Semiconductors, Diodes, Shockley's Equation

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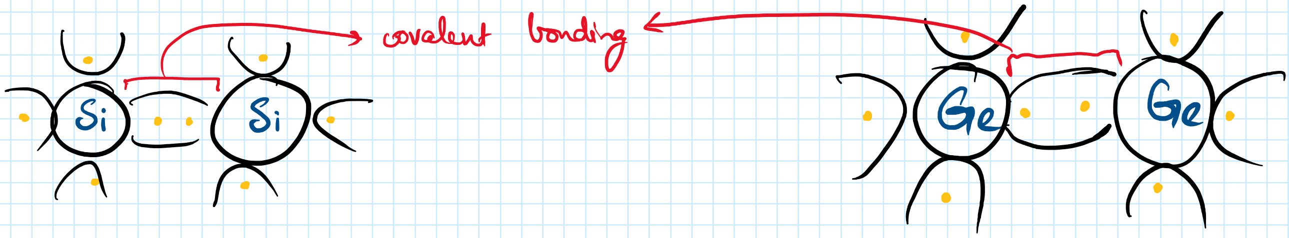
SEMICONDUCTORS

- Neither fully a conductor nor an insulator

Looking at two examples,

Si
- 4 valence electrons

Ge
- 4 valence electrons



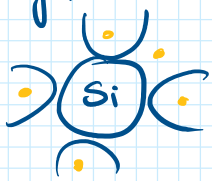
TYPES OF SEMICONDUCTORS

Intrinsic : Pure semiconductor, no impurities

Extrinsic : External impurities are added

n-type

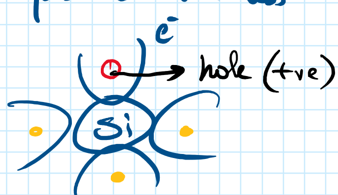
- pentavalent impurity added { antimony, arsenic, phosphorous
- n → negative → one extra e^-



- majority charge carriers: electrons

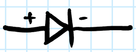
p-type

- trivalent impurity added { Boron, gallium, indium
- p → positive → one less e^-

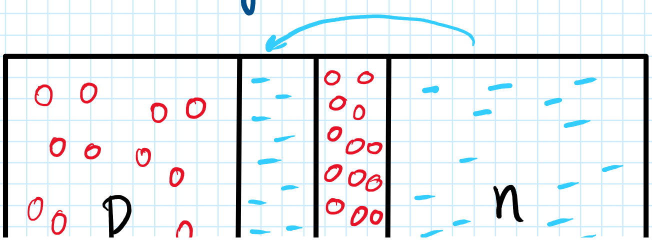


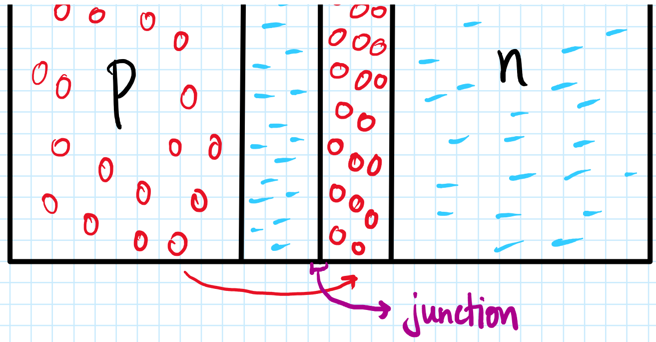
- majority charge carriers: holes/voids

DIODES



- has anode, cathode] → 2 electrodes
- combination of p-type, n-type; forms a depletion region at their junction
- allows current flow in one direction only (forward bias)
- acts as a one-way switch due to above





P-N JUNCTION DIODE

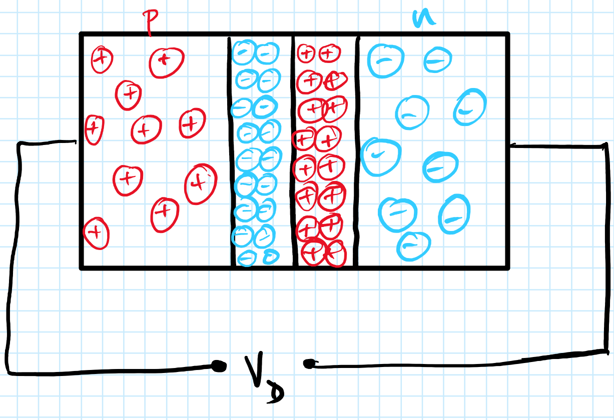
- After joining p-type, n-type, electrons from n-type near junction diffuse into p-region.
- IIIly, holes from p move into n region.
- This forms the depletion region.

→ creates a potential barrier, which has to be overcome by an external voltage source for flow of charges

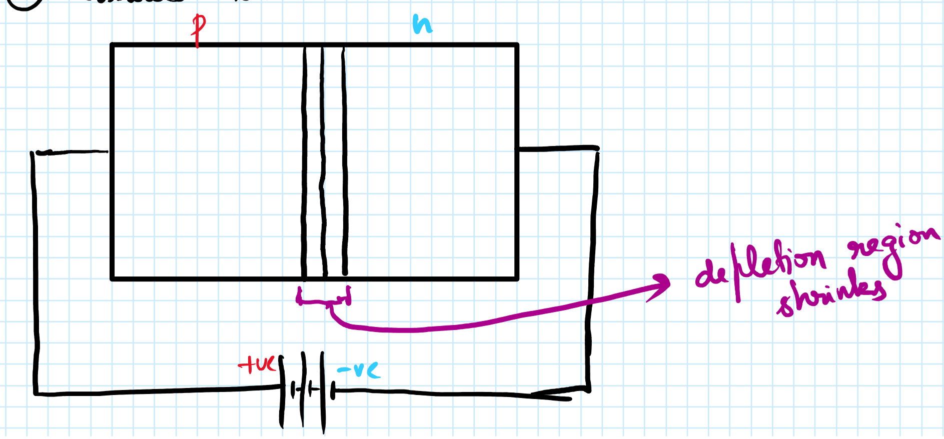
DIODE BIASING

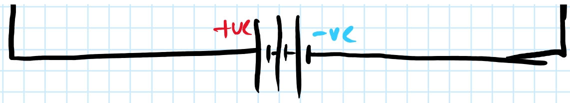
→ process of applying external voltage

① No bias

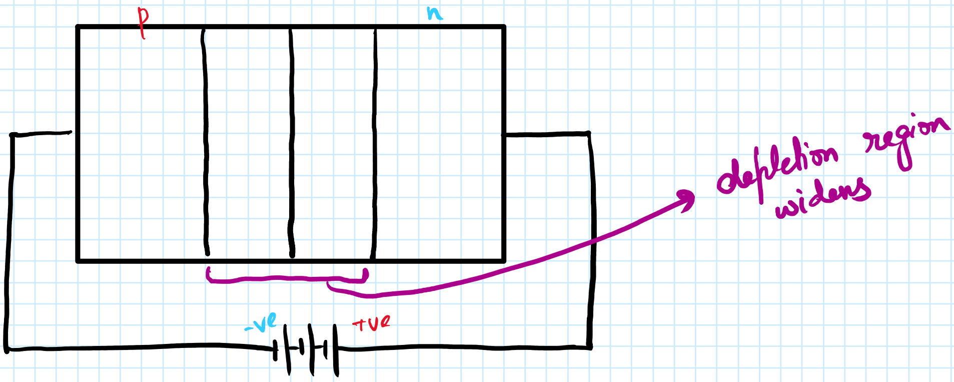


② Forward bias

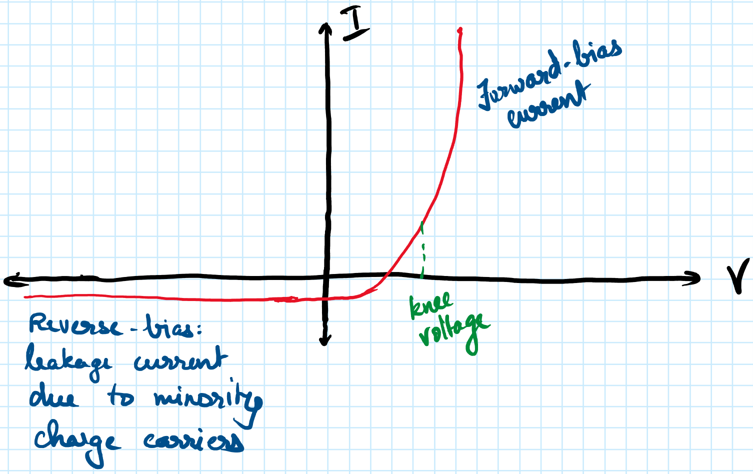




③ Reverse bias



FORWARD & REVERSE CHARACTERISTICS



Forward characteristics

- Knee voltage / cut in voltage: Forward voltage at which conduction happens and current starts rising rapidly
- Conduction does not occur on a significant scale until knee voltage is reached.
- Knee voltage / forward voltage drop for:
  Si → 0.7V   GaAs → 1.2V
  Ge → 0.3V
- Forward current rating: Current that flows in forward direction when diode is in forward bias
- Max. power dissipation: Max. power a diode can dissipate without damaging the device itself

Reverse characteristics

- Reverse saturation current: Reverse current caused by diffusion of minority charge carriers.
  Also called leakage current.

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- Reverse breakdown voltage: If large enough negative potential is applied, it will allow current flow in the reverse direction.

- Peak inverse voltage rating: Maximum voltage a diode can withstand in reverse bias condition before break down.

SHOCKLEY'S CURRENT EQUATION / DIODE EQUATION

to find current through diode at a certain temperature

- When V_D is negative

$$\boxed{I_D \sim I_S}$$

- When V_D is positive

$$\boxed{I_D \sim I_S\, e^{\frac{qV_D}{nkT}}}$$

In general,

$$\boxed{I_D = I_S\left[e^{\frac{qV_D}{nkT}} - 1\right]}$$

q: charge on electron $= 1.6 \times 10^{-19}$ C

V_D: diode voltage

I_D: diode current

I_S: saturation current

T: Temperature in Kelvin

k: Boltzmann's constant
$k = 1.380 \times 10^{-23}$ J/K

n: ideality factor
$n = 1$ → indirect semiconductors → Si, Ge
$n = 2$ → direct " → GaAs, InP

> **NOTE: Direct and indirect band gap semiconductors**
>
> CBM → conduction band minimum → min. energy e^- in conduction band can have
>
> VBM → valence band maximum → max. energy e^- in valence band can have
>
> k → momentum of e^- in crystal lattice
>
> Direct: CBM and VBM both occur at same k. Eg: LEDs, lasers
>
> Indirect: CBM and VBM occur at different k. Eg: Transistors

Here we have

Thermal voltage $= V_{th} = \dfrac{kT}{q}$

> **NOTE: What is thermal voltage?**
> Voltage produced within the p-n junction diode due to the action of temperature.

Substituting this in our equation, we get

$$\boxed{I_D = I_S\left[e^{\frac{V_d}{nV_{th}}} - 1\right]}$$

At $T = 300$ K,

$$V_{th} = \frac{kT}{q} = \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}}$$

$$V_{th} = \frac{KT}{q} = \frac{1.38\times 10 \quad \times 300}{1.6\times 10^{-19}}$$

$$\boxed{[V_{th}]_{300K} = 0.0258\ V = 25.8\ mV \approx 26\ mV}$$ } V_{th} at room temperature

NUMERICALS

① Calculate forward bias current of Si diode when forward bias voltage of 0.4 V is applied, the reverse saturation current is 1.17×10^{-9} A and thermal voltage is 25.2 mV.

Soln.

$$I_S = I_D\left[e^{\frac{V_d}{nV_{th}}} - 1\right]$$

Substituting,

$$I_s = 1.17\times10^{-9}\left[e^{\frac{0.4}{(1)(0.0252)}} - 1\right]$$

$$I_s = 9.15\times10^{-3}\ A$$

② Given a diode current of 8 mA and n=1, find the reverse saturation current (I_s) if the applied voltage is 0.5 V and the temperature is 25°C.

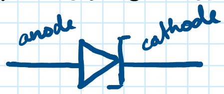
Soln

$$I_D = I_s\left[e^{\frac{qV_d}{nKT}} - 1\right]$$

$$\Rightarrow I_s = \frac{I_D}{\left[e^{\frac{qV_d}{nKT}} - 1\right]} = \frac{0.008}{e^{\frac{q(0.5)}{(1)(k)(298)}} - 1} = 2.848\times10^{-11}\ A$$

TYPES OF DIODES

① Zener diode



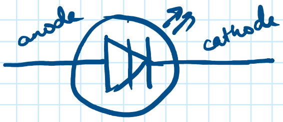
- heavily doped semiconductor
- designed to work in reverse bias

② Light Emitting Diode (LED)

- recombination of electrons and holes release light in the form of photons
- emitted light colour depends on energy gap of semiconductor used.

③ Laser Diode

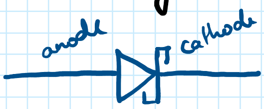
④ Varactor Diode



- Light Amplification by Simulated Emission of Radiation → LASER
- high powered light through glass lens

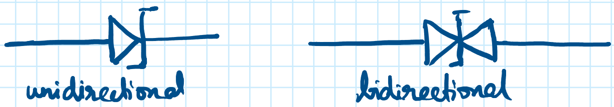
- Reverse biased p-n junction that can change its capacitance electrically
- Used for storing charge, not for flow of charge

⑤ Schottky Diode



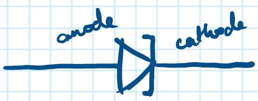
- very low forward voltage drop (knee voltage)
- p-type semiconductor is replaced by a metal like aluminium

⑥ TVS Diode
(transient - voltage - suppression)



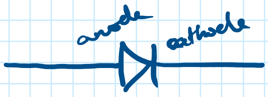
- protects electric components from sudden voltage spikes on connected wires

⑦ Tunnel Diode



- negative resistance, very high conductivity due to tunneling effect
- tunneling → electrons go straight through the depletion barrier

⑧ Rectifier Diode



- p-n junction diode
- Used to change AC to DC

NUMERICALS (cont.)

③ Calculate V_D if diode current is 6 mA, thermal voltage is 26 mV, ideality factor is 1, reverse saturation current is 1 nA.

$$I_D = I_s\left[e^{\frac{qV_D}{nkT}} - 1\right]$$

$$\frac{I_D}{I_s} + 1 = e^{\frac{qV_D}{nkT}}$$

$$\frac{6\times10^{-3}}{1\times10^{-9}} + 1 = e^{\frac{V_d}{V_{th}}}$$

$$\log(600001) = \frac{V_d}{26\times10^{-3}}$$

$$\Rightarrow V_d = 0.405 \text{ V}$$

$\Rightarrow V_d = 0.405\ V$

(4) Consider a Si diode with $\eta = 1.2$. Find change in voltage if current changes from 0.1 mA to 10 mA.

Soln. Say Si diode is at room temp. $\Rightarrow V_{th} = 0.026\ V$

$$\boxed{\text{Change in voltage } \Delta V = \eta V_{th} \ln\left(\frac{I_2}{I_1}\right)}$$

$$\Delta V = (1.2)(0.026) \ln\left(\frac{10 \times \cancel{10^{-3}}}{0.1 \times \cancel{10^{-3}}}\right)$$

$$= (1.2)(0.026) \ln(100)$$

$$= \underline{\underline{0.143\ V}}$$