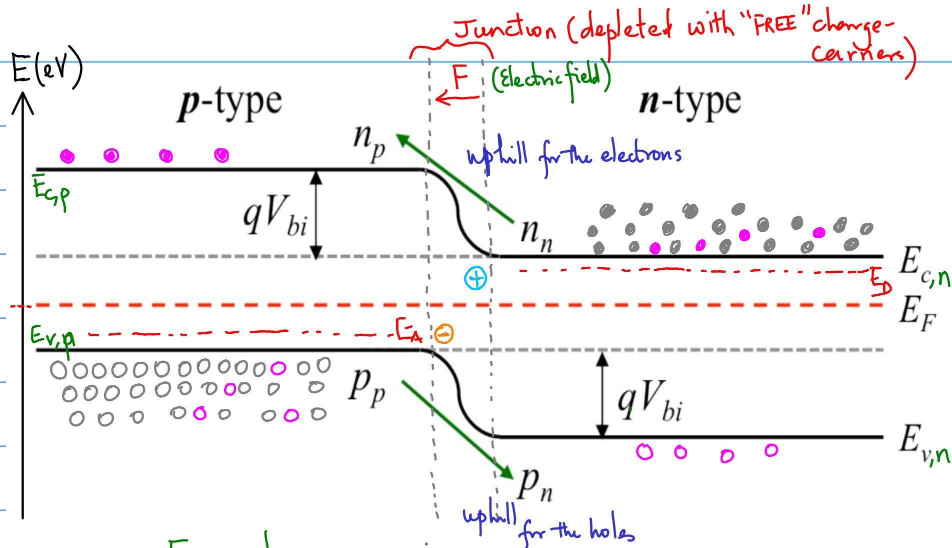
05.10.2023

p-n Homojunction Diode

1. Unbiased at 300K.



Dopants:

⊕ : Donor atoms

⊖ : Acceptor atoms

Bound charges within the junction region

n_n ≡ ● $\simeq N_D \approx 10^{15}\,cm^{-3}$

p_p ○ $\simeq N_A \approx 10^{15}\,cm^{-3}$

n_p ● $\simeq 10^5\,cm^{-3}$

p_n ○ $\simeq 10^5\,cm^{-3}$

Free charge-carriers :

● ≡ Electrons from the donor atoms
○ ≡ Holes from the acceptor atoms } Majority carriers "Extrinsic" Source

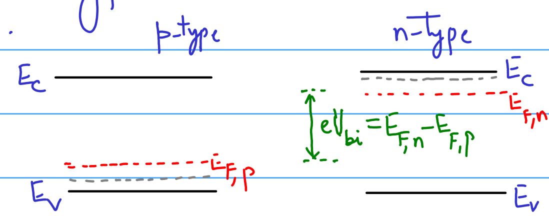
● ≡ Electrons due to excitation
○ ≡ Holes due to excitation of electrons } Minority carriers "Intrinsic" carriers

PARTICLE FLOW	CURRENT
Hole diffusion p ⟶ n	I_p(Diffusion) ⟶
Hole drift p ⟵ n	I_p(Drift) ⟵
Electron diffusion p ⟵ n	I_n(diffusion) ⟶
Electron drift p ⟶ n	I_n(drift) ⟵

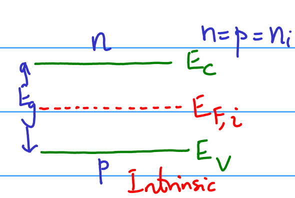
$$\boxed{I_p(\text{Diff}) + I_n(\text{diff}) = I_p(\text{Drift}) + I_n(\text{drift})}$$

$$I_{NET} = 0$$

Built-in voltage V_{bi} is simply the difference of the Fermi-levels in p- and n-type semiconductors before they are joined.



$$\Rightarrow \quad qV_{bi} = E_{F,n} - E_{F,p}$$



at any temperature T;

$$E_{F,n} = \underset{\sim}{E_{F_i}} + k_B T \ln\left(\frac{N_D}{n_i}\right) \quad \uparrow \text{ Towards } E_c$$

$$E_{F,p} = \underset{\sim}{E_{F_i}} - k_B T \ln\left(\frac{N_A}{n_i}\right) \quad \downarrow \text{ Towards } E_V$$

Subtract the two, we get

$$\boxed{V_{bi} = \frac{k_B T}{q} \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)}$$

Let's estimate for Silicon:
$T = 300K$
$\frac{k_B T}{e} = 25mV$
$N_A = N_D = 10^{15}\ cm^{-3}$
$n_i = 10^{10}\ cm^{-3}$
$V_{bi} = 25mV \ln\left(\frac{10^{30}}{10^{20}}\right)$
$V_{bi} = 0.6V$

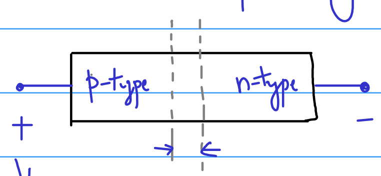
In steady-state,

$\boxed{\text{Diffussion current} = \text{Drift current}}$

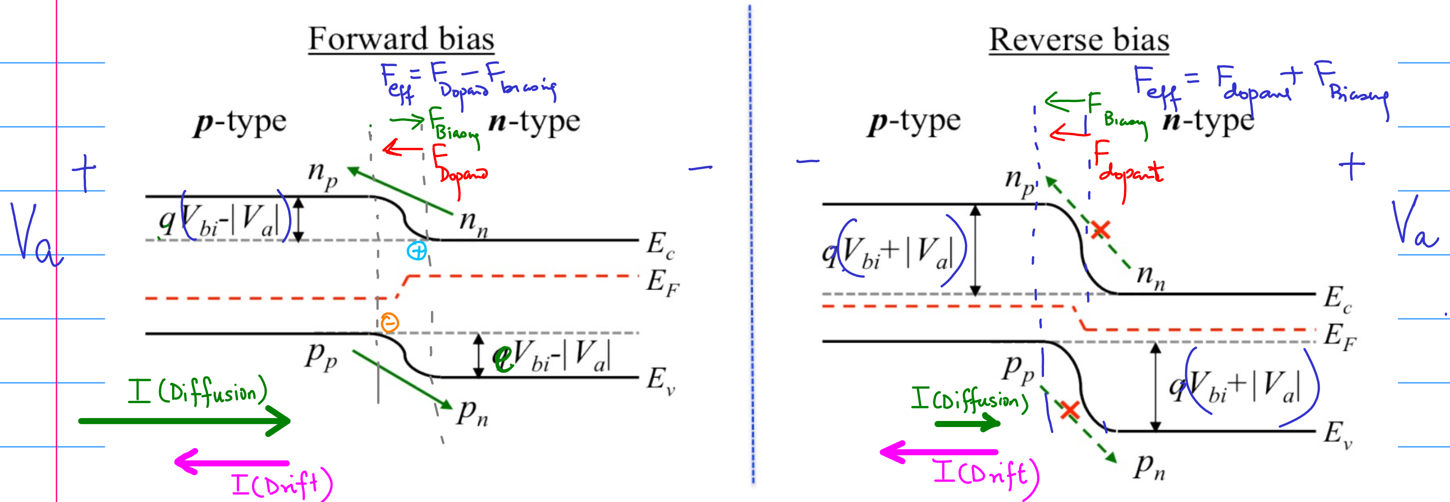
$\Rightarrow$ Net current is "ZERO"

2. Biased at 300K.

p-type = +ve terminal of the source
→ forward bias p-n junction



= −ve terminal of the source
→ Reverse bias p-n junction.



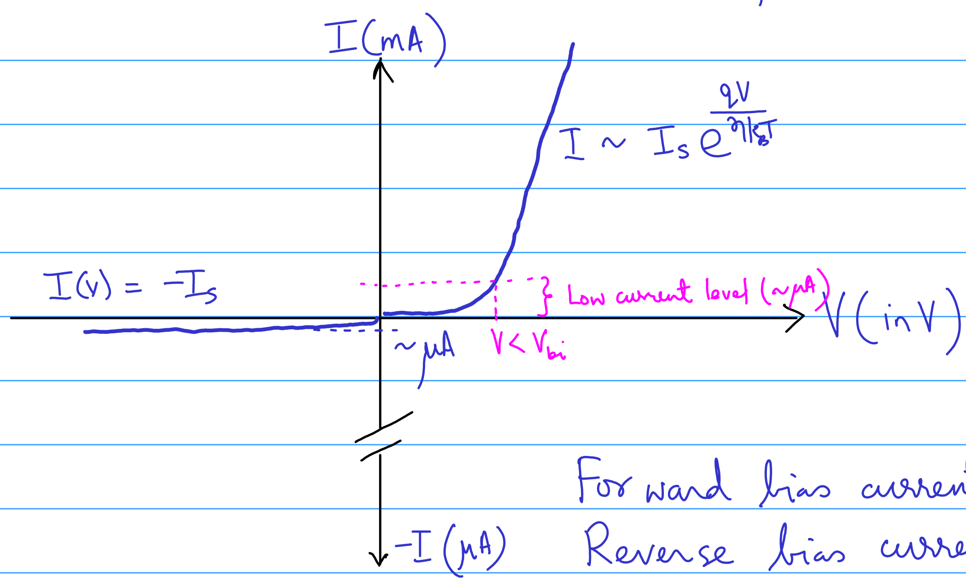
Current–Voltage Characteristics :

$$I(V,T) = I_s\left[\exp\left(\frac{qV}{\eta k_B T}\right) - 1\right]$$

where, I_s = Reverse saturation current

η = Ideality factor ; for ideal diode ; $\eta = 1$

for real diode ; $1 < \eta < 2$



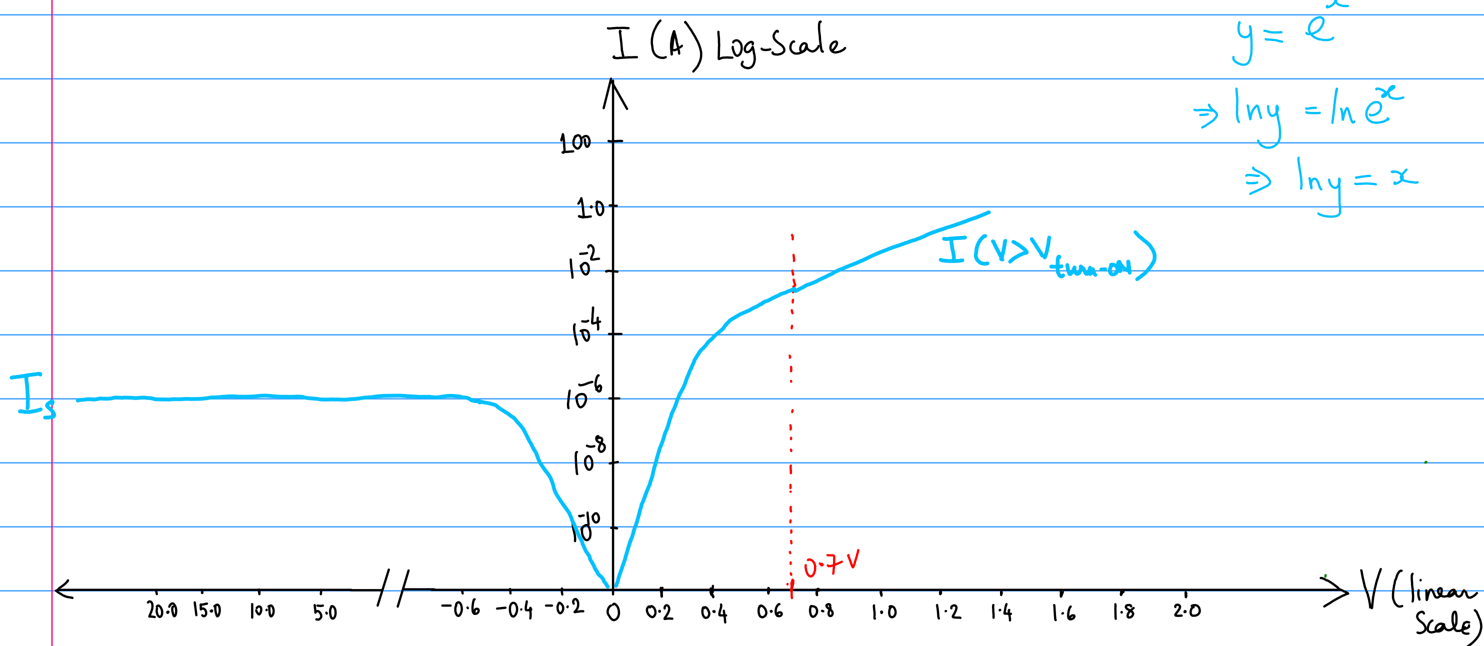
Forward bias current ~ mA

Reverse bias current ~ μA

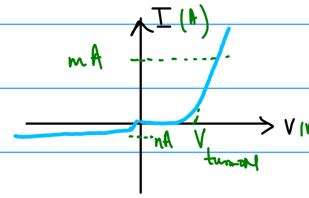
$y = e^x$

$\Rightarrow \ln y = \ln e^x$

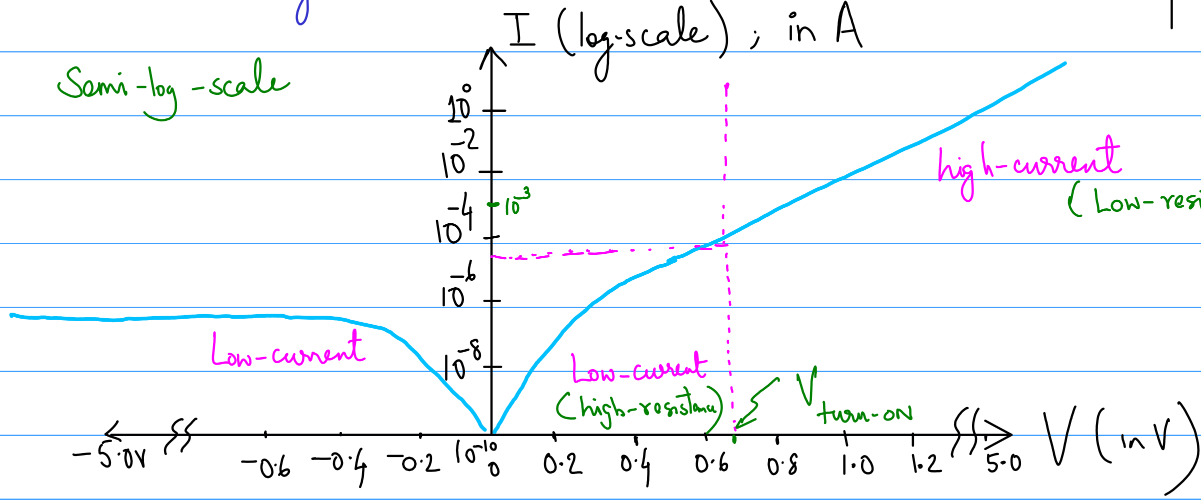
$\Rightarrow \ln y = x$



p-n Diode : Circuit Models



1. Current-Voltage Characteristics :

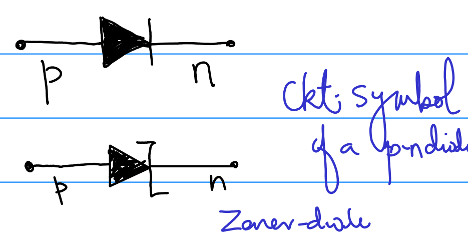


Conclusion: The current-voltage characteristics show two current levels :

(i) Low (μA) when $V \leq V_{turn-ON}$

(ii) high (mA) when $V > V_{turn-ON}$.

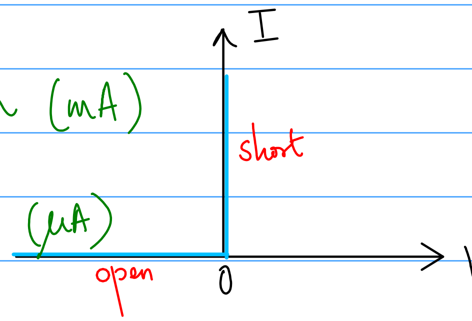
2) Circuit Model of a p-n diode :



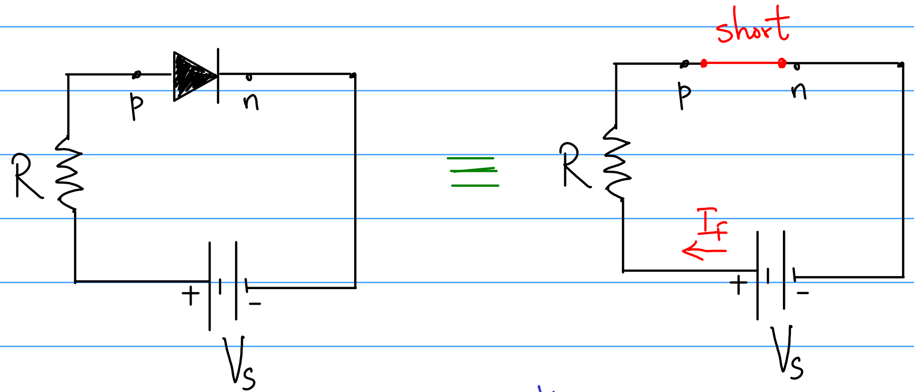
a) Ideal diode Model :

(+ve Bias) $V > 0$; $I \rightarrow$ high (mA)

(−ve Bias) $V < 0$; $I \rightarrow$ Low (μA)

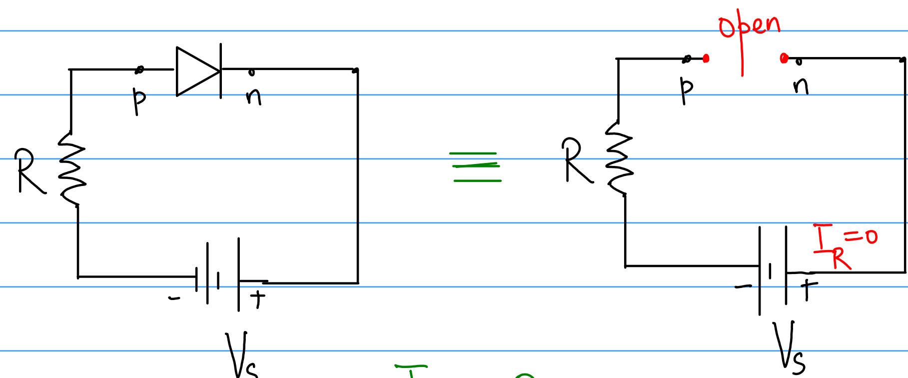


(i) Forward bias



$$I_F = \frac{V_s}{R}$$

(ii) Reverse-bias:

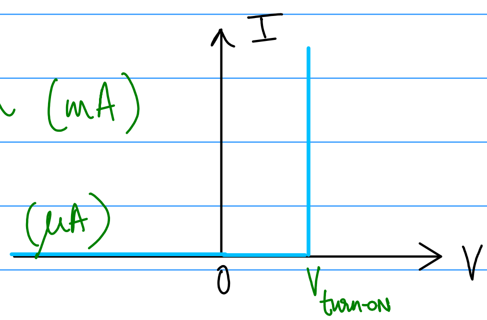


$$I_R = 0$$

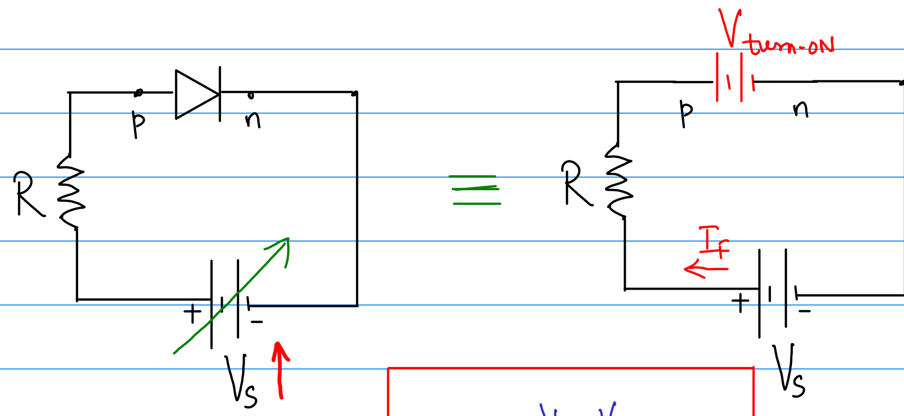
b) Modified Ideal Diode Model (Practical Model):

$V > V_{\text{turn-ON}}$; $I \rightarrow$ high (mA)

$V < V_{\text{turn-ON}}$; $I \rightarrow$ Low (μA)



(i) Forward bias



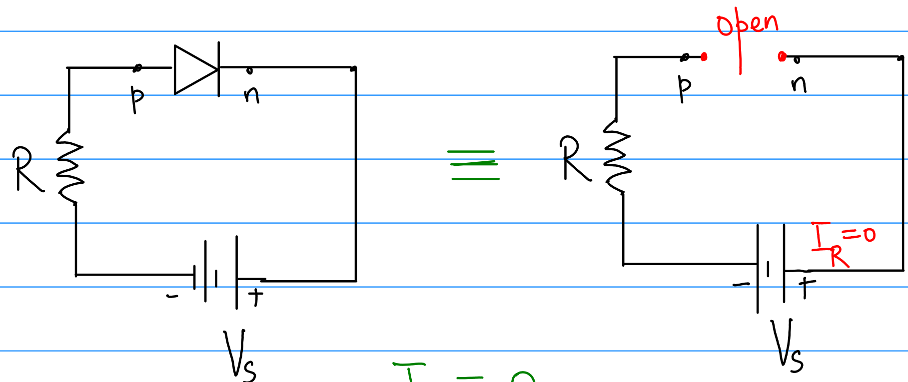
For I_F to exist, $V_s > V_{turn\text{-}ON}$

$$\boxed{I_F = \frac{V_s - V_{turn\text{-}ON}}{R}}$$

typically, for Silicon diode, $V_{turn\text{-}ON} \sim 0.7\,V$

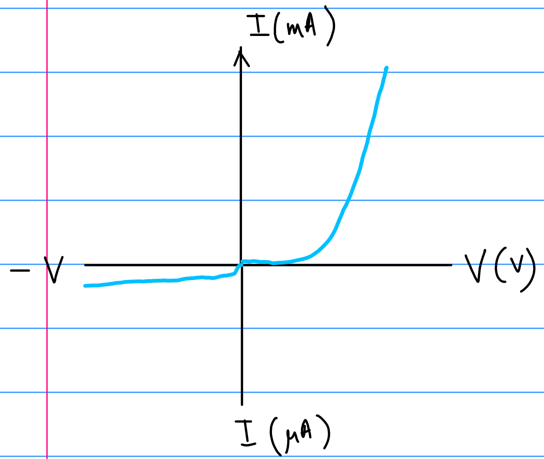
$$\boxed{I_F = \frac{V_s - 0.7\,V}{R}}$$

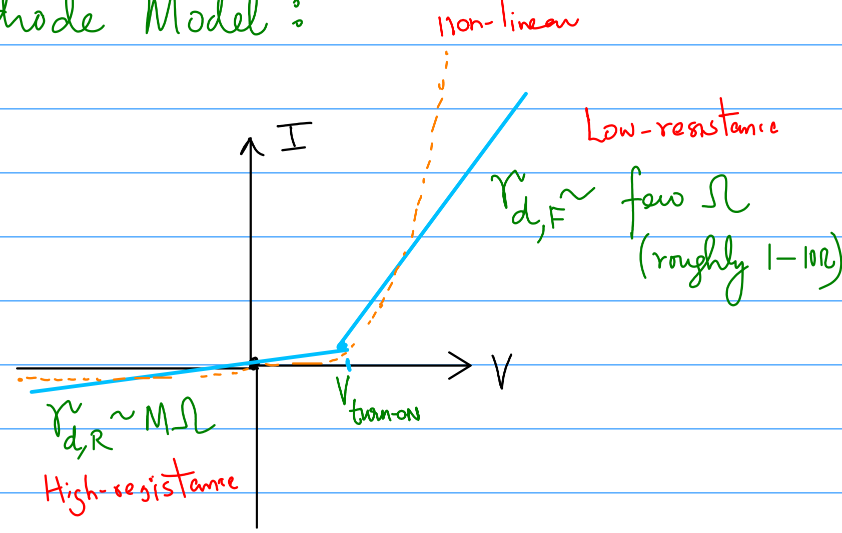
(ii) Reverse-bias:



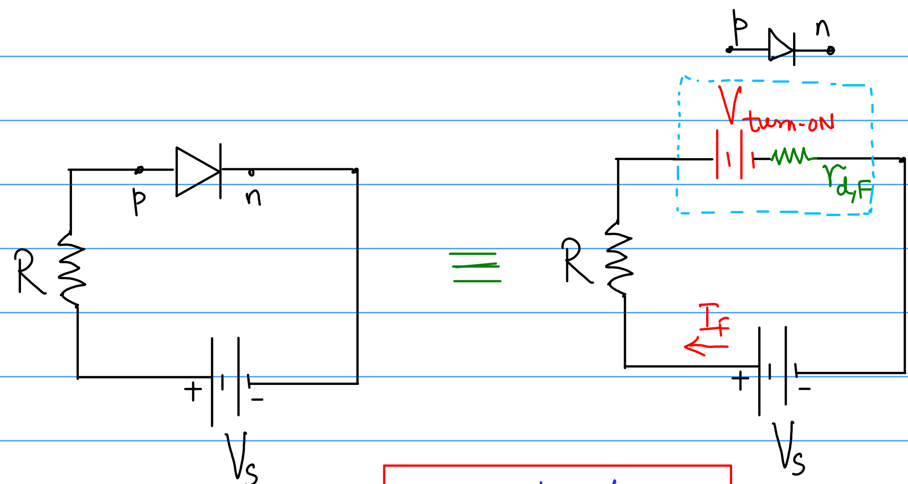
$I_R = 0$

3) Complete (Real) diode Model :



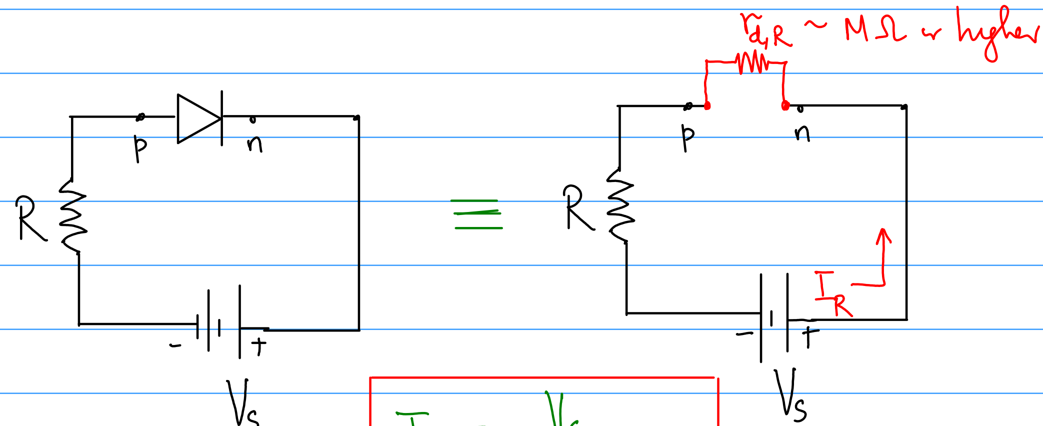


(i) Forward bias



$$\boxed{I_F = \frac{V_s - V_{turn\text{-}ON}}{R + r_{d,F}}}$$

(ii) Reverse-bias:



$r_{d,R} \sim 1M\Omega$

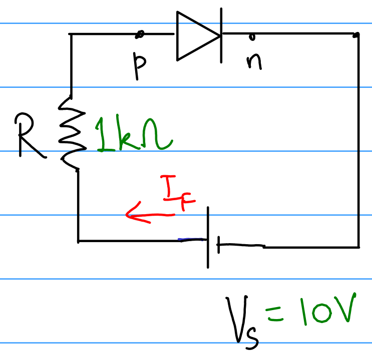
$R = 1k\Omega$

$V_s = 1V$

$$\Rightarrow I_R = \frac{1V}{1k\Omega + 1M\Omega} \approx 1\mu A$$

$$\boxed{I_R = \frac{V_s}{R + r_{d,R}}}$$

Example Problem:



Specification of the diode

$V_{turn\text{-}ON} = 0.6\,V$

$r_{d,F} = 10\,\Omega$

$r_{d,R} = 100k\Omega$

Let see forward-current (I_F) assuming the three models:

(i) Ideal model : Diode is replaced with "short".

$$I_F = \frac{V_s}{R} = \frac{10V}{1k\Omega} = 10mA$$

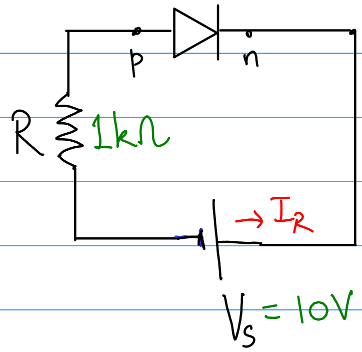
(ii) Modified Ideal Model : Diode is replaced with a "Voltage source" $= V_{turn\text{-}ON}$

$$I_F = \frac{V_s - V_{turn\text{-}ON}}{R} = \frac{10V - 0.6V}{1k\Omega} = 9.4mA$$

(iii) Real diode model : Diode is replaced with a voltage-source and a resistor $r_{d,F}$

$$I_F = \frac{V_s - V_{turn\text{-}ON}}{R + r_{d,F}} = \frac{10V - 0.6V}{1k\Omega + 10\Omega}$$

$$I_F = 9.3mA$$



(i) Ideal Model : $I_R = 0$ (diode = open)

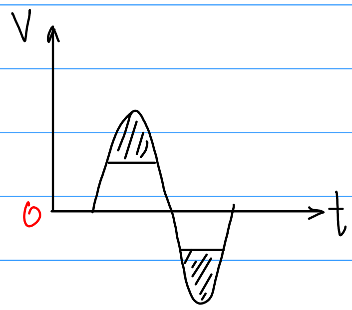
(ii) M.I.M. : $I_R = 0$ (open)

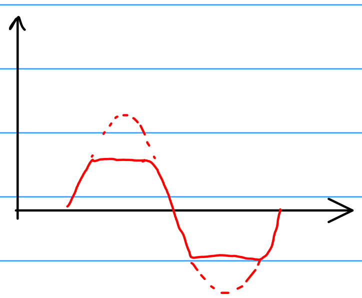
(iii) $\underbrace{\text{Real Model}}_{\text{Diode is replaced with a resistor } 'r_{d,R}'}$: $I_R = \dfrac{V_s}{R + r_{d,R}} = \dfrac{10V}{1k\Omega + 100k\Omega}$

$I_R = 100\mu A = 0.1 mA$

$$\frac{I_F}{I_R} = \frac{9.3mA}{0.1mA} \sim 93$$

$\boxed{I_F = 93 I_R}$ or, $\sim$ $\boxed{I_F \sim 100 I_R}$





Applications:
- → Switch
- → Rectifier (Half wave, Full wave)
- → Clipper
- → Clamper