Physics of Electronics:

7. Junction Diodes

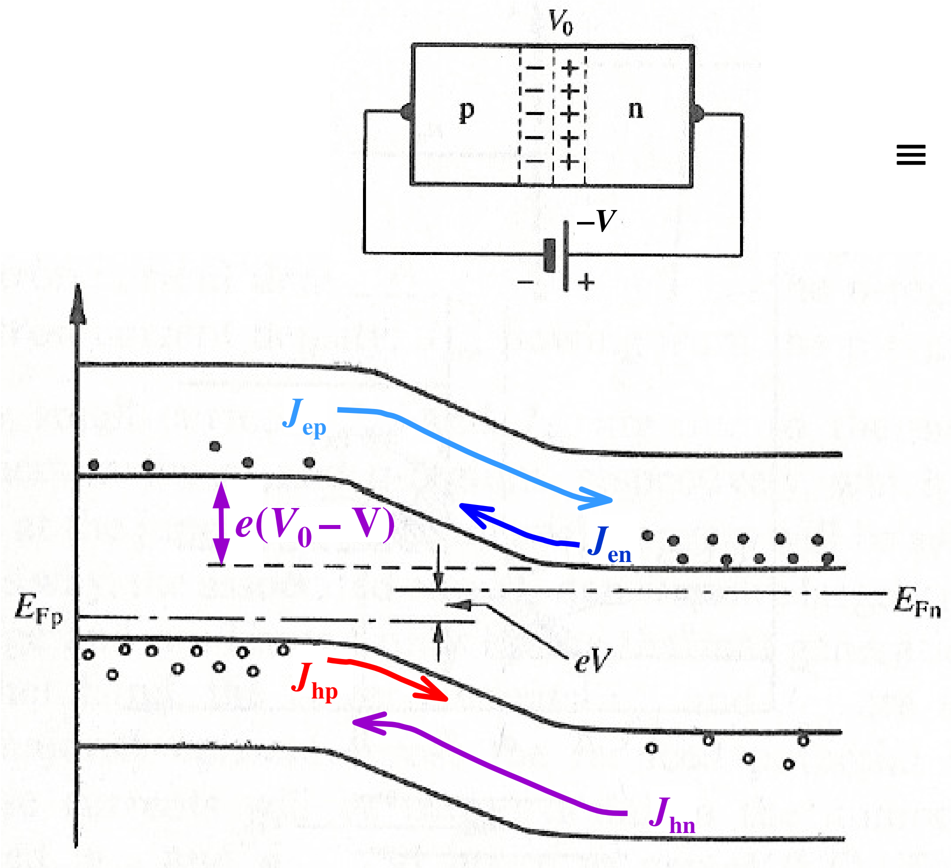
July – December 2008

Contents overview

- Small-signal equivalent circuit.
- Switching characteristics.
- Metal-semiconductor junctions.
- The Zener diode.
- The tunnel diode

Small-AC-signal equivalent circuit

- Reversed biased junction



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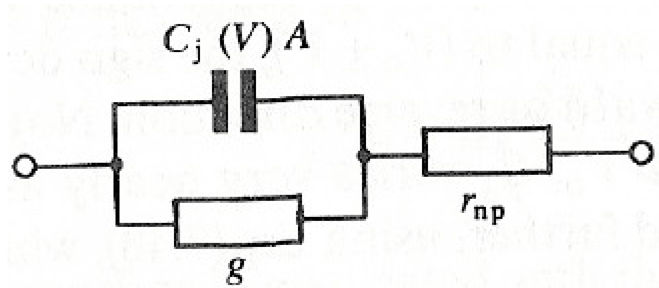


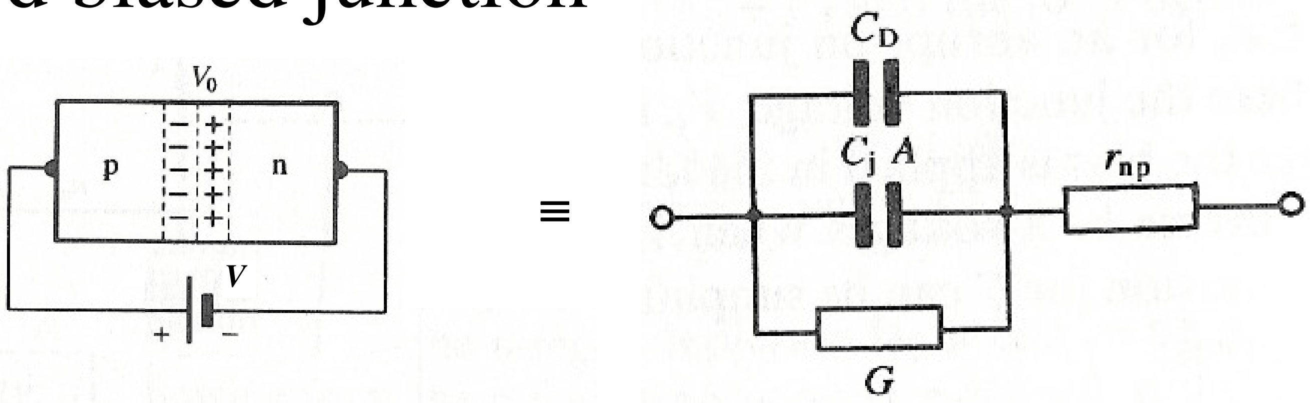
r_{np}: Resistance of the junction @ V=0

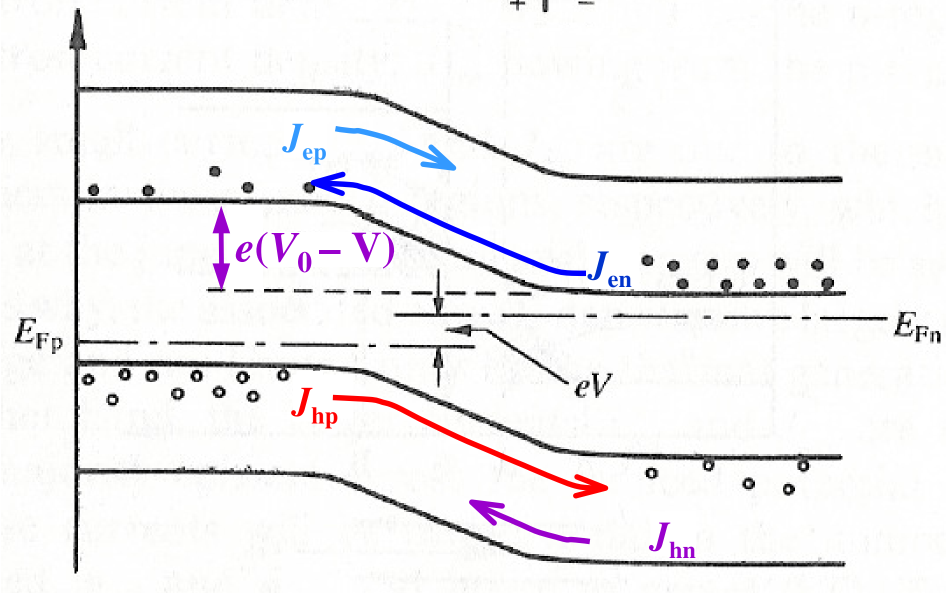
$C_j(V)$: Depletion layer capacitance

g: Conductance of the reverse flow

Small-AC-signal equivalent circuit

- Forward biased junction





r_{np}: Resistance of the junction @ V=0

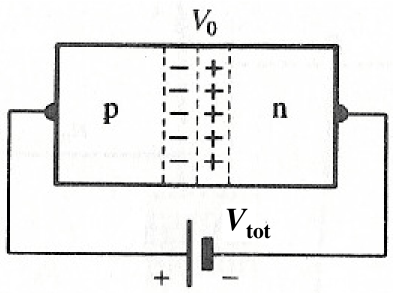
$C_j(V)$: Depletion layer capacitance

G: Conductance of the forward flow

C_D: Diffusion capacitance

Small-AC-signal equivalent circuit

- Forward biased junction



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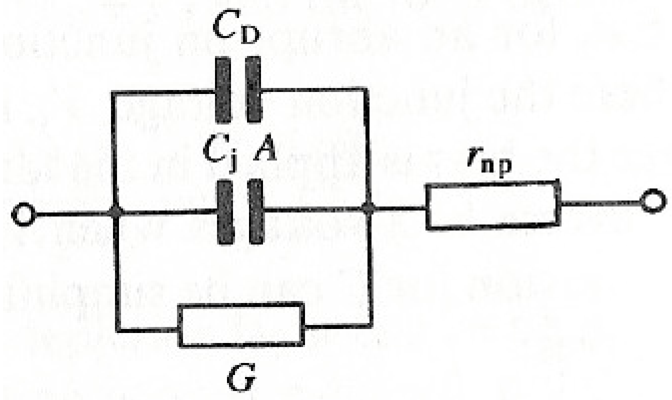


$$\left.\begin{aligned} V_{tot} &= V + V_1 \exp(i\omega t) \\ p_{n0} &= p_n \exp(eV/kT) \end{aligned}\right\} \Rightarrow p_{n0} = p_n \exp\left(\frac{e}{kT}[V + V_1 \exp(j\omega t)]\right)$$

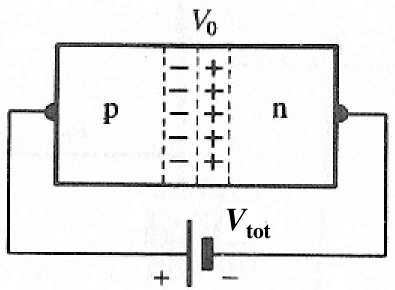
$$\xRightarrow{V_1 \ll V_0} \quad p_{n0} = \underbrace{p_n \exp\left(\frac{eV}{kT}\right)}_{\text{DC}} \underbrace{\left(1 + \frac{eV_1}{kT}\exp(j\omega t)\right)}_{\text{AC}}$$

- Therefore we can assume:

$$\delta p = p(x,t) - p_n = \underbrace{p_0(x)}_{\text{DC}} + \underbrace{p_1(x)\exp(j\omega t)}_{\text{AC}} - p_n$$

Small-AC-signal equivalent circuit

- Forward biased junction



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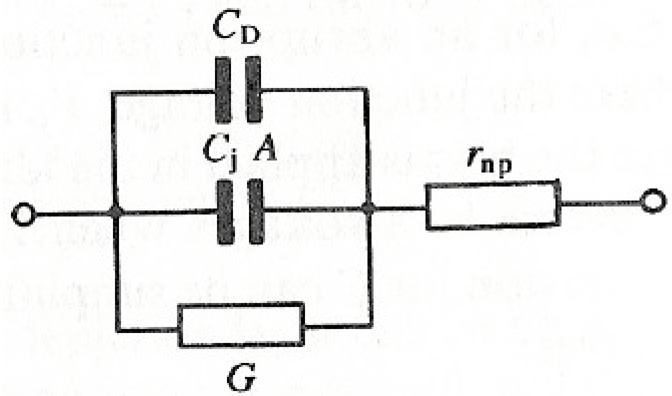


  – Applying continuity equation:

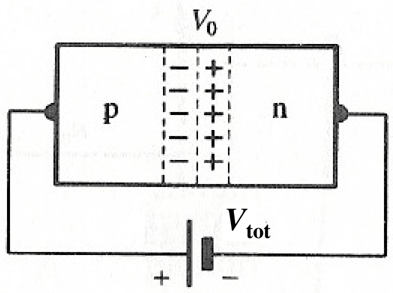
$$\frac{\partial(\delta p)}{\partial t} = -\frac{\delta p}{\tau_{Lh}} + \cancelto{0}{\mu_h \mathcal{E}_x} \frac{\partial(\delta p)}{\partial x} + D_h \frac{\partial^2(\delta p)}{\partial x^2} \Rightarrow \mathrm{j}\omega p_1 = \frac{-p_1}{\tau_{Lh}} + D_h \frac{\partial^2 p_1}{\partial x^2}$$

$$\Rightarrow \frac{\partial^2 p_1}{\partial x^2} = \frac{1 + \mathrm{j}\omega\tau_{Lh}}{L_h^2} p_1 \Rightarrow p_1 = C \exp\left(-\frac{(1 + \mathrm{j}\omega\tau_{Lh})^{1/2} x}{L_h} \right)$$

- But $p_1(x = 0) = p_{n0}$ $\Rightarrow$ $\boxed{p_1 = p_n \left(\frac{eV_1}{kT} \right) \exp\left(\frac{eV}{kT} \right) \exp\left(-\frac{(1 + \mathrm{j}\omega\tau_{Lh})^{1/2} x}{L_h} \right) \exp(\mathrm{j}\omega t)}$

Small-AC-signal equivalent circuit

- Forward biased junction



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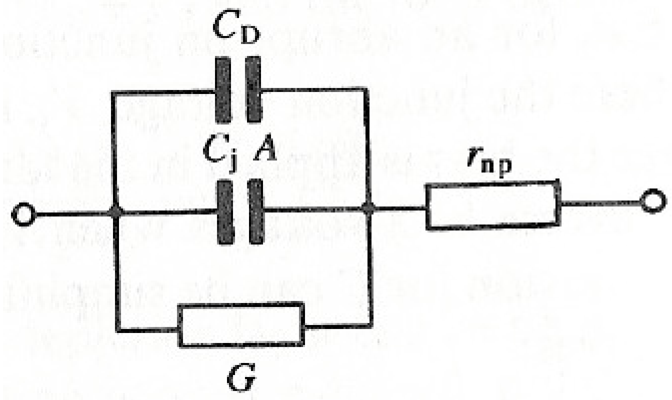


  – Alternating currents of holes injected into n-region:

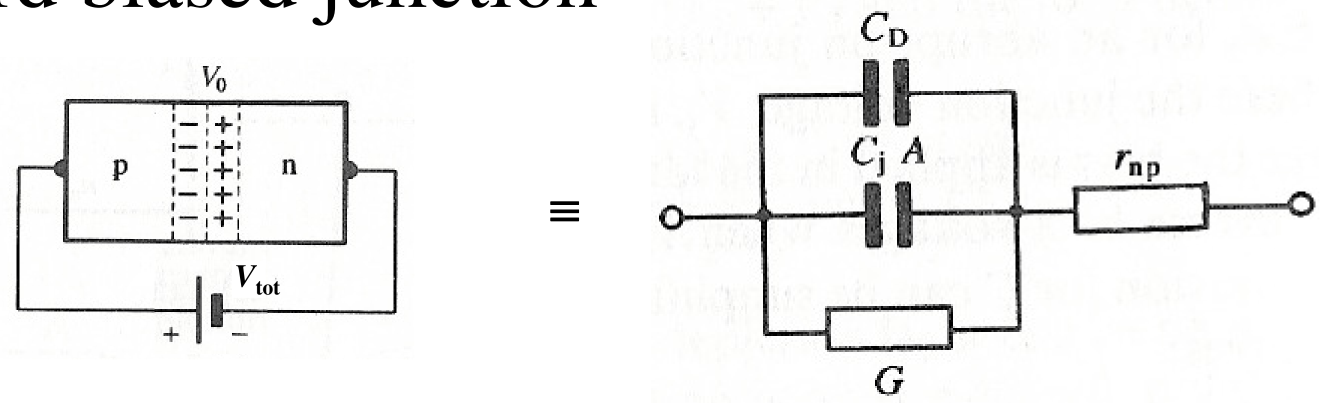
$$J_{h1} = -eD_h\left(\frac{dp_1(x)}{dx}\right)\bigg|_{x=0} = \frac{(1+i\,\omega\tau_{Lh})^{1/2}}{L_h}\,\frac{p_n D_h e^2 V_1}{kT}\exp\left(\frac{eV}{kT}\right)\exp(j\omega t)$$

  – Alternating currents of electrons injected into p-region:

$$J_{e1} = -eD_e\left(\frac{dn(x)}{dx}\right)\bigg|_{x=0} = \frac{(1+i\,\omega\tau_{Le})^{1/2}}{L_e}\,\frac{n_p D_e e^2 V_1}{kT}\exp\left(\frac{eV}{kT}\right)\exp(j\omega t)$$

Small-AC-signal equivalent circuit

- Forward biased junction



  – Total alternating currents of minority injected carriers:

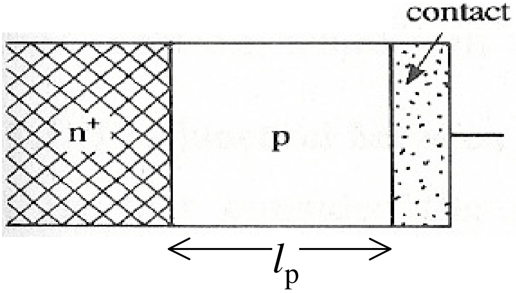
$$J_1 = J_{h1} + J_{e1}$$

  – Admittance ($Y_1 = J_1/V_1$) for $\omega\tau \ll 1$:

$$Y_1 \cong \underbrace{\frac{e^2}{kT}\exp\left(\frac{eV}{kT}\right)\left(\frac{D_h p_n}{L_h}+\frac{D_e n_p}{L_e}\right)}_{G} + \underbrace{\frac{j\omega e^2}{2kT}\left(\frac{D_h p_n \tau_{Lh}}{L_h}+\frac{D_e n_p \tau_{Le}}{L_e}\right)}_{C_D}$$

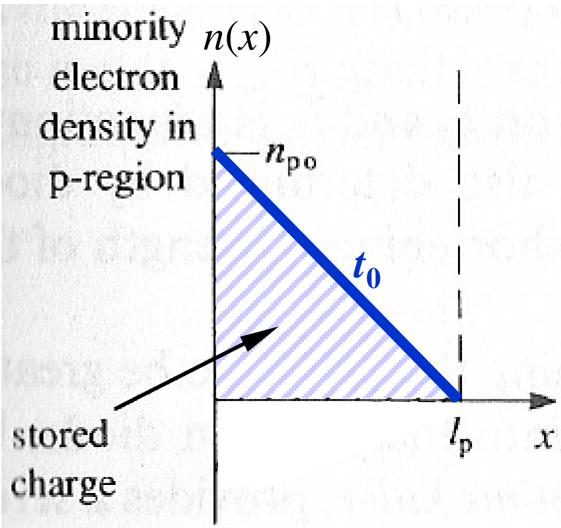
Switching Characteristics

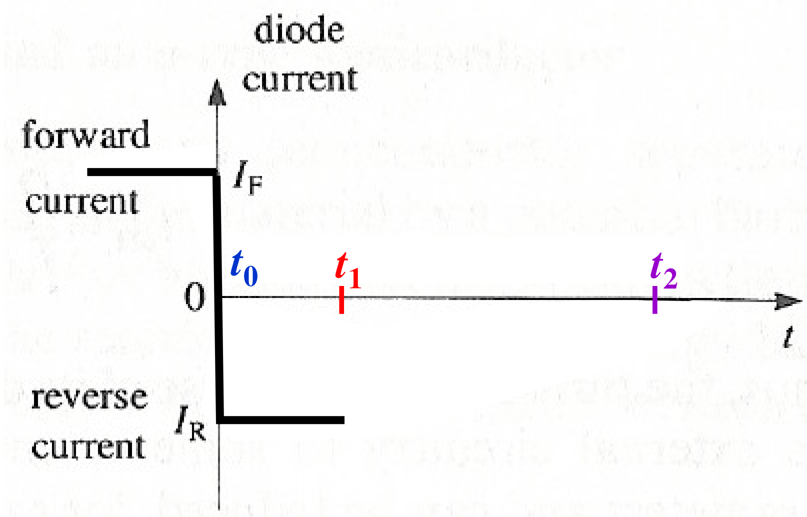
- Consider a forward biased np junction



$$n(x)=\left(\frac{n_p\exp(-l_p/L_e)+n_{p0}-n_p}{1-\exp(-2l_n/L_h)}\right)\exp(-x/L_e)$$
$$-\left(\frac{n_p\exp(-l_p/L_e)+n_{p0}-n_p}{1-\exp(-2l_p/L_e)}-(n_{p0}-n_p)\right)\exp(+x/L_e)+n_p$$

  – With $l_p \le L_e$, what if the junction is suddenly reversed?

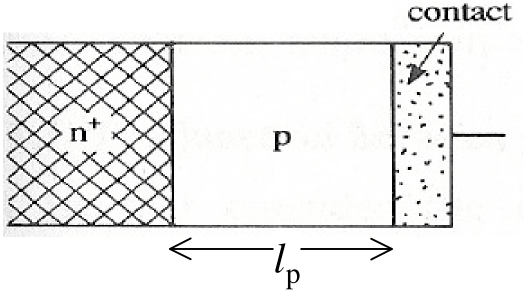




$t < t_0$: junction forward biased, $n(x)$ is linear.
$t = t_0$: junction reversed biased.
$t < t_1$: $n(x)$ starts decreasing but $I_R \cong I_F$.

Switching Characteristics

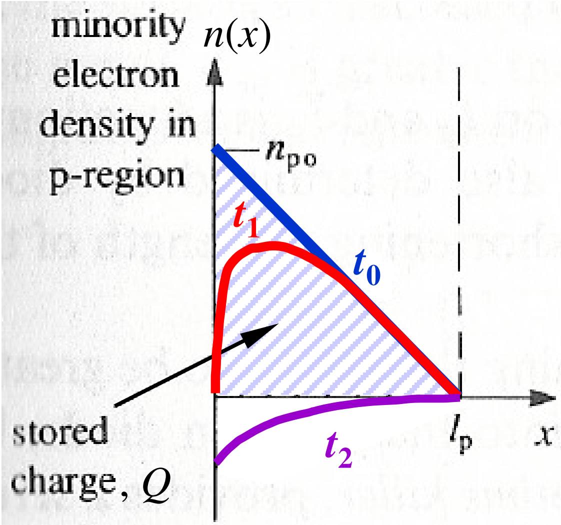
- Consider a forward biased np junction

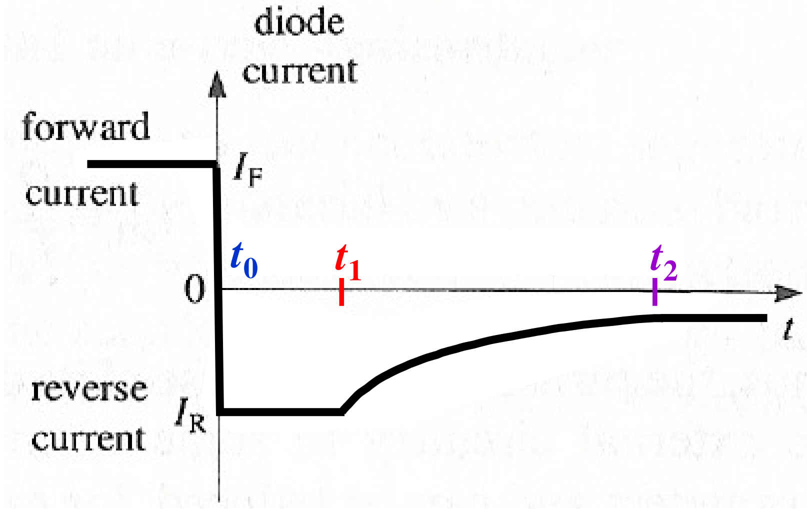


$$n(x)=\left(\frac{n_p\exp(-l_p/L_e)+n_{p0}-n_p}{1-\exp(-2l_n/L_h)}\right)\exp(-x/L_e)$$

$$-\left(\frac{n_p\exp(-l_p/L_e)+n_{p0}-n_p}{1-\exp(-2l_p/L_e)}-(n_{p0}-n_p)\right)\exp(+x/L_e)+n_p$$

  – With $l_p \le L_e$, what if the junction is suddenly reversed?





$t = t_1$: $n(x)$ keeps decreasing but I_R cannot be maintained.

$t < t_2$: $n(x)$ and current decrease further.

$t = t_2$: $n(x)$ and current reach the steady reversed values.

Switching Characteristics

- Estimation of the time t_{off} that takes to deplete the stored charge Q:
  - Q is given by:

$$Q = A\int_0^{l_p} \rho(x)\,dx \qquad \text{where} \qquad \rho(x) = n(x)e = en_{p0}(1 - x/l_p)$$

  - $n(x)$ can be expressed in terms of the currents:
    - Definition of density current $J_{Fe} = ev(x)n(x)$
    - Assuming only diffusion $J_{Fe} = eD_e\,dn/dx$
    - From the measured I_F $J_{Fe} = I_F/A$

$$\left.\begin{array}{l} J_{Fe} = ev(x)n(x) \\ J_{Fe} = eD_e\,dn/dx \\ J_{Fe} = I_F/A \end{array}\right\} \Rightarrow \rho(x) = I_F(l_p - x)/AD_e$$

$$\therefore \quad Q = I_F l_p^2/2D_e$$

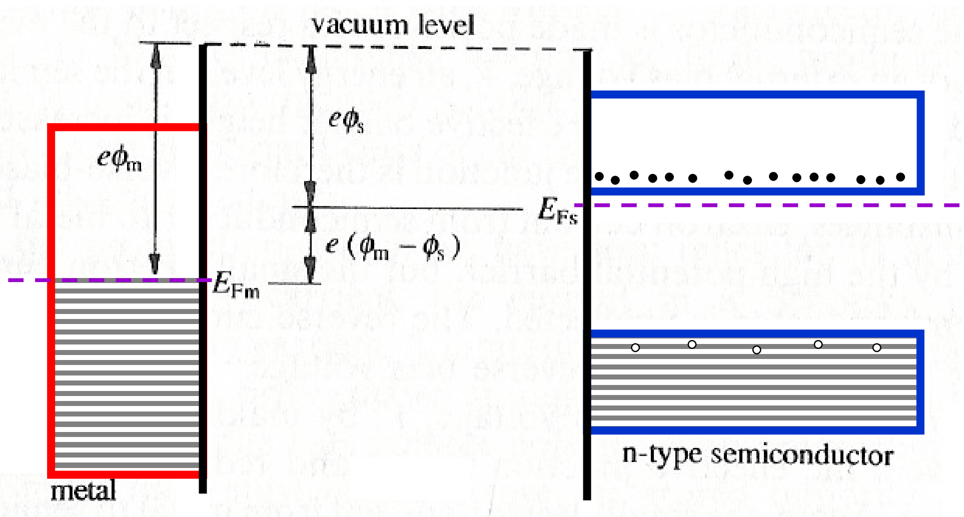
  - In average, the current I_R is then:

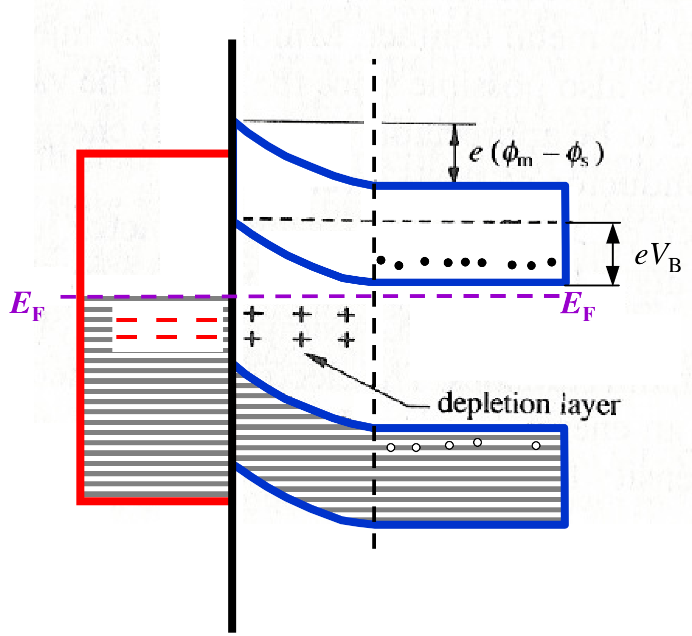
$$\bar{I}_R = Q/t_{off} \Rightarrow \boxed{t_{off} = \frac{I_F}{\bar{I}_R}\frac{l_p^2}{2D_e}}$$

It can be tailored!!!

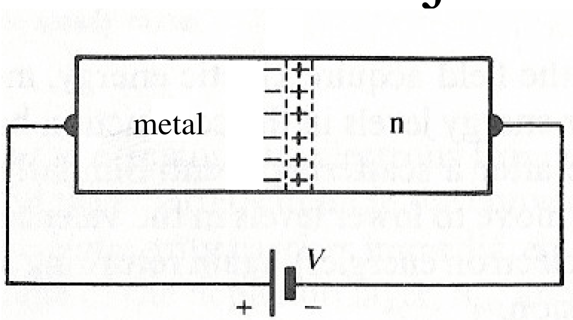
Metal-sC junctions

- Metal – n-type sC or Schottky junction ($\phi_m > \phi_s$):
  - Unbiased junction:





  - Biased junction:



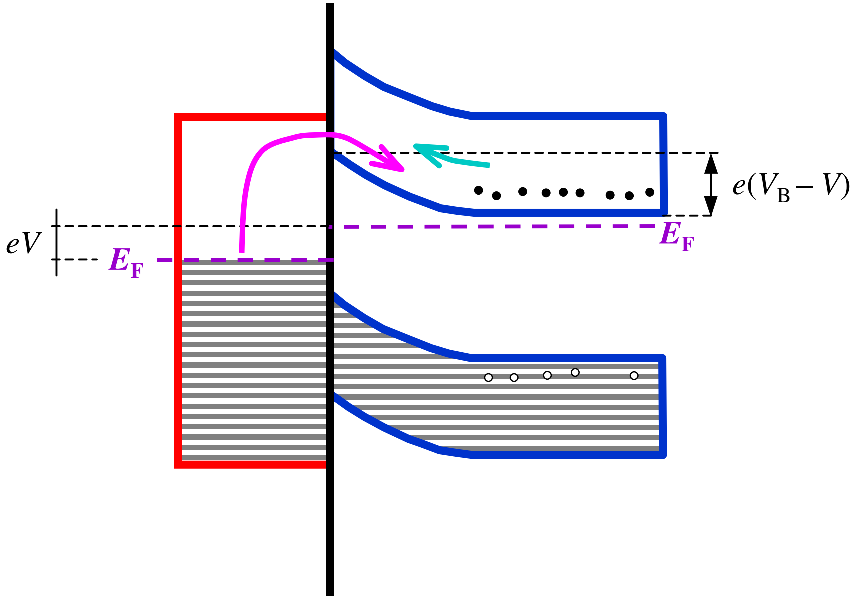
• Forward biased: $V_B \rightarrow V_B - V$ (sC-to-m currents fostered)

• Reversed biased: $V_B \rightarrow V_B + V$ (sC-to-m currents suppressed)

Contact is, therefore, not ohmic!!!!

Metal-sC junctions

- Metal – n-type sC or Schottky junction ($\phi_m > \phi_s$):
  - Currents in a forward biased junction:



$J_{ms} \propto \exp(-eV_B/kT)$

$J_{sm} \propto \exp[-e(V_B - V)/kT]$

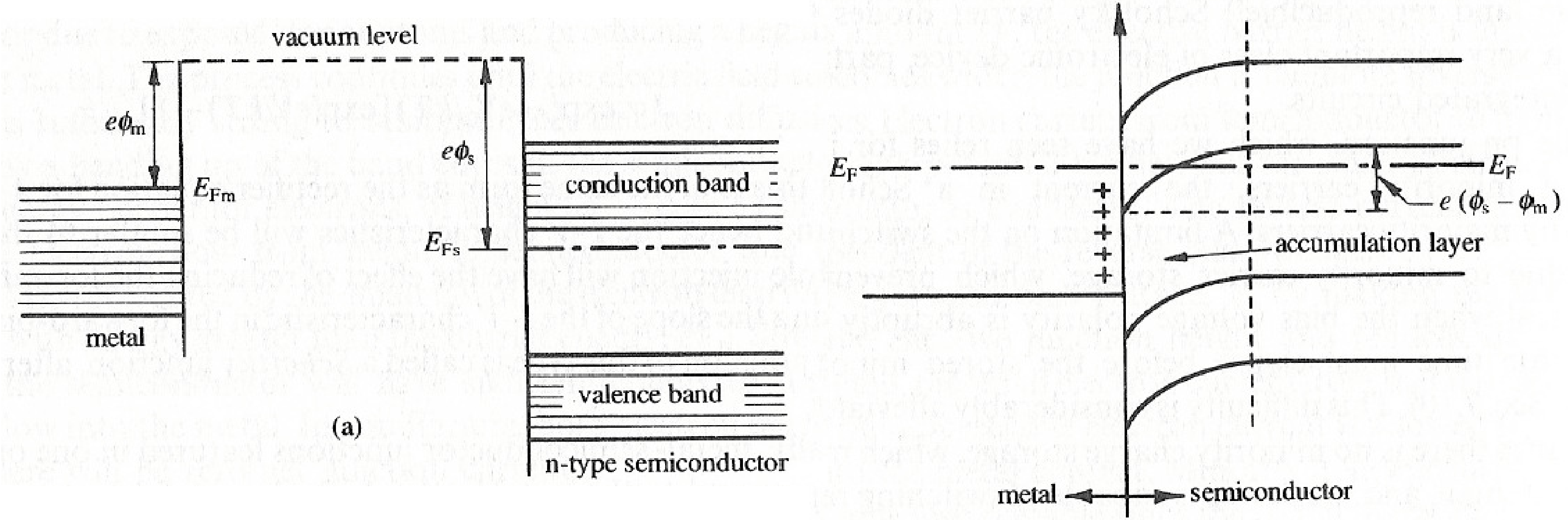
Electron majority current is then:

$$\boxed{J \propto \exp(-eV_B/kT)\,[\exp(eV/kT) - 1]}$$

  - Similar to pn junction but much faster when switching (no minority charge storage)

Metal-sC junctions

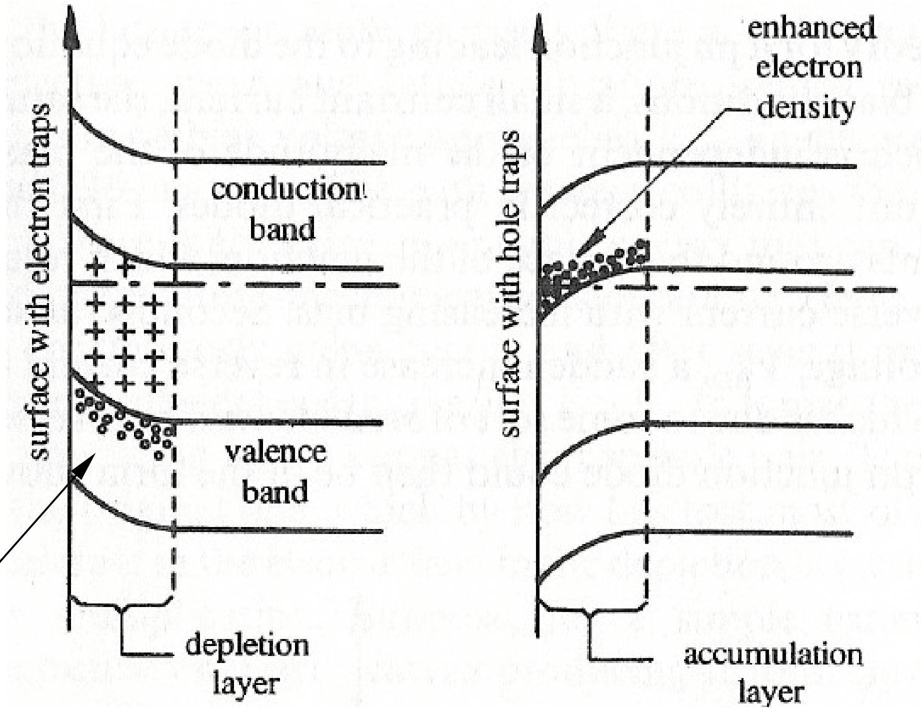
- Metal – n-type sC junction ($\phi_s > \phi_m$):
  - Unbiased junction:



    - No potential barrier is formed.
    - Ohmic contact (i.e. no rectification).
- Homework: analyze a metal – p-type sC junction.

Metal-sC junctions

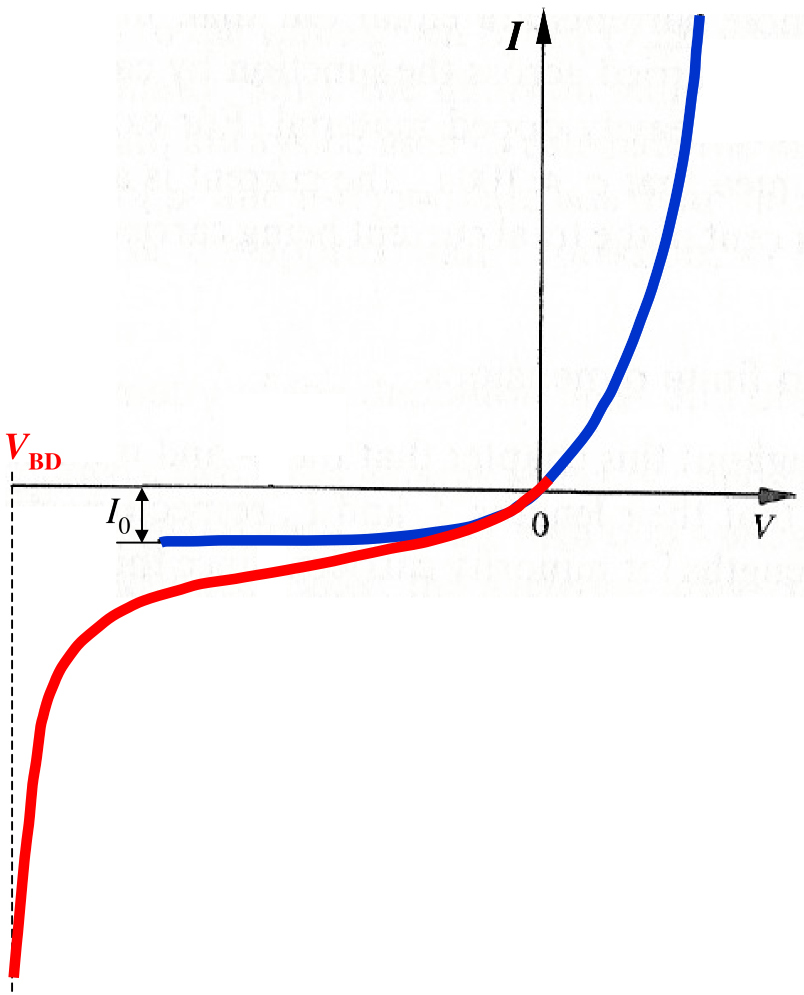
- Surface states:
  - The surface can be affected by oxidation/absorption of impurity atoms.
  - These states can act as electron/hole traps.
  - Consider an n-type sC:



Electrons are trapped and holes are created (p-type layer)

The Zener Diode

- Breakdown voltage

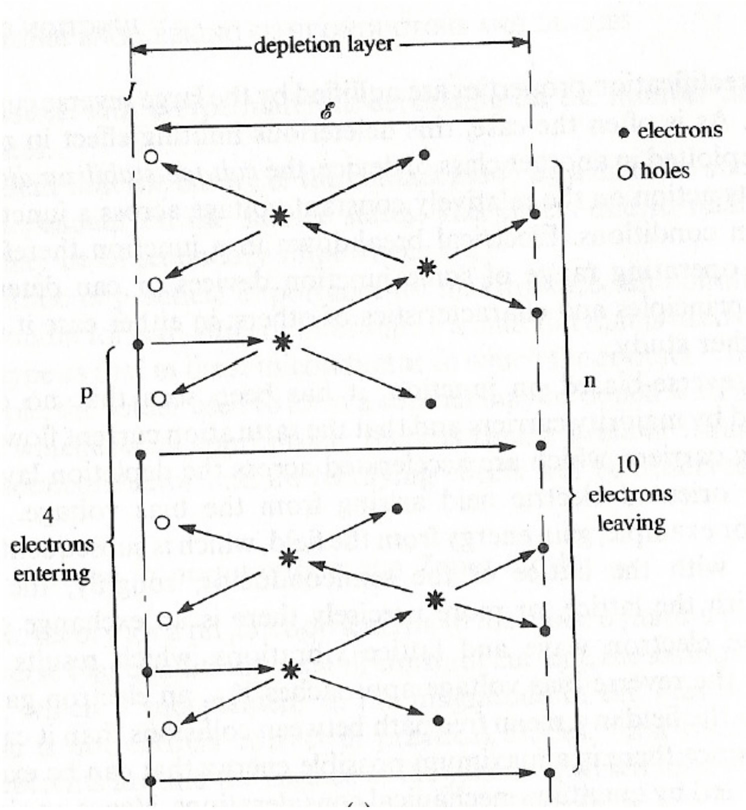


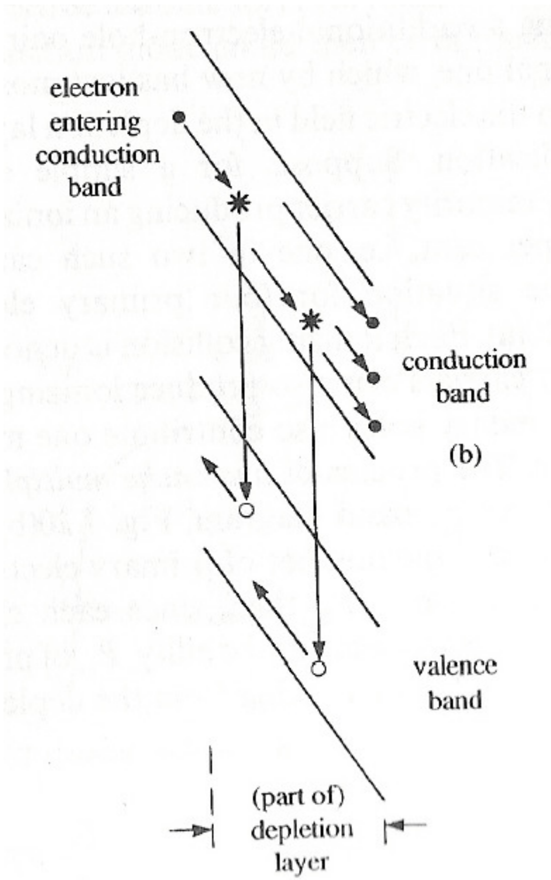
Ideal diode: current limited if reversed biased

Real diode: voltage limited if reversed biased

The Zener Diode

- Avalanche breakdown

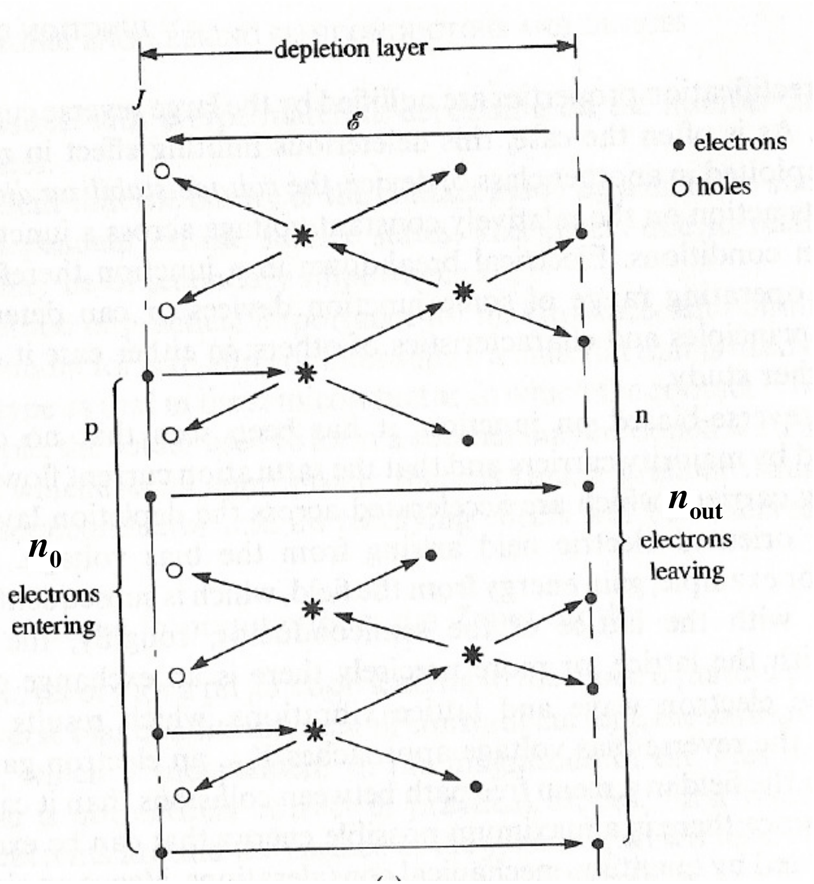




- Energy acquired by electrons is limited by collisions.
- Dominant effect in wider junctions and moderate doping.
- V_{BD} is T dependent (because mean free path is T dependent).

The Zener Diode

- Avalanche breakdown



1st collision 2nd collision

$$n_{out} = n_0 + P_i n_0 + P_i(P_i n_0) + \dots = n_0 \sum_{m=0}^{\infty} P_i^m$$

- Multiplication factor:

$$M = n_{out}/n_0 = \sum_{m=0}^{\infty} P_i^m = 1/(1 - P_i)$$

where $\quad P_i = 0$ when $V = 0$

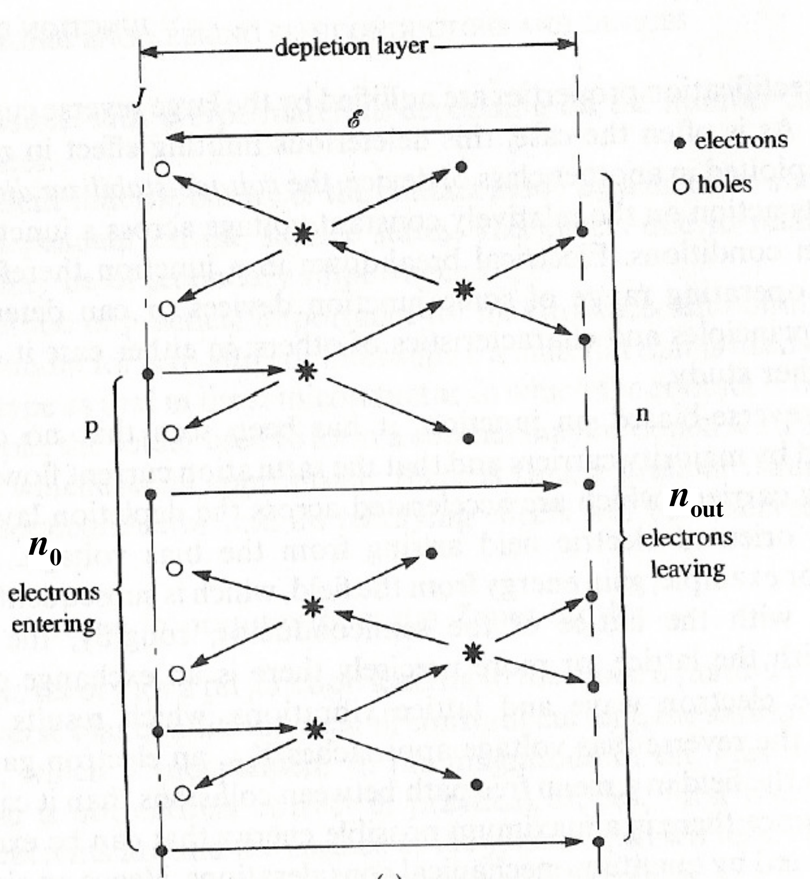
$\qquad\quad P_i \to 1$ as $V \to V_{BD}$

- Experimentally it is found:

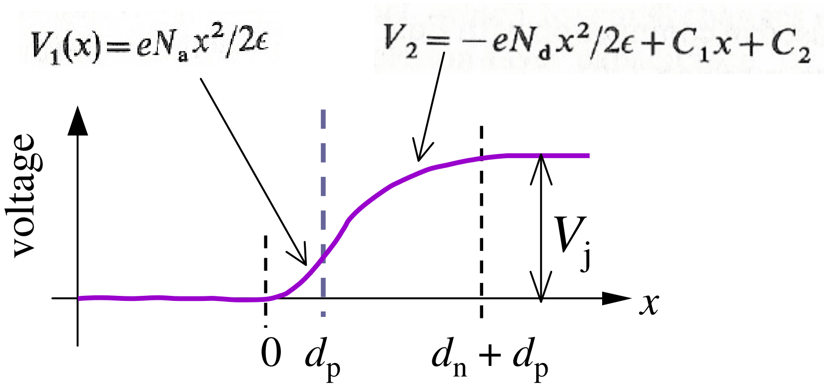
$$P_i = (V/V_{BD})^n \quad \Rightarrow \quad M = [1 - (V/V_{BD})^n]^{-1}$$

The Zener Diode

- Avalanche breakdown



- Through the depletion layer we found:



- Electric field in the depletion layer:

$$\frac{\partial V_2}{\partial x} = \mathscr{E} = \frac{-eN_d x}{\epsilon} + \frac{ed_p(N_a + N_d)}{\epsilon}$$

$$\mathscr{E}_{max} = ed_p N_a/\epsilon = \left(\frac{2eV_j N_d N_a}{\epsilon(N_a + N_d)}\right)^{1/2}$$

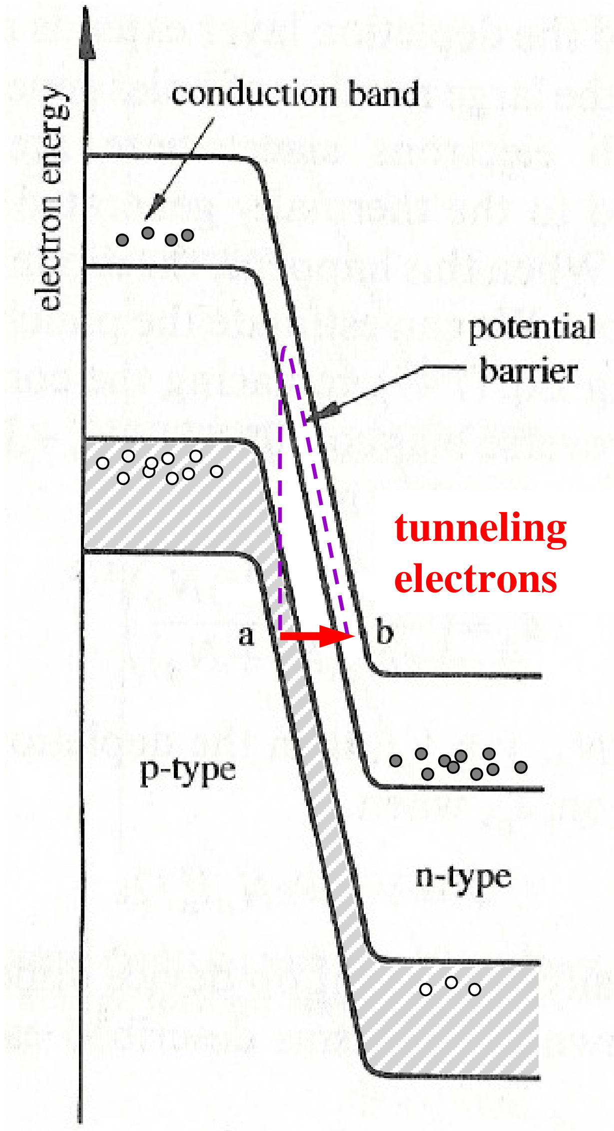
$$\mathscr{E}_{max,B} = \left(\frac{2eV_{BD} N_d N_a}{\epsilon(N_a + N_d)}\right)^{1/2}$$

$$\boxed{V_{BD} \propto \frac{N_a + N_d}{N_d N_a}}$$

It can be tailored!!!

The Zener Diode

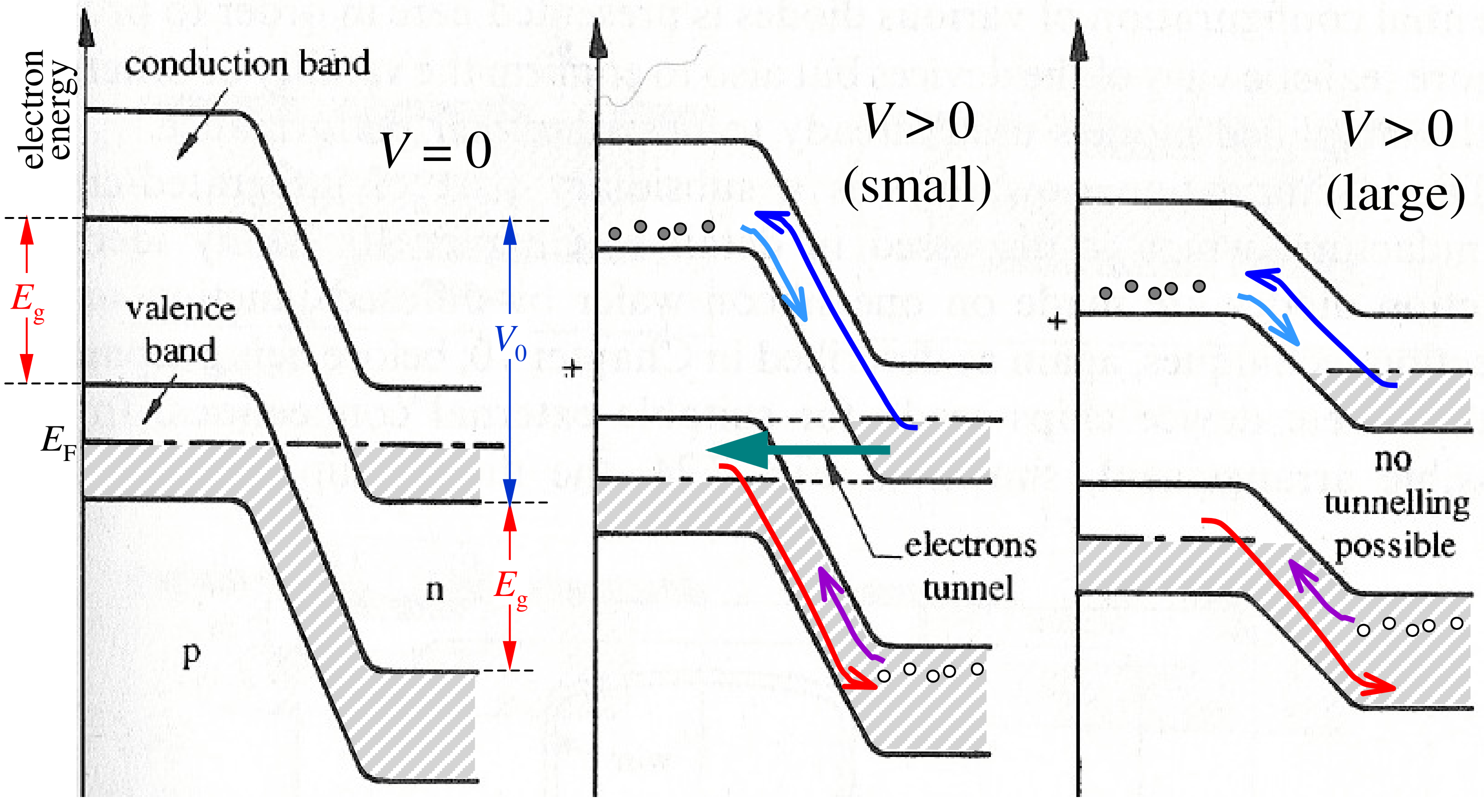
- Zener breakdown



- It occurs in highly doped junctions (thin depletion layer).
- Electrons in the valence band can tunnel to the conduction band.
- V_{BD} is T independent.

The Tunnel Diode

- Consider highly-doped pn junctions
  - Fermi energies cross the bands.
  - V_0 is large [$V_0 \simeq \frac{kT}{e} \log_e\left(\frac{N_d N_a}{n_i^2}\right)$] & d_p, d_n short [$d_p = \left(\frac{2\epsilon V_0 N_d}{eN_a(N_a+N_d)}\right)^{1/2}$]
  - Tunneling is favored.



The Tunnel Diode

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  - Tunneling is favored (very fast response).
  - Extra current source at V small.