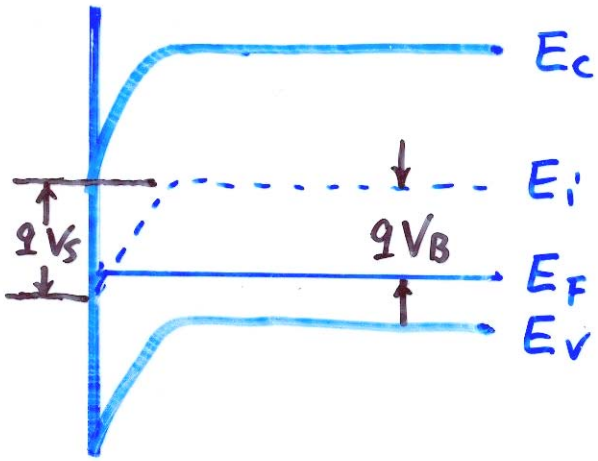
10.2 表面电场效应2

10.2.1 空间电荷层

表面势Vs—空间电荷层两端的电势差，表面比内部高为正

$$E_c(x) = E_{c0} - qV(x)$$

$$V_s = -\frac{E_{is} - E_{ib}}{q}$$

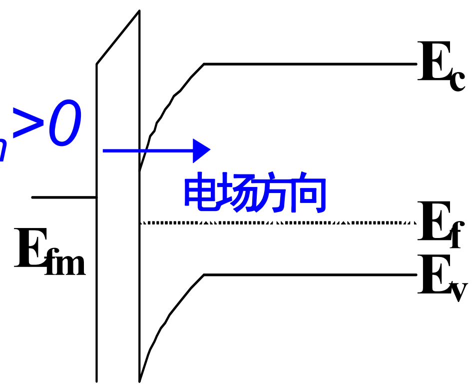


Q_m	V_s	Q_s	能带弯曲
+	+	−	↓
−	−	+	↑

助记例子：

Q_m	V_s	Q_s	能带弯曲
+	+	−	↓

$Q_m>0$



电力线从正电荷出发终止于负电荷，电势沿电力线方向减小

10.2 表面电场效应3

10.2.2 空间电荷层中的泊松方程

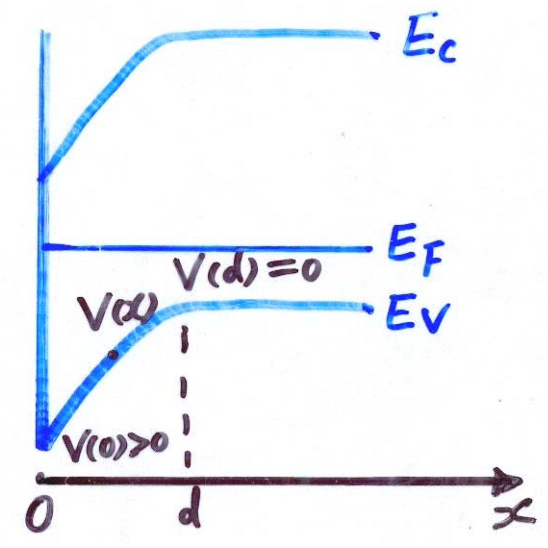
假设 1° 半导体表面是个无限大的面，其线度>>空间电荷层厚度→一维近似，（ρ, E, V）不依赖 y, z

2° 半导体厚度 >> 空间电荷层厚度→半导体体内电中性

3° 半导体均匀掺杂

4° 非简并统计适用于空间电荷层

5° 不考虑量子效应

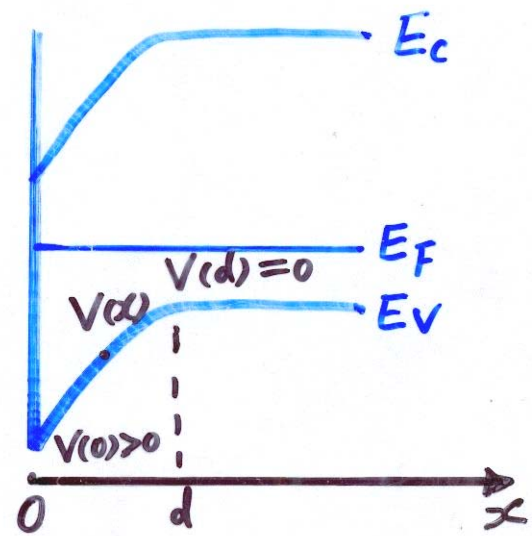


10.2 表面电场效应3

10.2.2 空间电荷层中的泊松方程

例子：一维p型半导体

$$\boxed{\frac{d^2V(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon_s}}$$ 泊松方程



$$\rho(x) = q\left(N_D^+ - N_A^- + p_p - n_p\right)$$

$$\left.\begin{aligned} n_p &= n_{p0}\exp(qV/kT) \\ p_p &= p_{p0}\exp(-qV/kT) \end{aligned}\right\}$$ 玻尔兹曼统计

已知 $x \to +\infty$ 时 $\rho(x) = 0 \longrightarrow N_D^+ - N_A^- = n_{p0} - p_{p0}$

$$\boxed{\frac{d^2V(x)}{dx^2} = \frac{dV}{dx}\cdot\frac{d\left(\frac{dV}{dx}\right)}{dV} = -\frac{q}{\varepsilon_s}\left\{p_{p0}\left[\exp(-qV/kT)-1\right] - n_{p0}\left[\exp(qV/kT)-1\right]\right\}}$$

10.2 表面电场效应4

10.2.2 空间电荷层中的泊松方程

例子：一维p型半导体

$$\frac{d^2V(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon_s}$$

$$\frac{d^2V(x)}{dx^2} = \frac{dV}{dx}\cdot\frac{d\left(\frac{dV}{dx}\right)}{dV} = -\frac{q}{\varepsilon_s}\left\{p_{p0}\left[\exp(-qV/kT)-1\right]-n_{p0}\left[\exp(qV/kT)-1\right]\right\}$$

两边乘以dV

$$\frac{dV}{dx}d\left(\frac{dV}{dx}\right) = -\frac{q}{\varepsilon_s}\left\{p_{p0}\left[\exp(-qV/kT)-1\right]-n_{p0}\left[\exp(qV/kT)-1\right]\right\}dV$$

从空间电荷层内边界积分到表面

$$\int_0^{\frac{dv}{dx}}\frac{dV}{dx}d\left(\frac{dV}{dx}\right) = \int_0^V\left(-\frac{q}{\varepsilon_s}\right)\left\{p_{p0}\left[\exp(-qV/kT)-1\right]-n_{p0}\left[\exp(qV/kT)-1\right]\right\}dV$$

$$E = -\frac{dV(x)}{dx}$$

$$\boxed{E^2(x) = \left(\frac{2kT}{q}\right)^2\left(\frac{q^2p_{p0}}{2\varepsilon_s kT}\right)\left\{\left[\exp\left(-\frac{qV}{kT}\right)+\frac{qV}{kT}-1\right]+\frac{n_{p0}}{p_{p0}}\left[\exp\left(\frac{qV}{kT}\right)-\frac{qV}{kT}-1\right]\right\}}$$

10.2 表面电场效应5

10.2.2 空间电荷层中的泊松方程

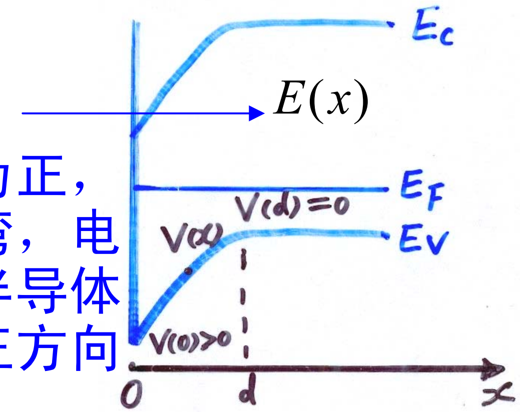
例子：一维p型半导体

$$E^2(x)=\left(\frac{2kT}{q}\right)^2\left(\frac{q^2p_{p0}}{2\varepsilon_s kT}\right)\left\{\left[\exp\left(-\frac{qV}{kT}\right)+\frac{qV}{kT}-1\right]+\frac{n_{p0}}{p_{p0}}\left[\exp\left(\frac{qV}{kT}\right)-\frac{qV}{kT}-1\right]\right\}$$

$$\boxed{E(x)=\pm\frac{2kT}{qL_D}F\left(\frac{qV(x)}{kT},\frac{n_{p0}}{p_{p0}}\right)}$$

"+" : $V>0$

"—" : $V<0$



表面势为正，能带下弯，电场指向半导体内部为正方向

$$L_D=\left(\frac{2\varepsilon_s kT}{q^2p_{p0}}\right)^{1/2}$$

德拜长度

(p型半导体)

$$F\left(\frac{qV}{kT},\frac{n_{p0}}{p_{p0}}\right)=\left\{\left[\exp\left(-\frac{qV}{kT}\right)+\frac{qV}{kT}-1\right]+\frac{n_{p0}}{p_{p0}}\left[\exp\left(\frac{qV}{kT}\right)-\frac{qV}{kT}-1\right]\right\}^{1/2}$$

F 函数， 无量纲数

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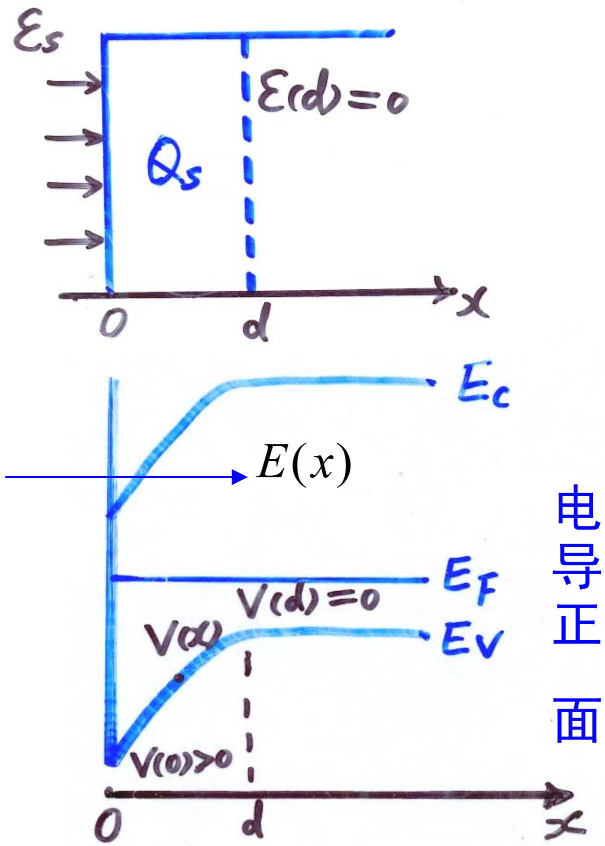
10.2.3 半导体表面电场、电势和电容



$$E(x)=\pm\frac{2kT}{qL_D}F\left(\frac{qV(x)}{kT},\frac{n_{p0}}{p_{p0}}\right)$$

$x = 0 \quad V(0) = V_s$

$$\boxed{E_s=\pm\frac{2kT}{qL_D}F\left(\frac{qV_s}{kT},\frac{n_{p0}}{p_{p0}}\right)}$$

电场指向半导体内部为正方向

面电荷密度 $Q_s=-\varepsilon_s E_s=\mp\frac{2\varepsilon_s kT}{qL_D}F\left(\frac{qV_s}{kT},\frac{n_{p0}}{p_{p0}}\right)$

$$C_s=\left|\frac{dQ_s}{dV_s}\right|=\frac{\varepsilon_s}{L_D}\left\{\left[-\exp\left(-\frac{qV_s}{kT}\right)+1\right]+\frac{n_{p0}}{p_{p0}}\left[\exp\left(\frac{qV_s}{kT}\right)-1\right]\right\}\Big/ F\left(\frac{qV_s}{kT},\frac{n_{p0}}{p_{p0}}\right)$$

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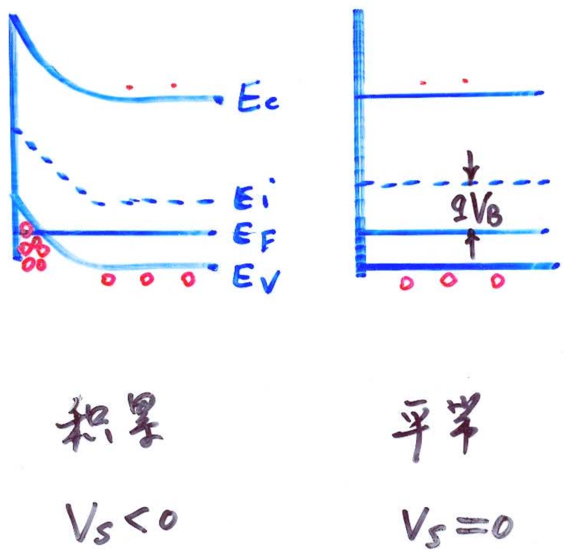
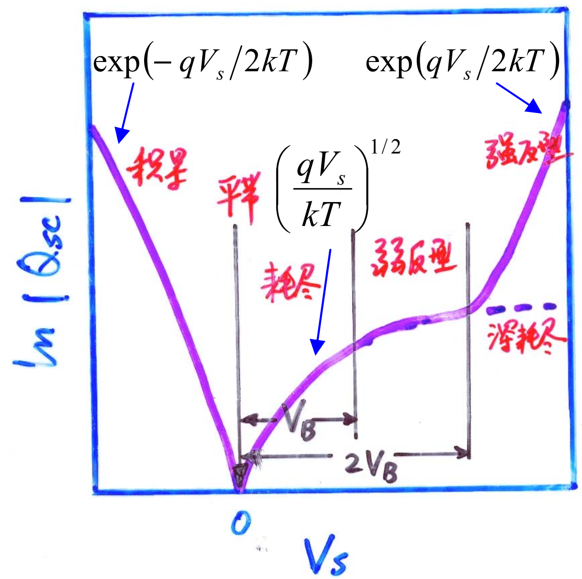
10.2.4 半导体表面层的五种基本状态

1° 多子堆积（积累）状态 $Q_s \propto \exp\left(-qV_s/2kT\right)$ Vs<0

2° 平带状态 $$C_{FBS} = \lim_{V_s \to 0} \frac{dQ_s}{dV_s} = \frac{\sqrt{2}\varepsilon_s}{L_D}\left(1+\frac{n_{p0}}{p_{p0}}\right)^{1/2} \approx \frac{\sqrt{2}\varepsilon_s}{L_D}$$ Vs=0

$$\boxed{Q_s \propto E_s \propto F\left(V_s\right)} = \left\{\left[\exp\left(-\frac{qV_s}{kT}\right)+\frac{qV_s}{kT}-1\right]+\frac{n_{p0}}{p_{p0}}\left[\exp\left(\frac{qV_s}{kT}\right)-\frac{qV_s}{kT}-1\right]\right\}^{1/2}$$





10.2 表面电场效应8

10.2.4 半导体表面层的五种基本状态

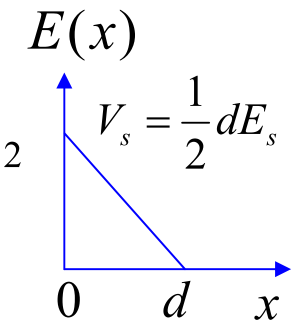
3° 耗尽状态 $V_B > V_s > 0$

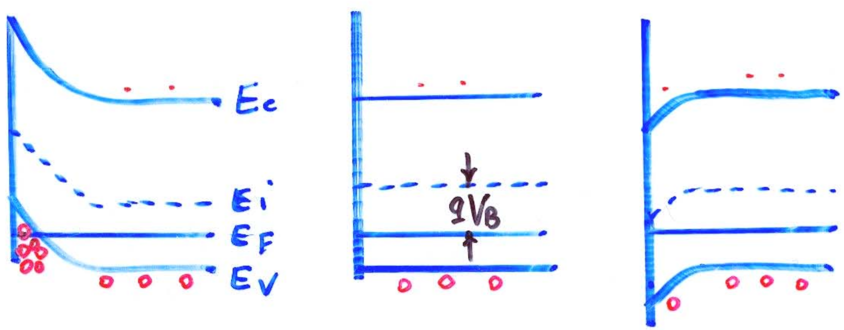
$$F\left(\frac{qV_s}{kT},\frac{n_{p0}}{p_{p0}}\right)=\left(\frac{qV_s}{kT}\right)^{1/2}\quad Q_s=-\frac{2\varepsilon_s kT}{qL_D}\left(\frac{qV_s}{kT}\right)^{1/2}\quad L_D=\left(\frac{2\varepsilon_s kT}{q^2 p_{p0}}\right)^{1/2}$$

另一种求解面电荷密度的途径—“耗尽层近似”

$$Q_s=-qN_A d \longrightarrow E_s=\left|\frac{qN_A d}{\varepsilon_s}\right|$$

$$Q_s=-qN_A\left(\frac{2\varepsilon_s}{q}\frac{V_s}{N_A}\right)^{1/2}=-\left(2\varepsilon_s qN_A V_s\right)^{1/2}\longleftarrow d=\left(\frac{2\varepsilon_s}{q}\frac{V_s}{N_A}\right)^{1/2}$$





积累 $V_s<0$　平带 $V_s=0$　耗尽 $V_s\in(0,V_B)$