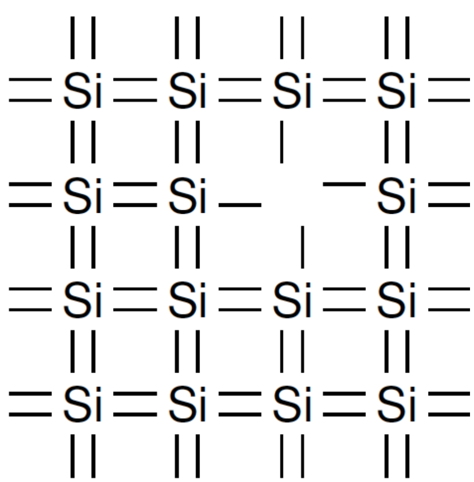
Doping

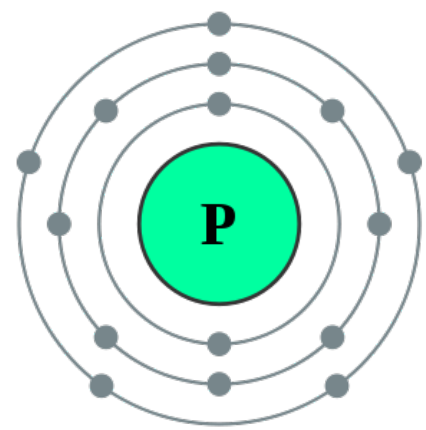
- Add impurities to Silicon Lattice
  - Replace a Si atom at a lattice site with another



Doping

- Add impurities to Silicon Lattice
  - Replace a Si atom at a lattice site with another
- Add a Group 15 element
  - *E.g.* P (Phosphorus)
  - How many valence electrons?





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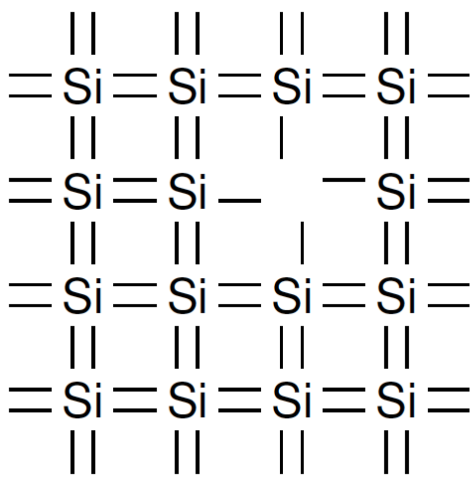
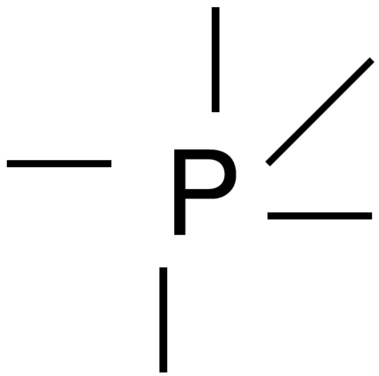
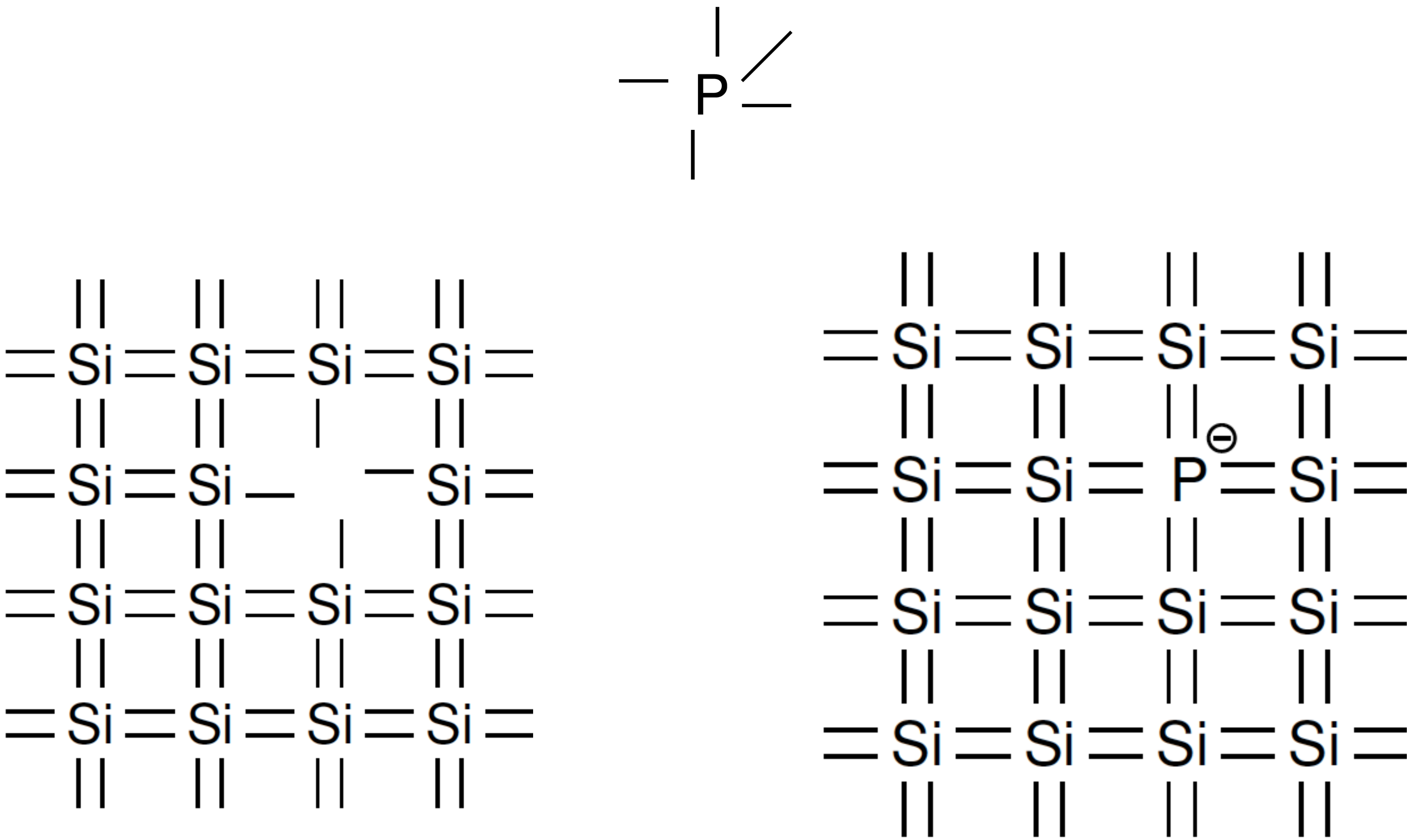


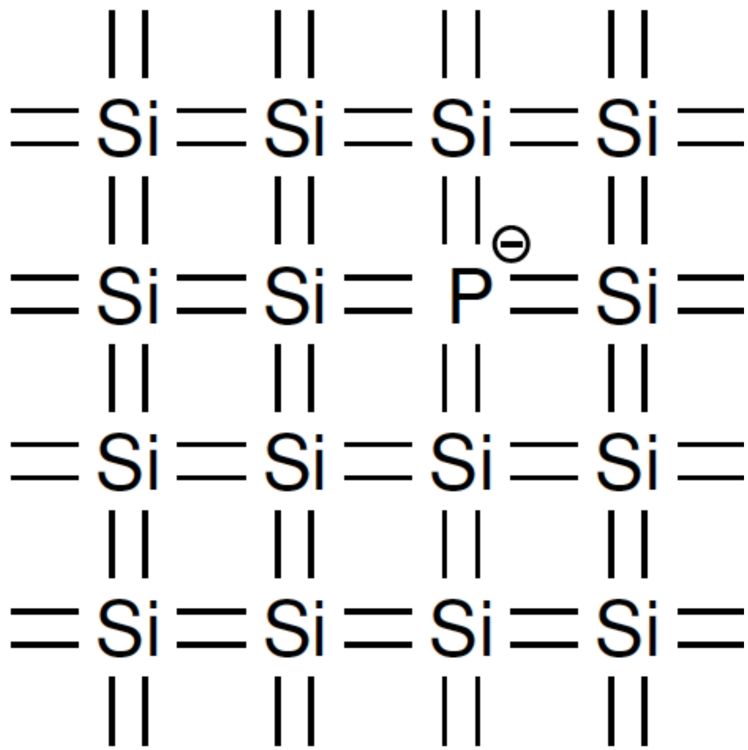


Doping with P



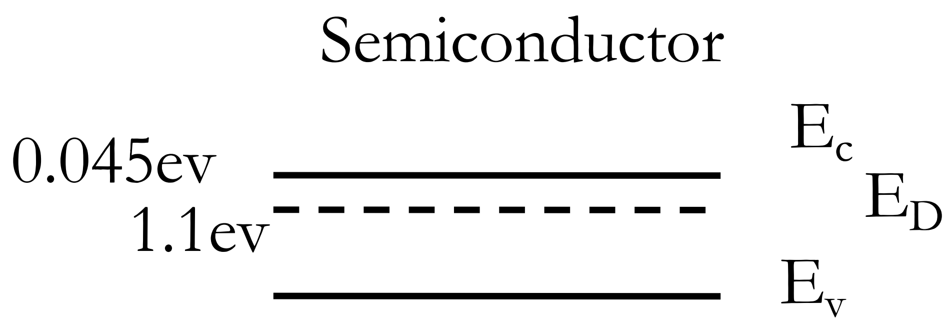
Doping with P

- End up with extra electrons
  - Donor electrons
- Not tightly bound to atom
  - Low energy to displace
  - Easy for these electrons to move



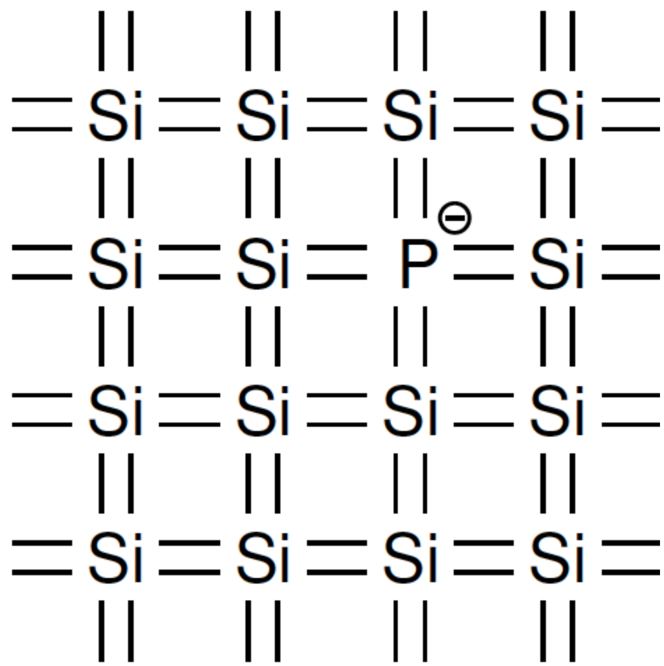
Doped Band Gaps

- Addition of donor electrons makes more metallic
  - Easier to conduct



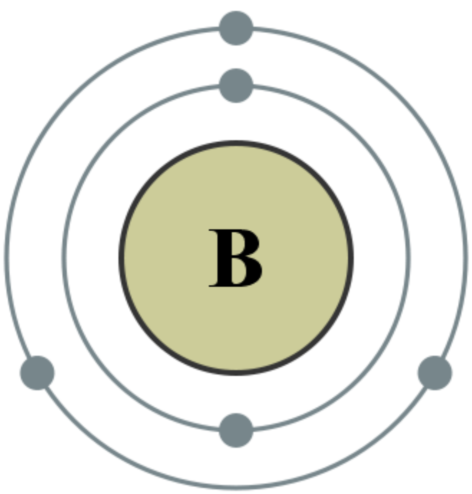
Localized

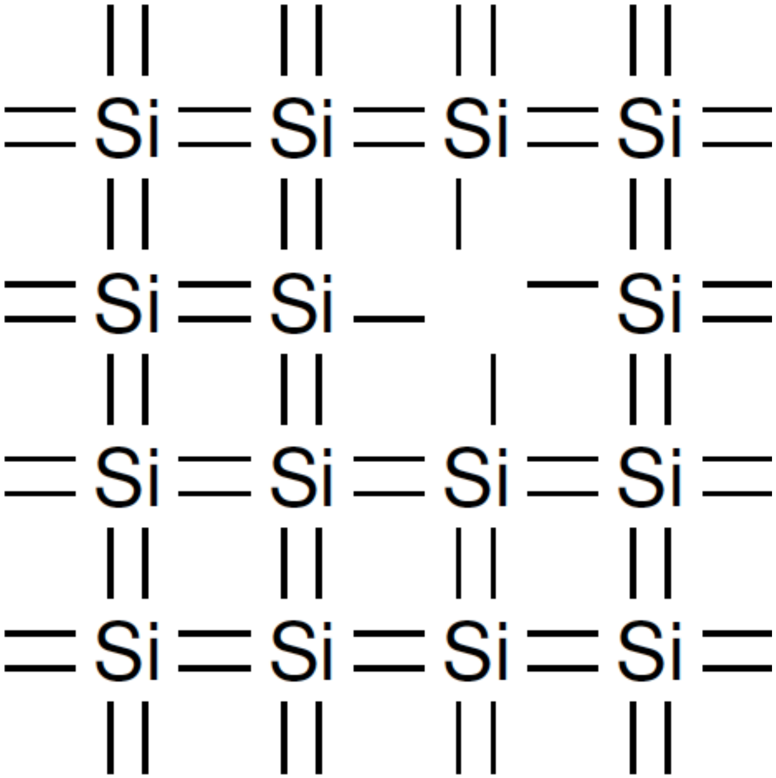
- Donor electron is localized
  - Won't go far if no low energy states nearby
- Increasing doping concentration
  - Ratio of P atoms to Si atoms
  - Decreases energy to conduct



Doping

- What happens if we replace Si atoms with group 13 atom instead?
  - E.g. B (Boron)
  - Valance band electrons?





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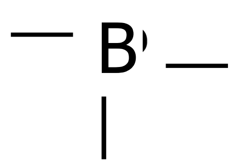
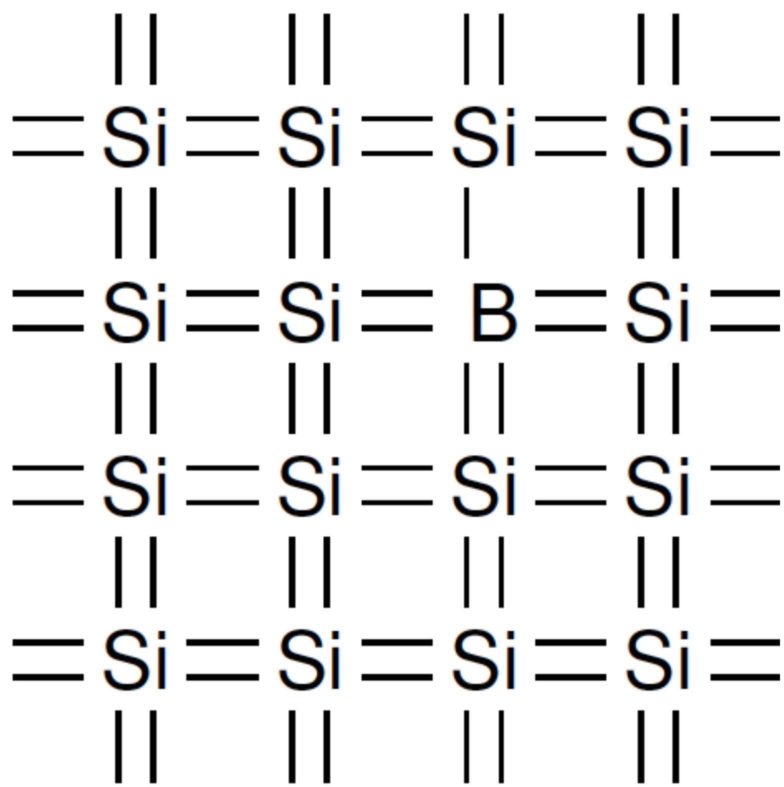
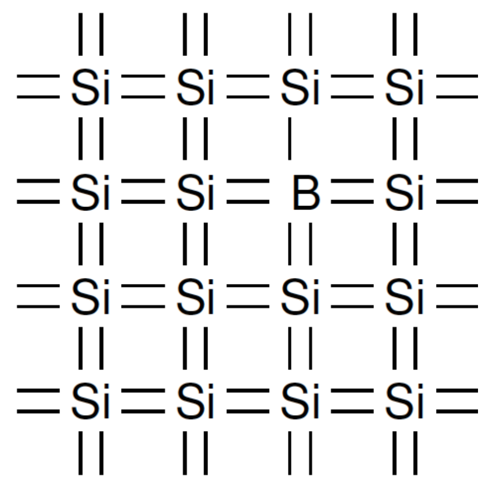




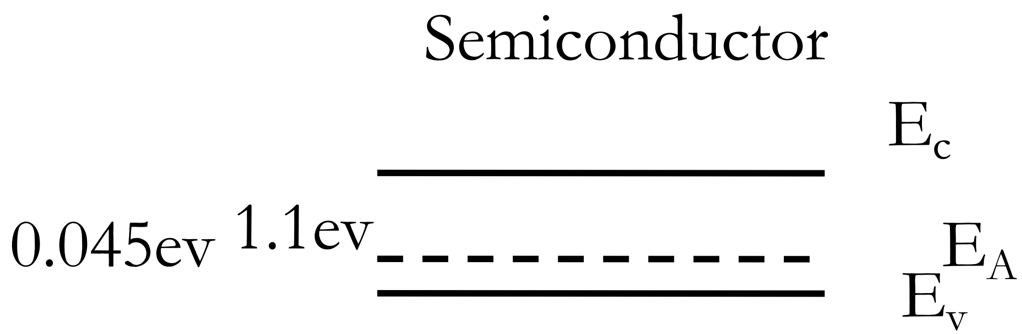
Doping with B

- End up with electron vacancies -- Holes
  - Acceptor electron sites
- Easy for electrons to shift into these sites
  - Low energy to displace
  - Easy for the electrons to move
    - Movement of an electron best viewed as movement of hole



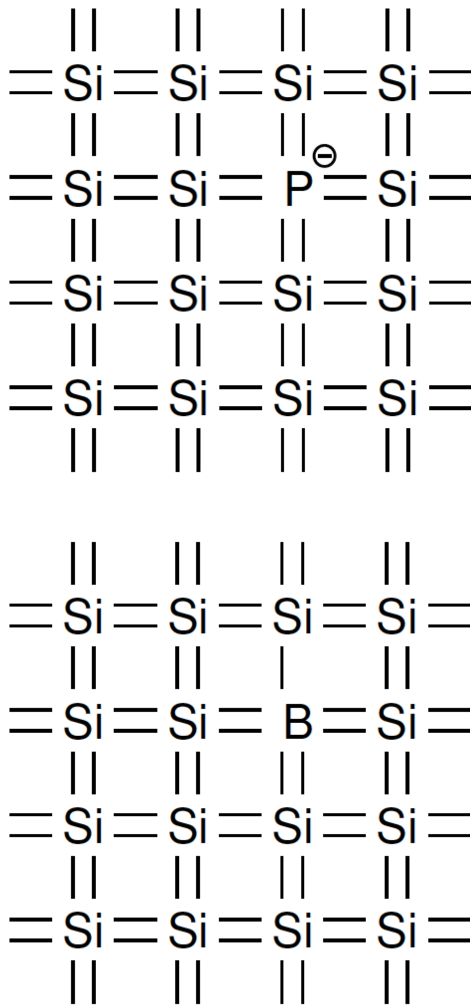
Doped Band Gaps

- Addition of acceptor sites makes more metallic
  - Easier to conduct



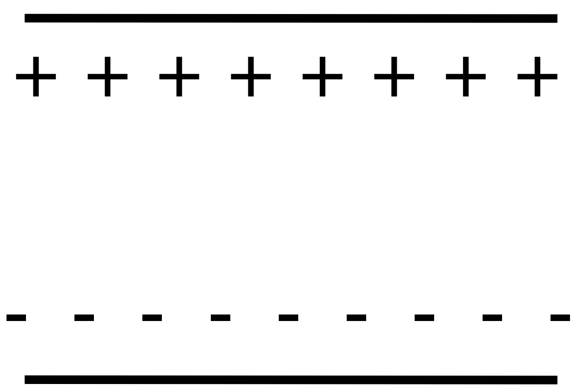
MOSFETs

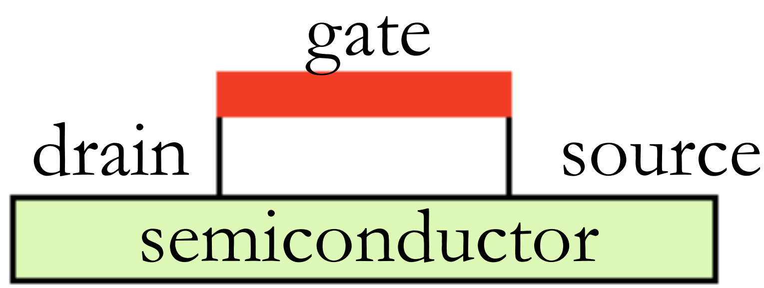
- Donor doping
  - Excess electrons
  - Negative or N-type material
  - NFET
- Acceptor doping
  - Excess holes
  - Positive or P-type material
  - PFET



Capacitor Charge

- Remember capacitor charge

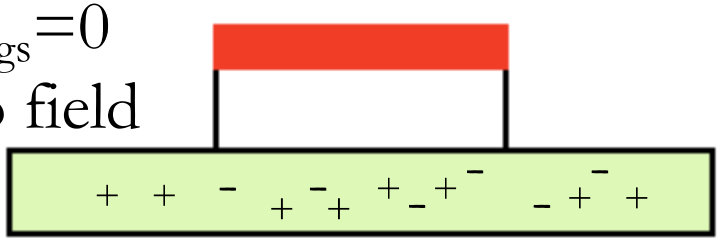




MOS Field?

- What does "capacitor" field do to the doped semiconductor channel?

V_{gs}=0
No field



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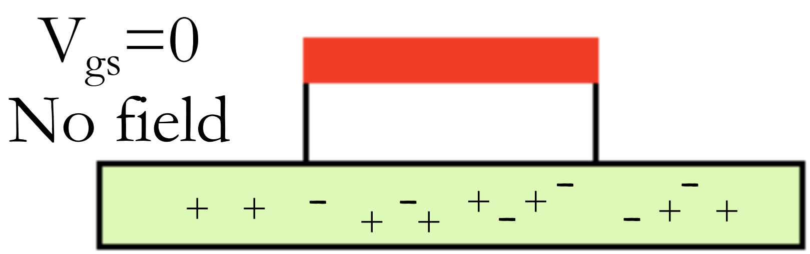

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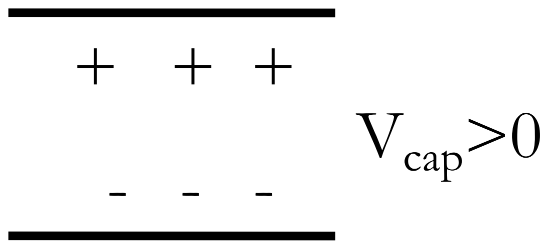

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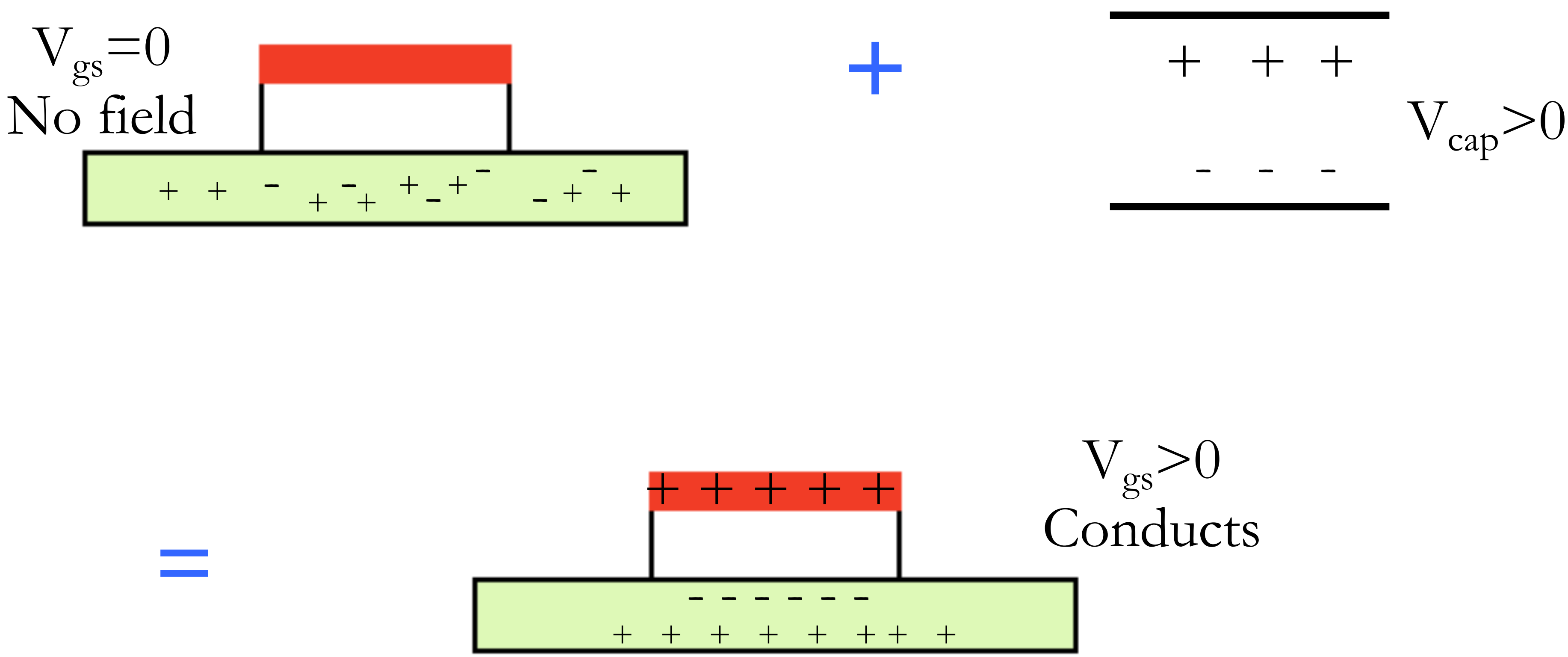

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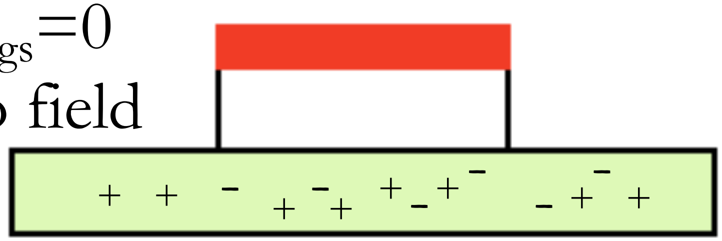

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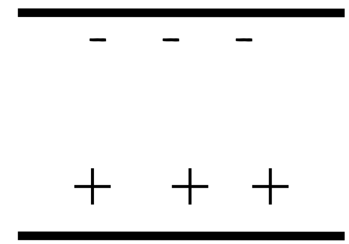
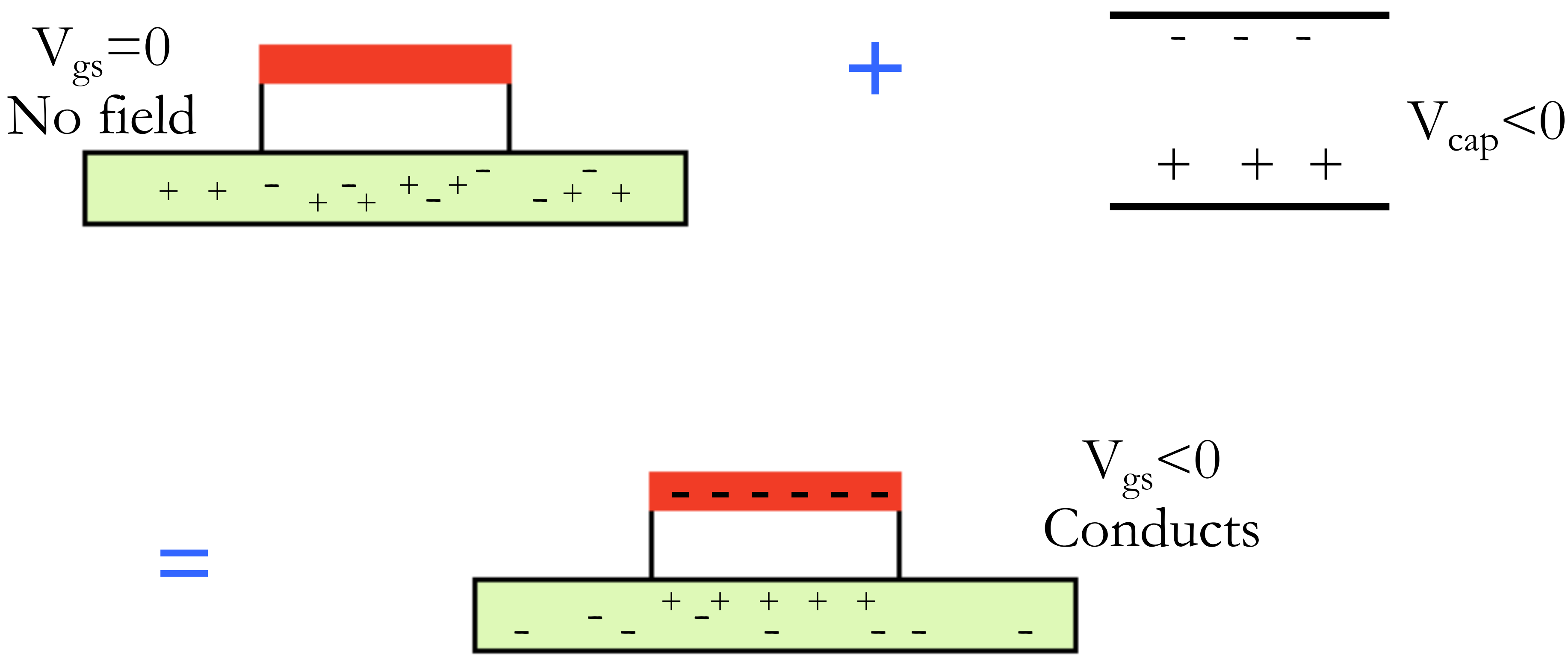


V_{cap}<0

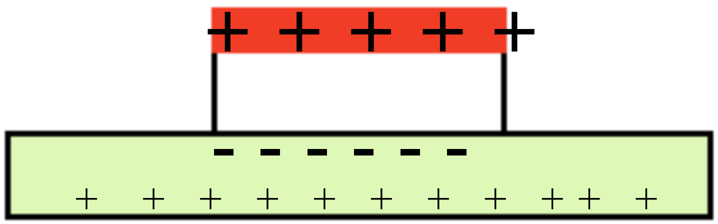
MOS Field?

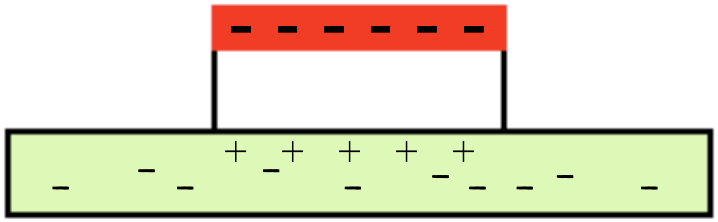
- What does "capacitor" field do to the doped semiconductor channel?



MOS Field Effect

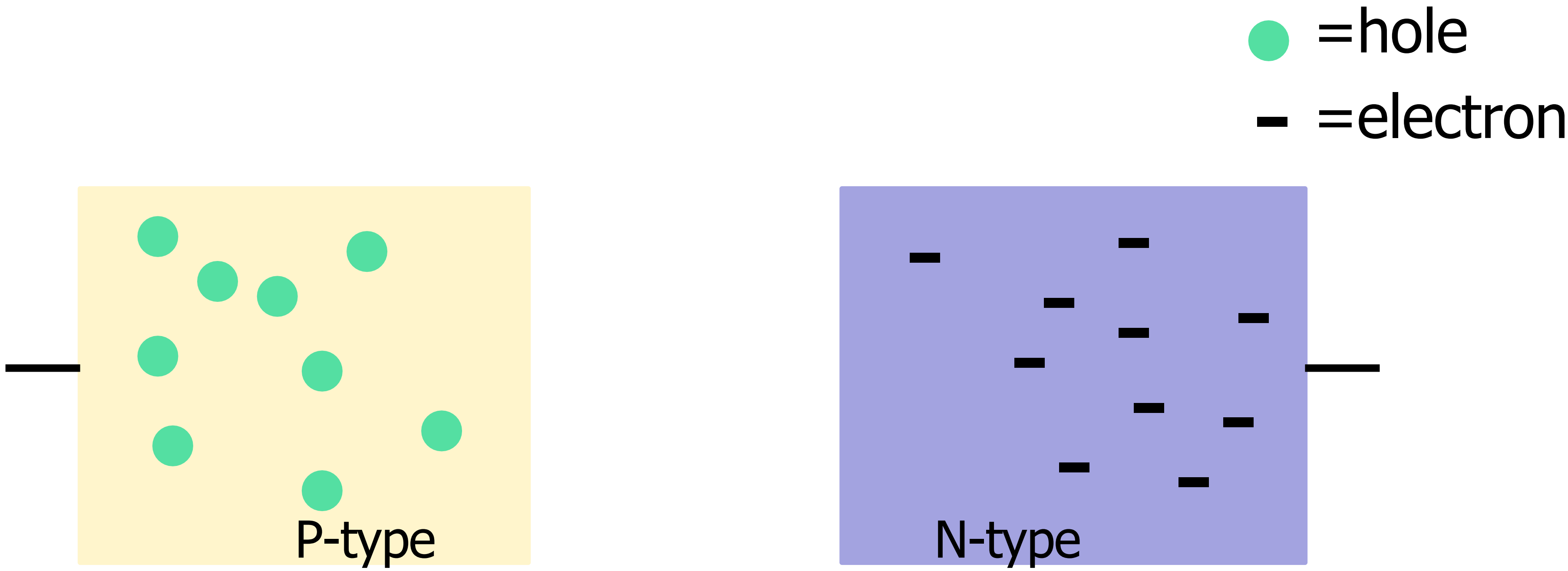
- Charge on capacitor
  - Attract or repel charges to form channel
  - NMOS: Positive field on p-type substrate
    - Attracts electrons to surface to form conducting channel
  - PMOS: Negative fiend on n-type substrate
    - Attracts holes to surface to form conducting channel





PN Junction

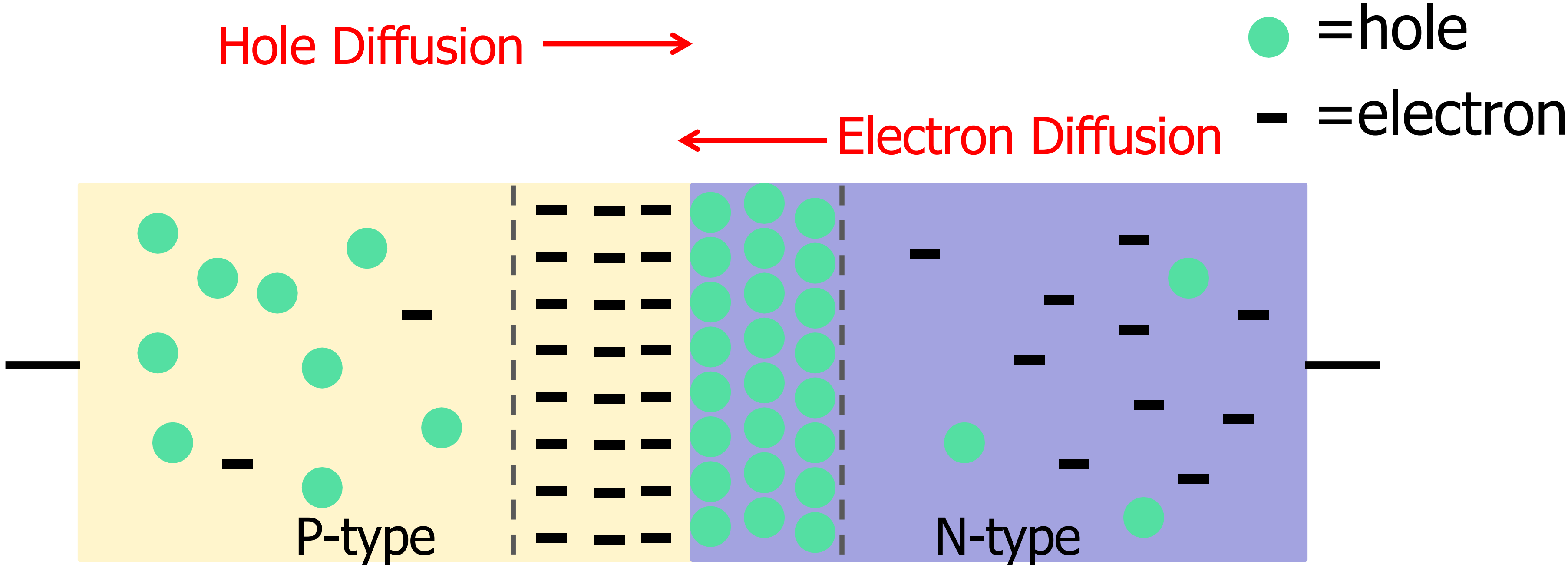
Doped Silicon



Excess holes

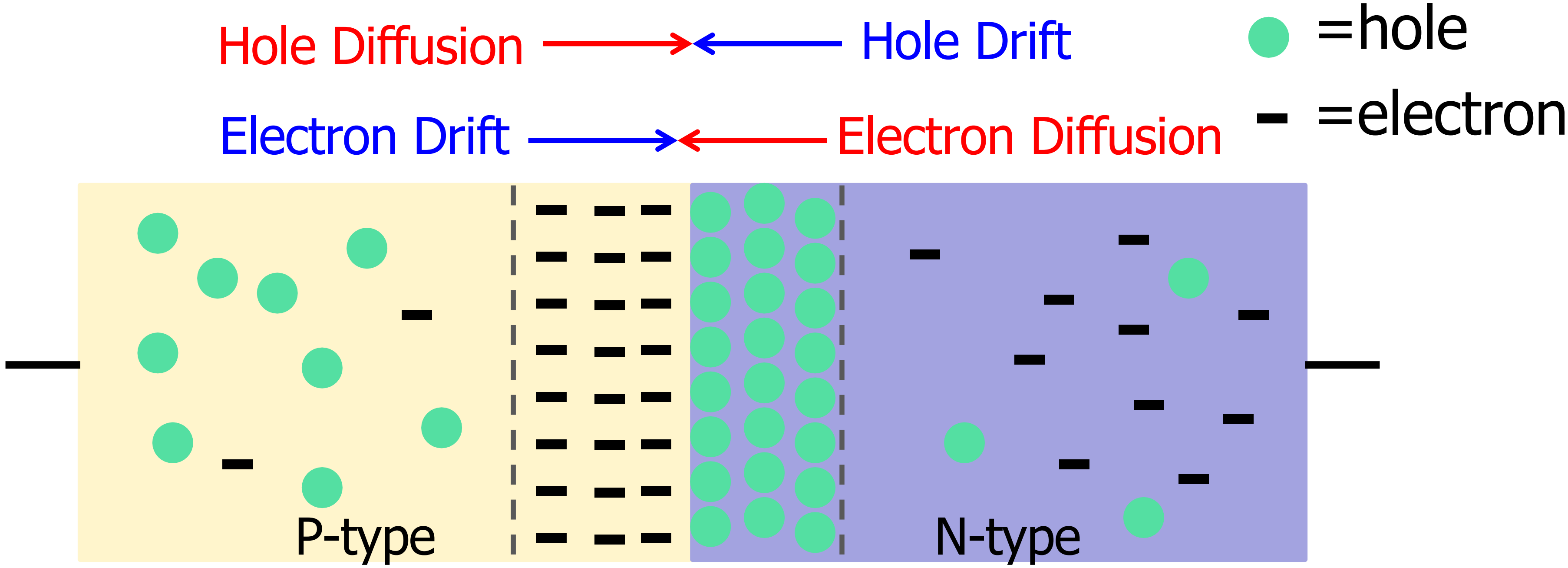
Excess electrons

PN Junction



- PN junction causes a depletion region to form
  - Electrons diffuse from N-type to P-type
  - Holes diffuse from P-type to N-type
    - Diffusion current caused by diffusion of carriers

PN Junction

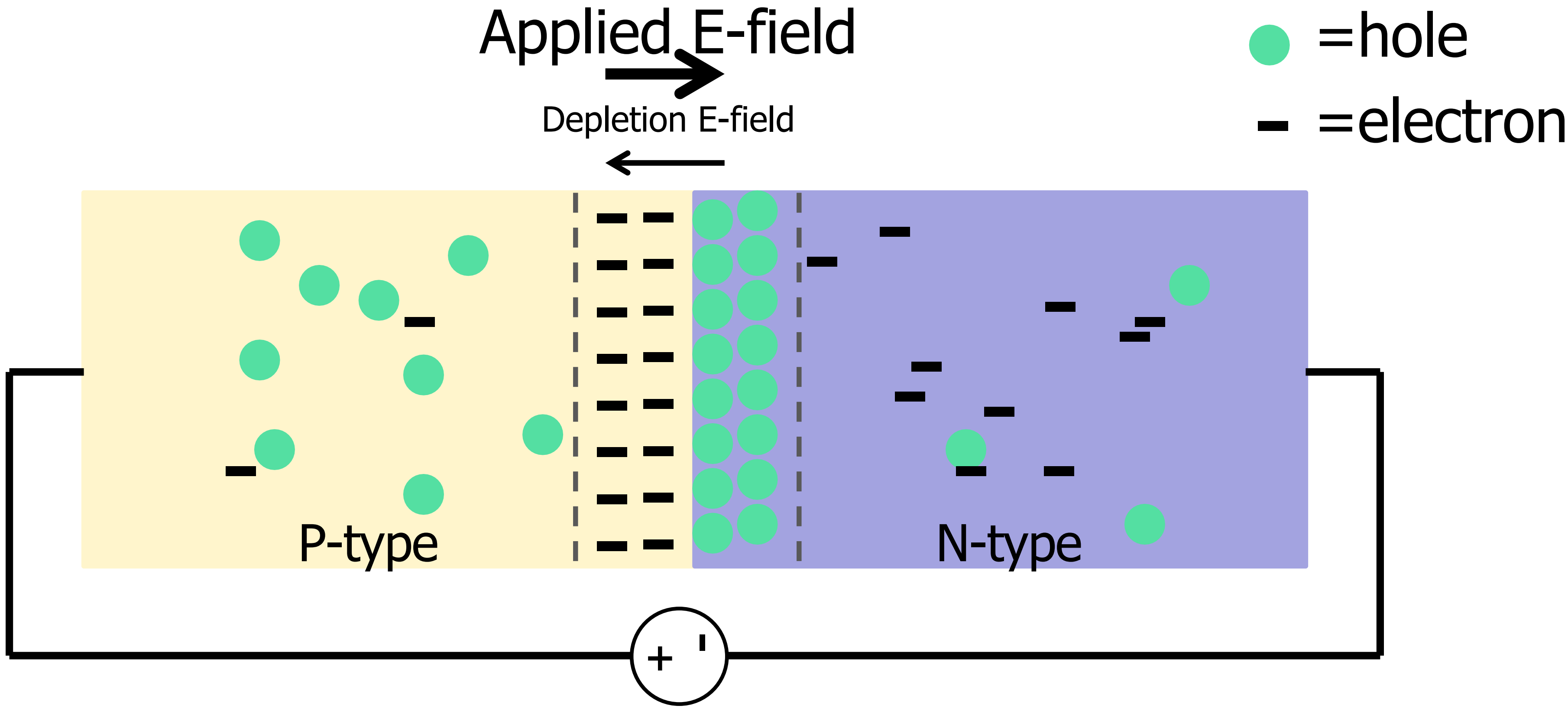


- PN junction causes a depletion region to form
  - Electrons diffuse from N-type to P-type
  - Holes diffuse from P-type to N-type
    - Diffusion current caused by diffusion of carriers
- Equilibrium achieved when V_{bi}, built-in potential, is formed across the depletion region
  - Drift current cause by E-field due to V_{bi} to counteract diffusion current

Drift/Diffusion Currents

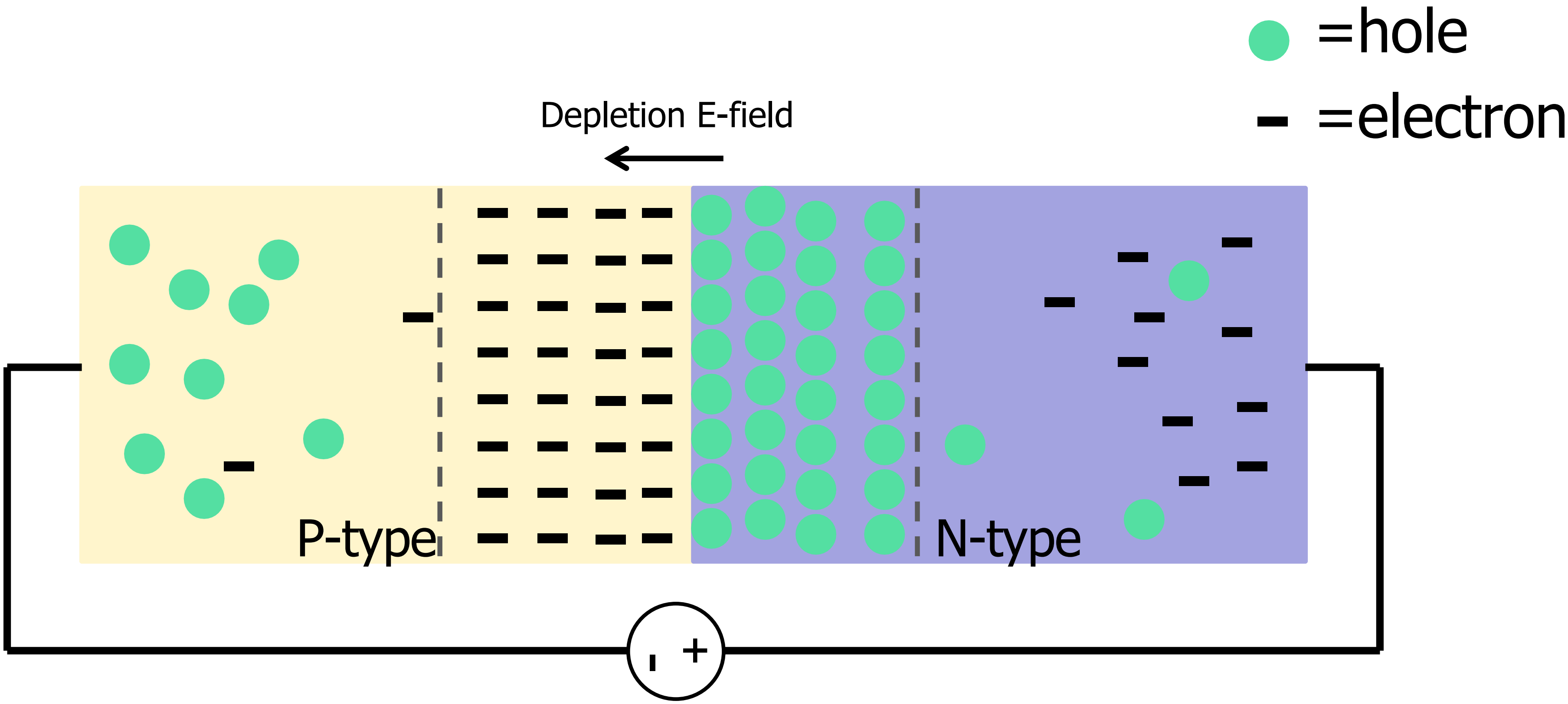
- Diffusion current
  - Current caused by semiconductor diffusion of holes and electrons
- Drift current
  - Current due to movement of holes and electrons caused by force from potential difference induced e-field

PN Junction – Forward Biasing



- Forward biasing connect positive terminal to p-type and negative terminal to n-type
  - Holes/electrons pushed towards depletion region, causing it to narrow
  - The applied voltage e-field continues to narrow the depletion region (i.e reduce the depletion e-field)
  - current flows through the device from p-type to n-type

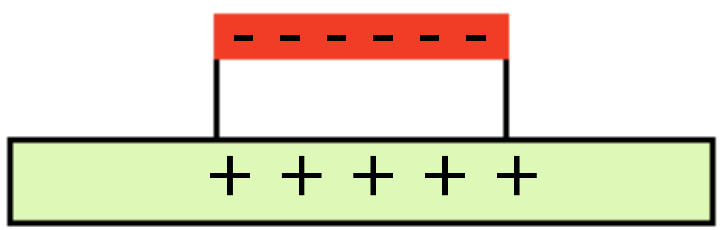
PN Junction – Reverse Biasing



- Reverse biasing connect positive terminal to n-type and negative terminal to p-type
    - Holes/electrons attracted away from depletion region, causing it to widen
        - No current flows through the device
    - If reverse bias increases past breakdown voltage, the depletion e-field increases until breakdown occurs and reverse biased current flows causing thermal damage to junction

Big Ideas: MOSFET

- Semiconductor can act like metal or insulator
- Use electric field to modulate conduction state of semiconductor



Admin

- HW 2 due Monday

- More Fabrication Videos:
  - From sand to silicon (intel) - https://www.youtube.com/watch?v=Q5paWn7bFg4
  - How microchips are made - https://www.youtube.com/watch?v=F2KcZGwntgg