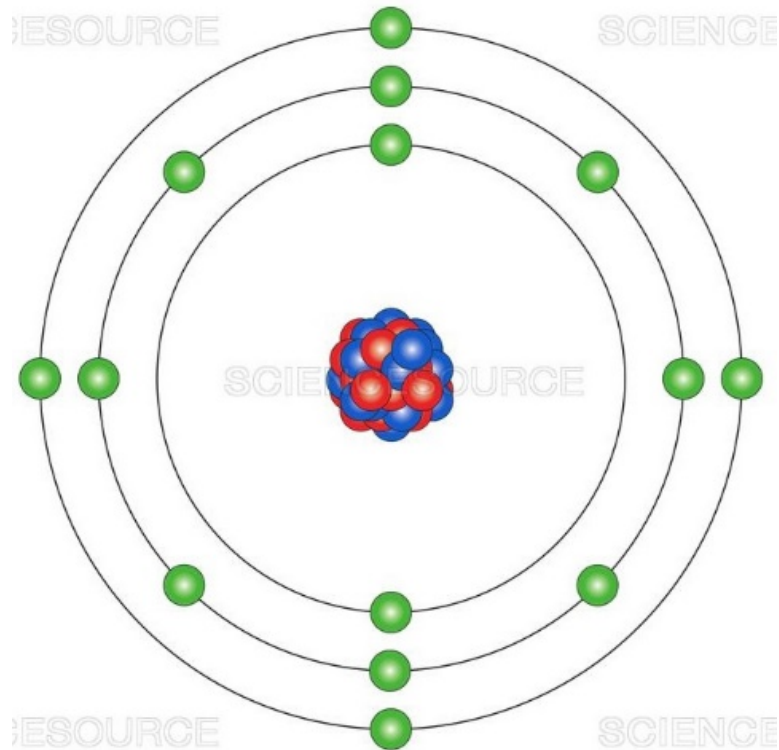


Devices I Outline

- Atomic structure of silicon
- Structural forms of silicon (what is a crystal?)
- Intrinsic and extrinsic semiconductors
 - > Electrons and Holes
 - > N-type and P-type
- p-n junction and diodes
 - > Depletion layer
 - > Diode operating modes and characteristics
- Energy levels and band diagrams
- Light emitting diodes (LEDs)

Atomic structure (single crystal)



Silicon atom

Symbol for silicon: Si

Electrons: 14 (3 shells/orbitals)

Shell 1: 2 electrons (max: 2)

Shell 2: 8 electrons (max: 8)

Shell 3: 4 electrons (max: 8)

Nucleus

14 protons (positive charge)

14 neutrons (neutral charge)

14 protons in the nucleus balanced by 14 electrons in orbit

Electrons in the outermost shell are called valence electrons

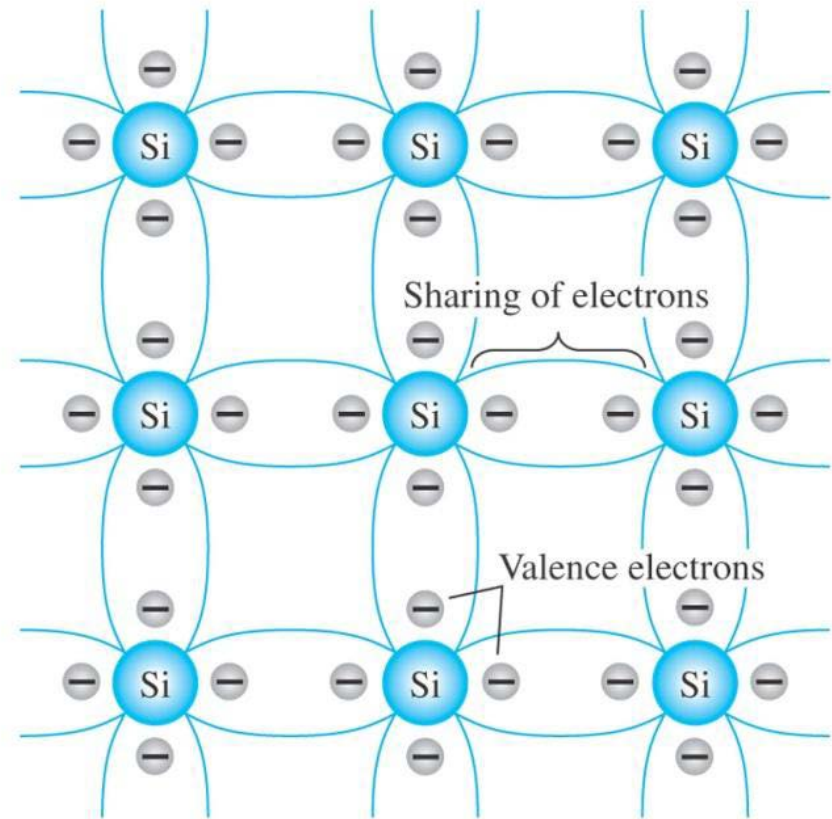
Atoms like Si with 4 valence electrons are called tetravalent

Covalent bonding in Si crystal

Each Si atom is bonded to 4 other Si atoms

Each Si atom contributes 1 valence electron to create a covalent bond

Covalent bonds arise from the sharing of valence electrons which strengthen the bond



Covalent bond: A bond created by sharing of valence electrons
8 valence electrons per atom to achieve stability

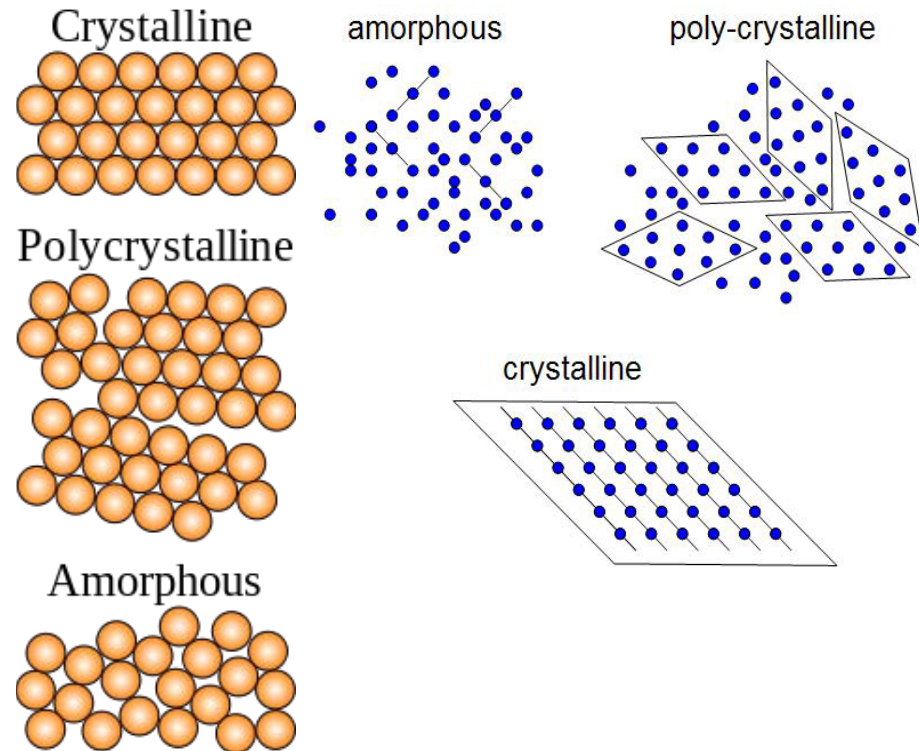
Silicon's structural forms

Silicon can exist in various structural forms in how the atoms are arranged:

- 1) Amorphous
- 2) Polycrystalline
- 3) **Crystalline***

The form will depend on the conditions for growing silicon

Conditions must be carefully controlled



Crystalline: Constituent atoms or molecules are ordered/organized over a long range

Amorphous: No organization/order of atoms or molecules over a long range but only in short range (e.g. glass is amorphous)

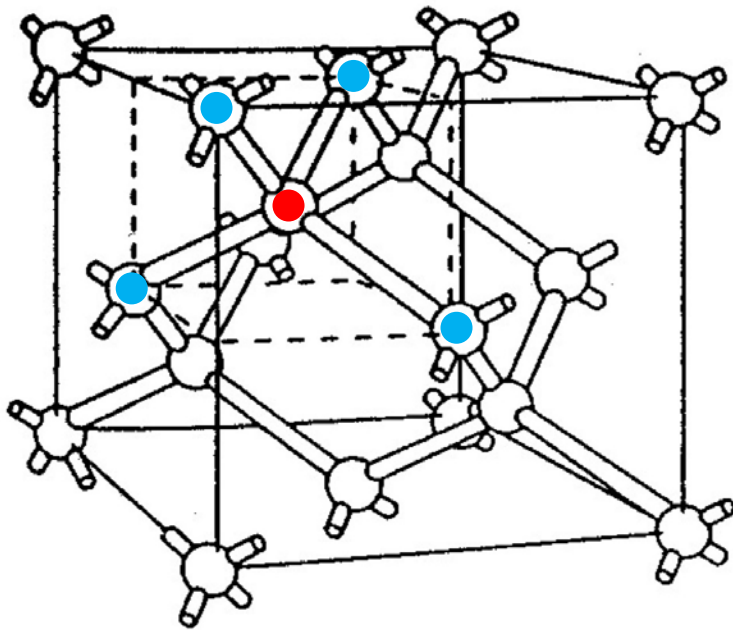
Polycrystalline: (Poly – many) Composed of many smaller crystals of varying size and orientation. These smaller crystals are referred to as grains.

Crystalline silicon

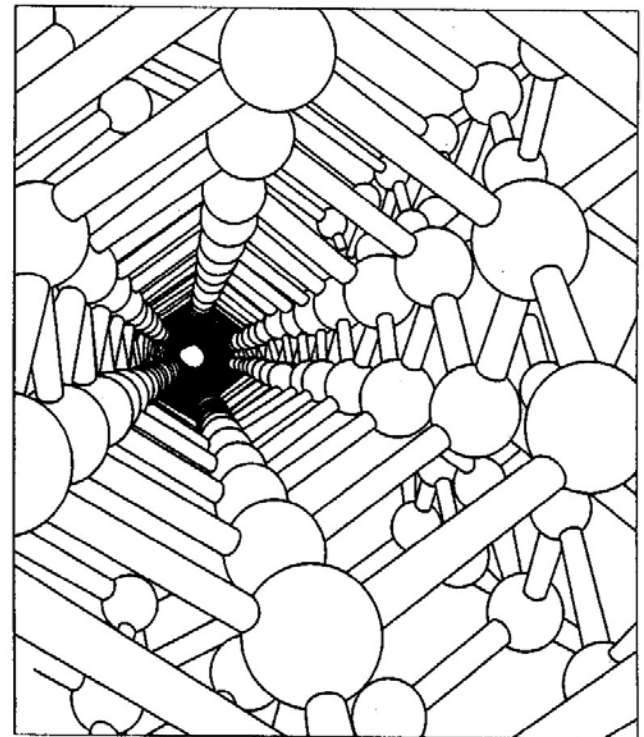
Crystalline silicon is important for chip manufacturing as it forms the base material of working transistors

Necessary for atoms to be arranged in a regular periodic architecture/structure

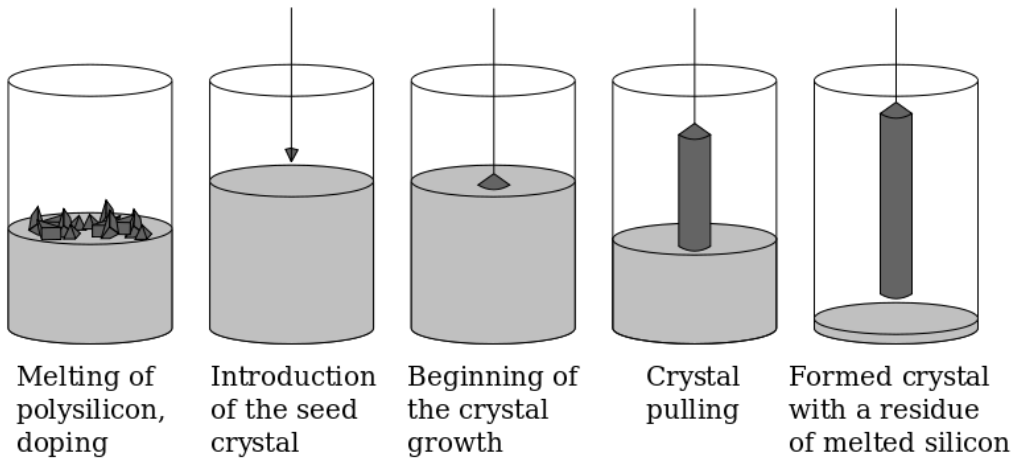
We focus on crystalline Si (c-Si) when covering semiconductor properties in this course



Each atom is linked to another 4 atoms



Growing crystalline silicon

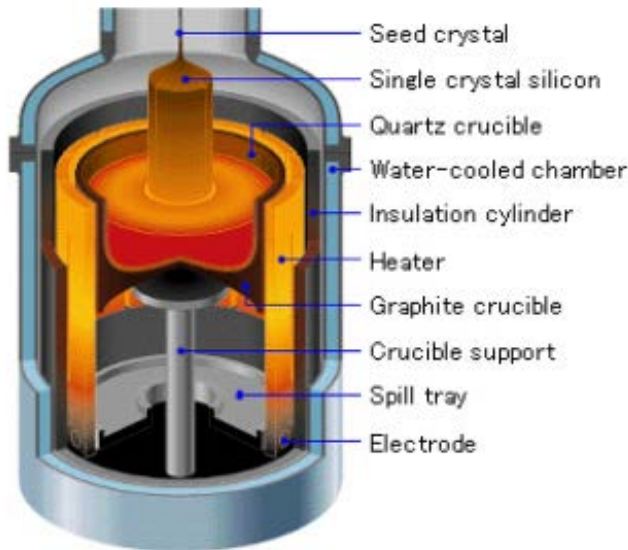


The ability to make wafers with larger diameters helps to reduce production costs (see Moore's law)

But the same defect free quality must be guaranteed

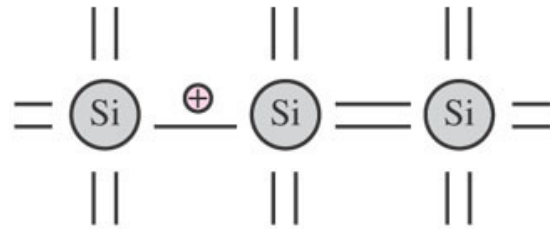
Step 1: Grow crystal

Step 2: Slice into wafers

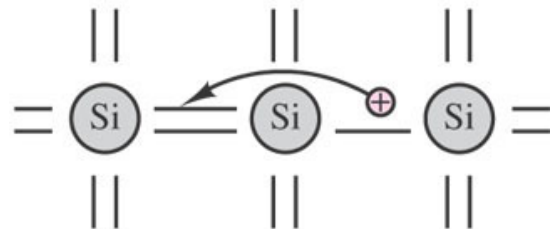


Intrinsic semiconductor

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⊕ = Hole Electron jumps to fill hole



The net effect is a hole moving to the right

A vacancy (or hole) is created whenever a free electron leaves the structure.

This “hole” can move around the lattice if other electrons replace the free electron.

If all the valence electrons were perfectly shared, there would not be free carriers.

But defects exist at room temperature such that an electron that would have been in a valence bond is free

This leaves a vacancy for an electron to fill (this vacancy is known as a **hole**)

Thus **electron – hole** pairs are formed intrinsically in a semiconductor

Intrinsic carrier concentration in Si: $1.5 \times 10^{10}/\text{cm}^3$

In Si: 10^{22} atoms/ cm^3

Probability: $\sim 10^{-12}$ (1 electron/hole per 10^{12} atoms)

Think of holes as positively charged free carriers

Carrier concentration

Recall: $J = nqv$

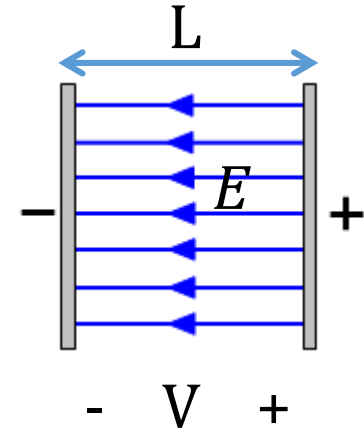
J : Current density (I/A)

n : carrier concentration

q : charge per carrier

v : velocity of charge carriers

What determines the velocity of the charge carrier?



$$E = V/L$$

E : Electric field

$$v = \mu E \quad \mu: \text{mobility}$$

$$J = nq\mu E$$

Higher carrier concentration reduces resistivity

$$1/\rho = nq\mu$$

Carrier concentration and resistivity

Copper (Metal)

Free carrier concentration:

$$n = 8.5 \times 10^{22} / \text{cm}^3$$

Resistivity:

$$\rho = 1.7 \times 10^{-6} \Omega \text{cm}$$

Silicon (Semiconductor)

Intrinsic carrier concentration:

$$n = 1.5 \times 10^{10} / \text{cm}^3$$

Resistivity:

$$3.4 \times 10^5 \Omega \text{cm}$$

$$\leftarrow \sim 10^{12} \rightarrow$$

$$1/\rho = nq\mu$$

n_i : intrinsic concentration of electrons

p_i : intrinsic concentration of holes

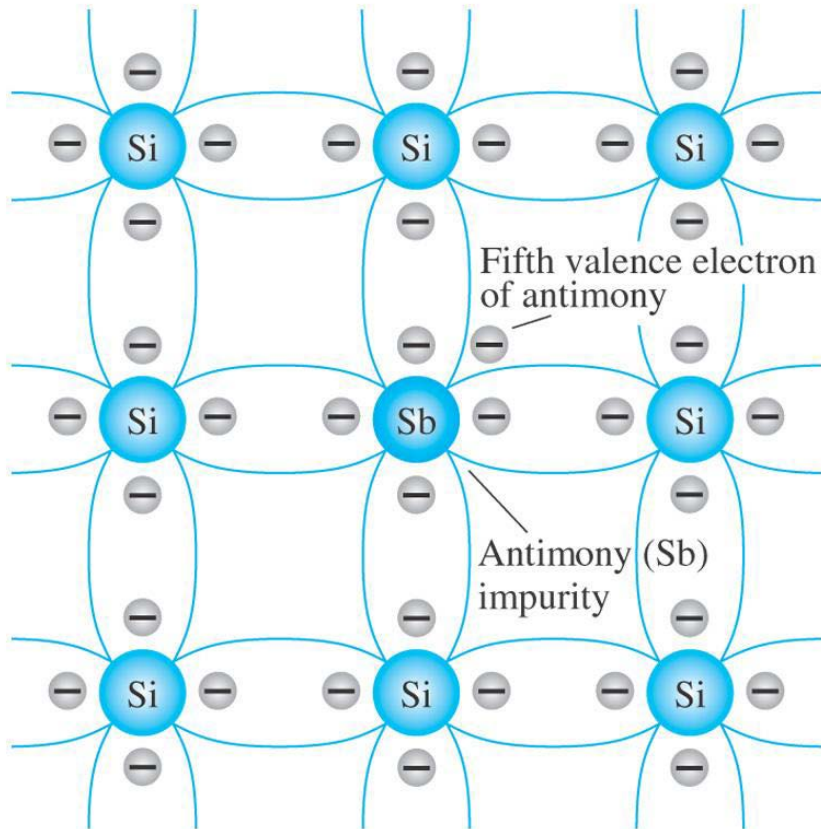
$$n_i = p_i$$

Increasing the carrier concentration will reduce resistivity

How do we increase the carrier concentration in a semiconductor?

Answer: Doping

N-type semiconductor doping



N-type semiconductors are created by adding elements with 5 valence electrons such as Sb (antimony), As (arsenic), and P (phosphorus)

These atoms that are added to the crystal are known as dopants

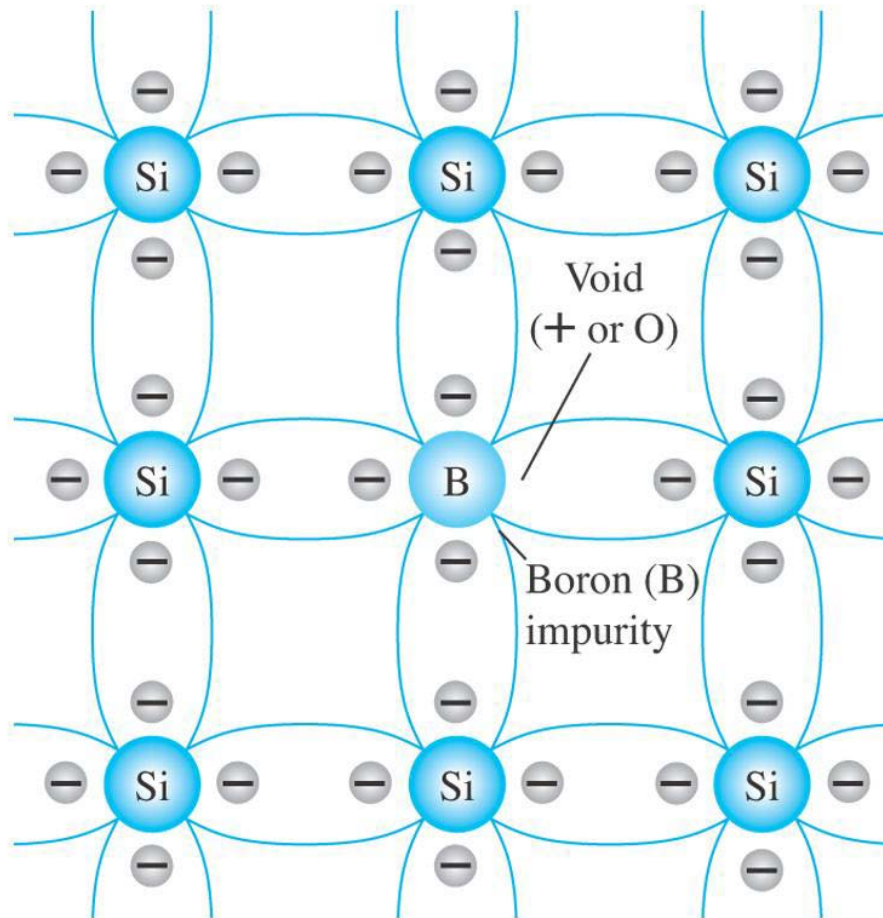
Each dopant substitutes each Si atom

5th valence electron due to the (Sb) atom not shared and thus free to move

Sb atom is called a donor atom (as it donates 1 electron)

*N-type: Majority carriers are **electrons** (remember: N for negative)*

P-type semiconductor doping



P-type semiconductors are created by adding atoms with 3 valence electrons such as (B) boron, (Ga) gallium, and (In) indium.

Here there is an insufficient number of electrons to complete the 4-pairs of covalent bonds/atom

Each B atom that substitutes a Si atom creates vacancy (hole) that is represented by a hole or + sign

These B atoms are known as acceptor atoms.

*P-type: Majority carriers are **holes** (remember: P for positive)*

Net charge in semiconductors

What is the net charge in the following type of semiconductors?

Intrinsic semiconductor ($n = p$)

p-type semiconductor ($n \ll p$)

n-type semiconductor ($n \gg p$)

Doped semiconductors are also referred to as extrinsic semiconductors because electrons/holes have been externally added to the crystal

Majority and minority carriers

Two sources of currents possible in semiconductors due to the existence of holes and electrons

N-type

Majority carriers: Electrons

Minority carriers: Holes

$n \gg p$

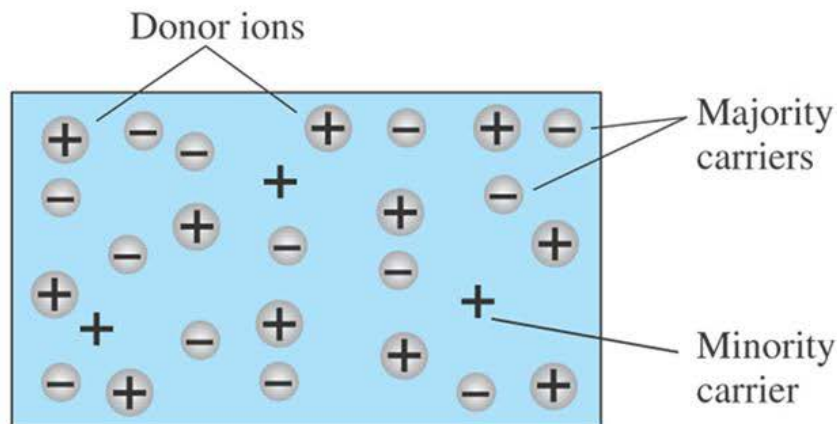
P-type

Majority carriers: Holes

Minority carriers: Electrons

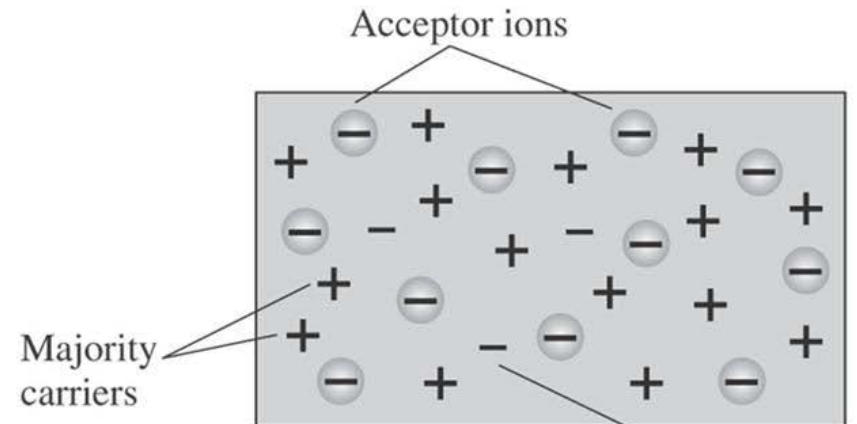
$p \gg n$

n: concentration of electrons; p: concentration of holes



n-type

What is the net charge?

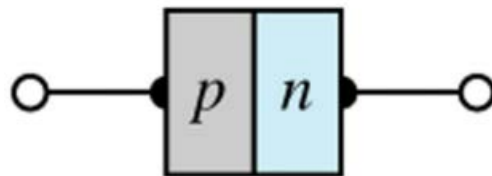


p-type

Minority carrier

P-N junction

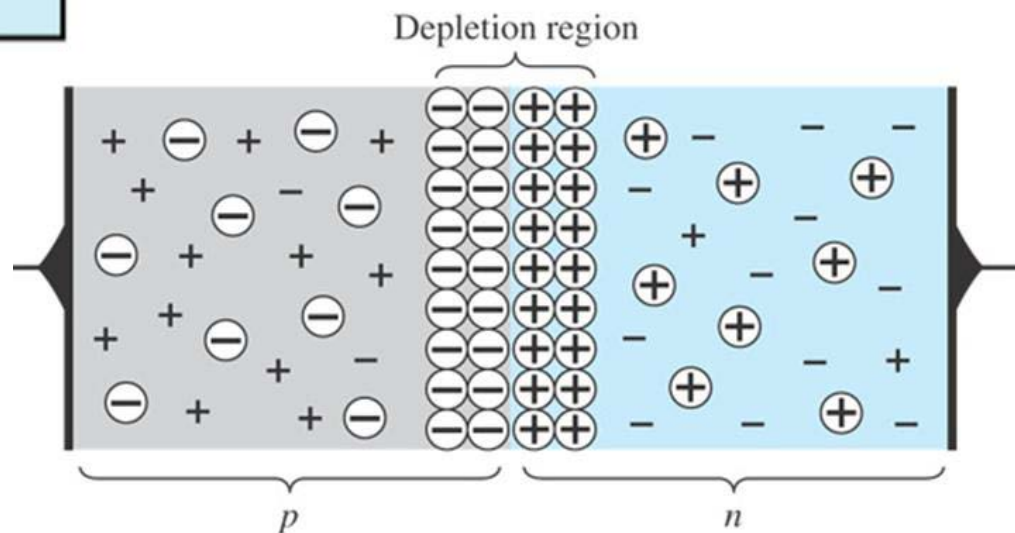
If one side of a semiconductor is doped p-type and the other is doped n-type, the result is a p-n junction



At the p-n junction:

Electrons on the n-type side are attracted to the holes on the p-type side and thus migrate across the junction to the p-type side

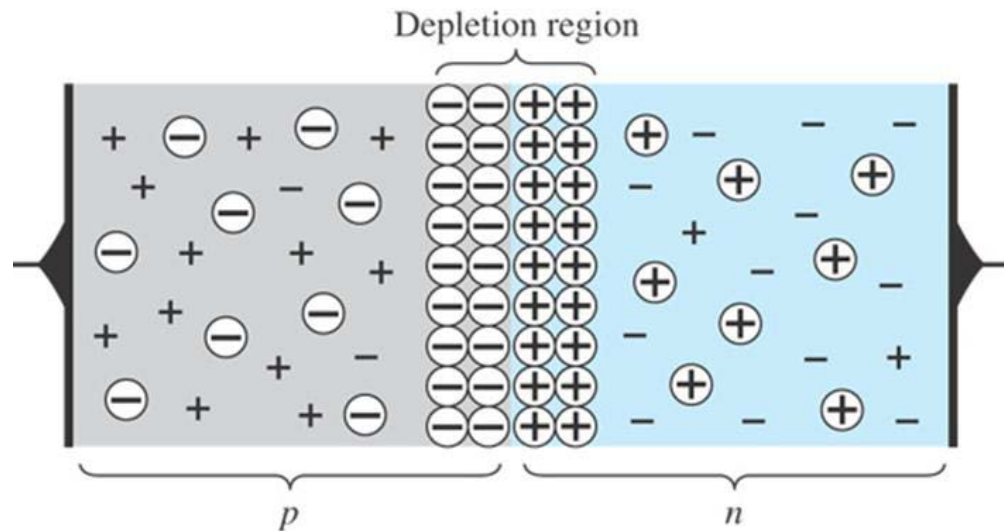
Electrons from n-type side fill the holes in the p-type side (can think about this vice versa)



N-type side: _____ charged

P-type side: _____ charged

Depletion region



At the junction:

Free electrons in the N-type side have migrated to the P-type: No more free electrons

Holes in the P-type side have been filled by the electrons from N-type side: No more holes for conduction

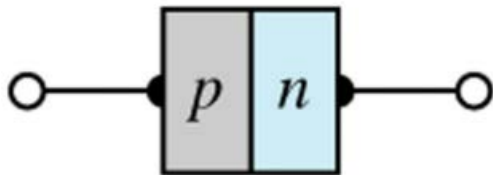
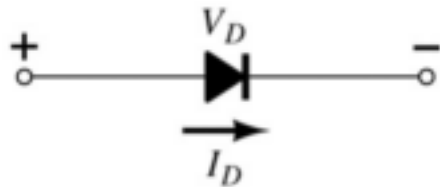
Depletion region: A region with no free carriers

Diode

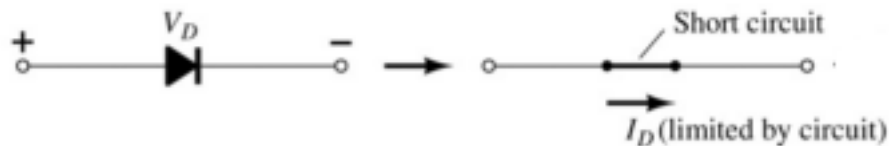
The p-n junction forms the basis for one type of electronic device known as diodes

Note: V_D is always defined as a drop in the forward bias direction

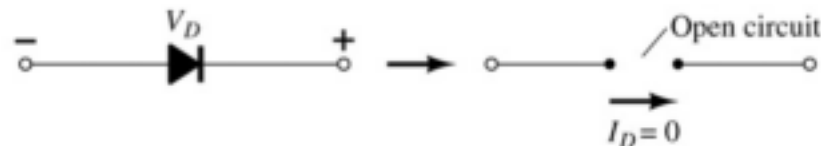
Diodes allow current to flow in one direction (p→n: arrow direction)



Forward bias



Reverse bias

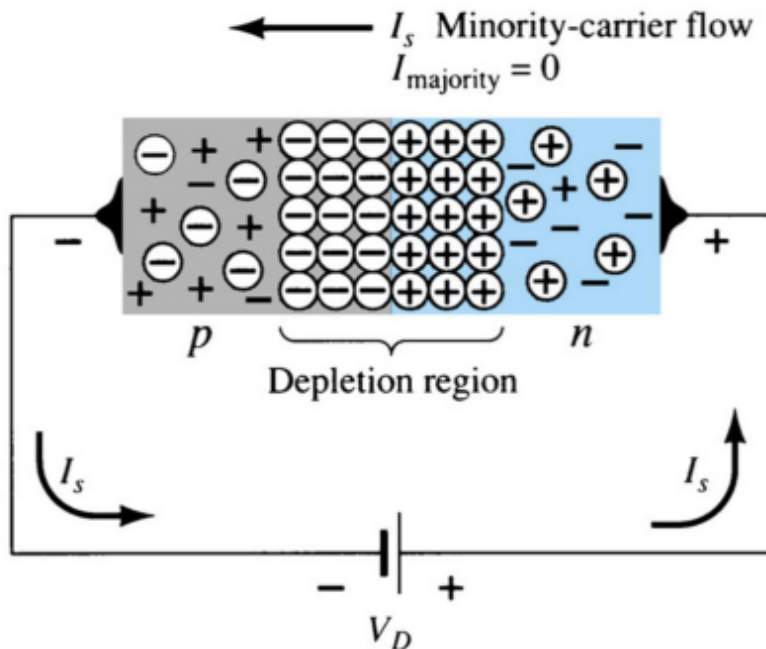
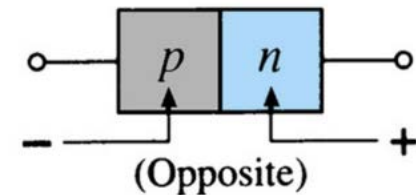
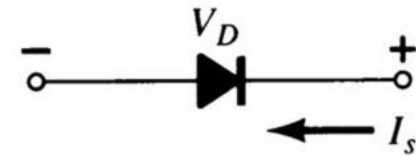


Diode operating modes

Reverse Bias

External voltage is applied across the p - n junction in the opposite polarity of the p - and n -type materials.

Very little current flow (due to minority carriers)

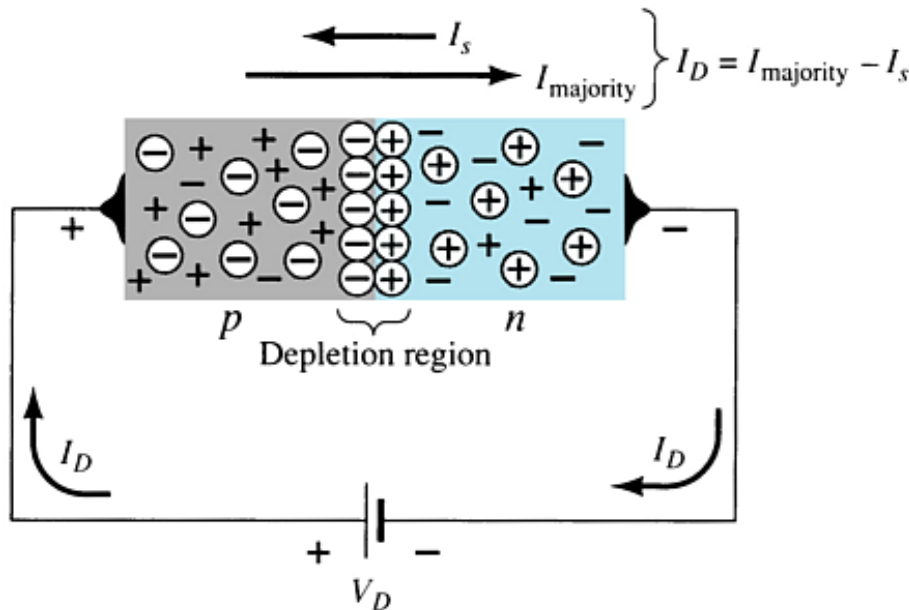
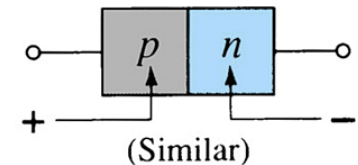
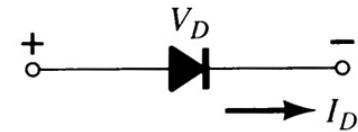


- The reverse voltage causes the depletion region to widen.
- The electrons in the n -type material are attracted toward the positive terminal of the voltage source.
- The holes in the p -type material are attracted toward the negative terminal of the voltage source.

Diode operating modes

Forward Bias

External voltage is applied across the p - n junction in the same polarity as the p - and n -type materials.



- The forward voltage causes the depletion region to narrow.
- The electrons and holes are pushed toward the p - n junction.
- The electrons and holes have sufficient energy to cross the p - n junction.

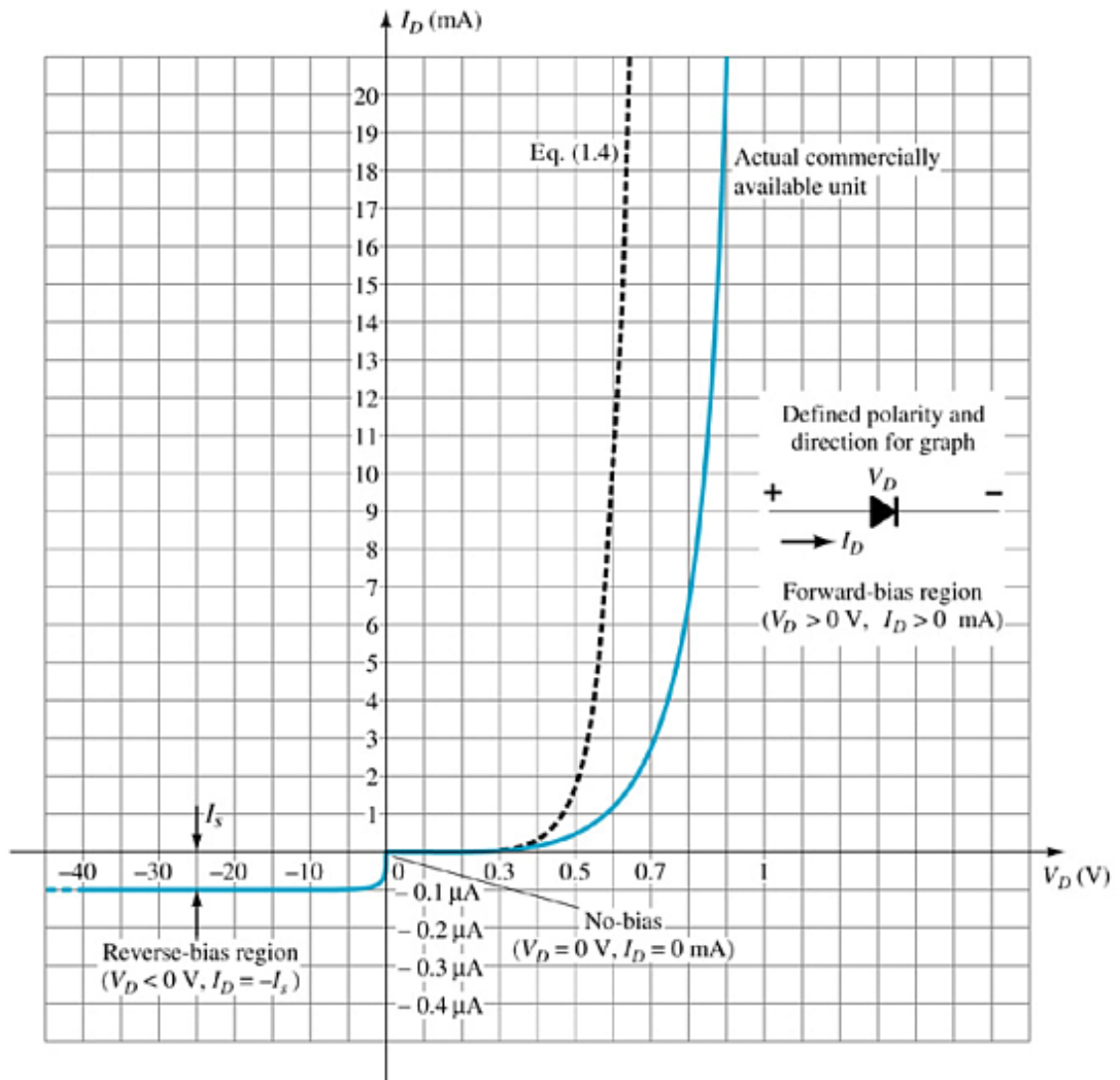
Diode characteristic

Reverse saturation current (I_S) seldom more than μA

Notice how once V_D reaches around 0.7V, V_D hardly changes when the current increases.

This is known as the **forward bias voltage**

For Si, the forward bias voltage is about 0.7V



Diode equation

$$I_D = I_S(e^{V_D/V_T} - 1)$$

$$V_T = \frac{kT}{q}$$

I_D : Forward-bias diode current

V_T : Thermal voltage

I_S : Reverse saturation current (due to minority carrier current)

V_D : Applied forward-bias voltage across the diode.

k : Boltzmann constant (1.38×10^{-23} J/K)

T : Temperature in Kelvins (K) = 273 + temperature in °C

q : Charge of an electron (1.6×10^{-19} C)

Approximation of diode behaviour

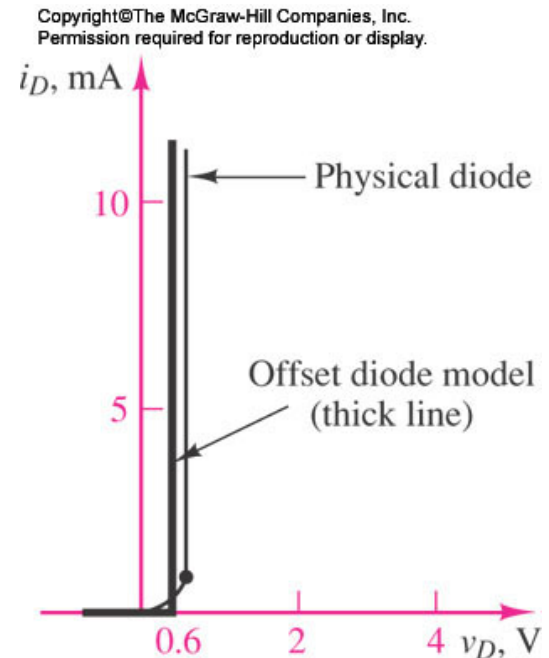
Forward bias:

V_D needs to reach 0.7V for the diode to turn on

Once the diode turns on, V_D stays at 0.7V

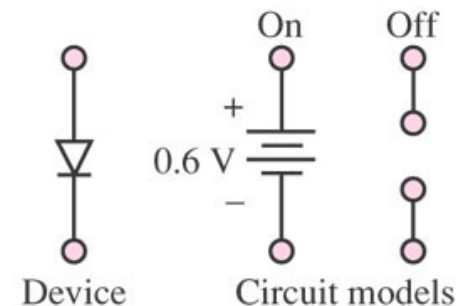
Diode current (I_D) can be any **positive** value

If these conditions are not met, the diode is in reverse bias



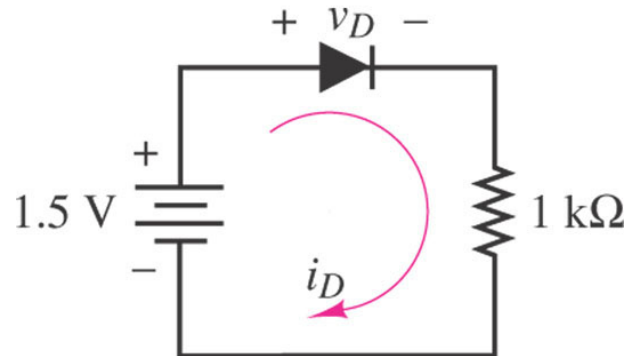
Reverse bias:

V_D does not reach 0.7V and the diode acts as an open circuit ($I_D = 0$)



Diode circuit example 1

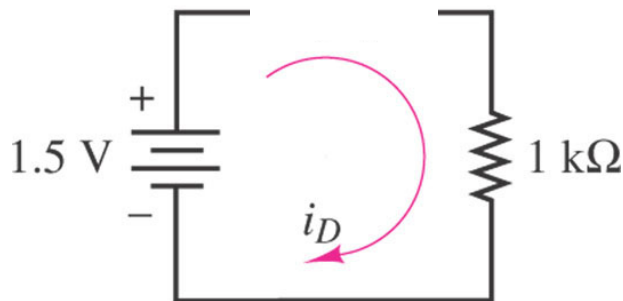
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Determine the state of the silicon diode
Find the value of i_D

Is there sufficient voltage to drop 0.7V across the diode? (i_D can be close to zero as long as it is positive)

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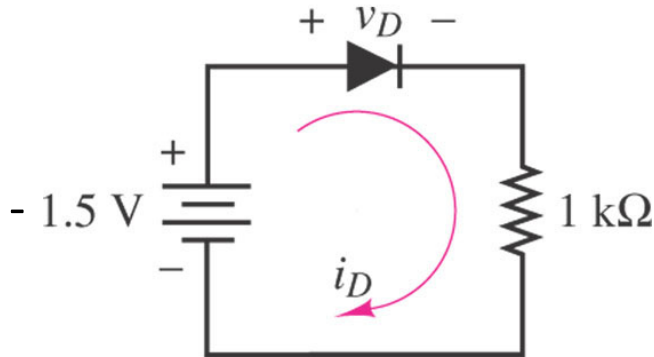
Voltage drop across 1kΩ:

$$I_D = \underline{\hspace{2cm}} / 1k = \underline{\hspace{2cm}}$$

Diode circuit example 1

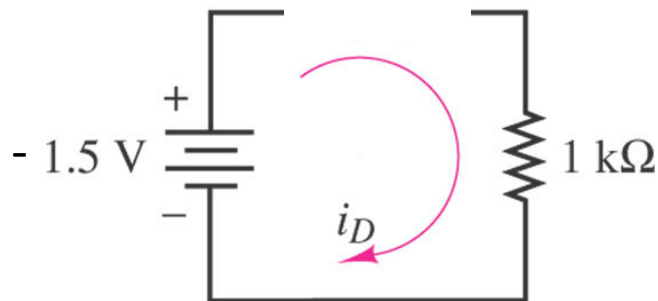
Rework the analysis with the polarity of the source reversed

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Is there sufficient voltage to drop 0.7 V across the diode? (i_D can be close to zero as long as it is positive)

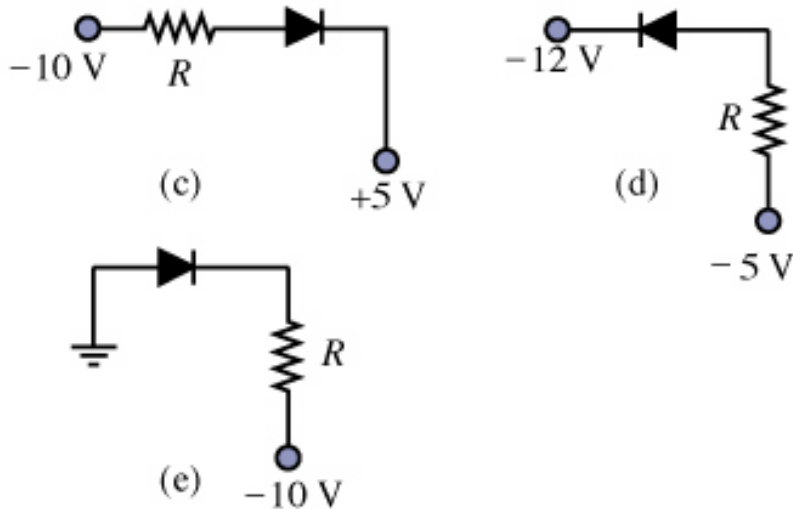
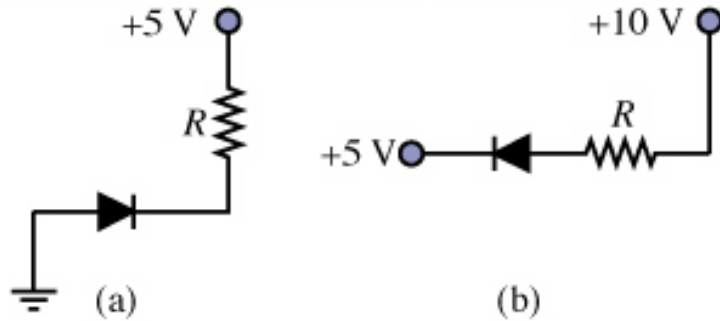
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What is the minimum value of the source to forward bias the silicon diode?

Diode circuit example 2

Determine which silicon diodes are ON and which are OFF



Hint: Find the voltage difference between the terminals

Diode circuit example 3

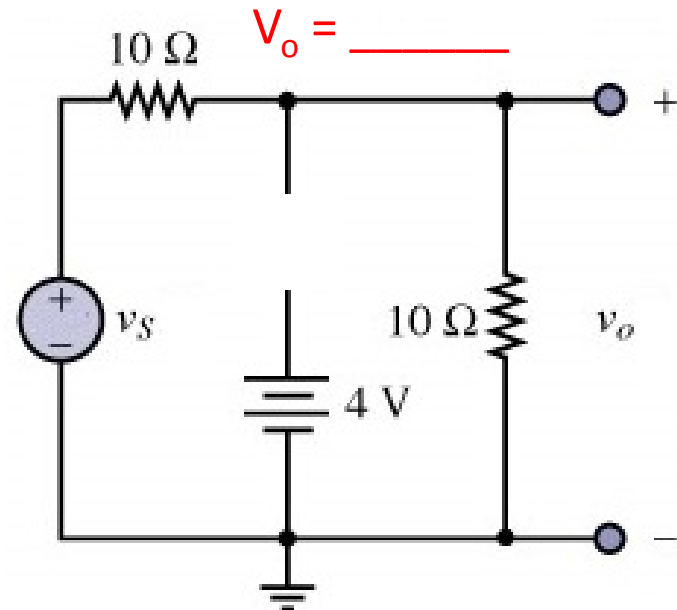
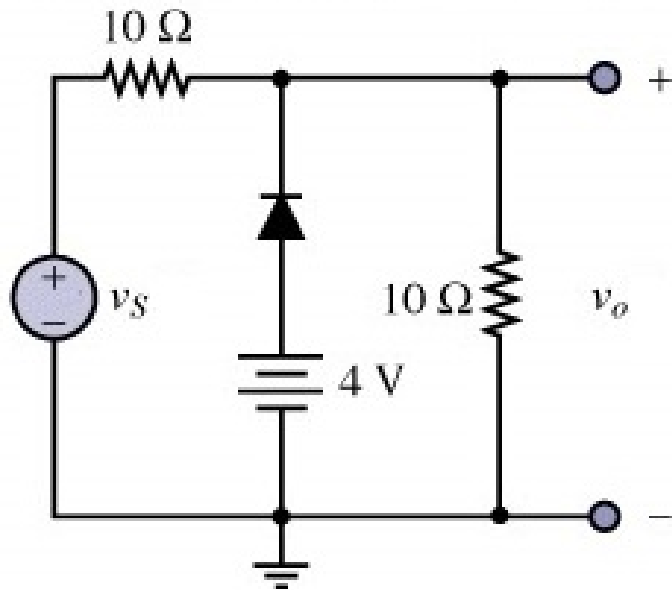
Determine the state of the diode when (i) $v_s = 10\text{V}$ and (ii) $v_s = 6\text{V}$

If the diode is on, find the forward bias current

If the diode is off, find the reverse bias voltage

In each case, determine the value of v_o .

When $v_s = 10\text{V}$: Assume off and find _____
_____ should be _____



Diode circuit example 3

When $v_s = 6V$

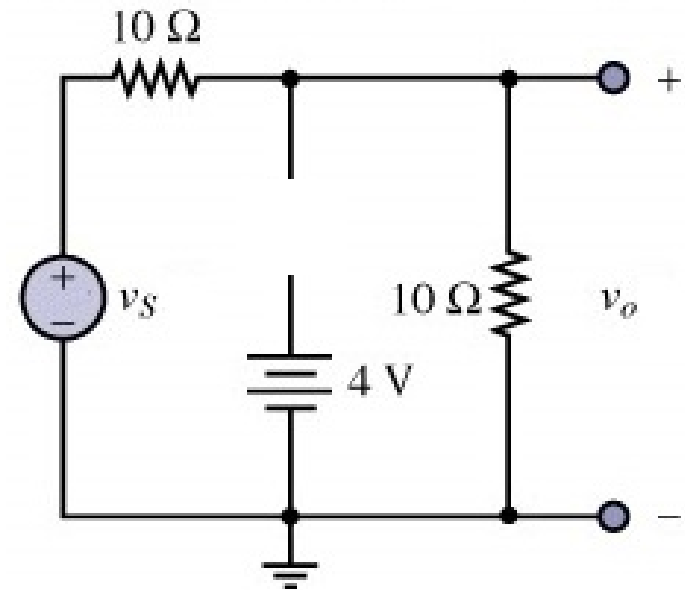
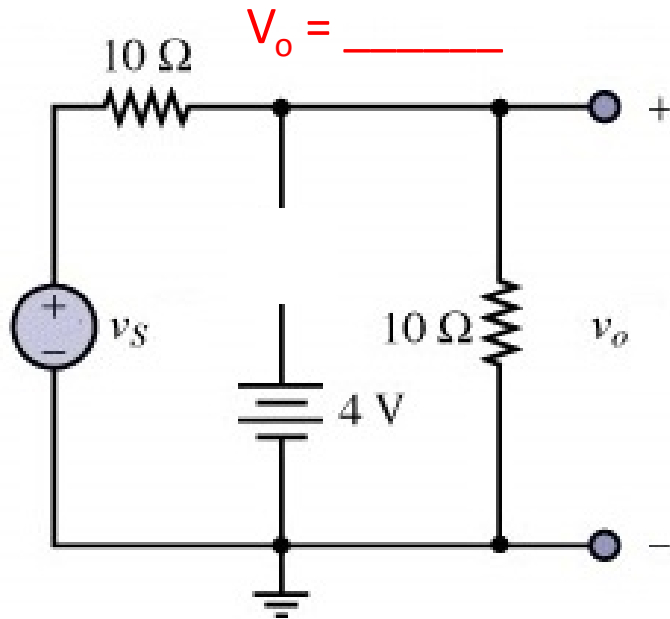
Assume off and find _____

_____ should be _____

Assume ON and find _____

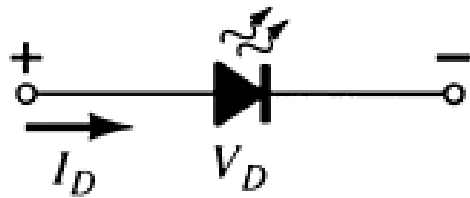
_____ should be _____

$V_o =$ _____



Light Emitting Diodes (LEDs)

An LED emits light (in the form of photons) when it is forward biased

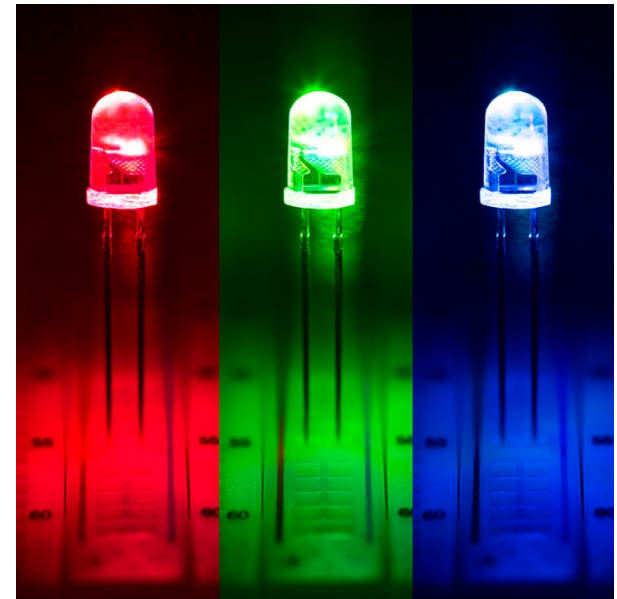


$$E = h f$$

h : Planck's constant ($6.626 \times 10^{-34} \text{ m}_2\text{kg/s}$)

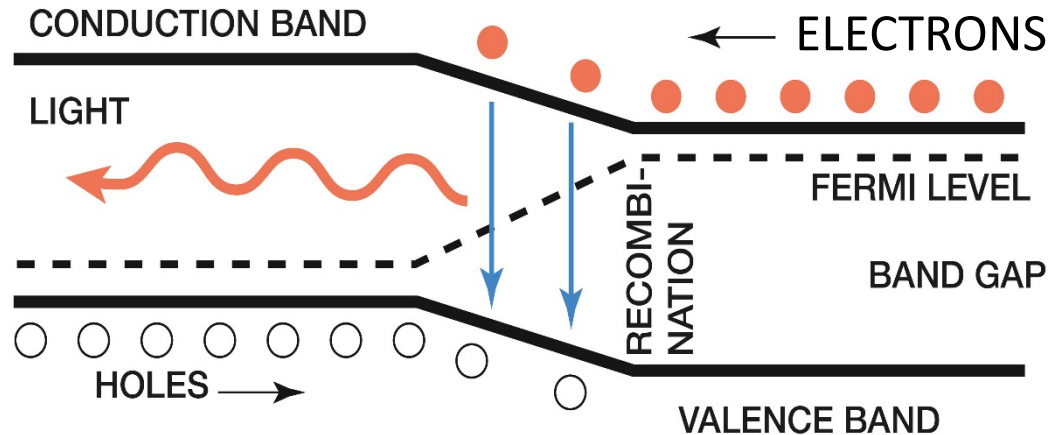
f : frequency

Colour	Material	V_D
Blue	GaN	5.0V
Green	GaP	2.2V
Red	GaAsP	1.8V



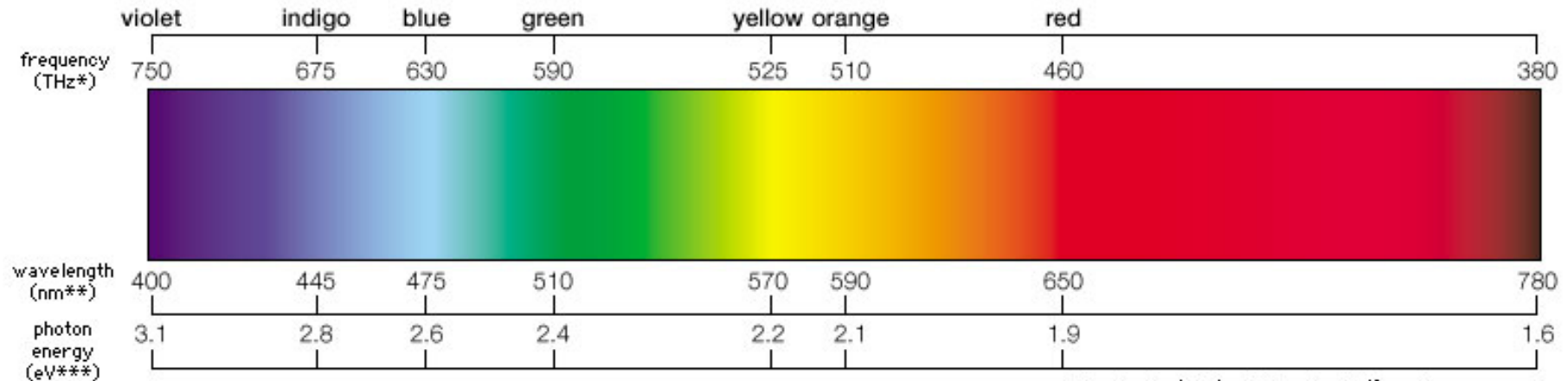
Colour of emission is related to the semiconductor material

How LEDs work



As electrons fall from the conduction band to the valence, a photon is released with an energy level corresponding to E_g

Light, the visible spectrum



* In terahertz (THz); 1THz = 1×10^{12} cycles per second.
 ** In nanometres (nm); 1nm = 1×10^{-9} metre.
 *** In electron volts (eV).