



第6章 MOSFET的电气特性

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- ❖6.1 MOS物理学
- ❖6.2 nFET电流-电压方程
- ❖6.3 FET的RC模型
- ❖6.4 pFET特性
- ❖6.5 小尺寸MOSFET模型

§ 6.1 MOS物理学



NMOS的电流和电压

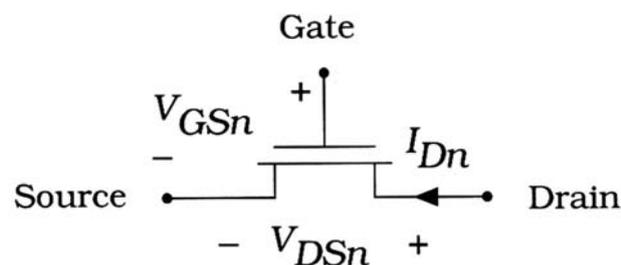


Figure 6.1 nFET current and voltages

$$I_{Dn} = I_{Dn}(V_{GSn}, V_{DSn})$$

§ 6.1 MOS物理学



MOS的结构

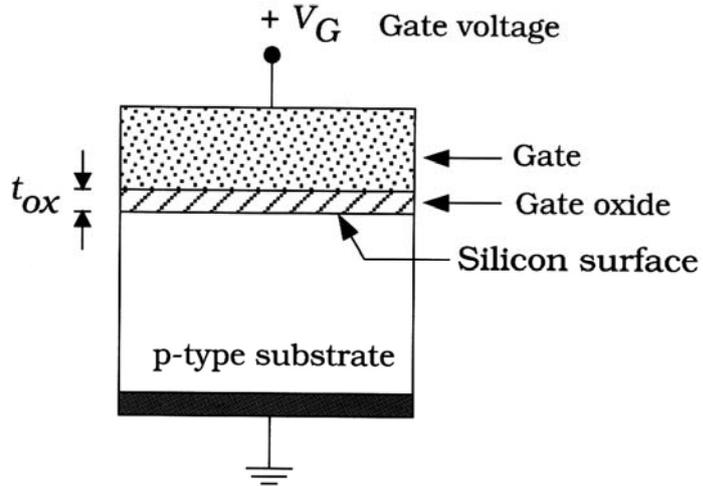


Figure 6.2 Structure of the MOS system

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} \quad \epsilon_{ox} = 3.9\epsilon_0, \epsilon_0 = 8.854 \times 10^{-14} \text{ F/cm}$$

§ 6.1 MOS物理学



MOS的结构中的电压

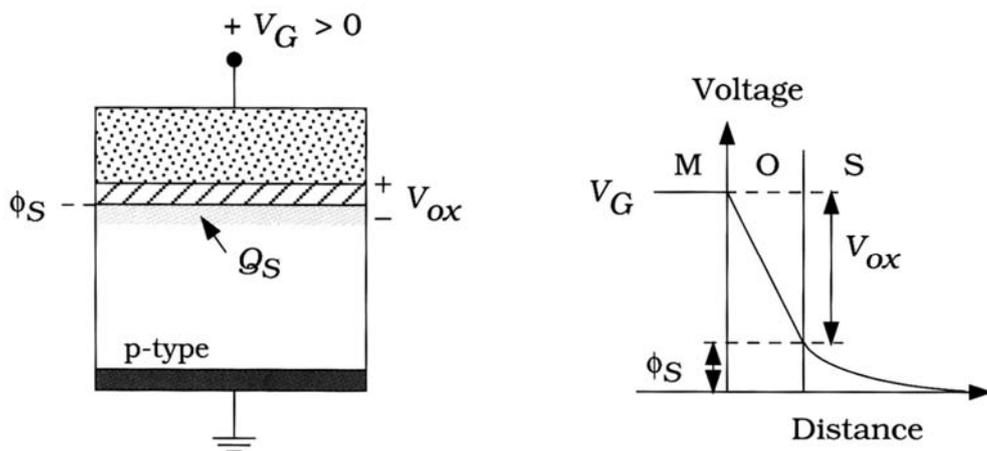


Figure 6.4 Voltages in the MOS system

$$V_G = V_{ox} + \phi_S \quad V_{ox}: \text{氧化层的电压降}; \phi_S: \text{表面电势}$$

$$Q_S = -C_{ox} V_{ox} \quad Q_S: \text{表面电荷密度, 单位: C/cm}^2$$

§ 6.1 MOS物理学



MOS结构中的体(耗尽)电荷

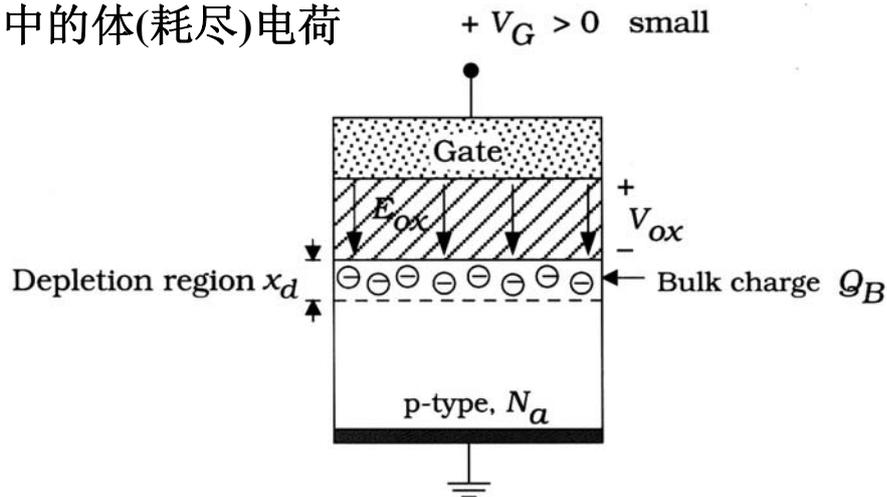


Figure 6.6 Bulk (depletion) charge in the MOS system

$$Q_B = -\sqrt{2q\epsilon_{Si}N_a\phi_s} \quad Q_B: \text{体电荷密度, 单位: C/cm}^2$$

$$\epsilon_{Si} = 11.8\epsilon_0; N_a: \text{衬底掺杂浓度}$$

§ 6.1 MOS物理学



MOS的结构中的电子电荷

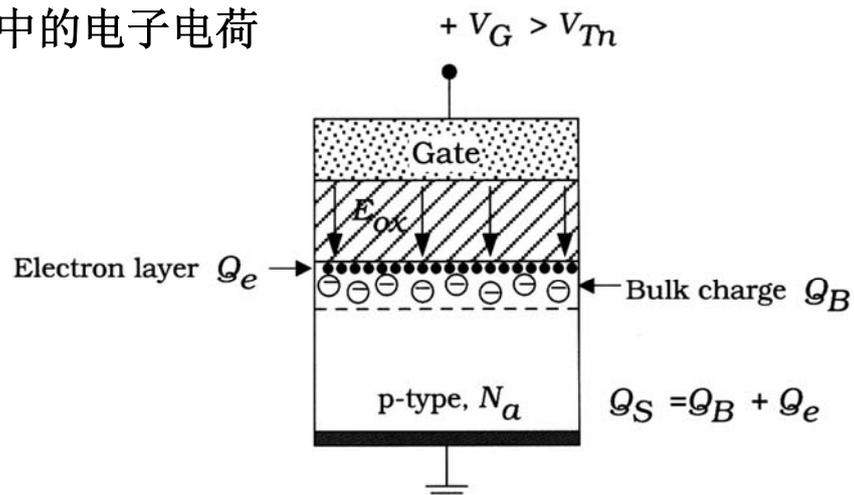


Figure 6.7 Formation of the electron charge layer

$$Q_S = Q_B + Q_e \quad Q_e: \text{反型层电子密度}$$

$$V_G > V_{Tn} \text{ 时, } Q_e = -C_{ox}(V_G - V_{Tn})$$



阈值电压公式

阈值电压：衬底表面形成强反型时的栅源电压。

强反型：反型层中的载流子浓度与衬底的多数载流子浓度相等。

当表面电势 $\phi_s = 2|\phi_F|$ 时，衬底表面出现强反型

$$|\phi_F|: \text{体费米电势}, |\phi_F| = \left(\frac{kT}{q} \right) \ln \left(\frac{N_a}{n_i} \right)$$

§ 6.1 MOS物理学



理想MOS结构的阈值电压

理想MOS：栅和衬底材料一样，氧化层没有电荷

$$V_{Tn} = \frac{1}{C_{ox}} \sqrt{2q\epsilon_{Si}N_a(2|\phi_F|)} + 2|\phi_F|$$

实际MOS结构的阈值电压

$$V_{Tn} = \frac{1}{C_{ox}} \sqrt{2q\epsilon_{Si}N_a(2|\phi_F|)} + 2|\phi_F| + V_{FB} \quad V_{FB}: \text{平带电压}$$

调整后的阈值电压公式

$$V_{Tn} = \frac{1}{C_{ox}} \sqrt{2q\epsilon_{Si}N_a(2|\phi_F|)} + 2|\phi_F| + V_{FB} + \frac{qD_I}{C_{ox}}$$

D_I : 注入剂量，即每平方厘米注入的离子数



§ 6.1 MOS物理学

例：已知 $T = 300\text{K}$, $N_a = 10^{15} / \text{cm}^3$, $t_{ox} = 50 \text{ \AA} = 50 \times 10^{-8} \text{ cm}$, $V_{FB} = -0.85\text{V}$, $D_I = 4 \times 10^{12} / \text{cm}^2$, 求 V_{Tn} 。

解： $\frac{kT}{q} = 0.026\text{V}$ $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.9 \times 8.854 \times 10^{-14}}{50 \times 10^{-8}} = 0.69 \times 10^{-6} \text{ F/cm}^2$

$$2|\phi_F| = 2 \times \frac{kT}{q} \times \ln \frac{N_a}{n_i} = 2 \times 0.026 \times \ln \frac{10^{15}}{1.45 \times 10^{10}} = 0.579\text{V}$$

$$\frac{1}{C_{ox}} \sqrt{2q\epsilon_{Si}N_a(2|\phi_F|)}$$

$$= \frac{1}{0.69 \times 10^{-6}} \times \sqrt{2 \times 1.6 \times 10^{-19} \times 11.8 \times 8.854 \times 10^{-14} \times 10^{15} \times 0.579} = 0.02\text{V}$$

$$\frac{qD_I}{C_{ox}} = \frac{1.6 \times 10^{-19} \times 4 \times 10^{12}}{0.69 \times 10^{-6}} = 0.928\text{V}$$

$$V_{Tn} = 0.02 + 0.579 - 0.85 + 0.928 = 0.677\text{V}$$



§ 6.1 MOS物理学

§ 6.2.2 体偏置效应

当源和体（衬底）之间存在 $V_{SBn} > 0$ 时

$$V_{Tn} = V_{T0n} + \gamma(\sqrt{2|\phi_F| + V_{SBn}} - \sqrt{2|\phi_F|})$$

体偏置系数： $\gamma = \frac{\sqrt{2q\epsilon_{Si}N_a}}{C_{ox}}$ ，单位 $\sqrt{\text{V}}$

体偏置效应使阈值电压增大！

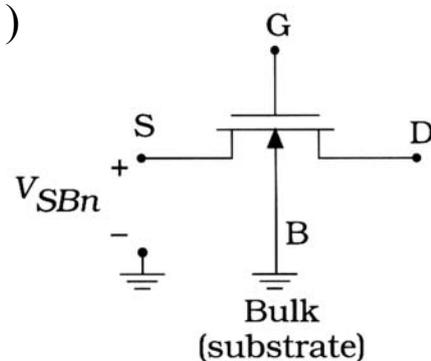


Figure 6.15 Bulk electrode and body-bias voltage

§ 6.1 MOS物理学

例6.3, 有一个nFET, 它的 $V_{T0n} = 0.70\text{V}$, $\gamma = 0.08\text{V}^{1/2}$, $2|\phi_F| = 0.58\text{V}$ 。
 阈值电压与体偏置电压 V_{SBn} 的关系为

$$V_{Tn} = 0.70 + 0.08(\sqrt{0.58 + V_{SBn}} - \sqrt{0.58})$$

$V_{SBn}(\text{V})$	$V_{Tn}(\text{V})$
0	0.70
1	0.74
2	0.77
3	0.79

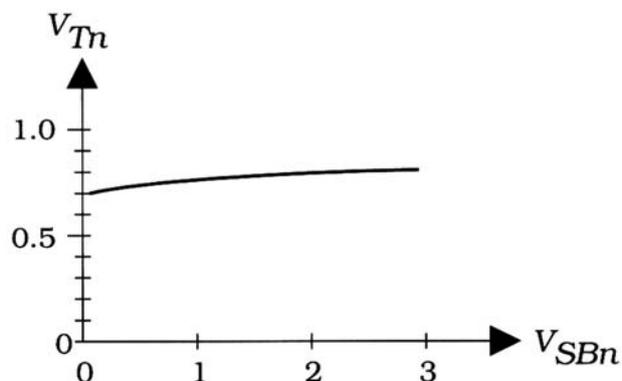


Figure 6.16 Body-bias effect

§ 6.2 nFET电流—电压方程

NMOS结构细节

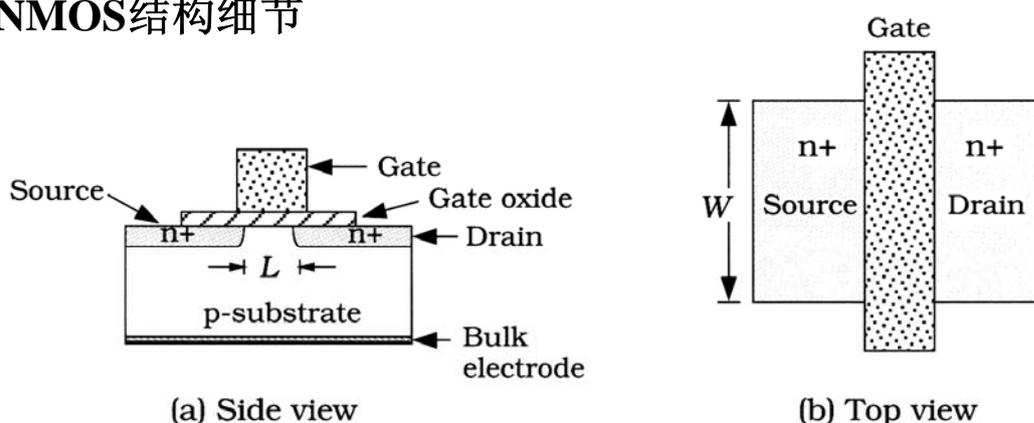


Figure 6.8 Details of the nFET structure

注: 本章讨论中所用的 W 和 L 值是从电气上考虑的尺寸即“有效”值, 不是版图设计时所画的尺寸。

$$L = L' - \Delta L \quad W = W' - \Delta W$$

§ 6.2 nFET电流—电压方程



NMOS电流—电压方程

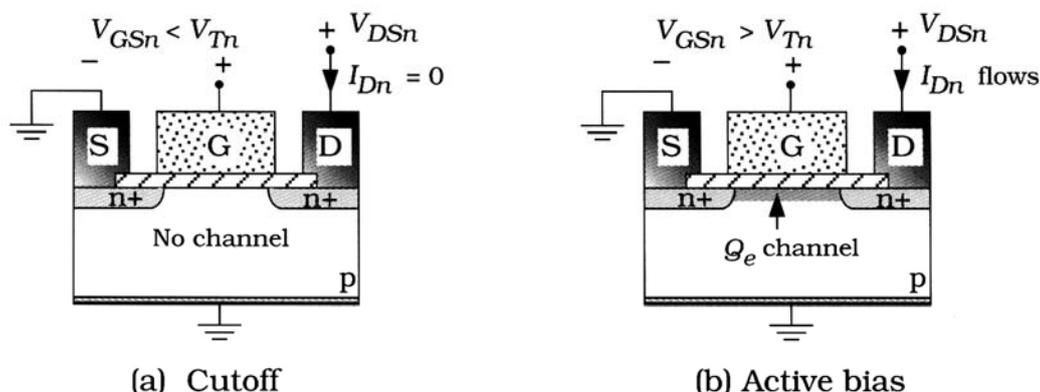


Figure 6.10 Controlling the channel in an nFET

§ 6.2 nFET电流—电压方程



NMOS电流—电压方程

截止区: $V_{GSn} < V_{Tn} \quad I_{Dn} = 0$

非饱和区 (线性区): $V_{GSn} - V_{Tn} > V_{DSn} > 0$

$$I_{Dn} = \mu_n C_{ox} \left(\frac{W}{L} \right) \left[(V_{GSn} - V_{Tn}) V_{DSn} - \frac{V_{DSn}^2}{2} \right] = \frac{\beta_n}{2} [2(V_{GSn} - V_{Tn}) V_{DSn} - V_{DSn}^2]$$

饱和区: $V_{DSn} > V_{GSn} - V_{Tn} > 0$

$$I_{Dn} = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L} \right) (V_{GSn} - V_{Tn})^2 = \frac{\beta_n}{2} (V_{GSn} - V_{Tn})^2$$

器件互导: $\beta_n = k_n' \left(\frac{W}{L} \right)$ 工艺互导: $k_n' = \mu_n C_{ox} = \frac{\mu_n \epsilon_{ox}}{t_{ox}}$



§ 6.2 nFET电流—电压方程

例6.1: 一个nFET, 其栅氧层厚度为 $t_{ox} = 12\text{nm}$,
电子迁移率为 $\mu_n = 540\text{cm}^2/(\text{V}\cdot\text{s})$

每 cm^2 的氧化层电容为

$$C_{ox} = \frac{3.9\epsilon_0}{t_{ox}} = \frac{3.9 \times 8.854 \times 10^{-14}}{1.2 \times 10^{-6}} = 2.88 \times 10^{-7} \text{F/cm}^2$$

工艺互导为

$$k'_n = \mu_n C_{ox} = 540 \times 2.88 \times 10^{-7} = 1.55 \times 10^{-4} \text{A/V}^2 = 155 \mu\text{A/V}^2$$

若氧化层厚度为 $t_{ox} = 8\text{nm}$,

则工艺互导为 $k'_n = 233 \mu\text{A/V}^2$, 说明器件更加灵敏。



§ 6.2 nFET电流—电压方程

例6.2: 一个具有下列特性的n沟道MOSFET:

$$t_{ox} = 10\text{nm}, \mu_n = 520\text{cm}^2/(\text{V}\cdot\text{s}), (W/L) = 8, V_{Tn} = 0.7\text{V},$$

氧化层电容

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.9 \times 8.854 \times 10^{-14}}{10 \times 10^{-7}} = 3.453 \times 10^{-7} \text{F/cm}^2$$

工艺互导为

$$k'_n = \mu_n C_{ox} = 520 \times 3.453 \times 10^{-7} = 1.8 \times 10^{-4} \text{A/V}^2 = 180 \mu\text{A/V}^2$$

$$\text{器件互导为 } \beta_n = k'_n \left(\frac{W}{L}\right) = 180 \mu\text{A} \times 8 = 1.44 \text{mA/V}^2$$



§ 6.2 nFET电流—电压方程

若nFET的电压 $V_{GSn} = 2V, V_{DSn} = 2V,$

$$V_{GSn} - V_{Tn} = 2 - 0.7 = 1.3V < V_{DSn} = 2V$$

nFET饱和, 所以

$$I_{Dn} = \frac{\beta_n}{2} (V_{GSn} - V_{Tn})^2 = \frac{1.44}{2} (2 - 0.7)^2 = 1.217mA$$

若nFET的电压 $V_{GSn} = 2V, V_{DSn} = 1.2V,$

$$V_{GSn} - V_{Tn} = 2 - 0.7 = 1.3V > V_{DSn} = 1.2V$$

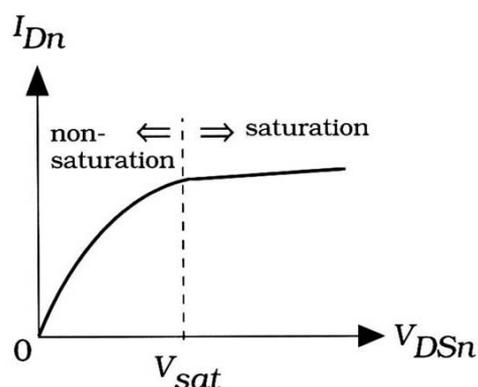
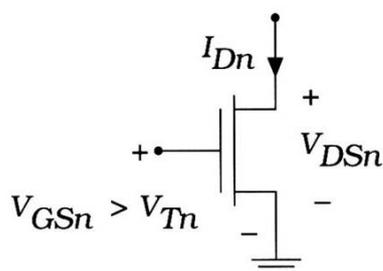
nFET非饱和, 所以

$$\begin{aligned} I_{Dn} &= \frac{\beta_n}{2} [2(V_{GSn} - V_{Tn})V_{DSn} - V_{DSn}^2] \\ &= \frac{1.44}{2} (2 \times 1.3 \times 1.2 - 1.2^2) = 1.210mA \end{aligned}$$



§ 6.2 nFET电流—电压方程

❖ 沟道长度调制效应



$$I_{Dn} \approx \frac{\beta_n}{2} (V_{GSn} - V_{Tn})^2 [1 + \lambda(V_{DSn} - V_{sat})]$$

λ : 沟道长度调制参数

饱和电压: $V_{sat} = V_{DSn} |_{\text{peak current}} = V_{GSn} - V_{Tn}$

§ 6.2 nFET 电流—电压方程

§ 6.2.1 SPICE Level 1 方程

$V_{GSn} < V_{Tn}$ 时:

$$I_{Dn} = 0$$

$V_{DSn} \leq V_{sat}$ 时:

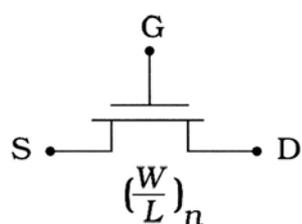
$$I_{Dn} = \frac{\beta_n}{2} [2(V_{GSn} - V_{Tn})V_{DSn} - V_{DSn}^2] (1 + \lambda V_{DSn})$$

$V_{DSn} \geq V_{sat}$ 时:

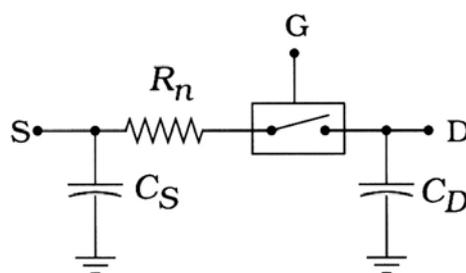
$$I_{Dn} = \frac{\beta_n}{2} (V_{GSn} - V_{Tn})^2 (1 + \lambda V_{DSn})$$

§ 6.3 FET 的 RC 模型

NMOS 的线性模型



(a) nFET Symbol



(b) Linear model for nFET

Figure 6.19 RC model of an nFET

§ 6.3 FET的RC模型



§ 6.3.1 漏源FET电阻

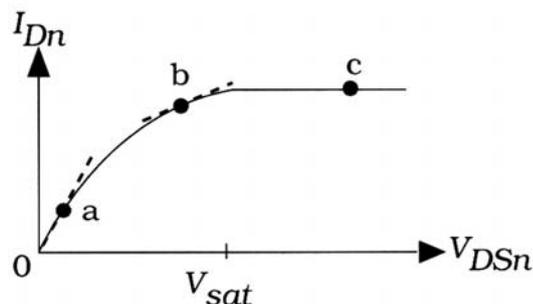
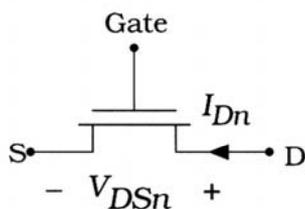


Figure 6.20 Determining the nFET resistance.

a点:
$$I_{Dn} = \frac{\beta_n}{2} [2(V_{GSn} - V_{Tn})V_{DSn} - V_{DSn}^2]$$

当 $V_{DSn} \ll 2(V_{GSn} - V_{Tn})$ 时: $I_{Dn} \approx \beta_n (V_{GSn} - V_{Tn})V_{DSn}$

$$R_n = \frac{V_{DSn}}{I_{Dn}} = \frac{1}{\beta_n (V_{GSn} - V_{Tn})}$$

§ 6.3 FET的RC模型

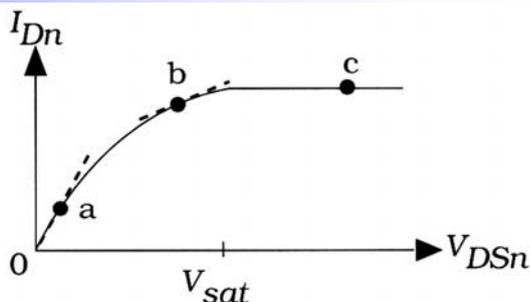
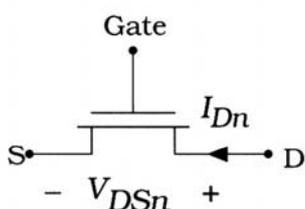


Figure 6.20 Determining the nFET resistance.

b点:
$$I_{Dn} = \frac{\beta_n}{2} [2(V_{GSn} - V_{Tn})V_{DSn} - V_{DSn}^2]$$

$$R_n = \frac{V_{DSn}}{I_{Dn}} = \frac{2}{\beta_n [2(V_{GSn} - V_{Tn}) - V_{DSn}]}$$

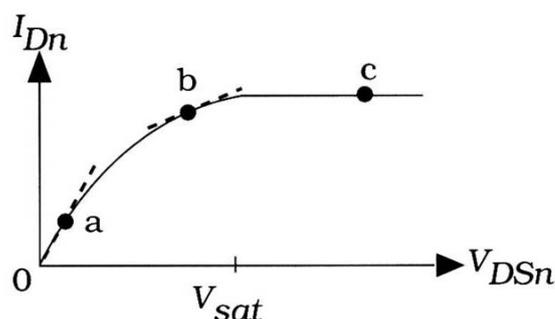
c点:
$$I_{Dn} = \frac{\beta_n}{2} (V_{GSn} - V_{Tn})^2 \quad R_n = \frac{V_{DSn}}{I_{Dn}} = \frac{2V_{DSn}}{\beta_n (V_{GSn} - V_{Tn})^2}$$

§ 6.3 FET的RC模型

a点: $R_n = \frac{V_{DSn}}{I_{Dn}} = \frac{1}{\beta_n (V_{GSn} - V_{Tn})}$

b点: $R_n = \frac{V_{DSn}}{I_{Dn}} = \frac{2}{\beta_n [2(V_{GSn} - V_{Tn}) - V_{DSn}]}$

c点: $R_n = \frac{V_{DSn}}{I_{Dn}} = \frac{2V_{DSn}}{\beta_n (V_{GSn} - V_{Tn})^2}$



简单公式：把电阻模拟成与晶体管宽长比有关的函数

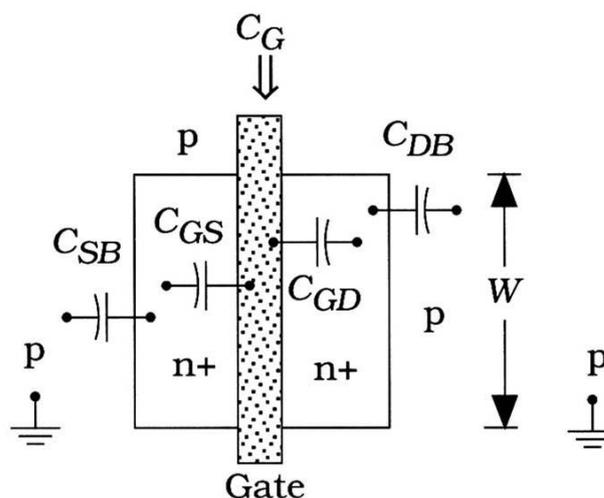
$$R_n = \frac{\eta}{\beta_n (V_{DD} - V_{Tn})}, \text{ 因子 } \eta = 1 \sim 6$$

简化公式，选择 $\eta = 1$: $R_n = \frac{1}{\beta_n (V_{DD} - V_{Tn})}$

§ 6.3 FET的RC模型

§ 6.3.2 FET电容

FET电容顶视图



•MOS电容: C_G, C_{GS}, C_{GD}

•结电容: C_{DB}, C_{SB}

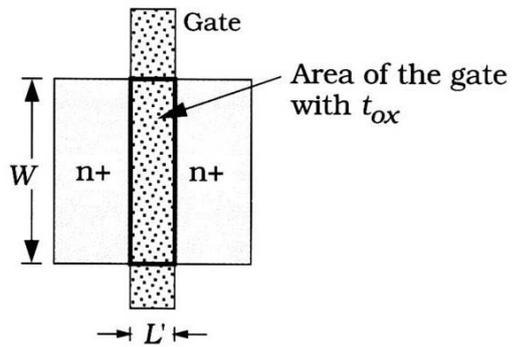
§ 6.3 FET的RC模型



1 MOS电容

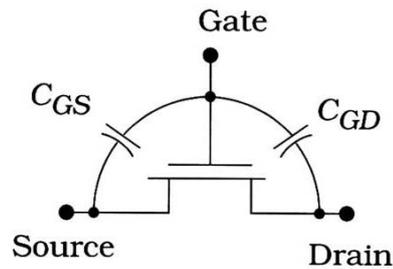
栅极电容:

$$C_G = C_{ox}WL'$$



栅源电容和栅漏电容:

$$C_{GD} \approx C_{GS} \approx \frac{1}{2}C_G$$



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§ 6.3 FET的RC模型



2 结电容

PN结零偏电容 C_0

$$C_0 = C_j A_{pn}$$

C_j : 单位面积零偏电容,

单位: F/cm^2

A_{pn} : PN结面积

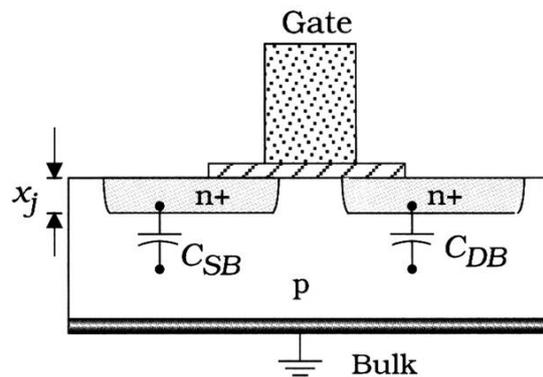


Figure 6.23 Junction capacitances in a MOSFET

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§ 6.3 FET的RC模型

FET的结电容

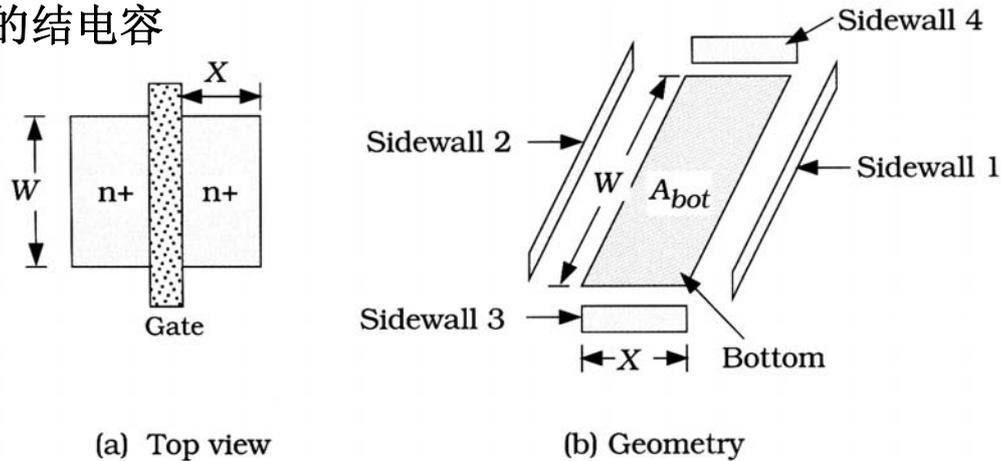


Figure 6.25 Calculation of the FET junction capacitance

底部电容 C_{bot} 底部面积: $A_{bot} = XW$
 底部电容: $C_{bot} = C_j A_{bot} = C_j XW$

§ 6.3 FET的RC模型

FET的结电容

侧壁电容 C_{sw}

侧壁面积:

$$A_{sw} = 2(W \times x_j) + 2(X \times x_j)$$

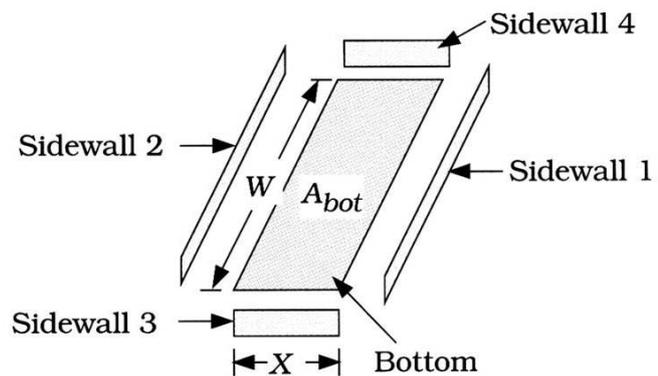
$$= x_j \times 2(W + X) = x_j P_{sw}$$

底部周长: $P_{sw} = 2(W + X)$

侧壁电容: $C_{sw} = C_j A_{sw} = C_j x_j P_{sw} = C_{jsw} P_{sw}$

C_{jsw} : 单位周长侧壁电容 $C_{jsw} = C_j x_j$

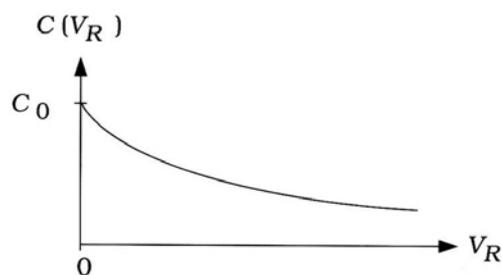
n+区的总零偏电容: $C_n = C_{bot} + C_{sw} = C_j A_{bot} + C_{jsw} P_{sw}$



§ 6.3 FET的RC模型

PN结加反偏压 V_R :
$$C = \frac{C_0}{\left(1 + \frac{V_R}{\phi_0}\right)^{m_j}}$$

ϕ_0 是结的内建电势:
$$\phi_0 = \frac{kT}{q} \ln\left(\frac{N_d N_a}{n_i^2}\right)$$



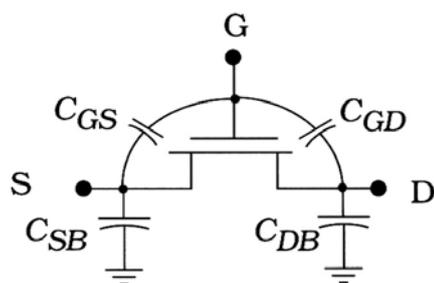
m_j 是结的台阶系数: 突变结 $m_j = 1/2$; 线性渐变结 $m_j = 1/3$

n+区的总反偏电容:
$$C_n = \frac{C_j A_{bot}}{\left(1 + \frac{V_R}{\phi_0}\right)^{m_j}} + \frac{C_{jsw} P_{sw}}{\left(1 + \frac{V_R}{\phi_{0sw}}\right)^{m_{jsw}}}$$

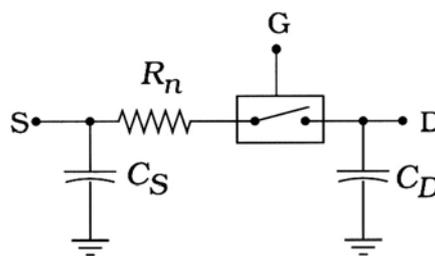
m_{jsw} 和 ϕ_{0sw} 是侧壁参数

§ 6.3 FET的RC模型

§ 6.3.3 模型建立



(a) nFET



(b) Linear model for nFET

Figure 6.27 Final construction of the nFET RC model

NMOS线性模型:

$$R_n = \frac{1}{\beta_n (V_{DD} - V_{Tn})}$$

$$C_S = C_{GS} + C_{SB}$$

$$C_D = C_{GD} + C_{DB}$$

§ 6.3 FET的RC模型



例6.6: 为图6.28中的nFET建立开关模型, 单位用微米 (μm) 表示。设电源电压 $V_{DD} = 3.3\text{V}$

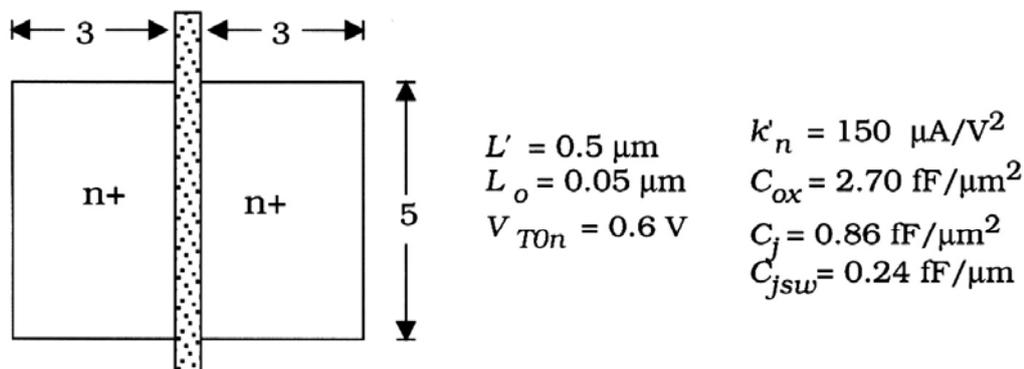
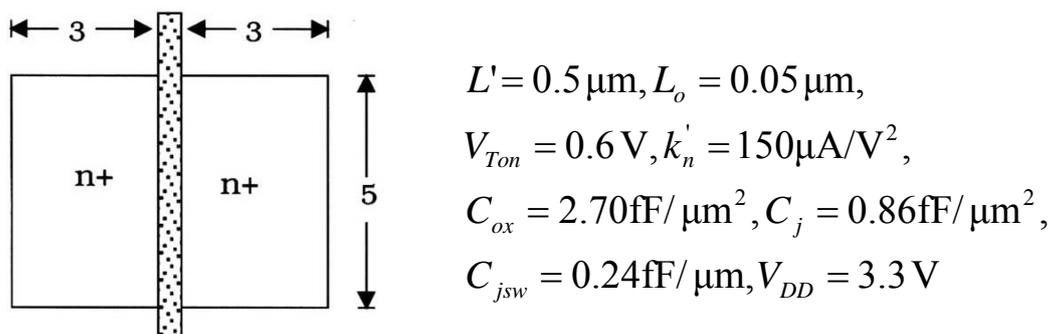


Figure 6.28 FET geometry for modeling example

§ 6.3 FET的RC模型



沟道电阻为:
$$R_n = \frac{1}{\frac{5}{0.4} \times 150 \times 10^{-6} \times (3.3 - 0.6)} = 197.5 \Omega$$

栅电容为:
$$C_G = 2.7 \times 5 \times 0.5 = 6.75 \text{fF} \quad \therefore C_{GS} = C_{GD} = \frac{1}{2} C_G = 3.375 \text{fF}$$

源或漏的结电容为:

$$C_n = C_j A_{bot} + C_{jsw} P_{sw} = 0.86 \times 5 \times 3.05 + 0.24 \times 2 \times (5 + 3.05) = 16.98 \text{fF}$$

最终源和漏电容为:
$$C_D = C_S = 16.98 + 3.375 = 20.36 \text{fF}$$



§ 6.4 pFET特性

PMOS电流—电压方程

截止区: $V_{SGp} < |V_{Tp}| \quad I_{Dp} = 0$

非饱和区 (线性区): $V_{SGp} - |V_{Tp}| > V_{SDp} > 0$

$$I_{Dp} = \mu_p C_{ox} \left(\frac{W}{L} \right) \left[(V_{SGp} - |V_{Tp}|) V_{SDp} - \frac{V_{SDp}^2}{2} \right] = \frac{\beta_p}{2} [2(V_{SGp} - |V_{Tp}|) V_{SDp} - V_{SDp}^2]$$

饱和区: $V_{SDp} > V_{SGp} - |V_{Tp}| > 0$

$$I_{Dp} = \frac{1}{2} \mu_p C_{ox} \left(\frac{W}{L} \right) (V_{SGp} - |V_{Tp}|)^2 = \frac{\beta_p}{2} (V_{SGp} - |V_{Tp}|)^2$$

器件互导: $\beta_p = k'_p \left(\frac{W}{L} \right)$ 工艺互导: $k'_p = \mu_p C_{ox} = \frac{\mu_p \epsilon_{ox}}{t_{ox}}$



§ 6.4 pFET特性

PMOS的RC模型

沟道电阻 $R_p = \frac{1}{\beta_p (V_{DD} - |V_{Tp}|)}$

电容 栅极电容 $C_{Gp} = C_{ox} W L'$

栅源和栅漏电容 $C_{GS} \approx C_{GD} \approx \frac{1}{2} C_{Gp}$

结电容 $C_p = C_j A_{bot} + C_{jsw} P_{sw}$



§ 6.5 小尺寸MOSFET模型

§ 6.5.1 尺寸缩小原理

1 恒定电场缩小 (CE: constant electrical field)

尺寸和电压按同一比例缩小 (全比例缩小): 尺寸缩小 $S(S>1)$ 倍, 电压减小 S 倍——理想模型

2 恒定电压缩小 (CV: constant voltage)

仅尺寸缩小 S 倍, 电压保持不变——最普遍的模式

3 准恒压缩小 (QCV: quasi-constant voltage)

尺寸和电压按不同比例缩小: 尺寸缩小 S 倍, 电压减小 $U(S>U>1)$ 倍——最实用的模型



§ 6.5 小尺寸MOSFET模型

各种尺寸缩小原理的比较

参数	CE	CV	QCV
器件最小尺寸	$1/S$	$1/S$	$1/S$
电压	$1/S$	1	$1/\sqrt{S}$
电场强度	1	S	\sqrt{S}
器件面积	$1/S^2$	$1/S^2$	$1/S^2$
C_{ox}	S	S	S
栅电容	$1/S$	$1/S$	$1/S$
工艺互导	S	S	S
电流	$1/S$	S	1
电流密度	S	S^3	S^2
器件导通电阻	1	$1/S$	$1/\sqrt{S}$
门延时	$1/S$	$1/S^2$	$1/S^{3/2}$
功率	$1/S^2$	S	$1/\sqrt{S}$
功率密度	1	S^3	$S^{3/2}$
功率-延时积	$1/S^3$	$1/S$	$1/S^2$



§ 6.5 小尺寸MOSFET模型

§ 6.5.2 小尺寸器件效应

1 短沟道效应 (SCE: Short-Channel Effect)

阈值电压随着沟道长度 L 的缩小而减小。

$$V_T = V_{T,long} - (\Delta V_T)_{SCE}$$

2 窄沟道效应 (NWE: Narrow-Width Effect)

阈值电压随着沟道宽度 W 的缩小而增加。

$$V_T = V_{T,long} + (\Delta V_T)_{NWE}$$



§ 6.5 小尺寸MOSFET模型

3 速度饱和效应

随着电场强度的增加，载流子的漂移速度最终达到饱和。

$$E = \frac{V_{DS}}{L} \quad v = \mu E$$

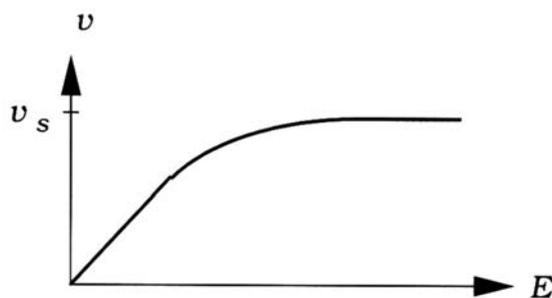


Figure 6.35 Velocity-field relation for charged particles in silicon

室温下硅中电子的饱和速度: $v_s = 10^7$ cm/s