

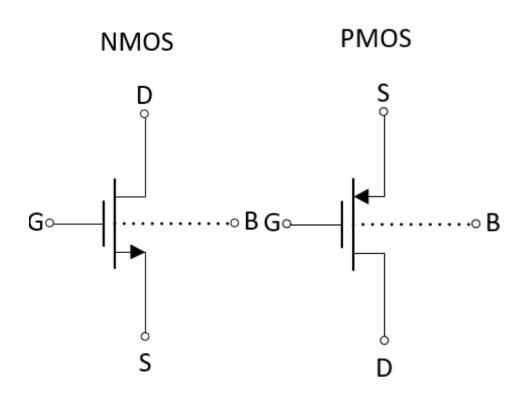
CMOS模拟集成电路设计

第一章: MOSFET

胡远奇

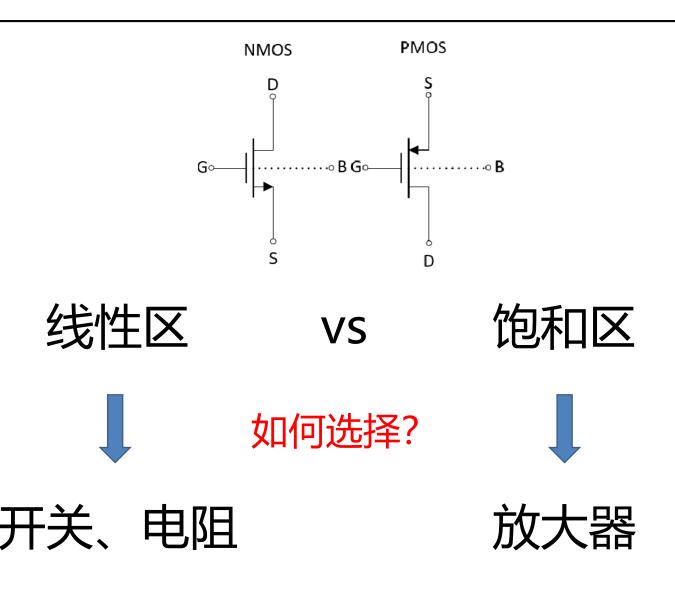
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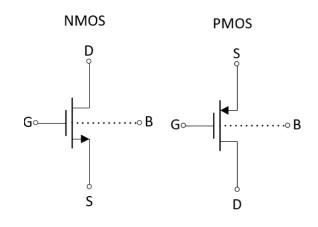


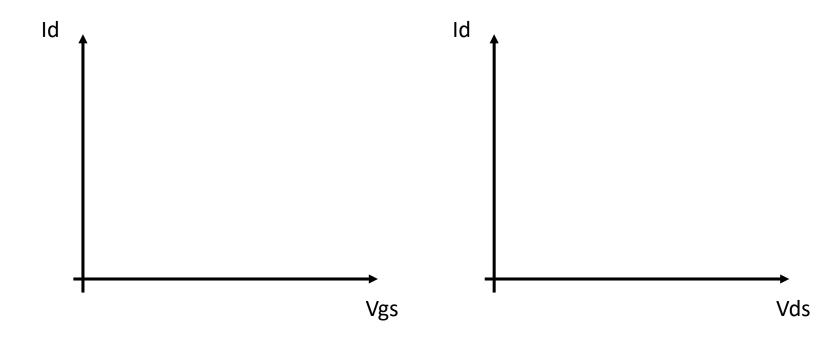
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MOSFET

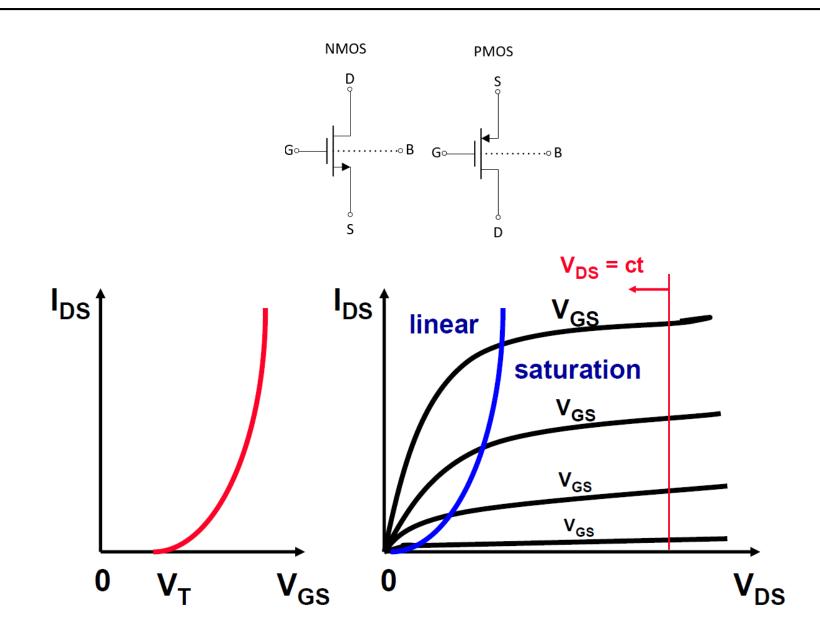


>>> MOSFET的I-V关系





>>> MOSFET的I-V关系



MOSFET

- ·晶体管工作在线性区: 电阻
- 晶体管工作在饱和区: 放大器
- 亚反型区/弱翻转区 (Weak Inversion)
- 速度饱和去 (Velocity Saturation)
- 特征频率



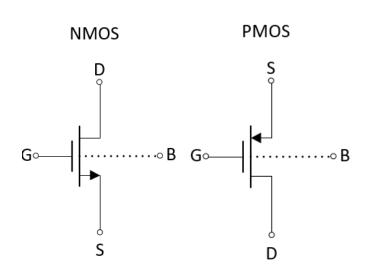
>>> MOSFET当作开关

线性区: $V_{DS} < V_{GS}$ - V_{TH}

$$I_D =$$

• 小信号导通电阻:

$$R=$$

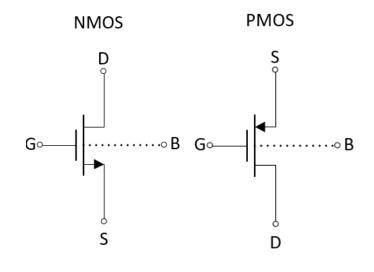




MOSFET当作开关



$$I_{D} = \mu C_{ox} \frac{W}{L} \left(V_{GS} - V_{TH} - \frac{V_{DS}}{2} \right) V_{DS}$$



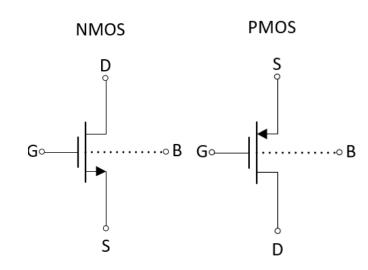
• 小信号导通电阻:

$$R \approx \frac{1}{\mu C_{ox} \frac{W}{L} (V_{GS} - V_{TH})}$$
 for $V_{GS} - V_{TH} >> V_{DS}$

>>> MOSFET参数

$$R \approx \frac{1}{\mu C_{ox} \frac{W}{L} (V_{GS} - V_{TH})}$$

- 电子迁移率u: $\mu_p \approx 250 \text{ cm}^2/\text{Vs}$ $\mu_n \approx 600 \text{ cm}^2/\text{Vs}$
- 栅氧层电容 C_{OX} : $C_{ox} = \frac{c_{ox}}{t_{ox}}$





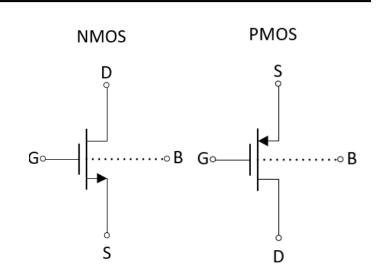
$L_{min} = 0.35 \mu m$

电子迁移率u: μ_p ≈ 250 cm²/Vs

 $\mu_n \approx 600 \text{ cm}^2/\text{Vs}$

• 栅氧层电容 C_{OX} : $C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \approx 5 \cdot 10^{-7} \text{ F/cm}^2$

 $KP_n \approx 300 \, \mu A/V^2$



>>> MOSFET电阻快速估算

 $L_{min} = 0.35 \ \mu m \ KP_n \approx 300 \ \mu A/V^2$

$$R \approx \frac{1}{\mu C_{ox} \frac{W}{L} (V_{GS} - V_{TH})}$$

 对于0.35um工艺方块NMOS晶体管, $E(S_{GS}-V_{TH}=1V)$ 的驱动电压下,其电阻约为:



MOSFET电阻快速估算

已知0.35um工艺方块NMOS晶体管,在 V_{GS} - V_{TH} =1V的驱动电压 下,其电阻约为3.4Kohm,请估算电阻值:

1. 0.35um工艺方块PMOS晶体管, V_{GS}-V_{TH}=1V

8.16K Ω

2. 0.18um工艺方块NMOS晶体管, V_{GS}-V_{TH}=1V

1.75K Ω

$$\mu_p \approx 250 \text{ cm}^2/\text{Vs}$$
 $\mu_n \approx 600 \text{ cm}^2/\text{Vs}$

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

MOSFET

- 晶体管工作在线性区: 电阻
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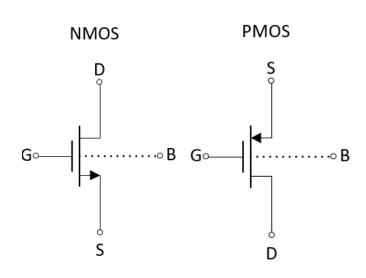
>>> MOSFET当作放大器

饱和区: $V_{DS} > V_{GS} - V_{TH}$

$$I_D =$$

• 小信号跨导:

$$g_m \approx$$

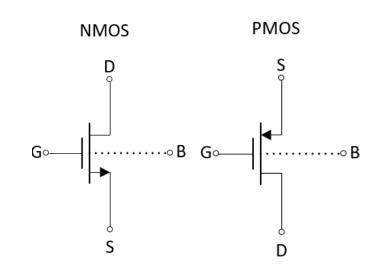




MOSFET当作放大器

饱和区: $V_{DS} > V_{GS} - V_{TH}$

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



• 小信号跨导:

$$g_m \approx \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_{DS}} = \frac{2I_{DS}}{V_{GS} - V_{TH}}$$

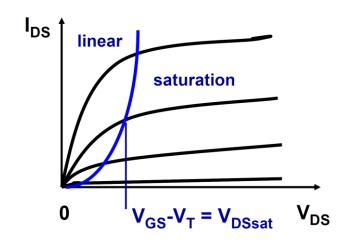
》)晶体管跨导gm

$$g_m \approx \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_{DS}} = \frac{2I_{DS}}{V_{GS} - V_{TH}}$$

问:小信号跨导gm与Ips的关系?



》输出电阻ro

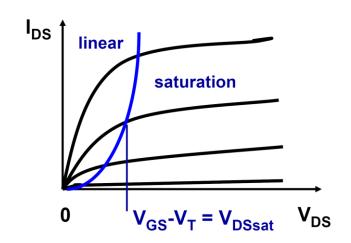


$$I_{DS} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS})$$

输出电阻:

$$r_0 =$$

》输出电阻ro



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

输出电阻:

$$r_0 \approx \frac{1}{\lambda I_{DS}} = \frac{V_E \cdot L}{I_{DS}}$$

$$V_{En} = 4 V/\mu mL$$

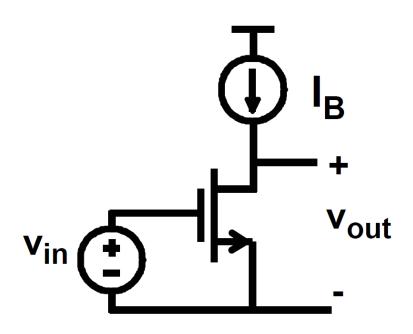
$$L = 1 \mu m$$

$$I_{DS} = 100 \ \mu A$$

$$r_0 = 40 \text{ k}\Omega$$

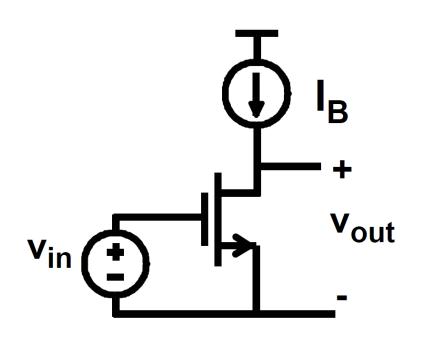


》)单晶体管放大器





>>> 单晶体管放大器



$$A_{v} = g_{m}r_{DS} = \frac{2 V_{E}L}{V_{GS}-V_{T}}$$

$$A_{\rm v} \approx 100$$

V_E**L** ≈ 10 V and $V_{GS}-V_T \approx 0.2 \text{ V}$



>>> 运放设计Trade-off

$$g_m pprox rac{2I_{DS}}{V_{GS} - V_{TH}}$$

$$A = rac{2 \cdot V_E \cdot L}{V_{GS} - V_{TH}}$$

$$A = \frac{2 \cdot V_E \cdot L}{V_{GS} - V_{TH}}$$

	高增益	高速
V_{GS} - V_{TH}		
L		



>>> 运放设计Trade-off

$$g_m pprox rac{2I_{DS}}{V_{GS} - V_{TH}}$$

$$A = rac{2 \cdot V_E \cdot L}{V_{GS} - V_{TH}}$$

$$A = \frac{2 \cdot V_E \cdot L}{V_{GS} - V_{TH}}$$

	高增益	高速
V_{GS} - V_{TH}		1
L	1	↓

MOSFET

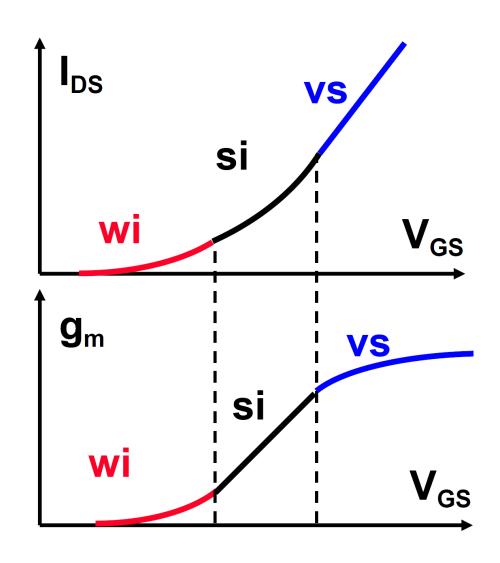
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>>> 弱反型区和速度饱和区

假设晶体管始终工作在饱和区: $V_{DS} > V_{GS} - V_{TH}$



))) 弱反型区 (weak inversion)



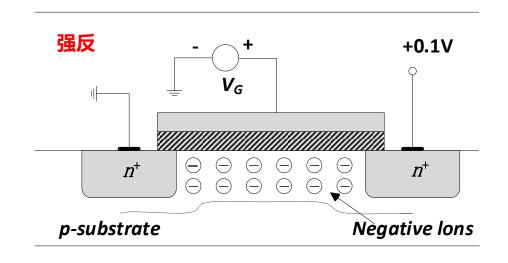
弱反型区:

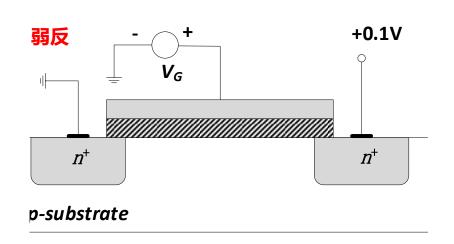
$$I_{D,wi} = I_{D0} \frac{W}{L} e^{\frac{V_{GS}}{nkT/q}}$$

$$g_{m,wi} = \frac{I_{D,wi}}{nkT/q}$$

n>1, 取决于偏置电压

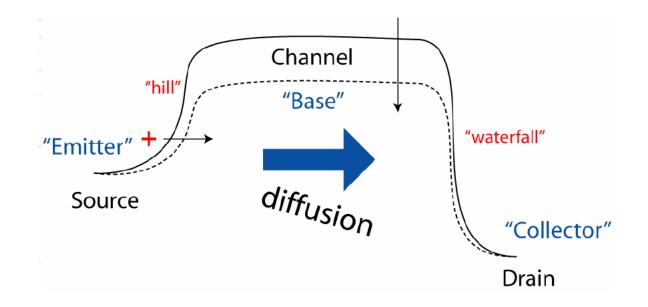
>>> 弱反型区





- 场效应管实际是一个水平的BJT三极管
- 漏极的反向偏置形成二极管,增加栅极电压将线性降低二极管的电势壁垒 (Potential Barrier)
- 主要的电流是扩散电流(diffusion)而非漂移电流(drift)
- 通道中电势几乎不变,离子浓度线性变化

>>> 弱反型区



$$I_{D,wi} = I_{D0} \frac{W}{L} \exp\left(\frac{V_{GS}}{nU_T}\right) \cdot \left[1 - \exp\left(-\frac{V_{DS}}{U_T}\right)\right]$$

$$I_{D,wi} = I_{D0} \frac{W}{L} \exp\left(\frac{V_{GS}}{nU_T}\right)$$
 for $V_{DS} > 4U_T$ (饱和)



>>> 弱反型与强反型

弱反型区(Weak Inversion)

强反型区(Strong Inversion)

$$g_{m,wi} = \frac{I_{DS}}{nkT/q}$$

$$g_{m,si} = \frac{2I_{DS}}{V_{GS} - V_{TH}}$$

$$\frac{g_{m,si}}{I_{DS}} = \frac{2}{V_{GS} - V_{TH}}$$

$$V_{GS} - V_{TH} = 2n \frac{kT}{q} \approx 70mV$$

>>> 弱-强反型区转换点

$$V_{GS} - V_{TH} = 2n \frac{kT}{q} \approx 70mV$$

- 强弱的转换点独立于工艺的尺寸
- 保证 V_{GS} - V_{TH} =0.2V 可以在不同工艺中均保证晶体管工作在强 反型区

• 转换点电流:
$$I_{DSt} = K'_n \frac{W}{L} (V_{GS} - V_{TH})^2$$

$$I_{DSt} = \frac{W}{L} \cdot \mathbf{0}. \mathbf{x} \, \mu A$$

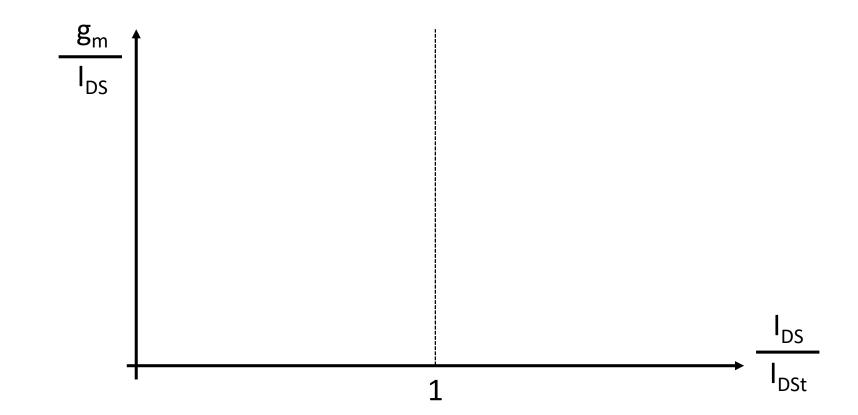


>>> 弱反型与强反型

弱反型区 (Weak Inversion)

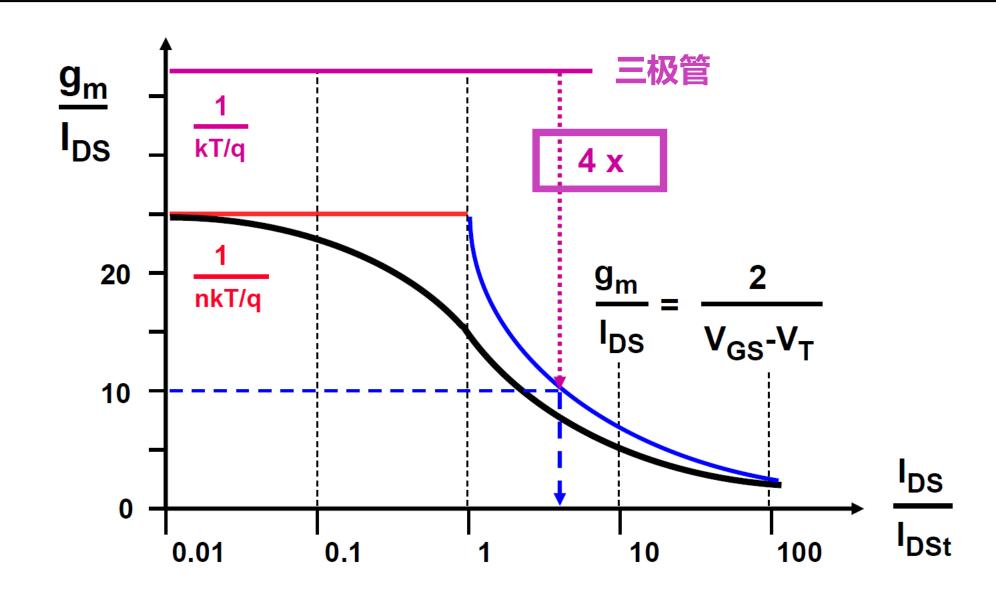
$$\frac{g_{m,wi}}{I_{DS}} = \frac{1}{nkT/q}$$

$$\frac{g_{m,si}}{I_{DS}} = \frac{2}{V_{GS} - V_{TH}}$$

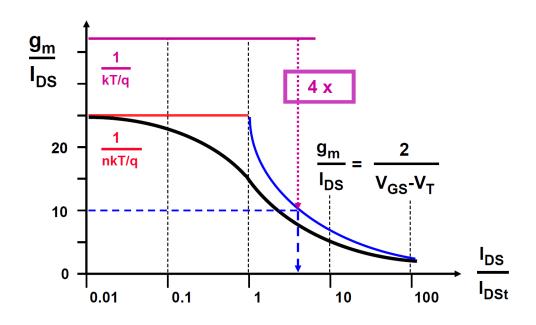




>>> 弱反型与强反型



》) 弱反型与强反型: EKV模型



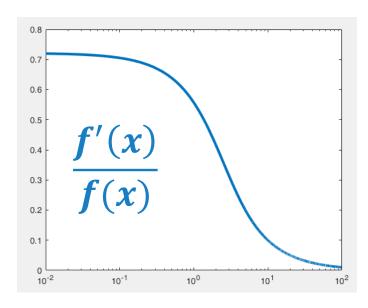
$$I_{DS} = K' \frac{W}{L} V_{GSTt}^2 \cdot ln^2 (1 + e^v)$$

$$v = \frac{V_{GST}}{V_{GSTt}}$$

能否通过一个公式同时 表述两种反型区?

$$\ln^2(1+e^v)$$





》) 弱反型与强反型: EKV模型

$$I_{DS} = K' \frac{W}{L} V_{GSTt}^2 \cdot ln^2 (1 + e^v), \quad v = \frac{V_{GST}}{V_{GSTt}}, \qquad V_{GSTt} = (V_{GS} - V_T)_t = 2n \frac{kT}{q}$$

• 弱反型区中:

• 强反型区中:

》) 弱反型与强反型:EKV模型

$$I_{DS} = K' \frac{W}{L} V_{GSTt}^2 \cdot ln^2 (1 + e^v), \quad v = \frac{V_{GST}}{V_{GSTt}}, \qquad V_{GSTt} = (V_{GS} - V_T)_t = 2n \frac{kT}{q}$$

• 弱反型区中: $ln(1+e^v) \approx e^v$

$$I_{DS} = K' \frac{W}{L} V_{GSTt}^2 \cdot e^{2v} = I_{DSt} \cdot \exp(\frac{V_{GS} - V_T}{nkT/q})$$

• 强反型区中: $ln(1+e^v) \approx v$

$$I_{DS} = K' \frac{W}{L} V_{GSTt}^2 \cdot v^2 = K' \frac{W}{L} (V_{GS} - V_T)^2$$

>>> 弱反型与强反型:反型系数

$$I_{DS} = K' \frac{W}{L} V_{GSTt}^2 \cdot ln^2 (1 + e^v), \quad v = \frac{V_{GST}}{V_{GSTt}}, \qquad V_{GSTt} = (V_{GS} - V_T)_t = 2n \frac{kT}{q}$$

反型系数i:
$$i = \frac{I_{DS}}{I_{DSt}} = ln^2(1 + e^v)$$



$$v = ln(e^{\sqrt{i}} - 1)$$

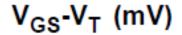


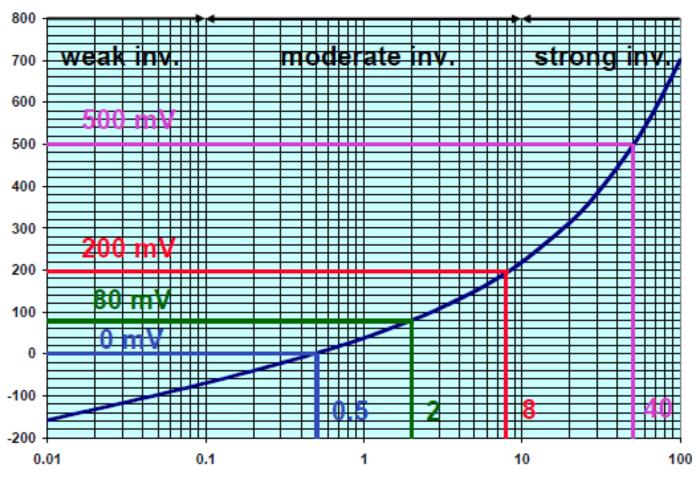
$$V_{GST} = V_{GSTt} \cdot ln(e^{\sqrt{i}} - 1)$$

$$V_{GSTt} = 2n \frac{kT}{q} \approx 70mV$$



>>> 弱反型与强反型:反型系数





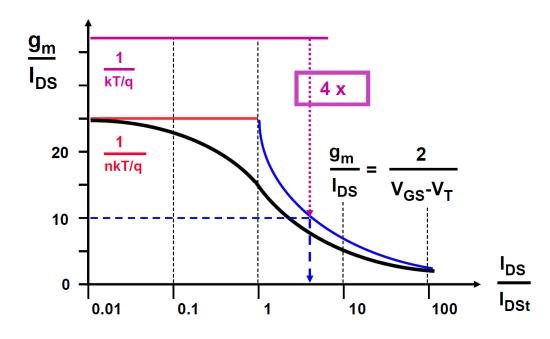
$$V_{GST} = V_{GSTt} \cdot ln(e^{\sqrt{i}} - 1)$$

$$V_{GSTt} = 2n \frac{kT}{q} \approx 70mV$$

$$i = \frac{I_{DS}}{I_{DSt}}$$



》) 弱反型与强反型:反型系数与gm/lps



晶体管最大的g_m/I_{DS}出现 在弱饱和区,且随着反型 系数增加而下降

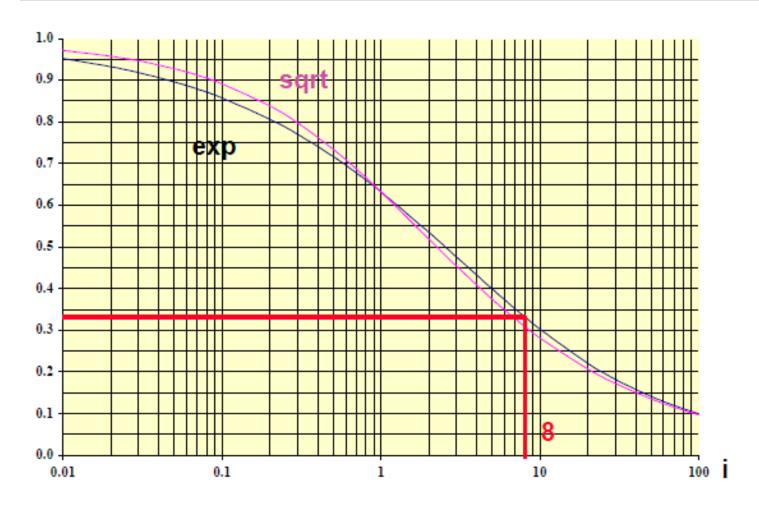
归一化效率 GM/ID:
$$GM/ID = \frac{g_m/I_{DS}}{(g_m/I_{DS})_{max}}$$

$$GM/ID = \frac{1 - e^{-\sqrt{i}}}{\sqrt{i}}$$





》) 弱反型与强反型:反型系数与gm/lps



$$GM/ID = \frac{1 - e^{-\sqrt{i}}}{\sqrt{i}}$$

• 反型系数为8,即 V_{GS} - V_{T} =200mV时,晶体管在跨导值和跨导效率中取得 一个较好的平衡。

>>> 弱反型与强反型

• 晶体管不会立即从弱反型区的指数行为切换为强反型区的二次项 行为。在这两个极端之间有一个平滑的过渡,其中漂移和扩散均 会产生电流。 对该区域进行建模非常困难,通常将其行为理解 为弱反型和强反型行为的混合体。

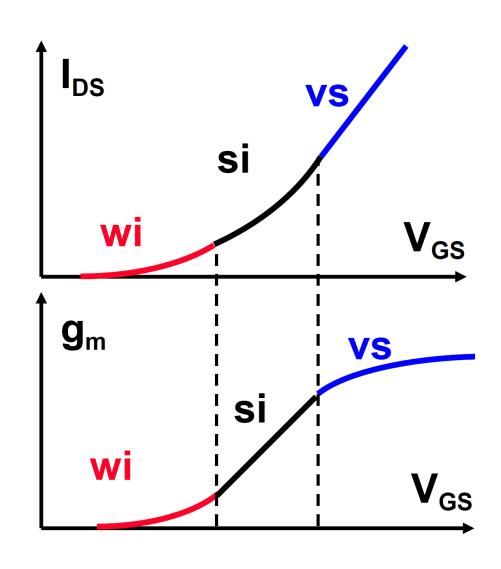
$$V_{GS} > V_T + 100 \text{mV}$$
 strong inversion $V_T + 100 \text{mV} > V_{GS} > V_T - 100 \text{mV}$ moderate inversion $V_{GS} < V_T - 100 \text{mV}$ weak inversion

MOSFET

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- ・速度饱和去 (Velocity Saturation)
- 特征频率



>>> 速度饱和区(Velocity Saturation)

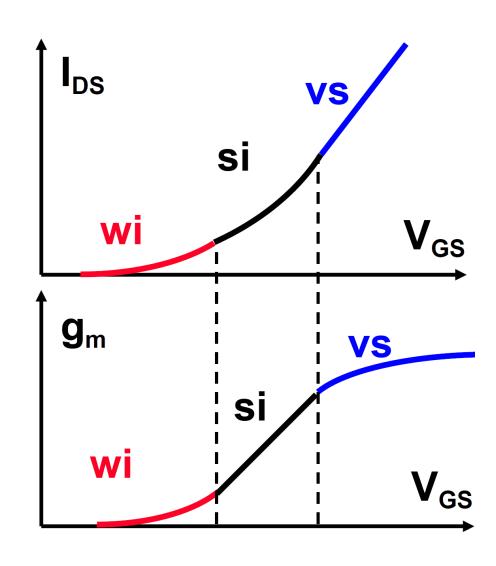


如何理解饱和区电流 中V_{GS}的平方项?

如何理解饱和区跨导 与V_Gs的线性关系



>>> 速度饱和区 (Velocity Saturation)

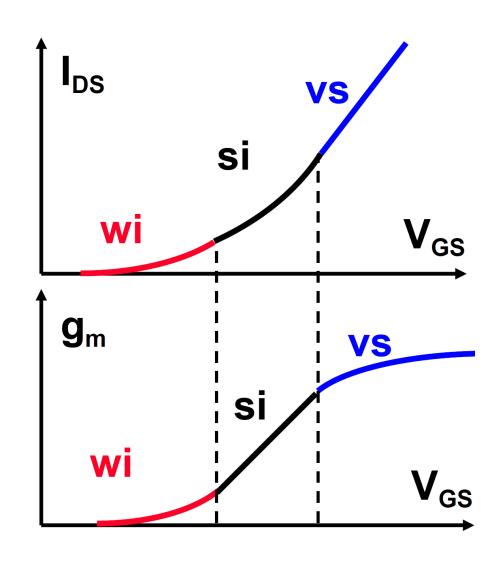


速度饱和区:

- ✓ 电子以最大速度流过 沟道
- 电流随着驱动电压线 性增加



>>> 速度饱和区(Velocity Saturation)



速度饱和区:

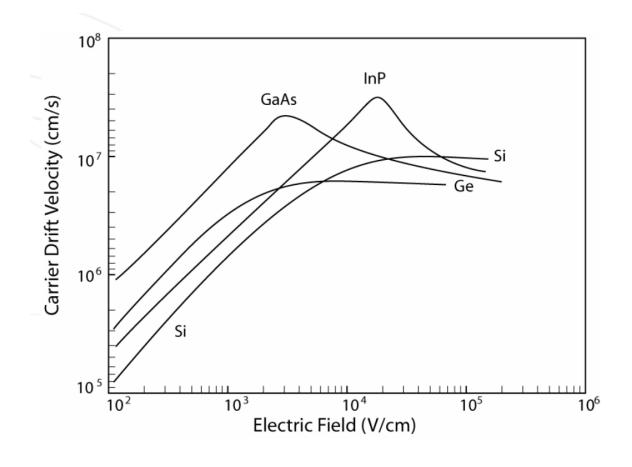
$$I_{DSvs} = WC_{ox}v_{sat} (V_{GS}-V_{T})$$

 $v_{sat} \approx 10^{7} \text{ cm/s}$

$$g_{msat} = WC_{ox}v_{sat}$$

跨导到达最大值!

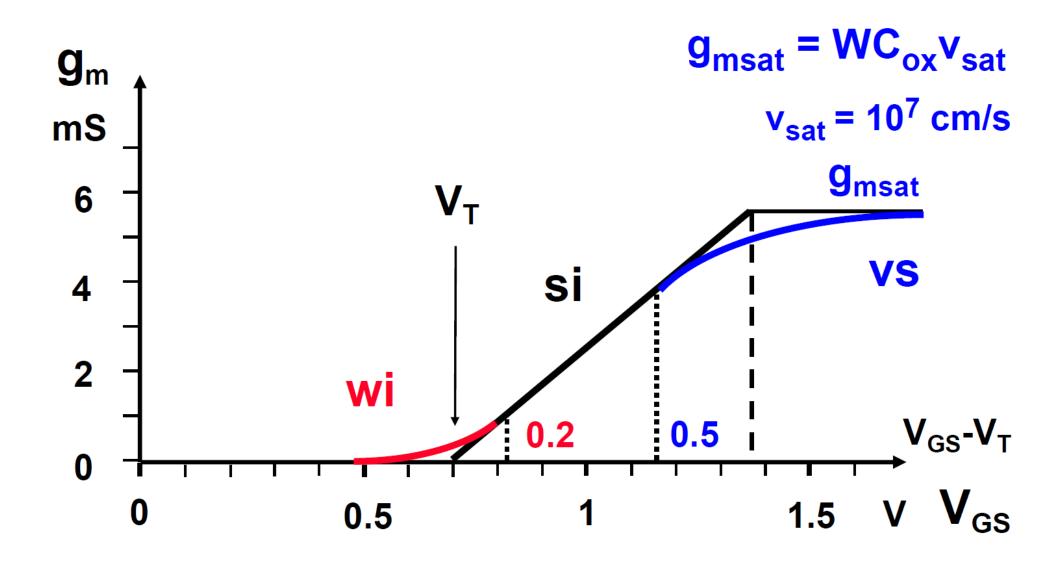
>>> 速度饱和区(Velocity Saturation)



$$g_{msat} = WC_{ox}v_{sat}$$

- g_{msat}/W只与工艺参数C_{OX}和物理参数v_{sat}有关
- 模拟电路中一般不使用该区域







》)速度饱和区

强反型区(Strong Inversion) 速度饱和区(Velocity Saturation)

$$g_{m,si} \approx \mu \, C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) \qquad \qquad g_{m,sat} = W C_{OX} v_{sat}$$

$$(V_{GS} - V_{TH})_{vs} = \frac{L \cdot v_{sat}}{\mu}$$

$$v_{sat} \approx 10^7 \text{ cm/s}$$

$$\mu_p \approx 250 \text{ cm}^2/\text{Vs}$$

$$\mu_n \approx 600 \text{ cm}^2/\text{Vs}$$



$$(V_{GS} - V_{TH})_{vs} = 0.58V$$

$$L_{min} = 0.35 \mu m$$

>>> 速度饱和区

强反型区(Strong Inversion)

$$g_{m,si} \approx \mu \, C_{ox} \frac{W}{L} (V_{GS} - V_{TH})$$

g_{m} mS **g**msat **VS** Si wi 0 1.5 $V V_{GS}$ 0.5

$$\frac{1}{g_m} = \frac{1}{g_{m,si}} + \frac{1}{g_{m,sat}}$$

速度饱和区(Velocity Saturation)

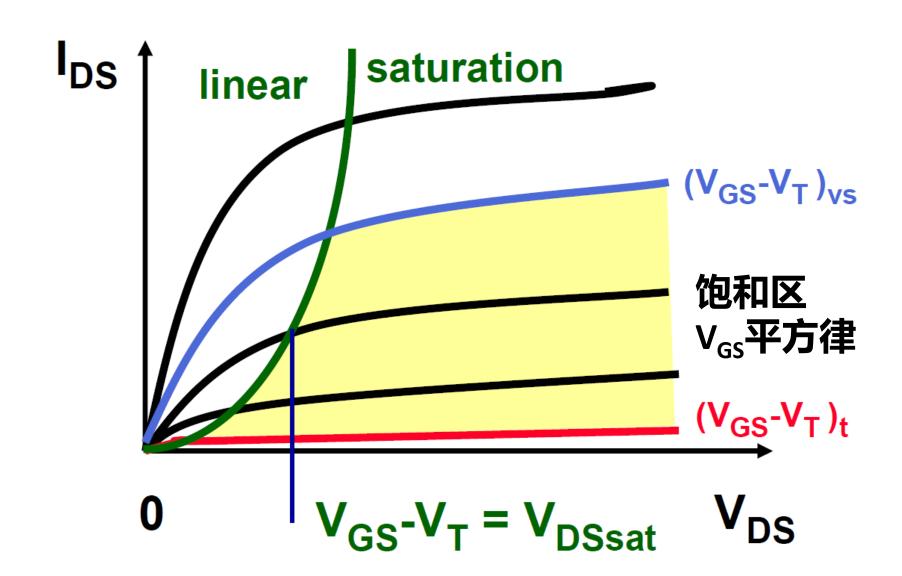
$$g_{m,sat} = WC_{OX}v_{sat}$$

真实的gm应该小于任意一个表达式 $g_m = min\{g_{m,si}, g_{m,sat}\}$

$$g_m \approx \frac{W}{L} \frac{17 \cdot 10^{-5}}{1 + 2.8 \cdot 10^4 \, L / V_{GST}}$$

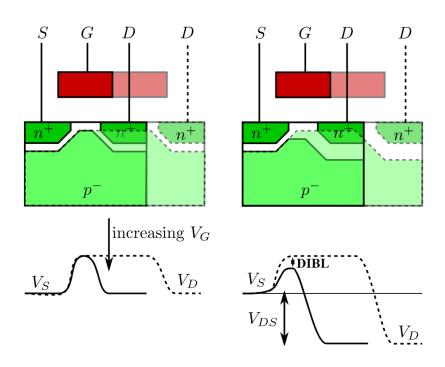


》)饱和区VS速度饱和区

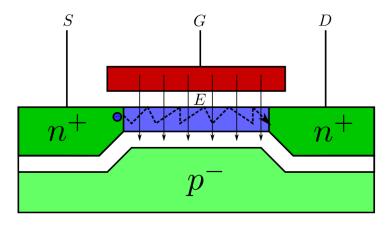




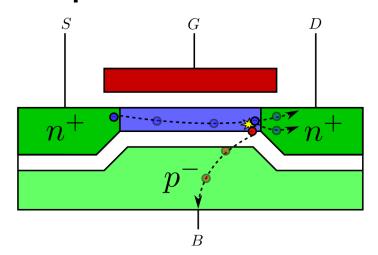
Drain-Induced Barrier Lowering (DIBL)



Surface Scattering



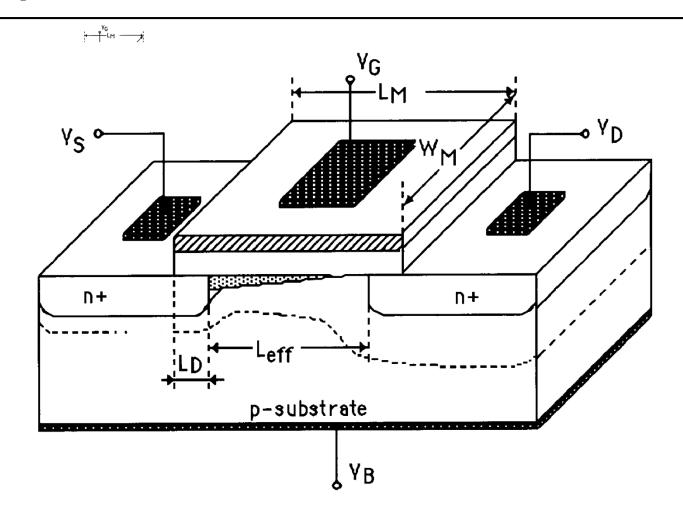
Impact ionization



MOSFET

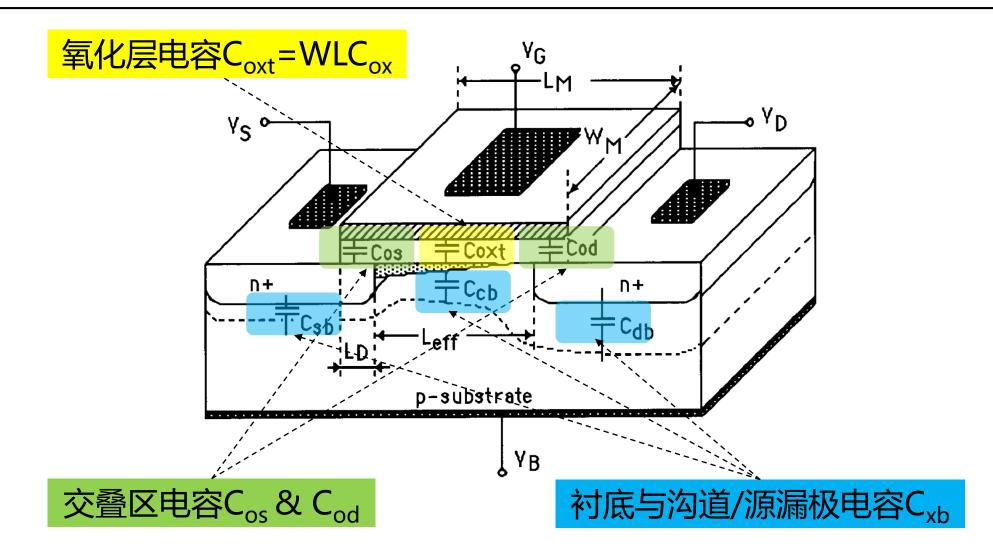
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- ・特征频率

>>> 特征频率f_T



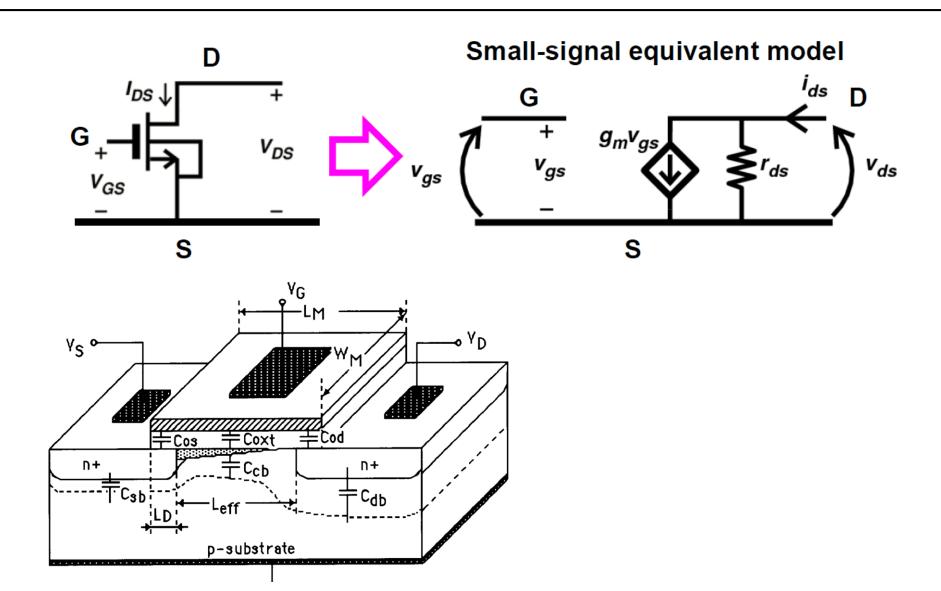
• 特征频率是表征晶体管在高频时放大能力的一个基本参量,主要由晶体管的**跨导**和**寄生电容**决定。

>>> 特征频率f_T



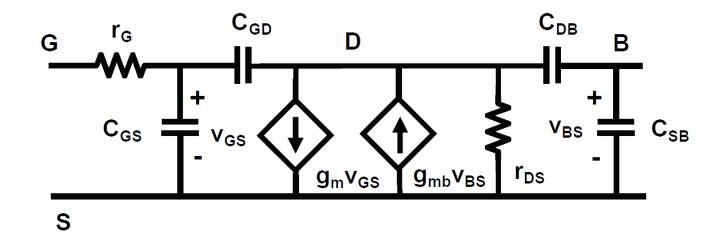


>>> 高频小信号模型





>>> 高频小信号模型

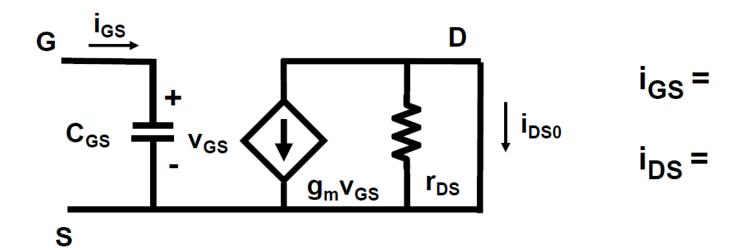


$$C_{GS} \approx \frac{2}{3} WLC_{ox} \approx 2W fF/um for Lmin$$

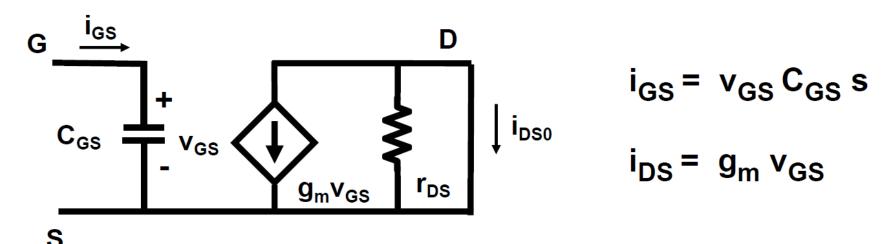
$$L_{min}C_{ox} \approx L_{min} \frac{\varepsilon_{ox}}{t_{ox}} \approx 50 \varepsilon_{ox} \approx 2 \text{ fF/}\mu\text{m}$$

$$C_{GD} = WC_{gdo}$$

>>> 特征频率f_{T,} i_{DS}= i_{GS}



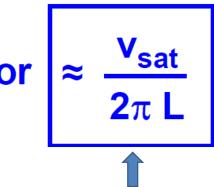
>>> 特征频率f_{T,} i_{DS}= i_{GS}



$$C_{GS} = \frac{2}{3}WLC_{ox}$$
 $g_m = 2K'\frac{W}{L}(V_{GS}-V_T)$ $K' = \frac{\mu C_{ox}}{2n}$

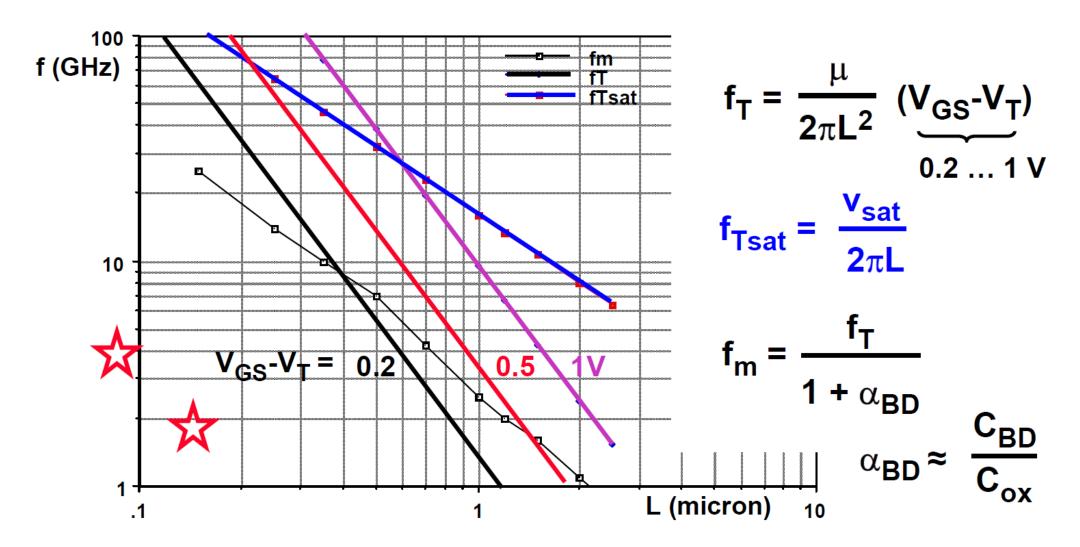
$$f_T = \frac{g_m}{2\pi C_{GS}} = \frac{1}{2\pi} \frac{3}{2n} \frac{\mu}{L^2} (V_{GS} - V_T)$$
 or $\approx \frac{V_{sat}}{2\pi L}$







)>> f_T与沟道长度L的关系



Processors



f_T与沟道长度L的关系

$$f_T = \frac{1}{L} \frac{13.5}{1 + 2.8 L/V_{GST}}$$
 GHz

L in µm

If
$$V_{GST}$$
 = 0.2 V, v_{sat} takes over for L < 65 nm
If V_{GST} = 0.5 V for L < 0.15 μ m

>>> f_T在强反型区和弱反型区中模型

$$\int GM/ID = \frac{g_m/I_{DS}}{(g_m/I_{DS})_{max}} = \frac{1 - e^{-\sqrt{i}}}{\sqrt{i}}$$

$$i = \frac{I_{DS}}{I_{DSt}}$$

$$f_T =$$

>>> f_T在强反型区和弱反型区中模型

$$\begin{cases} GM/ID = \frac{g_m/I_{DS}}{(g_m/I_{DS})_{max}} = \frac{1 - e^{-\sqrt{i}}}{\sqrt{i}} \\ i = \frac{I_{DS}}{I_{DSt}} \end{cases}$$

$$f_T = \frac{g_m}{2\pi C_{GS}} = \frac{1}{2\pi C_{GS}} \frac{I_{DSt}}{nkT/q} \sqrt{i} (1 - e^{\sqrt{i}})$$

$$= \frac{2\mu kT/q}{2\pi L^2} \cdot \sqrt{i}(1 - e^{\sqrt{i}})$$

尺寸设计 偏置设计

>>> 设计思路总结

- 1. 手工计算用来估算尺寸,精确设计依赖仿真结果。
- 2. 时刻牢记 g_m/I_D 的曲线及大致数值。
- 3. 低功耗电路取 V_{GS} - V_{TH} <-0.1V; 高增益电路取 V_{GS} - V_{TH} =0.2V; 高速电路取 V_{GS} - V_{TH} =0.5V。
- 4. 通过 f_T 的公式来估算设计的特征频率。



)>> 课程群(钉钉)



扫一扫二维码,加入班级

>>> 课后作业

- 1. 分别对于W/L=1um/1um的NMOS和PMOS,在0-1.8V的区域内,扫描V_{GS},同时令V_{DS}=1.8V,画出I_{DS},g_m和g_m/I_{DS}的曲线。(提示:改变坐标的刻度表现形式,以得到更直观的展示)
- 2. 估算 V_{GS} =0.5V, 0.8V和1.1V且 V_{DS} =1.8V时, W/L=1um/0.18um的NMOS的g_m和r₀。
- 3. 估算V_{GS}=0.5V, 0.8V和1.1V且V_{DS}=1.8V时, W/L=1um/0.18um的NMOS的特征频率f_T, 并通过AC仿真得到所求的特征频率。