半导体物理

主讲人：蒋玉龙

微电子学楼312室，65643768

Email: yljiang@fudan.edu.cn

http://10.14.3.121

第八章 p-n结

8.1 平衡p-n结特性

8.2 p-n结电流电压特性

8.3 p-n结电容

8.4 p-n结的击穿

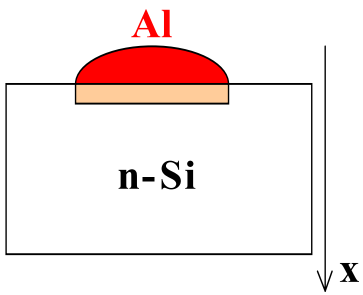
8.5 p-n结隧道效应

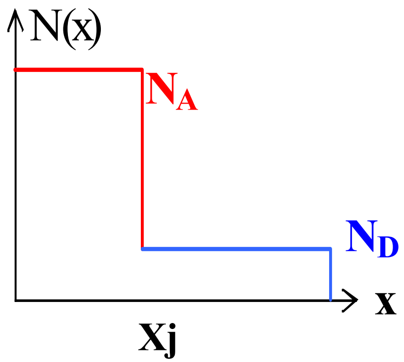
8.1 平衡p-n结特性1

8.1.1 p-n结的形成及杂质分布

P型	N型

一 合金法



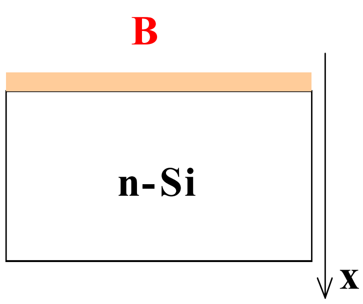


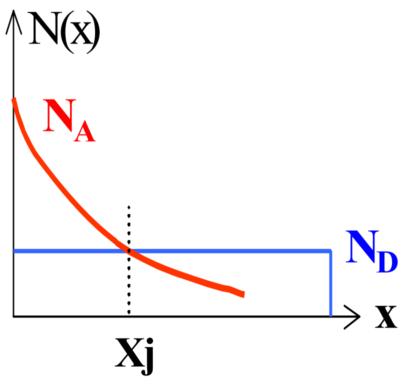
突变结

$N_A >> N_D$ $\boxed{p^+ - n}$

$N_D >> N_A$ $\boxed{n^+ - p}$

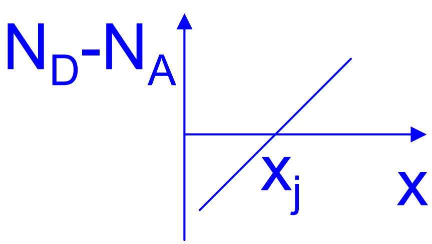
一 扩散法





$x < x_j$ $\quad$ $x > x_j$

$N_A > N_D$ $\quad$ $N_A < N_D$

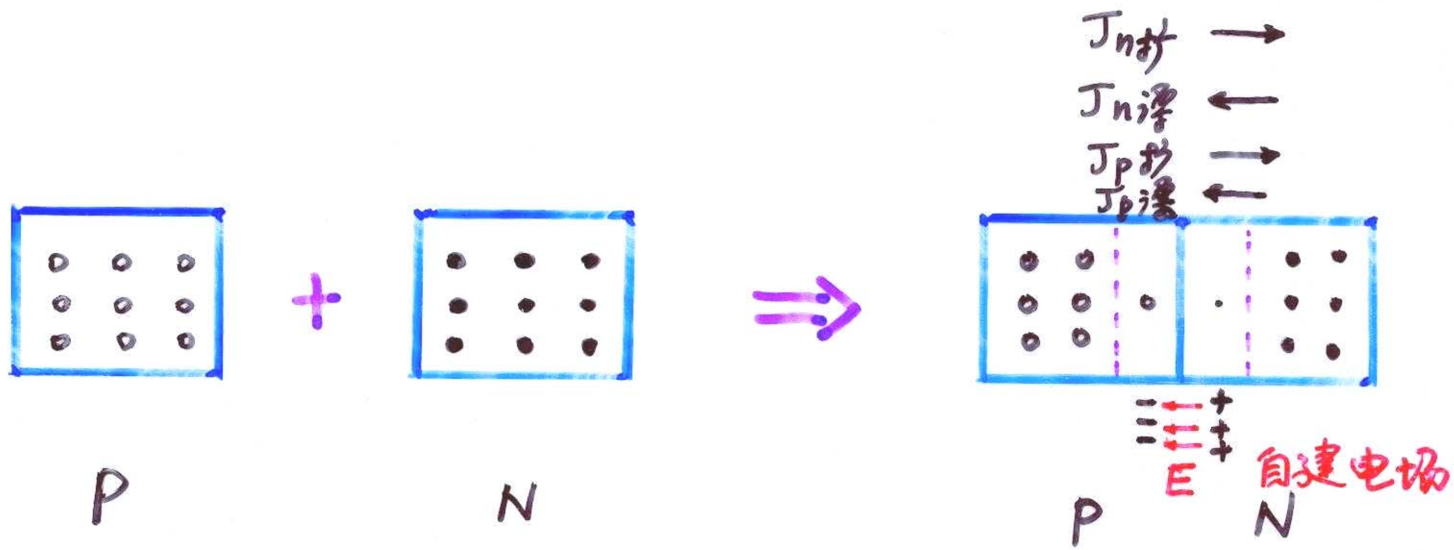


线性缓变结

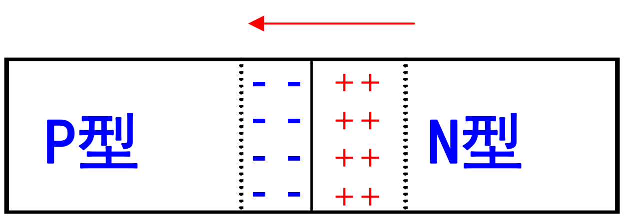
$$\boxed{N_D - N_A = \alpha_j (x - x_j)}$$

8.1 平衡p-n结特性2

8.1.2 空间电荷区



载流子浓度梯度 → 扩散 → 破坏电中性→ 自建电场 → 漂移电流 → 动态平衡→ 零净电流



$$J_n = J_{n,diff} + J_{n,dr} = 0$$

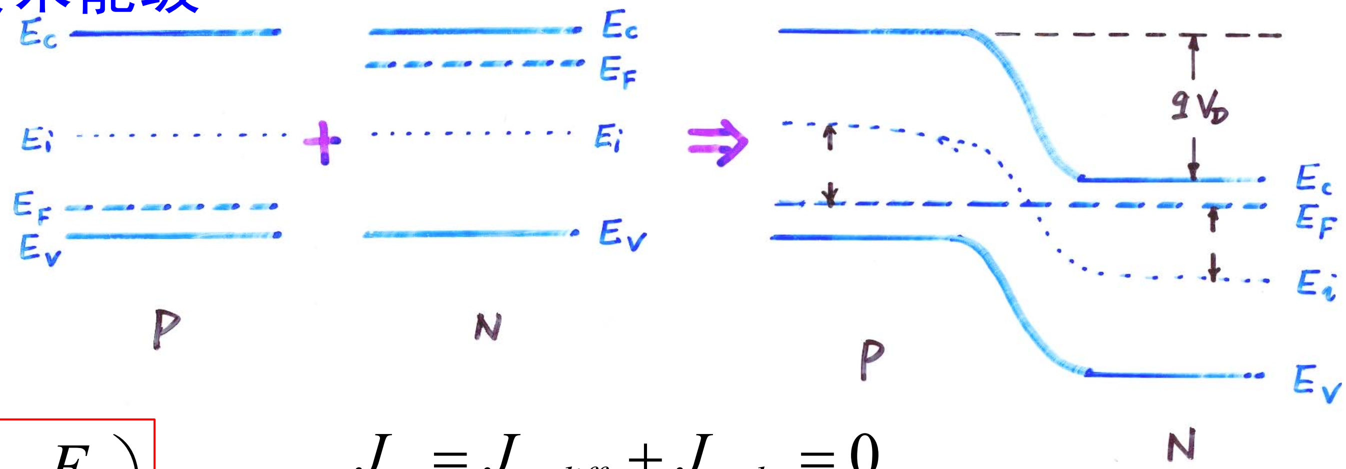
$$J_p = J_{p,diff} + J_{p,dr} = 0$$

by云墨一点

8.1 平衡p-n结特性3

8.1.3 平衡p-n结能带图

—平衡p-n结中费米能级



$$\boxed{n_0 = n_i \exp\left(\frac{E_F - E_i}{kT}\right)}$$

$$J_n = J_{n,diff} + J_{n,dr} = 0$$

$$J_n = q n_0 \mu_n E + q D_n \frac{dn_0}{dx}$$

$$\left.\begin{aligned} \frac{dn_0}{dx} &= -n_0 \frac{1}{kT}\frac{dE_i}{dx} + n_0 \frac{1}{kT}\frac{dE_F}{dx} \\ \frac{dE_i}{dx} &= -q\frac{dV(x)}{dx} = qE \end{aligned}\right\} \Rightarrow \frac{dn_0}{dx} = -n_0 \frac{qE}{kT} + n_0 \frac{1}{kT}\frac{dE_F}{dx}$$

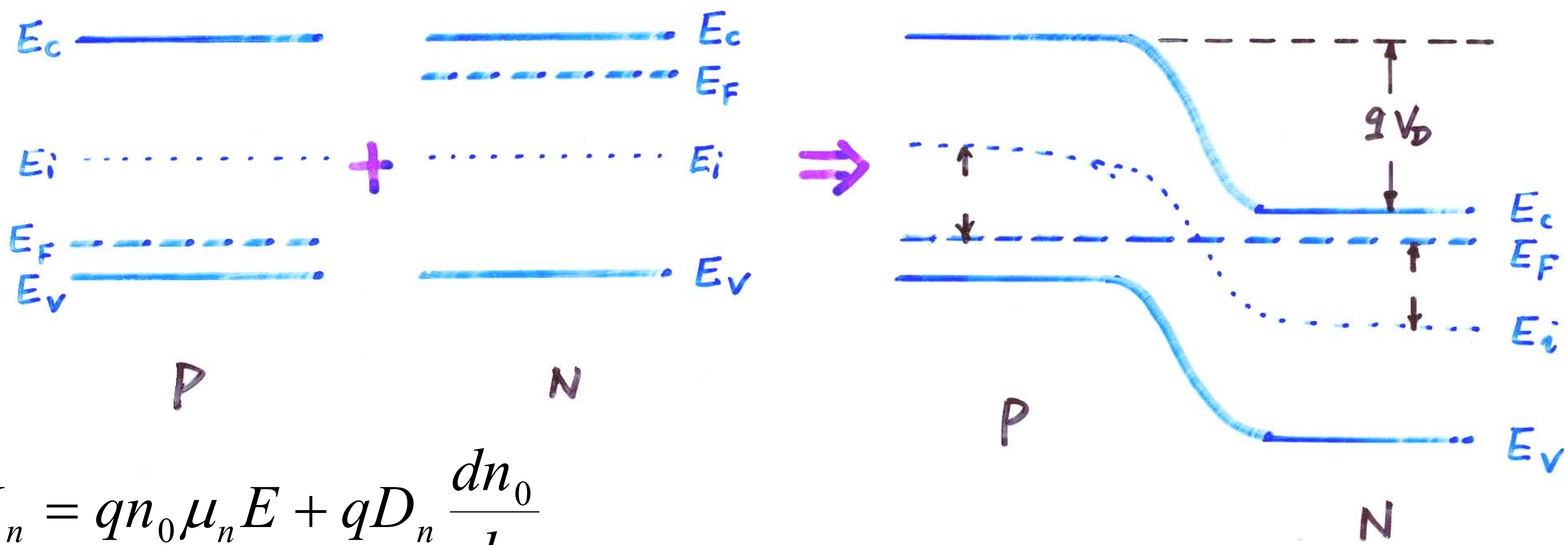
电场

by云墨一点

8.1 平衡p-n结特性4

8.1.3 平衡p-n结能带图

一平衡p-n结中费米能级



$$J_n = qn_0\mu_n E + qD_n \frac{dn_0}{dx}$$

$$\frac{dn_0}{dx} = -n_0 \frac{qE}{kT} + n_0 \frac{1}{kT}\frac{dE_F}{dx}$$

$$J_n = \cancel{qn_0\mu_n E} - \cancel{qD_n n_0 \frac{qE}{kT}} + n_0 \frac{qD_n}{kT}\frac{dE_F}{dx} = 0 \longrightarrow \boxed{\frac{dE_F}{dx} = 0}$$

by云墨一点

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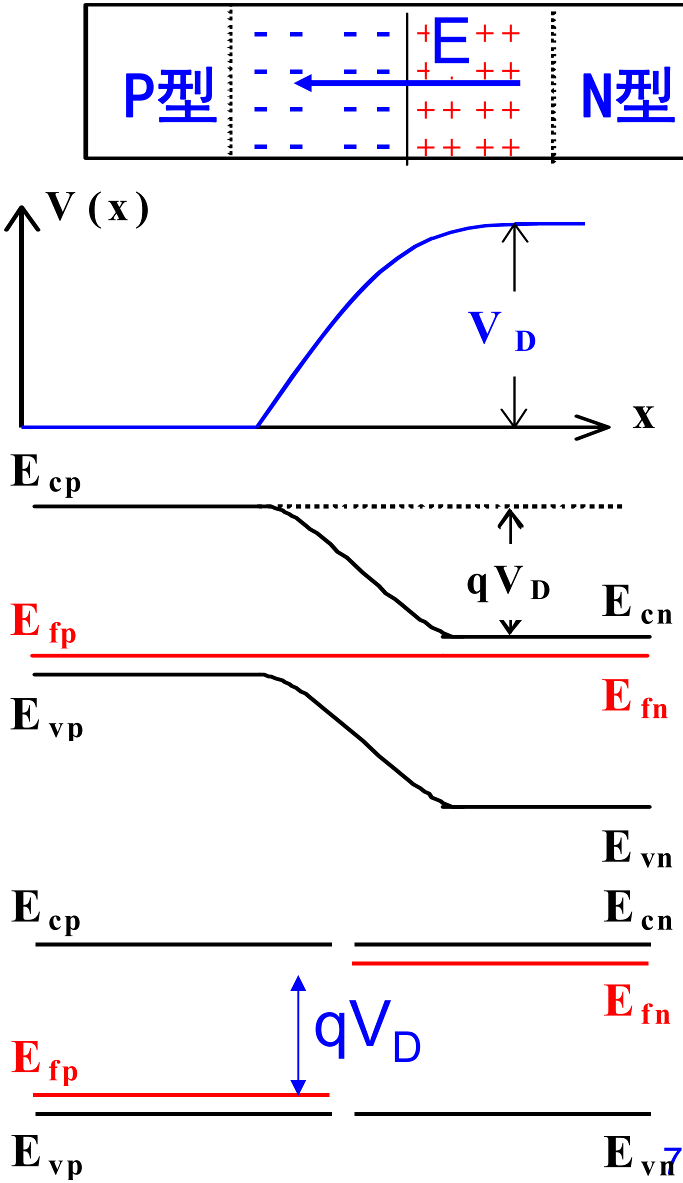
8.1.4 p-n结接触电势差

$$\boxed{qV_D = E_{F(n)} - E_{F(p)}}$$

$$\begin{cases} E_{F(n)} = E_i + kT\ln\left(N_D/n_i\right) \\ E_{F(p)} = E_i - kT\ln\left(N_A/n_i\right) \end{cases}$$

$$\boxed{V_D = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)}$$



例子：$N_A = 10^{17}\ \mathrm{cm^{-3}}$，$N_D = 10^{15}\ \mathrm{cm^{-3}}$

Si $V_D \approx 0.7$ V

Ge $V_D \approx 0.3$ V

8.1 平衡p-n结特性6

8.1.5 p-n结的载流子分布

$$n(x)=N_C\exp\left(-\frac{E_C(x)-E_f}{kT}\right)$$

$$+E_{cn}-E_{cn}$$

$$n(x)=n_{n0}\exp\left(-\frac{E_c(x)-E_{cn}}{kT}\right)$$

$$E_c(x)-E_{cn}=qV_D-qV(x)$$

$$n(-x_p)=n_{n0}\exp\left(-\frac{E_{cp}-E_{cn}}{kT}\right)=n_{n0}\exp\left(-\frac{qV_D}{kT}\right)=n_{p0}$$

$$\boxed{n(x)=n_{p0}\exp\left[\frac{qV(x)}{kT}\right]}$$

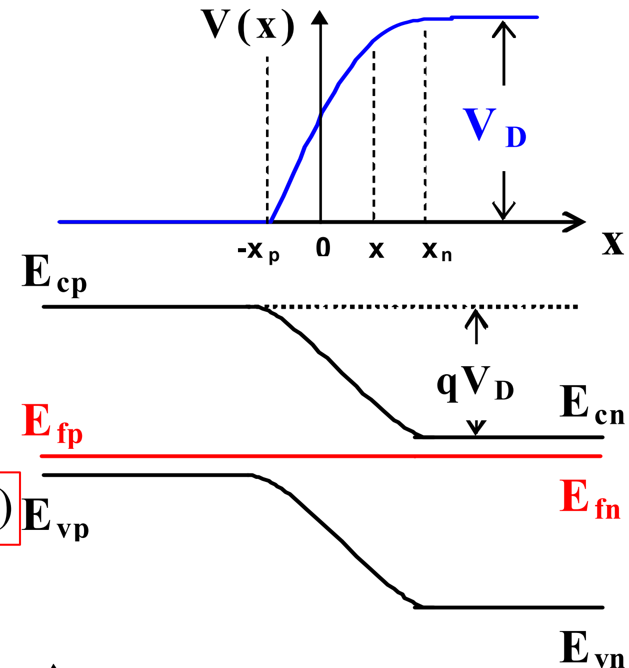
$$E_{Vp}-E_V(x)=qV(x)$$

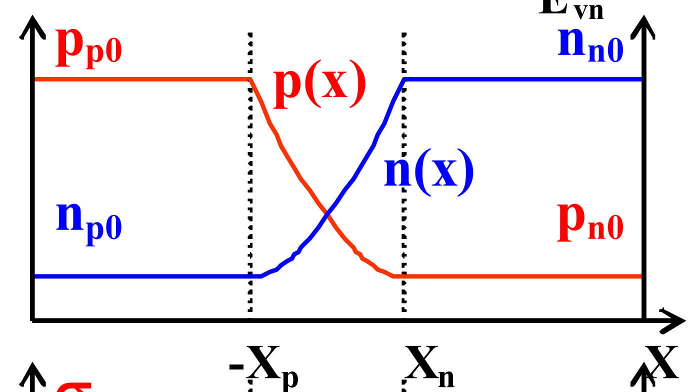
$$p(x)=N_V\exp\left(-\frac{E_f-E_V(x)}{kT}\right)=p_{p0}\exp\left(-\frac{E_{Vp}-E_V(x)}{kT}\right)$$

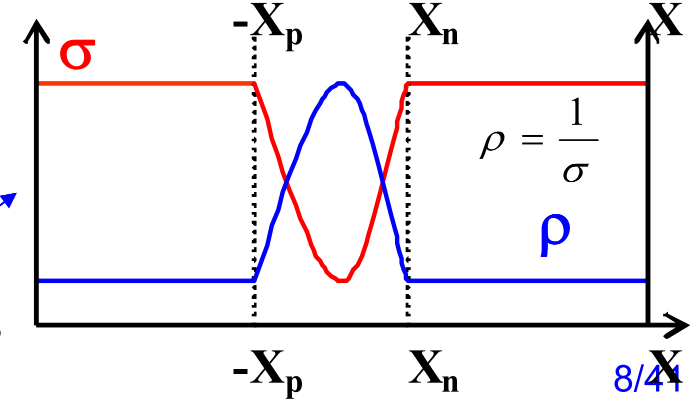
$$p(x_n)=p_{p0}\exp\left(-\frac{E_{vp}-E_{vn}}{kT}\right)=p_{p0}\exp\left(-\frac{qV_D}{kT}\right)=p_{n0}$$

$$\boxed{p(x)=p_{p0}\exp\left[-\frac{qV(x)}{kT}\right]}$$

$$\sigma=qn\mu_n+qp\mu_p$$



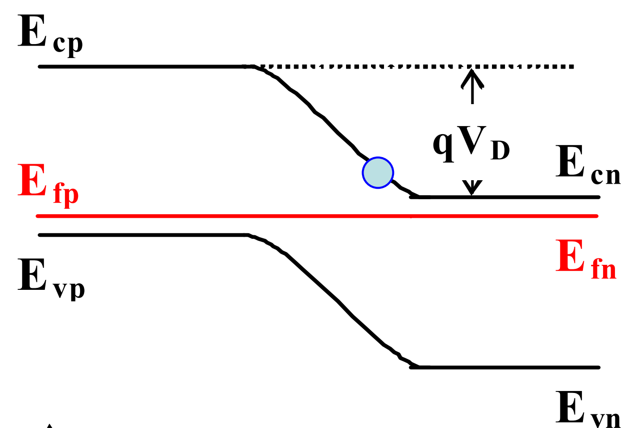




8.1 平衡p-n结特性7

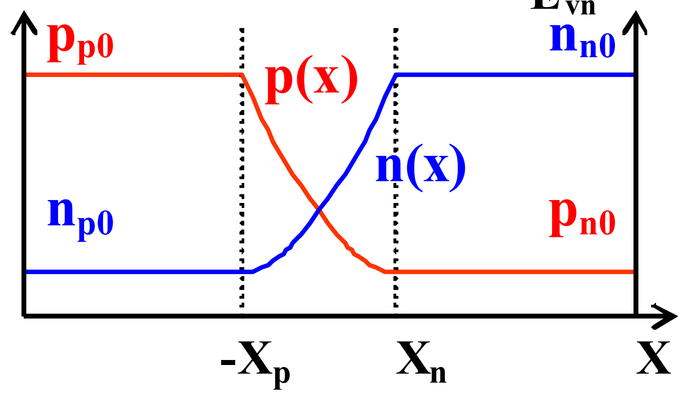
8.1.5 p-n结的载流子分布

—势垒区中的载流子浓度估算



$$\boxed{n(x) = n_{p0} \exp\left[\frac{qV(x)}{kT}\right] = n_{n0} \exp\left[\frac{qV(x) - qV_D}{kT}\right]}$$

$$\boxed{p(x) = p_{p0} \exp\left[-\frac{qV(x)}{kT}\right]}$$



若位置x满足 $E_c(x) = E_{cn} + 0.1eV \longrightarrow$

$$V(x) = V_D - 0.1eV$$

$T = 300K$

$V_D = 0.7eV$

$$\longrightarrow n(x) = n_{n0} \exp\left[-\frac{0.1}{0.026}\right] \approx \frac{N_D}{50} \quad p(x) = p_{p0} \exp\left[-\frac{0.6}{0.026}\right] \approx 10^{-10} N_A$$

耗尽层近似：势垒区中载流子浓度可以忽略，
空间电荷密度就等于电离杂质浓度