

Some

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Je reviendrai et je serai des millions. «Spartacus»

微电子器件物理

PN结的电流特性

曾琅

2020/09/18

PN结的连续性方程

$$\nabla \cdot \mathbf{E} = q(p - n + N_D^+ - N_A^-) \quad \text{能带图}$$

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot \mathbf{J}_N - r_N + g_N$$

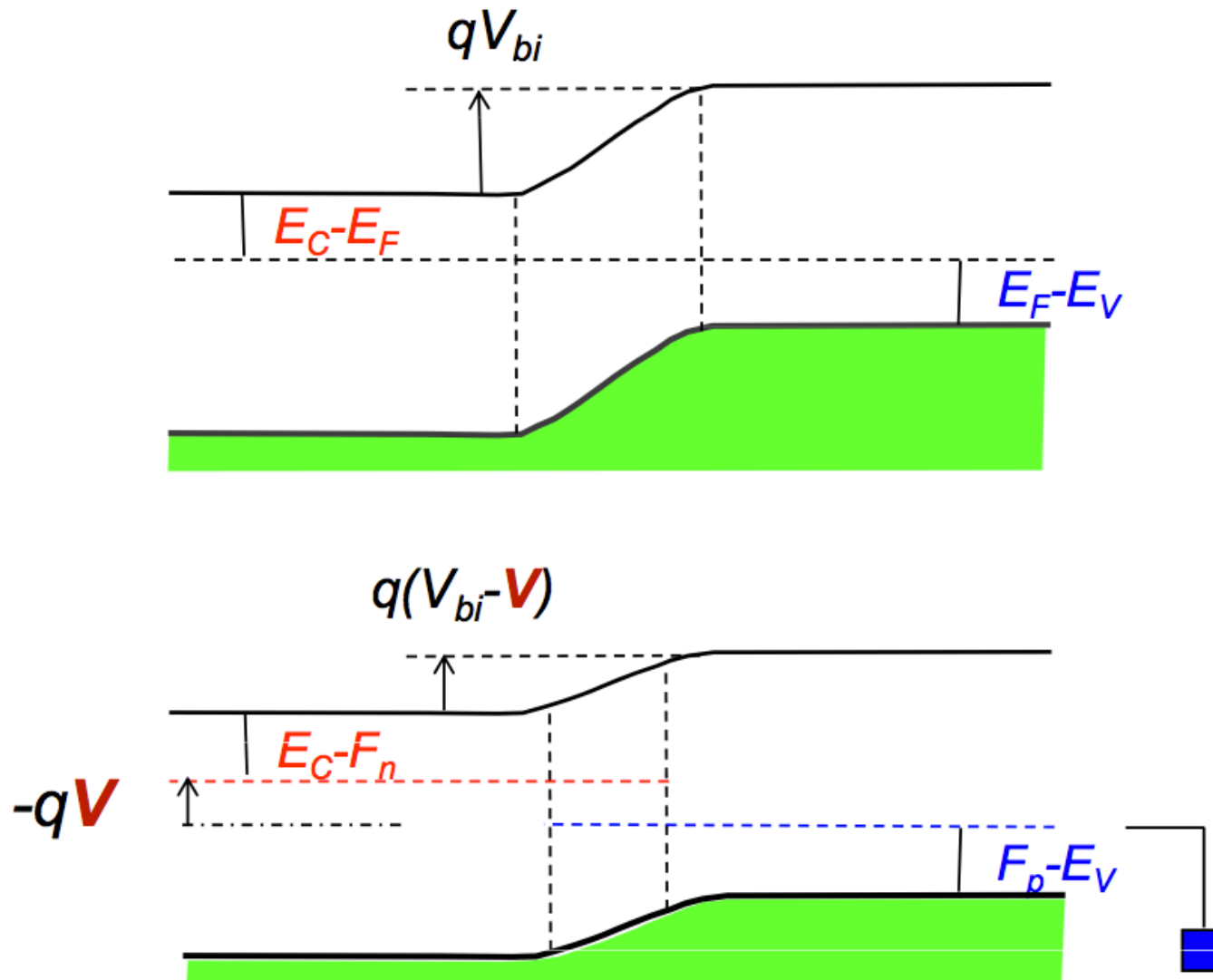
$$\mathbf{J}_N = qn\mu_N \mathbf{E} + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{1}{q} \nabla \cdot \mathbf{J}_P - r_P + g_P$$

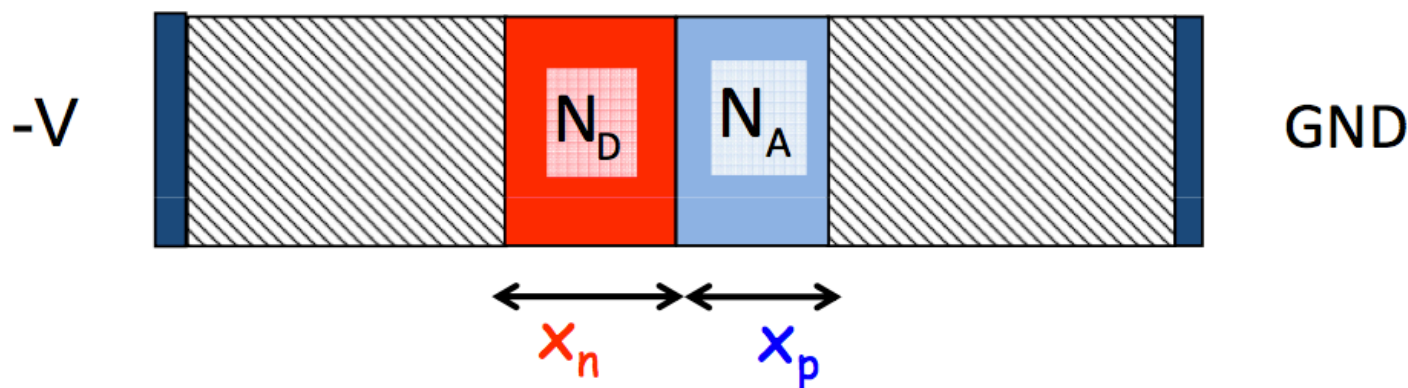
$$\mathbf{J}_P = qp\mu_P \mathbf{E} - qD_P \nabla p$$

正向电流和反向电流

PN结的正向偏置



耗尽区宽度



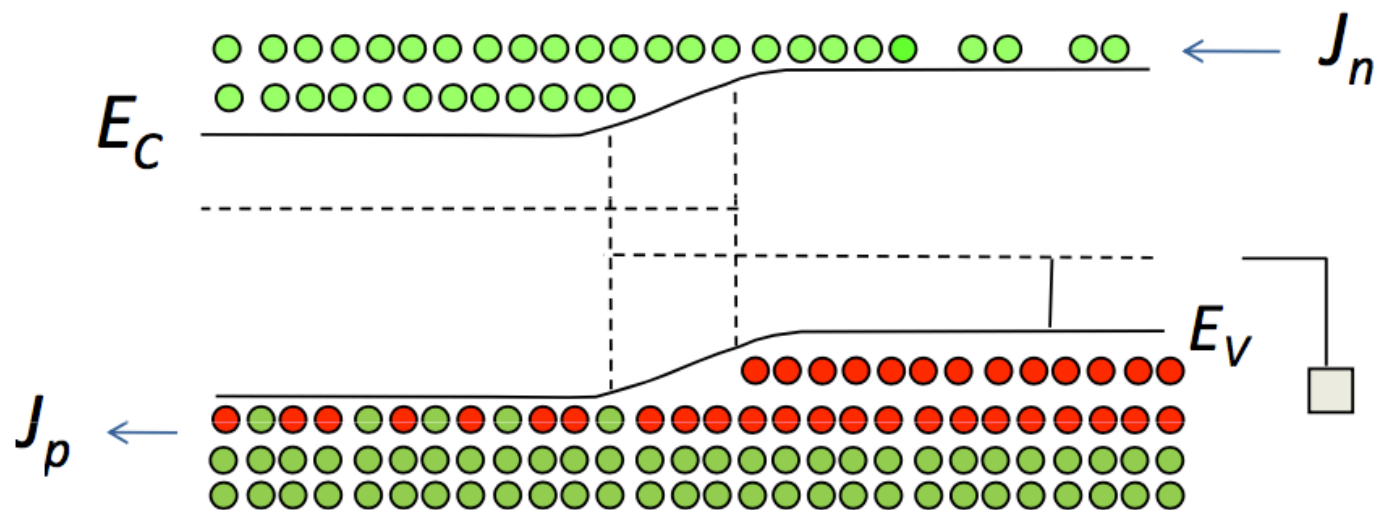
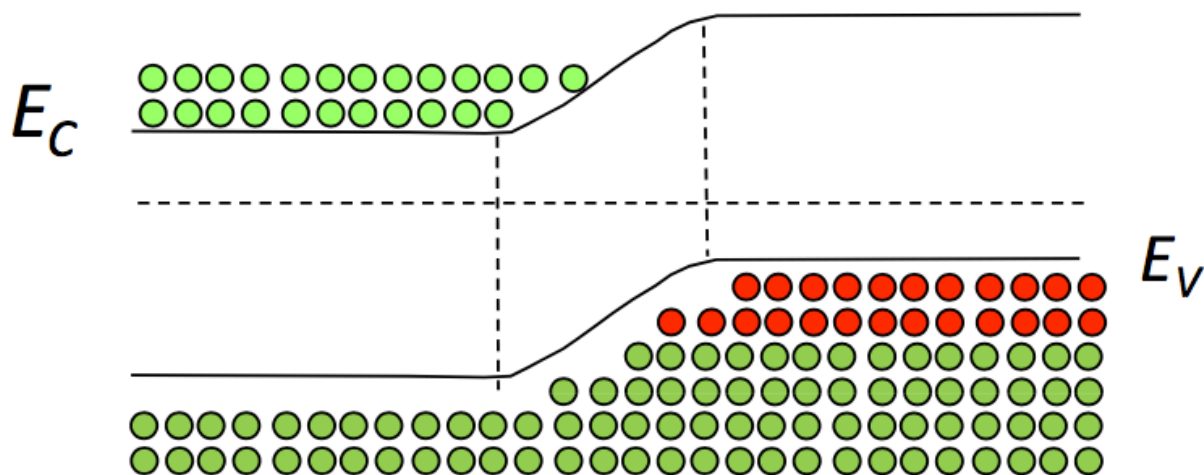
$$N_D x_n = N_A x_p$$

$$q(V_{bi} - V) = \frac{qN_D x_n^2}{2k_s \epsilon_0} + \frac{qN_A x_p^2}{2k_s \epsilon_0}$$

$$x_n = \sqrt{\frac{2k_s \epsilon_0}{q} \frac{N_A}{N_D (N_A + N_D)} (V_{bi} - V)}$$

$$x_p = \sqrt{\frac{2k_s \epsilon_0}{q} \frac{N_D}{N_A (N_A + N_D)} (V_{bi} - V)}$$

准费米能级



边界条件

$$n(x=0^+) = n_i e^{(F_n - E_i)\beta}$$

$$p(x=0^+) = n_i e^{-(F_p - E_i)\beta}$$

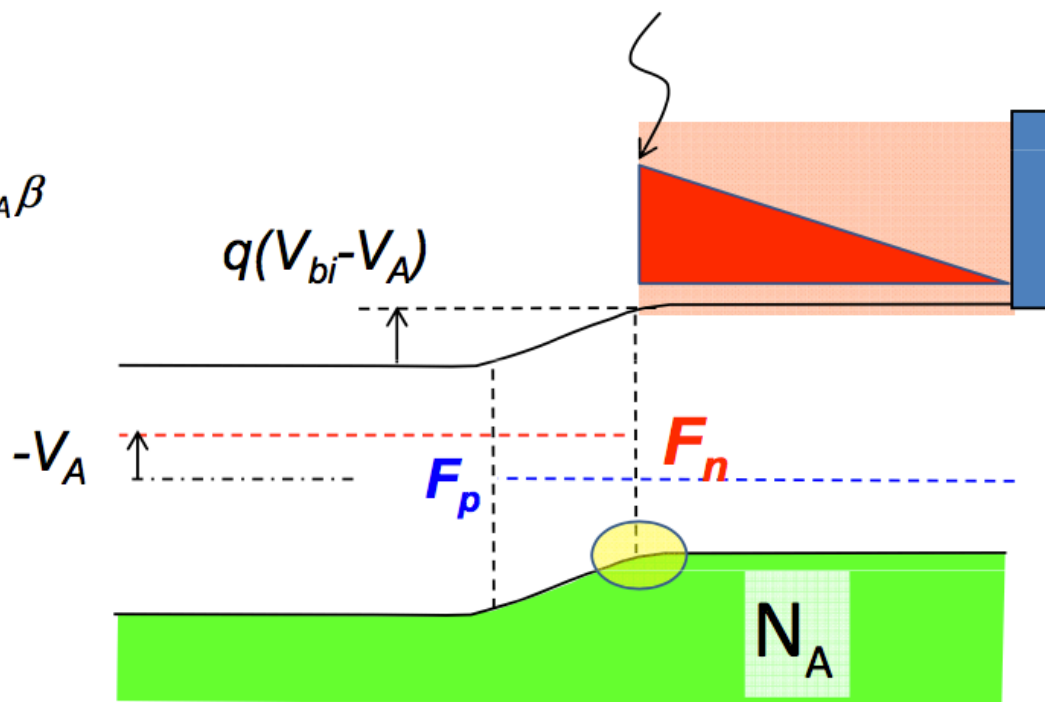
$$np = n_i^2 e^{(F_n - F_p)\beta} = n_i^2 e^{qV_A\beta}$$

$$p(0^+) = N_A$$

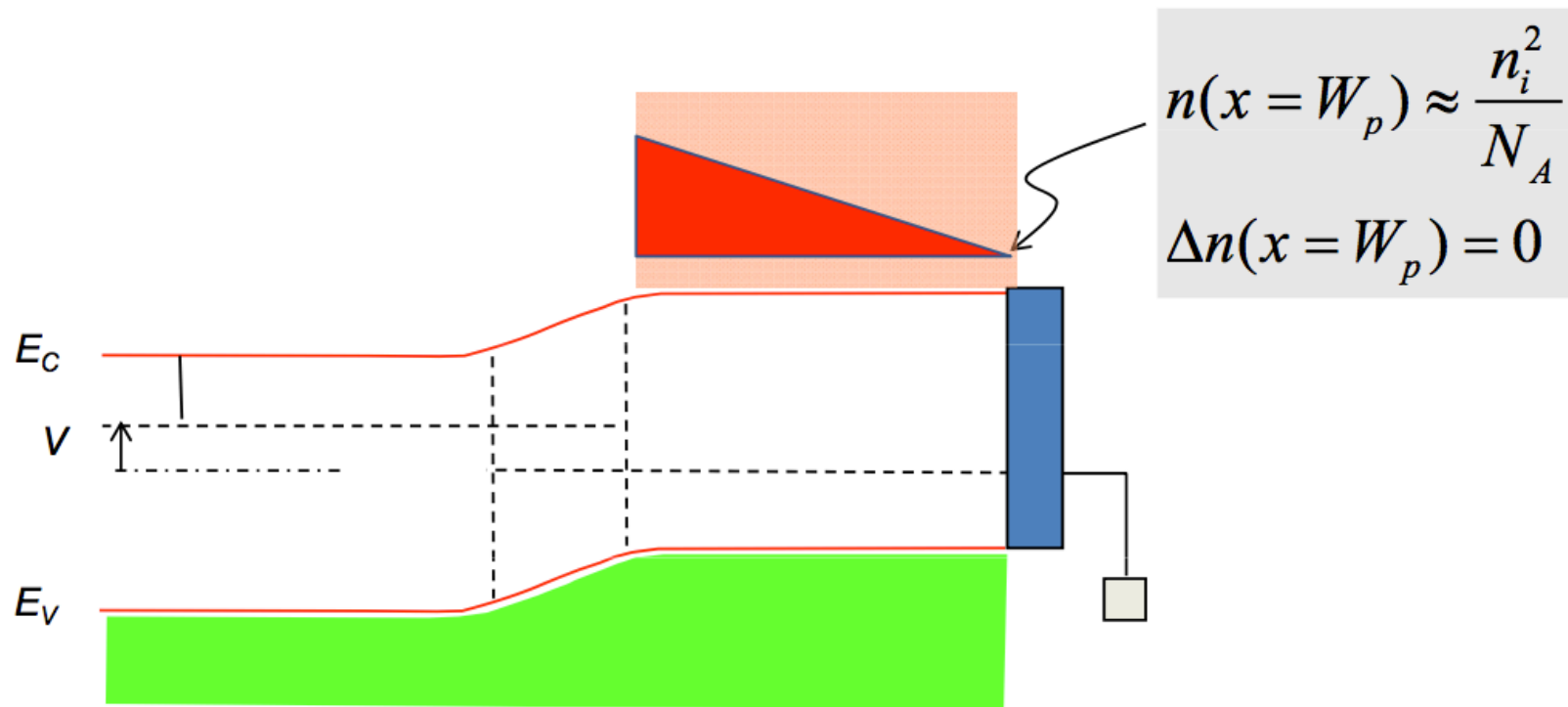
$$n(0^+) = \frac{n_i^2}{N_A} e^{qV_A\beta}$$

$$\Delta n(0^+) = n(0^+)_{V_G} - n(0^+)_{V_G=0}$$

$$= \frac{n_i^2}{N_A} (e^{qV_A\beta} - 1)$$



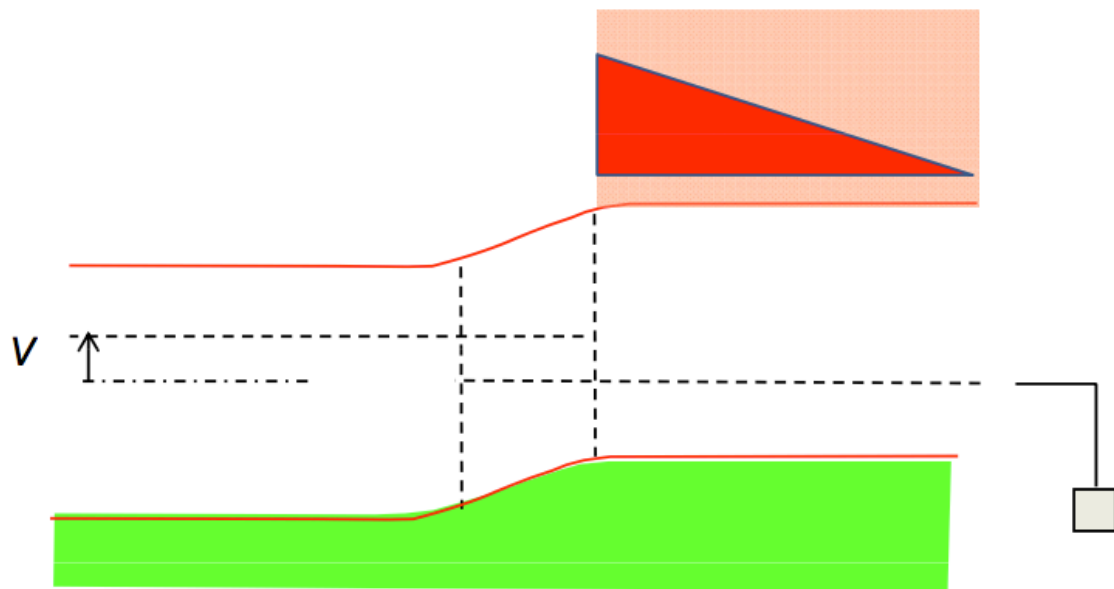
边界条件



边界条件

$$D_N \frac{d^2 n}{dx^2} = 0$$

$$\Delta n(x, t) = C + Dx$$



$$x = W_p, \quad \Delta n(x = W_p) = 0 \Rightarrow C = -DW_p$$

$$x = 0', \quad \Delta n(x = 0) = \frac{n_i^2}{N_A} \left(e^{qV_A \beta} - 1 \right) = C$$

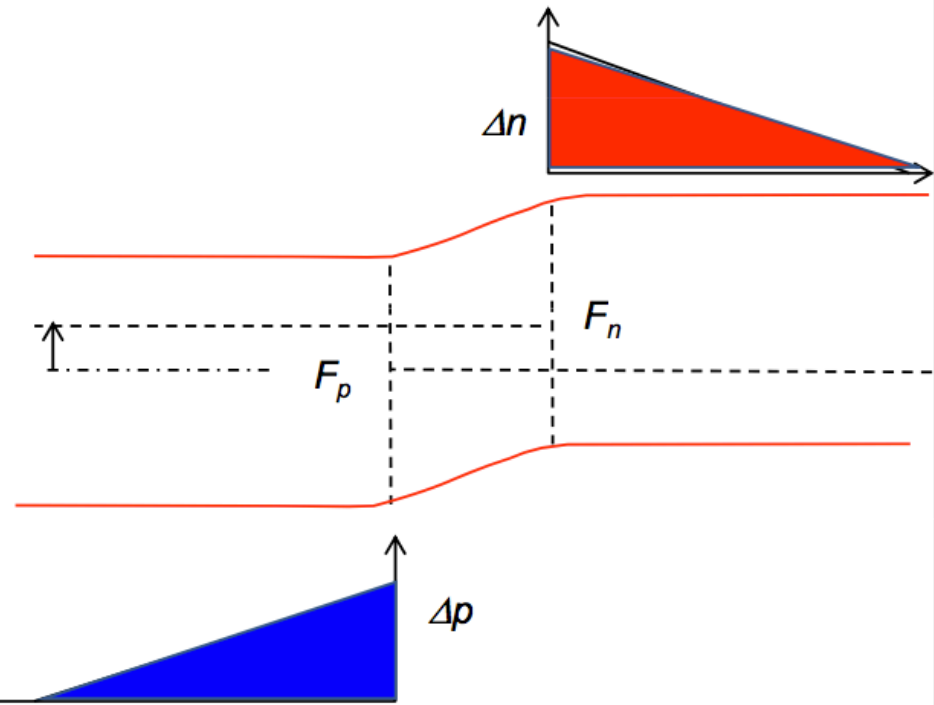
$$\Delta n(x, t) = \frac{n_i^2}{N_A} \left(e^{qV_A \beta} - 1 \right) \left(1 - \frac{x}{W_p} \right)$$

电子电流和空穴电流

$$\Delta n(x) = \frac{n_i^2}{N_A} (e^{qV_A\beta} - 1) \left(1 - \frac{x}{W_p}\right)$$

$$\mathbf{J}_N = qn\mu_N\boldsymbol{\mathcal{E}} + qD_N\nabla n$$

$$J_n = qD_n \left. \frac{dn}{dx} \right|_{x=0} = -\frac{qD_n}{W_p} \frac{n_i^2}{N_A} (e^{qV_A\beta} - 1)$$



$$J_p = -qD_p \left. \frac{dp}{dx} \right|_{x=0'} = -\frac{qD_p}{W_n} \frac{n_i^2}{N_D} (e^{qV_A\beta} - 1)$$

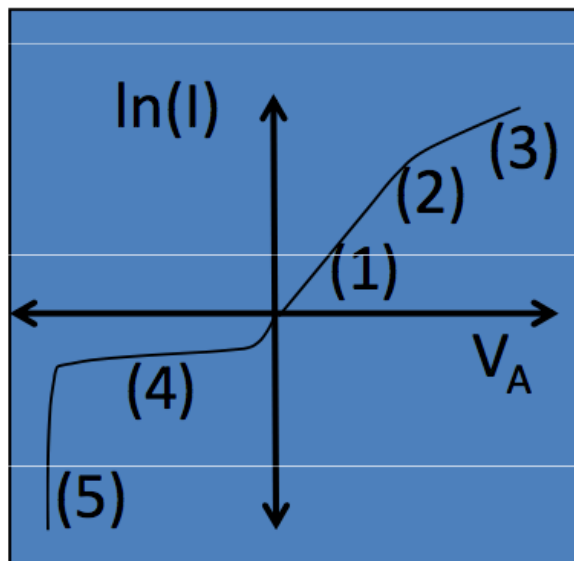
总电流

正向偏置

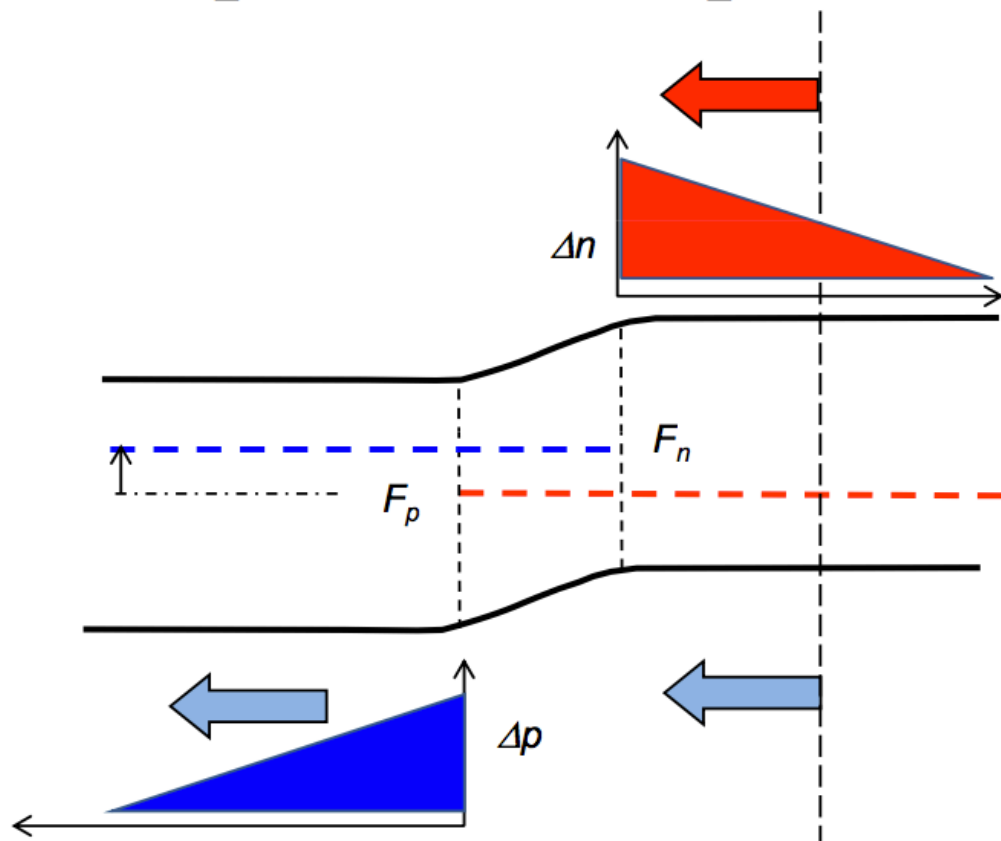
$$\ln J_T \approx qV_A/k_B T + \ln(const.)$$

反向偏置

$$J_T \approx const.$$



$$J_T = -q \left[\frac{D_n}{W_p} \frac{n_i^2}{N_A} + \frac{D_p}{W_n} \frac{n_i^2}{N_D} \right] (e^{qV_A\beta} - 1)$$



Thanks!
Q&A

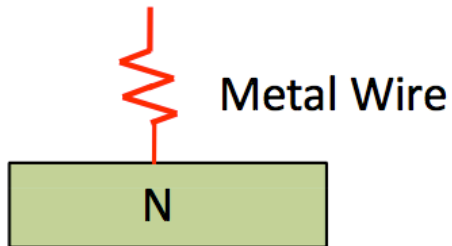
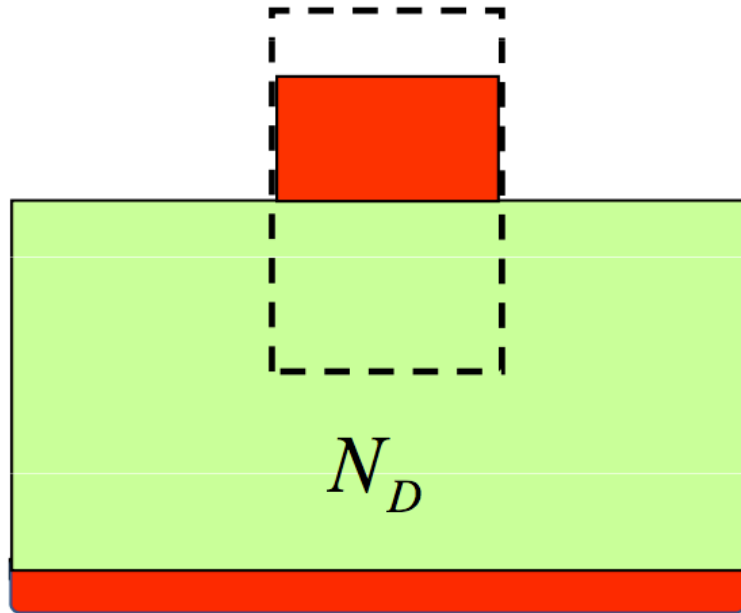
微电子器件物理

肖特基二极管

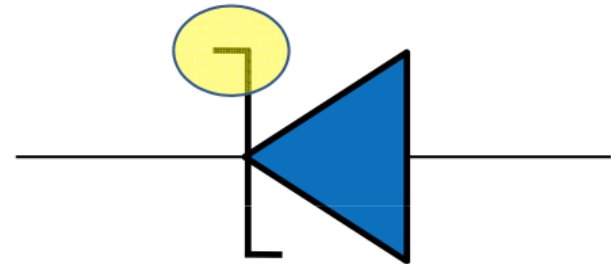
曾琅

2020/09/25

金属半导体二极管

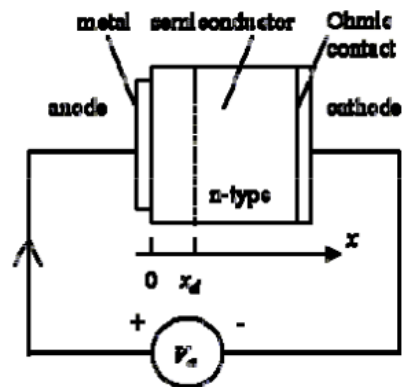


Symbols

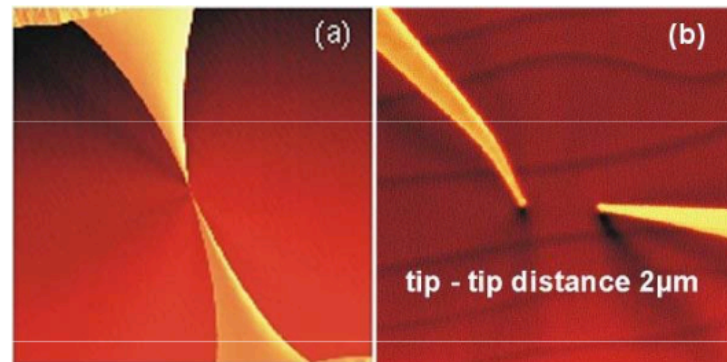


肖特基二极管的应用

矿石收音机



扫描隧道显微镜

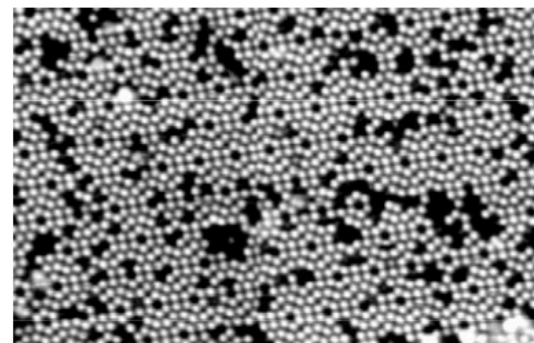
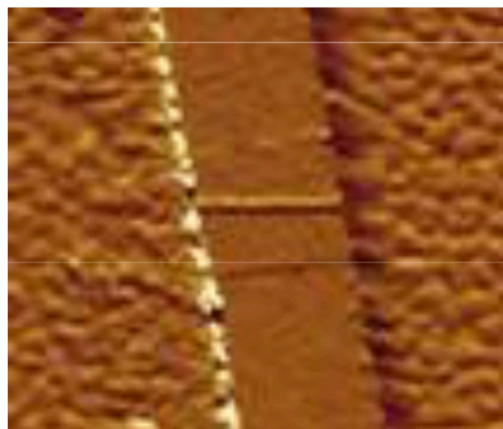


www.fz-juelich.de/ibn/index.php?index=674

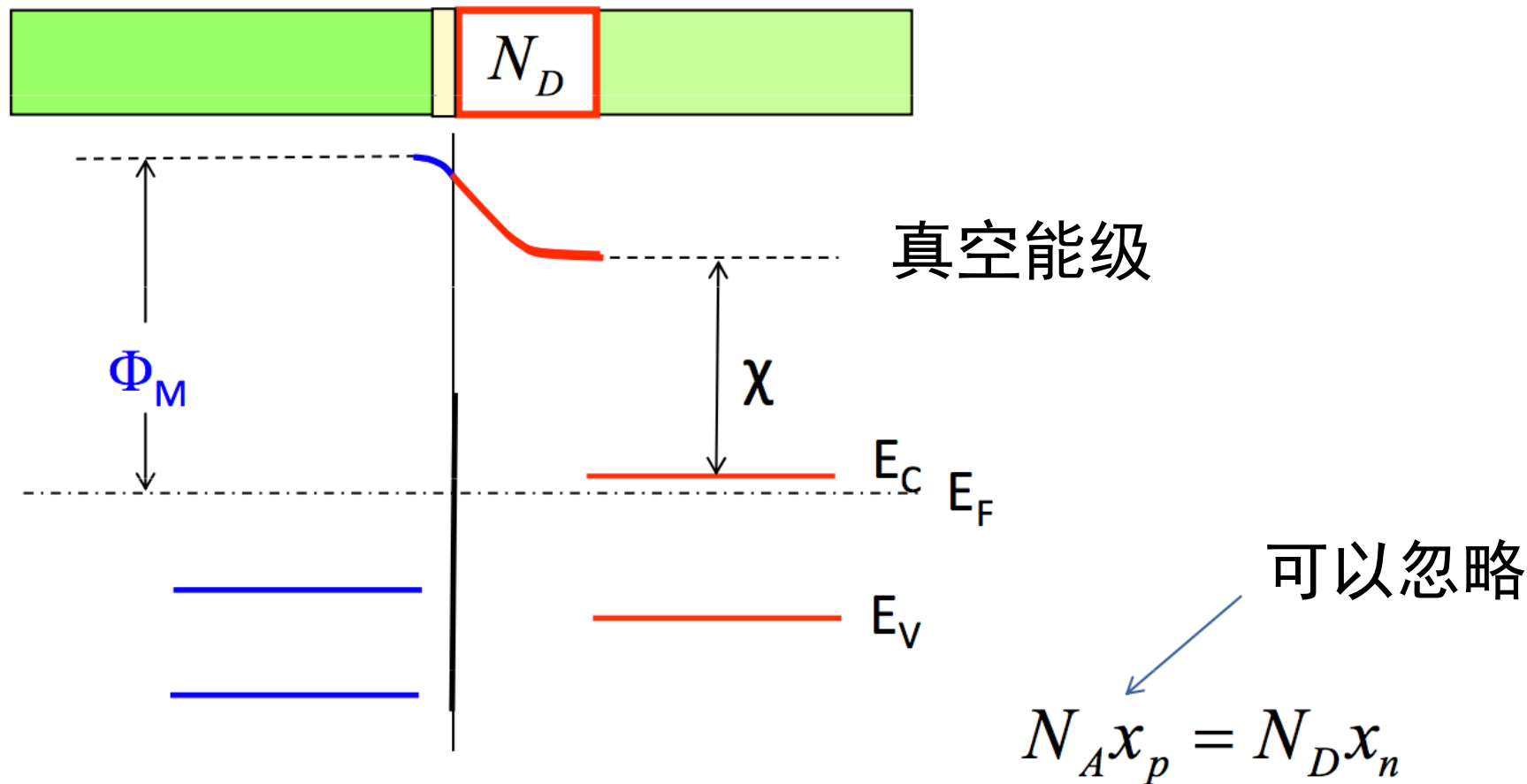
第一个晶体管



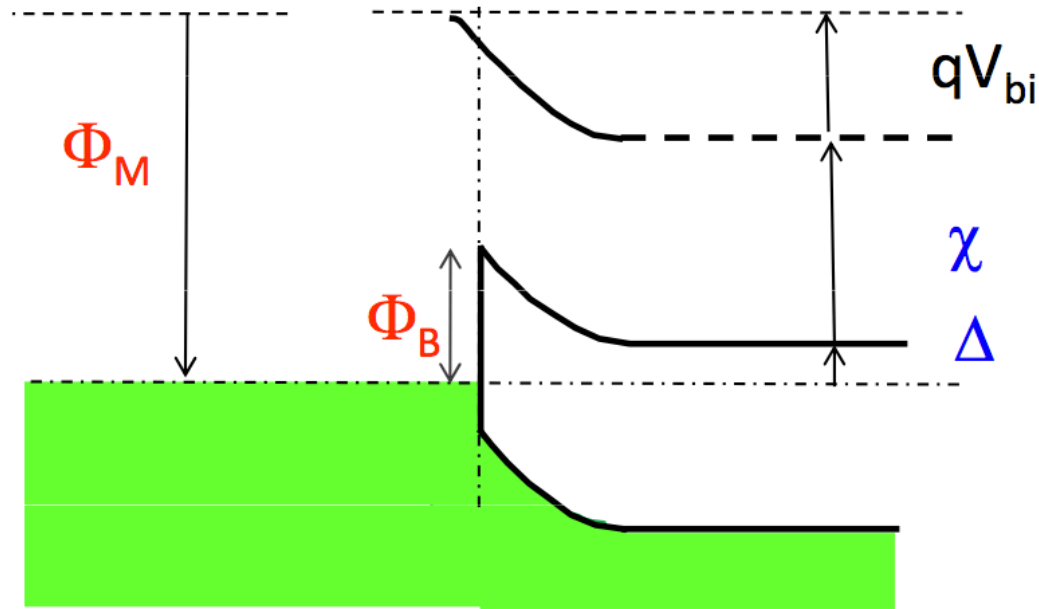
碳纳米管



肖特基二极管的能带图



肖特基二极管的能带图



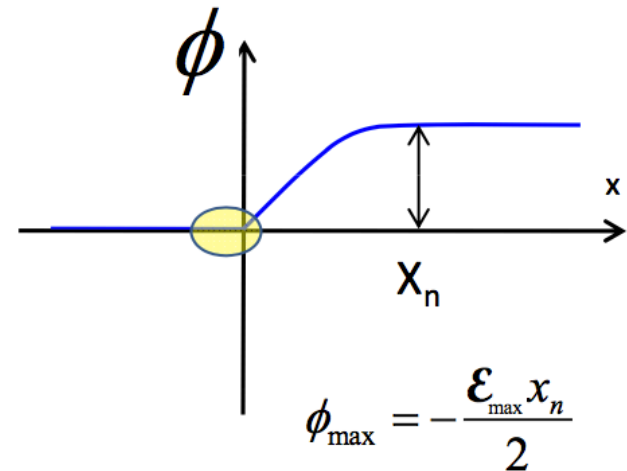
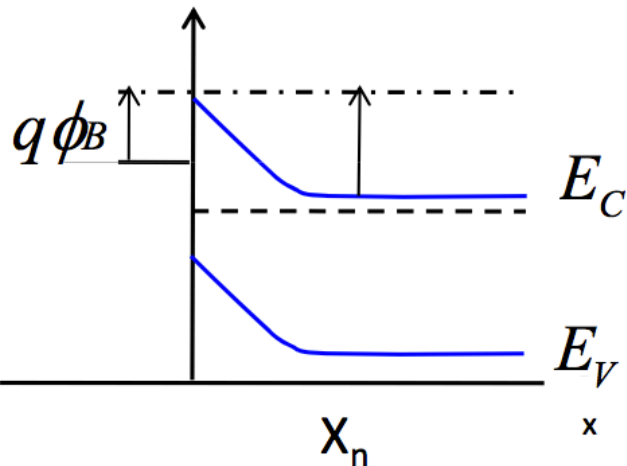
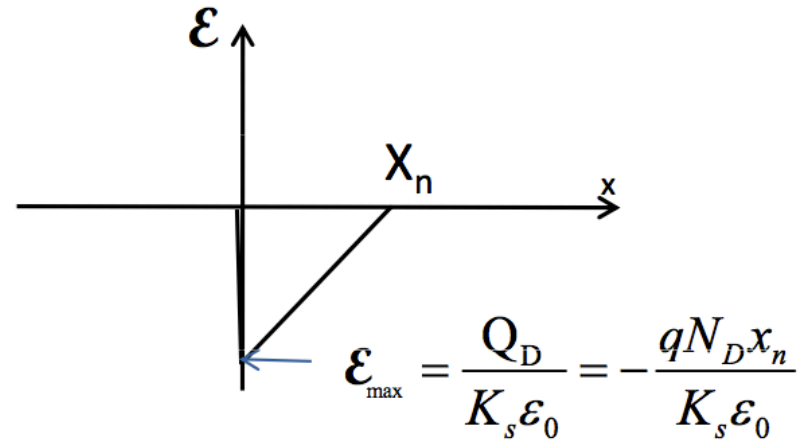
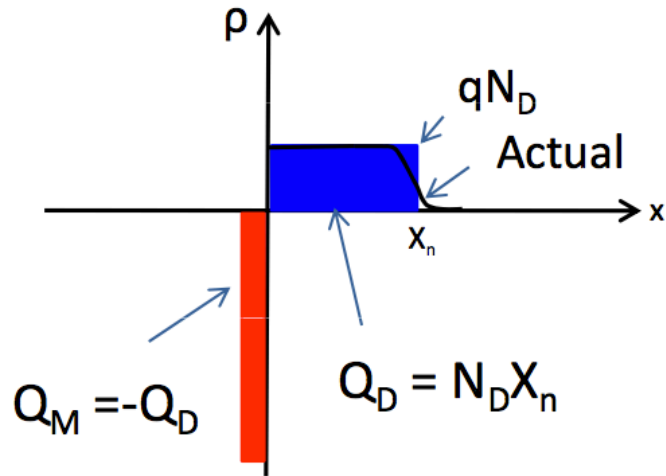
$$\Delta + \chi + qV_{bi} = \Phi_M$$

$$qV_{bi} = (\Phi_M - \chi) - \Delta \equiv \Phi_B - \Delta$$

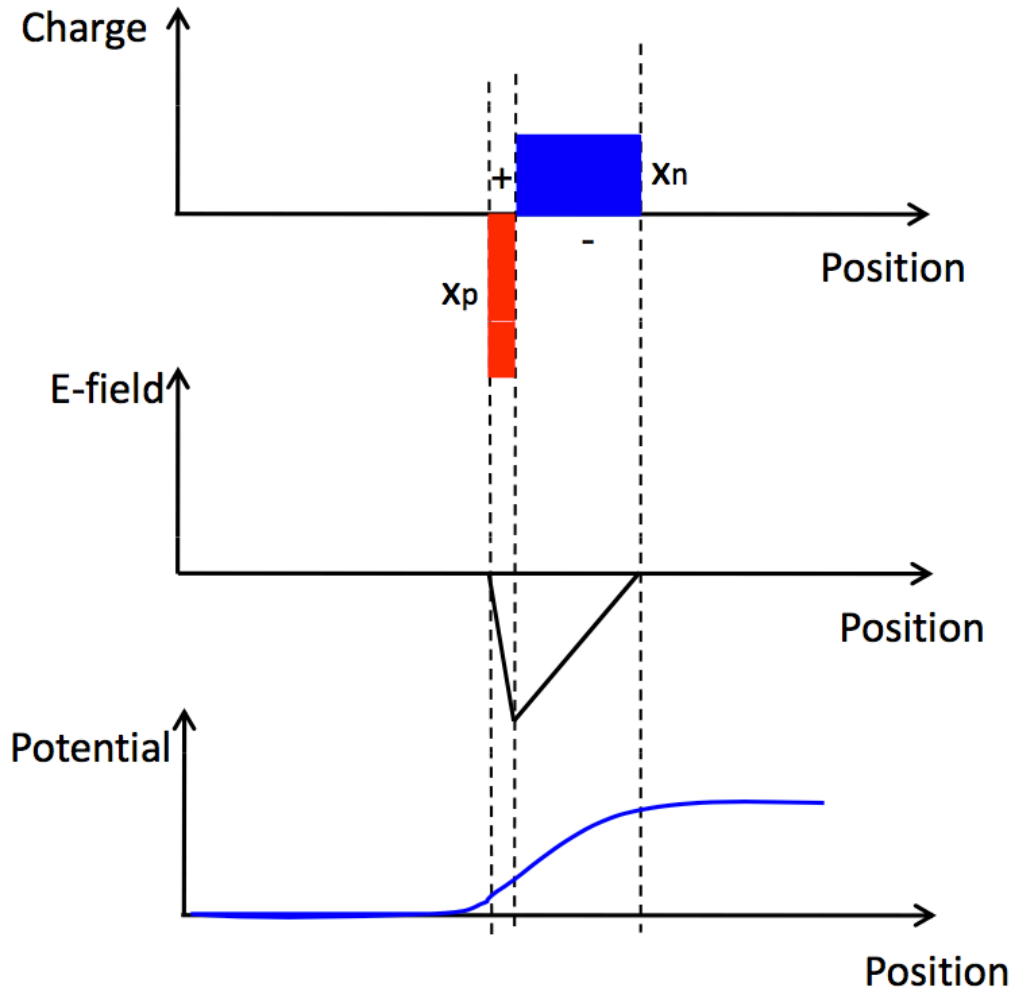
$$= \Phi_B - k_B T \ln \frac{N_D}{N_C}$$

肖特基二极管的能带图

Depletion Approximation



肖特基二极管的能带图



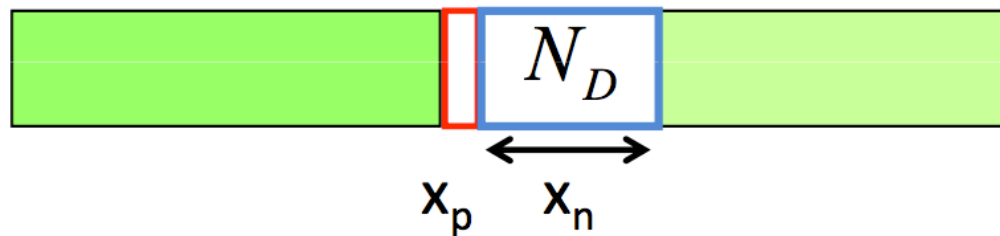
$$\mathcal{E}(0^+) = \frac{qN_D x_n}{k_s \epsilon_0}$$

$$\mathcal{E}(0^-) = \frac{qN_M x_p}{k_s \epsilon_0} \quad ?$$

$$\Rightarrow N_D x_n = N_M x_p$$

$$\begin{aligned} qV_{bi} &= \frac{\mathcal{E}(0^-) x_n}{2} + \frac{\mathcal{E}(0^+) x_p}{2} \\ &= \frac{qN_D x_n^2}{2k_s \epsilon_0} + \frac{qN_M x_p^2}{2k_s \epsilon_0} \end{aligned}$$

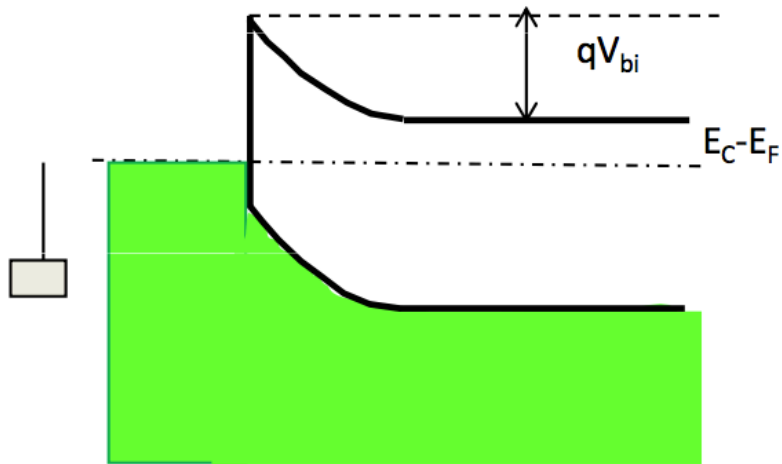
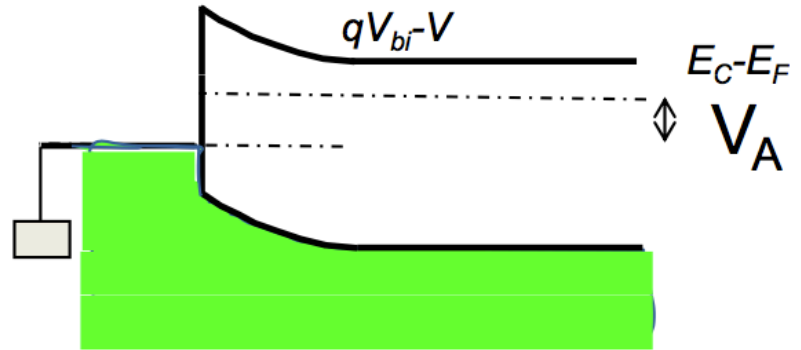
耗尽区



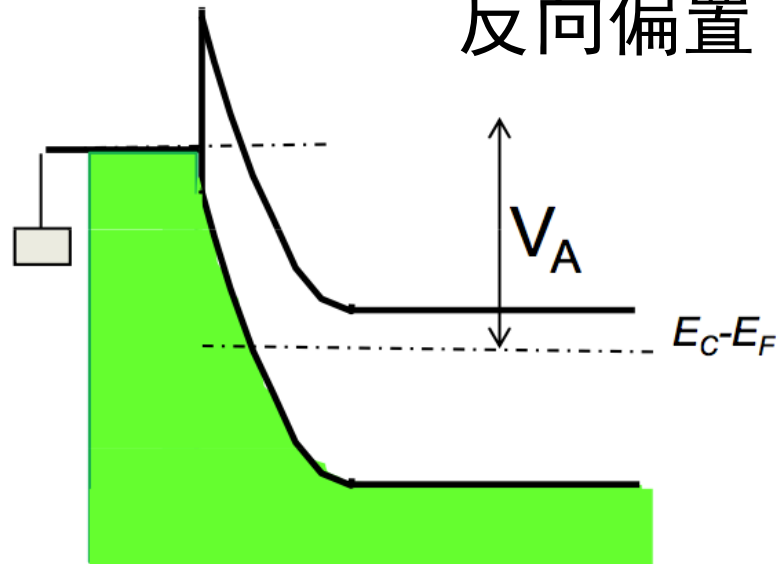
$$\left. \begin{aligned} N_D x_n &= N_M x_p \\ qV_{bi} &= \frac{qN_D x_n^2}{2k_s \epsilon_0} + \frac{qN_M x_p^2}{2k_s \epsilon_0} \end{aligned} \right\} \begin{aligned} x_n &= \sqrt{\frac{2k_s \epsilon_0}{q} \frac{N_M}{N_D (N_M + N_D)} V_{bi}} \rightarrow \sqrt{\frac{2k_s \epsilon_0}{q} \frac{1}{N_D} V_{bi}} \\ x_p &= \sqrt{\frac{2k_s \epsilon_0}{q} \frac{N_D}{N_M (N_M + N_D)} V_{bi}} \rightarrow 0 \end{aligned}$$

正向偏置与反向偏置

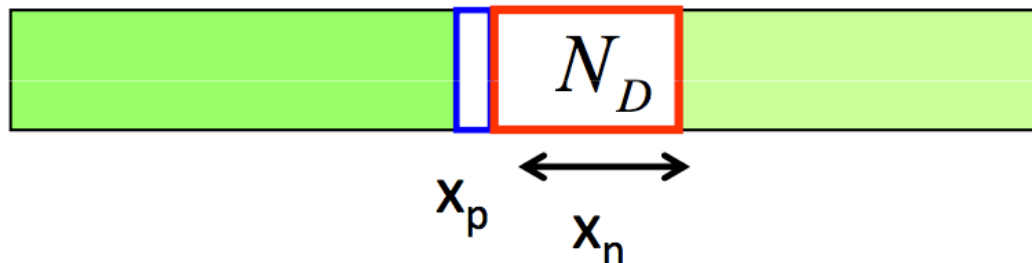
正向偏置



反向偏置



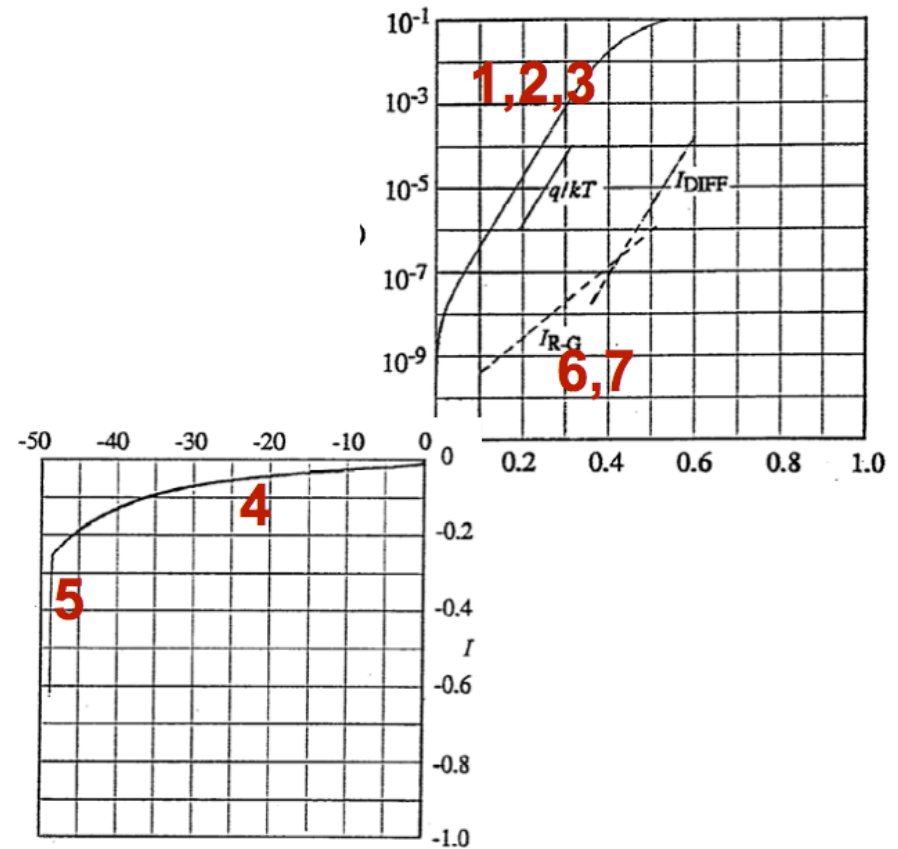
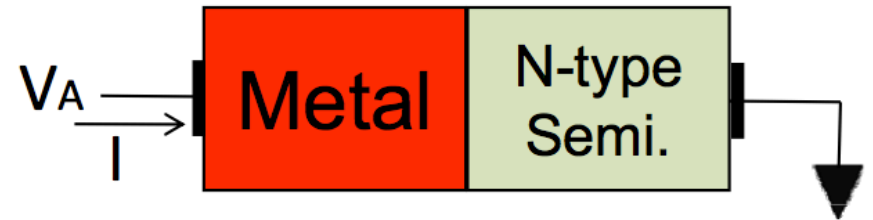
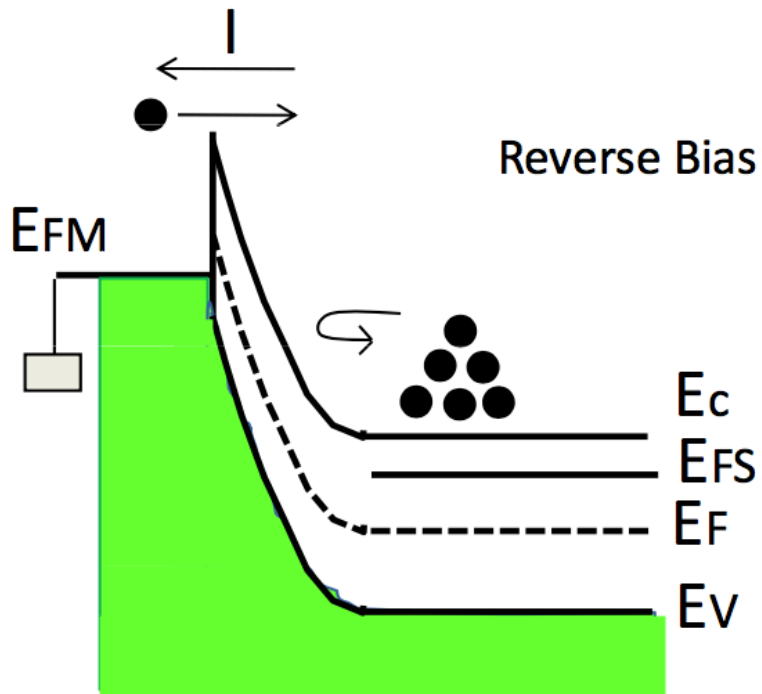
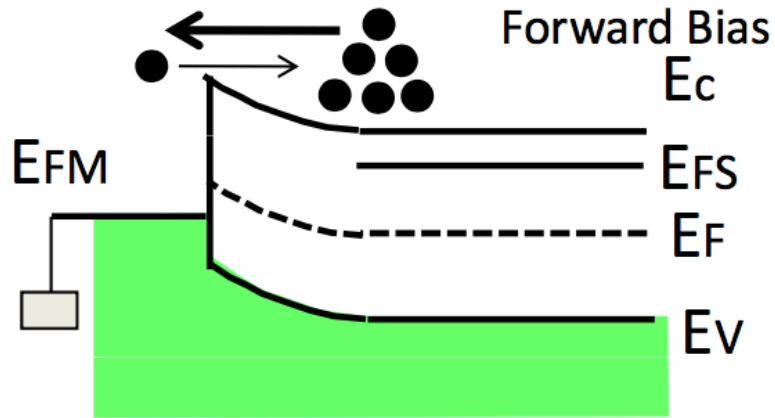
偏置下的耗尽区



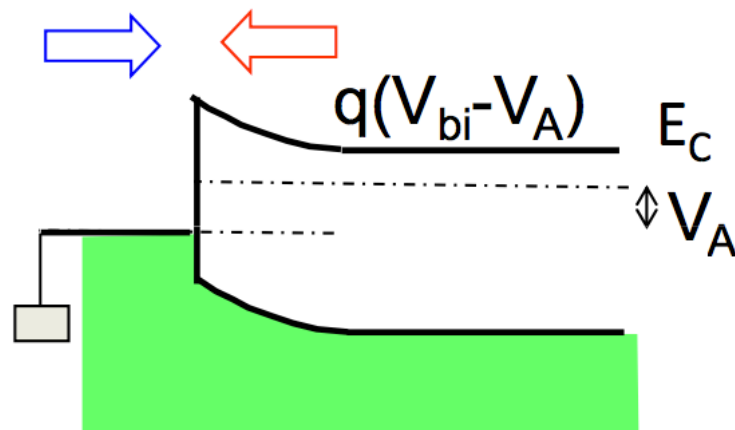
$$x_n = \sqrt{\frac{2k_s\epsilon_0}{q} \frac{N_M}{N_D(N_M + N_D)} V_{bi}} \rightarrow \sqrt{\frac{2k_s\epsilon_0}{q} \frac{1}{N_D} (V_{bi} - V_A)}$$

$$x_p = \sqrt{\frac{2k_s\epsilon_0}{q} \frac{N_D}{N_M(N_M + N_D)} V_{bi}} \rightarrow 0$$

电流特性



电流是如何流动的



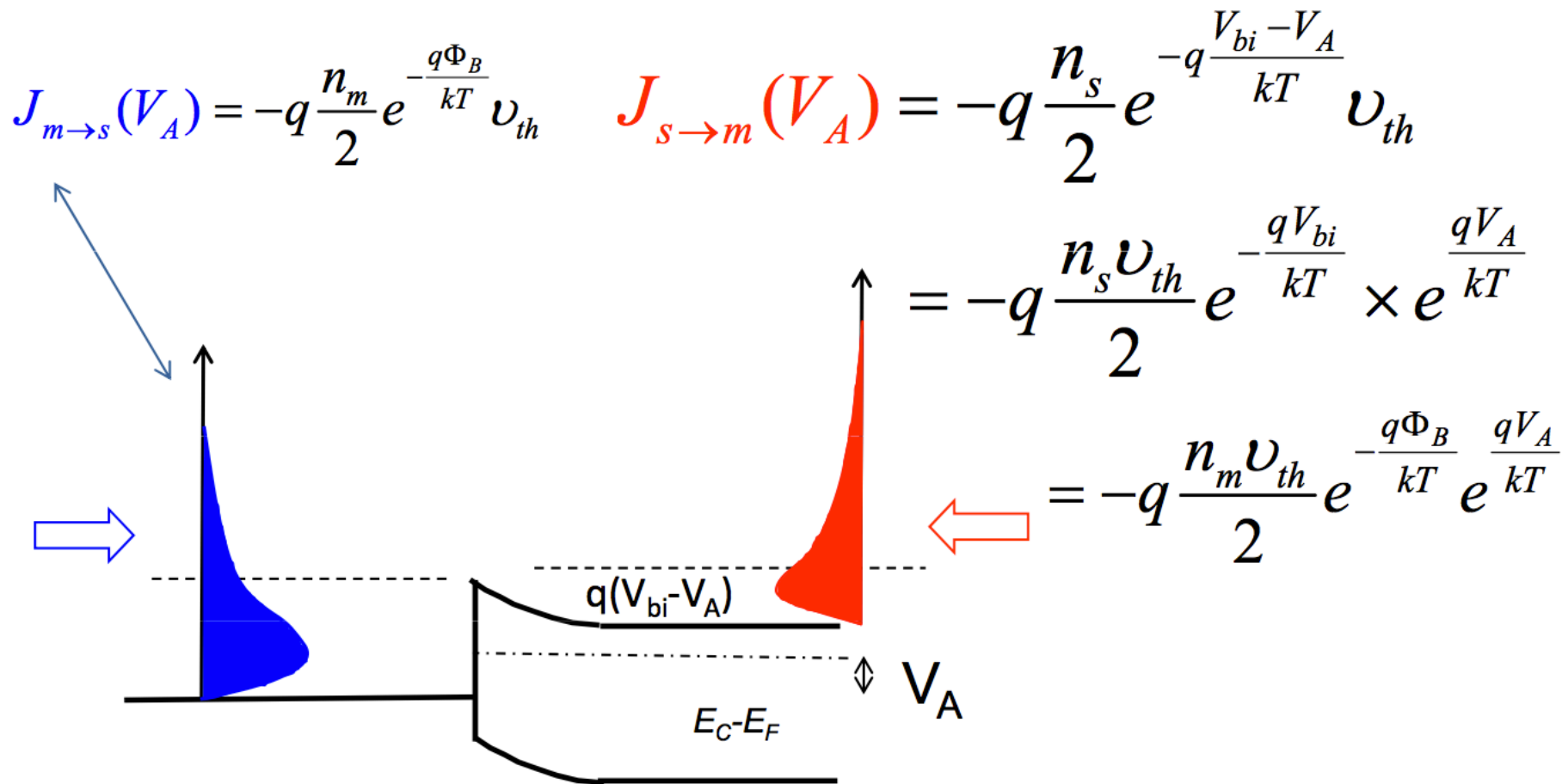
$$\begin{aligned} J_T(V_A) &= J_{m \rightarrow s}(V_A) - J_{s \rightarrow m}(V_A) \\ &= J_{m \rightarrow s}(0) - J_{s \rightarrow m}(V_A) \end{aligned}$$

$$J_T(V_A = 0) = 0 = J_{m \rightarrow s}(0) - J_{s \rightarrow m}(0) \quad \text{动态平衡}$$

$$\Rightarrow J_{m \rightarrow s}(0) = J_{s \rightarrow m}(0)$$

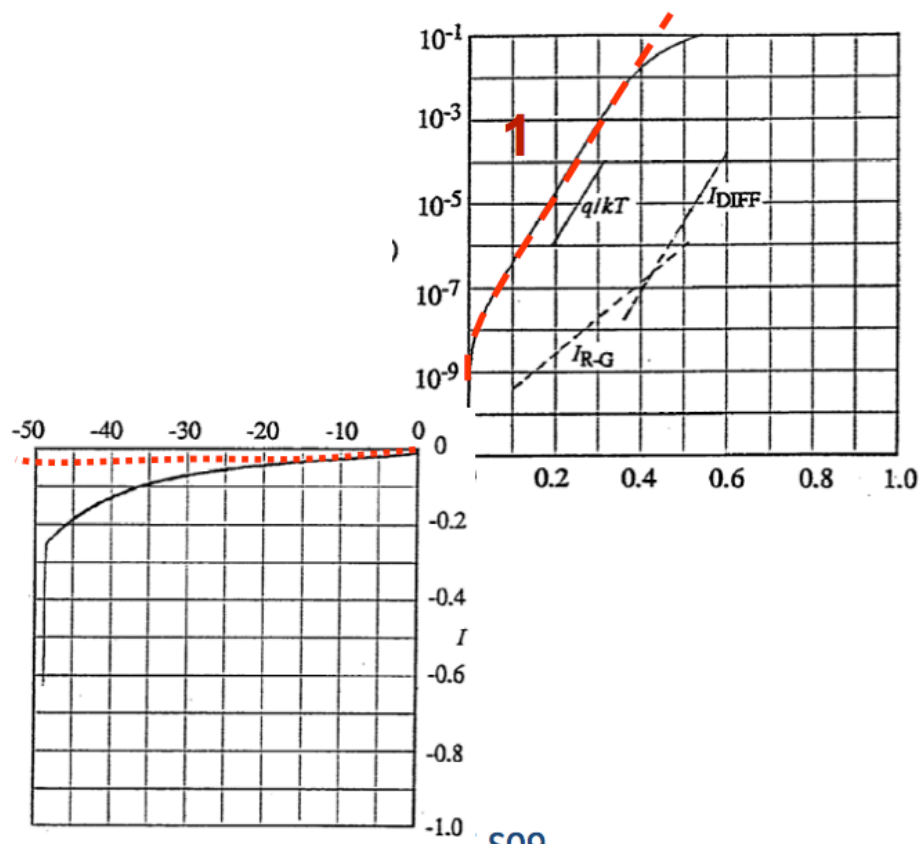
$$J_T(V_A) = J_{s \rightarrow m}(0) - J_{s \rightarrow m}(V_A)$$

半导体到金属的电流

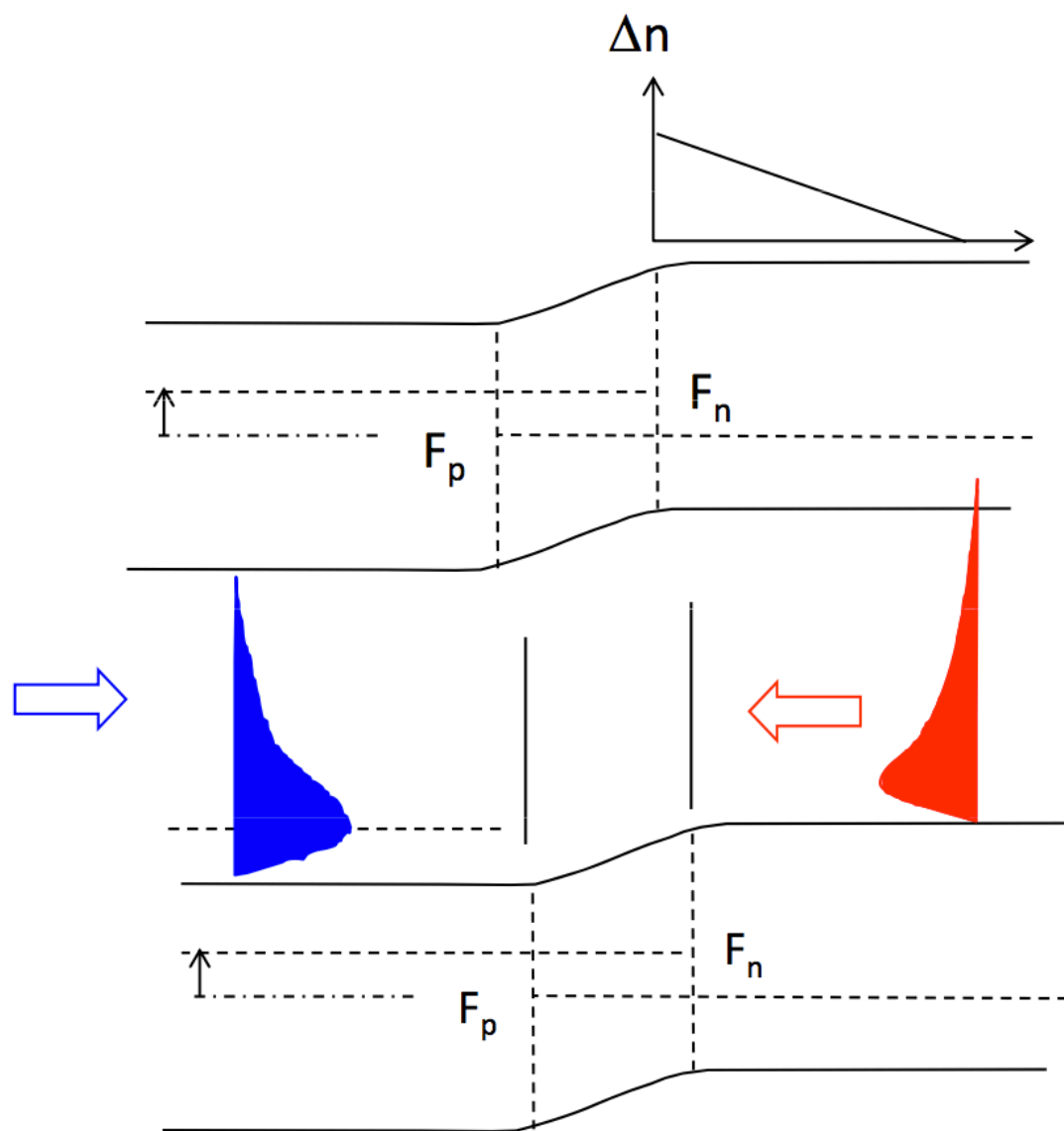


总电流

$$J_T = J_{s \rightarrow m}(0) - J_{s \rightarrow m}(V_A) = \frac{qn_m v_{th}}{2} e^{\frac{-q\Phi_m}{kT}} \left[e^{\frac{qV_A}{kT}} - 1 \right]$$

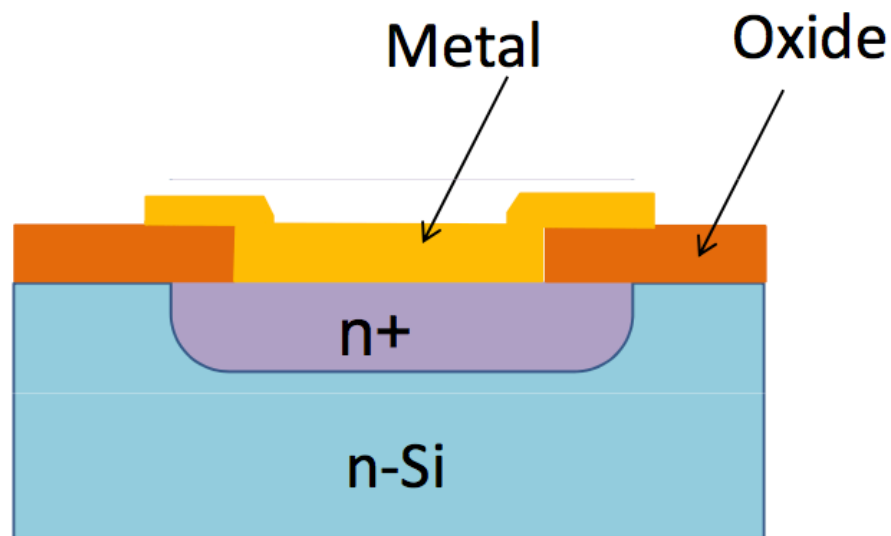


扩散电流 vs 热发射电流

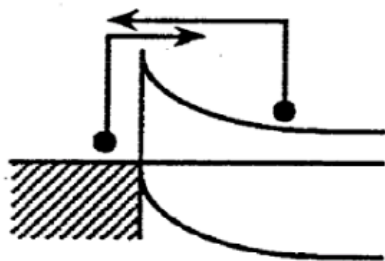


两者的电流特性
非常相似

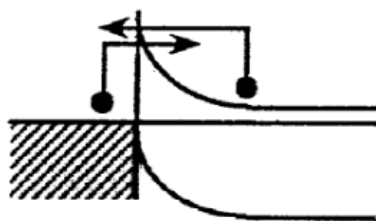
欧姆接触与肖特基接触



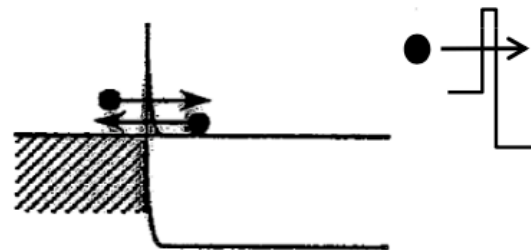
Low Doping



Moderate Doping

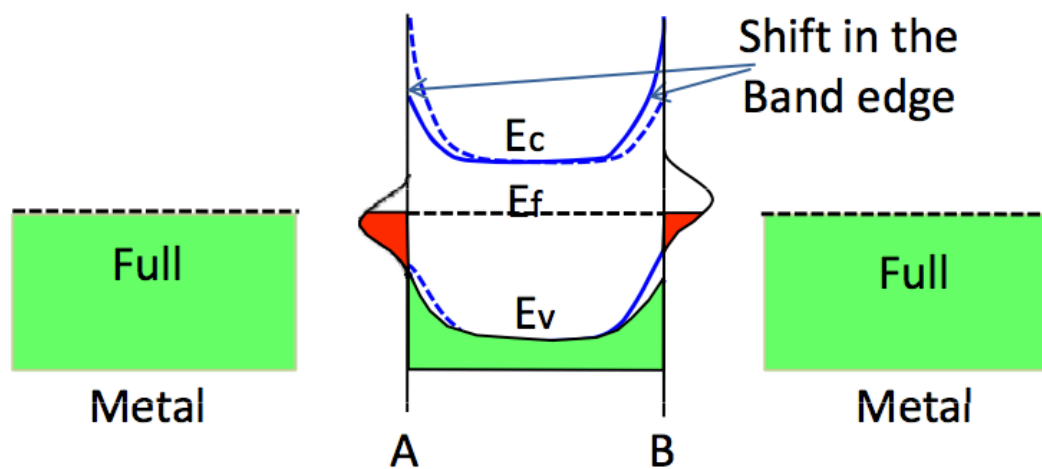
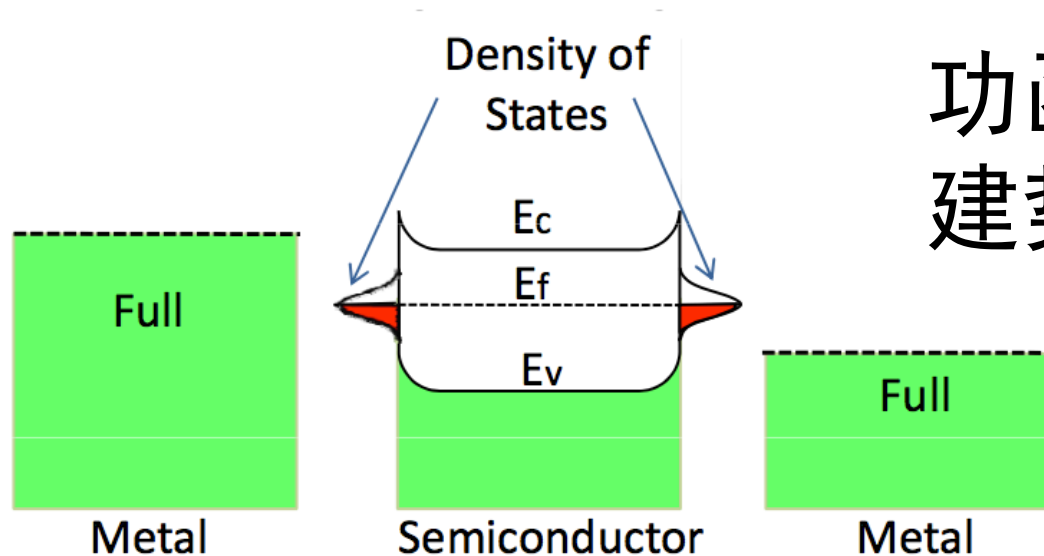


High Doping



费米钉扎效应

功函数无法调节内
建势



作业

- 《现代集成电路半导体器件》习题：4.1、4.3、4.4、4.12、4.19

Thanks!
Q&A