Solid State Devices

Course Outline

- Unit-1 Semiconductors
- Unit-2 Rectifiers
- Unit-3 Transistors
- Unit-4 Field Effect Transistor
- Unit-5 Feedback amplifiers and oscillators.

LECTURE NO. - 1

Semiconductors

Semiconductors are materials whose electrical properties lie between Conductors and Insulators.

Ex : Silicon and Germanium

Semiconductors

- semiconductor = material for which gap between valence band and conduction band is small; (gap width in Si is 1.1 eV, in Ge 0.7 eV).
- at T = 0, there are no electrons in the conduction band, and the semiconductor does not conduct (lack of free charge carriers);
- at T > 0, some fraction of electrons have sufficient thermal kinetic energy to overcome the gap and jump to the conduction band; fraction rises with temperature;

  e.g. at 20^{o} C (293 K), Si has 0.9×10^{10} conduction electrons per cubic centimeter; at 50^{o} C (323 K) there are 7.4×10^{10} .

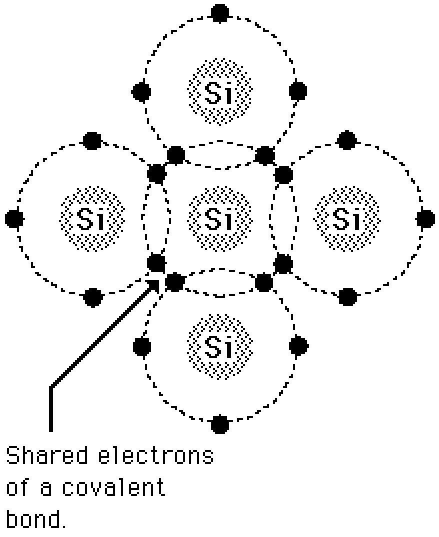
Types of Semiconductor

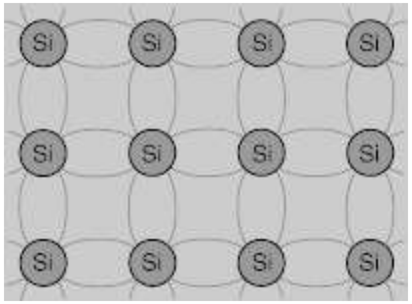
- Intrinsic semiconductors
- Extrinsic (doped) semiconductors
  - n-type materials
  - p-type materials

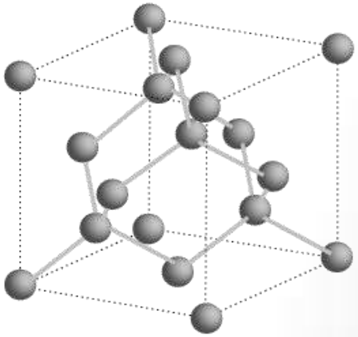
Intrinsic Semiconductor

- A Semiconductor, which is in its extremely pure form, is known as an intrinsic (or pure) semiconductor.

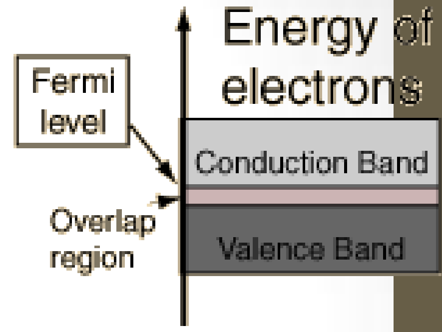
Silicon



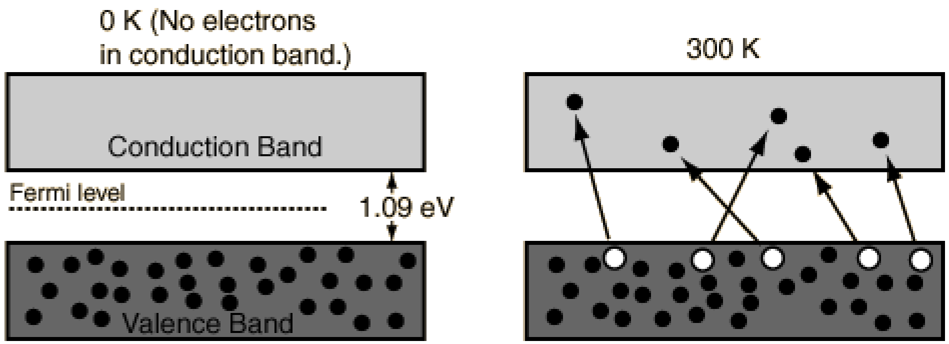




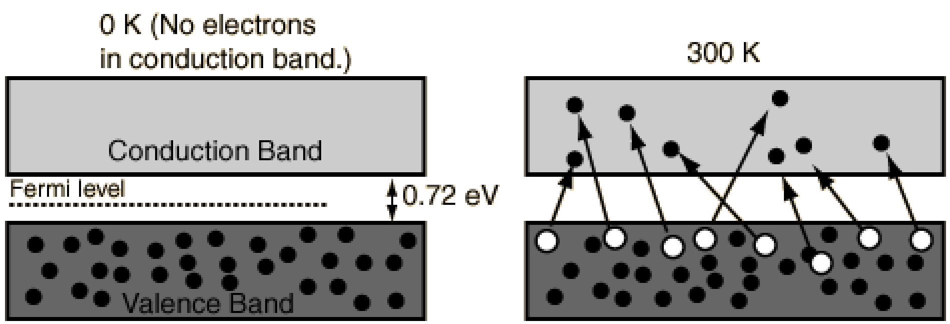
band gap conductor



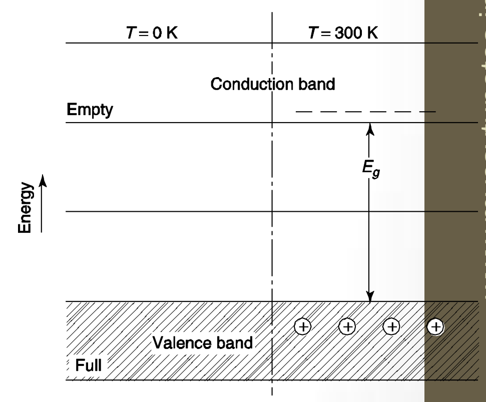
c. Conductor



silicon



germanium



With intrinsic systems (***only***), for every free electron, there is also a free hole.

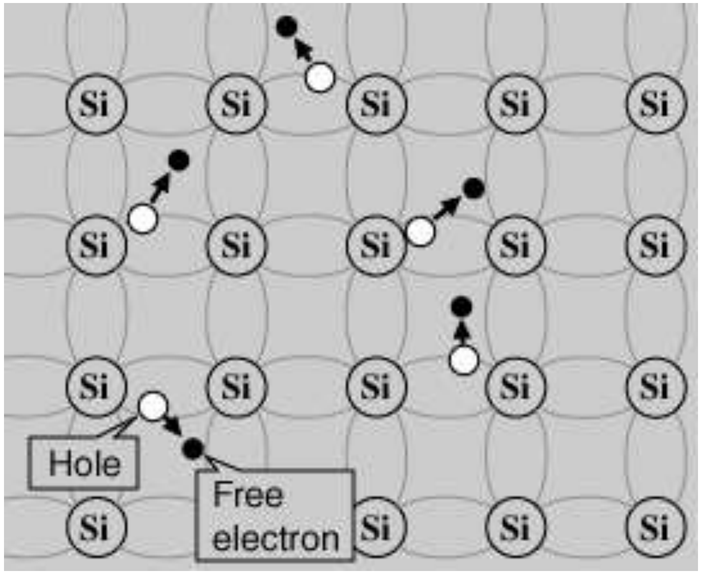
- # electrons = n = # holes = p = ni
- --true for pure Si, or Ge, etc.

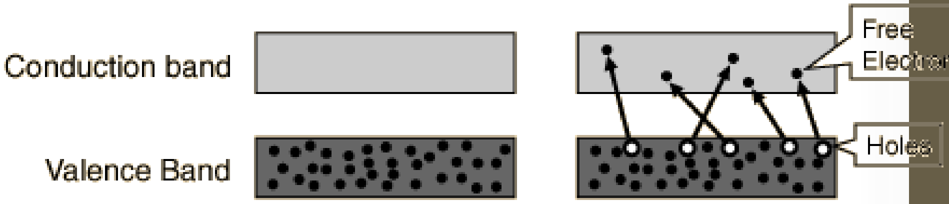
$$\sigma = n|e|\mu_e + p|e|\mu_h = n_i|e|(\mu_e + \mu_h)$$

μ_h is ~20% of μ_e

- Holes don't move as easily (mobility of holes is always less than for electrons), but still there are so many that they will contribute at least an extra 10-20% to the intrinsic conductivity.

Charge carriers: electrons and holes





$$\Rightarrow \quad \sigma = n_e q_e \mu_e + n_h q_h \mu_h = n_e q_e (\mu_e + \mu_h)$$

$$\text{with} \quad \mu_e > \mu_h$$

Analogy to metals

- As a general rule, as temperature increases, scattering also increases. This *decreases conductivity* drastically for metals.
- The mobility for an intrinsic semiconductor *will also diminish* with increasing temperature due to increased scattering.
- Still, the extra temperature provides lots of extra electrons and holes in the conduction band for intrinsic semiconductors. This causes *n* to increase exponentially with Temperature.

- n goes up so fast w/r to mobility that the excess electrons totally wash out the diminishing effect of extra scattering.

Thus, conductivity almost always increases with temperature for a semiconductor, the opposite of a metal.

LECTURE NO. - 2

Extrinsic Semiconductors

- A semi-conducting material for which the electrical behavior is determined by impurities.
- The process of adding other material to the crystal of intrinsic semiconductors to improves its conductivity is called doing. Doped semiconductor material is called extrinsic semiconductor.
- *The conductivity of silicon or germanium can be increased by a factor of up to 106 by adding a little as 0.01% of an impurity.*

Types of Extrinsic Semiconductors

- n-Type Semiconductor :- When a small amount of pentavalent impurity is added to a pure semiconductor, it is called n-type semiconductor. Such an impurity is called ***donor*** *impurity*.

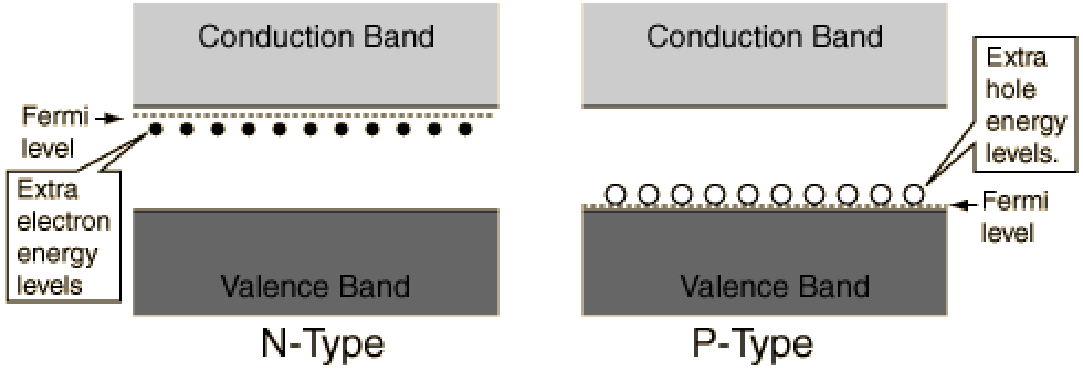
  Ex. *Arsenic, bismuth, phosphorous and antimony*.

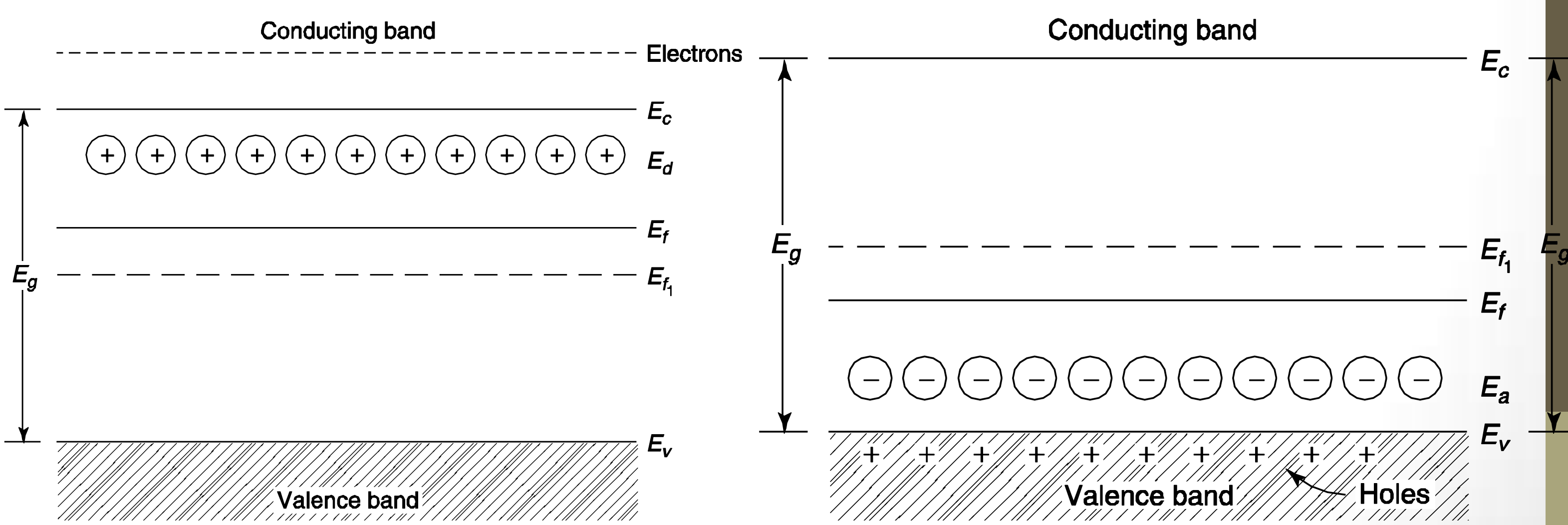
- p-Type Semiconductor :- When a small amount of trivalent impurity is added to a pure semiconductor, it is called p-type semiconductor. Such an impurity is called ***acceptor*** *impurity*.

  Ex. *Gallium, boron or indium.*

Extrinsic Semiconductors

Doping

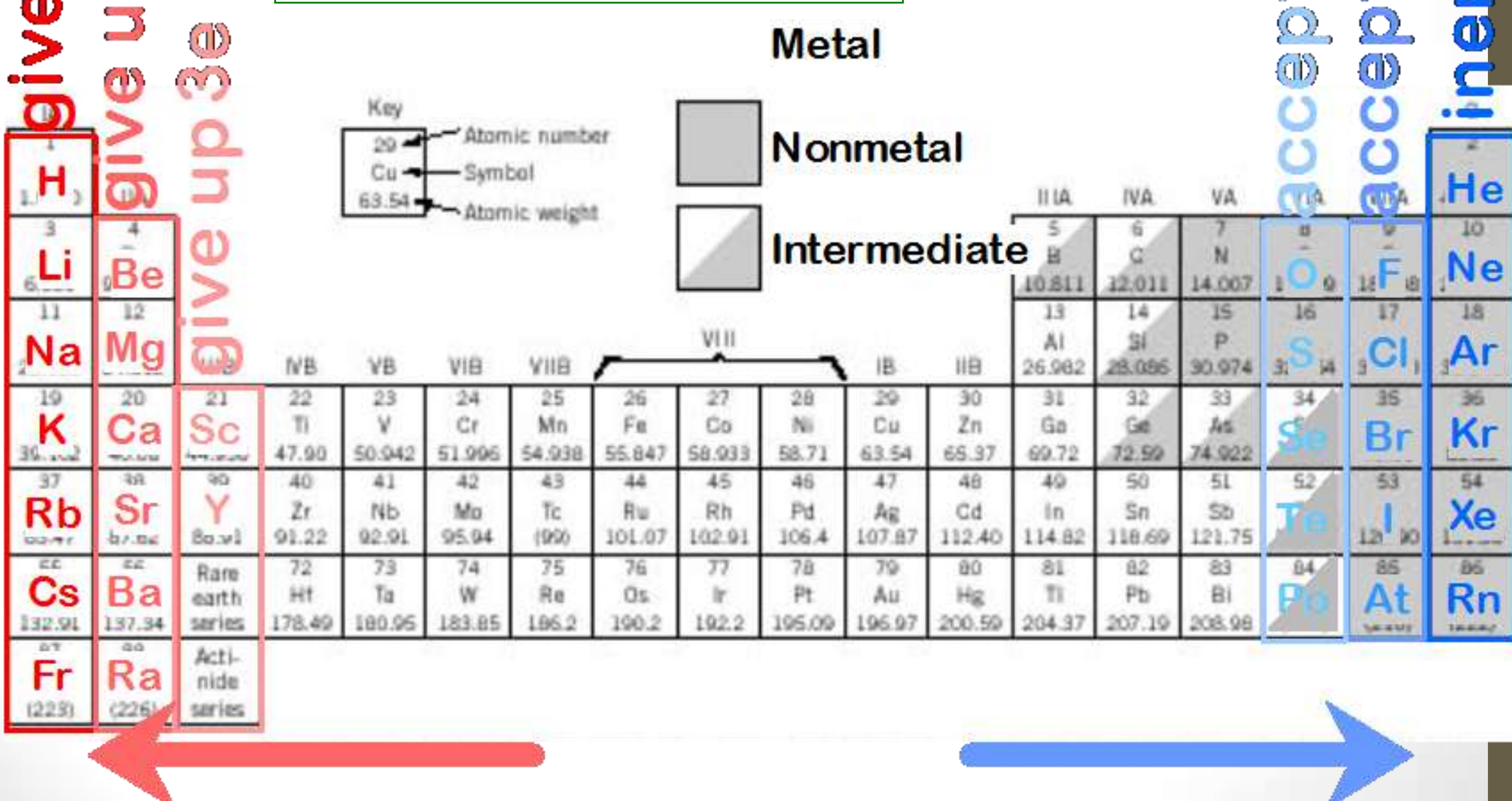




Typical Donor and Acceptor Dopants for Si

For Silicon:

- **Donors (n type):**
  - **P, As, Sb**
- **Acceptors (p type):**
  - **B, Al, Ga, In**



n-Type Semiconductor

- For every donor dopant atom (N_d) near the conduction band, there is another free electron (n)
  - NOTE no change in T is needed as for metals.
- Unlike for intrinsic semiconductors, free electron doesn't leave a mobile free hole behind. Instead, any holes are trapped in donor state and thus will ***not*** contribute substantially to conductivity as for intrinsic semiconductors (thus p~0).

$$\sigma = n|e|\mu_e + p|e|\mu_h \approx n|e|\mu_e = N_d|e|\mu_e$$

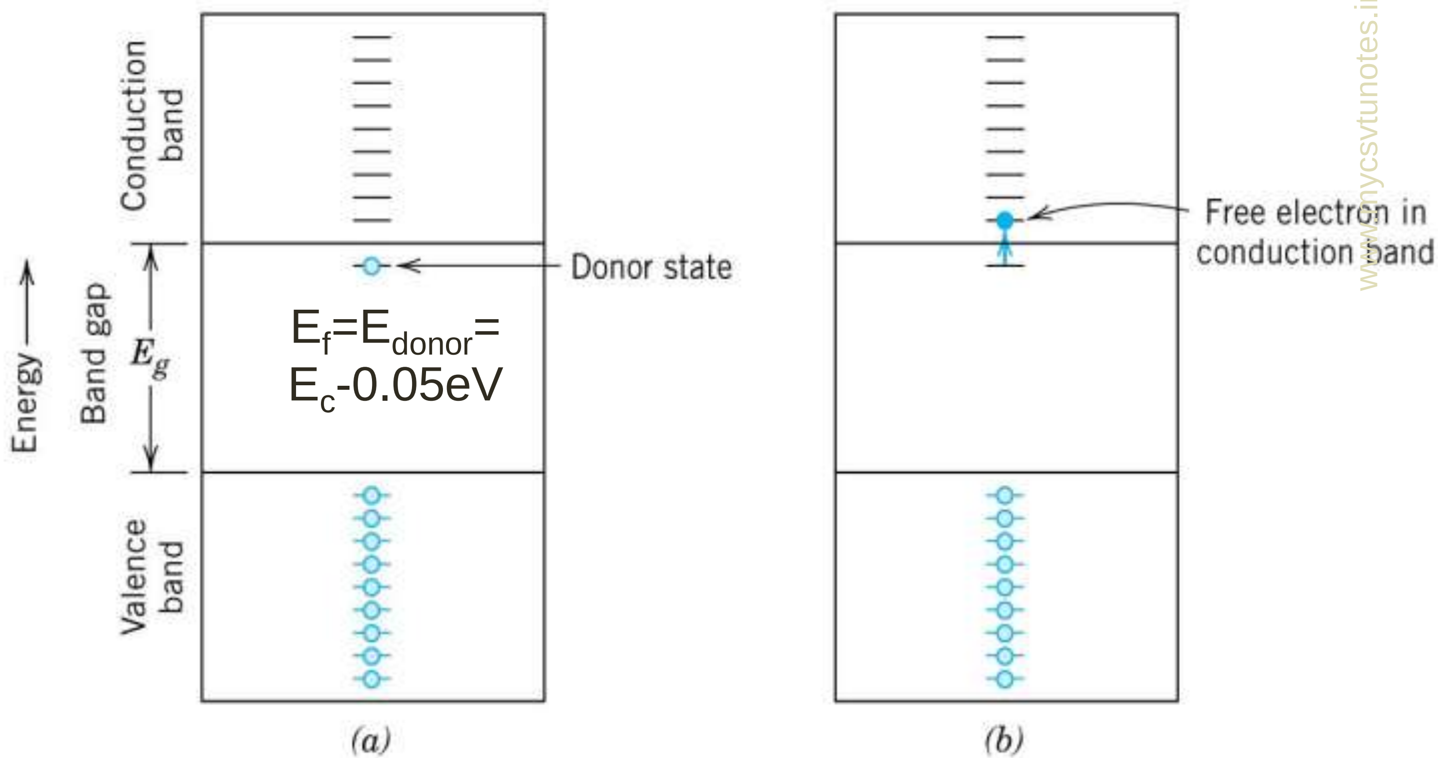


FIGURE 18.12 (*a*) Electron energy band scheme for a donor impurity level located within the band gap and just below the bottom of the conduction band. (*b*) Excitation from a donor state in which a free electron is generated in the conduction band.

Charge Density in Doped Semiconductors

$$N_D = N_D^0 + N_D^+$$

$$N_A = N_A^0 + N_A^-$$

Charge neutrality (accounting): $n + N_A^- = p + N_D^+$

Occupation of donors by electrons: $n_D = N_D^0 = N_D\{1 + \exp[(E_D - E_F)/kT]\}^{-1}$

Occupation of acceptors by holes: $p_A = N_A^0 = N_A\{1 + \exp[(E_F - E_A)/kT]\}^{-1}$

From now on: pure n-type semiconductor (pure p-type is similar)

$$n = N_{eff}^C e^{-(E_C - E_F)/kT}$$

$$N_D = N_D^0 + N_D^+$$

$$N_D^0 = N_D\{1 + \exp[(E_D - E_F)/kT]\}^{-1}$$

$$n = N_D^+ + p$$

$$n + N_A^- = p + N_D^+$$

$N_A^- = 0$ (Only one type of dopant at a time)

Approximation

$N_D^+ \gg n_i$ $\quad (np = n_i^2)$ → $n \approx N_D^+ = N_D - N_D^0$

$n_i = 1.5 \times 10^{10}\ \mathrm{cm}^{-3}$ at 300 K

p-Type Semiconductor

- We can do the same thing with "acceptor dopants."
- Every acceptor generates excess mobile holes ($p=N_a$).
- Now holes totally outnumber electrons, so conductivity equation switches to p domination.

$$\sigma = n|e|\mu_e + p|e|\mu_h \approx p|e|\mu_h = N_a|e|\mu_h$$

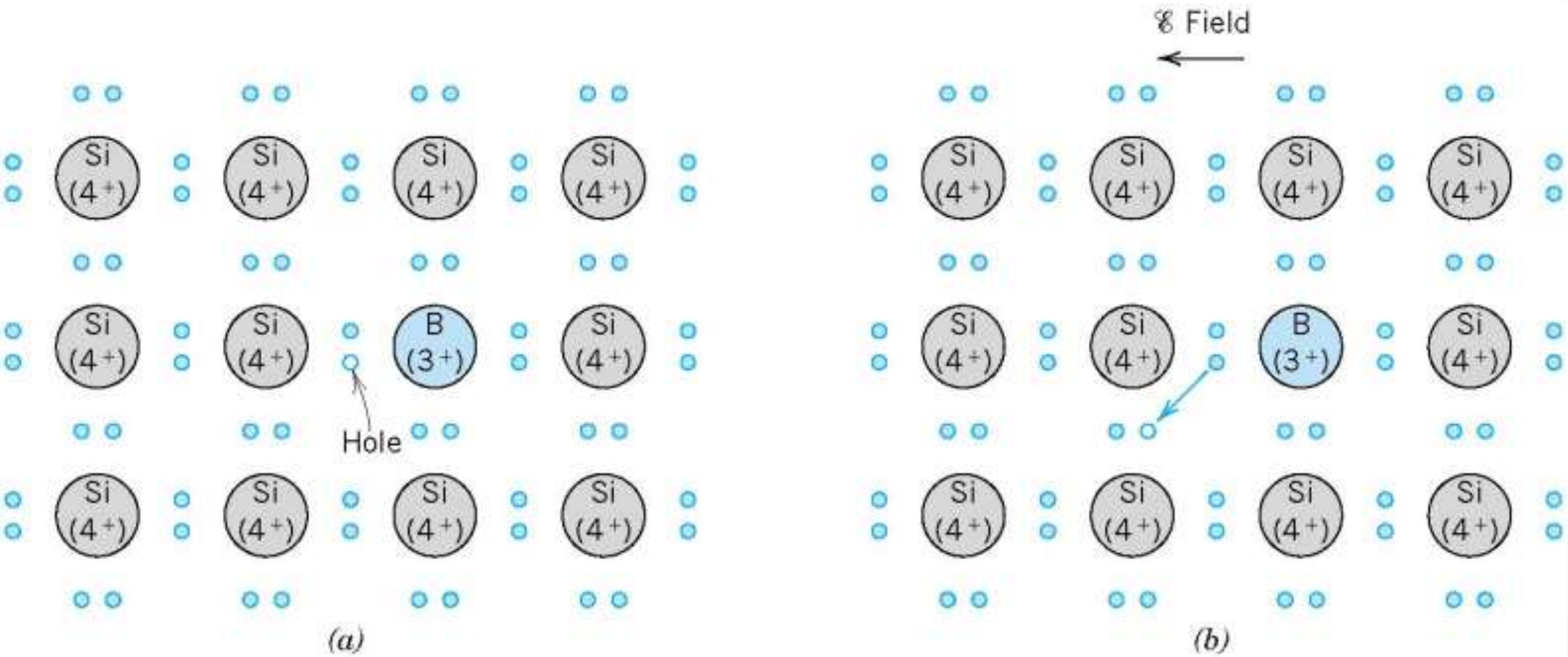


FIGURE 18.13 Extrinsic *p*-type semiconduction model (electron bonding). (*a*) An impurity atom such as boron, having three valence electrons, may substitute for a silicon atom. This results in a deficiency of one valence electron, or a hole associated with the impurity atom. (*b*) The motion of this hole in response to an electric field.

Summary: Intrinsic vs. Extrinsic (n or p)

- **Intrinsic**:
  \# electrons = # holes (n = p)
  --case for pure Si

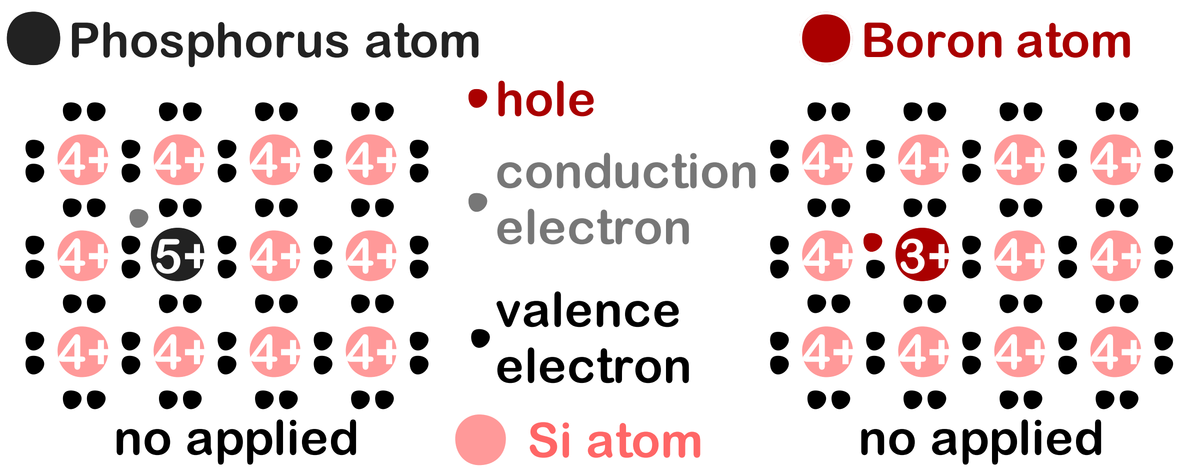
$$\sigma \approx n_i |e| (\mu_e + \mu_h)$$

- **Extrinsic**:
  --n ≠ p
  --occurs when DOPANTS are added with a different # valence electrons than the host (e.g., Si atoms)

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

- **N-type Extrinsic: (n >> p)**
- **P-type Extrinsic: (p >> n)**

$$\sigma \approx n|e|\mu_e$$



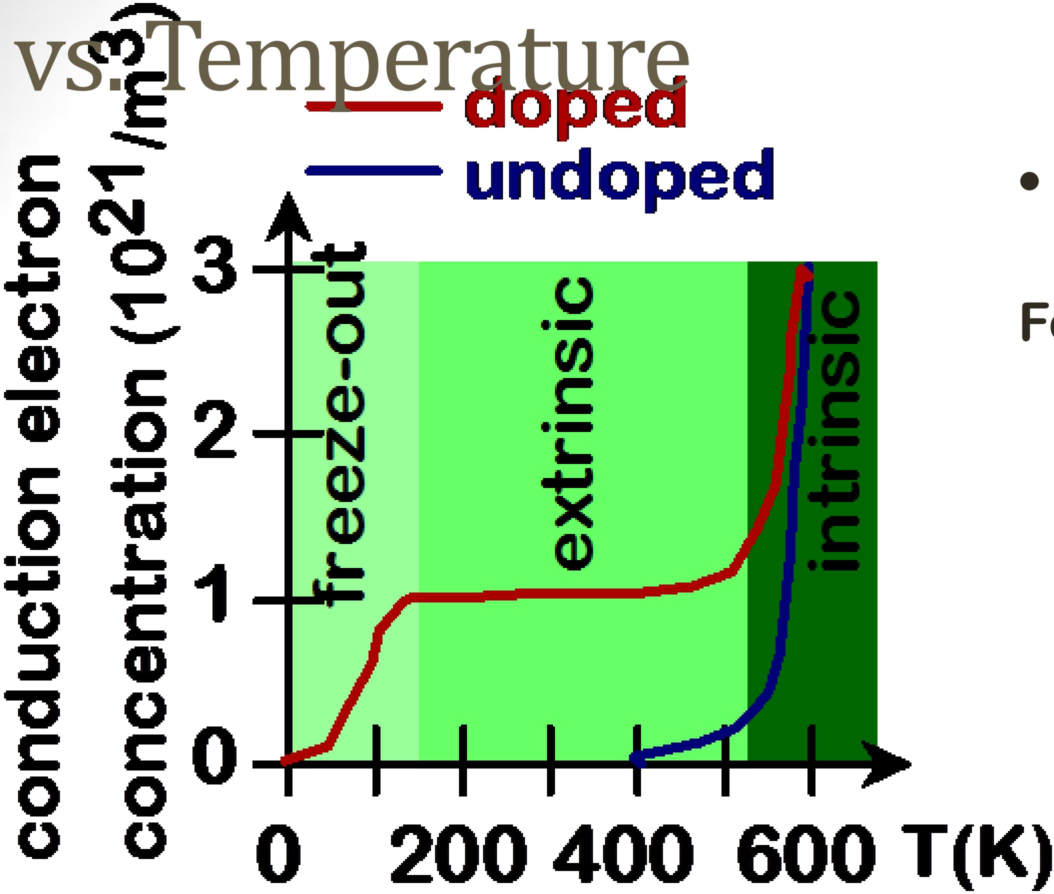
no applied electric field

no applied electric field

$$\sigma \approx p|e|\mu_h$$

$$n, p \geq n_i * 10^3$$

Intrinsic vs. Extrinsic—*charge concentration* vs. Temperature



- **Comparison: intrinsic vs extrinsic conduction...**

For an extrinsic doping level of: 10^{21}/m^3 of a n-type donor impurity (such as P).

--for T < 100K: ***"freeze-out"*** thermal energy only sufficient to excite a very few electrons.

--for 150K < T < 450K: ***"extrinsic"***

--for T >> 450K: ***"intrinsic"***

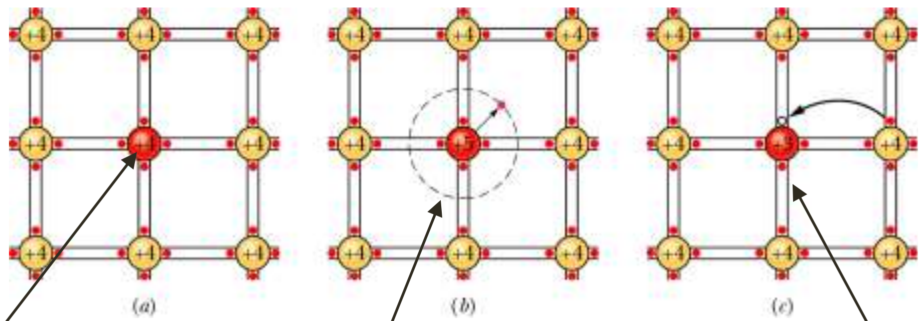
- The dopant sites essentially lower the activation energy to generate free electrons at room temperature.

LECTURE NO. – 3

What are P-type and N-type ?

- Semiconductors are classified in to P-type and N-type semiconductor
- P-type: A P-type material is one in which holes are majority carriers i.e. they are positively charged materials (++++)
- N-type: A N-type material is one in which electrons are majority charge carriers i.e. they are negatively charged materials (-----)

P Type and N Type Semiconductor

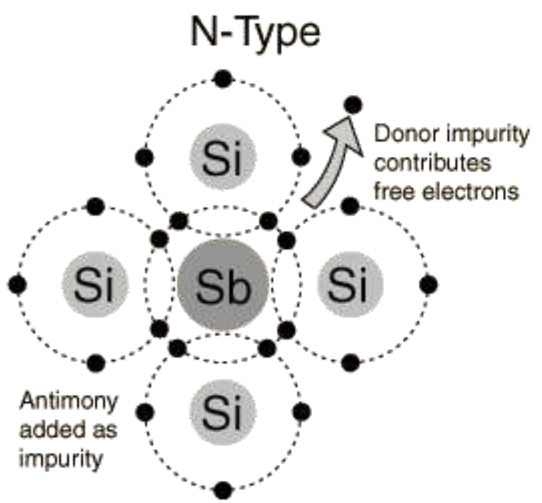


Silicon – an insulator, each atom shares electrons with 4 others.

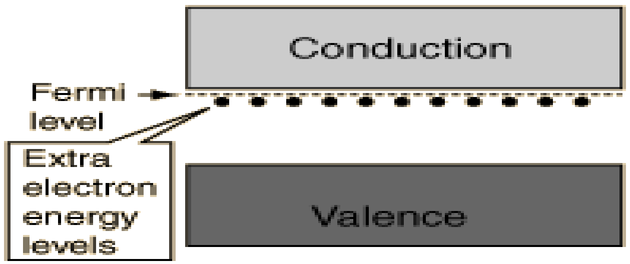
Silicon doped with phosphorous (P). P has 5 outer electrons. The spare electron goes into the conduction band ⇒ n-type semiconductor.

Silicon doped with boron (B). B has only 3 outer electrons. The absence of an electron adds a ‘hole’ to the valence band ⇒ p-type semiconductor.

N-Type Semiconductor

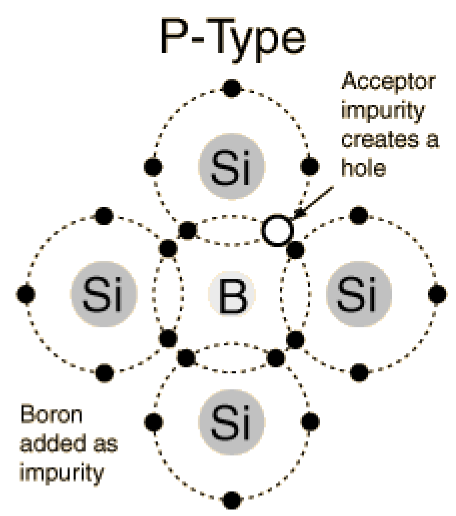


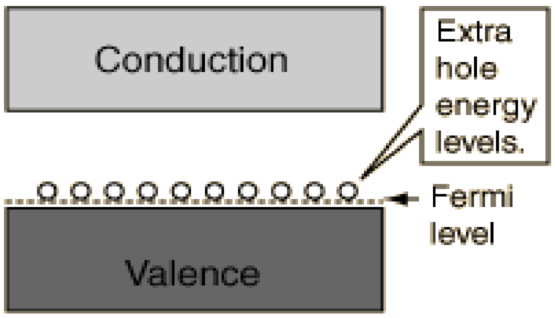
The addition of pentavalent impurities such as antimony, arsenic or phosphorous contributes free electrons, greatly increasing the conductivity of the *intrinsic semiconductor*. Phosphorous may be added by diffusion of phosphine gas (PH3).



P-Type Semiconductor

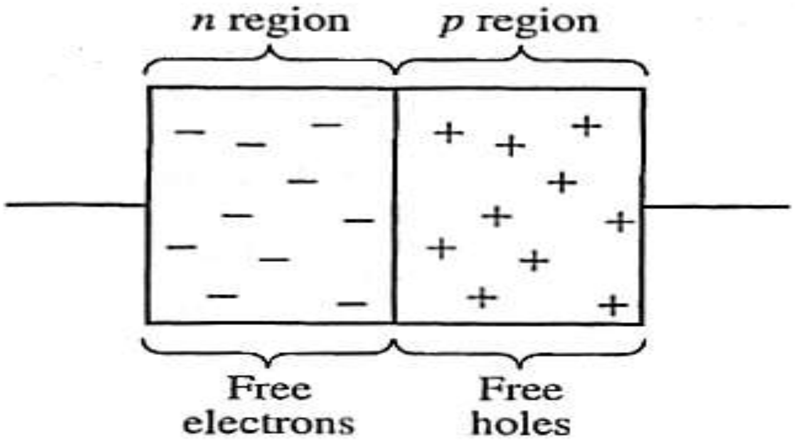
The addition of trivalent impurities such as boron, aluminum or gallium to an intrinsic semiconductor creates deficiencies of valence electrons, called "holes". It is typical to use B2H6 diborane gas to diffuse boron into the silicon material.



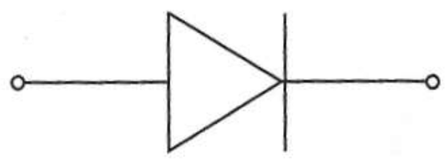


Theory of P-N Junction Diode

- The real power of semiconductor electronics occurs when P- and N-regions are brought into contact with each other, forming a **P-N junction**.



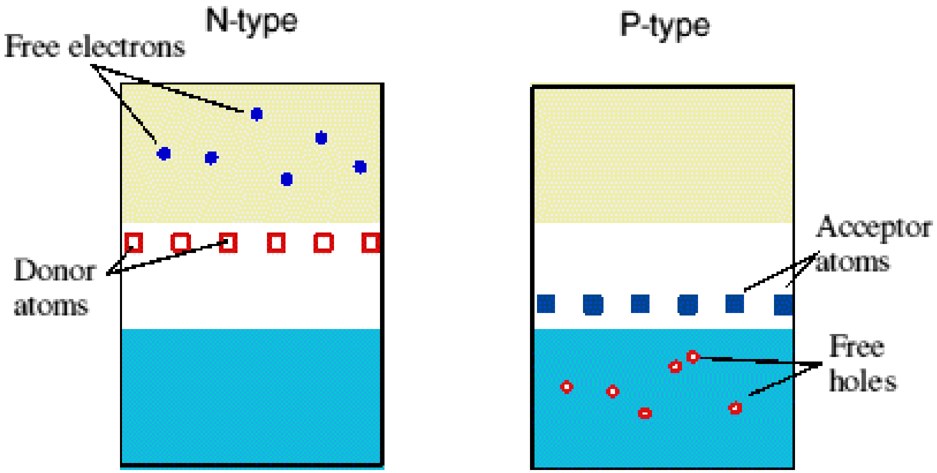
It is represented by the following symbol, where the arrow indicates the direction of positive current flow.



LECTURE NO. - 4

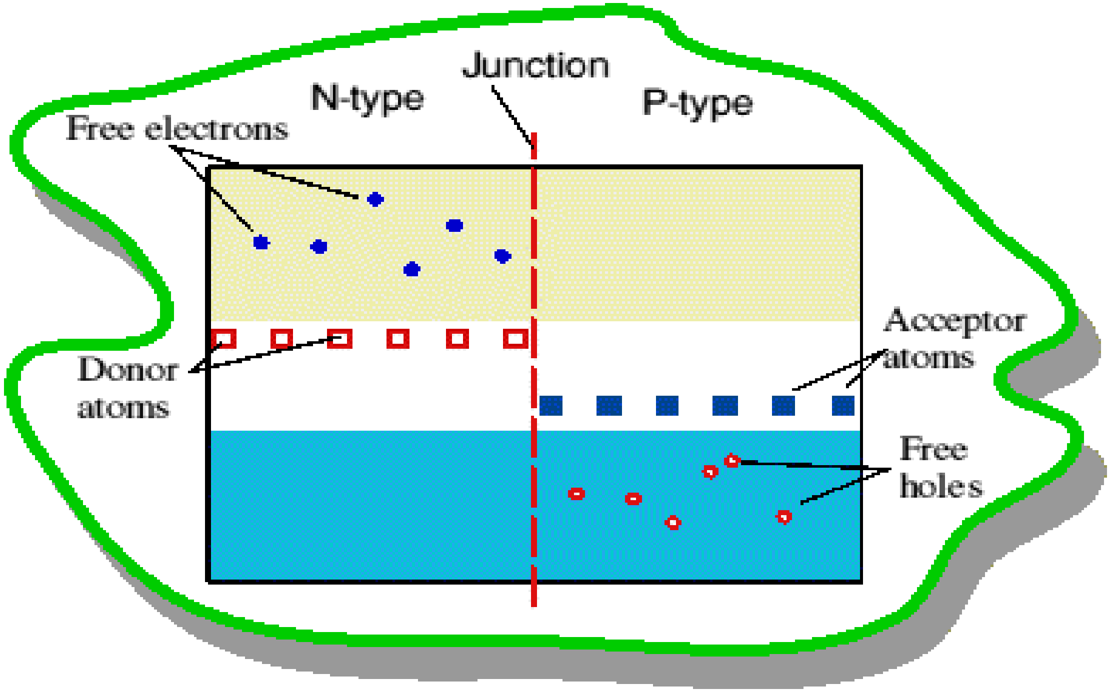
P-N Junction Diode

- To understand how a p-n junction diode works, begin by imagining two separate bits of semiconductor, one n-type, the other p-type.



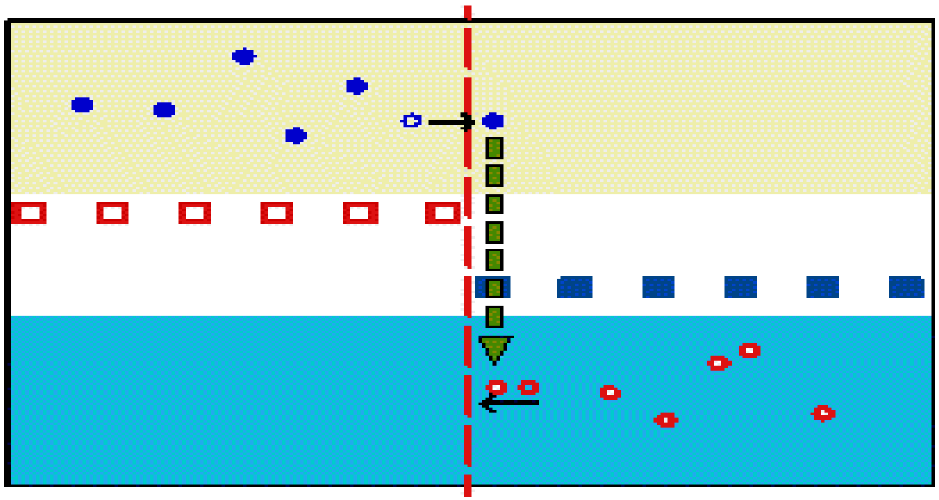
P-N Junction Diode

- Bring them together and join them to make one piece of semiconductor which is doped differently either side of the junction.



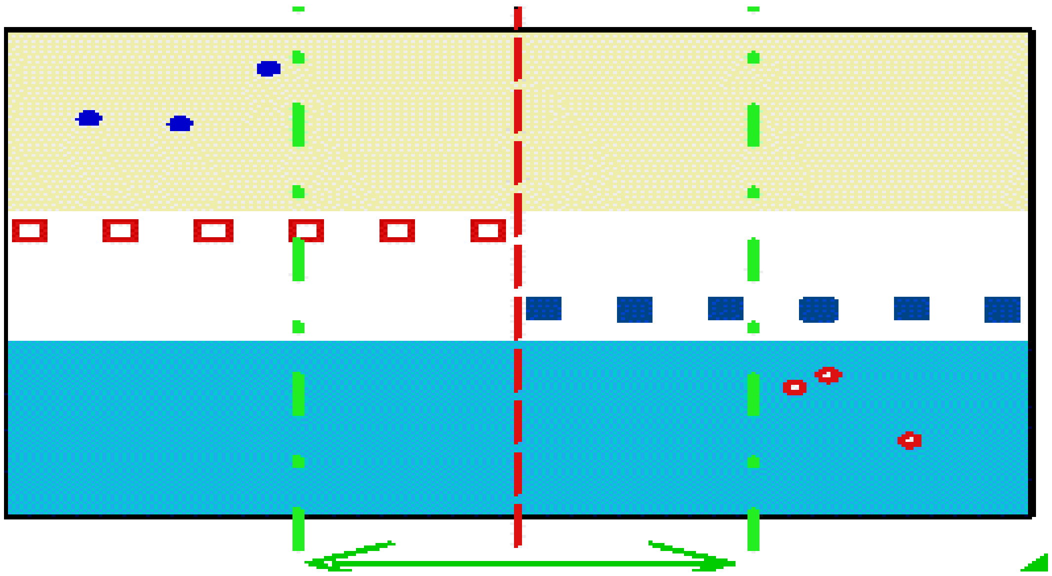
P-N Junction Diode

- Free electrons on the n-side and free holes on the p-side can initially wander across the junction. When a free electron meets a free hole it can 'drop into it'. So far as charge movements are concerned this means the hole and electron cancel each other and vanish.



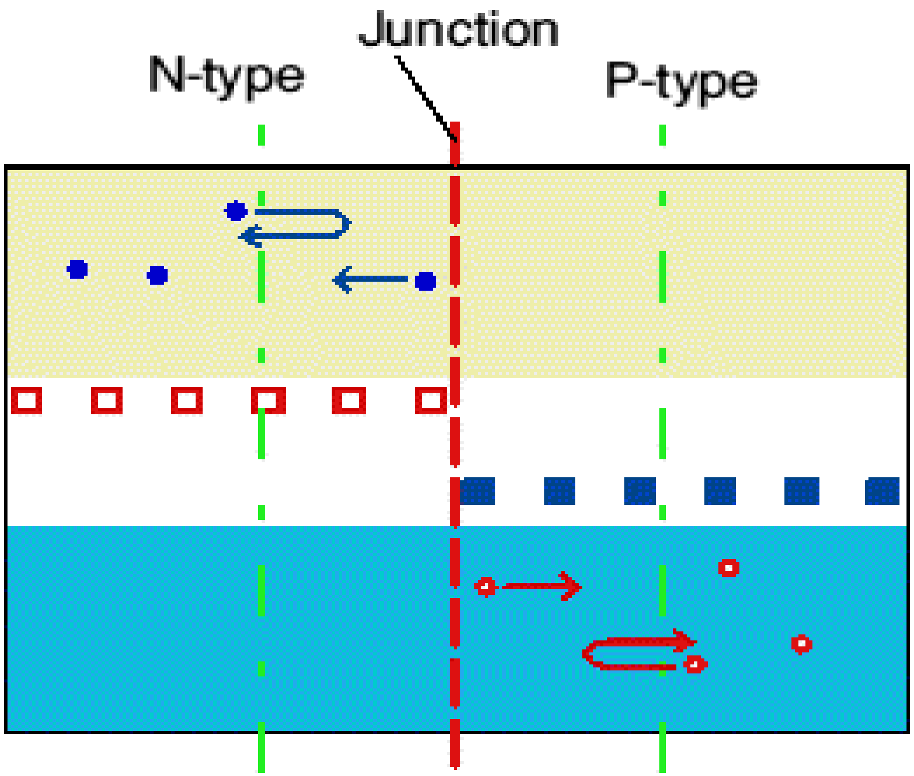
P-N Junction Diode

- As a result, the free electrons near the junction tend to eat each other, producing a region depleted of any moving charges. This creates what is called the depletion zone.

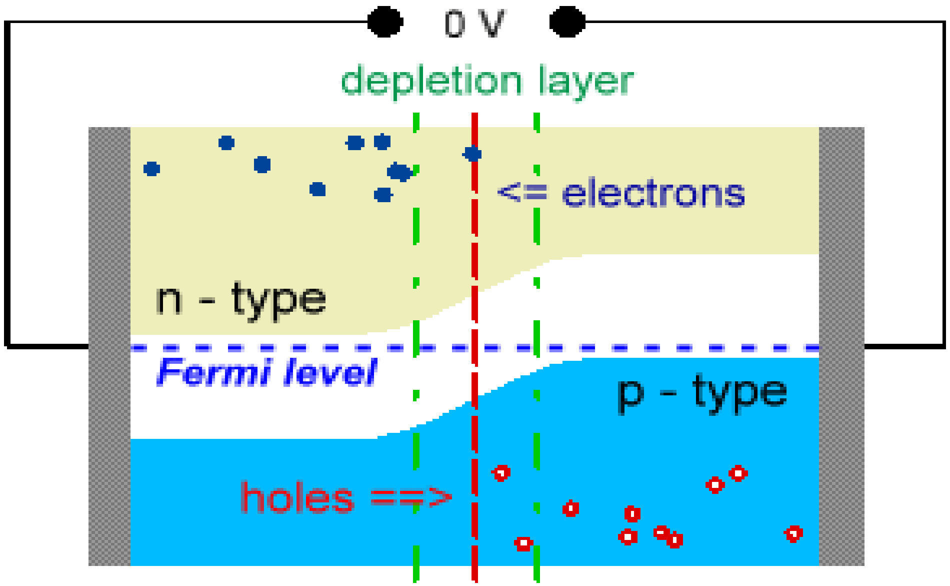


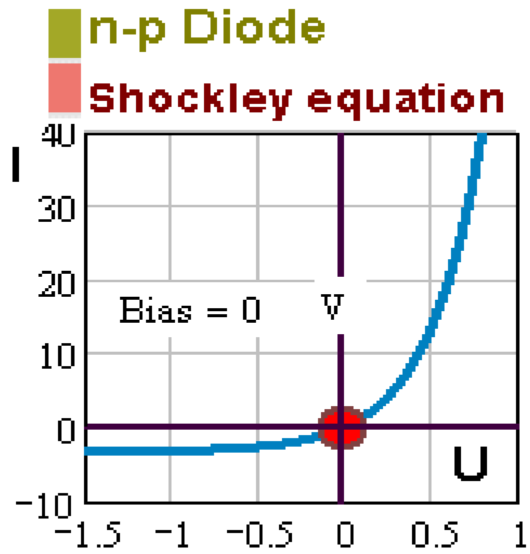
P-N Junction Diode

- Now, any free charge which wanders into the depletion zone finds itself in a region with no other free charges. Locally it sees a lot of positive charges (the donor atoms) on the n-type side and a lot of negative charges (the acceptor atoms) on the p-type side. These exert a force on the free charge, driving it back to its 'own side' of the junction away from the depletion zone.
  A free charge now requires some extra energy to overcome the forces from the donor/acceptor atoms to be able to cross the zone. The junction therefore acts like a barrier, blocking any charge flow (current) across the barrier.



We create a p-n junction by joining together two pieces of semiconductor, one doped n-type, the other p-type. This causes a *depletion zone* to form around the junction between the two materials. This zone controls the behavior of the diode.





When we apply a potential difference between the two wires in one direction we tend to pull the free electrons and holes away from the junction. This makes it even harder for them to cross the depletion zone.

When we apply the voltage the other way around we push electrons and holes towards the junction, helping to give them extra energy and giving them a chance to cross the junction.

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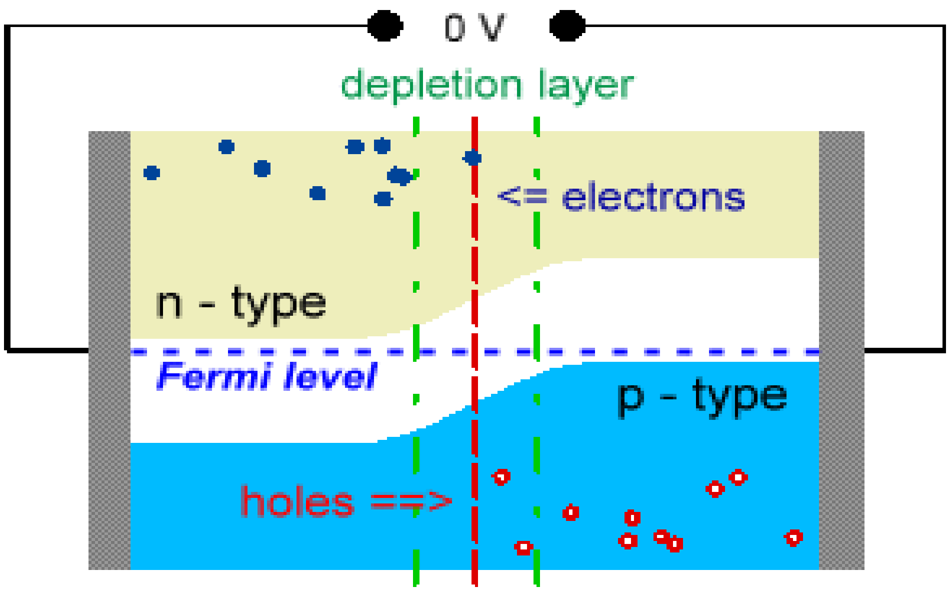

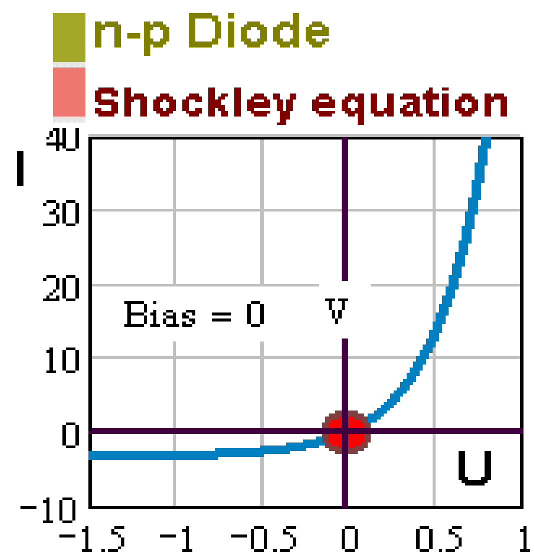

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summary

- Therefore, when a p-n junction is reverse biased, there will be no current flow because of majority carriers but a very small amount of current because of minority carriers crossing the junction.

  However, at normal operating temperatures, this small current may be neglected.

- In summary, the most important point to remember about the p-n junction diode is its ability to offer very little resistance to current flow in the forward-bias direction but maximum resistance to current flow when reverse biased.

LECTURE NO. – 5

BIASING

- "forward biased": p-side more positive than n-side;
- "reverse biased": n-side more positive than p-side;

Forward biased diode

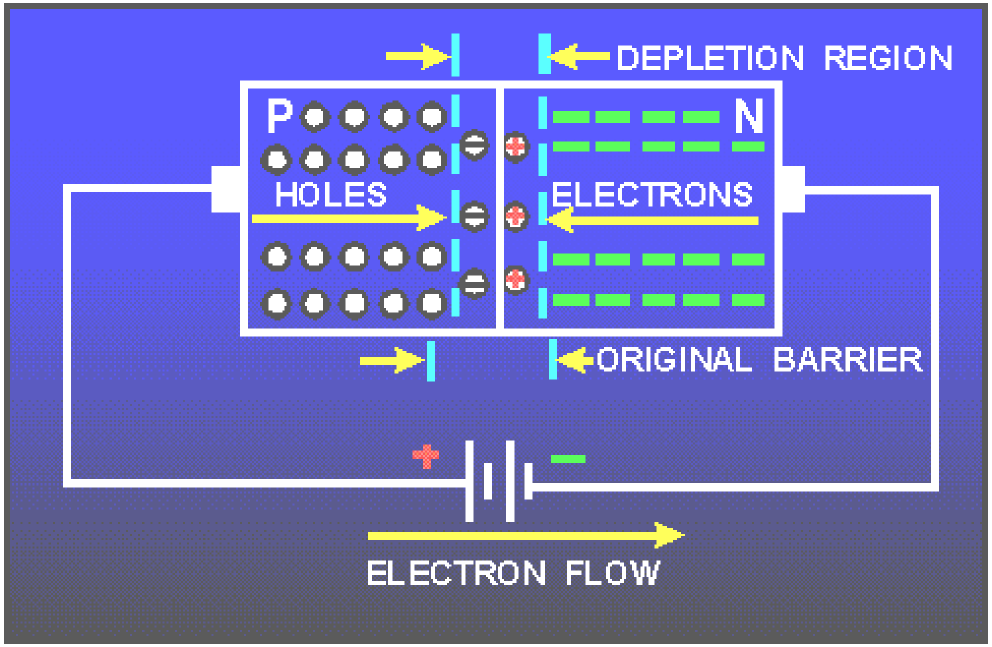
Diode = “biased p-n junction”, i.e. p-n junction with voltage applied across it

The direction of the electric field is from p-side towards n-side

< p-type charge carriers (positive holes) in p-side are pushed towards and across the p-n boundary,

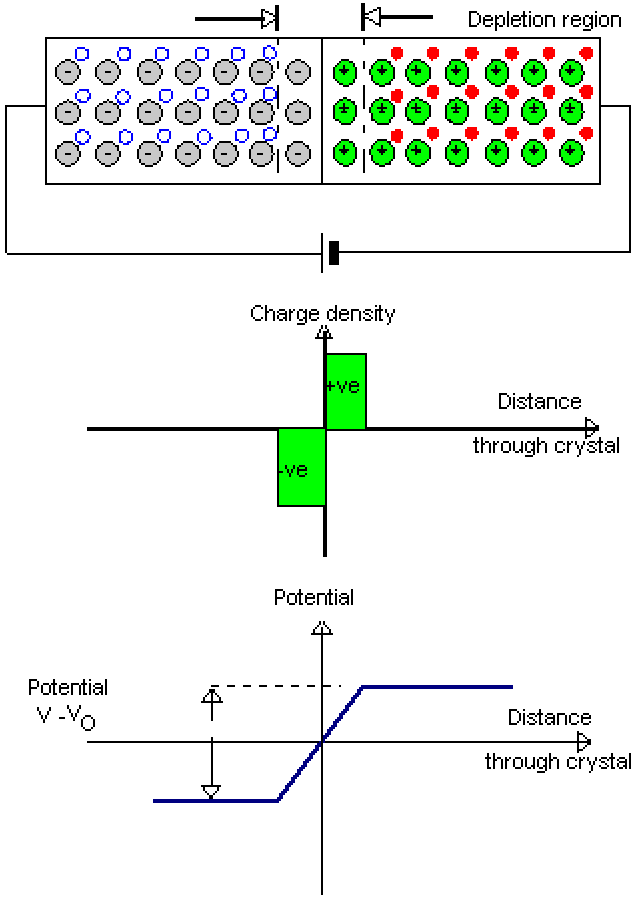
< n-type carriers (negative electrons) in n-side are pushed towards and across n-p boundary

⇒ current flows across p-n boundary



Forward biased pn-junction

- Depletion region and potential barrier reduced



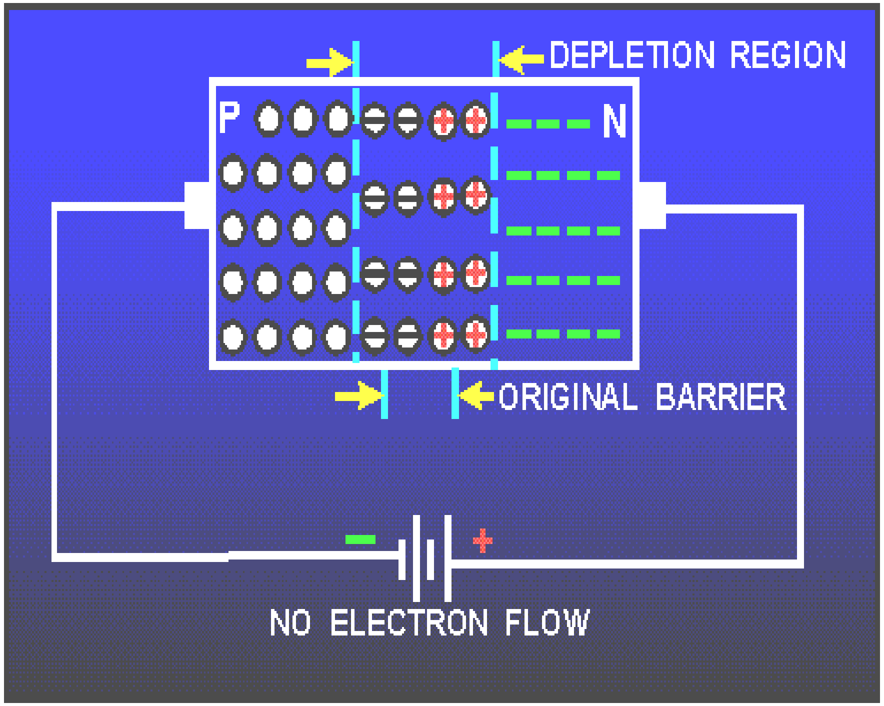
Reverse biased diode

Applied voltage makes n-side more positive than p-side

$\Rightarrow$ electric field direction is from n-side towards p-side

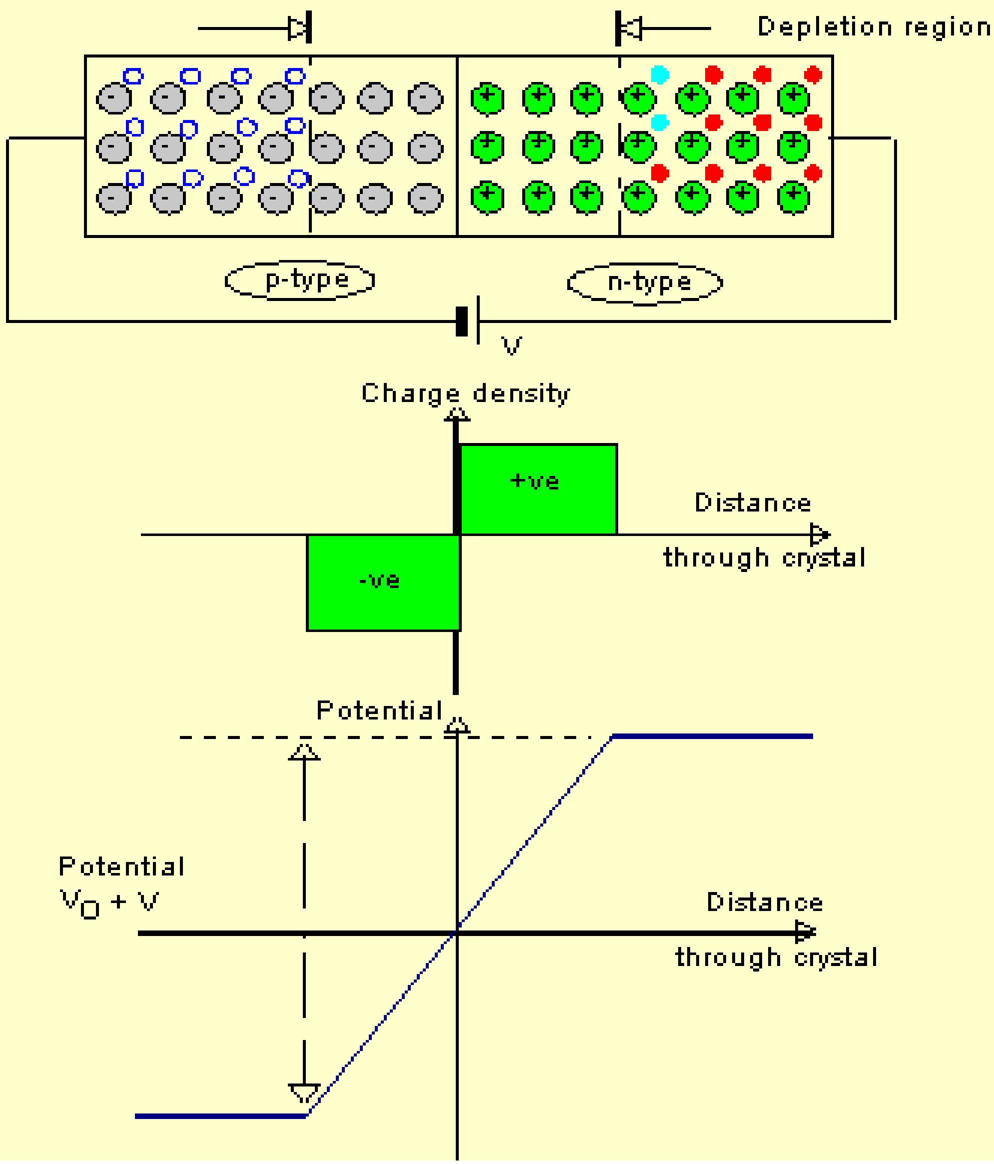
$\Rightarrow$ pushes charge carriers away from the p-n boundary

$\Rightarrow$ depletion region widens, and no current flows



Diode only conducts when positive voltage applied to p-side and negative voltage to n-side.
Diodes used in "rectifiers", to convert ac voltage to dc

- Depletion region becomes wider, barrier potential higher



LECTURE NO. – 6

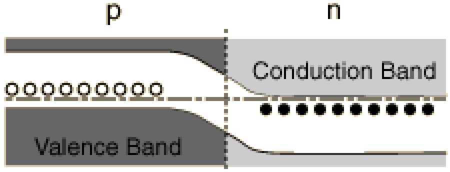
Rules for band diagrams

- • Valence states are filled with electrons, conduction bands
- are partially or completely empty.
- • Outer electrons from donor or acceptor dopants usually
- exist in isolated states within the bandgap (near the
- conduction or valence bands, respectively).
- • Electrons fall down in energy, holes ‘fall’ up.
- ***• For joined materials, the Fermi level is always flat.***
- *• For joined materials, the band edges shift and/or bend any*
- *way that is necessary to accommodate a flat Fermi level.*
- • Applied biases shift the Fermi level, *and* the conduction
- and valence bands, on the side with the bias.
- ***• A positive applied bias moves the bands down where it***
- ***is applied; a negative bias moves them up****.*
- *• Again, band bending occurs near the interfaces to*
- *accommodate applied biases.*

Energy Band Diagram

Equilibrium
– Electrons 'roll' downhill, so they are mostly stuck in the n side.
– Holes 'roll' uphill, so they are mostly stuck in the p side.

p-n junction



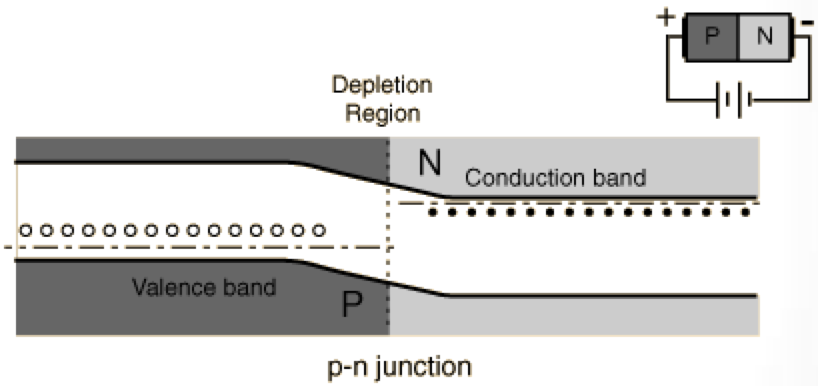
Energy bands at equilibrium

equilibrium

Energy Band Diagram

Voltage applied:
– Electrons always drawn towards positive terminal (holes to neg).
– BUT, they can't get there if there's a big barrier in the way.
– A positive bias moves the bands down where it is applied.
– A negative bias moves them up.

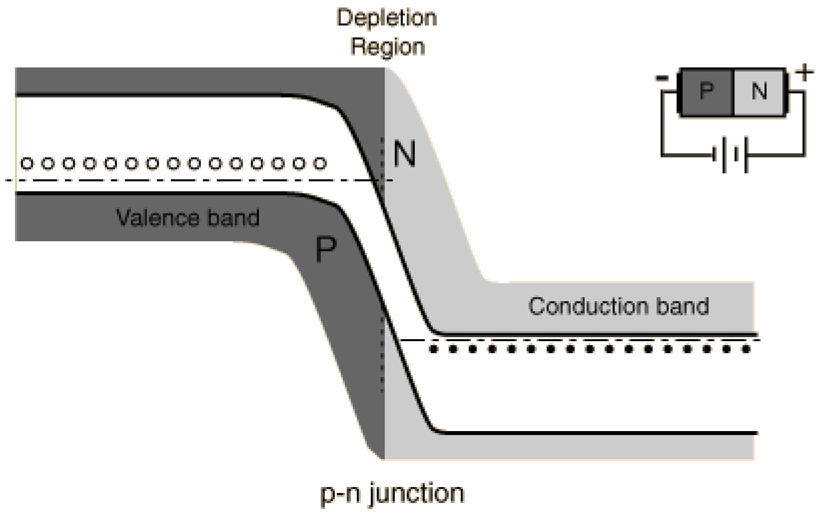
• pn: Forward Bias (+V to p side)
– Barrier gets smaller, so some electrons and holes can carry current.



forward

Energy Band Diagram

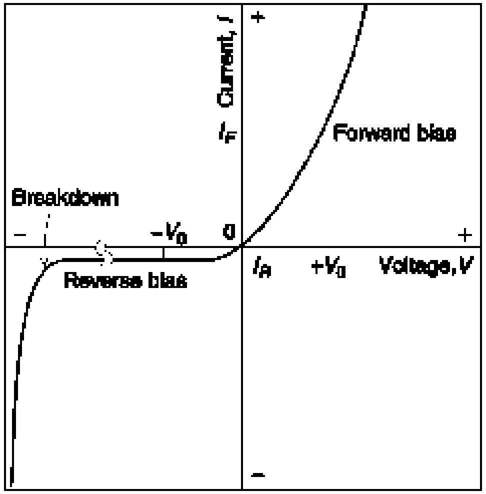
- pn: Reverse Bias (+V to n)
- Barrier is huge, so no electrons jump the barrier.



reverse

V-I Characteristics of Diodes

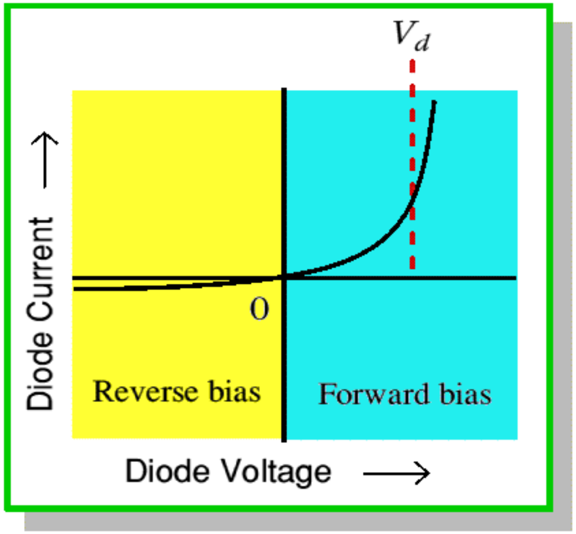
Starts conducting at 0.6V for silicon diode and 0.2V for germanium in forward bias. Voltage above this large current flows and exponential in nature. Current is due to majority carrier.



Very small current, constant (saturation) and almost negligible in reverse bias. Current is due to minority carrier. Breakdown at large potential difference and voltage is constant

LECTURE NO. – 7

V-I characteristics of P-N diode



Observation :-

* Cut-in voltage for Si & Ge diodes are 0.6 and 0.2v respectevely.

* Breakdown voltage of silicon diode is higher that that of the Ge diode. So SI. Diodes can withstand to a higher reverse voltage.

* The reverse saturation current Io for a Ge diode is few µA at room tempreture.

Effect of Temperature on the V-I Characteristics

- Reduction in the cut-in voltage takes place with increase in temperature.
- The breakdown voltage increases with increase in temperature.
- Reverse saturation current increases with increase in temperature.

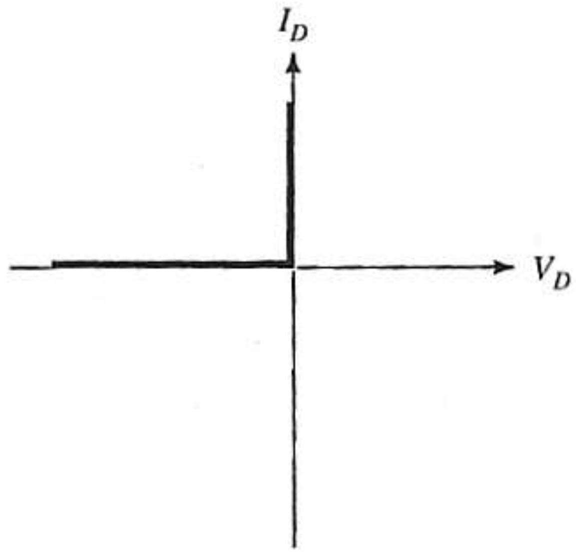
- For even rather small *forward bias* voltages the exponential is very large because the thermal voltage is very small, so the subtracted ‘1’ in the diode equation is negligible and the forward diode current is often approximated as

$$I = I_S e^{V_D/(nV_T)}$$

What is an ideal diode?

- An ideal diode is a perfect conductor with zero voltage drop in the forward bias direction…
- …and a perfect insulator in the reverse bias direction.

I-V characteristics of Ideal diode



- **Ideal diode in series with voltage source**

  Now let us consider the case when we add a voltage source in series with the diode in the form shown below:

LECTURE NO. - 8

Capacitance

- The charge in the diode carrying current I_Q is known to be

$$Q = I_Q \tau_F + Q_J$$

- where τ_F is the forward transit time of charge carriers:[2] The first term in the charge is the charge in transit across the diode when the current I_Q flows. The second term is the charge stored in the junction itself when it is viewed as a simple capacitor; that is, as a pair of electrodes with opposite charges on them. It is the charge stored on the diode by virtue of simply having a voltage across it, regardless of any current it conducts.
- In a similar fashion as before, the diode capacitance is the change in diode charge with diode voltage:

Diffusion Capacitance

$$C_D = \frac{dQ}{dV_Q} = \frac{dI_Q}{dV_Q}\tau_F + \frac{dQ_J}{dV_Q} \approx \frac{I_Q}{V_T}\tau_F + C_J$$

where

$$C_J = \frac{dQ_J}{dV_Q}$$

is the junction capacitance and the first term is called the diffusion capacitance, because it is related to the current diffusing through the junction.

- **Diffusion capacitance** is the capacitance due to transport of charge carriers between two terminals of a device, for example, the diffusion of carriers from anode to cathode in forward bias mode of a diode or from emitter to base (forward biased junction in active region) for a transistor.

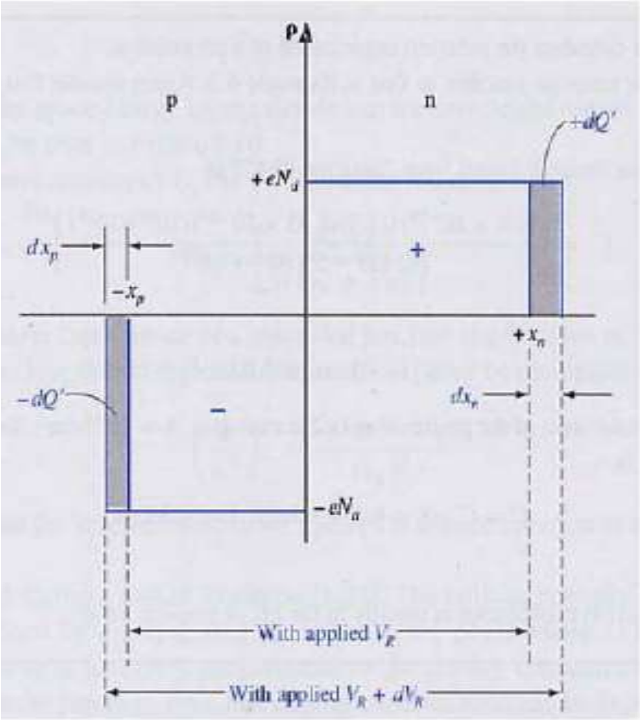
  In a semiconductor device with a current flowing through it at a particular moment there is necessarily some charge in the process of transit through the device. If the applied voltage changes to a different value and the current changes to a different value, a different amount of charge will be in transit in the new circumstances.

- The change in the amount of transiting charge divided by the change in the voltage causing it is the diffusion capacitance.
- The adjective "diffusion" is used because the original use of this term was for junction diodes, where the charge transport was via the diffusion mechanism. See Fick's law.

- the amount of charge in transit through the device at this particular moment, denoted *Q*, is given by
- $Q = I(V)\tau F$.
- Consequently, the corresponding diffusion apacitance:*Cdiff*.is

$$C_{diff} = \frac{dQ}{dV} = \frac{dI(V)}{dV}\tau_F$$

Depletion Capacitance



D.A. Neaman, *Semiconductor Physics & Devices*, 2[nd] Ed., Irwin

Per unit area

$$C_j = \frac{dQ}{dV} = \frac{qN_D dx_n}{dV} = \frac{qN_A dx_p}{dV} = qN_D \frac{dx_n}{dV}$$

$$x_n = \left[\frac{2\varepsilon_s (V_{bi} - V)}{q} \left(\frac{N_A}{N_D} \right) \left(\frac{1}{N_A + N_D} \right) \right]^{1/2}$$

$$C_j = \left[\frac{q\varepsilon_s N_A N_D}{2(V_{bi} - V)(N_A + N_D)} \right]^{1/2} = \frac{\varepsilon_s}{W}$$

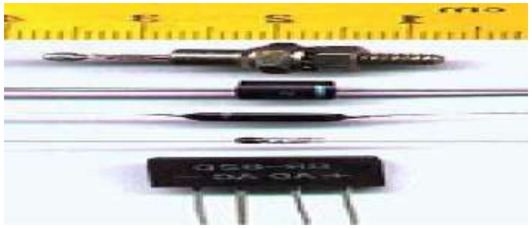
Similar to a parallel-plate capacitor

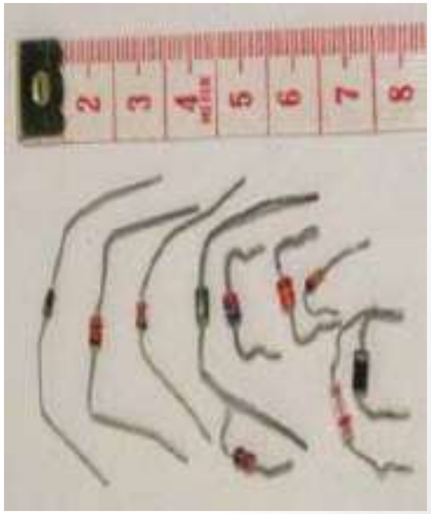
Reverse bias $V = -V_R$

$$C_j = \left[\frac{q\varepsilon_s N_A N_D}{2(V_{bi} + V_R)(N_A + N_D)} \right]^{1/2}$$

PN-junction diodes: Applications

- Diode applications:
  - Rectifiers
  - Switching diodes
  - Zener diodes
  - Varactor diodes
- Photodiodes
  - pn junction photodiodes
  - p-i-n and avalanche photodiodes
- Solar Cells
- Light Emitting Diodes
- Lasers





PN-junction diodes: Applications

- **Solid state lighting, photovoltaic,**
- **photo detection, radio demodulation**
- **over-voltage protection, Logic gates**
- **temperature measurement, etc.**

CONCEPT TEST

Atomic Physics

- How many electrons can be in the ground state of an atom?
  - Answer: 2 (s level)

- ...in the first excited state?
  - Answer: 8 (s and p levels)

- …in the second excited state?
  - Answer: 8 (s and p levels)

- In undoped semiconductors at warmer temperatures

A) The valence band is empty and the conduction band is full

- B) The conduction band is empty and the valence band is full
- C) The valence band is full and the conduction band is has some electrons
- D) None of these is a semiconductor
- E) All of these will be semiconductors

- In conductors

A) The valence band is empty and the conduction band is full

B) The conduction band is empty and the valence band is full

C) The valence band is full and the conduction band is partly full (perhaps 50%)

D) None of these is a conductor

E) All of these will be conductors

- In insulators

A)The valence band is empty and the conduction band is full

B) The conduction band is empty and the valence band is full

C) Either A or B will be an insulator

D) Neither A nor B will be an insulator

E) Need more information

- How many electrons are needed to fill the outermost energy level of Silicon?
  - Answer: 4
  - 2-D representation of Silicon Crystal

- How many valence electrons does Phosphorus ($_{15}P$) and Aluminum ($_{13}Al$) have?
  - Answers: 5 and 3

- When Si is doped with P to make n-Si

  A) The material has a net negative charge and conducts

- B) The material has a net positive charge and conducts
- C) The material has no net charge but conducts because there are electrons from P in the conduction band
- D) The material has no net charge but conducts because there are “holes” P in the valence band
- E) The material is an insulator

- Undoped semiconductors: As temperature is decreased
  A) The resistance of metals and semiconductors decreases
- B) The resistance of semiconductors decreases while the resistances of metals increases
- C) The resistance of metals and semiconductors increases
- D) The resistance of semiconductors increases while the resistances of metals decreases
- E) All of these will be semiconductors

Rectification

LECTURE NO. - 12

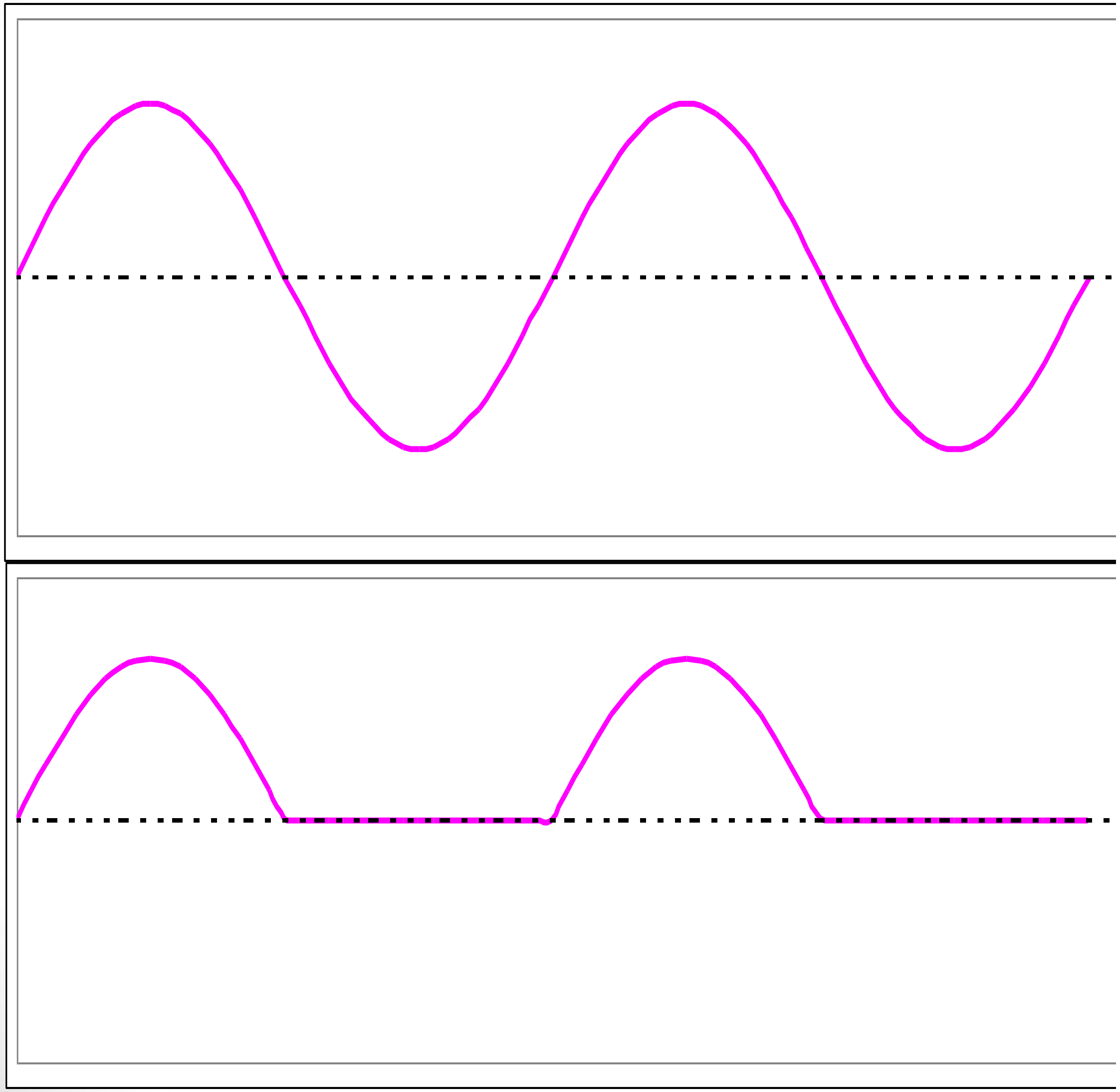
AC to DC

- Electricity distribution
  - Power stations
  - Transformers
  - Transmission lines
- AC
- Electronics
- DC
  - Smooth
  - Stable

Process of rectification

- Conversion of AC to DC
- Half-wave
- Full-wave
  - _ FWR With Centre taped transformer
  - _ FW Bridge Rectifier

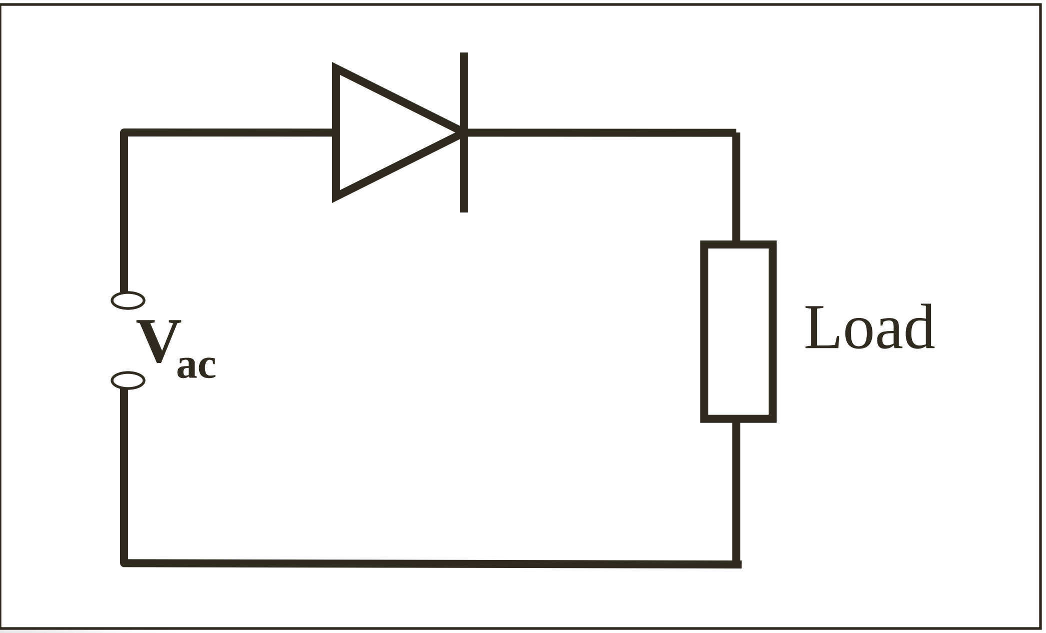
Half-wave rectification



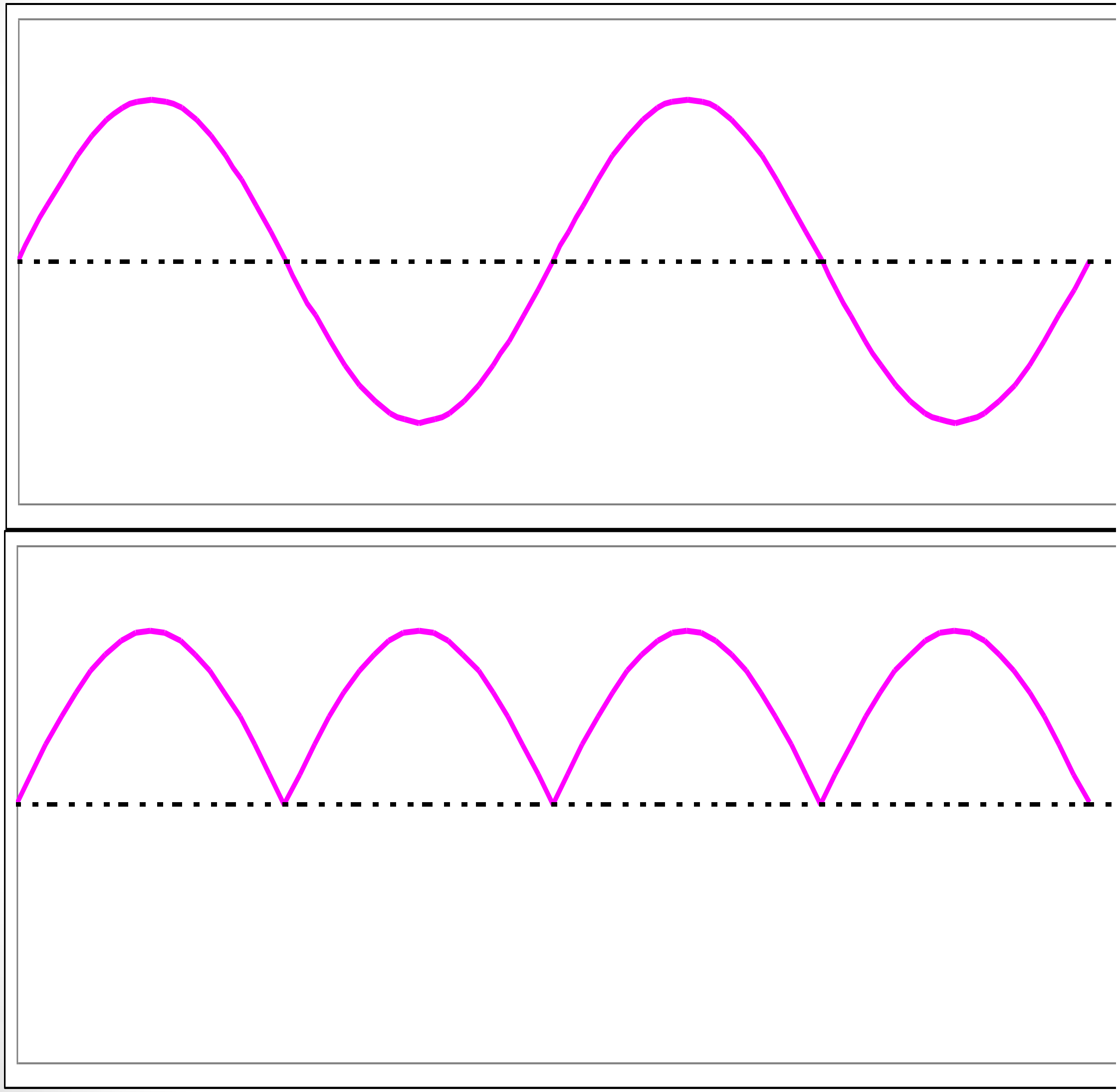
- Only the positive half-cycle of the AC supply is allowed to pass

Half-wave rectifier circuit

- Simple!
- Single diode
- ‘Load’
  - DC circuit…not really getting DC!



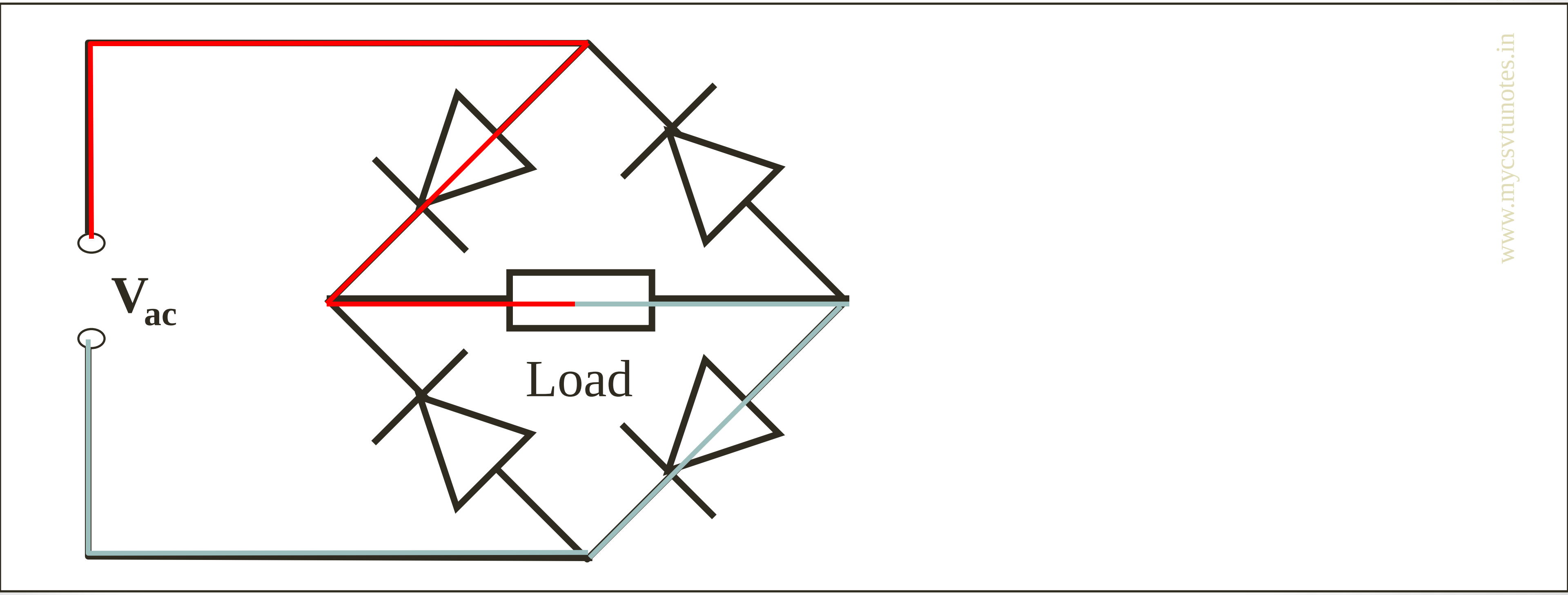
Full-wave rectification



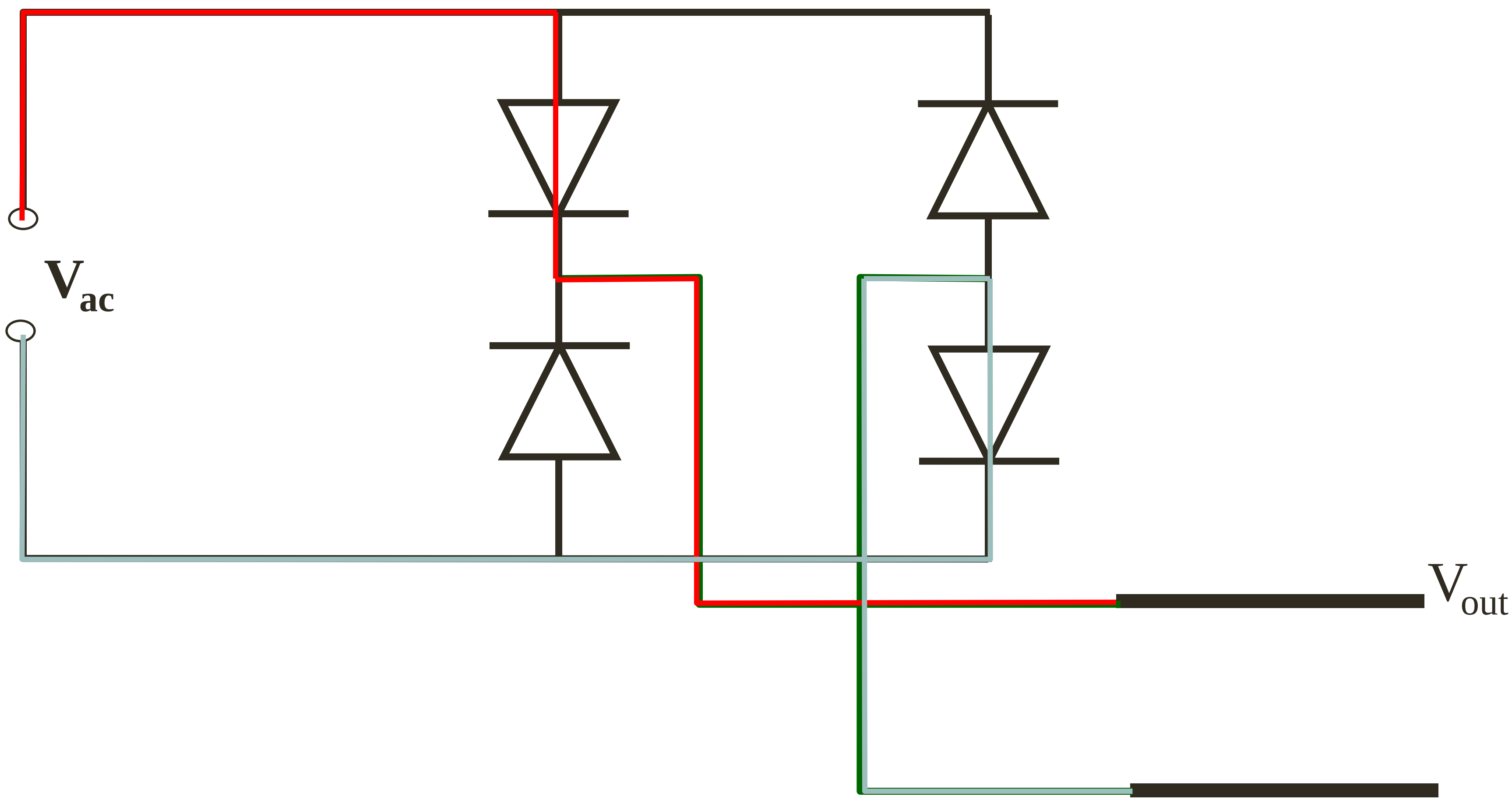
Positive AND negative half-cycles converted to ALL positive

Full-wave rectifier circuit

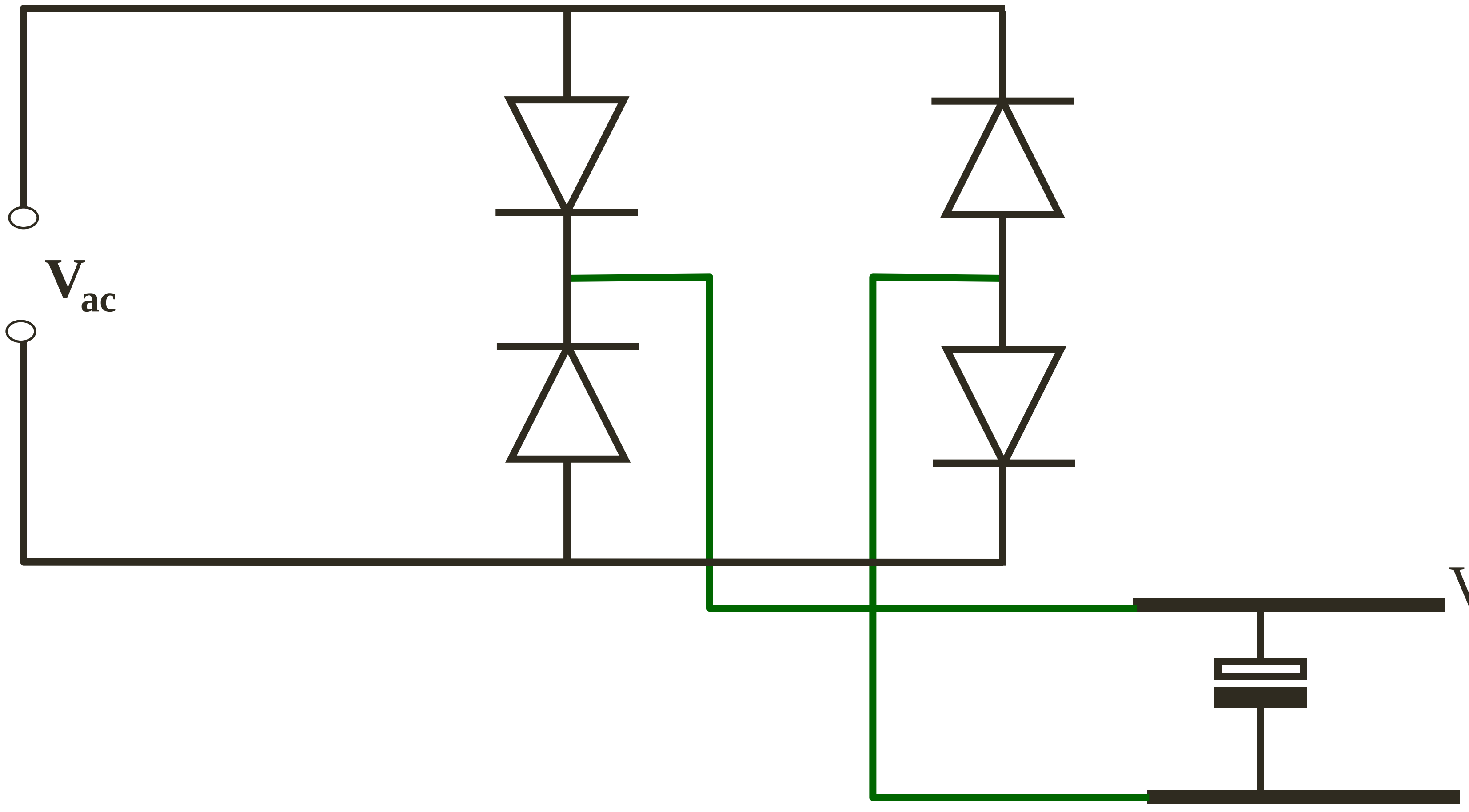
- *Bridge* circuit
- Load
  - Circuit requiring DC



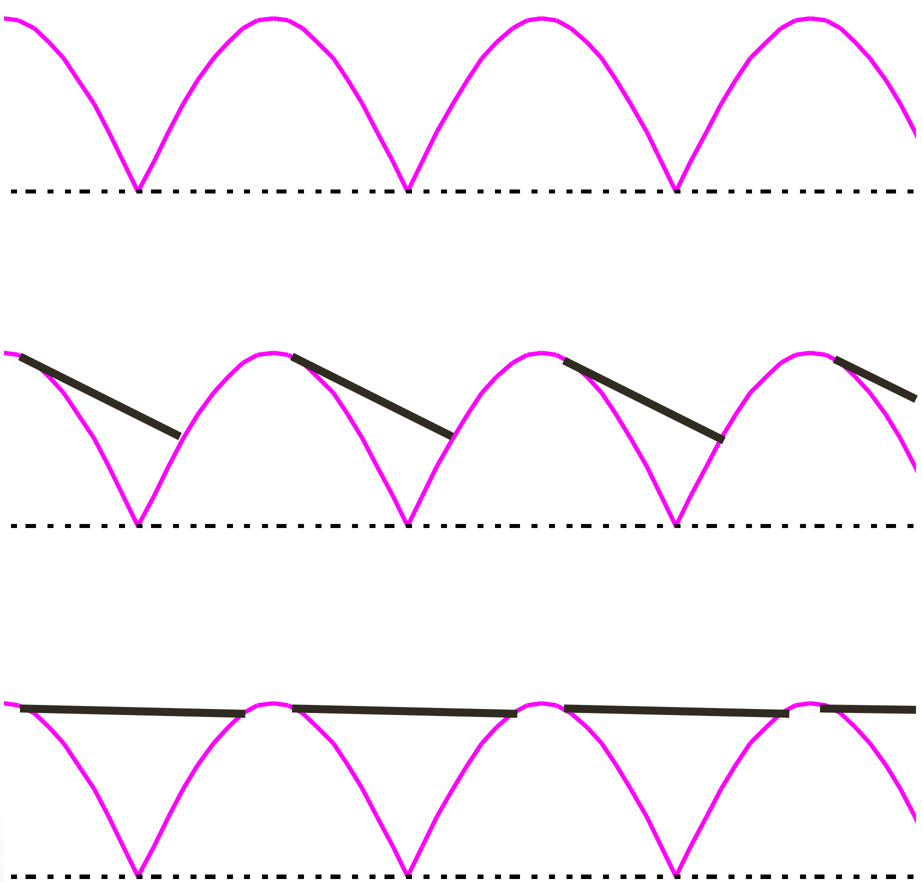
Bridge as two potential dividers



Capacitative smoothing



Smoothed output



- Un-smoothed
  - Large ripple voltage
  - Not true DC
- Low-value smoothing capacitor
  - $R_{load}C$ small
- High-value smoothing capacitor
  - $R_{load}C$ big