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

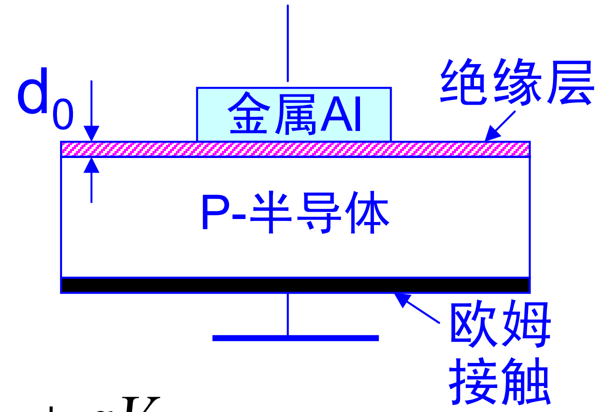
10.3 Si-SiO_2系统的性质

10.4 MIS结构的C-V特性

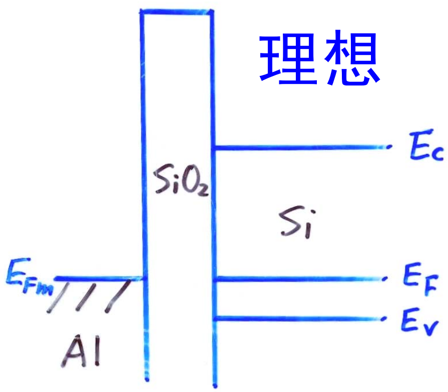
10.5 表面电导及迁移率

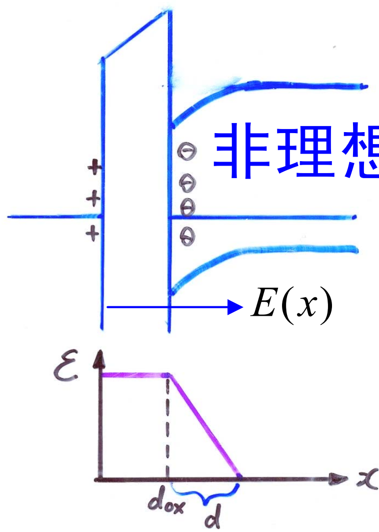
10.4 MIS结构的C-V特性1

10.4.1 MIS电容结构的能带图



1. 无外加电压



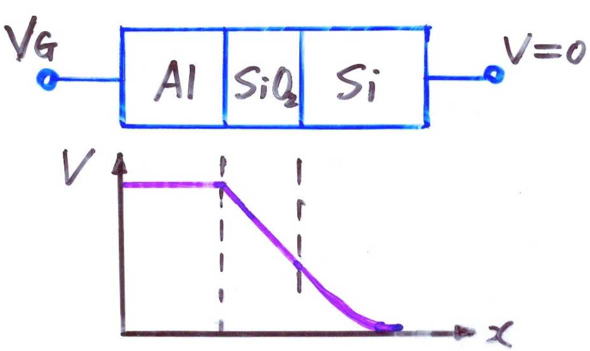


$$qV_{ms} = qV_{ox} + qV_s$$

$W_s - W_m$ 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

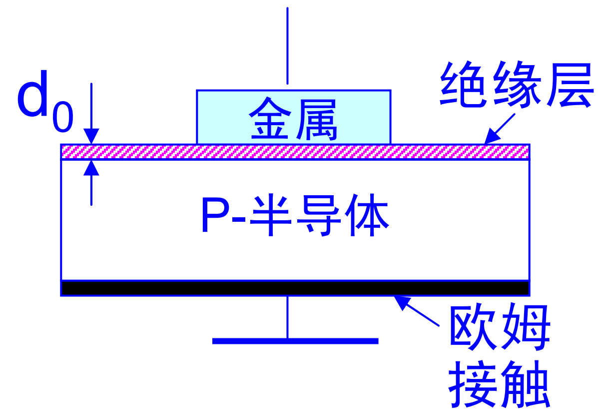
10.4.2 理想MIS电容的C—V特性

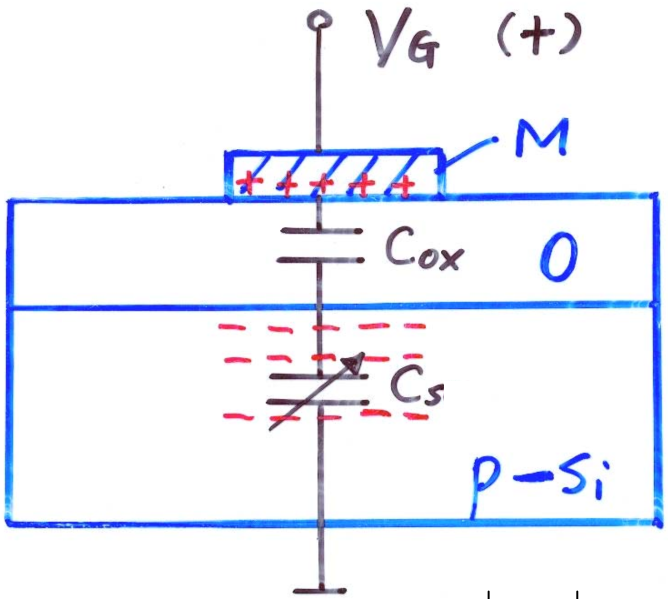
氧化层完全绝缘

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





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

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

$$C_{ox} = \frac{\varepsilon_{ox}}{d_{ox}} \qquad C_s = f(V_s)$$

随V_G变化

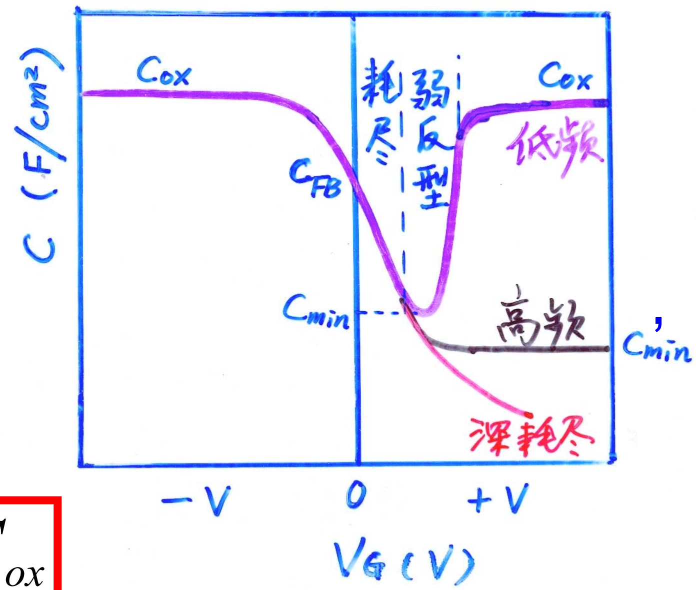
$$\boxed{\begin{array}{c}\varepsilon_r(\mathrm{SiO_2}) = 3.9 \\ \varepsilon_r(\mathrm{Si}) = 11.9\end{array}}$$

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

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)



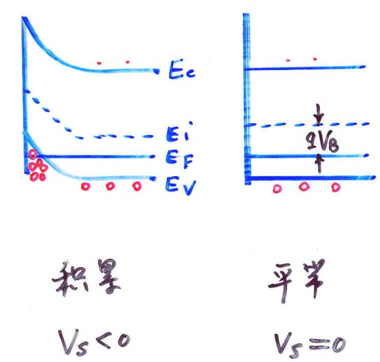
$$\boxed{\frac{1}{C}=\frac{1}{C_{ox}}+\frac{1}{C_s}} \quad C_{ox}=\frac{\varepsilon_{ox}}{d_{ox}} \quad C_s=f(V_s)$$

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

$$C_s=\frac{dQ_s}{dV_s}\propto \exp\left(q|V_s|/2kT\right)$$ >> C_{ox} → $\boxed{C\approx C_{ox}}$

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

$$\boxed{C_{FB}=C_{ox}\Bigg/\left[1+\frac{\varepsilon_{ox}}{d_{ox}}\left(\frac{kT}{q^2N_A\varepsilon_s}\right)^{\frac{1}{2}}\right]}$$

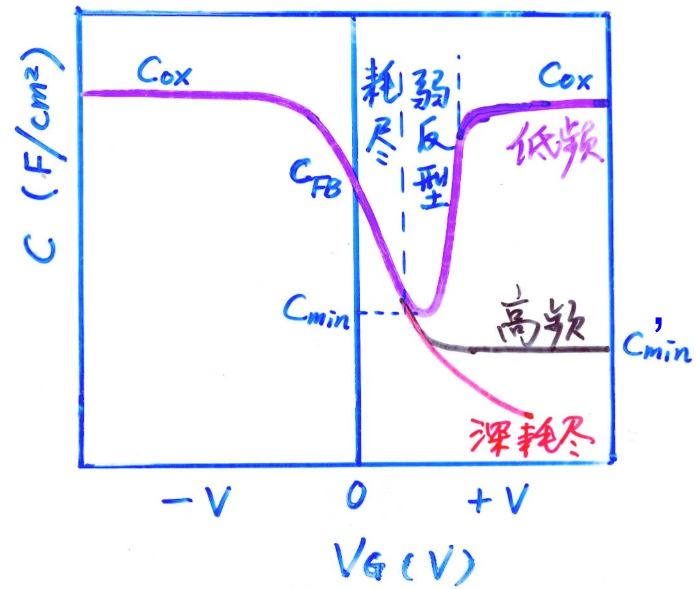


10.4 MIS结构的C-V特性3

10.4.2 理想MIS电容的C—V特性

低频情况(10~100 Hz)

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



3° $V_G > 0$,耗尽, V_G ↑ d ↑ C_s↓ C↓

平行板电容器等效

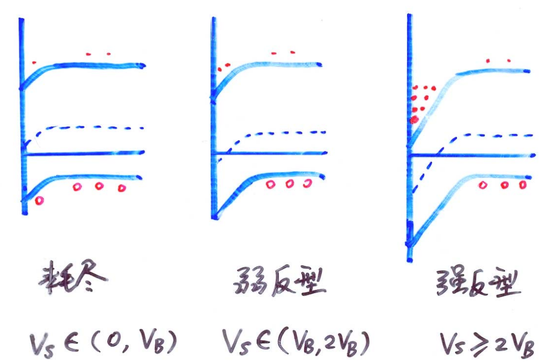
4° $V_G > 0$, 弱反型, V_G↑ d↑ Q_s：从$V_s^{1/2} \to \exp(qV_s/2kT)$

$$C_s=\frac{dQ_s}{dV_s}$$：从$V_s^{-1/2} \to \exp(qV_s/2kT)$ $\boxed{C \sim \downarrow \to \uparrow}$

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

$C_s >> C_{ox}$ $\boxed{C \approx C_{ox}}$

$V_s = 2V_B \to \boxed{V_G = V_T}$ 阈值电压 (开启电压)



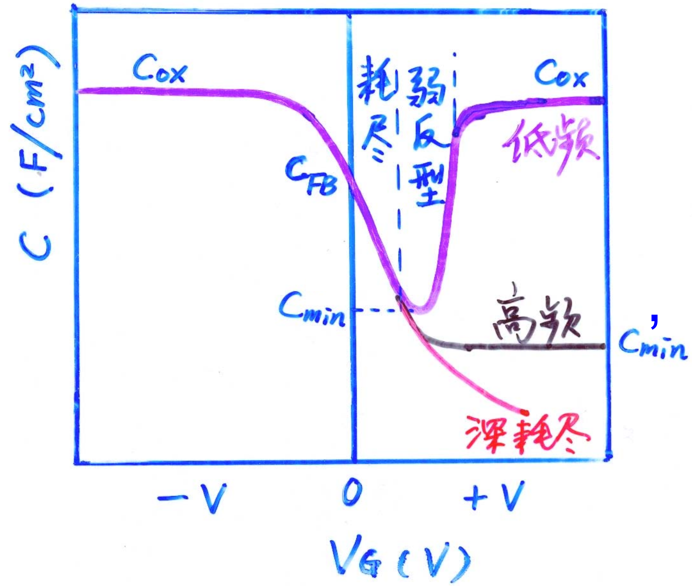
10.4 MIS结构的C-V特性4

10.4.2 理想MIS电容的C－V特性

高频情况(10^4~10^6 Hz)

—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。



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

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

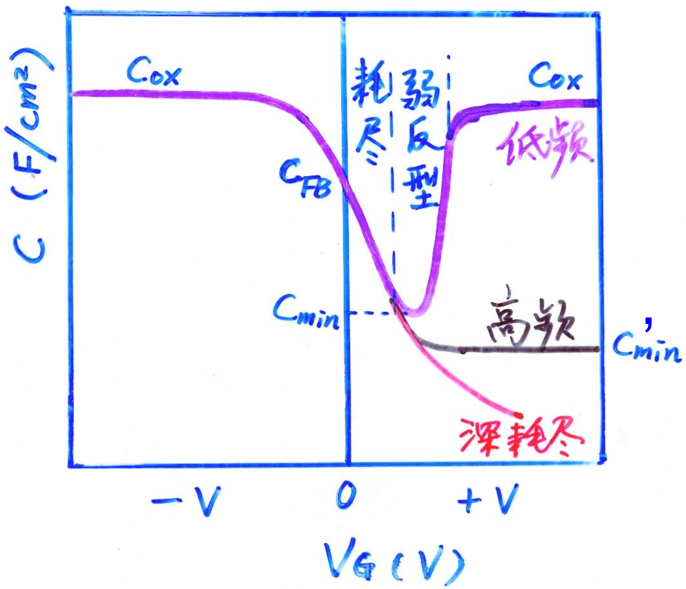
$$\frac{1}{C'_{\min}} = \frac{1}{C_{ox}} + \frac{1}{C_{s(d_{\max})}}$$

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

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10^0～10^2s！

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↓

10.4 MIS结构的C-V特性6

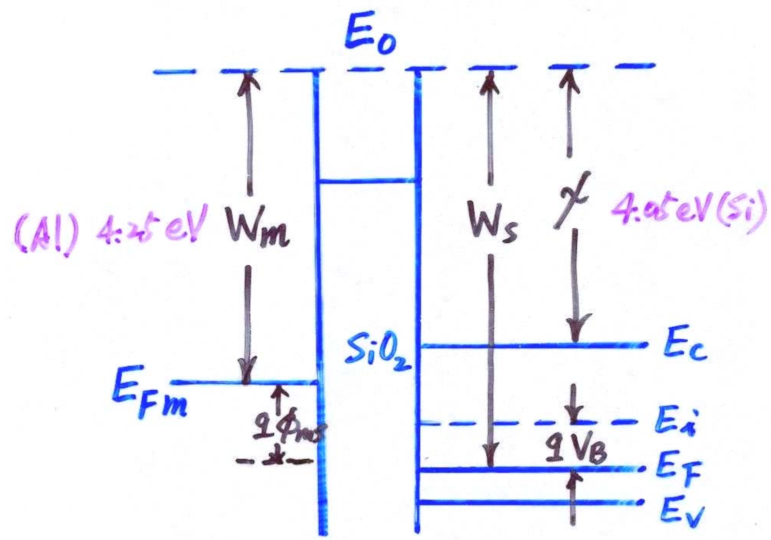
10.4.3 实际MIS电容的C－V特性

1. 金半接触电势差的影响

C-V曲线会平移，但形状不变

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

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

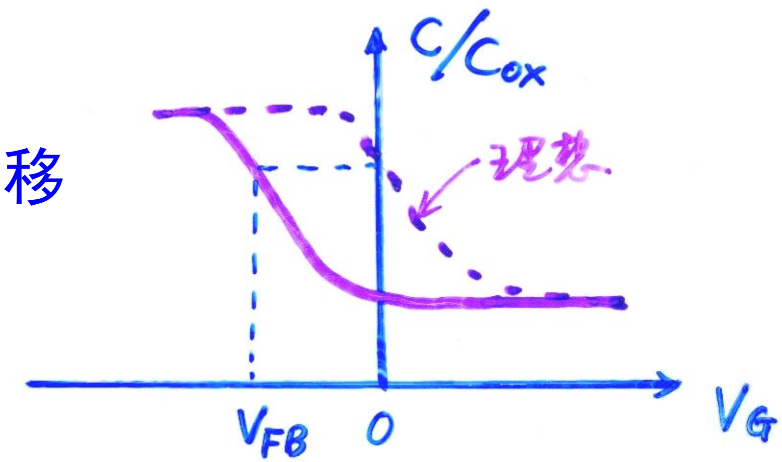


例子：Al 栅电极 & p-Si　$V_{ms} > 0$

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

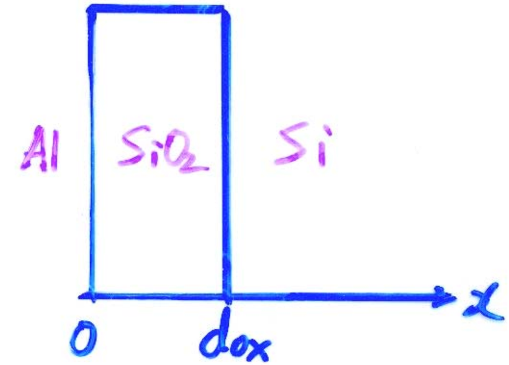
$V_{FB} \rightarrow V_{ms} \rightarrow W_m$



10.4 MIS结构的C-V特性7

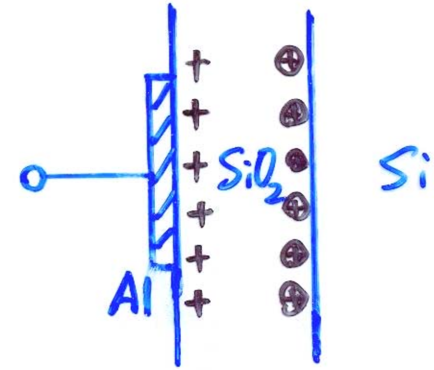
10.4.3 实际MIS电容的C－V特性

2. 绝缘层中电荷的影响



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

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

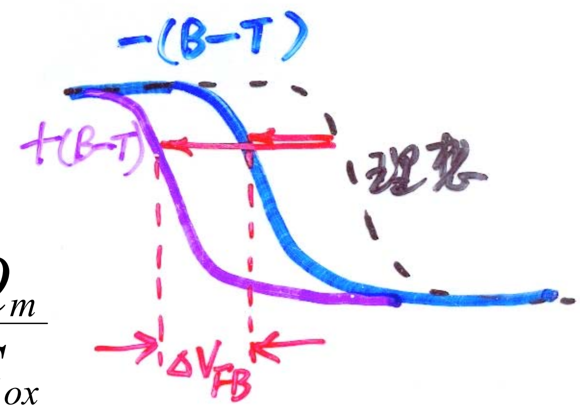


B−T实验

$$\left.\begin{aligned} &V = 10 \rightarrow -10\ \text{V} \\ &T = 150 \sim 250\ ^{o}\text{C} \end{aligned}\right\}\ 30\ \text{min.}$$

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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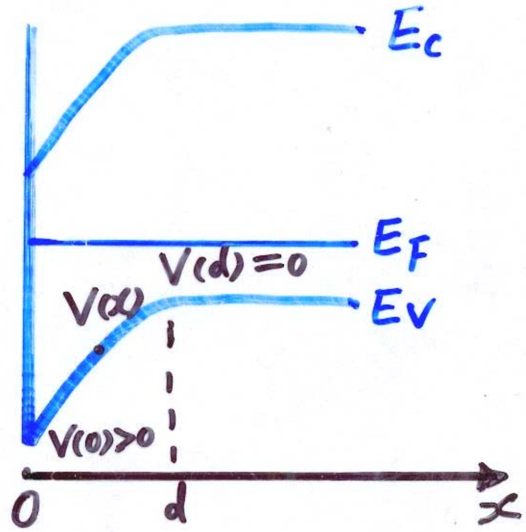
10.5 表面电导及迁移率

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

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

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

$$\boxed{\underset{\Omega^{-1}}{\Delta\sigma_s} = q(\mu_{ns}\underset{\mathrm{cm}^{-2}}{\Delta n_s} + \mu_{ps}\Delta p_s)}$$

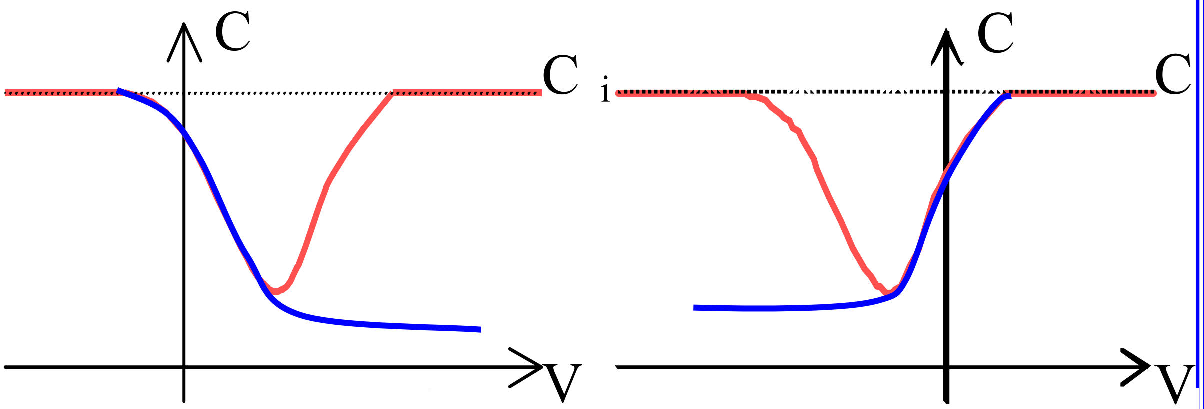
垂直于表面方向的电场
对表面电导起控制作用

$$\sigma_s(V_s) = \underset{\text{平带薄层电导}}{\sigma_s(0)} + q(\mu_{ns}\Delta n_s + \mu_{ps}\Delta p_s)$$

表面迁移率

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

本章小结



1. 高频 C-V

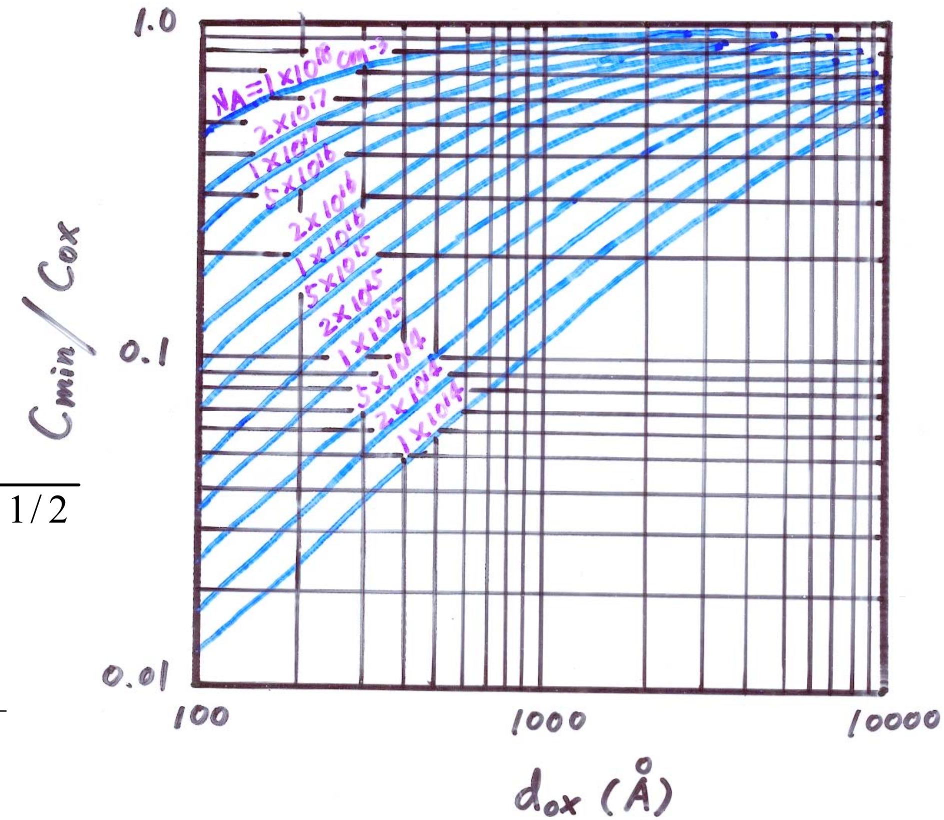
1° 获得衬底掺杂类型

2° 获得 $C'_{\min}/C_{ox}$

光学测量可知: d_{ox}

$\xrightarrow{\text{查表}}$ N_A or N_D

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



本章小结

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

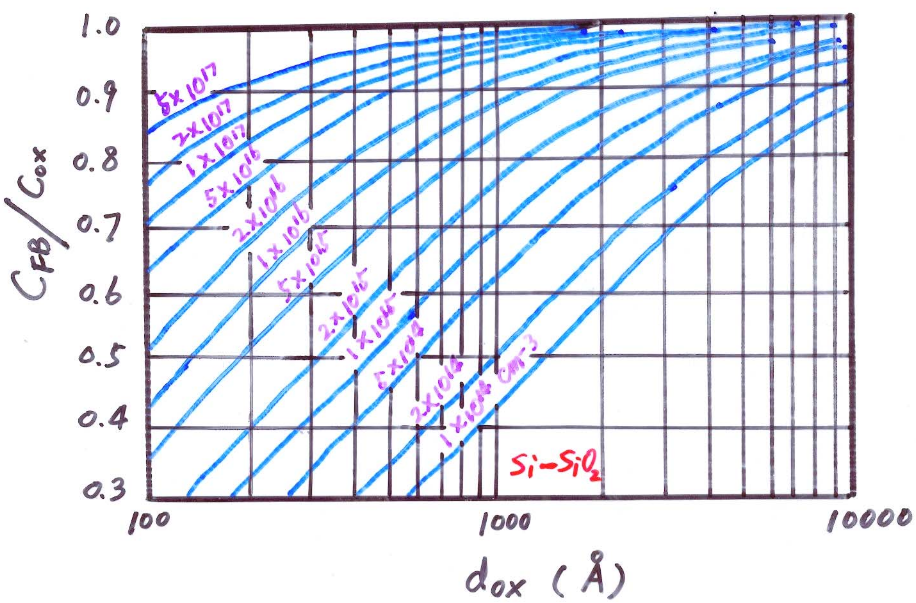
3o

$\left.\begin{matrix} N_A \text{ or } N_D \\ d_{ox} \end{matrix}\right\} \xrightarrow{\text{查表}} C_{FB}/C_{ox} \longrightarrow V_{FB}$

$\left.\begin{matrix} N_A \text{ or } N_D \\ \text{栅电极的功函数} \end{matrix}\right\} V_{ms}$

$\left.\begin{matrix} V_{FB} \\ V_{ms} \end{matrix}\right\} \longrightarrow \frac{Q_{ox}}{q}$

$\left.\begin{matrix} \frac{Q_{ox}}{q} \\ \text{(B-T)} \end{matrix}\right\} \longrightarrow \frac{Q_f}{q}$



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