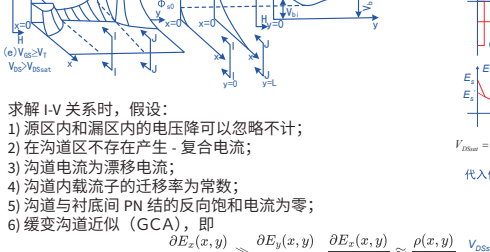
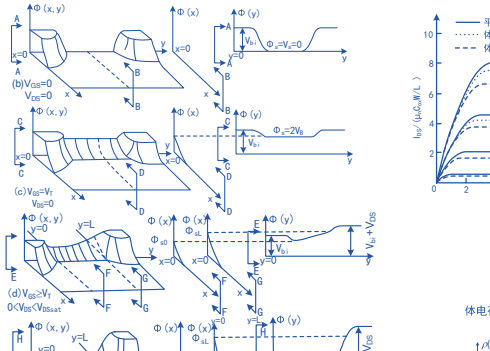
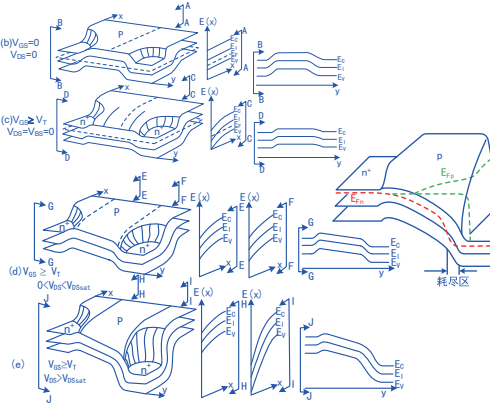
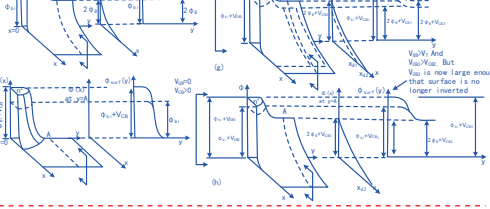
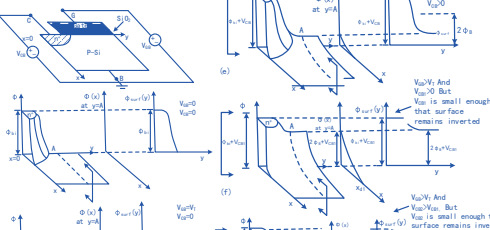
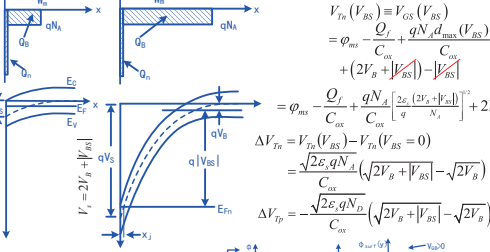
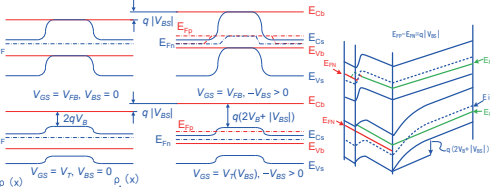
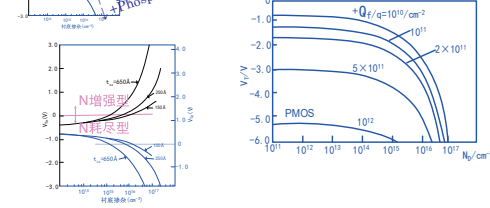
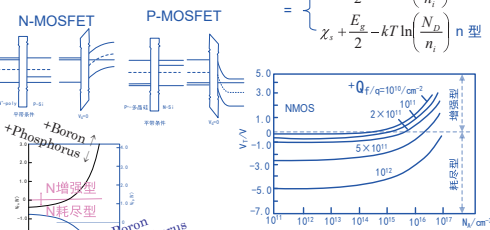


MOSFET	BJT
电场调节作用 ($E \uparrow \rightarrow \sigma \uparrow \rightarrow I_0 \uparrow$)	少子注入 → 扩散 → 收集
多子作用 (多子器件)	少子作用 (少子器件)
一种载流子 (单极)	两种载流子 (双极)
输入阻抗高	输入阻抗低
(MOS → 绝缘体 > $10^8 \Omega$)	(pn 结正偏, 共射 ~ $k\Omega$)
电压控制器件	电流控制器件
噪声低, 抗辐射能力强	$\sim f_{Tj} \sim N_A$
工艺要求高 (~ Q_{ox})	工艺要求低
频率范围小, 功耗低	高频, 大功率
集成度高	集成度低

$$V_{Tn} = \phi_{ms} - \frac{Q_f}{C_{ox}} + \frac{qN_A d_{max}}{C_{ox}} \ln \left(\frac{N_A}{n_i} \right) \quad q\phi_{ms} = W_m - W_s$$

$$V_{Tp} = \phi_{ms} - \frac{Q_f}{C_{ox}} + \frac{qN_D d_{max}}{C_{ox}} \ln \left(\frac{N_D}{n_i} \right) \quad W_s = \chi_s + \frac{E_g}{2} \pm qV_B$$

$$V_{FB} = \phi_{ms} - \frac{Q_f}{C_{ox}} + \frac{qN_D d_{max}}{C_{ox}} \ln \left(\frac{N_D}{n_i} \right) \quad V_{B1} = V_{B2} = 0$$



求解 I-V 关系时, 假设:

- 源区内和漏区内的电压降可以忽略不计;
- 在沟道区不存在产生-复合电流;
- 沟道电流为漂移电流;
- 沟道内载流子的迁移率为常数;
- 沟道与衬底间 PN 结的反向饱和电流为零;
- 缓变沟道近似 (GCA), 即

$$\frac{\partial E_x(x, y)}{\partial x} \gg \frac{\partial E_y(x, y)}{\partial y} \quad \frac{\partial E_x(x, y)}{\partial x} \approx \frac{\rho(x, y)}{\epsilon_x} \quad V_{Dsat} = V_{GS} - V_T > 2V_B, N_A \text{ 很小时} \rightarrow \frac{q\epsilon_s N_A}{C_{ox}^2 (V_{GS} - V_T)} \ll 1 \rightarrow I_{Dsat} \approx \frac{1}{2} \beta (V_{GS} - V_T)^2$$

$$V_{GS} = V_{ox}(y) + V_s(y) + V_{FB} \iff V_{ox}(y) = V_{GS} - 2V_B - V_{FB} - V(y)$$

$$\text{负电荷} = \text{反型电子} + \text{空间负电荷} \iff Q(y) = Q_n(y) - Q_B(d_{max}(y))$$

$$= -C_{ox}(V_{GS} - 2V_B - V_{FB} - V(y)) + (Q_B/C_{ox})$$

$$= -C_{ox}(V_{GS} - V_T - V(y))$$

$$I_D = \int_0^{V_D} J(x, y) dy = \int_0^{V_D} qn(x, y)\mu_n E_y dy = -qn(x, y)\mu_n \frac{dV(y)}{dy}$$

$$I_D = \int_0^{V_D} \int_0^{W_g} J(x, y) dx dy = W_g \int_0^{V_D} (-qn(x, y)\mu_n) \frac{dV(y)}{dy} dy$$

$$= W_g \mu_n Q_n(y) \cdot \frac{dV(y)}{dy} = -W_g \mu_n C_{ox} [V_{GS} - V_T - V(y)] \cdot \frac{dV(y)}{dy}$$

$$= \text{常数}$$

$$I_{Dsat} dy = W_g \mu_n C_{ox} [V_{GS} - V_T - V(y)] dV(y)$$

$$Q_n = -C_{ox} W L (V_{GS} - V(y) - V_T) = I_{Dsat} \cdot t$$

$$C_{ox} W L (V_{GS} - \frac{1}{2} V(y) - V_T) = I_{Dsat} L / v = I_{Dsat} \frac{L}{\mu_n V_{DS}}$$

$$\Rightarrow I_{Dsat} = \mu_n C_{ox} \frac{W}{L} ((V_{GS} - V_T) V_{DS} - \frac{1}{2} V_{DS}^2)$$

亚阈值特性:

弱反型时 $V_B < V_s < 2V_B$

J 漂移 < J 扩散

$I_{Dp} = qD_n A \frac{dn}{dy}$

$\frac{dI_{Dp}}{dV_g} = 0 \Rightarrow I_{Dp} = \text{const.}$

$= qD_n A \frac{n(L) - n(0)}{L}$

亚阈值摆幅 SS:

$$SS = \frac{dV_{GS}}{d(\log I_{Dsat})} = \frac{kT}{q} \ln 10 \cdot \frac{dV_{GS}}{dV_{ox}}$$

$$V_{GS} = V_{FB} + V_s + V_{ox}$$

$$E_s = \sqrt{\frac{2qN_A V_{ox}}{\epsilon_s}} \Rightarrow V_s = V_{GS} - V_{FB} - \frac{B}{C_{ox}} \left[\sqrt{1 + \frac{2C_{ox}^2 (V_{GS} - V_{FB})}{q\epsilon_s N_A}} - 1 \right], B = \frac{q}{C_{ox}} qN_A t_{ox}$$

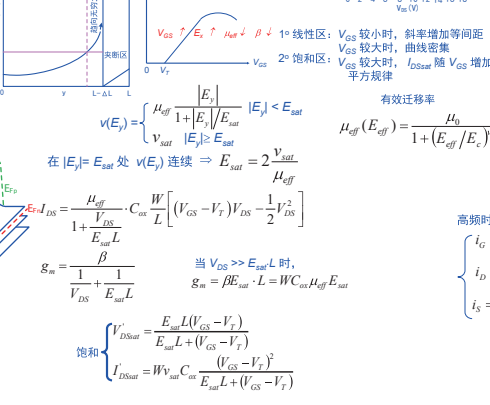
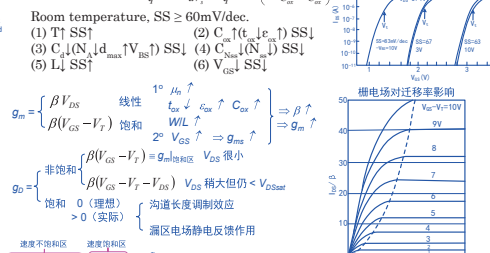
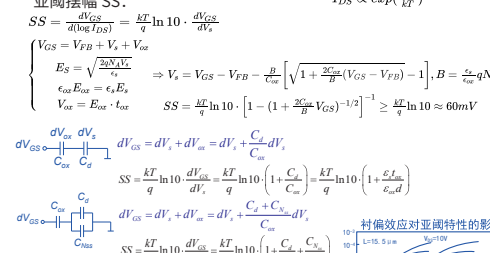
$$V_{ox} = \frac{kT}{q} \ln 10 \cdot [1 - (1 + \frac{2C_{ox}^2}{B^2} V_{GS})^{1/2}]^{-1} \geq \frac{kT}{q} \ln 10 \approx 60 \text{ mV}$$

$$dV_{GS} = \frac{dV_s}{C_{ox}} + \frac{dV_{ox}}{C_{ox}} \quad dV_{GS} = dV_s + dV_{ox} = dV_s + \frac{dV_{ox}}{C_{ox}}$$

$$SS = \frac{kT}{q} \ln 10 \cdot \frac{dV_{GS}}{dV_{ox}} = \frac{kT}{q} \ln 10 \cdot \left(1 + \frac{C_{ox}}{C_{ox}'} \right) = \frac{kT}{q} \ln 10 \cdot \left(1 + \frac{t_{ox}}{\epsilon_s d} \right)$$

$$dV_{GS} = \frac{dV_s}{C_{ox}} + \frac{dV_{ox}}{C_{ox}} \quad dV_{GS} = dV_s + dV_{ox} = dV_s + \frac{dV_{ox}}{C_{ox}}$$

$$SS = \frac{kT}{q} \ln 10 \cdot \frac{dV_{GS}}{dV_{ox}} = \frac{kT}{q} \ln 10 \cdot \left(1 + \frac{C_{ox}}{C_{ox}'} \right) = \frac{kT}{q} \ln 10 \cdot \left(1 + \frac{t_{ox}}{\epsilon_s d} \right)$$



平方律模型

$$I_{DS} = \mu_n C_{ox} \frac{W}{L} \left\{ [V_{GS} - V_{FB} - 2V_B - \frac{V_{DS}}{2}] V_{DS} - \frac{2}{3} \frac{\sqrt{2q\epsilon_s N_A}}{C_{ox}} [(V_{GS} + 2V_B)^{3/2} - (2V_B)^{3/2}] \right\}$$

1° 简单模型 (Square-law model) 高估 I_{Dsat} 约 20-50%

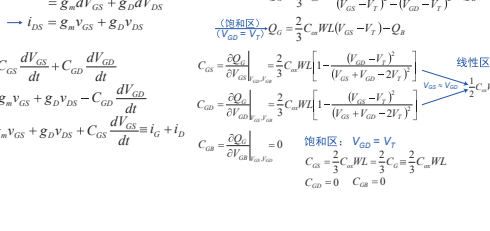
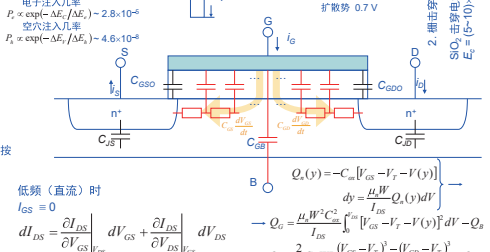
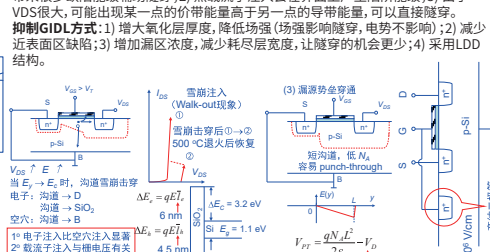
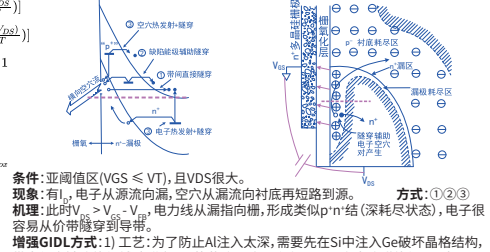
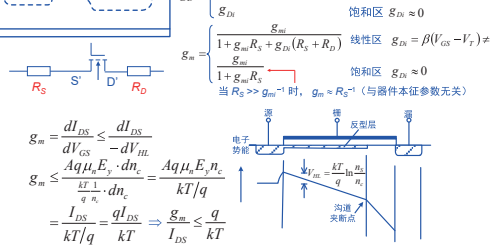
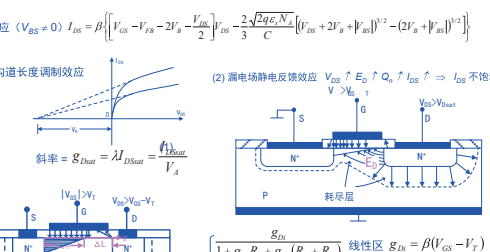
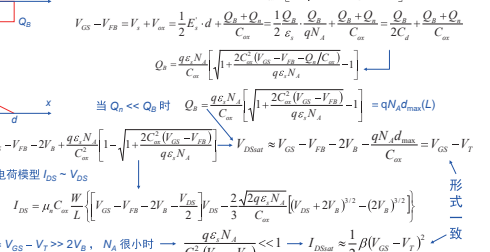
$N_A \uparrow \rightarrow I_{Dsat}$ 偏差 \uparrow

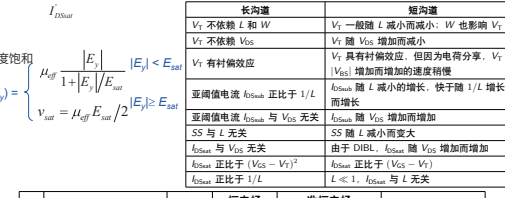
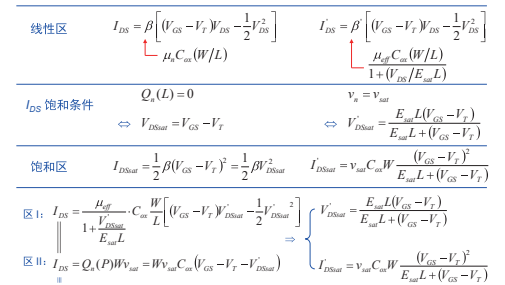
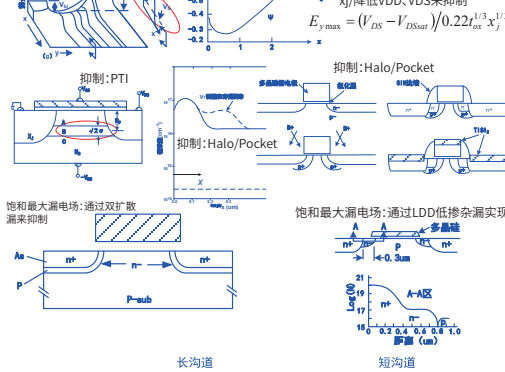
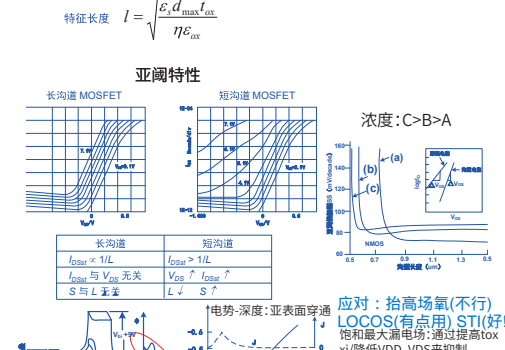
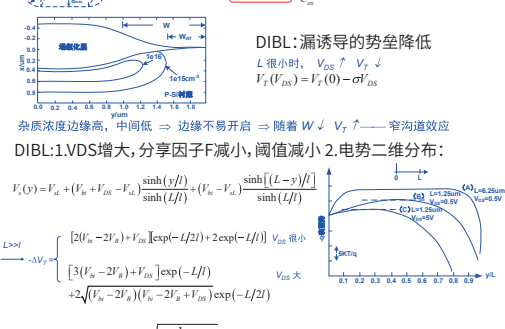
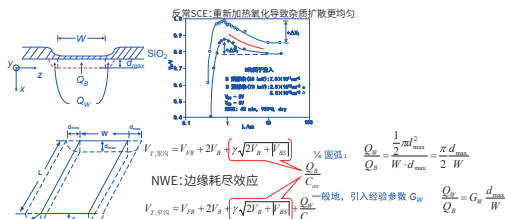
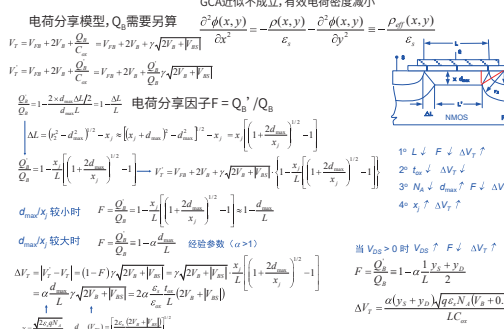
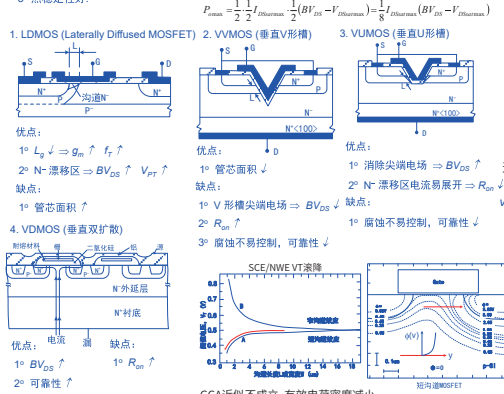
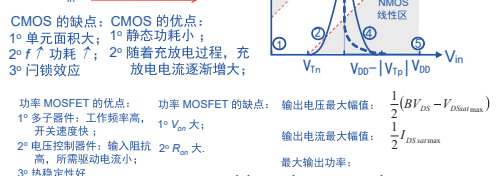
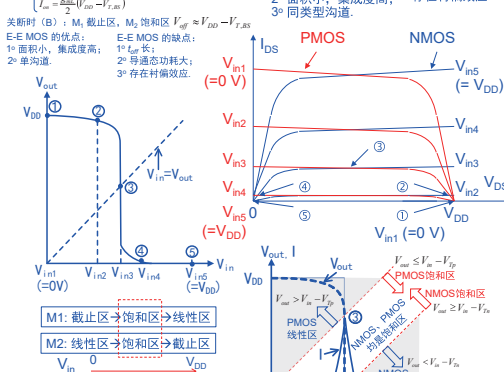
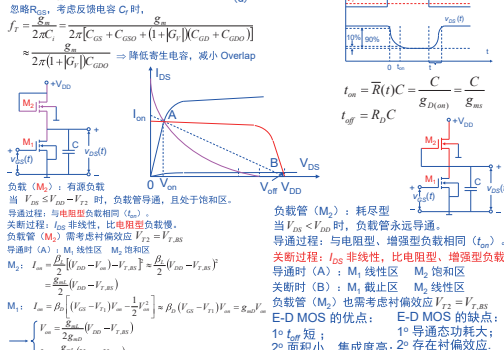
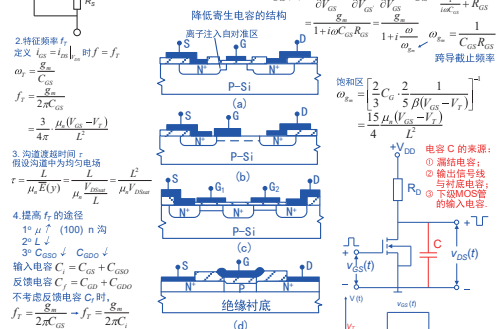
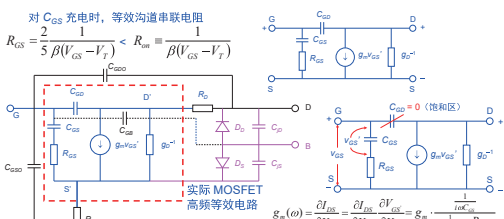
2° 简单模型 (Square-law model) 高估 V_{Dsat}

3° 当 $V_{DS} < 2V_B$ 时,

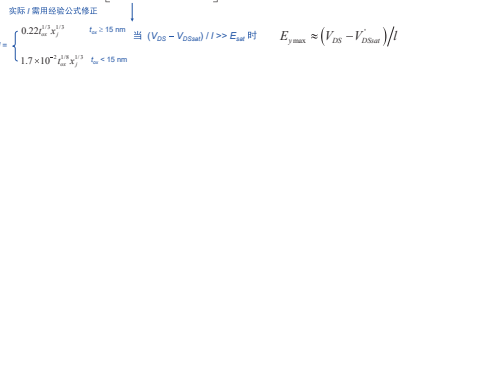
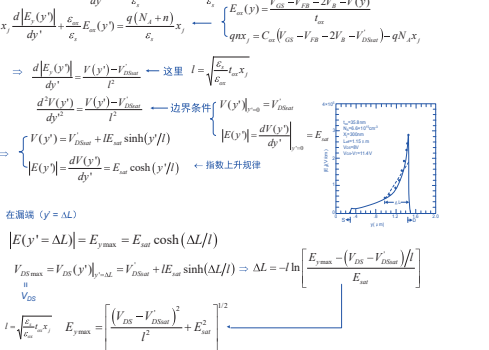
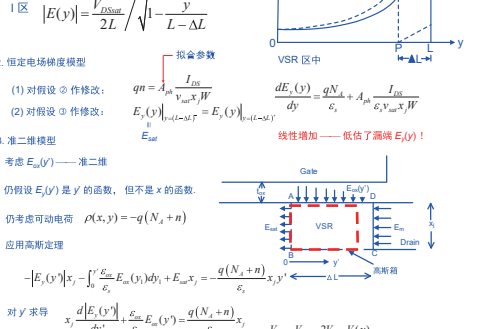
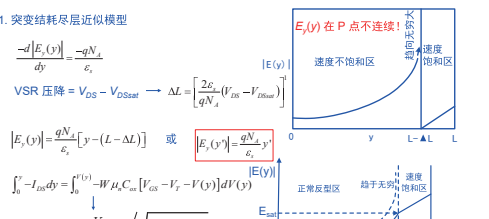
$$I_{DS} = \mu_n C_{ox} \frac{W}{L} [V_{GS} - V_{FB} - 2V_B - \sqrt{\frac{2q\epsilon_s N_A \cdot 2V_B}{C_{ox}}}] V_{DS}$$

$$= \beta (V_{GS} - V_T) V_{DS}$$





	恒电场	准恒电场
沟道长度	L	1/S
沟道宽度	W	1/S
栅氧厚度	t_{ox}	1/S
源漏结深	x_j	1/S
衬底掺杂浓度	N_A	S
工作电压	V_{GS}	1/S
电场强度	E	1
电势分布	ϕ	1/S
漏衬 pn 结耗尽区宽度	W_0	1/S
栅电容	C_G	1/S
源漏电流	I_{DS}	1/S
电流线密度/单位宽度驱动能力	I_{DS}/W	1
电流面密度	I_{DS}/A	S
RC 电路延迟	τ	1/S
功耗	P	1/S ²
功率密度	P/A	1
集成度 (CD)	1/A	S ²
阈值电压	V_T	1/S (难)
pn 结内建电势差	V_{bi}	$V_{bi} \ll V_{GS}$



	恒电场	准恒电场
沟道长度	L	1/S
沟道宽度	W	1/S
栅氧厚度	t_{ox}	1/S
源漏结深	x_j	1/S
衬底掺杂浓度	N_A	S
工作电压	V_{GS}	1/S
电场强度	E	1
电势分布	ϕ	1/S
漏衬 pn 结耗尽区宽度	W_0	1/S
栅电容	C_G	1/S
源漏电流	I_{DS}	1/S
电流线密度/单位宽度驱动能力	I_{DS}/W	1
电流面密度	I_{DS}/A	S
RC 电路延迟	τ	1/S
功耗	P	1/S ²
功率密度	P/A	1
集成度 (CD)	1/A	S ²
阈值电压	V_T	1/S (难)
pn 结内建电势差	V_{bi}	$V_{bi} \ll V_{GS}$