EE-612:
Lecture 32:
Heterojunction Diodes

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NCN

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outline

1) **The “Law of the Junction”** (for pn homojunctions)

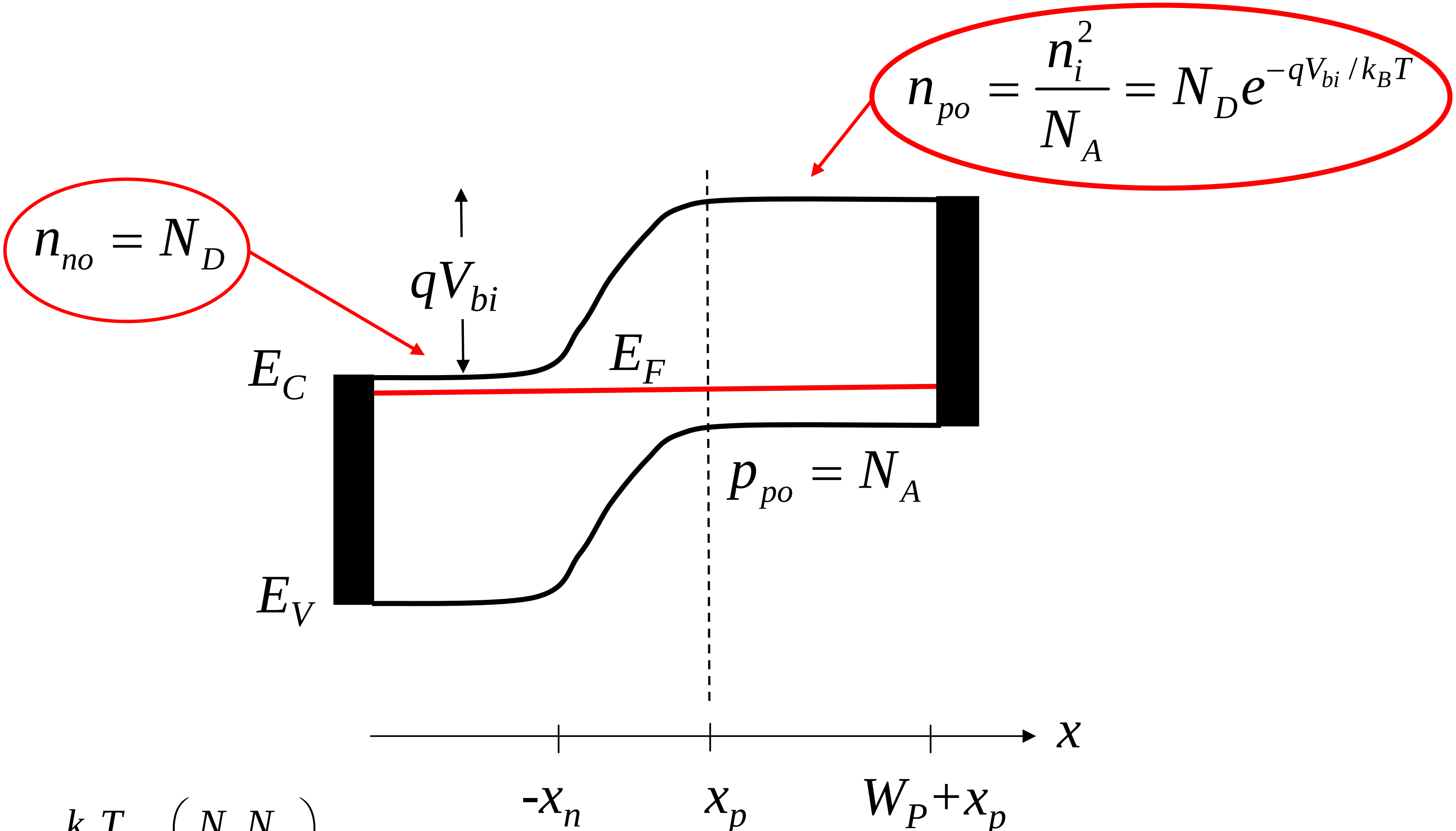
2) MS and Heterojunctions

3) Generalized “Law of the Junction” (homojunctions)

4) The Generalized Law for Heterojunctions

5) Summary

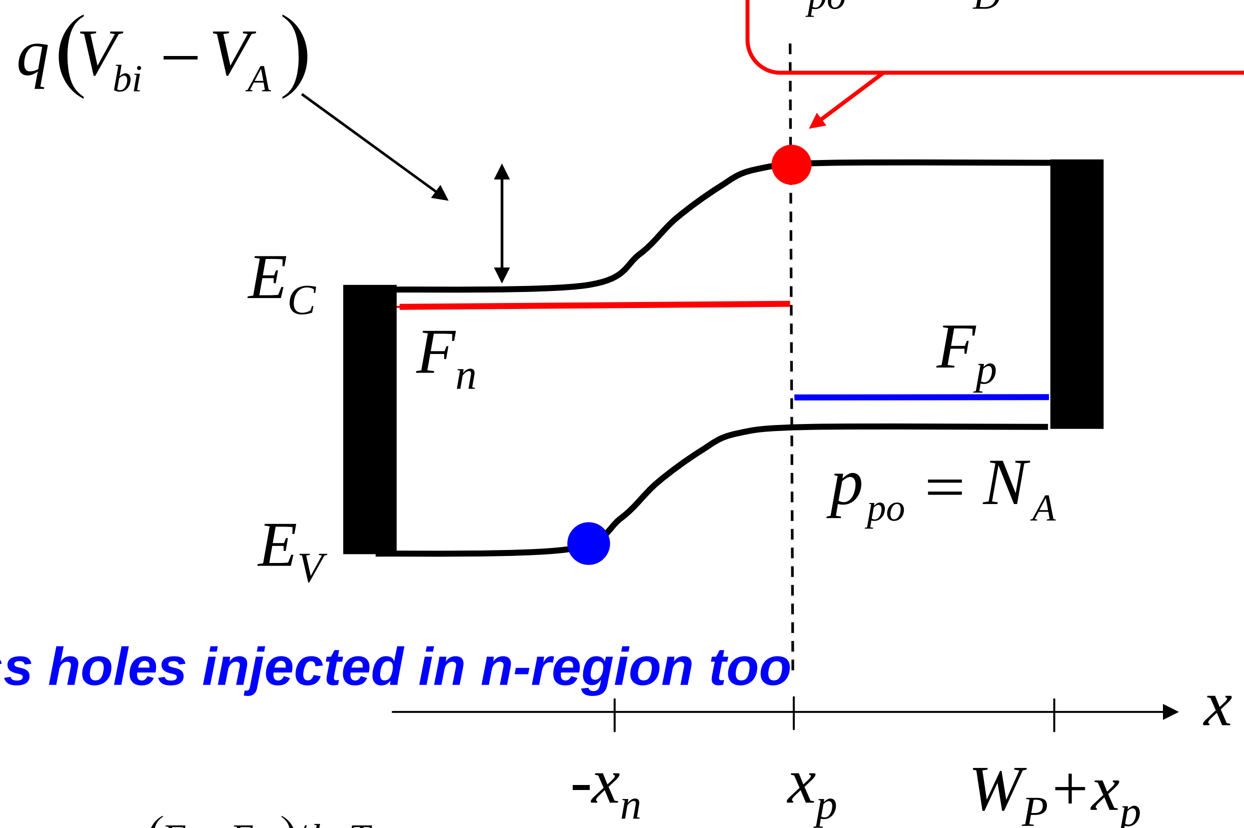
pn junction in equilibrium



$$V_{bi} = \frac{k_B T}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

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

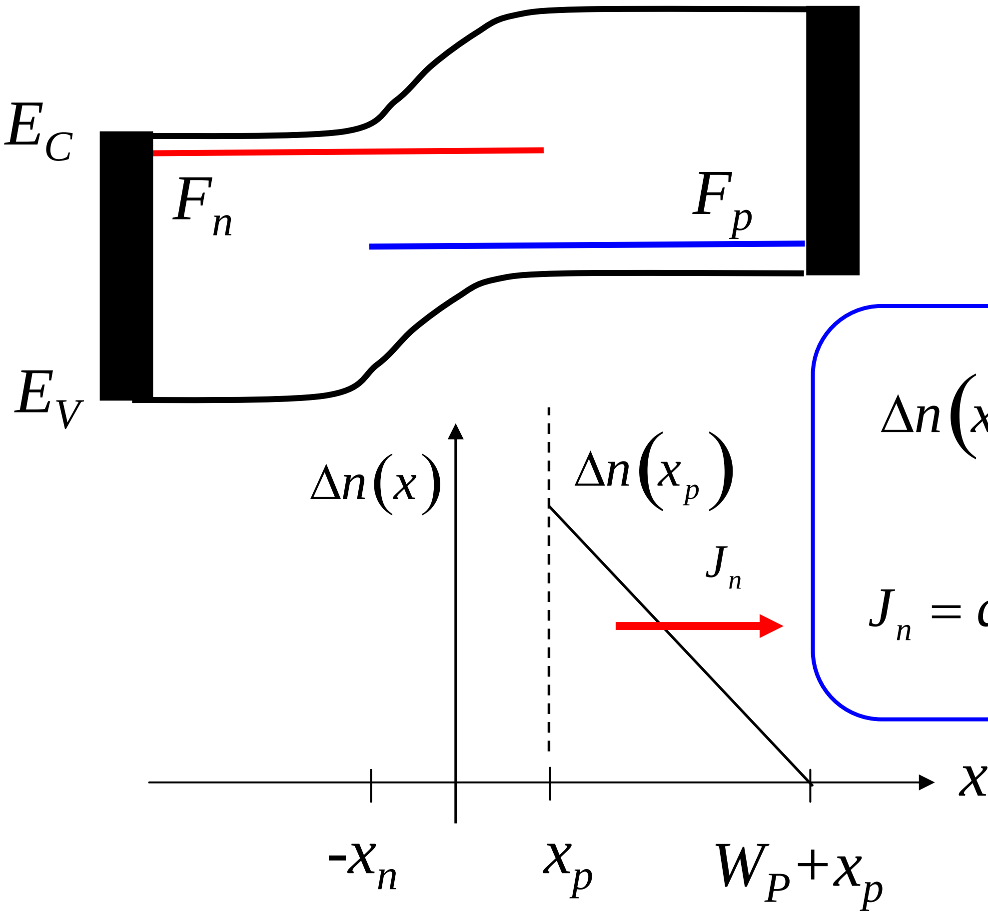
$$n_{po} = N_D e^{-q(V_{bi} - V_A)/k_B T} = \frac{n_i^2}{N_A} e^{qV_A/k_B T}$$



excess holes injected in n-region too

$$n = N_C e^{(F_n - E_C)/k_B T}$$

forward-biased current ($V_A > 0$)



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

$$J_n = qD_n \frac{\Delta n(x_p)}{W_p} = q\frac{n_i^2}{N_A}\frac{D_n}{W_p}\left(e^{qV_A/k_BT} - 1\right)$$

See: R.F. Pierret, *Semiconductor Fundamentals*, pp. 244-246, Addison-Wesley, 1996.

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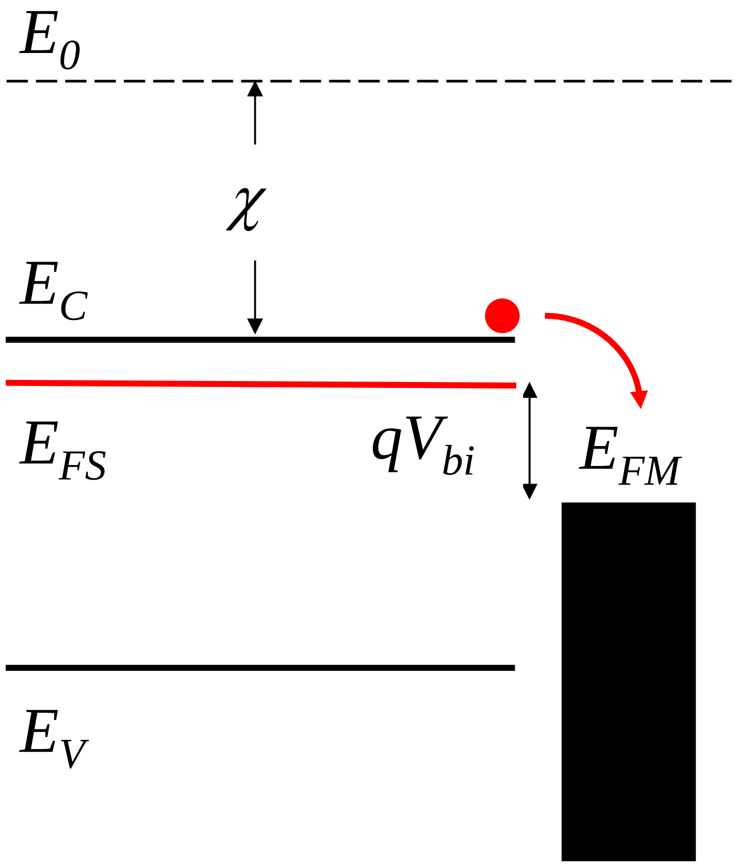
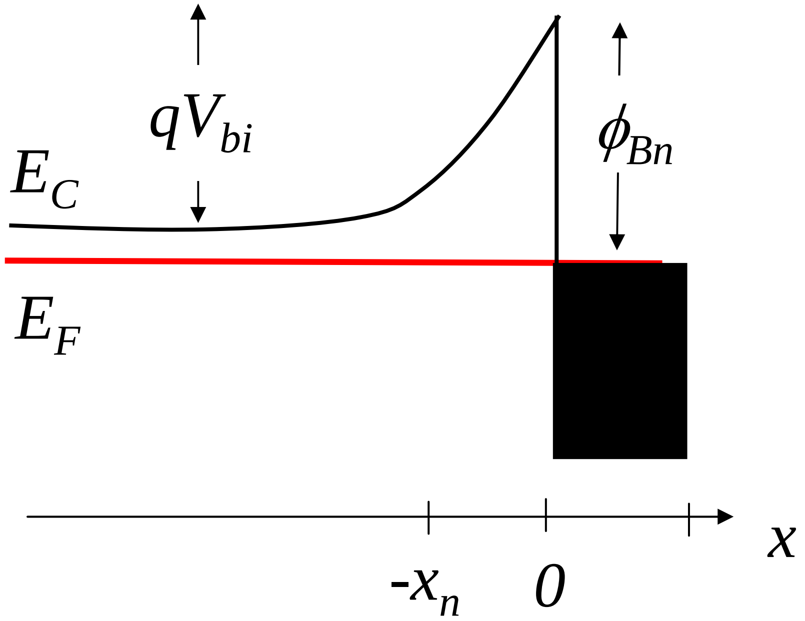
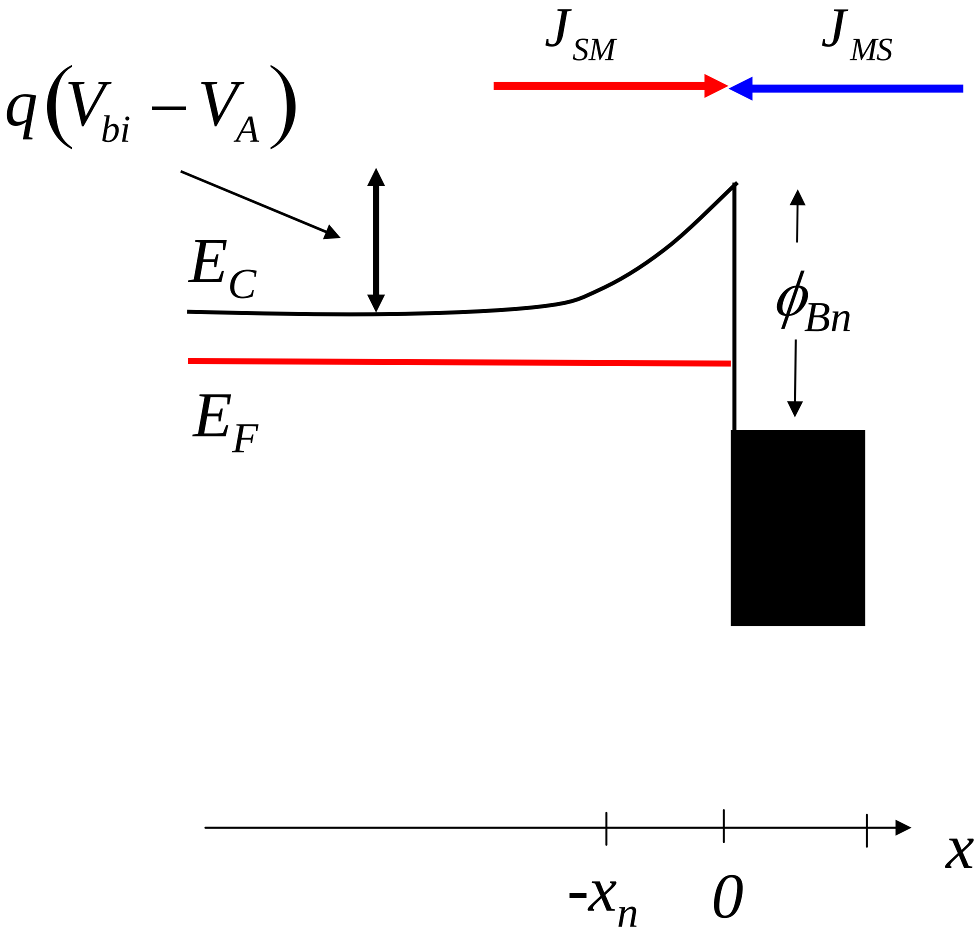
metal-semiconductor junction in equilibrium





metal-semiconductor junctions (forward bias)



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

$$\upsilon_T = \sqrt{\frac{2k_BT}{\pi m^*}} = 2\upsilon_R$$

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

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

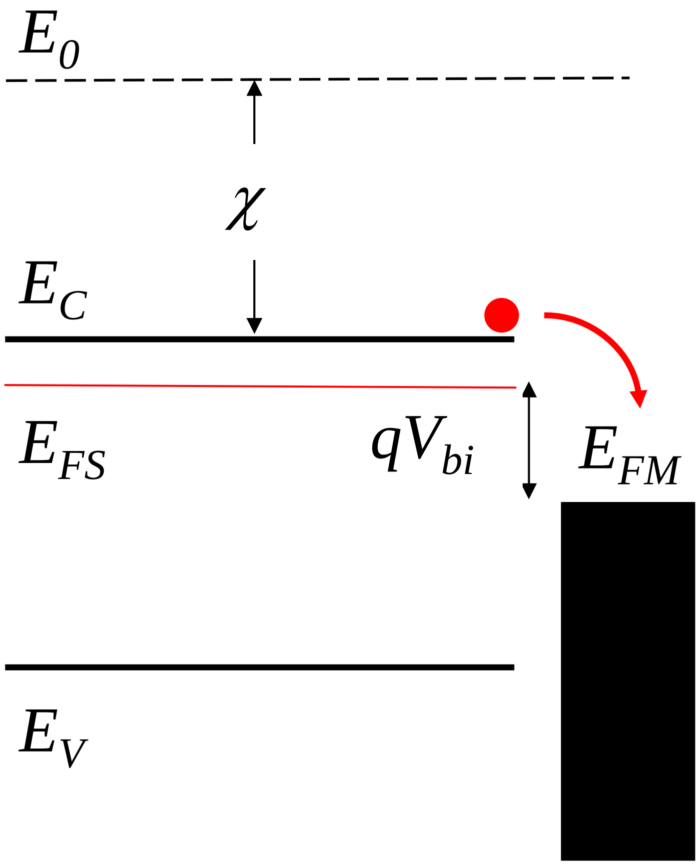
$$J = qN_D\,\upsilon_R e^{-qV_{bi}/k_BT}\left(e^{qV_A/k_BT} - 1\right)$$

metal-semiconductor junctions

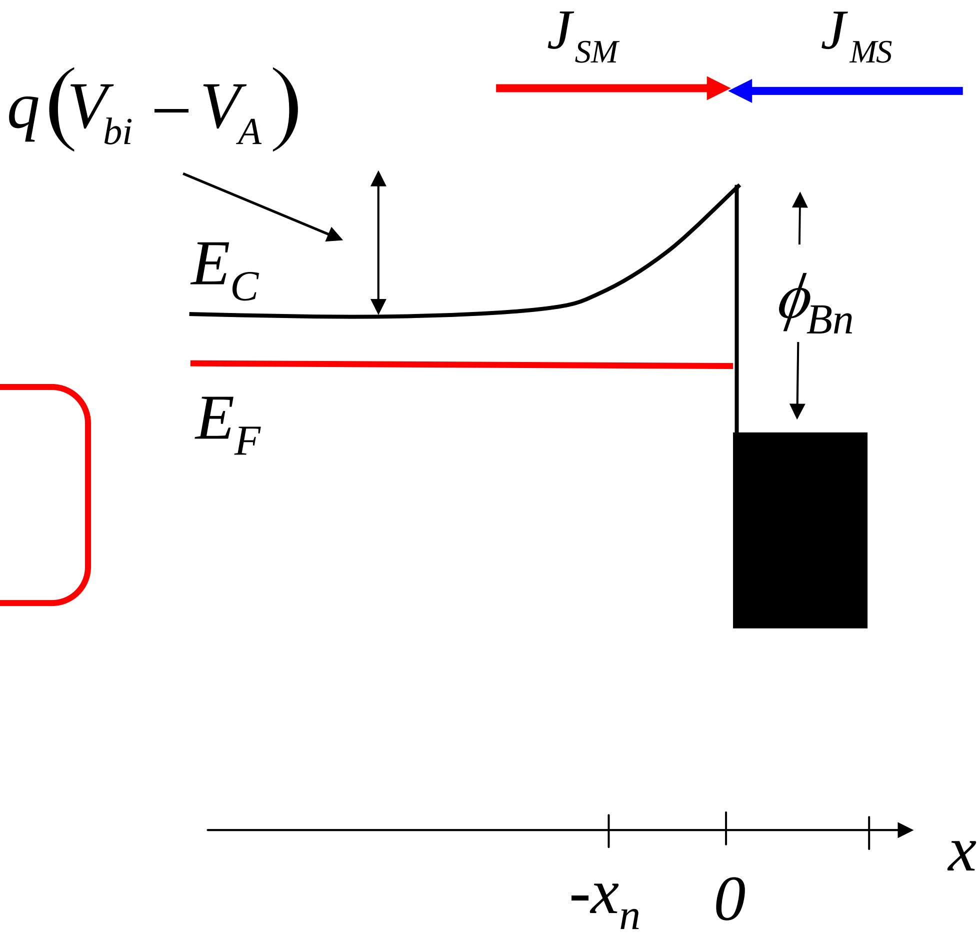
$$J = qN_D\,\upsilon_R e^{-qV_{bi}/k_BT}\left(e^{qV_A/k_BT} - 1\right)$$

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

$$J = qN_C\,\upsilon_R e^{-q\phi_{Bn}/k_BT}\left(e^{qV_A/k_BT} - 1\right)$$

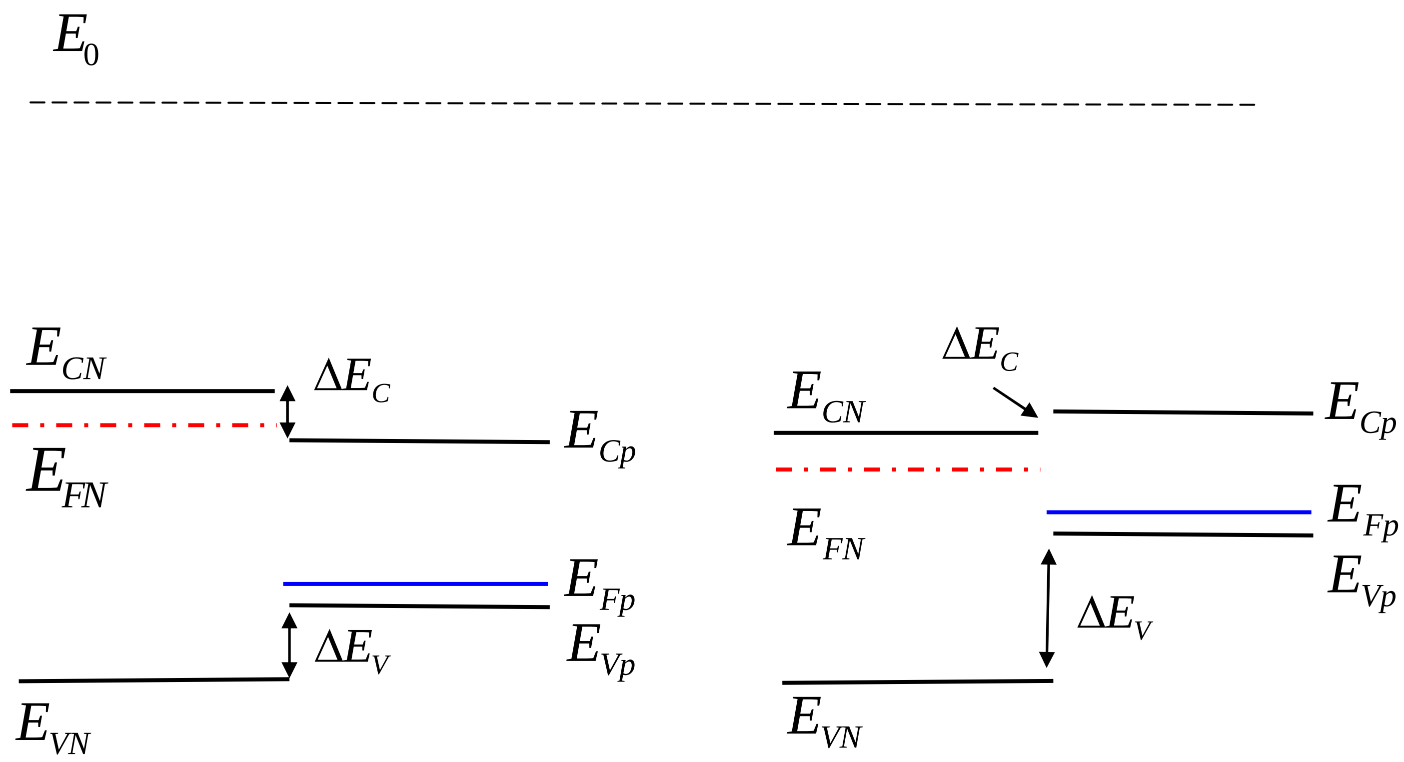


MS junction summary



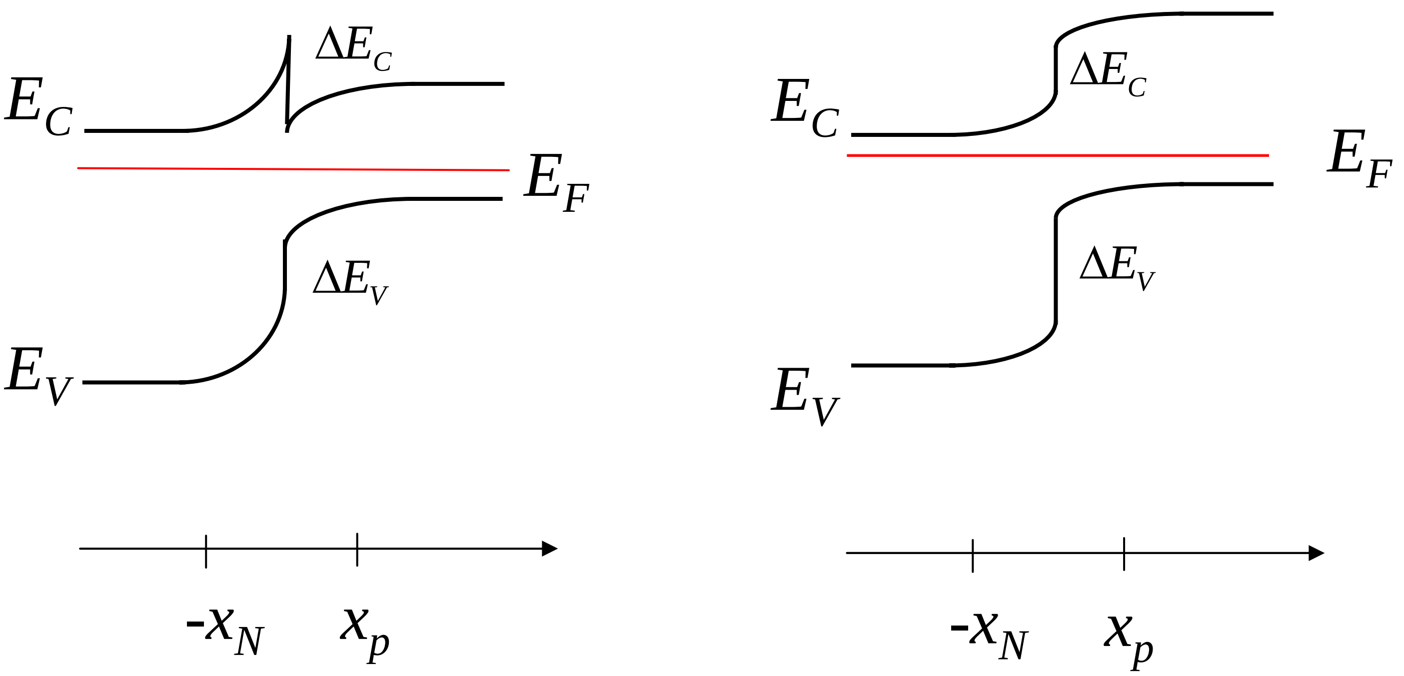
$$J = qN_C\, \upsilon_R e^{-q\phi_{Bn}/k_BT}\left(e^{qV_A/k_BT} - 1\right)$$

heterojunctions

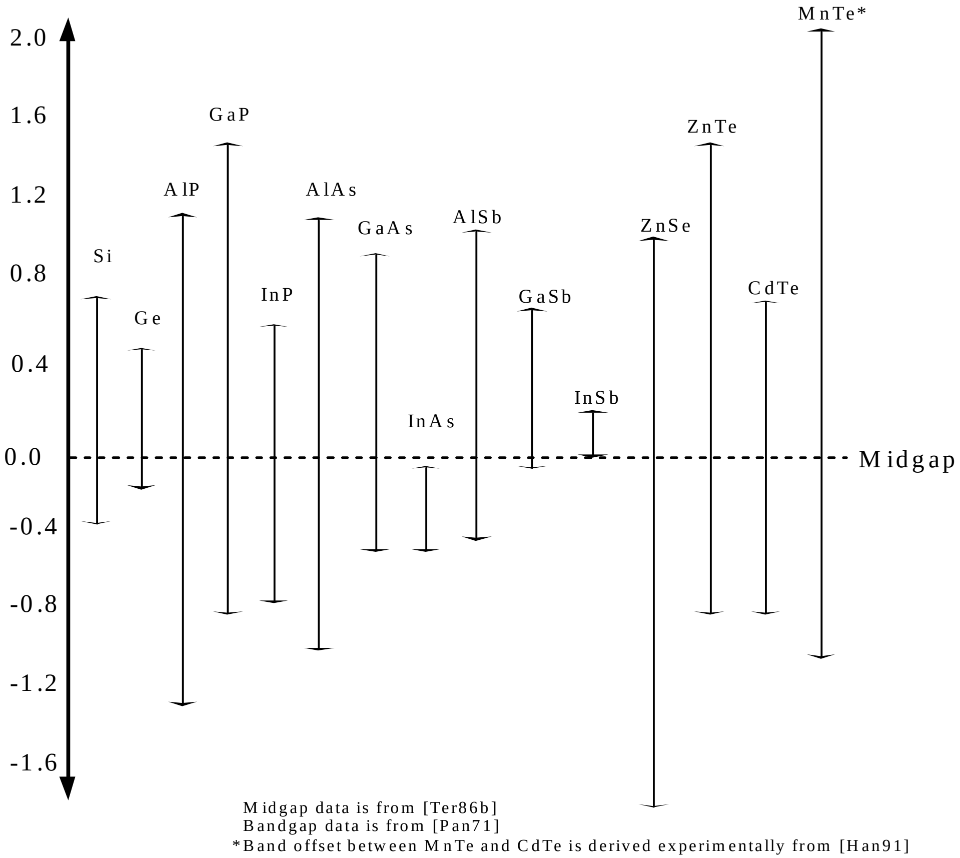


Np heterojunction e-band diagrams

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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4) The Generalized Law for Heterojunctions

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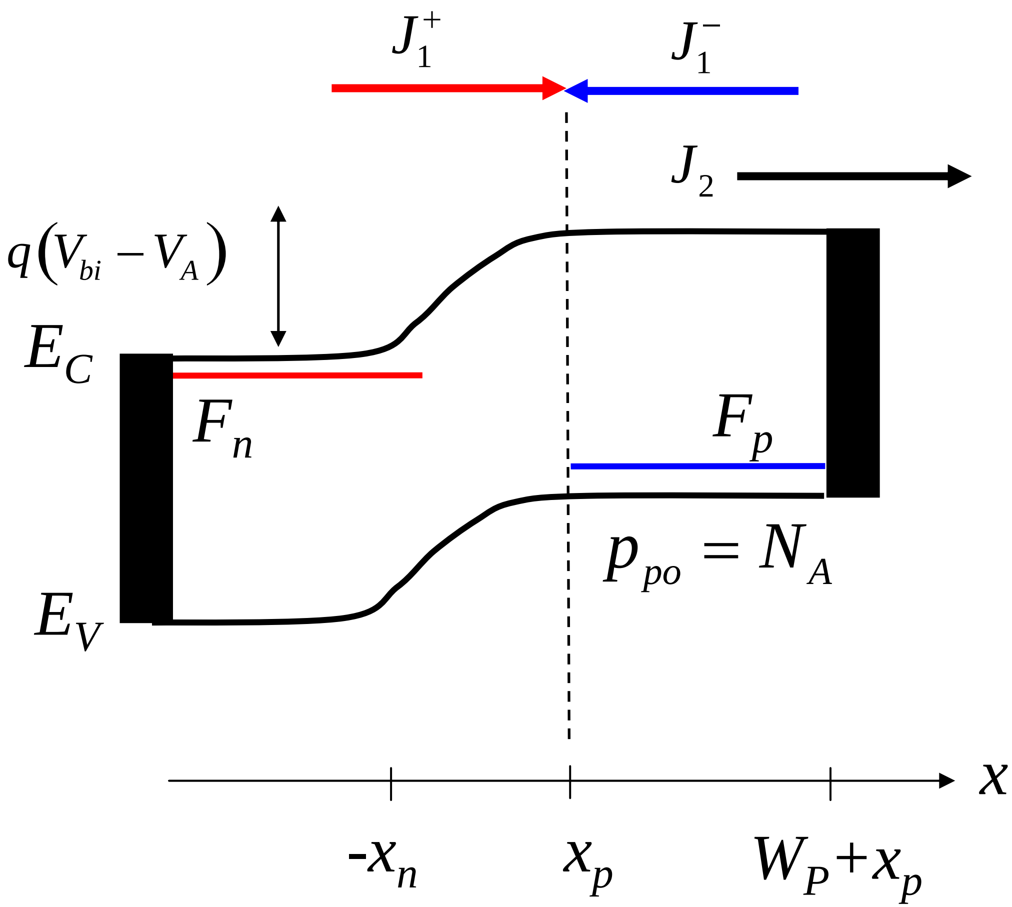
forward-biased homojunctions



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

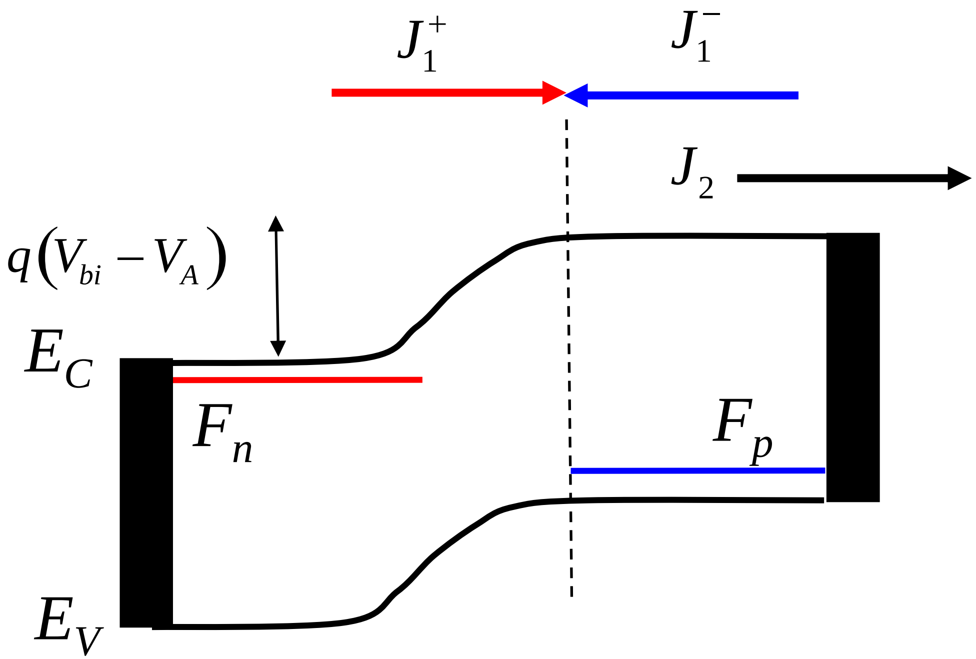
$$J_1^- = q\frac{n(x_p)}{2}\upsilon_T$$

$$J_2 = qD_n\frac{\Delta n(x_p)}{W_P} = q\Delta n(x_p)\upsilon_{Dp}$$

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

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

generalized law of the pn homojunction



$$\Delta n(x_p) = \left[\frac{1}{1 + \upsilon_{Dp}/\upsilon_R}\right]\left(\frac{n_i^2}{N_A}\right)\left(e^{qV_A/k_BT} - 1\right)$$

$\upsilon_{Dp} << \upsilon_R$

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

(base diffusion limited)

$\upsilon_{Dp} >> \upsilon_R$

$$\Delta n(x_p) = \left(\frac{n_i^2}{N_A}\right)\frac{\upsilon_R}{\upsilon_{Dp}}\left(e^{qV_A/k_BT} - 1\right)$$

(emission limited)

generalized law of the pn homojunction (ii)

$$\Delta n(x_p) = \left[\frac{1}{1+\upsilon_{Dp}/\upsilon_R}\right]\left(\frac{n_i^2}{N_A}\right)\left(e^{qV_A/k_BT}-1\right)$$

$$J_n = J_1^+ - J_1^- = J_2 = q\,\upsilon_{Dp}\Delta n\left(x_p\right)$$

$$J_n = q\left(\frac{n_i^2}{N_A}\right)\left[\frac{1}{1/\upsilon_{Dp}+1/\upsilon_R}\right]\left(e^{qV_A/k_BT}-1\right)$$

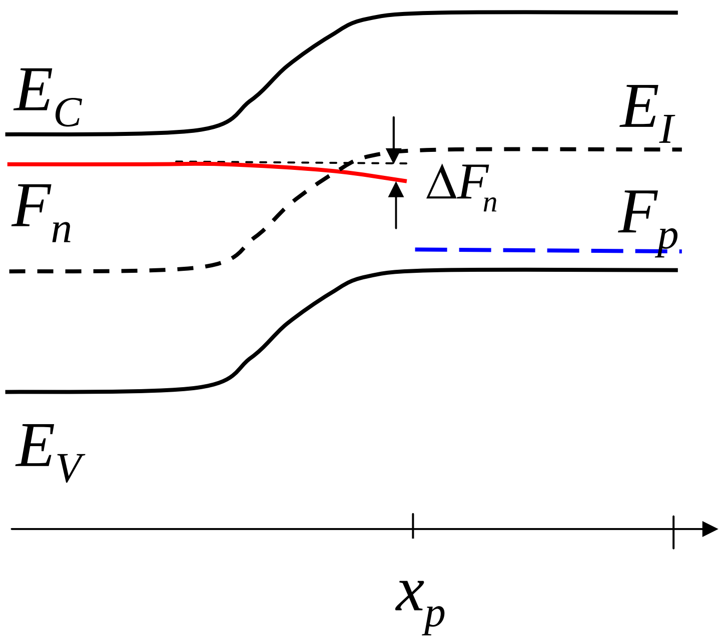
$$J_n = q\left(\frac{n_i^2}{N_A}\right)\upsilon_{Dp}\left(e^{qV_A/k_BT}-1\right)$$

$$\upsilon_{Dp} \ll \upsilon_R$$

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

$$\upsilon_{Dp} \gg \upsilon_R$$

Fermi level droop



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

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

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

$$\boxed{\Delta F_n = k_B T \ln\left(1 + \upsilon_{Dp}/\upsilon_R\right)}$$

if $\quad \upsilon_{Dp} << \upsilon_R$

$$\Delta F_n \approx 0$$

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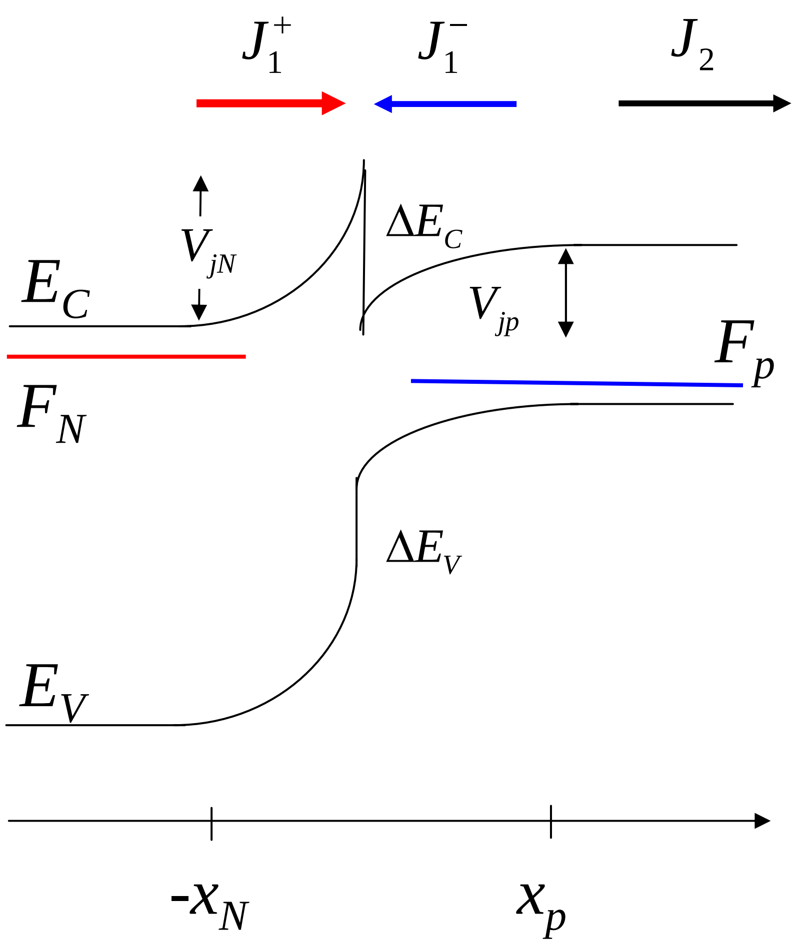
heterojunctions under bias



$$J_1^+ = q\frac{N_D}{2}\upsilon_{TN}e^{-qV_{jN}/k_BT}$$

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

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

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

$$J_2 = qD_n\frac{\Delta n(x_p)}{W_P} = q\Delta n(x_p)\upsilon_{Dp}$$

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

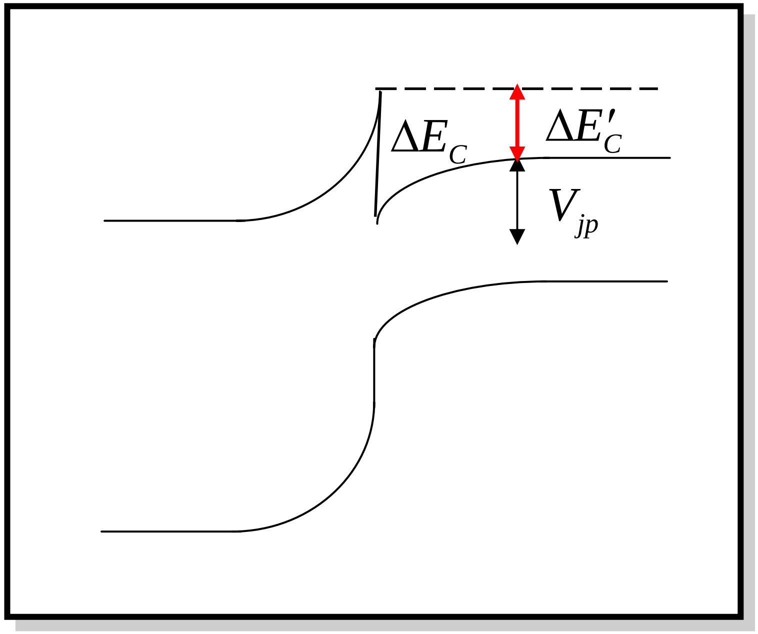
generalized law for heterojunctions

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

$$\upsilon_{ems} = \upsilon_{Rp} e^{-\Delta E_C'/k_BT} = \upsilon_{Rp} e^{-\left(\Delta E_C - qV_{jp}\right)/k_BT}$$

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

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



generalized law for heterojunctions (ii)

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

$$\upsilon_{ems} = \upsilon_{Rp} e^{-\Delta E_C'/k_BT} = \upsilon_{Rp} e^{-\left(\Delta E_C - qV_{jp}\right)/k_BT}$$

$$\Delta E_C << k_BT$$

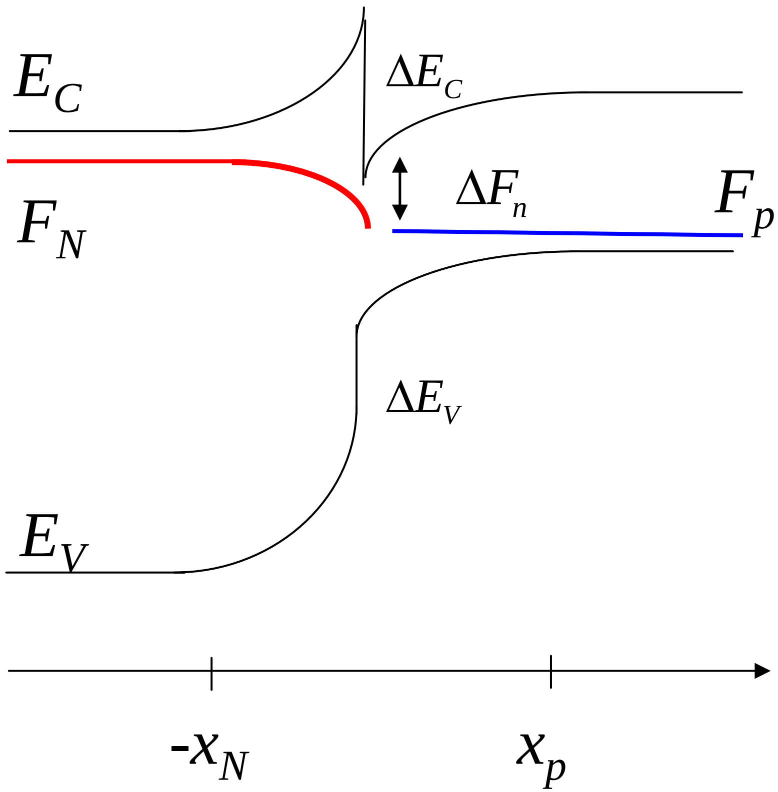
$$J_n = q\left(\frac{n_{ip}^2}{N_A}\right)\upsilon_{Dp}\left(e^{qV_A/k_BT} - 1\right)$$

$$\Delta E_C >> k_BT$$

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

band spikes suppress current

Fermi level droop



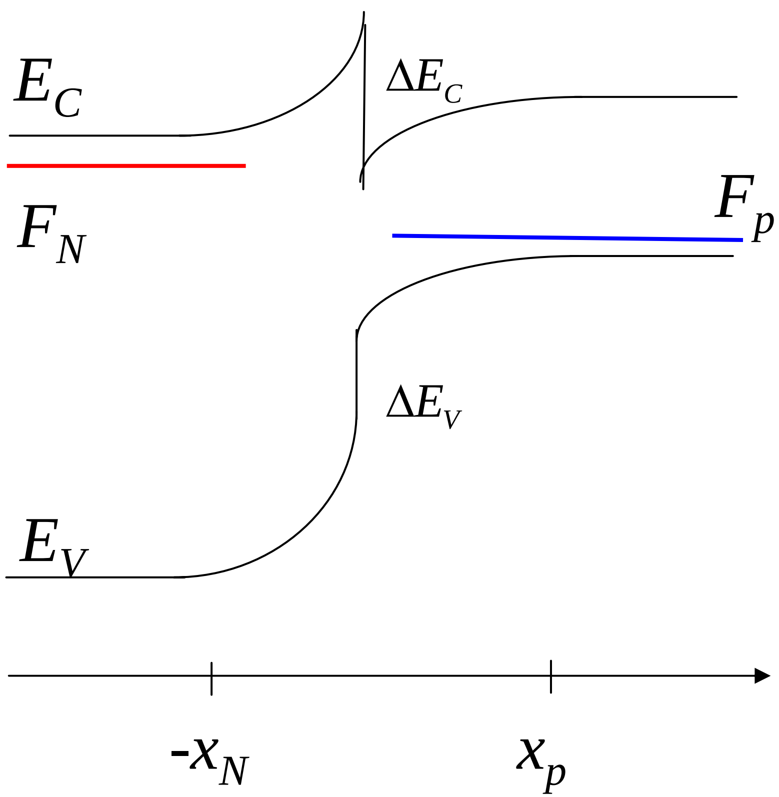
$$\Delta F_n = k_B T \ln\left(1 + \upsilon_{Dp} / \upsilon_{ems}\right)$$

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

$$\text{if} \quad \Delta E_C >> k_B T$$

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

band spikes and MS diodes



Np heterojunction

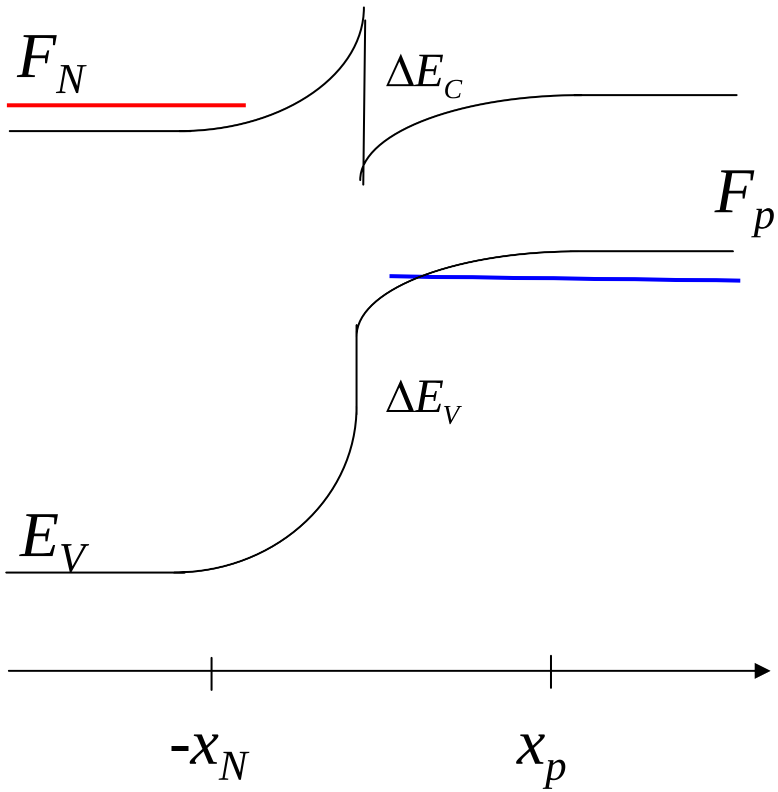
$$J_n = q\left(\frac{n_{ip}^2}{N_A}\right)\upsilon_{Rp}e^{-\Delta E_C/k_BT}\left(e^{qV_A/k_BT}-1\right)$$

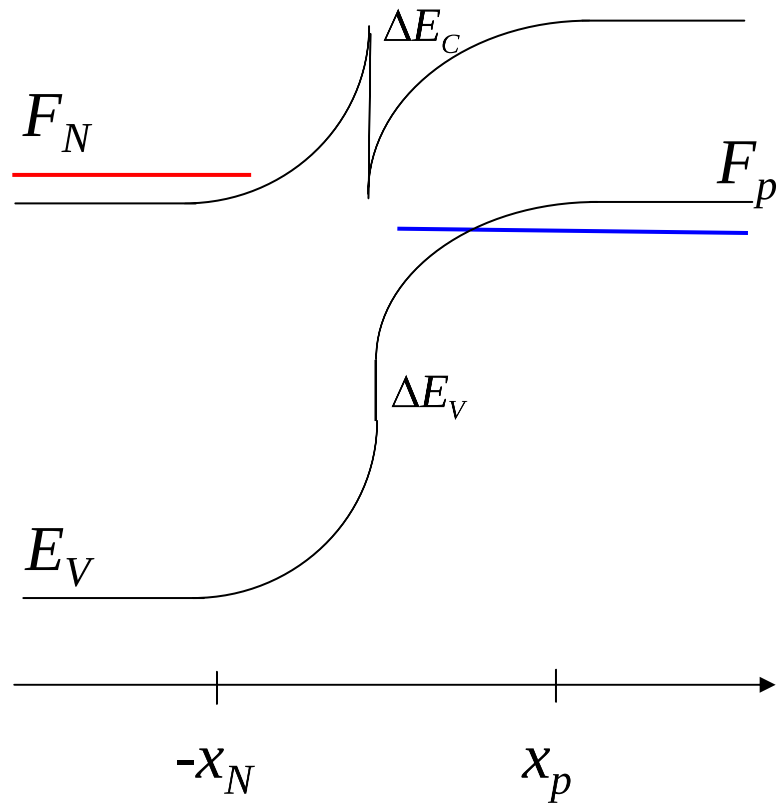
MS diode

$$J = qN_C\,\upsilon_R e^{-q\phi_{Bn}/k_BT}\left(e^{qV_A/k_BT}-1\right)$$

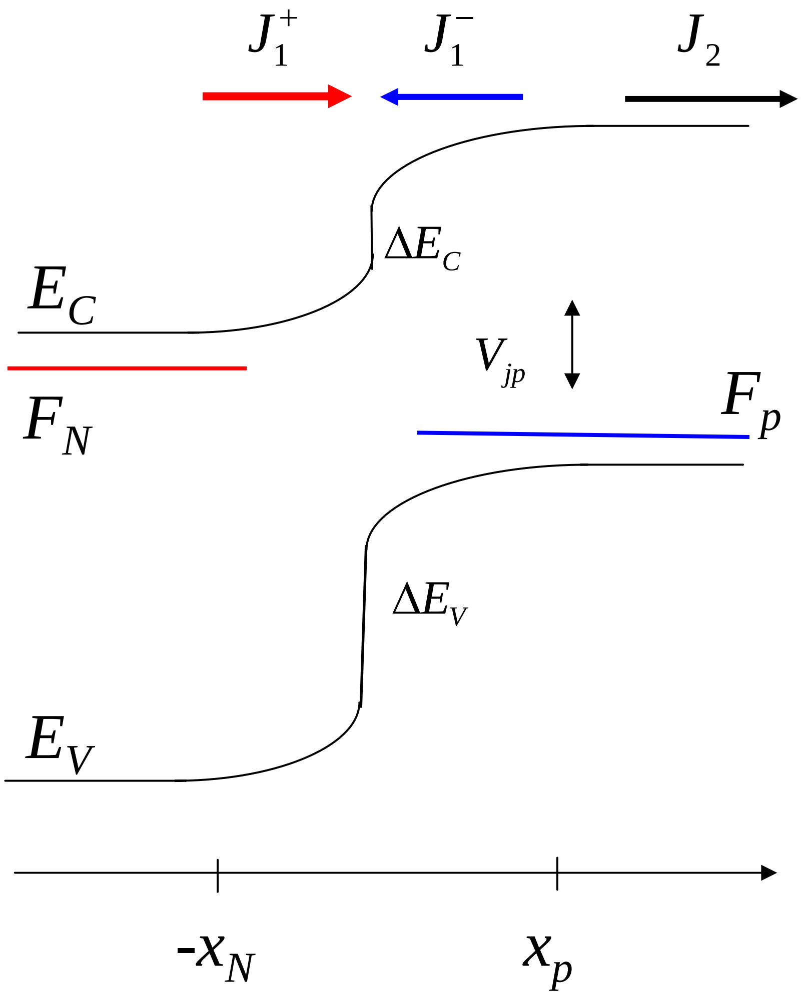
band spikes and junction bias

$\Delta E'_C$ is bias dependent!





heterojunctions with no band spike



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

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

$$J_2 = qD_n\frac{\Delta n(x_p)}{W_P} = q\Delta n(x_p)\upsilon_{Dp}$$

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

heterojunctions with no band spike (ii)

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

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

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summary

$$\Delta n(x_p) = \frac{1}{\left[1+\upsilon_{Dp}/\upsilon'_{Rp}\right]}\frac{n_{ip}^2}{N_A}\left(e^{qV_A/k_BT}-1\right)$$

$$J_n = q\left(\frac{n_{ip}^2}{N_A}\right)\frac{1}{\left[1/\upsilon_{Dp}+1/\upsilon'_{Rp}\right]}\left(e^{qV_A/k_BT}-1\right)$$

for homojunctions or heterojunctions with no band spike:

$$\upsilon'_{Rp} = \upsilon_{Rp} \qquad \upsilon'_{Rp} >> \upsilon_{Dp} \text{ (typically)}$$

for heterojunctions with a band spike

$$\upsilon'_{Rp} = \upsilon_{Rp} e^{-\left(\Delta E_C - qV_{jp}\right)/k_BT} \qquad \upsilon'_{Rp} << \upsilon_{Dp} \text{ (typically)}$$

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?