

Physics of Electronics:

6. Junction Diodes

July – December 2009

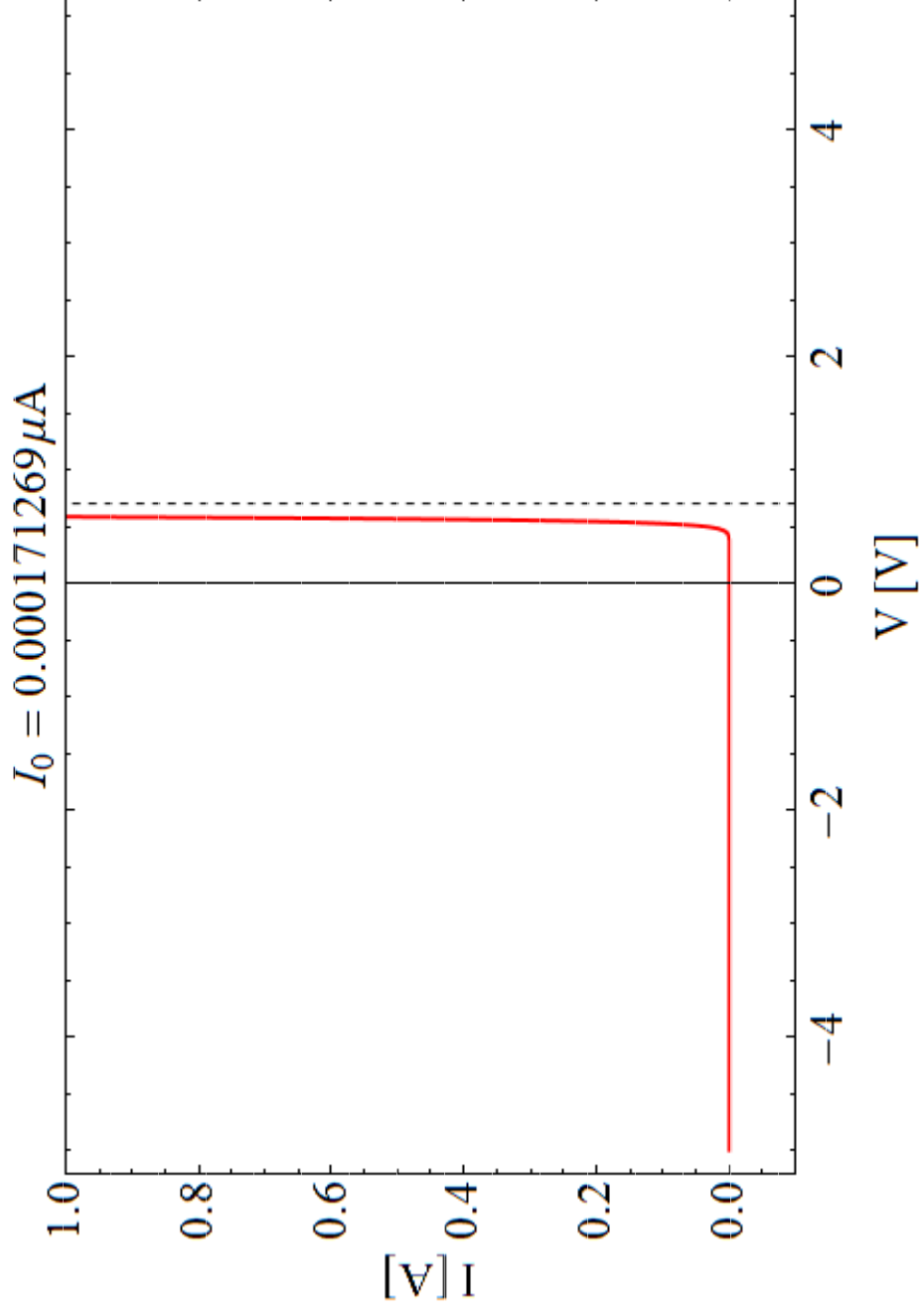
Contents overview

- Biased junction diode.
- Diode capacitance.
- Metal – semiconductor junctions.
- Zener diode.
- Tunnel diode.

Diode Equation

- Characteristic IV curve

$$J = J_h + J_e = e \left(\frac{D_h p_n}{L_h} + \frac{D_e n_p}{L_e} \right) [\exp(eV/kT) - 1]$$



Depletion-layer capacitance

- The depletion layer forms a capacitance (important for high frequency applications)

Using Poisson relation ($\partial^2 V / \partial x^2 = -\rho / \epsilon$)
and boundary conditions:

I: $V_1(x) = eN_a x^2 / 2\epsilon$

II: $V_2 = -eN_d x^2 / 2\epsilon + C_1 x + C_2$

$$C_1 = ed_p(N_a + N_d)/\epsilon \quad C_2 = -\frac{ed_p^2(N_a + N_d)}{2\epsilon}$$

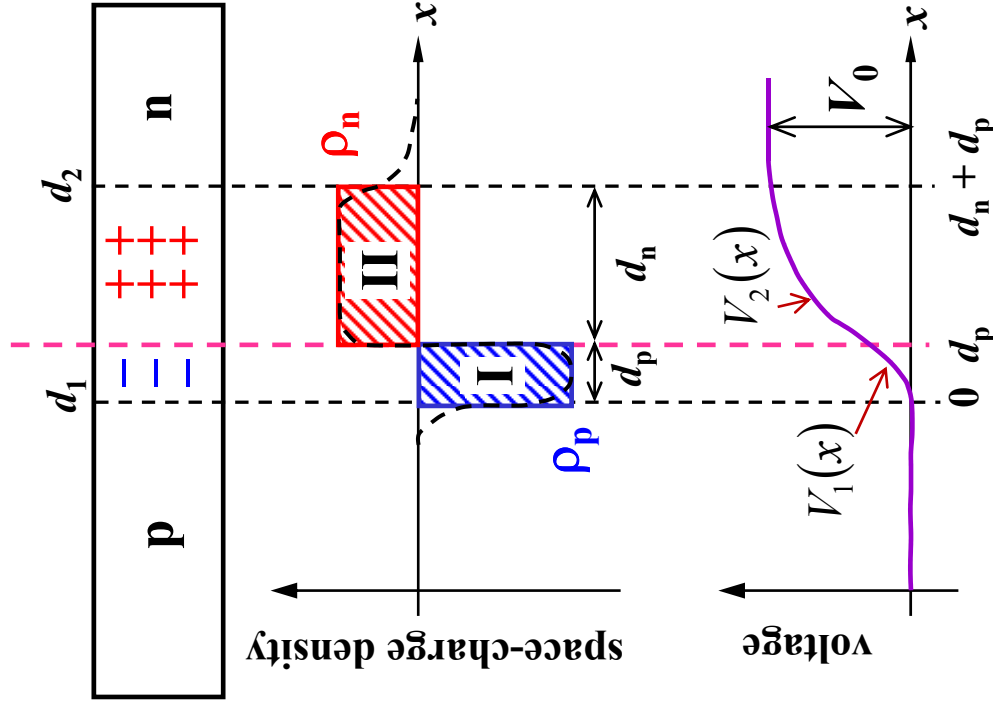
$$(\partial V_2 / \partial x)|_{d_n + d_p} = 0$$

$$d_p / d_n = N_d / N_a$$

$$V_2|_{d_n + d_p} = V_0$$

$$d_p = \left(\frac{2\epsilon V_0 N_d}{eN_a(N_a + N_d)} \right)^{1/2}$$

For a biased junction: $V_0 \leftrightarrow V_0 - V$



Depletion-layer capacitance

- Capacitance of the depletion layer:
 - Charge per unit area accumulated at the depletion layer

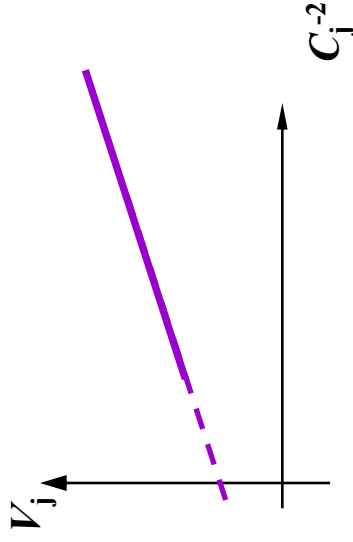
$$Q_j = eN_d d_n = eN_a d_p \quad \xrightarrow{V_j = V_0 \pm V} \quad Q_j = \left(\frac{2\epsilon e V_j N_a N_d}{N_a + N_d} \right)^{1/2}$$

- The capacitance per unit area ($C_j = dQ_j/dV_j$) is then:

$$C_j = \left(\frac{\epsilon e N_a N_d}{2(N_a + N_d)} \right)^{1/2} \frac{1}{V_j^{1/2}} \quad \xrightarrow{\hspace{1cm}} \quad C_j = \epsilon / (d_p + d_n)$$

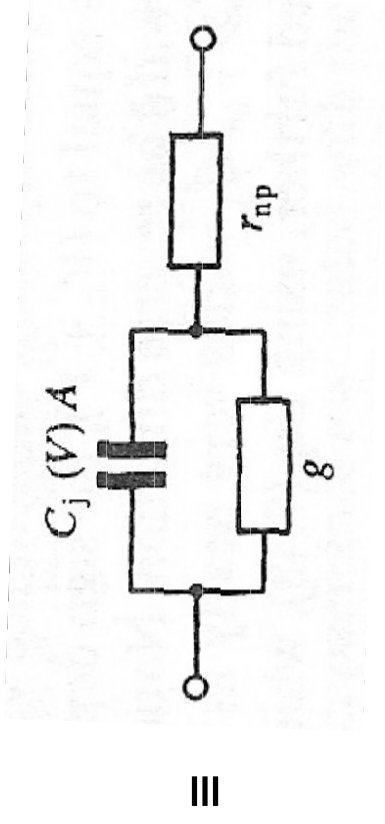
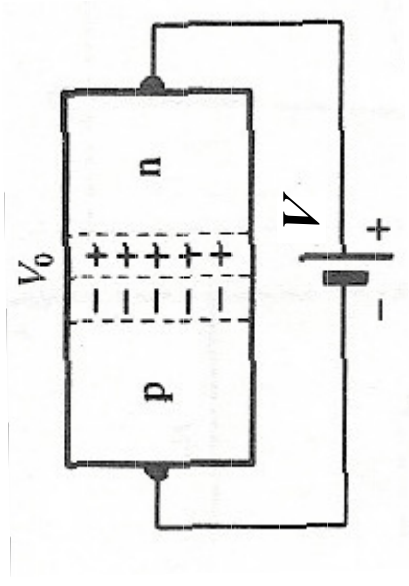
$$N_a \gg N_d$$

$$V_j = V_0 + V \simeq \frac{1}{C_j^2} \left(\frac{\epsilon e N_d}{2} \right)^{1/2}$$



Equivalent circuit

- Reversed biased junction:



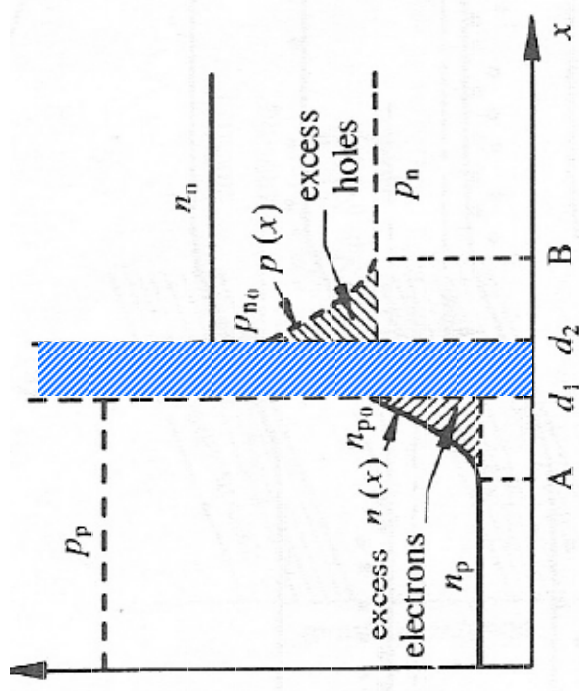
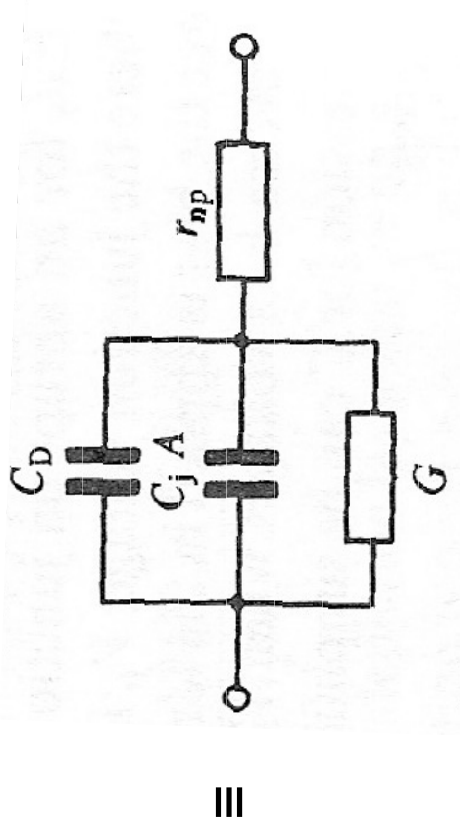
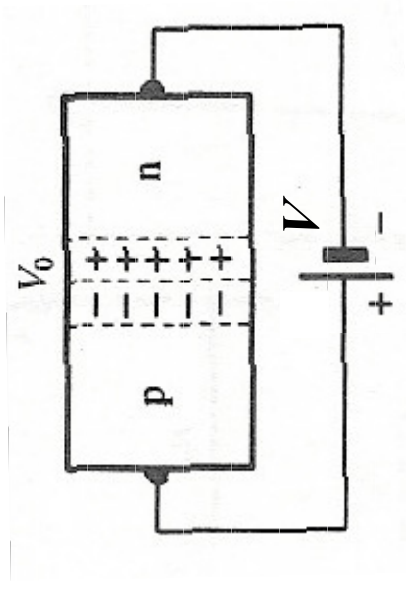
r_{np} : Resistance of the junction outside depletion layer

$C_j(V)$: Depletion layer capacitance

g : Conductance of the reverse flow

Equivalent circuit

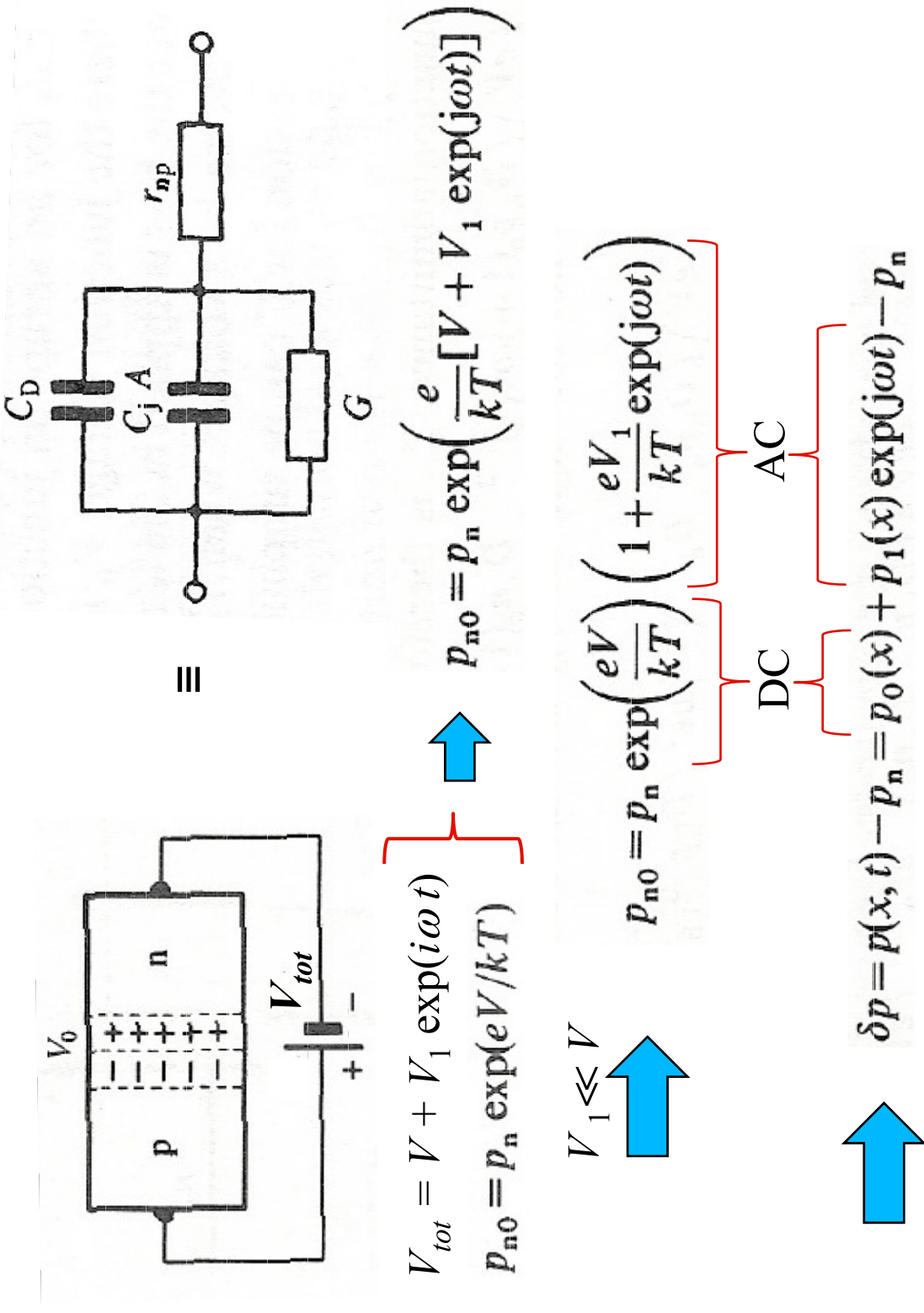
- Forward biased junction:



- r_{np} : Resistance of the junction outside depletion layer
- $C_j(V)$: Depletion layer capacitance
- G : Conductance of the forward flow
- C_D : Diffusion capacitance (due to excess holes and excess electrons)

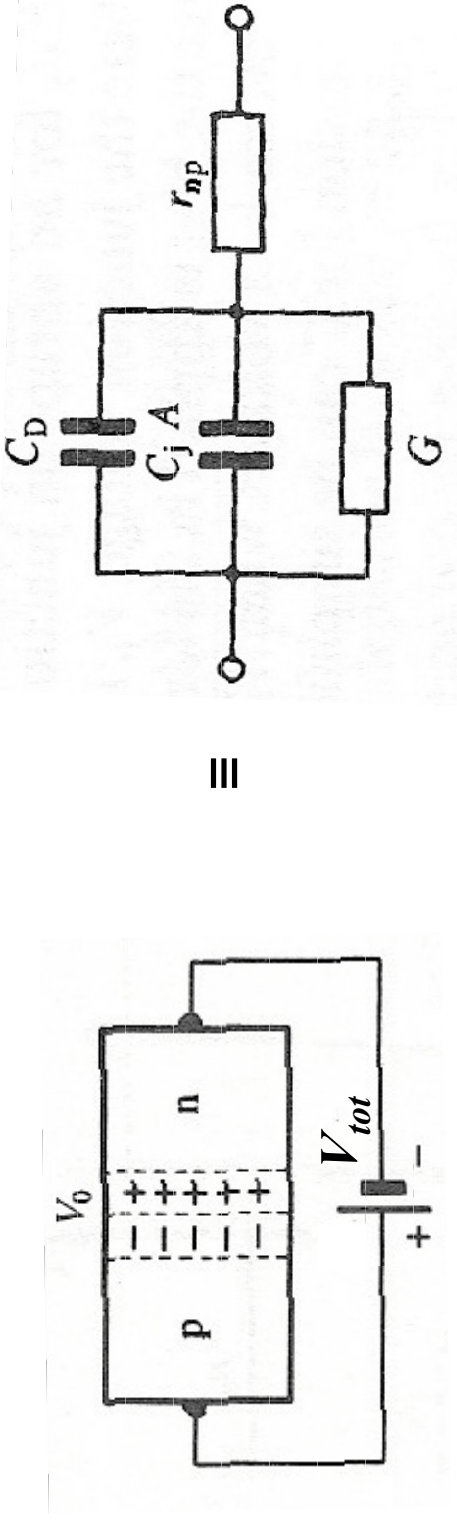
Equivalent circuit

- Forward biased junction with an AC signal:



Equivalent circuit

- Forward biased junction with an AC signal:



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

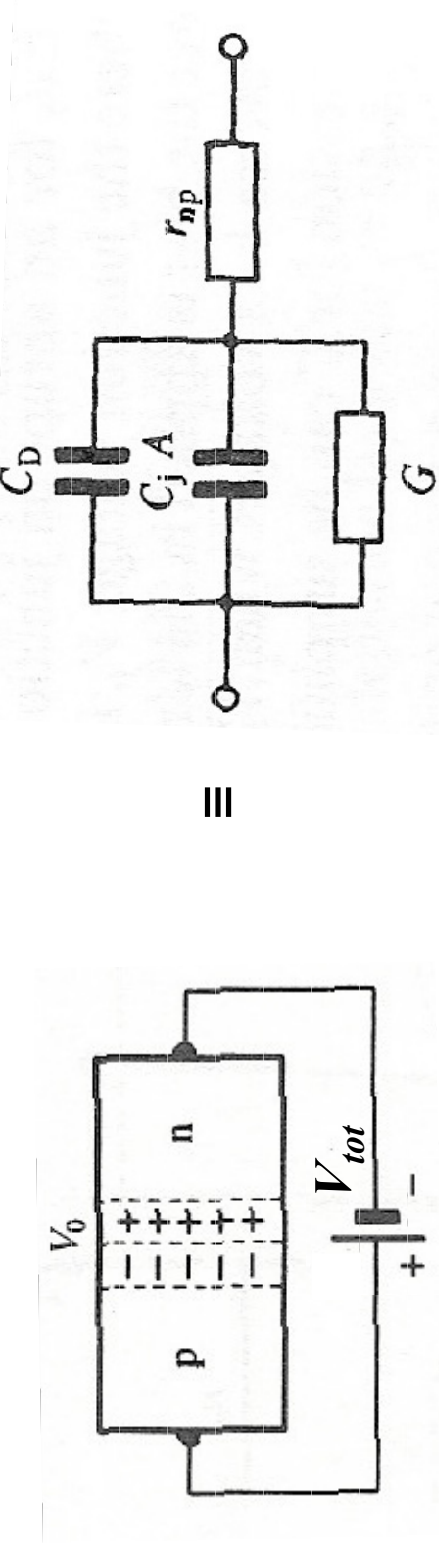
$$\rightarrow \frac{\partial^2 p_1}{\partial x^2} = \frac{1 + j\omega \tau_{Lh}}{L_h^2} p_1 \quad \rightarrow \quad p_1 = C \exp\left(-\frac{(1 + j\omega \tau_{Lh})^{1/2} x}{L_h}\right)$$

But:

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

Equivalent circuit

- Forward biased junction with an AC signal:



- Alternating currents of holes injected into n-region:

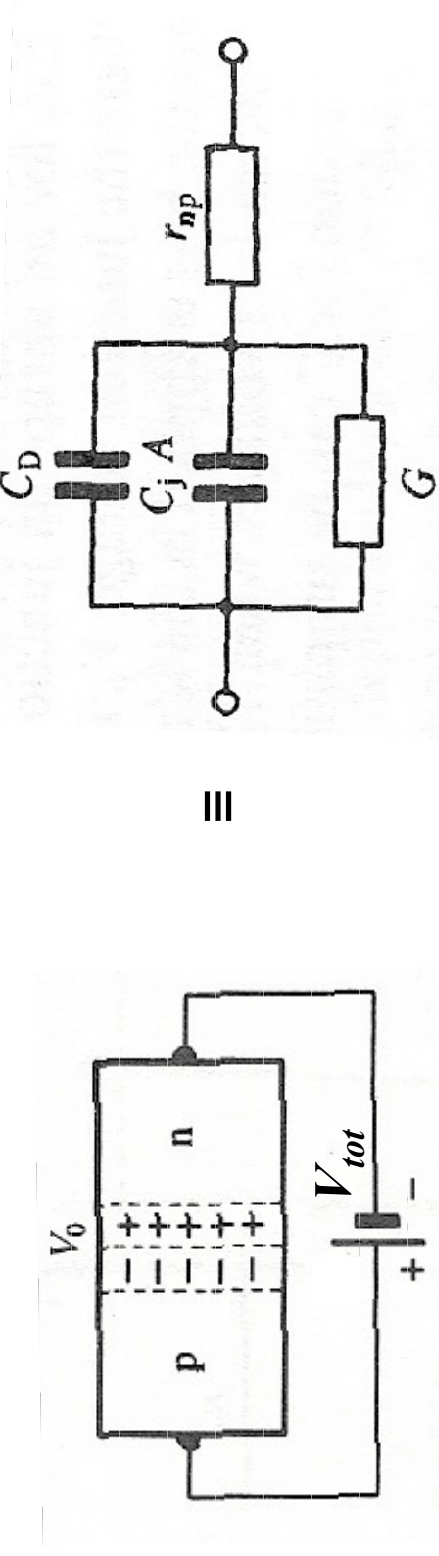
$$J_{h1} = -eD_h \left(\frac{dp(x)}{dx} \right) \bigg|_{x=0} = \frac{(1+i\omega\tau_{Lh})^{1/2}}{L_h} p_n D_h e^2 V_1 \exp\left(\frac{eV}{kT}\right) \exp(i\omega t)$$

- Alternating currents of electrons injected into p-region:

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

Equivalent circuit

- Forward biased junction with an AC signal:



- Total alternating currents of minority injected carriers:

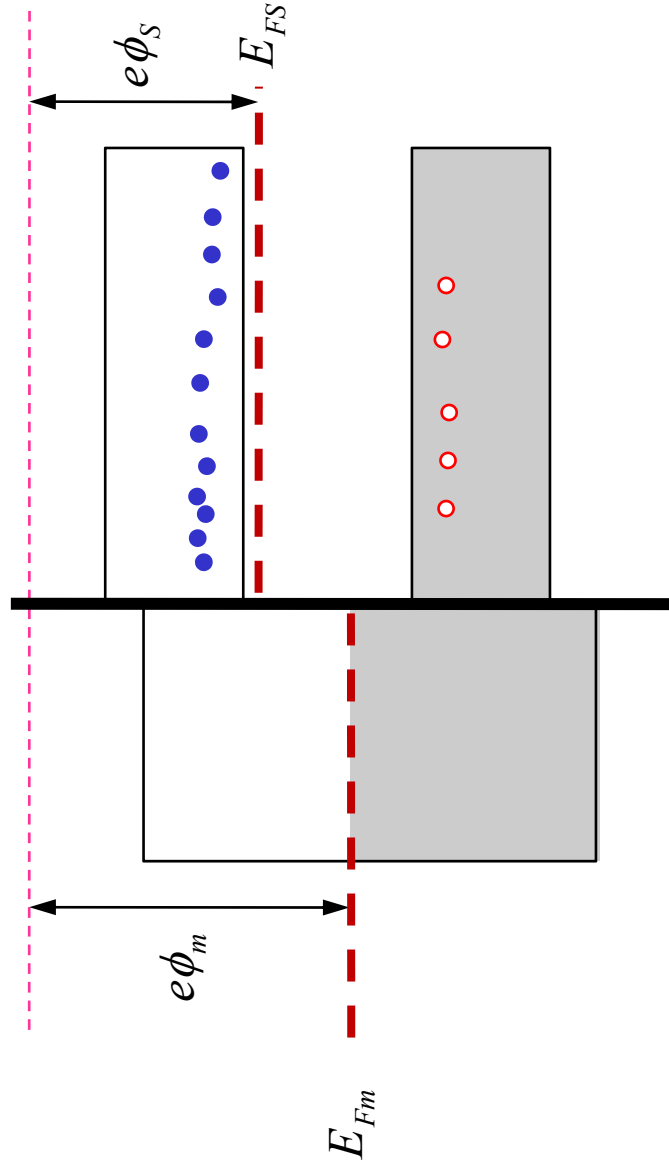
$$J_1 = J_{h1} + J_{e1}$$

- Admittance ($Y_1 = J_1/V_1$) for $\omega t \ll 1$:

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

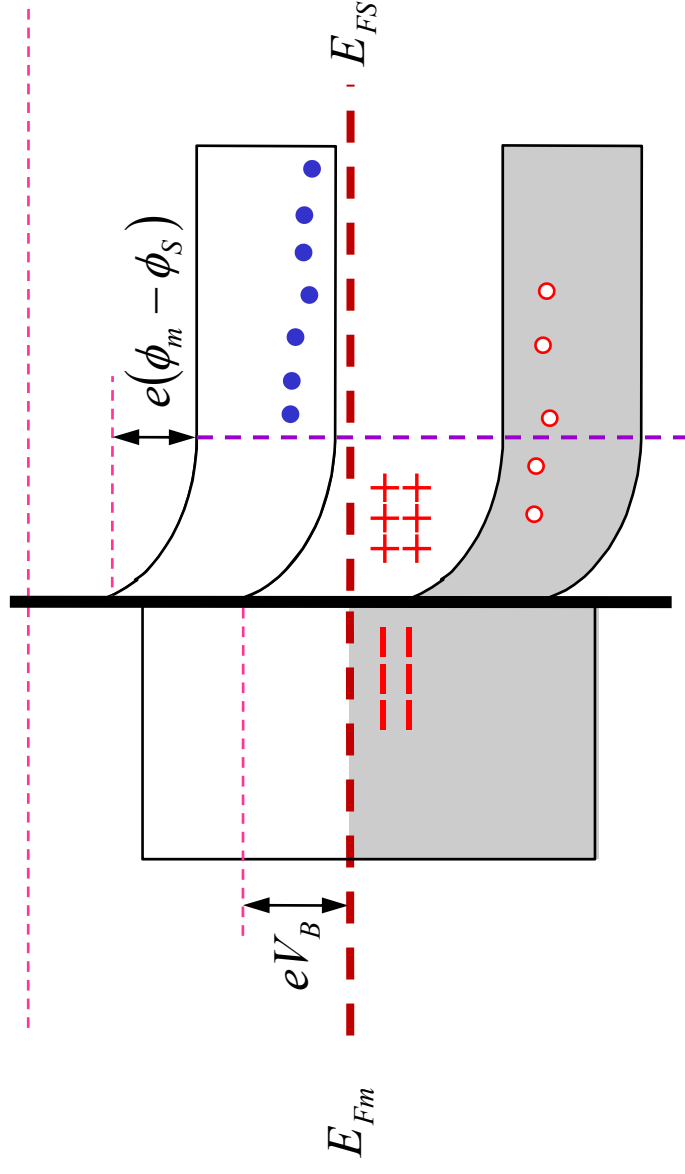
Metal-sC junctions

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



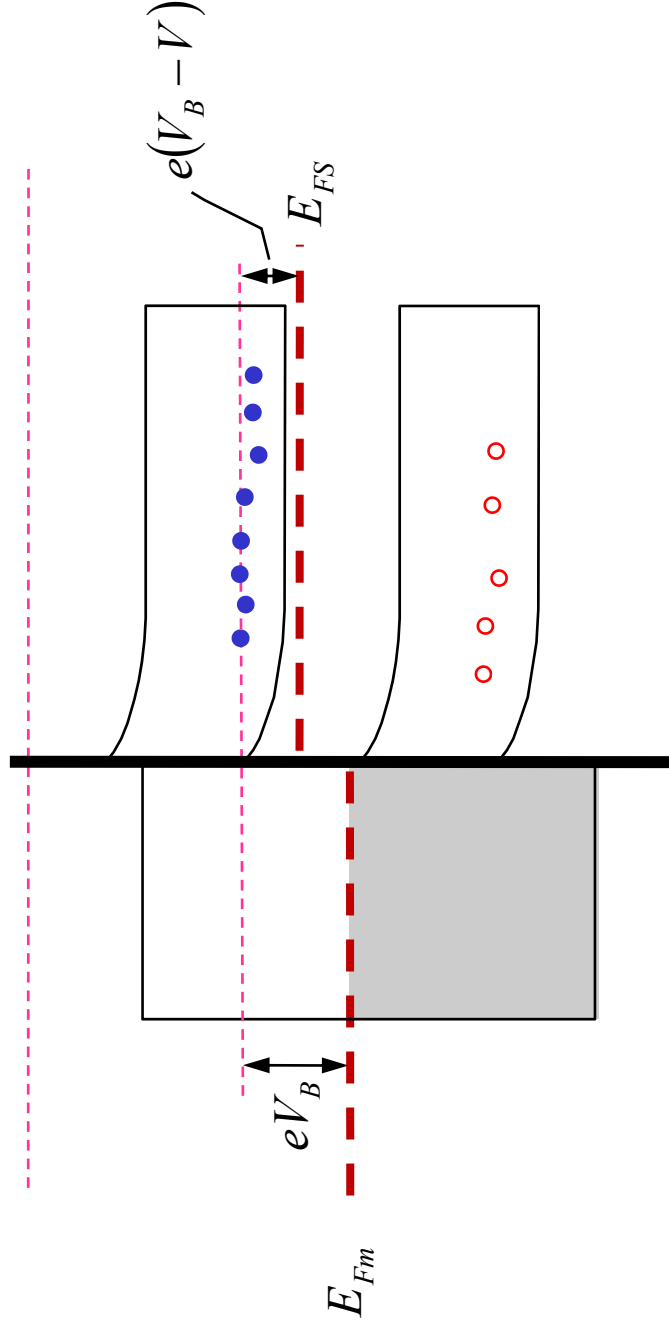
Metal-sC junctions

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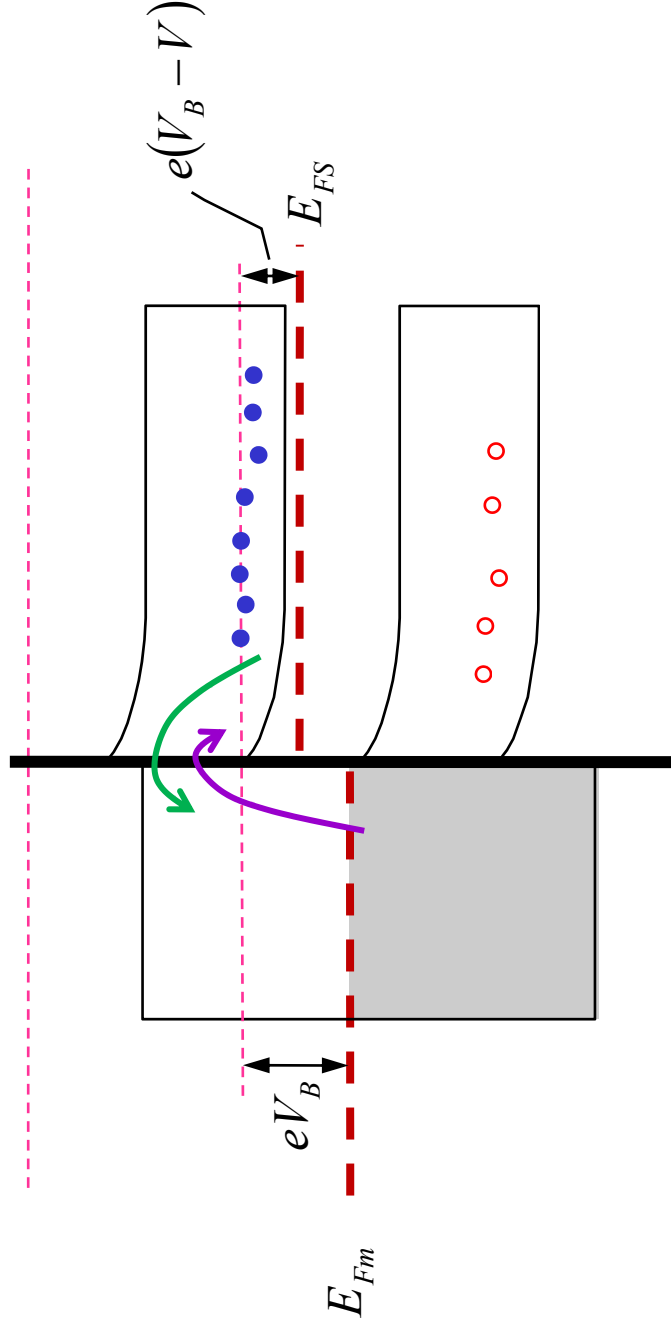
Metal-sC junctions

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



Metal-sC junctions

- Metal – n-type sC ($\phi_m > \phi_s$):
 - Forward biased junction – Current of majority carriers:



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

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

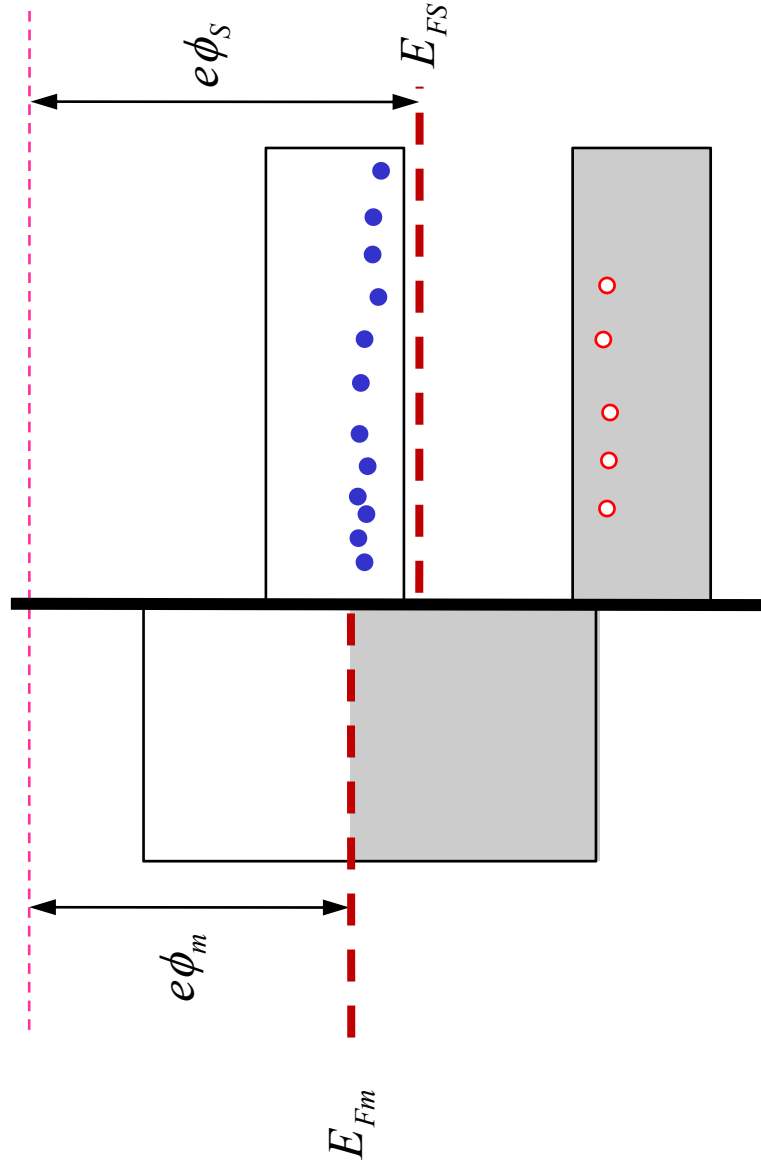


$$J \propto \exp(-eV_B/kT) [\exp(eV/kT) - 1]$$

Non ohmic contact!!!

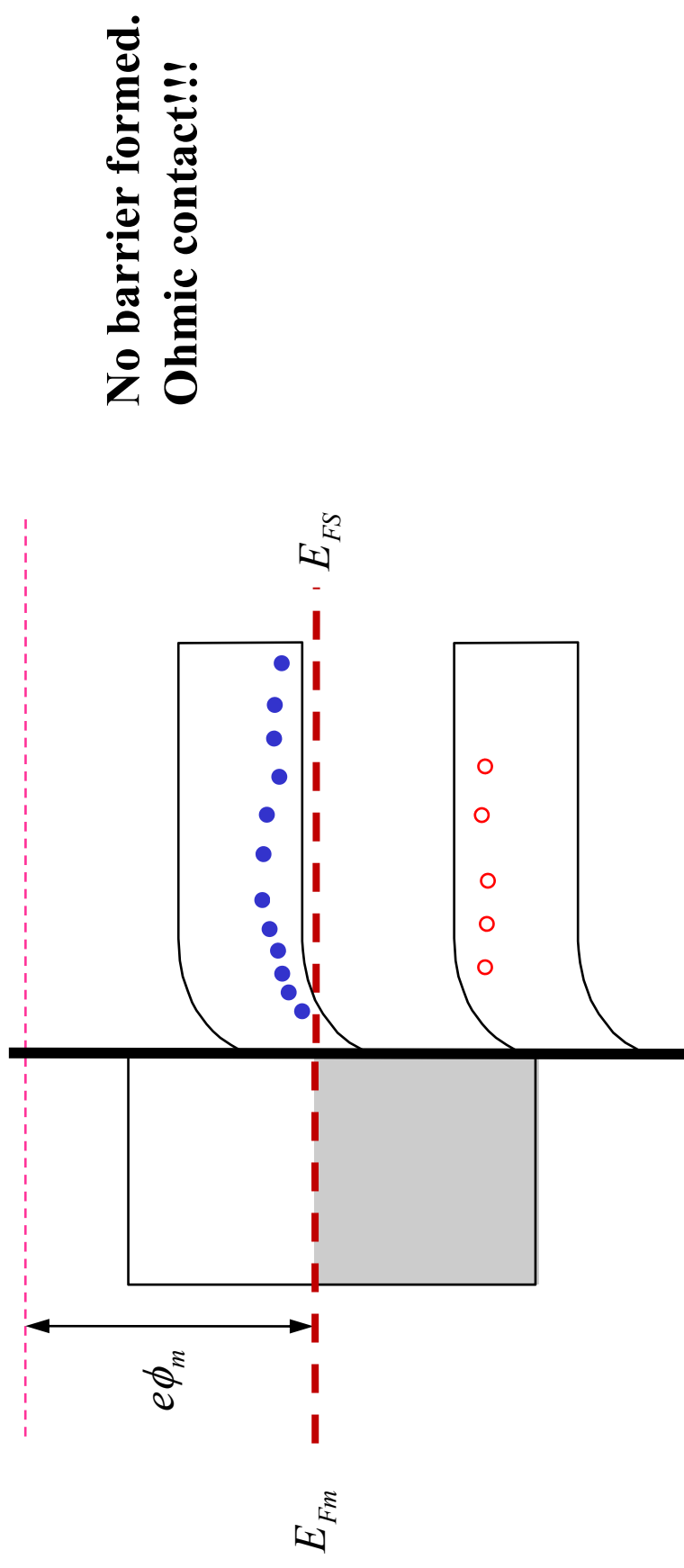
Metal-sC junctions

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



Metal-sC junctions

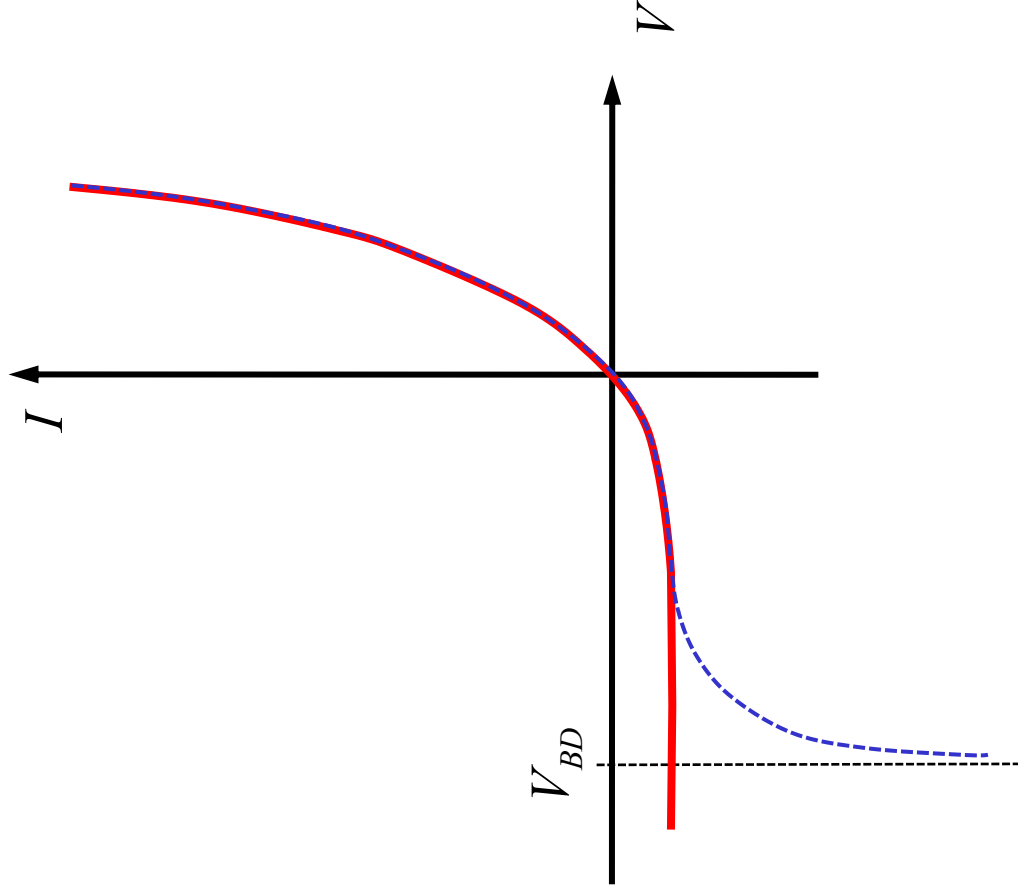
- Metal – n-type sC ($\phi_m < \phi_s$):
 - Unbiased junction - after:



- Homework: analyze a metal – p-type sC junction.

The Zener Diode

- Breakdown voltage:

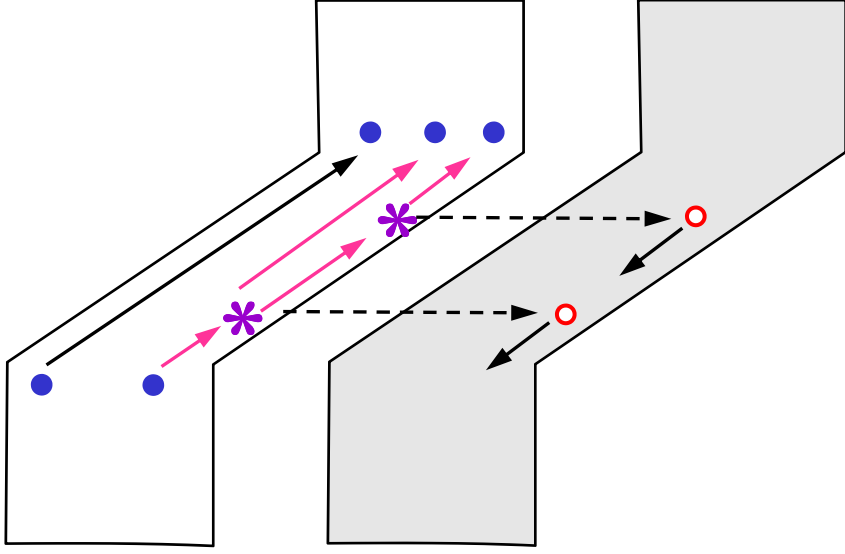


Ideal diode: current limited if reversed biased

Real diode: voltage limited if reversed biased

The Zener Diode

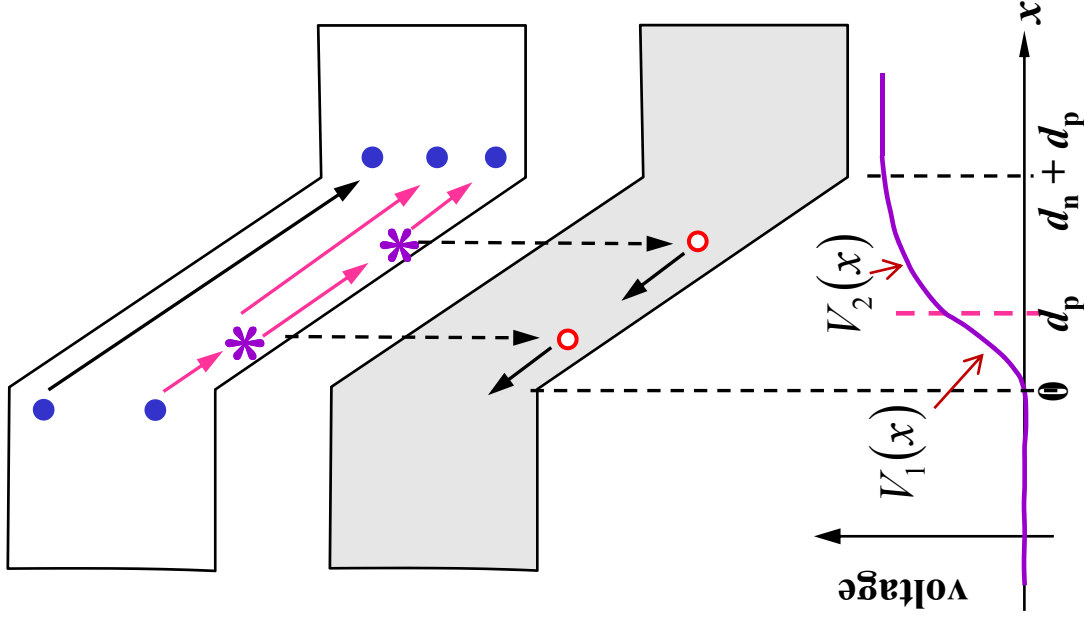
- Breakdown voltage:



- 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

- Breakdown voltage:



$$V_1(x) = eN_a x^2 / 2\epsilon$$

$$V_2 = -eN_d x^2 / 2\epsilon + C_1 x + C_2$$

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

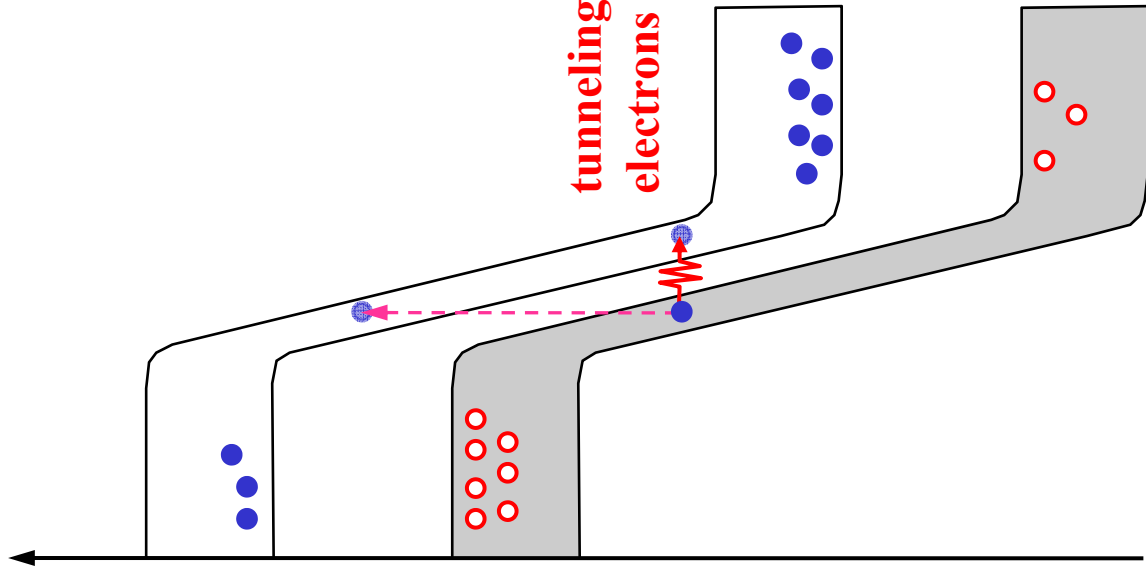
$$\mathcal{E}_{\max} = ed_p N_a / \epsilon = \left(\frac{2eV_j N_d N_a}{\epsilon(N_a + N_d)} \right)^{1/2}$$

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

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

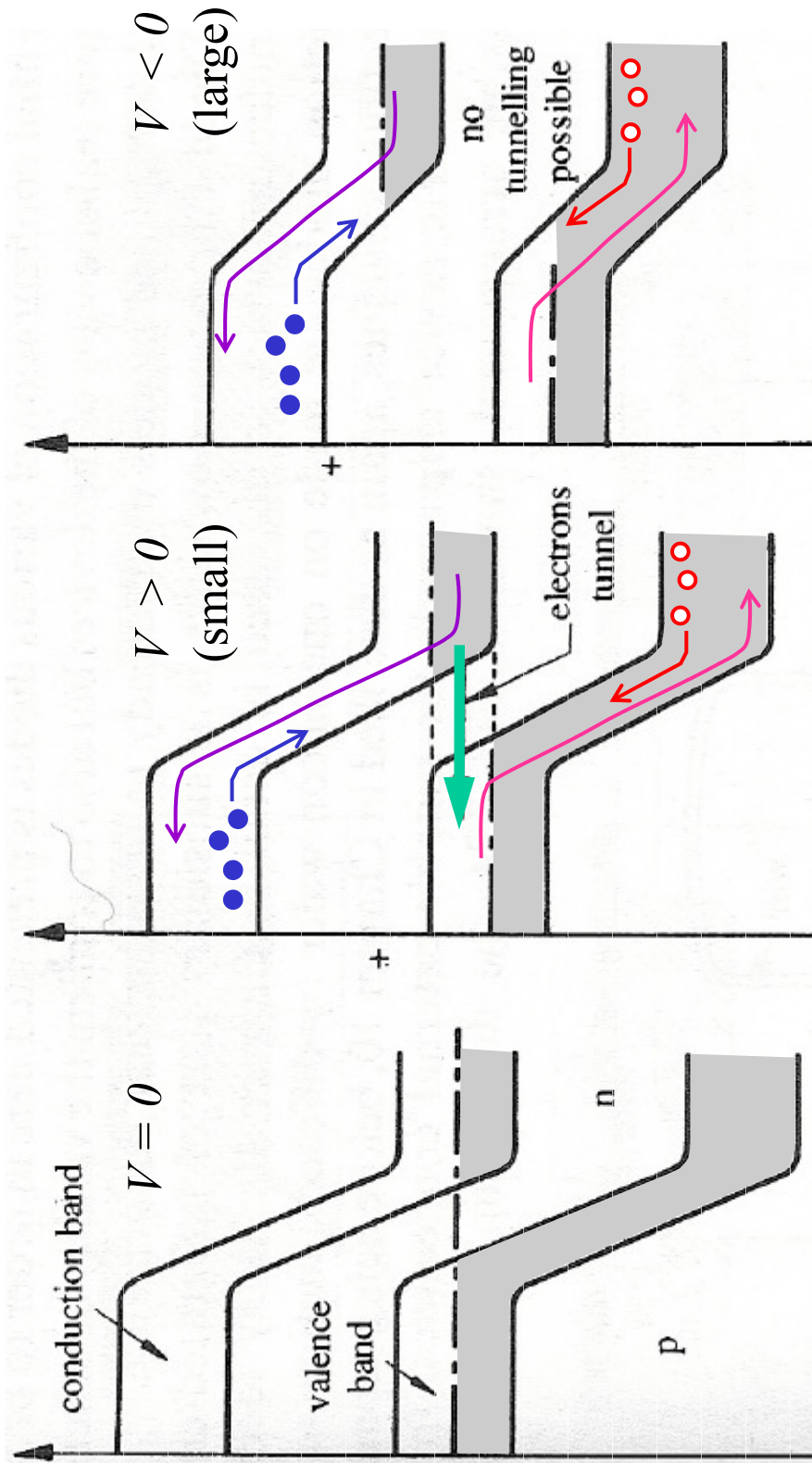
The Zener Diode

- Zener breakdown:
 - It occurs in highly doped junctions (thin depletion layer).
 - Tunneling favored over thermal transitions.
 - Electrons in the valence band can tunnel to the conduction band.
 - V_{BD} is T independent.



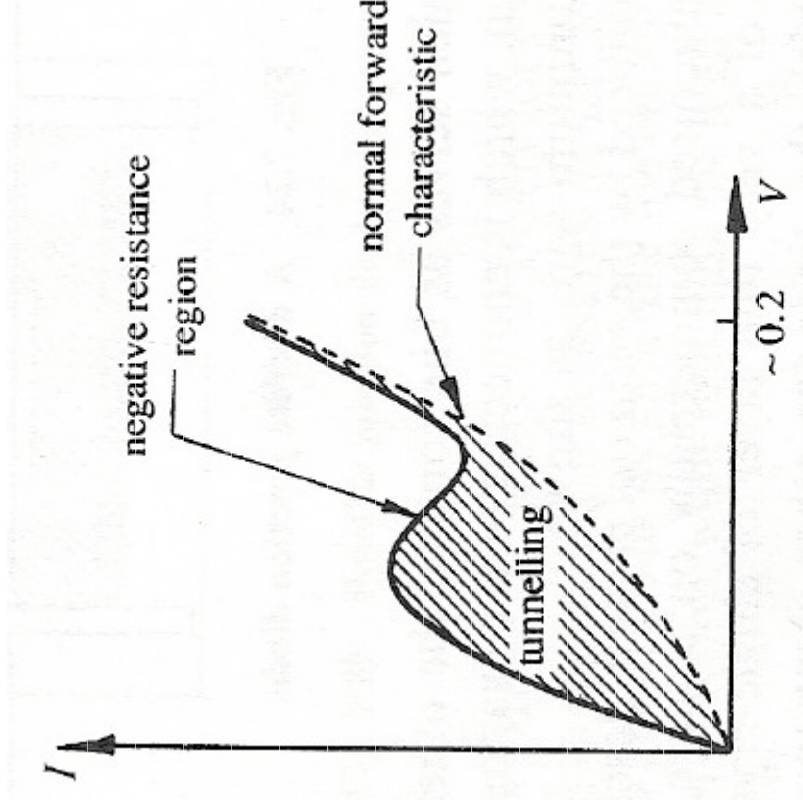
The Tunnel Diode

- Highly-doped pn junctions (V_0 is large & d_p, d_n short).
 - Fermi energy cross the bands.
 - Tunneling is favored.



The Tunnel Diode

- Highly-doped pn junctions (V_0 is large & d_p, d_n short).
 - Fermi energy cross the bands.
 - Tunneling is favored.
 - Extra current source at V small.



Conclusions

- The equivalent circuit of the diode was studied.
- The AC response was determined.
- Metal junctions were studied: ohmic and non-ohmic (Schottky diode).
- The Zener and tunnel diode were qualitatively studied.