08-Photovoltaics Part 1

ECEGR 4530

Renewable Energy Systems

Overview

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

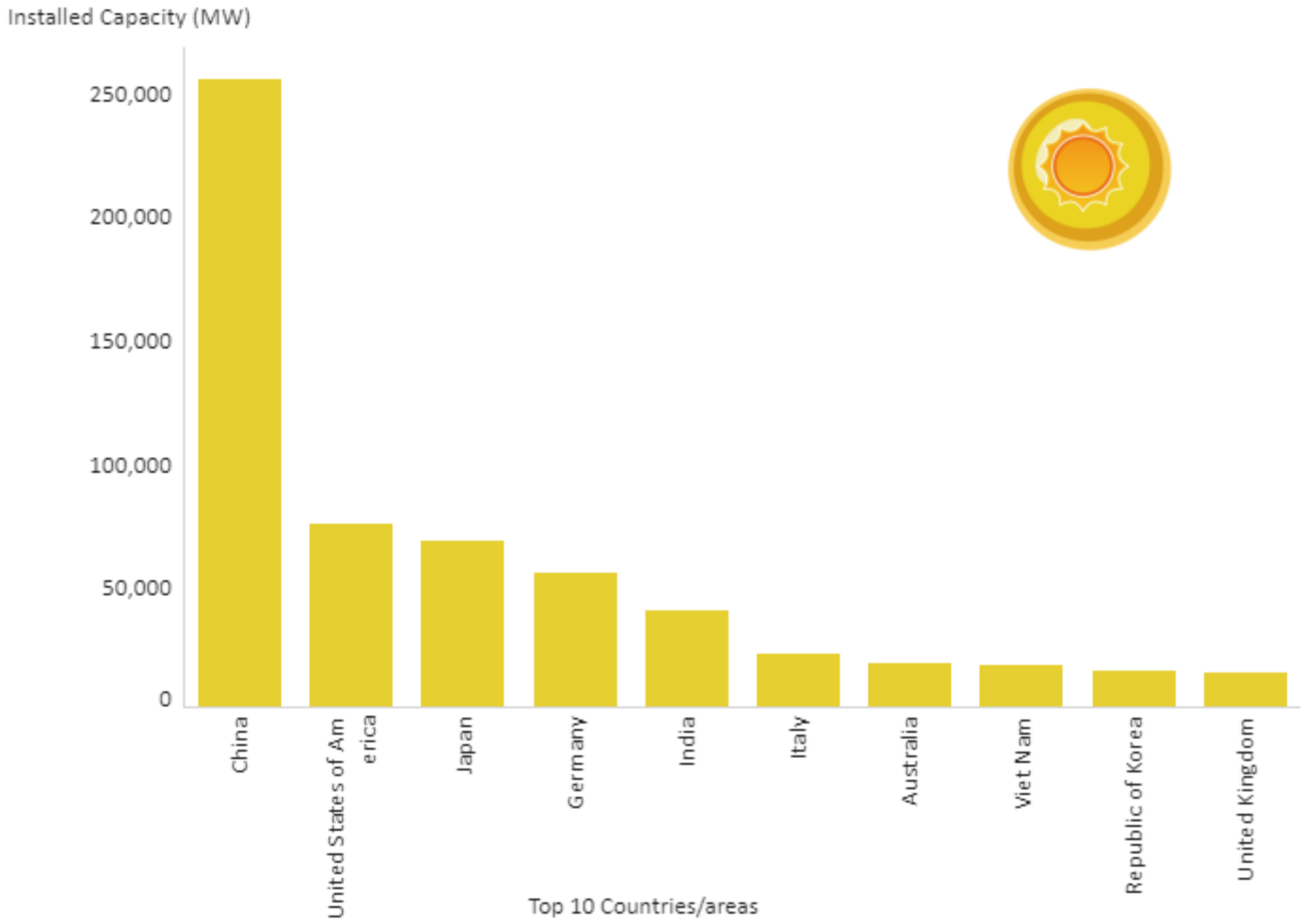
Introduction

- Photovoltiac 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

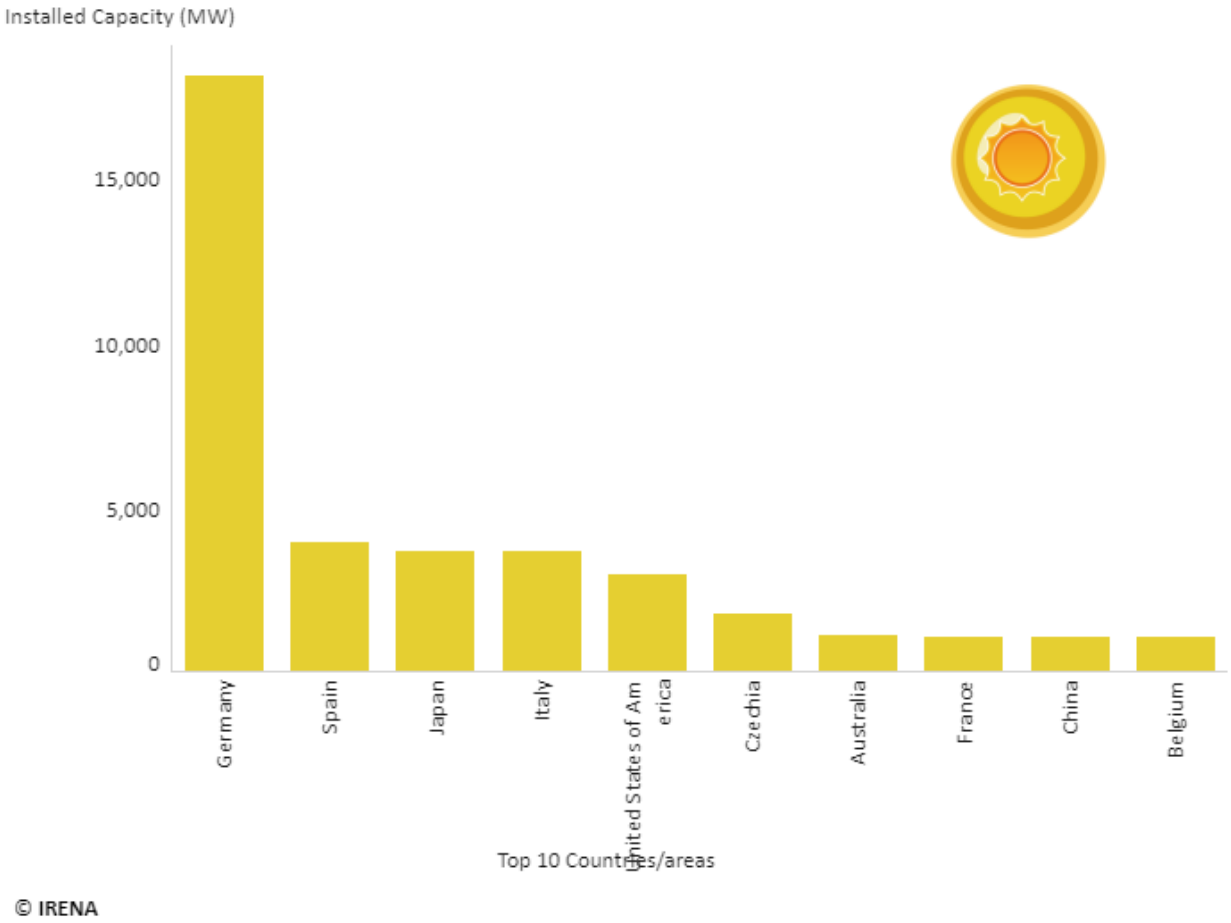
Global total: 700 GW

1. China: 254 GW
2. U.S.: 74 GW
3. Japan: 67 GW
4. Germany: 54 GW
5. India: 39 GW

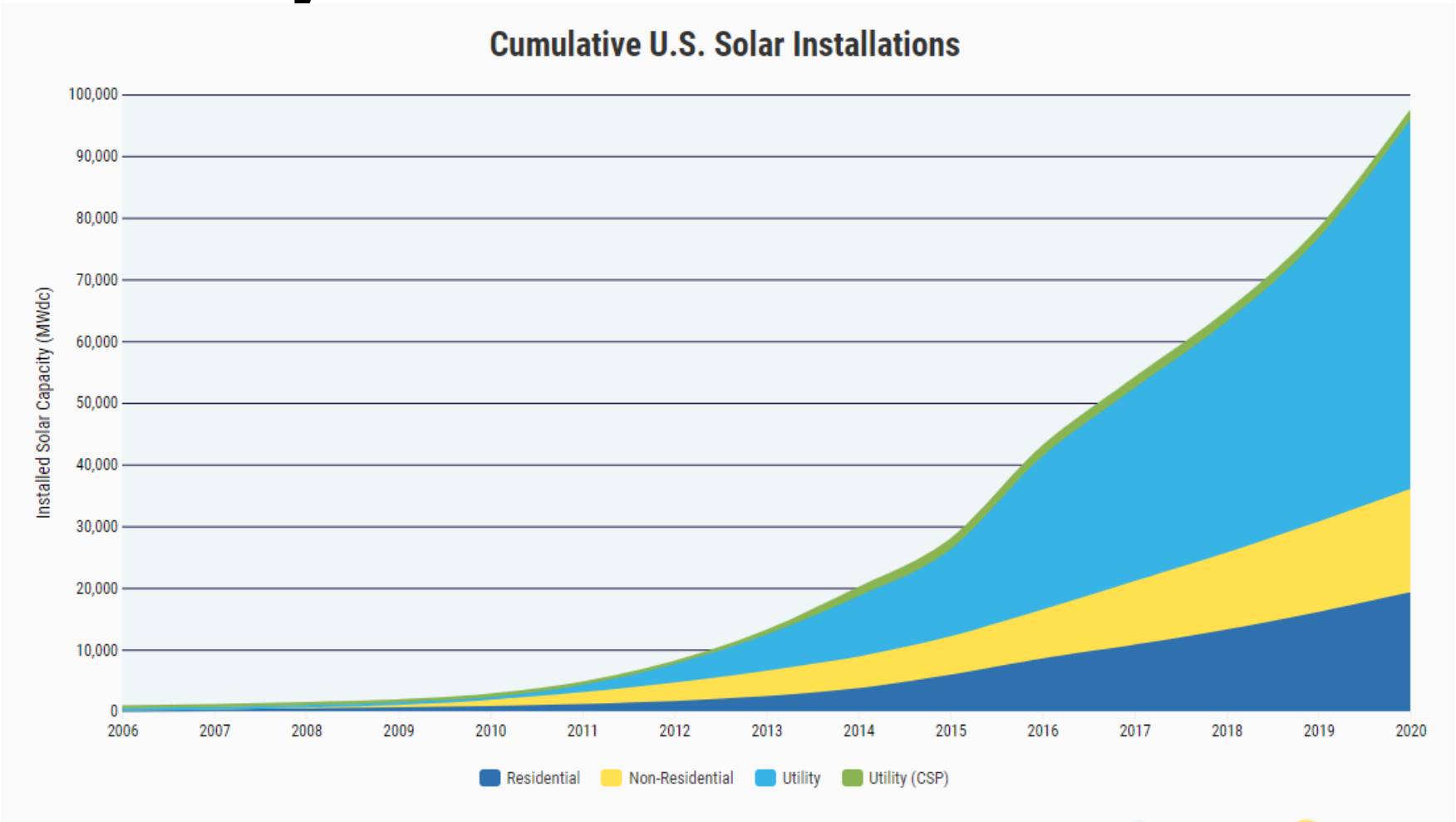


Leading Countries (2010)

1. Germany 18 GW
2. Spain 3.8 GW
3. Japan 3.6 GW
4. Italy 3.6 GW
5. U.S. 2.9 GW

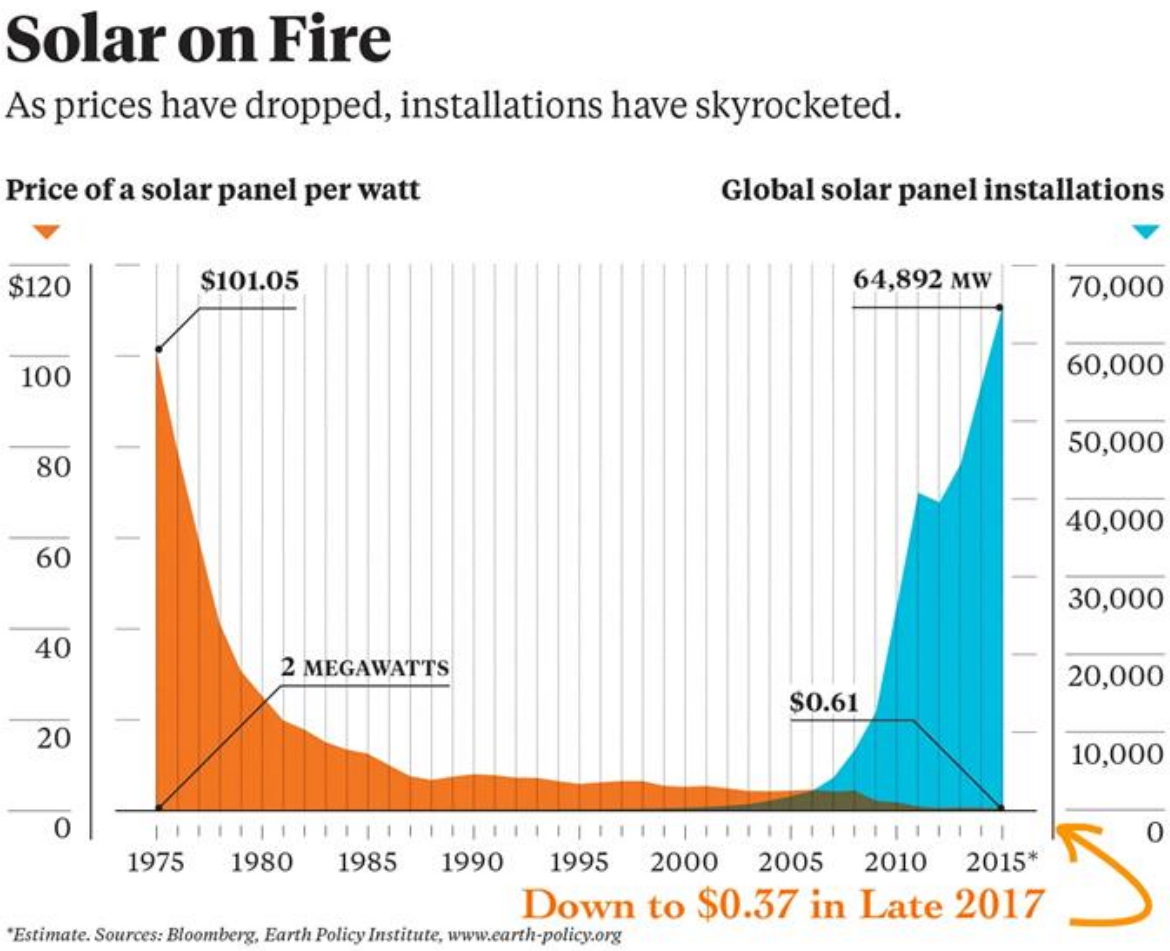


PV Industry in the US



Source: SEIA.org

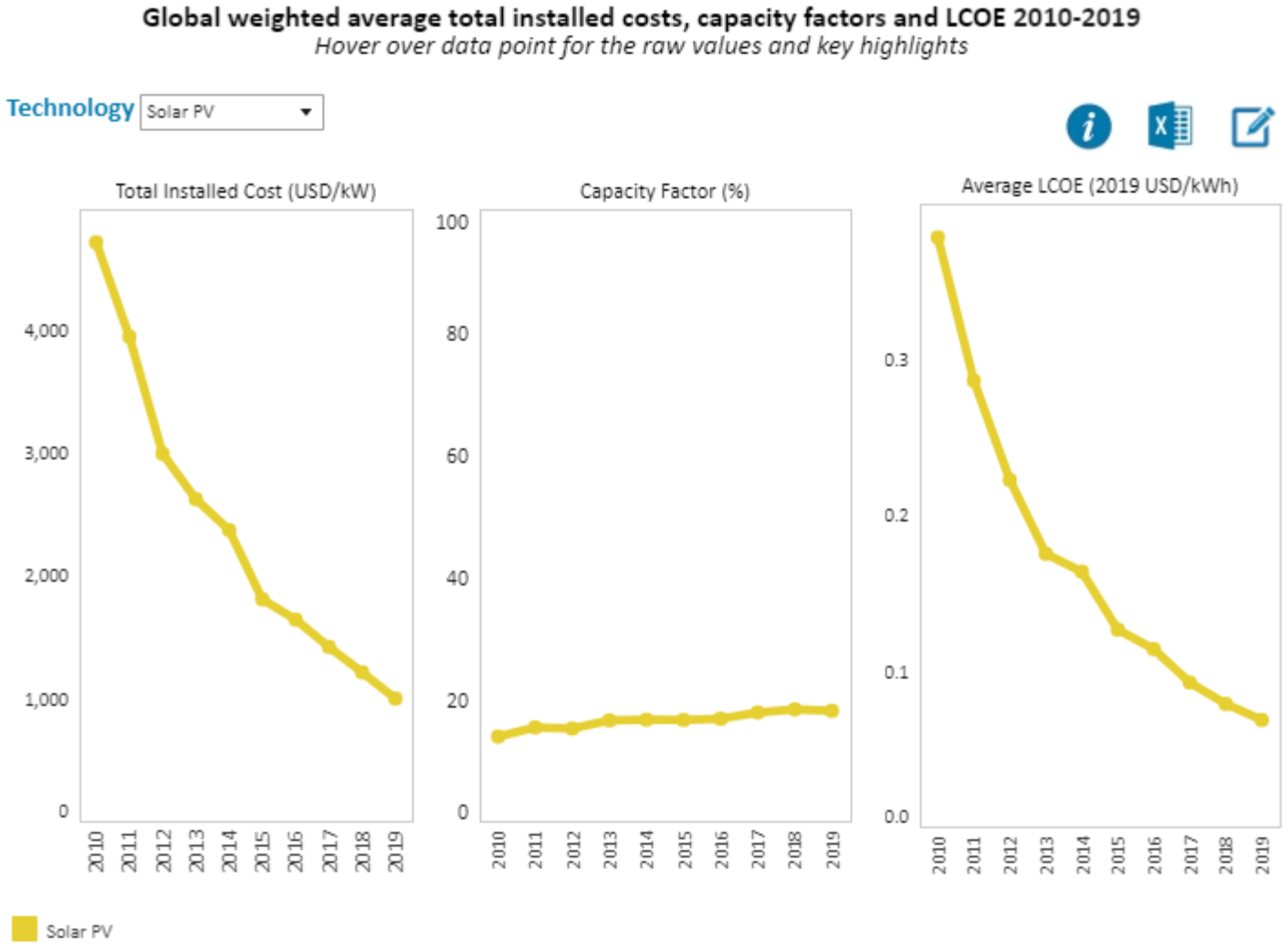
Solar Costs



PV panels cost
~$0.50/Watt

Solar Costs

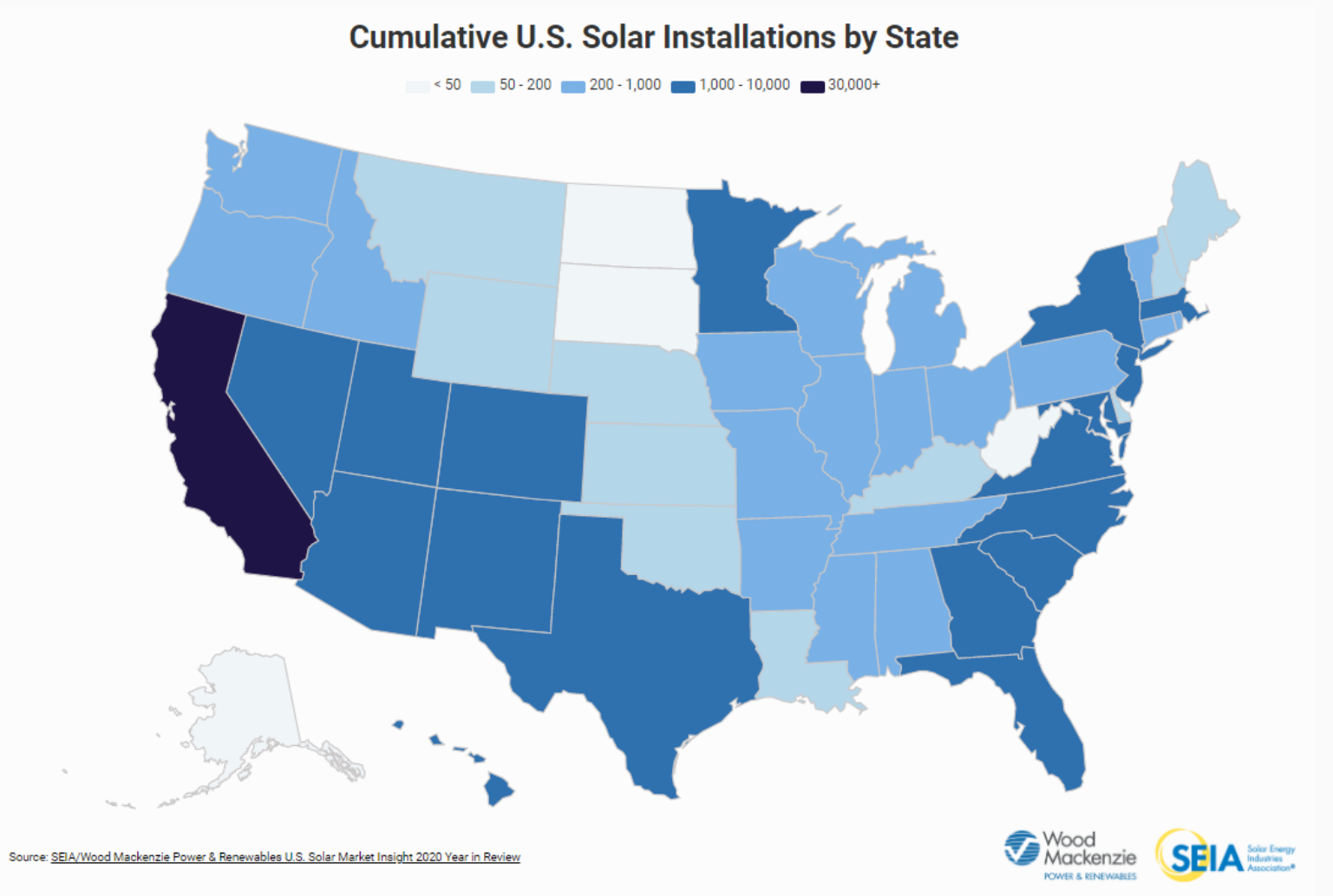
- Installed costs rapidly decreasing
- Levelized Cost of Energy rapidly decreasing
- Capacity Factor increasing



Note: All LCOE values are calculated based on project level data for total installed costs and capacity factors from the IRENA Renewable Cost Database, with other assumptions necessary for LCOE detailed in the source link below, notably an assumption of a weighted-average cost of capital of 7.5% real in the OECD and China and 10% elsewhere.

Source: IRENA (2020), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi
https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019

Solar in the U.S.



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

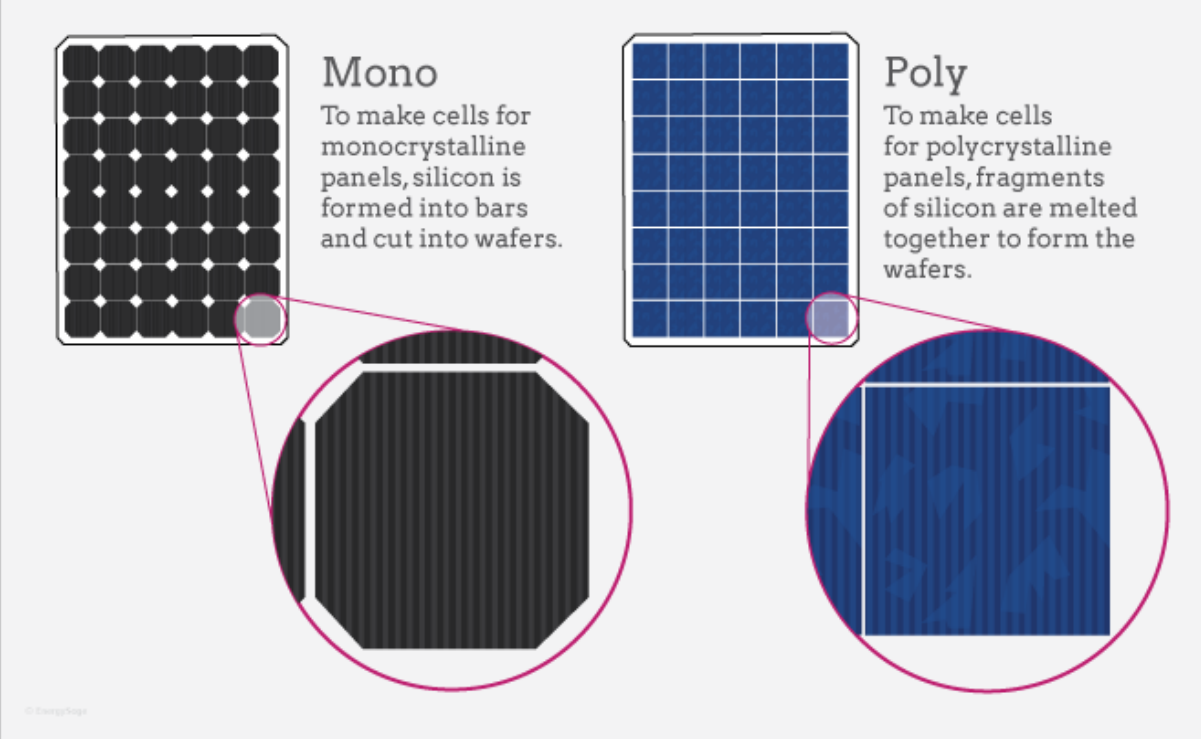
PV Industry

monocrystalline

polycrystalline

thin film

Physical Description



There are two common types of PV cells: mono-crystalline and poly-crystalline

A typical 0.156m x 0.156m (6.1in x 6.1 in) cell produces 2 to 4 W

source https://www.civicsolar.com/support/installer/articles/monocrystalline-cells-vs-polycrystalline-cells-whats-difference

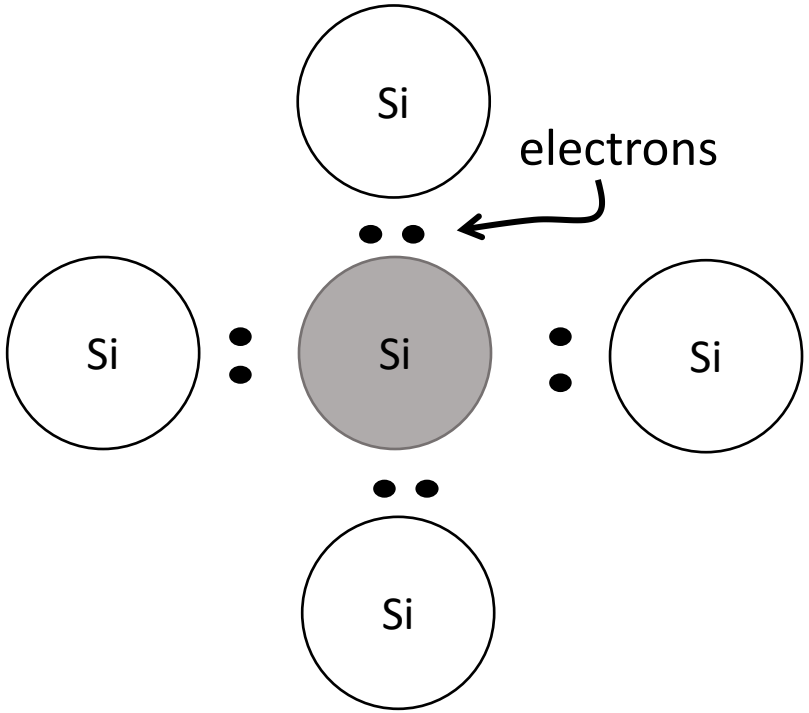
PV Basics

- 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

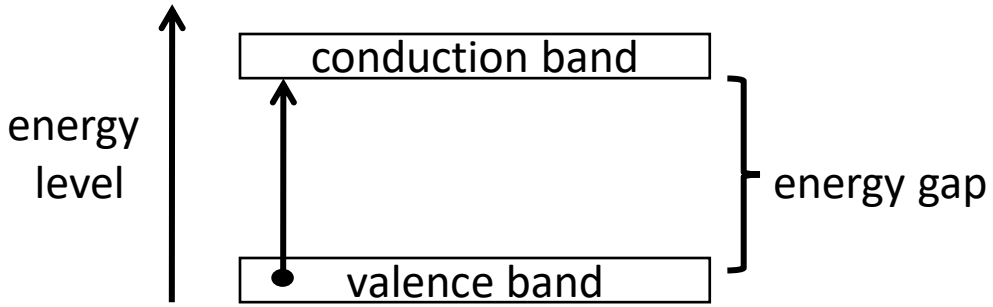


Silicon

- 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)



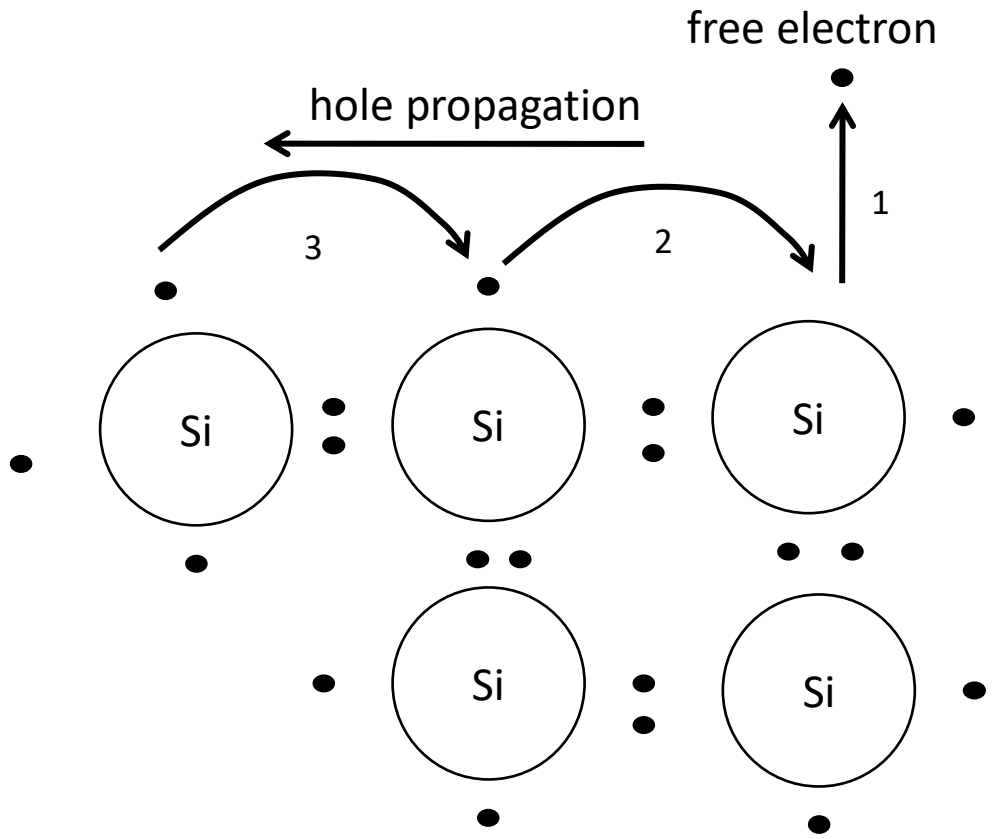
PV Physics

- 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, 1.6×10^{-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

Exercise

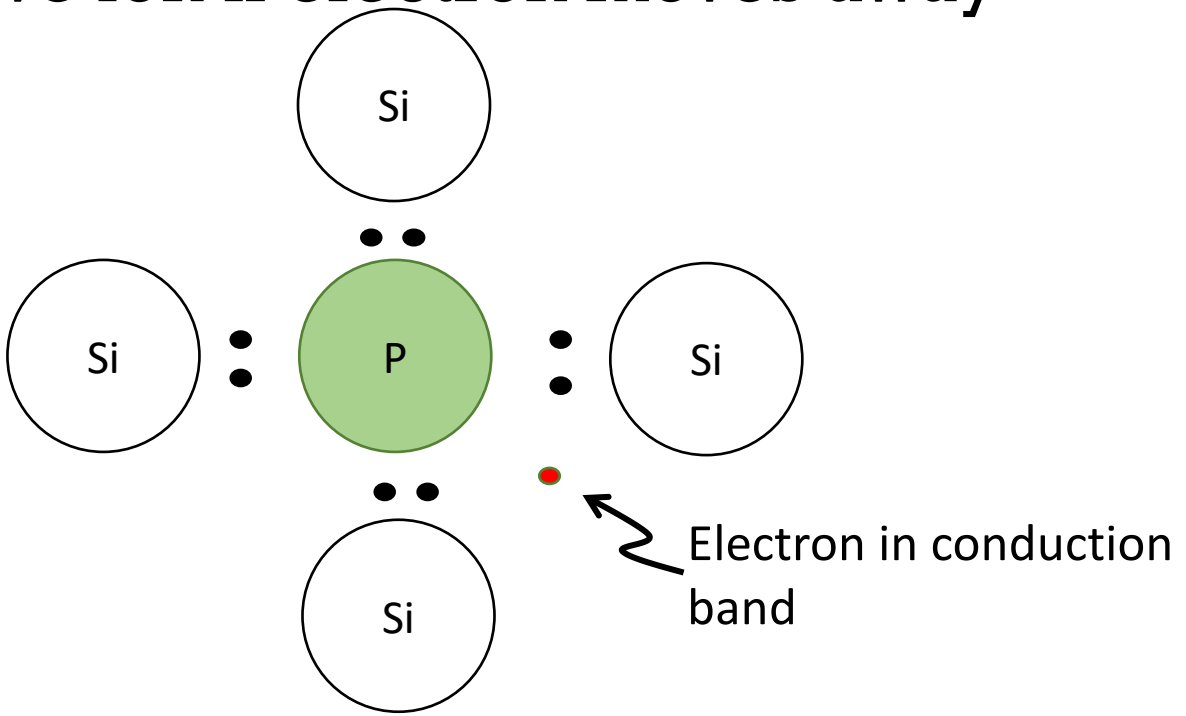
- Does P-doped silicon have a net charge?
  - Yes
  - No

Exercise

- 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

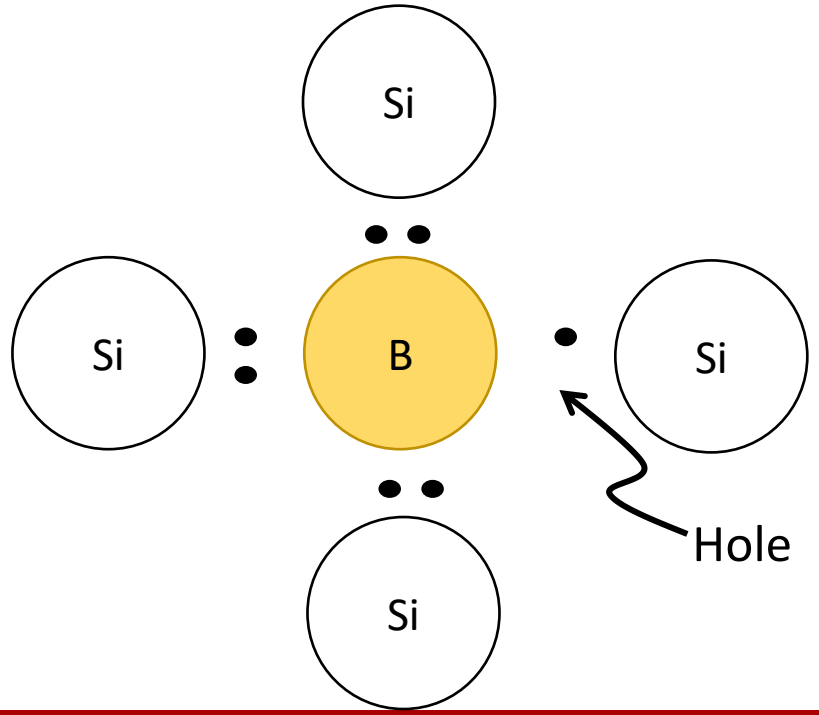
- Doping intrinsic Si with P
  - Increases the number of free electrons
  - Material becomes a conductor
  - Does not lead to an overall net charge
  - Does not create holes (though holes may exist due to thermal excitation of electrons, known as minority carriers in n-type material)
- Other elements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



Exercise

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

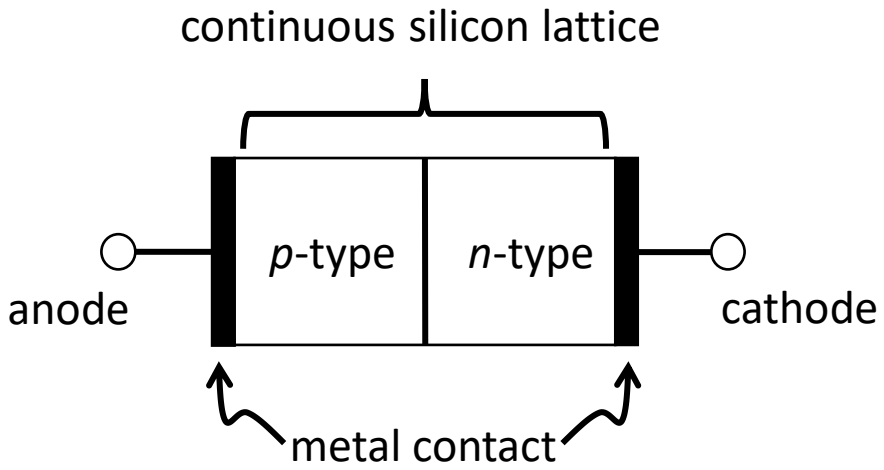
- P-type material has a positive charge
  - True
  - False

Exercise

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

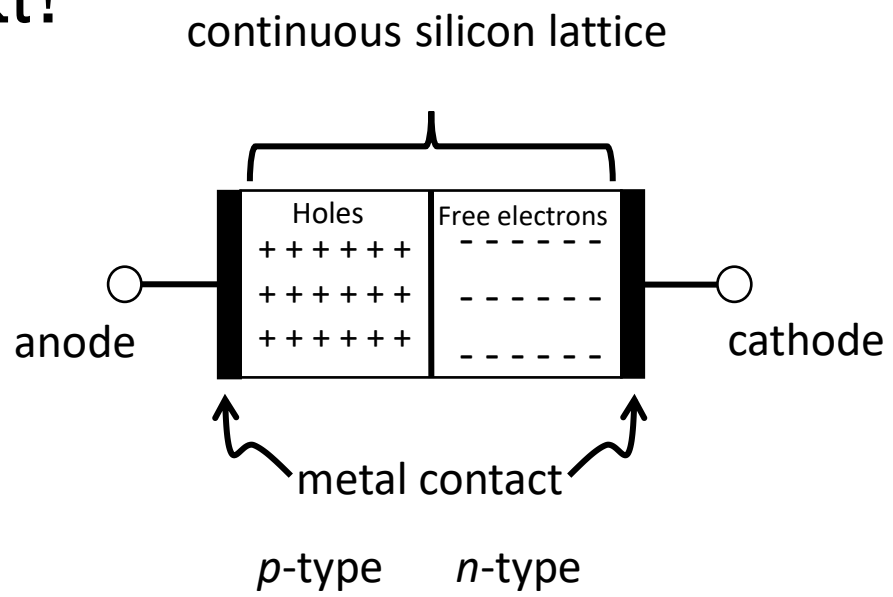
PN Junction

- 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



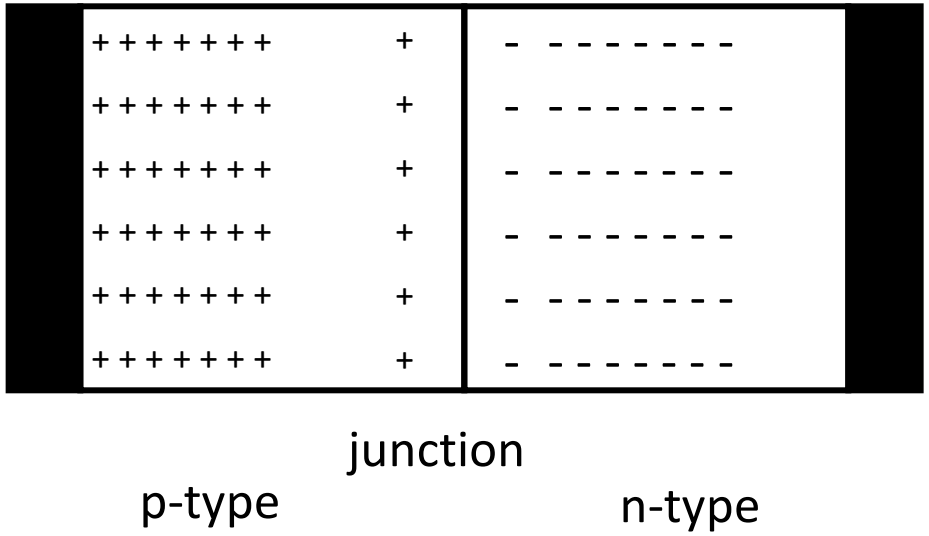
PN Junction

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



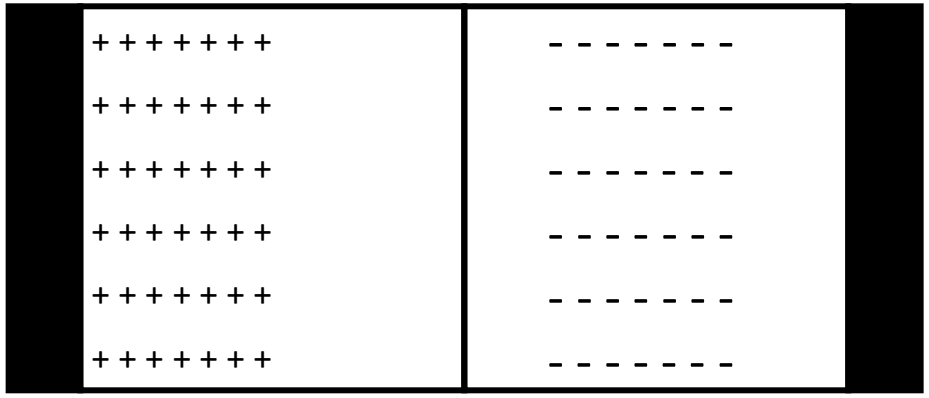
PN Junction

- Diffusion current from p-type to n-type



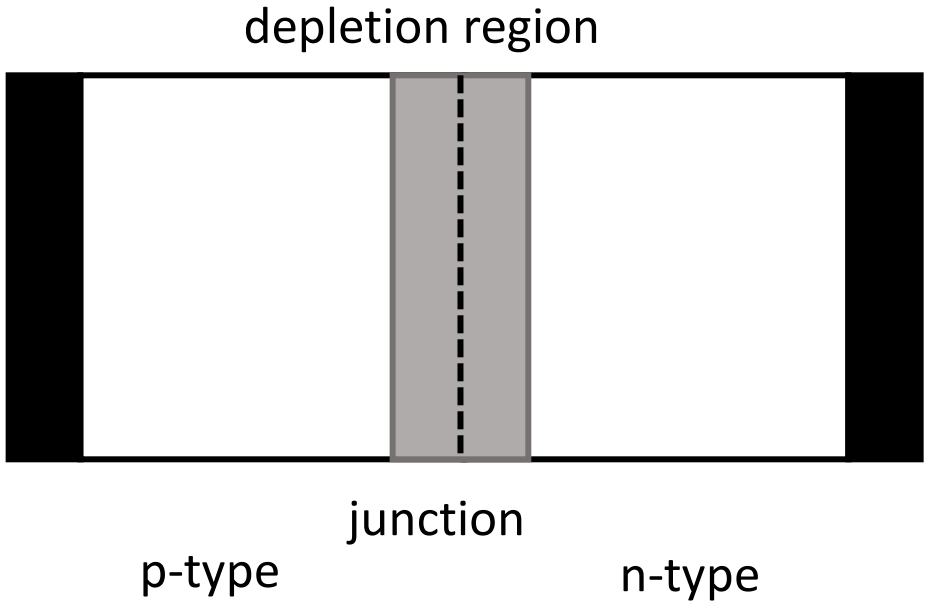
PN Junction

- 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

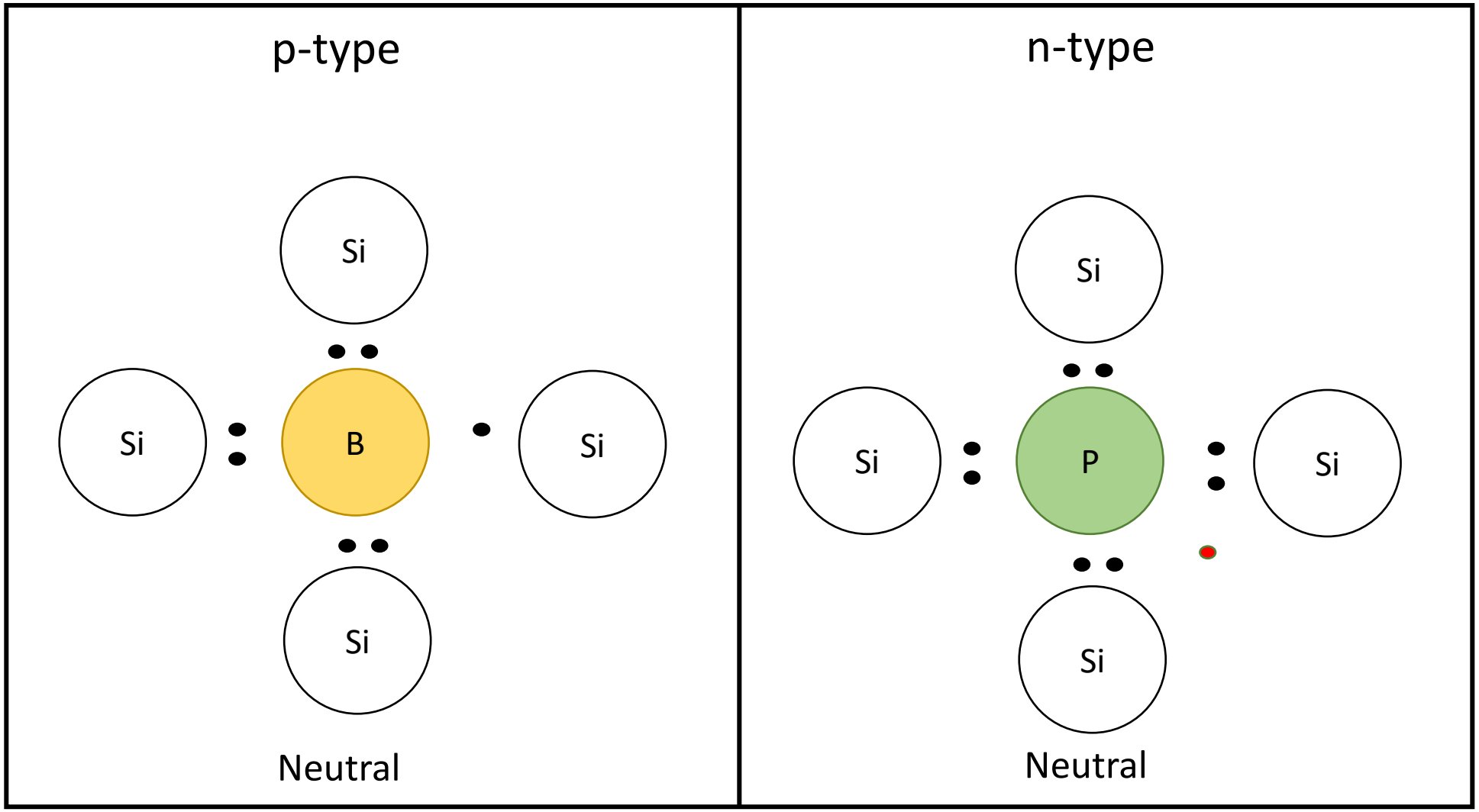


PN Junction

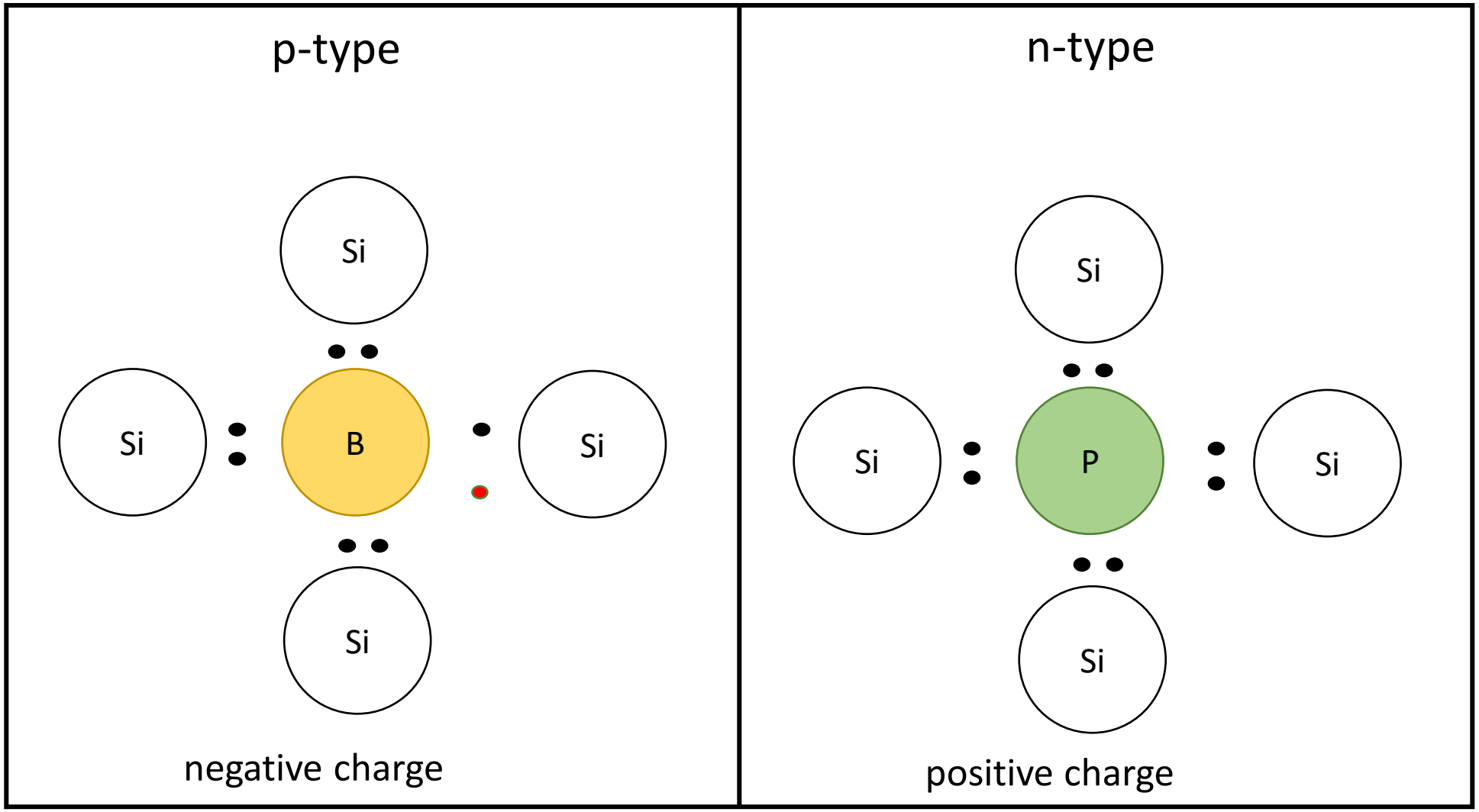
- Now the p-type material has more electrons than protons, so it develops a net negative charge (and electric field)
- Electric field opposes more electrons from moving from the n-type to the p-type



In the Depletion Region

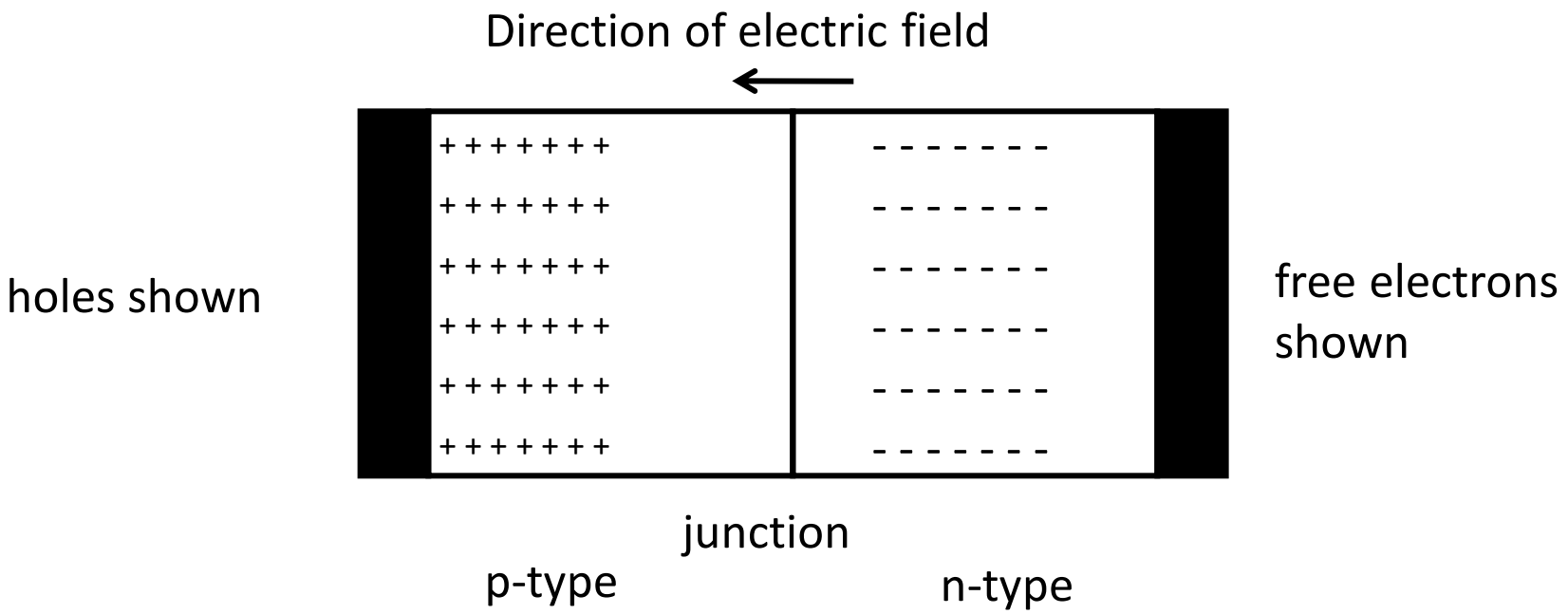


In the Depletion Region



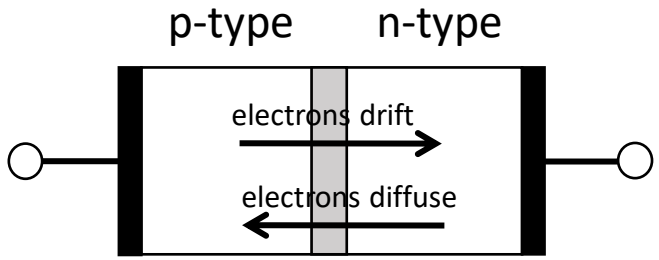
PN Junction

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



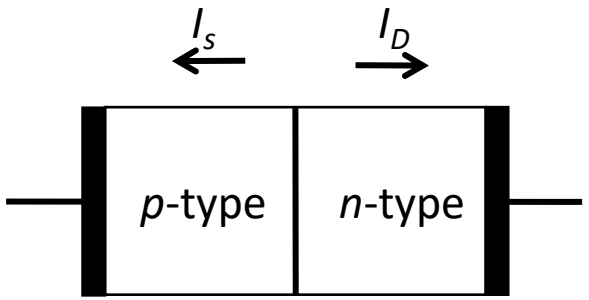
PN Junction

- 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



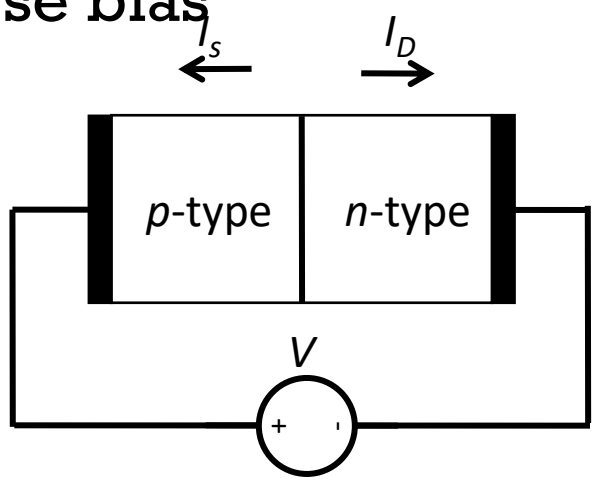
PN Junction

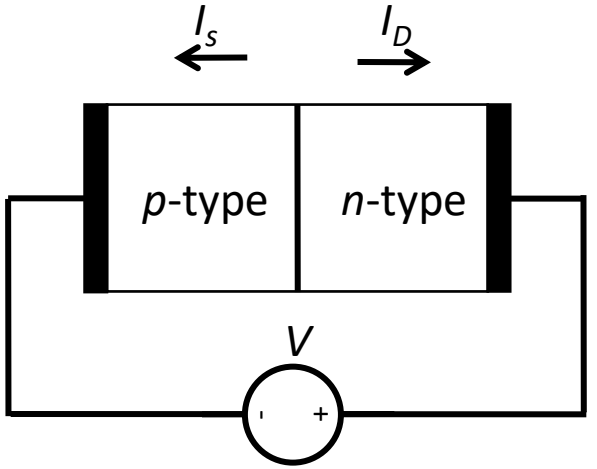
- In open circuit conditions, drift current (I_S) must equal diffusion (I_D) current $I_D = I_S$
  - For example, a minority electron diffusing to the n-type side will increase the concentration of electrons there which will cause increased diffusion across the depletion region



Bias

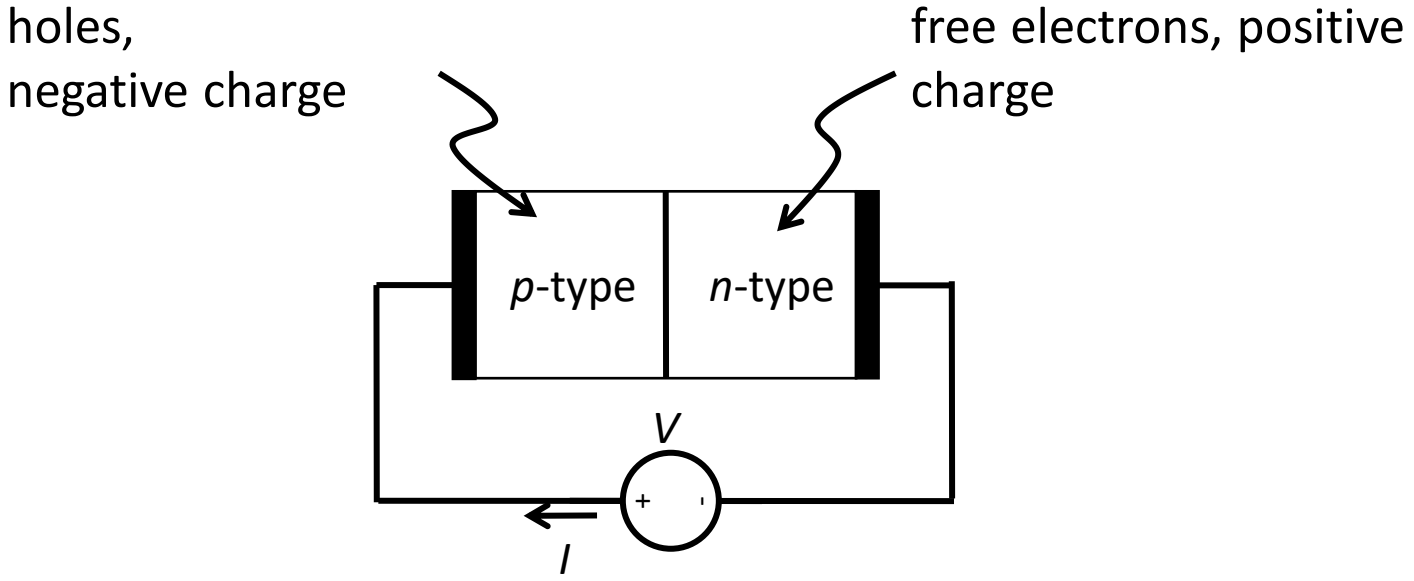
- Now assume a battery is connected to the contacts of the pn junction
- There are two ways of doing this
  - Forward bias
  - Reverse bias

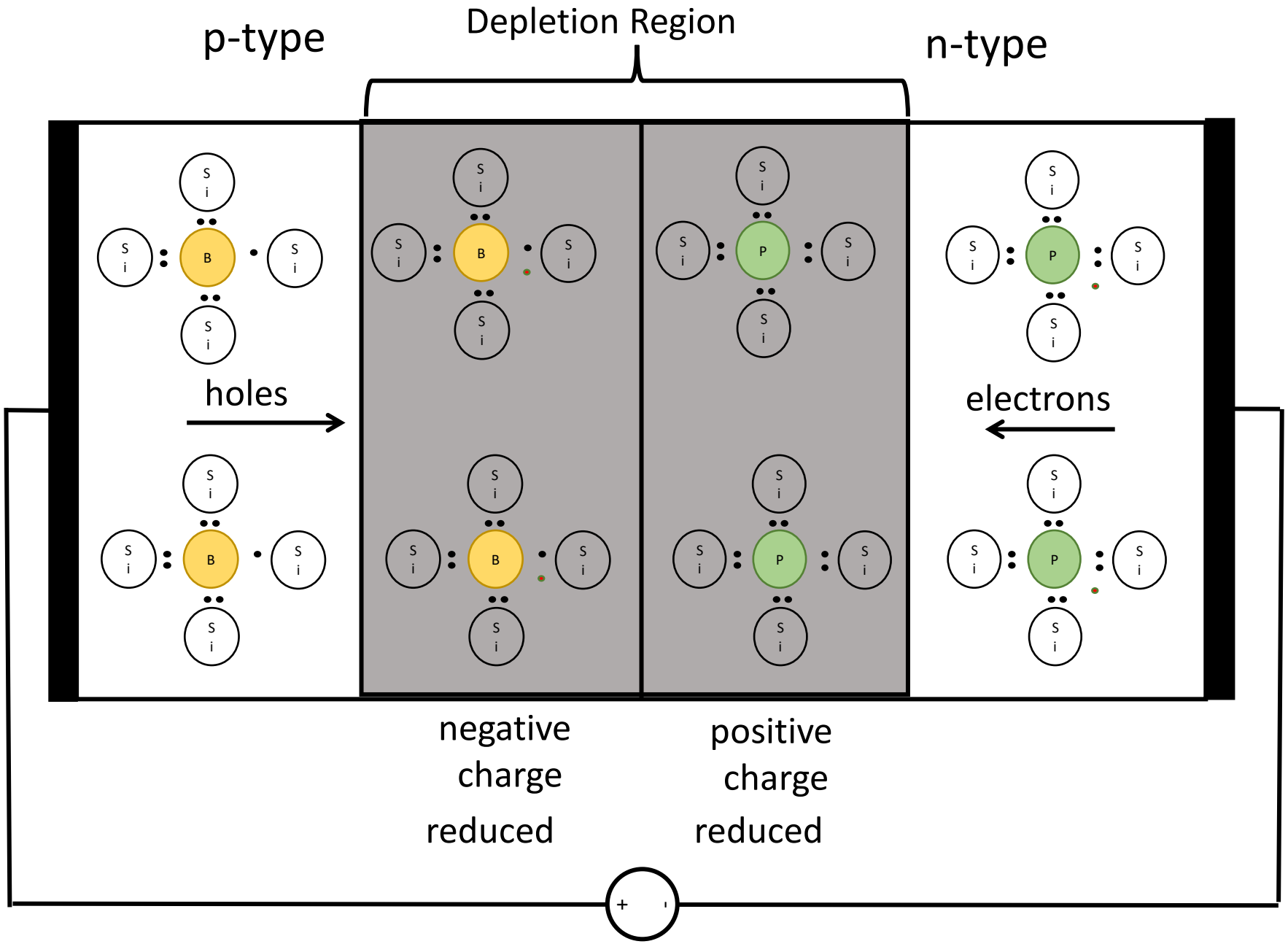




Forward Bias

- 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

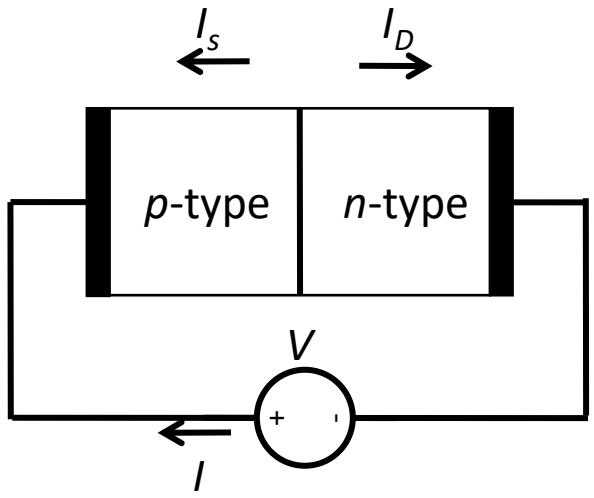



p-type
Depletion Region
n-type
holes
electrons
negative charge reduced
positive charge reduced
+
-

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:

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

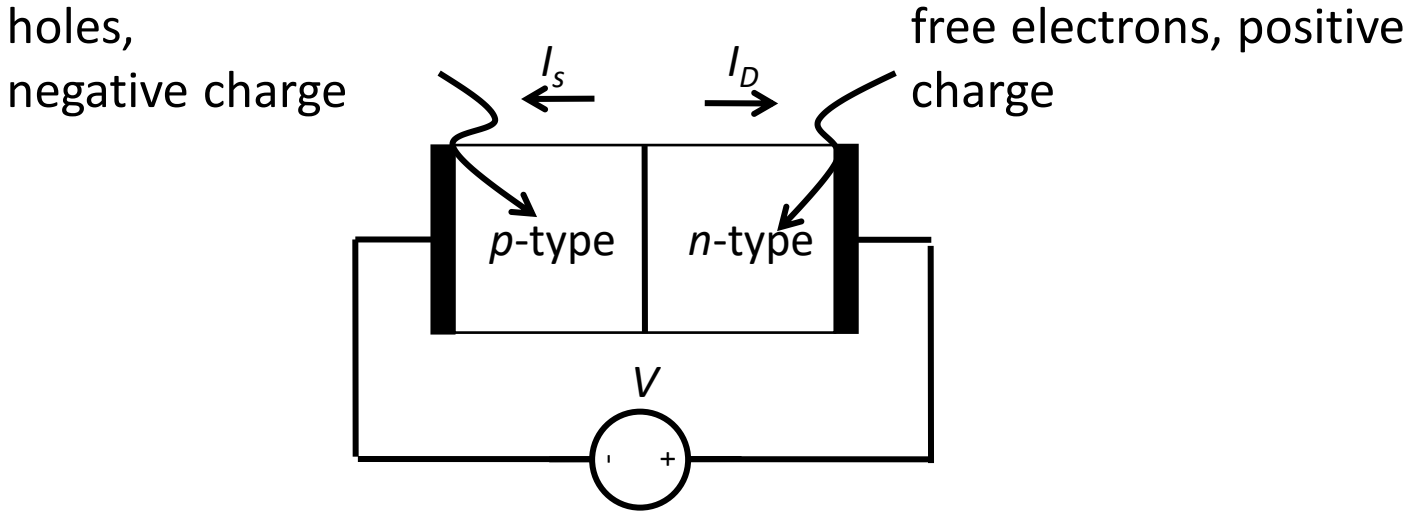
- Where:
  - k: Boltzmann's constant (1.38 x 10^{-23} J/K)
  - T: temperature in K
  - q: charge 1.602 x 10^{-19} (C)
  - I_{sat}: reverse bias saturation current (A)
- V_T is usually ~25mV

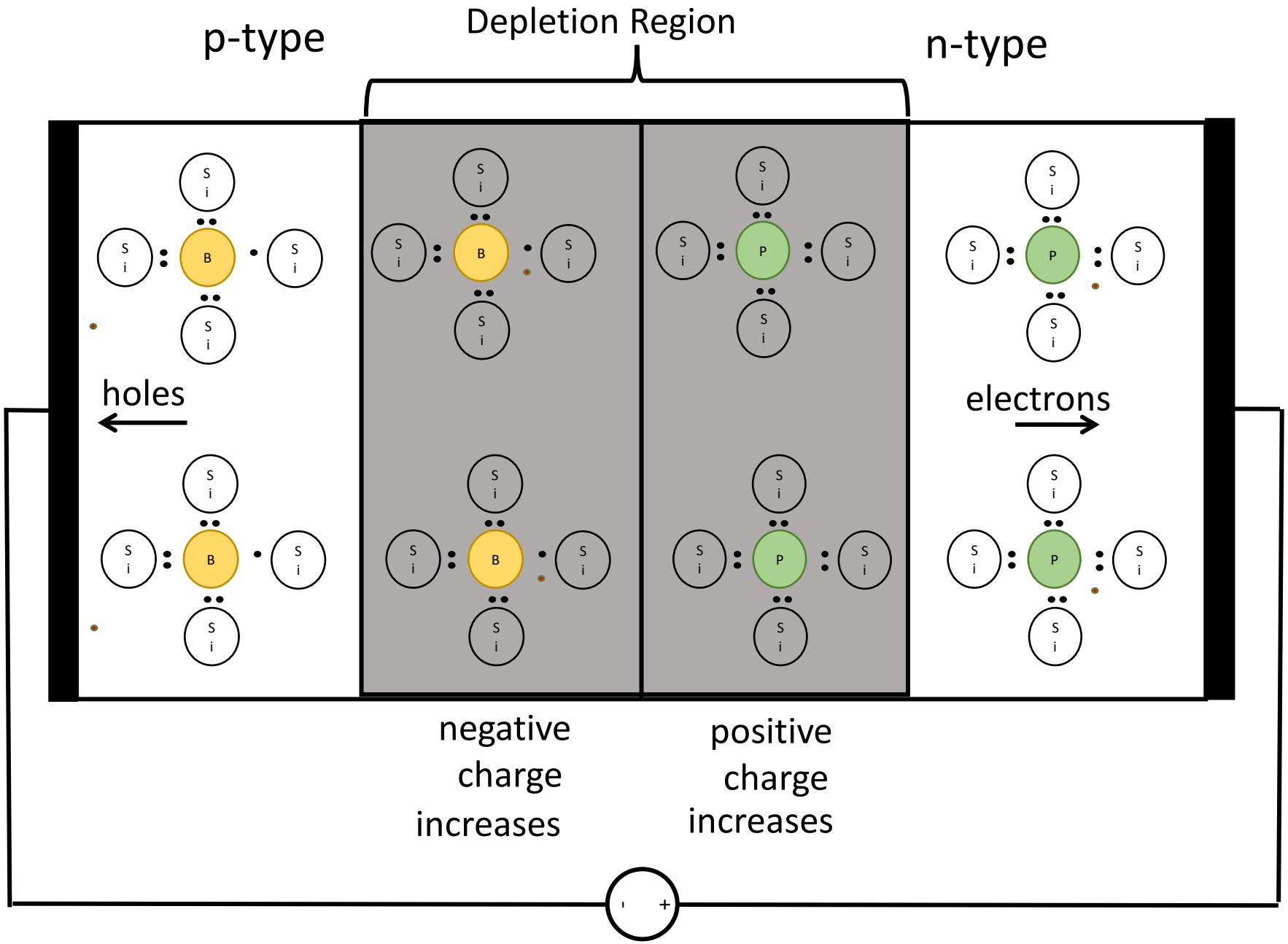
Forward Bias

- 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: depletion region increases

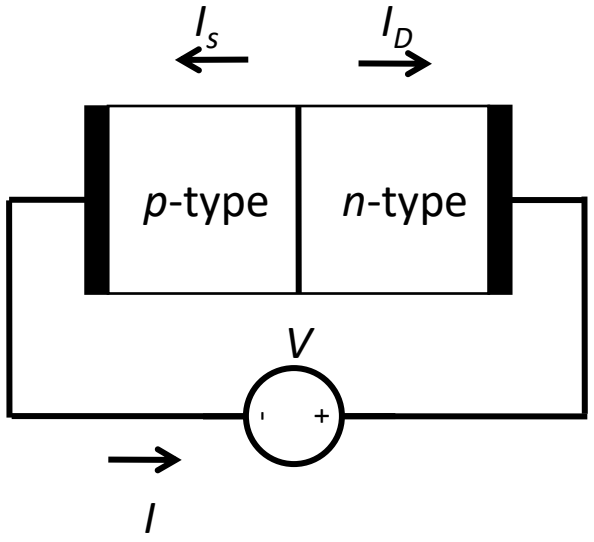



p-type
Depletion Region
n-type
holes
electrons
negative charge increases
positive charge increases

Reverse Bias

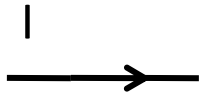
- Electric field increases strength
- Diffusion current decreases
- Drift current remains unaffected
- I remains small

$$I_D - I_s = I$$

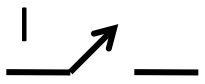


PN Junction

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



Forward Bias

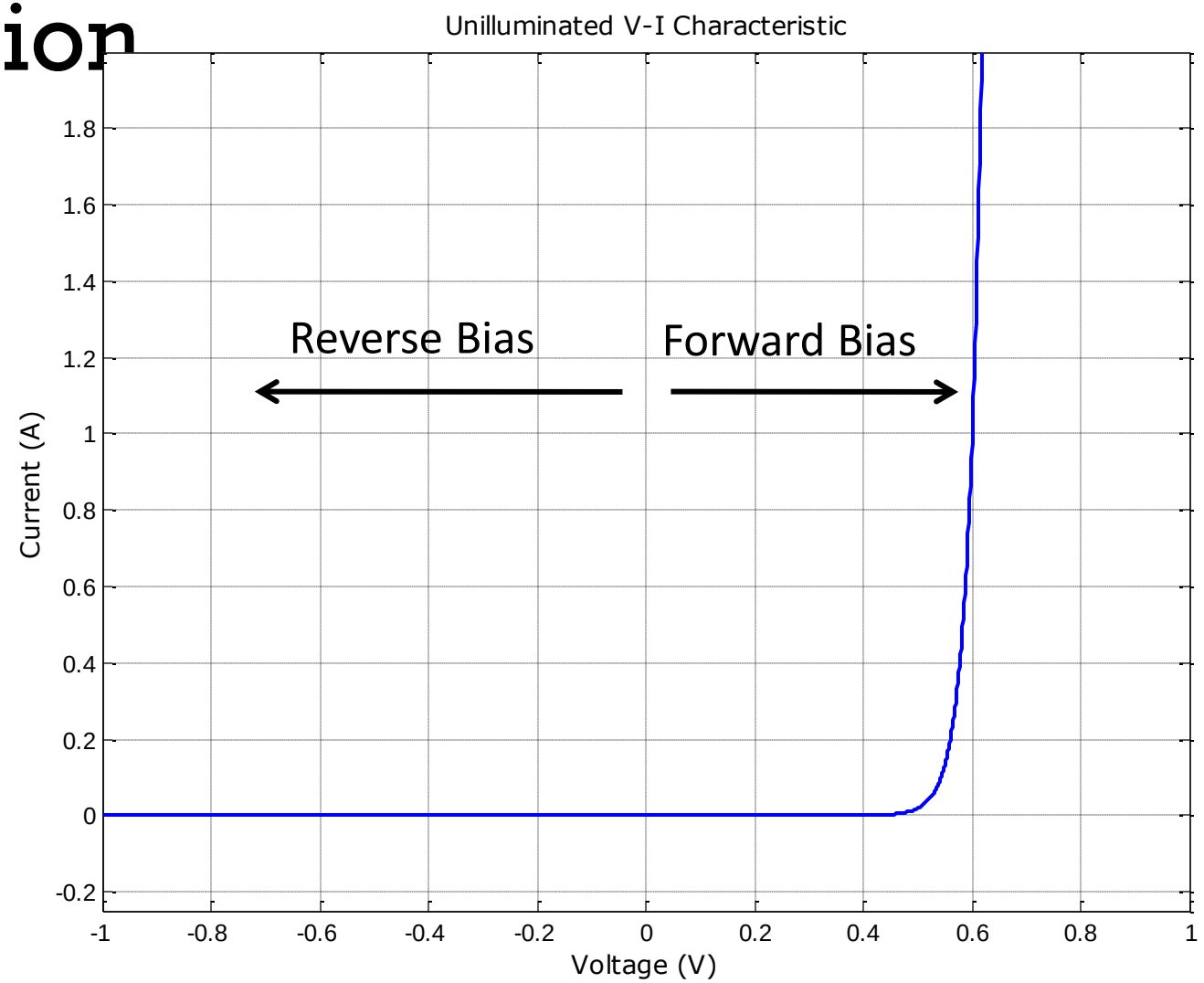


Reverse Bias

- Current through a diode:

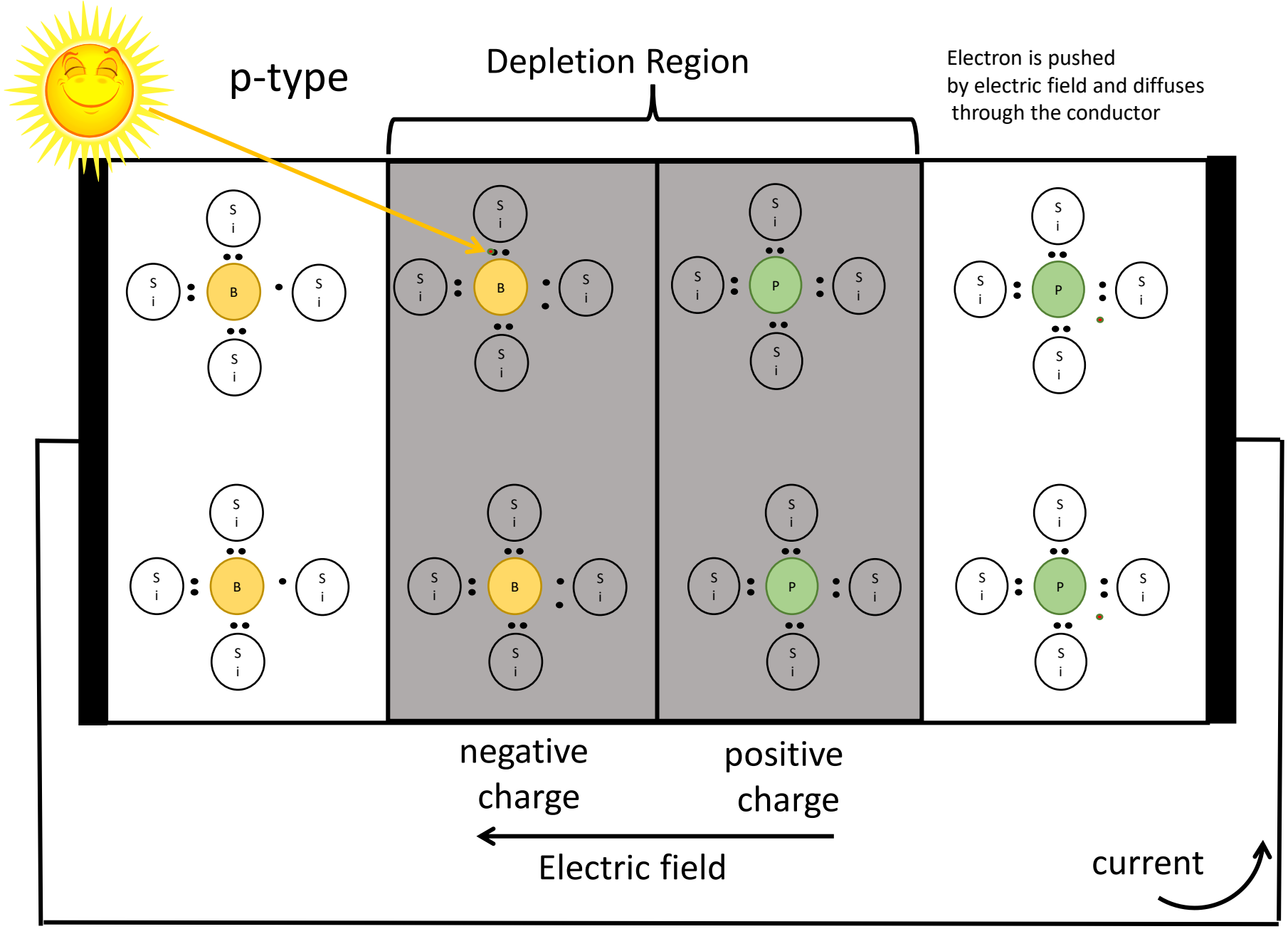
$$I = I_{Sat}\left(e^{V/V_T} - 1\right)$$

PN Junction


Unilluminated V-I Characteristic
Reverse Bias
Forward Bias
Current (A)
Voltage (V)
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

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 conductor
negative
charge
positive
charge
Electric field
current

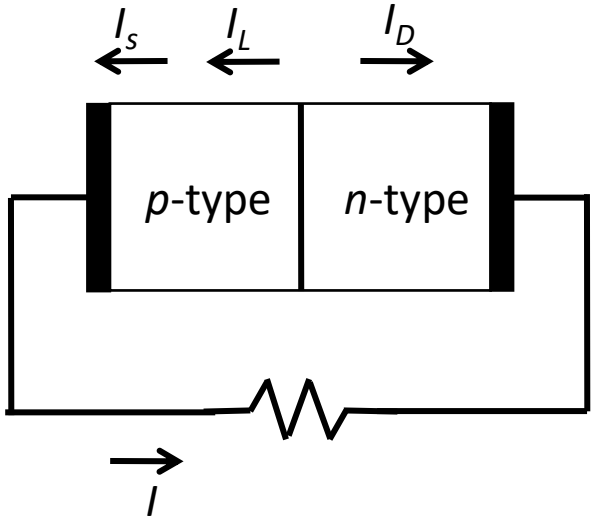
Illuminated PN Junction

- 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)

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

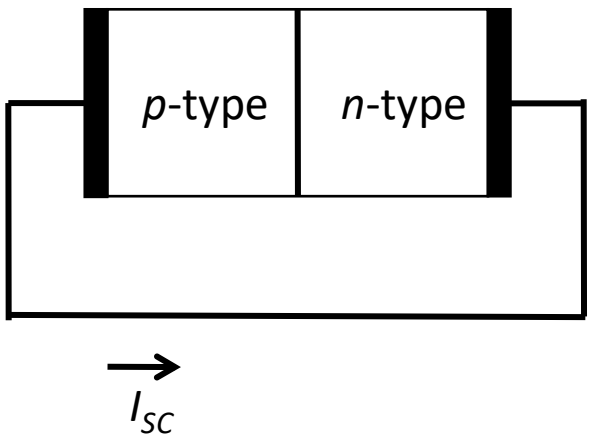
Illuminated PN Junction

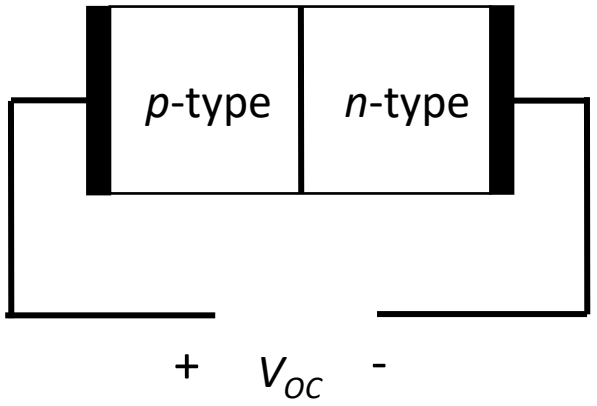
- Using active circuit convention



Illuminated PN Junction

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



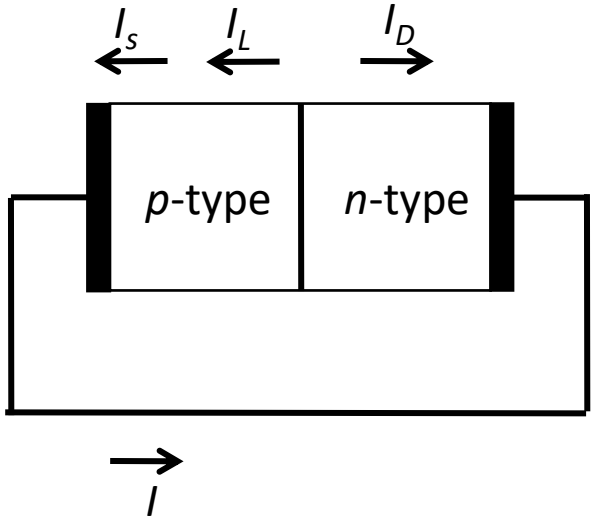


Illuminated PN Junction

- 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

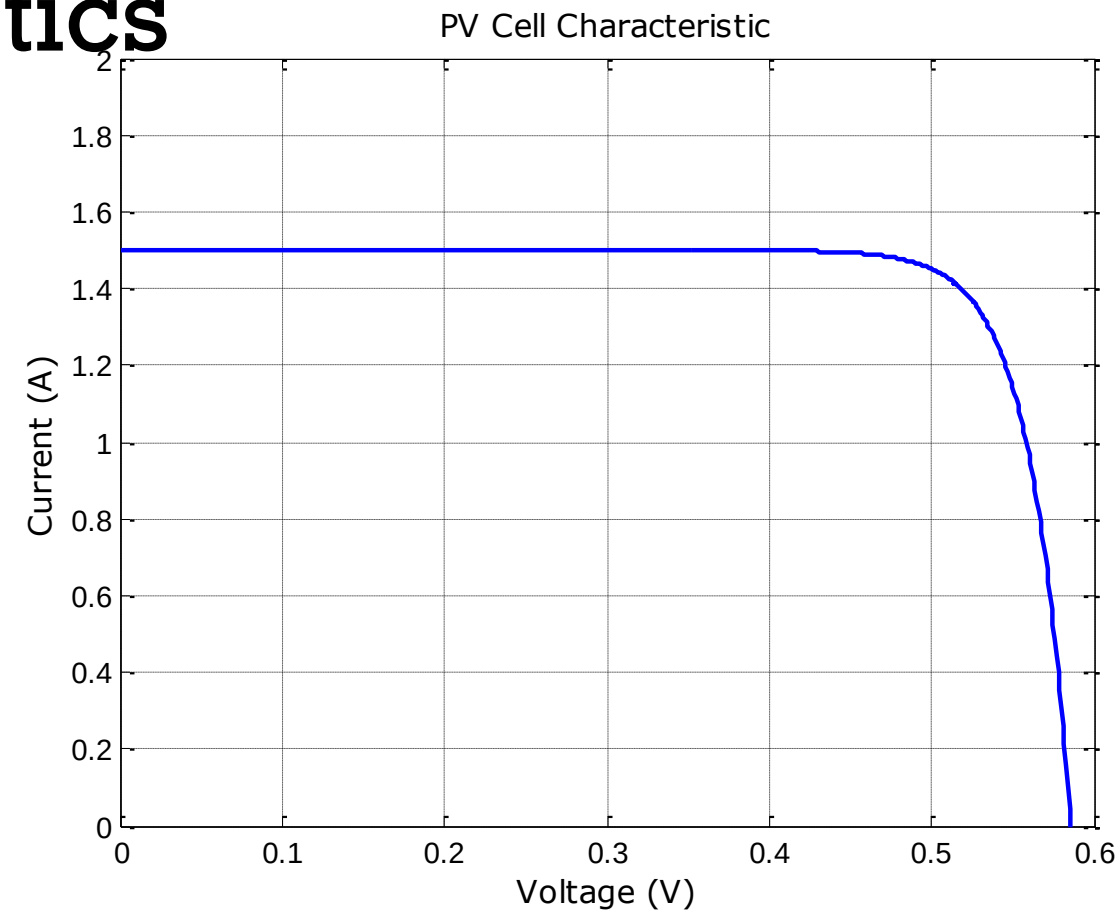
- Computing the open circuit voltage

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

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

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

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

V-I Characteristics

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