第一章 MOS器件基础

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目录

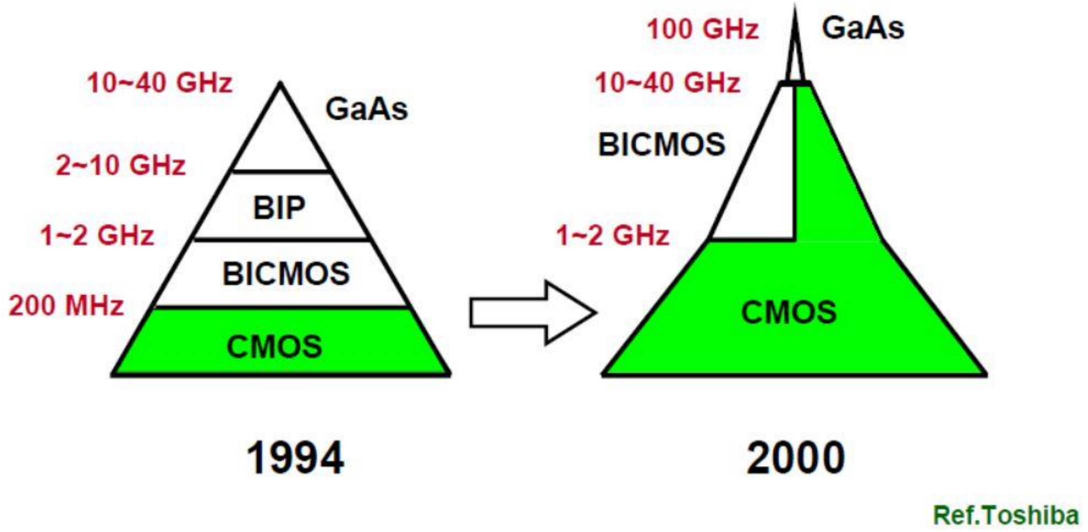
- 前言
- MOS管原理
- MOS管I-V特性
- 2阶效应
- MOS管模型
- 短沟道效应
- 仿真模型
- 工艺角

前言

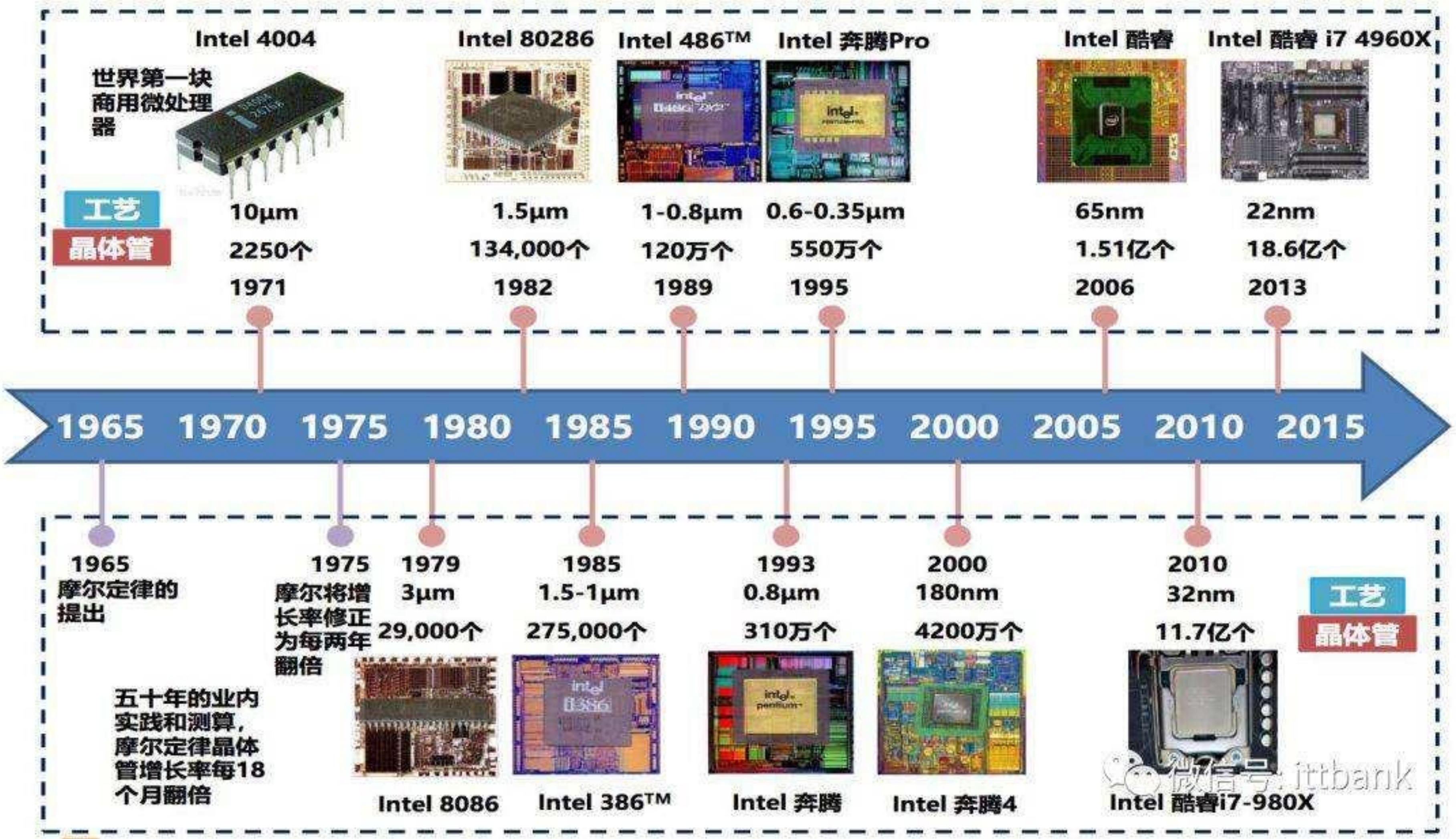
- MOS管的优势和缺点
- 摩尔定律
- 模拟电路学习的知识体系

MOS管优势和缺点

- 数字电路
  - 等比例缩小，速度显著提高，成本降低
  - 功耗低
  - 电路结构简单
- 模拟电路
  - 制造成本低
  - 数模混合
- 与Bipolar比较
  - 速度慢，噪声大
  - 尺寸小，低电压



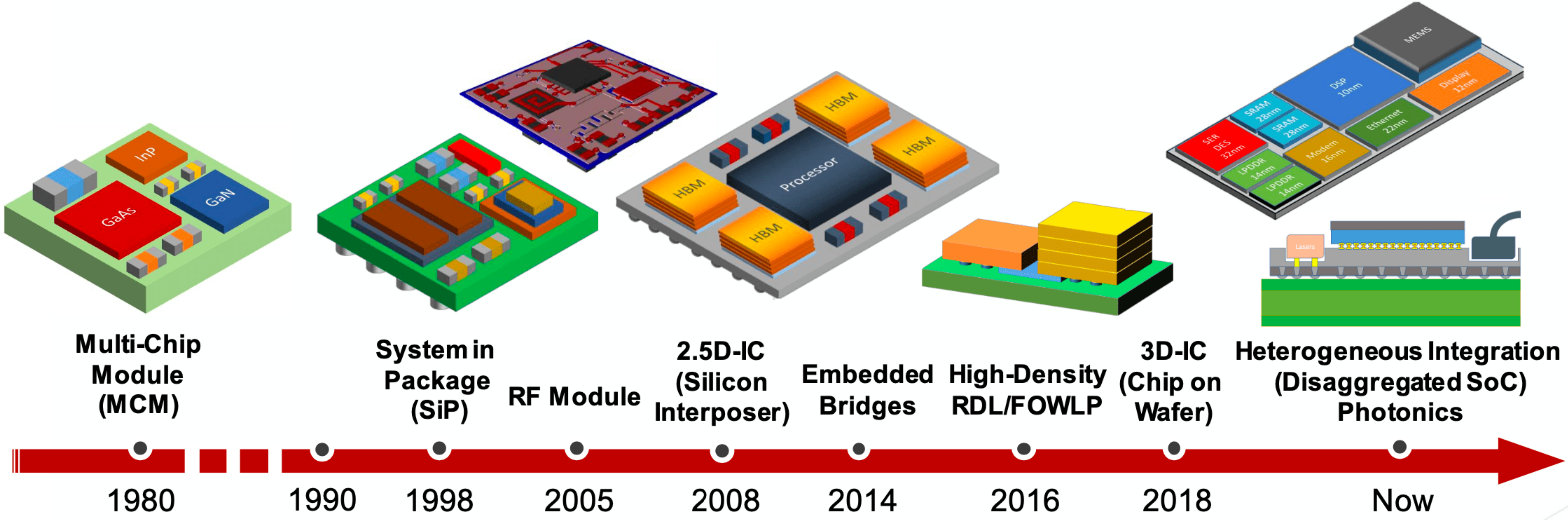
摩尔定律



- 苹果A17的基本信息
  - 2023年
  - 6核CPU和6核GPU
  - 主频3.7GHz
  - 3nm工艺
  - 人工智能加速

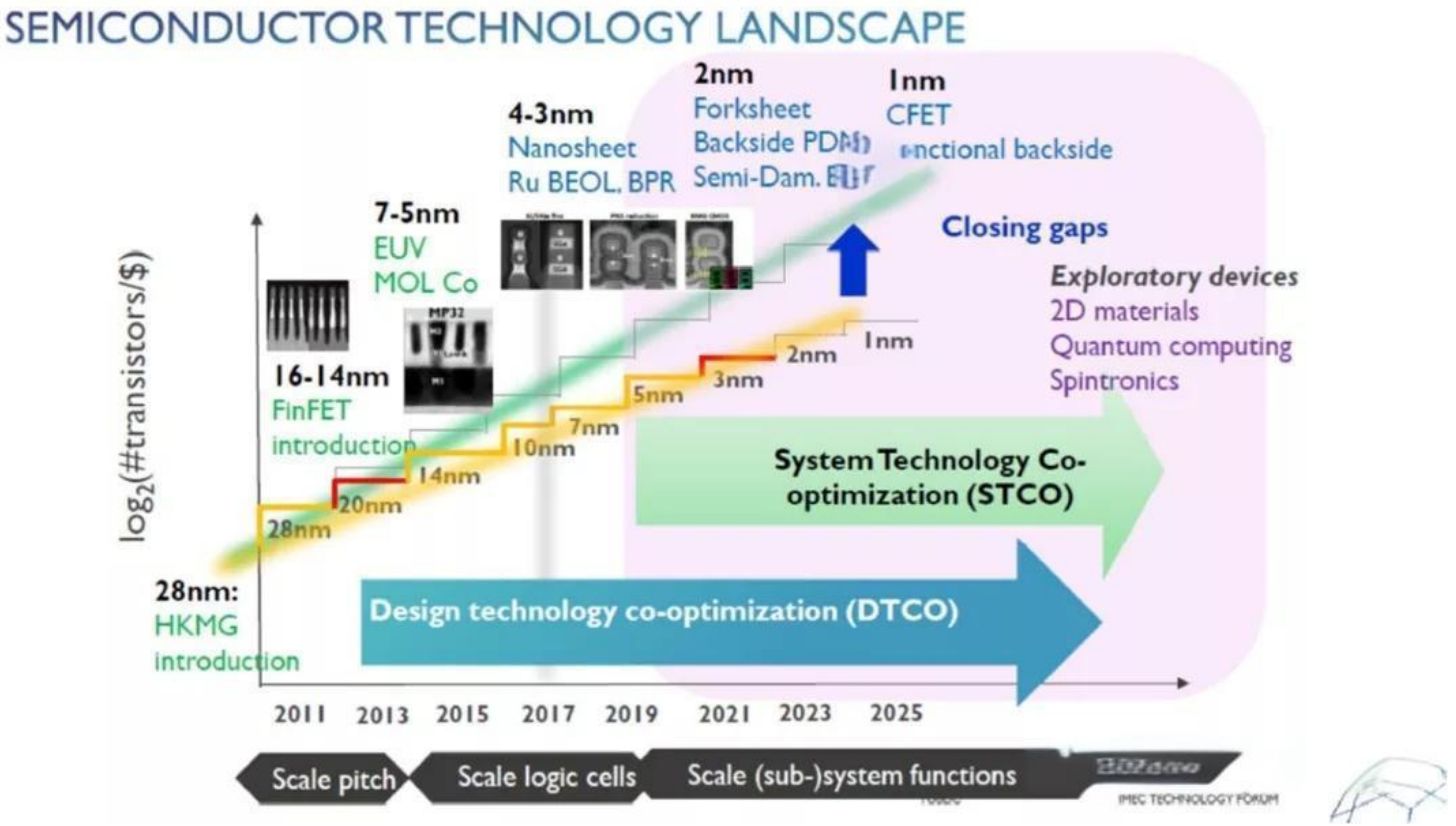
A16：160亿个晶体管

超摩尔定律

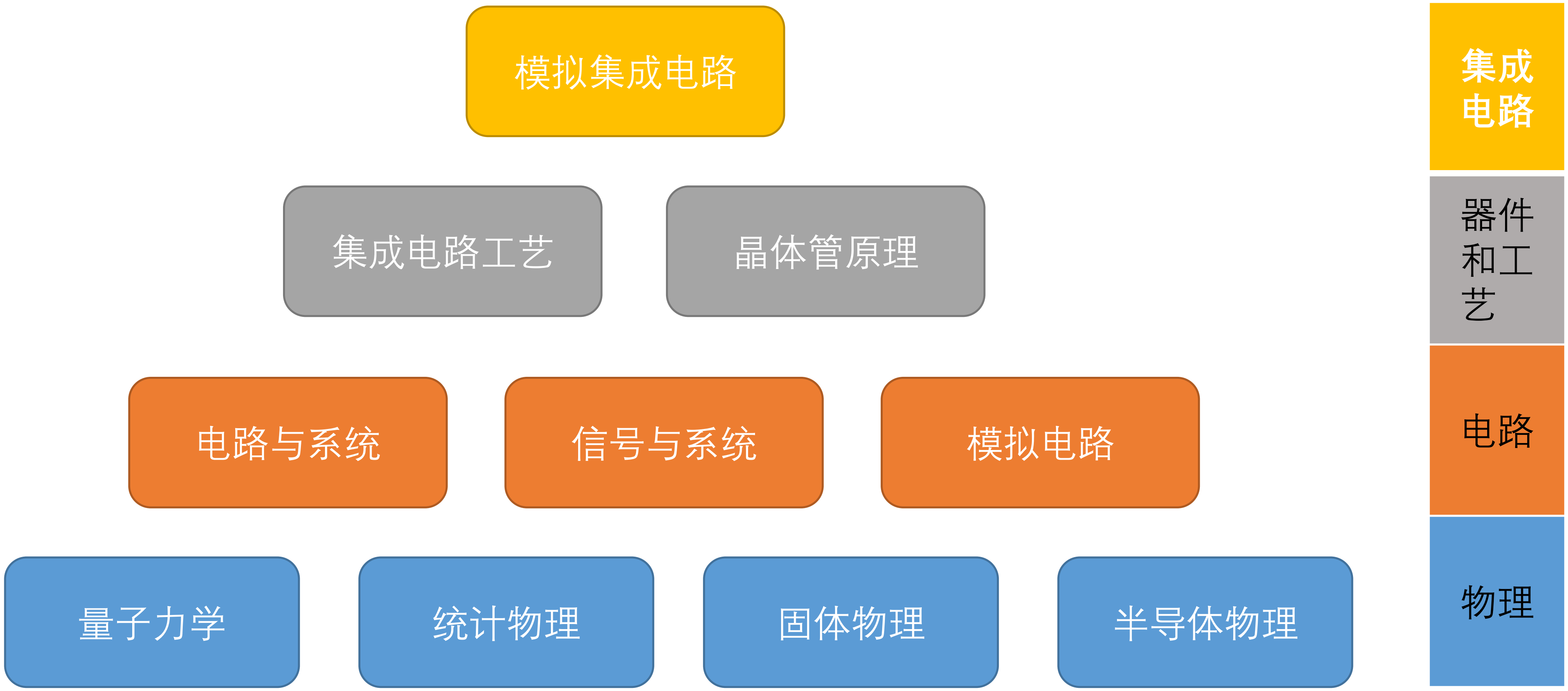


InP
GaAs
GaN
HBM
Processor
MEMS
DSP 10nm
Display 12nm
SRAM 28nm
Ethernet 22nm
SER DES 32nm
Modem 16nm
LPDDR 14nm
Multi-Chip Module (MCM)
System in Package (SiP)
RF Module
2.5D-IC (Silicon Interposer)
Embedded Bridges
High-Density RDL/FOWLP
3D-IC (Chip on Wafer)
Heterogeneous Integration (Disaggregated SoC) Photonics
1980
1990
1998
2005
2008
2014
2016
2018
Now

工艺节点和MOS晶体管结构



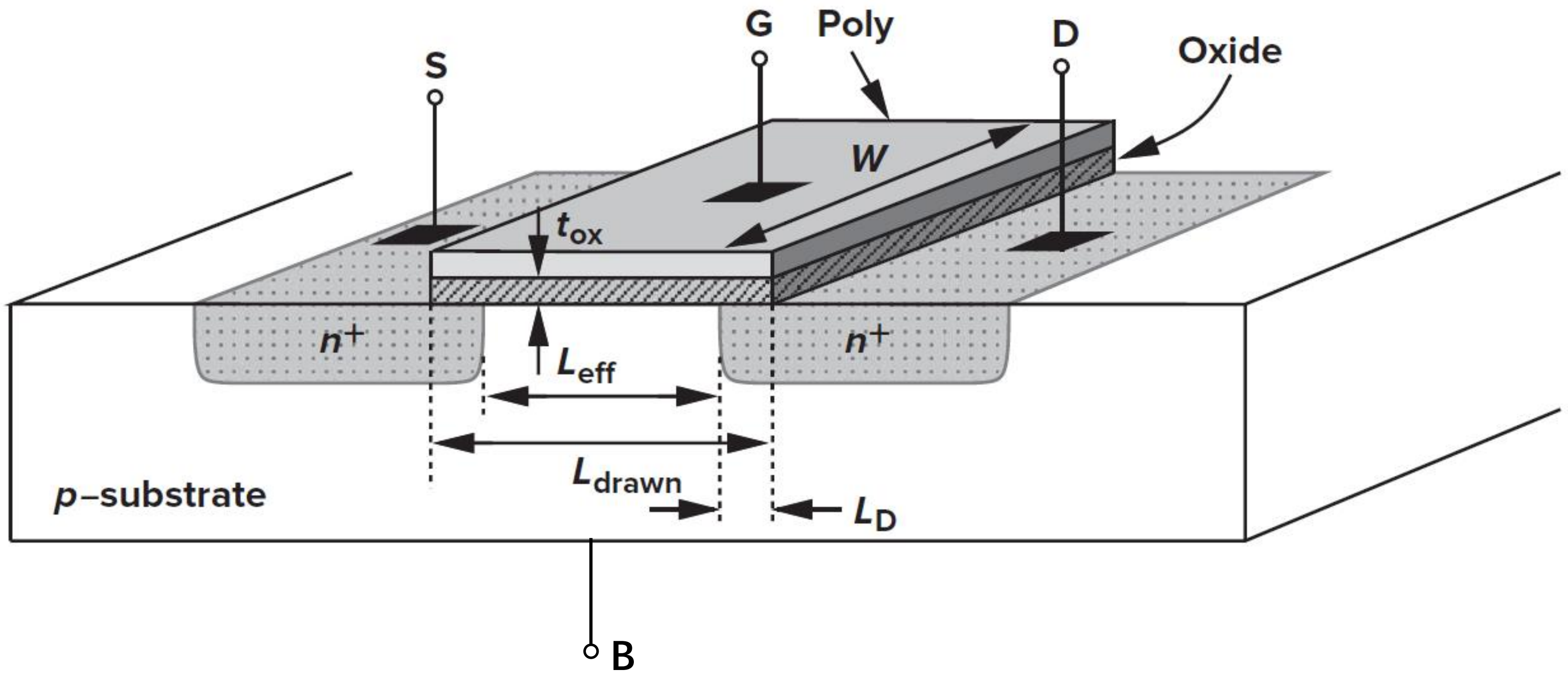
模拟电路设计的知识体系



MOS管原理

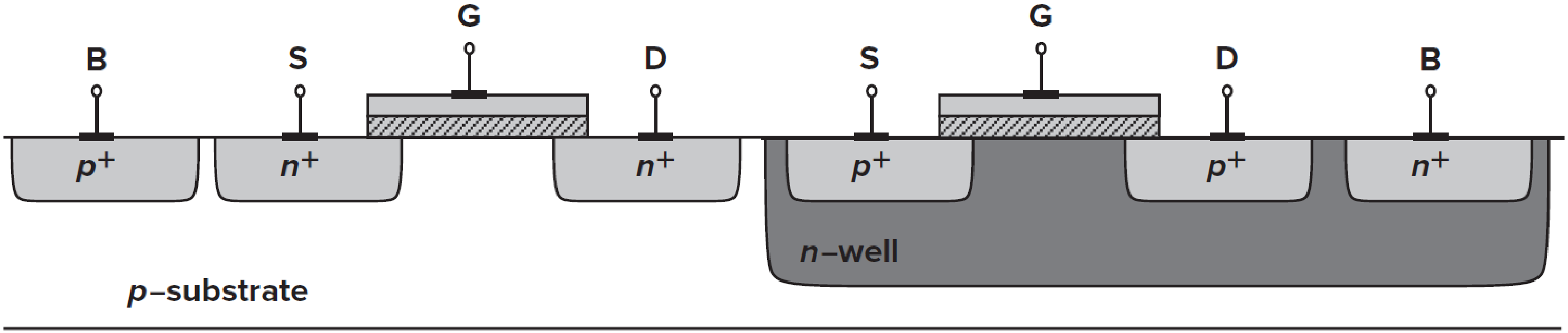
- MOS管结构
- 工作原理
- MOS管符号

MOS管结构-三维立体图

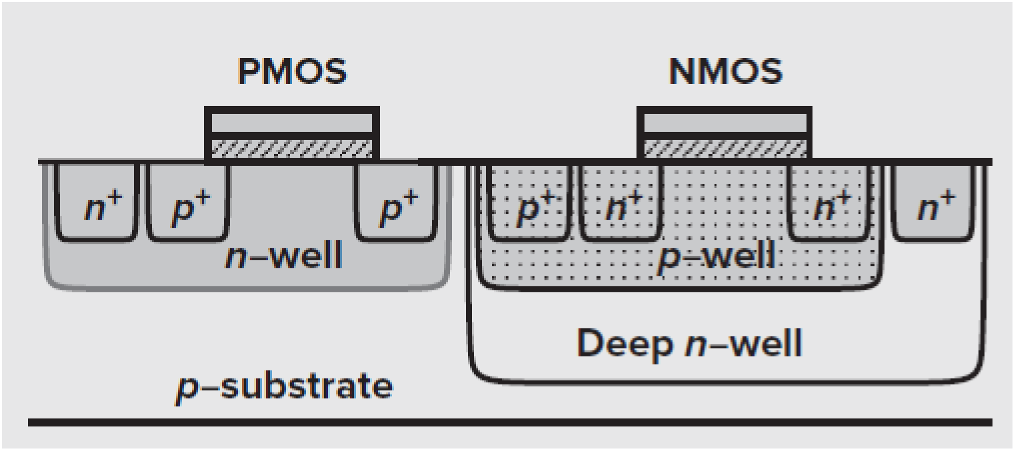


- 结构特点
  - 平面工艺
  - 四端器件
  - 对称结构
  - 衬底（阱）共享

MOS管结构-剖面图

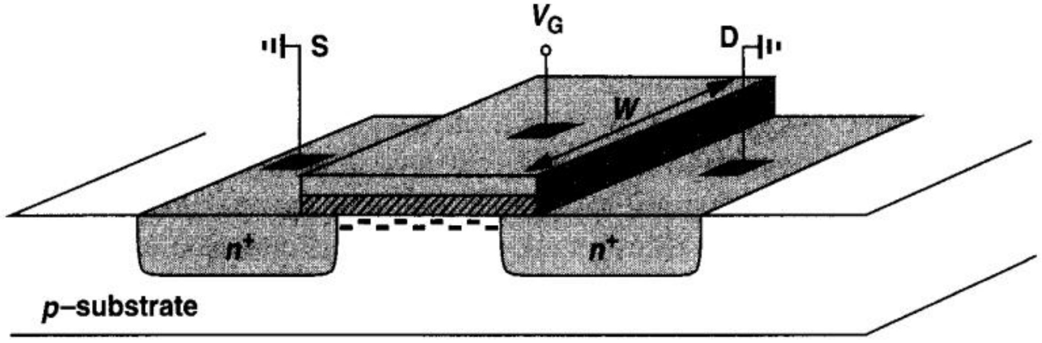


单阱结构

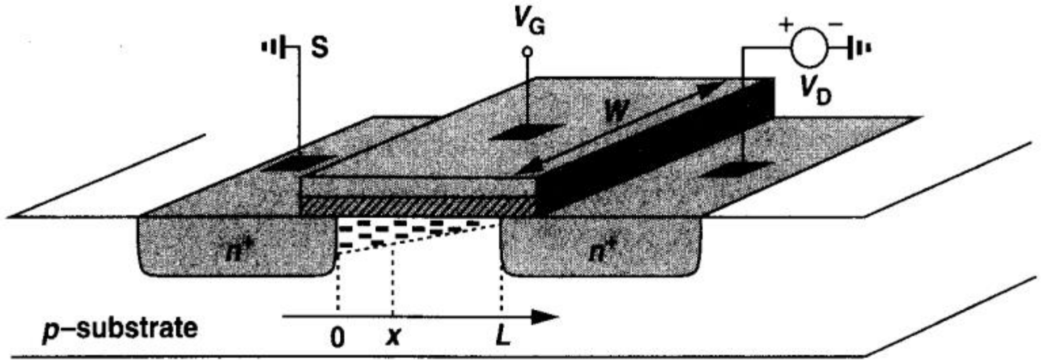


三阱结构

MOS管工作原理



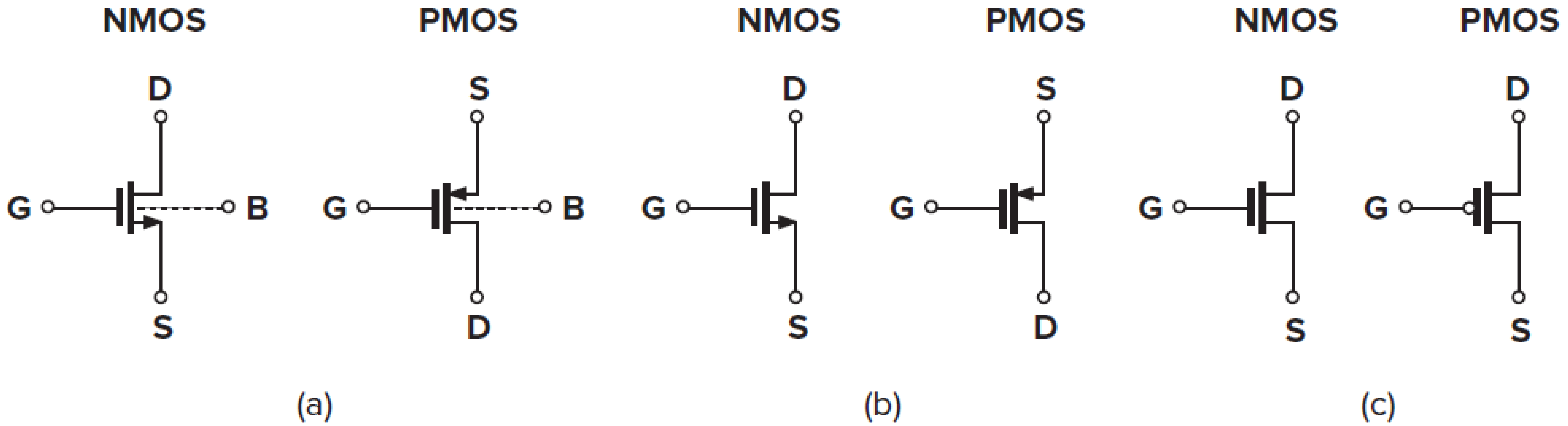
(a)



(b)

- 沟道形成（阈值电压）
- 电压（三维）控制沟道电阻，改变电流大小
- 载流子从源端流向漏端

MOS管符号



MOS管I-V特性

- 阈值电压
- I-V特性曲线
- 跨导计算

阈值电压的定义

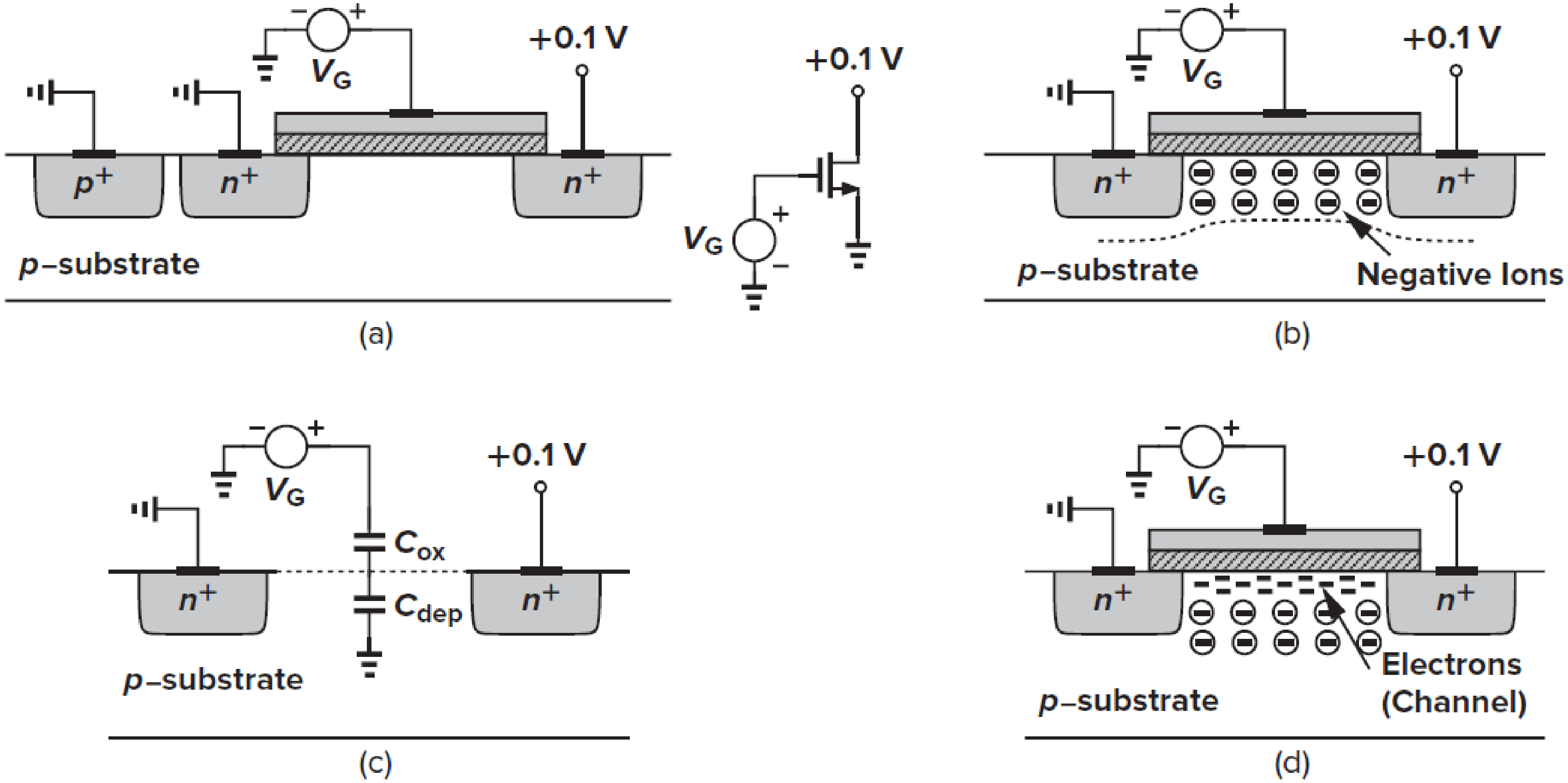


Figure 2.6 (a) A MOSFET driven by a gate voltage; (b) formation of depletion region; (c) onset of inversion; (d) formation of inversion layer.

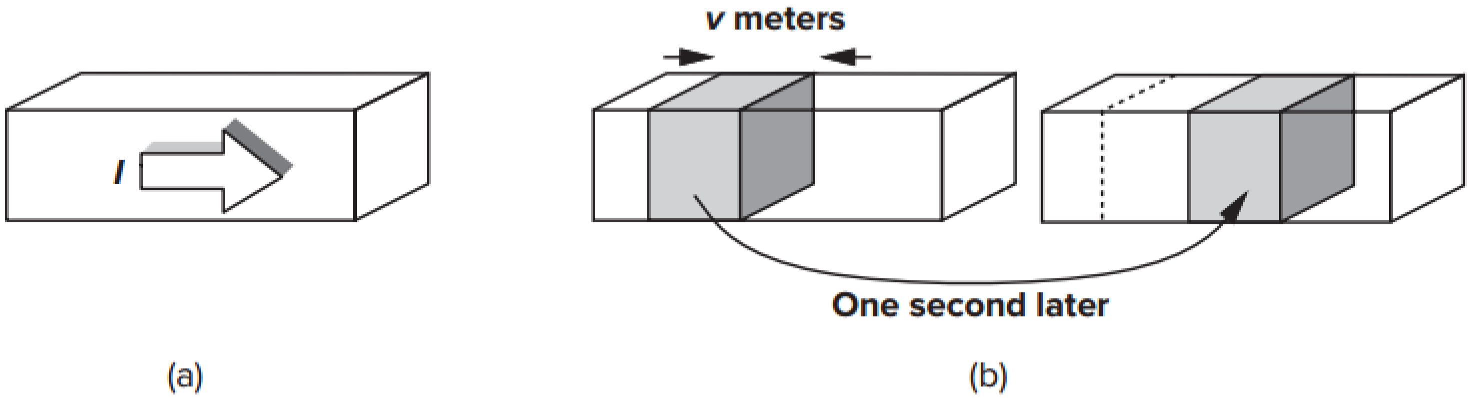
阈值电压的表达式

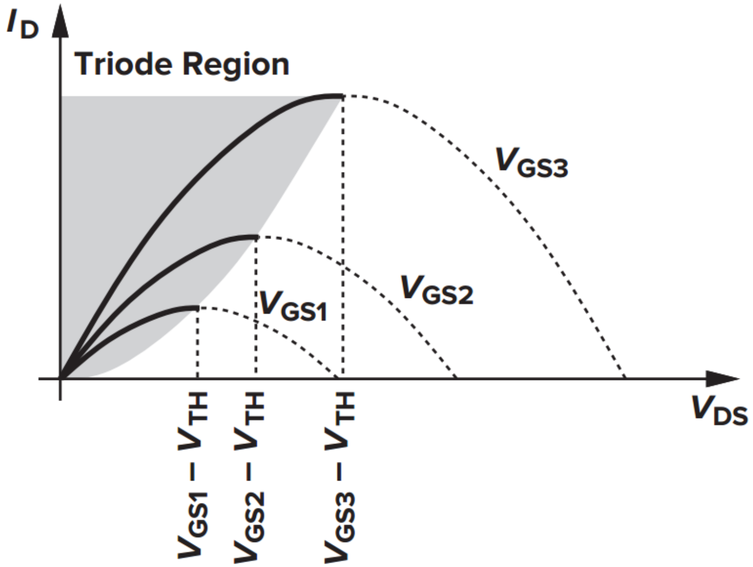
$$V_{TH} = \Phi_{MS} + 2\Phi_F + \frac{Q_{dep}}{C_{ox}}$$

- Φ_{MS}：多晶硅与硅衬底的功函数差
- Φ_F：费米势
- Q_{dep}：耗尽层电荷数
- C_{ox}：绝缘层电容

I-V特性曲线（1）

- 公式





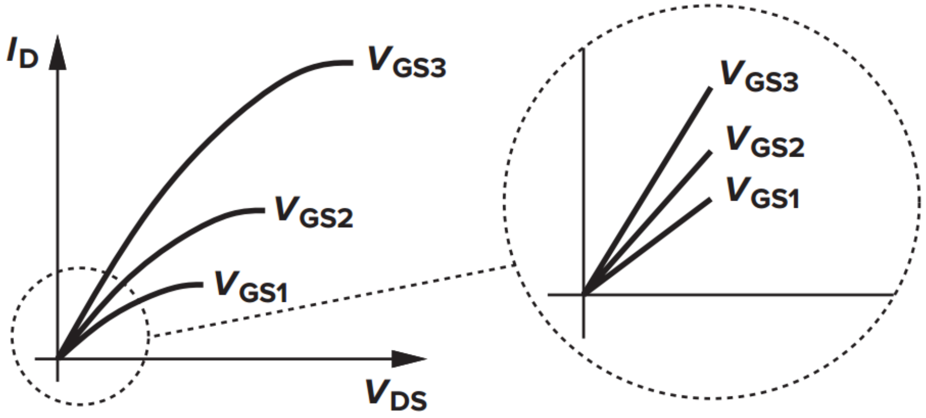
$$I_D = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{TH}) V_{DS} - \frac{1}{2} V_{DS}^2 \right]$$

$$I_{D,MAX} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} [(V_{GS} - V_{TH})^2]$$

I-V特性曲线（2）

线性区

$$I_D \approx \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) V_{DS} \quad \text{when} \quad V_{DS} \ll 2(V_{GS} - V_{TH})$$



$$R_{on} = \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})}$$

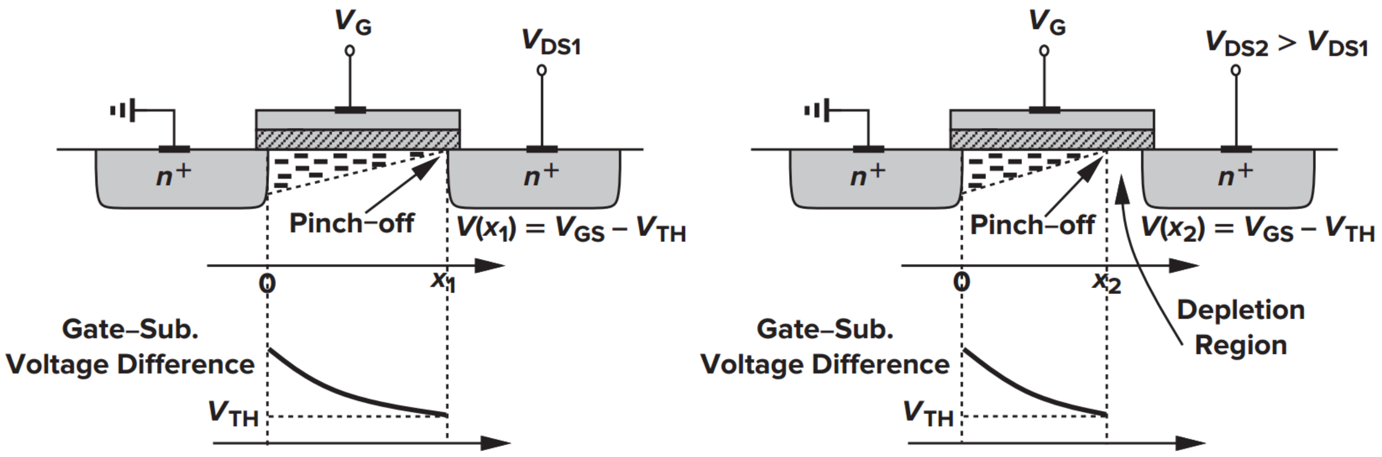
I-V特性曲线（3）

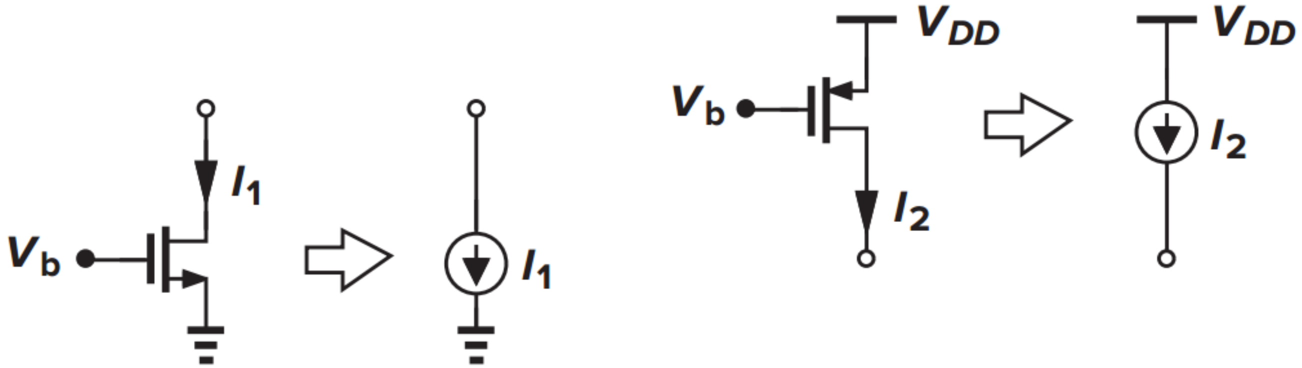
- 饱和区

when $V_{DS} = V_{GS} - V_{TH}$

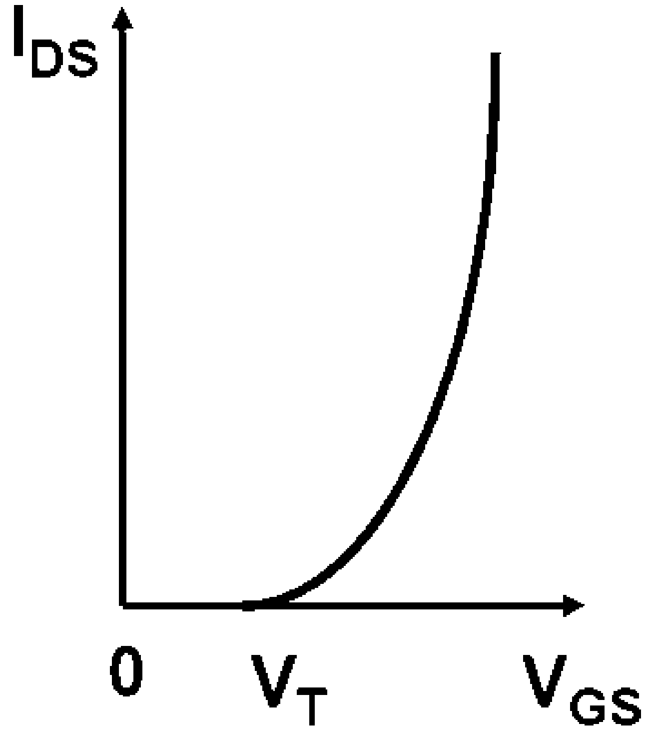
$$I_{D,NMOS} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2$$

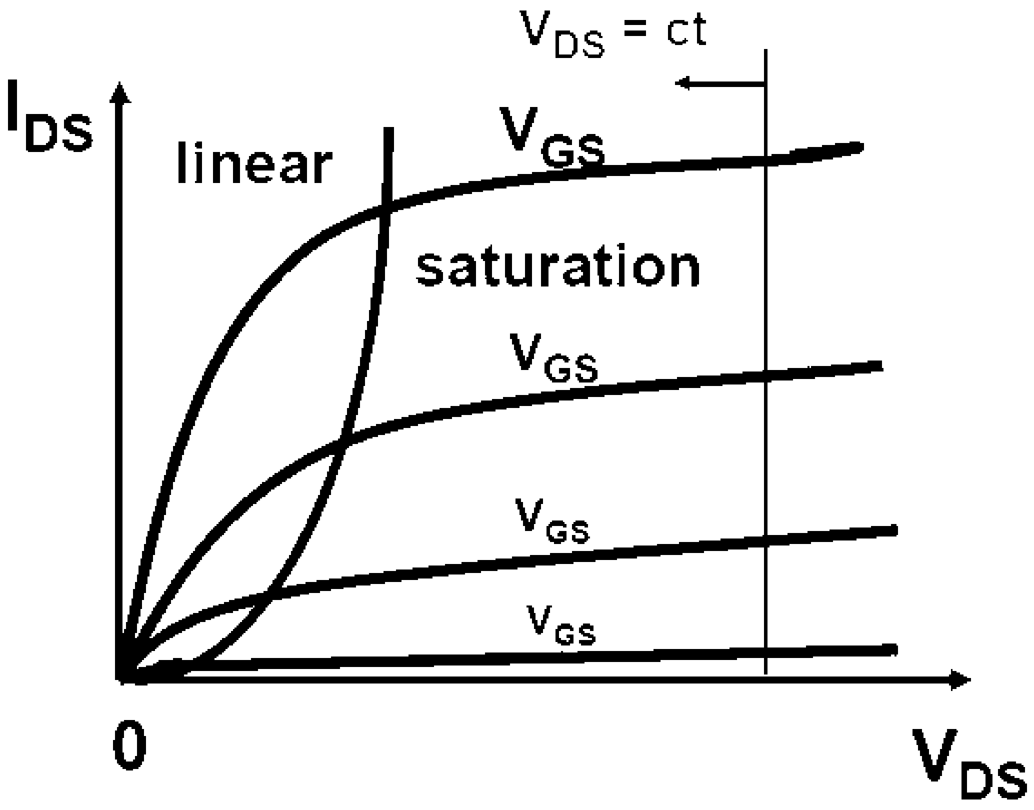
$$I_{D,PMOS} = -\frac{1}{2}\mu_p C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2$$





I-V特性曲线（4）





I-V特性曲线（5）

- 截止区 $\left|V_{GS}\right| \le \left|V_T\right|$ $\quad I_{sub} = I_0 e^{\frac{V_{GS}-V_T}{nKT}}(1 - e^{-\frac{qV_{DS}}{KT}})$

- 线性区 $\left|V_{GS}\right| > \left|V_{Tn,p}\right|, \left|V_{DS}\right| \le \left|V_{GS} - V_{Tn,p}\right|$

$$I_{DS,nmos} = k_n^{'} \frac{W}{L}[(V_{GS} - V_{Tn})V_{DS} - \frac{1}{2}V_{DS}^2]$$

$$k_{n,p}^{'} = \mu_{n,p} C_{ox}$$

$$I_{DS,pmos} = -k_p^{'} \frac{W}{L}[(V_{GS} - V_{Tp})V_{DS} - \frac{1}{2}V_{DS}^2]$$

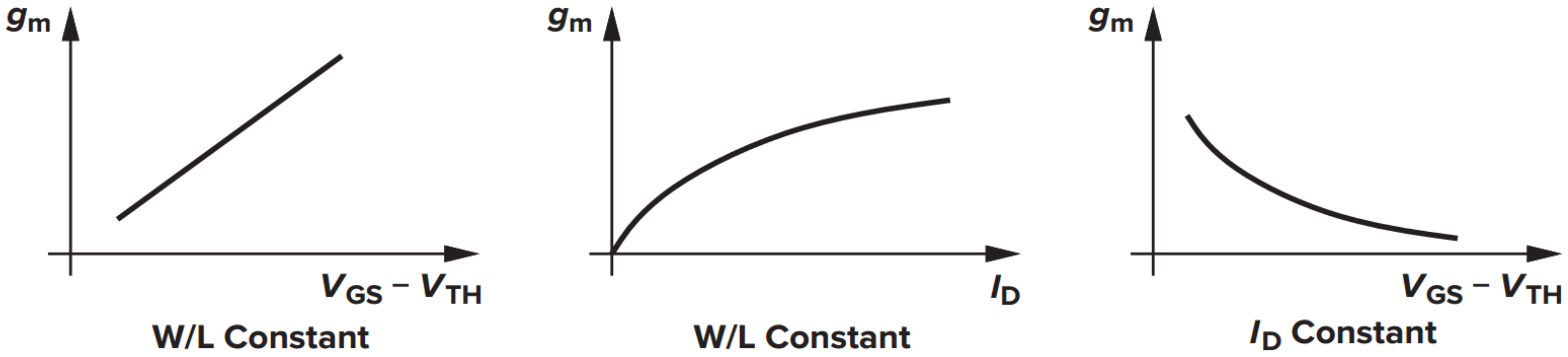
- 饱和区 $\left|V_{GS}\right| > \left|V_{Tn,p}\right|, \left|V_{DS}\right| > \left|V_{GS} - V_{Tn,p}\right| = \left|V_{ov}\right|$

$$I_{DS,nmos} = \frac{1}{2} k_n^{'} \frac{W}{L}(V_{GS} - V_{Tn})^2 (1 + \lambda V_{DS})$$

电流方程的各个参数

- 电流方程中各个变量
  - W： 栅宽
  - L ： 沟长
  - V_{GS}： 栅源电压
  - V_{DS}： 漏源电压
  - V_T： 阈值电压
  - V_{OV}： 过驱动电压，$V_{OV} = V_{GS} - V_T$
  - n： 比例系数，非理想因子
  - K: 工艺参数
  - λ： 沟长调制系数

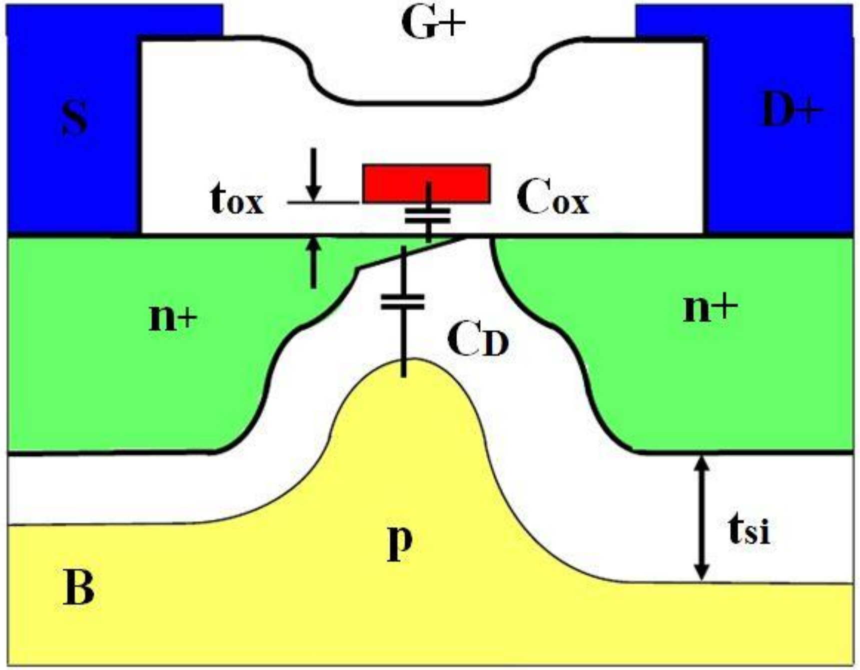
跨导计算



$$g_m = \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{VDS \text{ const.}}$$

$$= \mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{TH}) = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D} = \frac{2I_D}{V_{GS} - V_{TH}}$$

n的计算



$$C_D = \frac{\varepsilon_{si}}{t_{si}}$$

$$t_{si} = \sqrt{\frac{2\epsilon_{si}(\phi - V_{BD})}{qN_B}}$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

$$\frac{C_D}{C_{ox}} = n - 1$$

n计算实例

$$C_D = \frac{\varepsilon_{si}}{t_{si}} \qquad t_{si} = \sqrt{\frac{2\varepsilon_{si}(\phi - V_{BD})}{qN_B}}$$

$\varepsilon_{si} = 1$ pF/cm

$\varepsilon_{ox} = 0.34$ pF/cm

$\phi \approx 0.6$ V

$q = 1.6\ 10^{-19}$ C

$N_B \approx 4\ 10^{17}$ cm^{-3}

Example : L = 0.35 μm; W/L = 8

$V_{BD} = -3.3$ V : $\quad t_{si} = 0.1\ \mu m$

$C_D \approx 10^{-7}$ F/cm^2

$$t_{ox} = \frac{L_{min}}{50}$$

$t_{ox} = 7$ nm

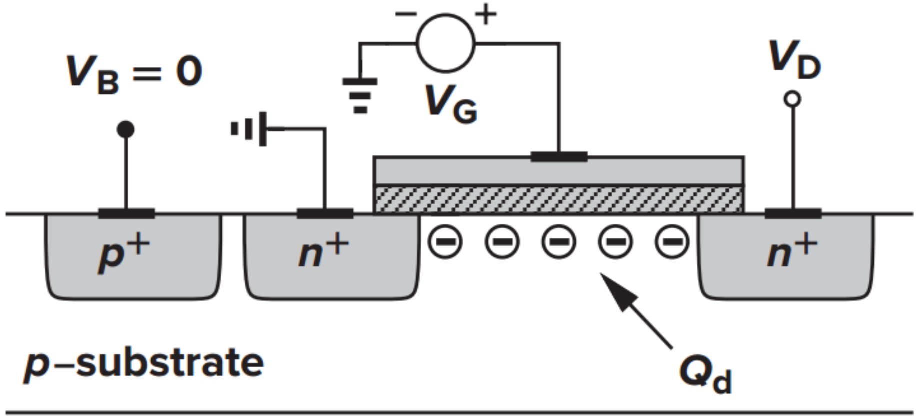
$C_{ox} \approx 5\ 10^{-7}$ F/cm^2

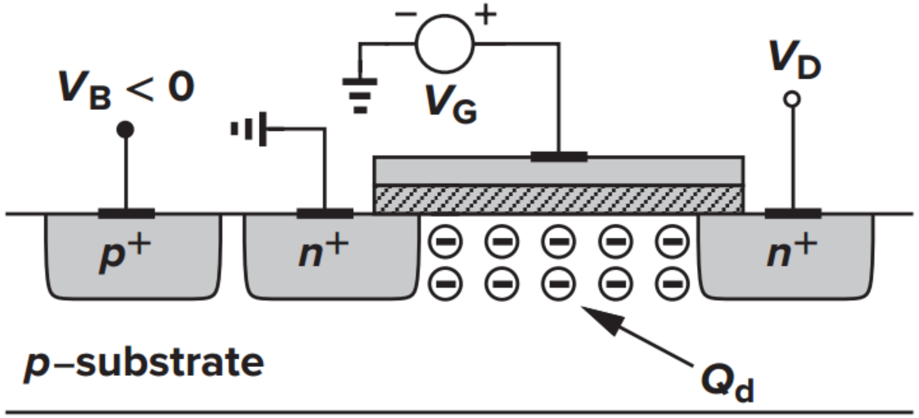
$$\frac{C_D}{C_{ox}} = n - 1 \approx 0.2$$

2阶效应

- 体效应
- 沟道调制效应
- 亚阈值效应

衬偏效应





$$V_{TH} = V_{TH0} + \gamma\left(\sqrt{2\Phi_F + V_{SB}} - \sqrt{|2\Phi_F|}\right)$$

$$\gamma = \frac{1}{C_{ox}}\sqrt{2q\varepsilon_{si}N_B}$$

$$V_{TH0} = \Phi_{MS} + 2\Phi_F + \frac{Q_{dep}}{C_{ox}}$$

$$\Phi_F = \frac{kT}{q} ln \frac{N_B}{n_i}$$

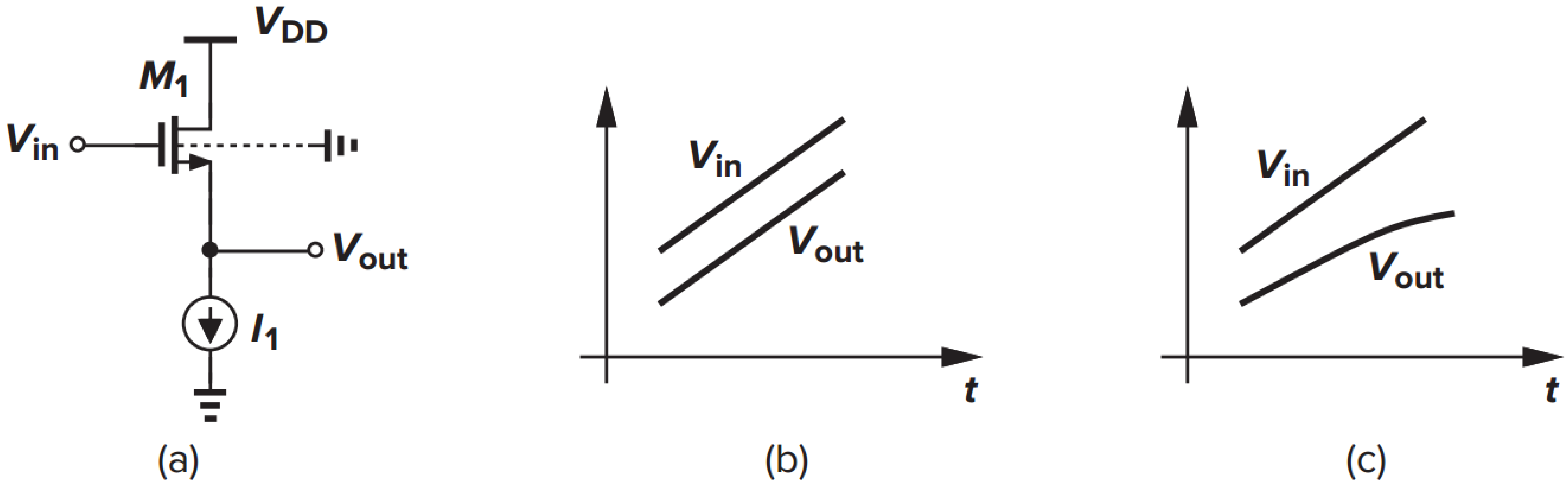
阈值电压与衬偏调制的关系

- 阈值电压的变化与耗尽区的反偏变化一致

	V_s=CT，$V_b\uparrow$	V_s=CT，$V_b\downarrow$	$V_s\uparrow$，V_b=CT	$V_s\downarrow$，V_b=CT
V_{TN}	—	+	+	—
$\lvert V_{TP}\rvert$	+	-	-	+

- 对性能的影响
  - 源端电位与衬不一致：叠栅，传输管
  - 体效应可以提高晶体管的驱动能力

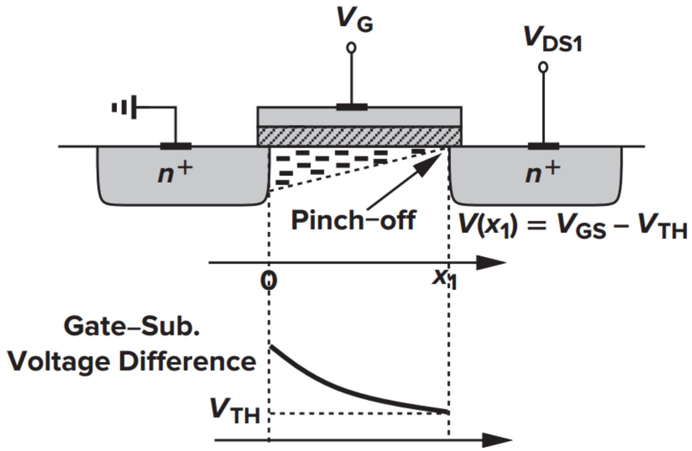
衬偏效应的影响（例）

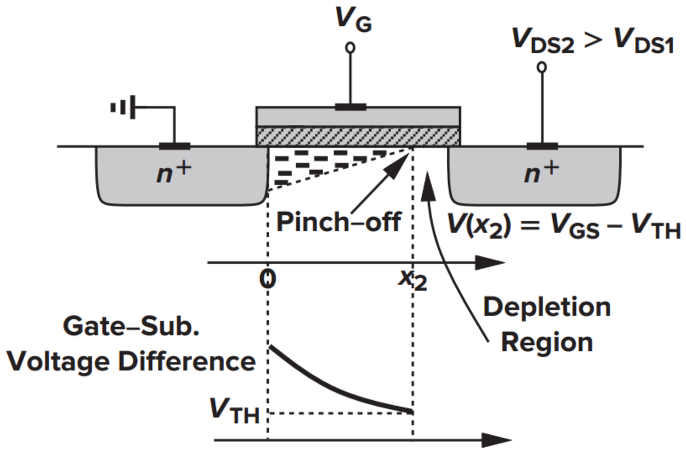


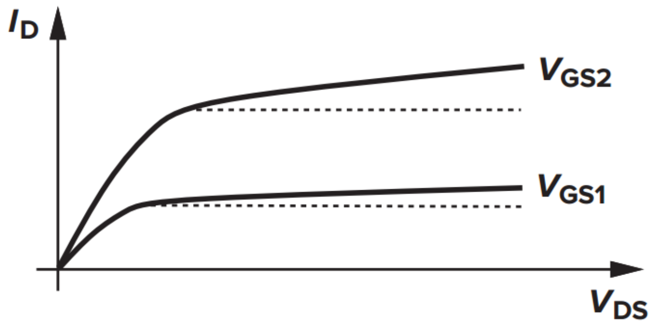
$$I_1 = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{out} - V_{TH})^2$$

沟道调制效应

- 沟道夹断后有效沟道长度受到漏源电压的调制

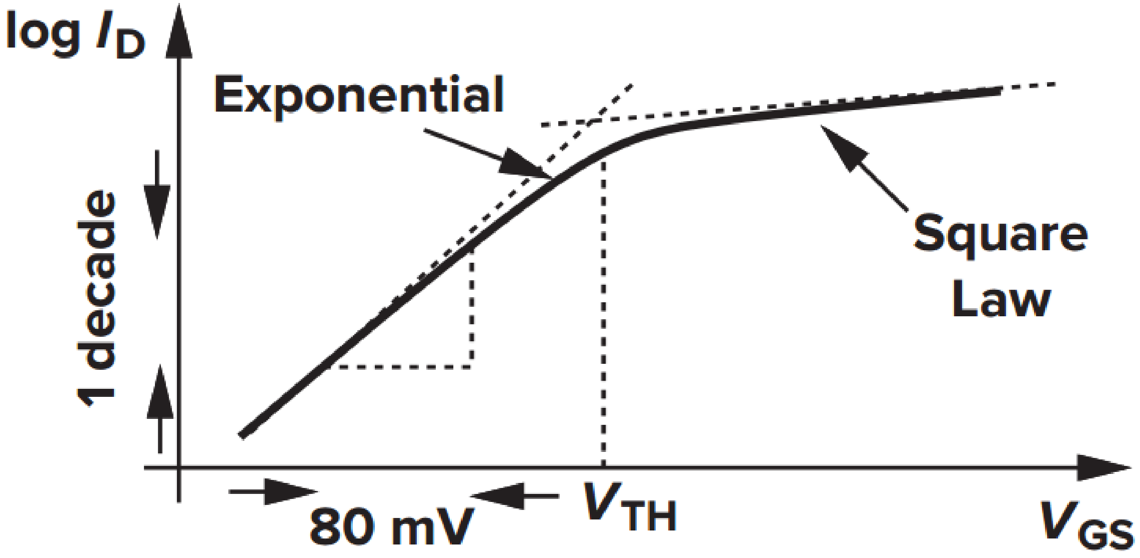






$$I_D \approx \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2(1 + \lambda V_{DS})$$

亚阈值效应



亚阈值电流方程

$$I_D = I_0 \exp\frac{V_{GS}}{nV_T}$$

亚阈值摆幅

$$S = \frac{dV_{GS}}{d\log I_D} = U_t \ln 10\, n \approx 58mV * n$$

非理想因子，就是n

$$n = 1 + {C_D}/{C_{ox}}$$

过驱动电压

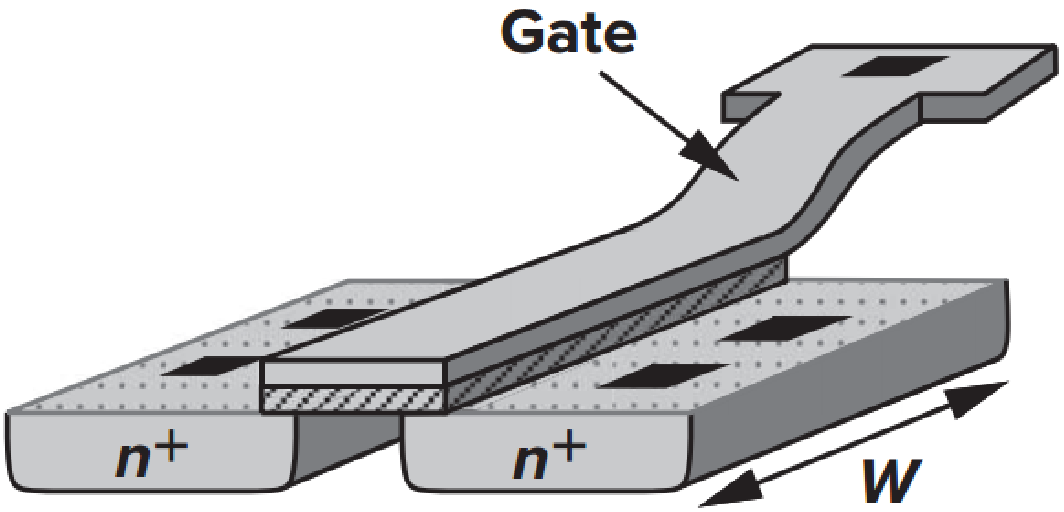
$$\frac{I_D}{nV_T} = \frac{2I_D}{(V_{GS} - V_T)} \Rightarrow (V_{GS} - V_T) = 2nU_t$$

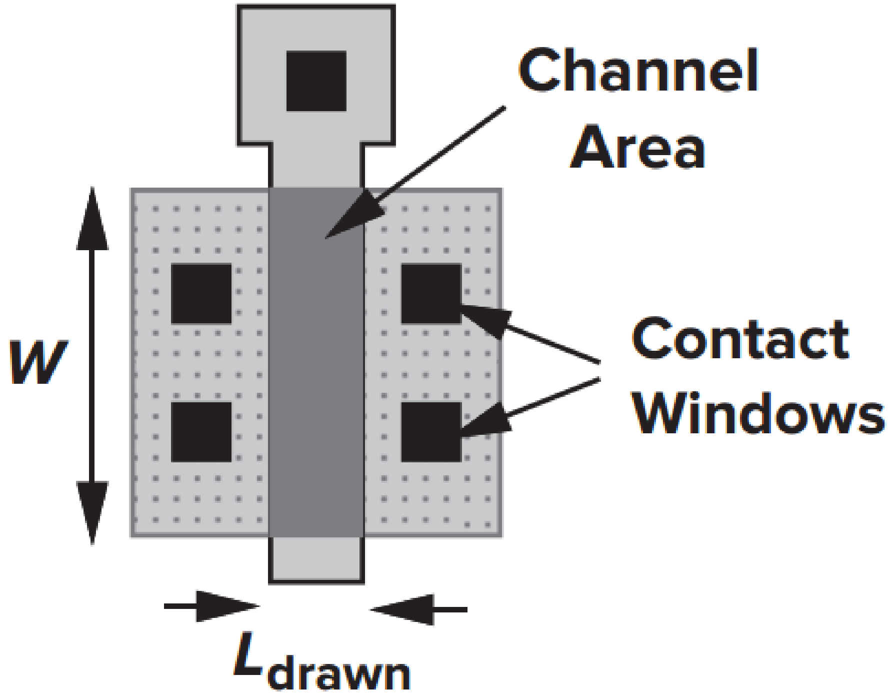
MOS管模型

- 版图
- MOS管的电容
- 小信号等效电路
- SPICE模型

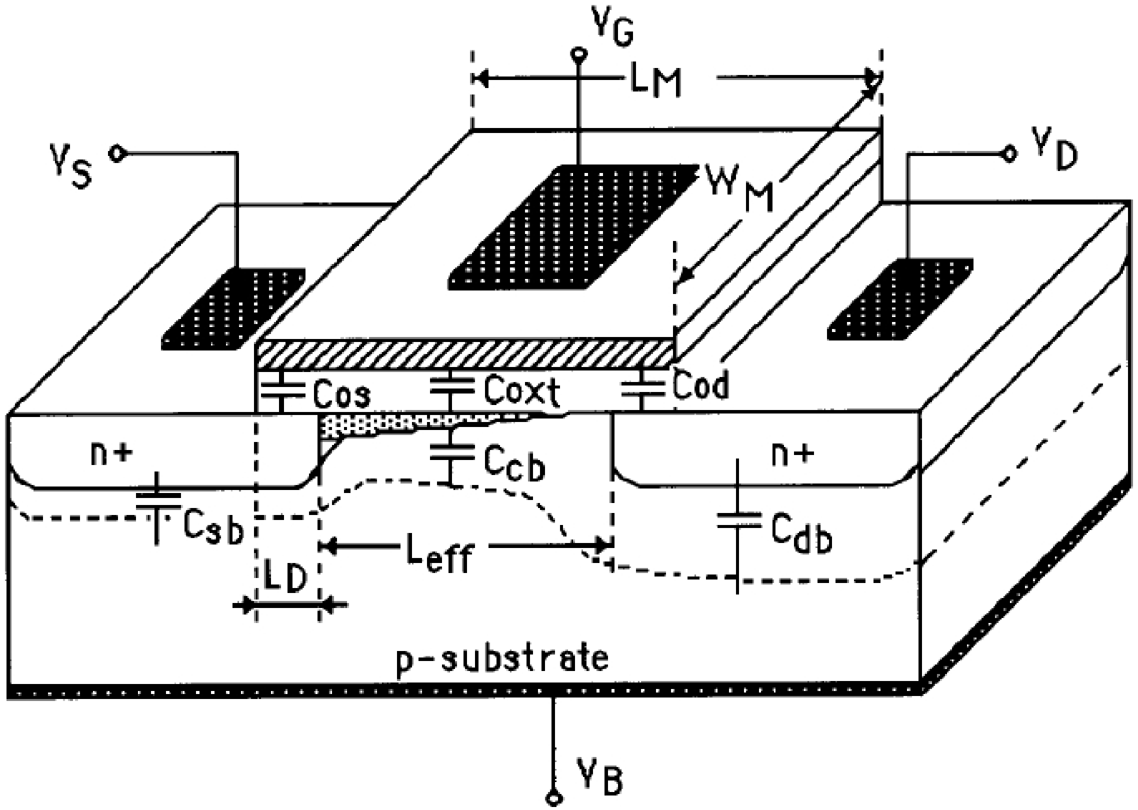
MOS管版图

- Bird’s eye view and vertical view



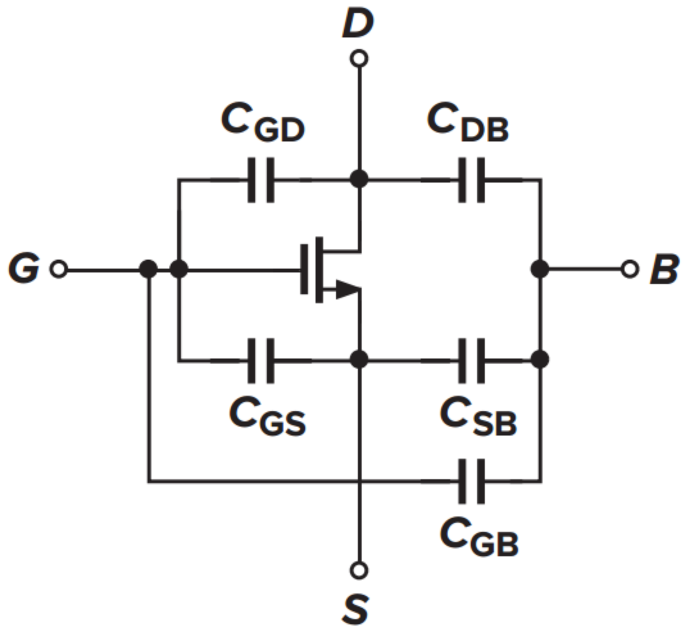


MOS管的电容分布



MOS管的电容（1）

- 电容模型



● 线形区

$$C_{gs} = C_{gd} = \frac{WLC_{ox}}{2} + WCov$$

● 饱和区

$$C_{gs} = \frac{2WLC_{ox}}{3} + WCov \quad C_{gd} = WC_{ov}$$

● 截至区

$$C_{gs} = C_{gd} = WC_{ov}$$

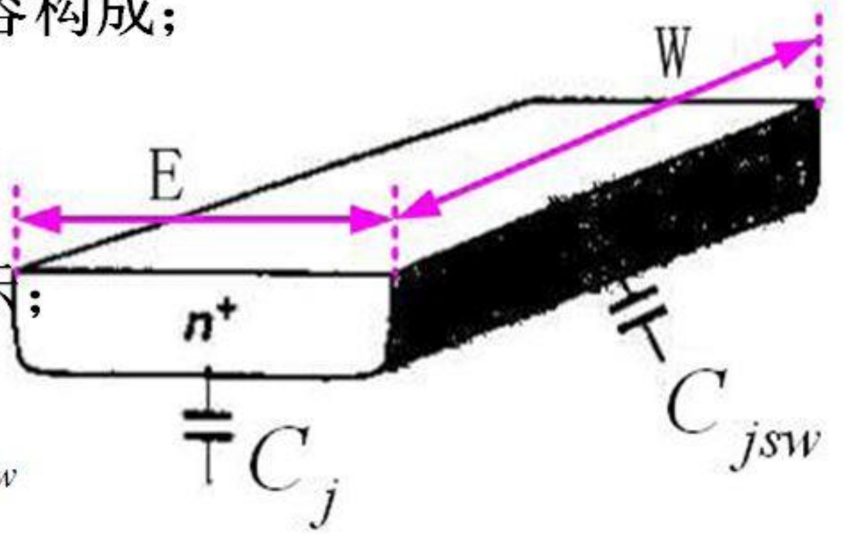
MOS管的电容（2）

- 结电容

$$C_{sb}=\frac{C_{sb0}}{\sqrt{1+\frac{V_{SB}}{\phi_0}}}\qquad C_{db}=\frac{C_{db0}}{\sqrt{1+\frac{V_{DB}}{\phi_0}}}$$

- ◆ $C_{s,b0}$是由底面电容和侧边电容构成；
- ◆ 单位面积底面电容用C_j表示；
- ◆ 单位长度侧边电容用C_{jsw}表示；

$$C_{s,db0}=WEC_j+2(W+E)C_{jsw}$$



MOS管的电容（例）

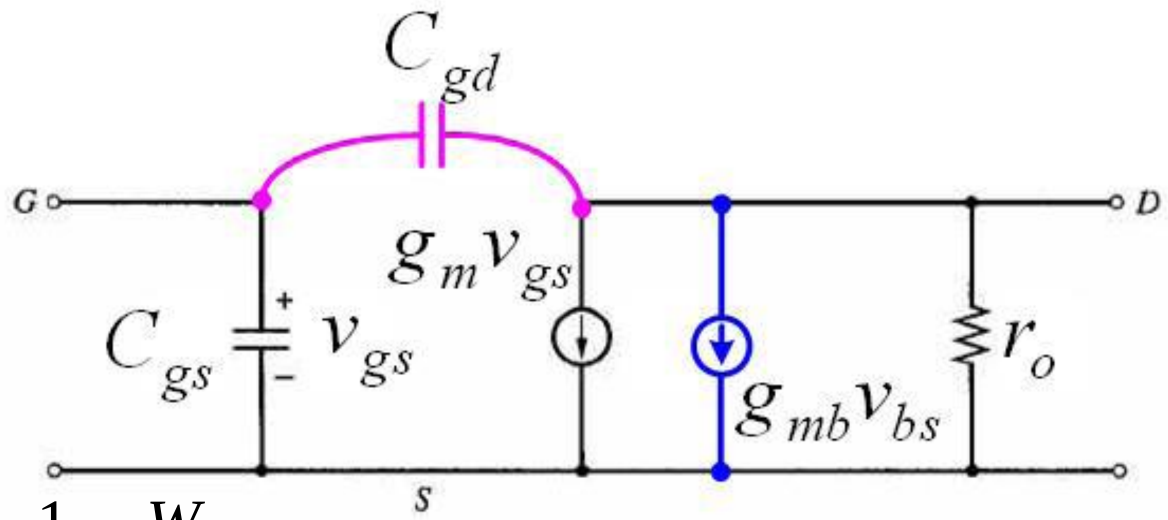
- UMC180， NMOS
  - W=0.24μm, $\mathrm{L = 0.18\mu m}$
  - $\mathrm{T_{ox} = 4.2e-9\ m}$
  - $\mathrm{C_{ox} = 8.22e-3\ F/m^2}$
  - $\mathrm{C_1 = WLC_{ox} = 0.355fF}$
  - $\mathrm{C_{ov}}$ ~ 1e-16 F/μm
  - $\mathrm{C_{db}}$~ 1e-15 F/μm ²

$\mathrm{C_{gs}}$: 0.1~1fF

$\mathrm{C_{ov,gs}, C_{ov,gd}}$: 0.01~0.1fF

$\mathrm{C_{db}}$: 0.1~1fF

NMOS小信号等效电路

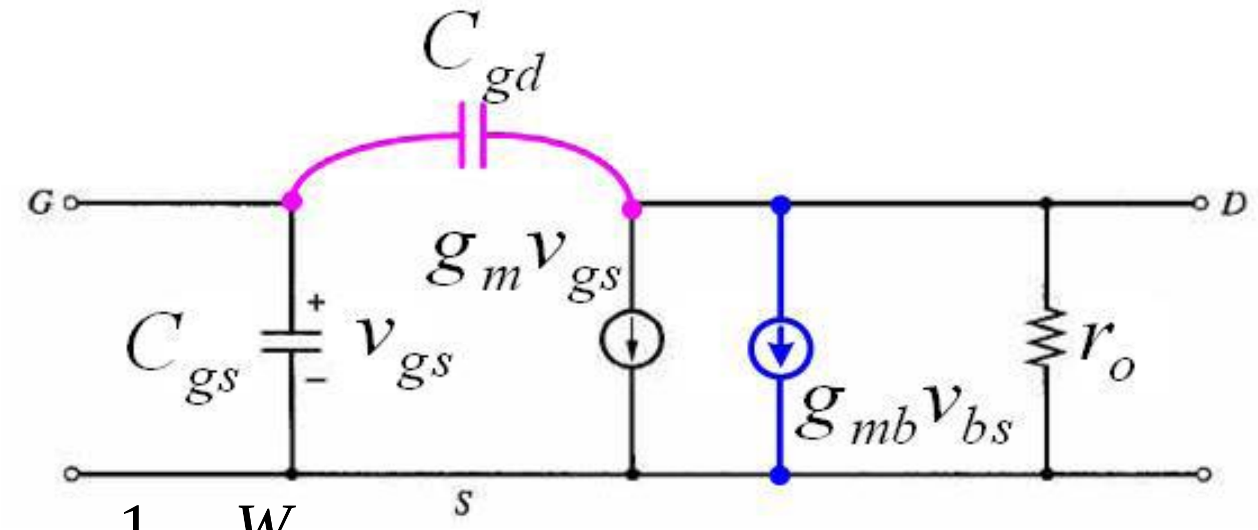


$$I_{DS,nmos} = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_{Tn})^2 (1 + \lambda V_{DS})$$

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} = \frac{2 I_{DS}}{V_{GS} - V_{Tn}} \qquad r_o = \frac{\partial V_{DS}}{\partial I_{DS}} = \frac{1}{\partial I_{DS} / \partial V_{DS}} \approx \frac{1}{\lambda I_{DS}}$$

$$g_{mb} = \frac{\partial I_{DS}}{\partial V_{BS}} = \frac{\partial I_{DS}}{\partial V_{Tn}} \frac{\partial V_{Tn}}{\partial V_{BS}} = g_m \frac{\gamma}{2\sqrt{2\phi_F + V_{SB}}} = \eta g_m$$

PMOS小信号等效电路



$$I_{DS,pmos} = -\frac{1}{2} k_n^{'} \frac{W}{L} (V_{GS} - V_{Tp})^2 (1 - \lambda V_{DS})$$

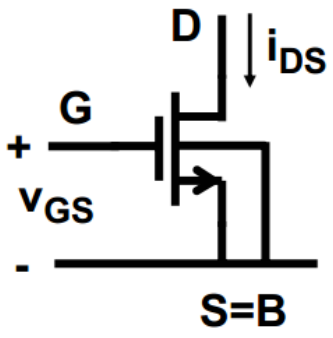
$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} = \frac{2 I_{DS}}{V_{GS} - V_{Tp}} \qquad r_o = \frac{\partial V_{DS}}{\partial I_{DS}} = \frac{1}{\partial I_{DS} / \partial V_{DS}} \approx \frac{1}{-\lambda I_{DS}}$$

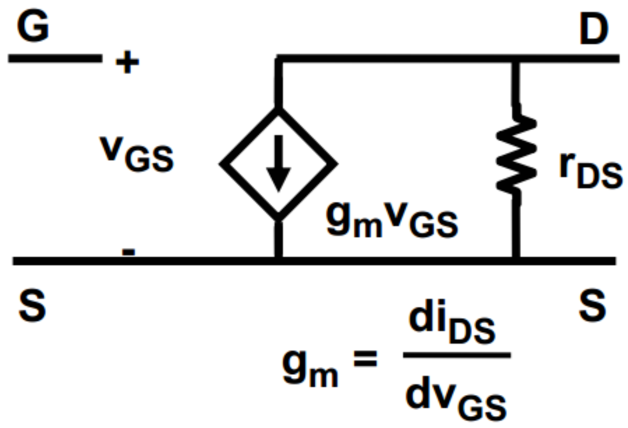
$$g_{mb} = \frac{\partial I_{DS}}{\partial V_{BS}} = \frac{\partial I_{DS}}{\partial V_{Tn}} \frac{\partial V_{Tn}}{\partial V_{BS}} = g_m \frac{\gamma}{2\sqrt{2\phi_F + V_{BS}}} = \eta g_m$$

沟道调制效应对放大倍数的影响

- 输出电阻

$$r_{DS} = r_O = \frac{1}{\lambda I_{DS}} \qquad \lambda = \frac{1}{V_E L}$$





- 跨导

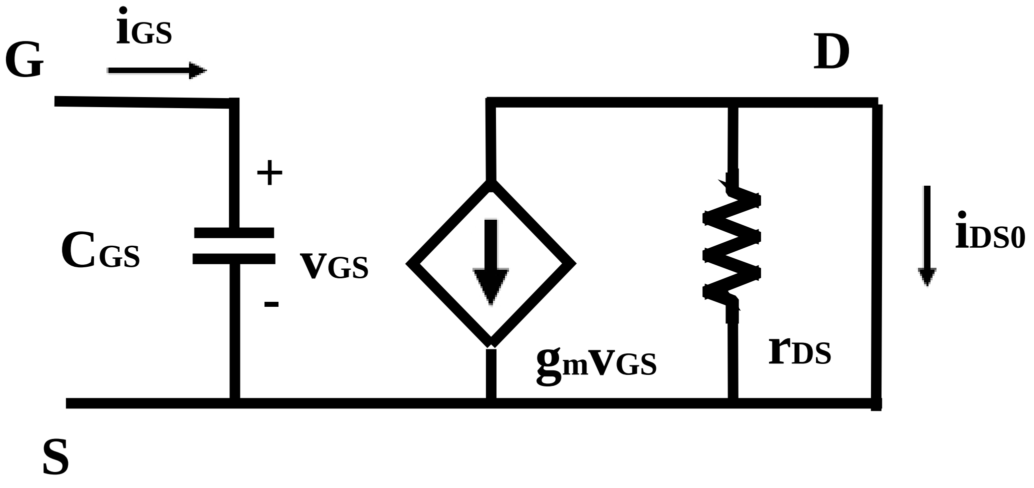
$$g_m = 2k_n' \frac{W}{L}(V_{GS} - V_T) = 2\sqrt{k_n' \frac{W}{L} I_{DS}} = \frac{2I_{DS}}{V_{GS} - V_T}$$

- 放大倍数

$$A_V = g_m r_{DS} = \frac{2I_{DS}}{V_{GS} - V_T} * \frac{1}{\lambda I_{DS}} = \frac{2}{\lambda(V_{GS} - V_T)} = \frac{2V_E L}{V_{ov}}$$

放大倍数与L成正比，与V_{ov}成反比！

特征频率



$$i_{GS} = V_{GS} C_{GS} s$$

$$i_{DS} = g_m V_{GS}$$

$$C_{GS} = \frac{2}{3} WLC_{OX}$$

$$g_m = 2k' \frac{W}{L}(V_{GS} - V_T)$$

$$\boxed{f_T = \frac{g_m}{2\pi C_{GS}} = \frac{1}{2\pi}\frac{3}{2n}\frac{\mu}{L^2}(V_{GS} - V_T)}$$

特征频率与V_{OV}成正比!

栅跨导和衬跨导比较

- η大多数情况下小于1

$$\eta \equiv \frac{g_{mb}}{g_m}$$

$$\eta \approx \frac{\gamma}{2(2\Phi_F + V_{SB})^{1/2}}$$

$$\varepsilon_{si} = 1\mathrm{pF/cm}$$

$$C_{ox} = 5 \times 10^7\ \mathrm{F/cm^2}$$

$$N_B = 4 \times 10^{17}\mathrm{cm}^3$$

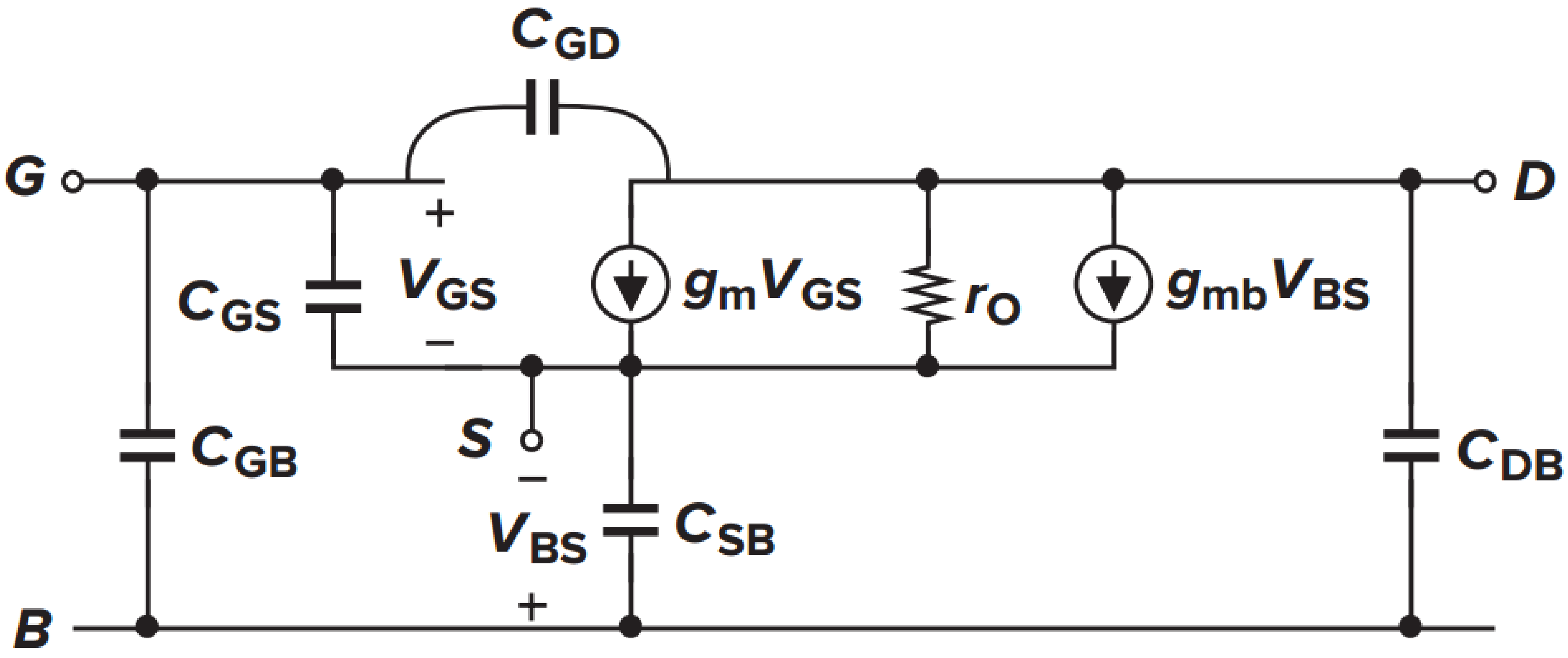
$$2\Phi_F = 0.6\mathrm{V}$$

$$V_{SB} = 1.8\mathrm{V}$$

$$\gamma = 0.714\mathrm{V}^{1/2}$$

$$\eta \approx 0.2$$

完整的小信号等效电路



短沟道效应的原因

- 电压降低并不能等比例降低电场；
- 内在电势不会降低或忽略；
- S/D结深不能轻易的减小；
- 迁移率随着衬底掺杂浓度的上升而下降；
- 亚阈值斜率无法等比例下降；

$$W_d = \sqrt{\frac{2\epsilon_{si}}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(\phi_B + V_R)}$$

短沟道效应

- 阈值电压起伏效应
- 反短沟效应
- 迁移率退化效应
- 速度饱和效应
- 热载流子效应
- 输出阻抗起伏效应

亚阈值斜率

- 亚阈值电流

$$I_D = \mu C_d \frac{W}{L} V_T^2 \left(\exp \frac{V_{GS} - V_{TH}}{\zeta V_T}\right)\left(1 - \exp \frac{-V_{DS}}{V_T}\right)$$

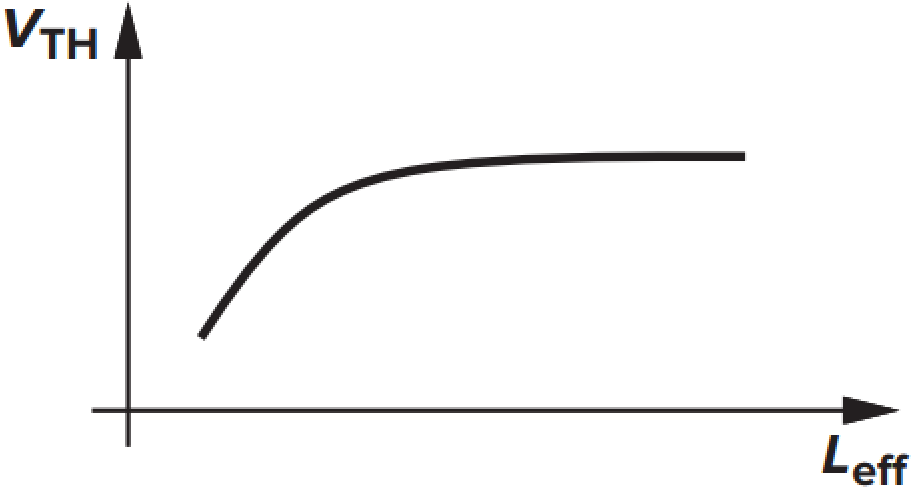
- 亚阈值斜率

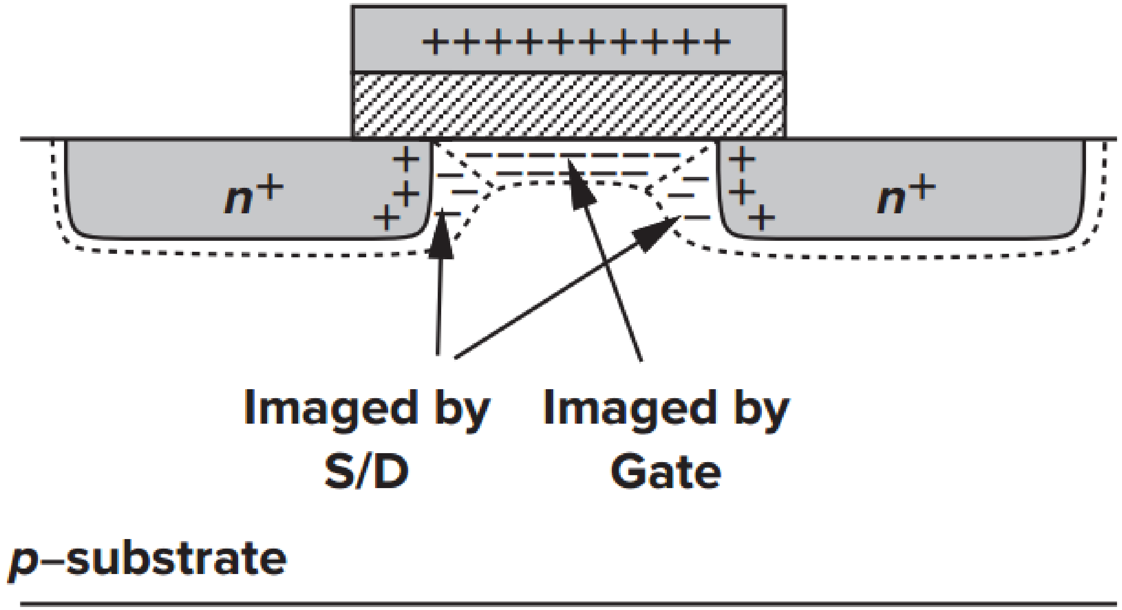
$$S = {}^{1}\Big/_{\frac{\partial(\log_{10} I_D)}{\partial V_{GS}}} = {}^{1}\Big/_{(\log_{10} e)\frac{1}{\zeta V_T}} = 2.3 V_T\left(1 + \frac{C_d}{C_{ox}}\right)\mathrm{V/dec}$$

亚阈值斜率无法等比例缩小限制了阈值的降低！

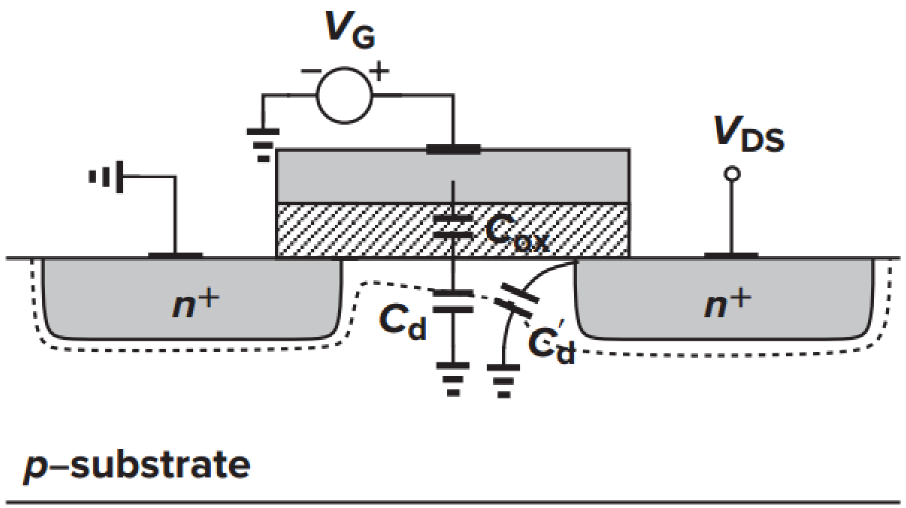
阈值与沟道长度的关系

- 源，漏镜像电荷影响了阈值的变化

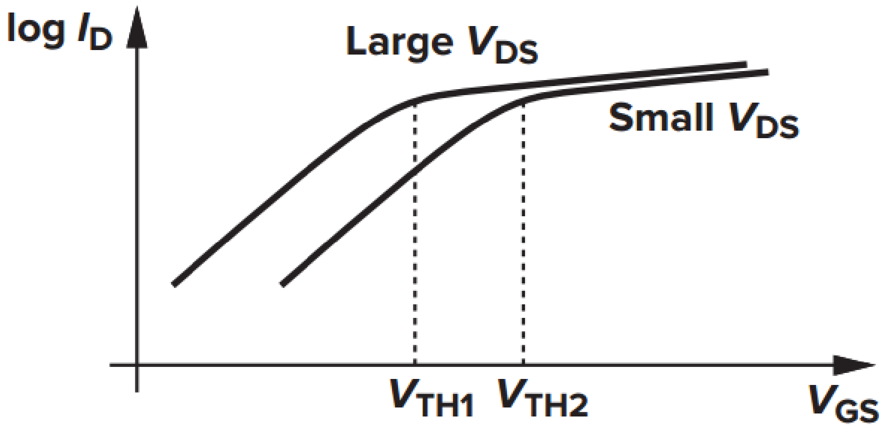




DIBL（drain-induced barrier lowering）效应



(a)



(b)

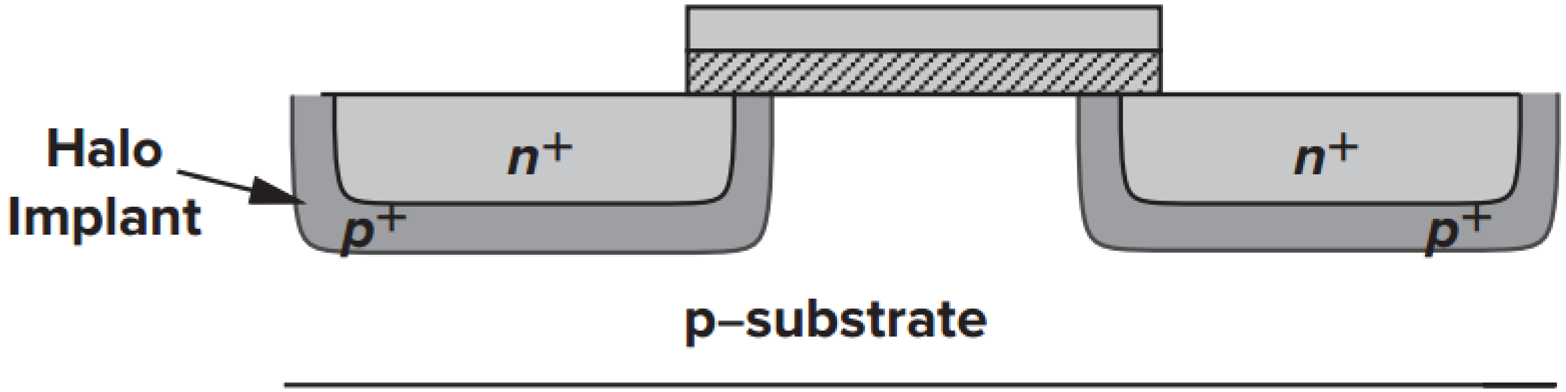
小尺寸场效应晶体管（FET）中所出现的一种不良现象，即是当沟道长度减小、电压Vds增加、使得漏结与源结的耗尽层靠近时，沟道中的电力线可以从漏区穿越到源区，并导致源极端势垒高度降低，从而源区注入到沟道的电子数量增加，结果漏极电流增加。沟道长度越短，DIBL效应就越严重。

a）使场效应晶体管的阈值电压降低，影响到器件的整个性能。

b）使输出伏安特性曲线不饱和，即导致输出交流电阻降低、器件的电压增益下降。（DIBL的这种作用与沟道长度调制效应的一样，都将导致小尺寸晶体管的电压增益下降。）

c）限制着小尺寸MOSFET 进一步缩小尺寸，实际上这往往也就是ULSI进一步提高集成度所受到的一种限制。

反短沟效应（Reverse Short-Channel Effect）



$$V_{TH} = \phi_{MS} + 2\phi_F + \frac{Q_{dep}}{C_{ox}}$$

$\phi_F = (kT/q)\ln(N_{sub}/n_i)$ $\quad Q_{dep} = \sqrt{4q\epsilon_{si}|\phi_F|N_{sub}}$ $\quad$ L↑， N_{sub}↓， V_{TH}↓

迁移率退化效应

- 强场下的晶格散射加强导致迁移率下降

$$\mu_{eff} = \frac{\mu_0}{1 + \theta(V_{GS} - V_{TH})} \qquad \theta \approx {10^{-7}}/{T_{ox}}$$

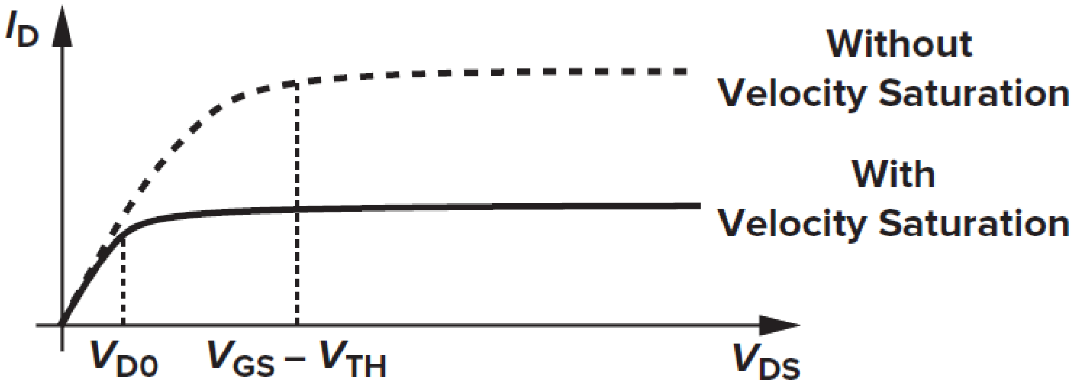
$$I_D = \frac{1}{2}\frac{\mu_0 C_{ox}}{1 + \theta(V_{GS} - V_{TH})}\frac{W}{L}(V_{GS} - V_{TH})^2$$

$$I_D \approx \frac{1}{2}\mu_0 C_{ox}\frac{W}{L}[(V_{GS} - V_{TH})^2 - \theta(V_{GS} - V_{TH})^3] \quad \text{if } \theta(V_{GS} - V_{TH}) \ll 1$$

速度饱和效应

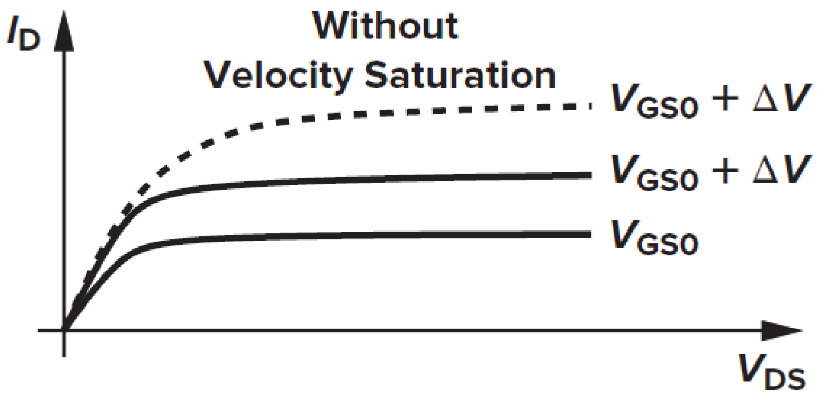
- 载流子的速度趋于饱和的主要原因是因为散射效应，也即是载流子间的碰撞导致的。

$$I_D = v_{sat} Q_d$$
$$= v_{sat} W C_{ox} (V_{GS} - V_{TH})$$



(a)

速度饱和效应



(b)

跨导减少

速度饱和的完整公式

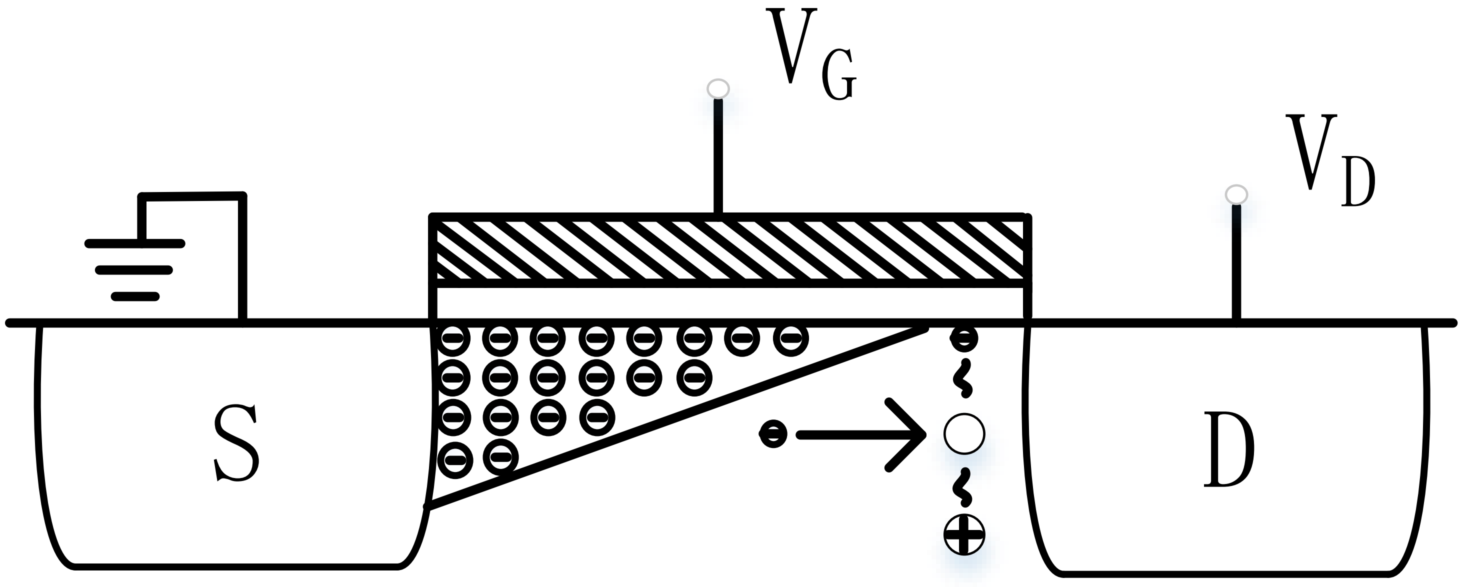
$$I_D = WC_{ox}v_{sat}\frac{(V_{GS}-V_{TH})^2}{V_{GS}-V_{TH}+2\dfrac{v_{sat}L}{\mu_{eff}}}$$

$$V_{DS,sat} = \frac{2\mu_{eff}L(V_{GS}-V_{TH})}{2\mu_{eff}L+V_{GS}-V_{TH}}$$

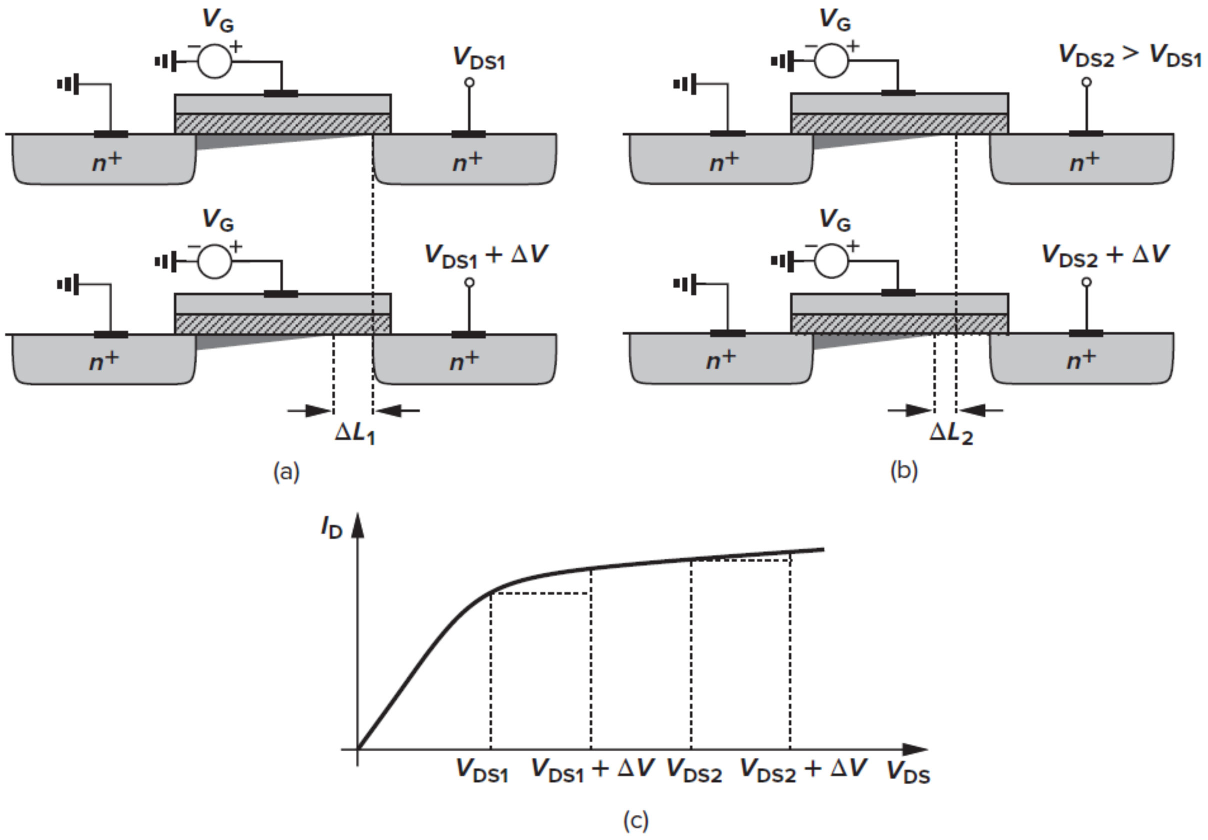
$$\begin{aligned}
I_D &= WC_{ox}v_{sat}\frac{(V_{GS}-V_{TH})^2}{V_{GS}-V_{TH}+\dfrac{2v_{sat}L}{\mu_0}[1+\theta(V_{GS}-V_{TH})]} \\
&= WC_{ox}v_{sat}\frac{(V_{GS}-V_{TH})^2}{\dfrac{2v_{sat}L}{\mu_0}+\left(1+\dfrac{2v_{sat}L\theta}{\mu_0}\right)(V_{GS}-V_{TH})} \\
&= \frac{1}{2}\mu_0 C_{ox}\frac{W}{L}\frac{(V_{GS}-V_{TH})^2}{1+\left(\dfrac{\mu_0}{2v_{sat}L}+\theta\right)(V_{GS}-V_{TH})}
\end{aligned}$$

热载流子效应

- 高速载流子引起电离激发，产生额外的电流

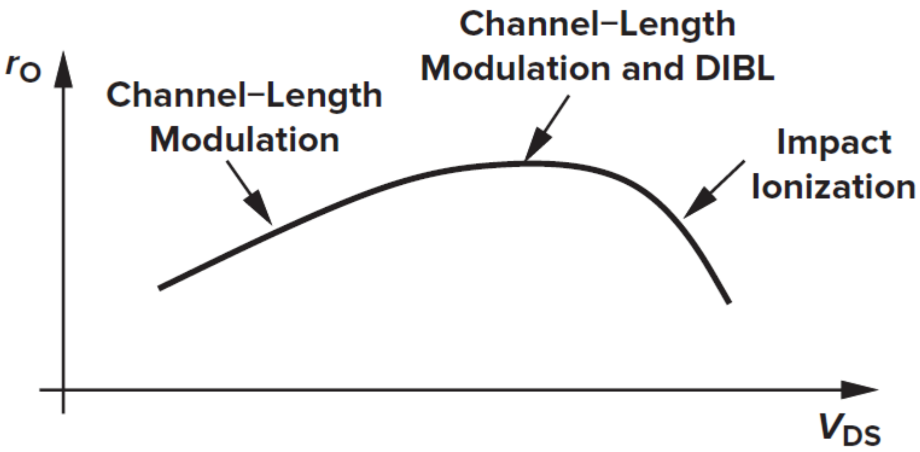


输出电阻起伏效应



沟长调制效应（a）小V_{DS}（b）大V_{DS}（c）斜率变化

$$r_O = \frac{2L}{1 - \dfrac{\Delta L}{L}} \frac{1}{I_D} \sqrt{\frac{qN_B}{2\epsilon_{si}}(V_{DS} - V_{DS,sat})}$$



输出电阻与V_{DS}的关系

SPICE模型

- BSIM1

NMOS Model			
LEVEL = 1	VTO = 0.7	GAMMA = 0.45	PHI = 0.9
NSUB = 9e+14	LD = 0.08e−6	UO = 350	LAMBDA = 0.1
TOX = 9e−9	PB = 0.9	CJ = 0.56e−3	CJSW = 0.35e−11
MJ = 0.45	MJSW = 0.2	CGDO = 0.4e−9	JS = 1.0e−8
PMOS Model			
LEVEL = 1	VTO = −0.8	GAMMA = 0.4	PHI = 0.8
NSUB = 5e+14	LD = 0.09e−6	UO = 100	LAMBDA = 0.2
TOX = 9e−9	PB = 0.9	CJ = 0.94e−3	CJSW = 0.32e−11
MJ = 0.5	MJSW = 0.3	CGDO = 0.3e−9	JS = 0.5e−8

VTO: threshold voltage with zero V_{SB} (unit: V)
GAMMA: body-effect coefficient (unit: $V^{1/2}$)
PHI: $2\Phi_F$ (unit: V)
TOX: gate-oxide thickness (unit: m)
NSUB: substrate doping (unit: cm^{-3})
LD: source/drain side diffusion (unit: m)
UO: channel mobility (unit: $cm^2/V/s$)
LAMBDA: channel-length modulation coefficient (unit: V^{-1})
CJ: source/drain bottom-plate junction capacitance per unit area (unit: F/m^2)
CJSW: source/drain sidewall junction capacitance per unit length (unit: F/m)
PB: source/drain junction built-in potential (unit: V)
MJ: exponent in CJ equation (unitless)
MJSW: exponent in CJSW equation (unitless)
CGDO: gate-drain overlap capacitance per unit width (unit: F/m)
CGSO: gate-source overlap capacitance per unit width (unit: F/m)
JS: source/drain leakage current per unit area (unit: A/m^2)

仿真模型

- LEVEL 1

$$I_D = \frac{1}{2} K_p \frac{W}{L - 2L_D}[2(V_{GS} - V_{TH})V_{DS} - V_{DS}^2](1 + \lambda V_{DS}) \qquad \text{线性区}$$

$$I_D = \frac{1}{2} K_p \frac{W}{L - 2L_D}(V_{GS} - V_{TH})^2 (1 + \lambda V_{DS}) \qquad \text{饱和区}$$

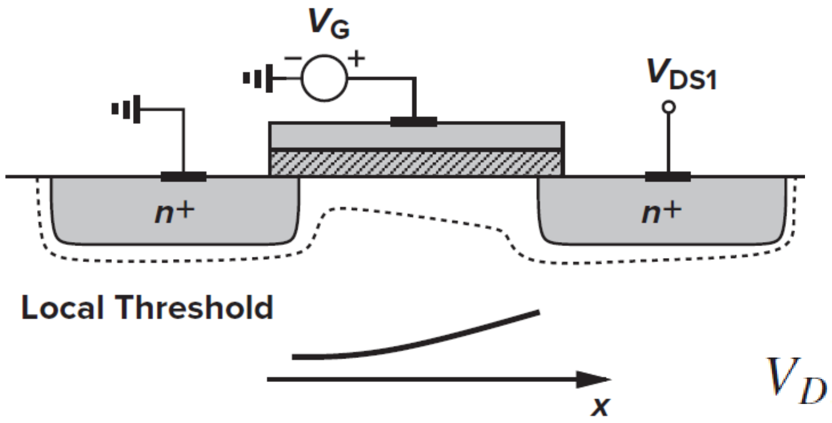
$$C_{GS} = \frac{2}{3} W L C_{ox} \left\{ 1 - \frac{(V_{GS} - V_{DS} - V_{TH})^2}{[2(V_{GS} - V_{TH}) - V_{DS}]^2} \right\} + W C_{ov}$$

$$C_{GD} = \frac{2}{3} W L C_{ox} \left\{ 1 - \frac{(V_{GS} - V_{TH})^2}{[2(V_{GS} - V_{TH}) - V_{DS}]^2} \right\} + W C_{ov}$$

$$C_{GB} = 0.$$

仿真模型

- LEVEL 2



阈值随沟道的变化

$$I_D = \mu C_{ox}\frac{W}{L}\{(V_{GS}-V_{TH0})V_{DS}-\frac{V_{DS}^2}{2}$$
$$-\frac{2}{3}\gamma[(V_{DS}-V_{BS}+2\phi_F)^{3/2}-(-V_{BS}+2\phi_F)^{3/2}]\}$$

$$V_{D,sat} = V_{GS}-V_{TH0}-\phi_F+\gamma^2\left[1-\sqrt{1+\frac{2}{\gamma^2}(V_{GS}-V_{TH0}+\phi_F)}\right]$$

$$I_{DS} = I_{D,sat}\frac{1}{1-\lambda V_{DS}}$$

$$\Delta L = \sqrt{\frac{2\epsilon_{si}}{qN_{sub}}[\phi_B+(V_{DS}-V_{D,sat})]}$$

仿真模型

- LEVEL 3

$$V_{TH} = V_{TH0} + F_s\gamma\sqrt{2\phi_F - V_{BS}} + F_n(2\phi_F - V_{BS}) + \xi\frac{8.15\times 10^{-22}}{C_{ox}L_{eff}^3}V_{DS}$$

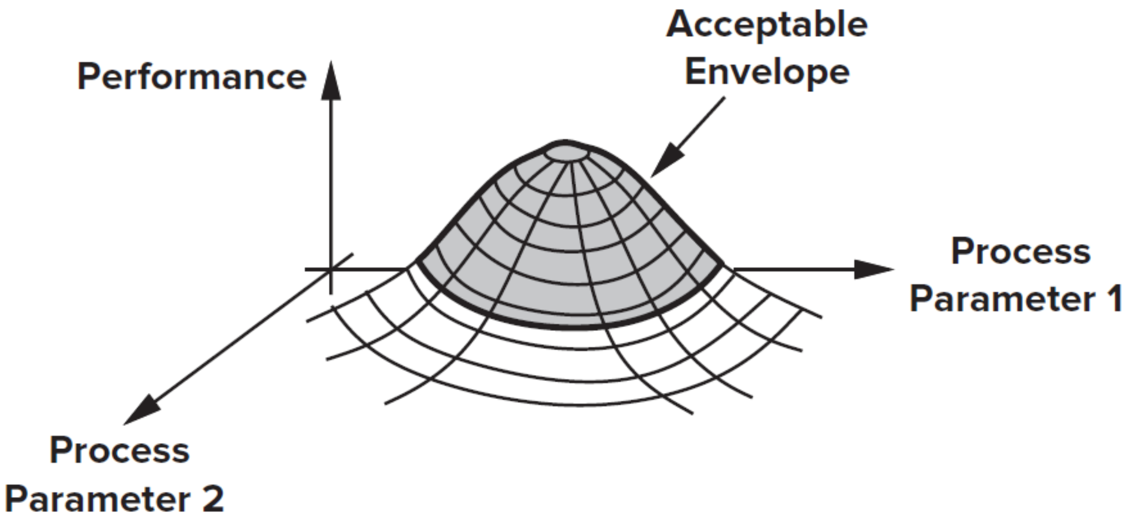
Fs：短沟道效应，Fn：窄沟道效应

$$\mu_1 = \frac{\mu_{eff}}{1 + \dfrac{\mu_{eff}V_{DS}}{v_{max}L_1}}$$

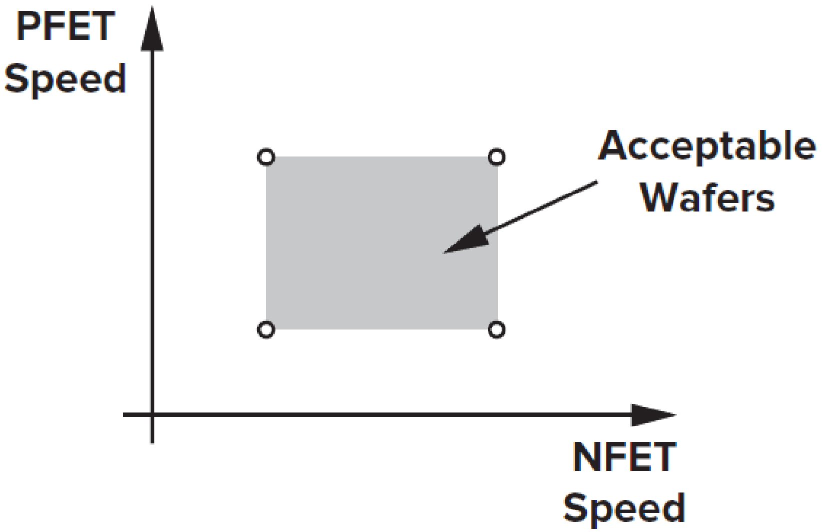
$$I_D = \mu_1 C_{ox}\frac{W_{eff}}{L_{eff}}\left[V_{GS} - V_{TH0} - \left(1 + \frac{F_s\gamma}{4\sqrt{2\phi_F - V_{BS}}} + F_n\right)\frac{V'_{DS}}{2}\right]V'_{DS}$$

模型的不连续性

工艺角



工艺参数对性能的影响



基于MOS管速度的工艺角

作业

- 2.9
- 2.13
- 2.14