

07-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

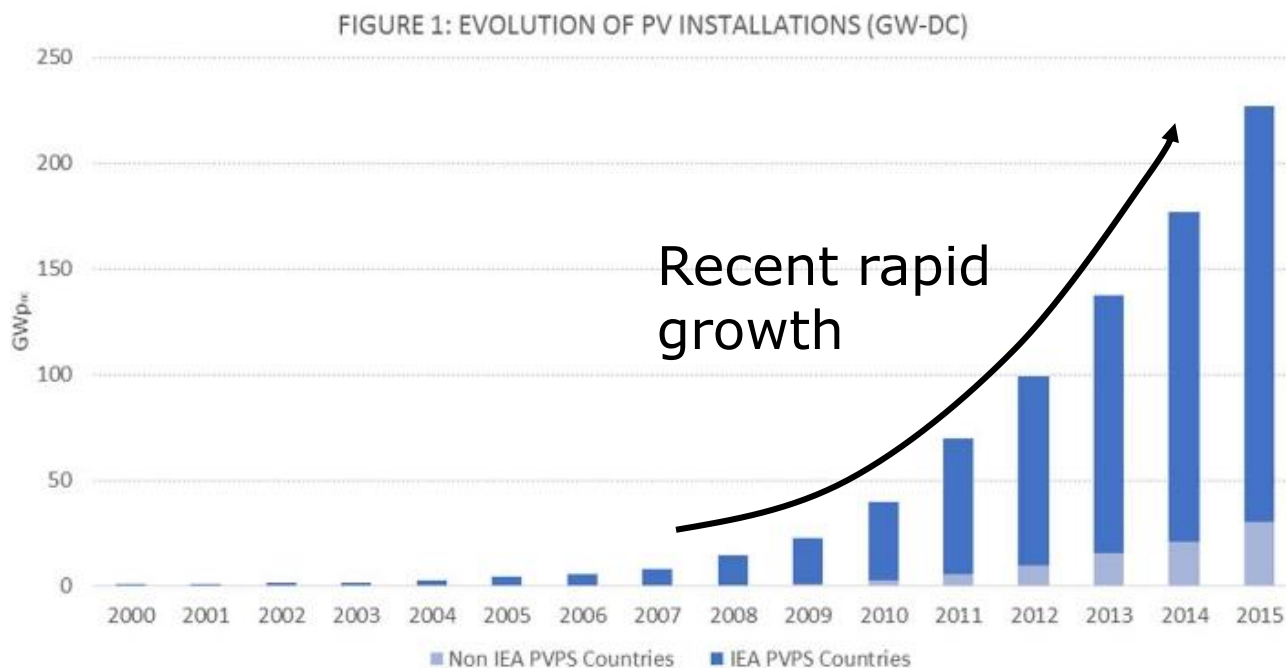
- Photoelectric Effect is the mechanism by which solar photovoltaic (PV) works
- Electricity is directly generated
- Discovered by Edmond Becquerel in 1839
- Established for power generation in 1954 by Chapin, Fuller and Pearson





PV Industry

- Reported installed PV capacity: 227 GW
 - ~50 GW added in 2015



©Snapshot of Global PV Markets – IEA PVPS



Leading Countries (2015)

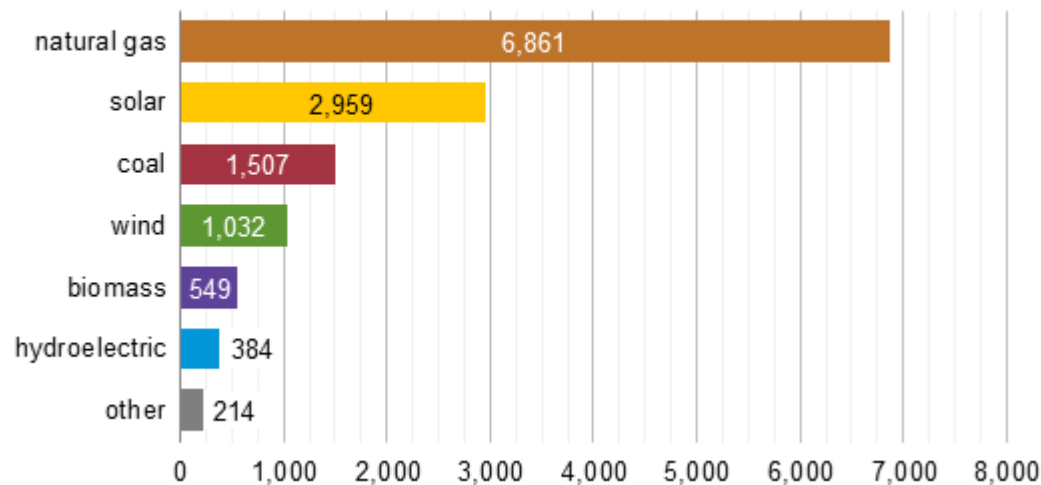
1. China: 43 GW
2. Germany: 40 GW
3. Japan: 34 GW
4. US: 26 GW
5. Italy: 19 GW



PV Industry

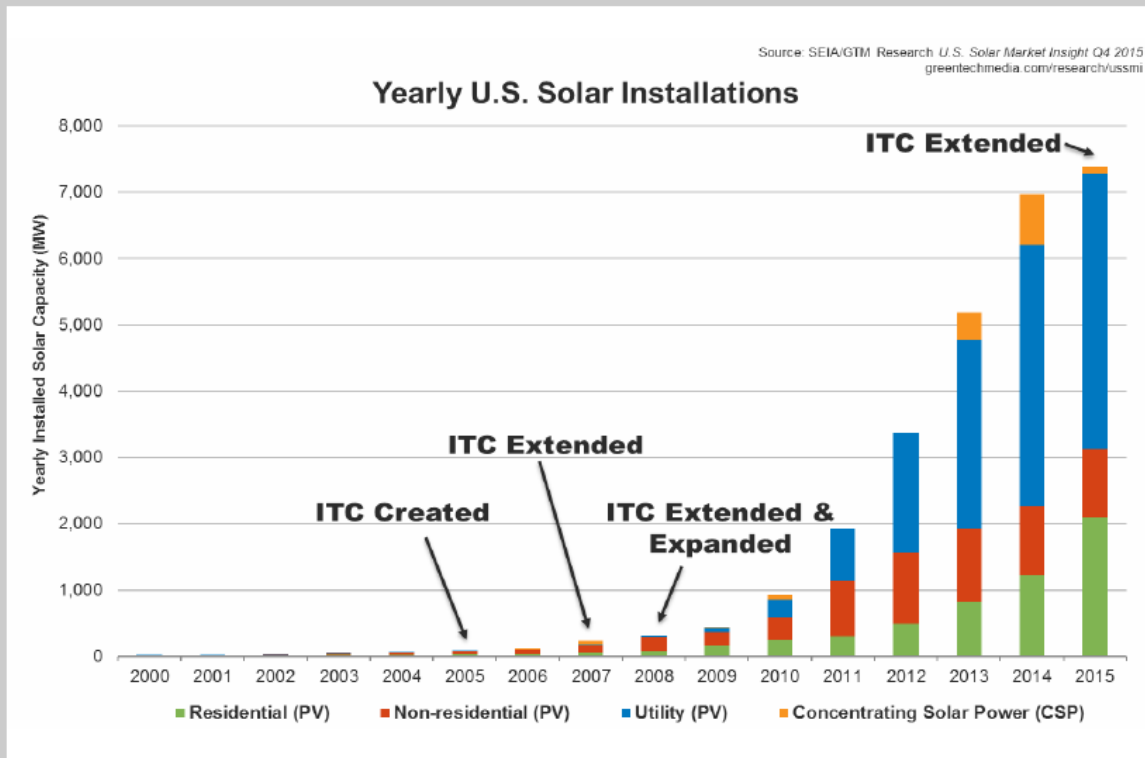
- Total US PV capacity: 13,000 MW (2014)
 - 4,751 MW added in 2013 (41% growth)

U.S. power plant capacity additions in 2013
megawatts (MW)





PV Industry



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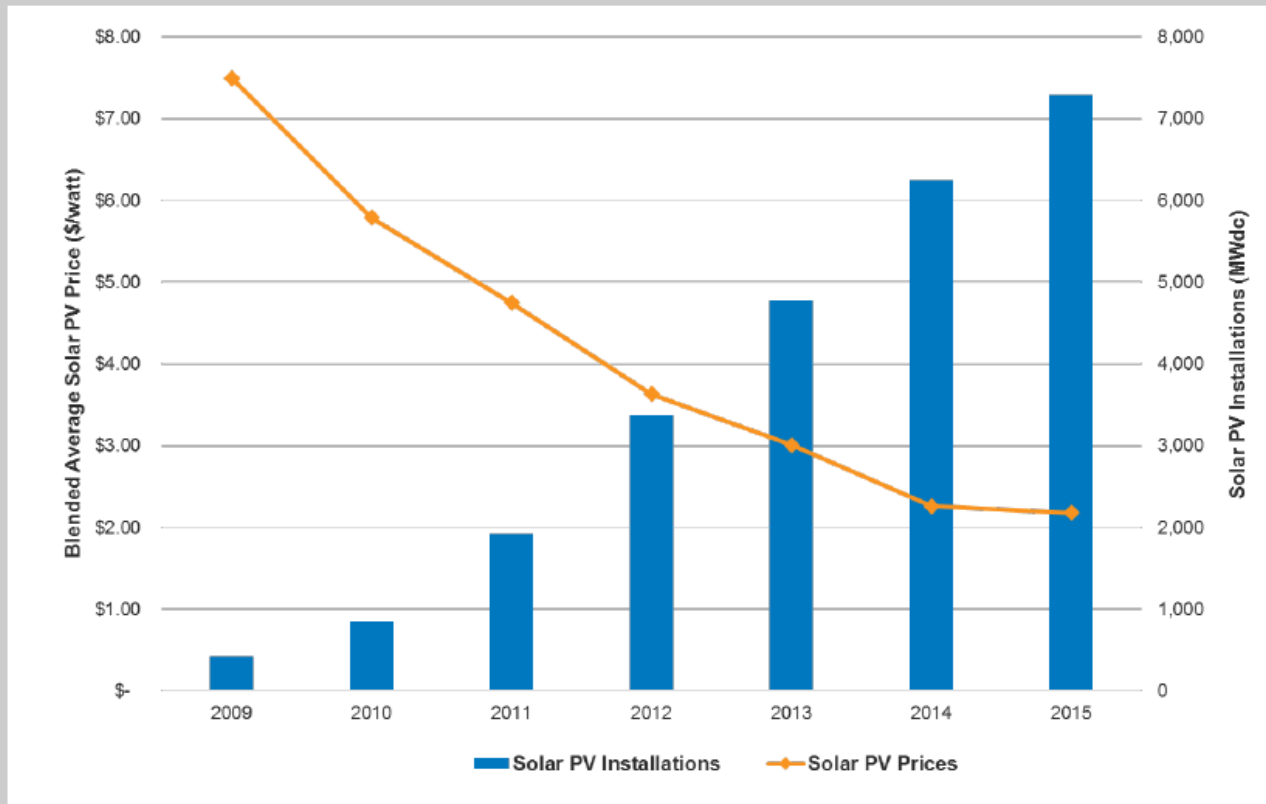
gtmresearch

SEIA
Solar Energy
Industries
Association*

Source: SEIA.org



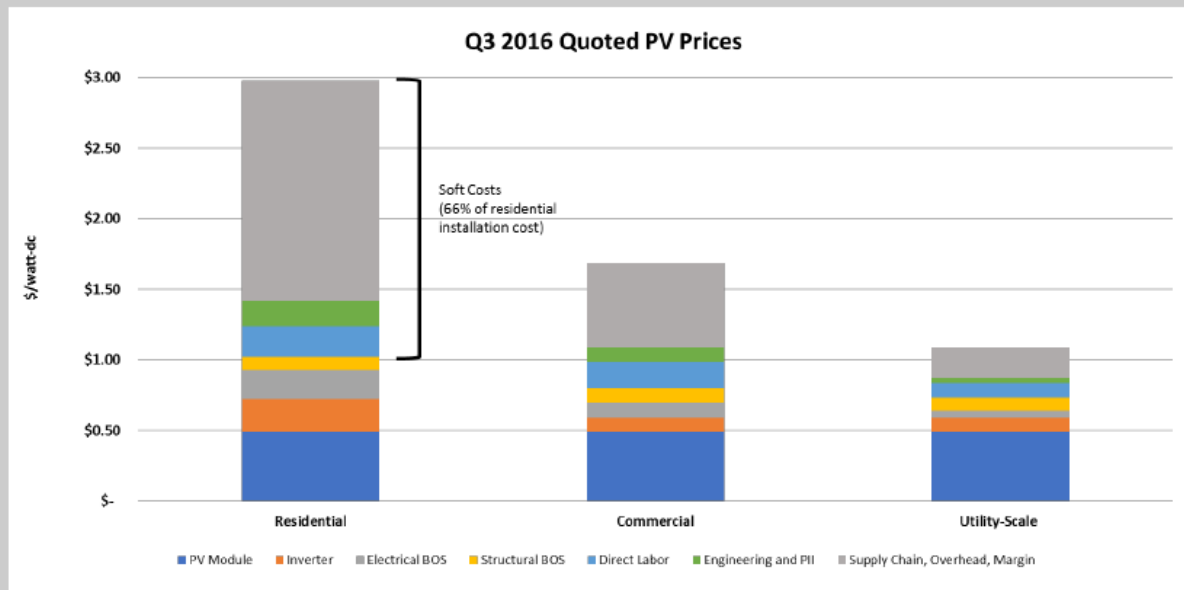
Solar Costs



Note: these
Are total costs,
not just for the panels



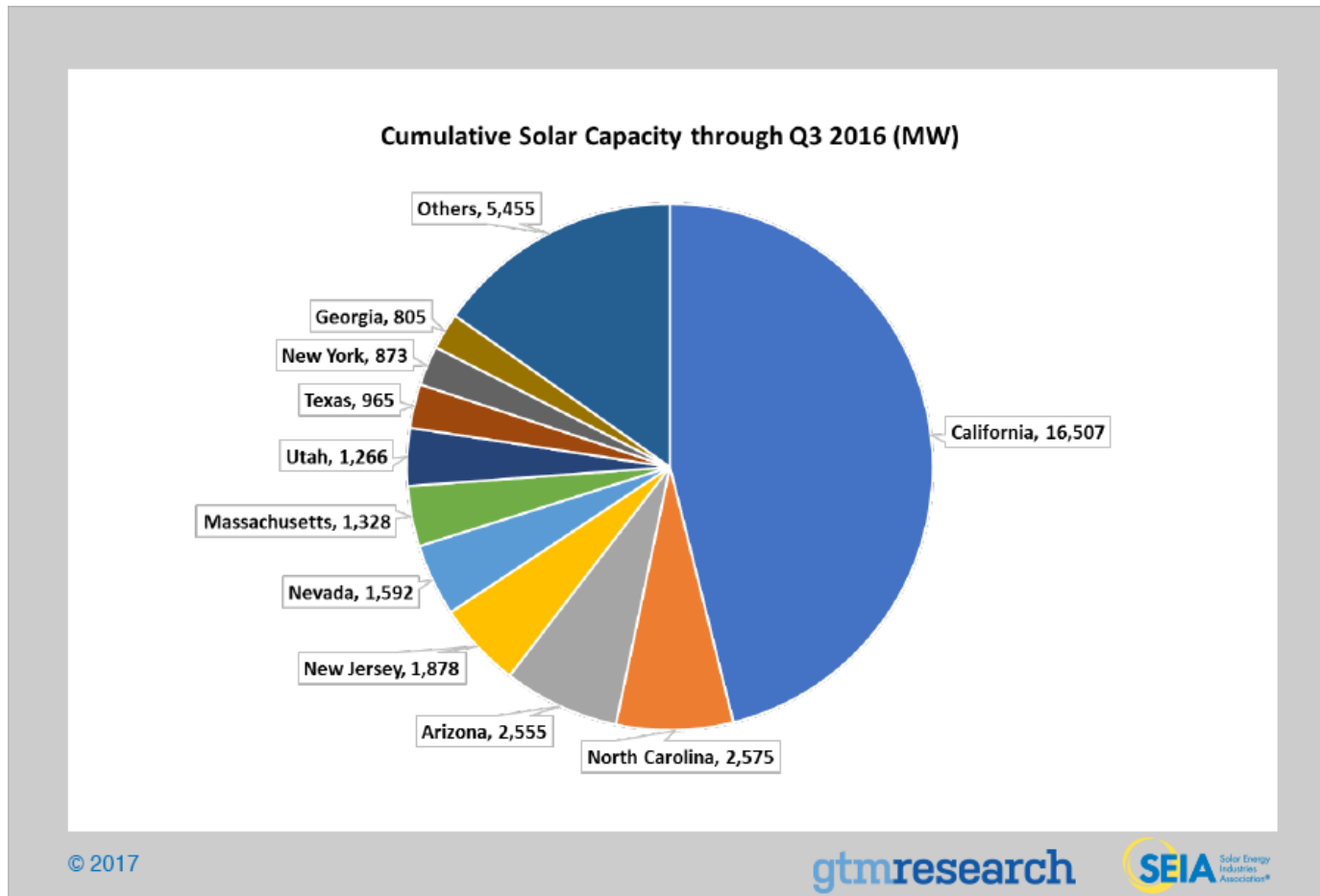
Solar Costs



PV panels cost
~\$0.50/Watt



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

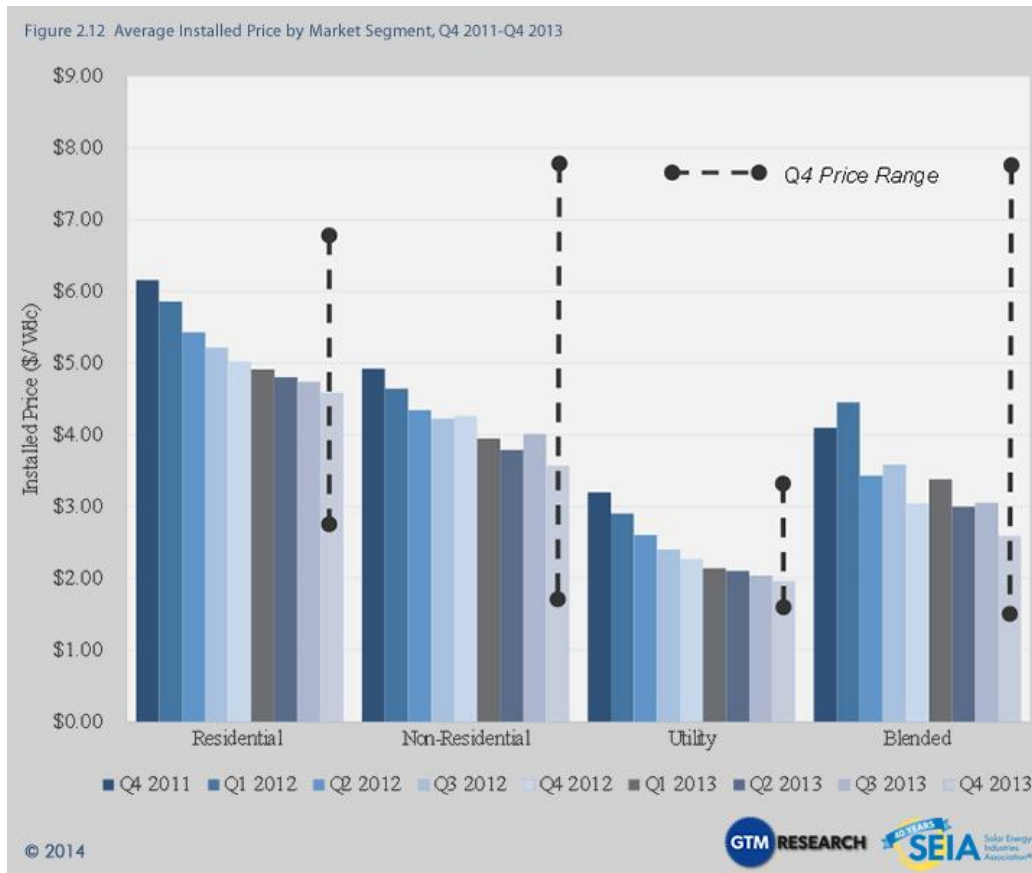


PV Basics

- 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



Solar PV Costs



Source: SEIA.org



PV Industry



monocrystalline



polycrystalline



thin film



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

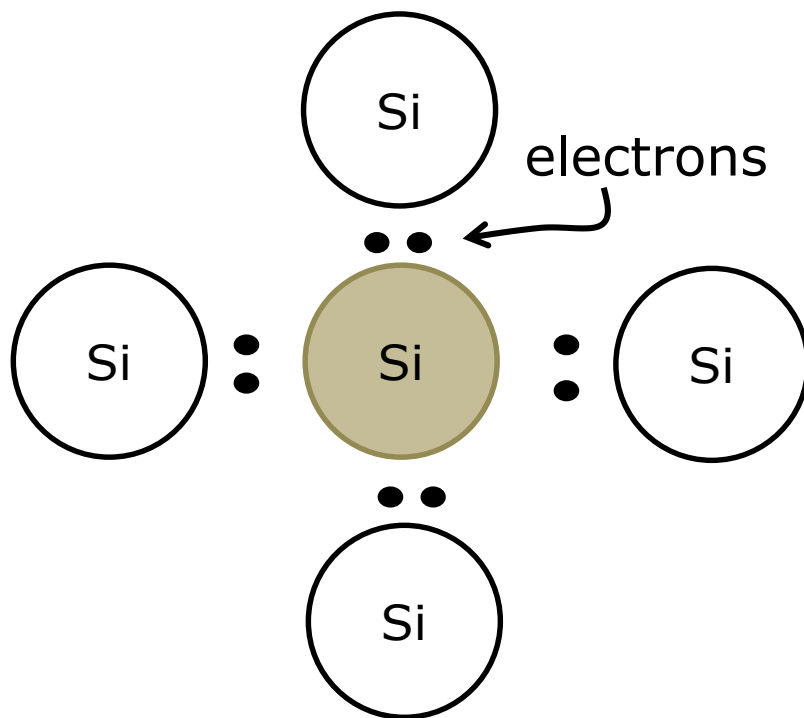


Silicon

- 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





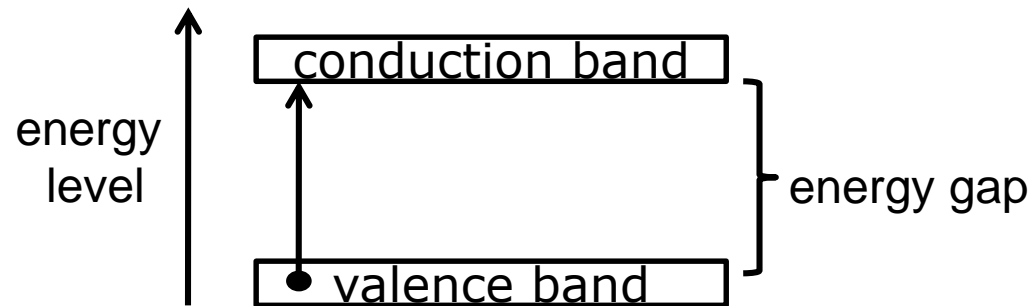
Silicon

- 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

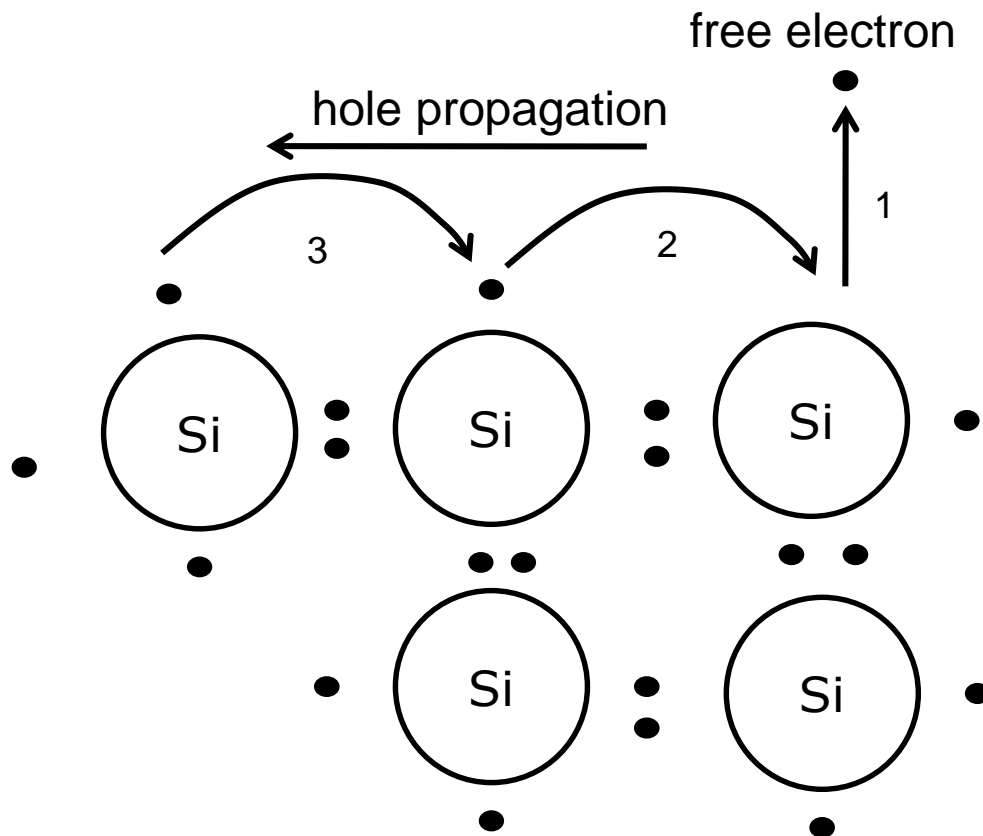


PV Physics

- 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



N-type Material

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



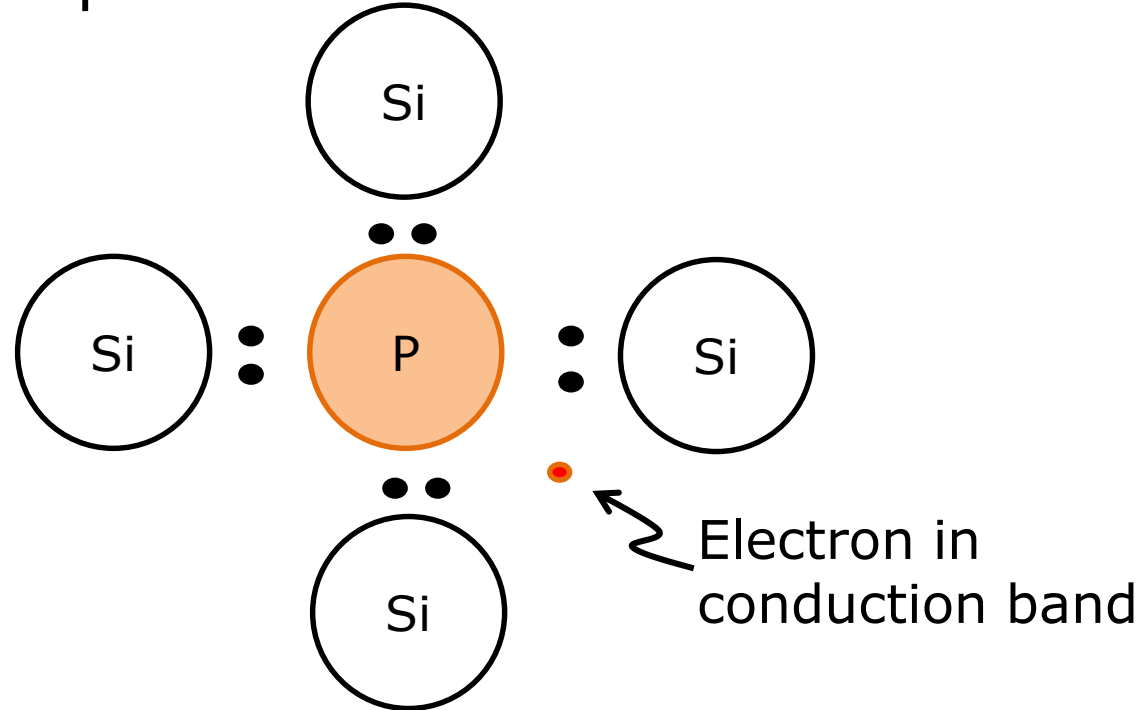
N-type Material

- 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



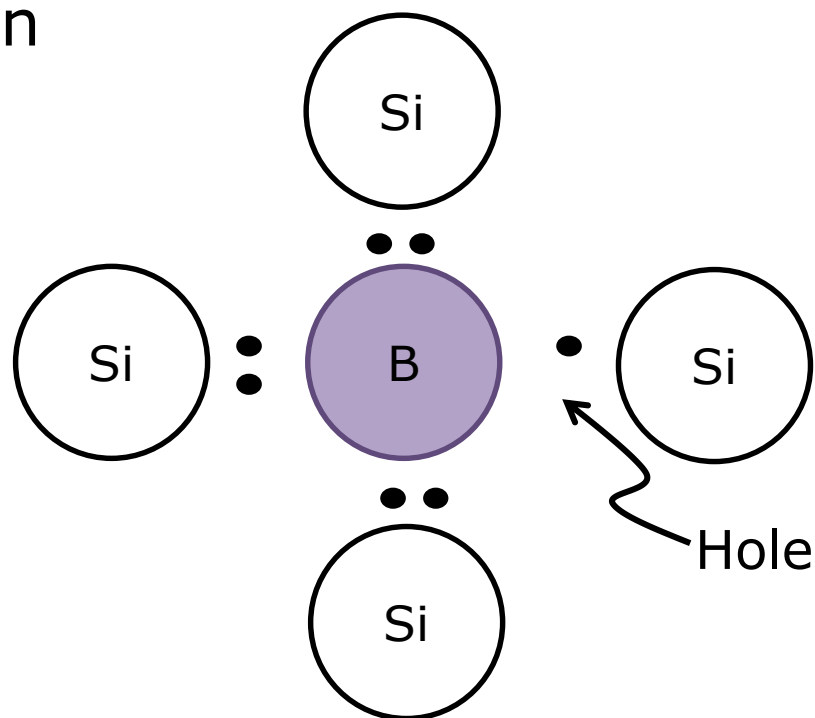
P-Type Material

- 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



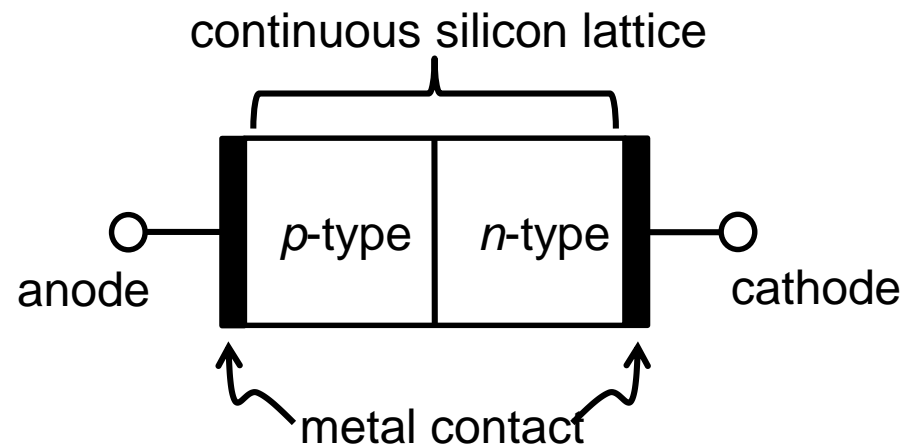
P-type Material

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



PN Junction

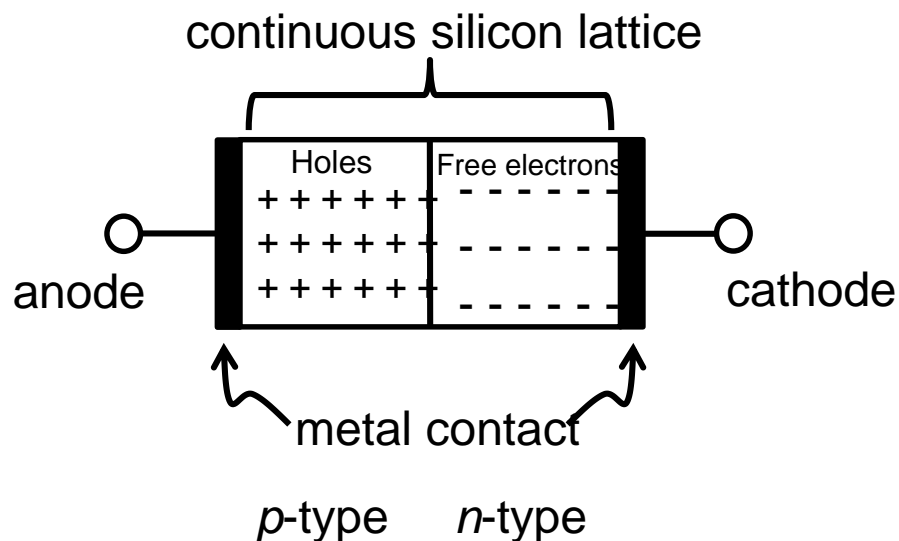
- What happens when p-type material and n-type material are placed next to each other?
 - Note: they are formed together from a continuous crystal, not a mechanical junction





PN Junction

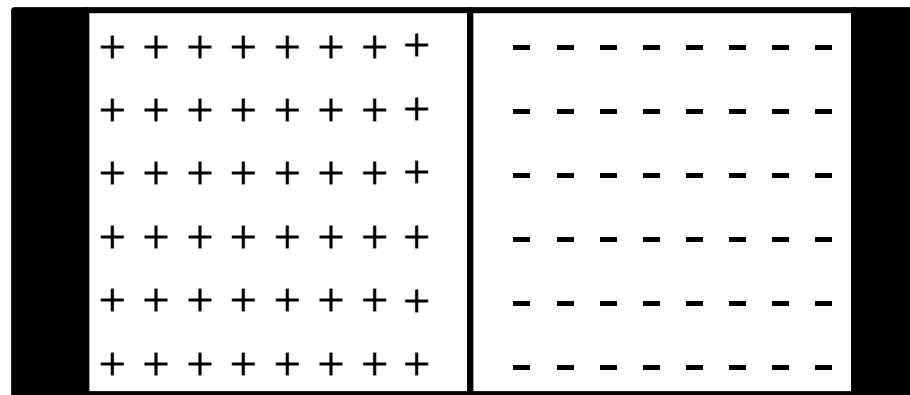
- Again, there is no net charge
- What happens next?
 - Diffusion!





PN Junction

- Diffusion current from p-type to n-type

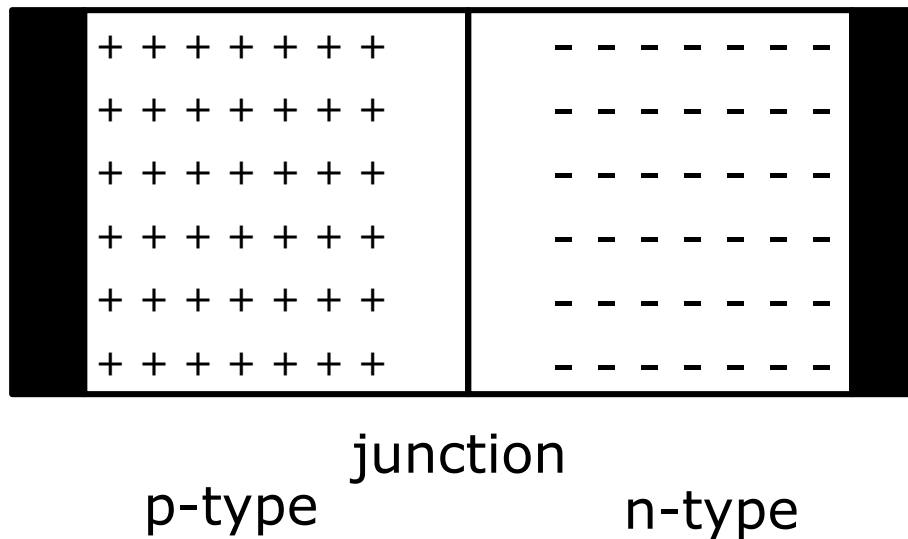


p-type junction n-type



PN Junction

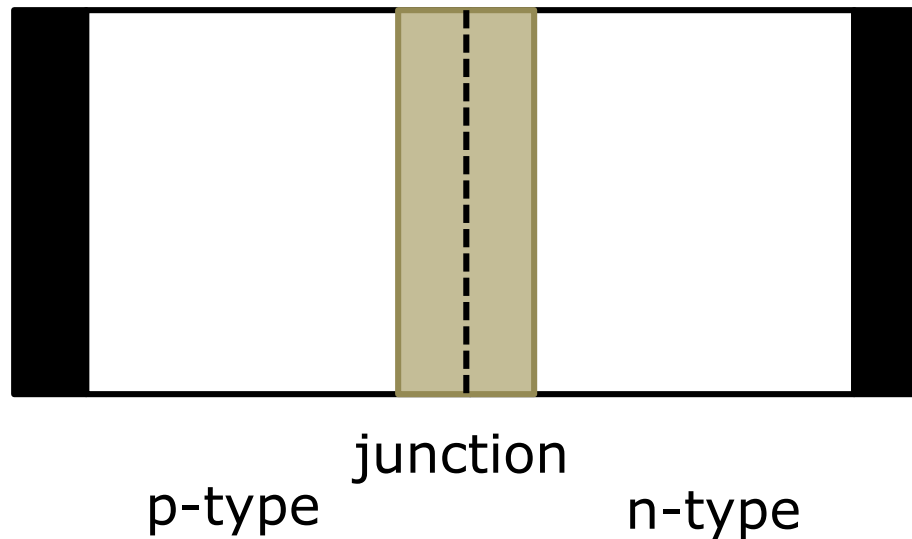
- As free electrons move from n-type to p-type they quickly find holes and recombine near the junction
 - Analogous process happens with holes leaving the p-type





PN Junction

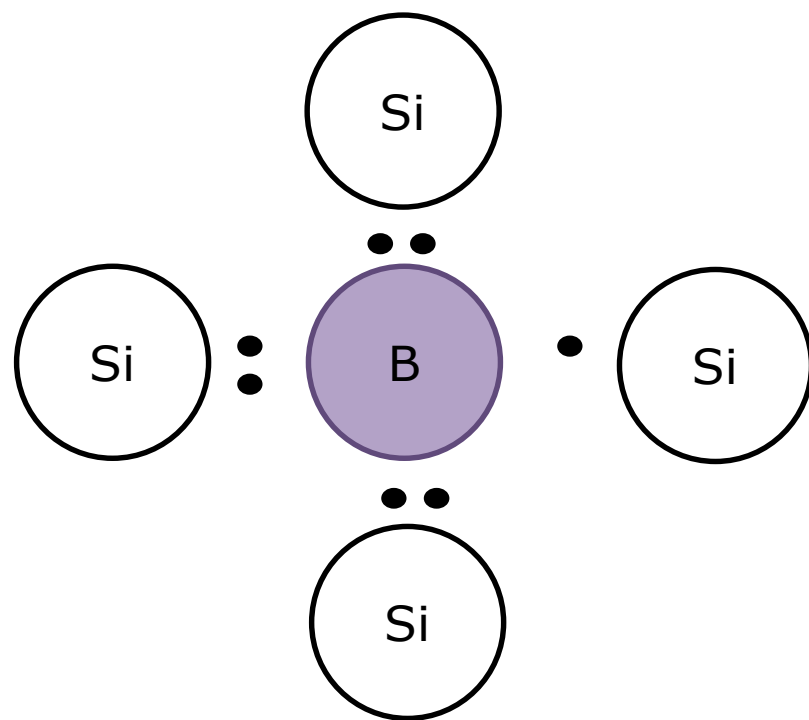
- Now the p-type material has more electrons than protons, so it develops a net negative charge (and electric field)
 - Electric field opposes more electrons from moving from the n-type to the p-type
- depletion region





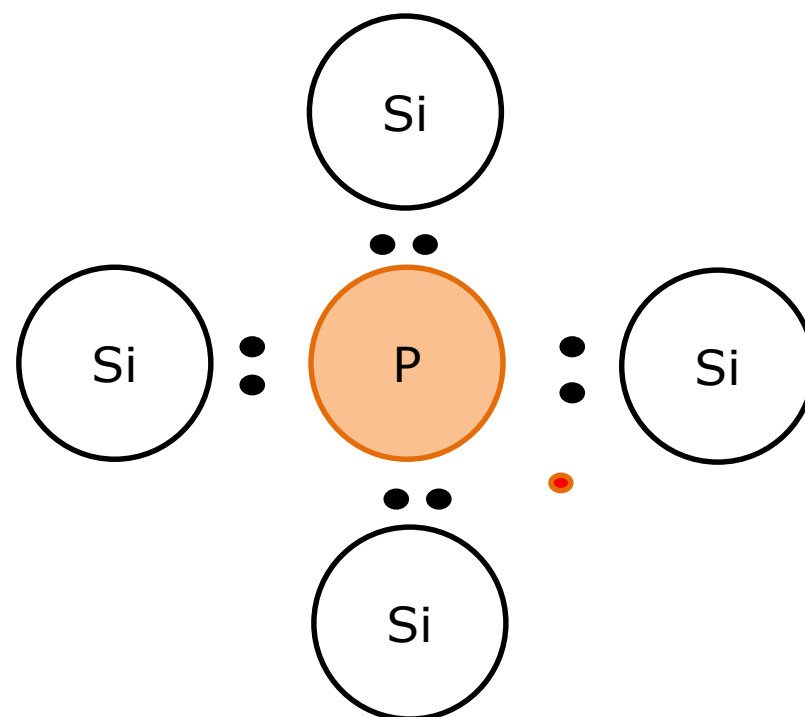
In the Depletion Region

p-type



Neutral

n-type

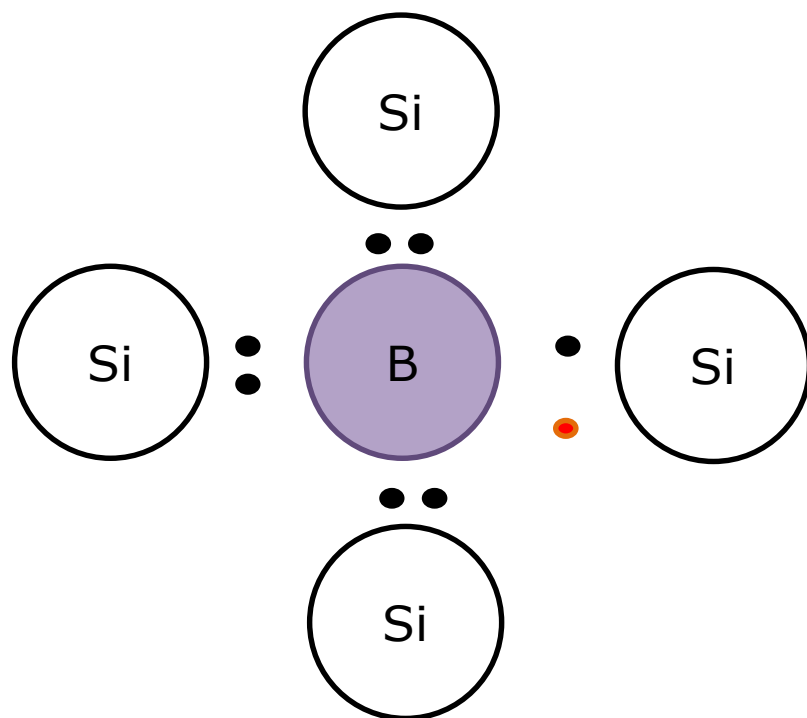


Neutral



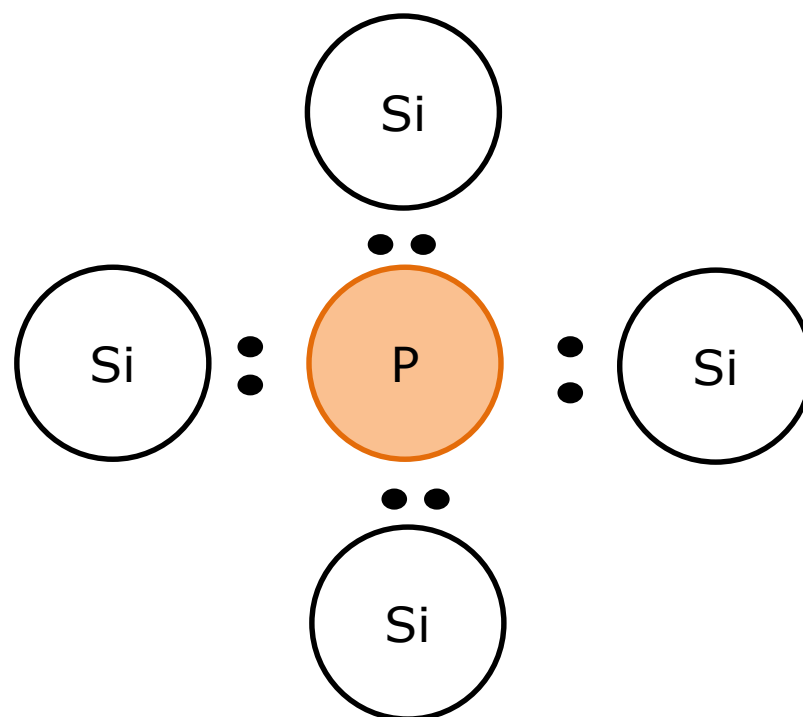
In the Depletion Region

p-type



negative charge

n-type

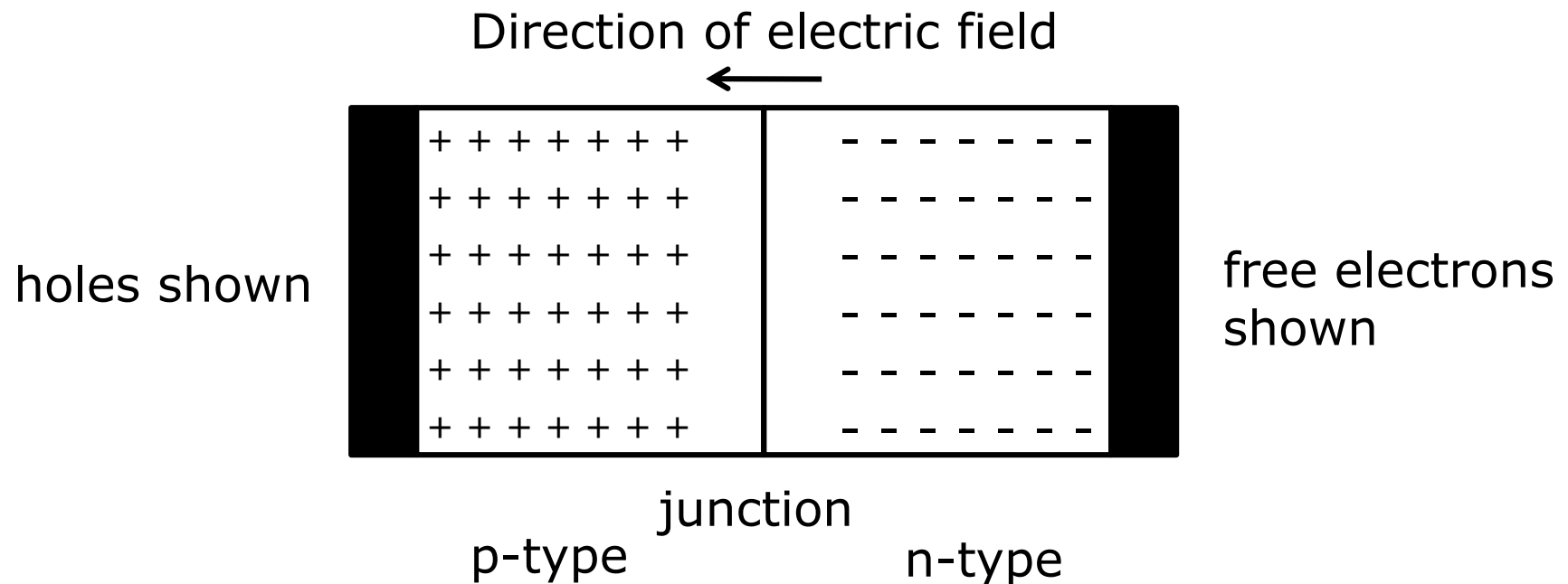


positive charge



PN Junction

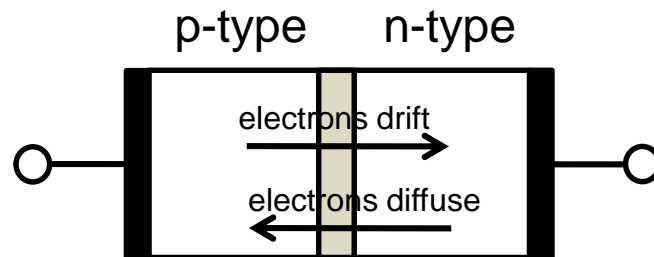
- V_0 : voltage across depletion region, usually 0.8 V at room temperature
- Note there still is no voltage across the entire material





PN Junction

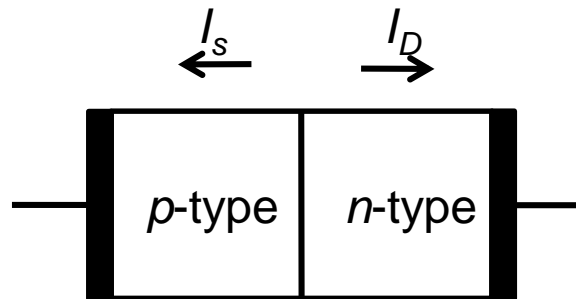
- Minority carriers on either side near or in the depletion region can be swept across the depletion region by the electric field
 - this is Drift current





PN Junction

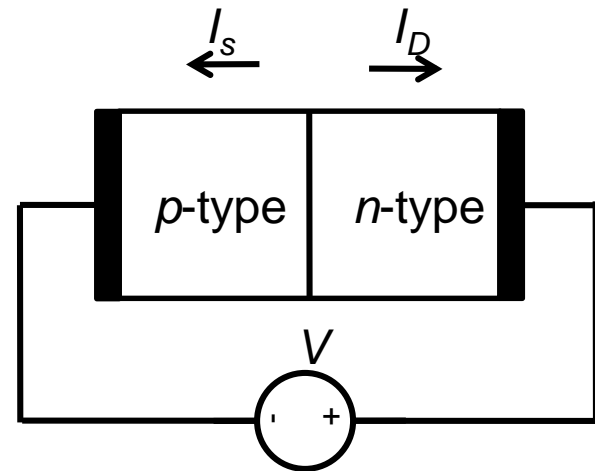
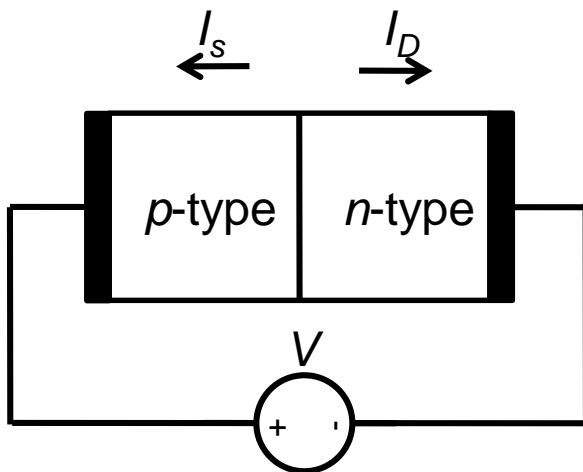
- In open circuit conditions, drift current must equal diffusion current $I_D = I_S$
 - For example, a minority electron diffusing to the n-type side will increase the concentration of electrons there which will cause increased diffusion across the depletion region





Bias

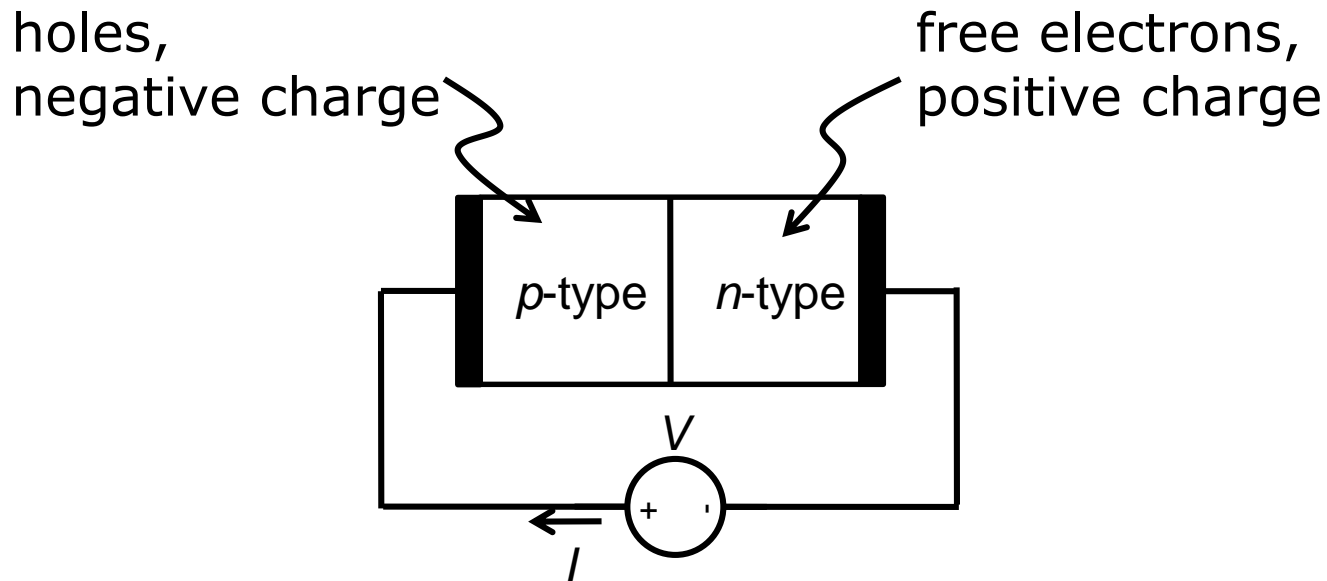
- Now assume a battery is connected to the contacts of the pn junction
- There are two ways of doing this
 - Forward bias
 - Reverse bias

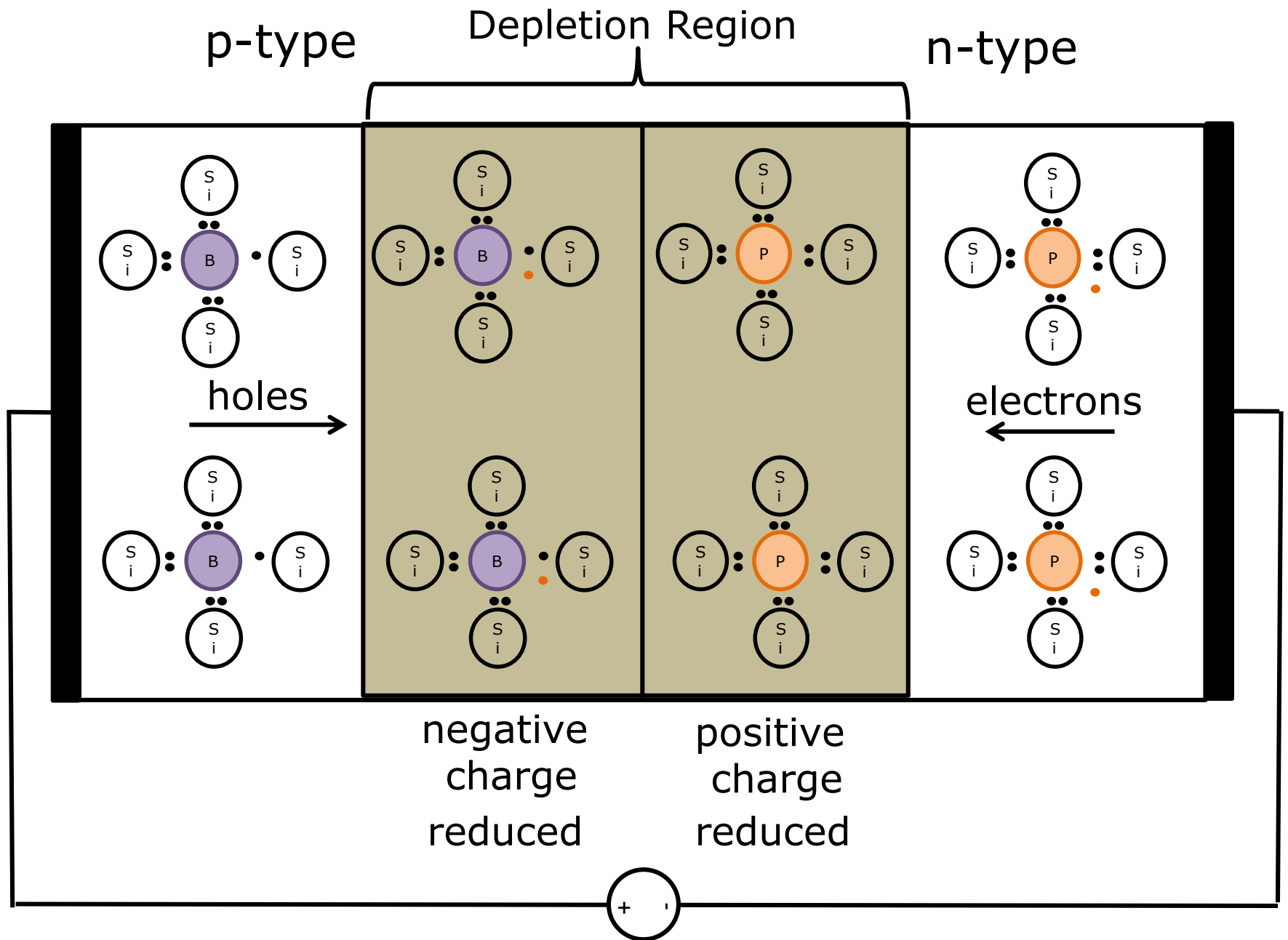




Forward Bias

- 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



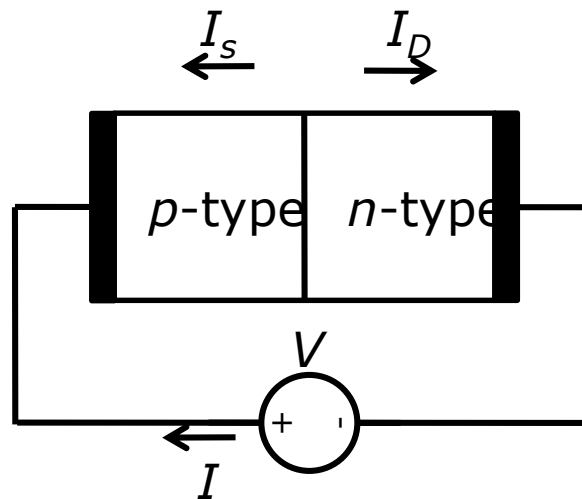




Forward Bias

- 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 (1.38×10^{-23} J/K)
 - T: temperature in K
 - q: charge 1.602×10^{-19} (C)
 - I_{sat} : reverse bias saturation current (A)
- V_t is usually $\sim 25\text{mV}$



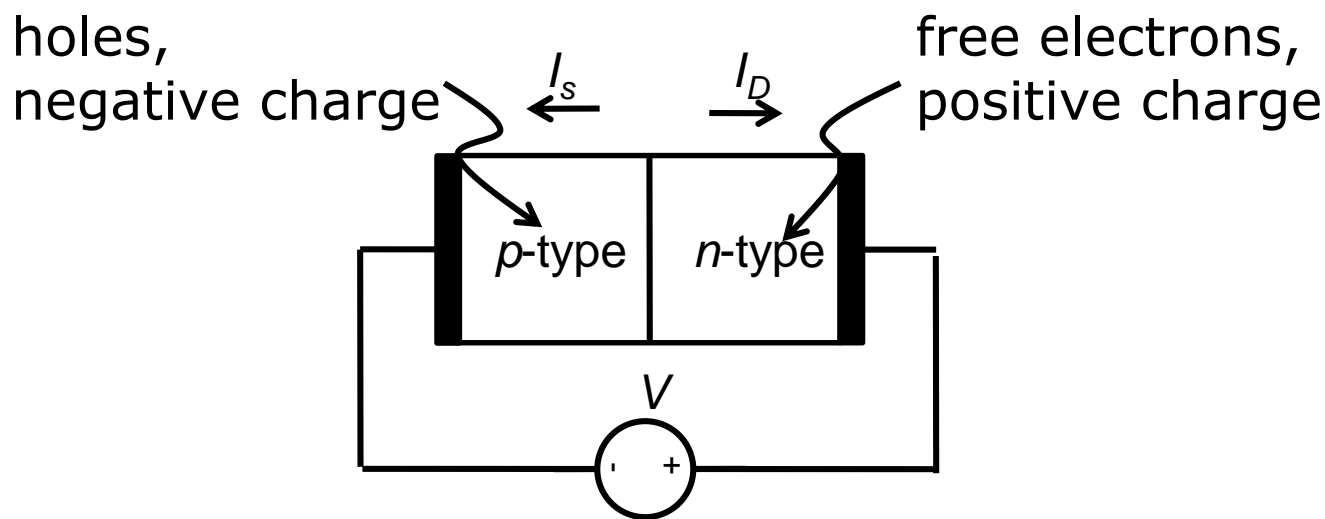
Forward Bias

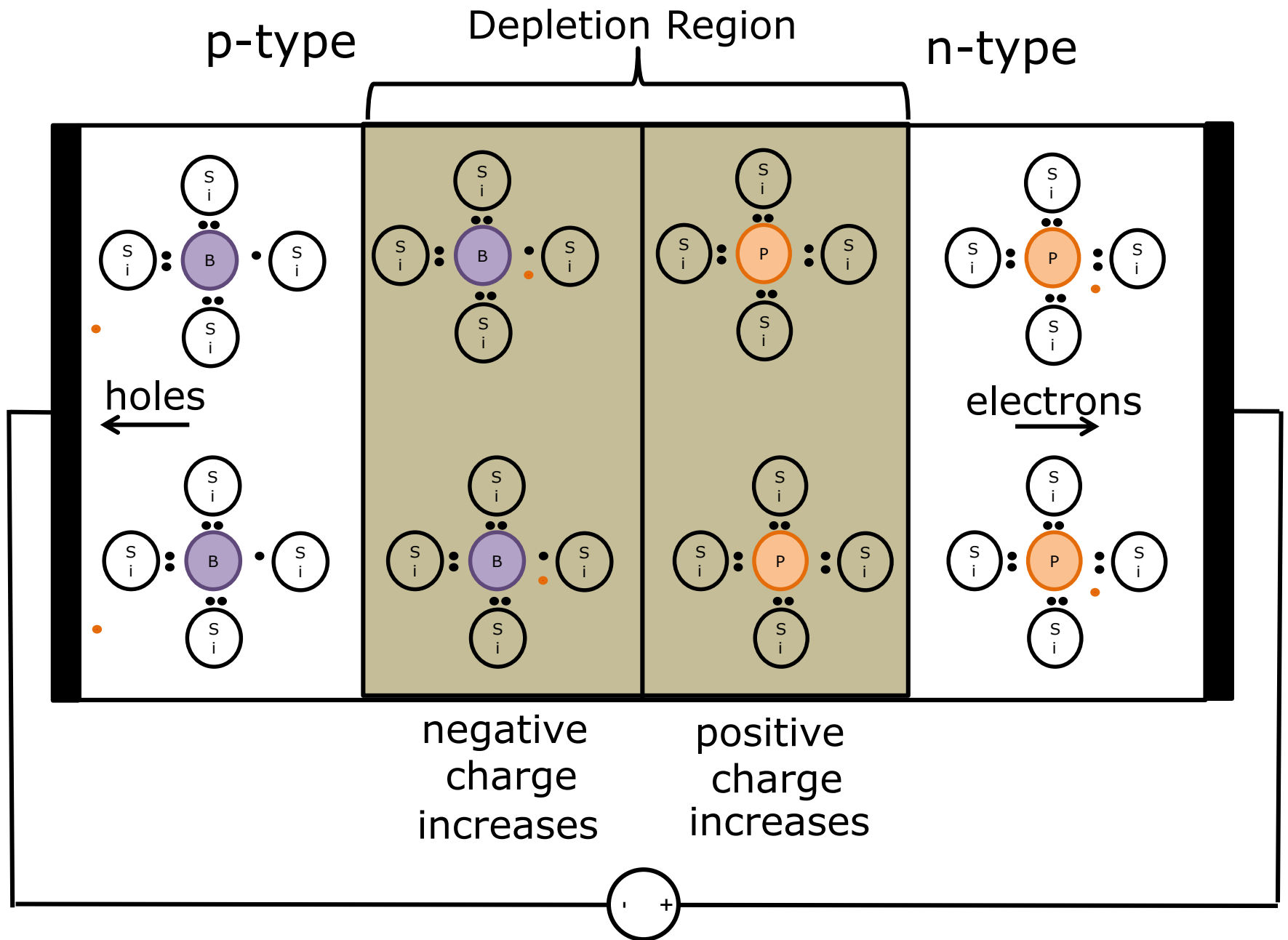
- I_{sat} is a function of temperature, junction area and other physical characteristics of the junction
 - Usually around 10^{-10} A (though could be several orders of magnitude larger or smaller)



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



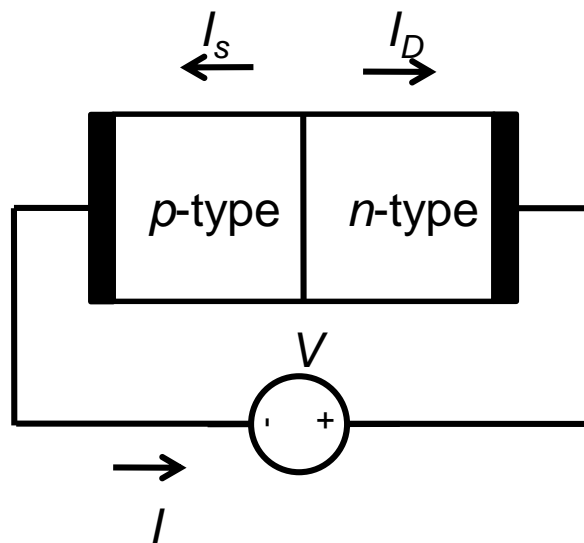




Reverse Bias

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

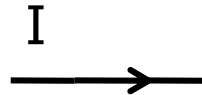
$$I_D - I_s = I$$





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

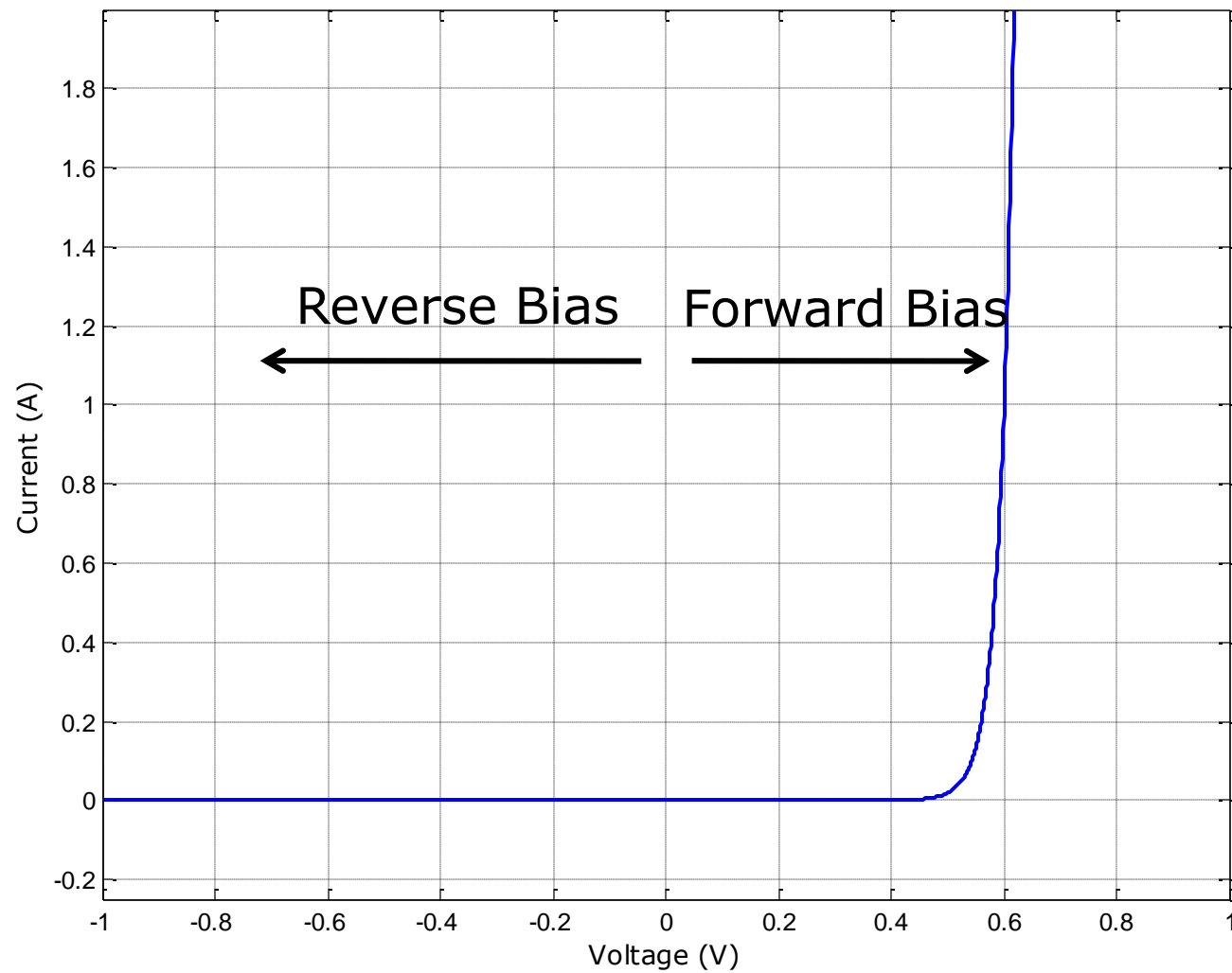
- Current through a diode:

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



PN Junction

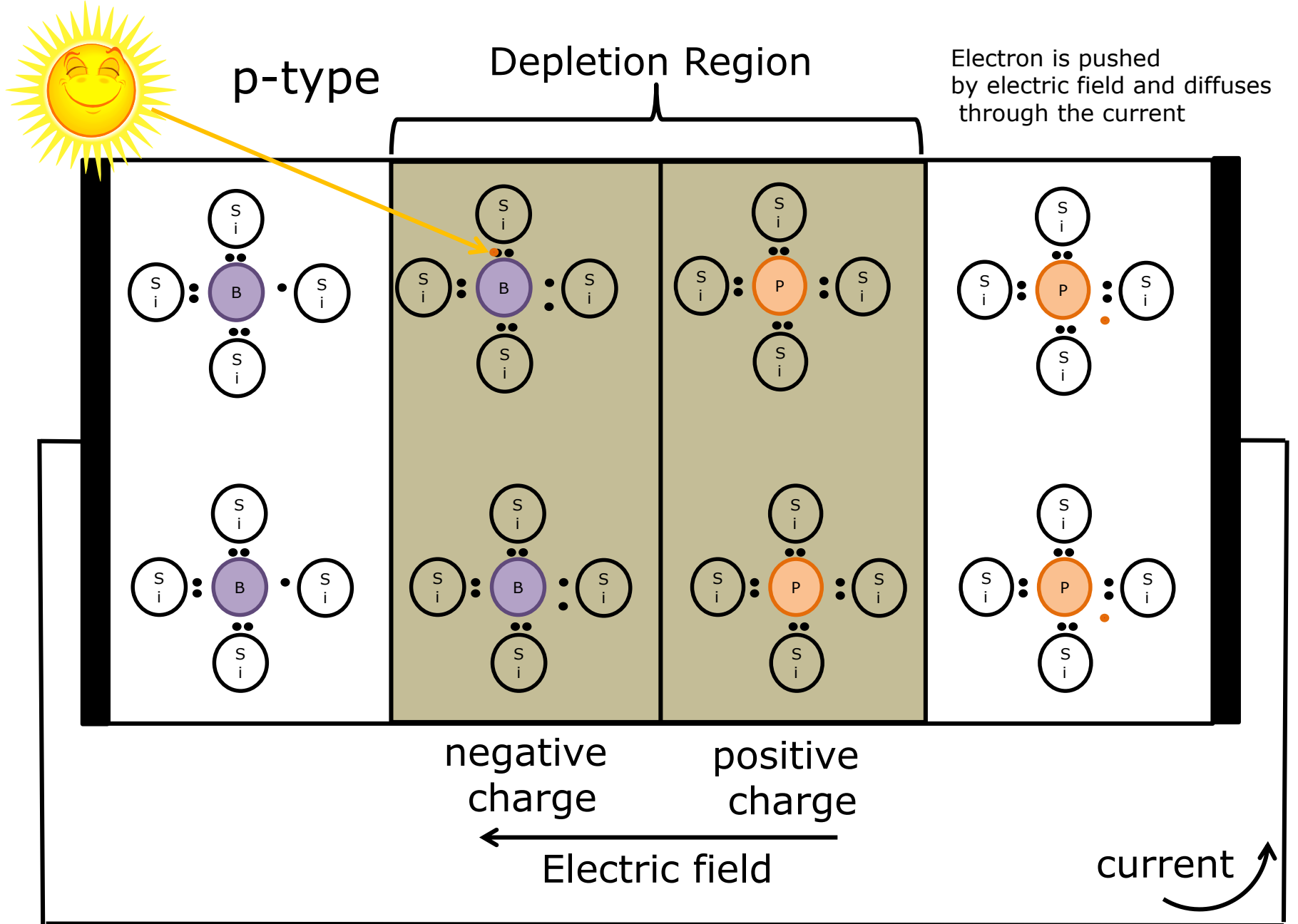
Unilluminated V-I Characteristic





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





Illuminated PN Junction

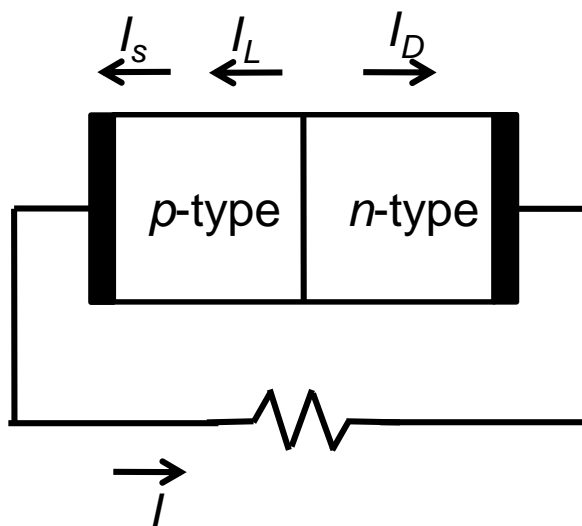
- If a photon hits an electron in the p-type material that is close to (or within) the depletion region, then the electron will be pushed across by the electric field
 - Drift current results
- This is called illumination current (I_L)

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



Illuminated PN Junction

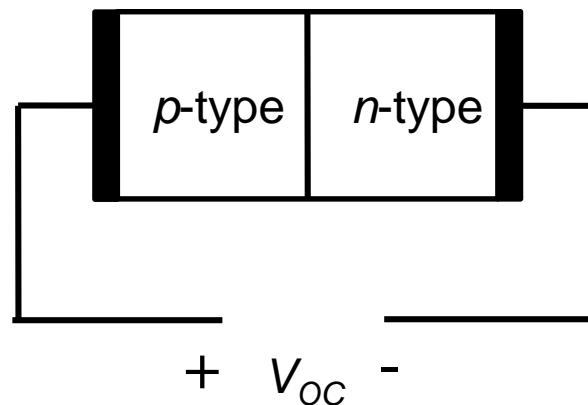
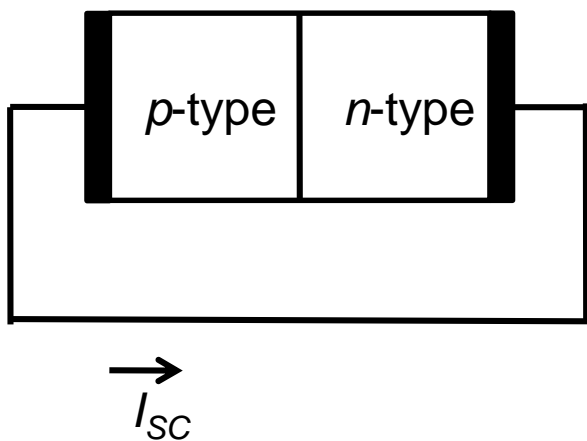
- Using active circuit convention





Illuminated PN Junction

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



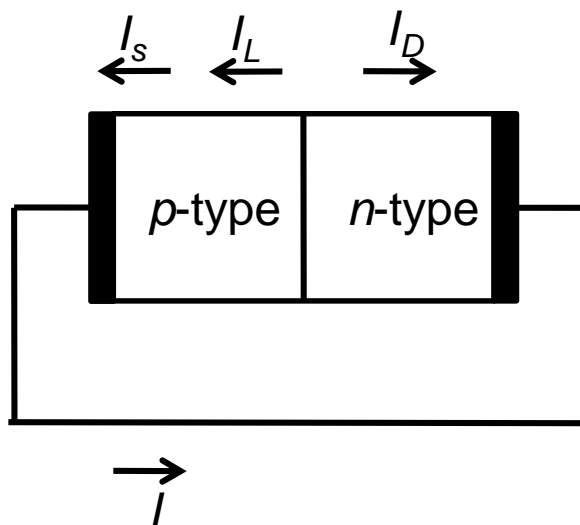


Illuminated PN Junction

- 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

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

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

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

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



V-I Characteristics

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

