PN-junction diode

Electrical resistivity ρ

Conductors $\rho \approx 10^{-8}\ \Omega m$

Semi-conductors $\rho \approx 1\ \Omega m$

Non-conductors $\rho \approx 10^{9}\ \Omega m$

Semiconductors e.g. silicon (Si)

n-type doping P in Si

→ Donor → Host

→ 5 electrons → 4 electrons

⇒ 1 donor atom ⇒ 1 free electron

⇒ n-type ⇒ negative sign

⇒ electron

p-type doping B in Si

→ 3 electrons → 4 electrons

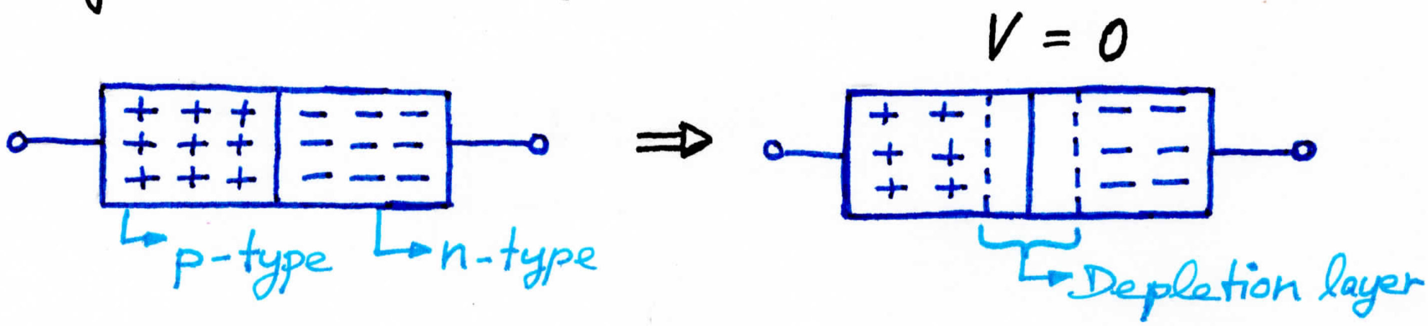
→ Acceptor → Host

⇒ 1 acceptor atom ⇒ 1 free hole

⇒ p-type ⇒ positive type

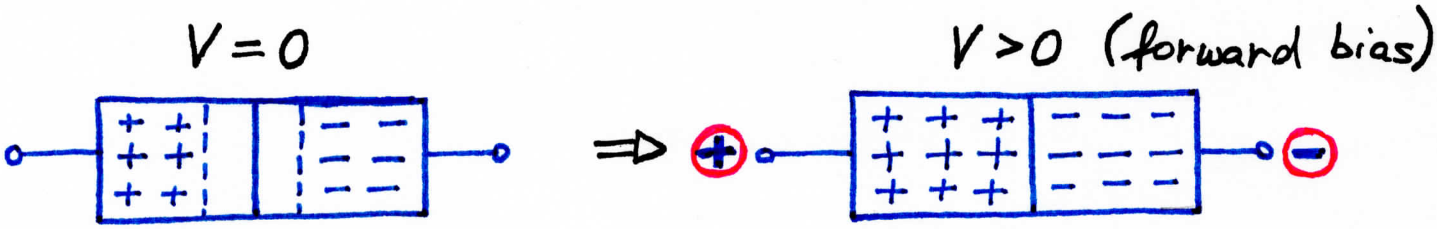
⇒ hole (electron deficiency)

pn junction $V = 0$



$\Rightarrow$ Depletion layer $\Rightarrow$ Diode is resistive at zero bias

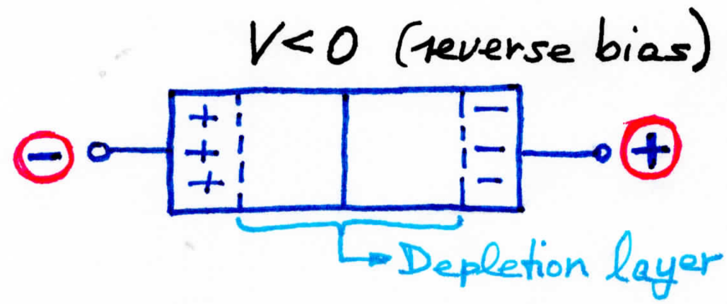
Forward bias $V > 0$



$\Rightarrow$ Diode voltage > 0 $\Rightarrow$ Diode conducts

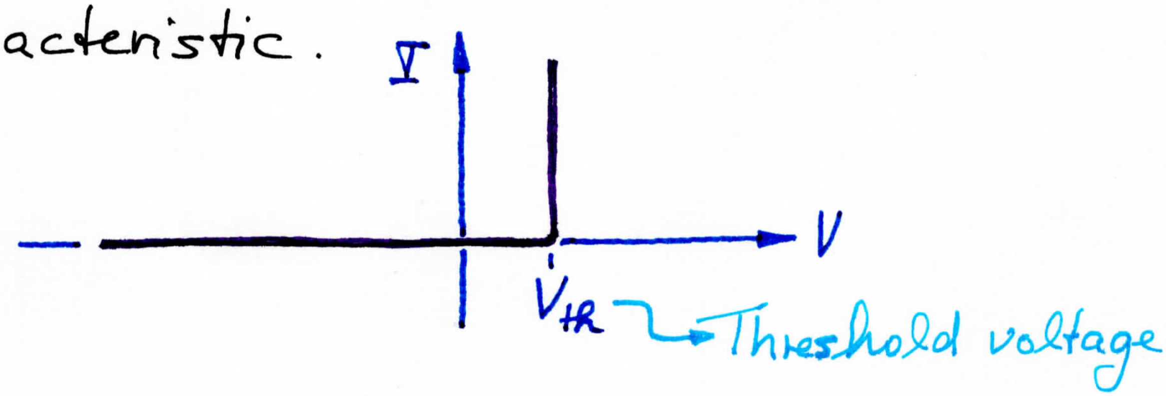
$\Rightarrow$ Threshold voltage required $\Rightarrow$ V_{th}

Reverse bias $V < 0$

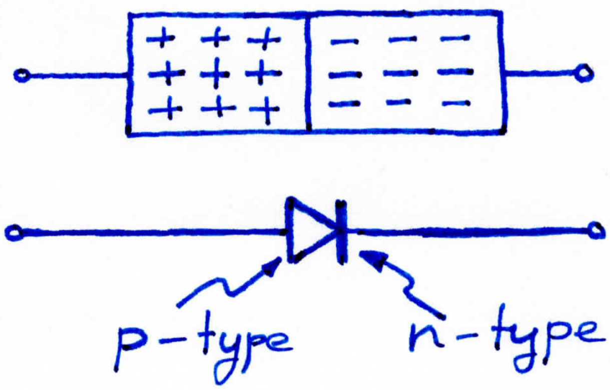


$\Rightarrow$ Diode voltage < 0 $\Rightarrow$ Diode insulates

Based on the qualitative understanding developed above, we construct the diode's IV characteristic.



Circuit symbol



Theoretical IV characteristic

$$\boxed{I = I_0 \left(e^{V/V_t} - 1 \right)}$$

V_t = Thermal voltage $= \dfrac{kT}{e} = 26$ mV

k = Boltzmann constant $= 1.38 \times 10^{-23}$ J/K

e = elementary charge $= 1.602 \times 10^{-19}$ C

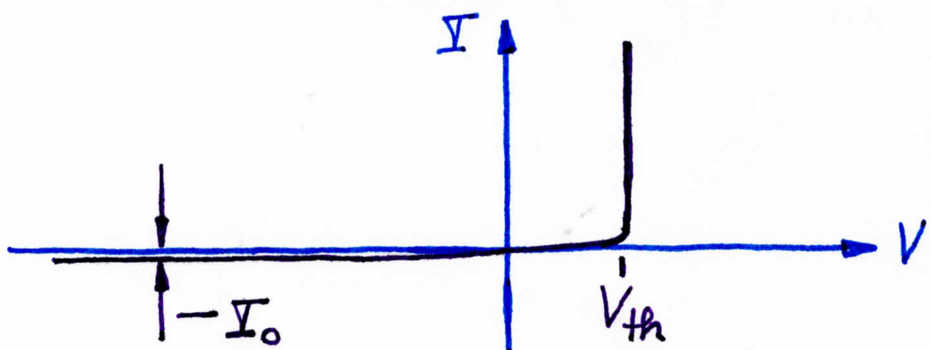
T = temperature $= 300$ K

I_0 = Reverse saturation current e.g. 10^{-10} A

Questions: $V = 0 \Rightarrow I = ?$

$V = -10V \Rightarrow I = ?$

$V > 0 \Rightarrow I$ grows exponentially



$\rightarrow V_{th} \approx 0.7V$ for Si

If we could freely choose parameters, what value would you choose for I_0? V_{th}?

Approximate IV characteristic for forward bias

Recall: $$I = I_0 \left(e^{V/V_t} - 1 \right)$$

For $V \gg V_t \Rightarrow V \gg 26\,mV$

$\Rightarrow$ e.g. $V = 200\,mV$

we realize $e^{V/V_t} \gg 1$

Therefore $$\boxed{I \approx I_0 \, e^{V/V_t}}$$

valid for $V \gg V_t$

thermal voltage

Diode differential resistance

Recall: $I = I_0 \, e^{V/V_t}$ (forward voltage regime)

Diode differential resistance

$$r_{Diode} = \frac{dV}{dI} = \left(\frac{dI}{dV}\right)^{-1} = \left(\frac{d}{dV} I_0 e^{V/V_t}\right)^{-1}$$

$$= \left(\underbrace{I_0 \, e^{V/V_t}}_{I} \frac{1}{V_t}\right)^{-1}$$

$$= \left(I \frac{1}{V_t}\right)^{-1} = \left(\frac{I}{V_t}\right)^{-1} = \frac{V_t}{I}$$

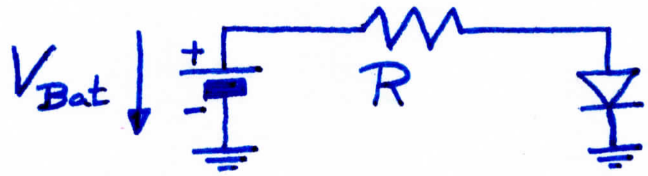
$$\Rightarrow \quad \boxed{r_{Diode} = V_t / I}$$

Example: $I = 1 A$

$$\Rightarrow \quad r_{Diode} = \frac{0.026 V}{1 A} = 0.026 \, \Omega$$

$\Rightarrow$ r_{Diode} is very small in the forward direction

Basic diode circuit



KVL $\qquad V_{Bat} = IR + V_{Diode}$

Recall: $\qquad I = I_{Diode} = I_0 \, e^{V/V_t}$

Insert in KVL: $\qquad V_{Bat} = \underbrace{I_0 \, e^{V_{Diode}/V_t}}_{\to I_R = I_{Diode}} R + V_{Diode}$

The equation has one unknown: V_{Diode}.

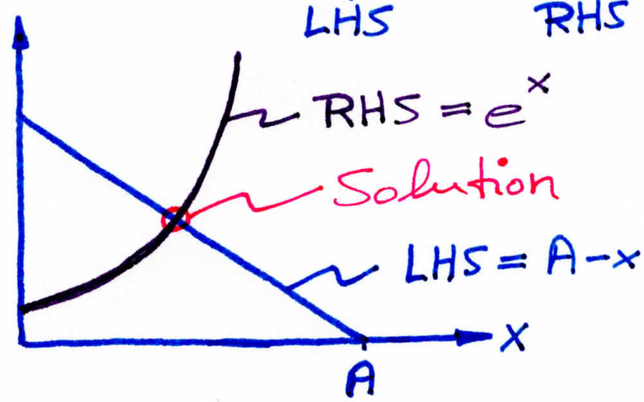
Solve for V_{Diode}? Can eqn. be solved?

Mathematically, the eqn. has the following form

$A = e^x + x \Rightarrow$ Cannot be solved.

$\Rightarrow$ Problem!

$$\underbrace{A - x}_{LHS} = \underbrace{e^x}_{RHS}$$

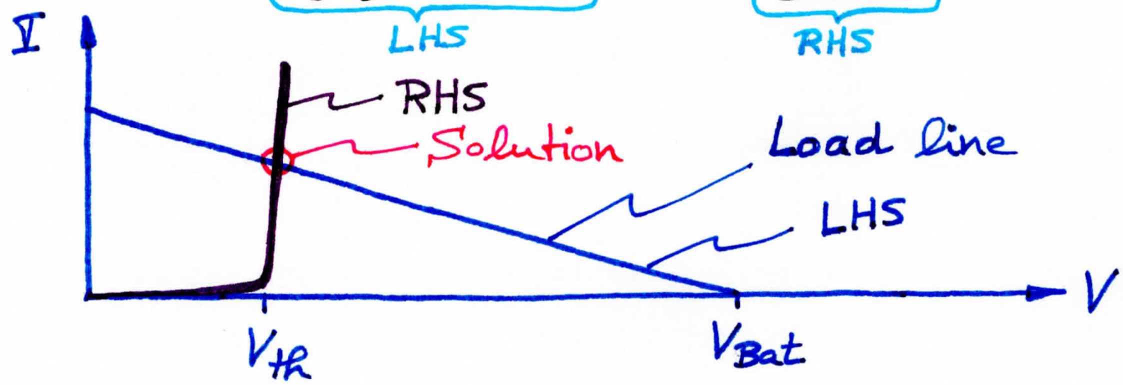


$\Rightarrow$ Graphical solution is possible!

Graphical solution

We showed: $V_{Bat} = IR + V_{Diode}$

$$\Rightarrow \quad \underbrace{V_{Bat} - IR}_{LHS} = \underbrace{V_{Diode}}_{RHS}$$



$\Rightarrow$ Graphical solution is possible

Approximate analytic solution

Assume $V_{Diode} = V_{th} = 0.7V$ (forward direction)

$$\Rightarrow \quad V_{Bat} = IR + V_{th}$$

$$= IR + 0.7V$$

$$\Rightarrow \quad I = (V_{Bat} - 0.7V)/R$$

$\Rightarrow$ Approximate analytic solution is possible!