微电子器件物理
MOSFET非理想特性

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2020/10/27

本节课提纲

1. 平方律回顾
2. 速度饱和效应

平方律回顾

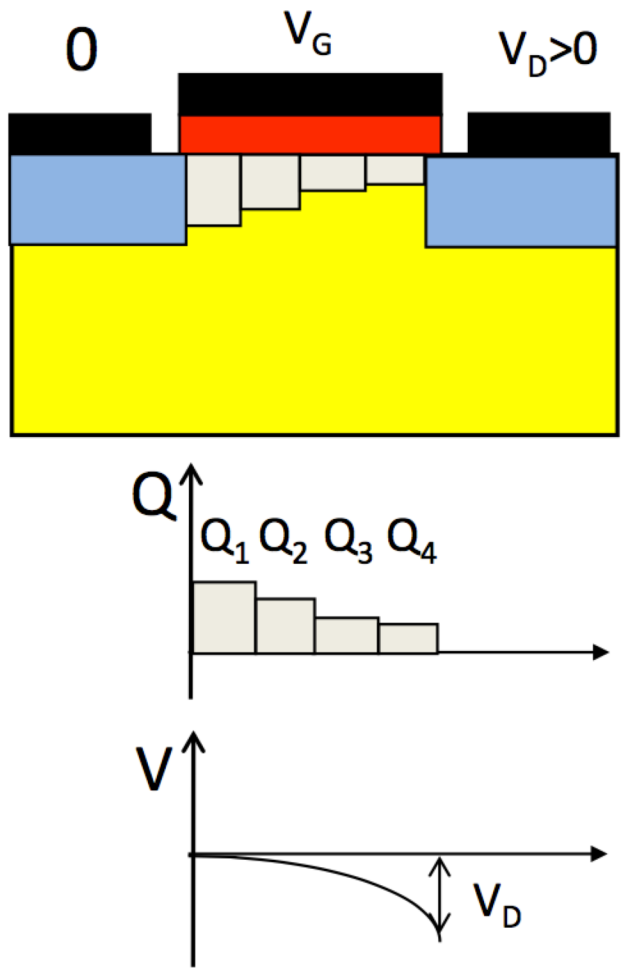
高场下不成立

$$J_i = Q_i \upsilon = Q_i \mu \mathcal{E}_1 = Q_i \mu \left.\frac{dV}{dy}\right|_i$$

$$\sum_{i=1,N} \frac{J_i dy}{\mu} = \sum_{i=1,N} Q_i dV$$

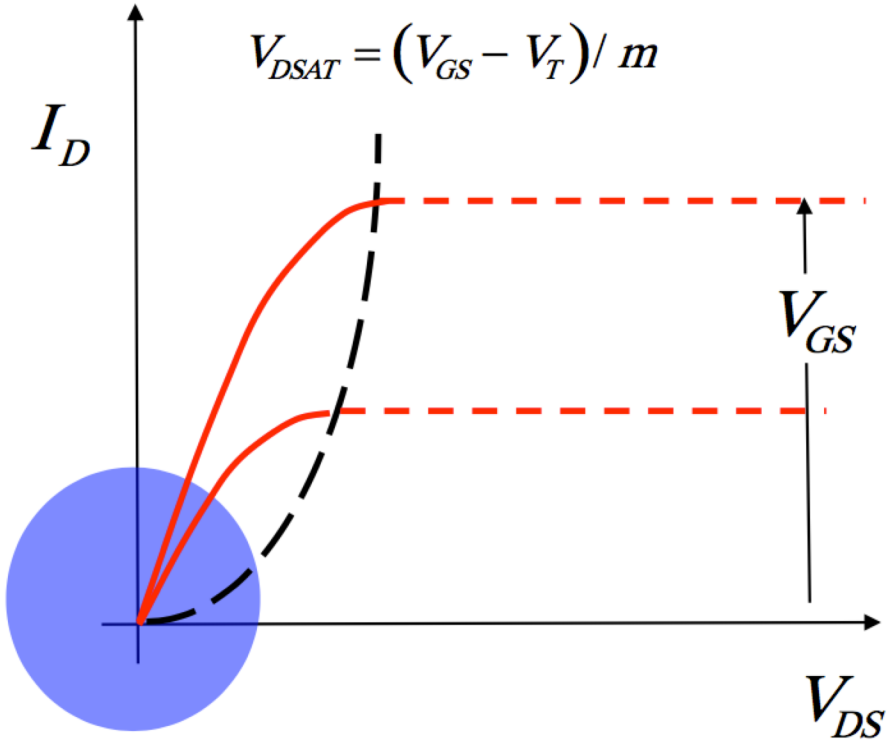
$$\frac{J_D}{\mu_0} \sum_{i=1,N} dy = \int_0^{V_D} C_{ox}(V_G - V_{th} - mV)dV$$

$$J_D = \frac{\mu_0 C_{ox}}{L_{ch}}\left[(V_G - V_{th})V_D - m\frac{V_D^{\,2}}{2}\right]$$



平方律回顾

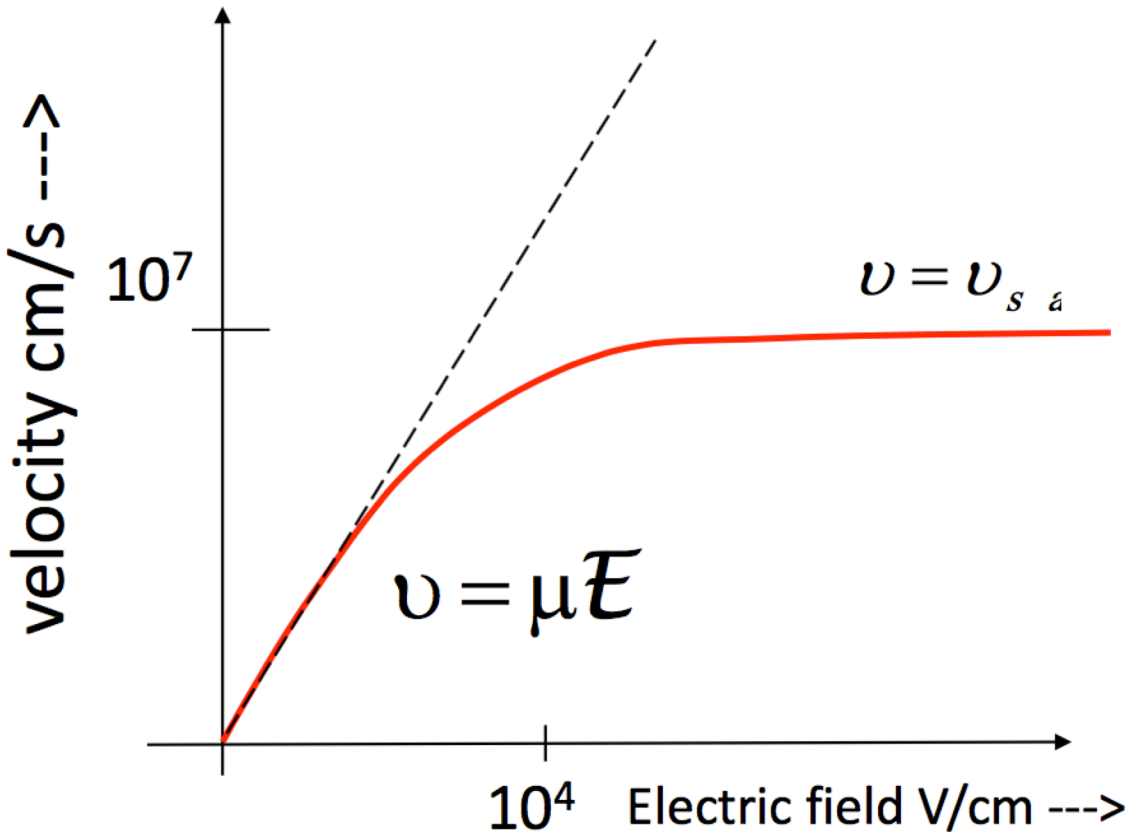
$$I_D = \frac{W\mu_0 C_{ox}}{L_{ch}}\left[(V_G - V_{th})V_D - m\frac{V_D^{\,2}}{2}\right]$$



$$I_D = \frac{W\mu_0 C_o}{2mL_{ch}}(V_G - V_T)^2$$

$$I_D = \mu_0 C_o \frac{W}{L}(V_G - V_T)V_D$$

速度与电场的关系



$$\upsilon_d = \frac{-\mu\mathcal{E}}{\left[1+(\mathcal{E}/\mathcal{E}_c)^2\right]^{1/2}}$$

$$\upsilon_d = \frac{-\mu\mathcal{E}}{1+(|\mathcal{E}|/\mathcal{E}_c)}$$

$$\upsilon_{d,sat} = \mu\mathcal{E}_c$$

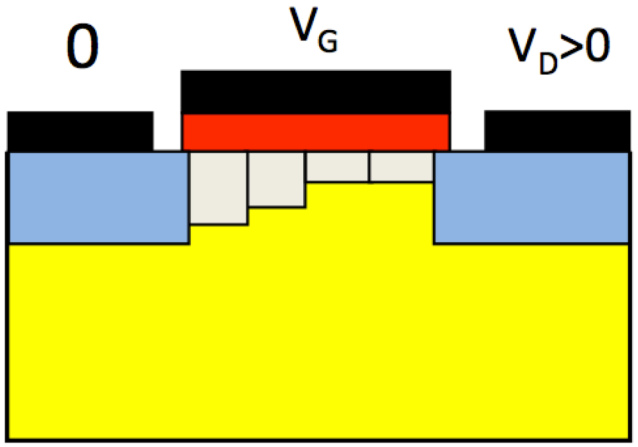
速度饱和

$$J_1 = Q_1 \mu_1 \mathcal{E}_1 = Q_1 \mu_1 \left.\frac{dV}{dy}\right|_1$$

$$J_2 = Q_2 \mu_2 \mathcal{E}_2 = Q_2 \mu_2 \left.\frac{dV}{dy}\right|_2$$

$$J_3 = Q_3 \mu_3 \mathcal{E}_3 = Q_3 \mu_3 \left.\frac{dV}{dy}\right|_3$$

$$J_4 = Q_4 \mu_4 \mathcal{E}_4 = Q_4 \mu_4 \left.\frac{dV}{dy}\right|_4$$



$$\Rightarrow \sum_{i=1,N} \frac{J_i dy}{\mu(y)} = \sum_{i=1,N} Q_i \, dV$$

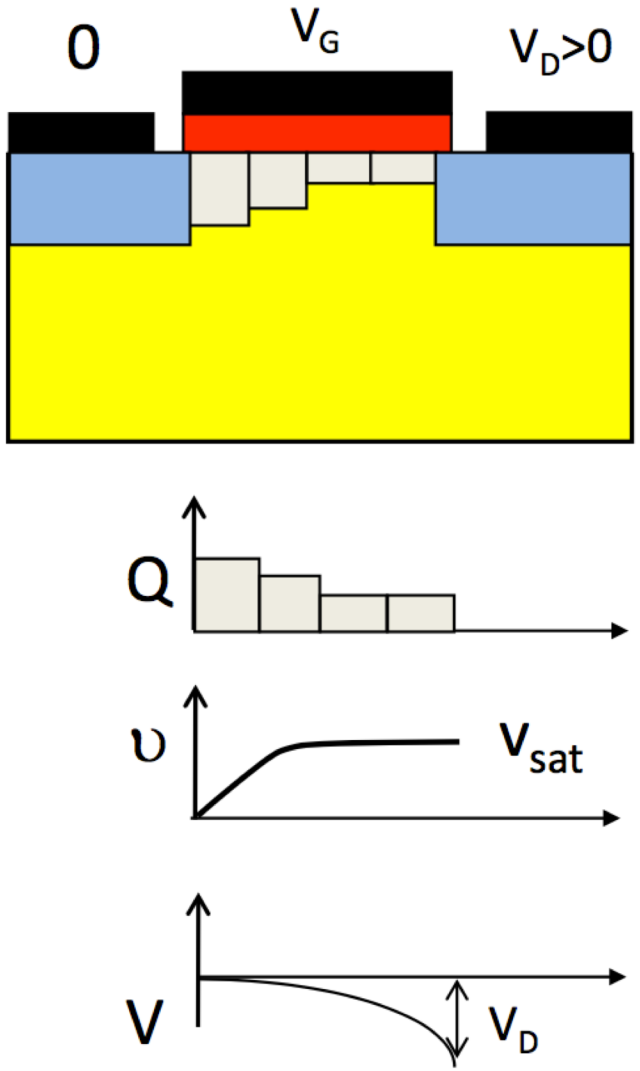
速度饱和

$$J_D \sum_{i=1,N} \frac{dy}{\mu_0 \Big/ \left[1+\frac{|\mathcal{E}|}{\mathcal{E}_c}\right]} = \int_0^{V_D} C_{ox}(V_G - V_{th} - mV)dV$$

$$\frac{J_D}{\mu_0}\int_0^{L_{ch}} dy\left[1+\frac{1}{\mathcal{E}_c}\frac{dV}{dy}\right] = C_{ox}\left[(V_G - V_{th})V_D - \frac{mV_D^{\,2}}{2}\right]$$

$$\int_0^{L_{ch}} J_D dy + \int_0^{V_{DS}} \frac{J_D}{E_c} dV = C_{ox}\left[(V_G - V_{th})V_D - \frac{mV_D^{\,2}}{2}\right]$$

$$J_D = \frac{\mu_0 C_{ox}}{L_{ch} + \frac{V_D}{\mathcal{E}_c}}\left[(V_G - V_{th})V_D - \frac{mV_D^{\,2}}{2}\right]$$



速度饱和

$$\frac{dI_D}{dV_{DS}} = 0$$

$$\frac{I_D}{W} = \frac{\mu_o C_{ox}}{L_{ch} + \frac{V_D}{\mathcal{E}_c}} \left[\left(V_G - V_{th} \right) V_D - m \frac{V_D^2}{2} \right]$$

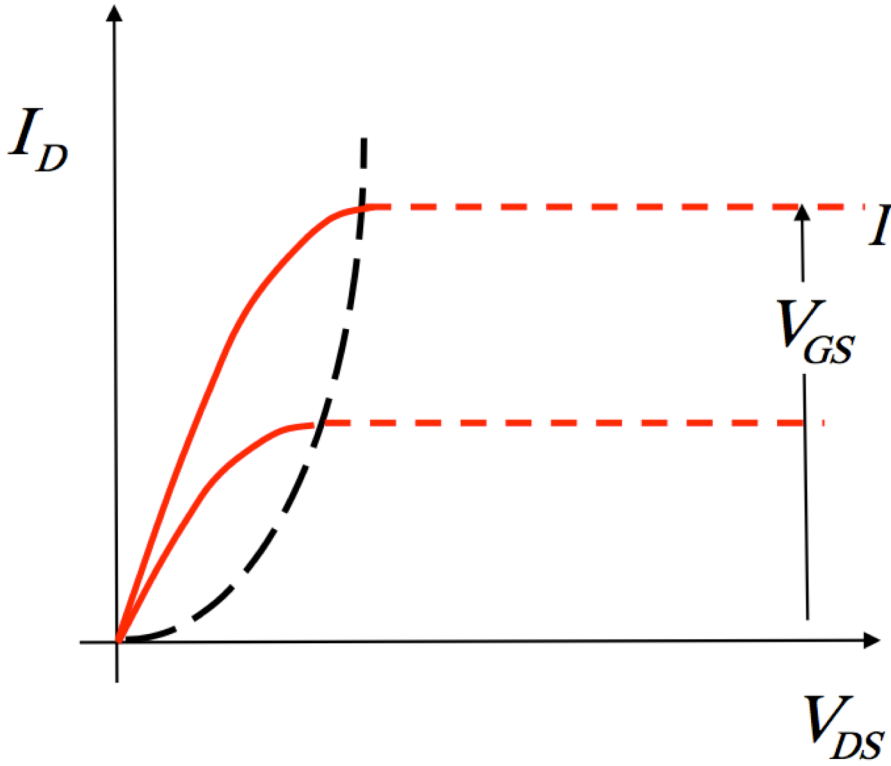
导数为零时，电流取极大值

$$V_{DSAT} = \frac{2\left(V_G - V_{th} \right) / m}{1 + \sqrt{1 + 2\mu_o \left(V_G - V_{th} \right) / m \upsilon_{sat} L_{ch}}} < \frac{\left(V_{GS} - V_T \right)}{m}$$

速度饱和

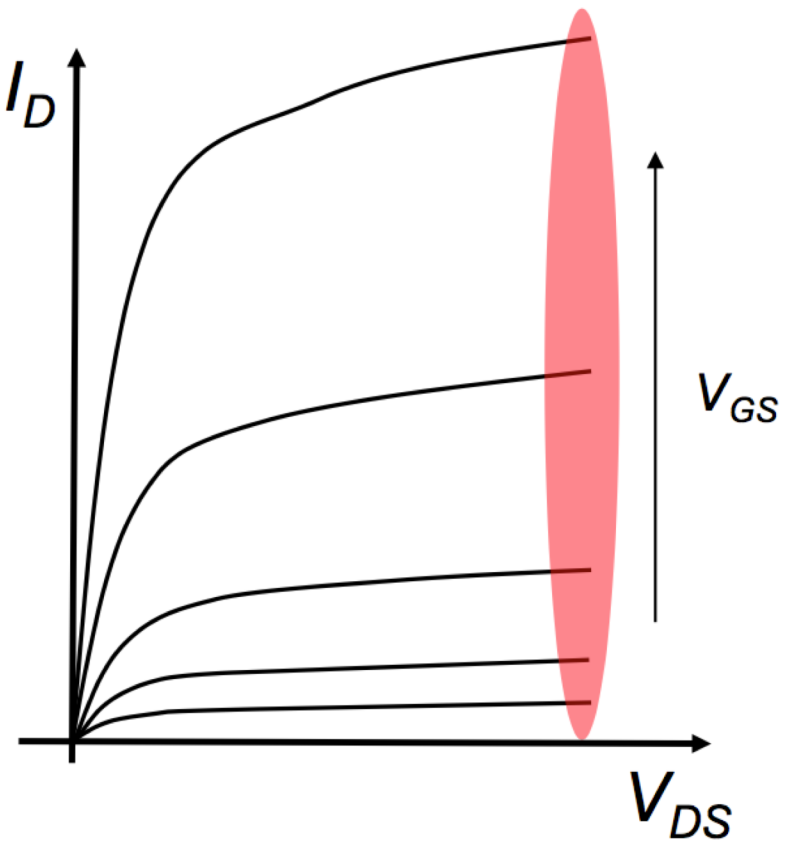
$$J_{D,sat}=\frac{\mu_0 C_{ox}}{L_{ch}+\frac{V_{D,sat}}{\mathcal{E}_C}}\left[(V_G-V_{th})V_{D,sat}-\frac{mV_{D,sat}^{\ 2}}{2}\right]$$

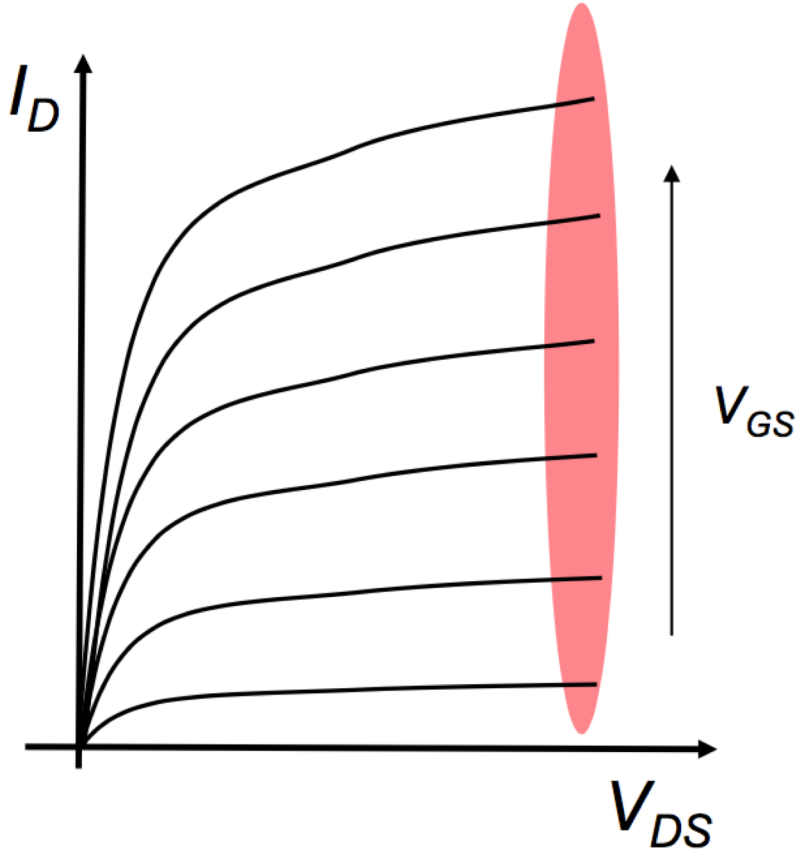
$$\sim\frac{\mu_0\mathcal{E}_C C_{ox}}{V_{D,sat}}\left[(V_G-V_{th})V_{D,sat}-\frac{mV_{D,sat}^{\ 2}}{2}\right]\sim\upsilon_{sat}C_{ox}(V_G-V_{th})$$



$$I_D=WC_{ox}\upsilon_{sat}(V_G-V_T)$$

速度饱和

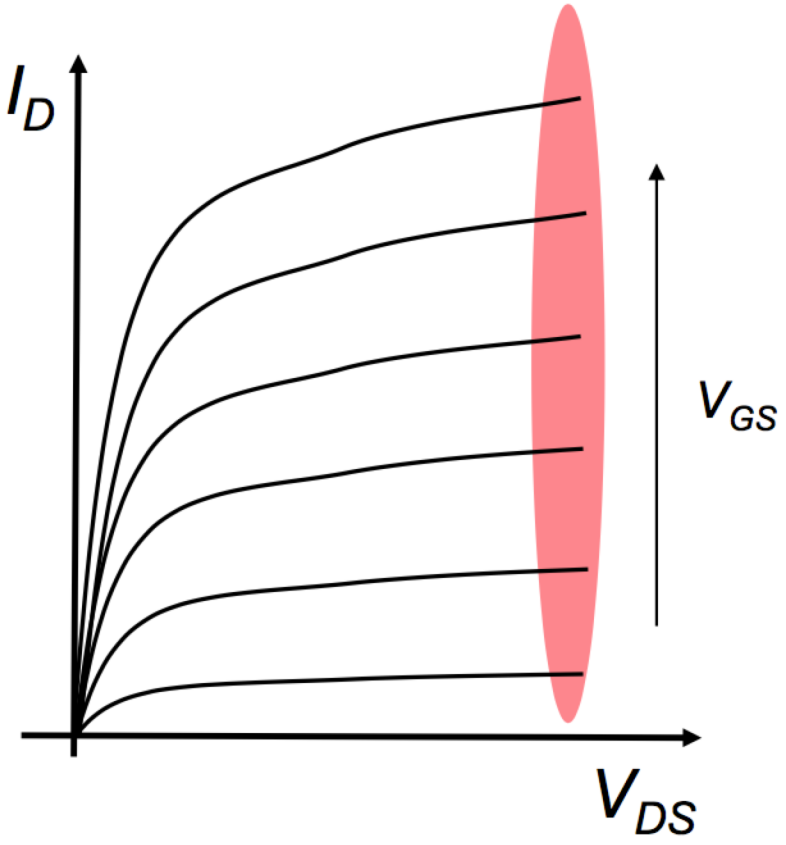




$$I_D = \frac{W}{2L_{ch}} \mu_0 C_{ox} \frac{(V_G - V_{th})^2}{m}$$

$$I_D = W \upsilon_{sat} C_{ox} (V_G - V_{th})$$

速度饱和的实际情况



$$I_D(V_D = V_{DD}) \sim (V_G - V_{th})^{\alpha}$$

$$1 < \alpha < 2$$

完全速度饱和

长沟道

反型层电荷

$$Q_i = -C_O(V_G - V_{th} - V) + q \frac{N_A}{}\left(W_T(V) - W_T(V=0)\right)$$

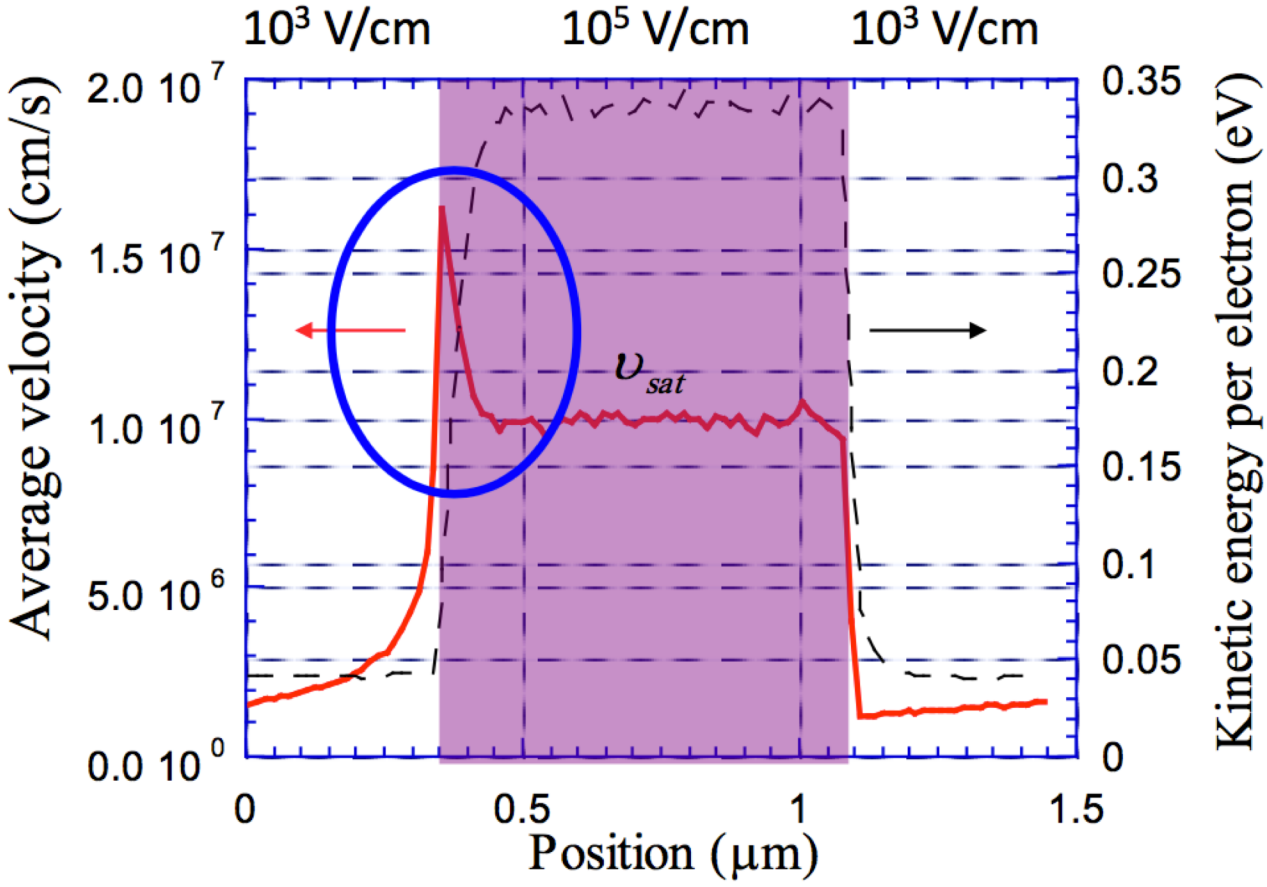
$$= -C_O(V_G - V_{th} - V) + \sqrt{2q\kappa_S\varepsilon_o N_A\left(2\phi_B + V\right)} - \sqrt{2q\kappa_S\varepsilon_o N_A\left(2\phi_B\right)}$$

Approximations:

$$Q_i \approx -C_{ox}(V_G - V_{th} - V)$$ 平方律近似

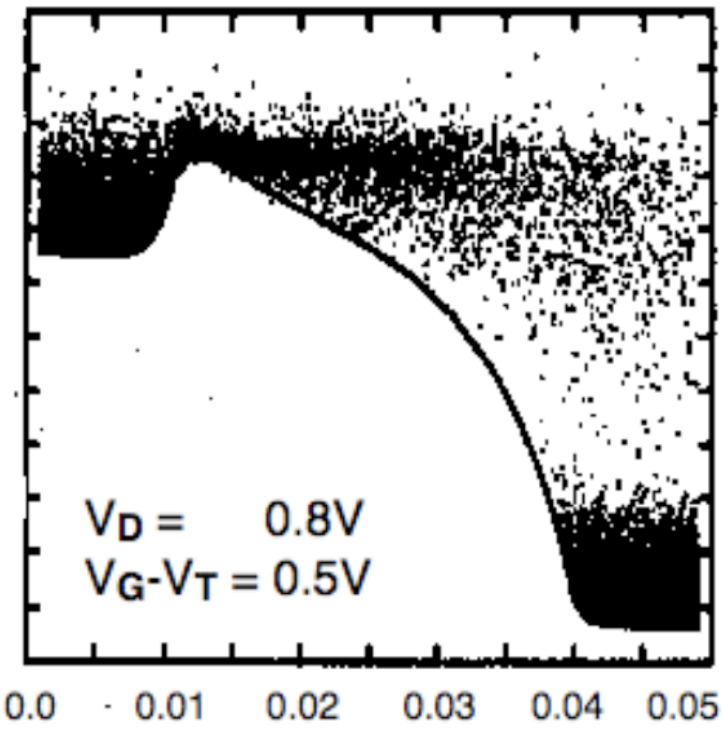
$$Q_i \approx -C_{ox}(V_G - V_{th} - mV)$$ 简化的体电荷近似

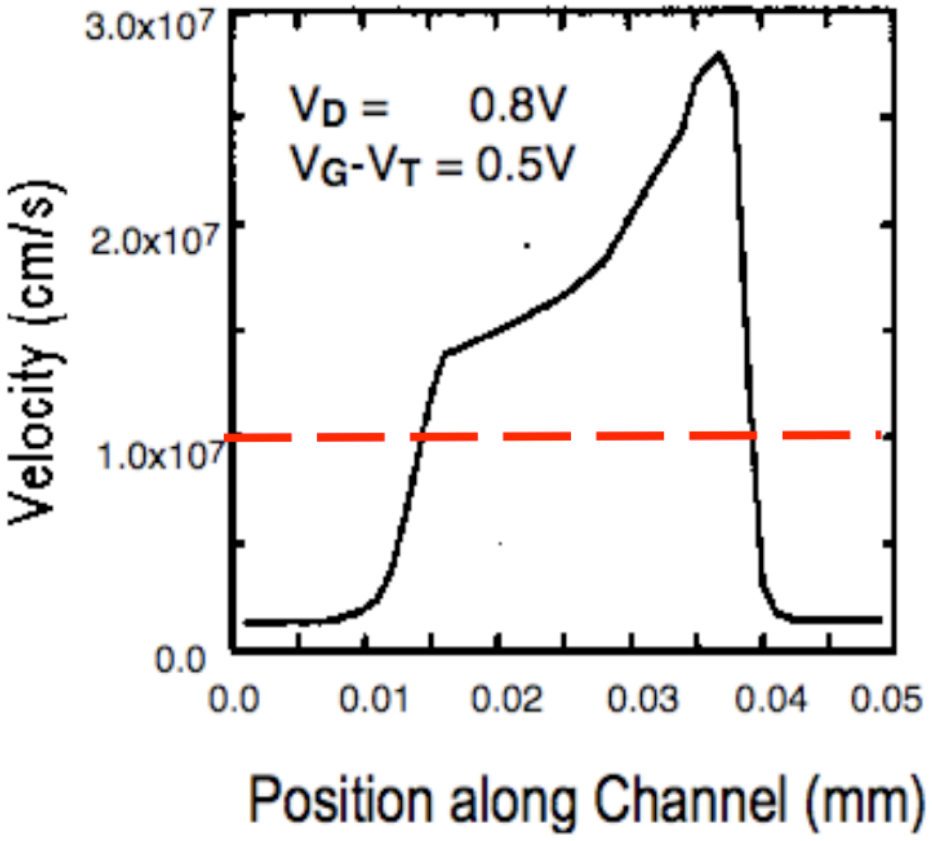
速度过冲



$$\upsilon \neq \mu_n(E)E$$

小尺寸器件中的速度过冲





Frank, Laux, and Fischetti, IEDM Tech. Dig., p. 553, 1992

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2. 陷阱电荷导致的阈值变化
3. 界面态

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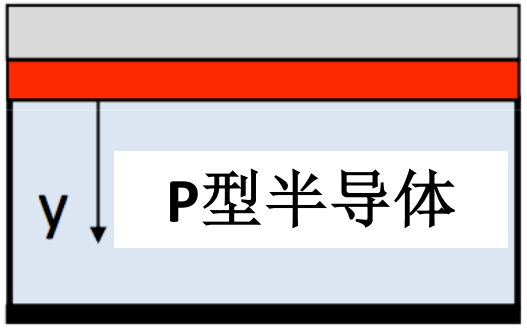
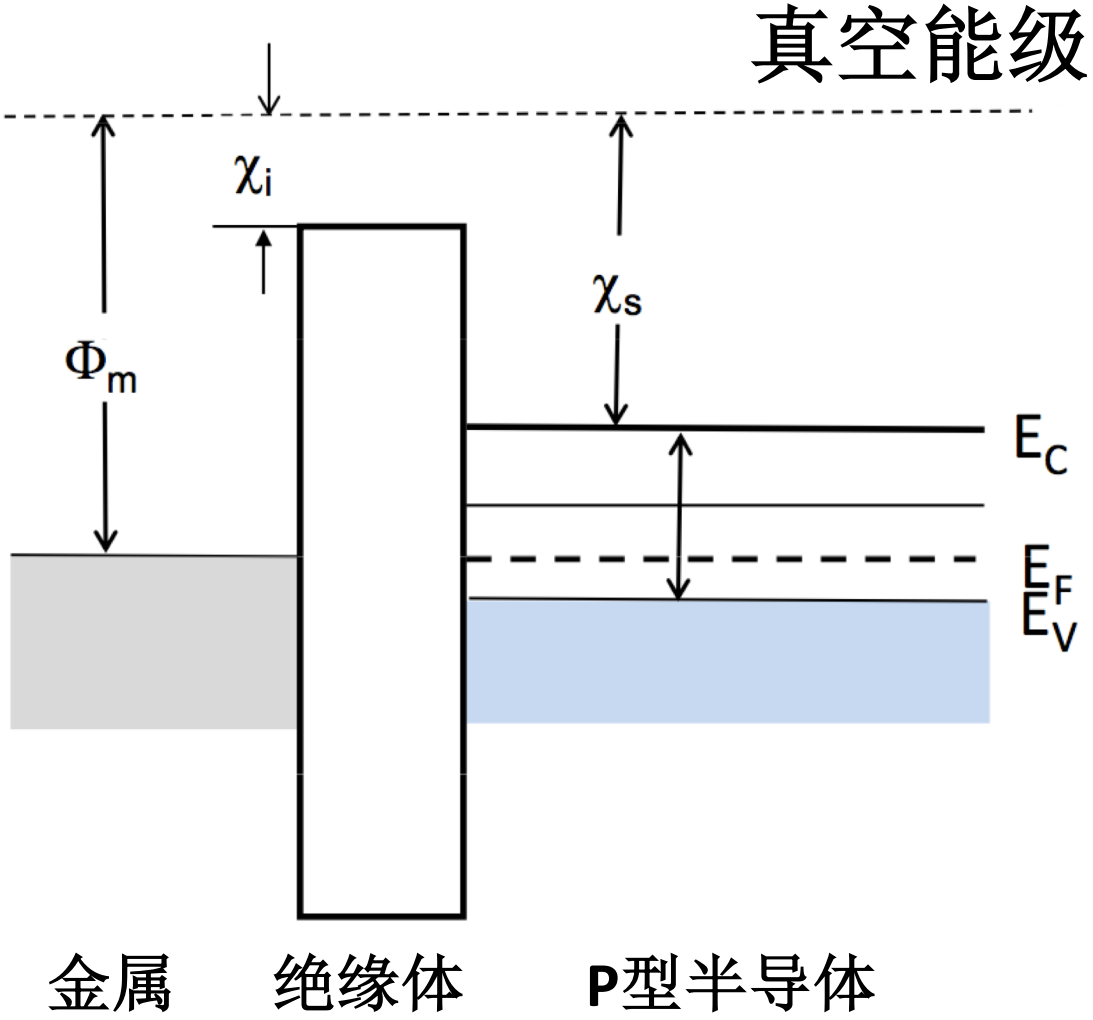
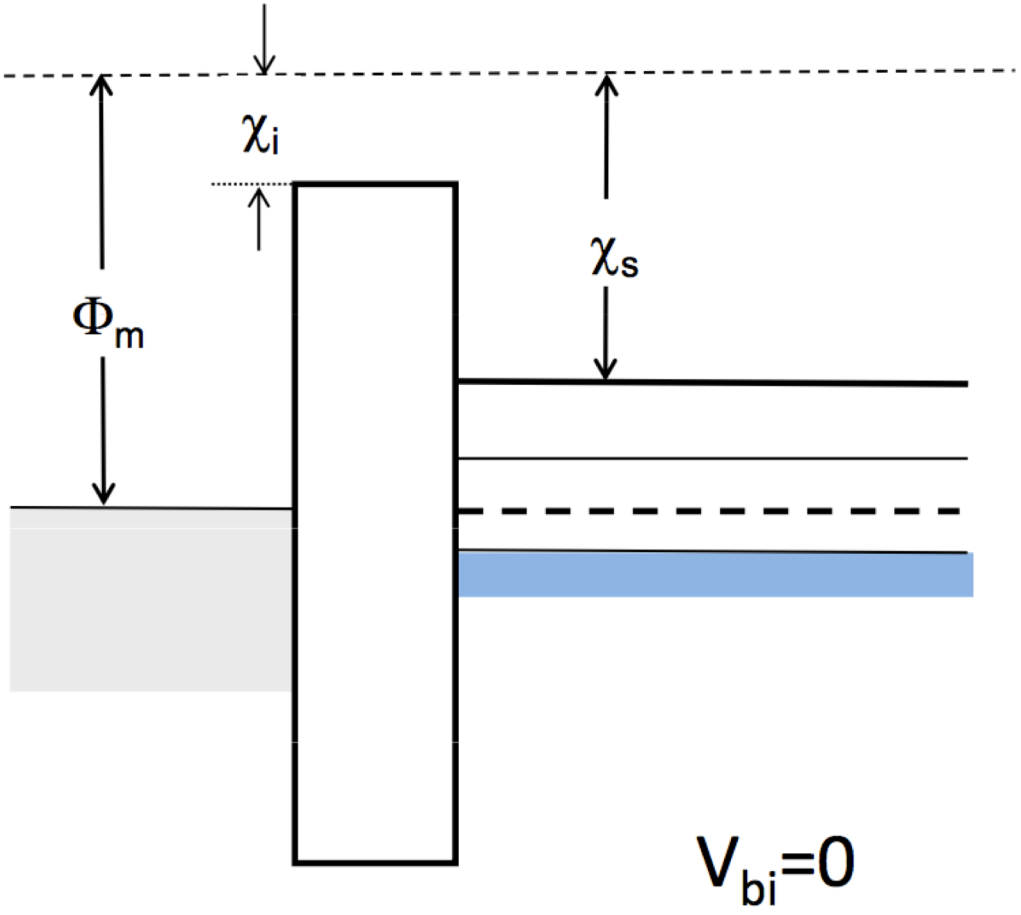


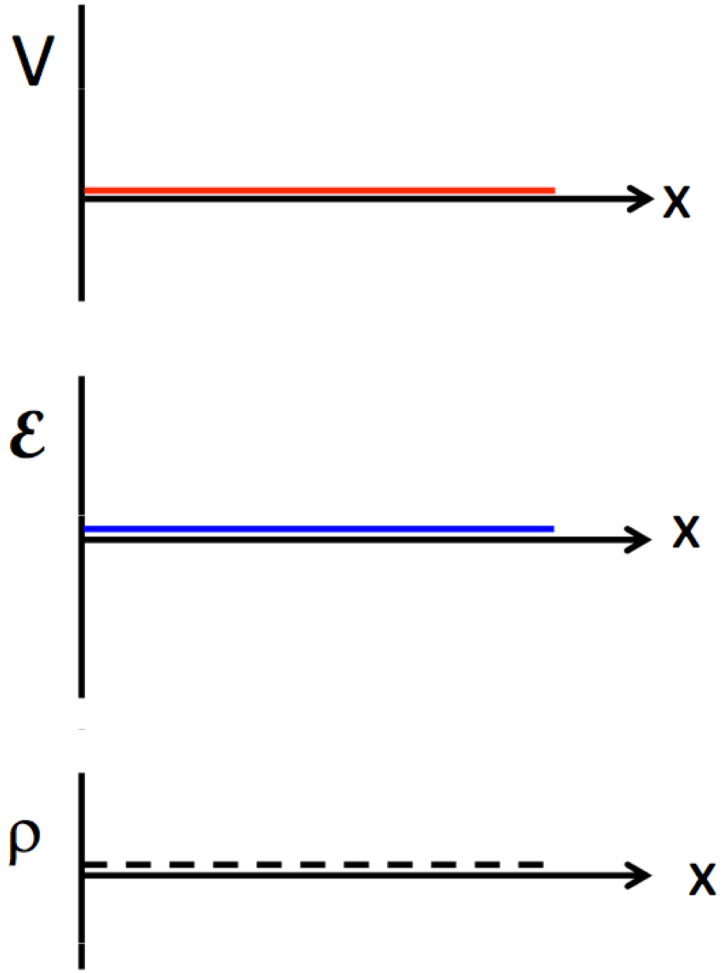


$$Q_i = C_{ox}(V_G - V_{th,ideal})$$

$$V_{th,ideal} = \psi_s - \left.\frac{Q_B}{C_{ox}}\right|_{\psi_s = 2\phi_F}$$

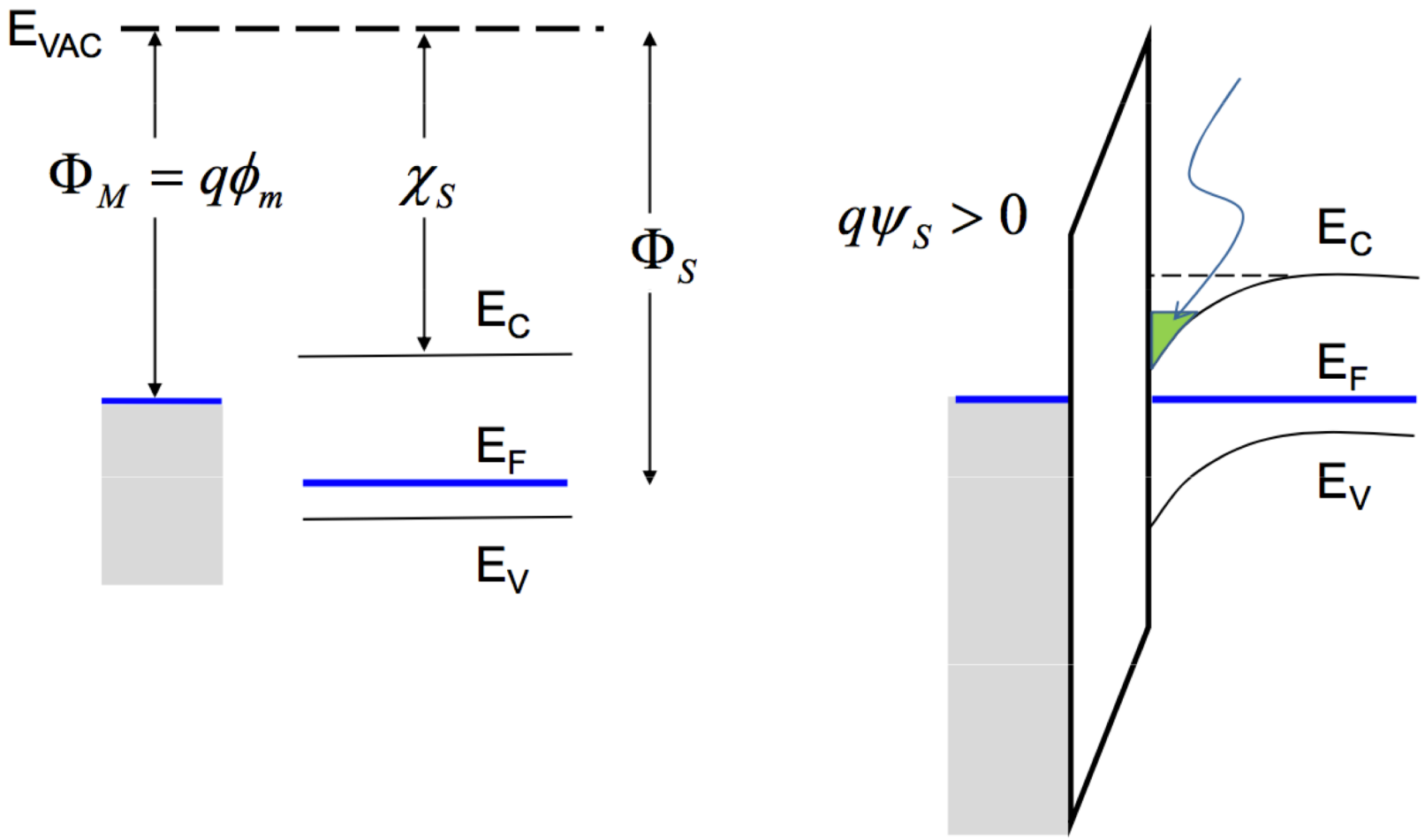
电势，电场与电荷





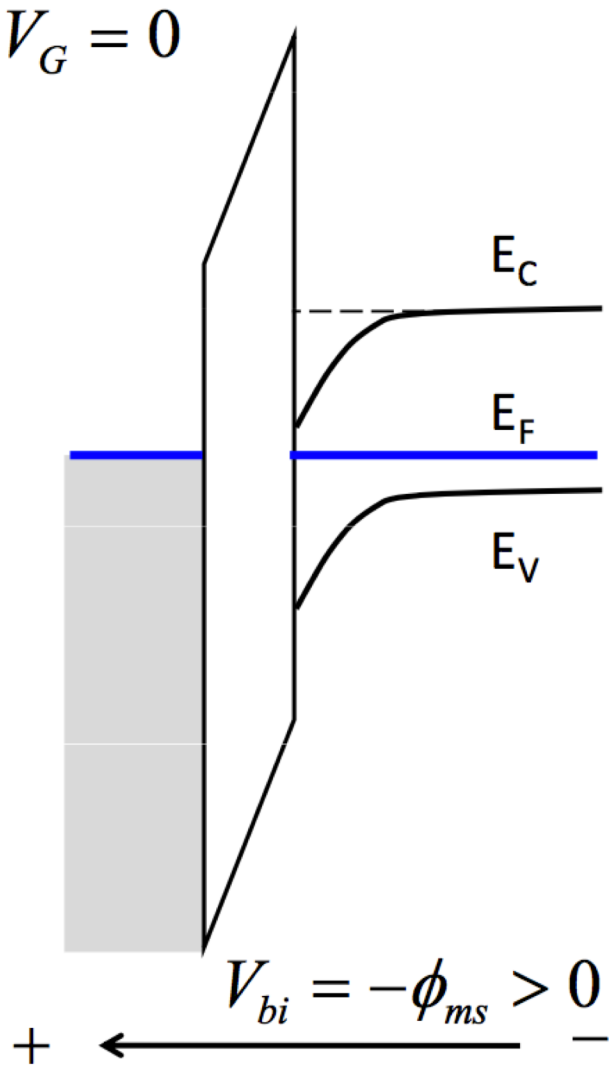
实际情况

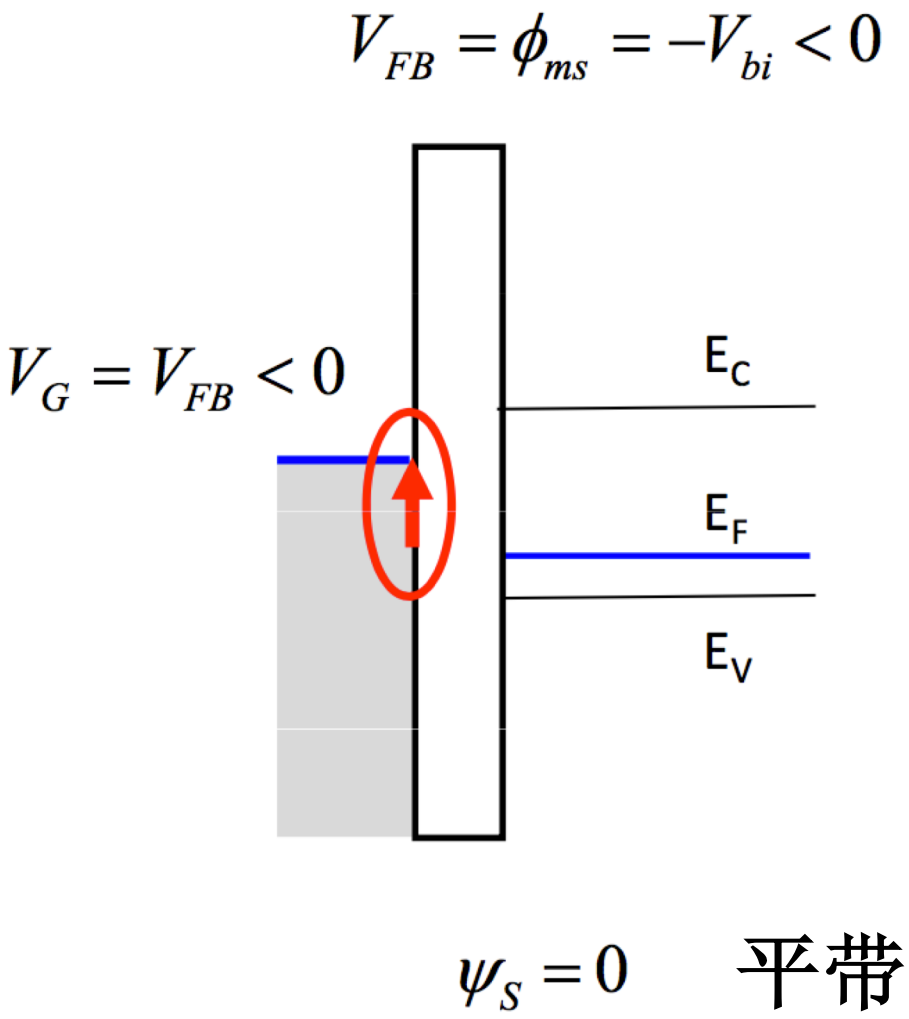
$\Phi_M < \Phi_S$



阈值电压Vth是增大还是减小？

平带电压的物理意义



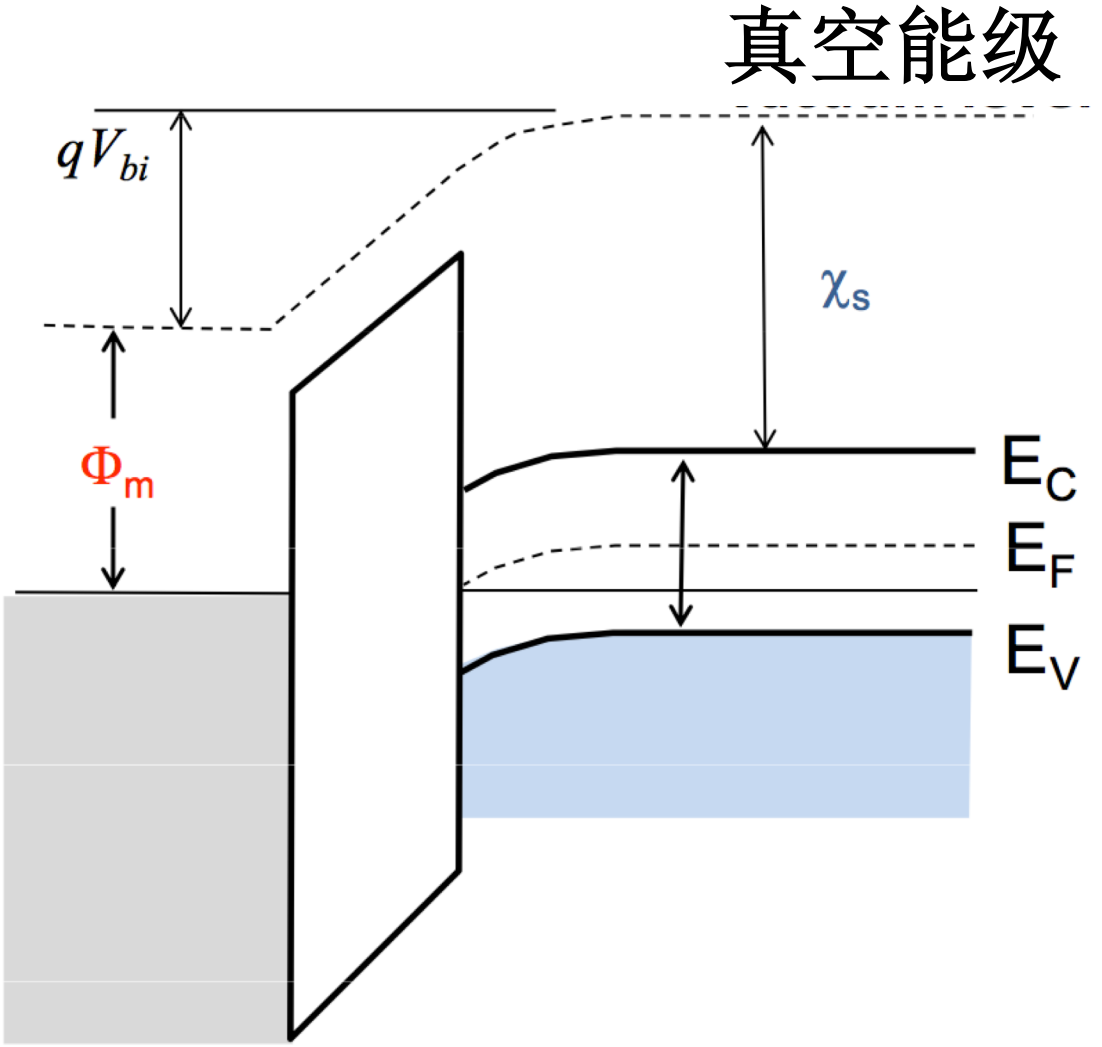


如何计算平带电压

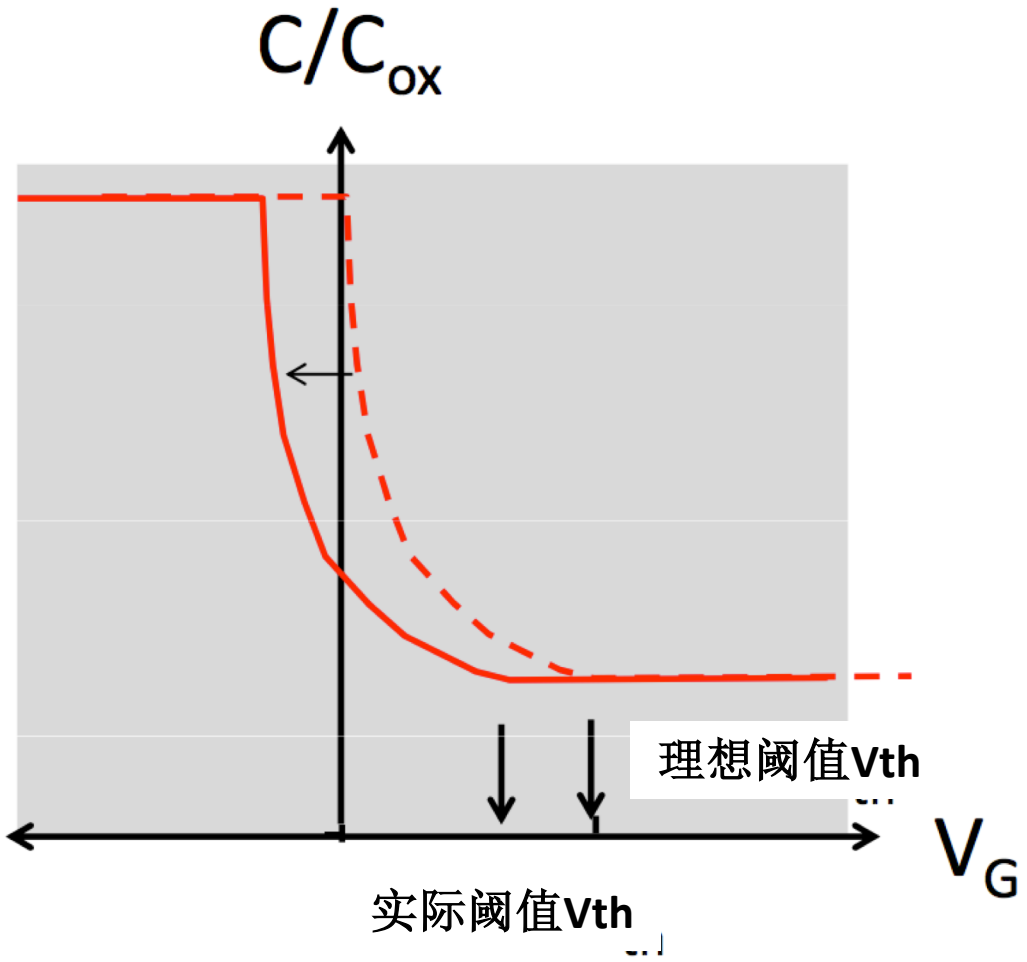
$$qV_{bi} = \left(\chi_s + E_g - \Delta_p\right) - \Phi_M$$
$$= qV_{FB} \equiv \phi_{MS}$$

$$Q_i = C_{ox}(V_G - V_{th})$$

$$V_{th} = \left(2\phi_F - \frac{Q_B}{C_{ox}}\right) + V_{FB}$$



平带电压的测量



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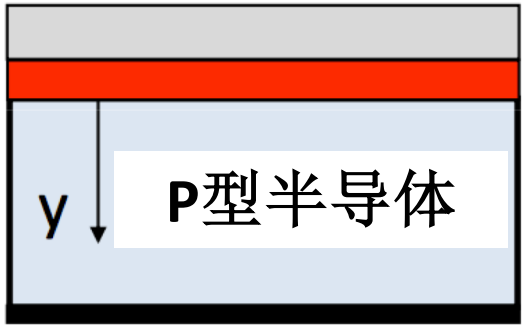
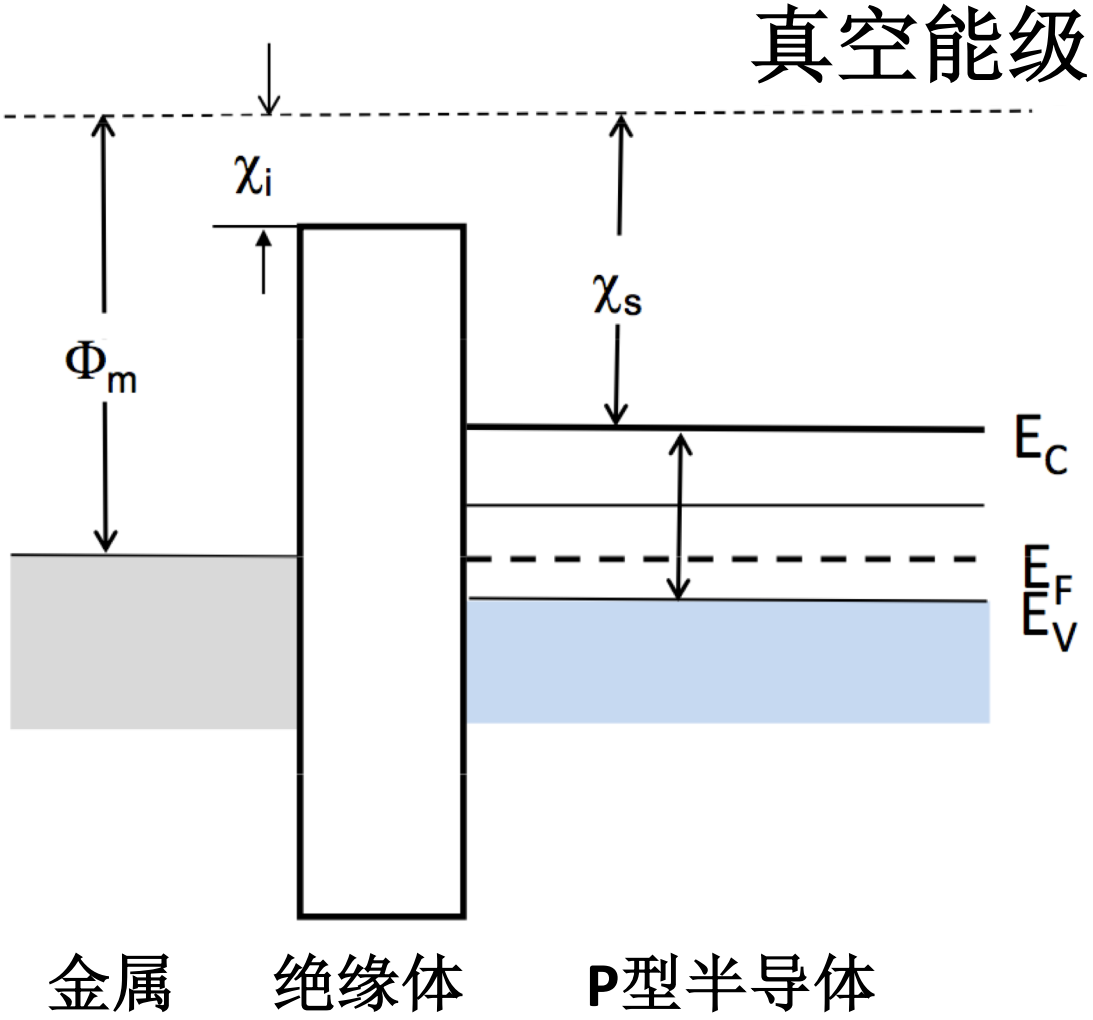
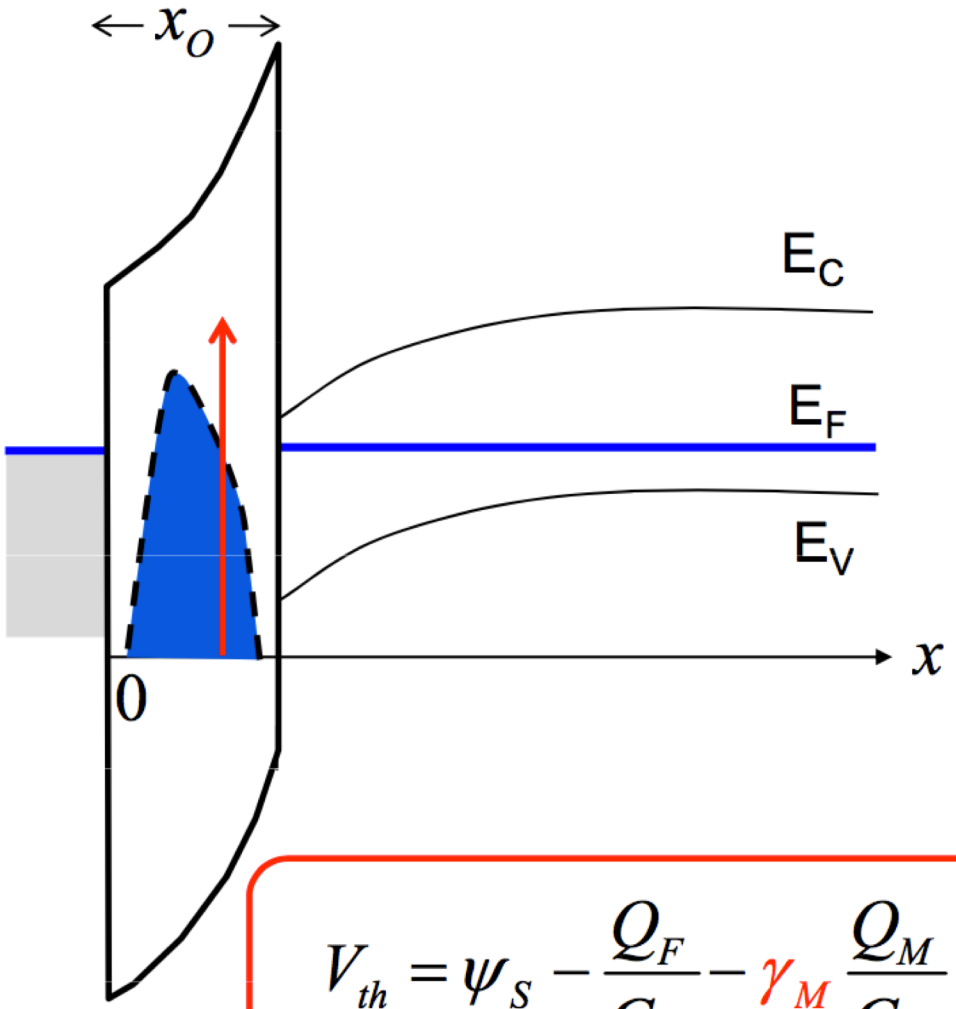




$$Q_i = C_{ox}(V_G - V_{th,ideal})$$

$$V_{th,ideal} = \psi_s - \left.\frac{Q_B}{C_{ox}}\right|_{\psi_s = 2\phi_F}$$

氧化层中有电荷



$$Q_M = \int_0^{X_O} \rho_{ox}(x)dx$$

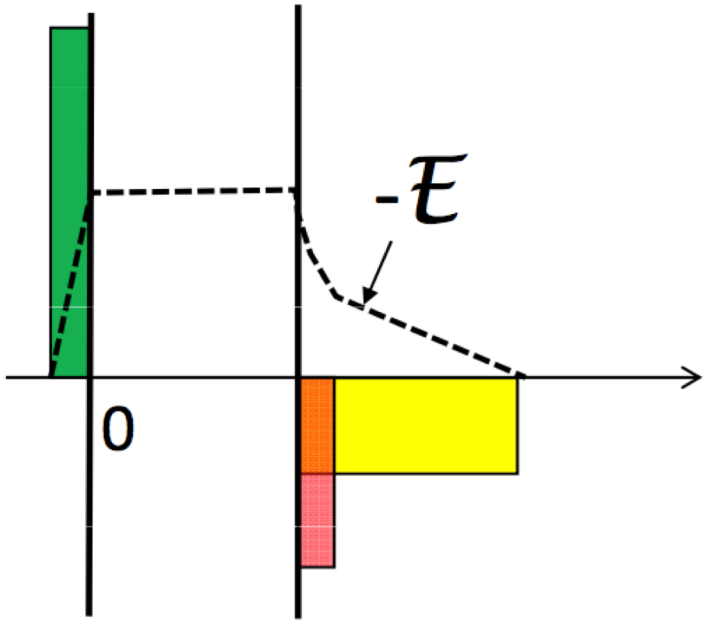
$$\gamma_M \equiv \frac{x_M}{x_0} = \frac{\int_0^{x_0} x\rho_{ox}(x)dx}{x_0 \int_0^{x_0} \rho_{ox}(x)dx}$$

$$V_{th} = \psi_S - \frac{Q_F}{C_{ox}} - \gamma_M \frac{Q_M}{C_{ox}}$$

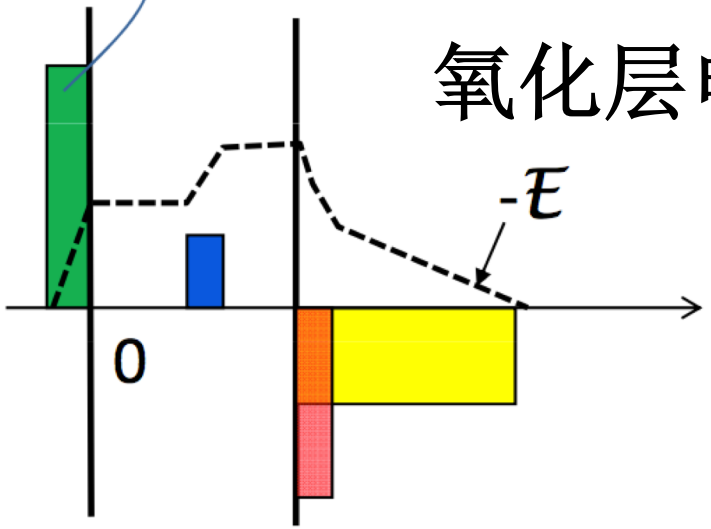
氧化层中有电荷

栅电荷减少

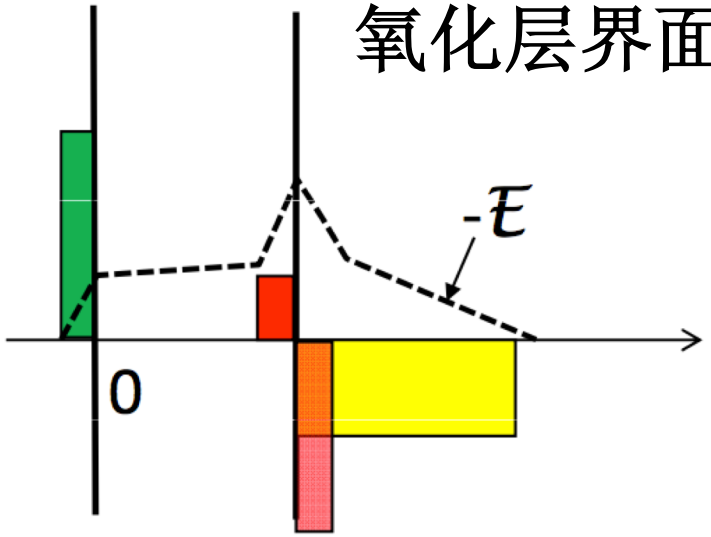
理想情况



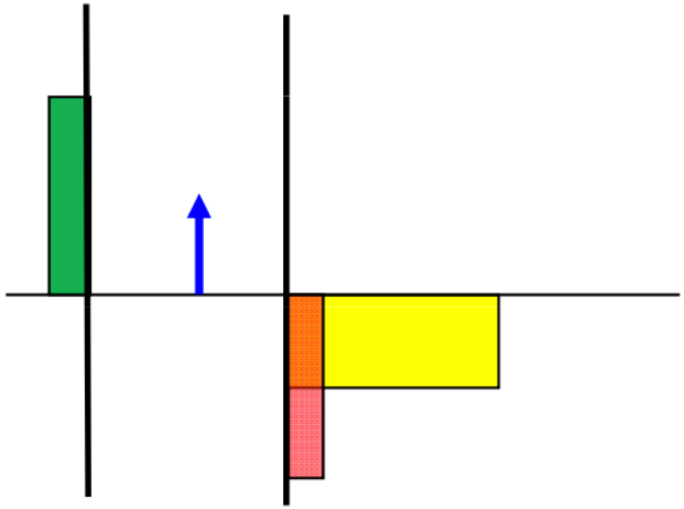
氧化层电荷



氧化层界面电荷

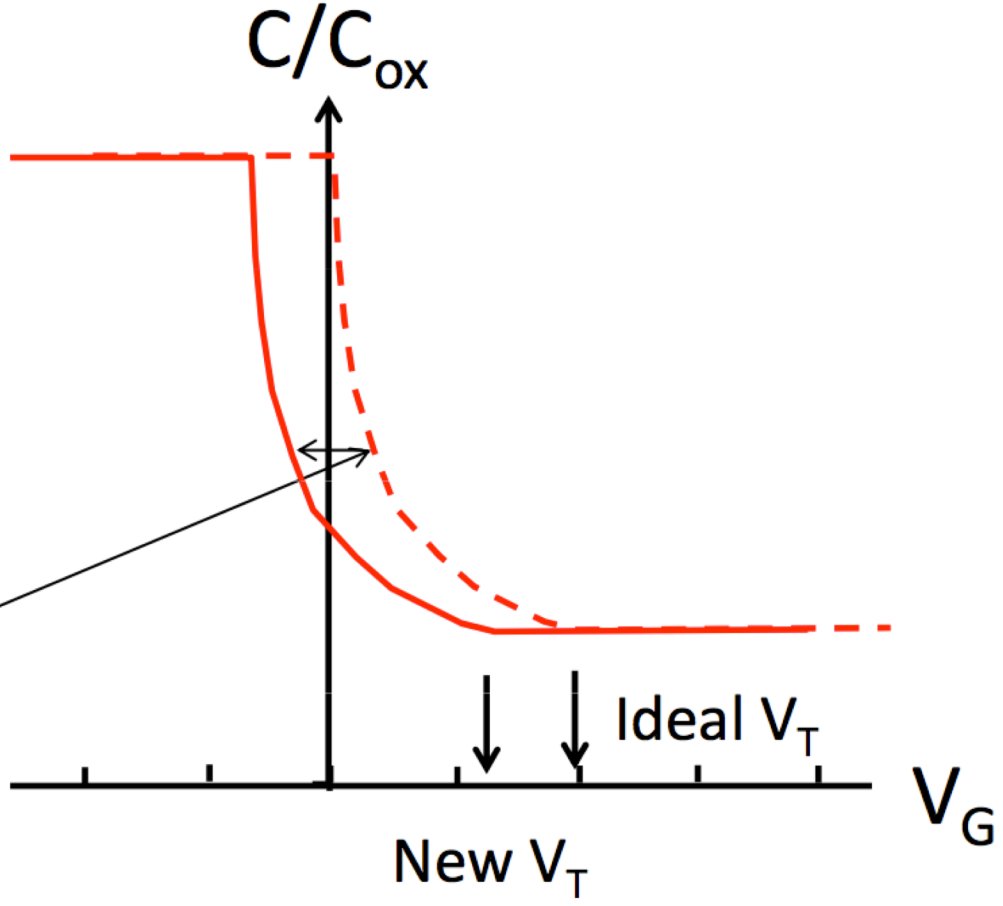


阈值漂移



$$V_{th} = V_{th,ideal} - \frac{1}{C_o x_0}\int_0^{x_0} x\rho_{ox}(x)\delta(x-x_1)dx$$

$$= V_{th,ideal} - \frac{x_1}{x_0}\frac{Q_M(x_1)}{C_o}$$



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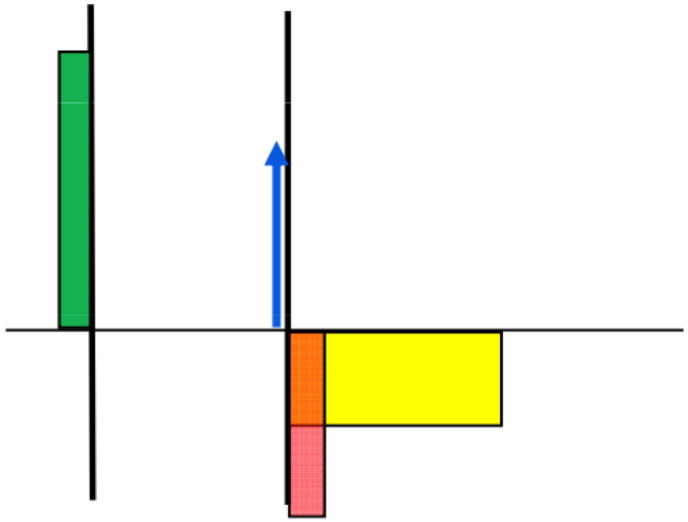
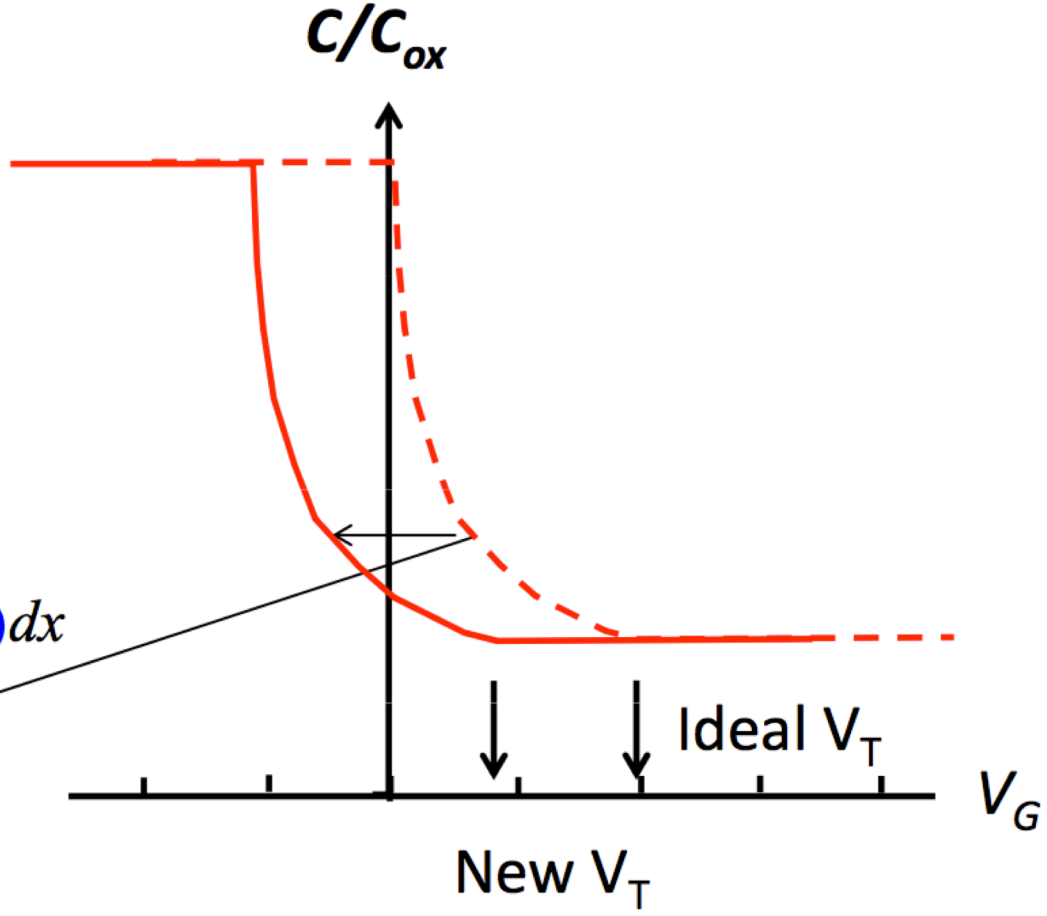
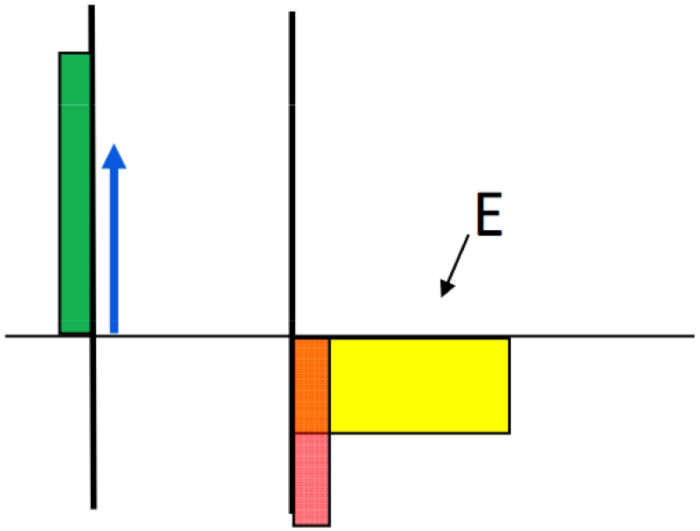


$$V_{th} = V_{th}^{*} - \frac{1}{C_o x_0}\int_0^{x_0} x\rho_{ox}(x)\delta(x - x_o)dx$$

$$= V_{th}^{*} - \frac{Q_F}{C_o}$$

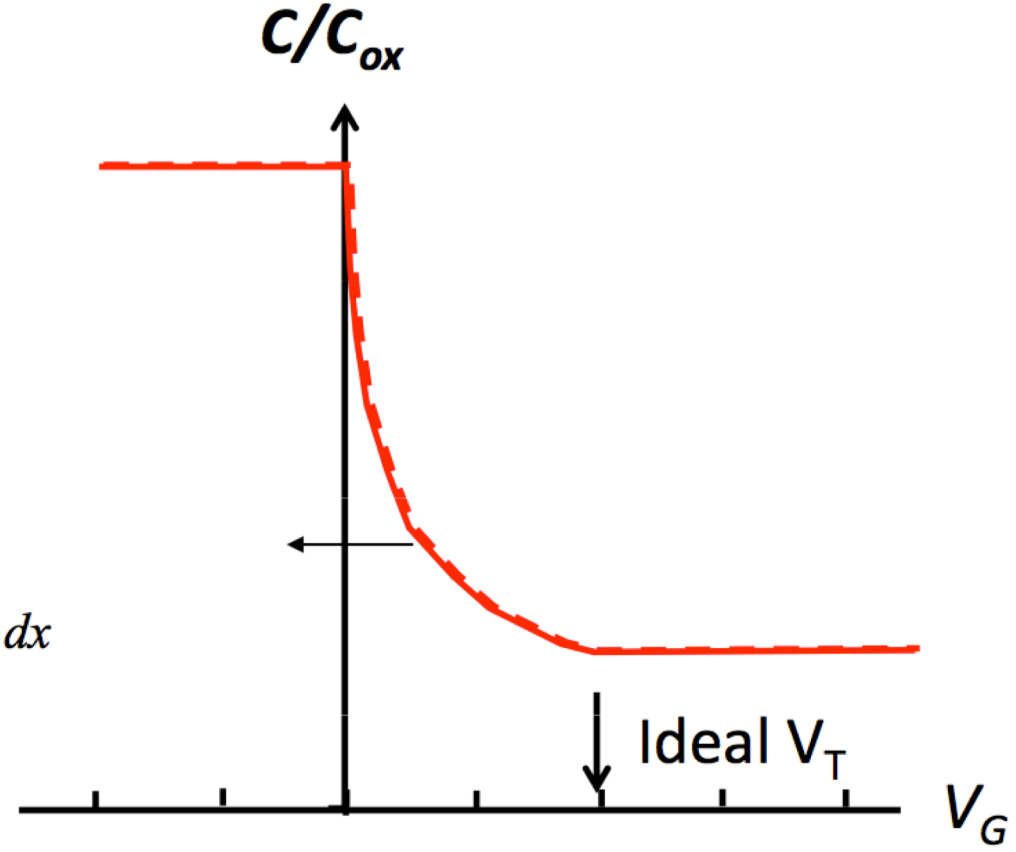


NaCl引起的阈值漂移



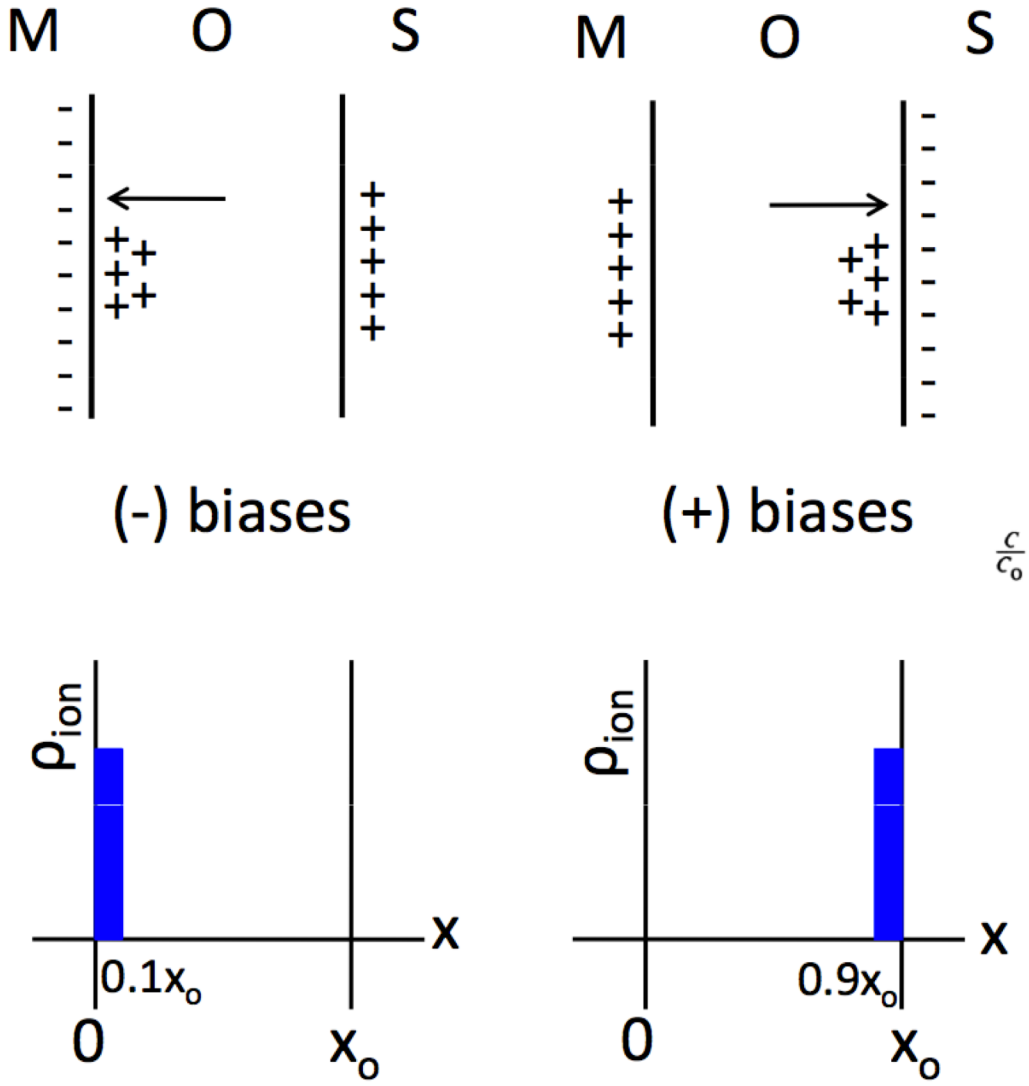
$$V_{th} = V_{th,ideal} - \frac{1}{C_{ox}x_0}\int_0^{x_0} xQ_{ox}(x) \times \delta(x - x_1(t))dx$$

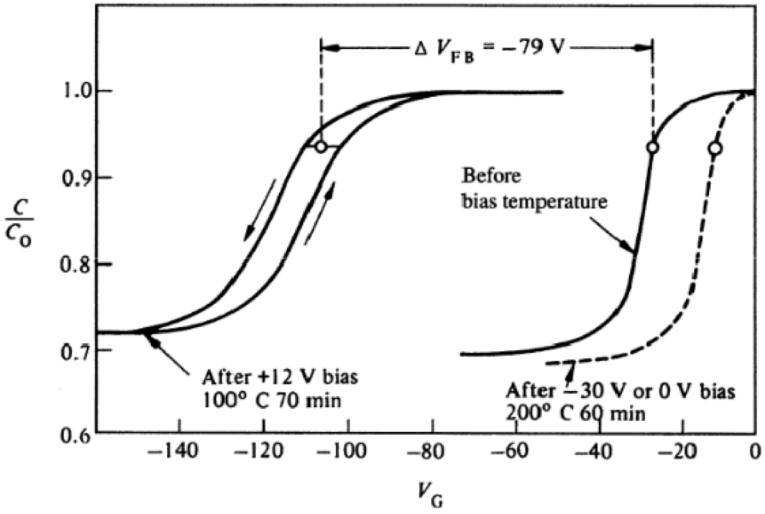
$$= V_{th,ideal} - \frac{x_1(t)}{x_0} \times \frac{Q_{ox}(x)}{C_{ox}}$$



Na离子引起的温度偏压不稳定性

温度偏压不稳定性


M O S
M O S
(-) biases
(+) biases
ρ_{ion}
ρ_{ion}
x
x
$0.1x_o$
$0.9x_o$
0
0
x_o
x_o


$\Delta V_{FB} = -79$ V
1.0
0.9
0.8
0.7
0.6
$\frac{C}{C_o}$
Before
bias temperature
After +12 V bias
100° C 70 min
After −30 V or 0 V bias
200° C 60 min
−140
−120
−100
−80
−60
−40
−20
0
V_G

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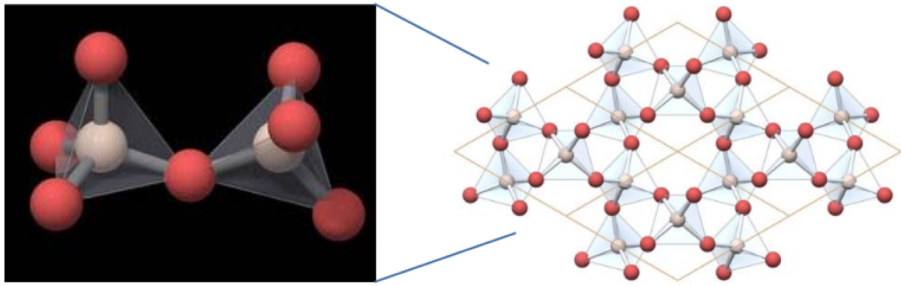
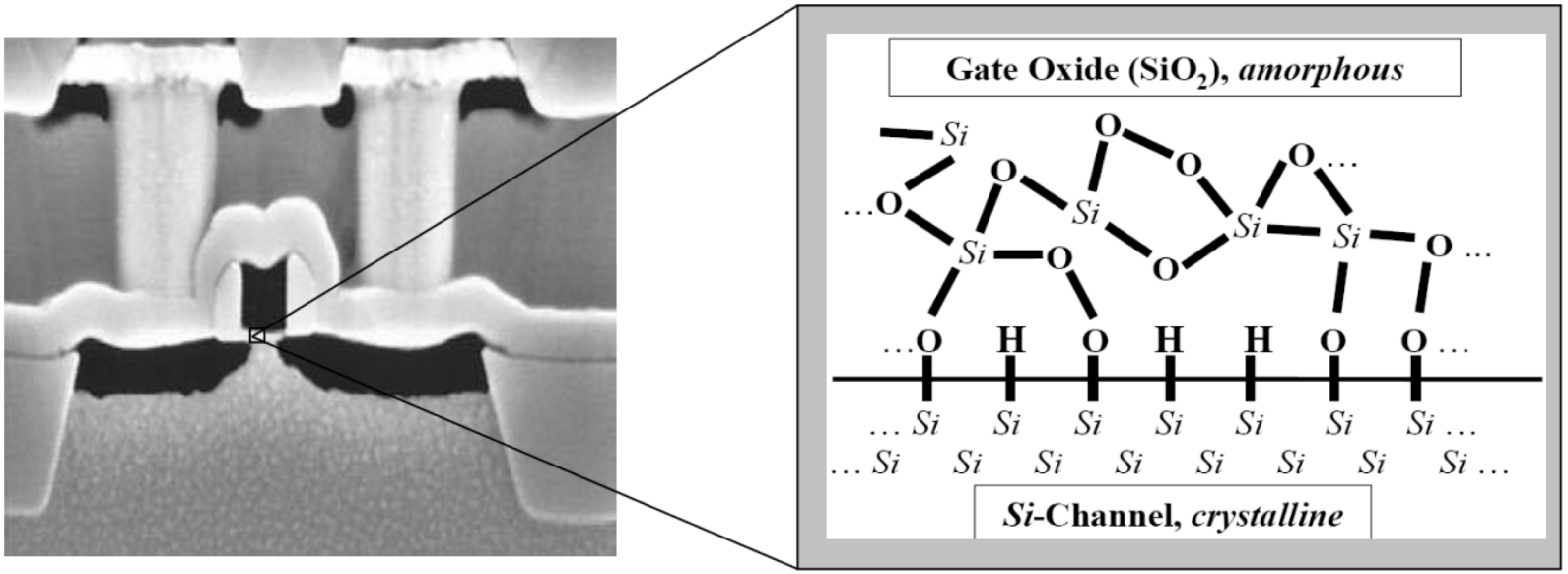
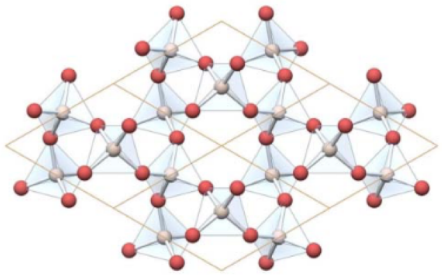
Si-O键和Si-H键

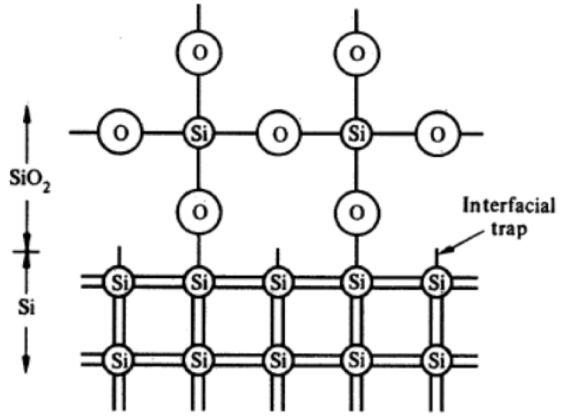
Google image

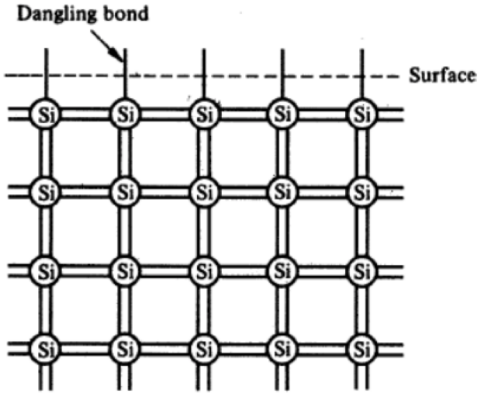


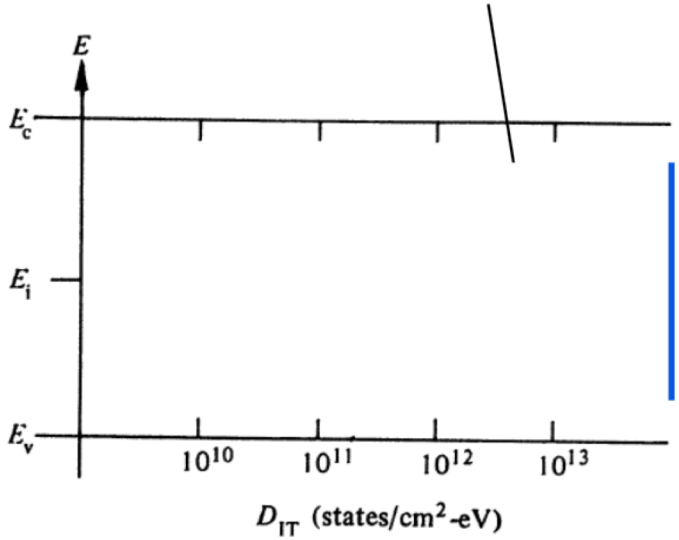


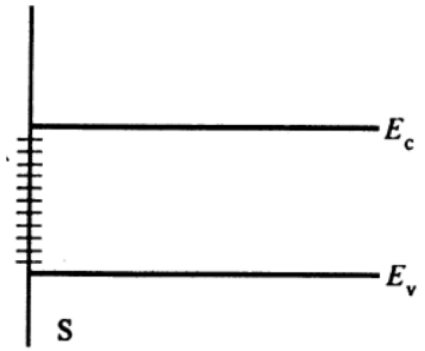


界面态


O
Si
SiO_2
Si
Interfacial trap

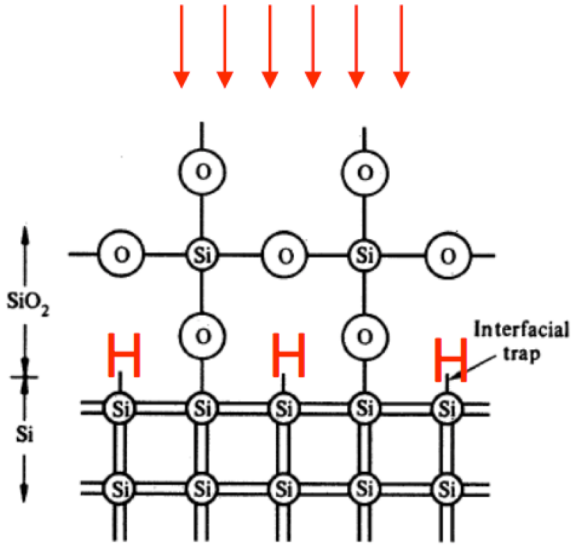

Dangling bond
Surface
Si

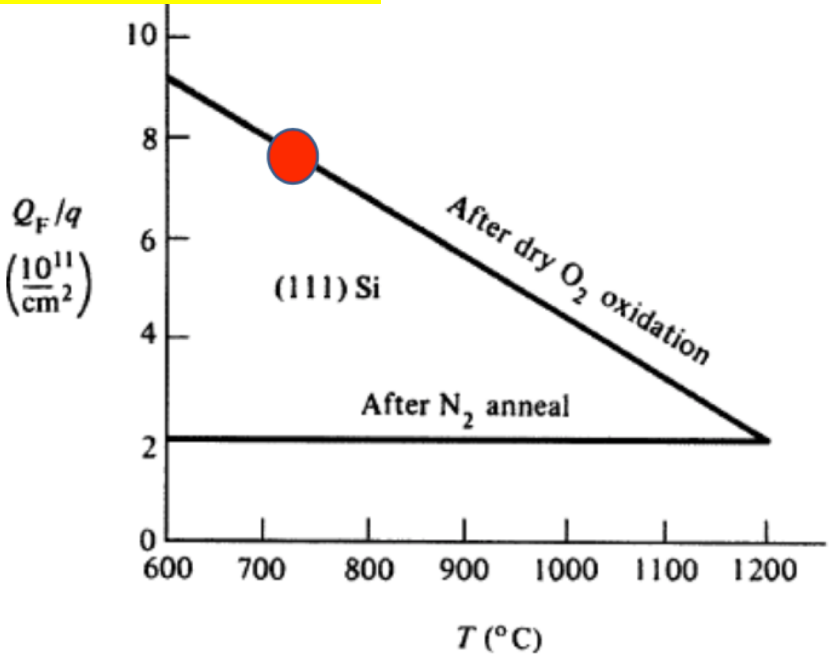

E
E_c
E_i
E_v
10^{10}
10^{11}
10^{12}
10^{13}
D_{IT} (states/cm^2-eV)

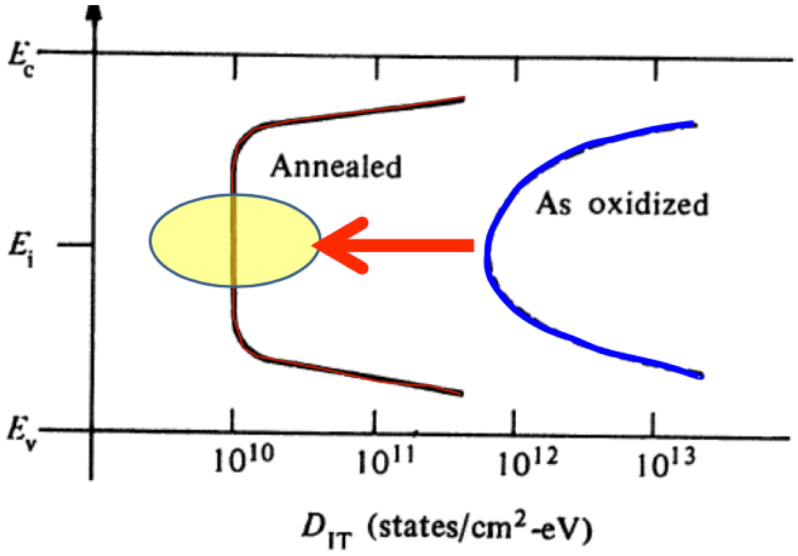

E_c
E_v
S

退火减少界面态

Forming gas anneal

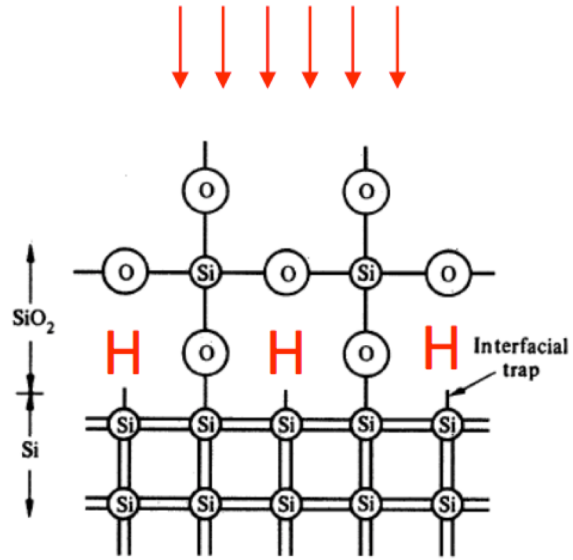


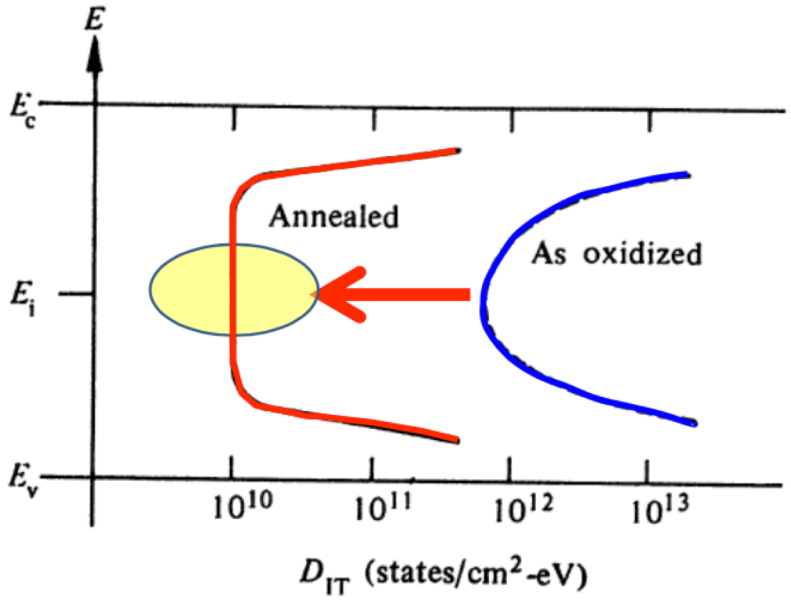


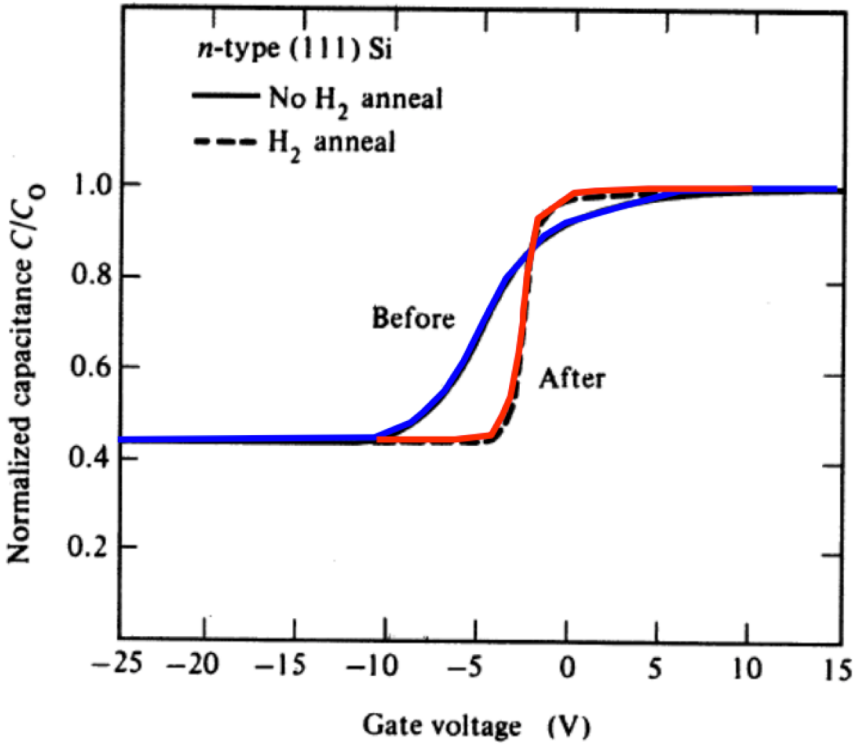


C-V测试

Forming gas anneal







Thanks!
Q&A