Session 8: Solid State Physics

MS Junction

Outline

- A
  - B
  - C
  - D
  - E
- F
  - G
- H
- I
- J

PN junctions – Before Being Joined

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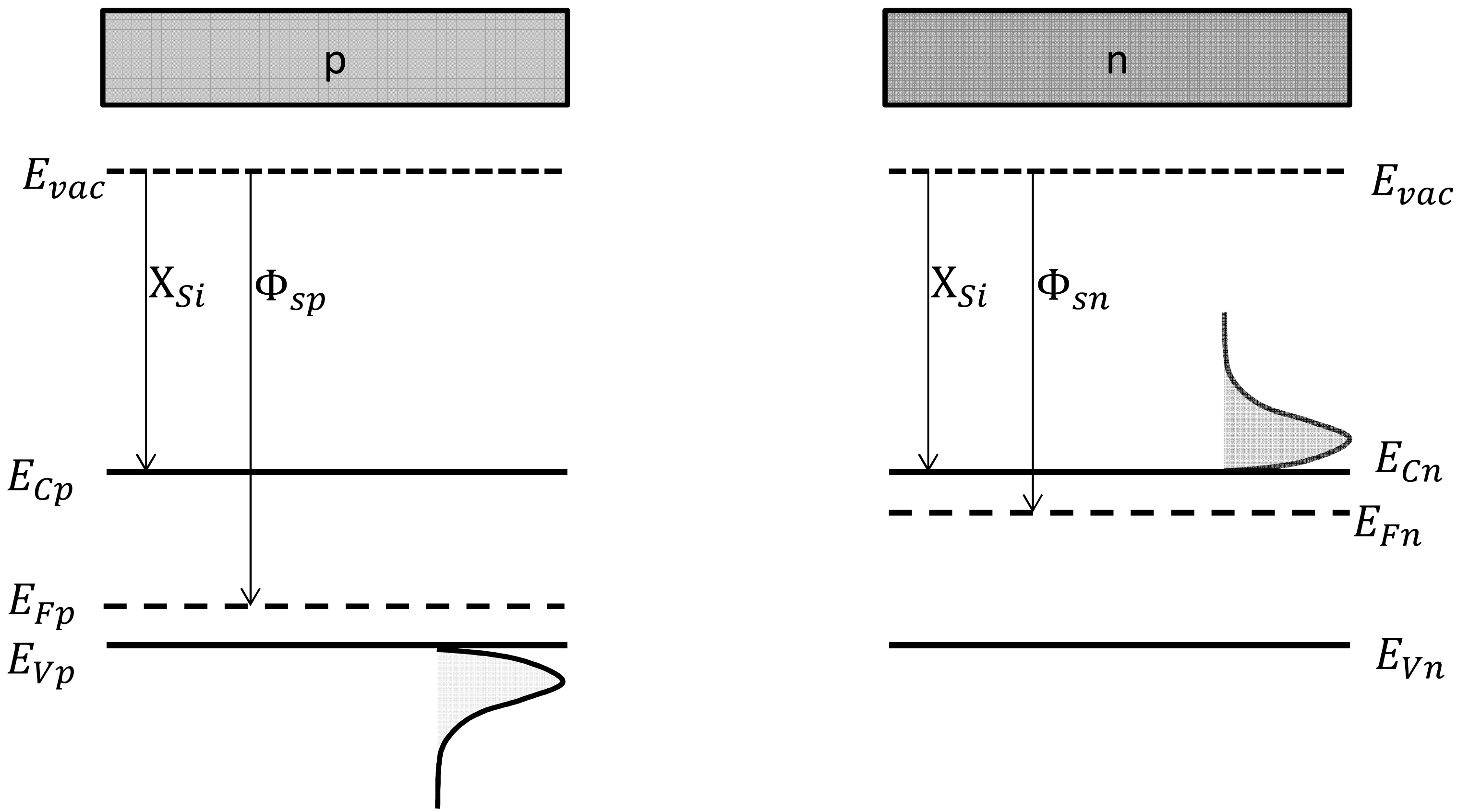


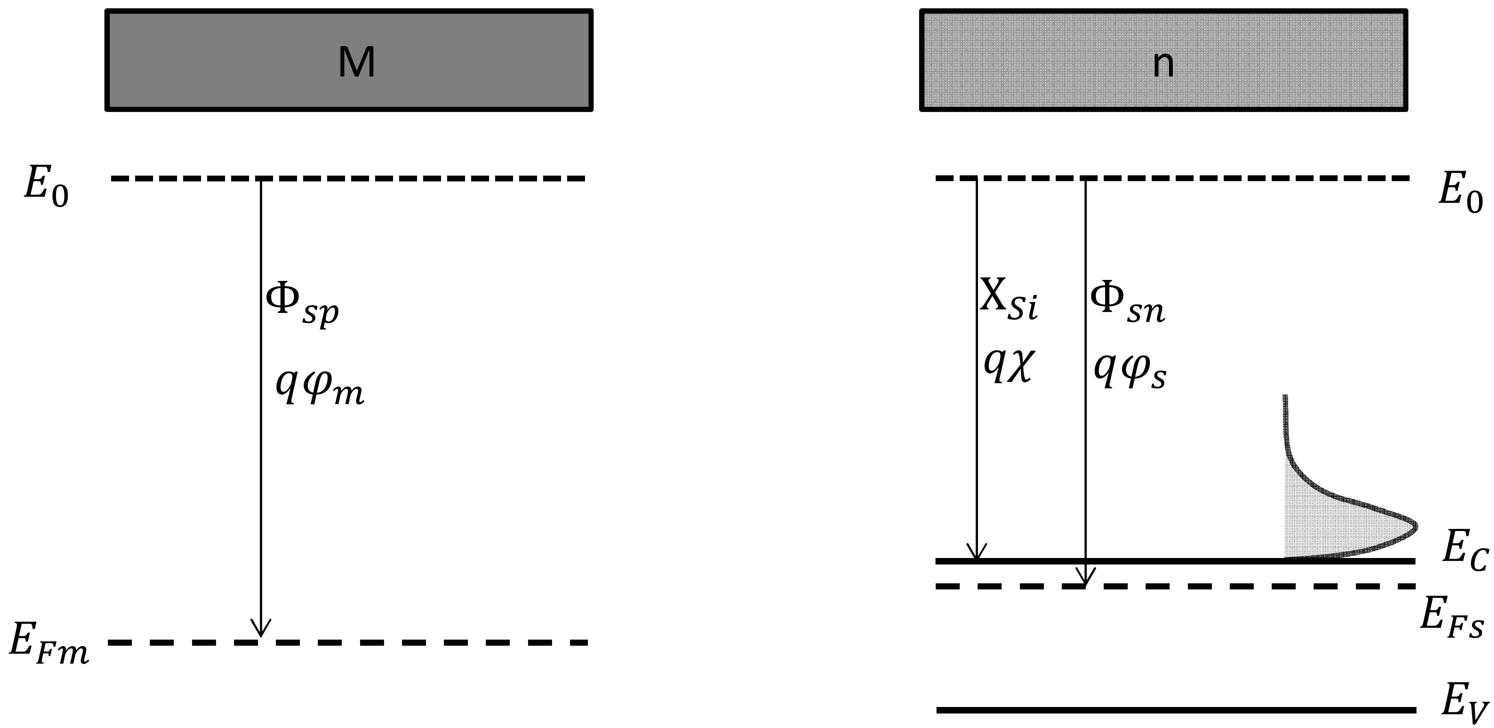
electrically neutral in every region

electron affinity : X_{Si}

work function Φ: $\Phi = E_{vac} - E_F$

$$\Phi_n \neq \Phi_p$$

MS junctions – Before Being Joined



$q\varphi_m$ work function $\varphi_{Au} = 4.75eV$, $\varphi_{Cu} = 4.5eV$, $\varphi_{Al} = 4.28eV$

$q\chi$ electron affinity $\chi_{Si} = 4.05eV$, $\chi_{Ge} = 4eV$, $\varphi_{GaAs} = 4.07eV$

Reminder

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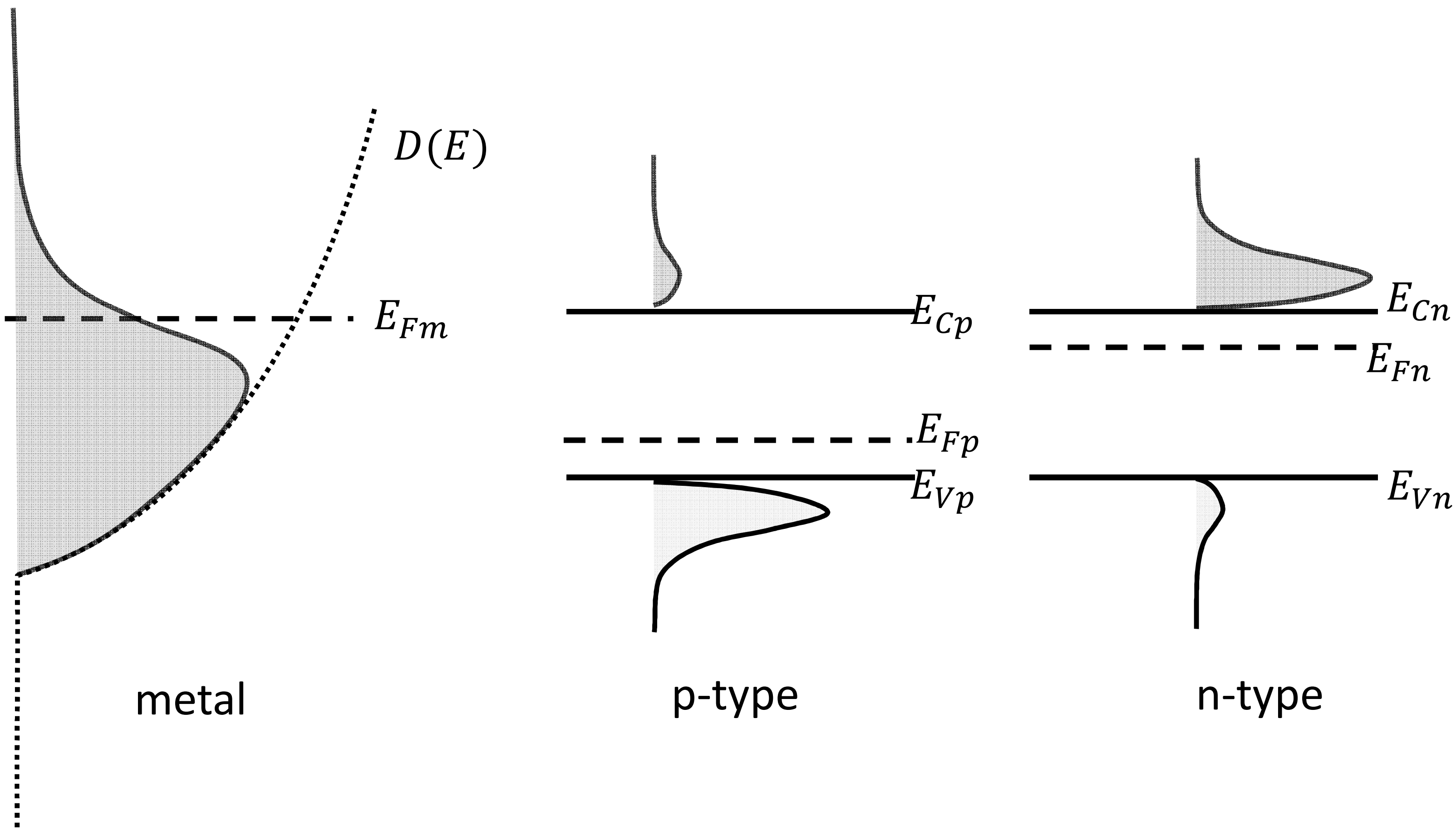

Plotting Energy Bands for MS Junction

Step by step:

1. Vacuum energy (E_0) is continuous.

2. E_G and χ are intrinsic properties of materials and should remain constant. (which means E_C, E_V, and E_0 are all parallel)

3. At equilibrium E_F is constant while by applying voltage $\Delta E_F = -qV$.

MS junctions – Before Being Joined

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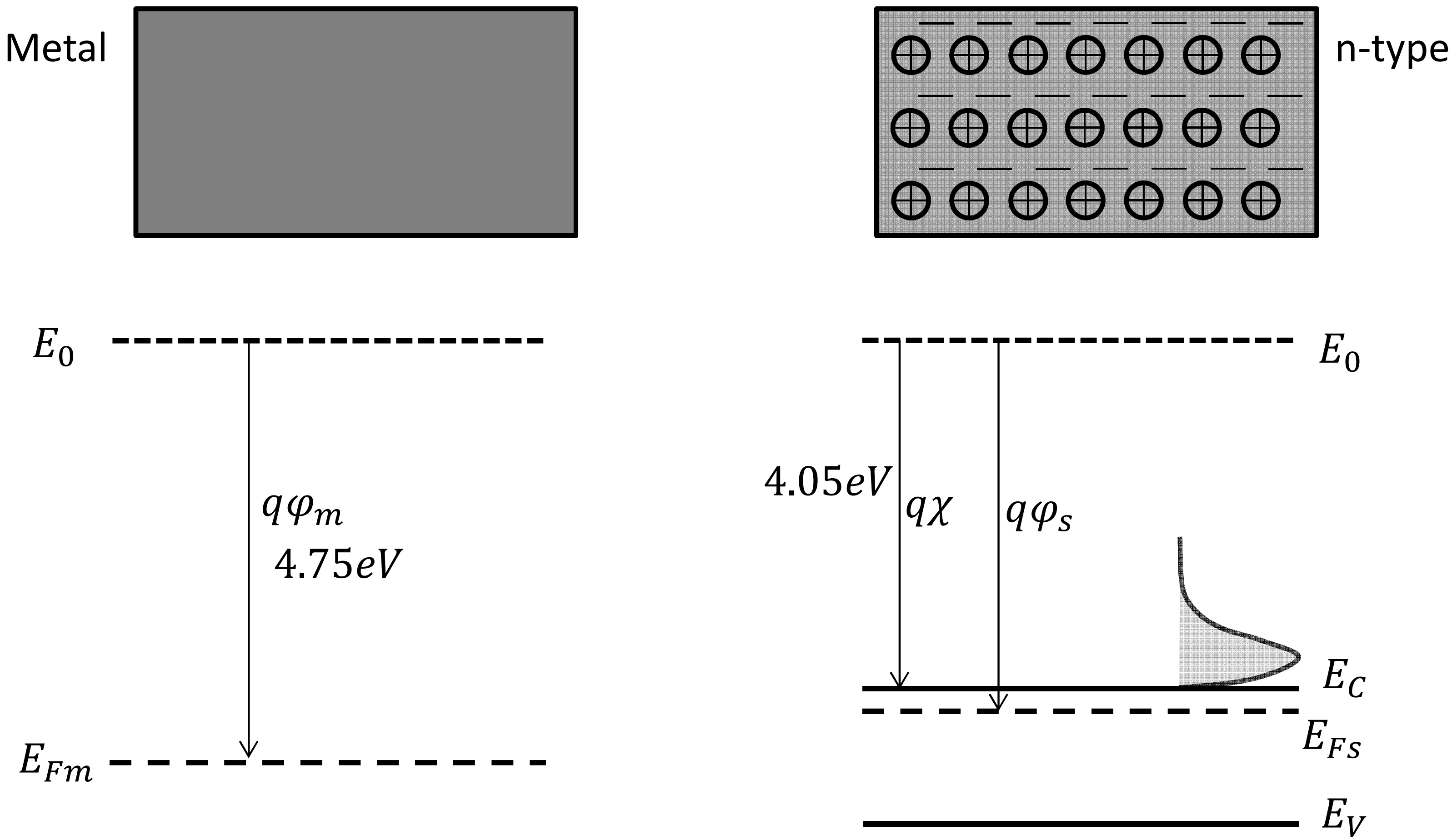

MS junctions – Qualitative

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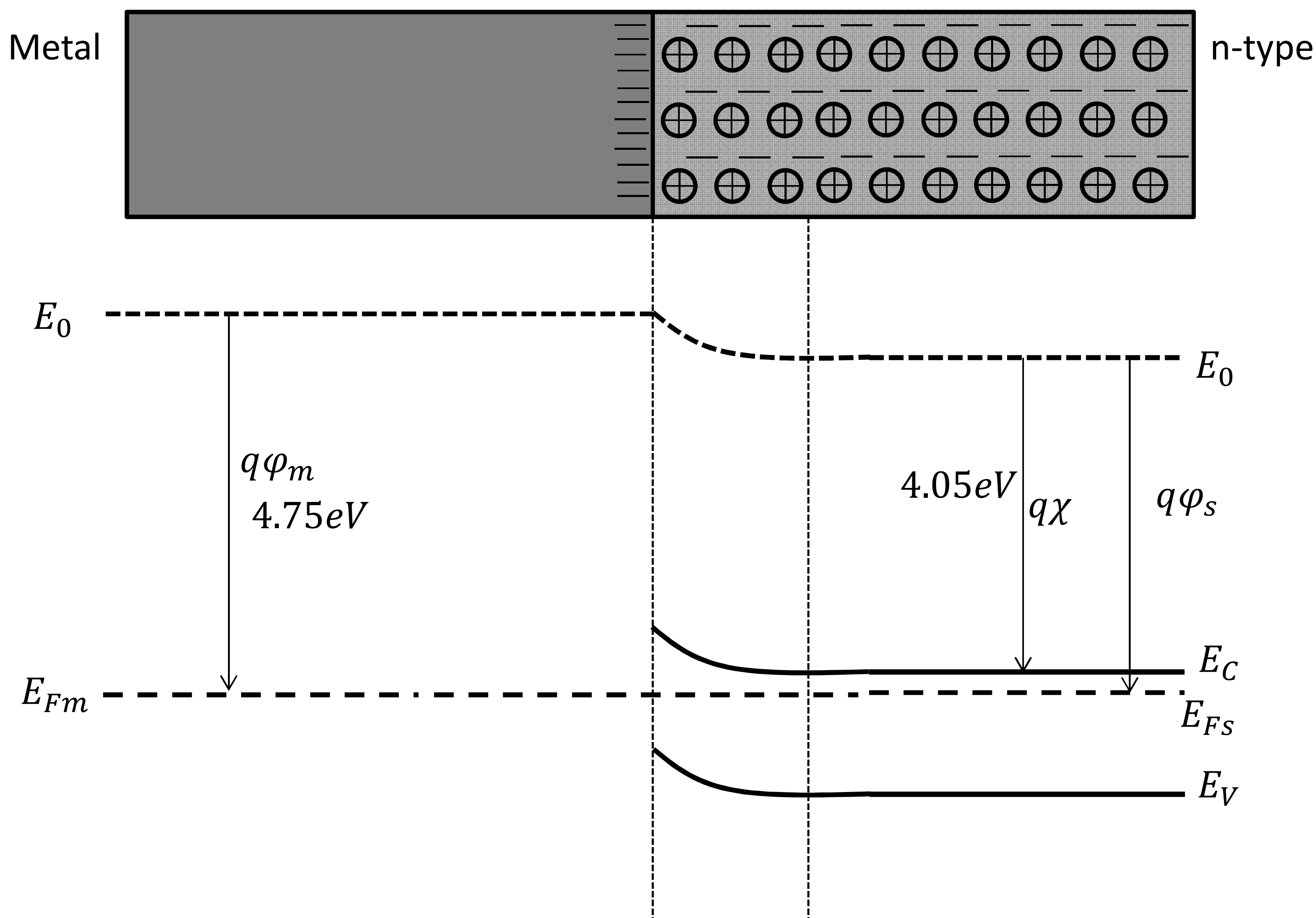
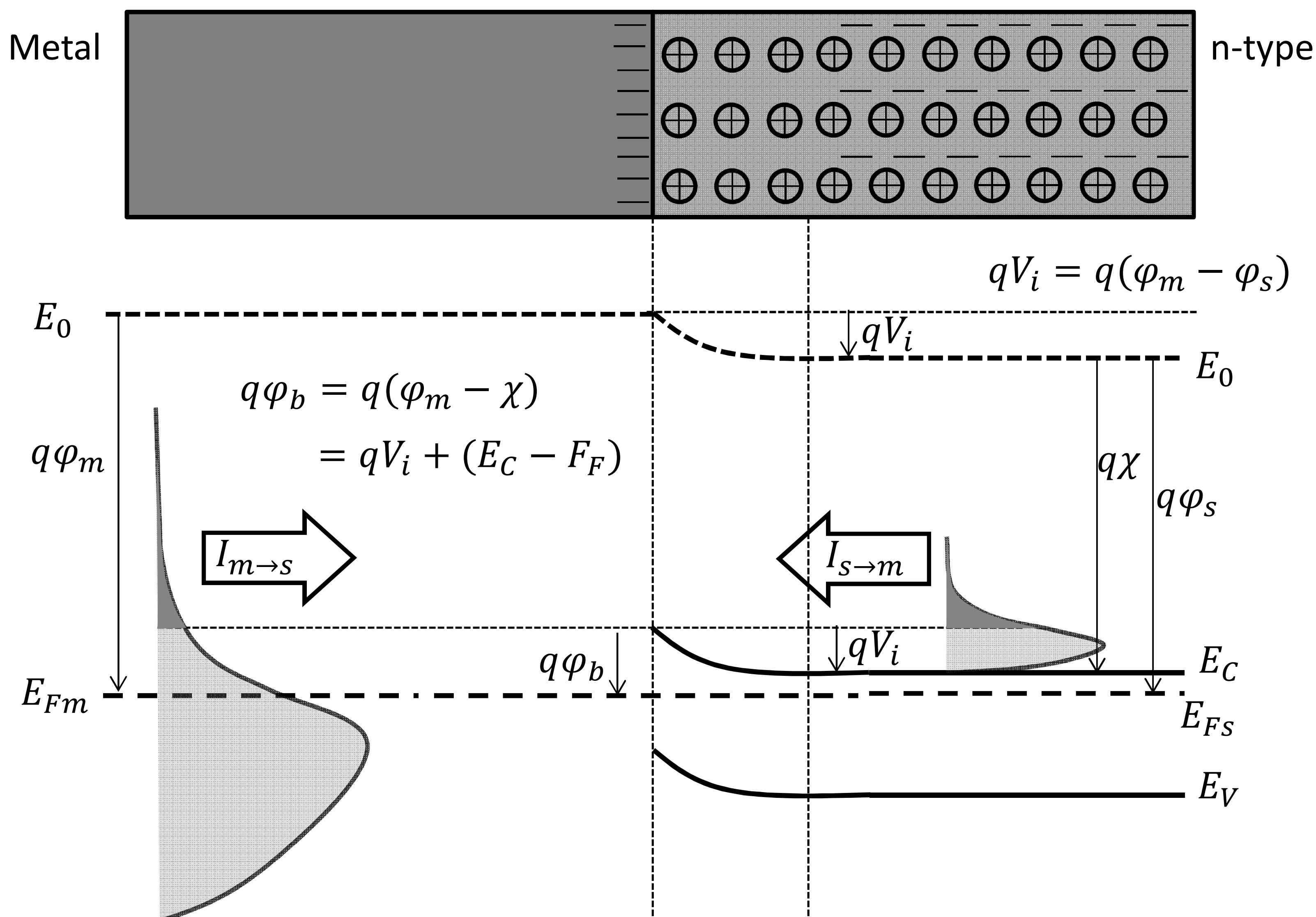


MS junctions – Qualitative



MS junctions – Qualitative

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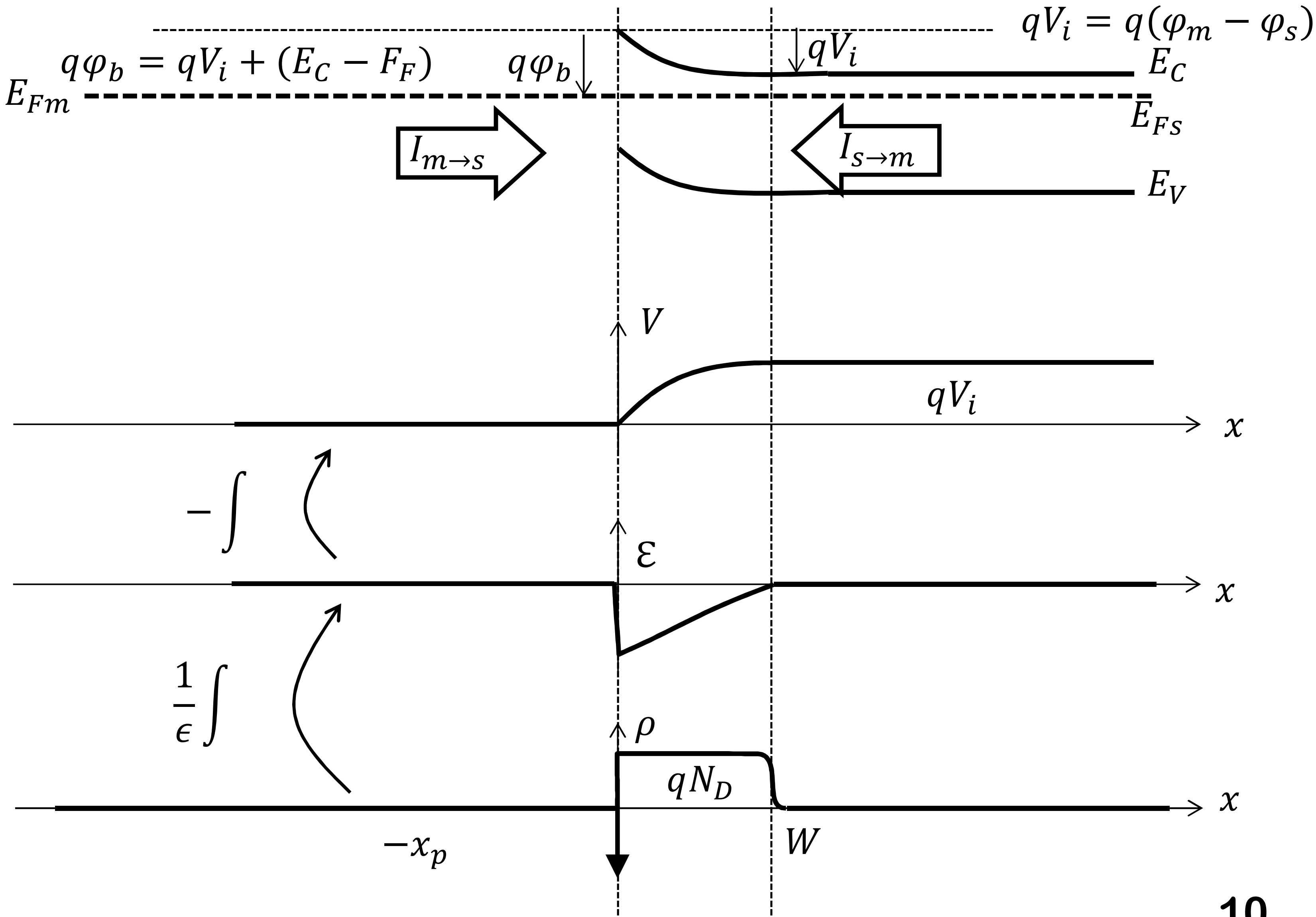

MS junctions - Schottky Effect

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$$\mathcal{E}(0) = -qN_D W/\epsilon$$

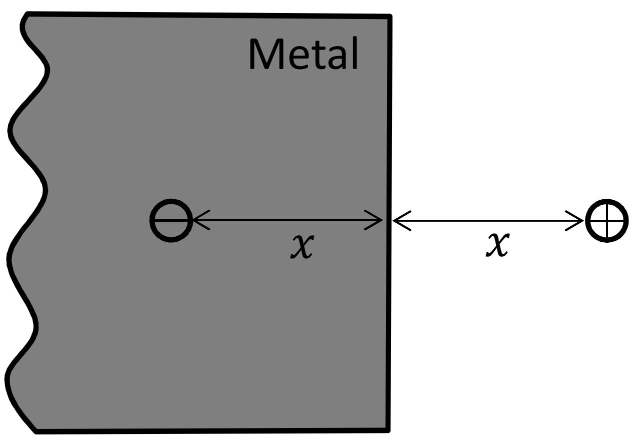
$$V_i = -\tfrac{1}{2}W\mathcal{E}(0) = qN_D W^2/2\epsilon$$

$$W = \sqrt{\frac{2\epsilon}{qN_D}(V_i - V_a)} \qquad \mathcal{E}(0) = -\sqrt{\frac{2qN_D}{\epsilon}(V_i - V_a)}$$

as $qV_i = q(\varphi_m - \varphi_s)$ seems that V_i is independent of the applied voltage

But it is not! This is known as “Schottky Effect” This will lower $V_i(\varphi_b)$ a little bit.

Image method



$$F(x) = \frac{-q^2}{16\pi\epsilon x^2}$$

$$\rightarrow \Phi(x) = -qV(x) = \frac{-q^2}{16\pi\epsilon x}$$

MS junctions, I-V Curve

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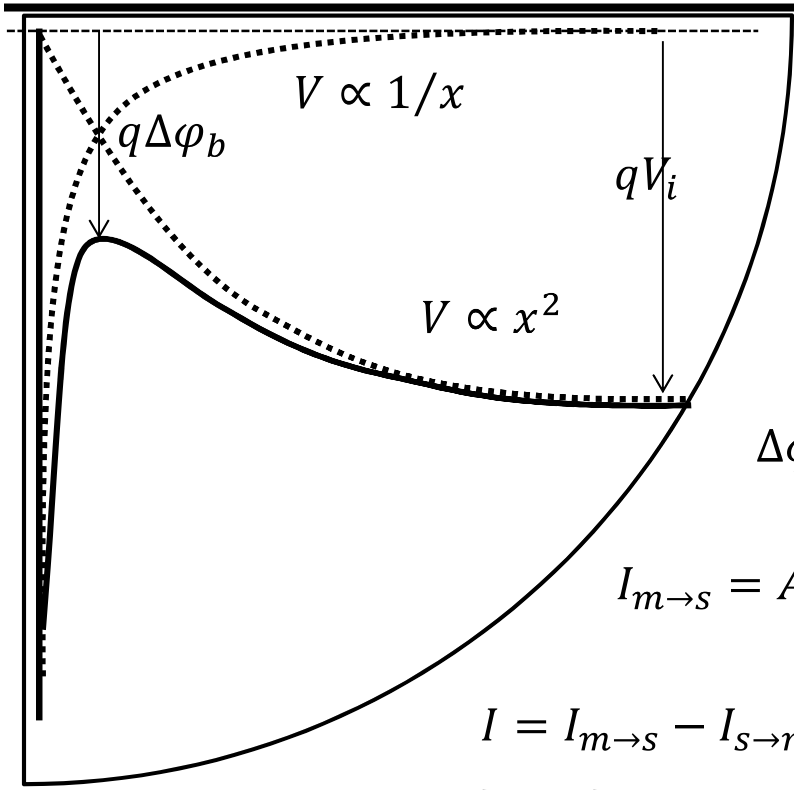
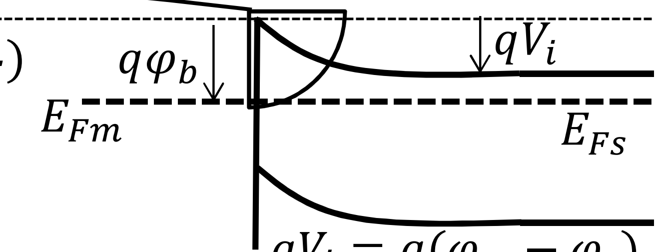


$$q\varphi_b = qV_i + (E_C - F_F)$$



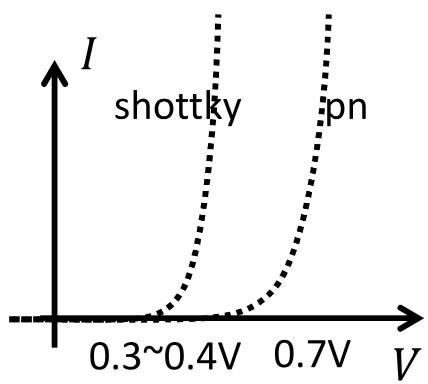
$$qV_i = q(\varphi_m - \varphi_s)$$

$$\varphi_b' = \varphi_b - \Delta\varphi_b$$

$$\Delta\varphi_b = \sqrt[4]{\frac{q^3 N_D}{8\pi^2\epsilon^2}(V_i - V_a)}$$

$$I_{m\to s} = AR^*T^2 e^{-q(\varphi_b' - V_a)/kT} \qquad I_{s\to m} = -AR^*T^2 e^{-q\varphi_b'/kT}$$

$$I = I_{m\to s} - I_{s\to m} = AR^*T^2 e^{-q\varphi_b'/kT}\left[e^{qV_a/kT} - 1\right] = I_s\left(e^{qV_a/kT} - 1\right)$$



$$I_{s_{schottky}} \cong 100 - 1000 I_{0_{pn}}$$

MS junctions – Ohmic Contact

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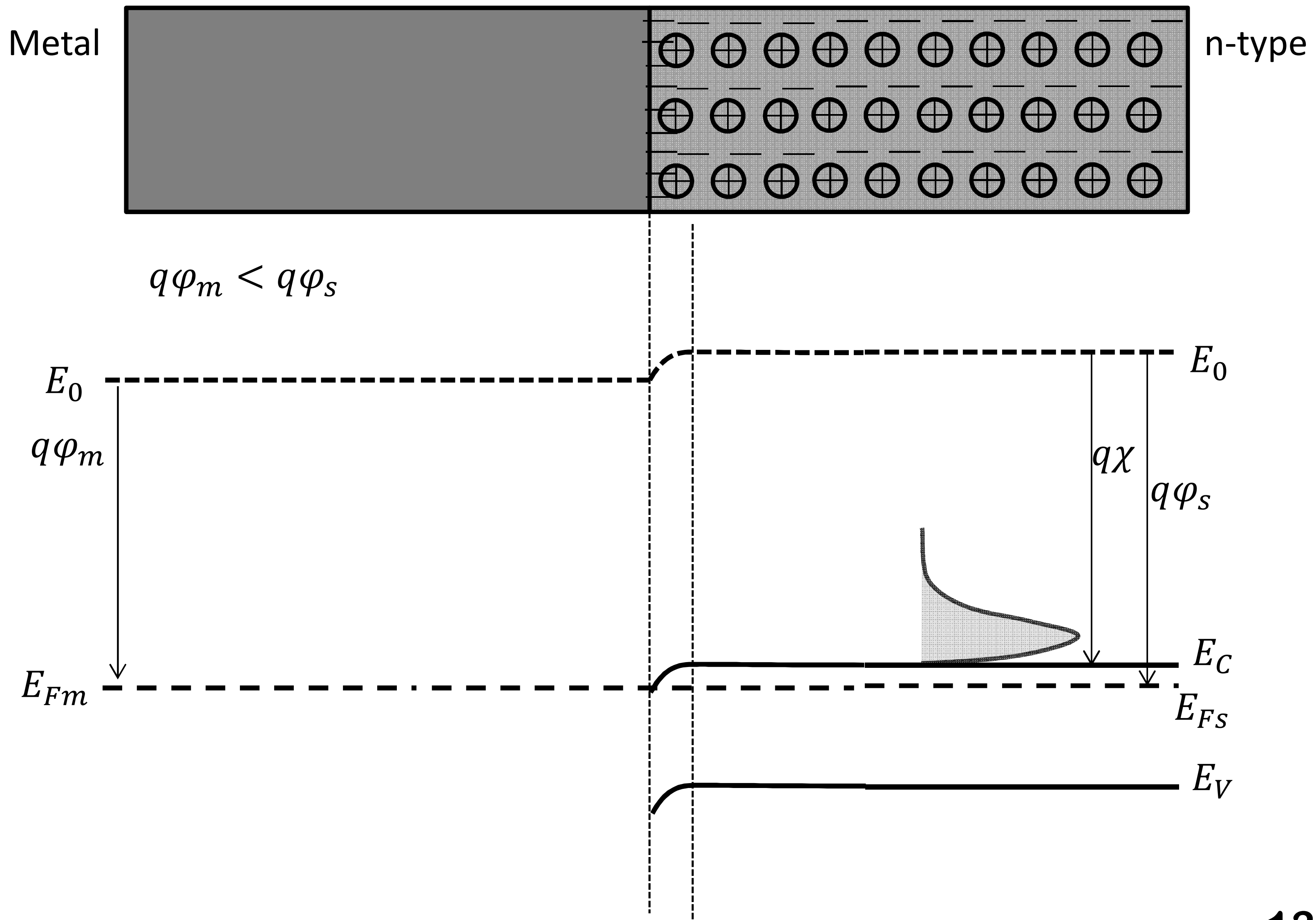

MS junctions – Ohmic Contact , Tunneling

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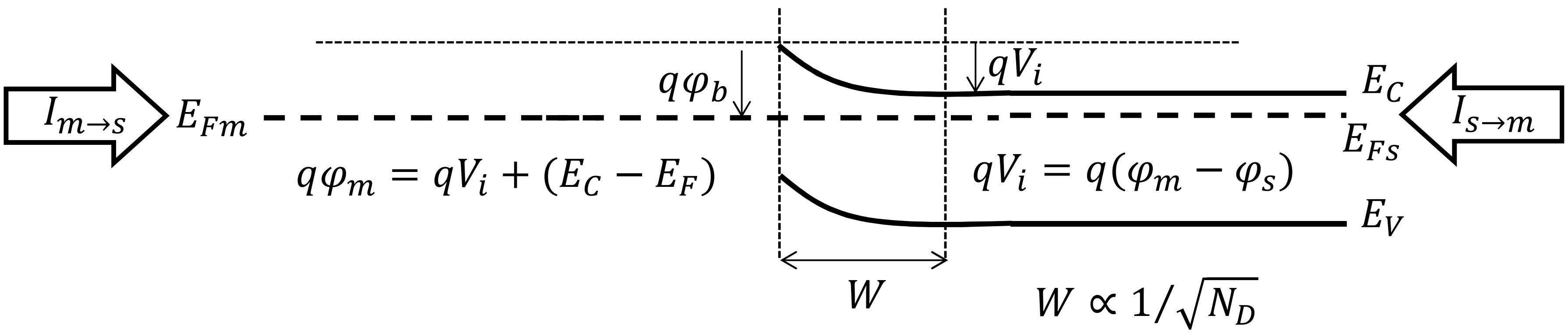

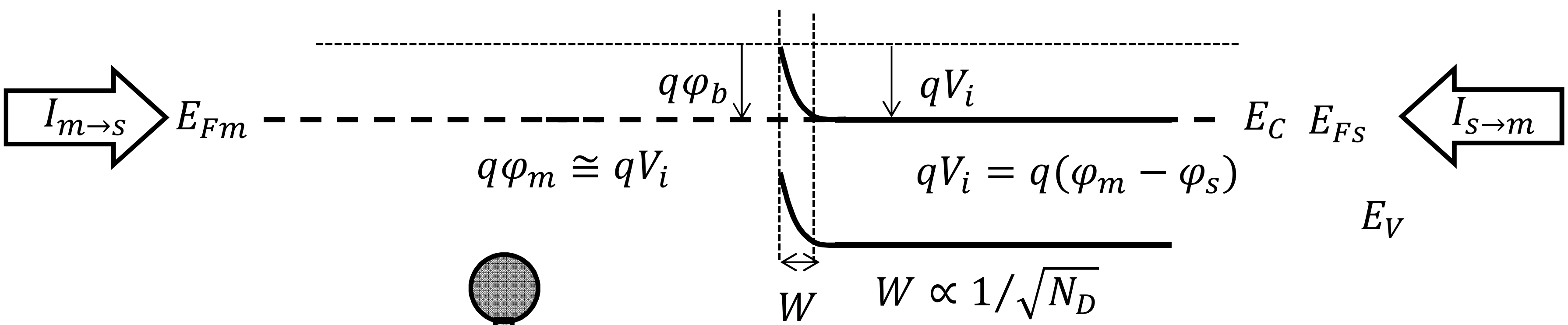

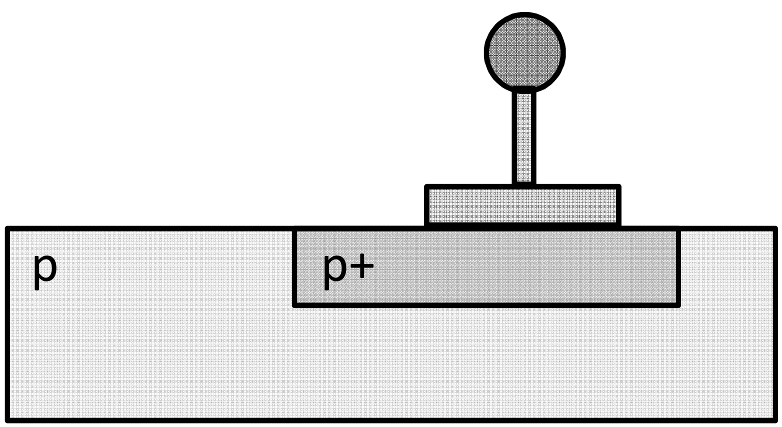

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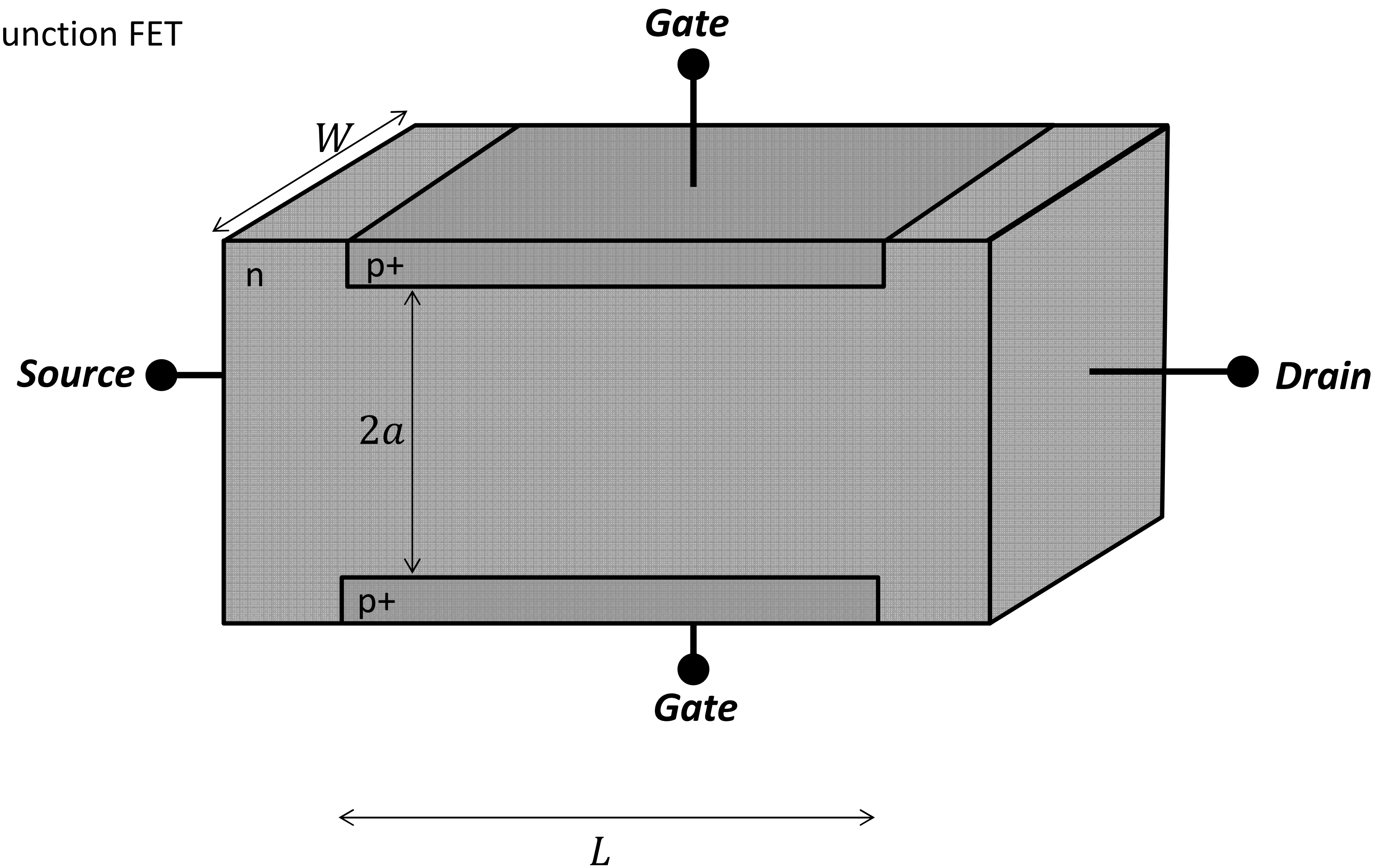
JFET (Qualitative)

Junction FET



JFET (Qualitative)

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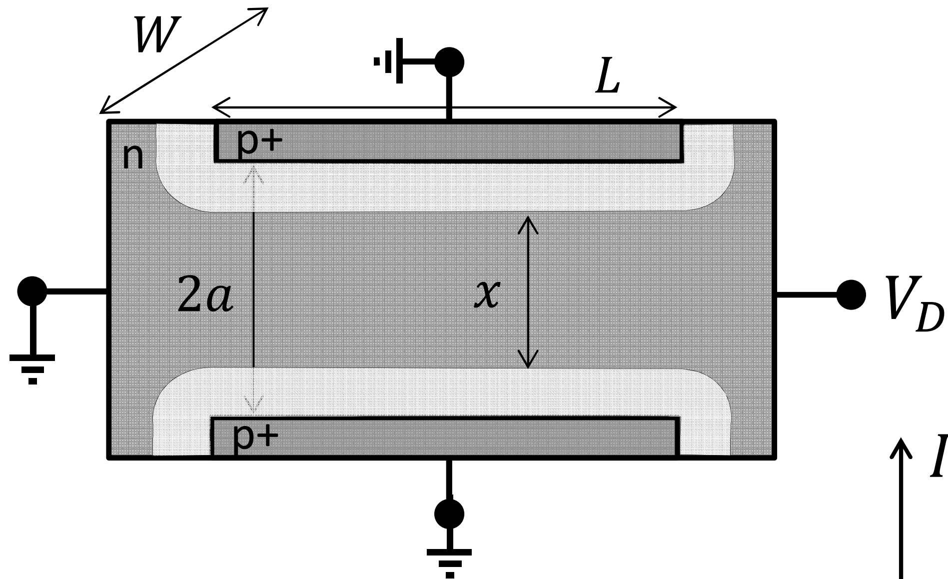

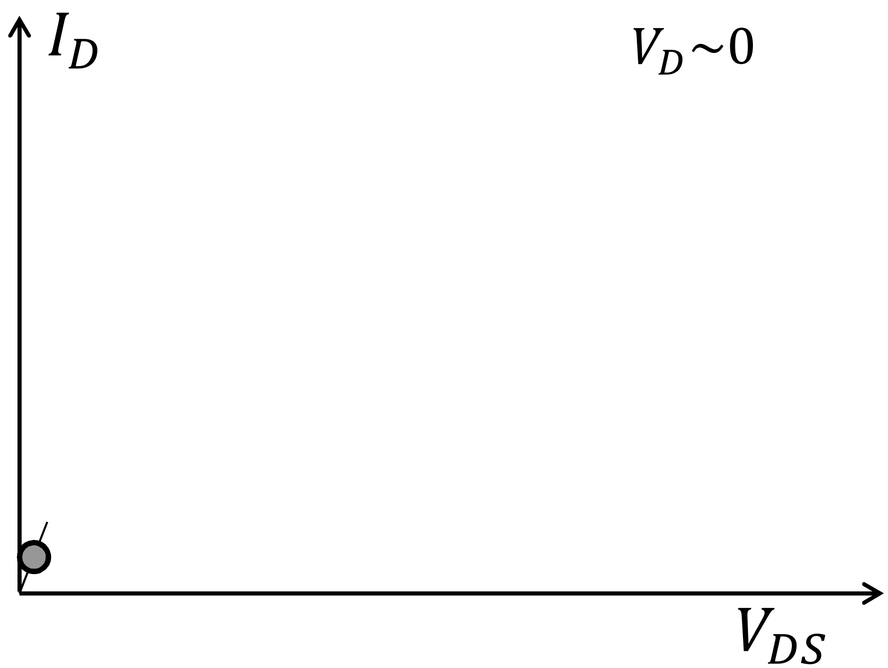

$$R = \rho \frac{L}{Wx}$$

JFET (Qualitative)

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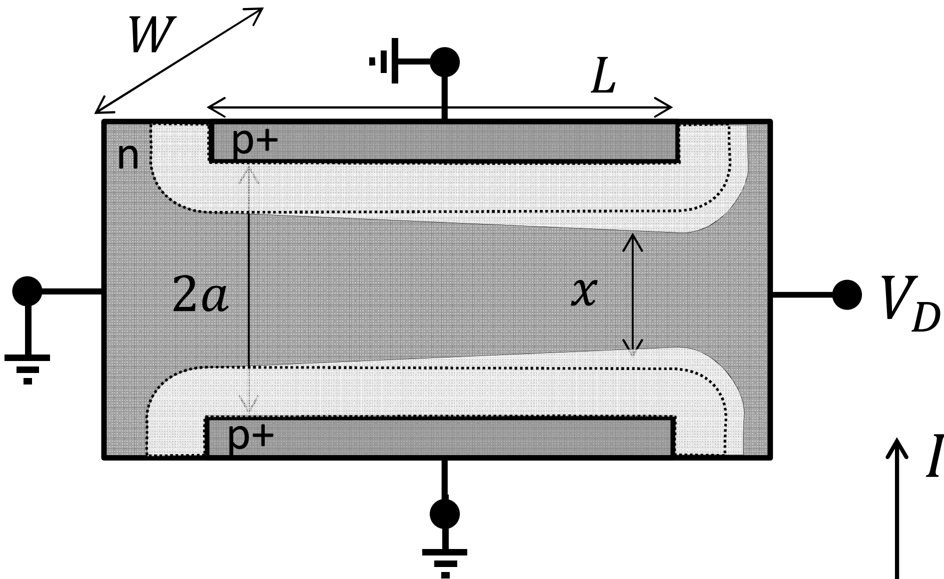
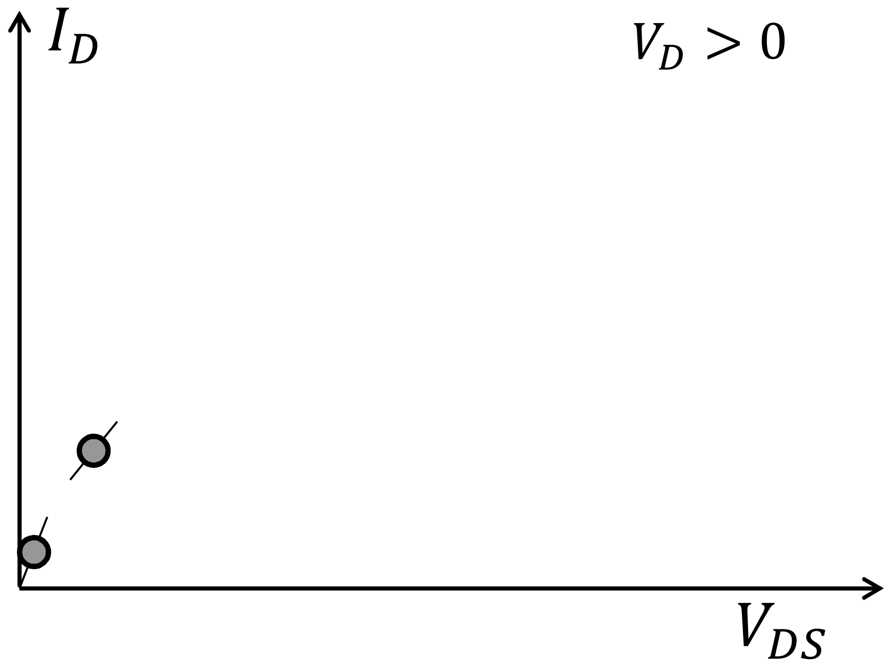


$$R = \rho \frac{L}{Wx}$$

$V_D > 0$



JFET (Qualitative)

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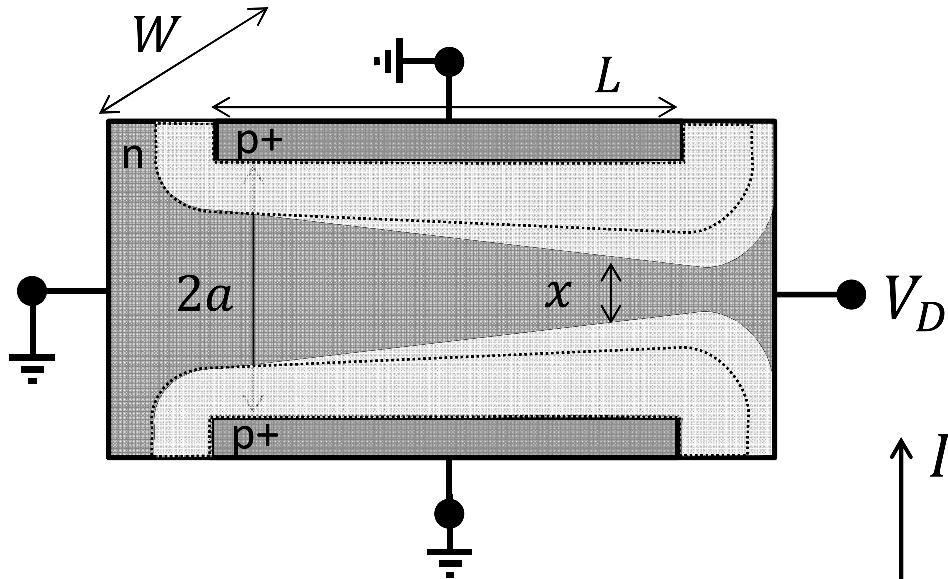
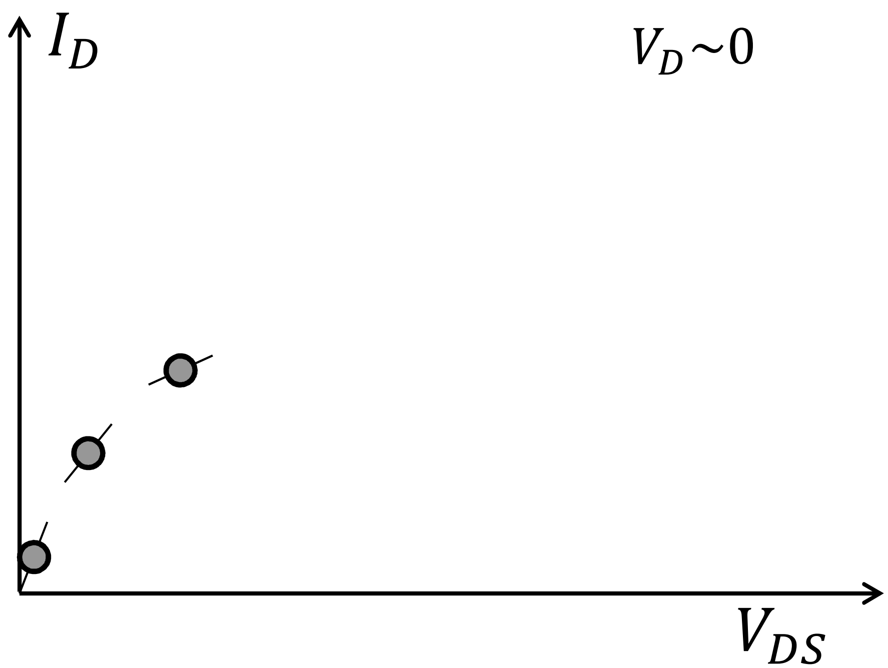


$$R = \rho \frac{L}{Wx}$$



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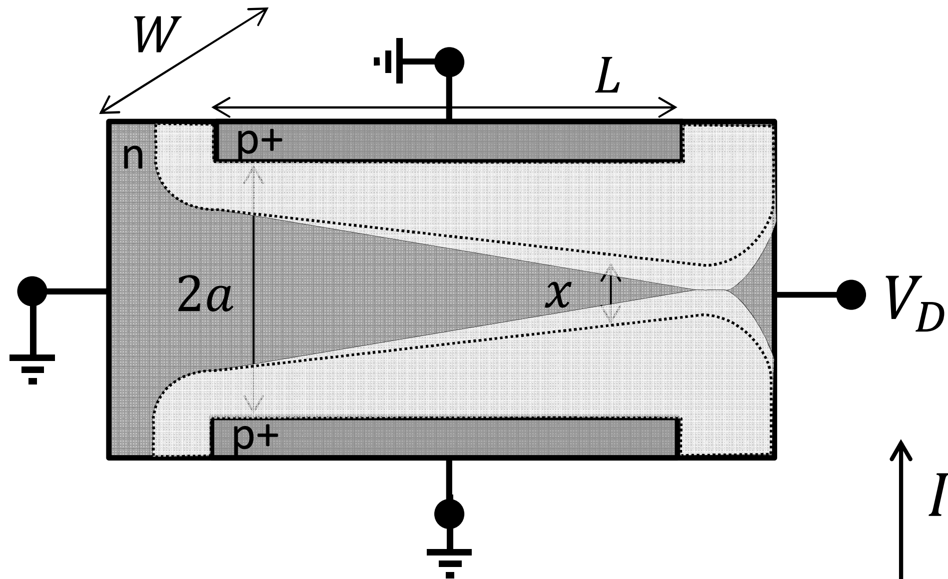
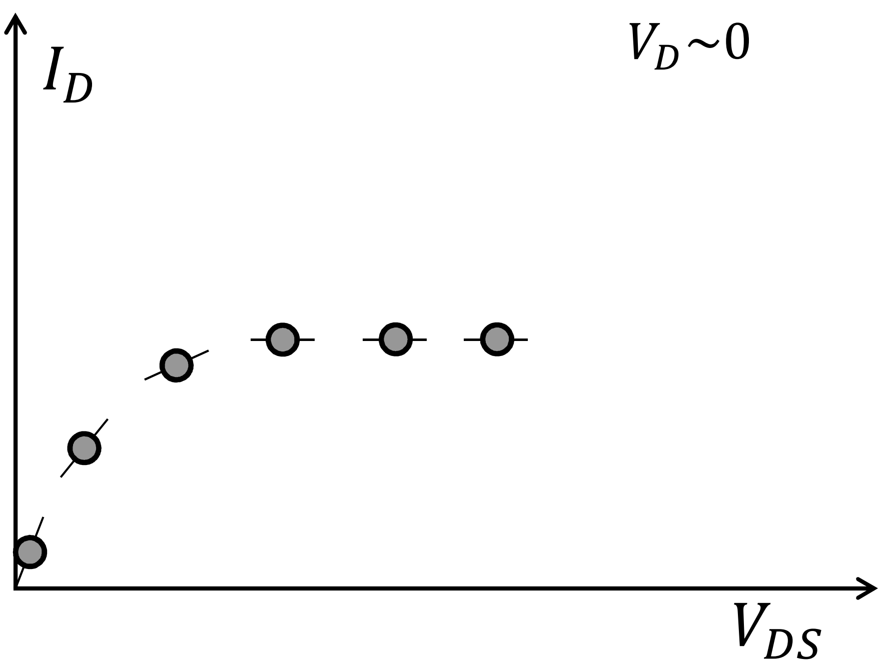
JFET (Qualitative)





$$R = \rho \frac{L}{Wx}$$

JFET (Qualitative)

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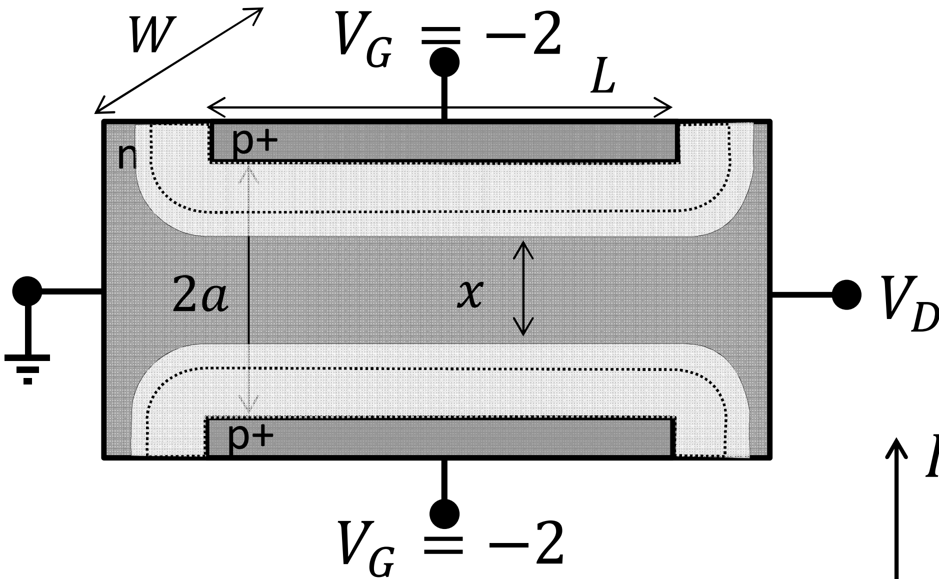

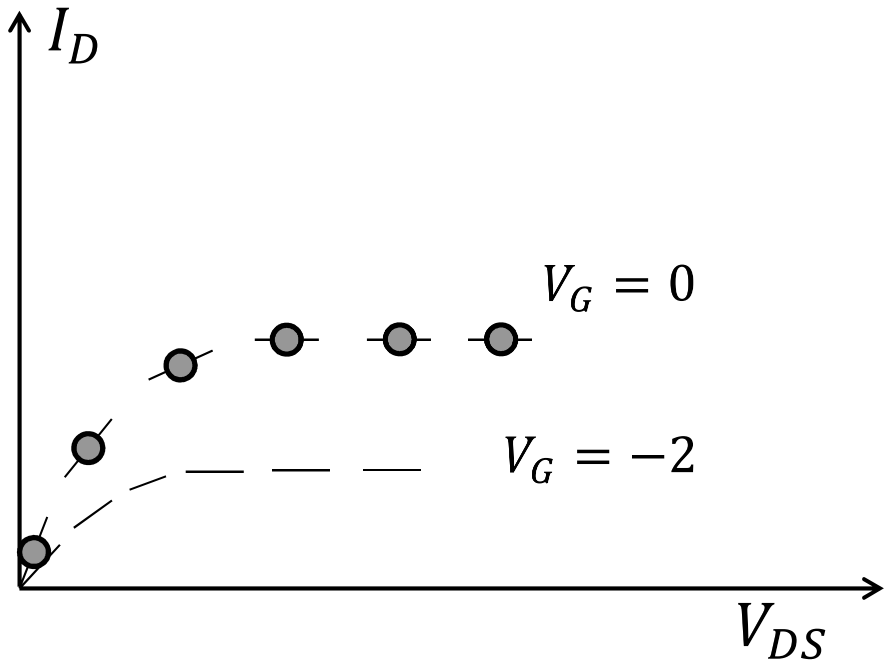

$$R = \rho \frac{L}{Wx}$$

JFET (Qualitative)

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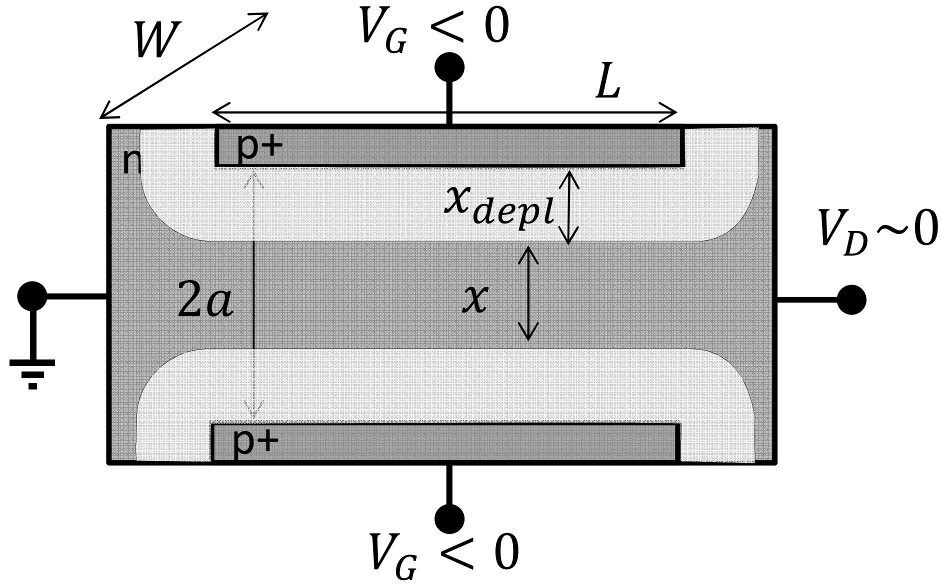

$$V_G = 0 \;\rightarrow\; x_{depl} = \sqrt{\frac{2\epsilon\varphi_0}{qN_D}}$$

$$\varphi_0 = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2}$$

$$\varphi_0 = \frac{E_G}{2q} + \frac{kT}{q}\ln\frac{N_D}{n_i}$$

$$x_{depl} = \sqrt{\frac{2\epsilon(\varphi_0 - V_G)}{qN_D}}$$

$$\delta I_D = \sigma\frac{A}{L}\delta V_D \;= q\mu_n N_D\frac{2\left(a - x_{depl}\right)W}{L}\delta V_D$$

Pinch-off $\quad x_{depl} = a \;\rightarrow V_p = \varphi_0 - \frac{qN_D a^2}{2\epsilon}$

JFET, I-V curve

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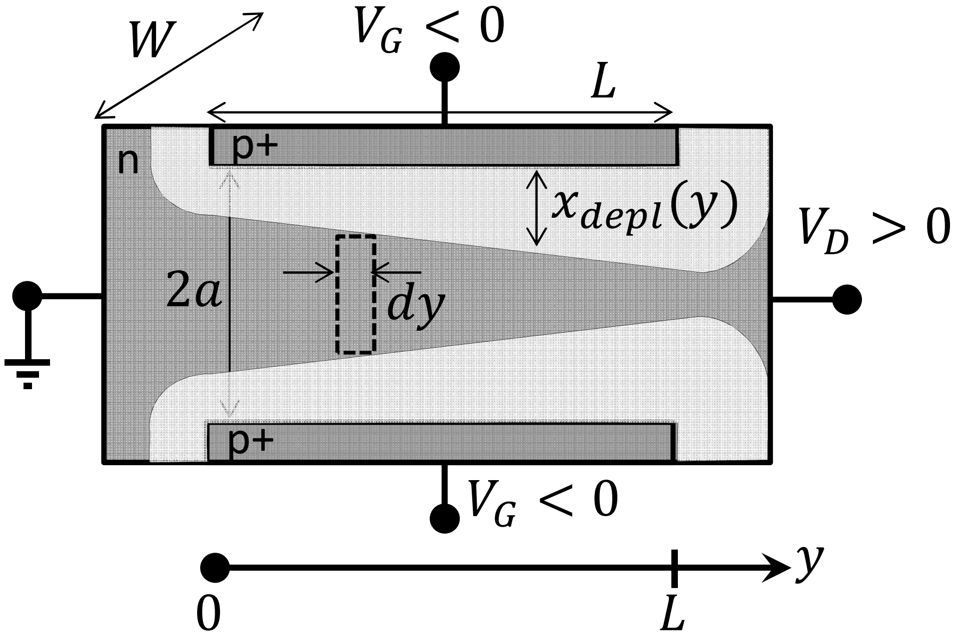


$$x_{depl} = \sqrt{\frac{2\epsilon(\varphi_0 - V_G + V(y))}{qN_D}}$$

B.C. $V(0) = 0, \qquad V(L) = V_D$

$$dR(y) = \frac{1}{q\mu_n N_D}\frac{dy}{2\big(a - x_{depl}(y)\big)W}$$

$$dV(y) = I_D dR(y)$$

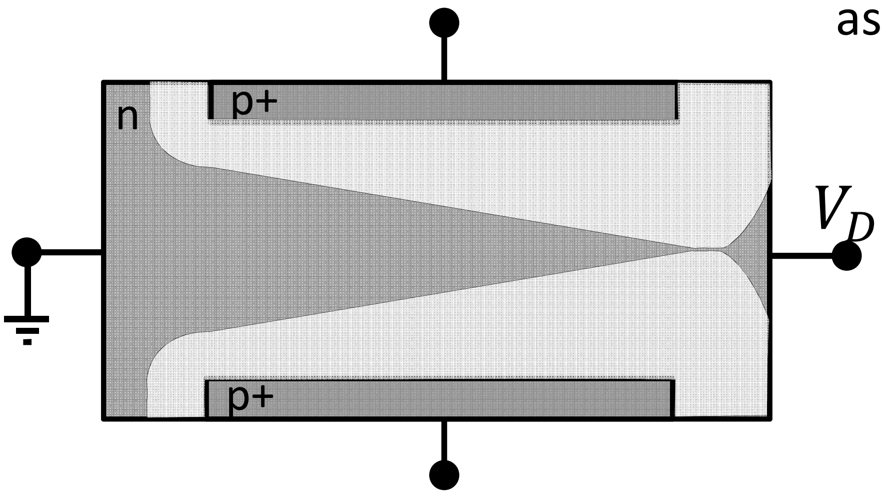
$$dV(y) = \frac{I_D}{q\mu_n N_D}\frac{dy}{2\big(a - x_{depl}(y)\big)W}$$

$$q\mu_n N_D \int_0^{V_D} \left[a - \sqrt{\frac{2\epsilon}{qN_D}(\varphi_0 - V_G + V(y))}\right] dV = I_D \int_0^L dy = I_D L$$

JFET, I-V curve

$$I_D = g_0 \left\{ V_D - \frac{2}{3}\sqrt{\frac{2\epsilon}{qN_D a^2}} \left[(V_D + \varphi_0 - V_G)^{3/2} - (\varphi_0 - V_G)^{3/2} \right] \right\}$$

as: $g_0 = 2q\mu_n N_D aW/L$



$$V_{D_{sat}} = V_G - V_p = V_G - \varphi_0 - \frac{qN_D a^2}{2\epsilon}$$

$$I_{D_{sat}} = I_D \Big|_{V_D = V_{D_{sat}}} = g_0 \left\{ \frac{qN_D a^2}{6\epsilon} - (\varphi_0 - V_G) + \frac{2}{3}\sqrt{\frac{2\epsilon}{qN_D a^2}} (\varphi_0 - V_G)^{3/2} \right\}$$

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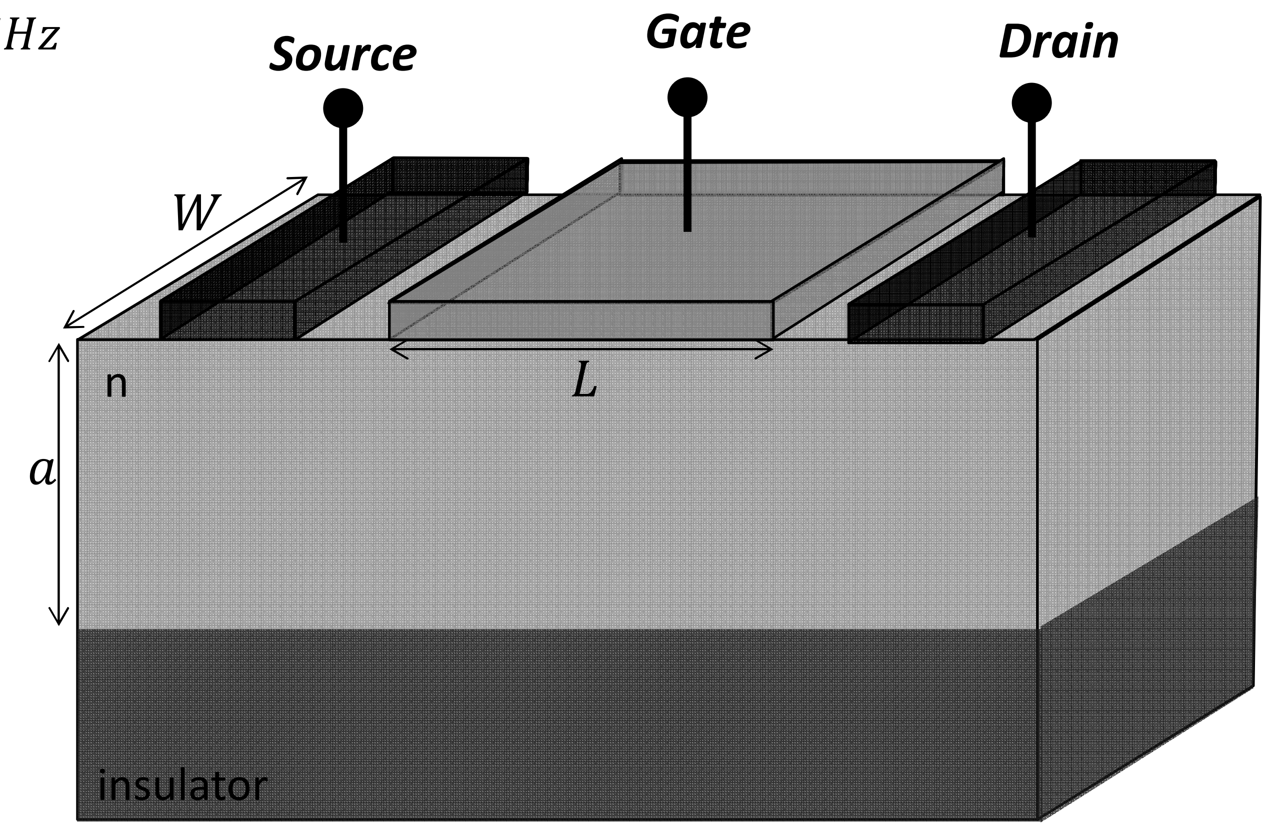
MESFET

MESFET (metal semiconductor field effect transistor)

$f_T > 100GHz$



MESFET (Qualitative)

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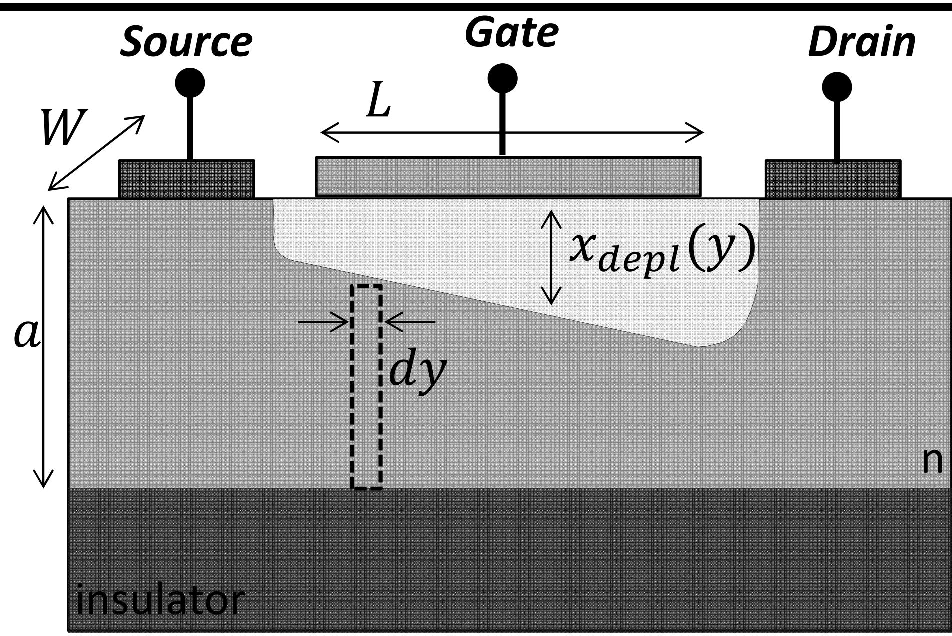

$$V_D = 0 \;\rightarrow x_{depl} = \sqrt{\frac{2\epsilon}{qN_D}(V_i - V_G)}$$

$$x_{delp}\Big|_{V_G=V_T} = a$$

$$\rightarrow V_T = V_i - \frac{qN_D a^2}{2\epsilon}$$

$$V_D > 0 \;\; \rightarrow x_{depl} = \sqrt{\frac{2\epsilon}{qN_D}(V_i - V_G + V(y))}$$

$$V(0) = 0\,, V(L) = V_D$$

$$dV = I_D dR =$$

$$= I_D \frac{1}{q\mu_n N_D} \frac{dy}{\left(a - x_{depl}(y)\right)W} = \frac{I_D dy}{q\mu_n N_D \left(a - \sqrt{\frac{2\epsilon}{qN_D}(V_i - V_G + V(y))}\right)W}$$

MESFET (Qualitative)

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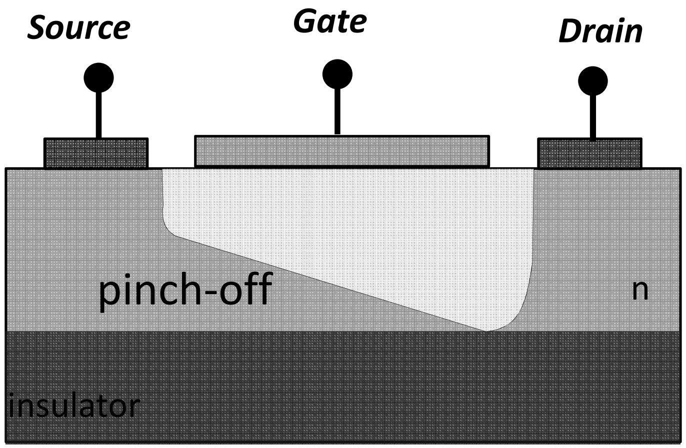
$$I_D = g_0 \left\{ V_D - \frac{2}{\sqrt{V_p}} \left[(V_D + V_i - V_G)^{3/2} - (V_i - V_G)^{3/2} \right] \right\}$$

$$g_0 = q\mu_n N_D W/L$$

$$V_p = \frac{qN_D a^2}{2\epsilon}$$



$$V_{D\,sat} = V_p - V_i + V_G = V_G - V_T$$

$$I_D = g_0 \left\{ \frac{V_p}{3} - \frac{2}{\sqrt[3]{V_p}} (V_i - V_G)^{3/2} - V_i + V_G \right\}$$

$$g_m = \left. \frac{\partial I_D}{\partial V_G} \right|_{V_D} = g_0 \left(1 - \sqrt{\frac{V_i - V_G}{V_p}} \right)$$