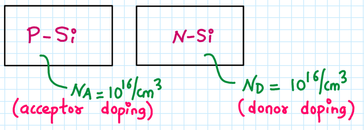
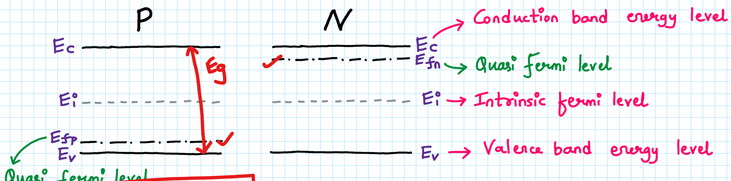
28 May 2021 20:47

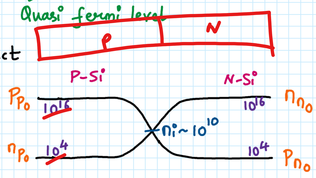
Todays topic:
PN junction under Zero bias

* PN Junction under zero bias :





① P and N type Si are brought in contact



② Diffusion of carriers takes place (ie holes diffuse from p to n-side and electrons diffuse from n to p-side)

$$n_{p_0} = \frac{n_i^2}{p_{p_0}} = \frac{(10^{10})^2}{10^{16}} \approx 10^4/cm^3$$

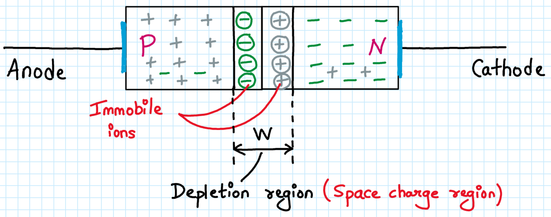
$$p_{n_0} = \frac{n_i^2}{n_{n_0}} = \frac{(10^{10})^2}{10^{16}} \approx 10^4/cm^3$$

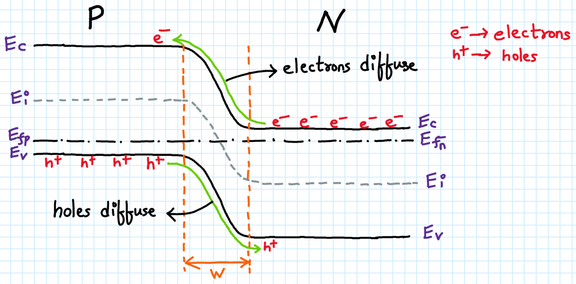
Real concentrations

Minority carriers

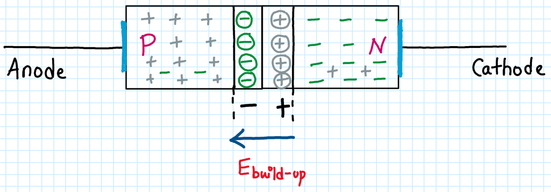
(Hypothetical number's)

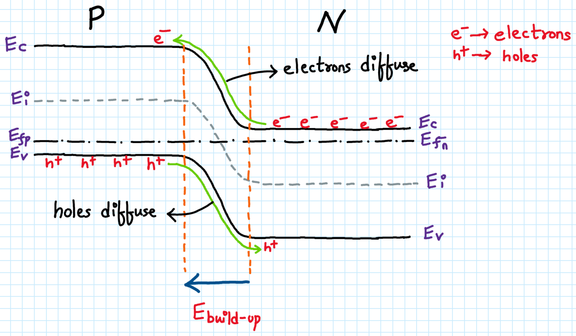
③ As electrons and holes leave from n-side and p-side they leave behind ionized immobile ions (which makes up the space-charge or depletion region)



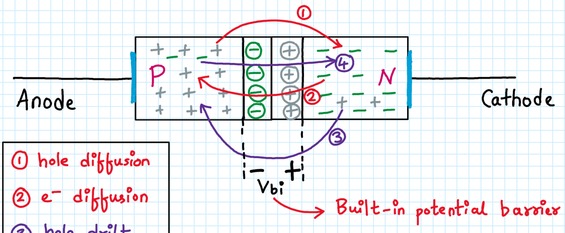


④ Due to separation of +ve & -ve immobile charges within the depletion region, an electric field is set-up ($E_{build-up}$)

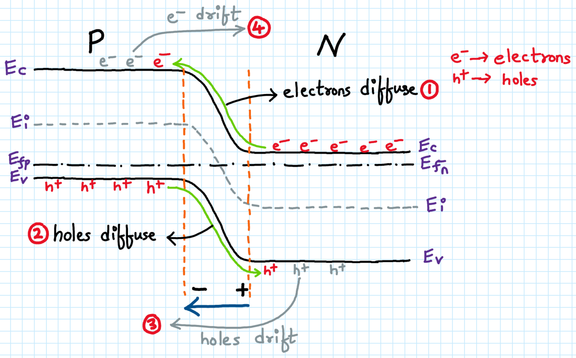




⑤ This internal electric field will drive the carriers back the other way providing opposition to diffusion
ie e⁻s drift from p to n side & holes drift from n to to p side under the influence of electric field



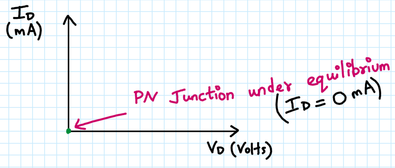
① hole diffusion
② e⁻ diffusion
③ hole drift
④ electron drift



⑥ Since, diffusion & drift process counter each other, equilibrium condition is established

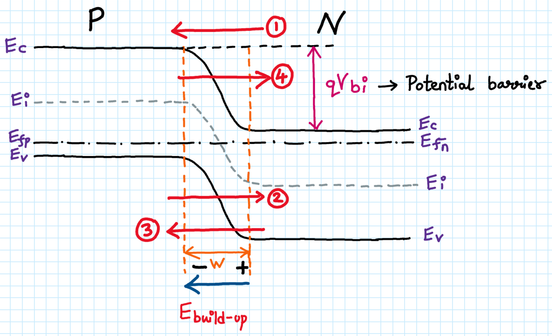
Diffusion current ⟷ drift currents Balanced by

⑦ **Result is no net current flow**
i.e we say PN Junction is in equilibrium



⑧ Note: Energy levels = − Voltage (or potential)
(i.e Position of energy bands)

Implication: When the energy goes up for e⁻s, that corresponds to being at a more negative potential



Energy band diagram of PN Junction (under equilibrium)

i) Depletion region width (W):

$$W = \sqrt{\frac{2\epsilon_s}{q} V_{bi} \left(\frac{N_A + N_D}{N_A N_D}\right)} \quad cm$$

ii) Build-in E-field ($E_{build-in}$)

$$E_{build-in} = -\frac{2V_{bi}}{W} \quad \frac{V}{cm}$$

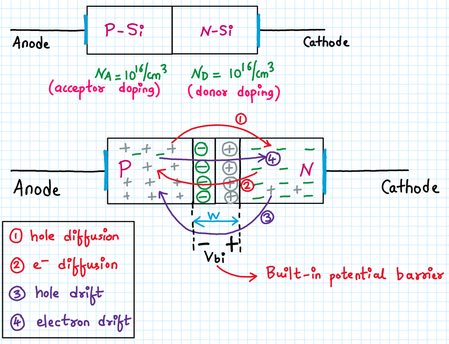
iii) Built-in potential (V_{bi})

$$V_{bi} = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) \quad Volts$$

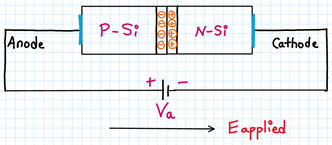
28 May 2021 20:47

Todays topic:
PN junction under forward bias

* PN Junction under forward bias:

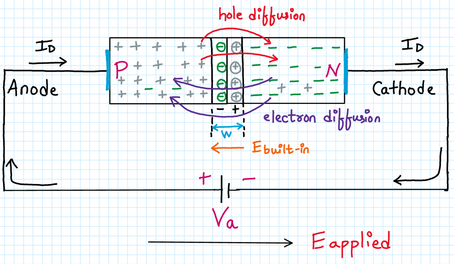


① Applying external potential to PN junction such p-side is connected to positive terminal and n-side is connected to negative terminal of external voltage supply makes the PN Junction forward bias

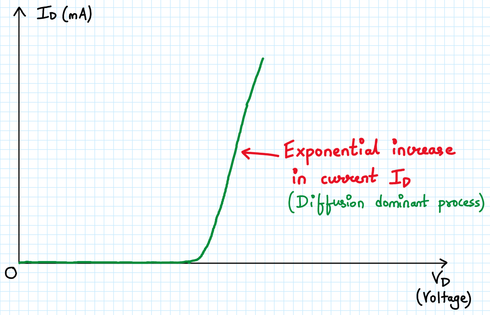


PN Junction in forward bias

② Applying forward bias lowers the potential barrier for carriers to diffuse i.e e⁻s on n-side see a lower barrier to diffuse to p-side & holes on p-side also see a lower barrier to diffuse to n-side



③ As the forward bias voltage increases → diffusion of charge carriers (i.e holes diffuse from p to n and electrons diffuse from n to p) increases tremendously → due to lowered potential barrier $q(V_{bi}-V_a)$ → effectively W ↓ses



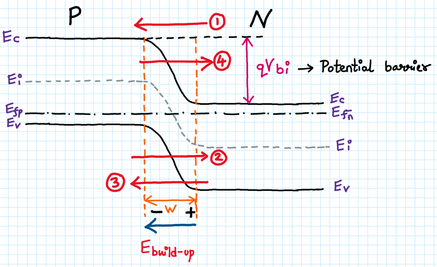
④ In forward bias, as we increase the forward bias voltage voltage, we are going to have very large (exponential) increase in forward current because of mostly due to diffusion process

⑤ Net current flow for PN junction in forward bias is from p side to n-side

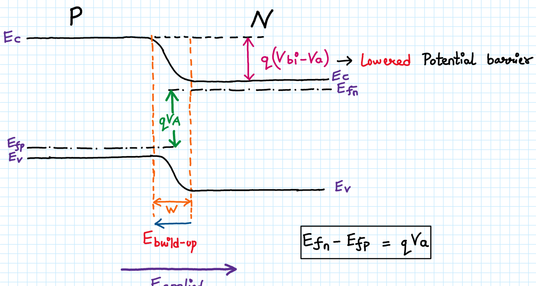
⑥ In a forward bias PN junction → minority carriers are injected (since electrons from n-side are injected into pside and holes from pside are injected into n-side)

⑦ In summary, in a forward PN junction, I_D increases exponentially due to slight increase in V_a and it is due to dominant diffusion process (diffusion is responsible for current flow in forward bias)

⑧ In forward bias → drift current exists but it is very small

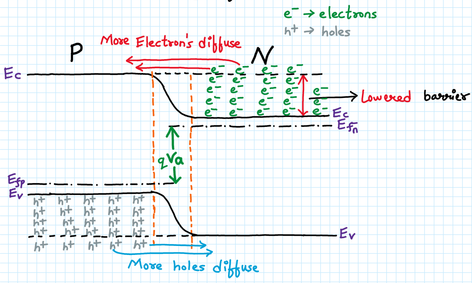


Energy band diagram of PN Junction (under equilibrium)



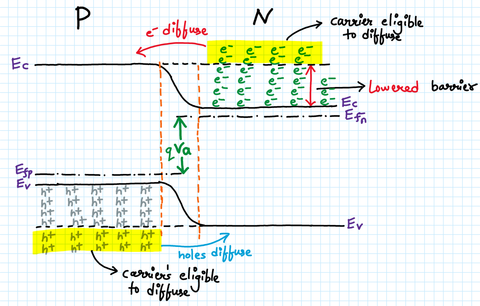
Energy band diagram of PN Junction (under forward bias)

i) Forward bias V_a raises the energy of n-side and lowers the energy of p-side semiconductor

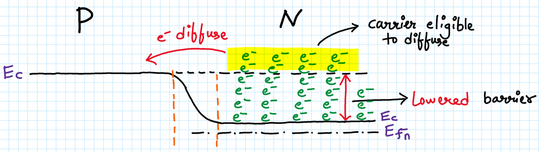


Heavy diffusion of charge carriers

ii) Let us see how, diffusion of carriers process increases as V_a increases



iii) Only charge carriers that were eligible to diffuse are the ones that have enough energy to surmount the barrier & go on the other side

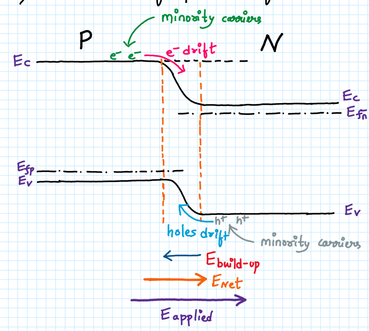


iv) N side has lot of carriers (electrons), but only carriers eligible can overcome the barrier and diffuse to p-side

v) P side has lot of carriers (holes), but only carriers eligible can overcome the barrier and diffuse to n-side

vi) As applied forward voltage V_a increases, more carriers get's eligible and hence more of them diffuse to the other side → causing a tremendous increase in current flow i.e I_D ↑ses exponentially with V_a

vii) What about drift process in forward bias?

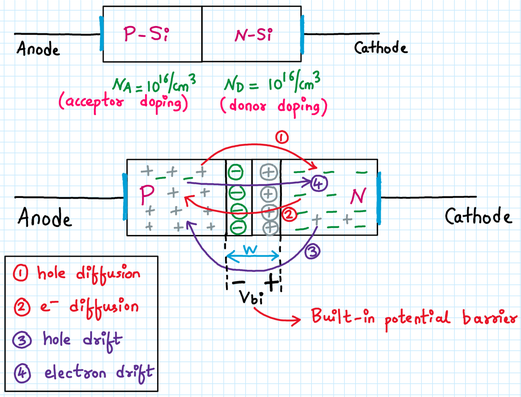


viii) Any minority carriers (e⁻s on p-side or holes on n-side) that reaches depletion region will be swept away by net electric field. Drift current is very very small because there are not many minority carriers available

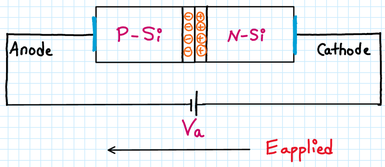
28 May 2021 20:47

Todays topic:
PN junction under reverse bias

* PN Junction under reverse bias:

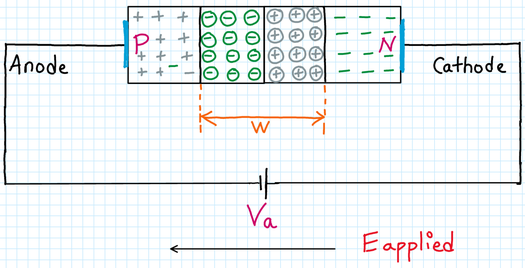


① Applying external potential to PN junction such n-side is connected to positive terminal and p-side is connected to negative terminal of external voltage supply makes the PN Junction **reverse bias**



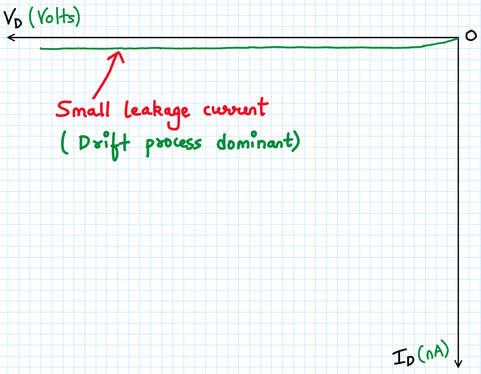
PN Junction in reverse bias

② Applying reverse bias increases the potential barrier for carriers to diffuse i.e e⁻s on n-side see a v.big barrier to diffuse to p-side & holes on p-side also see a large barrier to diffuse to n-side
Thus, diffusion process possibility is very very low



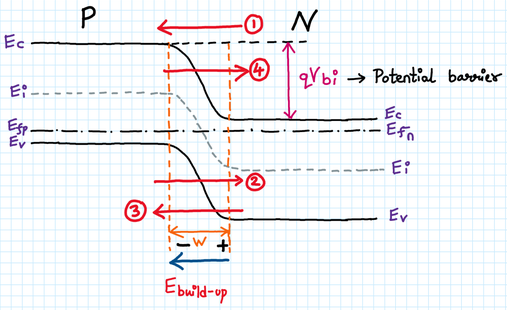
③ When PN junction is reverse bias, a very small reverse current ($I_{leakage}$) flows → only due to drift process

④ As reverse bias Va increases, majority carriers are driven away towards supply (e⁻s attracted to +ve terminals & holes are attracted to -ve terminal of supply) → This results in increase in the depletion region W

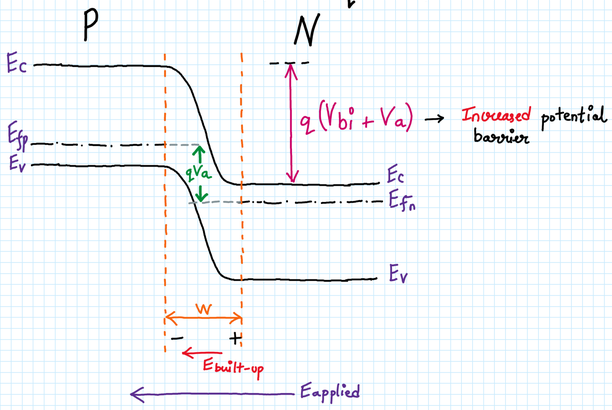


5) In summary, when PN junction is reverse-biased, negligible current flows → tiny drift current flows in nA range. Diffusion process is negligible in reverse bias

6) Also, in reverse bias → depletion region width increases because majority charge carriers are being pulled out of the bulk of the material



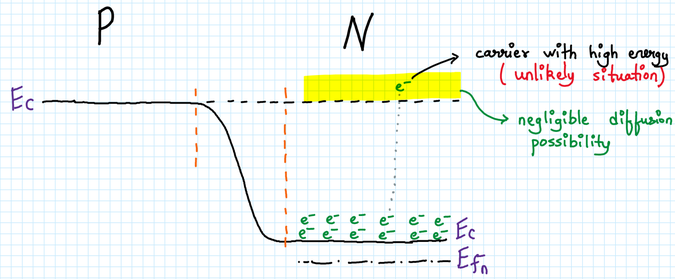
Energy band diagram of PN Junction (under equilibrium)



Energy band diagram of PN Junction (under reverse bias)

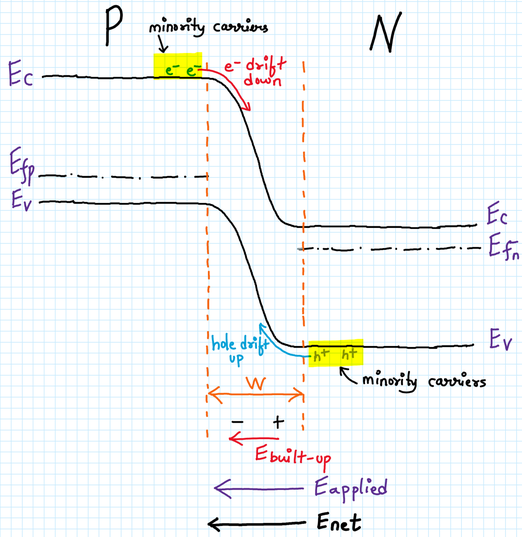
i) Forward bias Va raises the energy of p-side and lowers the energy of n-side semiconductor

ii) In reverse bias, diffusion process possibility is very low and drift process provide small tiny reverse current
Let us understand why this happens?



iii) In reverse-bias, the potential barrier is very large, so for diffusion to take place → eligible carriers should have very high energy state which is very unlikely event. Thus, diffusion possibility in reverse bias is almost negligible

iv) What about drift process in reverse bias?



v) In reverse bias, any minority carriers that reaches depletion region will be swept across the junction by a powerful net electric field (E_{net}) within the depletion region (i.e minority carriers are captured by depletion region)

vi) Since, the concentration of minority carriers are v.small thus the drift current is very small (~nA)

vii) Even with increase in reverse bias → drift current will not increase & remain in nA range for Si

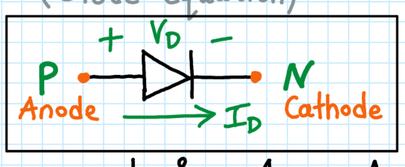
28 May 2021 20:52

Todays topic:
I-V characteristics of PN junction diode
Real Diodes

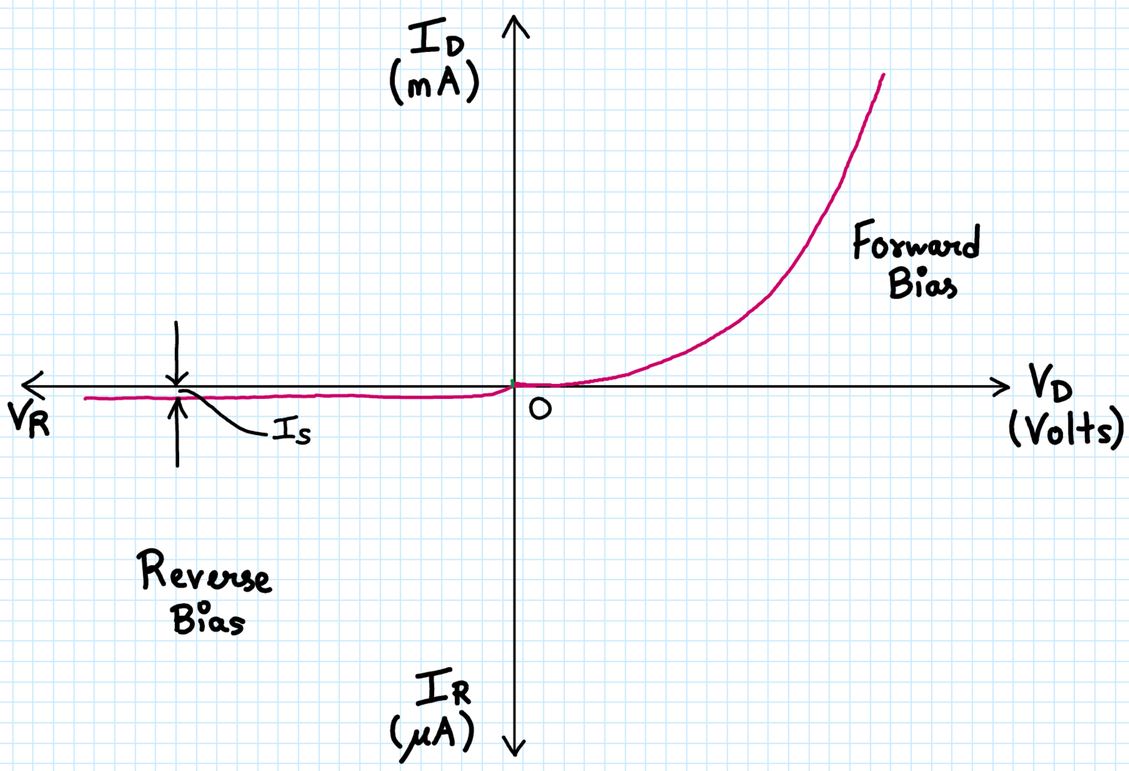
* Current-voltage relationship in a PN junction diode / Diode equation:

$$I_D = I_S\left(e^{\frac{V_D}{\eta V_T}} - 1\right)$$

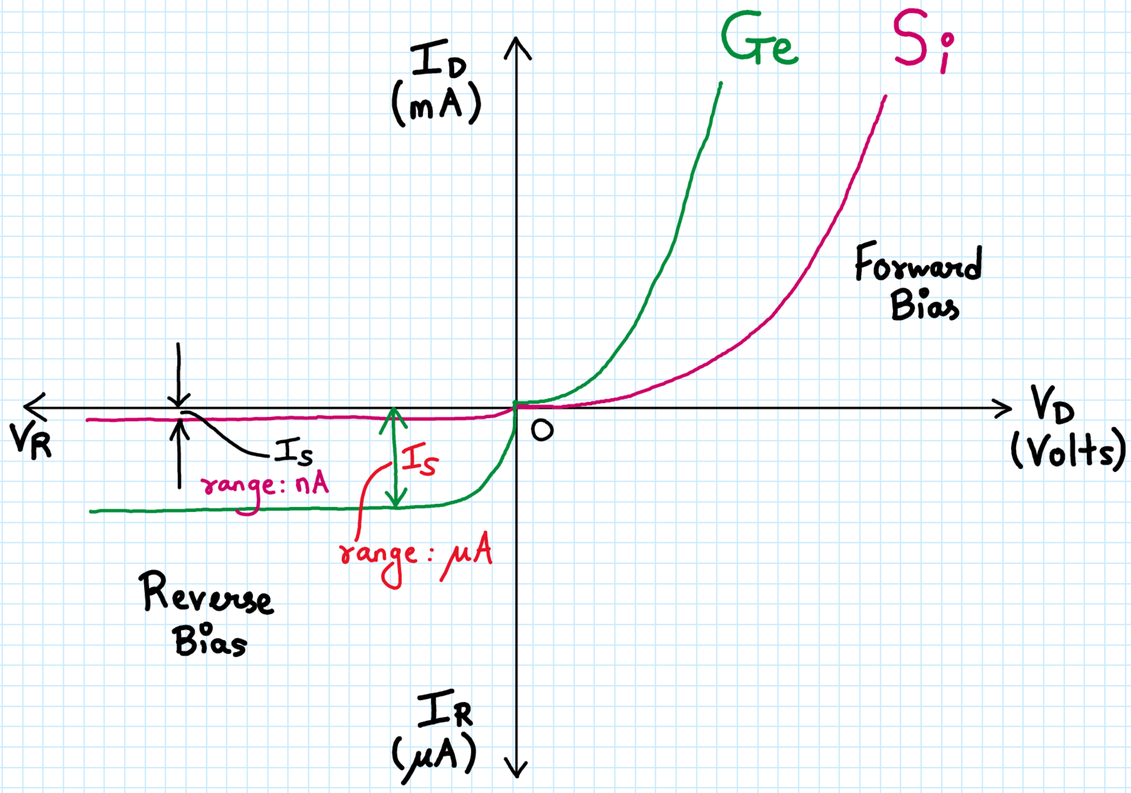
..... Shockley's equation (Diode equation)



where, I_D is diode current in mA
V_D is applied diode voltage in volts
I_S is leakage or reverse saturation current in μA or nA
η is ideality factor
η is 1 for Ge and η is 2 for Si
V_T is thermal voltage at $T = 300K$ (27°C)
$V_T = \frac{KT}{q} = \frac{T}{11600}$; $V_T = 26mV$ at $T = 300K$
V_T is also volt equivalent of temperature



I-V characteristics of diode



I-V characteristics of Si and Ge diode

* Observations (from I-V characteristics)

① Diode equation tells us how current I_D flows for given amount of applied voltage V_D

② In forward bias, I_D increases exponentially with applied forward voltage V_D as per diode equation

$$I_D = I_S\left(e^{\frac{V_D}{\eta V_T}} - 1\right)$$

Diode is forward biased if V_D positive (Anode is positive w.r.t cathode)

③ In reverse bias, V_D is negative (large value), thus

$$e^{\frac{-V_D}{\eta V_T}} \longrightarrow 0$$

$$I_D = -I_S$$ ..... in reverse bias

This means that the reverse current in a diode is constant and it is equal to I_S

i.e reverse current saturates to I_S in the reverse direction

(hence the name reverse saturation current)

④ In reverse bias, I_D is independent of applied reverse bias

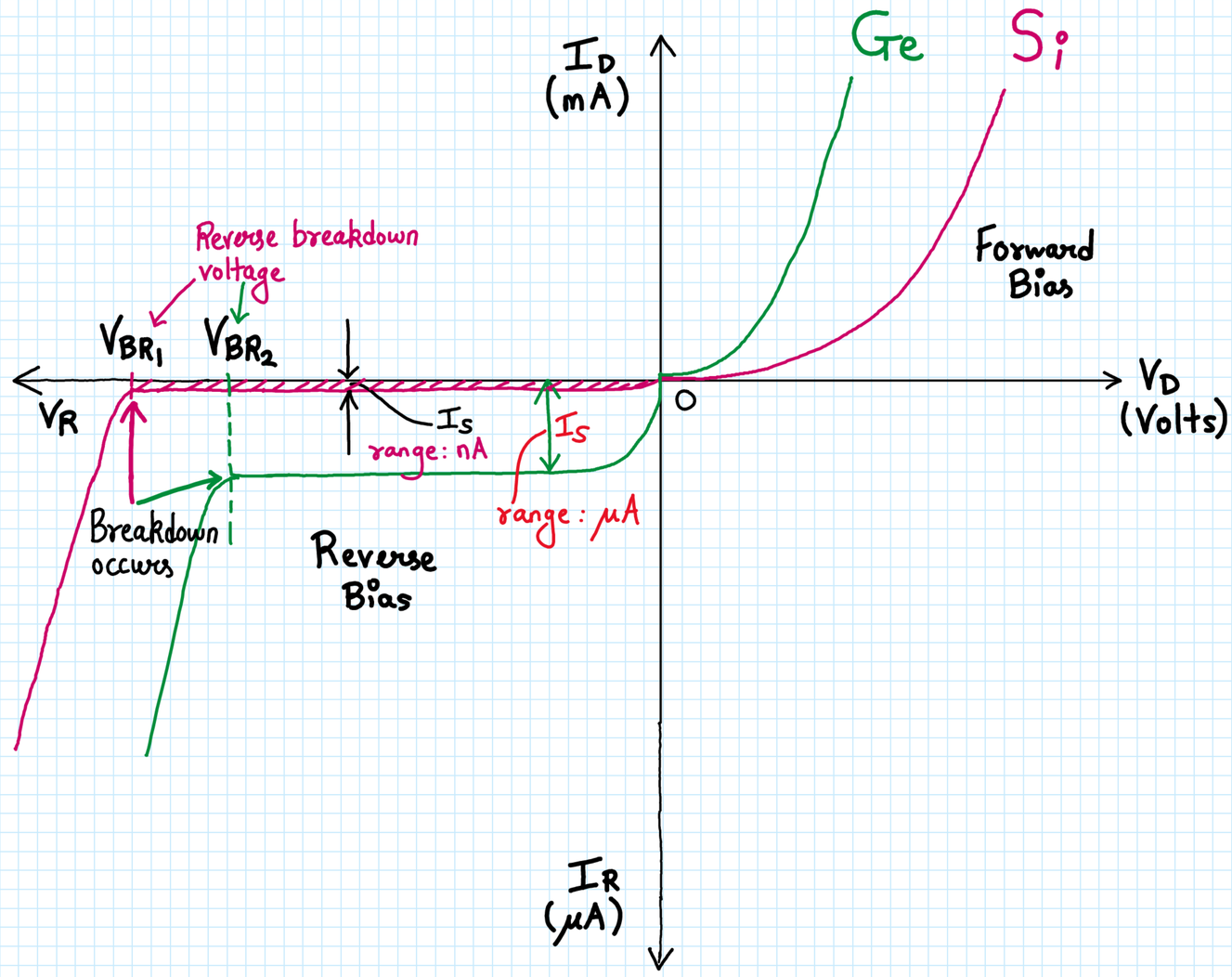
(A positive value of I_D means that current flows from pside to n-side)

* Real diodes: Zener & Avalanche

① As observed in reverse bias pn junction conduct very small current (in μA or nA) & it is constant

② It is true, until a critical reverse voltage is reached & junction breakdown occurs (There are two mechanisms of breakdown)

Zener breakdown | Avalanche breakdown



③ When reverse-bias voltage V_{BR_1} (say 50V) for Si diodes, then the reverse current in the diode increases rapidly

④ When breakdown occurs, the voltage across the diode terminals remains almost more or less constant

28 May 2021 20:55

Todays topic:
Numerical on Diode equation

* Numerical 1

Find the forward current in a Si diode at a forward voltage of 0.6V, reverse saturation current of 0.1μA and temperature of 27°C

$V_D = 0.6V$, $I_S = 0.1\mu A$, $V_T = 26mV$ $I_D = ?$

Now, if a reverse voltage of 10V is applied to the diode

$\eta = Si = 2$

Find the reverse current flowing through the diode

Solution:

① Diode equation is

$$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$$

$T = 27°C = 300K$

For Si, $\eta = 2$ (for Si)

$$\rightarrow \frac{V_D}{nV_T} = \frac{0.6}{2 \times 26mV}$$

$$\rightarrow \frac{V_D}{nV_T} = \boxed{X_1}$$

$X_1 = 11.53$

$$\rightarrow I_D = 0.1 \times 10^{-6} \times \left(e^{X_1} - 1\right)$$

$I_D = \boxed{X_2} = 10.178\ mA$

$\boxed{I_D \approx X_2}$ ..... Forward current in a Si diode

$V_T = \frac{KT}{q}$; $1eV = 1.6 \times 10^{-19} V$

$K = 8.617 \times 10^{-5} \frac{eV}{K}$ .... Boltzman's constant

$$V_T = \frac{8.617 \times 10^{-5} \times \cancel{1.6 \times 10^{-19}} \times 300}{\cancel{1.6 \times 10^{-19}}}$$

$V_T = 25.851 \times 10^{-3}\ V$

$\boxed{V_T \approx 26\ mV}$ at $T = 27°C$

$$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$$

$\rightarrow V_D = -10V$;

$$I_D = I_S\left(e^{\frac{-10}{2 \times 26mV}} - 1\right)$$

$I_D = I_S(\boxed{X_3} - 1)$ $X_3 = 0$

$I_D \approx -I_S = -0.1 \times 10^{-6}$ $\boxed{I_D = -0.1\mu A}$

$\boxed{I_D = \boxed{X_4}}$ .... reverse current in a Si diode

* Numerical 2

The reverse saturation current of a Ge diode at 27°C is 5μA

Find the forward voltage at which the current is 25mA

Solution:

① Given: $T = 27°C = 300K$, $I_S = 5\mu A$

$I_D = 25mA$, $\eta = 1$ (for Ge)

② Diode equation is

$$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$$; $V_T = 26mV$ at 27°C

$$I_D + I_S = I_S\, e^{\frac{V_D}{1 \times V_T}}$$

$$e^{\frac{V_D}{1 \times V_T}} = 1 + \frac{I_D}{I_S} = 1 + \frac{25 \times 10^{-3}}{5 \times 10^{-6}}$$

$$e^{\frac{V_D}{1 \times V_T}} = \boxed{y1}$$

$$\frac{V_D}{V_T} = \ln(\boxed{y1}) = \boxed{y2}$$

$$V_D = \boxed{y2} \times 26 \times 10^{-3}$$

$\boxed{V_D = \boxed{y3}}$ .... Forward voltage of Ge diode

28 May 2021 20:57

Todays topic:
Temperature dependence on I-V characteristics and numericals

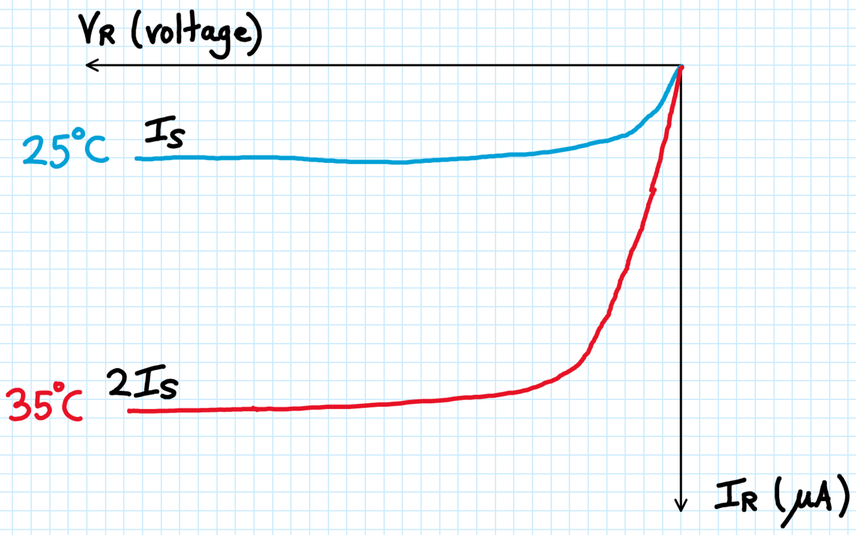
* Temperature dependence on diode I-V characteristics:

① Temperature have significant effect on the diode characteristics

② V_T and I_S in diode equation are temperature dependent terms

③ Increase in temperature results in increased thermal activity and decreased diode resistance, which influences both the forward and the reverse characteristics of the diode

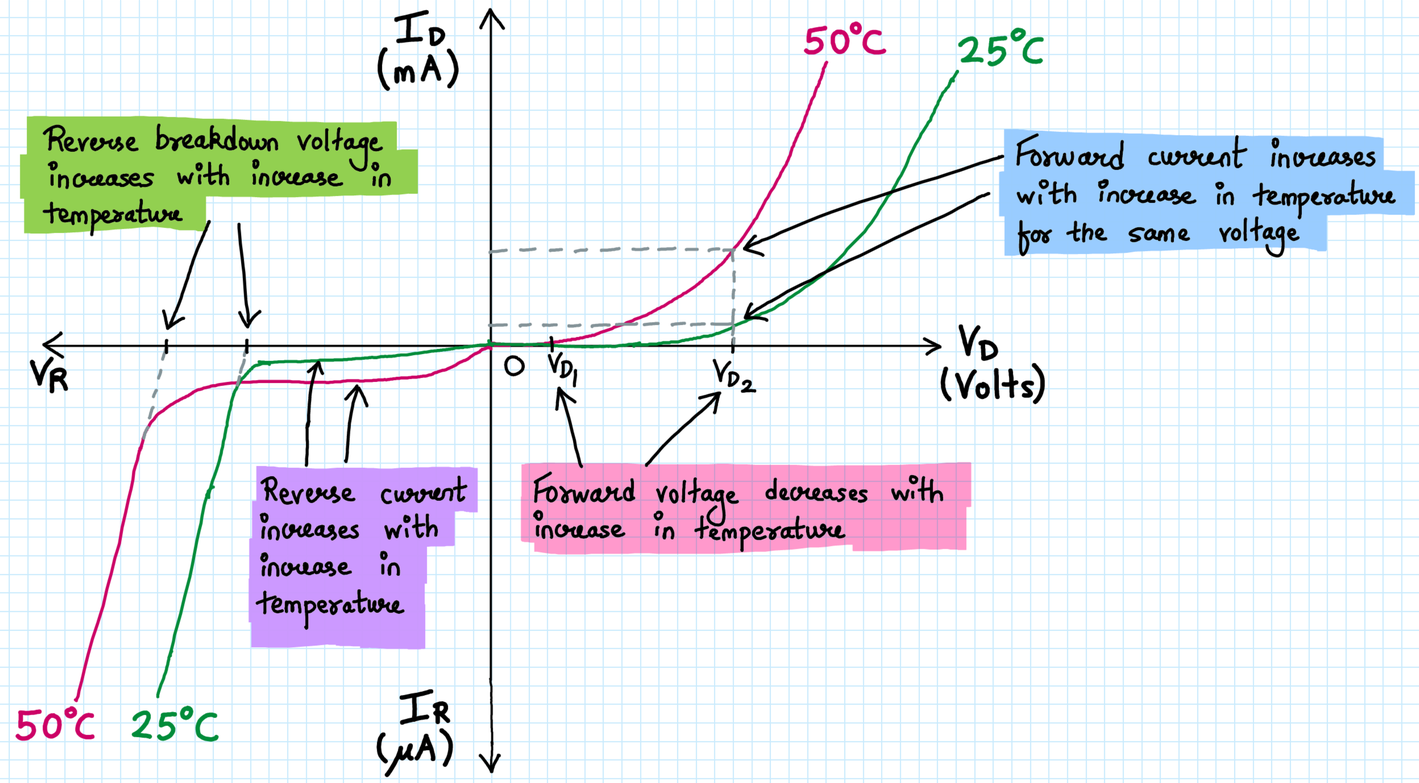
④ Fact: Diode forward voltage decreases by 2.5mV per degree rise in temperature



Effect of temperature on reverse characteristics of diode

⑤ Reverse saturation current and breakdown voltage increases with increase in temperature

⑥ Fact: The reverse saturation current gets doubled for every 10°C rise in temperature



Effect of temperature on the diode characteristics