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

$$\nabla \bullet E = q\left(p - n + N_D^+ - N_A^-\right)$$

能带图

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

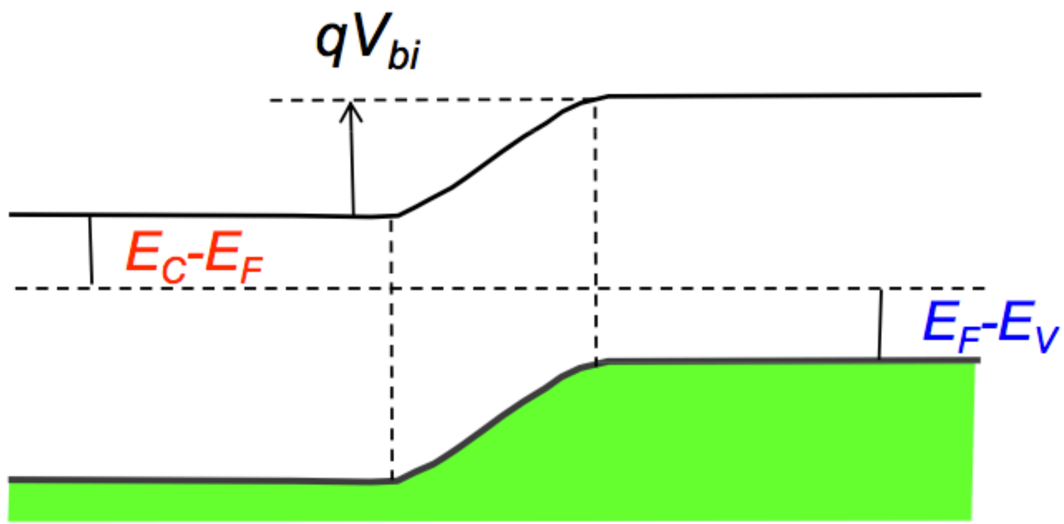
$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

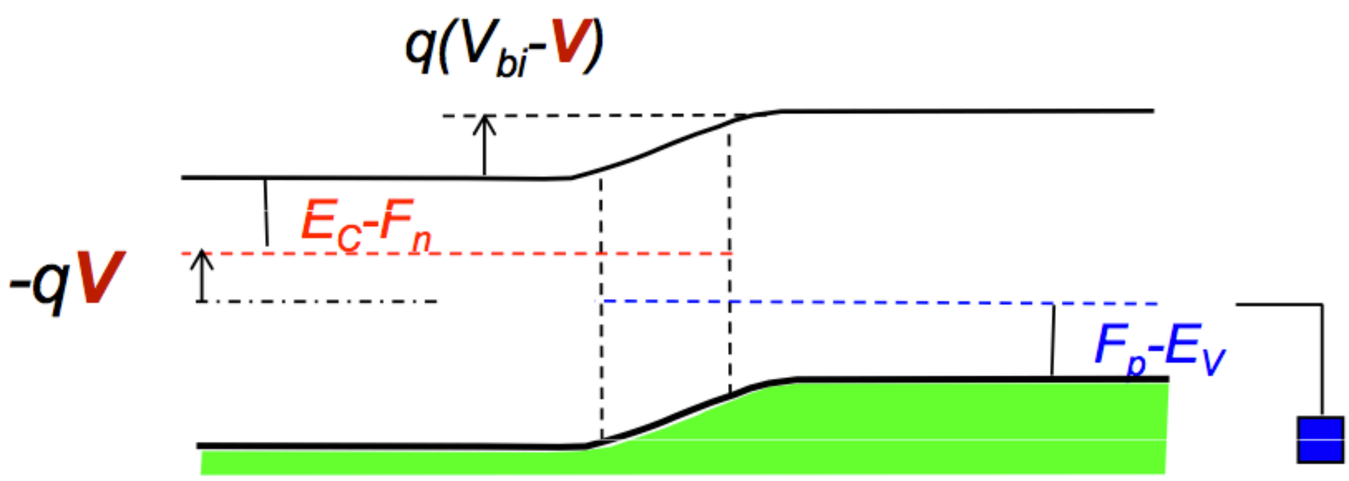
$$\frac{\partial p}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

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

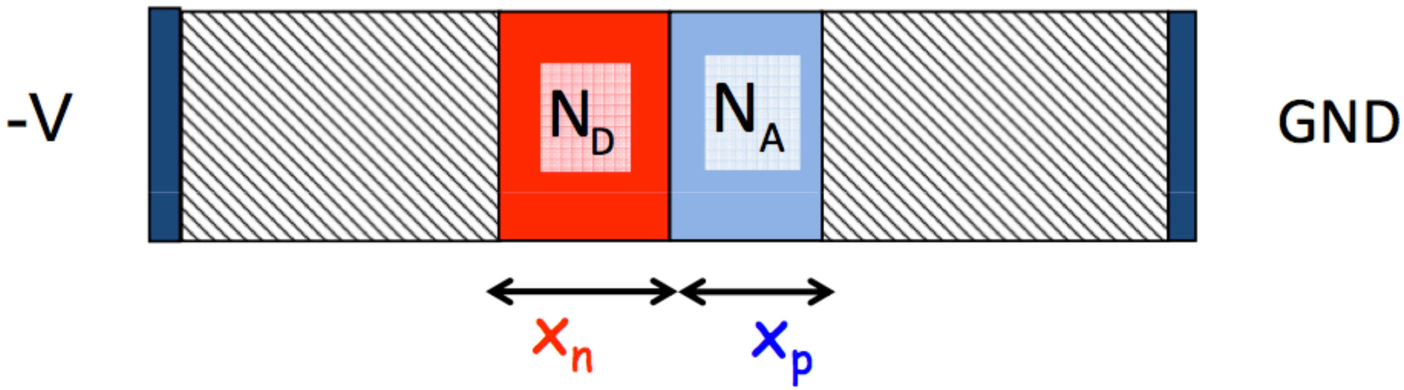
正向电流和反向电流

PN结的正向偏置





耗尽区宽度



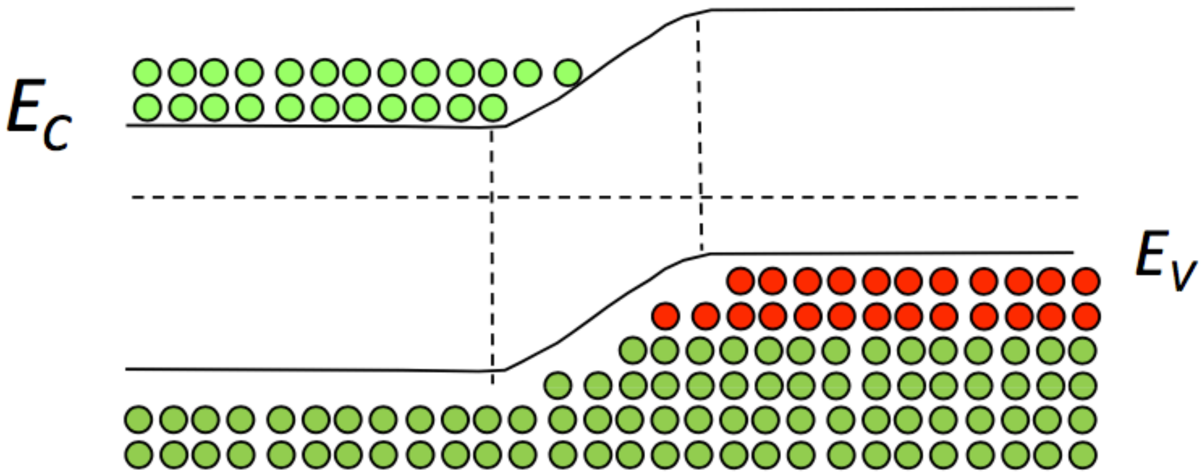
$$N_D x_n = N_A x_p$$

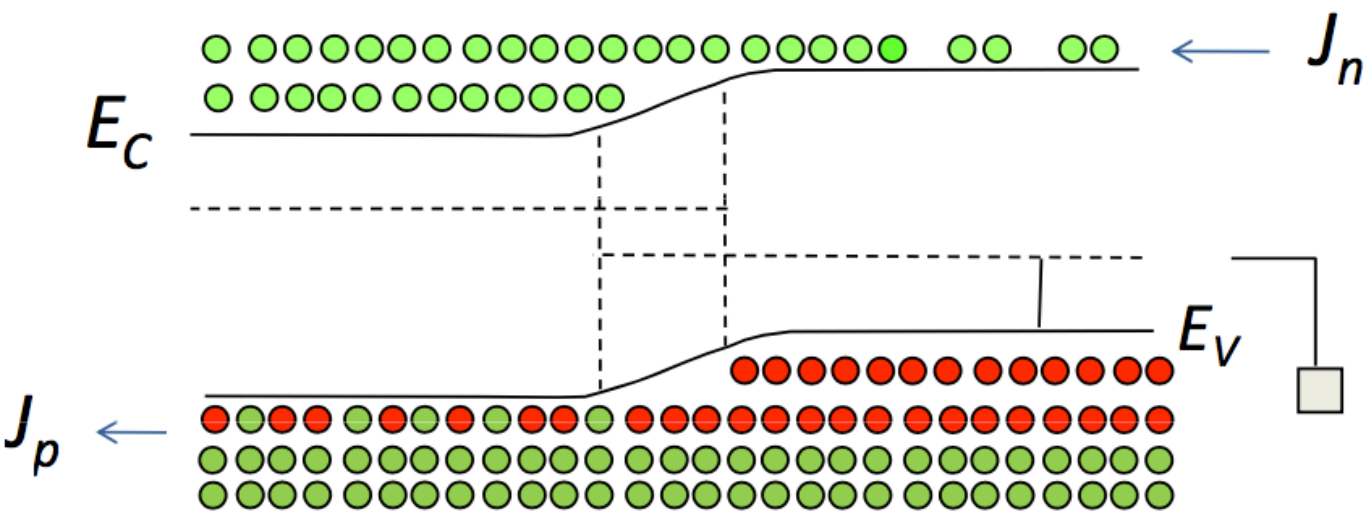
$$q\left(V_{bi} - V\right) = \frac{qN_D x_n^{\ 2}}{2k_s\varepsilon_0} + \frac{qN_A x_p^{\ 2}}{2k_s\varepsilon_0}$$

$$x_n = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_A}{N_D\left(N_A + N_D\right)}(V_{bi} - V)}$$

$$x_p = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_D}{N_A\left(N_A + N_D\right)}(V_{bi} - V)}$$

准费米能级





边界条件

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

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

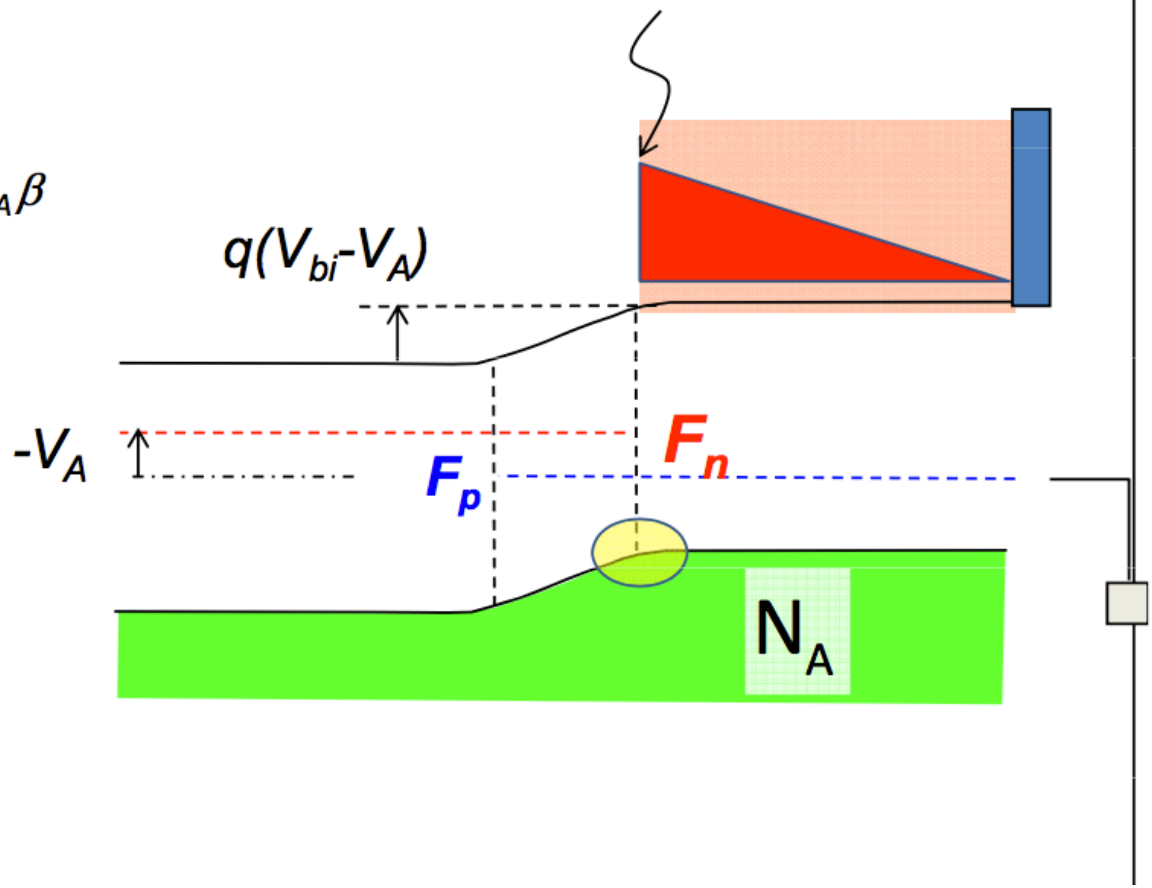
$$n(x=0^+) = n_i\, e^{(F_n - E_i)\beta}$$

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

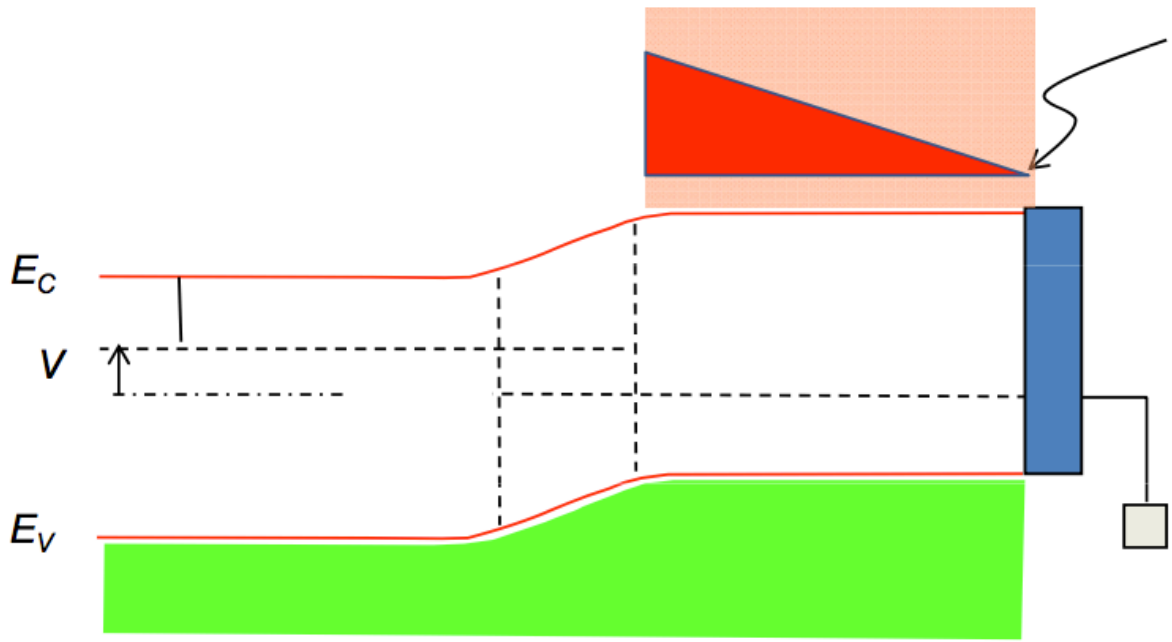
$$np = n_i^2 e^{(F_n - F_p)\beta} = n_i^2 e^{qV_A\beta}$$

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

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



边界条件



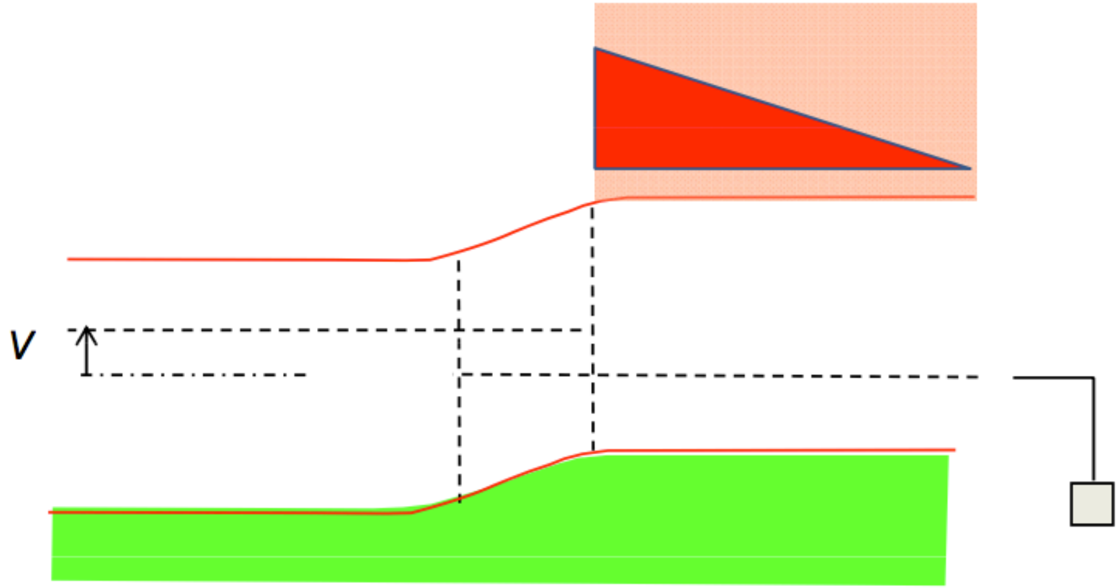
$$n(x = W_p) \approx \frac{n_i^2}{N_A}$$

$$\Delta n(x = W_p) = 0$$

边界条件

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

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



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

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

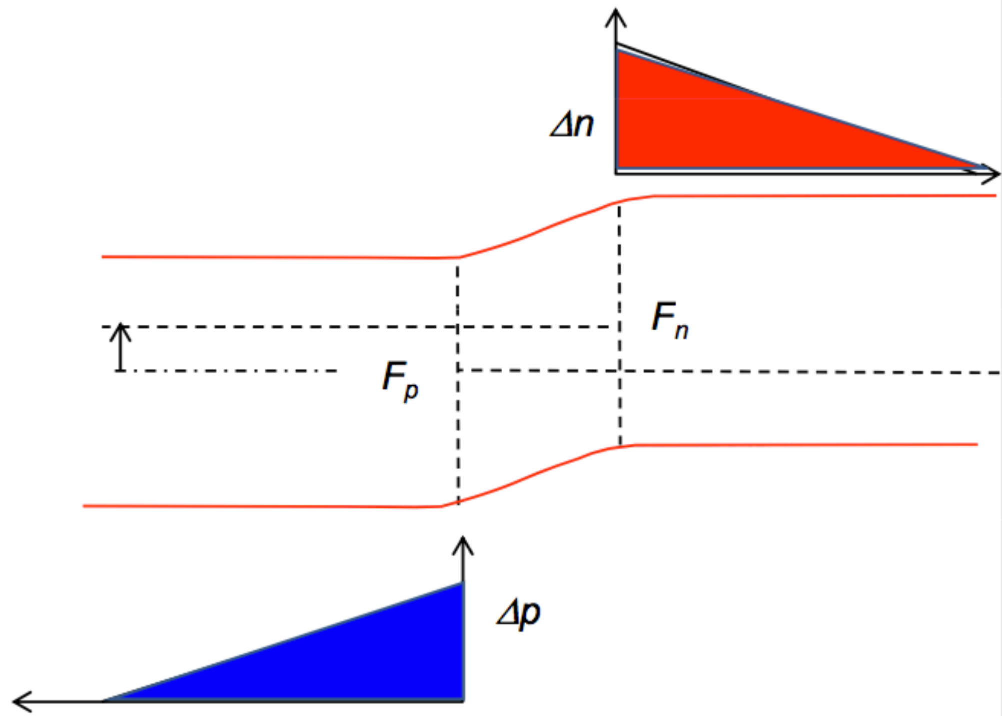
$$\Delta n(x,t) = \frac{n_i^2}{N_A}\left(e^{qV_A\beta} - 1\right)\left(1 - \frac{x}{W_p}\right)$$

电子电流和空穴电流

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

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

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



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

总电流

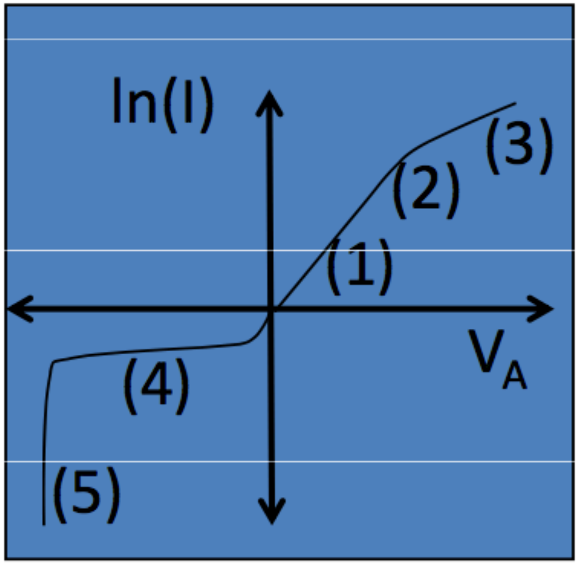
$$J_T = -q\left[\frac{D_n}{W_p}\frac{n_i^2}{N_A} + \frac{D_p}{W_n}\frac{n_i^2}{N_D}\right]\left(e^{qV_A\beta} - 1\right)$$

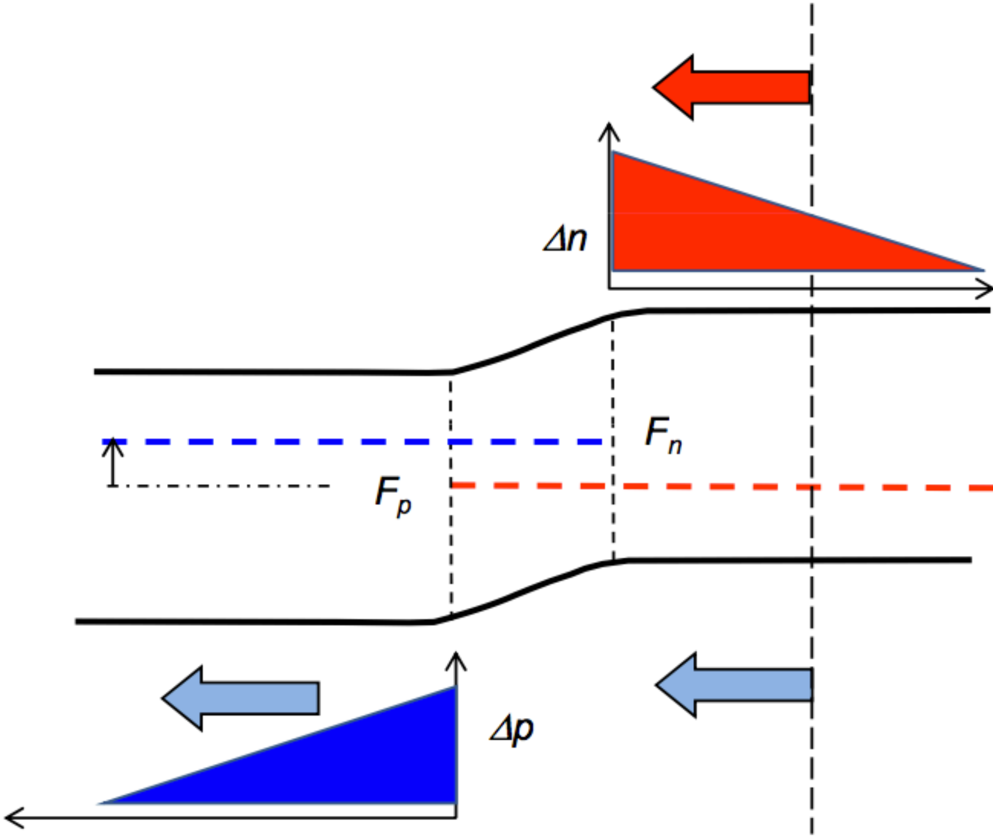
正向偏置

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

反向偏置

$$J_T \approx const.$$





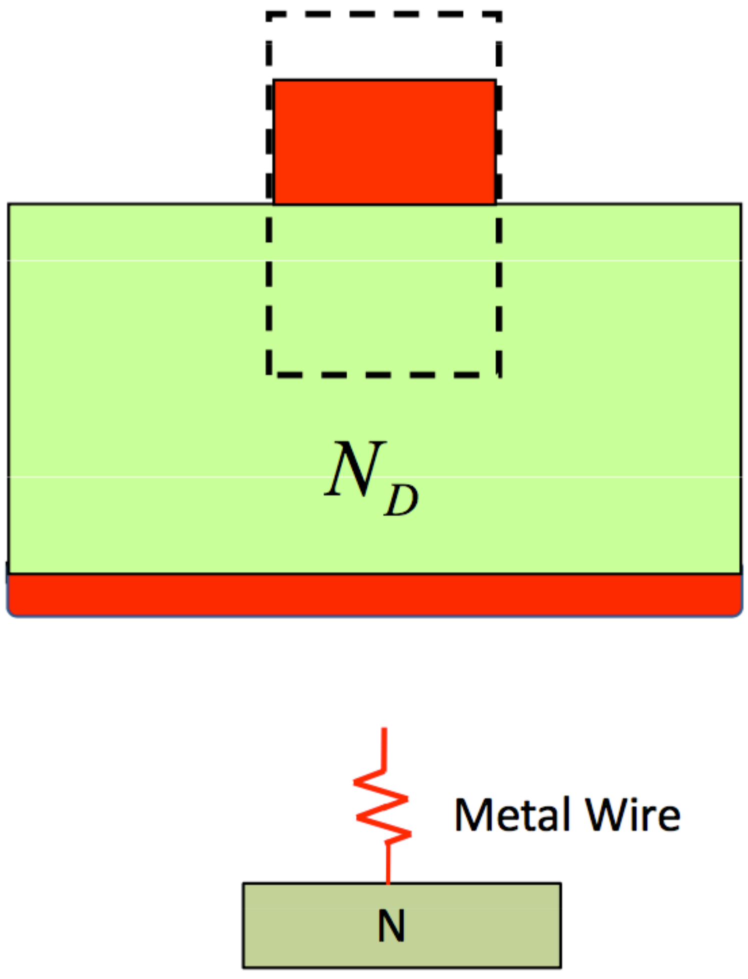
Thanks!
Q&A

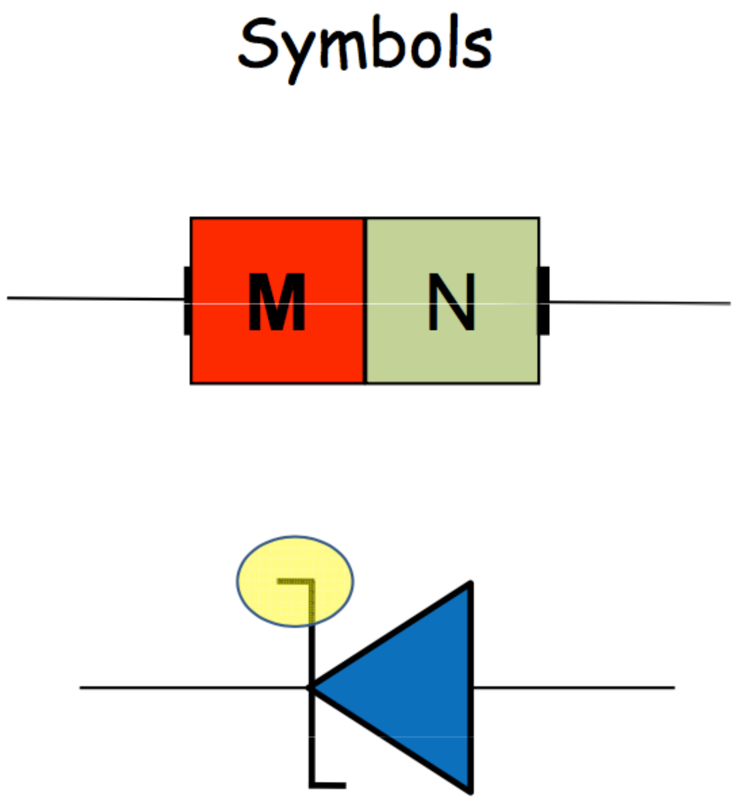
微电子器件物理
肖特基二极管

曾琅

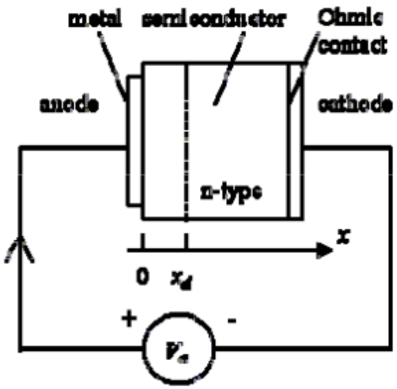
2020/09/25

金属半导体二极管

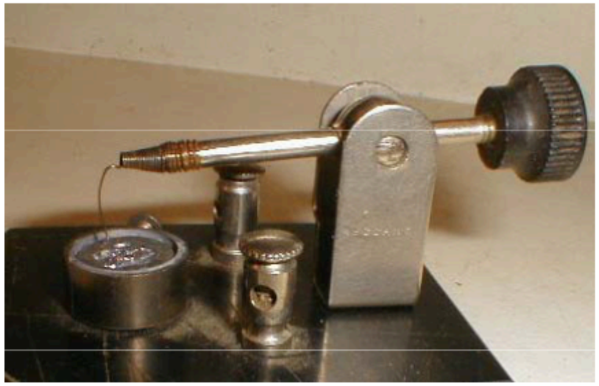




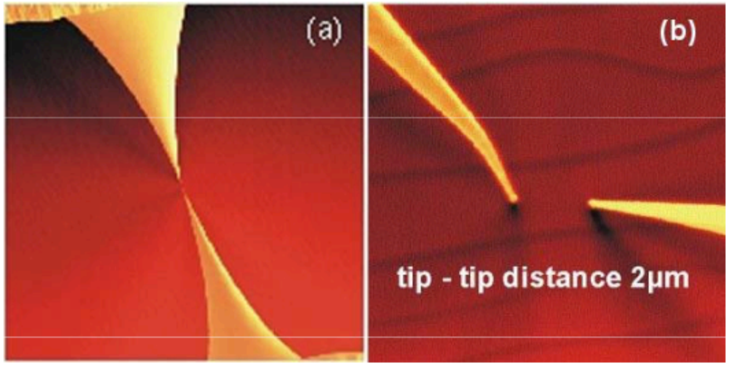
肖特基二极管的应用



矿石收音机



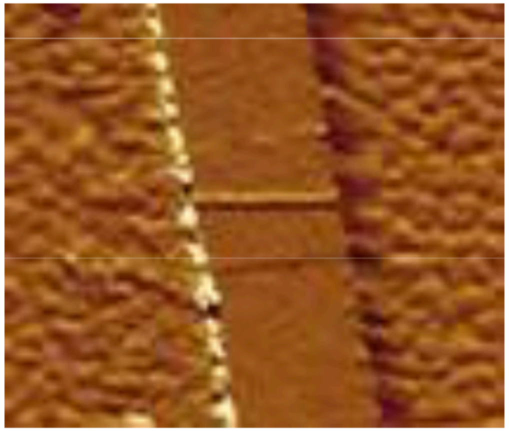
扫描隧道显微镜

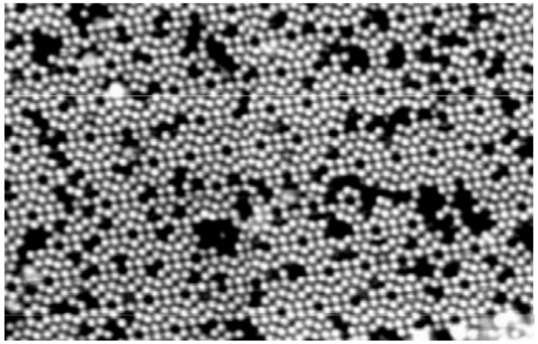


www.fz-juelich.de/ibn/index.php?index=674

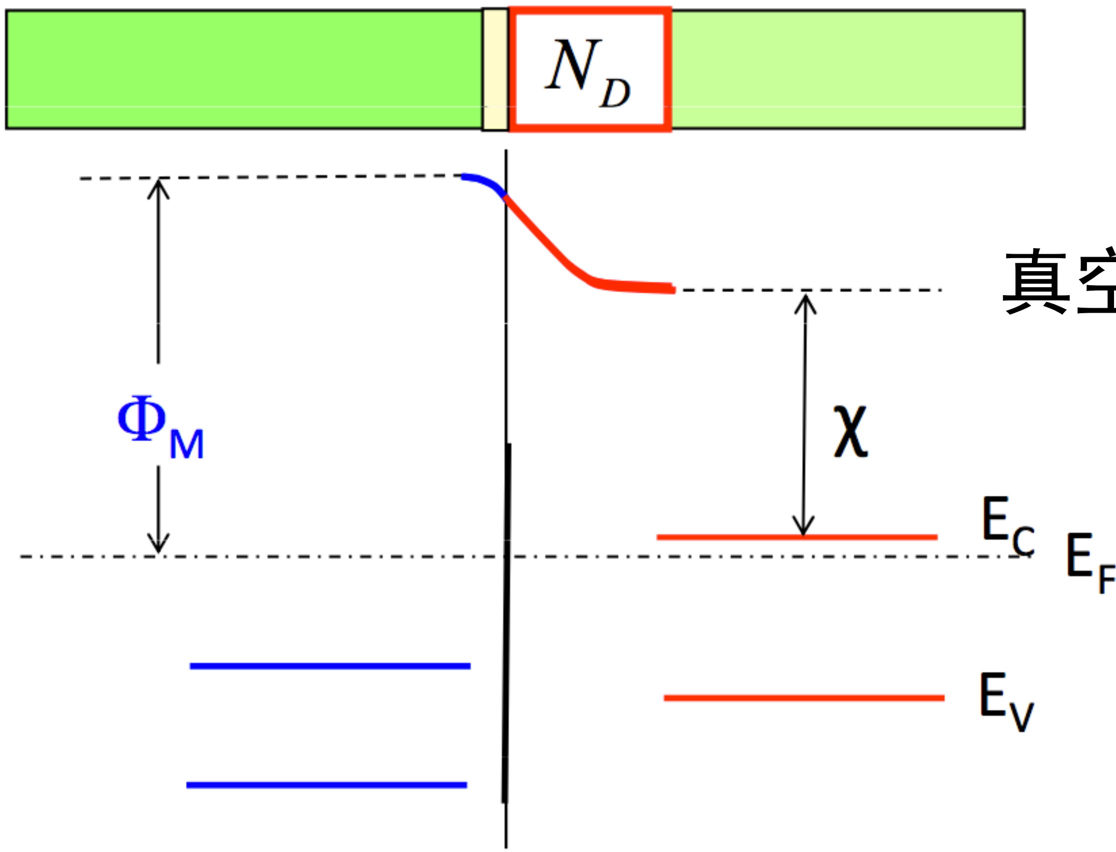
第一个晶体管

碳纳米管



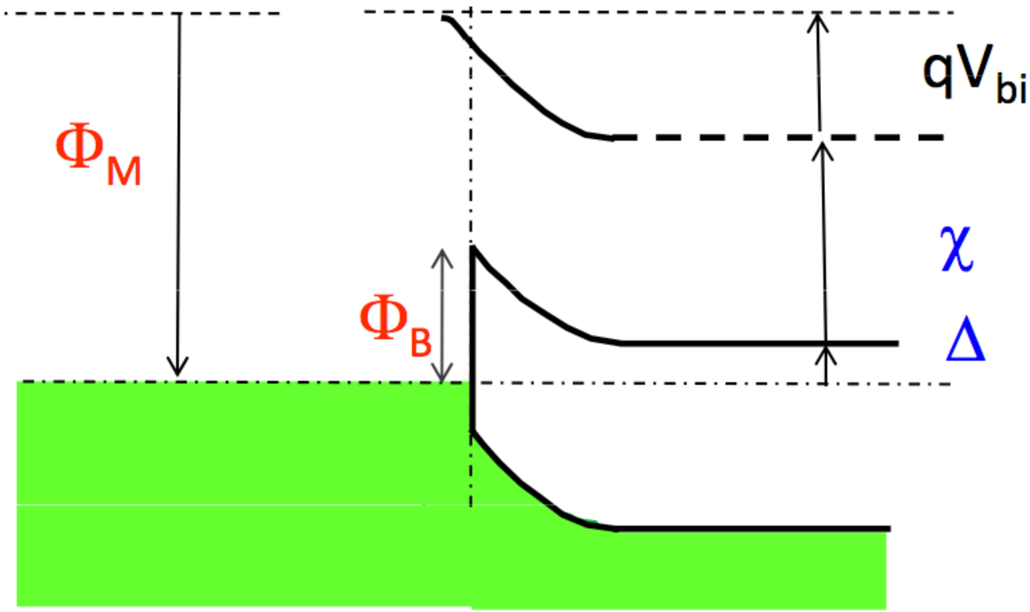


肖特基二极管的能带图



$$N_A x_p = N_D x_n$$

肖特基二极管的能带图

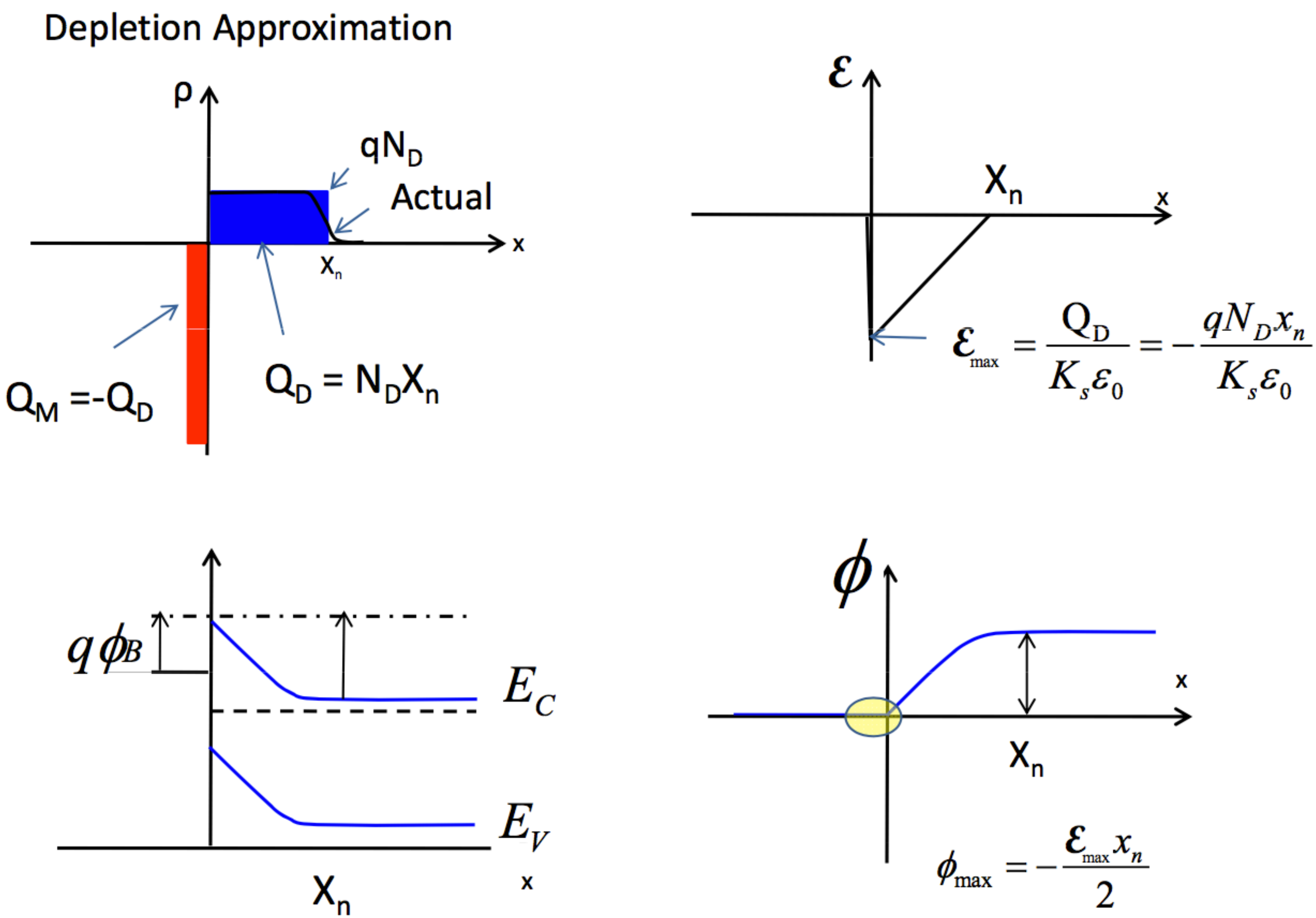


$$\Delta + \chi + qV_{bi} = \Phi_M$$

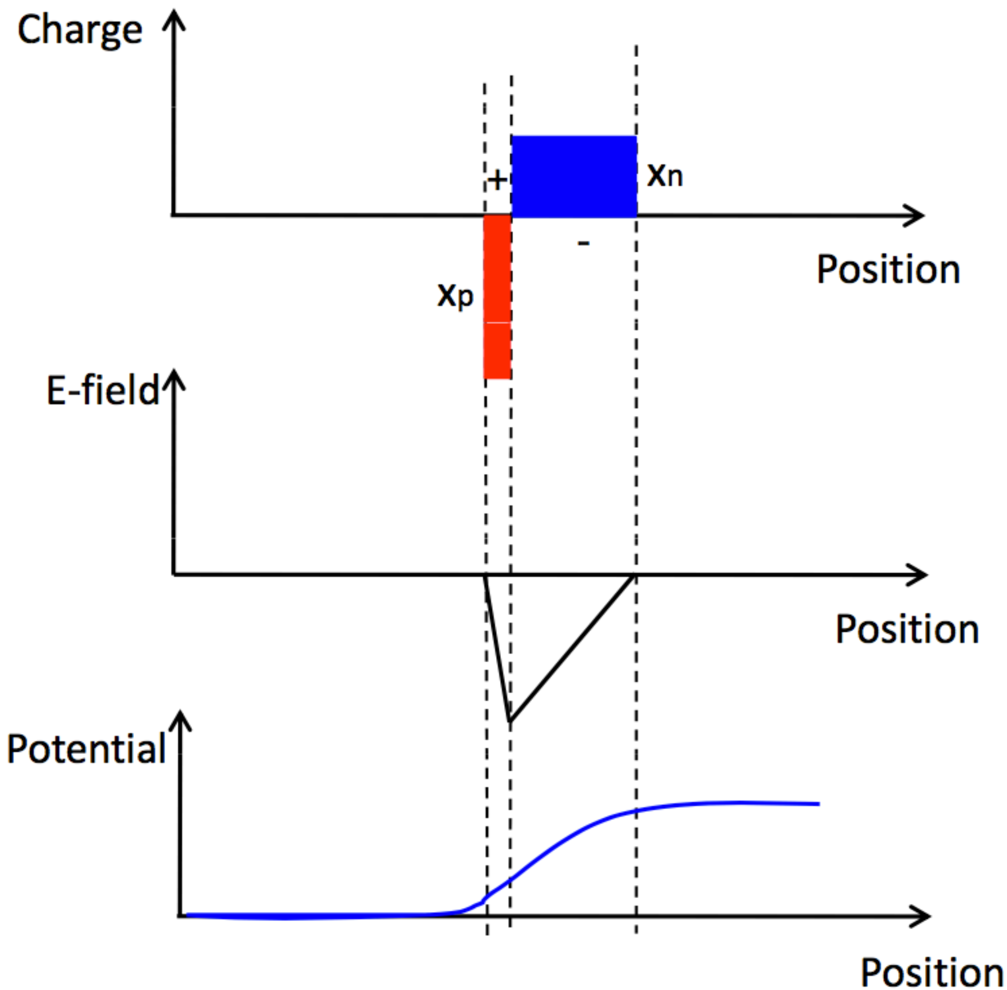
$$qV_{bi} = (\Phi_M - \chi) - \Delta \equiv \Phi_B - \Delta$$

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

肖特基二极管的能带图


Depletion Approximation
ρ
qN_D
Actual
x
x_n
$Q_M = -Q_D$
$Q_D = N_D X_n$
$\mathcal{E}$
X_n
x
$\mathcal{E}_{\max} = \frac{Q_D}{K_s \varepsilon_0} = -\frac{qN_D x_n}{K_s \varepsilon_0}$
$q\phi_B$
E_C
E_V
X_n
x
ϕ
x
X_n
$\phi_{\max} = -\frac{\mathcal{E}_{\max} x_n}{2}$

肖特基二极管的能带图



$$\mathcal{E}\left(0^{+}\right)=\frac{qN_{D}x_{n}}{k_{s}\varepsilon_{0}}$$

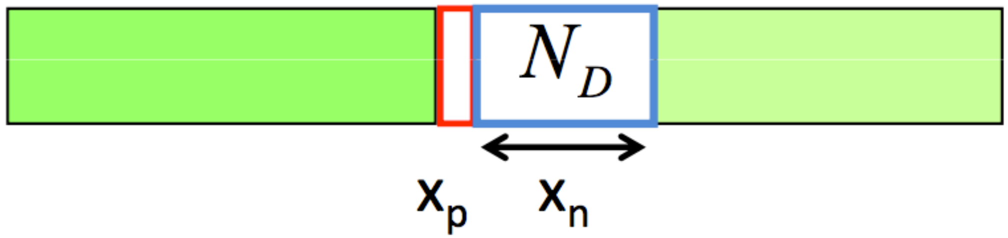
$$\mathcal{E}\left(0^{-}\right)=\frac{qN_{M}x_{p}}{k_{s}\varepsilon_{0}} \ ?$$

$$\Rightarrow N_{D}x_{n}=N_{M}x_{p}$$

$$qV_{bi}=\frac{\mathcal{E}\left(0^{-}\right)x_{n}}{2}+\frac{\mathcal{E}\left(0^{+}\right)x_{p}}{2}$$

$$=\frac{qN_{D}x_{n}^{2}}{2k_{s}\varepsilon_{0}}+\frac{qN_{M}x_{p}^{2}}{2k_{s}\varepsilon_{0}}$$

耗尽区

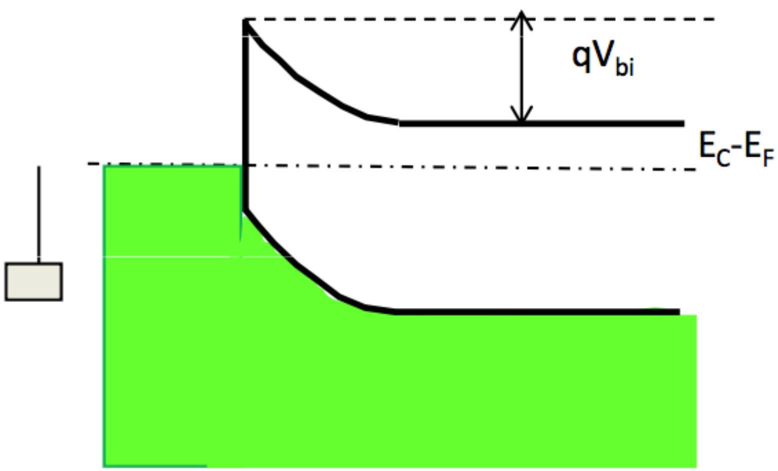


$$\left.\begin{aligned} N_D x_n &= N_M x_p \\ qV_{bi} &= \frac{qN_D x_n^{\;2}}{2k_s\varepsilon_0} + \frac{qN_M x_p^{\;2}}{2k_s\varepsilon_0} \end{aligned}\right\}$$

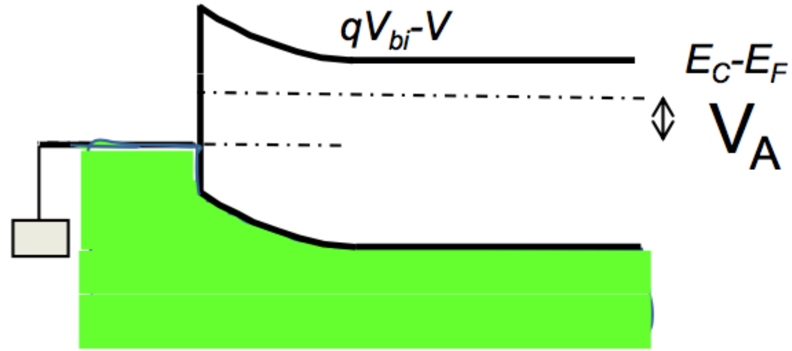
$$x_n = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_M}{N_D\left(N_M+N_D\right)}V_{bi}} \to \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{1}{N_D}V_{bi}}$$

$$x_p = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_D}{N_M\left(N_M+N_D\right)}V_{bi}} \to 0$$

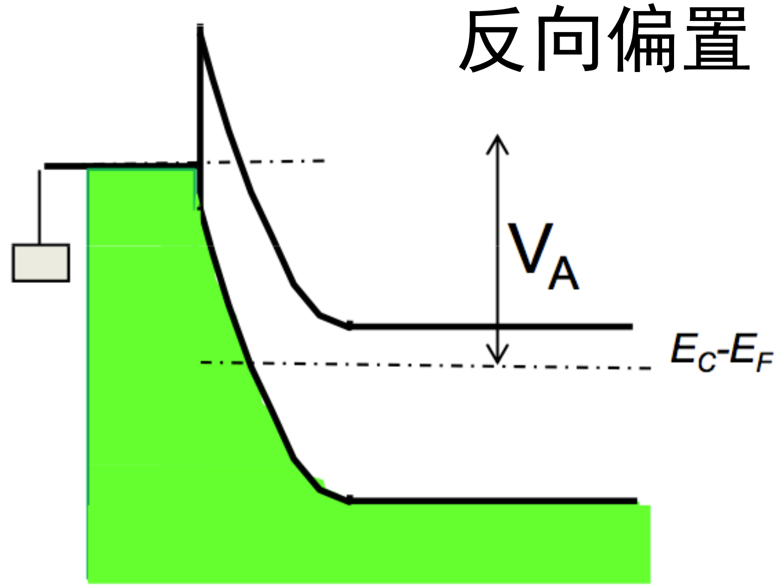
正向偏置与反向偏置



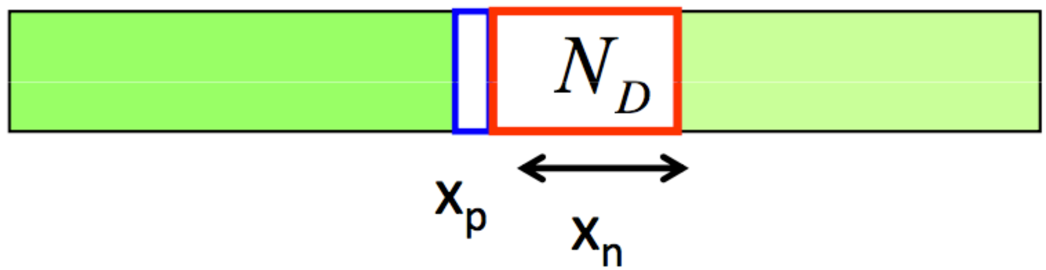
正向偏置



反向偏置



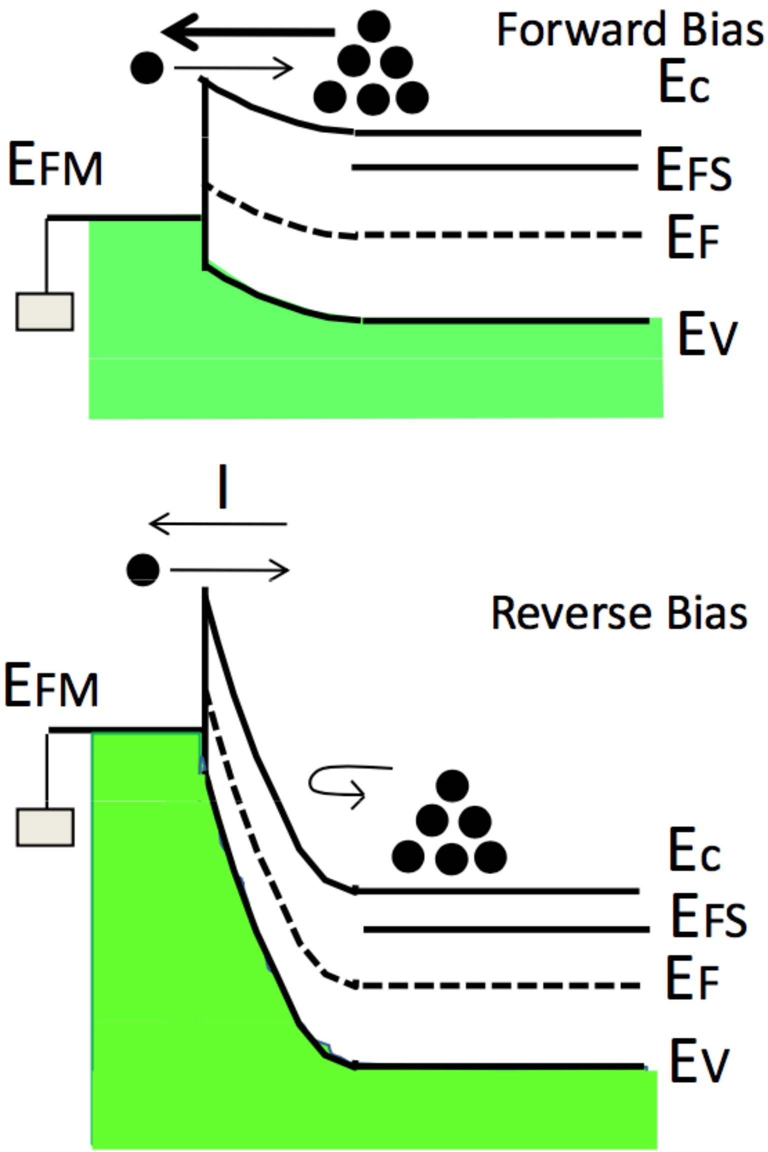
偏置下的耗尽区



$$x_n = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_M}{N_D\left(N_M+N_D\right)}V_{bi}} \rightarrow \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{1}{N_D}\left(V_{bi}-V_A\right)}$$

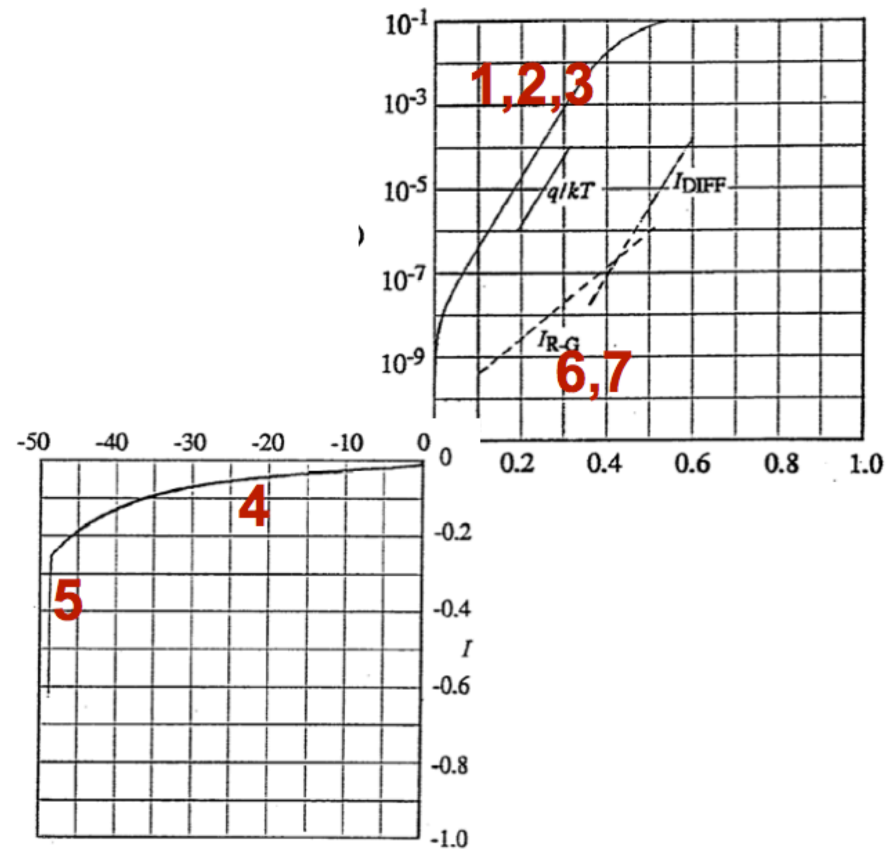
$$x_p = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_D}{N_M\left(N_M+N_D\right)}V_{bi}} \rightarrow 0$$

电流特性



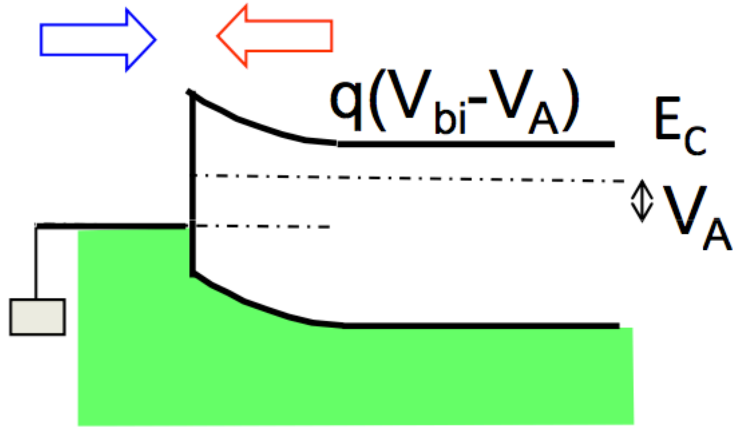
Forward Bias
Ec
EFM
EFS
EF
Ev
I
Reverse Bias
EFM
Ec
EFS
EF
Ev

VA
I
Metal
N-type
Semi.



10-1
10-3
10-5
10-7
10-9
1,2,3
q/kT
IDIFF
IR-G
6,7
0
0.2
0.4
0.6
0.8
1.0
-50
-40
-30
-20
-10
0
4
5
-0.2
-0.4
I
-0.6
-0.8
-1.0

电流是如何流动的



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

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

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

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

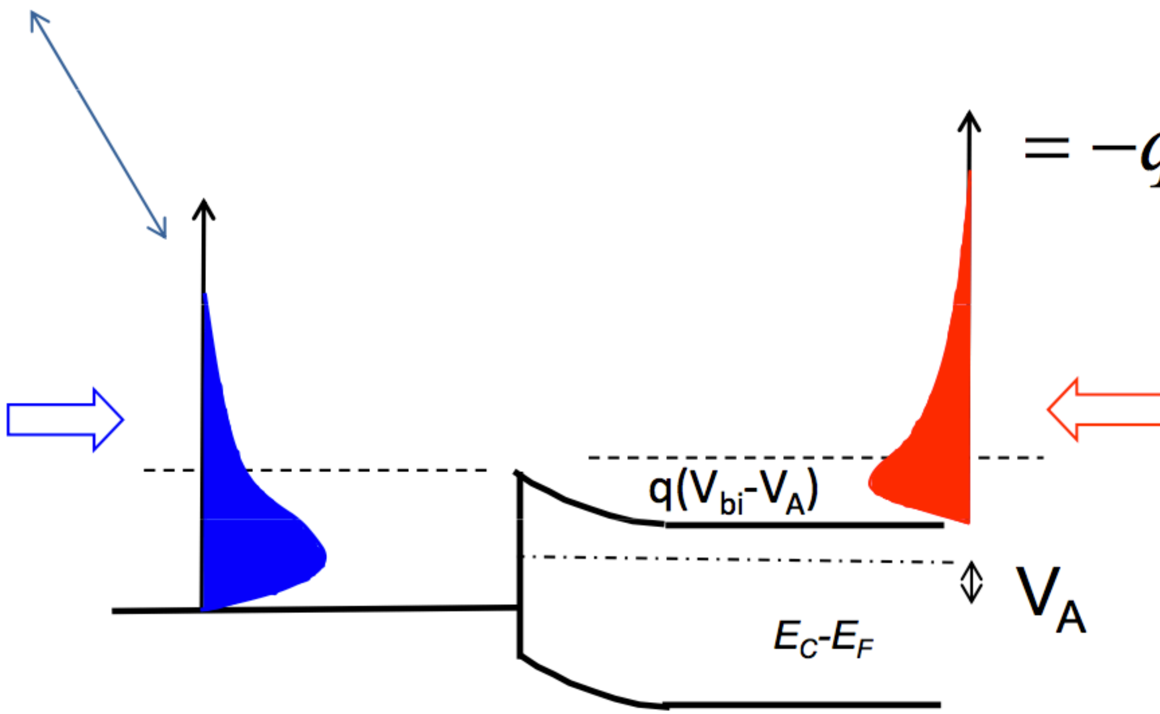
半导体到金属的电流

$$J_{m\to s}(V_A) = -q\frac{n_m}{2}e^{-\frac{q\Phi_B}{kT}}\upsilon_{th}$$

$$J_{s\to m}(V_A) = -q\frac{n_s}{2}e^{-q\frac{V_{bi}-V_A}{kT}}\upsilon_{th}$$

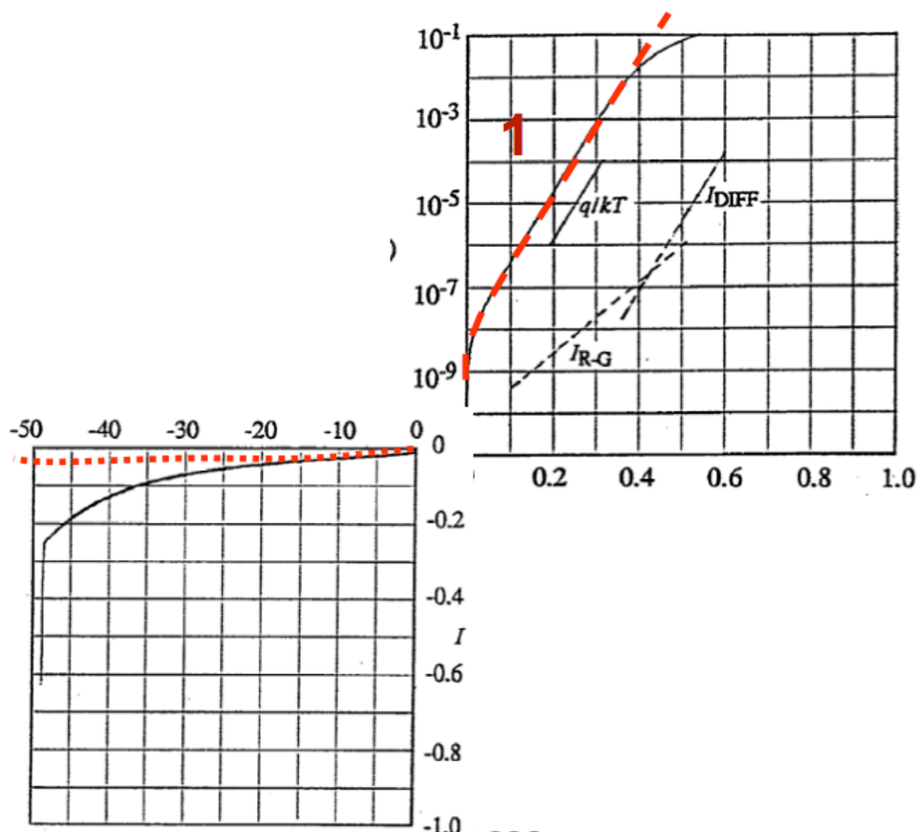
$$= -q\frac{n_s\upsilon_{th}}{2}e^{-\frac{qV_{bi}}{kT}}\times e^{\frac{qV_A}{kT}}$$

$$= -q\frac{n_m\upsilon_{th}}{2}e^{-\frac{q\Phi_B}{kT}}e^{\frac{qV_A}{kT}}$$

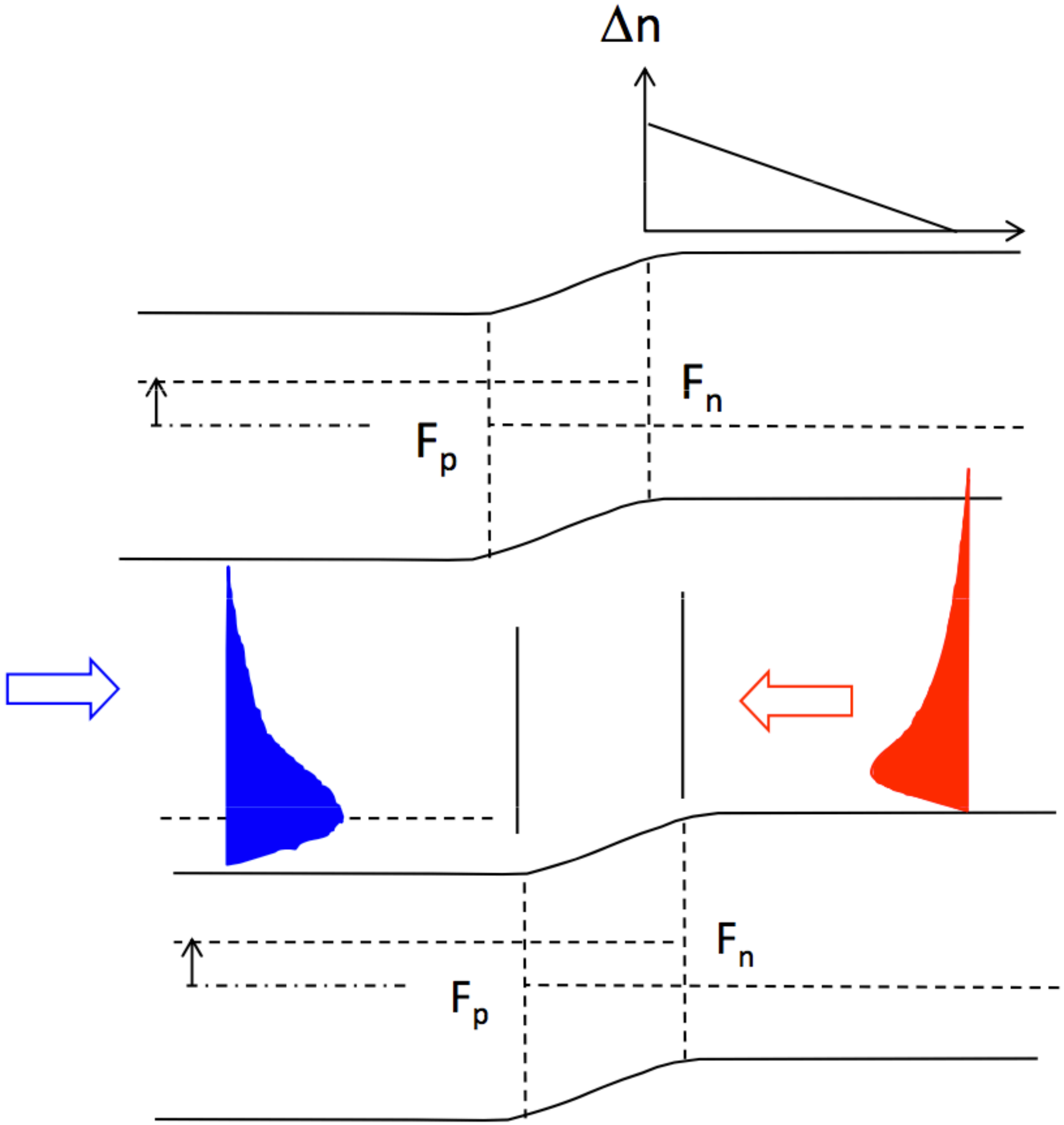


总电流

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

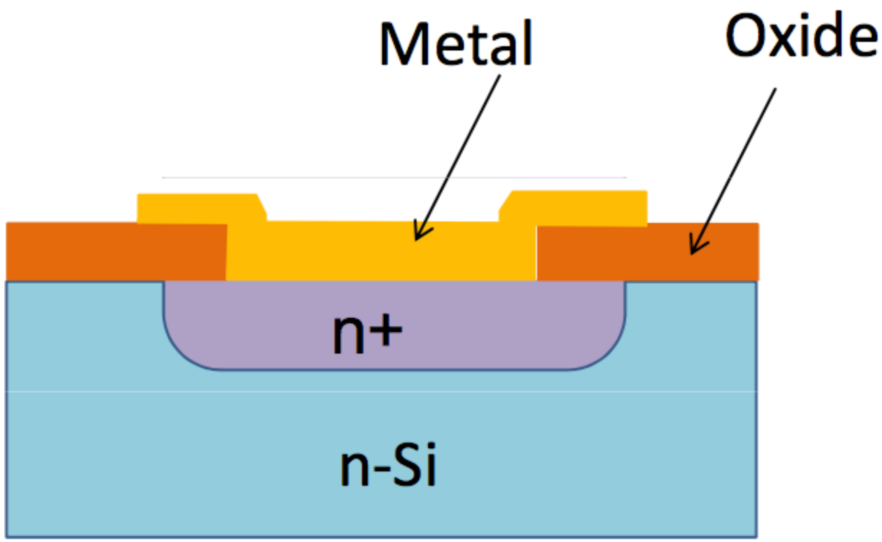


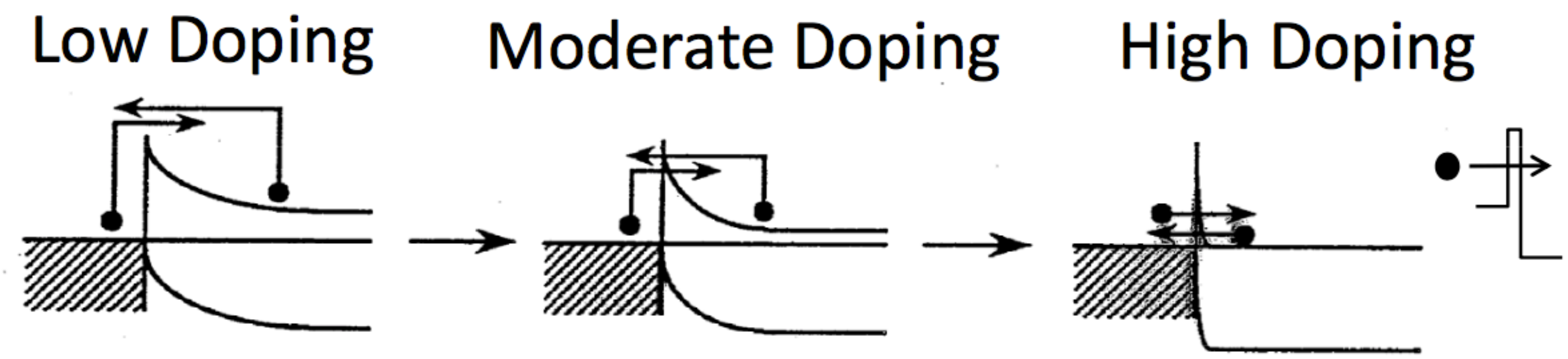
扩散电流 vs 热发射电流



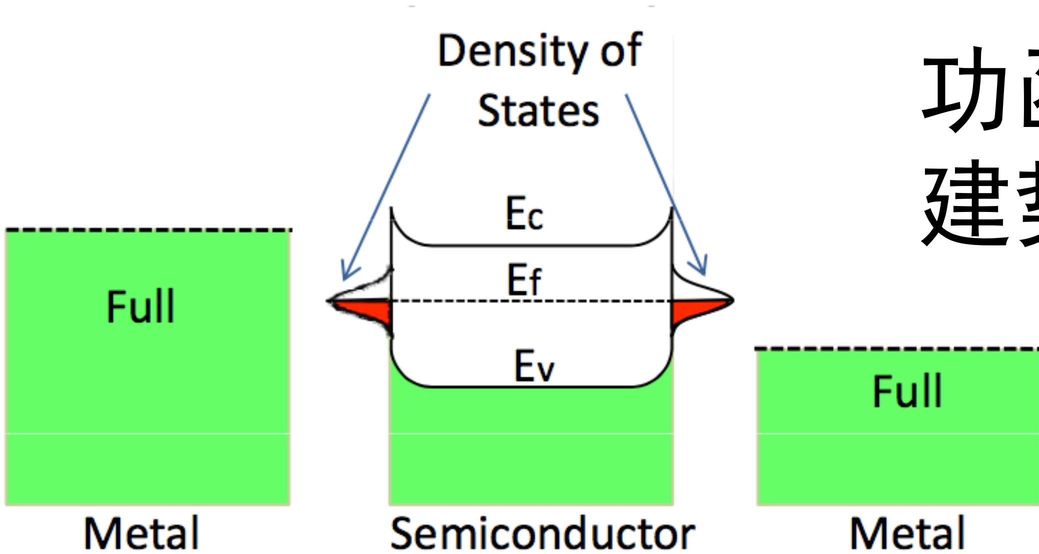
两者的电流特性非常相似

欧姆接触与肖特基接触

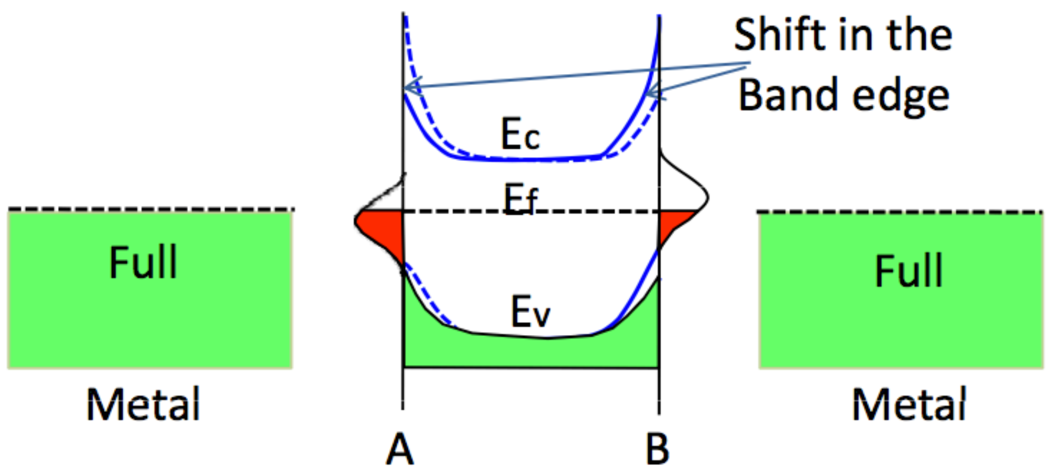




费米钉扎效应



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