EE40 Lec 17

PN Junctions

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10/27/2009

Reading: Chapter 10 of Hambley

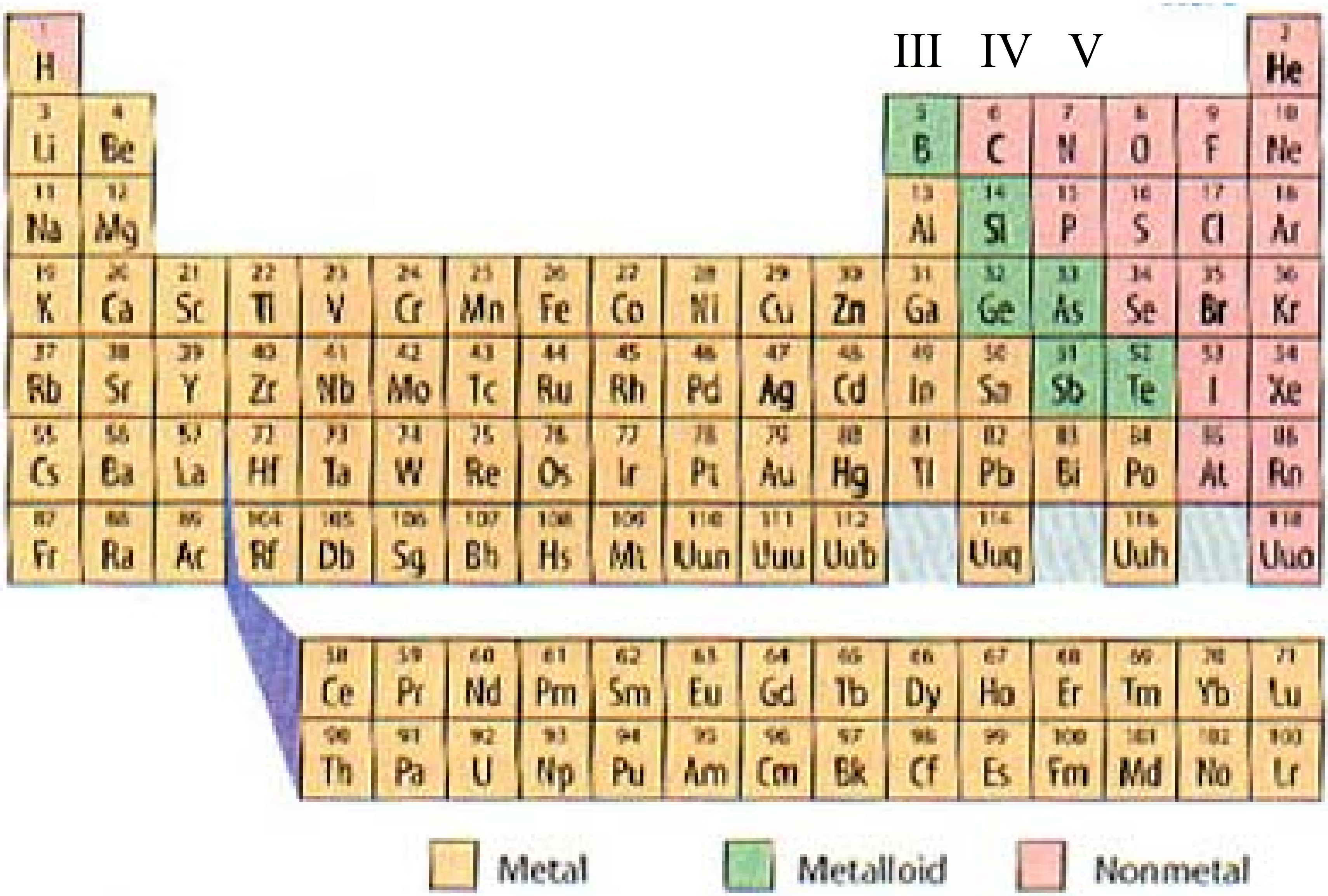
Basic Device Physics Handout (optional)

PN Junctions

- ***Semiconductor Physics of pn junctions (for reference only)***

- Diode Current and Equation
- Solar Cells, Photo Detectors, Zener Diodes
- Load Line Analysis

The Periodic Table

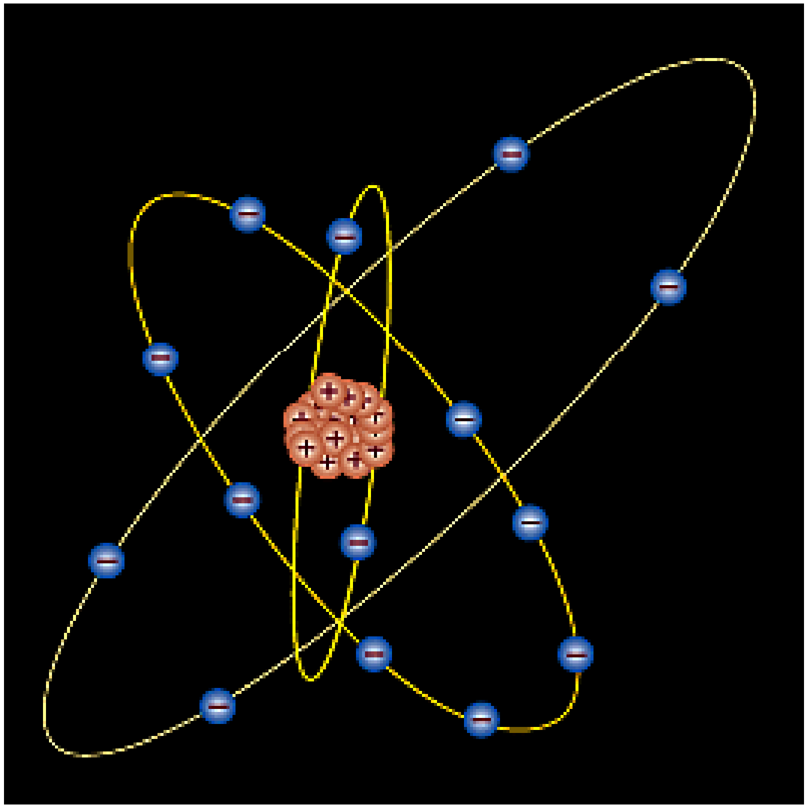


•4 nearest neighbors
•unit cell length = 5.43Å

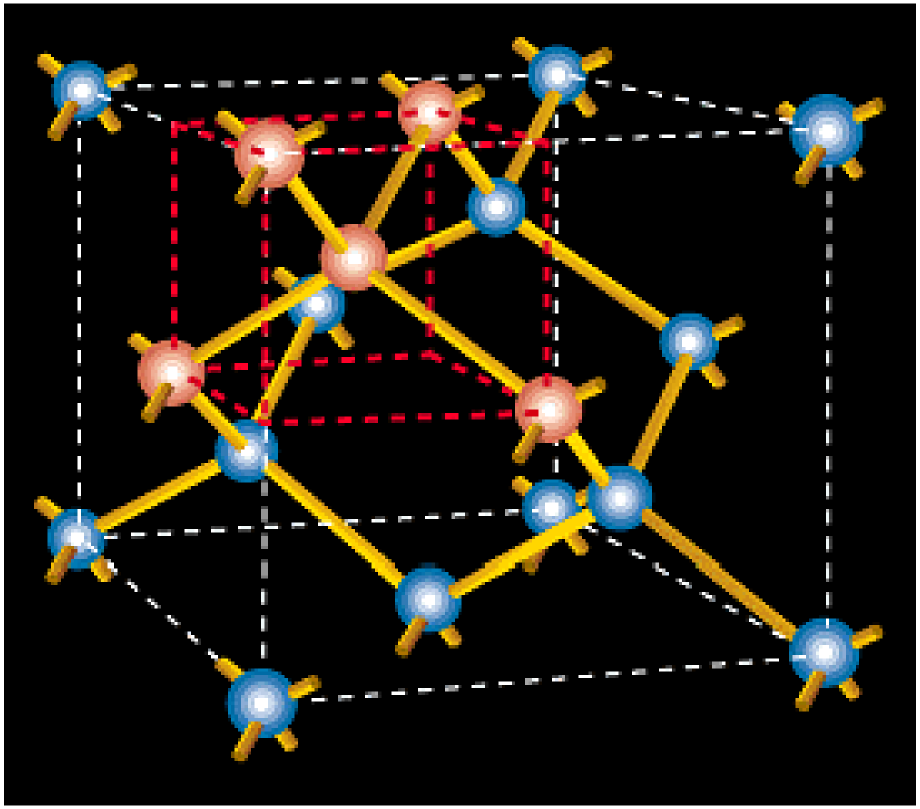
1s, 2s, 2p orbitals filled by 10 electrons
3s, 3p orbitals filled by 4 electrons

•5×10^{22} atoms/cm^3

The Si Atom

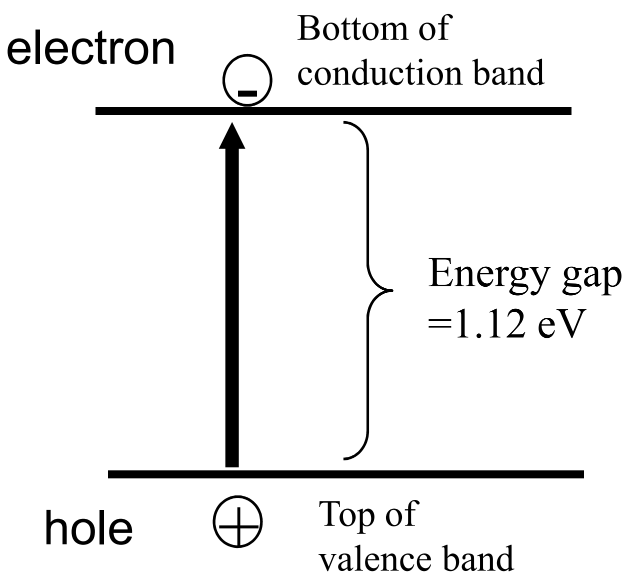


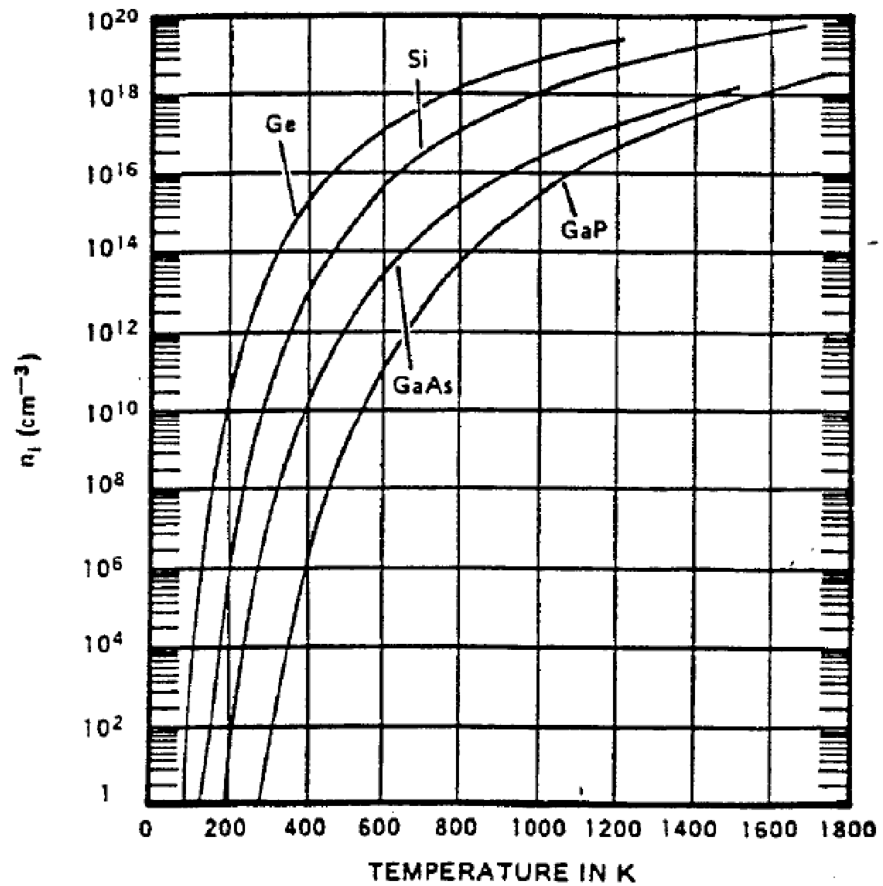
The Si Crystal



"diamond cubic " structure

Pure Si is not very conductive





n (electron conc)
= p (hole conc)
= n_i

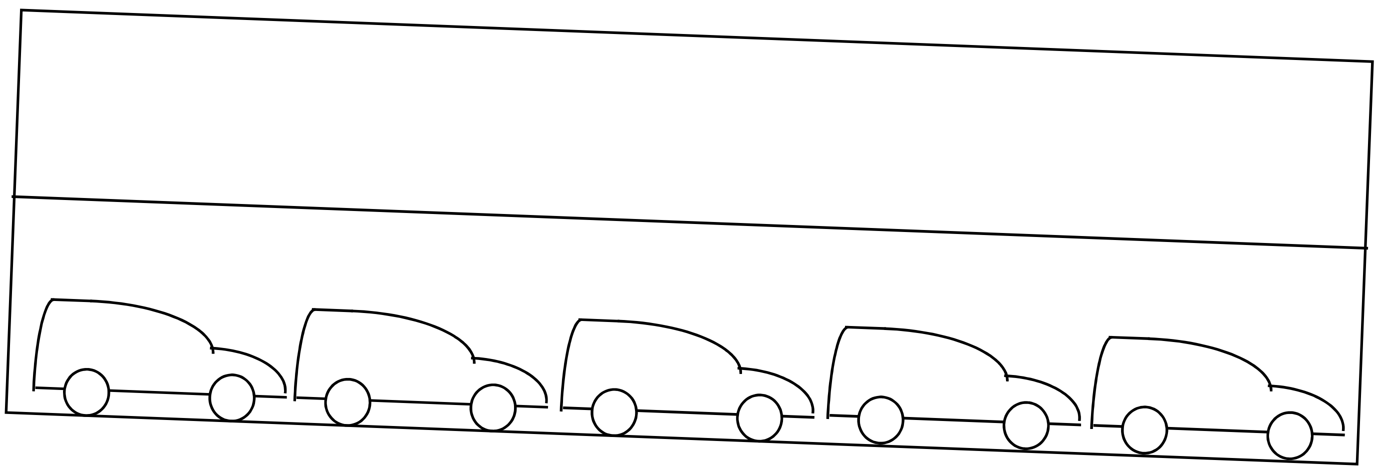
For Si

$$n_i = 3.9 \times 10^{16} T^{3/2} e^{-\frac{0.605eV}{kT}} /cm^3$$

$\boxed{n_i \cong 1.45*10^{10}\ cm^{-3} \text{ at room temperature}}$

Shockley's Parking Garage Analogy for Conduction in Si

Two-story parking garage on a hill:

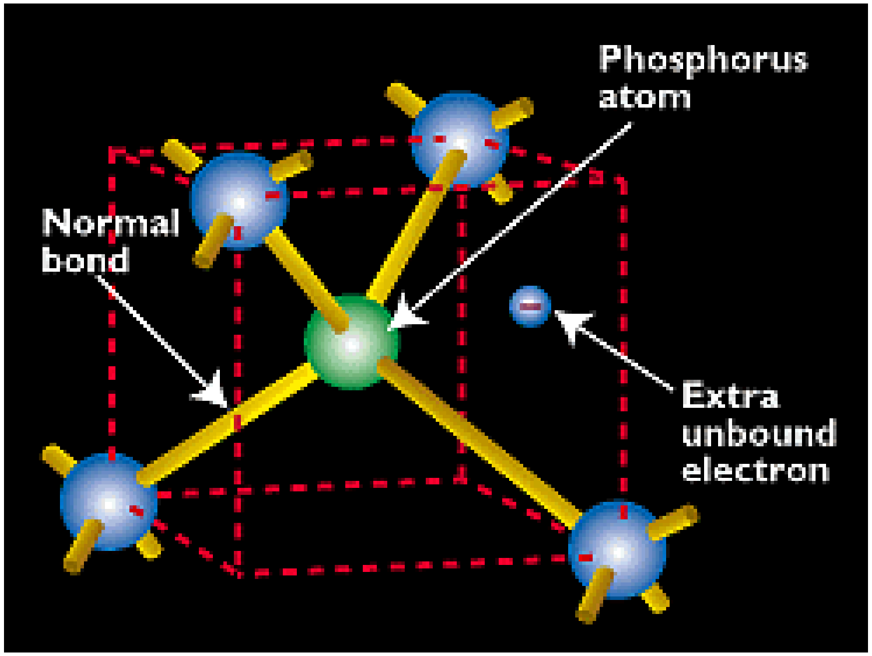


If the lower floor is full and top one is empty, no traffic is possible.   Analog of an insulator. All electrons are locked up.

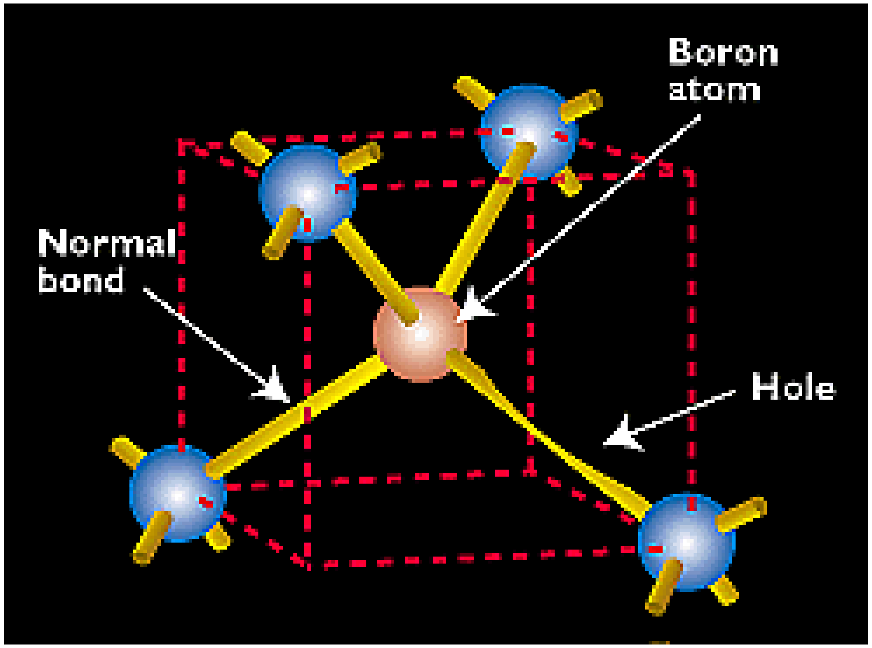
Doping

By <u>substituting</u> a Si atom with a special impurity atom (Column V or Column III element), a conduction electron or hole is created.

<u>Donors</u>: P, As, Sb

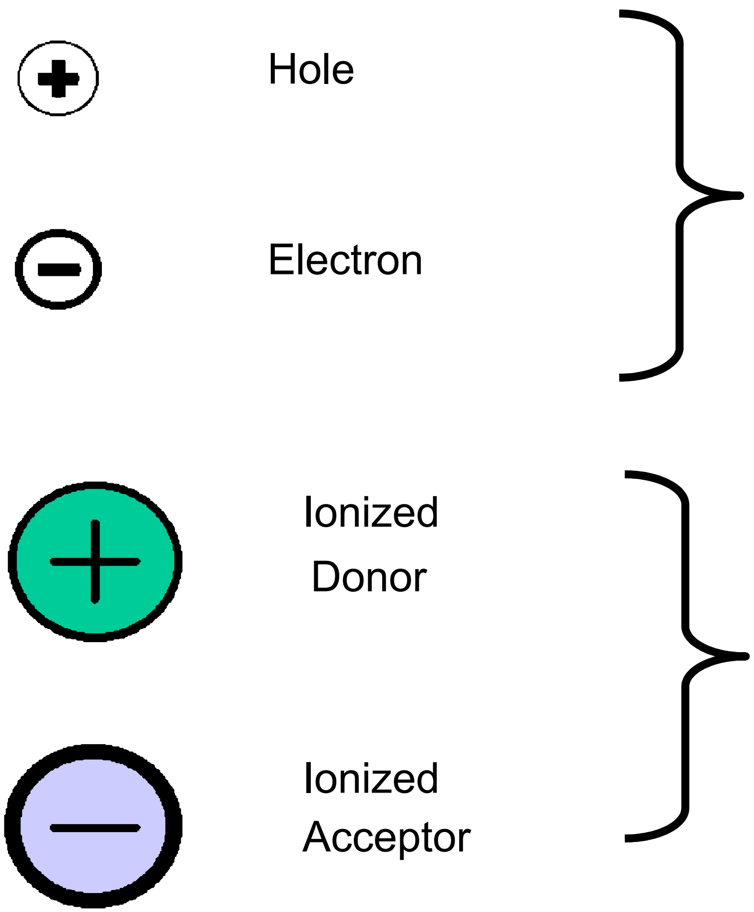


<u>Acceptors</u>: B, Al, Ga, In



Dopant concentrations typically range from 10^{14} cm^{-3} to 10^{20} cm^{-3}

Semiconductor with both acceptors and donors has 4 kinds of charge carriers

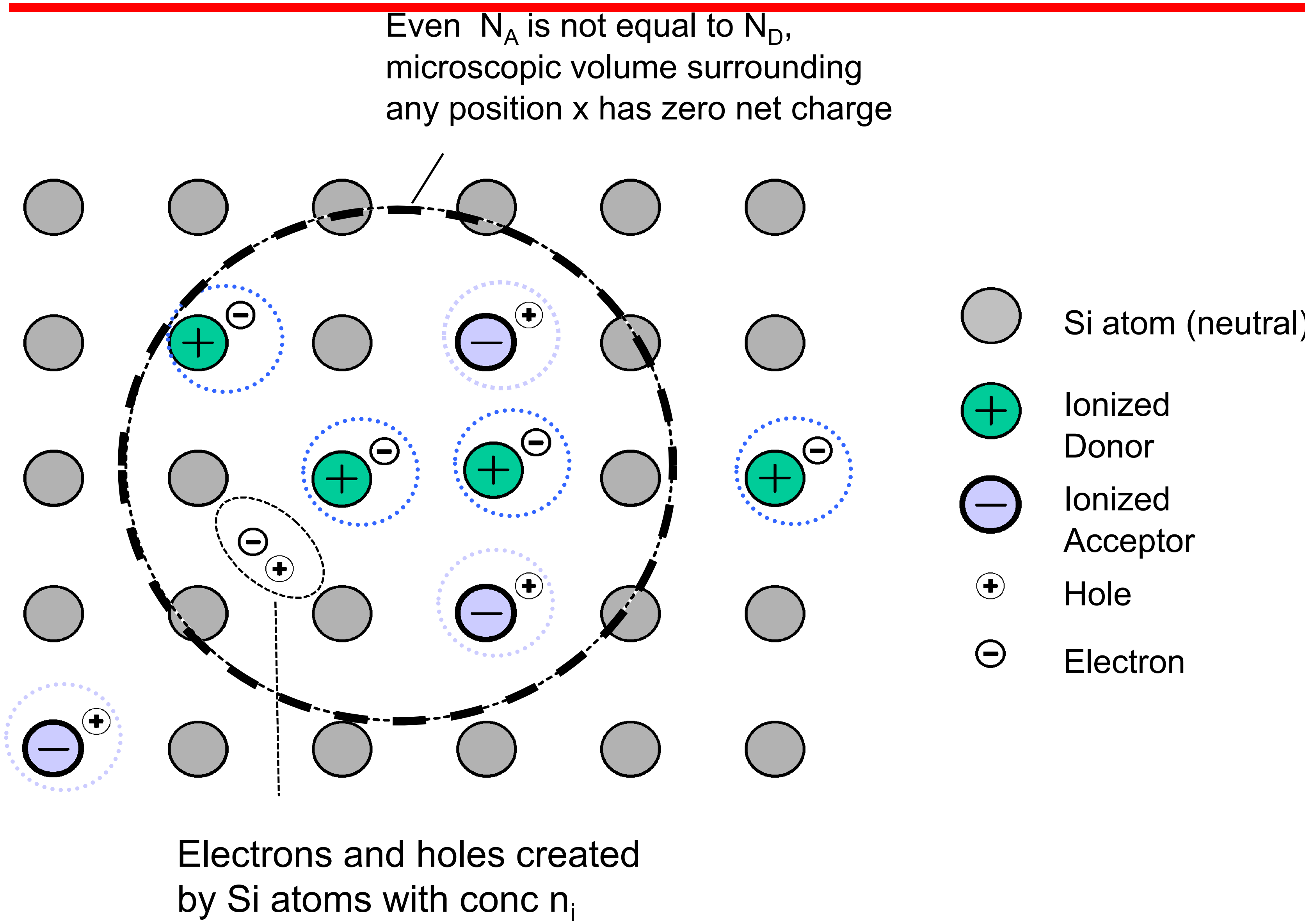


Mobile Charge Carriers
they contribute to current flow with electric field is applied.

Immobile Charges
they DO NOT contribute to current flow with electric field is applied. However, they affect the local electric field

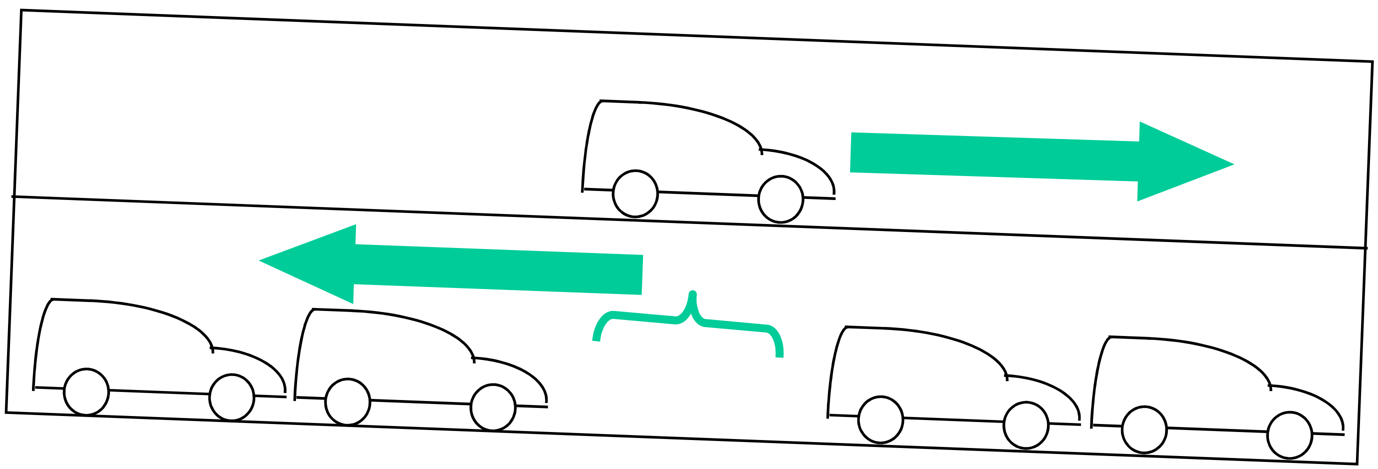
Charge Neutrality Condition

Valid for homogeneously doped semiconductor at thermal equilibrium



Shockley's Parking Garage Analogy for Conduction in Si

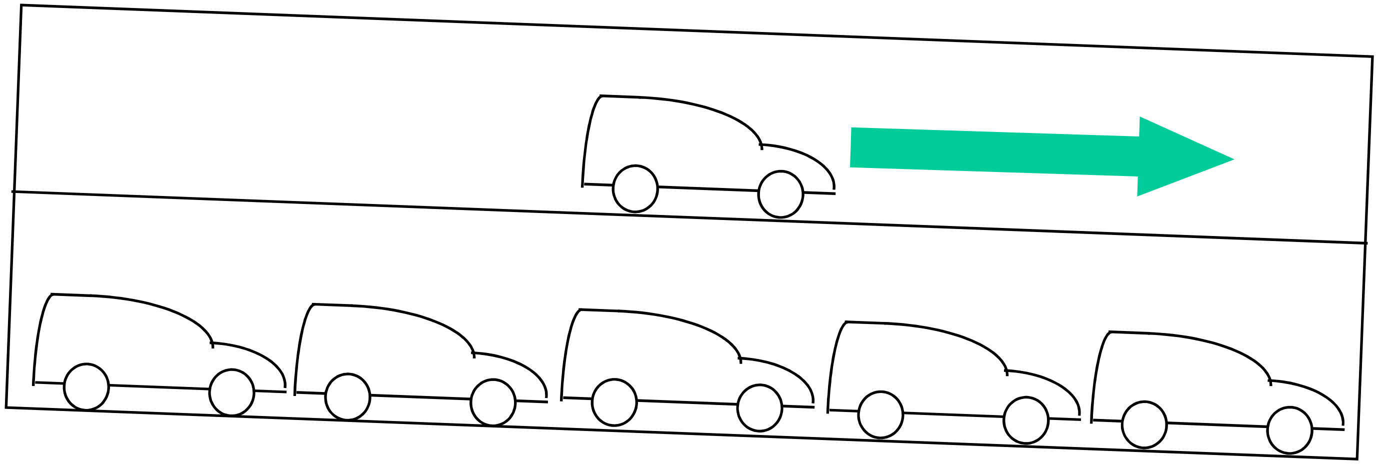
Two-story parking garage on a hill:



If one car is moved upstairs, it can move AND THE HOLE ON THE LOWER FLOOR CAN MOVE. Conduction is possible. Analog to warmed-up semiconductor. Some electrons get free (and leave "holes" behind).

Shockley's Parking Garage Analogy for Conduction in Si

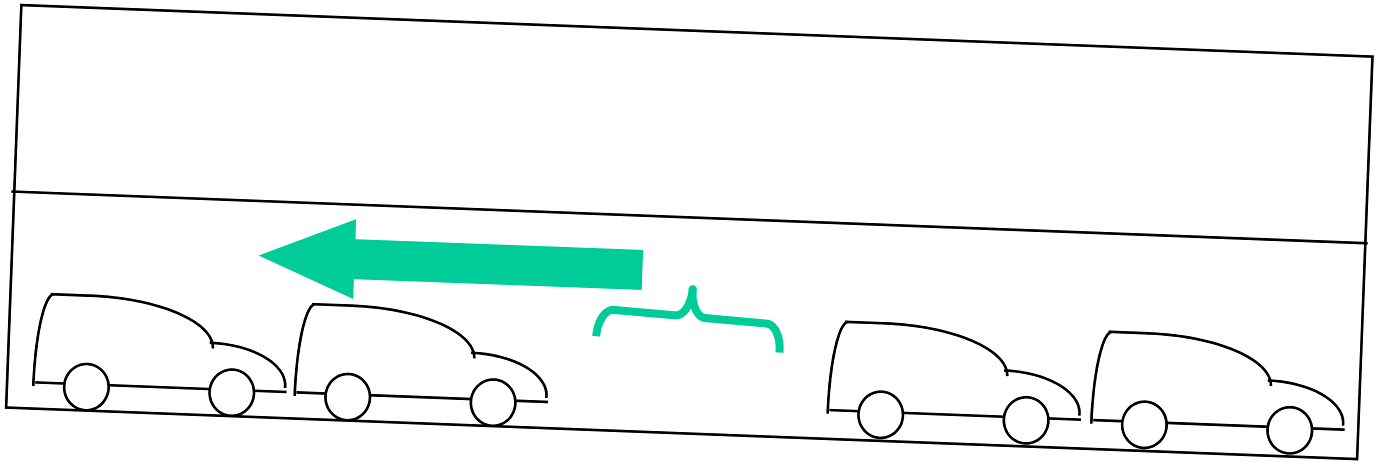
Two-story parking garage on a hill:



If an extra car is "donated" to the upper floor, it can move. Conduction is possible. *Analog to N-type semiconductor.* (An electron donor is added to the crystal, creating free electrons).

Shockley's Parking Garage Analogy for Conduction in Si

Two-story parking garage on a hill:



If a car is removed from the lower floor, it leaves a HOLE which can move. Conduction is possible. *Analog to P-type semiconductor.* (Acceptors are added to the crystal, "consuming" bonding electrons,creating free holes).

Summary of n- and p-type silicon

Pure silicon is an insulator. At high temperatures it conducts weakly.

If we add an impurity with extra electrons (e.g. arsenic, phosphorus) these extra electrons are set free and we have a pretty good conductor (n-type silicon).

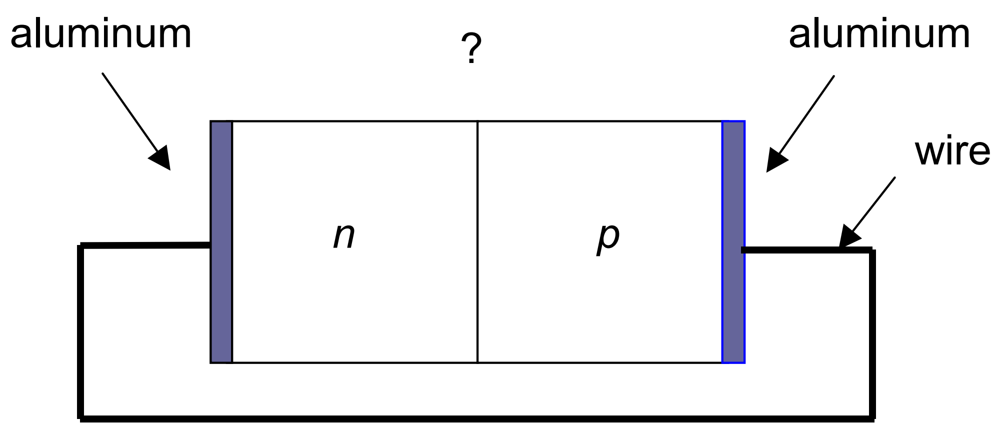
If we add an impurity with a deficit of electrons (e.g. boron) then bonding electrons are missing (holes), and the resulting holes can move around … again a pretty good conductor (p-type silicon)

Now what is really interesting is when we join n-type and p-type silicon, that is make a pn junction. It has interesting electrical properties.

Junctions of n- and p-type Regions

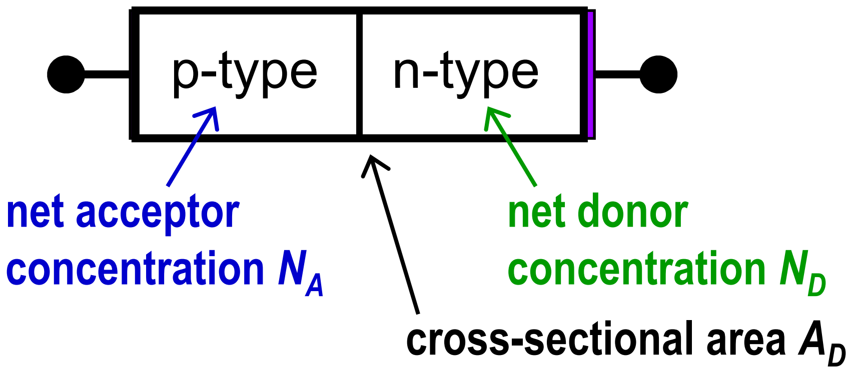
What happens to the electrons and holes when

***n* and *p* regions are brought into contact :**

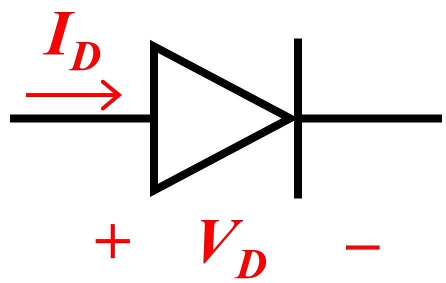


The *pn* Junction Diode

Schematic diagram

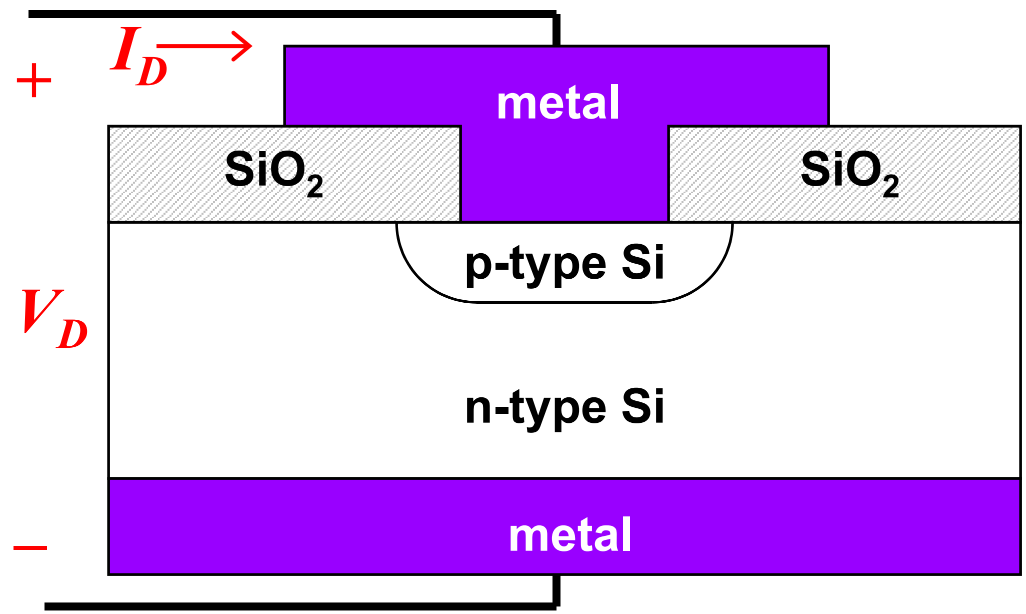


Circuit symbol



Physical structure:

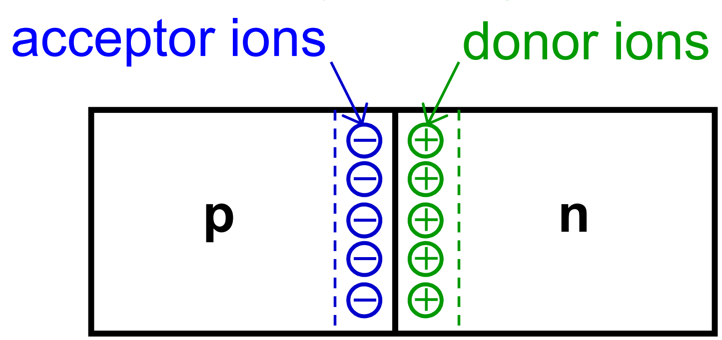
(an example)



For simplicity, assume that the doping profile changes abruptly at the junction.

Depletion Region *Approximation*

- When the junction is first formed, mobile carriers ***diffuse*** across the junction (due to the concentration gradients)
  - Holes diffuse from the p side to the n side, leaving behind negatively charged immobile acceptor ions
  - Electrons diffuse from the n side to the p side, leaving behind positively charged immobile donor ions

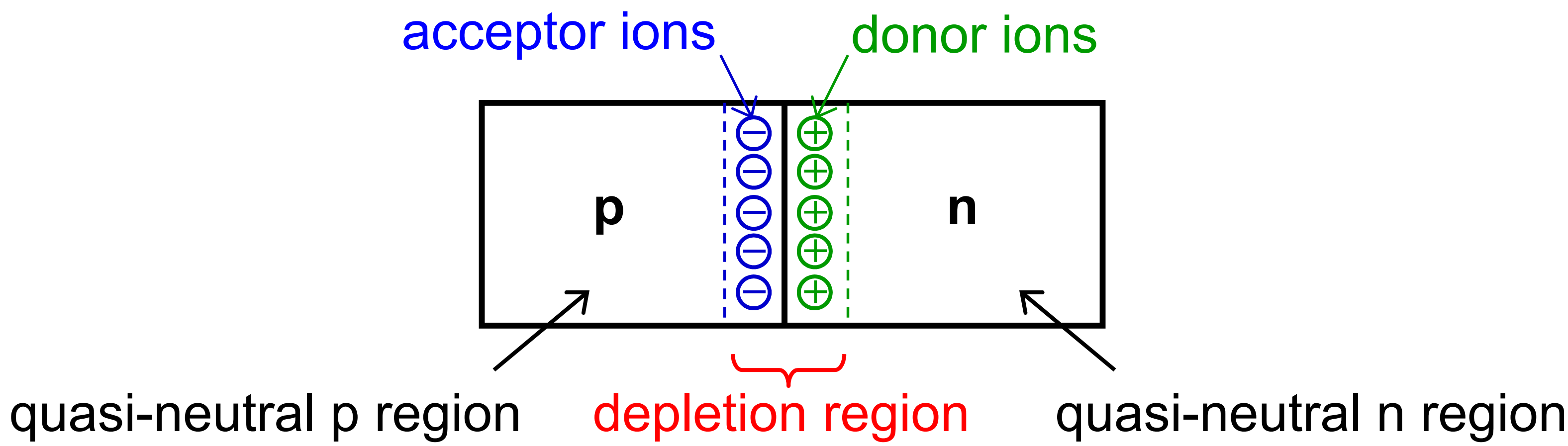


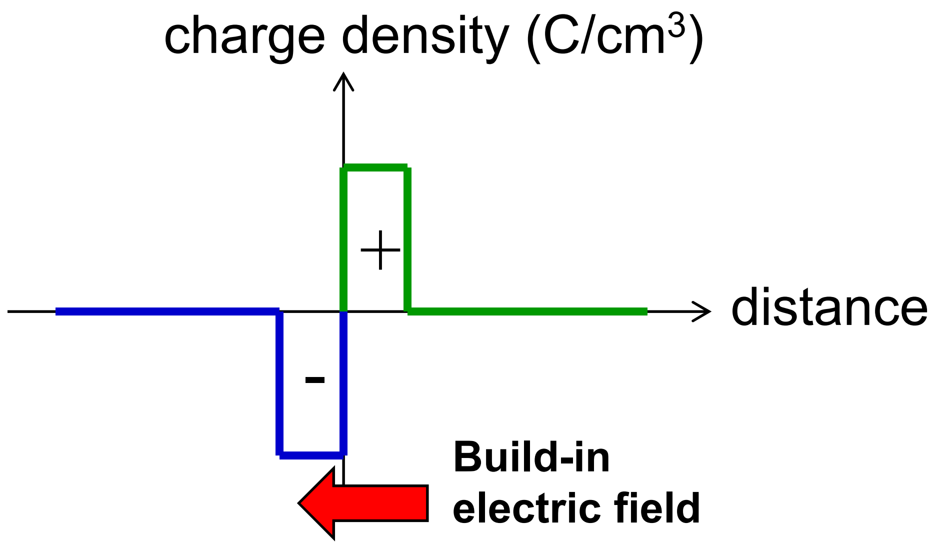
→A region *depleted of mobile carriers* is formed at the junction.

- The space charge due to immobile ions in the depletion region establishes an electric field that opposes carrier diffusion.

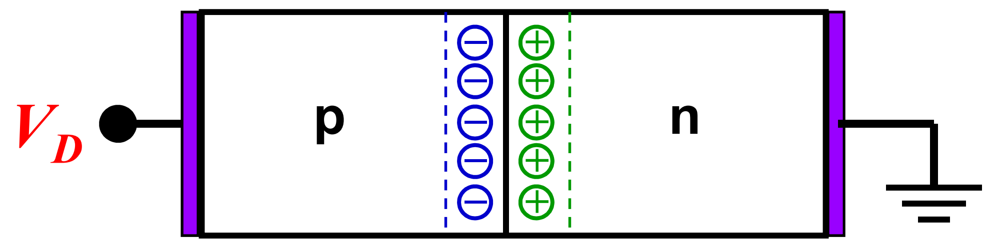
Charge Density Distribution and Electric Field

Unbalanced Charge is created in the depletion region.



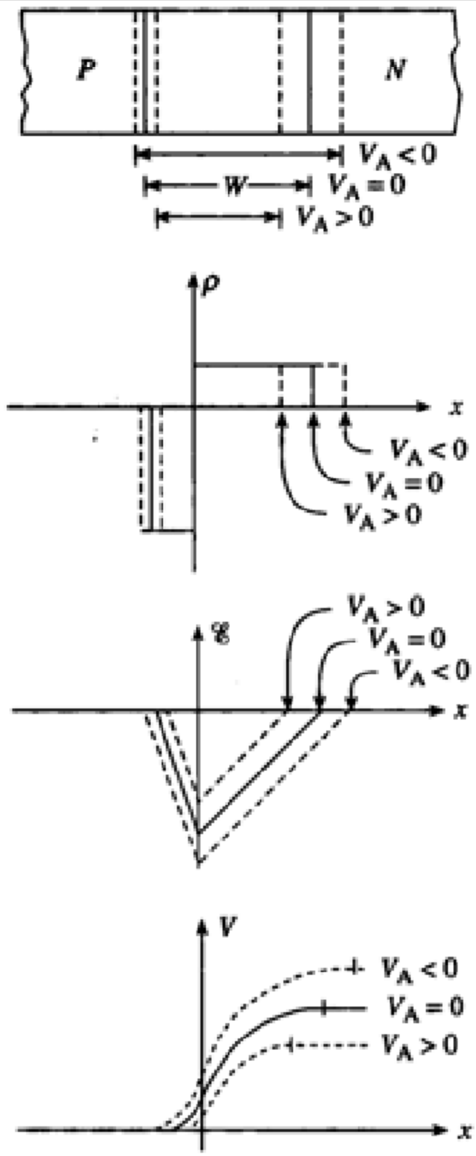


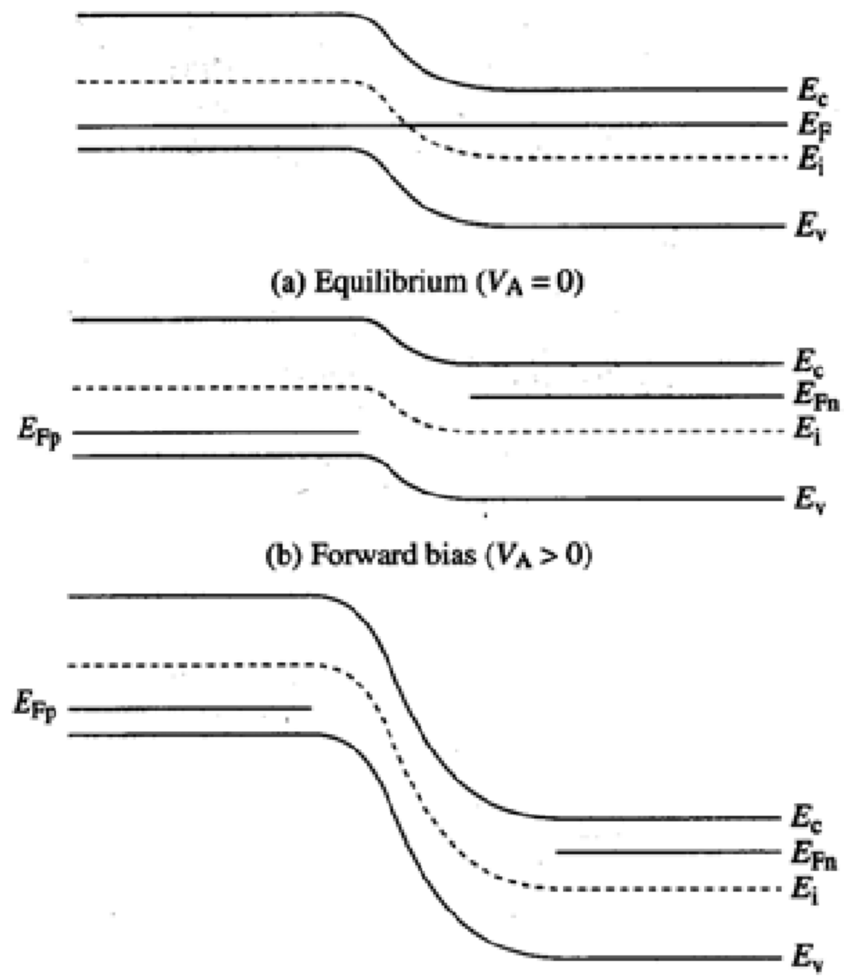
Effect of Applied Voltage



- The quasi-neutral p and n regions have low resistivity, whereas the depletion region has high resistivity. Thus, when an external voltage V_D is applied across the diode, almost all of this voltage is dropped across the depletion region. (Think of a voltage divider circuit.)
- If $V_D > 0$ (***forward bias***), depletion charge reduced
- If $V_D < 0$ (***reverse bias***), depletion charge increased

Effect of Bias on Electrostatics



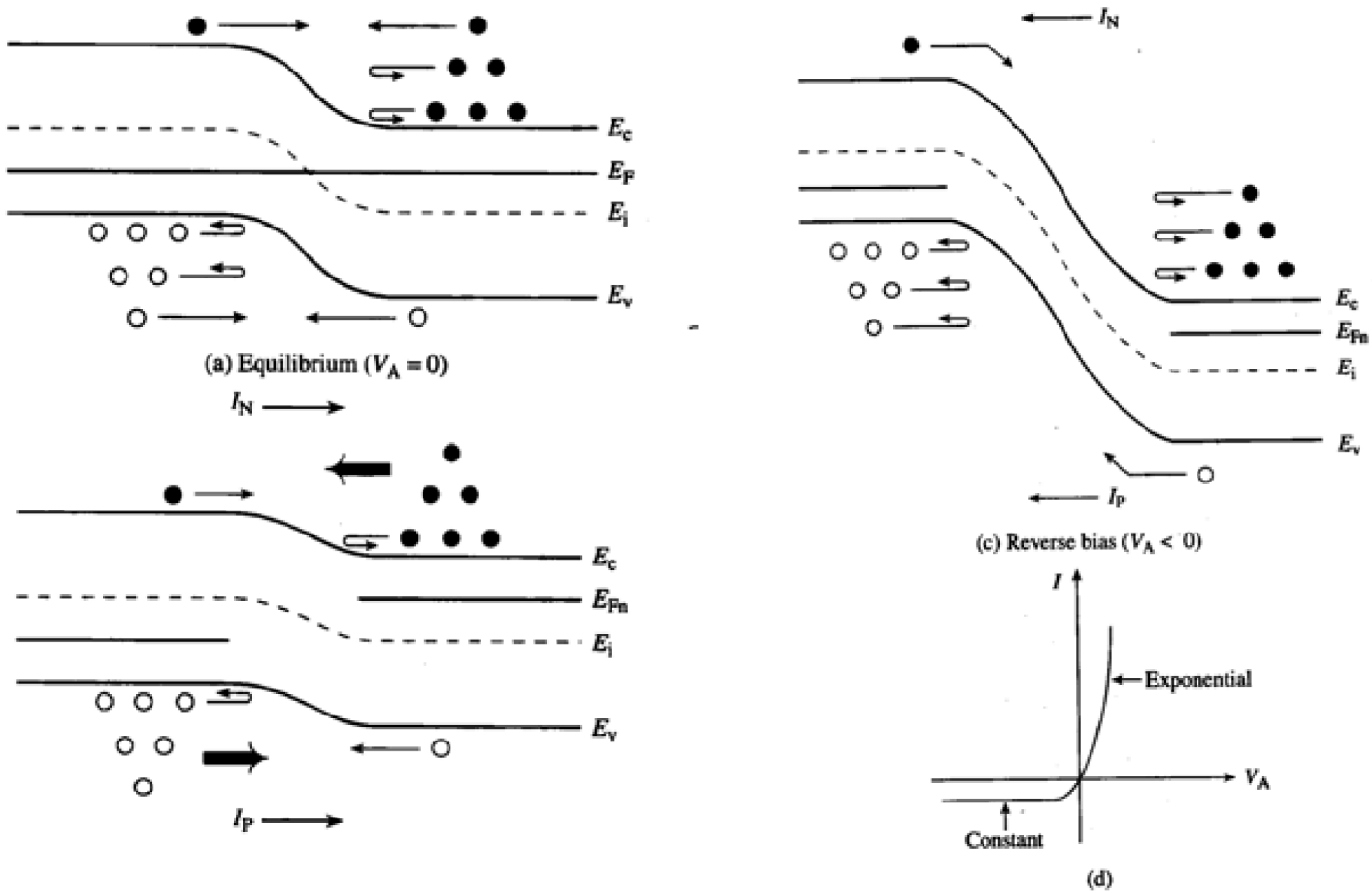


(a) Equilibrium ($V_A = 0$)

(b) Forward bias ($V_A > 0$)

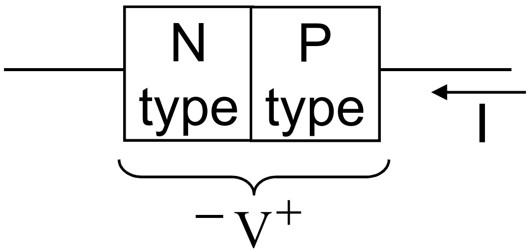
(c) Reverse bias ($V_A < 0$)

Current Flow - Qualitative

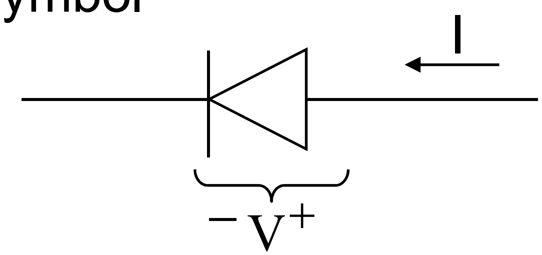


Diode Physical Behavior and Equation

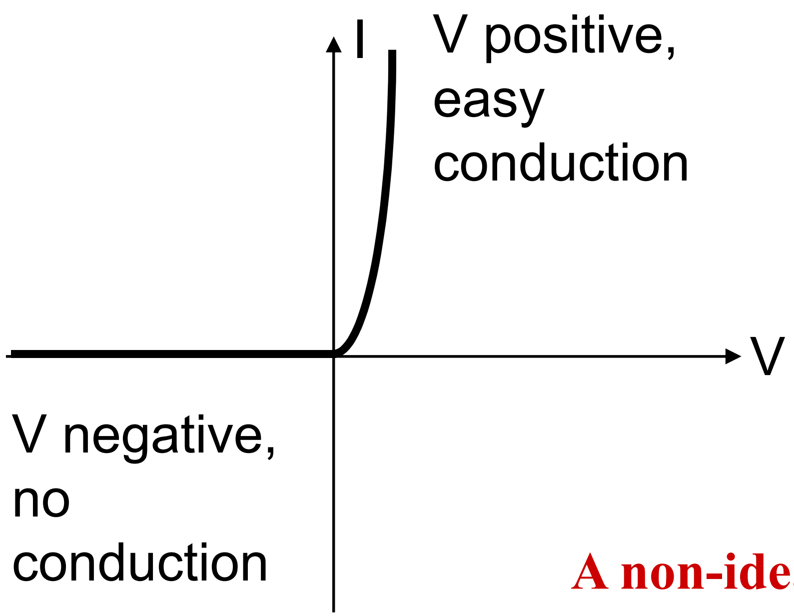
Schematic Device



Symbol



Qualitative I-V characteristics:



Quantitative I-V characteristics:

$$\mathbf{I = I_0(e^{qV/kT} - 1)}$$

In which kT/q is 0.026V and I_O is a constant depending on diode area. Typical values: 10^{-12} to 10^{-16} A..

A non-ideality factor n times kT/q is often included.

The pn Junction I vs. V Equation

I-V characteristic of PN junctions

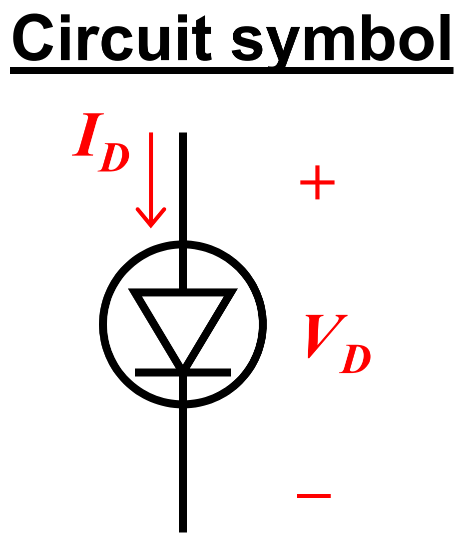
In EECS 105, 130, and other courses you will learn why the I vs. V relationship for PN junctions is of the form

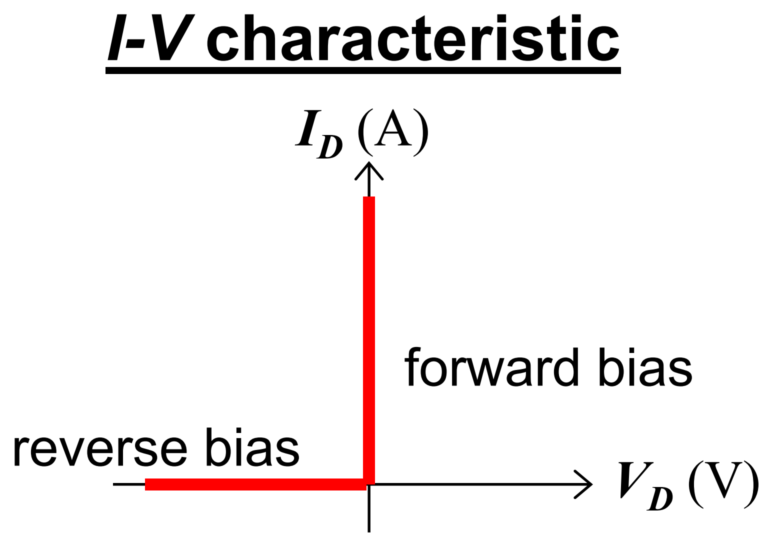
$$\boxed{I = I_0(e^{qV/kT} - 1)}$$

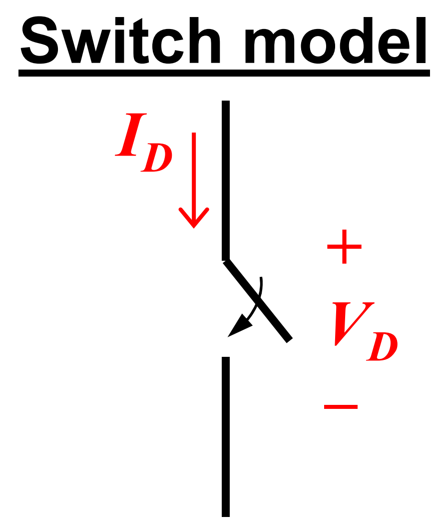
where I_0 is a constant proportional to junction area and depending on doping in P and N regions, $q = \text{electronic charge} = 1.6 \times 10^{-19}$, k is Boltzman constant, and T is absolute temperature.
$KT/q = 0.026\text{V at}300°\text{K}$, a typical value for I_0 is $10^{-12} - 10^{-15}\text{A}$

We note that in forward bias, I increases **exponentially** and is in the μA-mA range for voltages typically in the range of 0.6-0.8V. In reverse bias, the current is essentially zero.

Ideal Diode Model of PN Diode





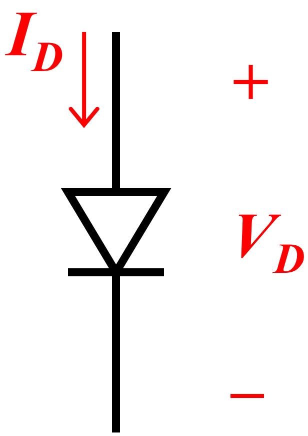


- An ideal diode passes current only in one direction.
- An ***ideal diode*** has the following properties:
  - when $I_D > 0$, $V_D = 0$
  - when $V_D < 0$, $I_D = 0$

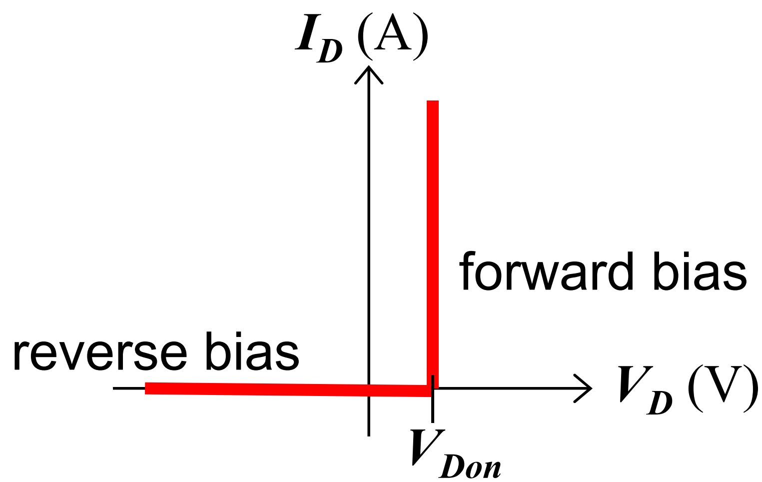
Diode behaves like a switch:
- **closed in forward bias mode**
- **open in reverse bias mode**

Piecewise Linear Model

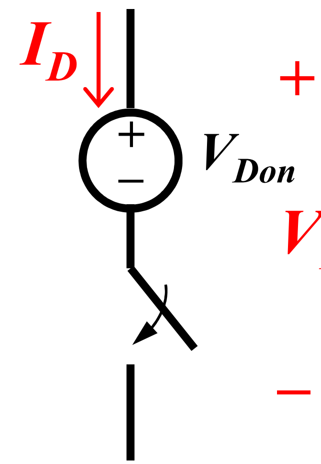
Circuit symbol



I-V characteristic



Switch model



For a Si pn diode, $V_{Don} \cong 0.7$ V

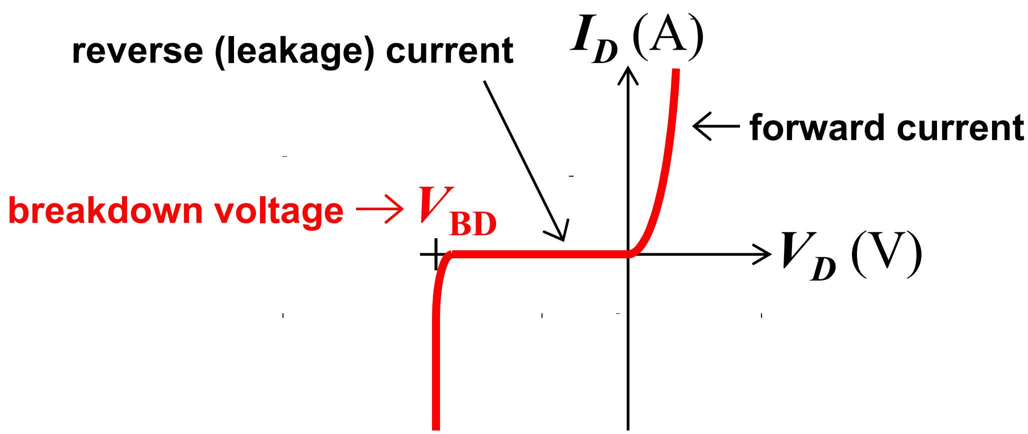
RULE 1: When $I_D > 0$, $V_D = V_{Don}$

RULE 2: When $V_D < V_{Don}$, $I_D = 0$

$\}$ **Diode behaves like a voltage source in series with a switch:**
- **closed in forward bias mode**
- **open in reverse bias mode**

pn-Junction Reverse Breakdown

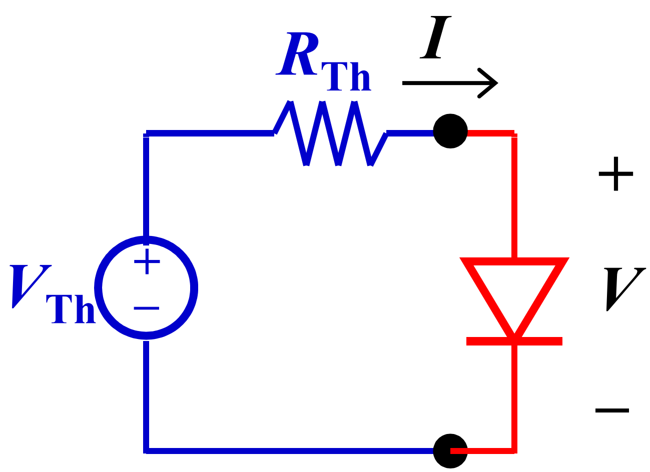
- As the reverse bias voltage increases, the peak electric field in the depletion region increases. When the electric field exceeds a critical value ($E_{crit} \cong 2x10^5$ V/cm), the reverse current shows a dramatic increase:

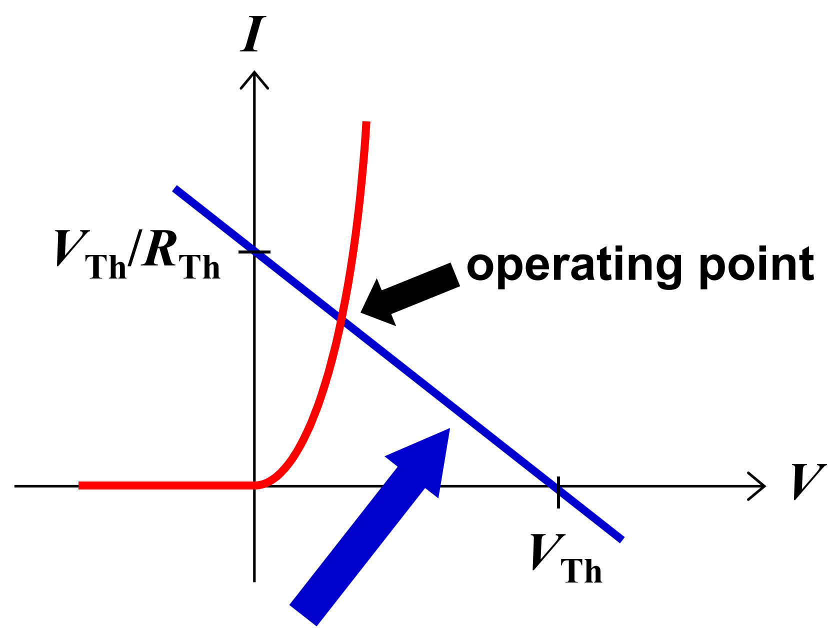


- 10 to -100V

Load Line Analysis Method

1. Graph the *I-V* relationships for the non-linear element and for the rest of the circuit
2. The operating point of the circuit is found from the intersection of these two curves.

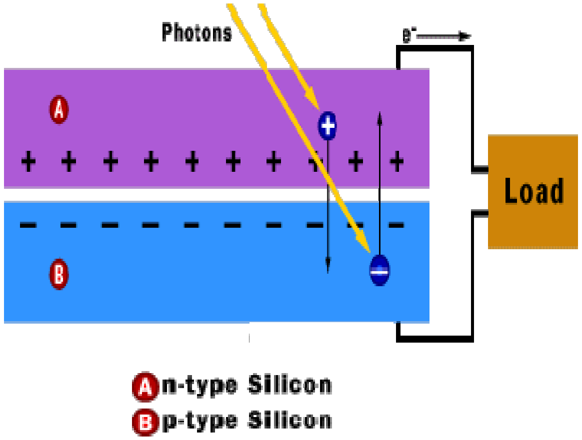




The *I-V* characteristic of all of the circuit except the non-linear element is called the *load line*

Solar cell: Example of simple PN junction

- What is a solar cell?
  - Device that converts sunlight into electricity
- How does it work?
  - In simple configuration, it is a diode made of PN junction
  - Incident light is absorbed by material
  - Creates electron-hole pairs that transport through the material through
    - Diffusion (concentration gradient)
    - Drift (due to electric field)



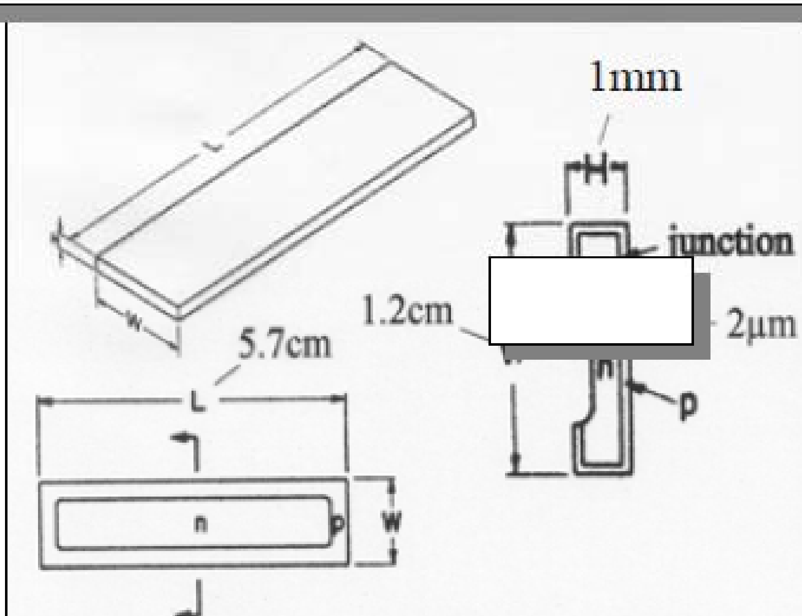
PN Junction Diode

The Birth of Silicon Photovoltaics

A New Silicon *p-n* Junction Photocell for Converting Solar Radiation into Electrical Power

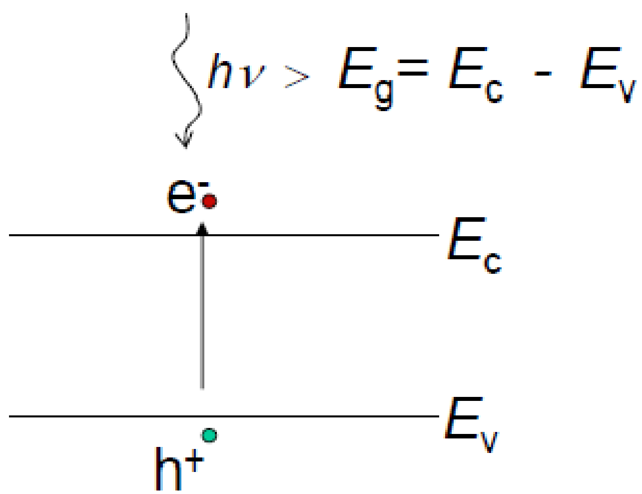
D. M. CHAPIN, C. S. FULLER, AND G. L. PEARSON
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey
(Received January 11, 1954)

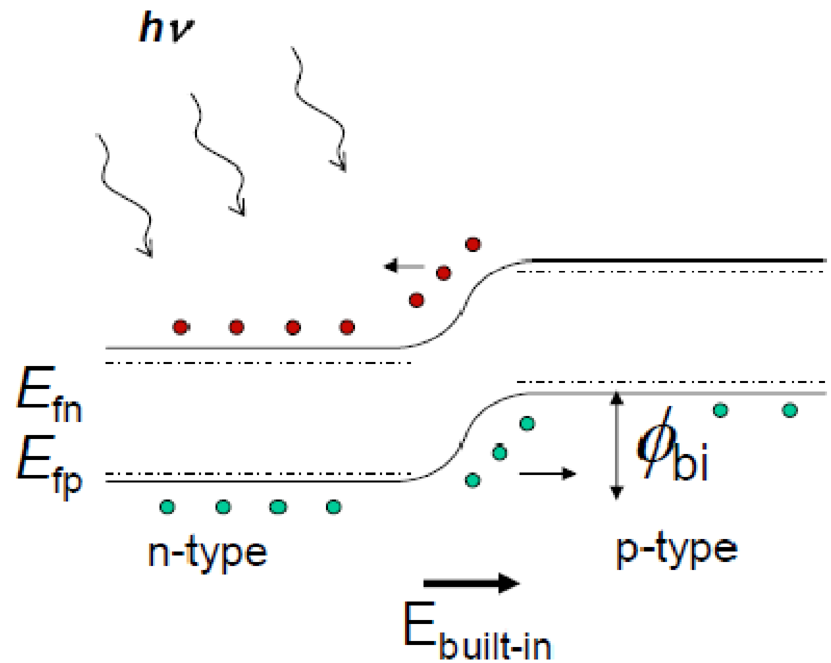
Efficiency $\eta \approx 6$ %



How PVs work

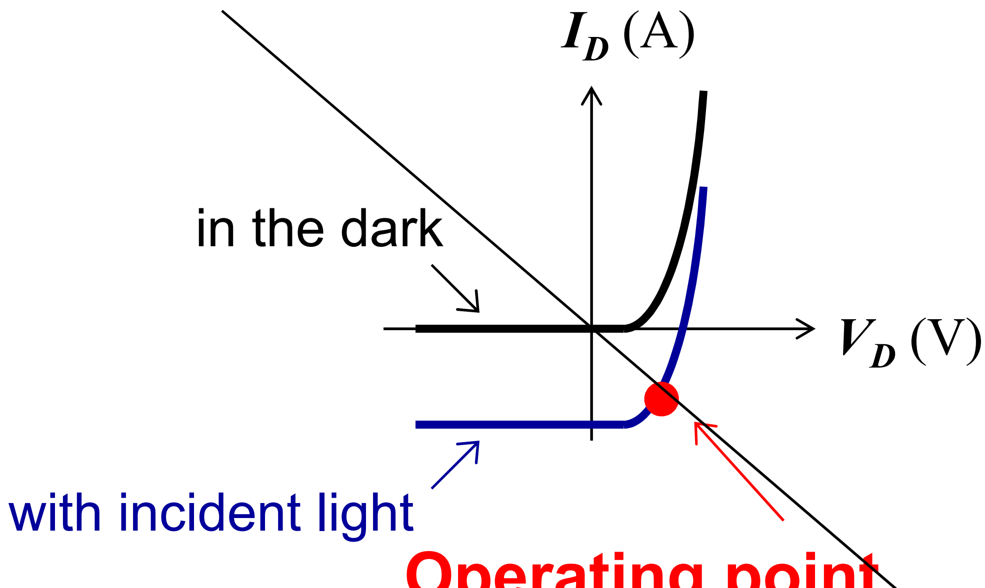
- Semiconductor can absorb light (photons) and convert them to current (carriers)
- We modify the semiconductor (create a pn junction) to "harvest" the carriers





Photovoltaic (Solar) Cell

$$I_D = I_S(e^{qV_D/kT} - 1) \boxed{- I_{optical}}$$



Operating point

The load line a simple resistor.

Cell Efficiencies

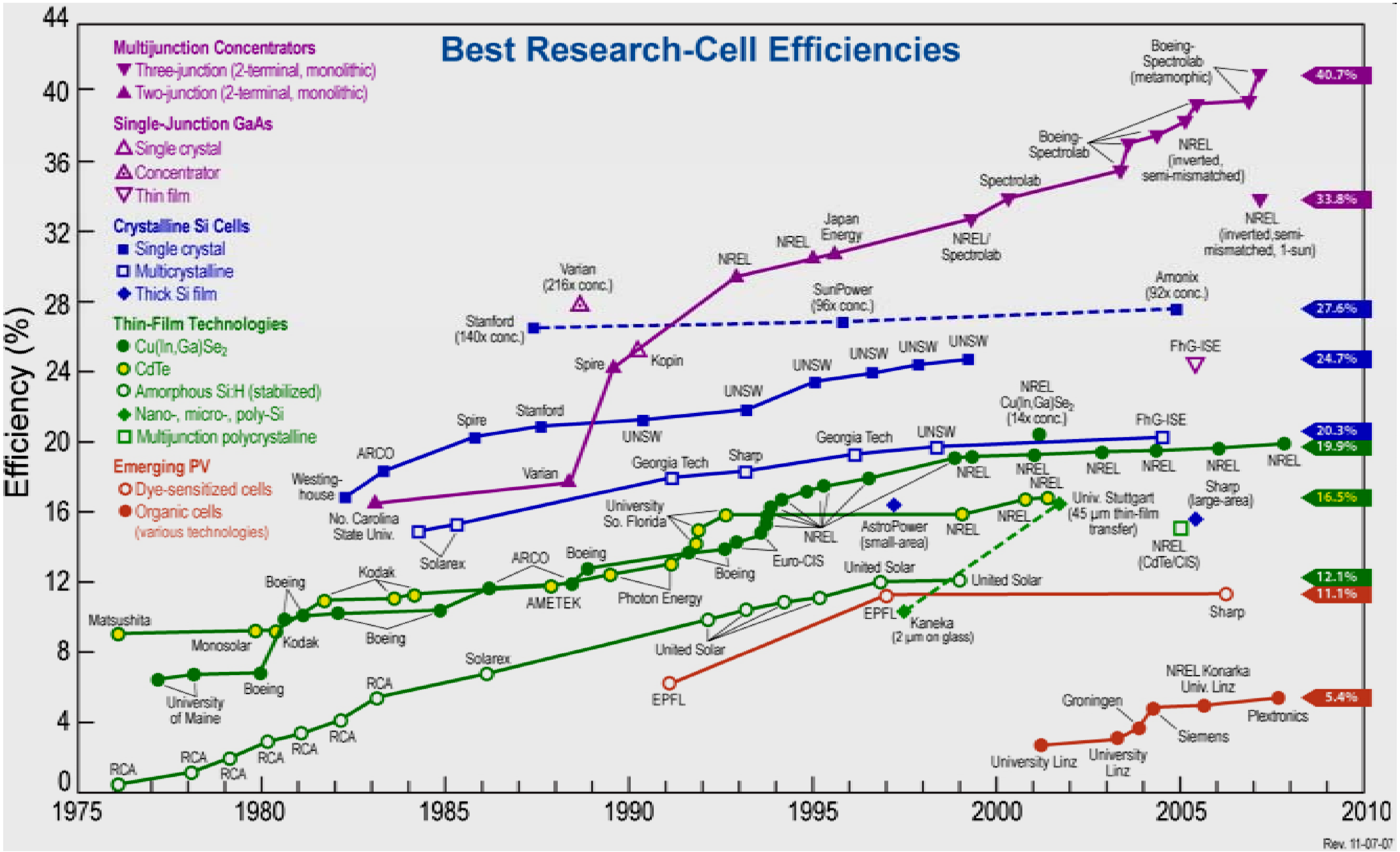
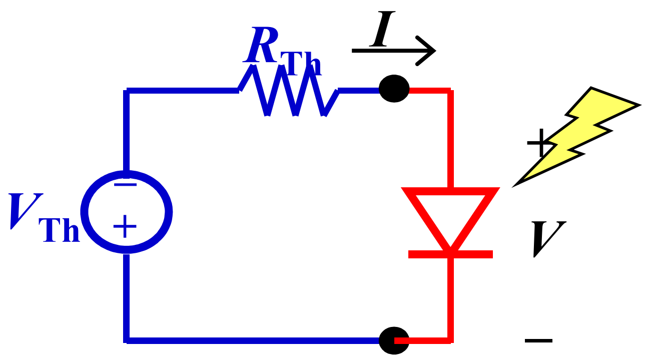
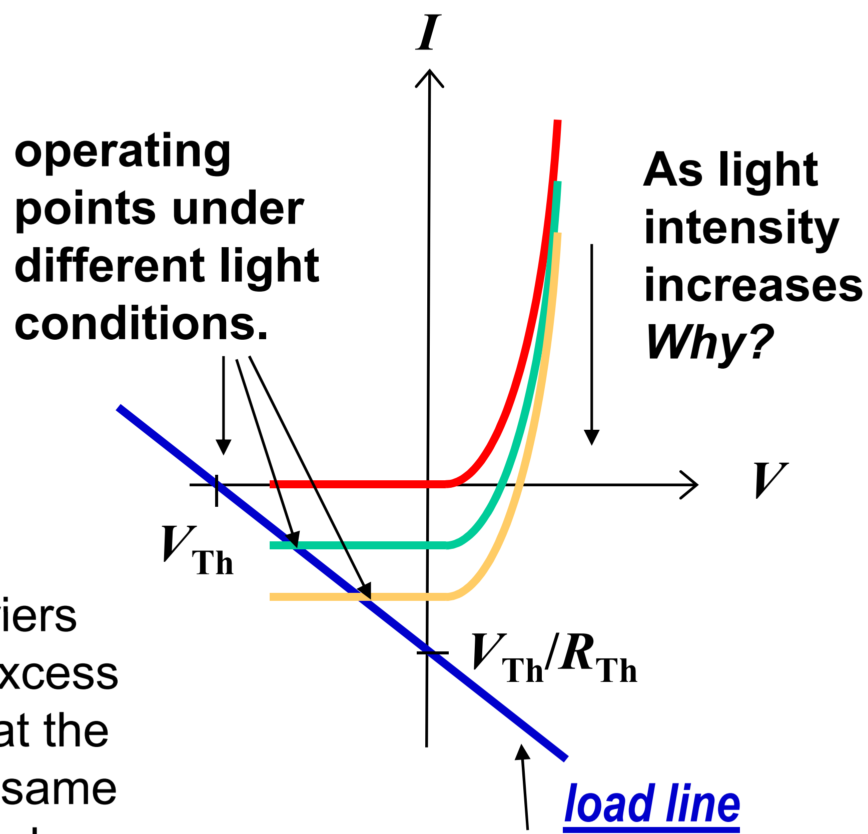


Photo Diode

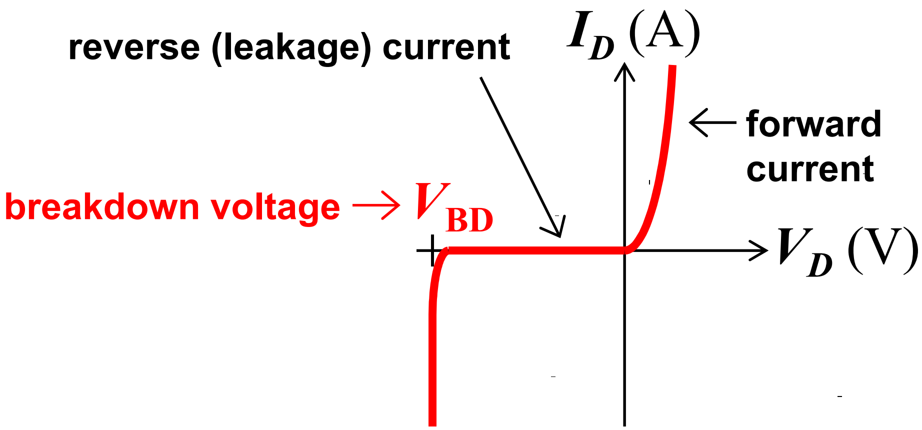




As light shines on the photodiode, carriers are generated by absorption. These excess carriers are swept by the electric field at the junction creating drift current, which is same direction as the reverse bias current and hence negative current. The current is proportional to light intensity and hence can provide a direct measurement of light intensity → ***photodetector***.

Zener Diode

A ***Zener diode*** is designed to operate in the breakdown mode
With a well defined breakdown voltage.



<u>Example</u>: