09-Photovoltaics Part 1

ECEGR 452
Renewable Energy Systems

Overview

- PV Industry
- PV Basics
- Silicon
- PV Physics
- Diffusion and Drift
- N- and P-Type Material
- PN Junction
- Bias

Introduction

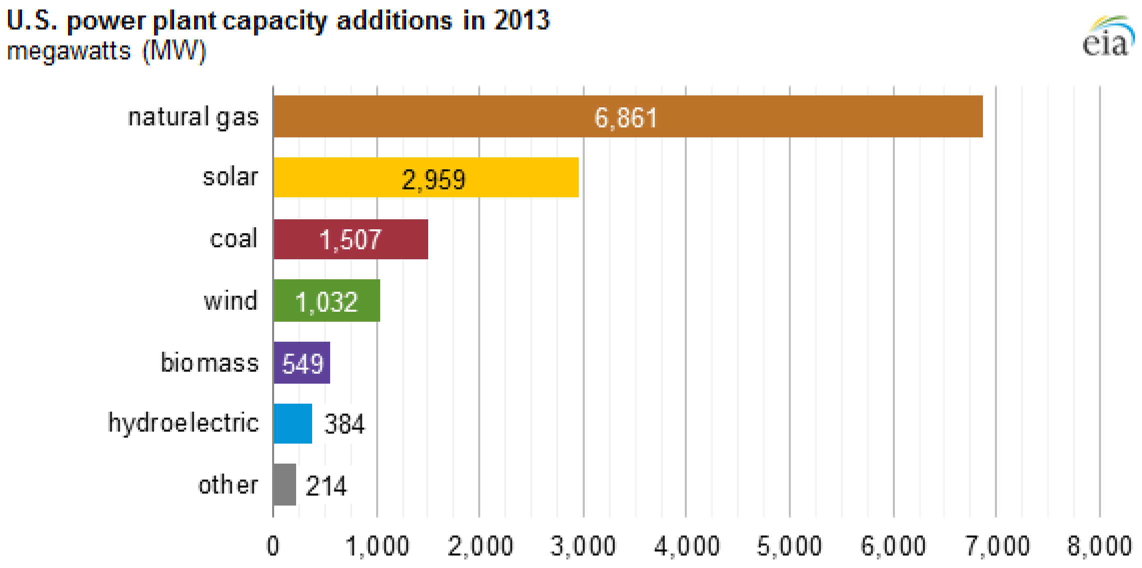
- Photoelectric Effect is the mechanism by which solar photovoltaic (PV) works
- Electricity is directly generated
- Discovered by Edmond Becquerel in 1839
- Established for power generation in 1954 by Chapin, Fuller and Pearson

PV Industry

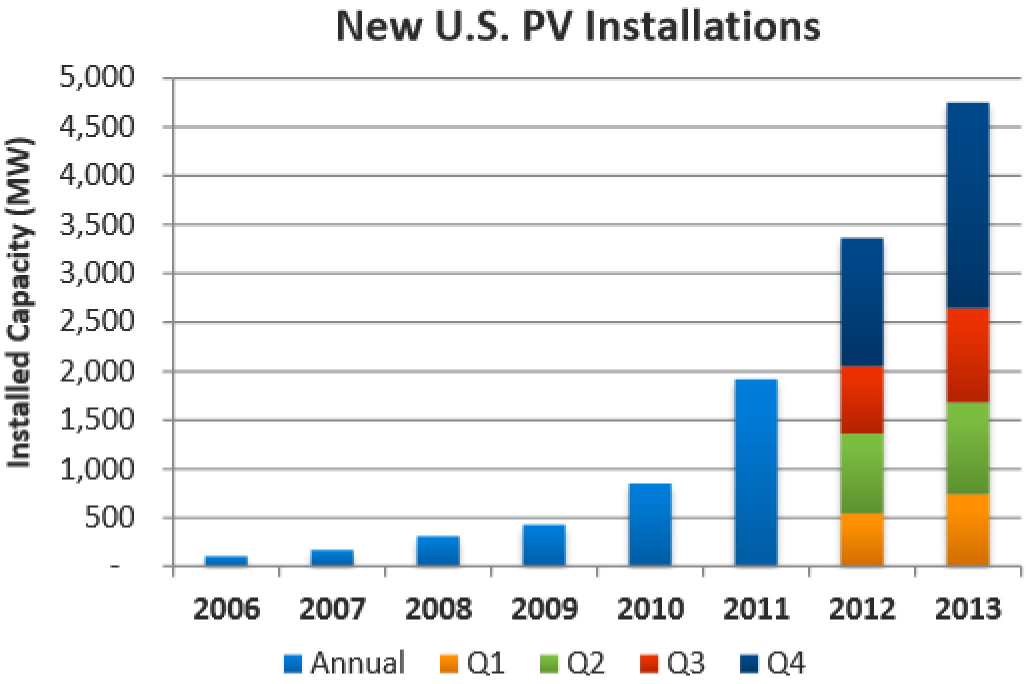
- Solar (thermal and PV) supplies less than 1% of the electrical energy in the US
- Germany is the world leader in PV (36 GW), China, US are catching up
- Volatile market
    - Price dropping

PV Industry

- Total US PV capacity: 13,000 MW (2014)
  - 4,751 MW added in 2013 (41% growth)



PV Industry



Source: SEIA.org

PV Basics

- Advantages of PV
    - Zero fuel costs
    - Availability of fuel (still produces energy if there is no DNI)
    - No moving parts (no noise, reduces maintenance)
    - Modular design (can also be integrated into buildings)
    - No emissions

PV Basics

- Disadvantages of PV
  - high capital costs (decreasing)
  - low efficiency
  - use of toxic materials in some manufacturing processes
  - need for power electronic inverter (DC/AC converter) for grid-connected applications
  - intermittent and variable
  - cloud cover is difficult to predict

Solar PV Costs

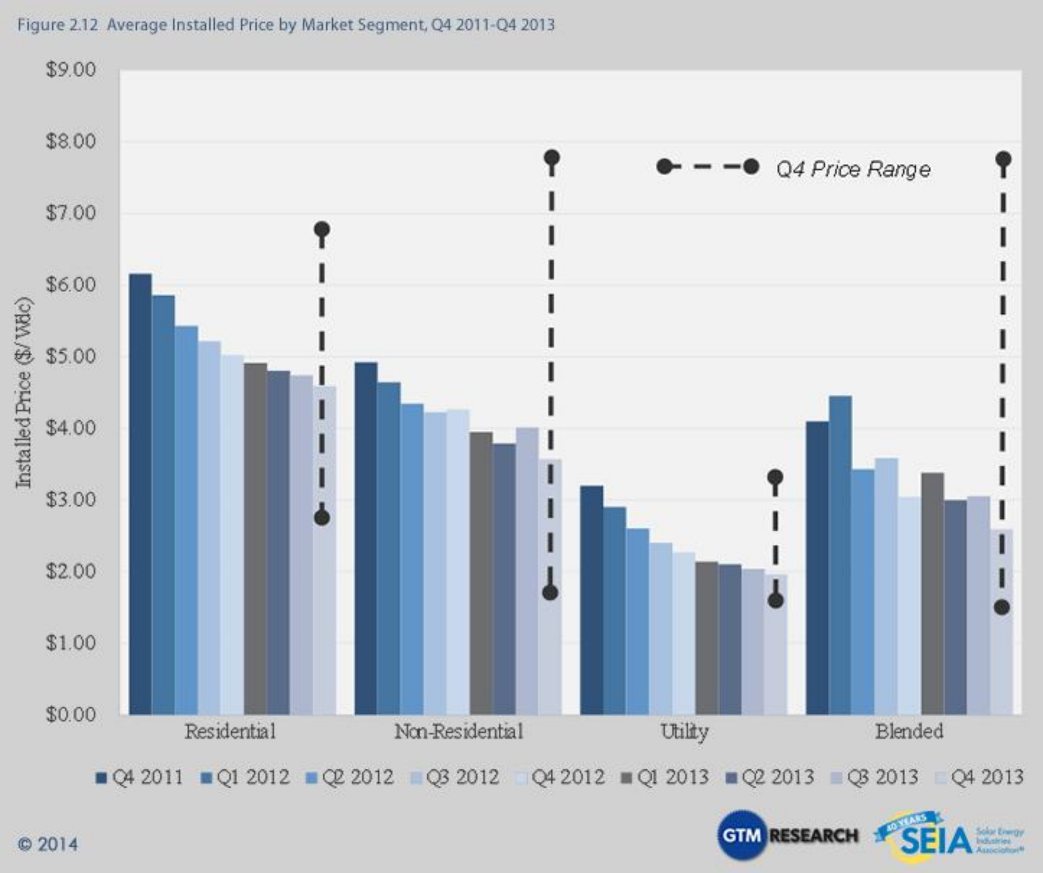


Figure 2.12 Average Installed Price by Market Segment, Q4 2011-Q4 2013

Source: SEIA.org

PV Industry

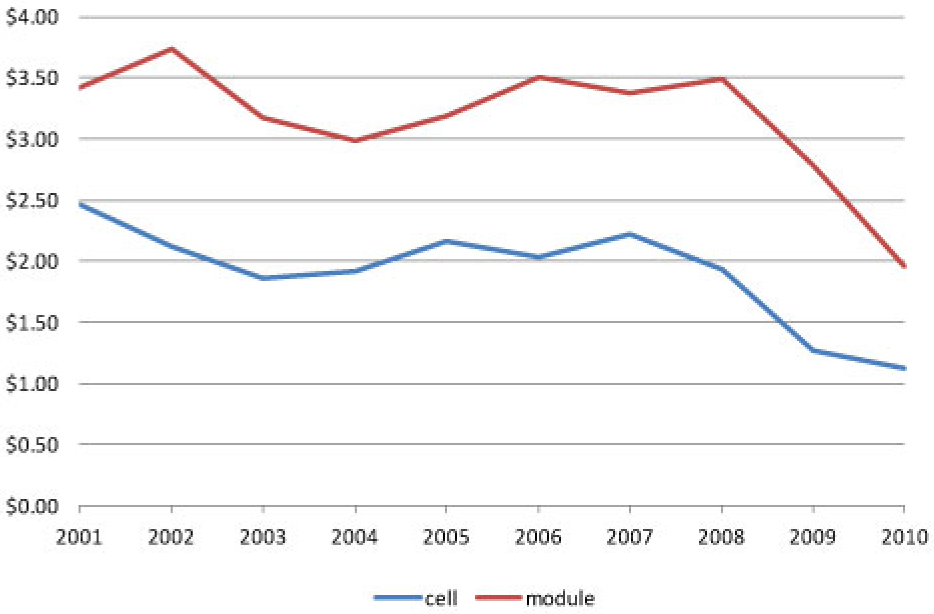
monocrystalline

polycrystalline

thin film

PV Industry

Figure 2. Average price of photovoltaic cells and modules, 2001-2010
dollars per peak watt



Source: U.S. Energy Information Administration (EIA), Form EIA-63B, Annual Photovoltaic Cell/Module Shipments Report."

What are possible causes of the price drop?

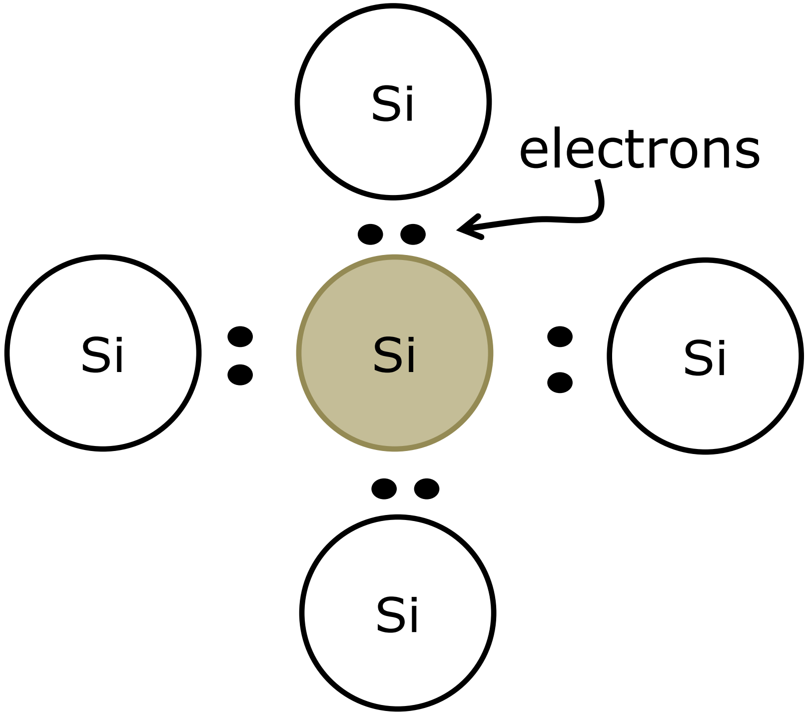
PV Basics

- PV cells produce electricity when photons illuminate a pn junction
- Photon excites an electron out of the valence band into the conduction band
- Built-in electrostatic field pushes the electron through the circuit
- pn junctions are common in semiconductors

Silicon

- Silicon (Si) is often used in semiconductors
- 2nd most abundant element on Earth
- Si is Group 14 Element (old IUPAC Group IV)
    - 4 outer (valence) electrons
    - Silicon crystal forms a diamond lattice
    - Each Si atom shares 2 electrons with its neighbors

Silicon

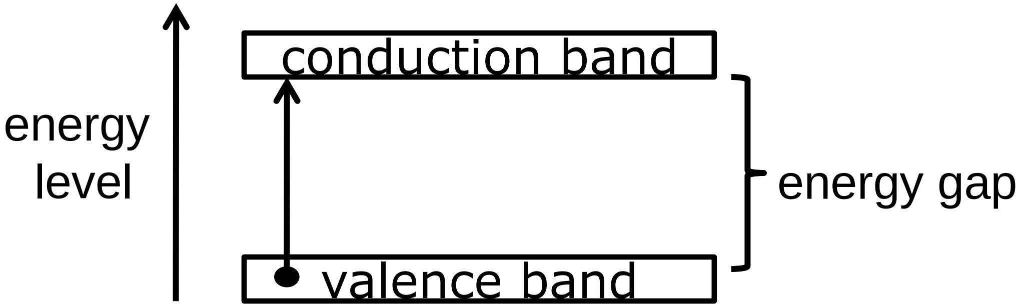


Silicon

- Valence electrons largely dictate the electrical properties of a material
- Silicon crystal: all valence electrons are tightly held in covalent bonds
- Energy of the electron must fall within well-defined bands (quantum theory)

PV Physics

- Add enough energy to an electron in the valence band and it “jumps” to the conduction band
- Free electron: electron in the conduction band
- Free electrons can flow through the circuit or drop back into the valence band (recombination)



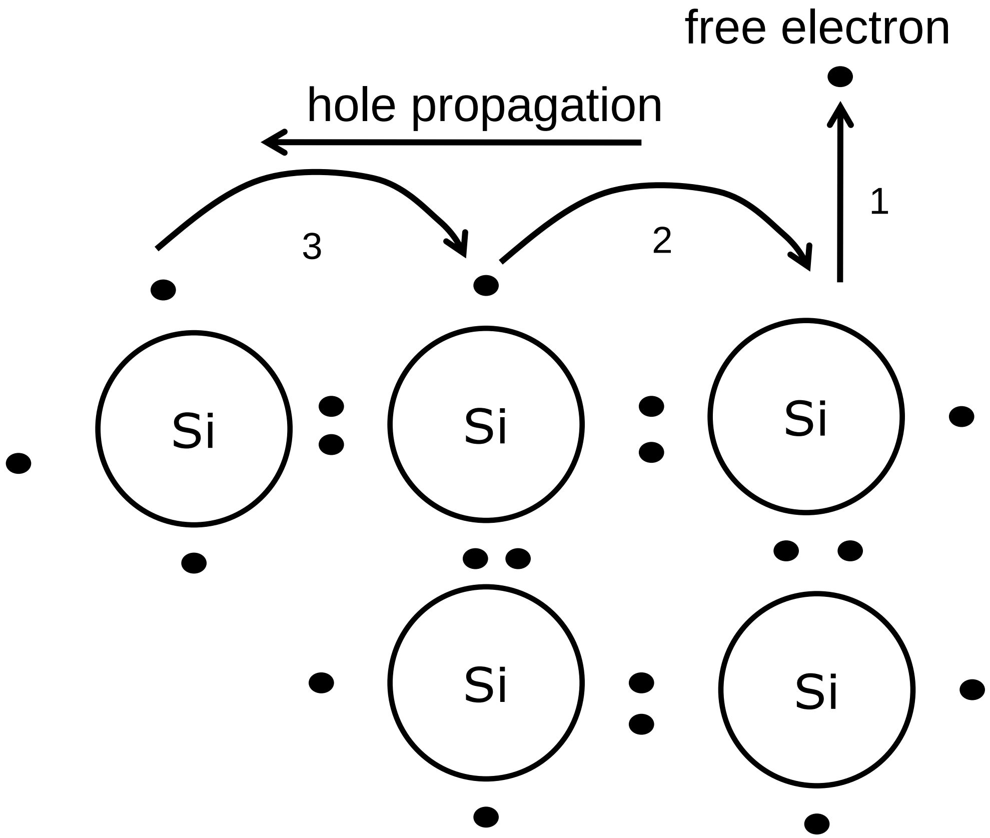
PV Physics

- The required energy is known as the Energy Gap
- Energy Gap is fundamental to the operation of PV
- Energy Gap varies with type of semiconductor
  - Crystalline Si: 1.1 eV (electron-volt, 1.6 x 10^{-19})
  - Amorphous Si: ~1.75 eV

PV Physics

- Hole: silicon with a missing electron (net positive charge)
- Hole may attract an electron from a neighbor
- Process may repeat and hence, the hole propagates

PV Physics



Diffusion and Drift

- Holes and free electrons move through the Si crystal by two mechanisms: diffusion and drift
- Note: current flows in a direction opposite of the direction of the electrons
- If free electrons are evenly distributed and there is no external electric field, then the free electrons move randomly
  - No net current

Diffusion and Drift

- If concentrations of electrons exist, then:
  - Diffusion (I_D): process of electrons distributing themselves from regions of high concentration to low concentration, independent of an applied electric field
- External electric field causes movement:
  - Drift (I_S): electrons move toward positive electric field (current away from positive)

Doped Silicon

- In pure Si (intrinsic) there are very few free electrons (recombination quickly occurs)
    - Intrinsic Si is an insulator
- To promote free electrons, Si is doped
    - n-type material
    - p-type material

N-type Material

- Introduce Phosphorus into the Si lattice
  - P
  - Atomic weight 15
  - 5 valence electrons
- 4 valence electrons form bonds with neighboring Si, the 5th must be in the conduction band

N-type Material

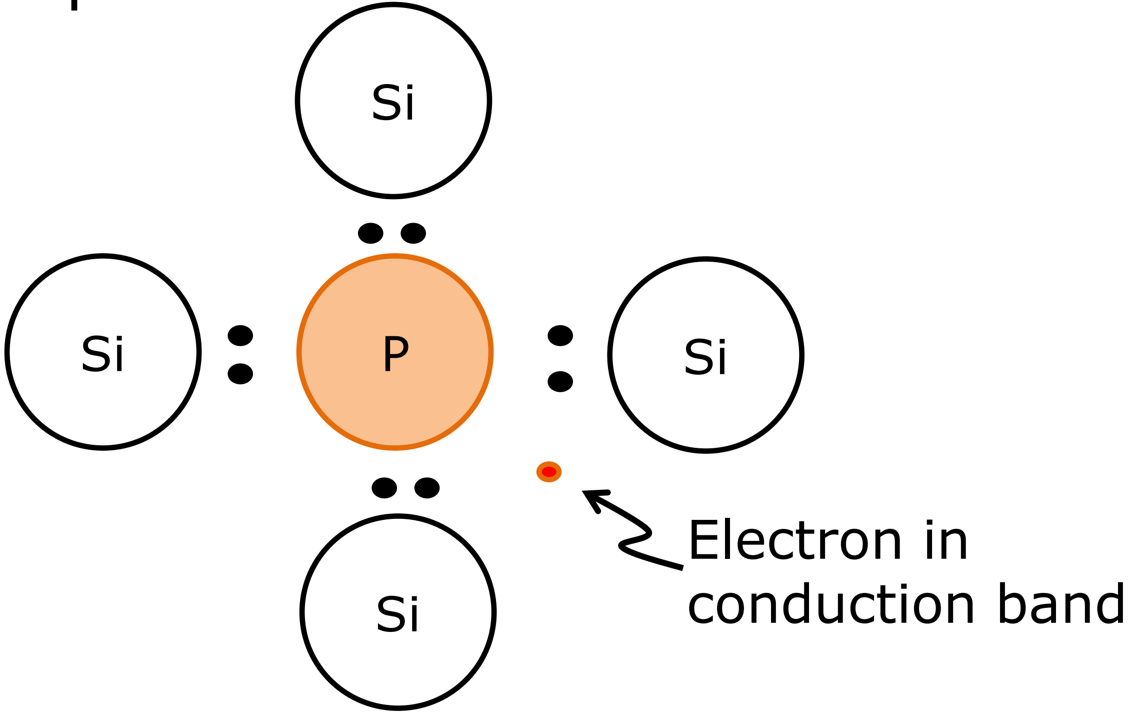
- Does P-doped silicon have a net charge?
  - Yes
  - No

N-type Material

- Does P-doped silicon have a net charge?
    - Yes
    - [✓ No]
- electrons = protons

N-type Material

- Note: no hole is generated, even if free electron moves away
- No net charge
- P becomes a positive ion if electron moves away



N-type Material Recap

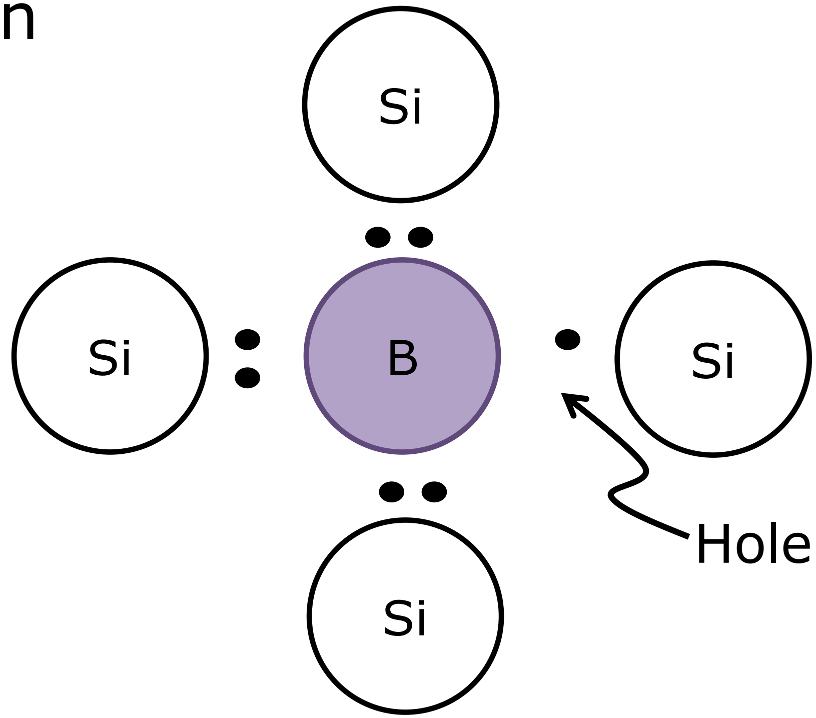
- Doping intrinsic Si with P
  - Increases the number of free electrons
  - Material becomes a conductor
  - Does not lead to an overall net charge
  - Does not create holes (though holes may exist due to thermal excitation of electrons, known as minority carriers in n-type material)
- Other elements (known as donors) other than P (Group V) can be added

P-Type Material

- Introduce Boron into the Si lattice
  - B
  - Atomic weight 13
  - 3 valence electrons
- 3 valence electrons form covalent bond
- 1 hole remains
- Free electrons may exist due to thermal excitation (free electrons are minority carriers in p-type material)

P-Type Material

- No free electrons are generated
- No net charge
- If a free electron fills the hole, then B is a negative ion



P-type Material

- P-type material has more free electrons than N-type material
  - True
  - False

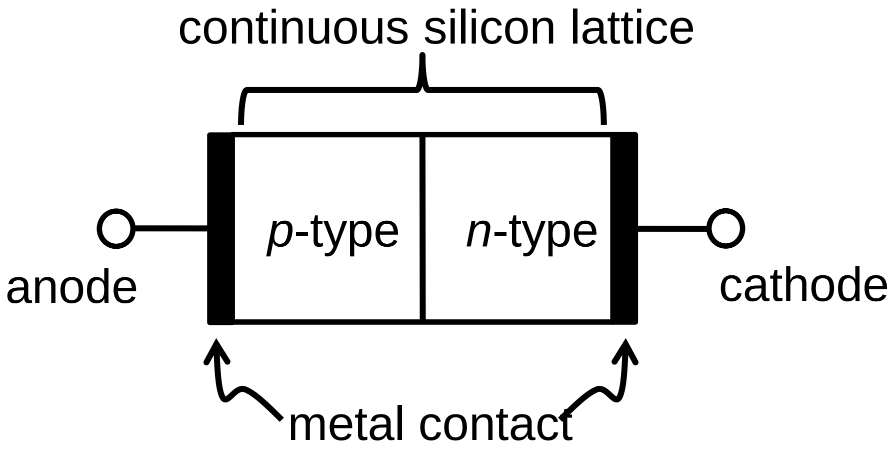
- P-type material has a positive charge
  - True
  - False

P-type Material

- P-type material has more free electrons than N-type material
  - True
  - [✓ False]
- P-type material has a positive charge
  - True
  - [✓ False]

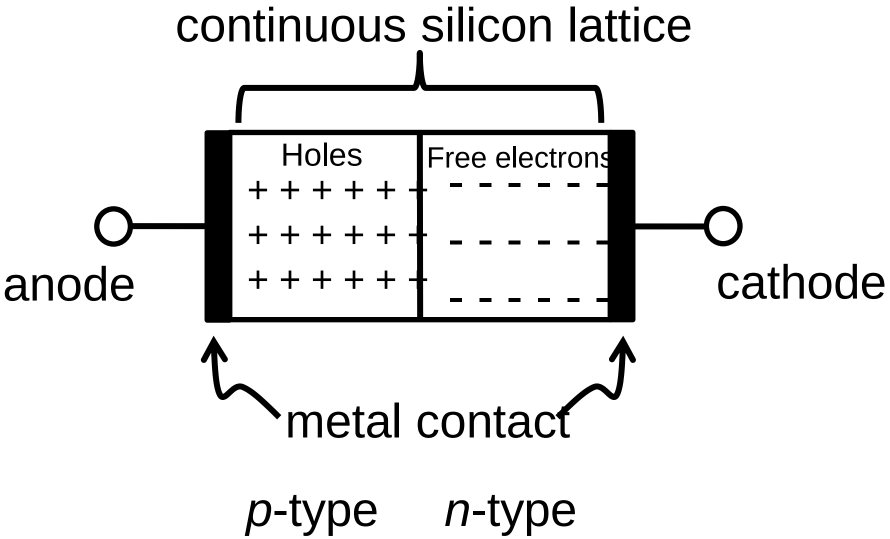
PN Junction

- What happens when p-type material and n-type material are placed next to each other?
  - Note: they are formed together from a continuous crystal, not a mechanical junction



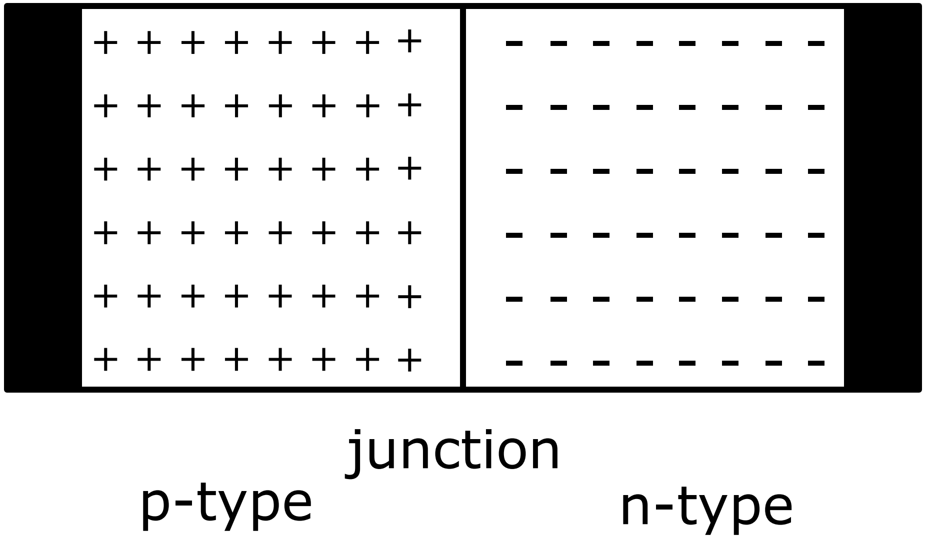
PN Junction

- Again, there is no net charge
- What happens next?
  - Diffusion!



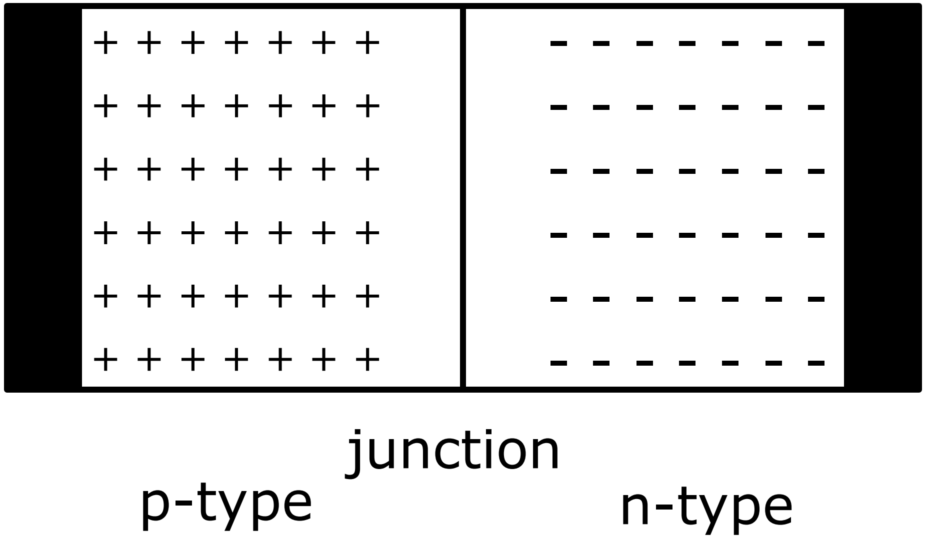
PN Junction

- Diffusion current from p-type to n-type



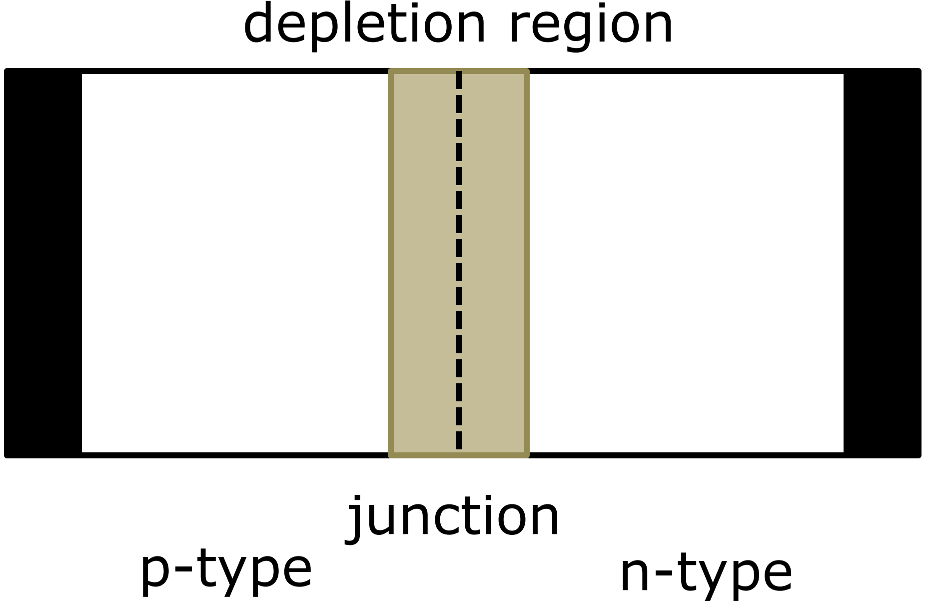
PN Junction

- As free electrons move from n-type to p-type they quickly find holes and recombine near the junction
    - Analogous process happens with holes leaving the p-type

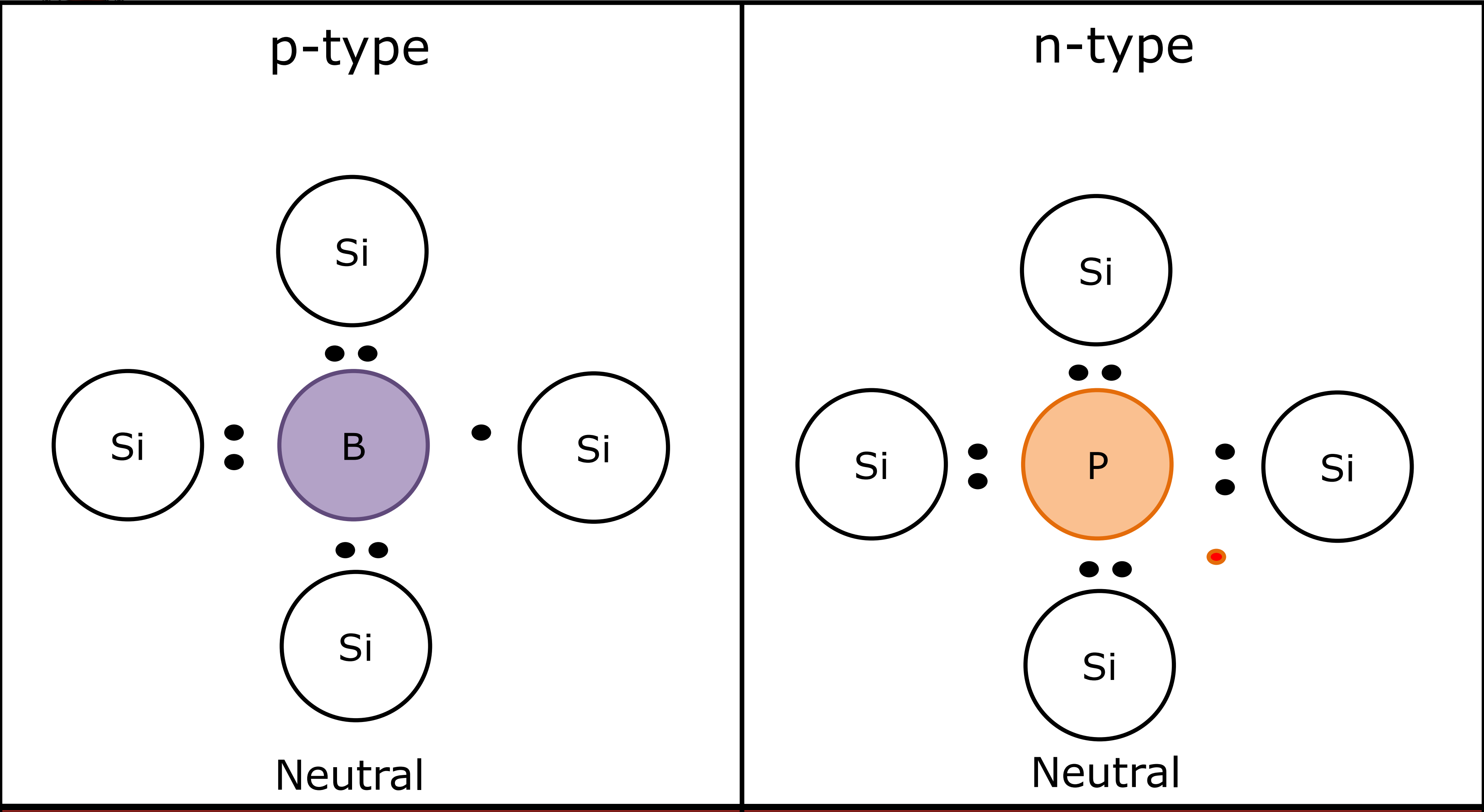


PN Junction

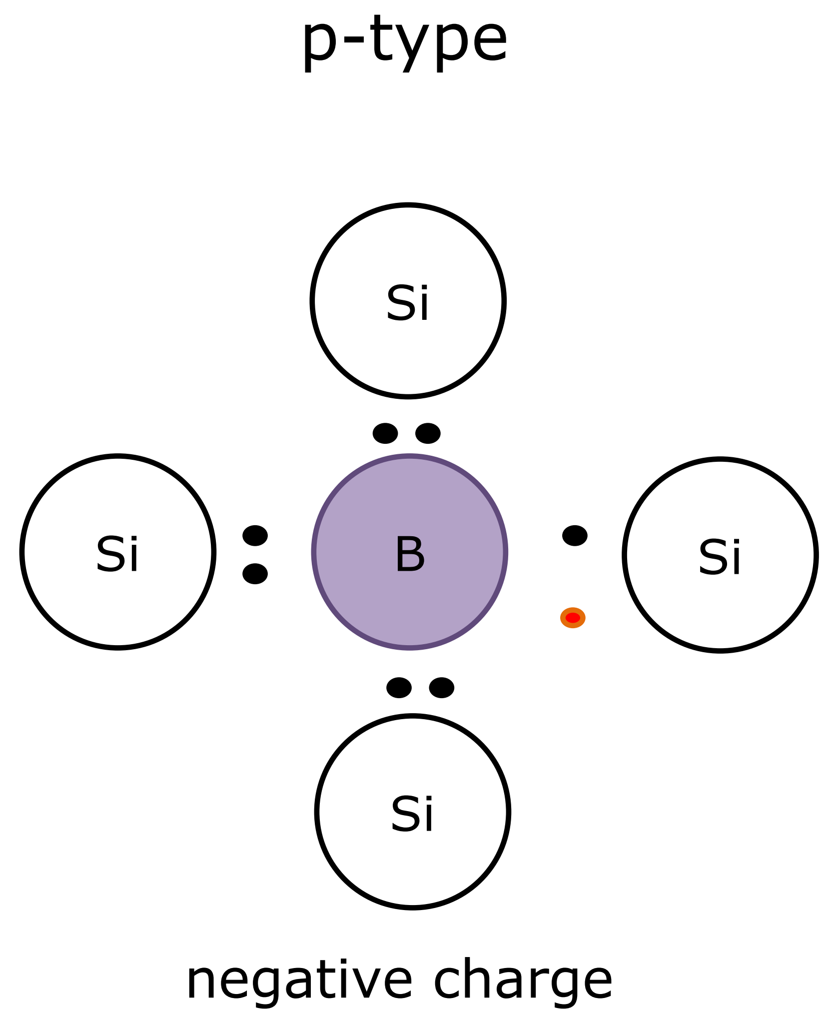
- Now the p-type material has more electrons than protons, so it develops a net negative charge (and electric field)
- Electric field opposes more electrons from moving from the n-type to the p-type

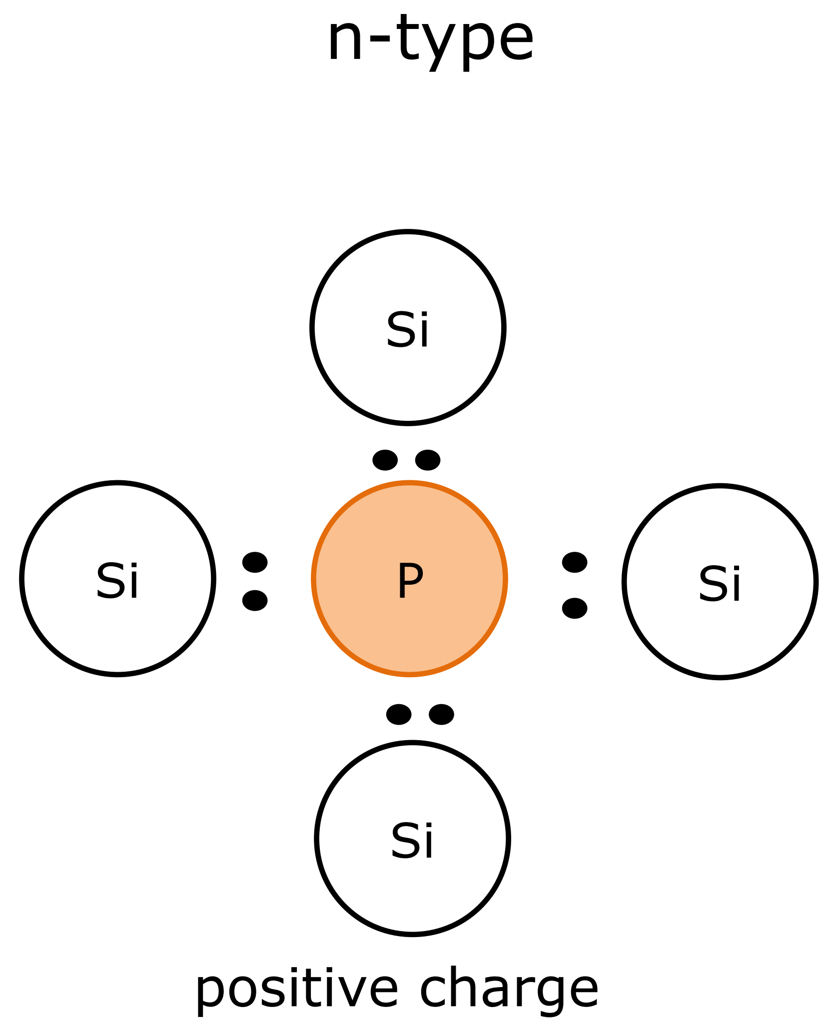


In the Depletion Region



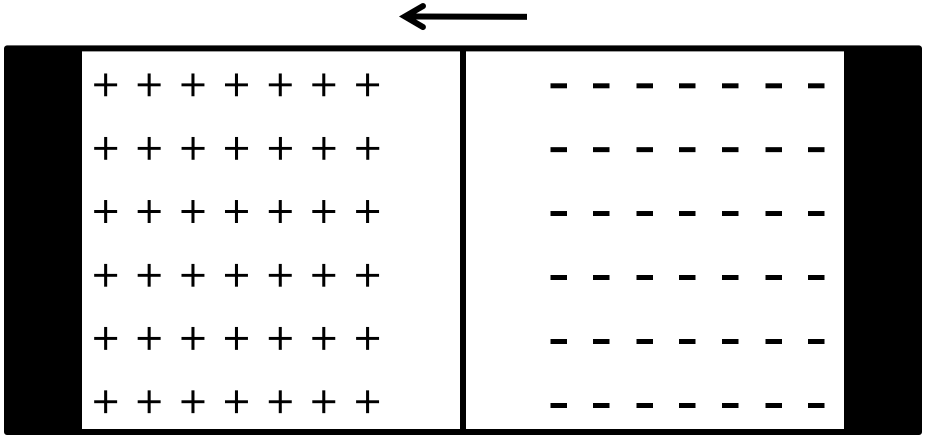
In the Depletion Region





PN Junction

- V_0: voltage across depletion region, usually 0.8 V at room temperature
- Note there still is no voltage across the entire material



Direction of electric field

holes shown

free electrons shown

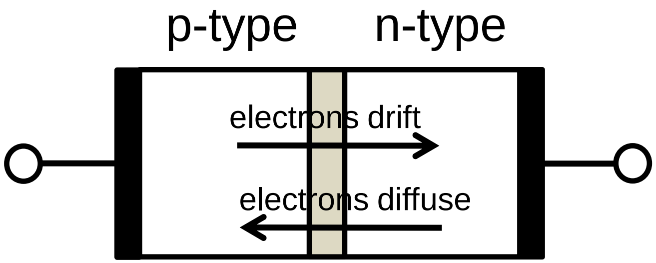
junction

p-type

n-type

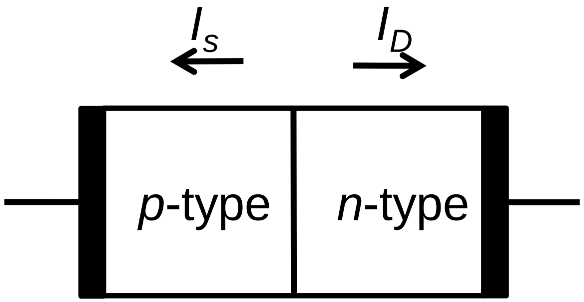
PN Junction

- Minority carriers on either side near or in the depletion region can be swept across the depletion region by the electric field
  - this is Drift current



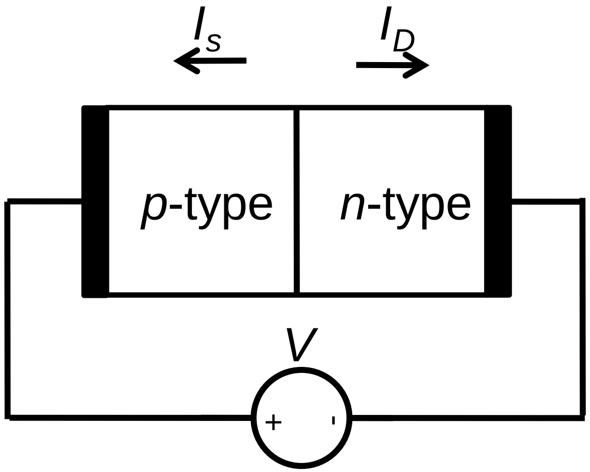
PN Junction

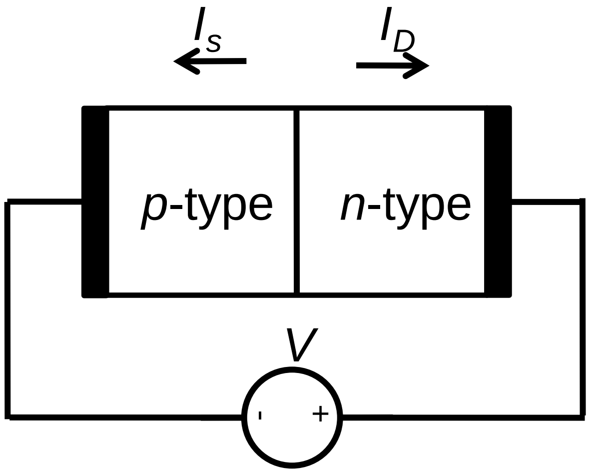
- In open circuit conditions, drift current must equal diffusion current $I_D = I_S$
  - For example, a minority electron diffusing to the n-type side will increase the concentration of electrons there which will cause increased diffusion across the depletion region



Bias

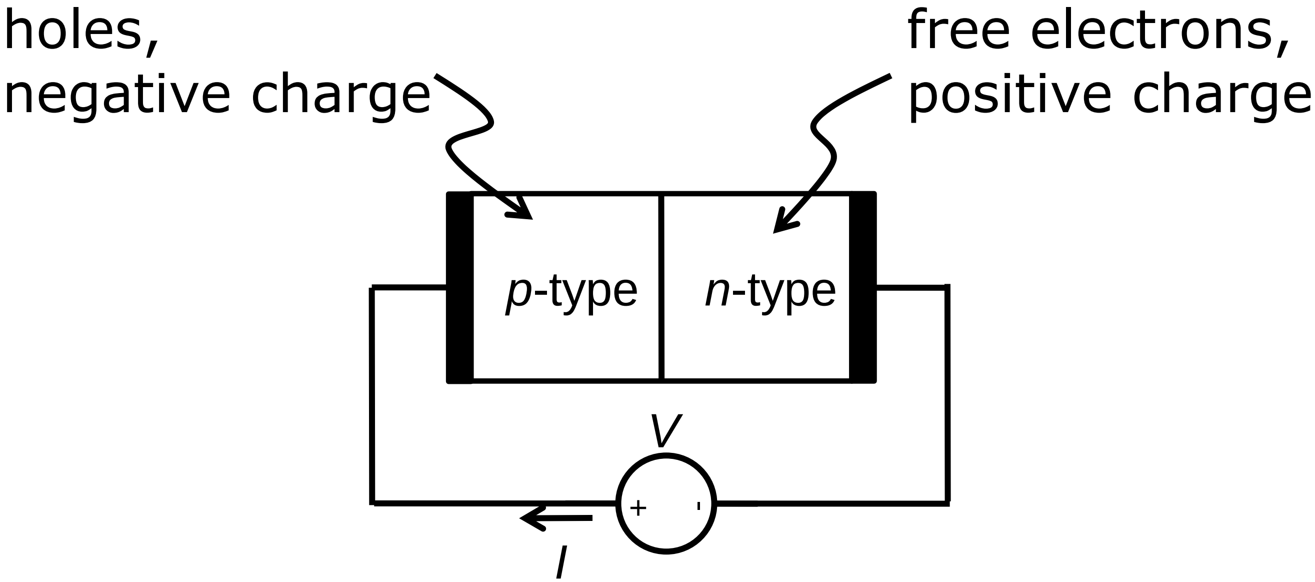
- Now assume a battery is connected to the contacts of the pn junction
- There are two ways of doing this
  - Forward bias
  - Reverse bias

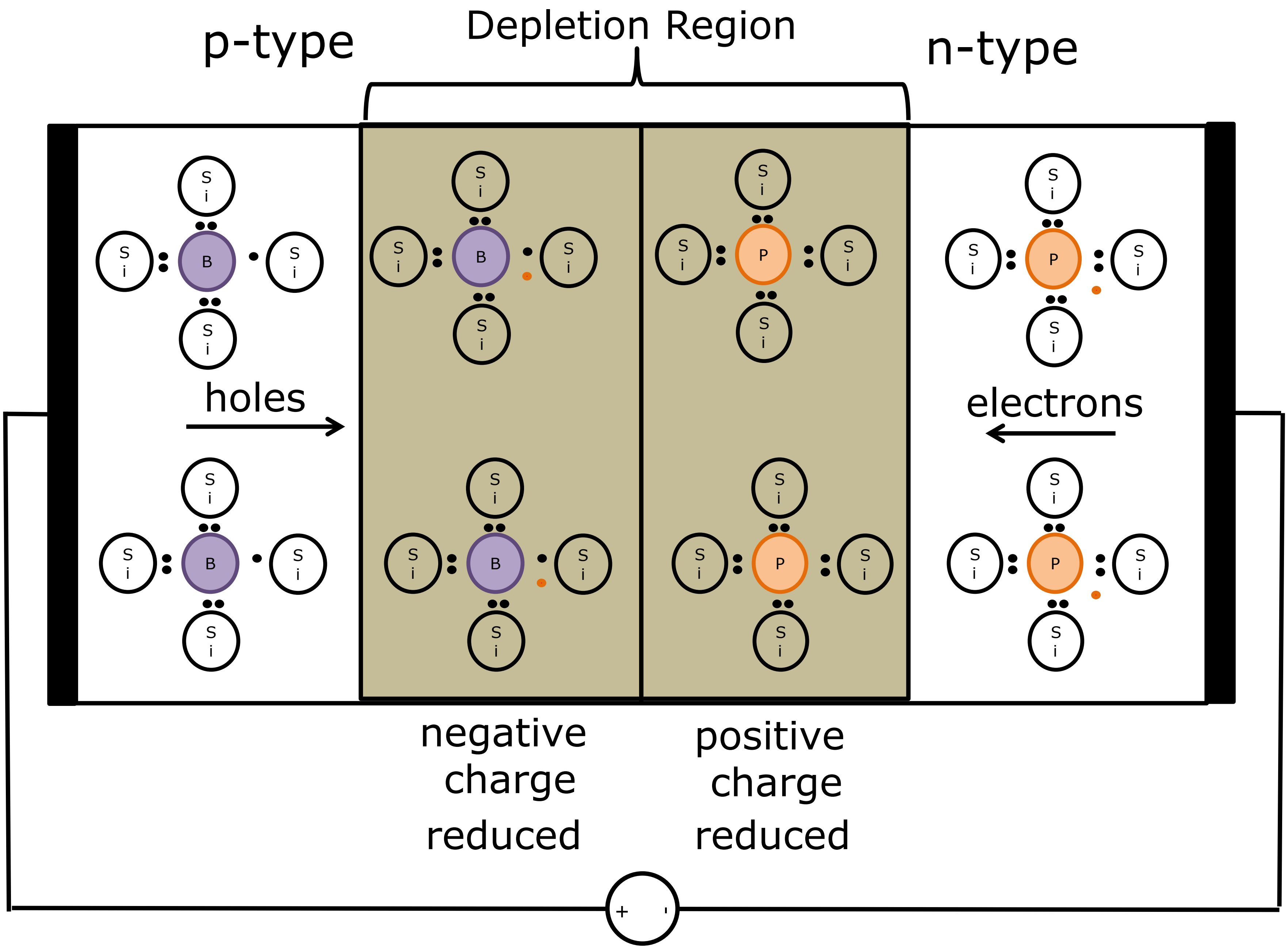




Forward Bias

- Positive charge from the battery pushes the holes in the p-type toward the depletion zone
- Negative charge from the battery pushes the free electrons in the n-type toward the depletion zone





p-type

Depletion Region

n-type

holes

electrons

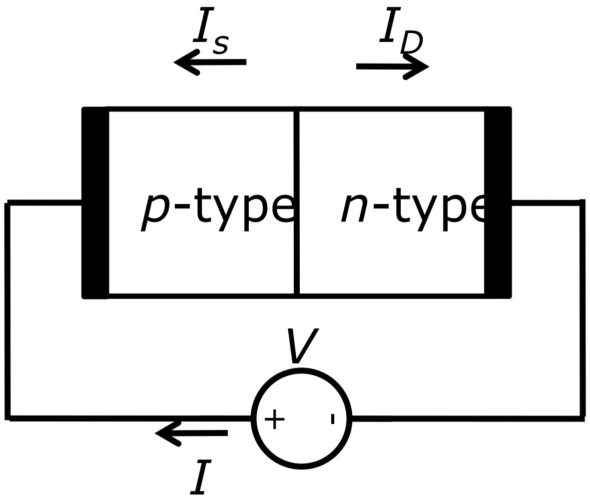
negative
charge
reduced

positive
charge
reduced

Forward Bias

- Net result is that the electric field preventing diffusion decreases
- Diffusion current increases (I_D)

$$I_D - I_s = I$$



Forward Bias

- The current is determined from:

$$I = I_{Sat}\left(e^{V/V_T} - 1\right) \quad \text{and} \quad V_T = \frac{kT}{q}$$

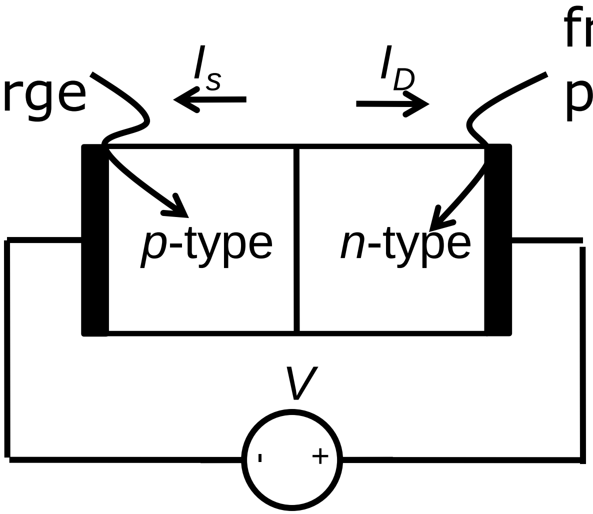
- Where:
    - k: Boltzmann's constant (1.38 x 10^{-23} J/K)
    - T: temperature in K
    - q: charge 1.602 x 10^{-19} (C)
    - I_{sat}: reverse bias saturation current (A)
- V_t is usually ~25mV

Forward Bias

- I_{sat} is a function of temperature, junction area and other physical characteristics of the junction
  - Usually around 10^{-10} A (though could be several orders of magnitude larger or smaller)

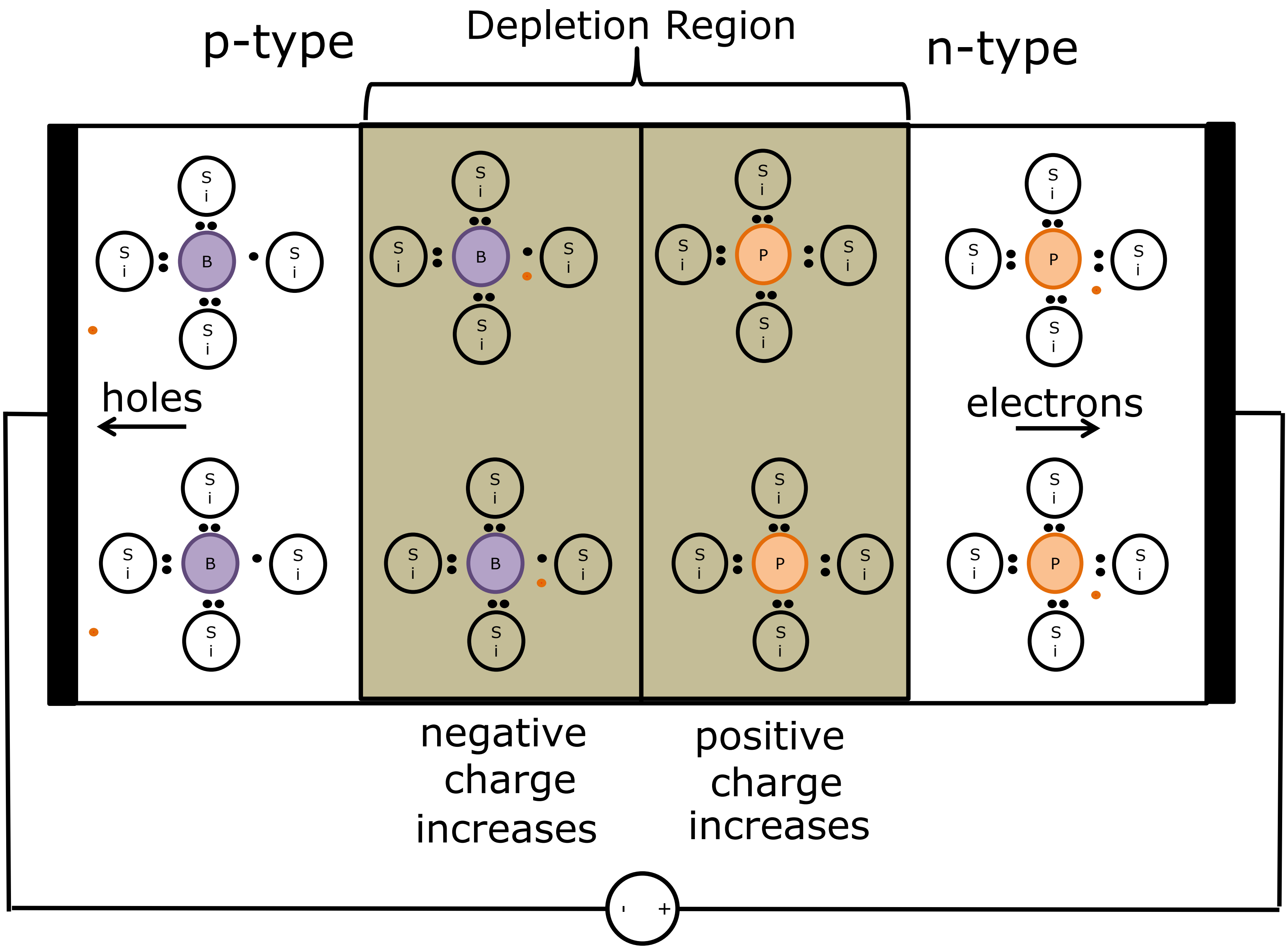
Reverse Bias

- Holes in the p-type material are pulled away from the junction
- Electrons are pulled away from the n-type material
- Net result: <u>depletion region increases</u>



holes,
negative charge

free electrons,
positive charge



p-type

Depletion Region

n-type

holes

electrons

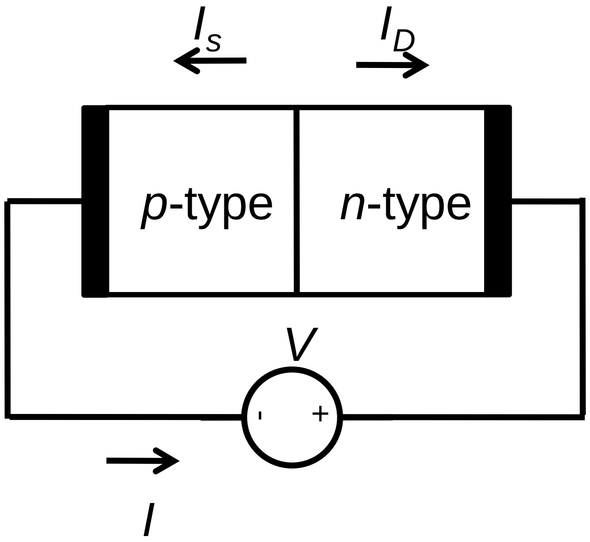
negative charge increases

positive charge increases

Reverse Bias

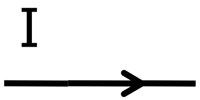
- Electric field increases strength
- Diffusion current decreases
- Drift current remains unaffected
- I remains small

$$I_D - I_s = I$$

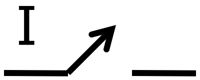


PN Junction

- The described operation is exactly the same as a diode
- Forward Bias: large current
- Reverse Bias: <u>very</u> small current



Forward Bias

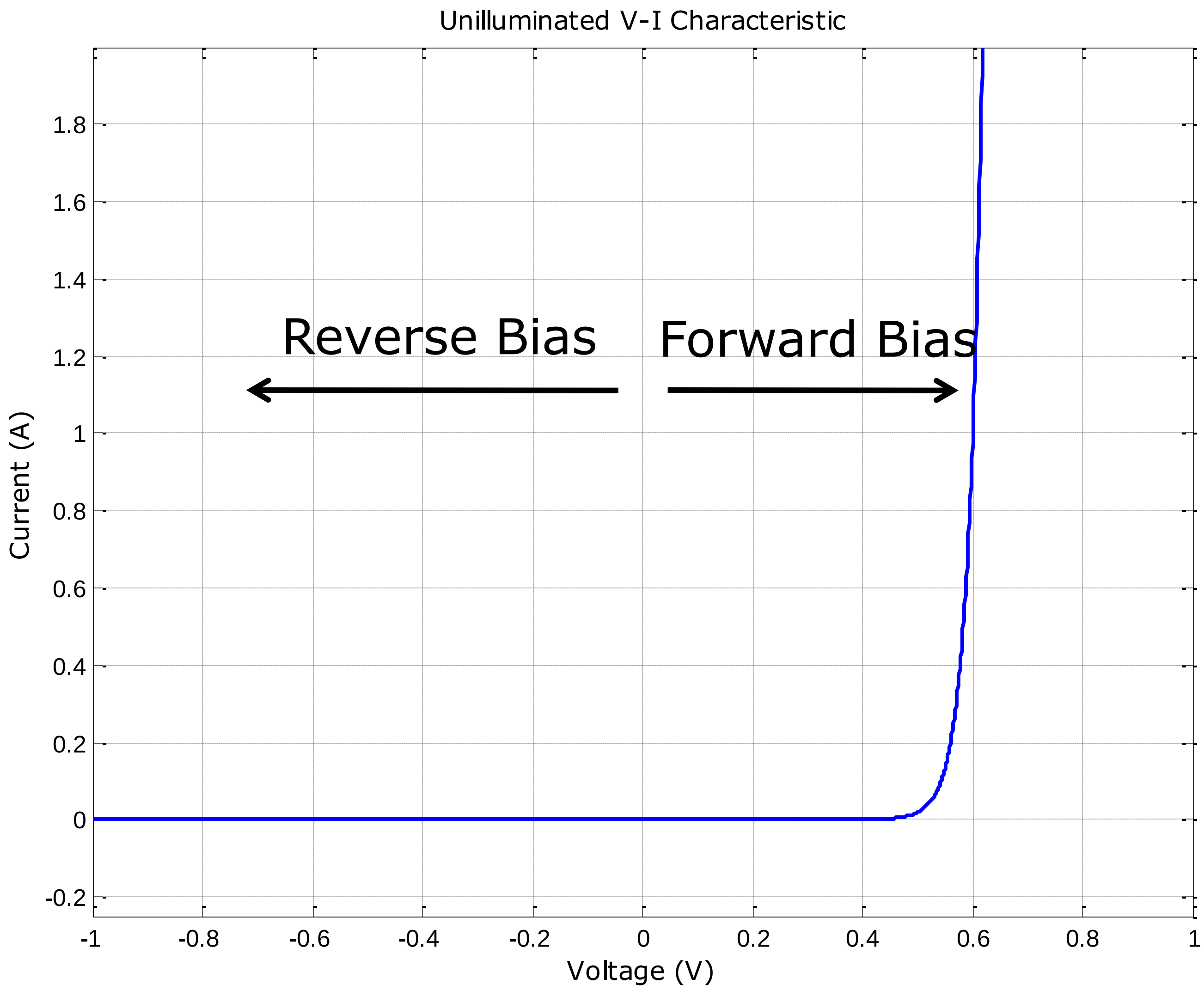


Reverse Bias

- Current through a diode:

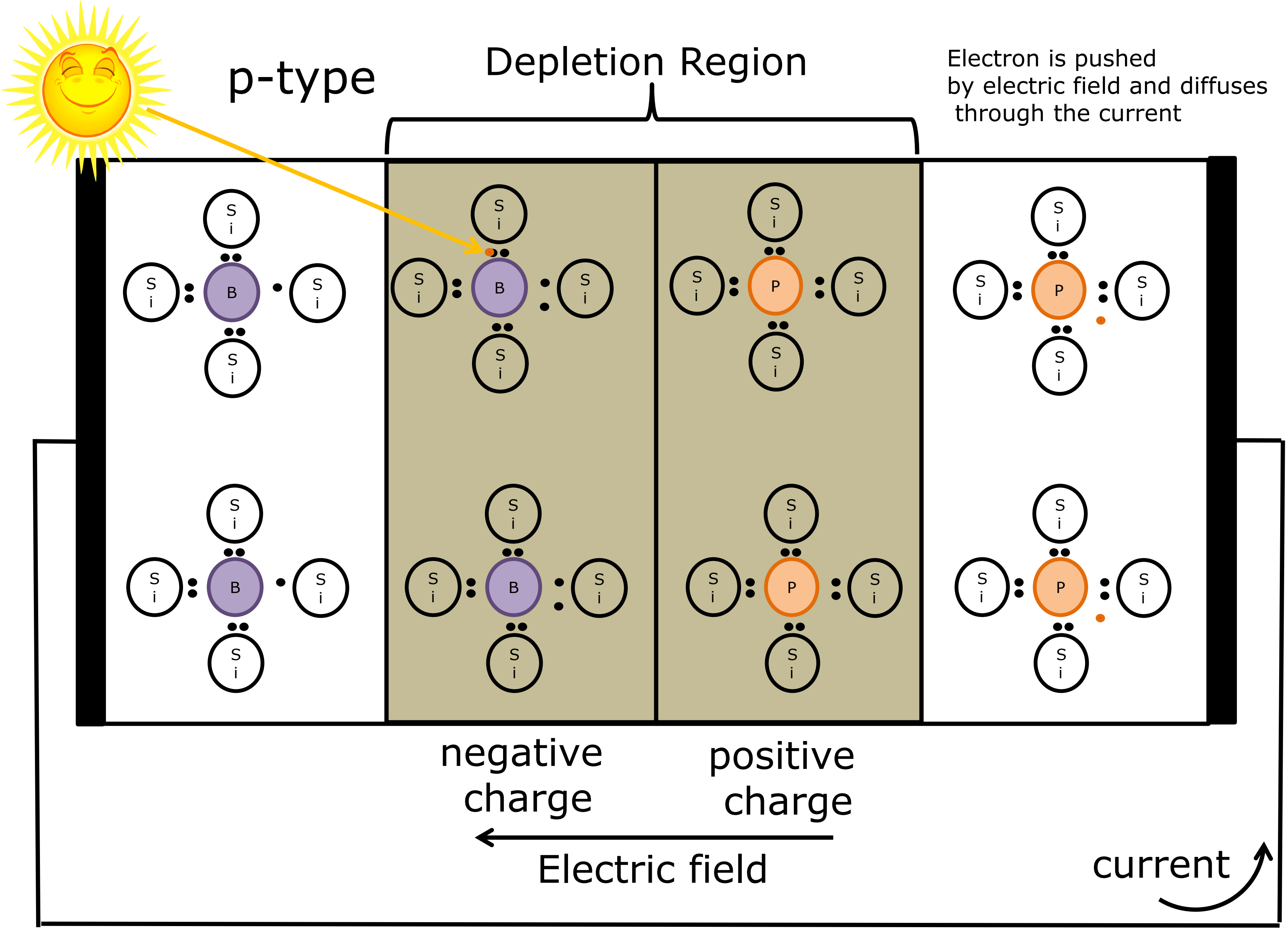
$$I = I_{Sat}\left(e^{V/V_T} - 1\right)$$

PN Junction


Unilluminated V-I Characteristic
Reverse Bias
Forward Bias
Current (A)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Voltage (V)

Illuminated PN Junction

- No net current flows in un-illuminated PN junction
  - Exception: external battery connected
- What happens when a photon hits the PN Junction?
- Recall:
  - Photons can excite electrons into the conduction band



p-type

Depletion Region

Electron is pushed
by electric field and diffuses
through the current

negative
charge

positive
charge

Electric field

current

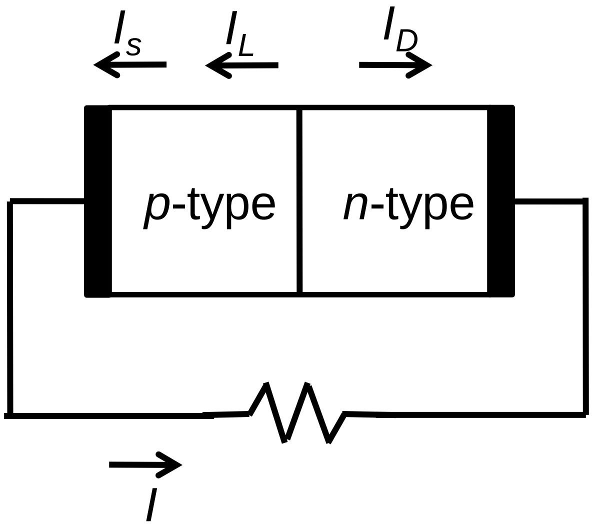
Illuminated PN Junction

- If a photon hits an electron in the p-type material that is close to (or within) the depletion region, then the electron will be pushed across by the electric field
    - Drift current results
- This is called illumination current (I_L)

$$I = I_L - I_{Sat}\left(e^{V/V_T} - 1\right)$$

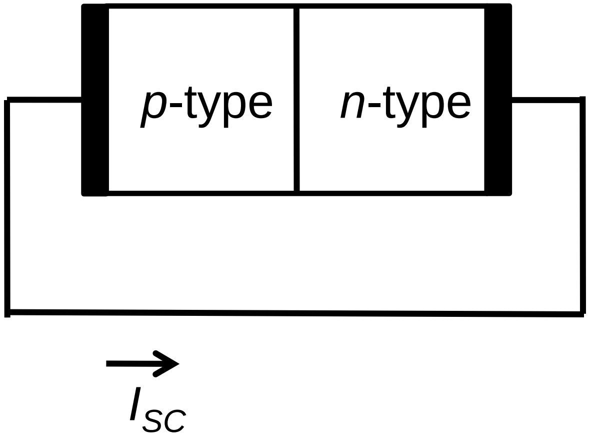
Illuminated PN Junction

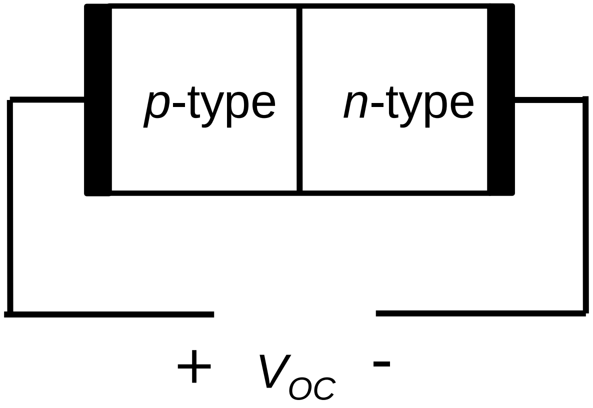
- Using active circuit convention



Illuminated PN Junction

- We are interested in the short circuit current and open circuit voltage of a PV cell



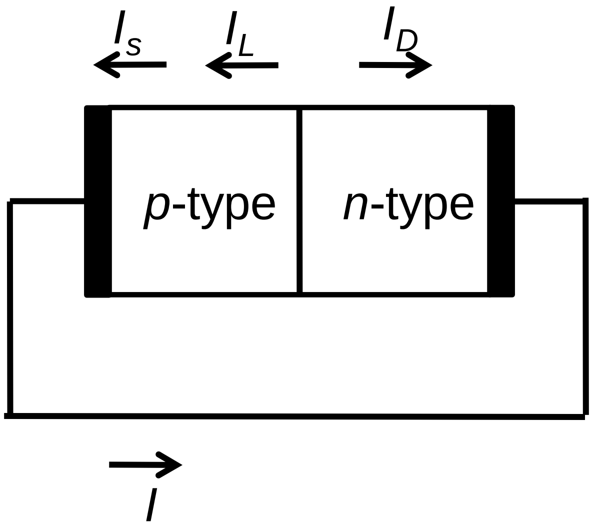


Illuminated PN Junction

- Under short circuit conditions

$$I_{SC} = I_L - I_{Sat}\left(e^{0/V_T} - 1\right)$$

$$\Rightarrow I_{SC} = I_L$$



Illuminated PN Junction

- Computing the open circuit voltage

$$I = I_L - I_{Sat}\left(e^{V_{OC}/V_T} - 1\right) = 0$$

$$\Rightarrow \frac{I_L}{I_{Sat}} + 1 = \left(e^{V_{OC}/V_T}\right) \cong \frac{I_L}{I_{Sat}} \quad \text{since } I_L >> I_{Sat}$$

$$\Rightarrow \ln\left(\frac{I_L}{I_{Sat}}\right) = V_{OC}/V_T$$

$$\Rightarrow V_T \ln\left(\frac{I_L}{I_{Sat}}\right) = V_{OC} \quad (\textit{open circuit})$$

V-I Characteristics

- $I_{sat} = 10^{-10}$
- $V_t = 25\text{mV}$
- $I_L = 1.5\ \text{A}$