

EE-612: Lecture 32: Heterojunction Diodes

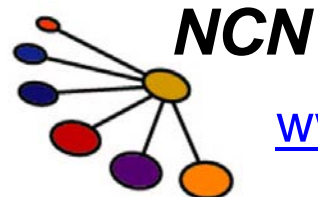
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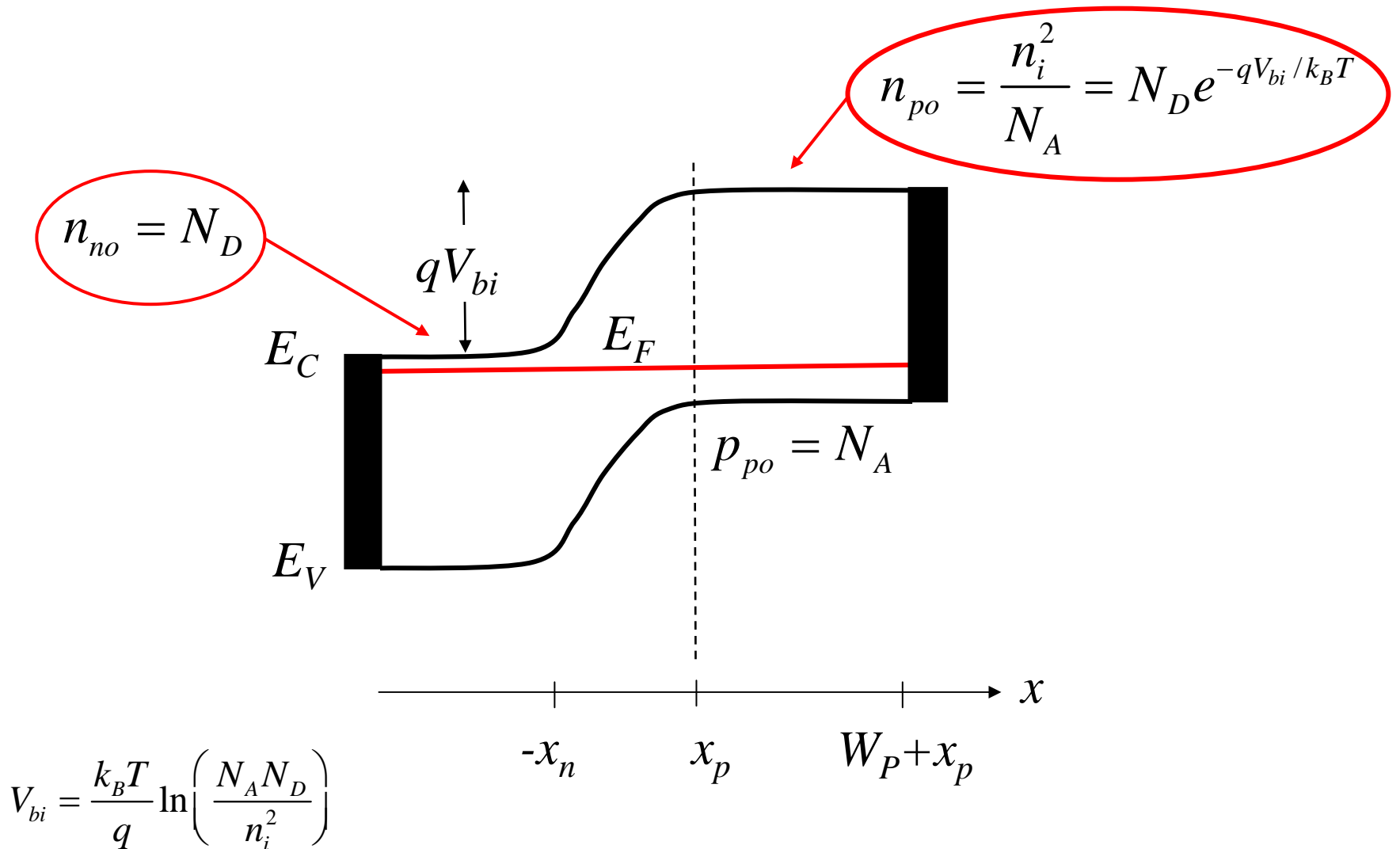


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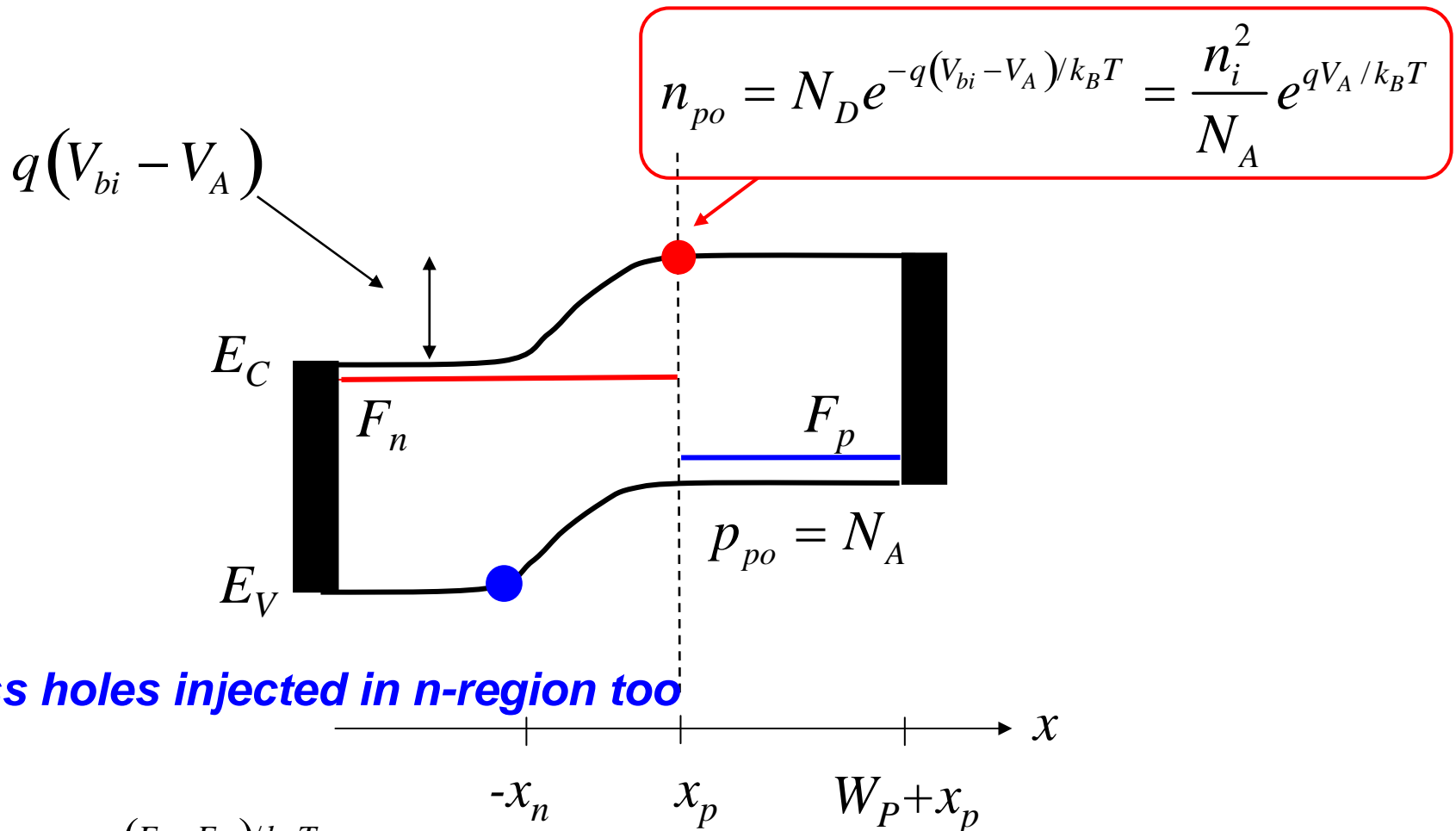
outline

- 1) **The “Law of the Junction”** (for pn homojunctions)
- 2) MS and Heterojunctions
- 3) Generalized “Law of the Junction” (homojunctions)
- 4) The Generalized Law for Heterojunctions
- 5) Summary

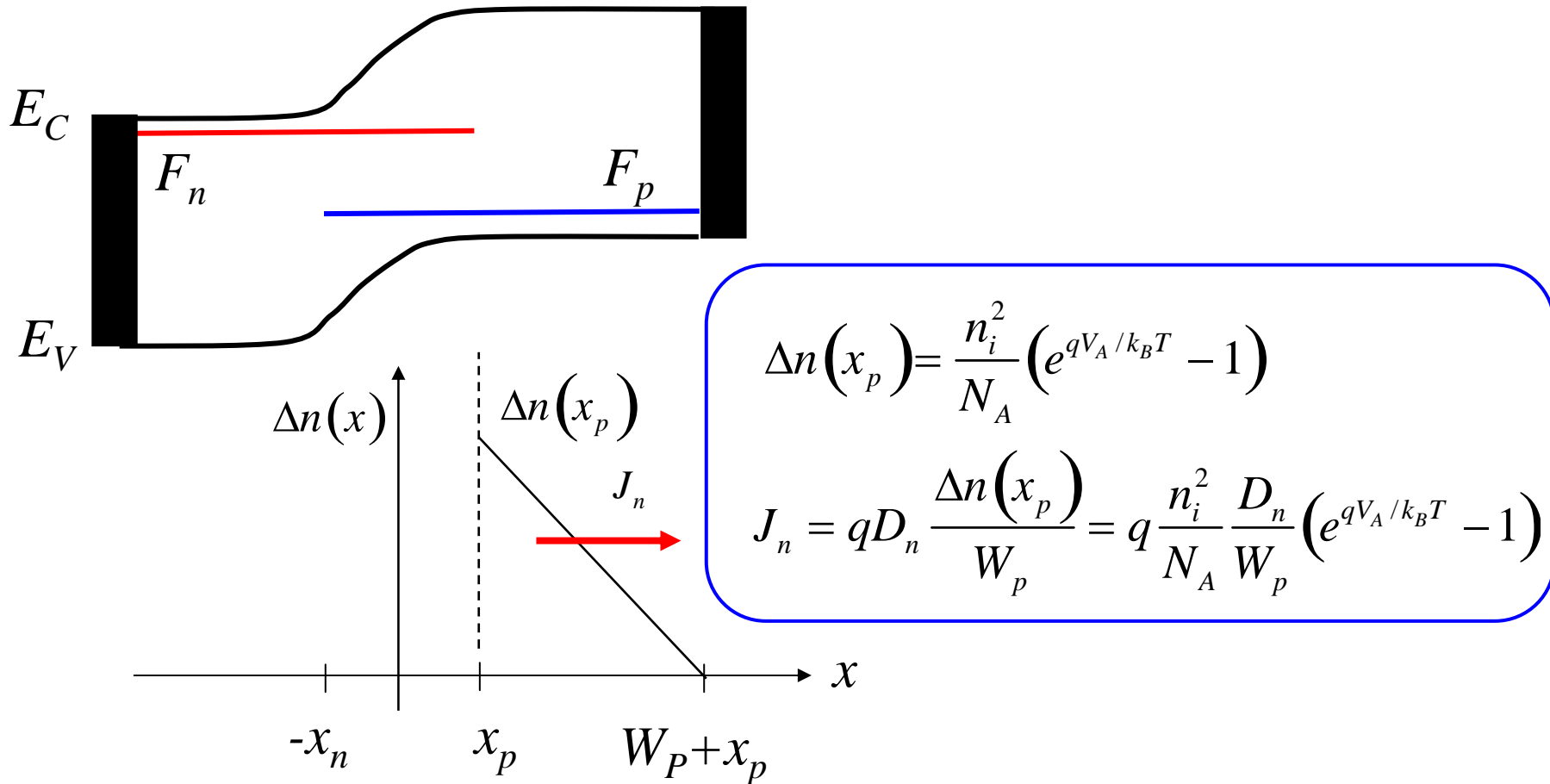
pn junction in equilibrium



pn junction under forward bias ($V_A > 0$)



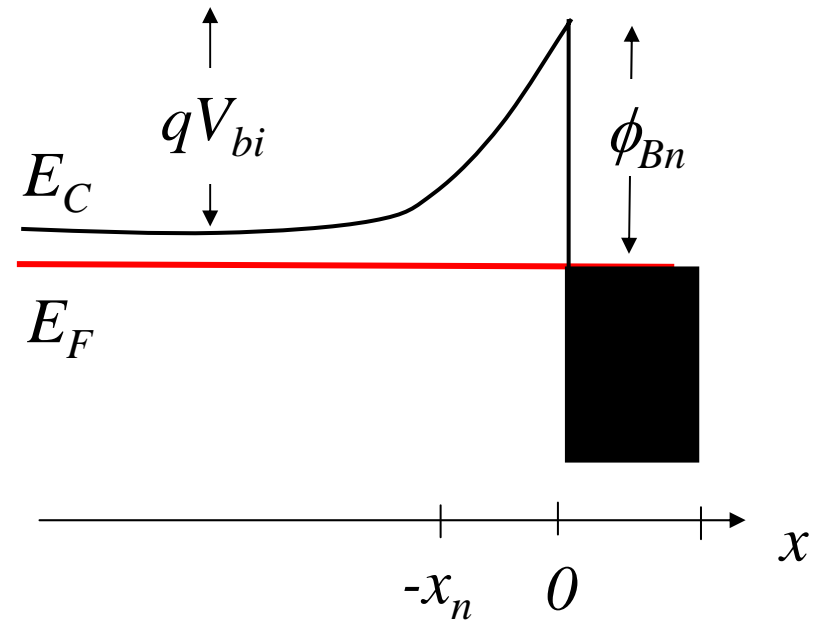
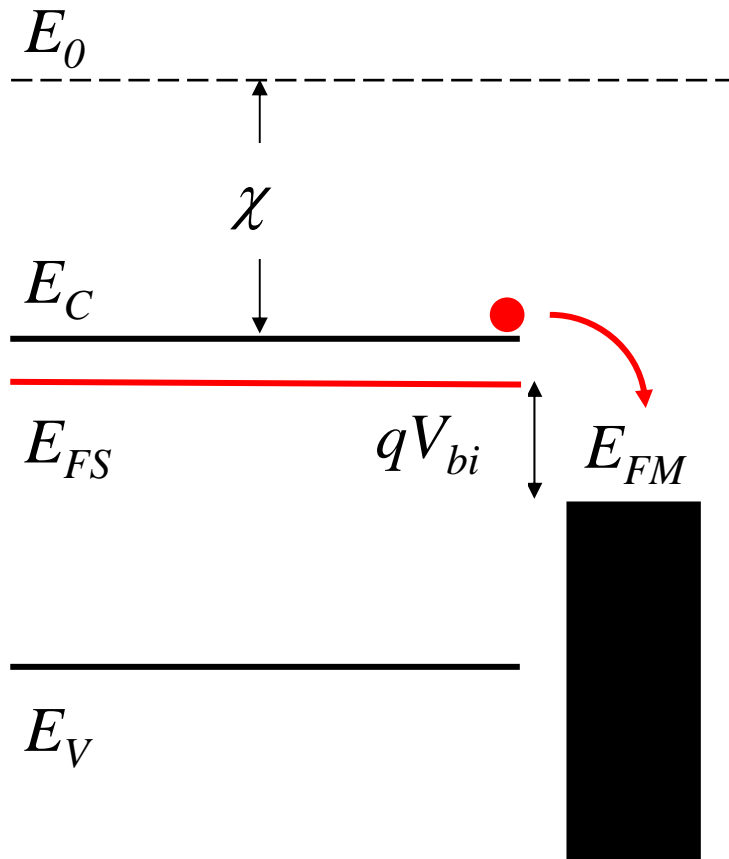
forward-biased current ($V_A > 0$)



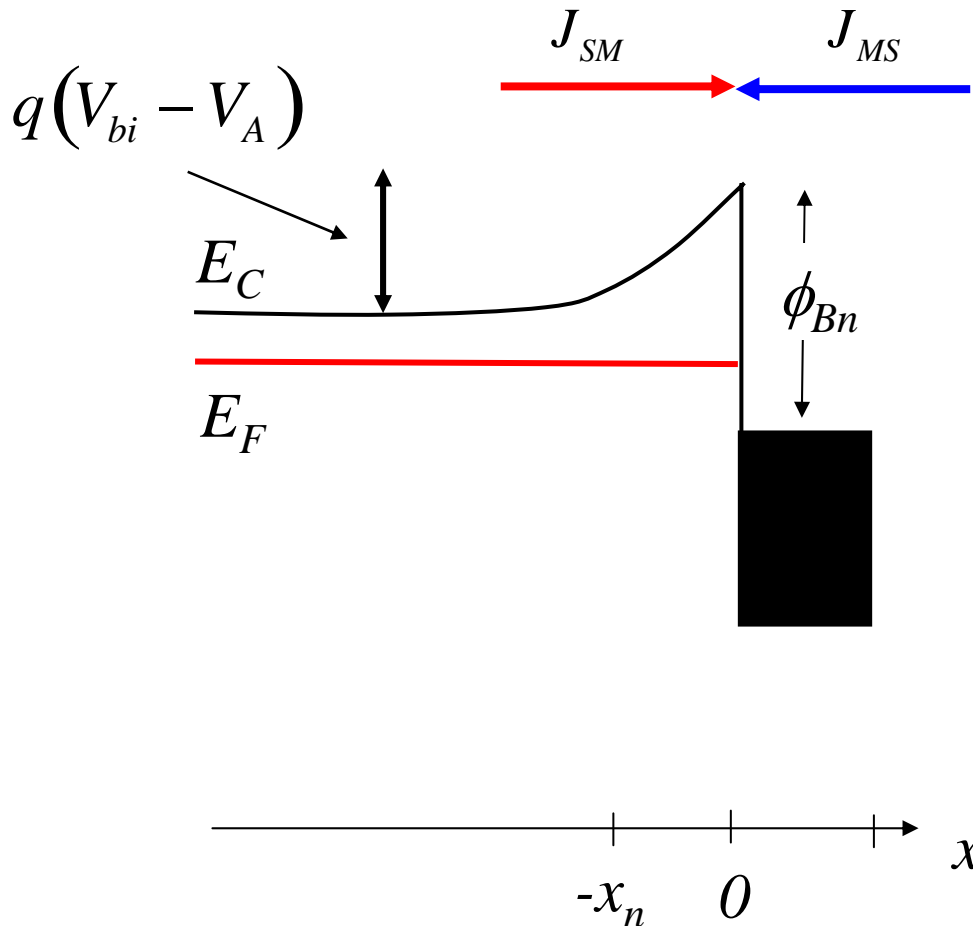
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metal-semiconductor junction in equilibrium



metal-semiconductor junctions (forward bias)



$$J_{SM} = q \left(\frac{N_D}{2} \right) v_T e^{-q(V_{bi} - V_A)/k_B T}$$

$$v_T = \sqrt{\frac{2k_B T}{\pi m^*}} = 2v_R$$

$$J_{MS} = q \left(\frac{N_D}{2} \right) v_T e^{-qV_{bi}/k_B T}$$

$$J = J_{SM} - J_{MS}$$

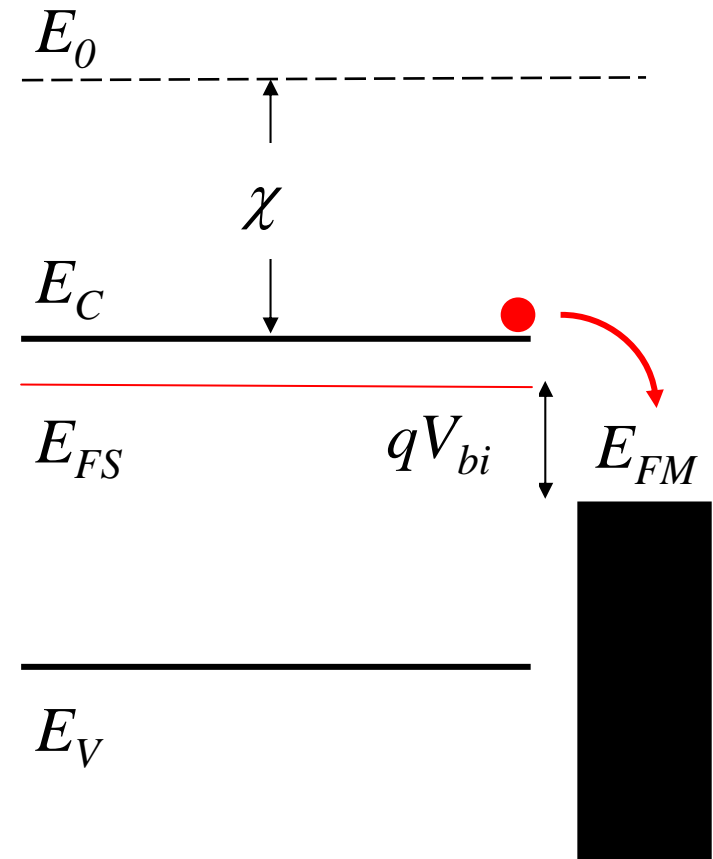
$$J = qN_D v_R e^{-qV_{bi}/k_B T} \left(e^{qV_A/k_B T} - 1 \right)$$

metal-semiconductor junctions

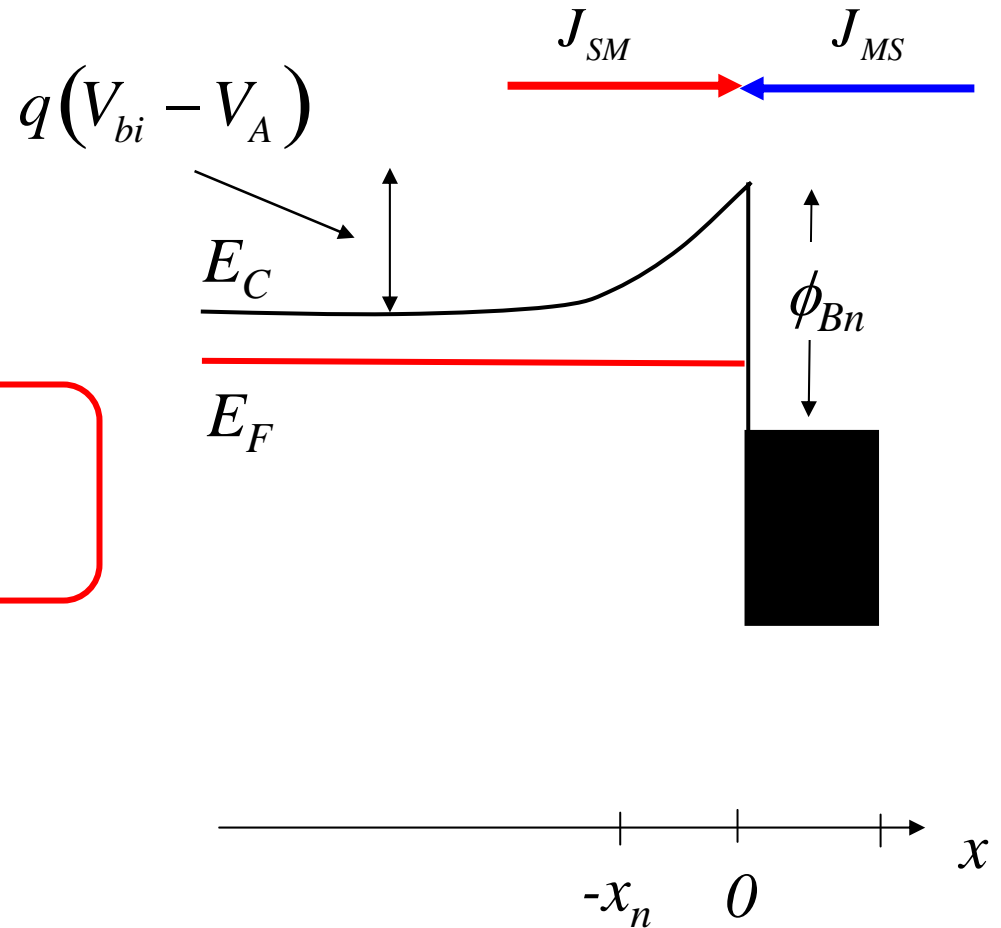
$$J = qN_D v_R e^{-qV_{bi}/k_B T} (e^{qV_A/k_B T} - 1)$$

$$\begin{aligned} qV_{bi} &= E_{FS} - E_{FM} \\ &= E_{FS} - E_C + E_C - E_{FM} \\ &= k_B T \ln(N_D/N_C) + q\phi_{Bm} \end{aligned}$$

$$J = qN_C v_R e^{-q\phi_{Bn}/k_B T} (e^{qV_A/k_B T} - 1)$$

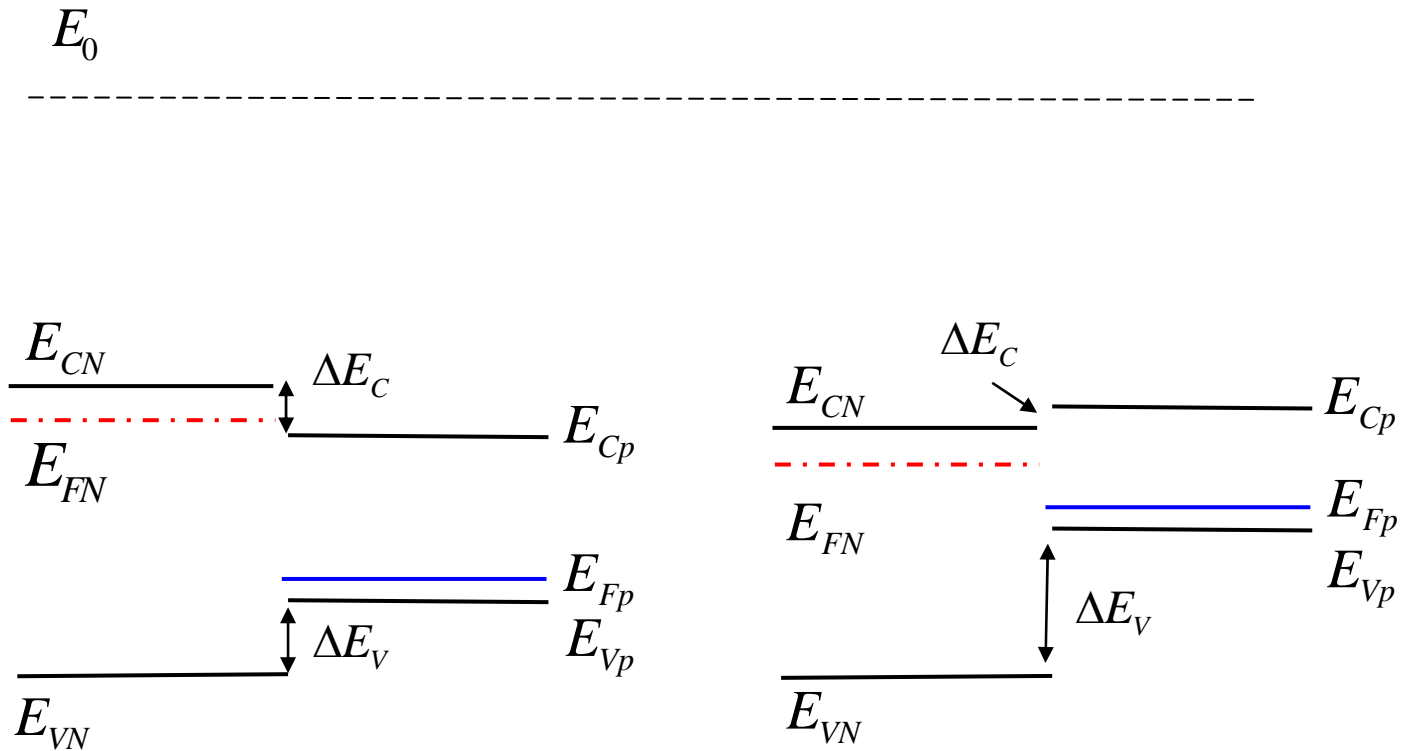


MS junction summary



$$J = qN_C v_R e^{-q\phi_{Bn}/k_B T} (e^{qV_A/k_B T} - 1)$$

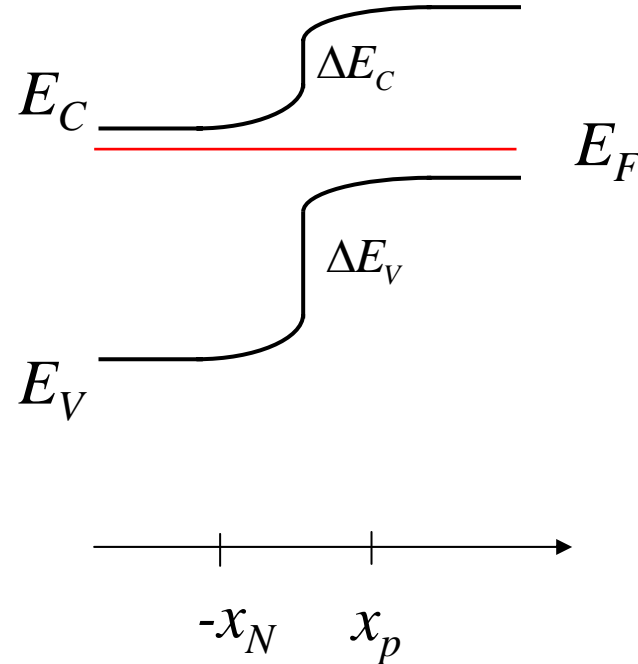
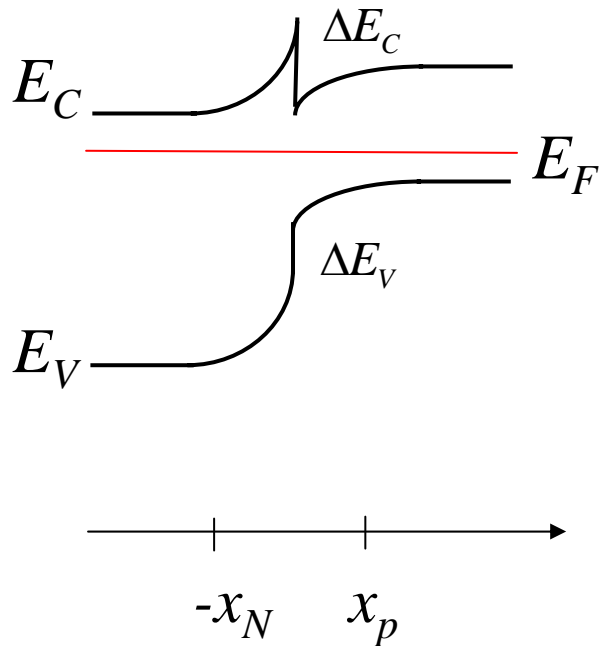
heterojunctions



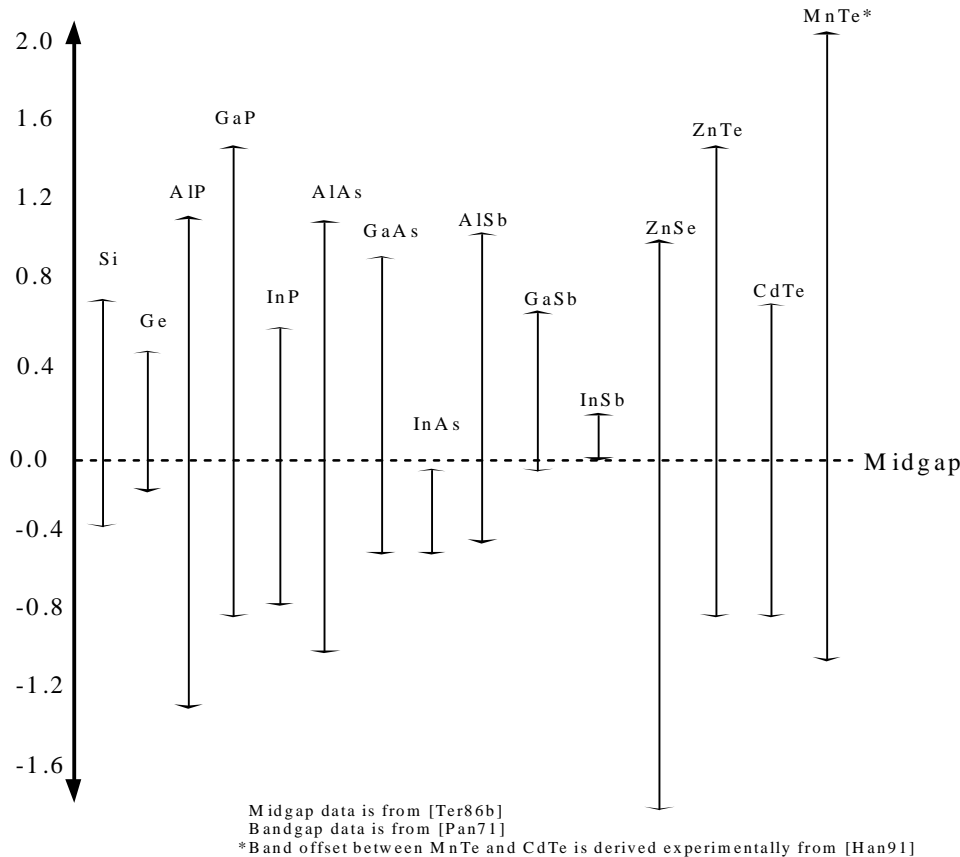
Np heterojunction e-band diagrams

conduction band “spike”

no spike



band line-ups



Observed band line-ups
 (courtesy of Jung Han,
 now at Yale Univ.)

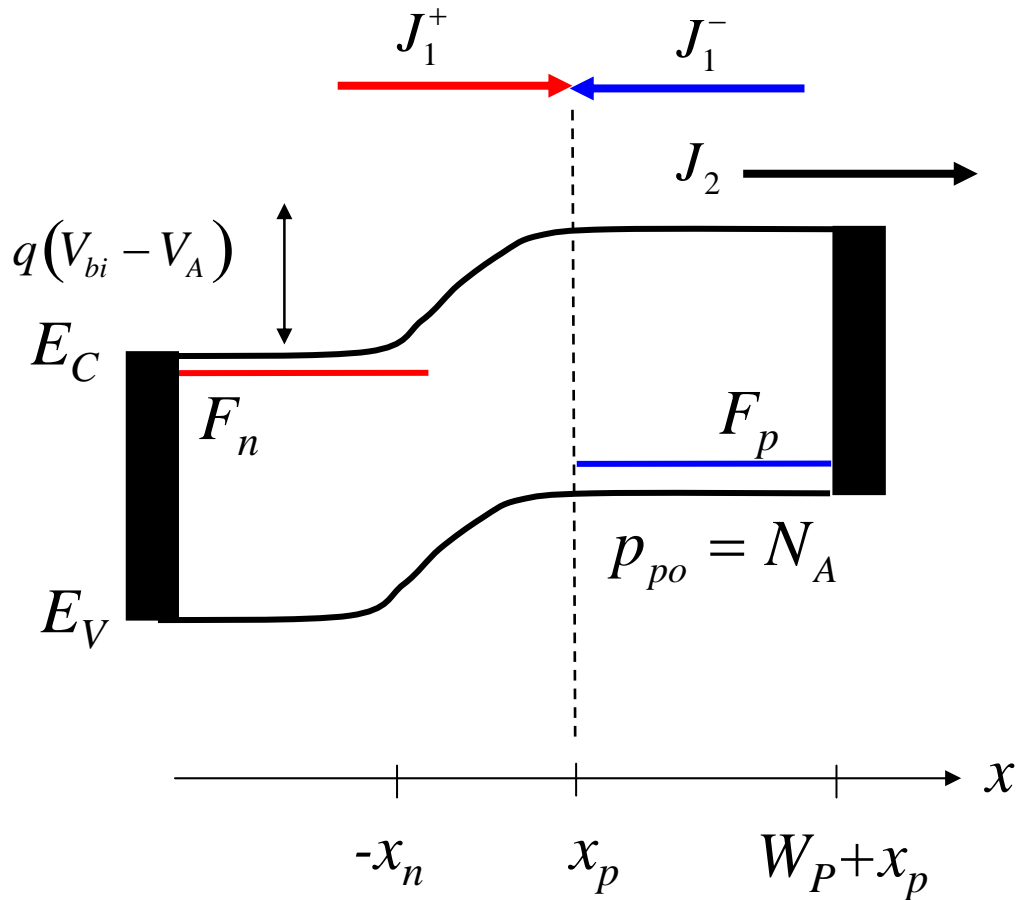
See also:
 “Heterostructure Fundamentals”
 unpublished notes by
 M.S. Lundstrom

[Ter86b] J. Tersoff, Phys. Rev. Lett. 56, 2755 (1986).
 [Pan71] J.I. Pankove, Optical processes in semiconductors, Dover Publications, Inc., NY (1971).
 [Han91] J. Han et al., J. Cryst. Growth 111, 767 (1991).

outline

- 1) The “Law of the Junction” (for pn homojunctions)
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- 3) **Generalized “Law of the Junction”** (homojunctions)
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forward-biased homojunctions



$$J_1^+ = q \frac{N_D}{2} v_T e^{-q(V_{bi} - V_A)/k_B T}$$

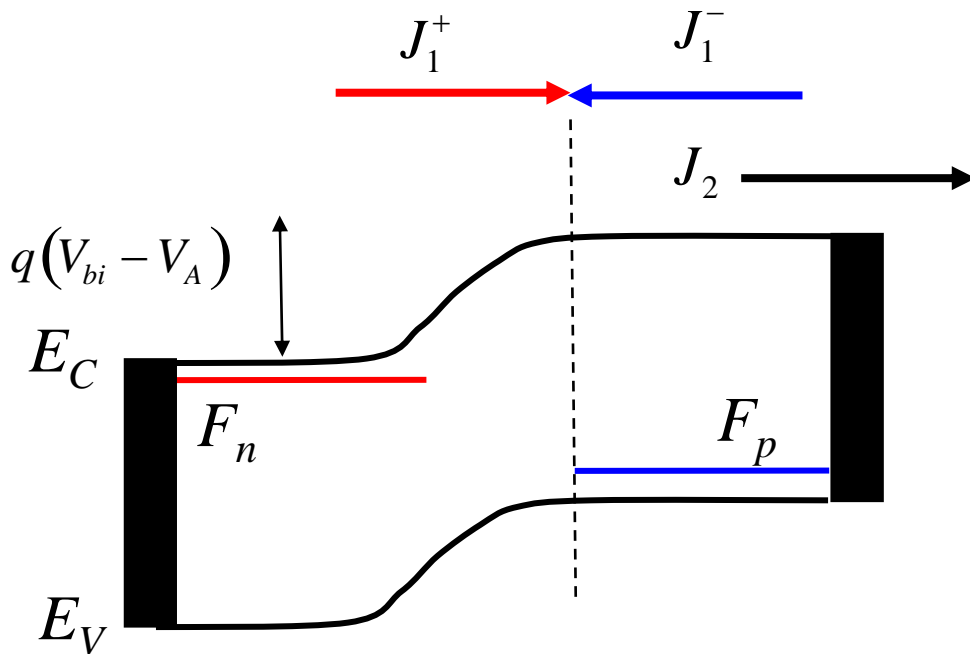
$$J_1^- = q \frac{n(x_p)}{2} v_T$$

$$J_2 = q D_n \frac{\Delta n(x_p)}{W_P} = q \Delta n(x_p) v_{Dp}$$

$$v_{Dp} = \frac{D_n}{W_P}$$

$$J_n = J_1^+ - J_1^- = J_2$$

generalized law of the pn homojunction



$$\Delta n(x_p) = \left[\frac{1}{1 + v_{Dp}/v_R} \right] \left(\frac{n_i^2}{N_A} \right) \left(e^{qV_A/k_B T} - 1 \right)$$

$$v_{Dp} \ll v_R$$

$$\Delta n(x_p) = \left(\frac{n_i^2}{N_A} \right) \left(e^{qV_A/k_B T} - 1 \right)$$

(base diffusion limited)

$$v_{Dp} \gg v_R$$

$$\Delta n(x_p) = \left(\frac{n_i^2}{N_A} \right) \frac{v_R}{v_{Dp}} \left(e^{qV_A/k_B T} - 1 \right)$$

(emission limited)

generalized law of the pn homojunction (ii)

$$\Delta n(x_p) = \left[\frac{1}{1 + \nu_{Dp}/\nu_R} \right] \left(\frac{n_i^2}{N_A} \right) \left(e^{qV_A/k_B T} - 1 \right)$$

$$J_n = J_1^+ - J_1^- = J_2 = q \nu_{Dp} \Delta n(x_p)$$

$$J_n = q \left(\frac{n_i^2}{N_A} \right) \left[\frac{1}{1/\nu_{Dp} + 1/\nu_R} \right] \left(e^{qV_A/k_B T} - 1 \right)$$

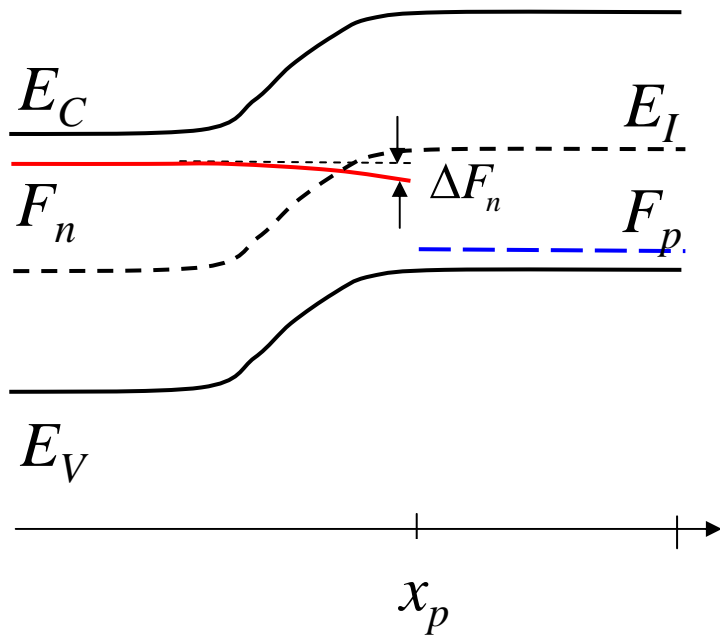
$$J_n = q \left(\frac{n_i^2}{N_A} \right) \nu_{Dp} \left(e^{qV_A/k_B T} - 1 \right)$$

$$\nu_{Dp} \ll \nu_R$$

$$J_n = q \left(\frac{n_i^2}{N_A} \right) \nu_R \left(e^{qV_A/k_B T} - 1 \right)$$

$$\nu_{Dp} \gg \nu_R$$

Fermi level droop



$$N_D = n_i e^{(F_n(-\infty) - E_i(-\infty))/k_B T}$$

$$n(x_p) = n_i e^{(F_n(x_p) - E_i(x_p))/k_B T}$$

$$\Delta F_n = F_n(-\infty) - F_n(x_p)$$

$$\Delta F_n = k_B T \ln \left(1 + \nu_{Dp} / \nu_R \right)$$

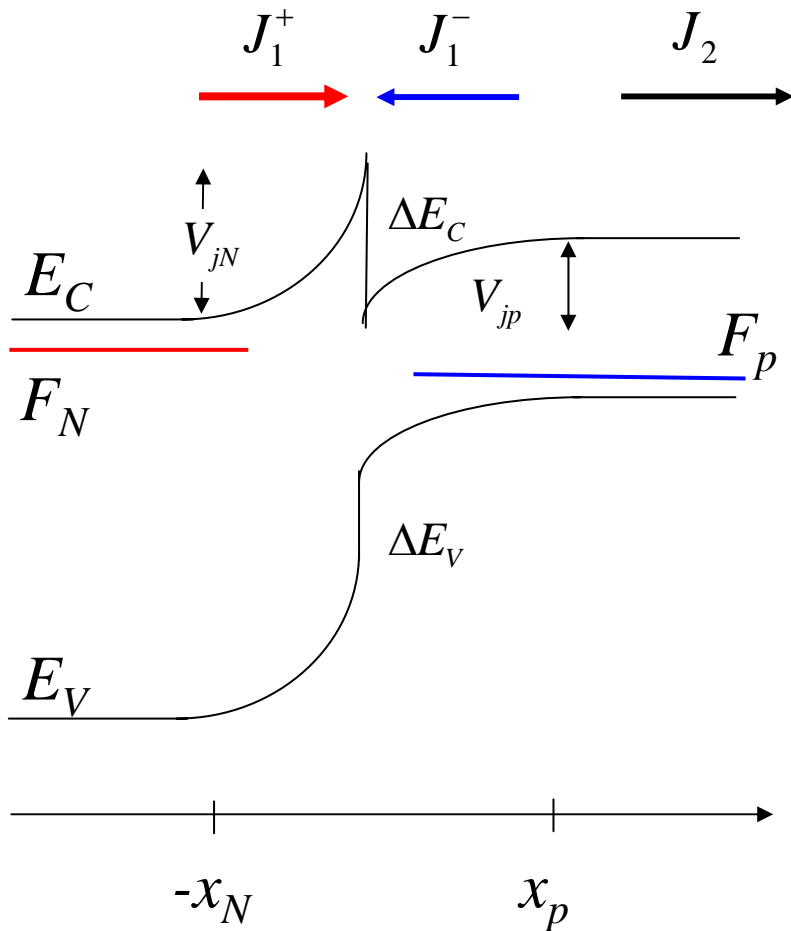
if $\nu_{Dp} \ll \nu_R$

$$\Delta F_n \approx 0$$

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heterojunctions under bias



$$J_1^+ = q \frac{N_D}{2} v_{TN} e^{-qV_{jN}/k_B T}$$

$$J_1^- = q \frac{n(x_p)}{2} v_{Tp} e^{-(\Delta E_C - qV_{jp})/k_B T}$$

$$J_{1o}^+ = J_{1o}^-$$

$$N_D v_{RN} e^{-qV_{bi}/k_B T} = n_o(x_p) v_{Rp} e^{-\Delta E_C/k_B T}$$

$$J_2 = q D_n \frac{\Delta n(x_p)}{W_P} = q \Delta n(x_p) v_{Dp}$$

$$J_n = J_1^+ - J_1^- = J_2$$

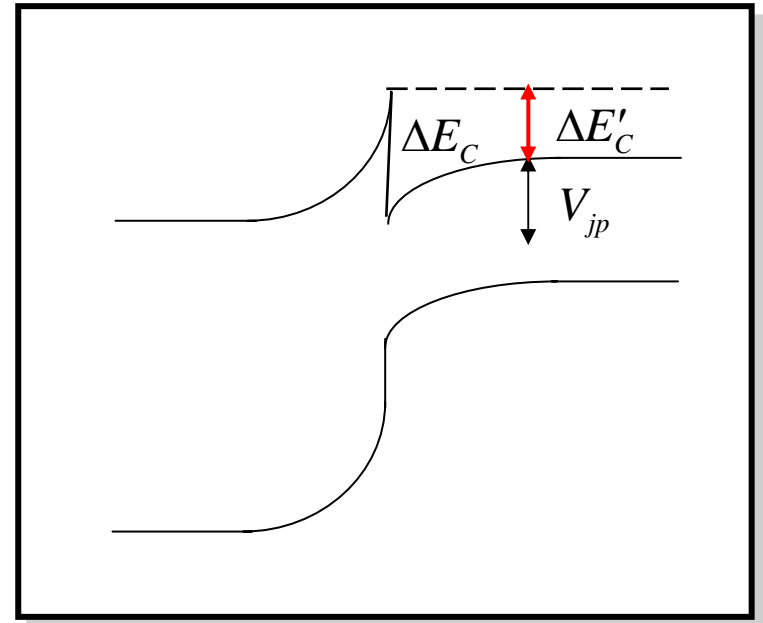
generalized law for heterojunctions

$$\Delta n(x_p) = \frac{1}{\left[1 + \nu_{Dp} / \nu_{ems}\right]} \frac{n_{ip}^2}{N_A} \left(e^{qV_A / k_B T} - 1\right)$$

$$\nu_{ems} = \nu_{Rp} e^{-\Delta E'_C / k_B T} = \nu_{Rp} e^{-(\Delta E_C - qV_{jp}) / k_B T}$$

$$J_n = J_2 = q \Delta n(x_p) \nu_{Dp}$$

$$J_n = q \left(\frac{n_{ip}^2}{N_A} \right) \frac{1}{\left[1 / \nu_{Dp} + 1 / \nu_{ems}\right]} \left(e^{qV_A / k_B T} - 1\right)$$



generalized law for heterojunctions (ii)

$$J_n = q \left(\frac{n_{ip}^2}{N_A} \right) \frac{1}{\left[1/\nu_{Dp} + 1/\nu_{ems} \right]} \left(e^{qV_A/k_B T} - 1 \right)$$

$$\nu_{ems} = \nu_{Rp} e^{-\Delta E_C'/k_B T} = \nu_{Rp} e^{-(\Delta E_C - qV_{jp})/k_B T}$$

$$\Delta E_C \ll k_B T$$

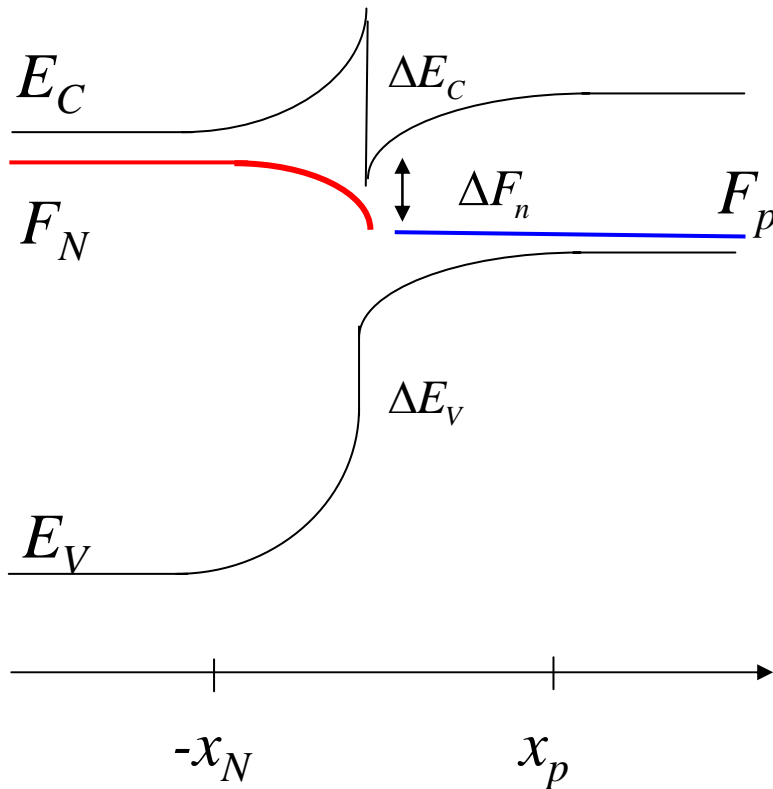
$$J_n = q \left(\frac{n_{ip}^2}{N_A} \right) \nu_{Dp} \left(e^{qV_A/k_B T} - 1 \right)$$

$$\Delta E_C \gg k_B T$$

$$J_n = q \left(\frac{n_{ip}^2}{N_A} \right) \nu_{Rp} e^{-\Delta E_C/k_B T} \left(e^{qV_A/k_B T} - 1 \right)$$

band spikes suppress current

Fermi level droop



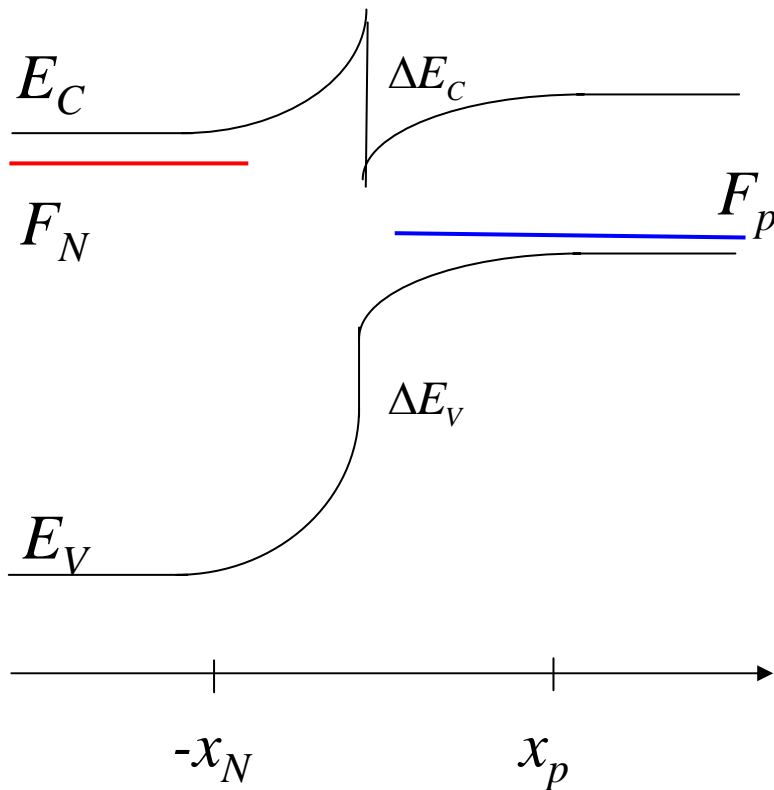
$$\Delta F_n = k_B T \ln \left(1 + \nu_{Dp} / \nu_{ems} \right)$$

$$\Delta F_n = k_B T \ln \left[1 + \left(\nu_{Dp} / \nu_{Rp} \right) e^{\Delta E'_C / k_B T} \right]$$

if $\Delta E_C \gg k_B T$

$$\Delta F_n \approx \Delta E_C$$

band spikes and MS diodes



Np heterojunction

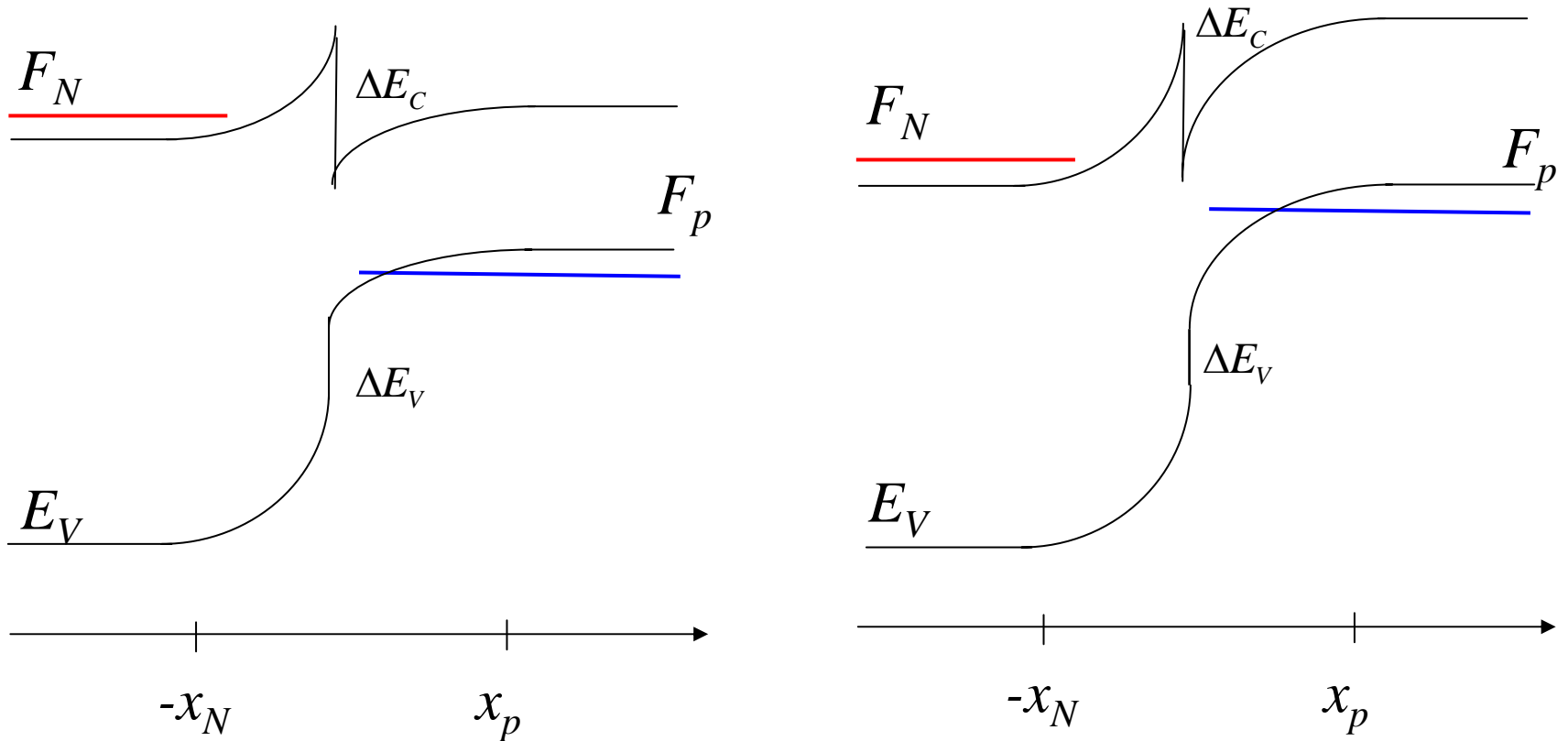
$$J_n = q \left(\frac{n_{ip}^2}{N_A} \right) v_{Rp} e^{-\Delta E_C / k_B T} \left(e^{qV_A / k_B T} - 1 \right)$$

MS diode

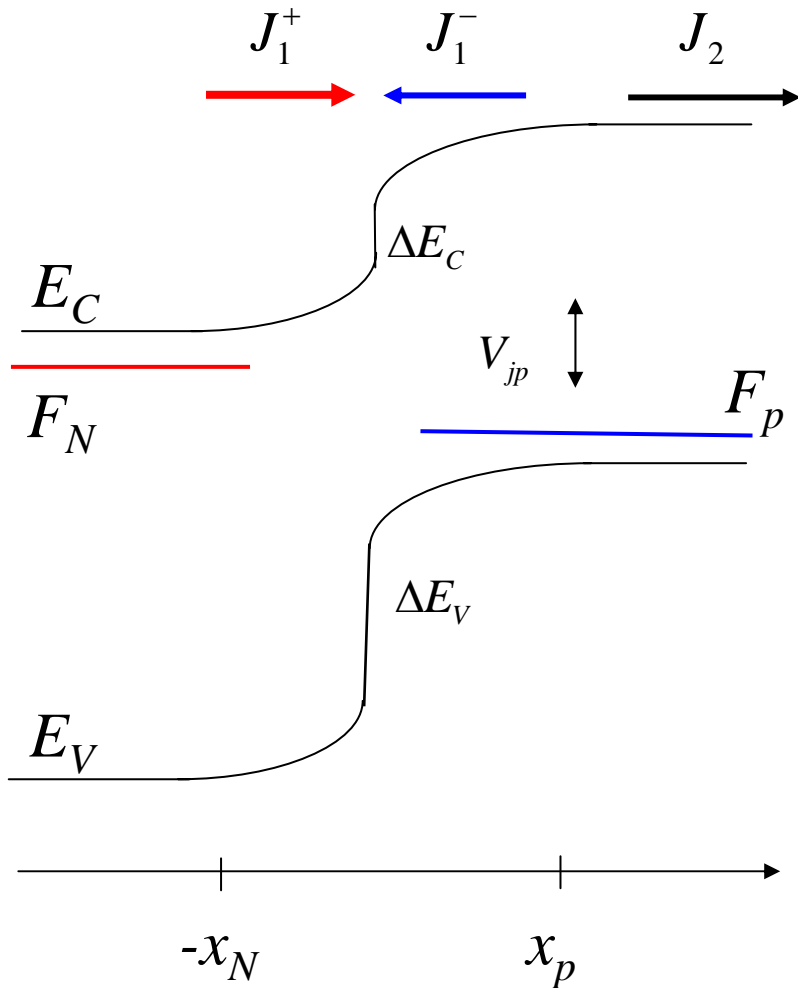
$$J = q N_C v_R e^{-q\phi_{Bn} / k_B T} \left(e^{qV_A / k_B T} - 1 \right)$$

band spikes and junction bias

$\Delta E'_C$ is bias dependent!



heterojunctions with no band spike



$$J_1^+ = q \frac{N_D}{2} v_{TN} e^{-q(V_{bi} - V_A + \Delta E_C)/k_B T}$$

$$J_1^- = q \frac{n(x_p)}{2} v_{Tp}$$

$$J_2 = q D_n \frac{\Delta n(x_p)}{W_P} = q \Delta n(x_p) v_{Dp}$$

$$J_n = J_1^+ - J_1^- = J_2$$

heterojunctions with no band spike (ii)

$$\Delta n(x_p) = \frac{1}{\left[1 + \nu_{Dp} / \nu_{Rp}\right]} \frac{n_{ip}^2}{N_A} \left(e^{qV_A/k_B T} - 1\right)$$

$$J_n = q \left(\frac{n_{ip}^2}{N_A} \right) \frac{1}{\left[1/\nu_{Dp} + 1/\nu_{Rp}\right]} \left(e^{qV_A/k_B T} - 1\right)$$

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summary

$$\Delta n(x_p) = \frac{1}{\left[1 + \nu_{Dp} / \nu'_{Rp}\right]} \frac{n_{ip}^2}{N_A} \left(e^{qV_A/k_B T} - 1\right)$$

$$J_n = q \left(\frac{n_{ip}^2}{N_A}\right) \frac{1}{\left[1/\nu_{Dp} + 1/\nu'_{Rp}\right]} \left(e^{qV_A/k_B T} - 1\right)$$

for homojunctions or heterojunctions with no band spike:

$$\nu'_{Rp} = \nu_{Rp} \quad \nu'_{Rp} \gg \nu_{Dp} \quad (\text{typically})$$

for heterojunctions with a band spike

$$\nu'_{Rp} = \nu_{Rp} e^{-\left(\Delta E_C - qV_{ip}\right)/k_B T} \quad \nu'_{Rp} \ll \nu_{Dp} \quad (\text{typically})$$

question

Without using the formal derivation presented here, can you clearly explain using only words and figures (and perhaps, some very simple equations) why a band spike suppresses the current?