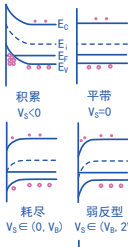
MOSFET	BJT
电场调节作用 （$E\uparrow\to\sigma\uparrow\to I_D\uparrow$）	少子注入 → 扩散 → 收集
多子作用（多子器件）	少子作用（少子器件）
一种载流子（单极）	两种载流子（双极）
输入阻抗高 （MOS → 绝缘体 > $10^9\,\Omega$）	输入阻抗低 （pn 结正偏，共射~ kΩ）
电压控制器件	电流控制器件
噪声低，抗辐射能力强	~ $\tau_{p\text{-}p}$ ~ N_d
工艺要求高（~ Q_{ss}）	工艺要求低
频率范围小，功耗低	高频，大功率
集成度高	集成度低



$$V_{Tn}=\phi_{ms}-\frac{Q_f}{C_{ox}}+\frac{qN_Ad_{max}}{C_{ox}}+\frac{2kT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

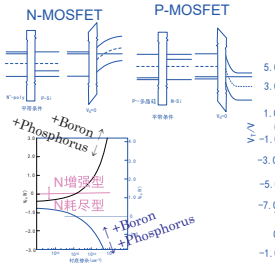
$$V_{Tp}=\phi_{ms}-\frac{Q_f}{C_{ox}}-\frac{qN_Dd_{max}}{C_{ox}}-\frac{2kT}{q}\ln\left(\frac{N_D}{n_i}\right)$$

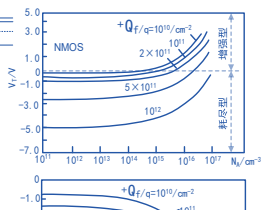
V_{FB}　Q_B/C_{OX}　$2V_B$

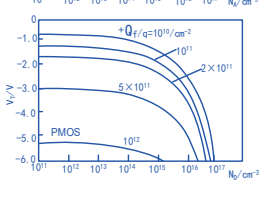
$$q\phi_{ms}=W_m-W_s\equiv -qV_{ms}$$

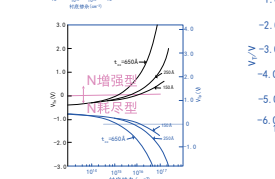
$$W_s=\chi_s+\frac{E_g}{2}\pm qV_B$$

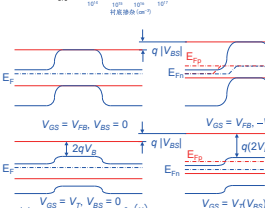
$$=\begin{cases}\chi_s+\dfrac{E_g}{2}+kT\ln\left(\dfrac{N_A}{n_i}\right) & \text{p 型}\\[2ex] \chi_s+\dfrac{E_g}{2}-kT\ln\left(\dfrac{N_D}{n_i}\right) & \text{n 型}\end{cases}$$

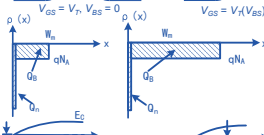










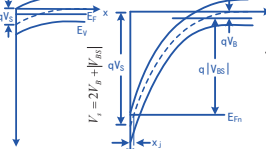


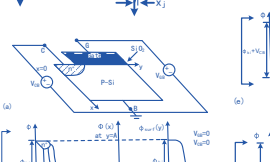
$$V_{Tn}(V_{BS})\equiv V_{GS}(V_{BS})=\varphi_{ms}-\frac{Q_f}{C_{ox}}+\frac{qN_Ad_{max}(V_{BS})}{C_{ox}}+(2V_B+|V_{BS}|)-|V_{BS}|$$

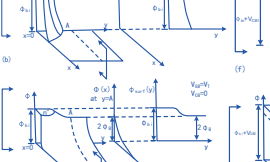
$$=\varphi_{ms}-\frac{Q_f}{C_{ox}}+\frac{qN_A}{C_{ox}}\left[\frac{2\varepsilon_s(2V_B+|V_{BS}|)}{q\ N_A}\right]^{1/2}+2V_B$$

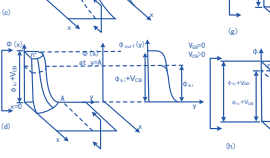
$$\Delta V_{Tn}=V_{Tn}(V_{BS})-V_{Tn}(V_{BS}=0)=\frac{\sqrt{2\varepsilon_sqN_A}}{C_{ox}}\left(\sqrt{2V_B+|V_{BS}|}-\sqrt{2V_B}\right)$$

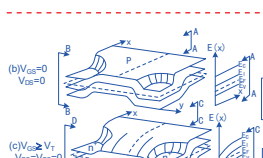
$$\Delta V_{Tp}=-\frac{\sqrt{2\varepsilon_sqN_D}}{C_{ox}}\left(\sqrt{2V_B+|V_{BS}|}-\sqrt{2V_B}\right)$$

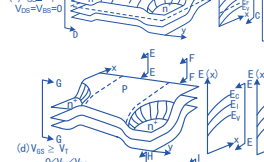


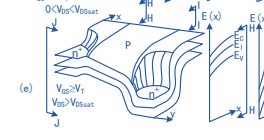


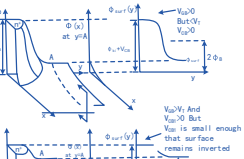


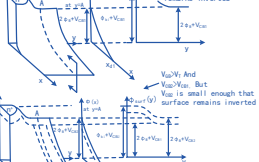


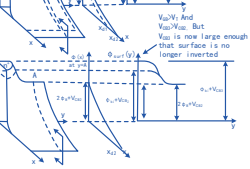


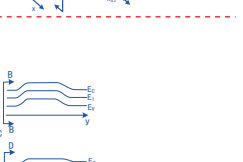


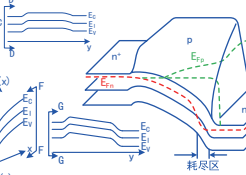


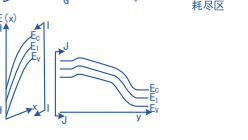


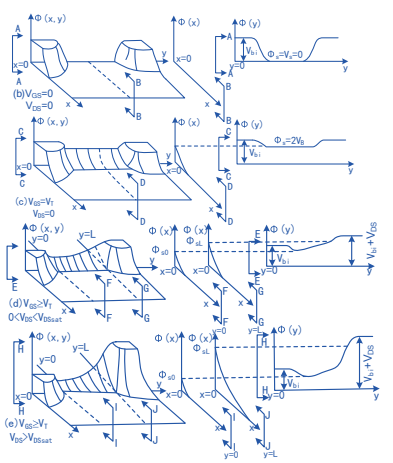


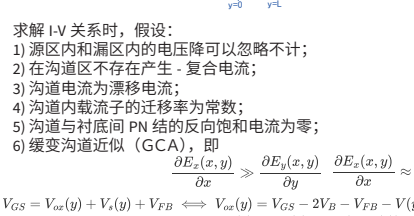


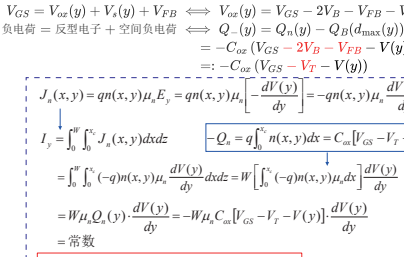


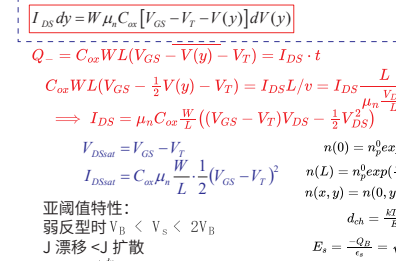












求解 I-V 关系时，假设：

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

$$\frac{\partial E_x(x,y)}{\partial x}\gg\frac{\partial E_y(x,y)}{\partial y}\quad\frac{\partial E_x(x,y)}{\partial x}\approx\frac{\rho(x,y)}{\varepsilon_s}$$

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

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

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

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

$$J_n(x,y)=qn(x,y)\mu_nE_y=qn(x,y)\mu_n\left[-\frac{dV(y)}{dy}\right]=-qn(x,y)\mu_n\frac{dV(y)}{dy}$$

$$I_y=\int_0^W\int_0^{x_c}J_n(x,y)dxdz\qquad \boxed{-Q_n=q\int_0^{x_c}n(x,y)dx=C_{ox}[V_{GS}-V_T-V(y)]}$$

$$=\int_0^W\int_0^{x_c}(-q)n(x,y)\mu_n\frac{dV(y)}{dy}dxdz=W\left[\int_0^{x_c}(-q)n(x,y)\mu_ndx\right]\frac{dV(y)}{dy}$$

$$=W\mu_nQ_n(y)\cdot\frac{dV(y)}{dy}=-W\mu_nC_{ox}[V_{GS}-V_T-V(y)]\cdot\frac{dV(y)}{dy}$$

$$=\text{常数}$$

$$\boxed{I_{DS}dy=W\mu_nC_{ox}[V_{GS}-V_T-V(y)]dV(y)}$$

$$Q_-=C_{ox}WL(V_{GS}-V(y)-V_T)=I_{DS}\cdot t$$

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

$$\Longrightarrow I_{DS}=\mu_nC_{ox}\frac{W}{L}((V_{GS}-V_T)V_{DS}-\tfrac{1}{2}V_{DS}^2)$$

$$V_{DSsat}=V_{GS}-V_T$$

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

$$n(0)=n_p^0exp(\tfrac{qV_s}{kT})$$

$$n(L)=n_p^0exp(\tfrac{q(V_s-V_{DS})}{kT})$$

$$n(x,y)=n(0,y)exp(\tfrac{-x}{d_{ch}})$$

$$d_{ch}=\frac{kT/q}{E_s}$$

$$E_s=\frac{-Q_B}{\varepsilon_s}=\sqrt{\frac{2qN_AV_s}{\varepsilon_s}}$$

$$I_{DS}=-I_y=q\frac{WkT}{qE_sL}D_nn_p^0exp(\tfrac{qV_s}{kT})[1-exp(\tfrac{-qV_{DS}}{kT})]$$

$$=\frac{W\mu_n}{L}(\frac{kT}{q})^2q\sqrt{\frac{\varepsilon_s}{2qN_AV_s}}\frac{n_i^2}{N_A}exp(\tfrac{qV_s}{kT})[1-exp(\tfrac{-q(V_{DS})}{kT})]$$

$$when\ V_{DS}>=3kT/q\to[1-exp(\tfrac{-qV_{DS}}{kT})]\approx1$$

$$I_{DS}\propto exp(\tfrac{qV_s}{kT})$$

亚阈值特性：

弱反型时 $V_B<V_S<2V_B$

J 漂移 <J 扩散

$$I_y=qD_nA\frac{dn}{dy}$$

$$\frac{\partial I_y}{\partial y}=0\Rightarrow I_y=const.$$

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

亚阈摆幅 SS：

$$SS=\frac{dV_{GS}}{d(\log I_{DS})}=\frac{kT}{q}\ln10\cdot\frac{dV_{GS}}{dV_s}$$

$$\begin{cases}V_{GS}=V_{FB}+V_s+V_{ox}\\ E_S=\sqrt{\dfrac{2qN_AV_s}{\varepsilon_s}}\\ \varepsilon_{ox}E_{ox}=\varepsilon_sE_s\\ V_{ox}=E_{ox}\cdot t_{ox}\end{cases}\Rightarrow V_s=V_{GS}-V_{FB}-\frac{B}{C_{ox}}\left[\sqrt{1+\frac{2C_{ox}}{B}(V_{GS}-V_{FB})}-1\right],B=\frac{\varepsilon_s}{\varepsilon_{ox}}qN_At_{ox}$$

$$SS=\frac{kT}{q}\ln10\cdot\left[1-(1+\tfrac{2C_{ox}}{B}V_{GS})^{-1/2}\right]^{-1}\geq\frac{kT}{q}\ln10\approx60mV$$

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

$$SS=\frac{kT}{q}\ln10\cdot\frac{dV_{GS}}{dV_s}=\frac{kT}{q}\ln10\cdot\left(1+\frac{C_d}{C_{ox}}\right)=\frac{kT}{q}\ln10\cdot\left(1+\frac{\varepsilon_sd_{dm}}{\varepsilon_{ox}d}\right)$$

$$dV_{GS}=dV_s+dV_{ox}=dV_s+\frac{C_d+C_{N_{ss}}}{C_{ox}}dV_s$$

$$SS=\frac{kT}{q}\ln10\cdot\frac{dV_{GS}}{dV_s}=\frac{kT}{q}\ln10\cdot\left(1+\frac{C_d}{C_{ox}}+\frac{C_{N_{ss}}}{C_{ox}}\right)$$

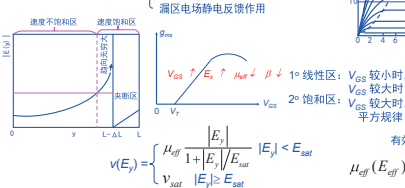
Room temperature, SS ≥ 60mV/dec.

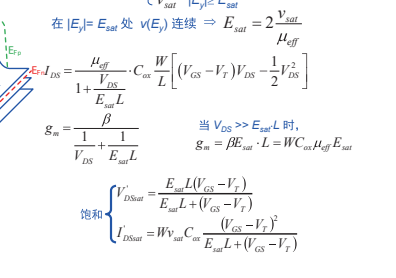
(1) T↑ SS↑　(2) C_{ox}↑(t_{ox}↓ε_{ox}↑) SS↓
(3) C_d↓(N_A↓d_{max}↑V_{BS}↑) SS↓　(4) C_{Nss}↓(N_{ss}↓) SS↓
(5) L↓ SS↑　(6) V_{GS}↓ SS↓

$$g_m=\begin{cases}\beta V_{DS} & \text{线性}\\ \beta(V_{GS}-V_T) & \text{饱和}\end{cases}\quad\begin{matrix}1^\circ\ \mu_n\uparrow\\ t_{ox}\downarrow\ \varepsilon_{ox}\uparrow\ C_{ox}\uparrow\\ W/L\uparrow\\ 2^\circ\ V_{GS}\uparrow\end{matrix}\Rightarrow\beta\uparrow\Rightarrow g_m\uparrow$$

$$g_D=\begin{cases}\beta(V_{GS}-V_T)=g_m|_{饱和区} & V_{DS}\text{ 很小}\\ \beta(V_{GS}-V_T-V_{DS}) & V_{DS}\text{ 稍大但仍}<V_{DSsat}\end{cases}$$

饱和　0（理想）
　　>0（实际）　沟道长度调制效应；漏区电场静电反馈作用





$$v(E_y)=\begin{cases}\dfrac{\mu_{eff}\left|\dfrac{E_y}{E_{sat}}\right|}{1+\left|\dfrac{E_y}{E_{sat}}\right|} & |E_y|<E_{sat}\\ v_{sat} & |E_y|\geq E_{sat}\end{cases}$$

在 $|E_y|=E_{sat}$ 处 $v(E_y)$ 连续 $\Rightarrow E_{sat}=2\dfrac{v_{sat}}{\mu_{eff}}$

$$I_{DS}=\frac{\mu_{eff}}{1+\frac{V_{DS}}{E_{sat}L}}\cdot C_{ox}\frac{W}{L}\left[(V_{GS}-V_T)V_{DS}-\frac{1}{2}V_{DS}^2\right]$$

$$g_m=\frac{\beta}{\frac{1}{V_{DS}}+\frac{1}{E_{sat}L}}$$

当 $V_{DS}>>E_{sat}L$ 时，

$$g_m=\beta E_{sat}\cdot L=WC_{ox}\mu_{eff}E_{sat}$$

饱和
$$\begin{cases}V'_{DSsat}=\dfrac{E_{sat}L(V_{GS}-V_T)}{E_{sat}L+(V_{GS}-V_T)}\\ I'_{DSsat}=WV_{sat}C_{ox}\dfrac{(V_{GS}-V_T)^2}{E_{sat}L+(V_{GS}-V_T)}\end{cases}$$

$$d_{max}(y)=\sqrt{\frac{2\varepsilon_s}{q}\frac{2V_B}{N_A}}\to\sqrt{\frac{2\varepsilon_s}{q}\frac{2V_B+V(y)}{N_A}}$$

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

1° 简单模型（Square-law model）高估 I_{DS} 约 20~50%
　$N_A\uparrow$　I_{DS} 偏差 ↑
2° 简单模型（Square-law model）高估 V_{DSsat}
3° 当 $V_{DS}<<2V_B$ 时，

$$I_{DS}=\mu_nC_{ox}\frac{W}{L}\left(V_{GS}-V_{FB}-2V_B-\frac{\sqrt{2q\varepsilon_sN_A\cdot2V_B}}{C_{ox}}\right)V_{DS}=\beta(V_{GS}-V_T)V_{DS}$$

计算 V_{DSsat}

体电荷模型　$Q_n(L)=\Rightarrow-C_{ox}[V_{GS}-V_{FB}-2V_B-V(y)]+\sqrt{2q\varepsilon_sN_A[2V_B+V(y)]}=0$　（V_{DSsat}）

$$V_{DSsat}=V_{GS}-V_{FB}-2V_B+\frac{q\varepsilon_sN_A}{C_{ox}^2}\left[1-\sqrt{1+\frac{2C_{ox}^2(V_{GS}-V_{FB})}{q\varepsilon_sN_A}}\right]$$

$$V_{GS}-V_{FB}=V_s+V_{ox}=\frac{1}{2}E_s\cdot d+\frac{Q_B+Q_n}{C_{ox}}=\frac{1}{2}\frac{Q_B}{\varepsilon_s}\cdot\frac{Q_B}{qN_A}+\frac{Q_B+Q_n}{C_{ox}}=\frac{Q_B}{2C_d}+\frac{Q_B+Q_n}{C_{ox}}$$

$$Q_n=\frac{q\varepsilon_sN_A}{C_{ox}}\left[\sqrt{1+\frac{2C_{ox}^2(V_{GS}-V_{FB}-Q_n/C_{ox})}{q\varepsilon_sN_A}}-1\right]$$

当 $Q_n<<Q_B$ 时　$Q_n=\dfrac{q\varepsilon_sN_A}{C_{ox}}\left[\sqrt{1+\dfrac{2C_{ox}^2(V_{GS}-V_{FB})}{q\varepsilon_sN_A}}-1\right]=qN_Ad_{max}(L)$

$$V_{DSsat}=V_{GS}-V_{FB}-2V_B+\frac{q\varepsilon_sN_A}{C_{ox}^2}\left[1-\sqrt{1+\frac{2C_{ox}^2(V_{GS}-V_{FB})}{q\varepsilon_sN_A}}\right]\to V_{DSsat}\approx V_{GS}-V_{FB}-2V_B-\frac{qN_Ad_{max}}{C_{ox}}=V_{GS}-V_T$$

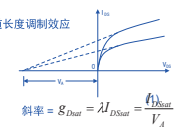
形式一致

代入体电荷模型 $I_{DS}\sim V_{DS}$

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

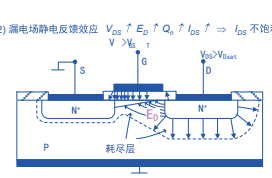
衬偏效应（$V_{BS}\neq0$）$I_{DS}=\beta\left\{\left[V_{GS}-V_{FB}-2V_B-\dfrac{V_{DS}}{2}\right]V_{DS}-\dfrac{2}{3}\dfrac{\sqrt{2q\varepsilon_sN_A}}{C}\left[(V_{DS}+2V_B+|V_{BS}|)^{3/2}-(2V_B+|V_{BS}|)^{3/2}\right]\right\}$

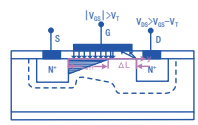
沟道长度调制效应

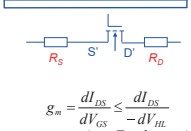


斜率 $g_{Dsat}=\lambda I_{DSsat}=\dfrac{I_{DSsat}}{V_A}$

(2) 漏电场静电反馈效应　$V_{DS}\uparrow E_D\uparrow Q_n\uparrow I_{DS}\uparrow\Rightarrow I_{DS}$ 不饱和







$$g_D=\begin{cases}\dfrac{g_{Di}}{1+g_{mi}R_s+g_{Di}(R_s+R_D)} & \text{线性区}\ g_{Di}=\beta(V_{GS}-V_T)\\ g_{Di} & \text{饱和区}\ g_{Di}\approx0\end{cases}$$

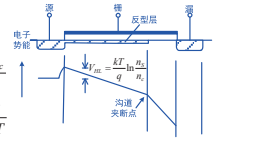
$$g_m=\begin{cases}\dfrac{g_{mi}}{1+g_{mi}R_s+g_{Di}(R_s+R_D)} & \text{线性区}\ g_{Di}=\beta(V_{GS}-V_T)\neq0\\ \dfrac{g_{mi}}{1+g_{mi}R_s} & \text{饱和区}\ g_{Di}\approx0\end{cases}$$

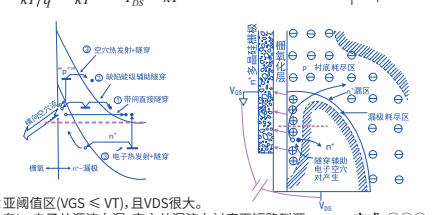
当 $R_S>>g_{mi}^{-1}$ 时，$g_m\approx R_S^{-1}$（与器件本征参数无关）

$$g_m=\frac{dI_{DS}}{dV_{GS}}\leq\frac{dI_{DS}}{-dV_{HL}}$$

$$g_m\leq\frac{Aq\mu_nE_y\cdot dn_c}{\frac{kT}{q}\frac{1}{n_c}\cdot dn_c}=\frac{Aq\mu_nE_yn_c}{kT/q}$$

$$=\frac{I_{DS}}{kT/q}=\frac{qI_{DS}}{kT}\Rightarrow\frac{g_m}{I_{DS}}\leq\frac{q}{kT}$$





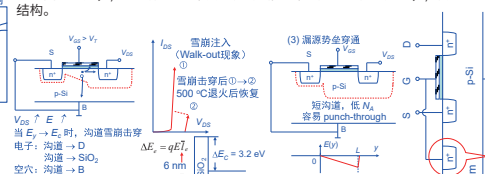
条件：亚阈值区(VGS ≤ VT)，且VDS很大。

现象：有I_D，电子从源流向漏，空穴从漏流向衬底再短路到源。　**方式**：①②③

机理：此时$V_G>V_{GS}-V_{GD}$，电力线从漏指向栅，形成类似p+n+结（深耗尽状态），电子很容易从价带隧穿到导带。

增强GIDL方式：1) 工艺：为了防止AI注入太深，需要先在Si中注入Ge破坏晶格结构，带来很多缺陷能级辅助隧穿；2) 热载流子注入会在界面上产生陷阱能级；3) 由于VDS很大，可能出现某一点的价带能量高于另一点的导带能量，可以直接隧穿。

抑制GIDL方式：1) 增大氧化层厚度，降低场强（场强影响隧穿，电势不影响）；2) 减少近表面区缺陷；3) 增加漏区浓度，减少耗尽层宽度，让隧穿的机会更少；4) 采用LDD结构。



有效迁移率

$$\mu_{eff}(E_{eff})=\frac{\mu_0}{1+(E_{eff}/E_c)^\gamma}$$

低频（直流）时

$$I_{GS}=0$$

$$dI_{DS}=\frac{\partial I_{DS}}{\partial V_{GS}}\Big|_{V_{DS}}dV_{GS}+\frac{\partial I_{DS}}{\partial V_{DS}}\Big|_{V_{GS}}dV_{DS}$$

$$=g_mdV_{GS}+g_DdV_{DS}$$

$$\to i_{DS}=g_mv_{GS}+g_Dv_{DS}$$

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

$$dy=\frac{\mu_nW}{I_{DS}}Q_n(y)dV$$

$$\to Q_G=\frac{\mu_nW^2C_{ox}^2}{I_{DS}}\int_{V_{DS}}^{V_{GS}}[V_{GS}-V_T-V(y)]^2dV-Q_B$$

（线性区）$Q_G=\frac{2}{3}C_{ox}WL\frac{(V_{GS}-V_T)^3-(V_{GD}-V_T)^3}{(V_{GS}-V_T)^2-(V_{GD}-V_T)^2}-Q_B$

（饱和区）$(V_{GD}=V_T)$ $Q_G=\frac{2}{3}C_{ox}WL(V_{GS}-V_T)-Q_B$

高频时

$$\begin{cases}i_G=C_{GS}\dfrac{dV_{GS}}{dt}+C_{GD}\dfrac{dV_{GD}}{dt}\\ i_D=g_mv_{GS}+g_Dv_{DS}-C_{GD}\dfrac{dV_{GD}}{dt}\\ i_S=g_mv_{GS}+g_Dv_{DS}+C_{GS}\dfrac{dV_{GS}}{dt}\equiv i_G+i_D\end{cases}$$

$$C_{GS}=\frac{\partial Q_G}{\partial V_{GS}}\Big|_{V_{GD},V_{GB}}=\frac{2}{3}C_{ox}WL\left[1-\frac{(V_{GD}-V_T)^2}{(V_{GS}+V_{GD}-2V_T)^2}\right]$$

$$C_{GD}=\frac{\partial Q_G}{\partial V_{GD}}\Big|_{V_{GS},V_{GB}}=\frac{2}{3}C_{ox}WL\left[1-\frac{(V_{GS}-V_T)^2}{(V_{GS}+V_{GD}-2V_T)^2}\right]$$

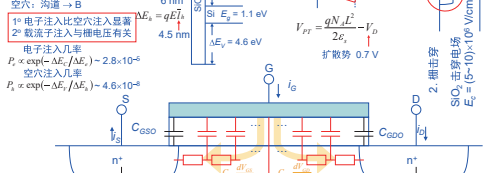
$$C_{GB}=\frac{\partial Q_G}{\partial V_{GB}}\Big|_{V_{GS},V_{GD}}=0$$

线性区　$V_{GS}=V_{GD}$　$\frac{1}{2}C_{ox}WL$

饱和区：$V_{GD}=V_T$

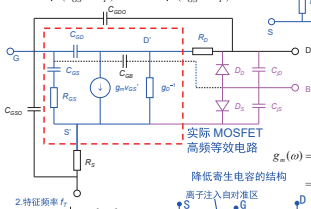
$$C_{GS}=\frac{2}{3}C_{ox}WL=\frac{2}{3}C_C=\frac{2}{3}C_{ox}WL$$

$$C_{GD}=0\quad C_{GB}=0$$

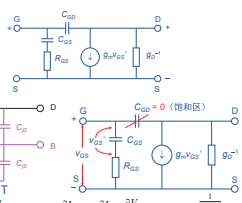


对 C_{GS} 充电时，等效沟道串联电阻

$$R_{GS}=\frac{2}{5\,\beta(V_{GS}-V_T)}<R_{on}=\frac{1}{\beta(V_{GS}-V_T)}$$



实际 MOSFET
高频等效电路



$C_{DD}=0$（饱和区）

$$g_m(\omega)=\frac{\partial I_{DS}}{\partial V_{GS}}=\frac{\partial I_{DS}}{\partial V_{GS'}}\frac{\partial V_{GS'}}{\partial V_{GS}}=g_m\cdot\frac{1}{i\omega C_{GS}}\Big/\frac{1}{i\omega C_{GS}}+R_{GS}$$

$$=\frac{g_m}{1+i\omega C_{GS}R_{GS}}=\frac{g_m}{1+i\frac{\omega}{\omega_m}}\qquad \omega_m=\frac{1}{C_{GS}R_{GS}}$$

跨导截止频率

2.特征频率 f_T

定义 $i_{GS}=i_{DS}|_{\omega_m}$ 时 $f=f_T$

$$\omega_T=\frac{g_m}{C_{GS}}$$

$$f_T=\frac{g_m}{2\pi C_{GS}}=\frac{3}{4\pi}\frac{\mu_n(V_{GS}-V_T)}{L^2}$$

3. 沟道渡越时间 τ

假设沟道中为均匀电场

$$\tau=\frac{L}{\mu_n E(y)}=\frac{L}{\mu_n\frac{V_{DSsat}}{L}}=\frac{L^2}{\mu_n V_{DSsat}}$$

4.提高 f_T 的途径

1° $\mu\uparrow$（100）n 沟

2° $L\downarrow$

3° $C_{GSO}\downarrow$ $C_{GDO}\downarrow$

输入电容 $C_i=C_{GS}+C_{GSO}$

反馈电容 $C_f=C_{GD}+C_{GDO}$

不考虑反馈电容 C_f 时，

$$f_T=\frac{g_m}{2\pi C_{GS}}\rightarrow f_T=\frac{g_m}{2\pi C_i}$$

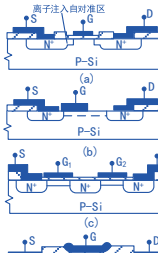
忽略R_{GS}，考虑反馈电容 C_f 时，

$$f_T=\frac{g_m}{2\pi C_i}=\frac{g_m}{2\pi\left[C_{GS}+C_{GSO}+(1+|G_T|)(C_{GD}+C_{GDO})\right]}$$

$$\approx\frac{g_m}{2\pi(1+|G_T|)C_{GDO}}\Rightarrow$$ 降低寄生电容，减小 Overlap

降低寄生电容的结构

离子注入自对准区



饱和区

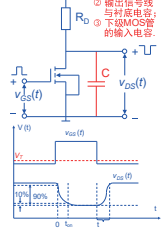
$$\omega_{Bm}=\left[\frac{2}{3}C_G\cdot\frac{2}{3}\frac{1}{\beta(V_{GS}-V_T)}\right]^{-1}=\frac{15}{4}\frac{\mu_n(V_{GS}-V_T)}{L^2}$$

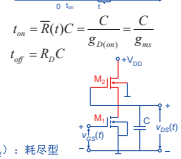
电容 C 的来源：

① 漏结电容；

② 输出信号线与对底电容；

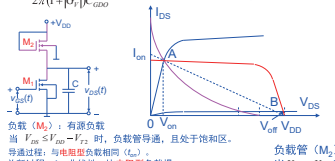
③ 下级MOS管的输入电容.





$$t_{on}=\overline{R}(t)C=\frac{C}{g_{D(on)}}=\frac{C}{g_{mS}}$$

$$t_{off}=R_DC$$



负载管（M_2）：有源负载

当 $V_{DS}\le V_{DD}-V_{T2}$ 时，负载管导通，且处于饱和区。

导通过程：与电阻型负载相同（t_{on}）。

关断过程：I_{DS} 非线性，比电阻型负载慢。

负载管（M_2）需考虑时偏效应 $V_{T2}=V_{T_BS}$

导通时（A）M_1 线性区 M_2 饱和区

$$M_2:\ I_{on}=\frac{\beta_L}{2}(V_{DD}-V_{on})-V_{T_BS}\Big]^2\approx\frac{\beta_L}{2}(V_{DD}-V_{T_BS})^2$$

$$=\frac{g_{mL}}{2}(V_{DD}-V_{T_BS})$$

$$M_1:\ I_{on}=\beta_D\left[(V_{GS}-V_{T1})V_{on}-\frac{1}{2}V_{on}^2\right]\approx\beta_D(V_{GS}-V_{T1})V_{on}=g_{mD}V_{on}$$

$$\rightarrow\begin{cases}V_{on}=\dfrac{g_{mL}}{2g_{mD}}(V_{DD}-V_{T_BS})\\ I_{on}=\dfrac{g_{mL}}{2}(V_{DD}-V_{T_BS})\end{cases}$$

关断时（B）：M_1 截止区，M_2 饱和区 $V_{off}\approx V_{DD}-V_{T_BS}$

E-E MOS 的优点：

1° 面积小，集成度高；

2° 单沟道.

E-E MOS 的缺点：

1° t_{off} 长；

2° 导通态功耗大；

3° 存在衬偏效应.

负载管（M_2）：耗尽型

当 $V_{DS}<V_{DD}$ 时，负载管永远导通。

导通过程：与电阻型、增强型负载相同（t_{on}）。

关断过程：I_{DS} 非线性，比电阻型、增强型负载快

导通时（A）：M_1 线性区 M_2 饱和区

关断时（B）：M_1 截止区 M_2 线性区

负载管（M_2）也需考虑时偏效应 $V_{T2}=V_{T_BS}$

E-D MOS 的优点：

1° t_{off} 短；

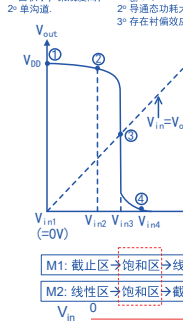
2° 面积小，集成度高；

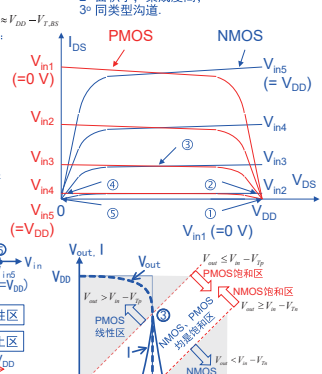
3° 同类型沟道.

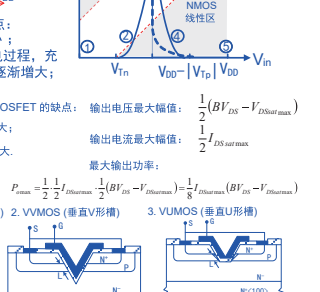
E-D MOS 的缺点：

1° 导通态功耗大；

2° 存在衬偏效应.







M1: 截止区→饱和区→线性区

M2: 线性区→饱和区→截止区

CMOS 的缺点：

1° 单元面积大；

2° $f\uparrow$ 功耗 $\uparrow$；

3° 闩锁效应

CMOS 的优点：

1° 静态功耗小；

2° 随着充放电过程，充放电电流逐渐增大；

功率 MOSFET 的优点：

1° 多子器件；工作频率高，开关速度快；

2° 电压控制器件；输入阻抗高，所需驱动电流小；

3° 热稳定性好.

功率 MOSFET 的缺点：

1° V_{on} 大；

2° R_{on} 大.

输出电压最大幅值：$\frac{1}{2}(BV_{DS}-V_{DSsat\max})$

输出电流最大幅值：$\frac{1}{2}I_{DS\,sat\max}$

最大输出功率：

$$P_{o\max}=\frac{1}{2}\cdot\frac{1}{2}I_{DSsat\max}\cdot\frac{1}{2}(BV_{DS}-V_{DSsat\max})=\frac{1}{8}I_{DSsat\max}(BV_{DS}-V_{DSsat\max})$$

1. LDMOS (Laterally Diffused MOSFET)

优点：

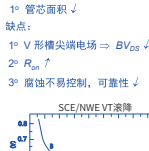
1° $L_B\downarrow\Rightarrow g_m\uparrow$ $f_T\uparrow$

2° N-漂移区 $\Rightarrow BV_{DS}\uparrow$ $V_{PT}\uparrow$

缺点：

1° 管芯面积 $\uparrow$

2. VVMOS（垂直V形槽）



优点：

1° 管芯面积 $\downarrow$

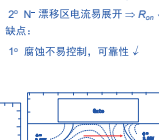
缺点：

1° V 形槽尖端电场 $\Rightarrow BV_{DS}\downarrow$

2° $R_{on}\uparrow$

3° 腐蚀不易控制，可靠性 $\downarrow$

3. VUMOS（垂直U形槽）



优点：

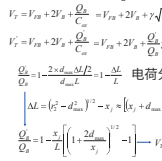
1° 消除尖端电场 $\Rightarrow BV_{DS}\uparrow$

2° N- 漂移区电流易展开 $\Rightarrow R_{on}\downarrow$

缺点：

1° 腐蚀不易控制，可靠性 $\downarrow$

4. VDMOS（垂直双扩散）



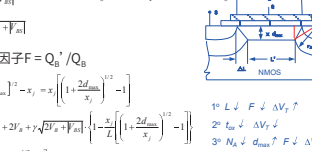
优点：

1° $BV_{DS}\uparrow$

2° 可靠性 $\uparrow$

缺点：

1° $R_{on}\uparrow$



电荷分享模型，Q_B需要另算

$$V_T=V_{FB}+2V_B+\frac{Q_B}{C_{ox}}=V_{FB}+2V_B+\gamma\sqrt{2V_B+|V_{BS}|}$$

$$V_T'=V_{FB}+2V_B+\frac{Q_B}{C_{ox}}=V_{FB}+2V_B+\frac{Q_B}{Q_B'}\gamma\sqrt{2V_B+|V_{BS}|}$$

$$\frac{Q_B}{Q_B'}=1-\frac{2\times d_{max}\Delta L/2}{d_{max}L}=1-\frac{\Delta L}{L}$$

电荷分享因子F = Q_B'/Q_B

$$\Delta L=\left[(r_j'+d_{max}')^2-x_j'\right]^{1/2}-\left[(r_j+d_{max})^2-d_{max}^2\right]^{1/2}-x_j=x_j\left[\left(1+\frac{2d_{max}}{x_j}\right)^{1/2}-1\right]$$

$$\frac{Q_B}{Q_B'}=1-\frac{x_j}{L}\left[\left(1+\frac{2d_{max}}{x_j}\right)^{1/2}-1\right]\rightarrow V_T'=V_{FB}+2V_B+\gamma\sqrt{2V_B+|V_{BS}|}\cdot\left[1-\frac{x_j}{L}\left[\left(1+\frac{2d_{max}}{x_j}\right)^{1/2}-1\right]\right]$$

d_{max}/x_j 较小时 $\quad F=\frac{Q_B'}{Q_B}=1-\frac{x_j}{L}\left[\left(1+\frac{2d_{max}}{x_j}\right)^{1/2}-1\right]\approx1-\frac{d_{max}}{L}$

d_{max}/x_j 较大时 $\quad F=\frac{Q_B'}{Q_B}=1-\alpha\frac{d_{max}}{L}$ 经验参数（$\alpha>1$）

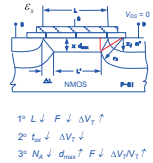
$$\Delta V_T=\left|V_T'-V_T\right|=(1-F)\gamma\sqrt{2V_B+|V_{BS}|}=\gamma\sqrt{2V_B+|V_{BS}|}\cdot\frac{x_j}{L}\left[\left(1+\frac{2d_{max}}{x_j}\right)^{1/2}-1\right]$$

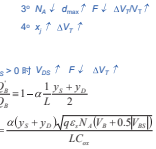
$$=\alpha\frac{d_{max}}{L}\gamma\sqrt{2V_B+|V_{BS}|}=2\alpha\frac{\varepsilon_s}{C_{ox}}\frac{L}{L}(2V_B+|V_{BS}|)$$

$$\gamma=\frac{\sqrt{2\varepsilon_s qN_A}}{C_{ox}}\qquad d_{max}(V_{BS})=\left[\frac{2\varepsilon_s(2V_B+|V_{BS}|)}{q\quad N_A}\right]^{1/2}$$

GCA近似不成立，有效电荷密度减小

$$\frac{\partial^2\phi(x,y)}{\partial x^2}=-\frac{\rho(x,y)}{\varepsilon_s}-\frac{\partial^2\phi(x,y)}{\partial y^2}=-\frac{\rho_{eff}(x,y)}{\varepsilon_s}$$





1° $L\downarrow$ $F\downarrow$ $\Delta V_T\uparrow$

2° $t_{ox}\downarrow$ $\Delta V_T\downarrow$

3° $N_A\downarrow$ $d_{max}\uparrow$ $F\downarrow$ $\Delta V_T/V_T\uparrow$

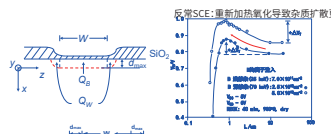
4° $x_j\uparrow$ $\Delta V_T\uparrow$

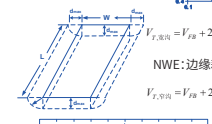
当 $V_{DS}>0$ 时 $V_{DS}\uparrow$ $F\downarrow$ $\Delta V_T\uparrow$

$$F=\frac{Q_B'}{Q_B}=1-\alpha\frac{1}{L}\frac{y_S+y_D}{2}$$

$$\Delta V_T=\frac{\alpha(y_S+y_D)\sqrt{q\varepsilon_s N_A(V_B+0.5|V_{BS}|)}}{LC_{ox}}$$

反常SCE：重新加热氧化导致杂质扩散更均匀





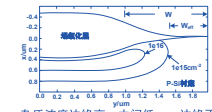
$$V_{T,宽沟}=V_{FB}+2V_B+\gamma\sqrt{2V_B+|V_{BS}|}$$

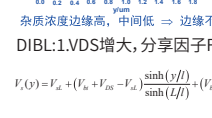
NWE：边缘耗尽效应

$$V_{T,窄沟}=V_{FB}+2V_B+\gamma\sqrt{2V_B+|V_{BS}|}+\frac{Q_{BW}}{C_{ox}}$$

¼ 圆弧：$\frac{Q_{BW}}{Q_B}=\frac{1}{2}\frac{\pi d^2}{W\cdot d_{max}}=\frac{\pi}{2}\frac{d_{max}}{W}$

一般地，引入经验参数 G_W $\quad\frac{Q_{BW}}{Q_B}=G_W\frac{d_{max}}{W}$





杂质浓度边缘高，中间低 $\Rightarrow$ 边缘不易开启 $\Rightarrow$ 随着 $W\downarrow$ $V_T\uparrow$——窄沟道效应

DIBL：漏诱导的势垒降低

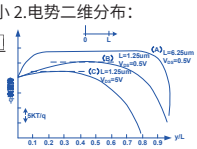
L 很小时，$V_{DS}\uparrow$ $V_T\downarrow$

$V_T(V_{DS})=V_T(0)-\sigma V_{DS}$

DIBL:1.VDS增大，分享因子F减小，阈值减小 2.电势二维分布：

$$V_s(y)=V_{sL}+(V_{bi}+V_{DS}-V_{sL})\frac{\sinh(y/l)}{\sinh(L/l)}+(V_{bi}-V_{sL})\frac{\sinh[(L-y)/l]}{\sinh(L/l)}$$

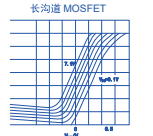
$$\rightarrow\Delta V_T=\begin{cases}\left[2(V_{bi}-2V_B)+V_{DS}\right]\left[\exp(-L/2l)+2\exp(-L/l)\right] & V_{DS}\text{ 很小}\\ \left[3(V_{bi}-2V_B)+V_{DS}\right]\exp(-L/l)+2\sqrt{(V_{bi}-2V_B)(V_{bi}-2V_B+V_{DS})}\exp(-L/2l) & V_{DS}\text{ 大}\end{cases}$$



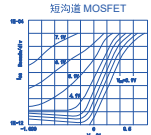
特征长度 $\quad l=\sqrt{\frac{\varepsilon_s d_{max}t_{ox}}{\eta\varepsilon_{ox}}}$

亚阈特性

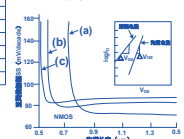
长沟道 MOSFET



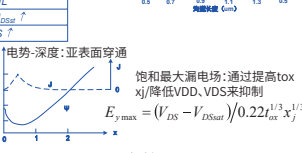
短沟道 MOSFET



浓度：C>B>A



长沟道	短沟道
$I_{DSat}\propto 1/L$	$I_{DSat}\ge 1/L$
I_{DSat} 与 V_{DS} 无关	$V_{DS}\uparrow$ $I_{DSat}\uparrow$
S 与 L 无关	$L\downarrow$ $S\uparrow$

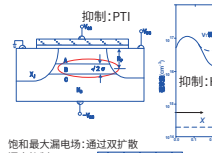


电势-深度：亚表面穿通

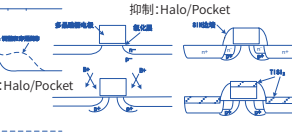
饱和最大漏电场：通过提高tox xj/降低VDD、VDS来抑制

$$E_{y\max}=(V_{DS}-V_{DSsat})/0.22t_{ox}^{1/3}x_j^{1/3}$$

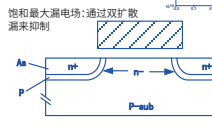
抑制：PTI



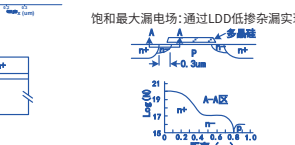
抑制：Halo/Pocket



饱和最大漏电场：通过双扩散漏来抑制



饱和最大漏电场：通过LDD低掺杂漏实现



	长沟道	短沟道
线性区	$I_{DS}=\beta\left[(V_{GS}-V_T)V_{DS}-\frac{1}{2}V_{DS}^2\right]$，$\mu_n C_{ox}(W/L)$	$I'_{DS}=\beta'\left[(V_{GS}-V_T)V_{DS}-\frac{1}{2}V_{DS}^2\right]$，$\frac{\mu_{eff}C_{ox}(W/L)}{1+(V_{DS}/E_{sat}L)}$
I_{DS} 饱和条件	$Q_n(L)=0\Leftrightarrow V_{DSsat}=V_{GS}-V_T$	$v_n=v_{sat}\Leftrightarrow V'_{DSsat}=\frac{E_{sat}L(V_{GS}-V_T)}{E_{sat}L+(V_{GS}-V_T)}$
饱和区	$I_{DSsat}=\frac{1}{2}\beta(V_{GS}-V_T)^2=\frac{1}{2}\beta V_{DSsat}^2$	$I'_{DSsat}=v_{sat}C_{ox}W\frac{(V_{GS}-V_T)^2}{E_{sat}L+(V_{GS}-V_T)}$

区 I：$I_{DS}=\frac{\mu_{eff}}{1+\frac{V_{DSsat}}{E_{sat}L}}\cdot C_{ox}\frac{W}{L}\left[(V_{GS}-V_T)V'_{DSsat}-\frac{1}{2}V'^2_{DSsat}\right]$

区 II：$I_{DS}=Q_n(P)Wv_{sat}=Wv_{sat}C_{ox}(V_{GS}-V_T-V'_{DSsat})$

$$\Rightarrow\begin{cases}V'_{DSsat}=\dfrac{E_{sat}L(V_{GS}-V_T)}{E_{sat}L+(V_{GS}-V_T)}\\ I'_{DSsat}=v_{sat}C_{ox}W\dfrac{(V_{GS}-V_T)^2}{E_{sat}L+(V_{GS}-V_T)}\end{cases}$$

I'_{DSsat}

速度饱和

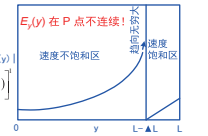
$$v(E_y)=\begin{cases}\mu_{eff}\dfrac{|E_y|}{1+\left[\dfrac{|E_y|}{E_{sat}}\right]} & |E_y|<E_{sat}\\ v_{sat}=\mu_{eff}E_{sat}/2 & |E_y|\ge E_{sat}\end{cases}$$

		恒电场	准恒电场	
微缩规则	沟道长度	L	$1/S$	$1/S$	
	沟道宽度	W	$1/S$	$1/S$	
	栅氧厚度	t_{ox}	$1/S$	$1/S$	
	源漏结深	x_j	$1/S$	$1/S$	
	衬底掺杂浓度	N_A	S	US	
	工作电压	V_{DD}	$1/S$	U/S	
器件参数变化	电场强度	E	1	U	
	电势分布	ϕ	$1/S$	U/S	
	漏衬 pn 结耗尽区宽度	W_D	$1/S$	$1/S$	
	栅总电容	C_G	$1/S$	$1/S$	
	漏源电流	I_{DS}	$1/S$	U^2/S	
	电流线密度/单位宽度驱动能力	I_{DS}/W	1	U^2	不适用于亚阈值区
	电流面密度	I_{DS}/A	S	U^2S	不适用于亚阈值区
电路特性	RC 电路延时	τ	$1/S$	$1/(US)$	
	功耗	P	$1/S^2$	U^3/S^2	
	功率密度	P/A	1	U^3	
能	集成度（CD）	$1/A$	S^2	S^2	
瓶颈	阈值电压	V_T	$1/S$（难）	U/S（更容易实现）	
	pn 结内建电势差	V_{bi}	$V_{bi}\ll V_{DD}$	$V_{bi}\ll V_{DD}$	一般不适用

1. 突变结耗尽层近似模型

$$\frac{-d\left[E_y(y)\right]}{dy}=\frac{-qN_A}{\varepsilon_s}$$

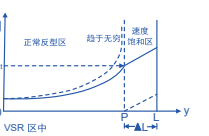
VSR 压降 $=V_{DS}-V_{DSsat}\longrightarrow\Delta L=\left[\frac{2\varepsilon_s}{qN_A}(V_{DS}-V_{DSsat})\right]^{\frac{1}{2}}$



$$\left|E_y(y)\right|=\frac{qN_A}{\varepsilon_s}\left[y-(L-\Delta L)\right]\quad\text{或}\quad\left|E_y(y)\right|=\frac{qN_A}{\varepsilon_s}y'$$

$$\int_0^{y'}-I_{DS}dy=\int_0^{E(y)}-W\mu_n C_{ox}\left[V_{GS}-V_T-V(y)\right]dV(y)$$

I 区 $\quad\left|E(y)\right|=\frac{V_{DSsat}}{2L}\sqrt{1-\frac{y}{L-\Delta L}}$



2. 恒定电场梯度模型

(1) 对假设 ② 作修改：$\quad qn=A_{ph}\frac{I_{DS}}{v_{sat}x_jW}$ ← 拟合参数

(2) 对假设 ③ 作修改：$\quad E_y(y)\big|_{y=(L-\Delta L)'}=E_y(y)\big|_{y=(L-\Delta L)'}$

$\qquad\qquad\qquad