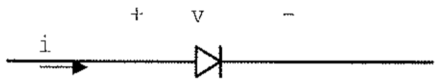
Voltage-current relationship of a p-n junction diode



$i = I_S(e^{qV/nkT} - 1)$

$V_T = kT/q$

I_S saturation current (reverse saturation), $I_S > 0$

k Boltzmann's constant; $k = 1.38\times10^{-23}$ joules/K = 8.62×10^{-5} eV/K

T Absolute temperature = 273 + temperature in °C

q 1.60×10^{-19} coulombs = 1 e

n an adjusting factor (emission coefficient), $1 \le n \le 2$

V_T volt-equivalent of temperature, thermal voltage
= T/116000 volts
≅ 25 mV at room temperature (20 °C, T = 293 K)
≅ 26 mV at temperature 25 °C

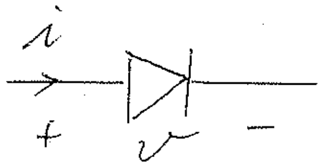
When v > the cut-in voltage, $i \cong I_S\, e^{qv/nkT} = I_S \exp(qv/kT)$.

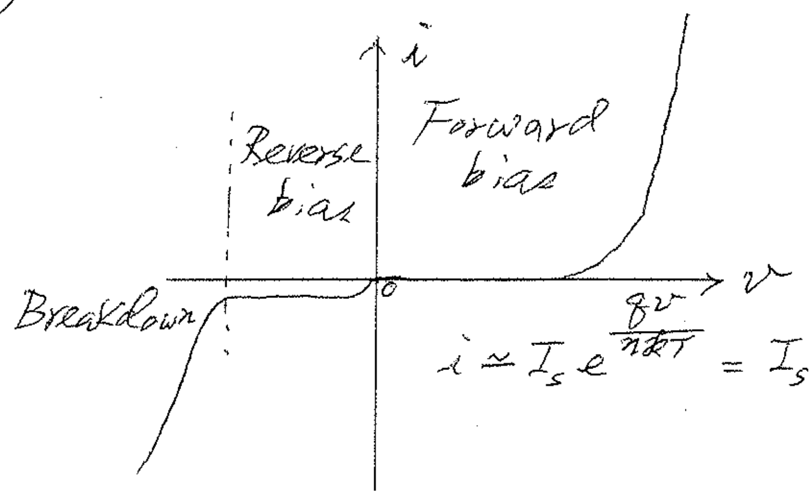
Cut-in voltage 0.2 to 0.3 volts for a germanium diode
0.5 to 0.6 volts for a silicon diode

$I_S(T) = I_S(T_1) \times 2^{(T-T_1)/10}$ A

$$\frac{dv}{dT} \cong -2.2mV/°C \qquad (\cong -2mV/°C)$$

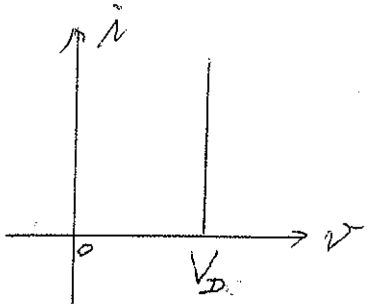
Modeling the diode

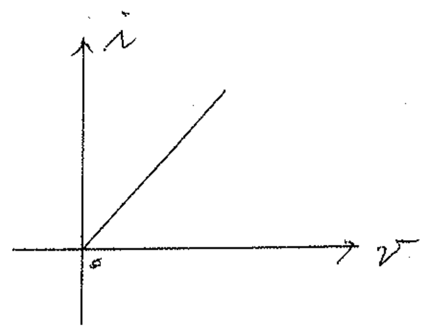




$$i \simeq I_s e^{\frac{qv}{nkT}} = I_s e^{\frac{v}{nV_T}}$$

Forward-biased diode piecewise linear characteristics



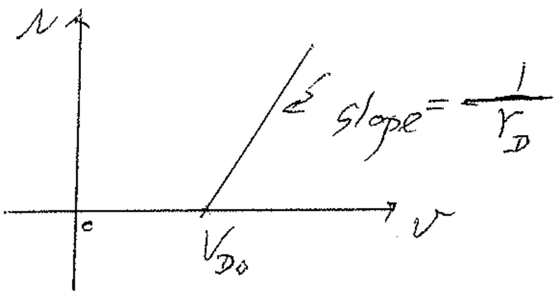


Small signal model

$$\frac{di}{dv} \simeq I_s \cdot \frac{1}{nV_T} e^{\frac{v}{nV_T}}$$

$$r_d \simeq \frac{nV_T}{i}$$

Incremental resistance



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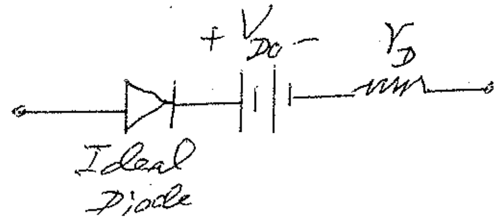
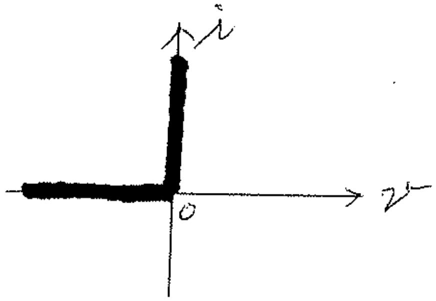


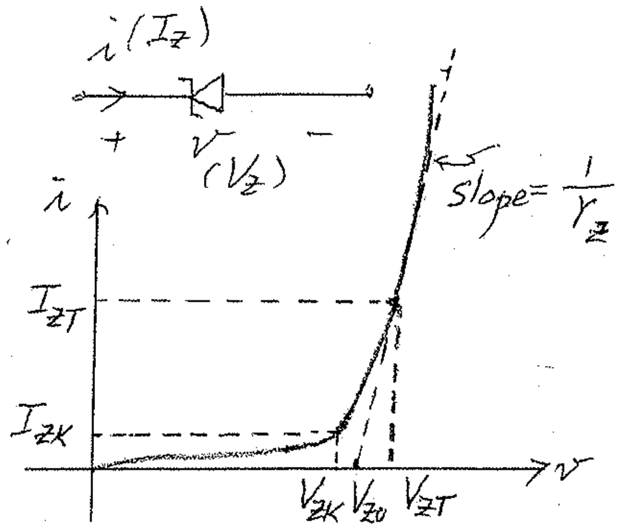
Ideal diode characteristic



$v < 0 \Rightarrow i = 0$

$i > 0 \Rightarrow v = 0$

Zener Diode (Breakdown diode)



dynamic resistance (incremental resistance)

$$r_Z = \frac{\Delta V_Z}{\Delta I_Z}$$

$$\Delta V_Z = r_Z \cdot \Delta I_Z$$

Ideally, $r_Z = 0$, $\Delta V_Z = 0$
V_Z is a constant.

Typically, $10\ V < V_Z < 6\ V$; $r_Z \approx$ a few ohms
Otherwise, $r_Z \approx$ hundreds of ohms
$V_Z < 5\ V$: negative temperature coefficient (TC)
Higher V_Z: postive temperature coefficient

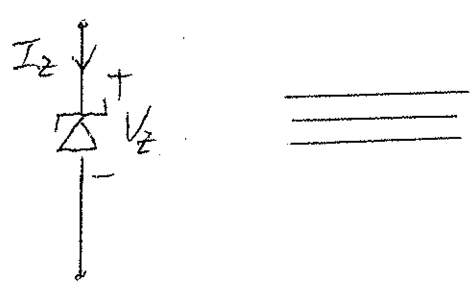
- I_{ZK} knee current (minimum current) for a good regulation
- V_{ZK} breakdown voltage (Zener voltage) at I_{ZK}
- I_{ZT} test current
- V_{ZT} Zener voltage at I_{ZT}
- r_Z dynamic resistance at I_{ZT} and V_{ZT}
- P_Z Power rating (Watts); $P_Z = I_{ZT} V_{ZT}$

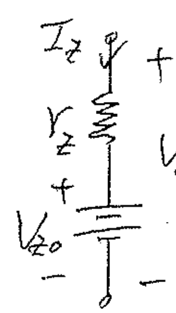
Equivalent circuit model of a Zener diode

$$v = V_{Z0} + r_Z i$$

or

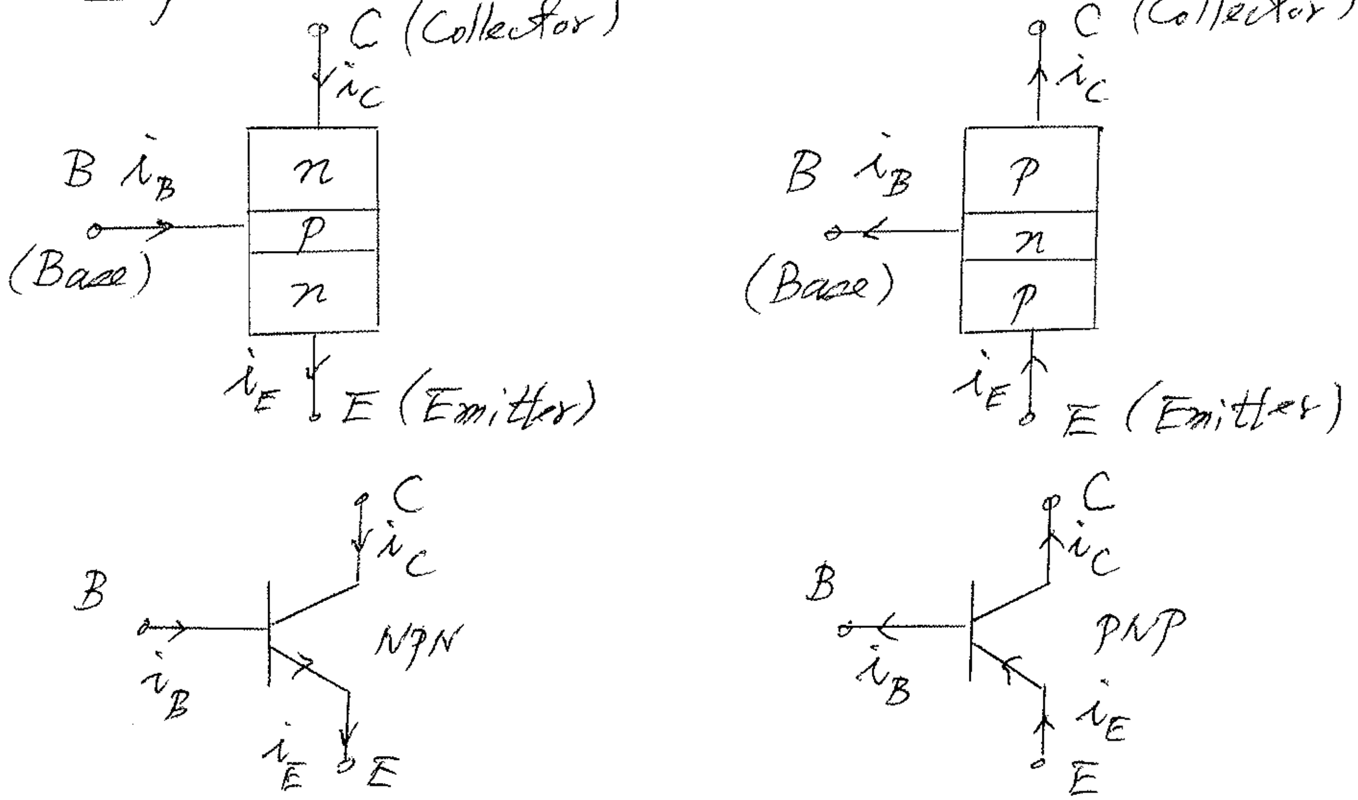
$$V_Z = V_{Z0} + r_Z \cdot I_Z$$





if $I_Z \geq I_{ZK}$ and $V_Z \geq V_{ZK}, V_{Z0}$

Bipolar Junction Transistor (BJT)



$$i_B + i_C = i_E$$

Four Regions of Operations

① Cutoff — Both junctions reverse biased.

② Active — EB forward biased, CB reverse biased
(Normal, Forward)

③ Saturation — Both junctions forward biased

④ Reverse active — EB reverse biased, CB forward biased
(Inverted active)

Cutoff Region

$I_E = 0$, $I_C = I_{Co}$ (Reverse leakage Current)
$= I_{CBO}$ (Very small)

$I_B = - I_C$

$I_B \simeq 0$, $I_C \simeq 0$ and $I_E = 0$

Active Region

$$|V_{BE}| = 0.7\,V \,, \quad I_B > 0$$

$$I_C = \beta I_B \,, \quad I_E = (\beta + 1) I_B$$

Saturation Region

$V_{CE} = 0.2$ to 0.4 V for NPN BJT

$V_{EC} = 0.2$ to 0.4 V for PNP BJT

$|V_{BE}| = 0.75$ V to 0.8 V

$$I_C \leq \beta I_B$$

$$\frac{I_C}{I_B} = \beta_{forced} \leq \beta$$

$$\frac{\beta}{\beta_{forced}} = \text{overdrive factor}$$