

第十章 半导体表面与MIS结构

10.1 表面态概念

10.2 表面电场效应

10.3 Si-SiO₂系统的性质

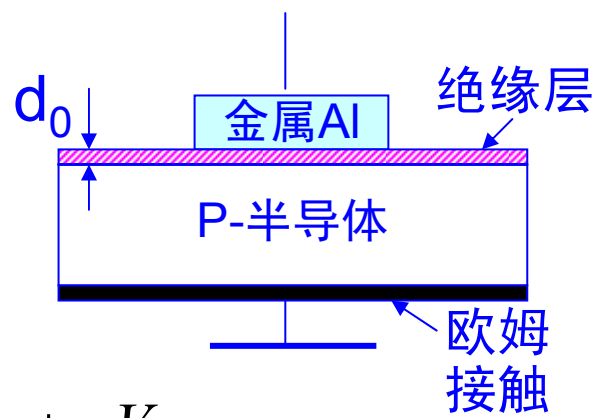
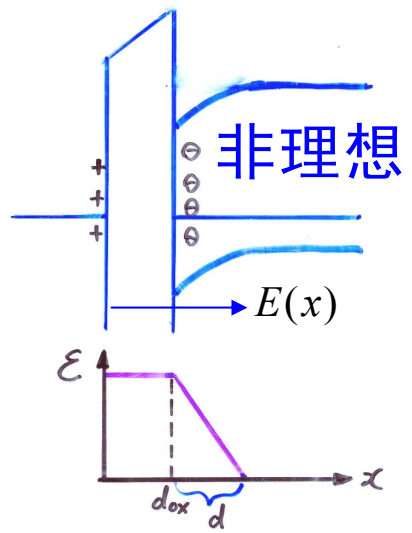
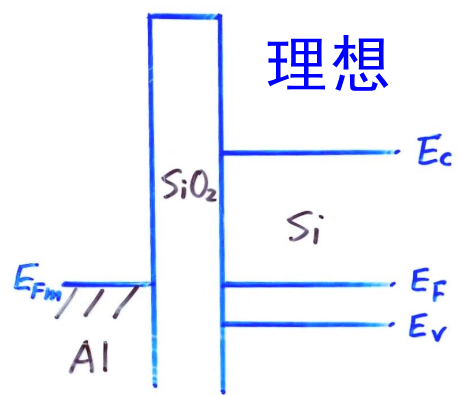
10.4 MIS结构的C-V特性

10.5 表面电导及迁移率

10.4 MIS结构的C-V特性₁

10.4.1 MIS电容结构的能带图

1. 无外加电压

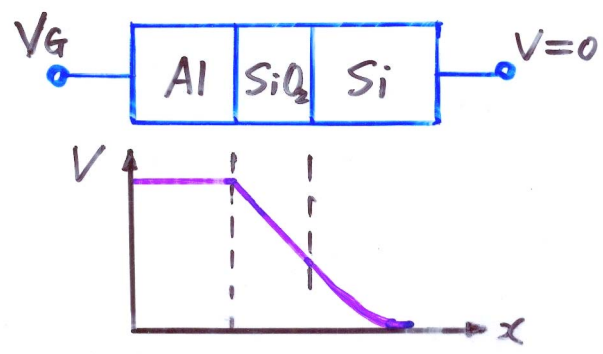


$$qV_{ms} = qV_{ox} + qV_s$$

$W_s - W_m$ 接触电势差

表面势

2. 有外加电压



$$V_G = V_{ox,ext} + V_{s,ext}$$

体现外加场影响

10.4 MIS结构的C-V特性₂

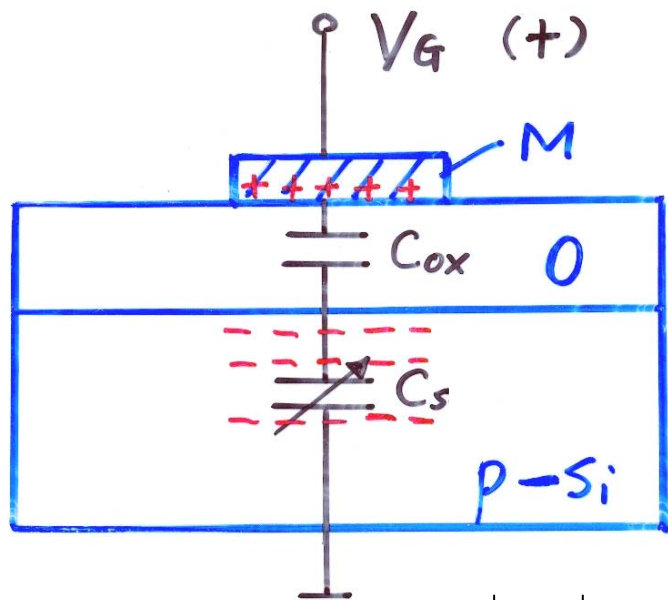
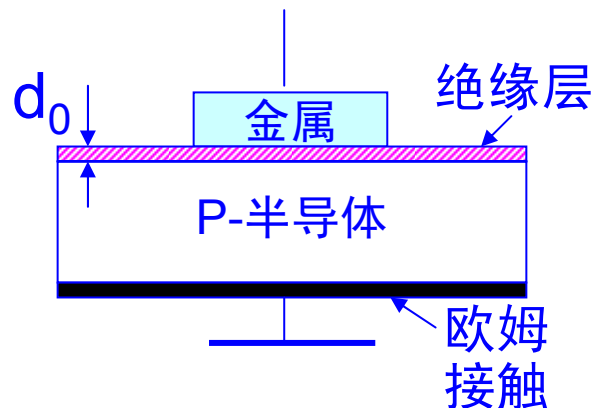
10.4.2 理想MIS电容的C-V特性

氧化层完全绝缘

氧化层中不存在任何电荷

在氧化层与半导体界面上无界面态

忽略金属与半导体的接触电势差



$$V_G = V_{ox} + V_s \quad Q_m = -Q_s = Q$$

$$C = \frac{dQ}{dV_G} \rightarrow \frac{1}{C} = \frac{dV_G}{dQ} = \left| \frac{dV_{ox}}{dQ_m} \right| + \left| \frac{dV_s}{dQ_s} \right| = \frac{1}{C_{ox}} + \frac{1}{C_s}$$

$$C_{ox} = \frac{\epsilon_{ox}}{d_{ox}}$$

$$C_s = f(V_s)$$

随 V_G 变化

$$\epsilon_r(\text{SiO}_2) = 3.9$$

$$\epsilon_r(\text{Si}) = 11.9$$

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

10.4 MIS结构的C-V特性₃

10.4.2 理想MIS电容的C-V特性

低频情况(10~100 Hz)

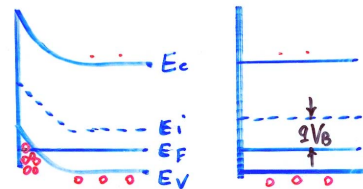
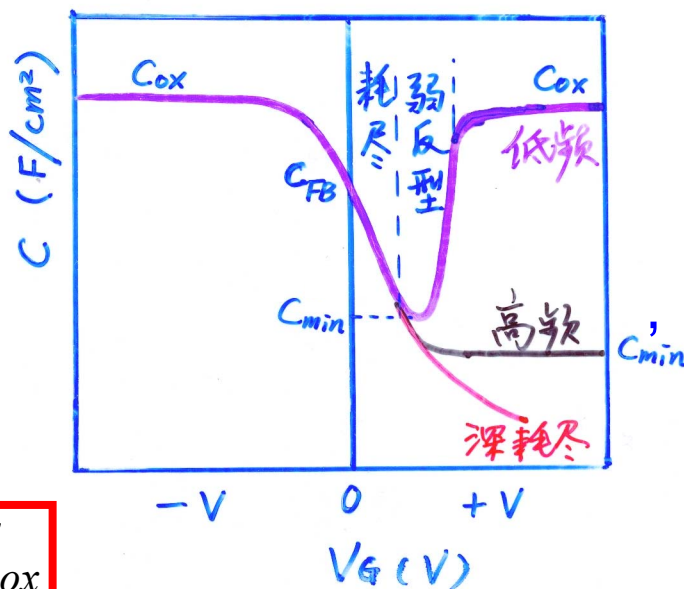
$$\frac{1}{C} = \frac{1}{C_{ox}} + \frac{1}{C_s} \quad C_{ox} = \frac{\epsilon_{ox}}{d_{ox}} \quad C_s = f(V_s)$$

1° $V_G < 0$, 积累, $Q_s \propto \exp(q|V_s|/2kT)$

$$C_s = \frac{dQ_s}{dV_s} \propto \exp(q|V_s|/2kT) \gg C_{ox} \rightarrow C \approx C_{ox}$$

2° $V_G = 0$, 平带, $C_{FBS} = \lim_{V_s \rightarrow 0} \frac{dQ_s}{dV_s} = \frac{\sqrt{2}\epsilon_s}{L_D} \left(1 + \frac{n_{p0}}{p_{p0}} \right)^{1/2} \approx \frac{\sqrt{2}\epsilon_s}{L_D}$

$$C_{FB} = C_{ox} / \left(1 + \frac{\epsilon_{ox}}{d_{ox}} \left(\frac{kT}{q^2 N_A \epsilon_s} \right)^{1/2} \right)$$



积累

$V_s < 0$

平带

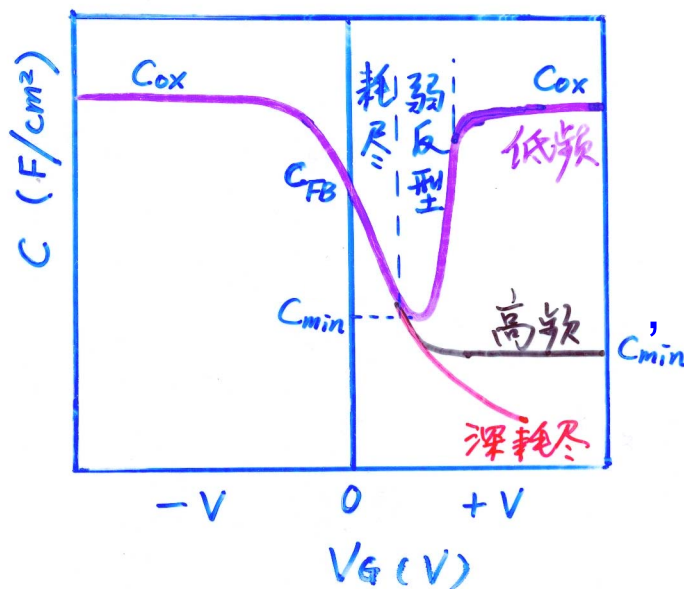
$V_s = 0$

10.4 MIS结构的C-V特性₃

10.4.2 理想MIS电容的C-V特性

低频情况(10~100 Hz)

$$\frac{1}{C} = \frac{1}{C_{ox}} + \frac{1}{C_s} \quad C_{ox} = \frac{\epsilon_{ox}}{d_{ox}} \quad C_s = f(V_s)$$



3° $V_G > 0$, 耗尽, $V_G \uparrow \quad d \uparrow \quad C_s \downarrow \quad C \downarrow$
平行板电容器等效

4° $V_G > 0$, 弱反型, $V_G \uparrow \quad d \uparrow \quad Q_s : \text{从 } V_s^{1/2} \rightarrow \exp(qV_s/2kT)$

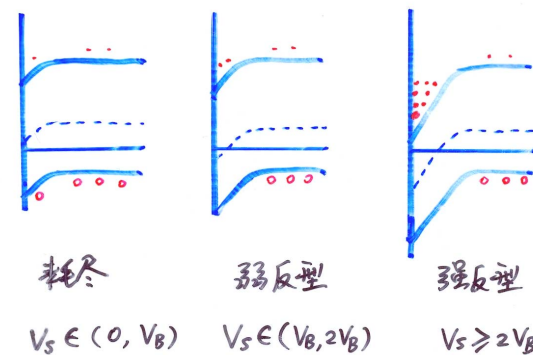
$$C_s = \frac{dQ_s}{dV_s} : \text{从 } V_s^{-1/2} \rightarrow \exp(qV_s/2kT)$$

$C \sim \downarrow \rightarrow \uparrow$

5° $V_G > 0$, 强反型, $Q_s \propto \exp(qV_s/2kT)$

$$C_s \gg C_{ox} \quad C \approx C_{ox}$$

$V_s = 2V_B \rightarrow V_G = V_T$ 阈值电压 (开启电压)



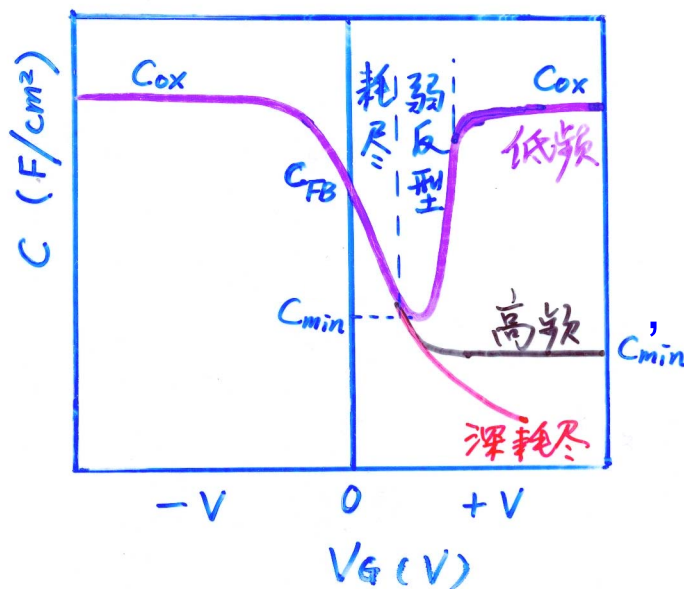
10.4 MIS结构的C-V特性⁴

10.4.2 理想MIS电容的C-V特性

高频情况($10^4 \sim 10^6$ Hz)

一反型层中电子的产生与复合跟不上高频信号的变化，即反型层中电子的数量不能随高频信号而变。此时，反型层中的电子对电容没有贡献。

— Q_s 的变化只能靠耗尽层的电荷变化实现，强反型时耗尽层已达最大厚度。



$$C_s = C_{s(d_{\max})} = \frac{\epsilon_s}{d_{\max}}$$

$$d_{\max} = \left(\frac{2\epsilon_s}{q} \frac{2V_B}{N_A} \right)^{1/2}$$

$$\frac{1}{C'_{\min}} = \frac{1}{C_{ox}} + \frac{1}{C_{s(d_{\max})}}$$

$$\frac{C'_{\min}}{C_{ox}} = \frac{1}{1 + \frac{\epsilon_{ox}}{\epsilon_s} \left[\frac{4\epsilon_s kT}{q^2 N_A} \ln \left(\frac{N_A}{n_i} \right) \right]^{1/2} d_{ox}}$$

10.4 MIS结构的C-V特性⁵

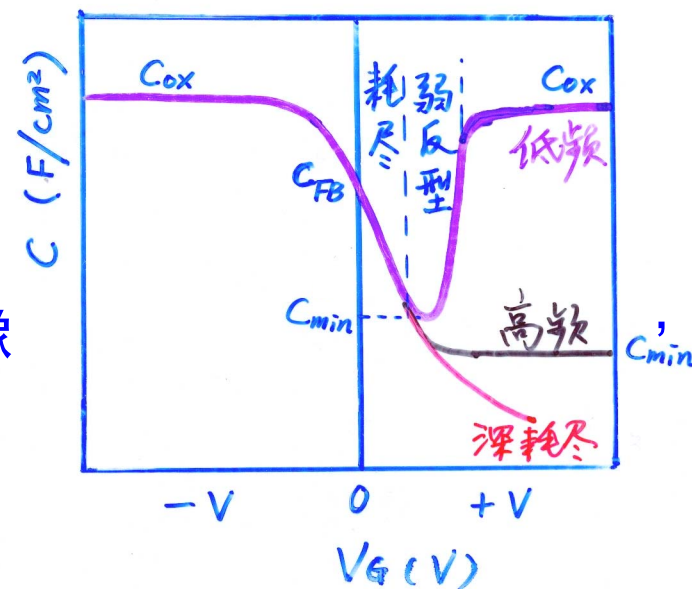
10.4.2 理想MIS电容的C-V特性

深耗尽情况(快速C-V扫描)

从深耗尽到热平衡反型层态所需的热驰豫时间 τ_{th} 为 $10^0 \sim 10^2 s$!

反型层的建立不是一个很快的过程!

快速直流偏压扫描导致反型层不能建立, “耗尽层近似”依然适用, $d > d_{max}$ $C_s \propto V_s^{-1/2} \rightarrow C \downarrow$



10.4 MIS结构的C-V特性₆

10.4.3 实际MIS电容的C-V特性

1. 金半接触电势差的影响

C-V曲线会平移，但形状不变

$$qV_{ms} = W_s - W_m$$

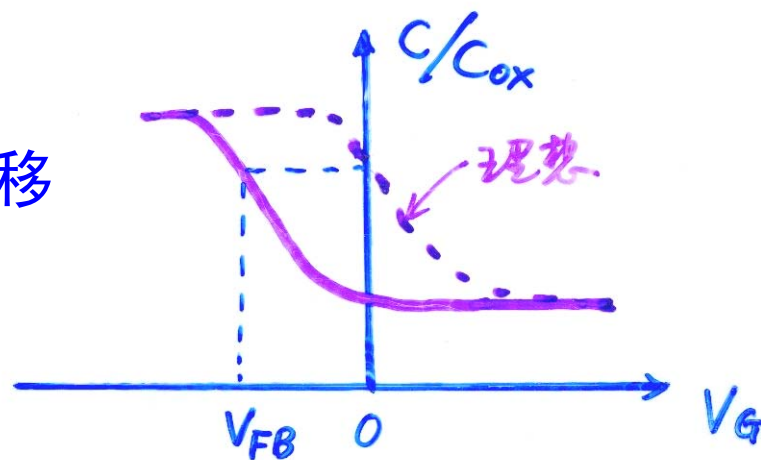
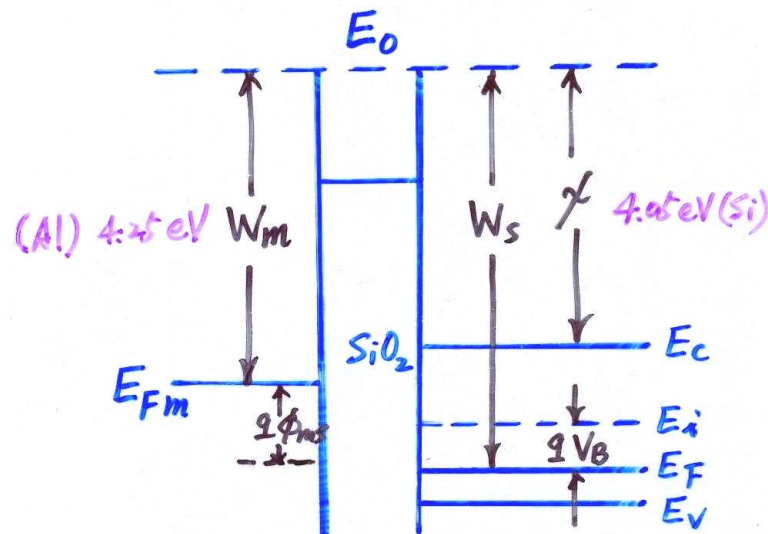
$$V_{FB} = -V_{ms}$$

例子：Al 栅电极 & p-Si $V_{ms} > 0$

C-V曲线整体向电压轴负方向平移

通过与理想 C-V对比，得到

$$V_{FB} \rightarrow V_{ms} \rightarrow W_m$$



10.4 MIS结构的C-V特性₇

10.4.3 实际MIS电容的C-V特性

2. 绝缘层中电荷的影响

$$Q_f \text{ [C/cm}^2\text{]} \quad Q_m, Q_{ot} \Rightarrow \rho(x) \text{ [C/cm}^3\text{]}$$

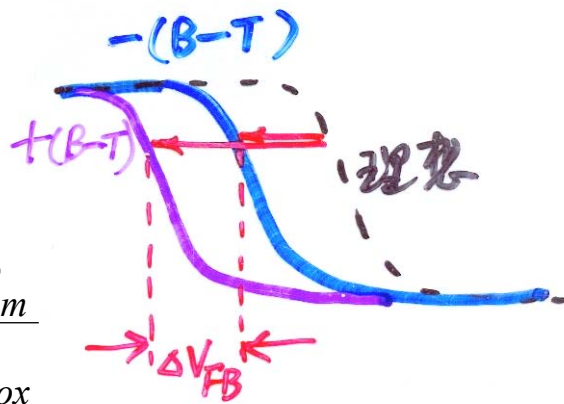
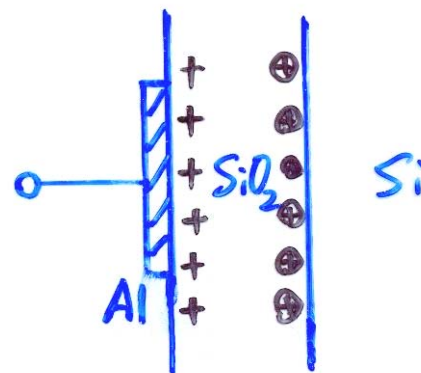
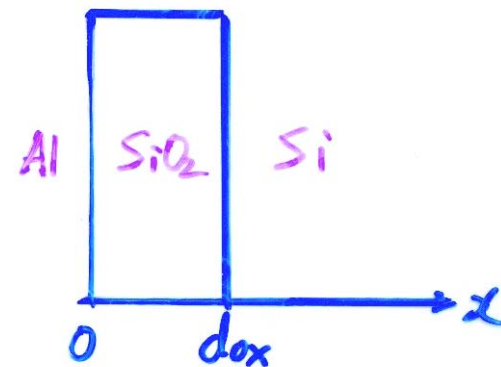
$$V_{FB} = -V_{ms} - \frac{Q_f}{C_{ox}} - \frac{1}{C_{ox}} \int_0^{d_{ox}} \frac{x}{d_{ox}} \rho(x) dx$$

B-T实验

$$\left. \begin{array}{l} V = 10 \rightarrow -10 \text{ V} \\ T = 150 \sim 250 \text{ } ^\circ\text{C} \end{array} \right\} 30 \text{ min.}$$

外电场和温度场下Na⁺ 可动

正电压下Na⁺迁移至氧化层靠近半导体一侧，导致较大负V_{FB}，再施加负电压，Na⁺部分迁至氧化层靠近金属一侧，部分恢复V_{FB}。



$$\Delta V_{FB} = \frac{Q_m}{C_{ox}}$$

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10.5 表面电导及迁移率₁

10.5.1 表面电导

$$n_p = n_{p0} \exp(qV/kT)$$

$$p_p = p_{p0} \exp(-qV/kT)$$

单位面积的表面层中载流子改变量

$$\Delta p = \int_0^\infty (p_p - p_{p0}) dx = \int_0^\infty p_{p0} \left[\exp\left(-\frac{qV}{kT}\right) - 1 \right] dx \propto V_s$$

$$\Delta n = \int_0^\infty (n_p - n_{p0}) dx = \int_0^\infty n_{p0} \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] dx \propto V_s$$

$$\Delta \sigma_s = q(\mu_{ns} \Delta n_s + \mu_{ps} \Delta p_s)$$

垂直于表面方向的电场
对表面电导起控制作用

Ω^{-1}

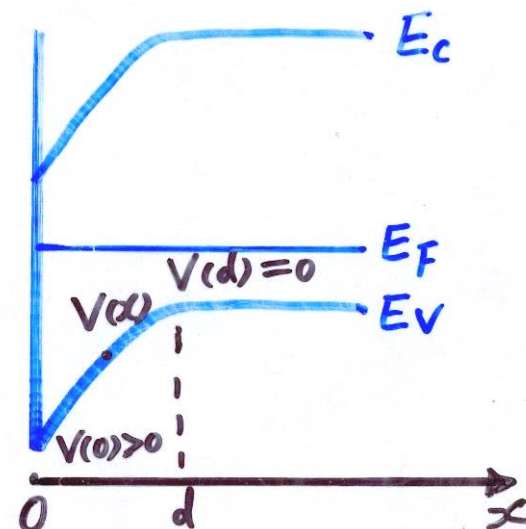
cm^{-2}

$$\sigma_s(V_s) = \sigma_s(0) + q(\mu_{ns} \Delta n_s + \mu_{ps} \Delta p_s)$$

平带薄层电导

表面迁移率

$$\mu_s \approx \frac{1}{2} \mu_b \leftarrow \text{表面散射}$$



本章小结

1. 高频 C-V

1° 获得衬底掺杂类型

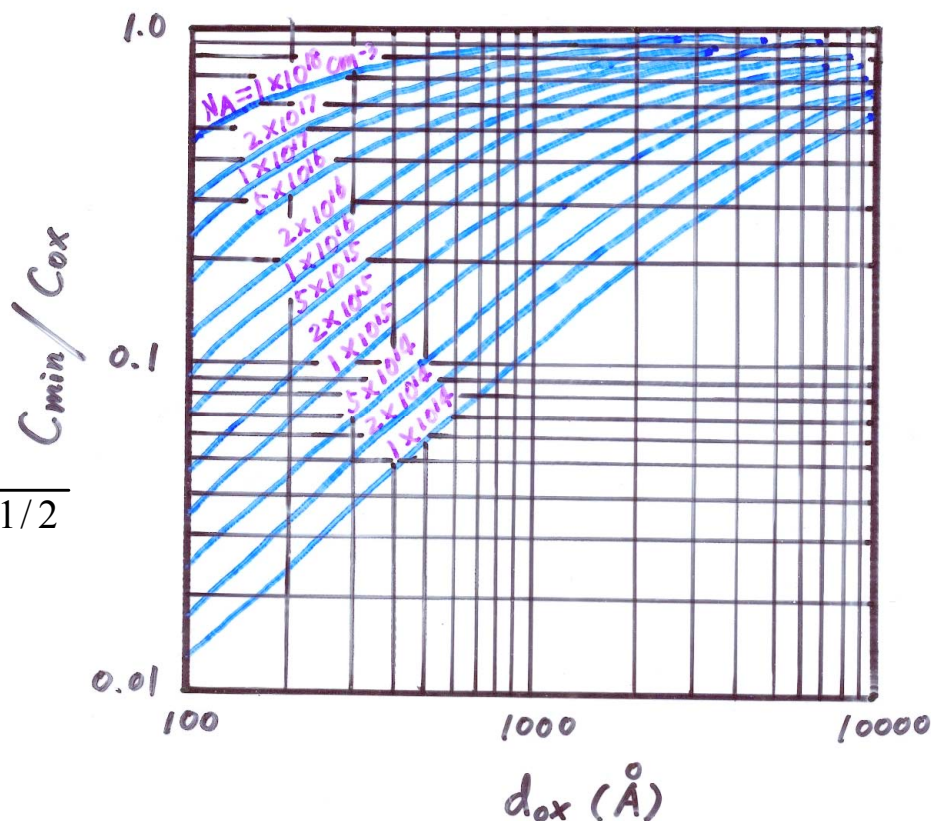
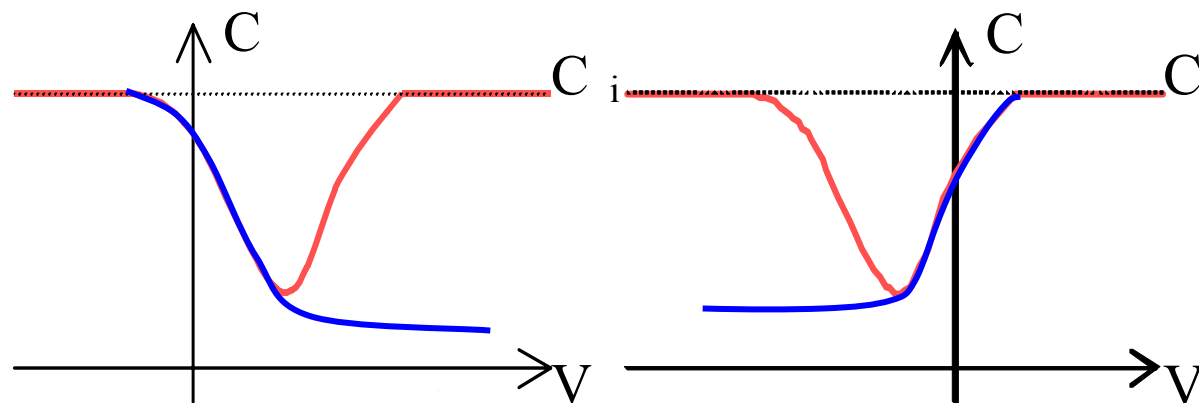
2° 获得 C'_{\min}/C_{ox}

光学测量可知: d_{ox}

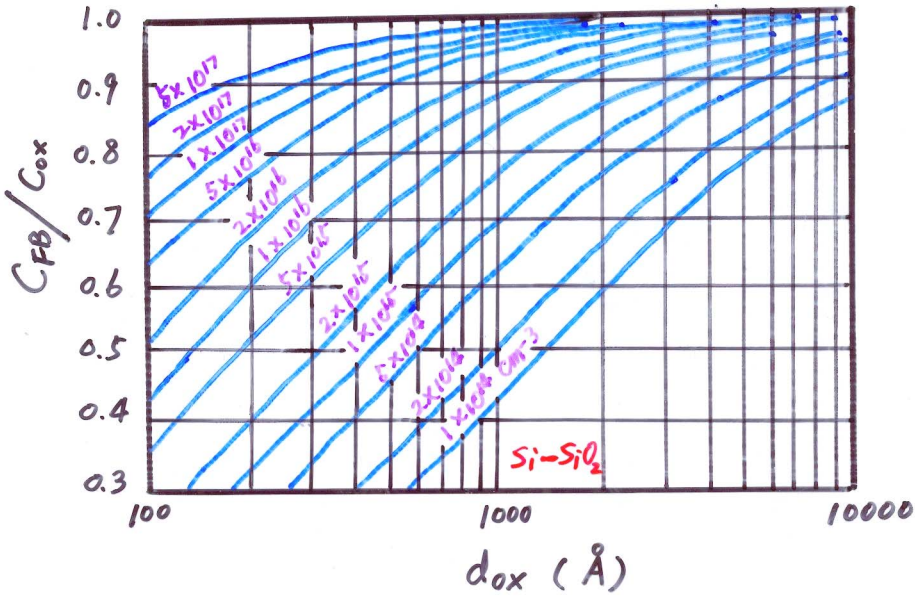
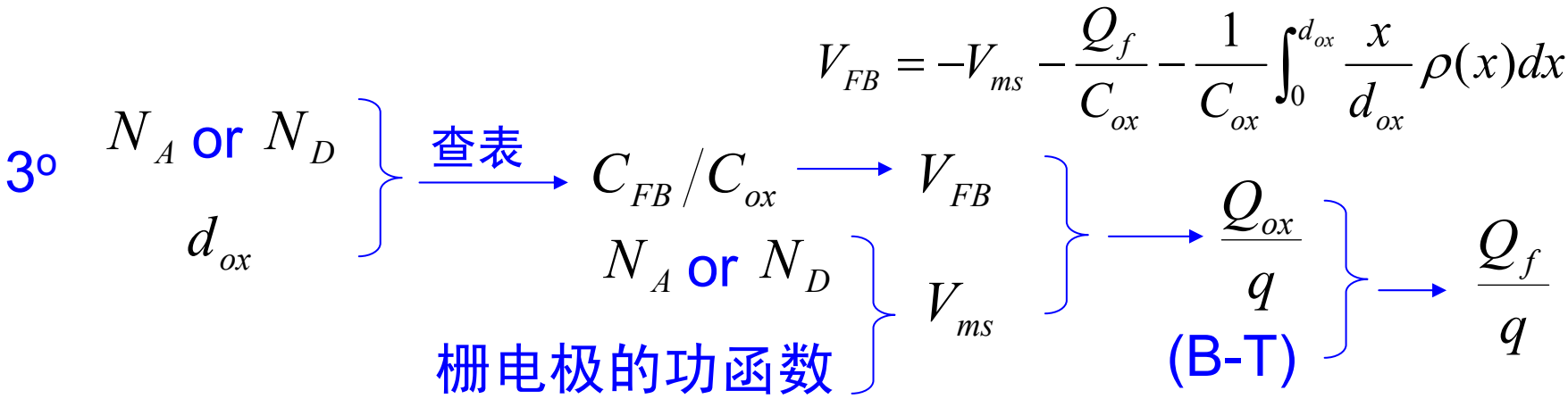
查表

→ N_A or N_D

$$\frac{C'_{\min}}{C_{ox}} = \frac{1}{1 + \frac{\epsilon_{ox}}{\epsilon_s} \left[\frac{4\epsilon_s kT}{q^2 N_A} \ln \left(\frac{N_A}{n_i} \right) \right]^{1/2} d_{ox}}$$



本章小结



$$\frac{C_{FB}}{C_{ox}} = \frac{1}{1 + \frac{\epsilon_{ox}}{d_{ox}} \left(\frac{kT}{q^2 N_A \epsilon_s} \right)^{\frac{1}{2}}}$$