### Some

Author: Pannenets.F

Date: September 22, 2020

Je reviendrai et je serai des millions. «Spartacus»

### 0.1 MOSFET



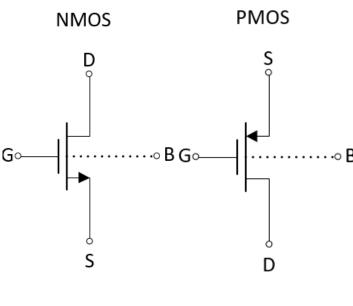
# CMOS模拟集成电路设计

第一章: MOSFET

胡远奇

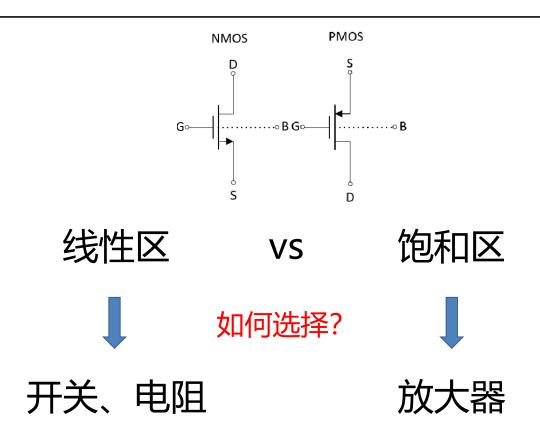
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## >>> MOSFET

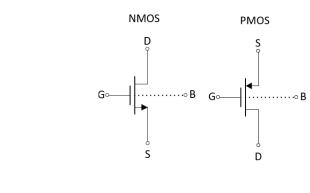


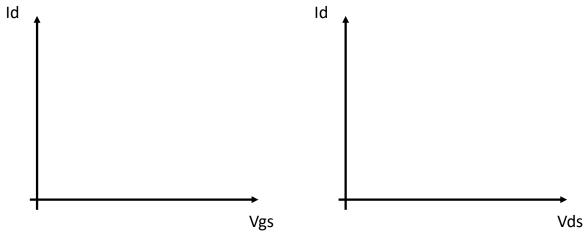
Id=?

## **MOSFET**

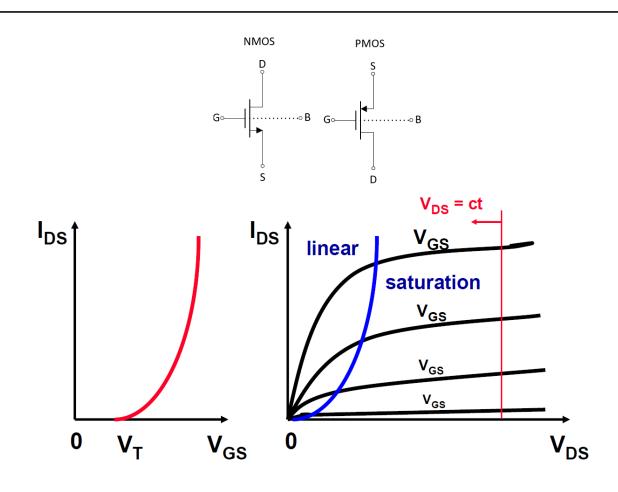


## >>> MOSFET的I-V关系





## **>>> MOSFET的I-V关系**

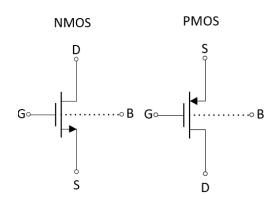


## >>> MOSFET

- ・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:  $V_{DS} < V_{GS}$  -  $V_{TH}$ 



$$I_D =$$

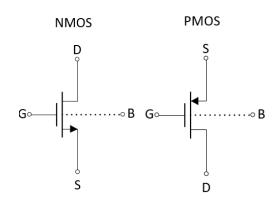
• 小信号导通电阻:

R=

### >>> MOSFET当作开关

线性区:  $V_{DS} < V_{GS}$  -  $V_{TH}$ 

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



小信号导通电阻:

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

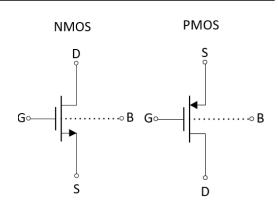
## **>>> MOSFET参数**

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



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

• 栅氧层电容 $C_{OX}$ :  $C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$ 



### >>> MOSFET参数

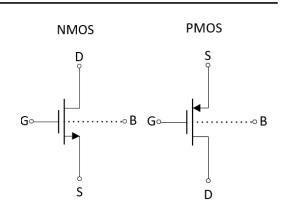
# $L_{min} = 0.35 \mu m$

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

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



### >>> 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,  $EV_{GS}-V_{TH}=1V$ 的驱动电压下,其电阻约为:

3.4K $\Omega$ 

### >>> 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<sub>GS</sub>-V<sub>TH</sub>=1V

8.16K $\Omega$ 

2. 0.18um工艺方块NMOS晶体管, V<sub>GS</sub>-V<sub>TH</sub>=1V

1.75K $\Omega$ 

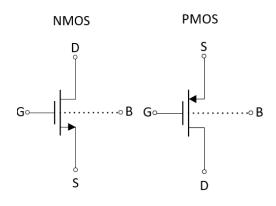
$$\mu_p \approx 250 \text{ cm}^2/\text{Vs}$$
  
 $\mu_p \approx 600 \text{ cm}^2/\text{Vs}$ 
 $t_{ox} =$ 

### **MOSFET**

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

## >>> MOSFET当作放大器

饱和区:  $V_{DS} > V_{GS} - V_{TH}$ 



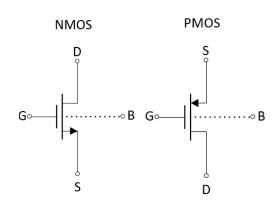
$$I_D=$$

• 小信号跨导:

$$g_m \approx$$

### >>> MOSFET当作放大器

饱和区:  $V_{DS} > V_{GS}$  -  $V_{TH}$ 



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

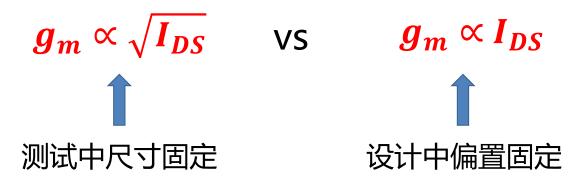
小信号跨导:

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

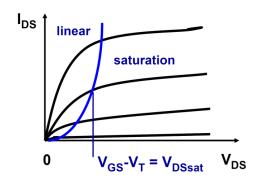
## 》)》晶体管跨导gm

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

问:小信号跨导gm与IDS的关系?



## 》)输出电阻r<sub>o</sub>

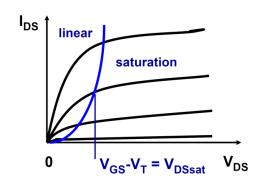


$$I_{DS} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS})$$

输出电阻:

$$r_0 =$$

## 》) 输出电阻r<sub>0</sub>



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

• 输出电阻:

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

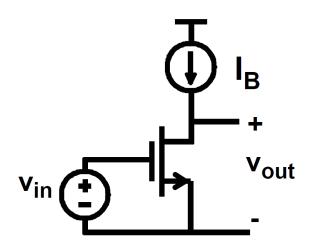
$$V_{En} = 4 V/\mu mL$$

$$L = 1 \mu m$$

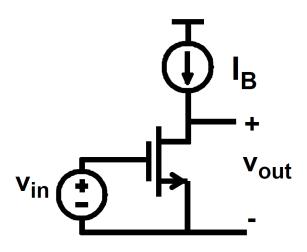
$$I_{DS}$$
 = 100  $\mu$ A

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

## **>>>** 单晶体管放大器



## **>>>** 单晶体管放大器



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

$$A_v \approx 100$$

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

## >>> 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 <sub>GS</sub> -V <sub>TH</sub>		
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 <sub>GS</sub> -V <sub>TH</sub>	<b>↓</b>	1
L	1	<b>↓</b>

### **)))** MOSFET

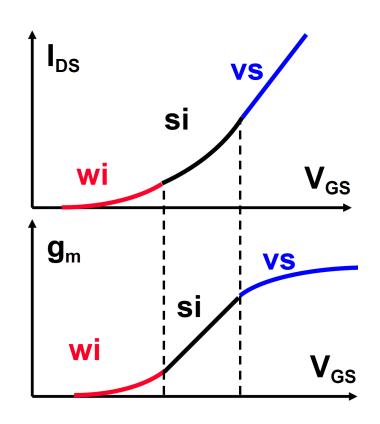
- 晶体管工作在线性区: 电阻
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- 特征频率

## >>> 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)



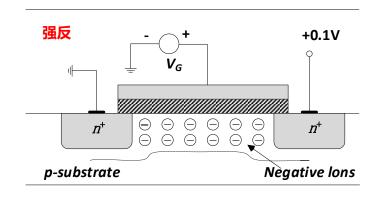
### 弱反型区:

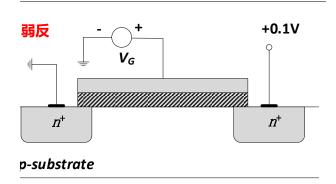
$$I_{D,wi} = I_{D0} \frac{W}{L} e^{\frac{V_{GS}}{nkT/q}}$$

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

n>1, 取决于偏置电压

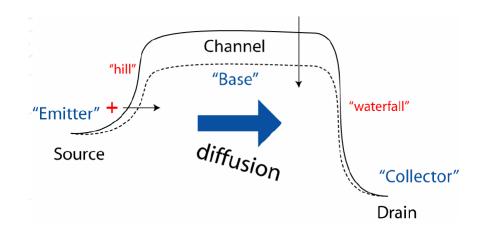
## >>> 弱反型区





- 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)

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

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

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

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

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

### >>> 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

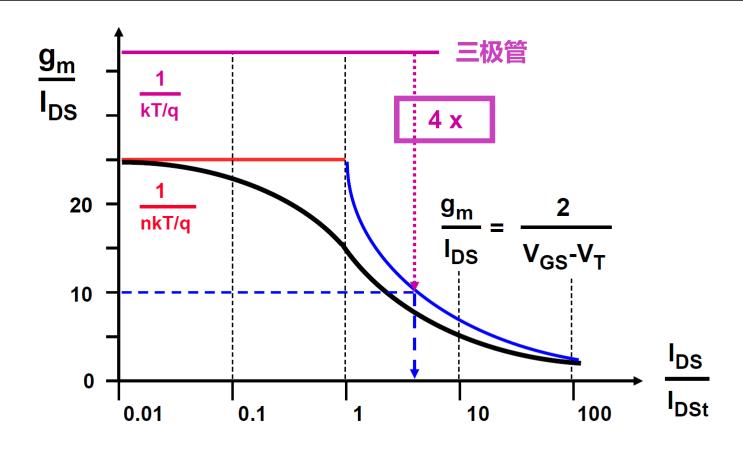
弱反型区 (Weak Inversion)

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

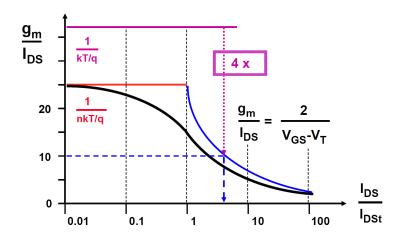
$$\frac{g_{m,si}}{I_{DS}} = \frac{2}{V_{GS} - V_{TH}}$$



## >>> 弱反型与强反型



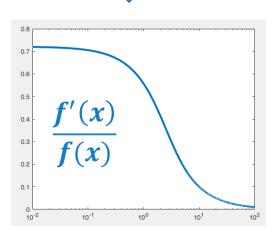
### 》) 弱反型与强反型: EKV模型



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

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:  $ln(1+e^v) \approx v$ 

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

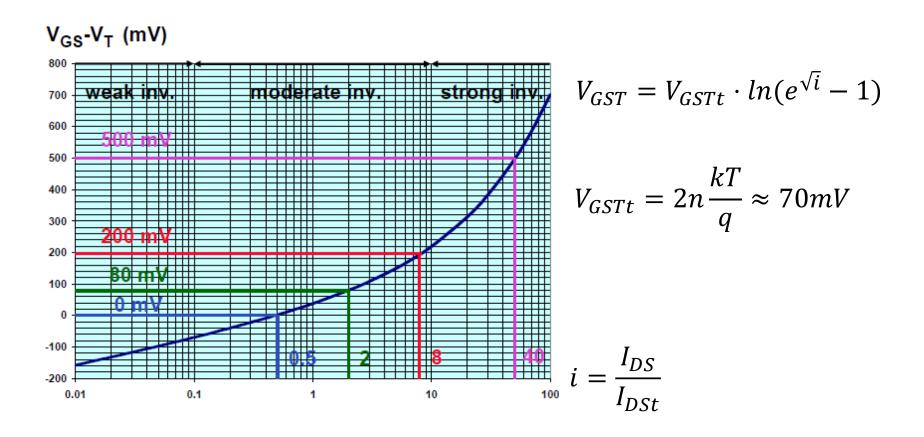
## >>> 弱反型与强反型:反型系数

$$I_{DS} = K' \frac{W}{L} V_{GSTt}^2 \cdot ln^2 (1 + e^v), \quad v = \frac{V_{GST}}{V_{GSTt}}, \quad V_{GSTt} = (V_{GS} - V_T)_t = 2n \frac{kT}{q}$$
 反型系数i:  $i = \frac{I_{DS}}{I_{DSt}} = ln^2 (1 + e^v)$  
$$v = ln(e^{\sqrt{l}} - 1)$$
 
$$V_{GST} = V_{GSTt} \cdot ln(e^{\sqrt{l}} - 1)$$

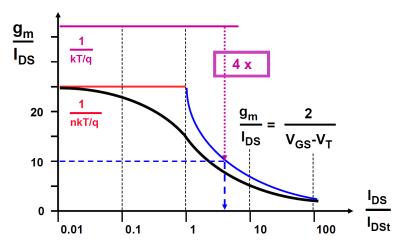
$$V_{GSTt} = 2n \frac{kT}{q} \approx 70mV$$



#### >>> 弱反型与强反型:反型系数



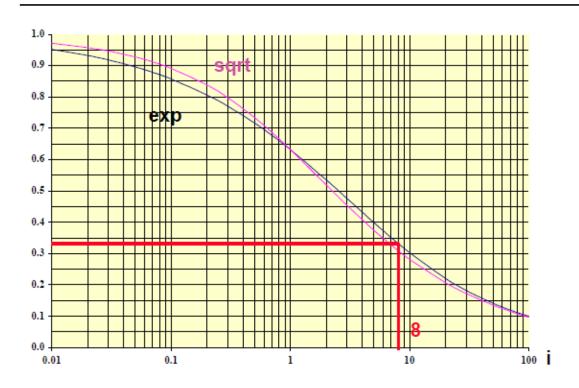
### 》) 弱反型与强反型:反型系数与gm/lps



晶体管最大的g<sub>m</sub>/I<sub>DS</sub>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: 
$$GM/ID = \frac{g_m/I_{DS}}{(g_m/I_{DS})_{max}}$$

### 》) 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

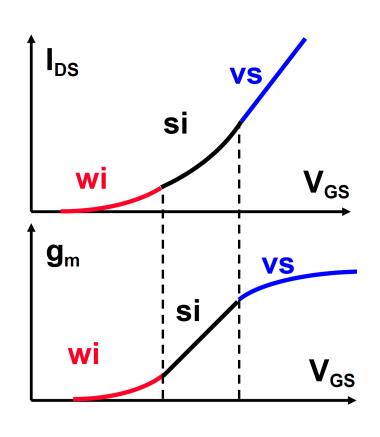
• 晶体管不会立即从弱反型区的指数行为切换为强反型区的二次项 行为。在这两个极端之间有一个平滑的过渡,其中漂移和扩散均 会产生电流。 对该区域进行建模非常困难,通常将其行为理解 为弱反型和强反型行为的混合体。

$V_{GS} > V_T + 100 \text{mV}$	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

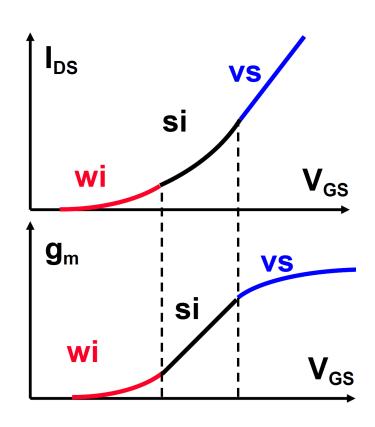
### >>> 速度饱和区 (Velocity Saturation)



□ 如何理解饱和区电流 中V<sub>GS</sub>的平方项?

□ 如何理解饱和区跨导 与V<sub>GS</sub>的线性关系

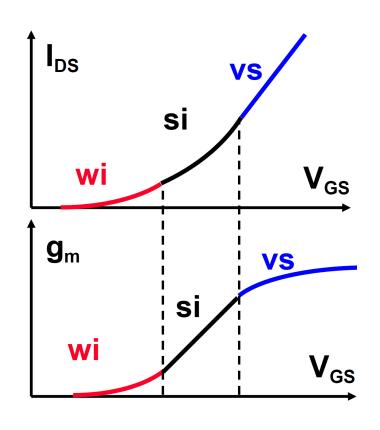
## >>>> 速度饱和区 (Velocity Saturation)



#### • 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)



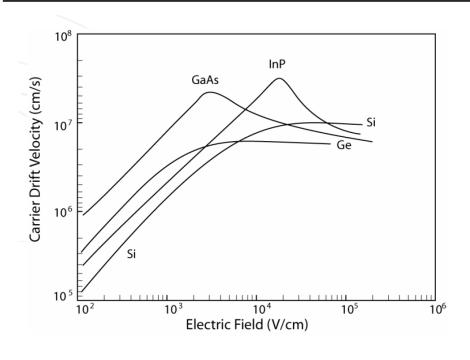
• 速度饱和区:

$$I_{DSvs} = WC_{ox}v_{sat} (V_{GS}-V_{T})$$
  
 $v_{sat} \approx 10^{7} \text{ cm/s}$ 

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

跨导到达最大值!

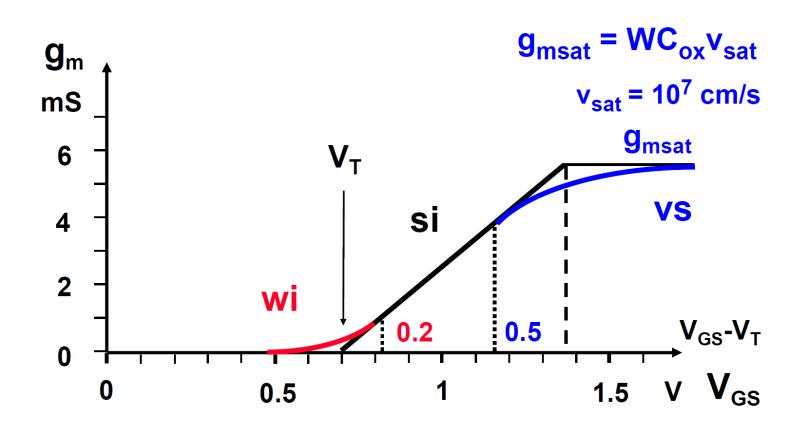
## >>>> 速度饱和区 (Velocity Saturation)



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

- g<sub>msat</sub>/W只与工艺参数C<sub>OX</sub>和物理参数v<sub>sat</sub>有关
- 模拟电路中一般不使用该区域

### >>> 速度饱和区



#### >>> 速度饱和区

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

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

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

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

$$\mu_p \approx$$
 250 cm<sup>2</sup>/Vs

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



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

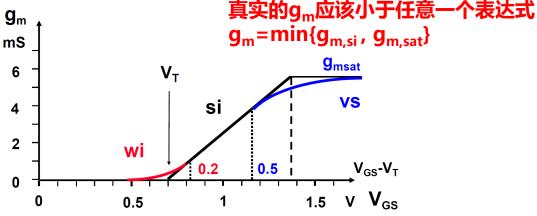
$$L_{min} = 0.35 \mu m$$

#### >>> 速度饱和区

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

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

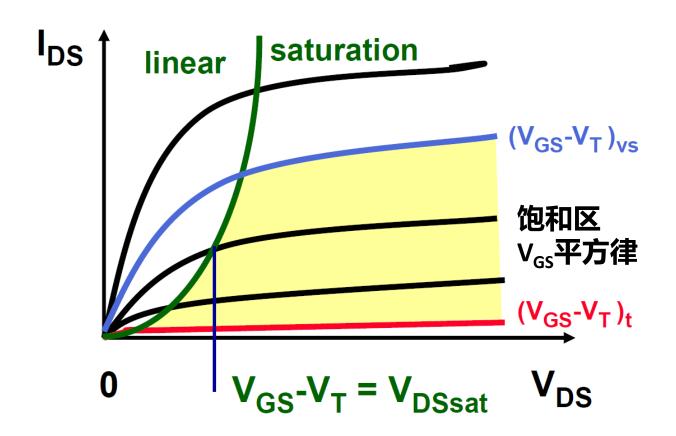
$$g_{m,sat} = WC_{OX}v_{sat}$$



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

$$g_{\rm m} \approx \frac{W}{L} \frac{17 \cdot 10^{-5}}{1 + 2.8 \cdot 10^4 \, \text{L} / \text{V}_{\rm GST}} \bigg|_{\text{in cm}}$$

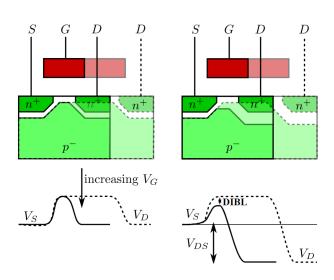
#### 》)饱和区VS速度饱和区



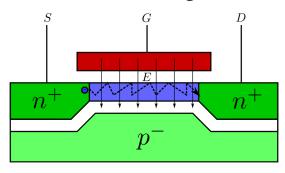


### **>>>** 其他因素

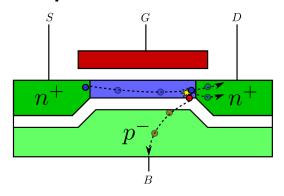
#### **Drain-Induced Barrier** Lowering (DIBL)



#### **Surface Scattering**



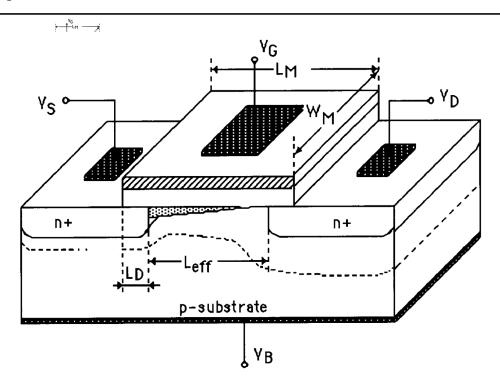
#### **Impact ionization**



#### **>>>** MOSFET

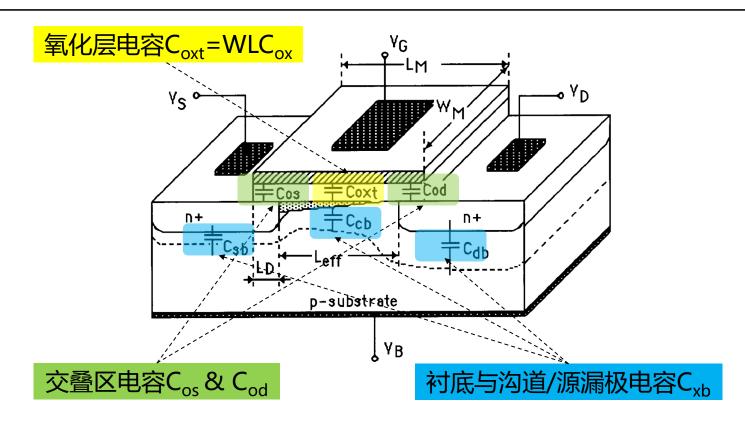
- 晶体管工作在线性区: 电阻
- 晶体管工作在饱和区: 放大器
- 亚反型区/弱翻转区 (Weak Inversion)
- 速度饱和去 (Velocity Saturation)
- ・特征频率

## >>> 特征频率f<sub>T</sub>

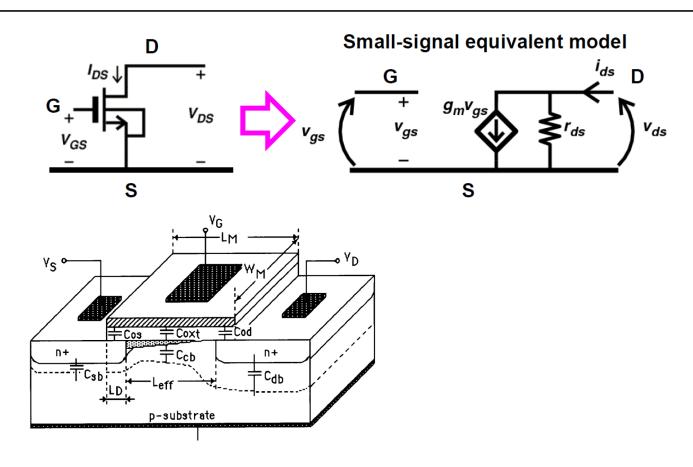


• 特征频率是表征晶体管在高频时放大能力的一个基本参量,主要由晶体管的**跨导**和**寄生电容**决定。

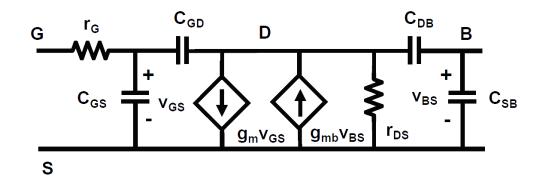
### >>> 特征频率f<sub>T</sub>



### >>> 高频小信号模型



#### >>> 高频小信号模型

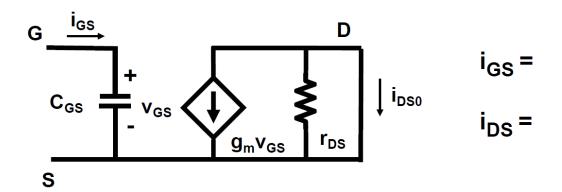


$$C_{GS} \approx \frac{2}{3} WLC_{ox} \approx 2W fF/um for Lmin$$

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

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

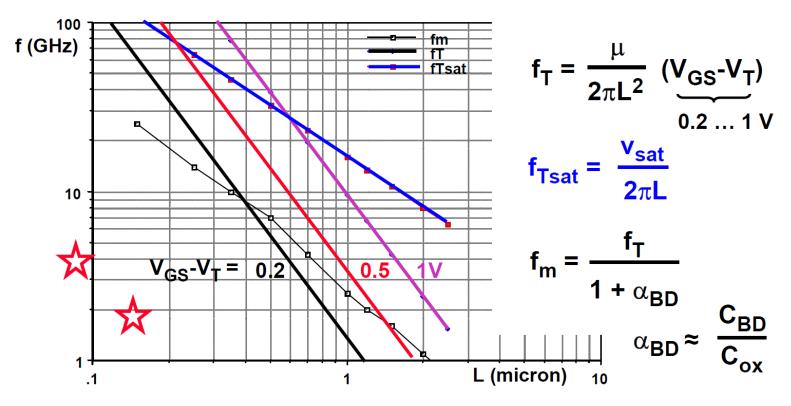
# >>> 特征频率f<sub>T,</sub> i<sub>DS</sub>= i<sub>GS</sub>



## >>> 特征频率f<sub>T,</sub> i<sub>DS</sub>= i<sub>GS</sub>

$$G \xrightarrow{i_{GS}} \xrightarrow{I} V_{GS} \xrightarrow{I$$

## >>> f<sub>T</sub>与沟道长度L的关系



**Processors** 

### f<sub>T</sub>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  $\mu$ m

## >>> f<sub>T</sub>在强反型区和弱反型区中模型

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

$$f_T =$$

### >>> f<sub>T</sub>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

- 分别对于W/L=1um/1um的NMOS和PMOS,在0-1.8V的区域内,扫描V<sub>GS</sub>,同时令V<sub>DS</sub>=1.8V,画出I<sub>DS</sub>,g<sub>m</sub>和g<sub>m</sub>/I<sub>DS</sub>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<sub>GS</sub>=0.5V, 0.8V和1.1V且V<sub>DS</sub>=1.8V时, W/L=1um/0.18um的NMOS的g<sub>m</sub>和r<sub>0</sub>。
- 3. 估算V<sub>GS</sub>=0.5V, 0.8V和1.1V且V<sub>DS</sub>=1.8V时, W/L=1um/0.18um的NMOS的特征频率f<sub>T</sub>, 并通过AC仿真得到所求的特征频率。

0.2



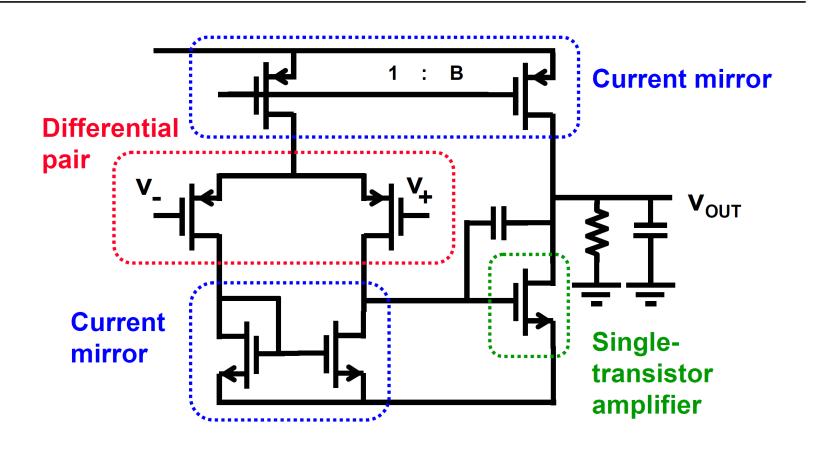
# CMOS模拟集成电路设计

第二章:模拟电路的基本构成

胡远奇

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### >>> 运算放大器

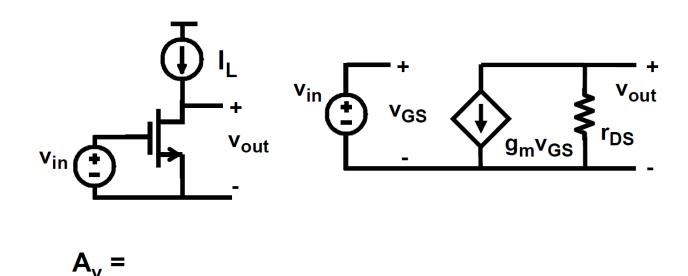


#### >>> 模拟电路的基本结构

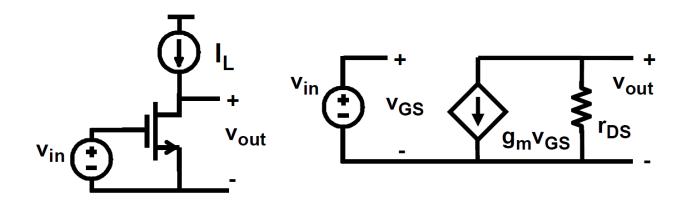
#### 1. 单晶体管放大器

- 2. 源极跟随器
- 3. Cascode (共源共栅极)
- 4. 电流镜
- 5. 差分对

## **>>>** 单晶体管放大器



#### **>>>** 单晶体管放大器



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

 $A_V \approx 100$  if  $V_E L \approx 10 \text{ V}$  and  $V_{GS} - V_T \approx 0.2 \text{ V}$ 

#### **>>>** 单晶体管放大器

#### 如何获得高增益?



降低V<sub>GS</sub>-V<sub>T</sub>



0.15-0.2V

进一步减小会牺牲信噪 比SNR和跨导gm



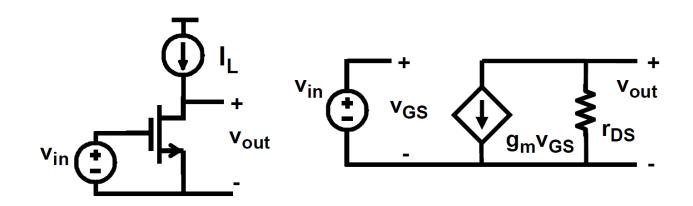
增加L



4-5x minL

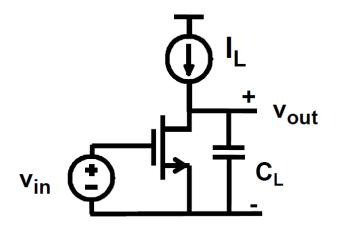
进一步增大会牺牲速度 和面积

## **>>>** 单晶体管放大器



口问:对于一个55nm工艺的单晶体管放大器,其典型的放大倍数是多少?  $(V_E=4V/um)$ 

• 如果只有大的负载电容



For all single-stage **Operational amplifiers** 

$$A_{v0} = g_m r_{DS}$$

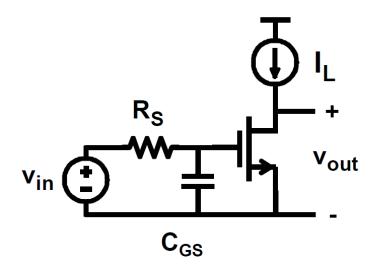
$$BW = \frac{1}{2\pi r_{DS}C_{L}}$$

$$GBW = \frac{g_{m}}{2\pi C_{L}}$$

□设计指标GBW=100M,负载电容2pF的NMOS单晶体放大器, 根据工艺指标计算相应的直流偏置电流和典型晶体管尺寸。

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

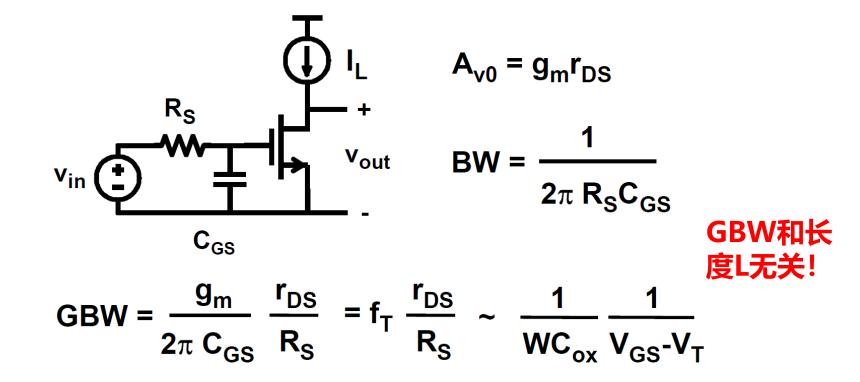
• 如果只有大的输入电容



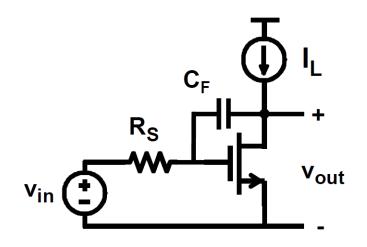
$$A_{v0} = g_{m}r_{DS}$$

$$BW = \frac{1}{2\pi R_{S}C_{GS}}$$

·如果只有大的**输入**电容



#### • 如果只有大的反馈电容



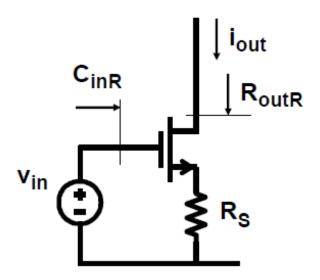
$$A_{v0} = g_m r_{DS}$$

$$BW = \frac{1}{2\pi R_S A_{v0} C_F}$$

$$\Rightarrow \qquad \mathsf{GBW} = \frac{1}{2\pi \, \mathsf{R}_{\mathsf{S}} \, \mathsf{C}_{\mathsf{F}}}$$

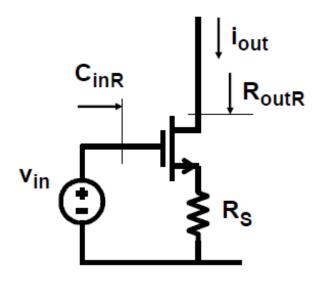


GBW和晶体管的参数无关!



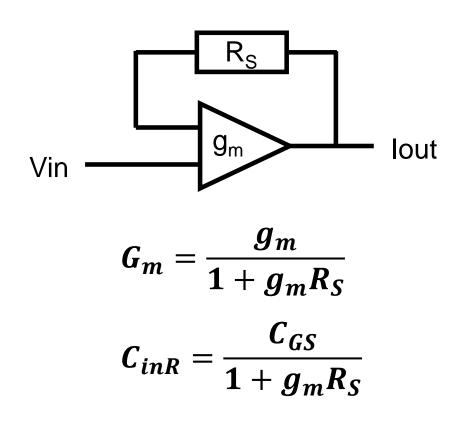
Source Degeneration

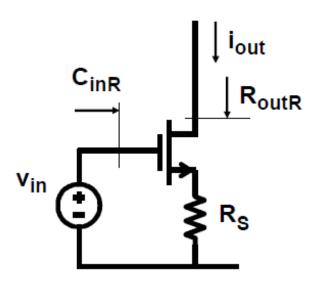
是一种负反馈形式



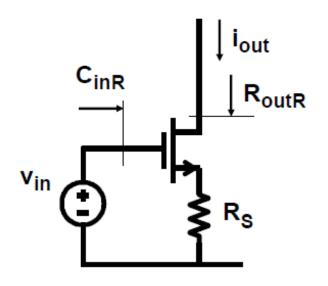
Source Degeneration

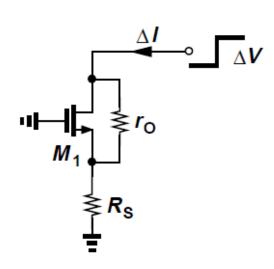
是一种负反馈形式





• 在输出端施加电压变化ΔV并测量输出电流的最终变化ΔI





•  $R_{outR} = r_{DS} (1 + g_m R_S) \approx (g_m r_{DS}) R_S$ 

Rs造成额外的噪声

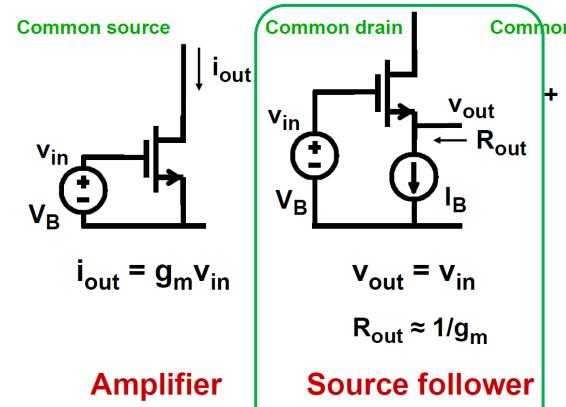
## >>> 模拟电路的基本结构

1. 单晶体管放大器

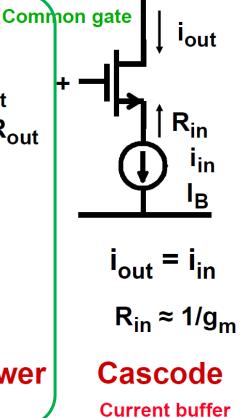
#### 2. 源极跟随器

- 3. Cascode (共源共栅极)
- 4. 电流镜
- 5. 差分对

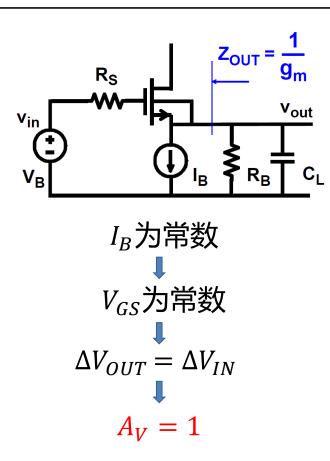
# >>> 源极跟随器 (Source Follower)

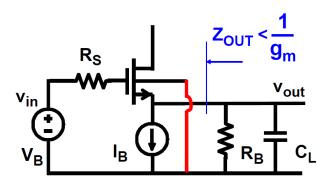


Voltage buffer



### >>> 源极跟随器 (Source Follower)

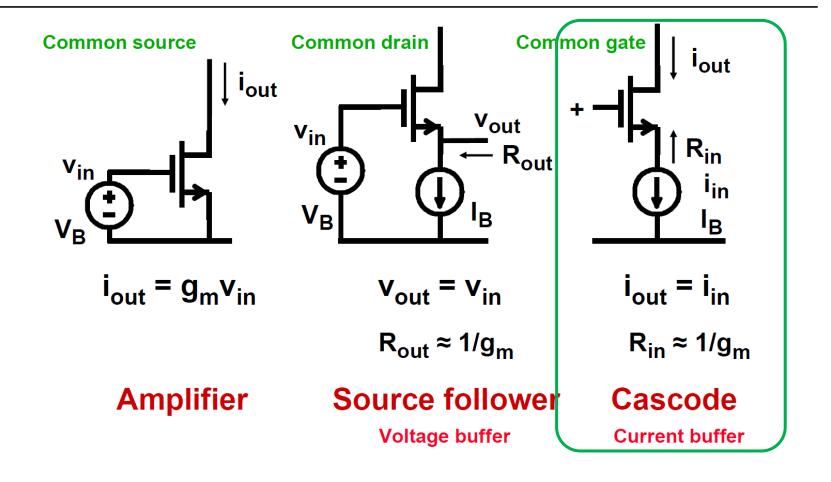




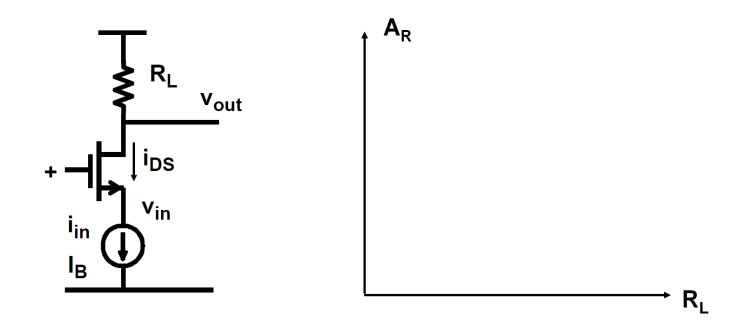
#### >>> 模拟电路的基本结构

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#### Cascode

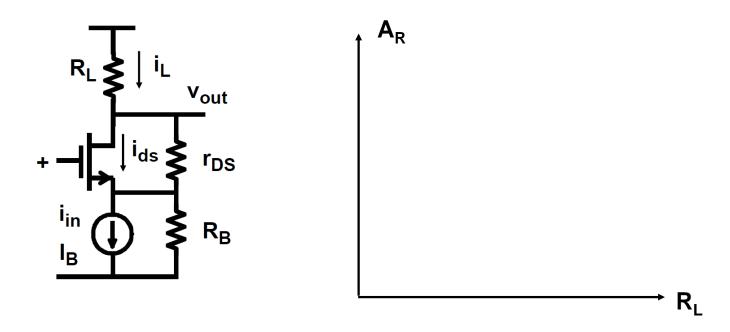


## >>> Cascode



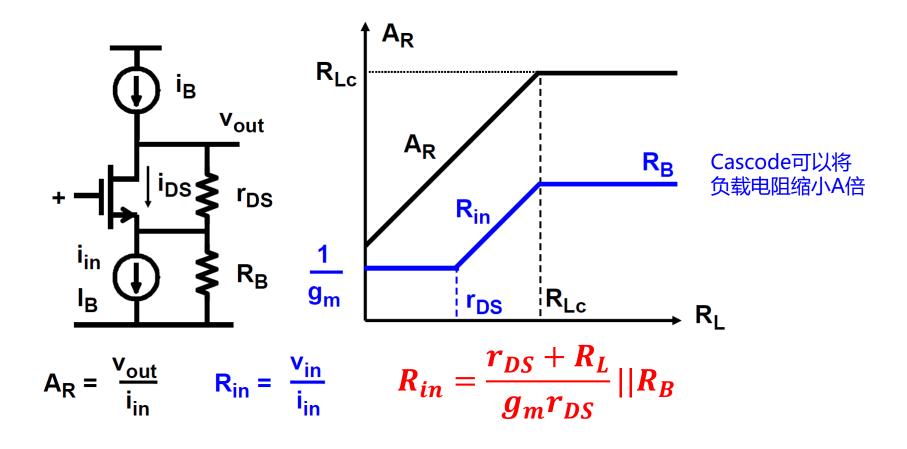
• 定义跨阻增益 A<sub>R</sub>=V<sub>out</sub>/i<sub>in</sub>

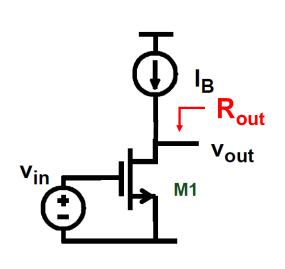
## >>> Cascode



• 分析输入电阻R<sub>in</sub>

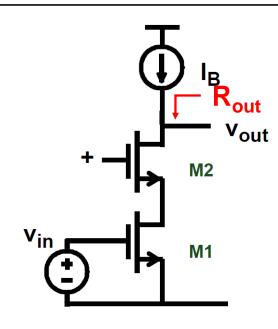
#### >>> Cascode





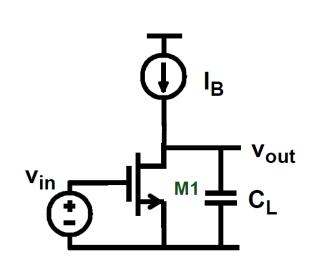
$$A_v = (g_m r_{DS})_1$$

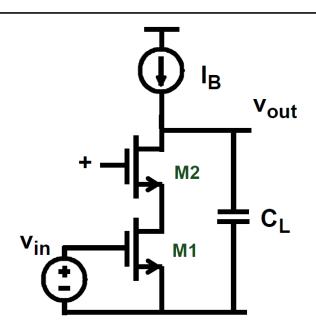
$$R_{out} = r_{DS1}$$



$$A_v = (g_m r_{DS})_1 (g_m r_{DS})_2$$

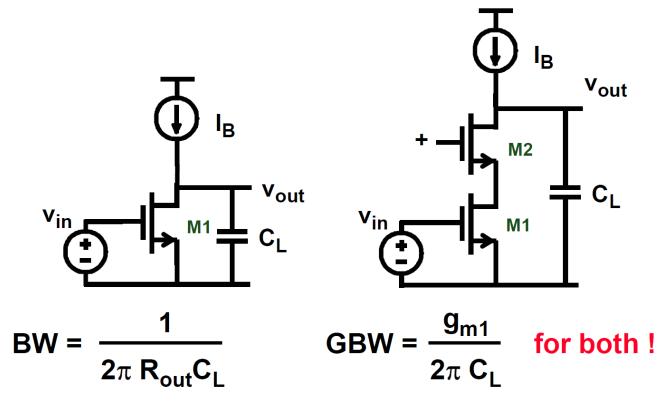
$$R_{out} = r_{DS1} (g_m r_{DS})_2$$



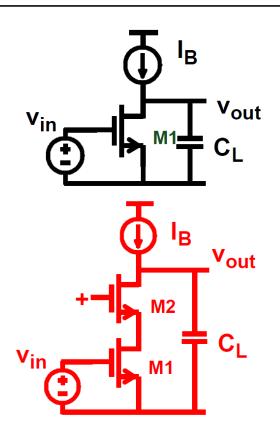


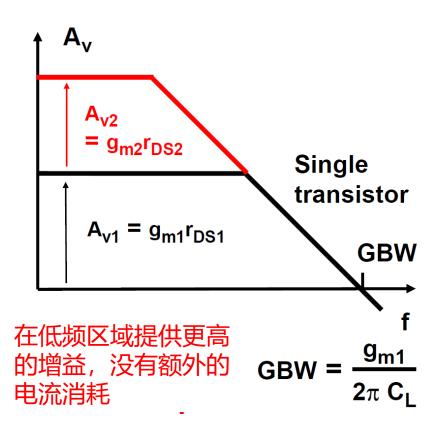
BW =

GBW =

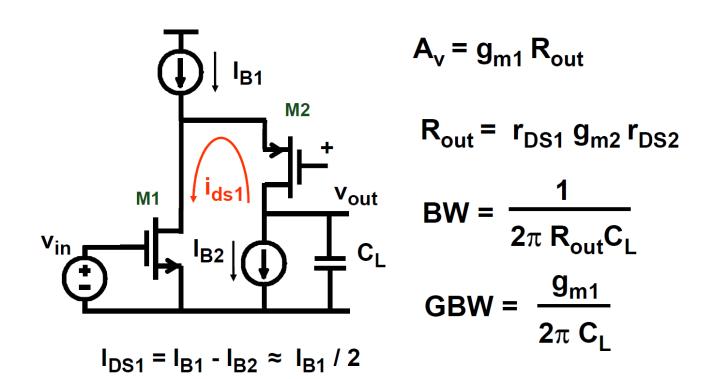


• 增益带宽积不变!



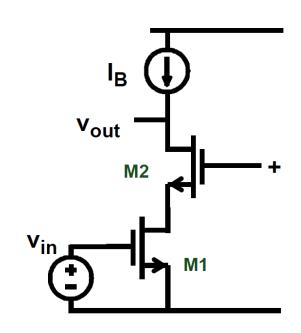


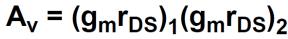
#### **} )**

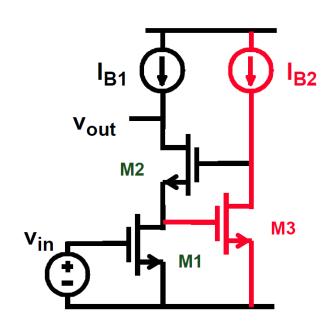


• 主要参数指标与套筒式一致, 功耗是其两倍!

# 》) 调节式 (Regulated) Cascode

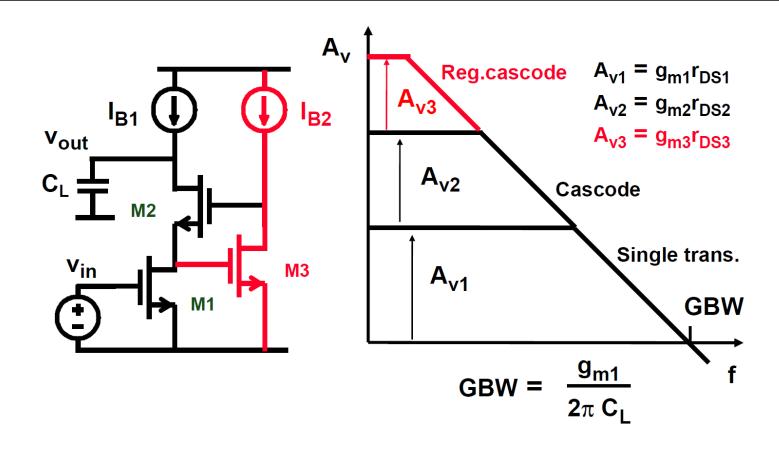




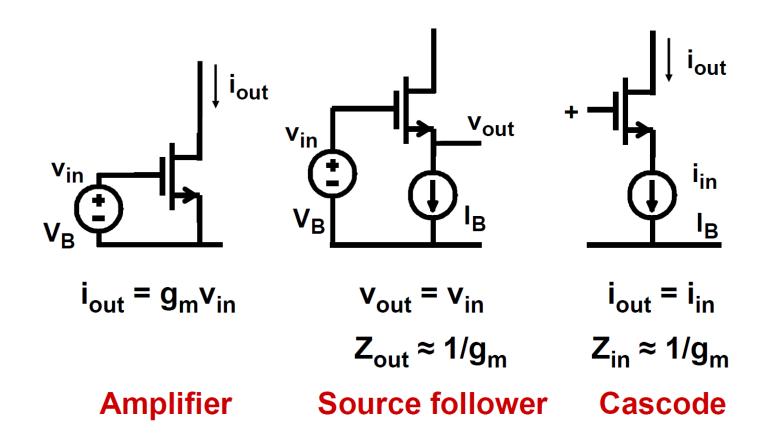


$$A_v = (g_m r_{DS})_1 (g_m r_{DS})_2$$
  $A_v = (g_m r_{DS})_1 (g_m r_{DS})_2 (g_m r_{DS})_3$ 

# 》) 调节式 (Regulated) Cascode

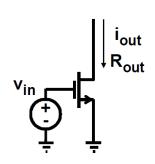


# >>> 单晶体管结构对比



### >>> 低频特性对比

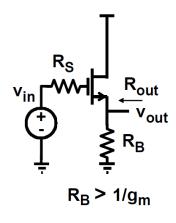
• 放大器



 $g_{\mathsf{m}}$ 

**R**in  $\infty$ 

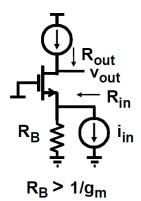
 $R_{out}$  $r_o$  • 源极跟随器



 $\infty$ 

1/g<sub>m</sub>

Cascode



 $g_m r_o R_B$ 

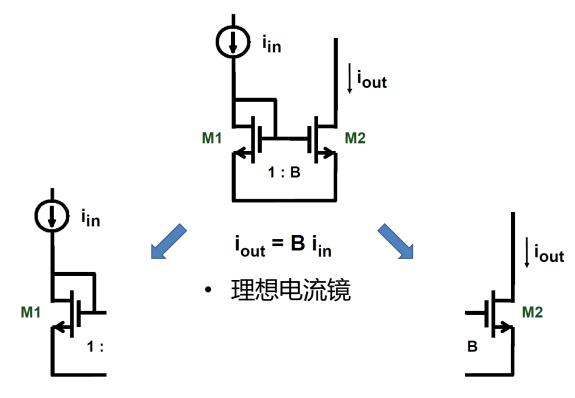
 $R_{\mathsf{B}}$ 

 $g_{m}r_{o}R_{B} \\$ 

### >>> 模拟电路的基本结构

- 1. 单晶体管放大器
- 2. 源极跟随器
- 3. Cascode (共源共栅极)
- 4. 电流镜
- 5. 差分对

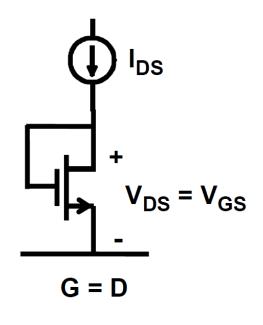
# >>> 电流镜 (Current Mirror)



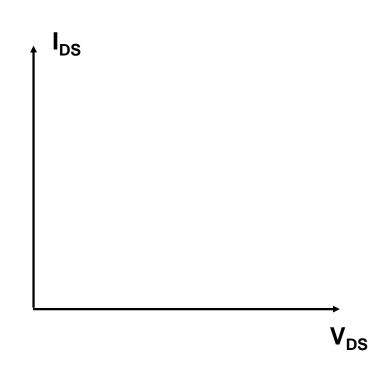
• 二极管连接晶体管

• 单晶体管放大器

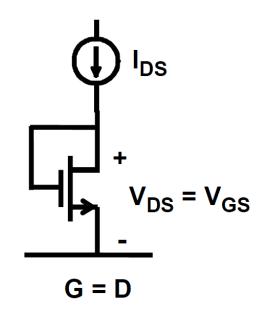
## >>> 二极管连接晶体管 (Diode-connected)



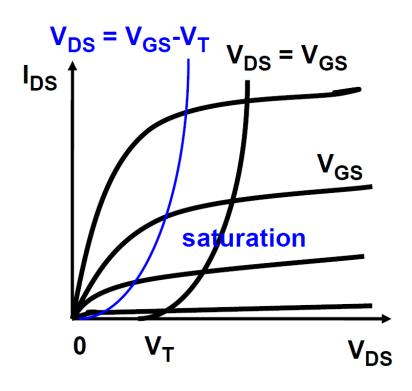
$$I_{DS} = K_n^{'} \frac{W}{L} (V_{DS} - V_T)^2$$



# >>> 二极管连接晶体管 (Diode-connected)

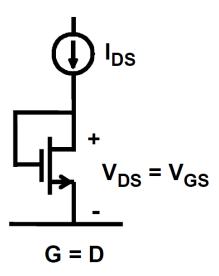


$$I_{DS} = K'_{n} \frac{W}{L} (V_{DS} - V_{T})^{2}$$

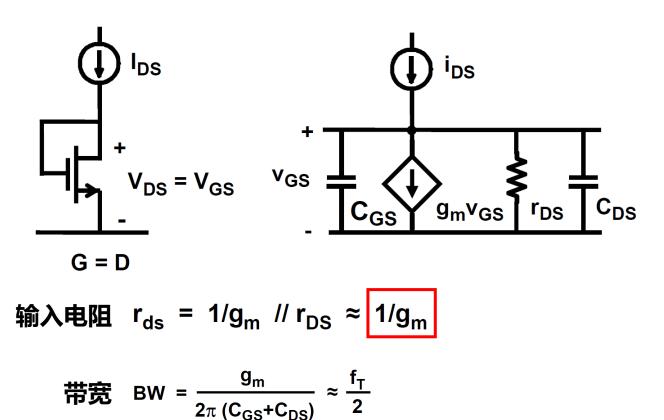


### >>> 二极管连接的小信号模型

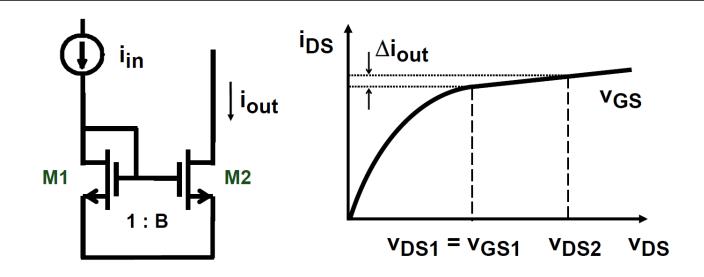
#### □求二极管连接方式的输入电阻和带宽?



#### >>> 二极管连接的小信号模型



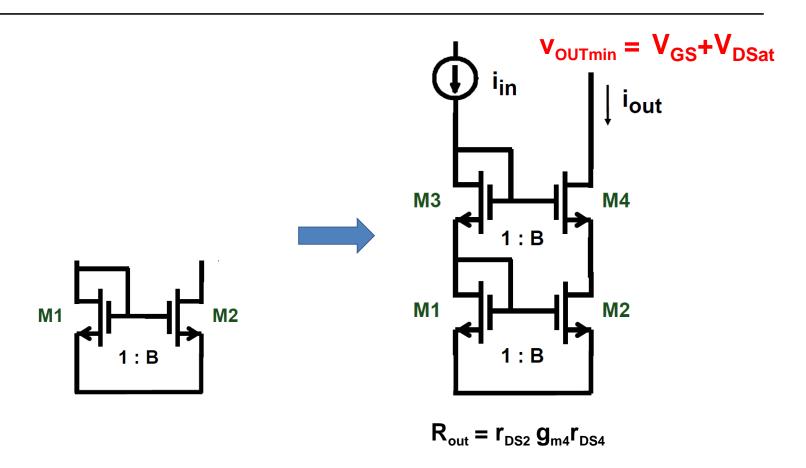
#### >>> 电流镜的输出特性



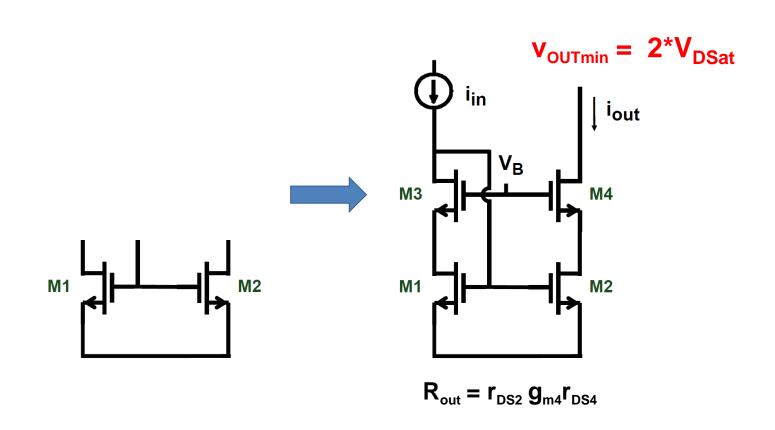
- 电流镜的输出阻抗即是单晶体管放大器的输出阻抗
- 电流镜的输出精度可以描述为

$$\frac{\Delta i_{out}}{i_{out}} =$$

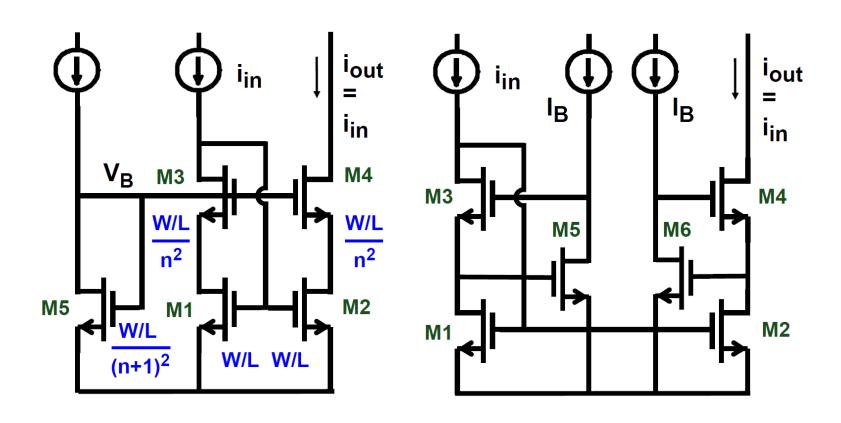
### >>> 改进型的电流镜



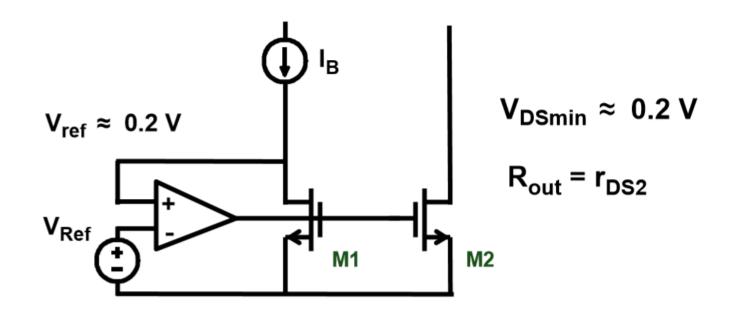
### >>> 改进型的电流镜



### >>> 电流镜案例



## >>> 低电压电流镜

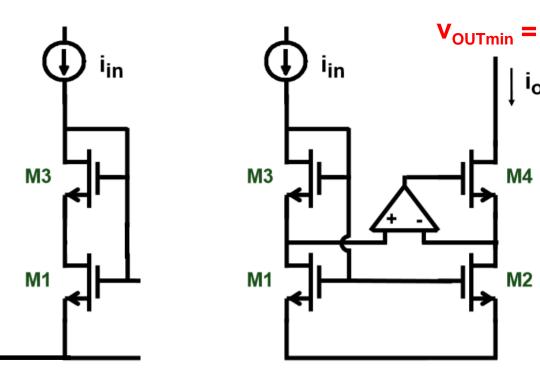


- 该电路不能改善输出电阻
- 该电路可以改善系统性失配问题

### >>> 超低电压电流镜

□此结构是否是合 适的Cascode?

不是!



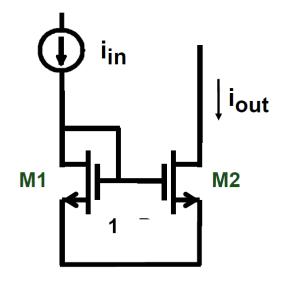
lout

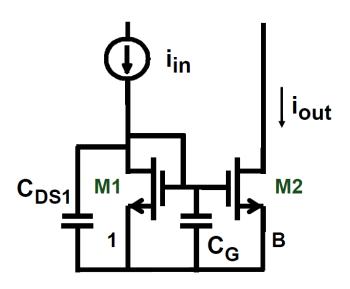
**M4** 

**M2** 

电流镜晶体管工作在线性区,通过运放锁定Vds,使得两个晶体管工作电压 完全一致!

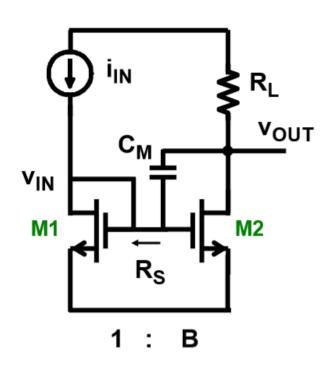
# >>> 电流镜的高频特性





BW = 
$$\frac{g_{\text{m}}}{2\pi (C_{\text{G}} + C_{\text{DS1}})} \approx f_{\text{T}} \frac{1}{(2 + B)}$$

## >>> 电流镜中的密勒效应



### Miller effect:

$$f_{-3dB} = \frac{1}{2\pi R_S A_{v2} C_M}$$

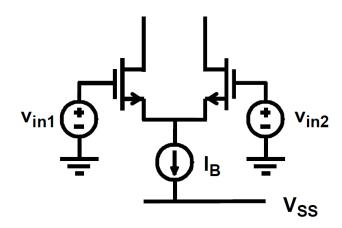
$$R_S = 1/g_{m1}$$
  $A_{v2} = g_{m2}R_L$ 

$$f_{-3dB} = \frac{1}{2\pi (1+B)C_M R_L}$$

### >>> 模拟电路的基本结构

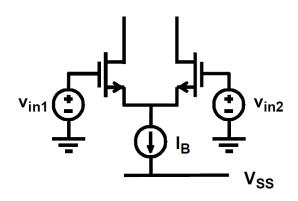
- 1. 单晶体管放大器
- 2. 源极跟随器
- 3. Cascode (共源共栅极)
- 4. 电流镜
- 5. 差分对

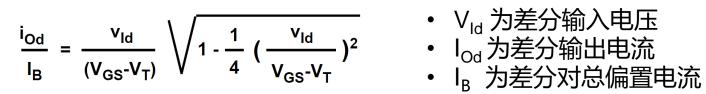
# 》》 差分对 (Differential Pair)

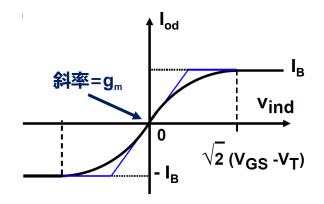


- 差分对的本质依旧是电压输入电流输出
- 差分对中的信号均以差分形式体现
- 差分对的能效是单晶体放大器的一半

# 差分对 (Differential Pair)



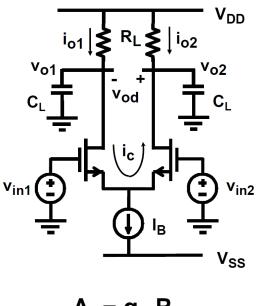




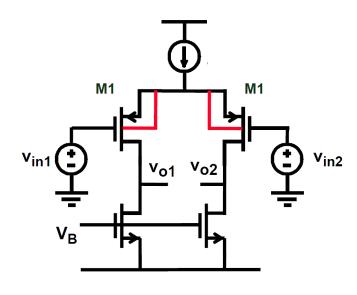
・ V<sub>GS</sub>-V<sub>T</sub>决定gm和直流范围

### **>>>** 差分放大器

• 差分放大器 = 差分对+负载



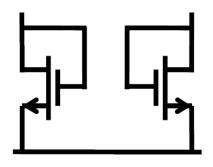
$$A_v = g_m R_L$$

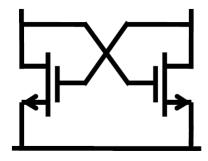


$$A_{v} = g_{m1}(r_{DS1}//r_{DS2})$$

# >>> 特殊形态的负载-交叉耦合对

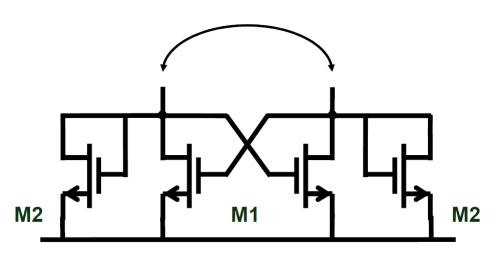
• 交叉耦合对 (Cross Coupled Pair)





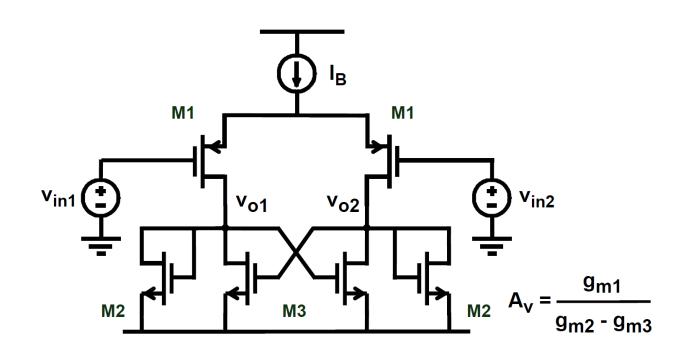
## >>> 特殊形态的负载-交叉耦合对





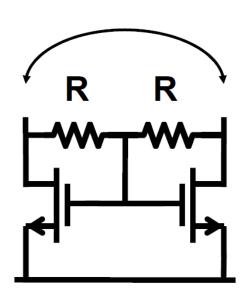
实际使用中受到匹配(matching)的限制

# >>> 特殊形态的负载-交叉耦合对



实际使用中受到匹配(matching)的限制

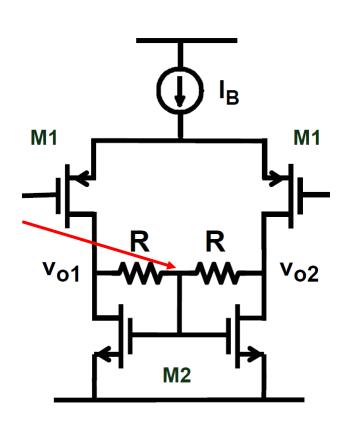
# >>> 特殊形态的负载-共模反馈



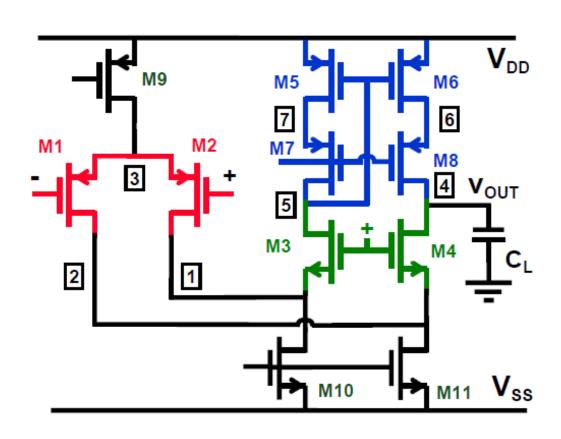
### >>> 特殊形态的负载

• 本质上是一种共模反馈形式

$$A_v = g_{m1} (R // r_o)$$
  
 $r_o = r_{o1} // r_{o2}$ 



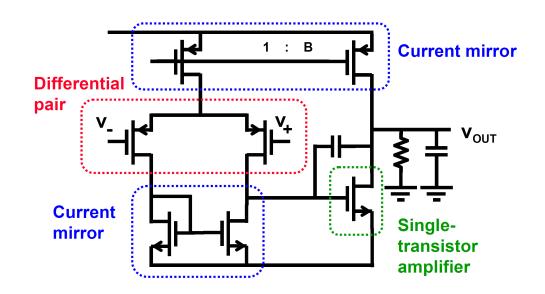
## >>> Cascode



□求该折叠套筒型运 放的第一和第二高阻 点的阻值,用公式表 示。

# 》总结

- □ 模拟电路的基本构成单元:
  - 1. 单晶体管
    - 放大器
    - 源极跟随器
    - Cascode
  - 2. 多晶体管
    - 差分对
    - 电流镜



## >>> 作业1

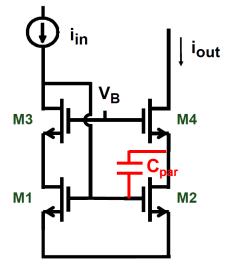
•利用仿真结果,找到我们所使用工艺的u<sub>0p,n</sub>, C<sub>ox</sub>, V<sub>THn</sub>, V<sub>THp</sub>

# >>> 作业2

• 通过公式描述V<sub>B</sub>的取值范围(提示:晶体管M1-M4均需要工作在饱和区)

• 在Cascode电流镜中,假设有寄生电容C<sub>par</sub>,利用公式估算并用仿真 验证该电流镜的频率特性。 (可以自由设置偏置、晶体管的尺寸以及

寄生电容)



### >>> 作业3

- 假设差分对偏置电流为200uA,W/L=20um/1um,根据理论分析和仿真验证。
  - 1. 计算g<sub>m</sub>>99%\*g<sub>m,max</sub>的区间。
  - 2. 计算差分输出电流为198uA时的差分输入电压。
  - 3. 如果需要把问题2中求得的电压扩大一倍,差分对的W需要如何修改?