

第十二章 带隙基准

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内容

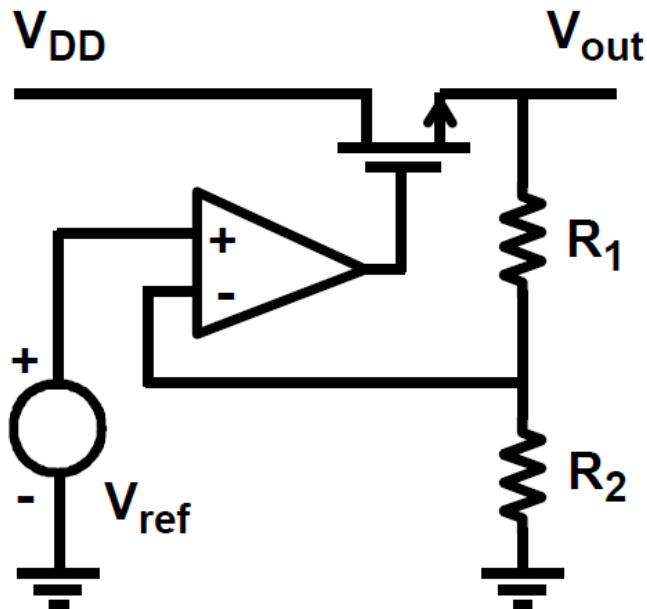
- 概述
- 偏置与启动
- 基本原理
- 带隙基准电路
- PTAT电流
- 速度与噪声
- 带隙基准设计实例

概述

- 产生基准的目的
 - 建立一个与电源和工艺无关、且具有确定温度特性的直流电压与电流。
 - 温度特性
 - (1) 与绝对温度成正比；
 - (2) 常数 G_m 特性；
 - (3) 与温度无关；

概述

● 应用实例1: LDO

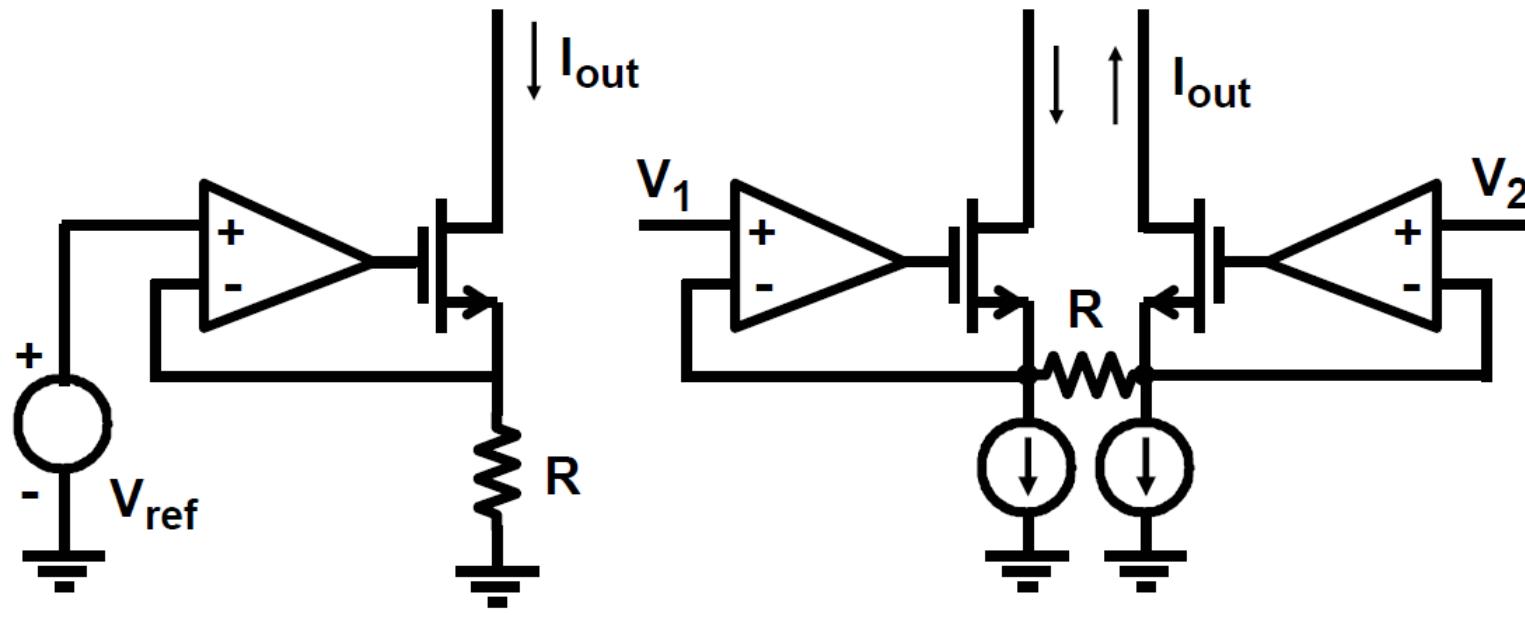


$$V_{out} = V_{ref} \frac{R_1 + R_2}{R_2}$$

(基本线性稳压器电路)

概述

- 应用实例2: 电流基准



$$I_{out} = \frac{V_{ref}}{R}$$

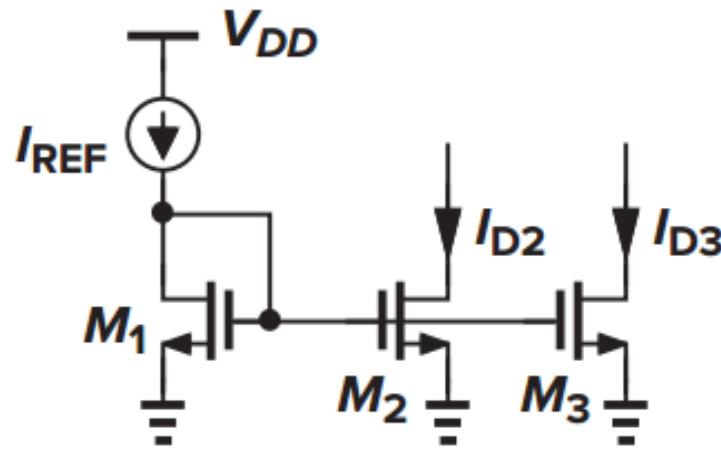
$$I_{out} = \frac{V_1 - V_2}{R}$$

内容

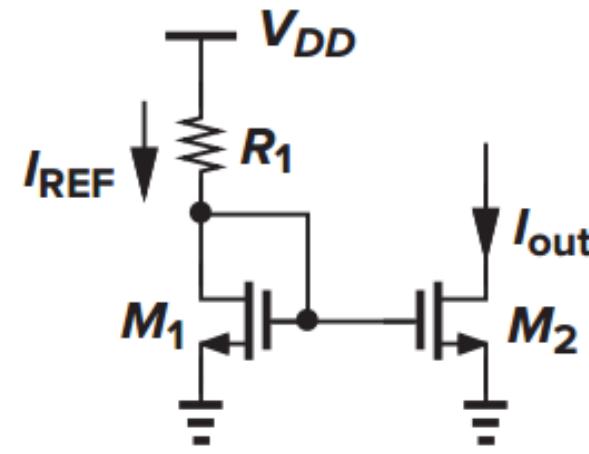
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偏置与启动

● 电流镜



(a)

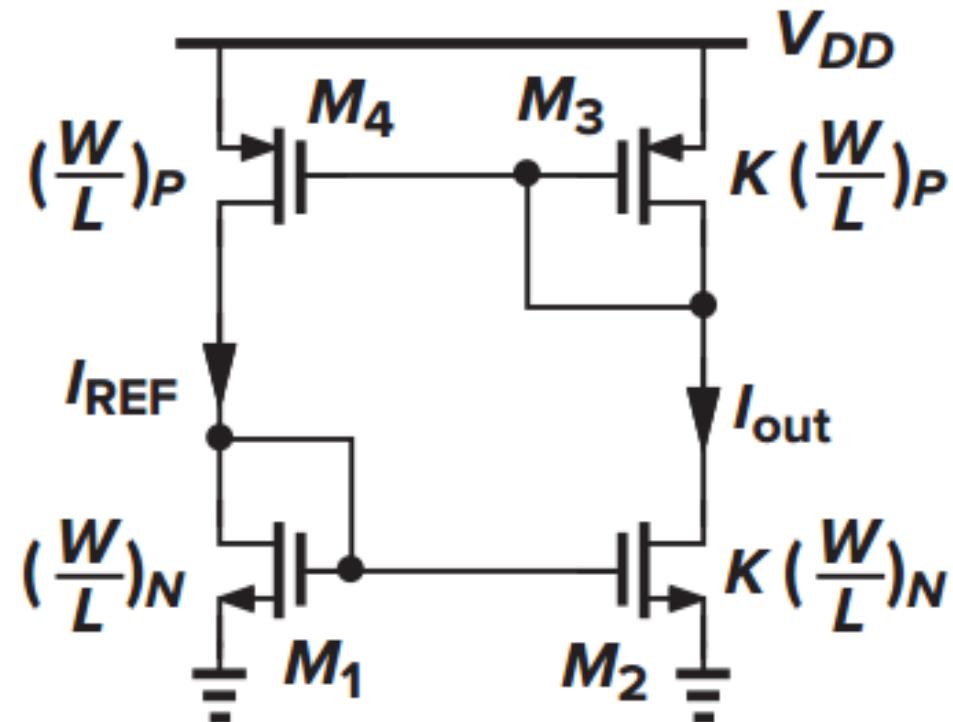


(b)

$$\Delta I_{out} = \frac{\Delta V_{DD}}{R_1 + 1/g_m} \cdot \frac{(W/L)_2}{(W/L)_1}$$

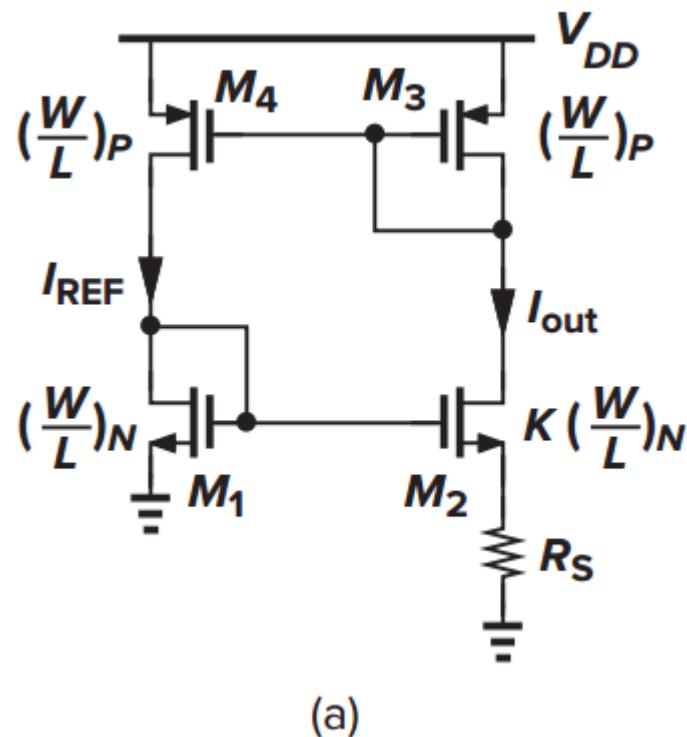
偏置与启动

- 与电压无关的简单电流镜

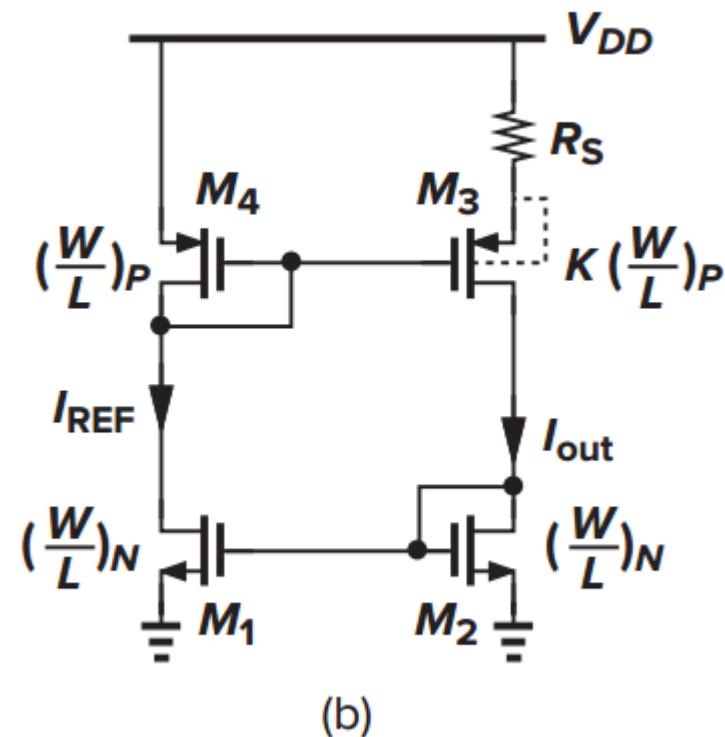


偏置与启动

● 确定电流大小的方法



(a)

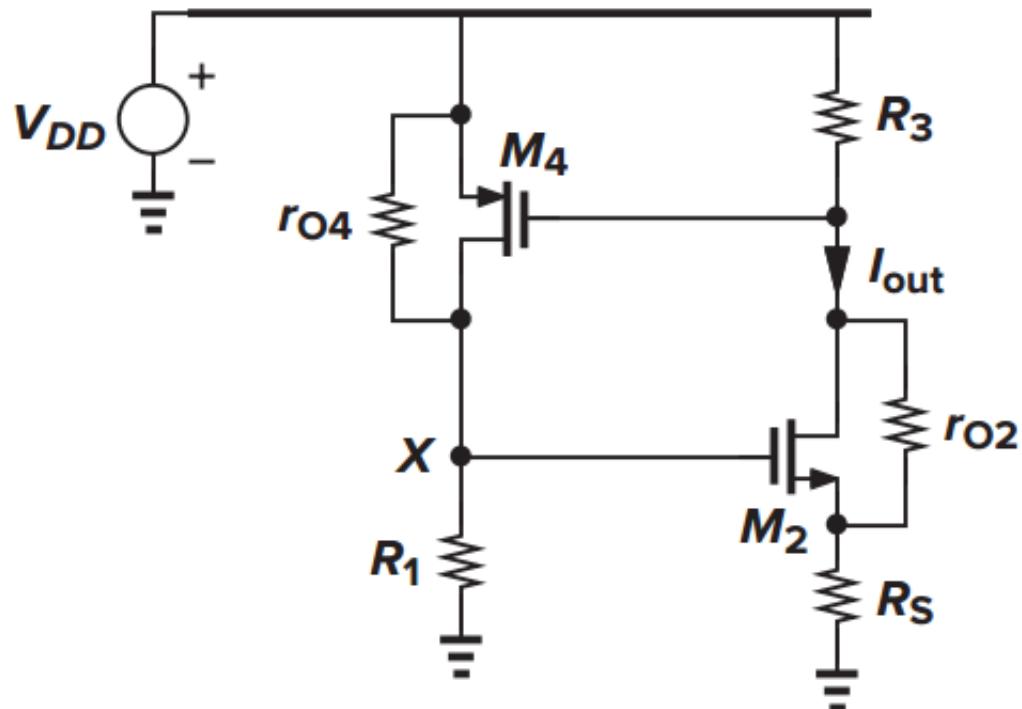


(b)

$$I_{out} = \frac{2}{\mu_n C_{ox} (W/L)_N} \frac{1}{R_S^2} \left(1 - \frac{1}{\sqrt{K}} \right)^2$$

偏置与启动

● 例



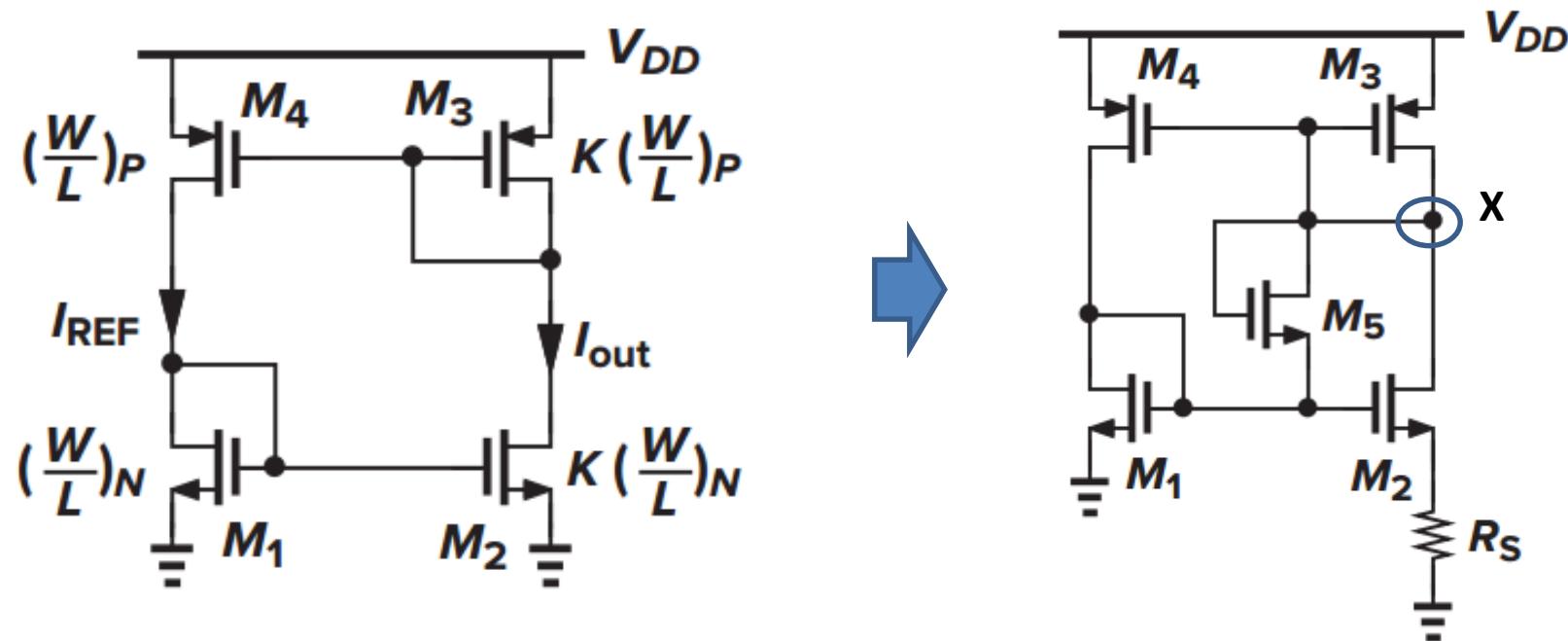
$$\frac{V_{DD} - V_X}{r_{O4}} + I_{out} R_3 g_{m4} = \frac{V_X}{R_1}$$

$$\frac{I_{out}}{V_{DD}} = \frac{1}{r_{O4}} \left[\frac{1}{G_{m2}(r_{O4} \parallel R_1)} - g_{m4} R_3 \right]^{-1}$$

$$G_{m2} = \frac{g_{m2} r_{O2}}{R_S + r_{O2} + (g_{m2} + g_{mb2}) R_S r_{O2}}$$

偏置与启动

- 解决“简并”偏置点的方法

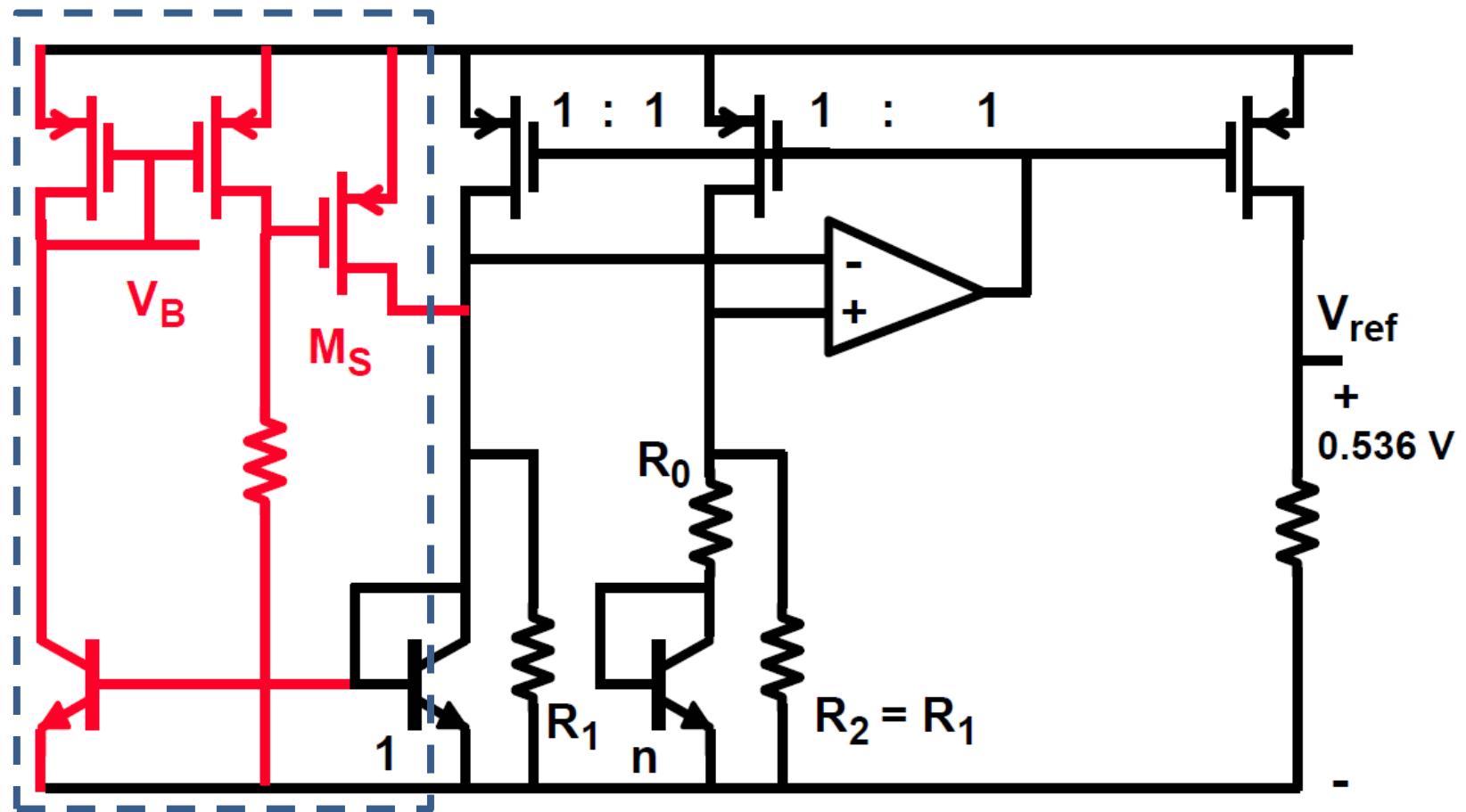


启动条件 $V_{TH1} + V_{TH5} + |V_{TH3}| < V_{DD}$

关闭条件 $V_{GS1} + V_{TH5} + |V_{GS3}| > V_{DD}$

偏置与启动

● 例



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- 基本原理
- 带隙基准电路
- PTAT电流
- 速度与噪声
- 带隙基准设计实例

基本原理

- 构造一个与温度无关的基准
- 采用两个具有相反温度系数电压源组合构成基准

$$V_{REF} = \alpha_1 V_1 + \alpha_2 V_2$$

$$\frac{\partial V_{REF}}{\partial T} = \alpha_1 \frac{\partial V_1}{\partial T} + \alpha_2 \frac{\partial V_2}{\partial T} = 0$$

基本原理

- 负温度系数电压

$$I_C = I_S \exp \frac{V_{BE}}{V_T}$$

$$\mu_i \propto \mu_0 T^m \quad m \approx -3/2$$

$$I_S \propto \mu_i k T n_i^2$$

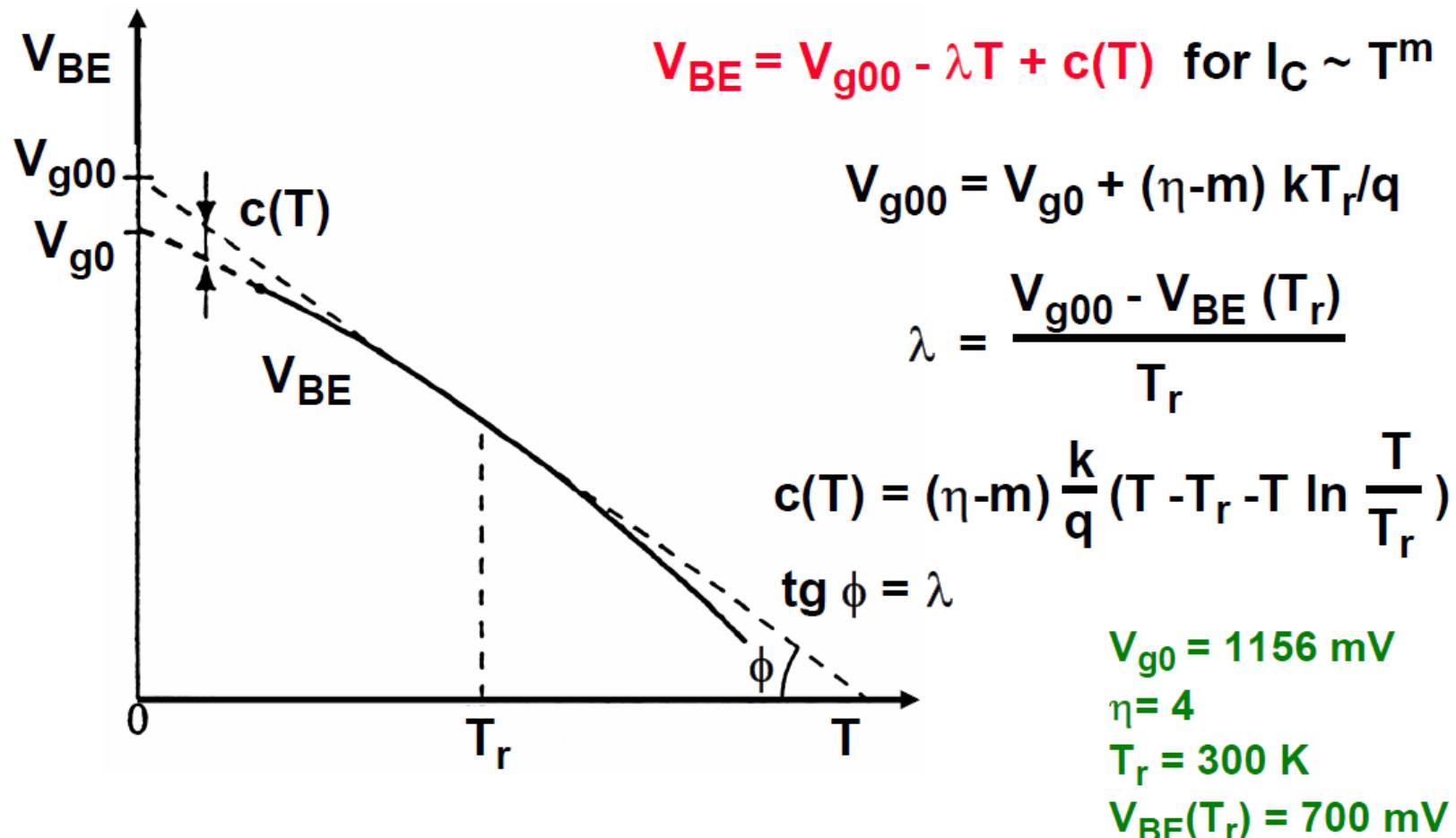
$$n_i^2 \propto T^3 \exp[-E_g/kT]$$

$$I_S = b T^{4+m} \exp \frac{-E_g}{kT}$$

$$\begin{aligned}\frac{\partial V_{BE}}{\partial T} &= \frac{V_{BE} - (4+m)V_T - E_g/q}{T} \\ &\approx -1.5 \text{mV/K}\end{aligned}$$

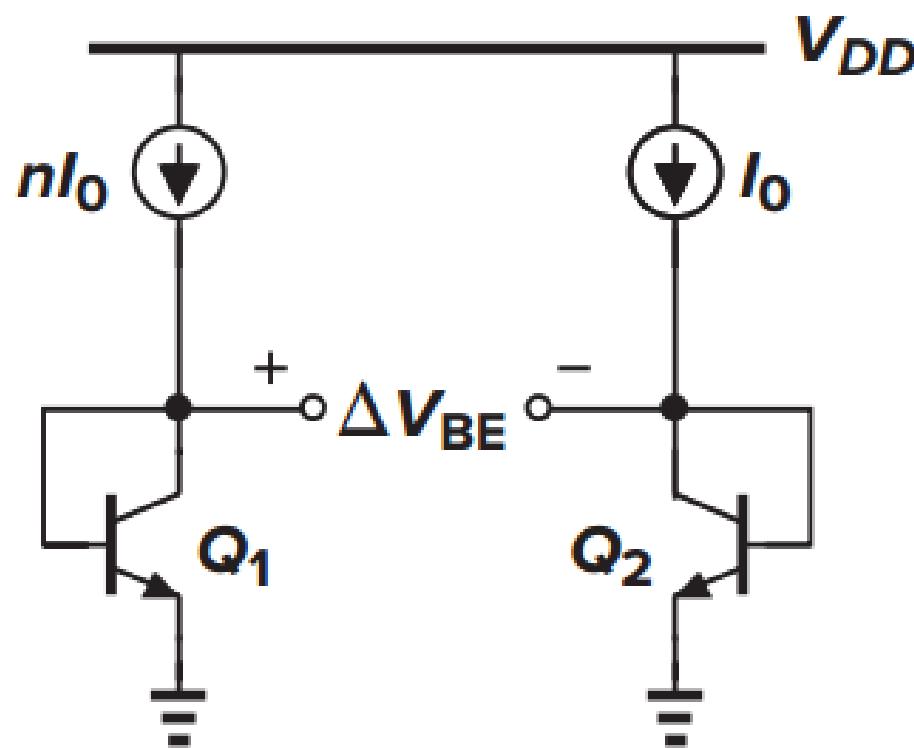
基本原理

● V_{BE} 与T的关系式



基本原理

- 正温度系数电压



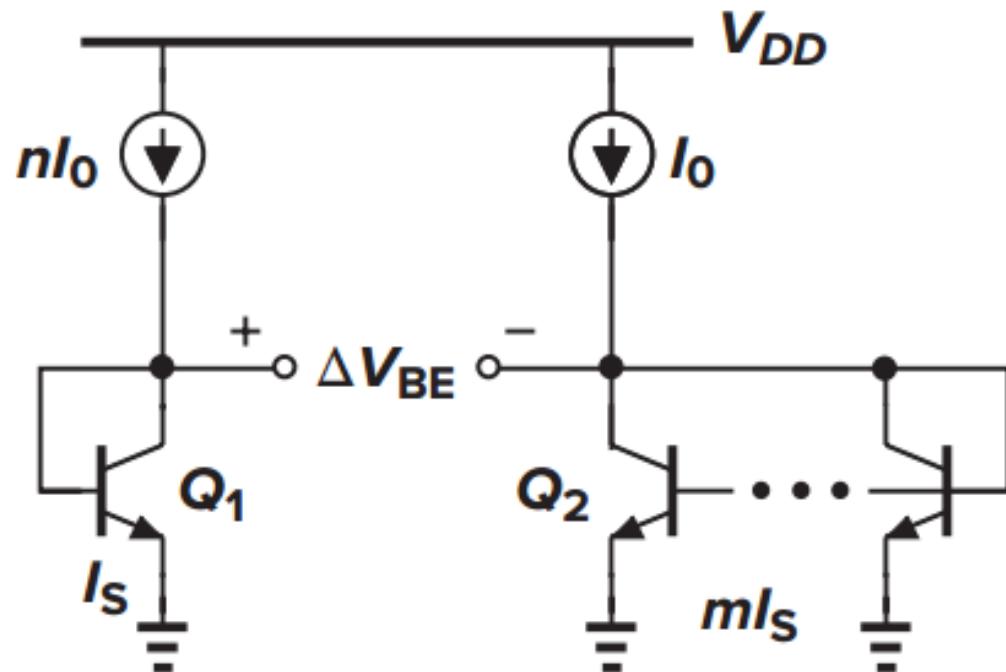
$$\begin{aligned}\Delta V_{BE} &= V_{BE1} - V_{BE2} \\ &= V_T \ln \frac{n I_0}{I_{S1}} - V_T \ln \frac{I_0}{I_{S2}} \\ &= V_T \ln n\end{aligned}$$

$$\frac{\partial \Delta V_{BE}}{\partial T} = \frac{k}{q} \ln n$$

当 $\frac{k}{q} \ln n = 1.5 \text{mV/K}$

$$\rightarrow \ln n \approx 17.2$$

基本原理

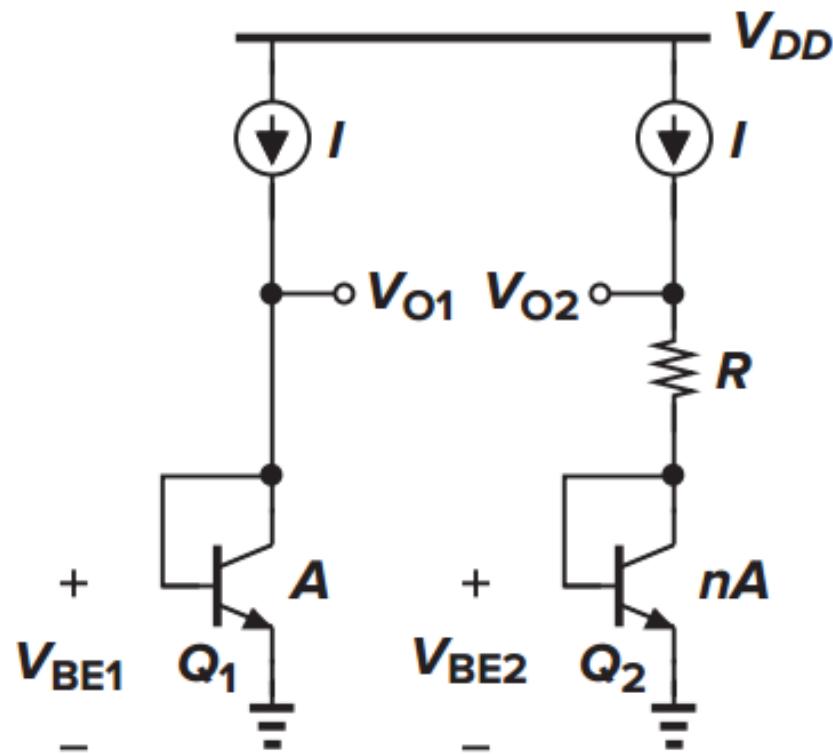


$$\Delta V_{BE} = V_T \ln \frac{nI_0}{I_S} - V_T \ln \frac{I_0}{mI_S}$$

$$= V_T \ln(nm)$$

基本原理

● 带隙基准原理图



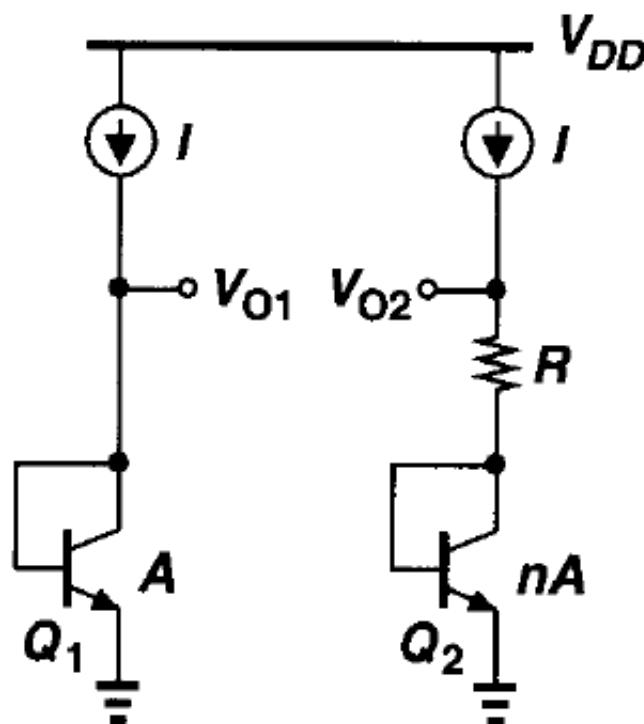
$$I_1 = I_2$$

$$V_{O1} = V_{O2}$$

$$V_{REF} = V_{O2} = V_{BE2} + V_T \ln n$$

基本原理

- 带隙基准电压



$$V_{REF} \approx V_{BE} + 17.2V_T \approx 1.25V$$

$$V_{REF} = \frac{E_g}{q} + (4 + m)V_T$$

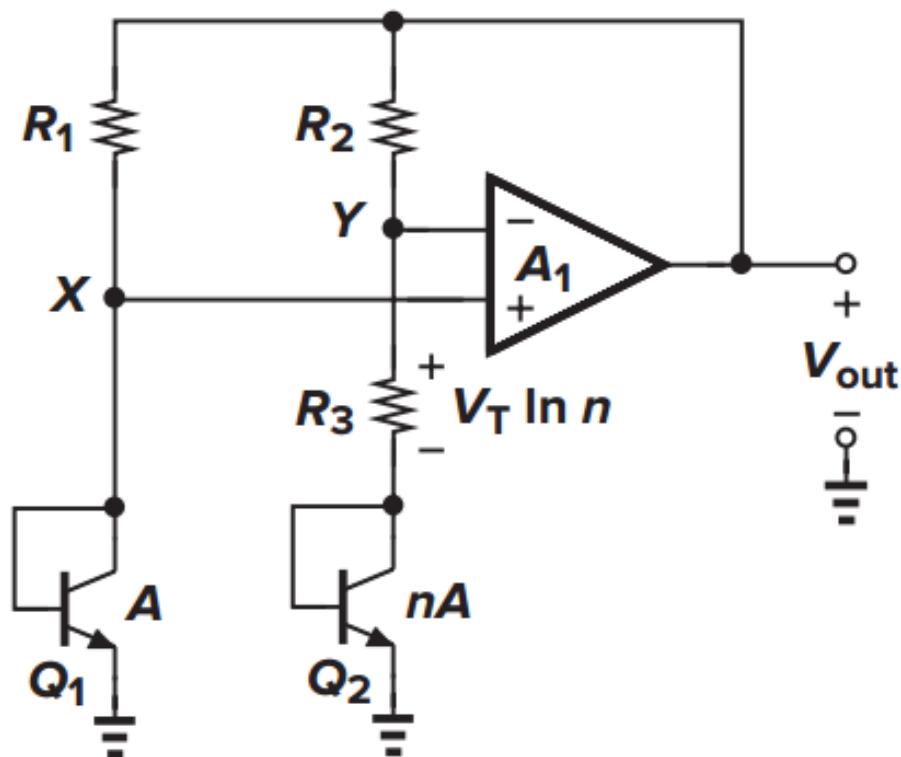
推导过程见书P468

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带隙基准电路

- 带隙基准实际电路图



$$V_X \approx V_Y$$

$$V_{out} = V_{BE2} + \frac{V_T \ln n}{R_3} (R_3 + R_2)$$

$$= V_{BE2} + (V_T \ln n) \left(1 + \frac{R_2}{R_3} \right)$$

带隙基准电路

- 集电极电流的影响

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T} \ln \frac{I_C}{I_S} + V_T \left(\frac{1}{I_C} \frac{\partial I_C}{\partial T} - \frac{1}{I_S} \frac{\partial I_S}{\partial T} \right)$$

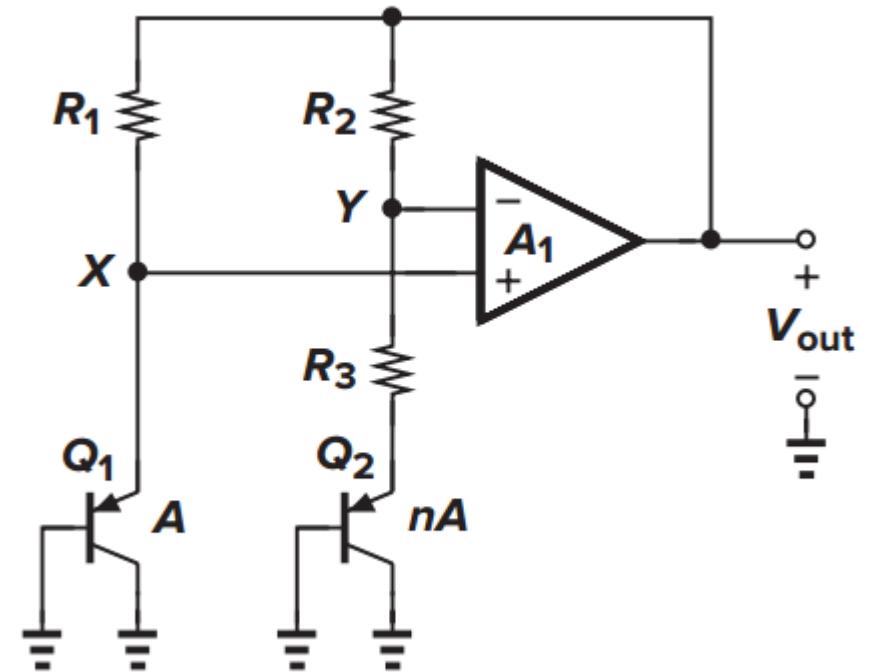
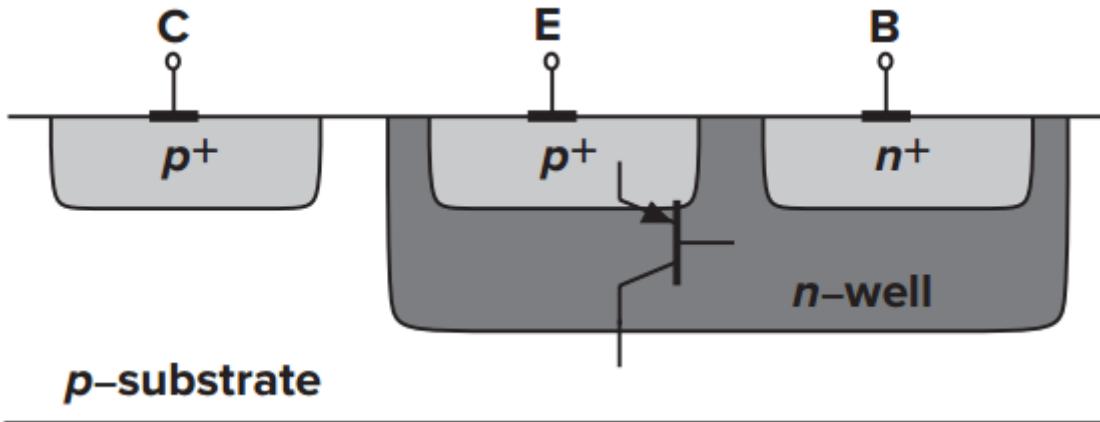
因为 $\partial I_C / \partial T \approx (V_T \ln n) / (R_3 T) = I_C / T$

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T} \ln \frac{I_C}{I_S} + \frac{V_T}{T} - \frac{V_T}{I_S} \frac{\partial I_S}{\partial T}$$

$$\frac{\partial V_{BE}}{\partial T} = \frac{V_{BE} - (3 + m)V_T - E_g/q}{T}$$

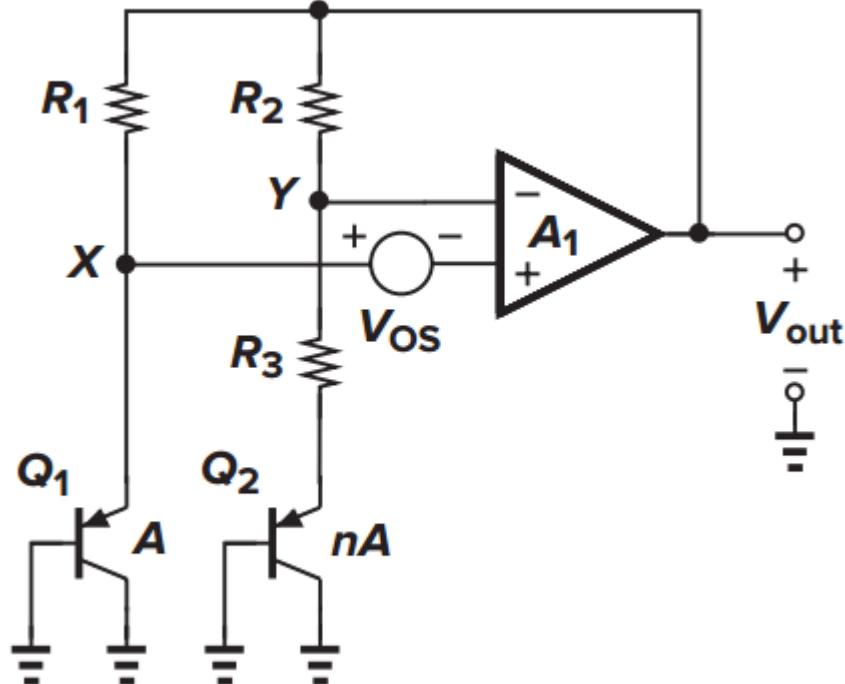
带隙基准电路

- 兼容CMOS工艺的PNP管



带隙基准电路

● 运放失调电压的影响



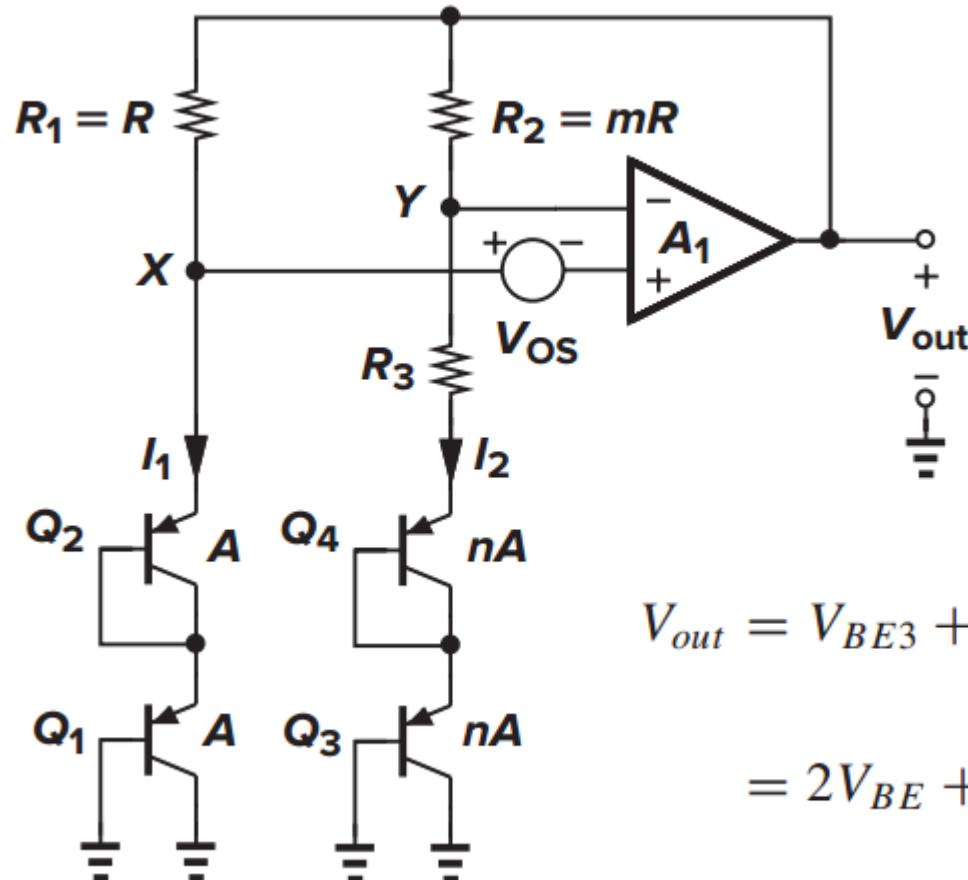
$$\begin{aligned}V_{out} &= V_{BE2} + (R_3 + R_2) \frac{V_{BE1} - V_{BE2} - V_{OS}}{R_3} \\&= V_{BE2} + \left(1 + \frac{R_2}{R_3}\right) (V_T \ln n - V_{OS})\end{aligned}$$

失调电压的影响:

- (1) 输出电压误差
- (2) 增大了温度系数
- (3) 需要自启动电路

带隙基准电路

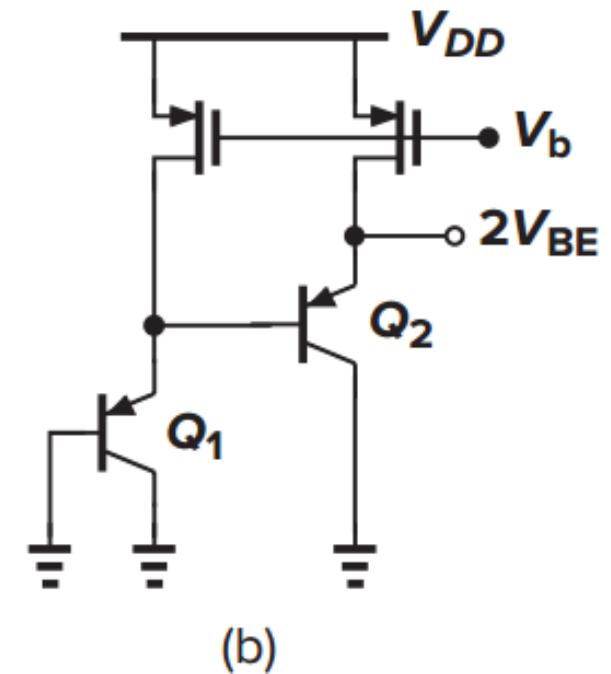
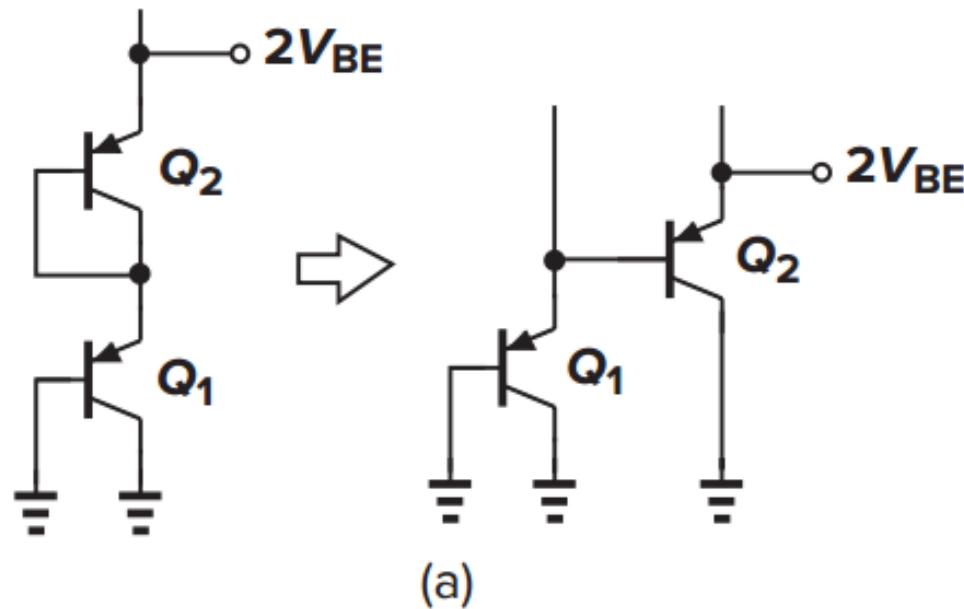
● 减小运放失调原理



$$\begin{aligned}V_{out} &= V_{BE3} + V_{BE4} + (R_3 + R_2) \frac{2V_T \ln(mn) - V_{OS}}{R_3} \\&= 2V_{BE} + \left(1 + \frac{R_2}{R_3}\right) [2V_T \ln(mn) - V_{OS}]\end{aligned}$$

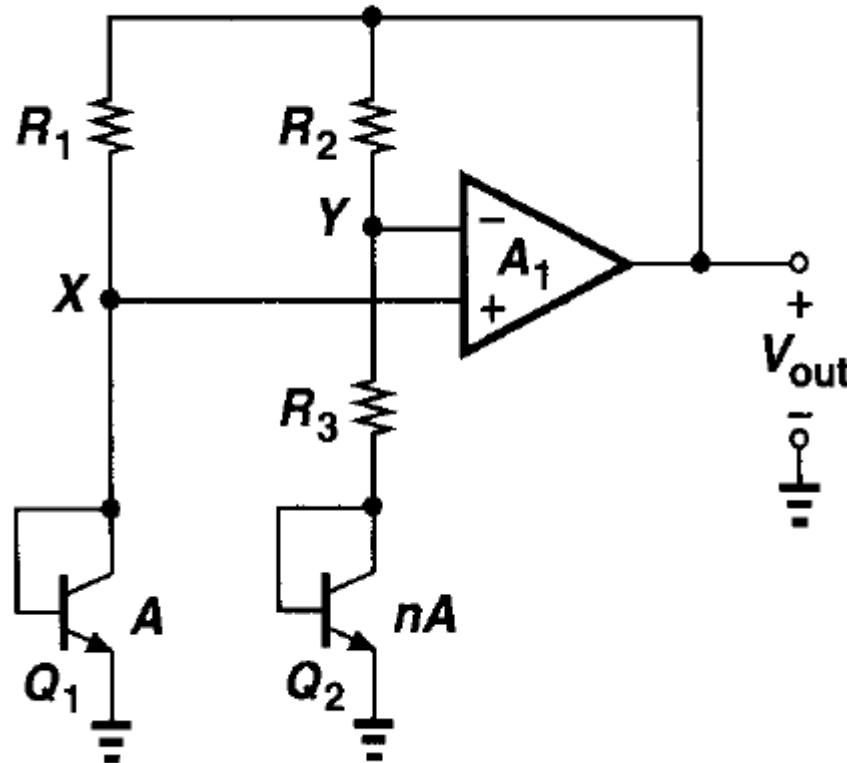
带隙基准电路

● 实际电路图



带隙基准电路

- 反馈极性（负反馈）



$$\beta_N = \frac{1/g_{m2} + R_3}{1/g_{m2} + R_3 + R_2}$$

$$\beta_P = \frac{1/g_{m1}}{1/g_{m1} + R_1}$$

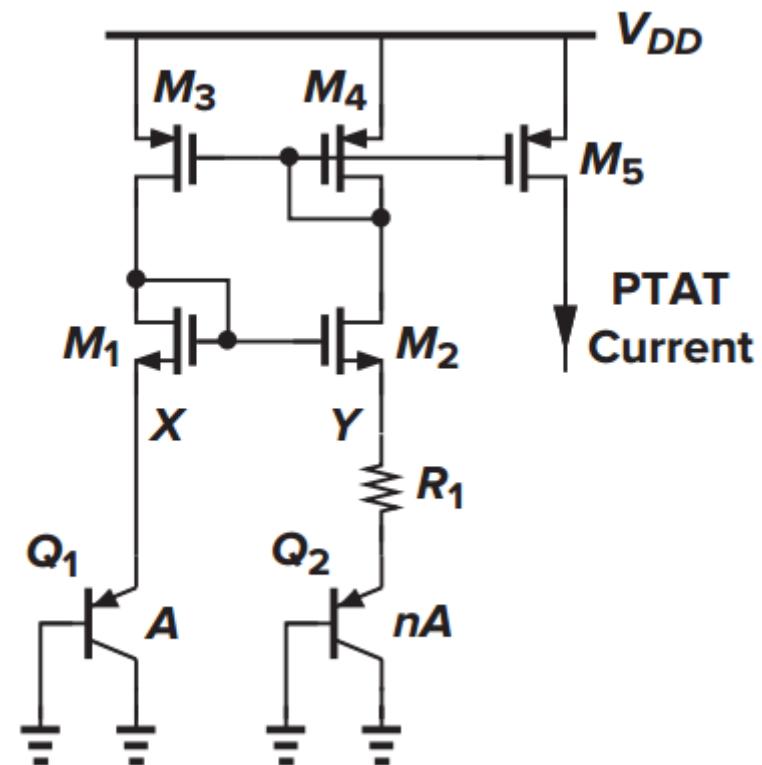
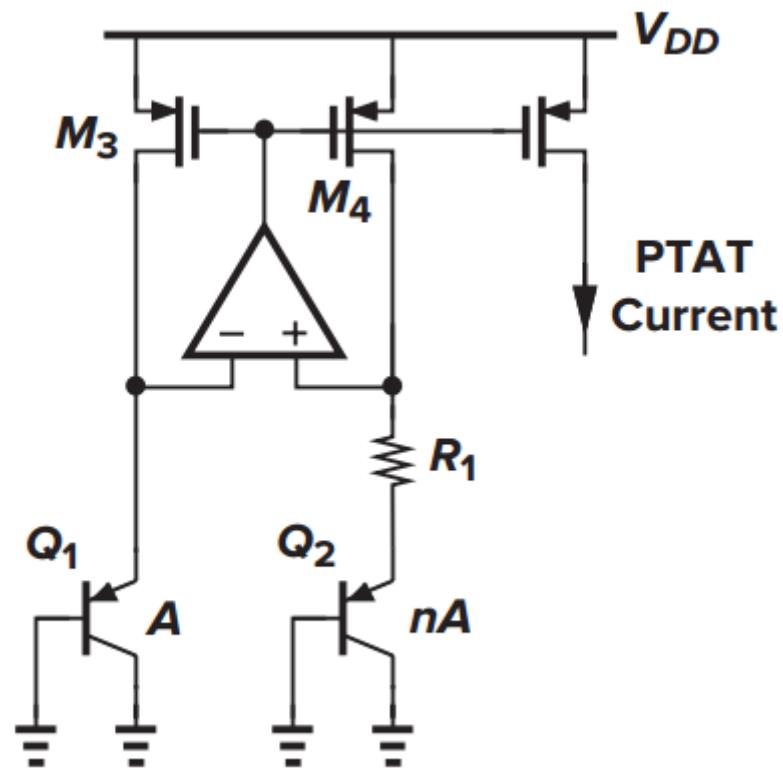
$$\beta_P < \beta_N, \beta_P \approx 1/2\beta_N$$

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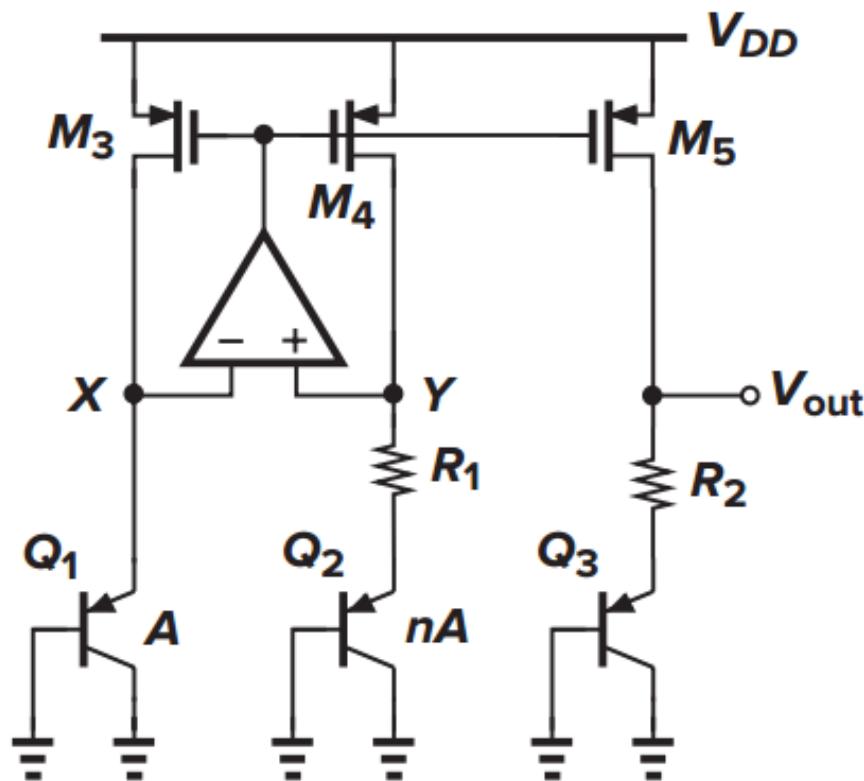
PTAT电流

● 电路图



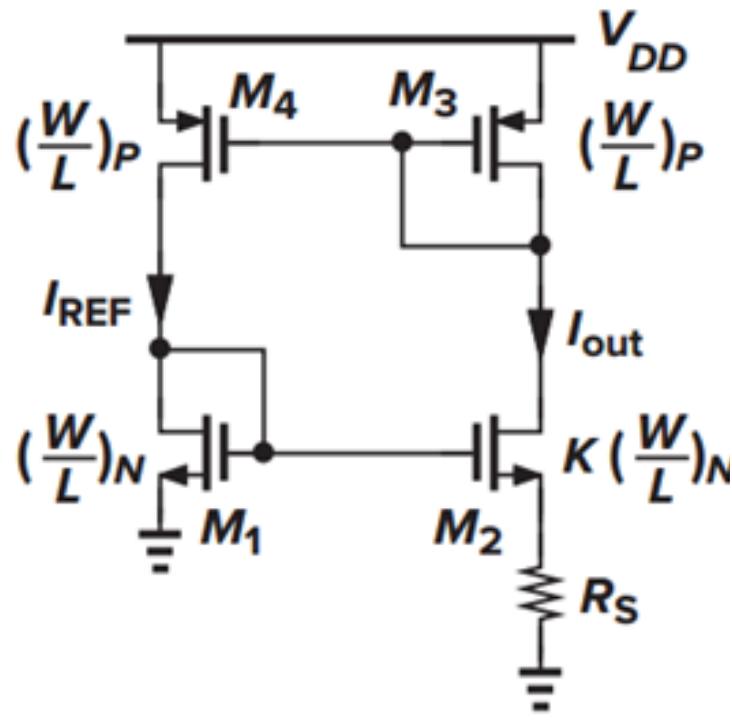
PTAT电流

- 与温度无关的电压



恒定G_m偏置

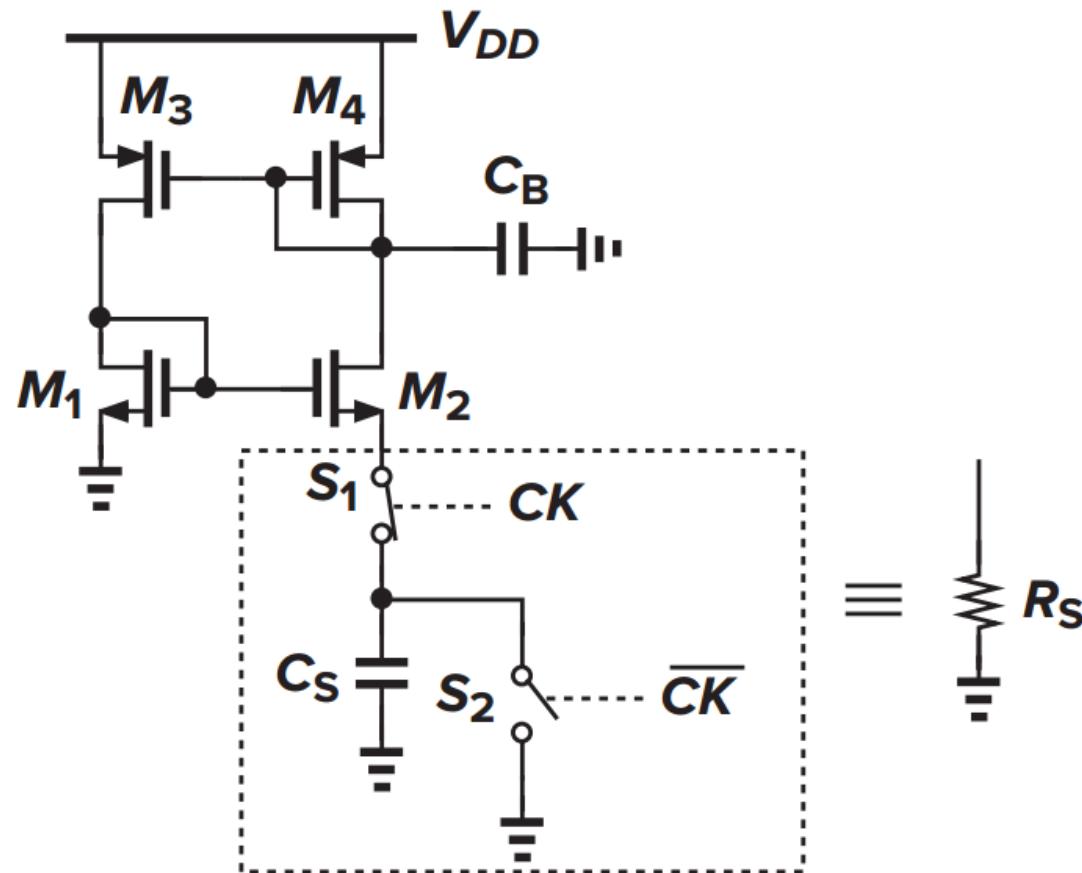
- 与电源无关偏置电路的跨导



$$I_{out} = \frac{2}{\mu_n C_{ox} (W/L)_N} \frac{1}{R_S^2} \left(1 - \frac{1}{\sqrt{K}} \right)^2$$
$$g_{m1} = \sqrt{2\mu_n C_{ox} \left(\frac{W}{L} \right)_N I_{D1}}$$
$$= \frac{2}{R_S} \left(1 - \frac{1}{\sqrt{K}} \right)$$

恒定 G_m 偏置

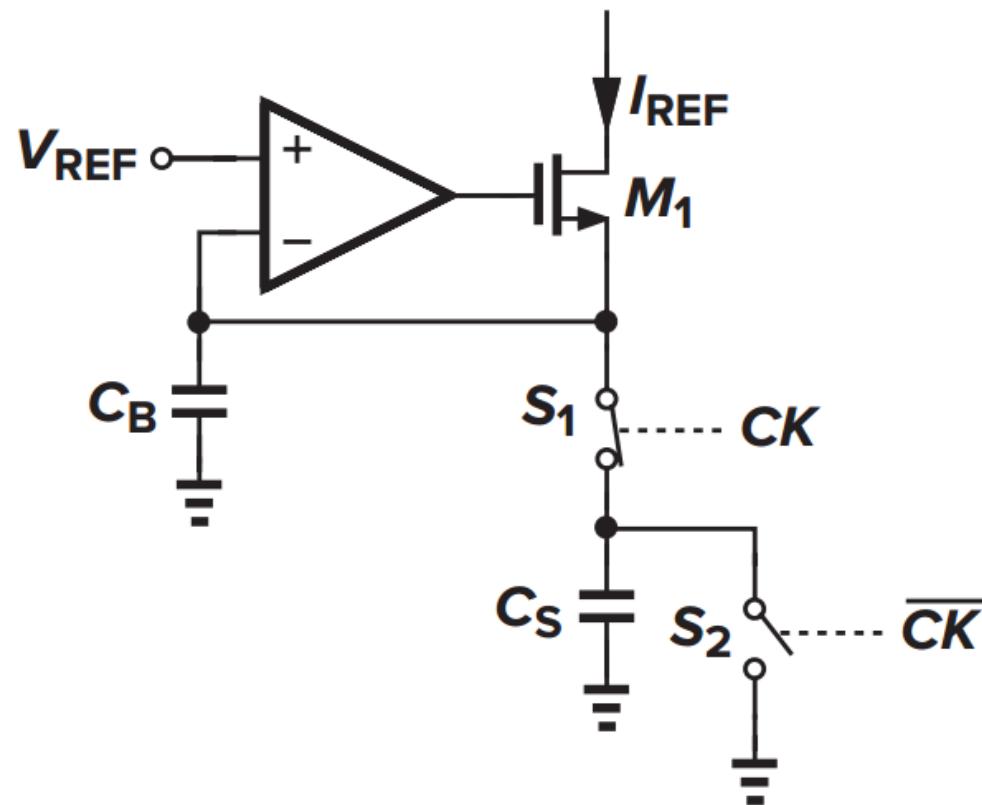
- 通过开关电容的“电阻”实现恒定的 G_m 偏置



$$\overline{R_s} = (C_s f_{CK})^{-1}$$

恒定 G_m 偏置

- 开关电容电路的应用

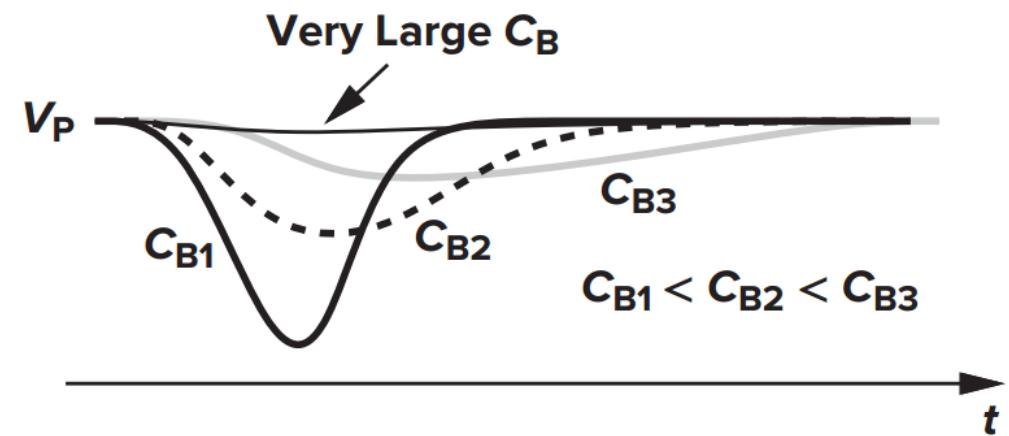
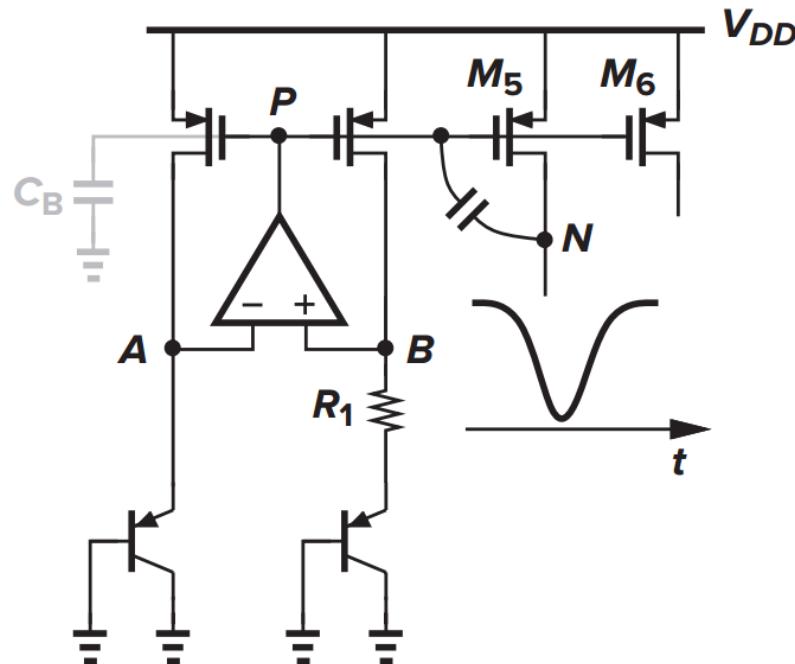


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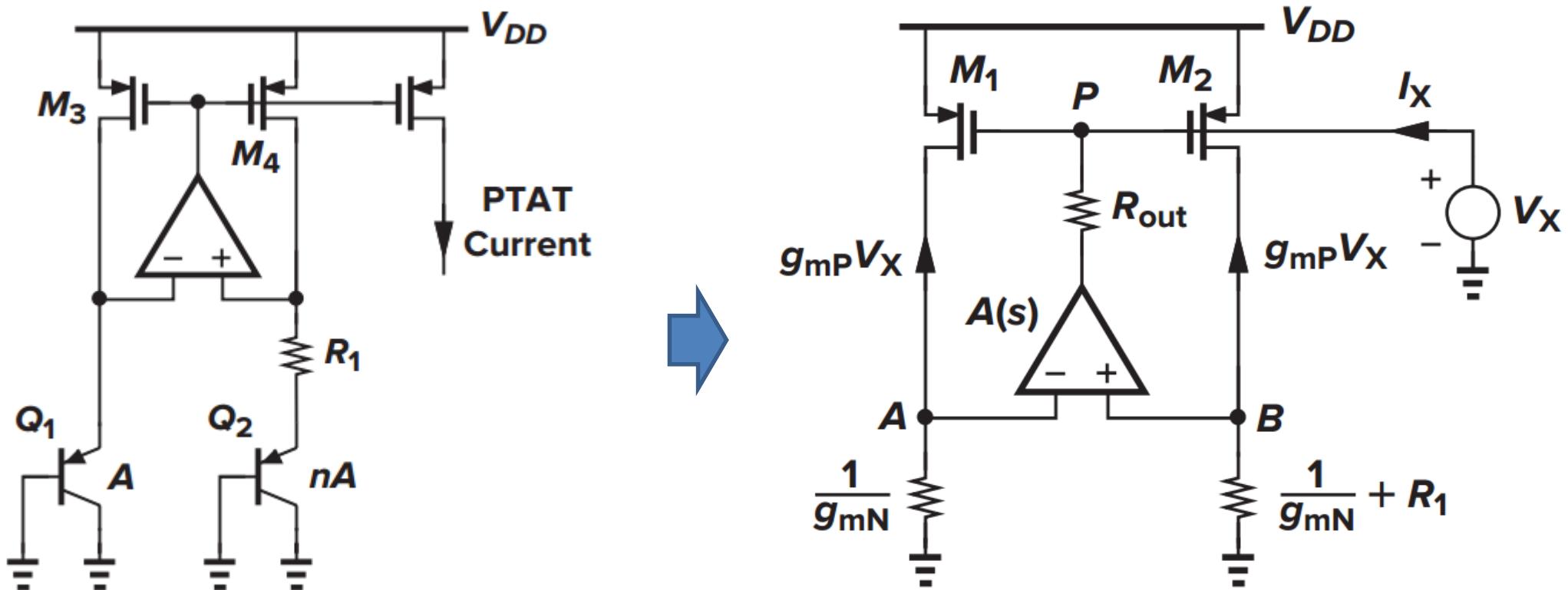
速度与噪声问题

- 基准电压和电流上的电路瞬变影响
 - “串扰”引起



速度与噪声问题

- 例：求输出阻抗和分析频率特性



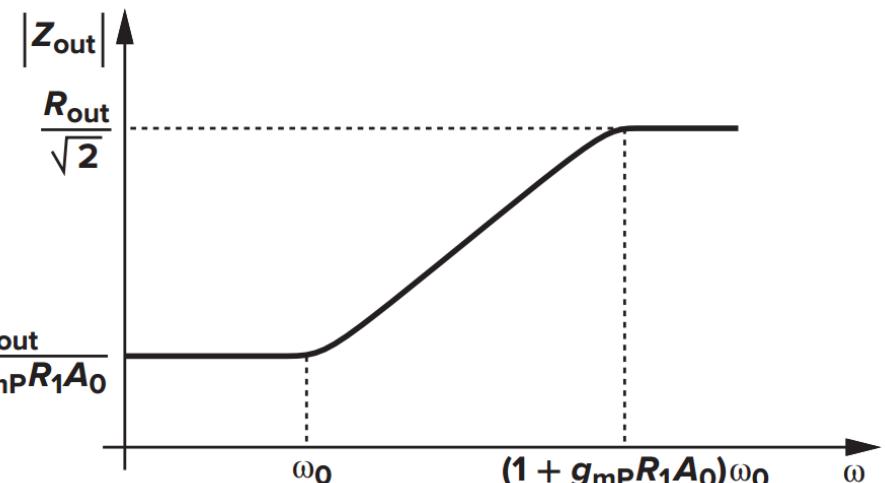
速度与噪声问题

● 例 (续) :

$$\begin{aligned} V_{AB} &= -g_{mP} V_X \frac{1}{g_{mN}} + g_{mP} V_X \left(\frac{1}{g_{mN}} + R_1 \right) \\ &= g_{mP} V_X R_1 \end{aligned}$$

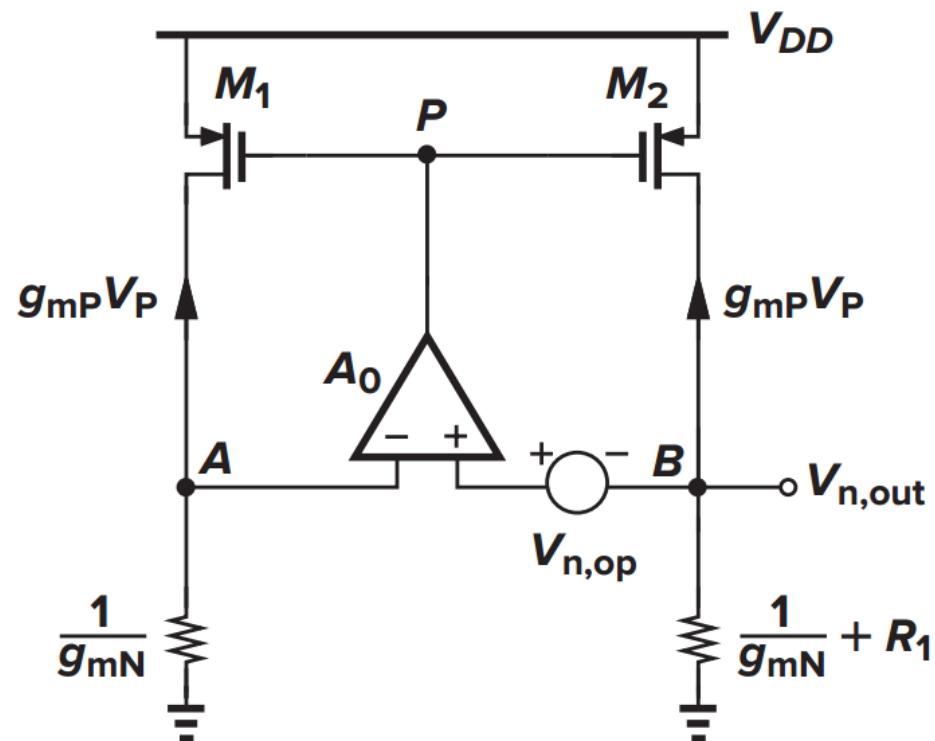
$$I_X = \frac{V_X + g_{mP} V_X R_1 A(s)}{R_{out}}$$

$$\frac{V_X}{I_X} = \frac{R_{out}}{1 + g_{mP} R_1 A_0} \frac{1 + \frac{s}{\omega_0}}{1 + \frac{s}{(1 + g_{mP} R_1 A_0) \omega_0}}$$



速度与噪声问题

● 计算基准发生器噪声



$$\frac{V_{n,out}}{R_1 + g_{mN}^{-1}} \cdot \frac{1}{g_{mN}} - \frac{V_{n,out}}{g_{mP}A_0(R_1 + g_{mN}^{-1})} = V_{n,op} + V_{n,out}$$

$$V_{n,out} \left[\frac{1}{R_1 + g_{mN}^{-1}} \left(\frac{1}{g_{mN}} - \frac{1}{g_{mP}A_0} \right) - 1 \right] = V_{n,op}$$

$$g_{mP}A_0 \gg g_{mN} \gg R_1^{-1}$$

$$|V_{n,out}| \approx V_{n,op}$$

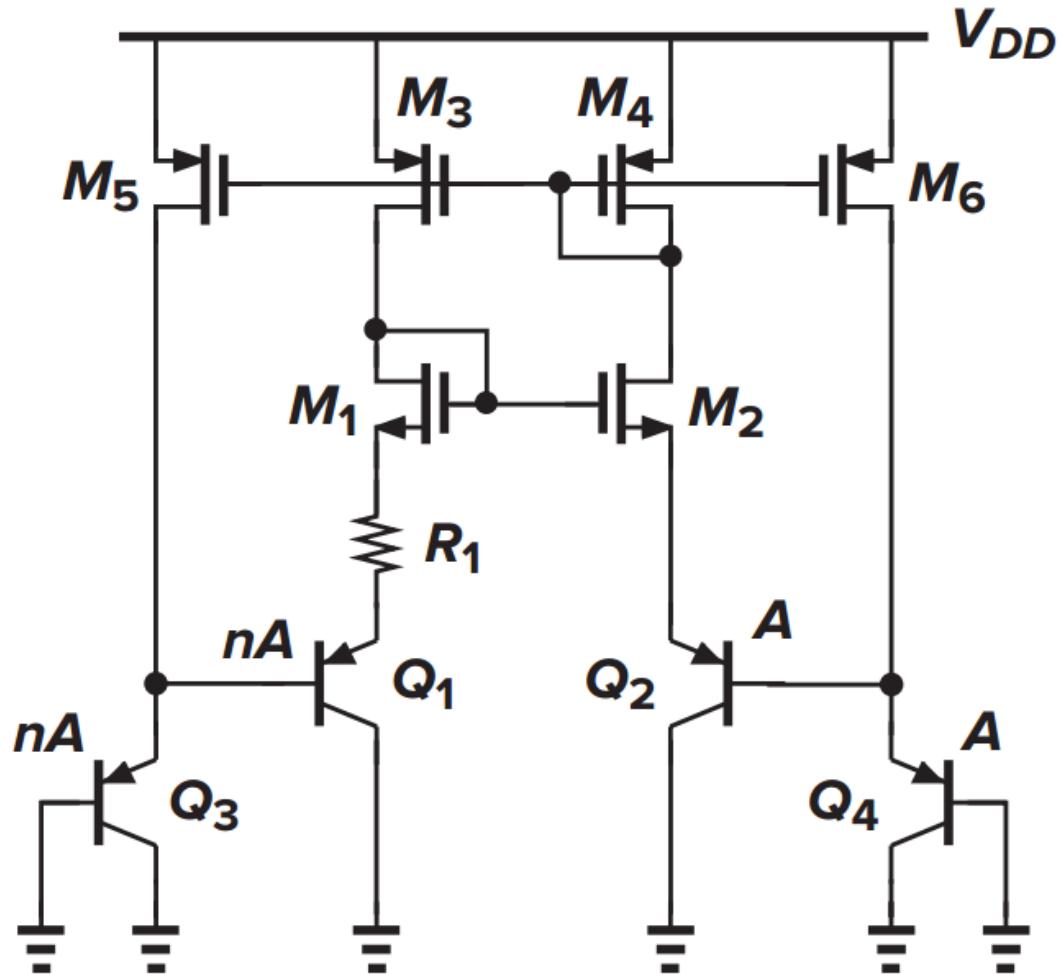
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带隙基准设计实例

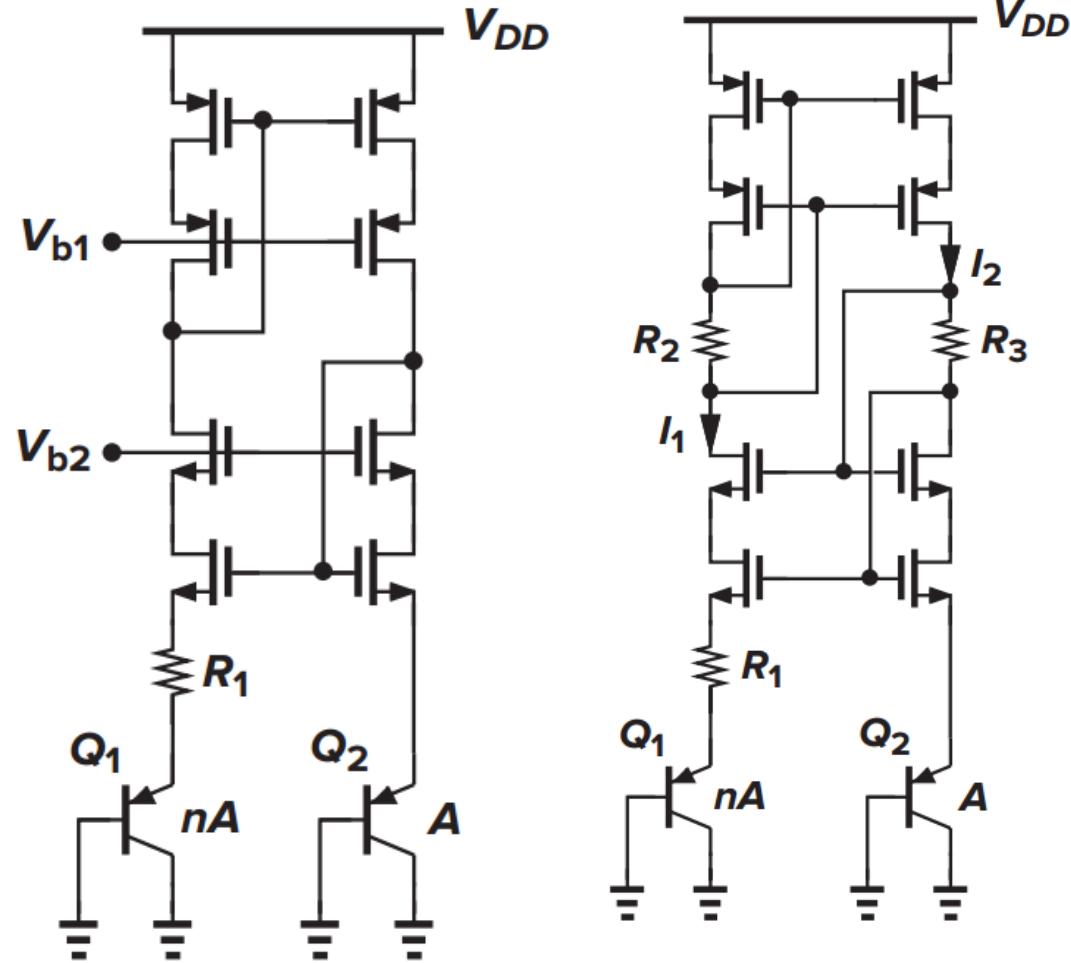
- 例1

- 电路原理



带隙基准设计实例

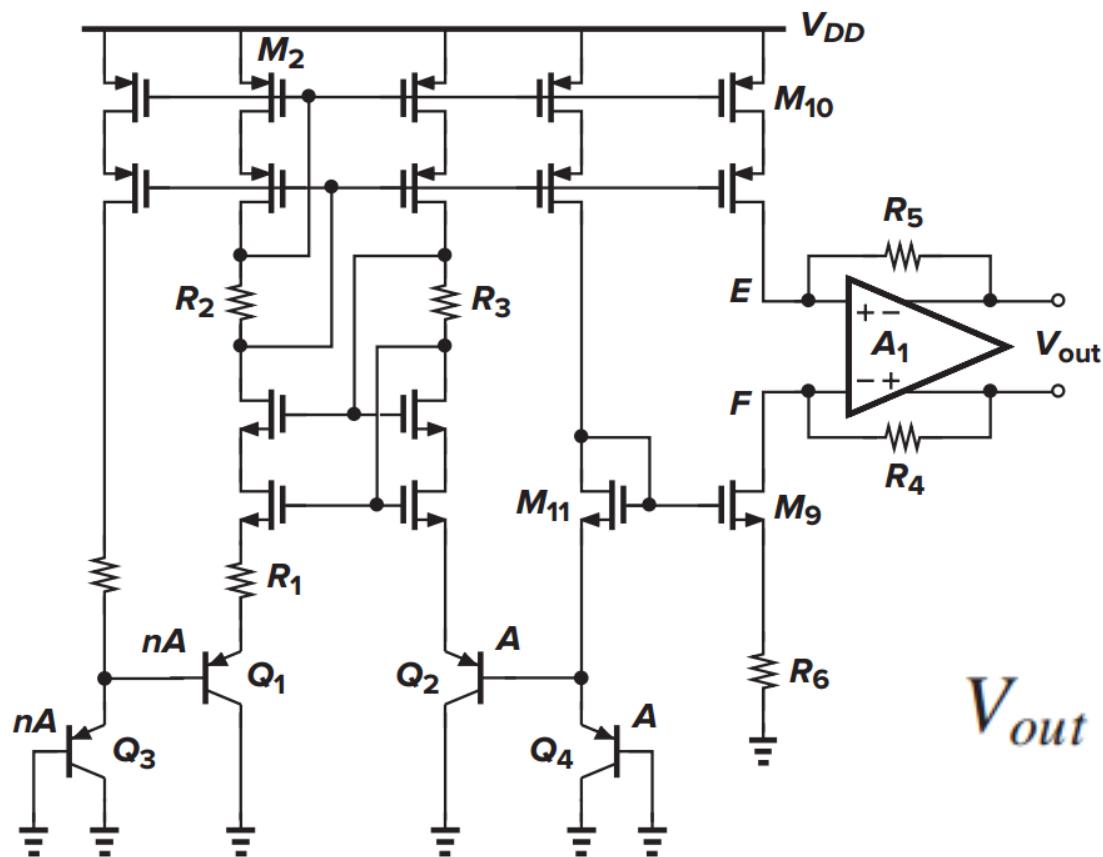
- 例1
- 电流镜设计



带隙基准设计实例

● 例1

● 浮动基准电压的产生

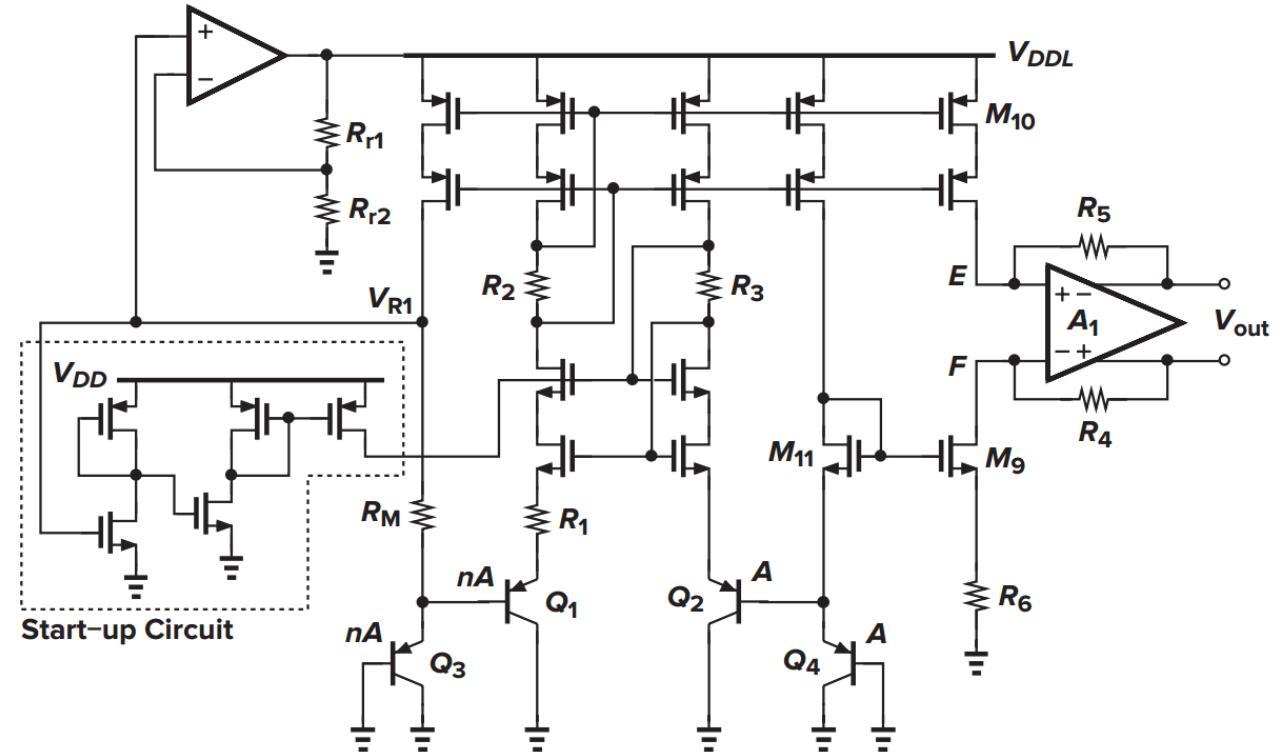
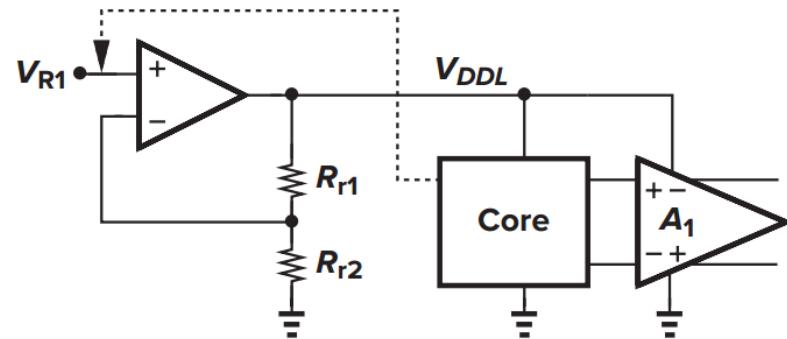


$$V_{out} = \frac{R_4}{R_6} V_{BE4} + 2 \frac{R_5}{R_1} V_T \ln n$$

带隙基准设计实例

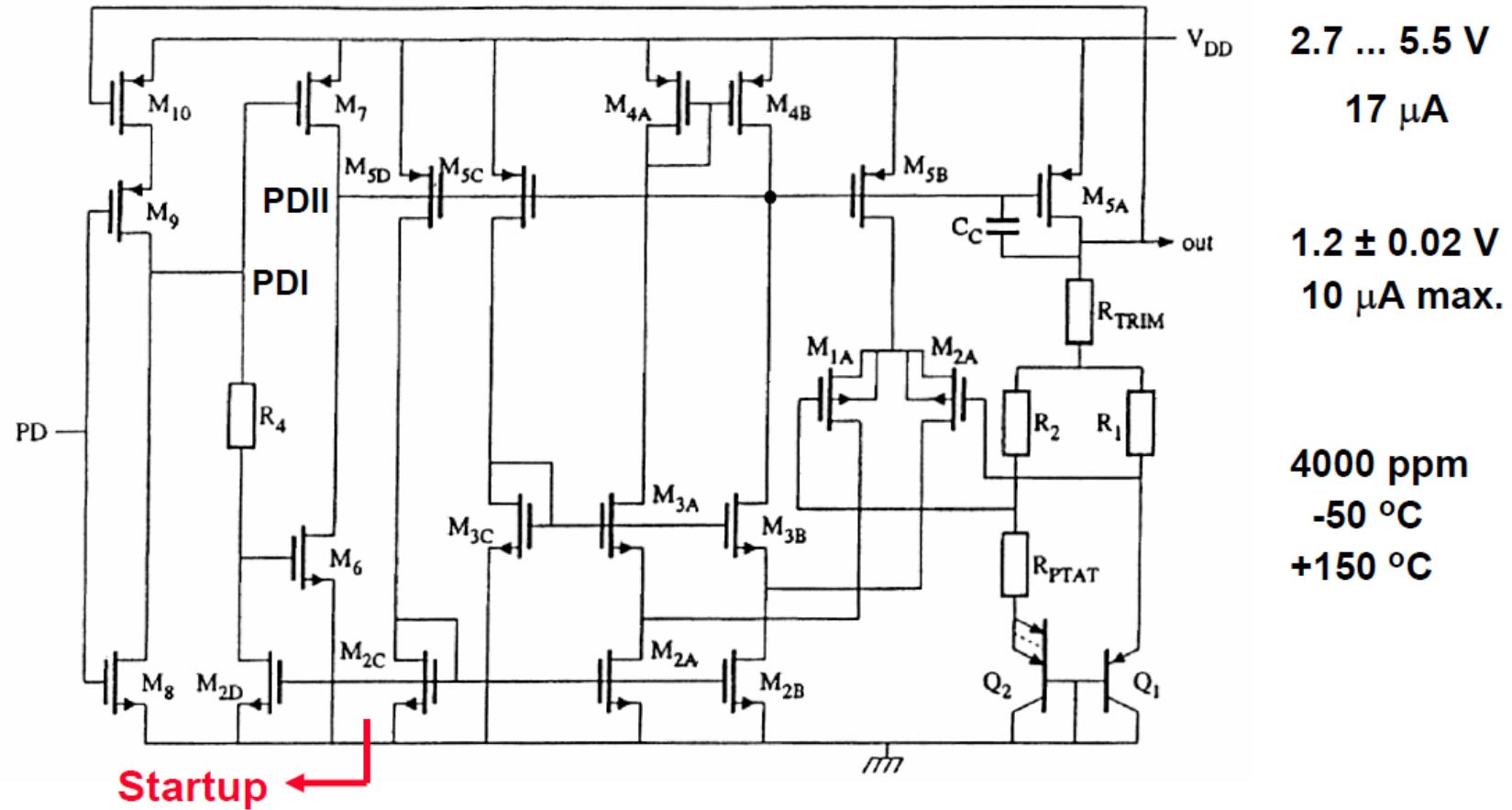
- 例1

- 为提高电源抑制而调节运放和核心电路的电源电压



带隙基准设计实例

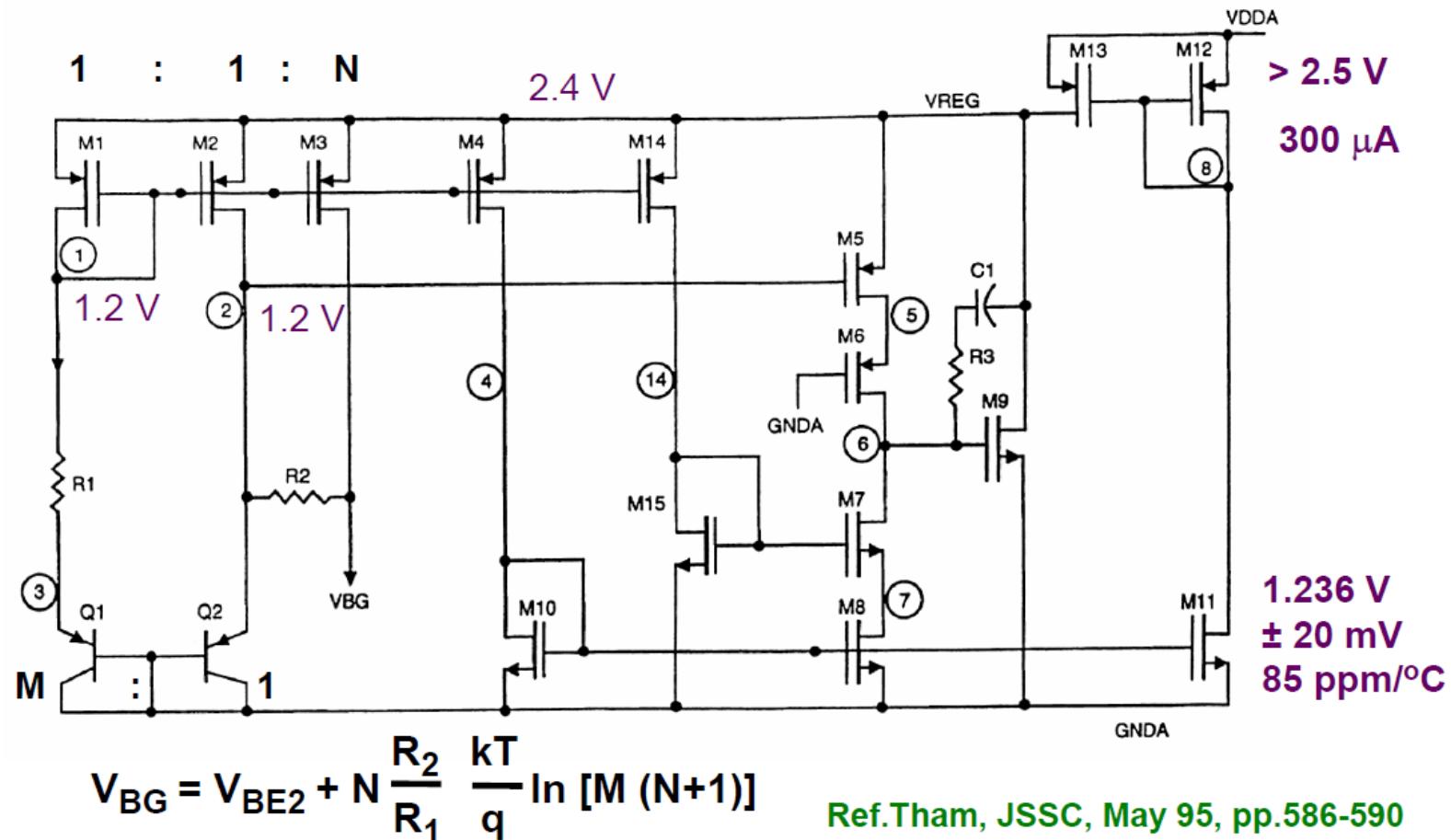
● 例2



Ref. MIETEC; Meijer, ACD, Kluwer 1995

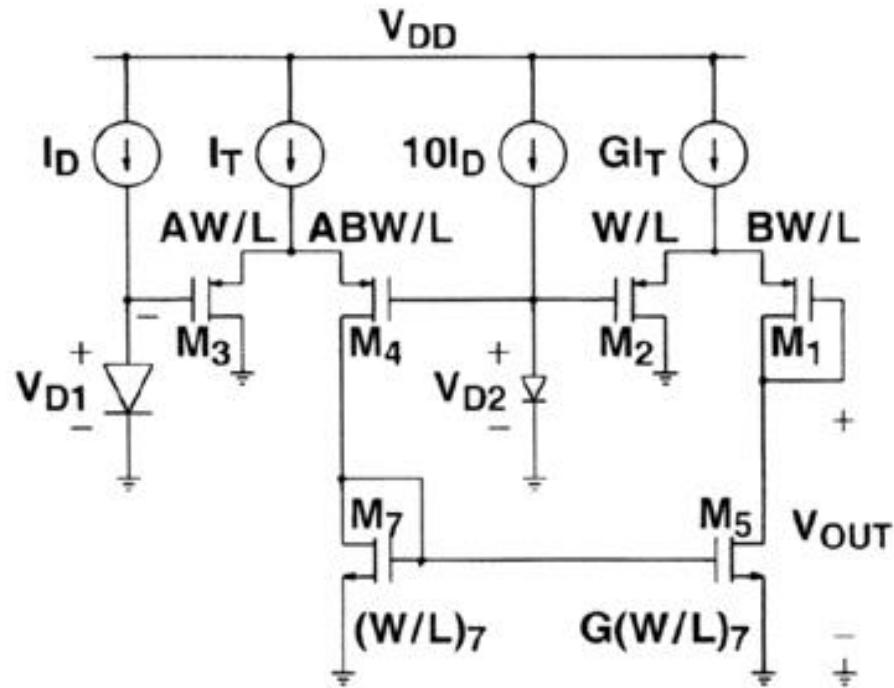
带隙基准设计实例

● 例3 高电源抑制比的基准



带隙基准设计实例

● 例4 不带电阻的基准



$$\Delta V_D = V_{D2} - V_{D1}$$

$$V_{OUT} = V_{D2} + \sqrt{AG}\Delta V_D$$

$$V_{OUT} \approx 1.12V$$

$$A = 1.5$$

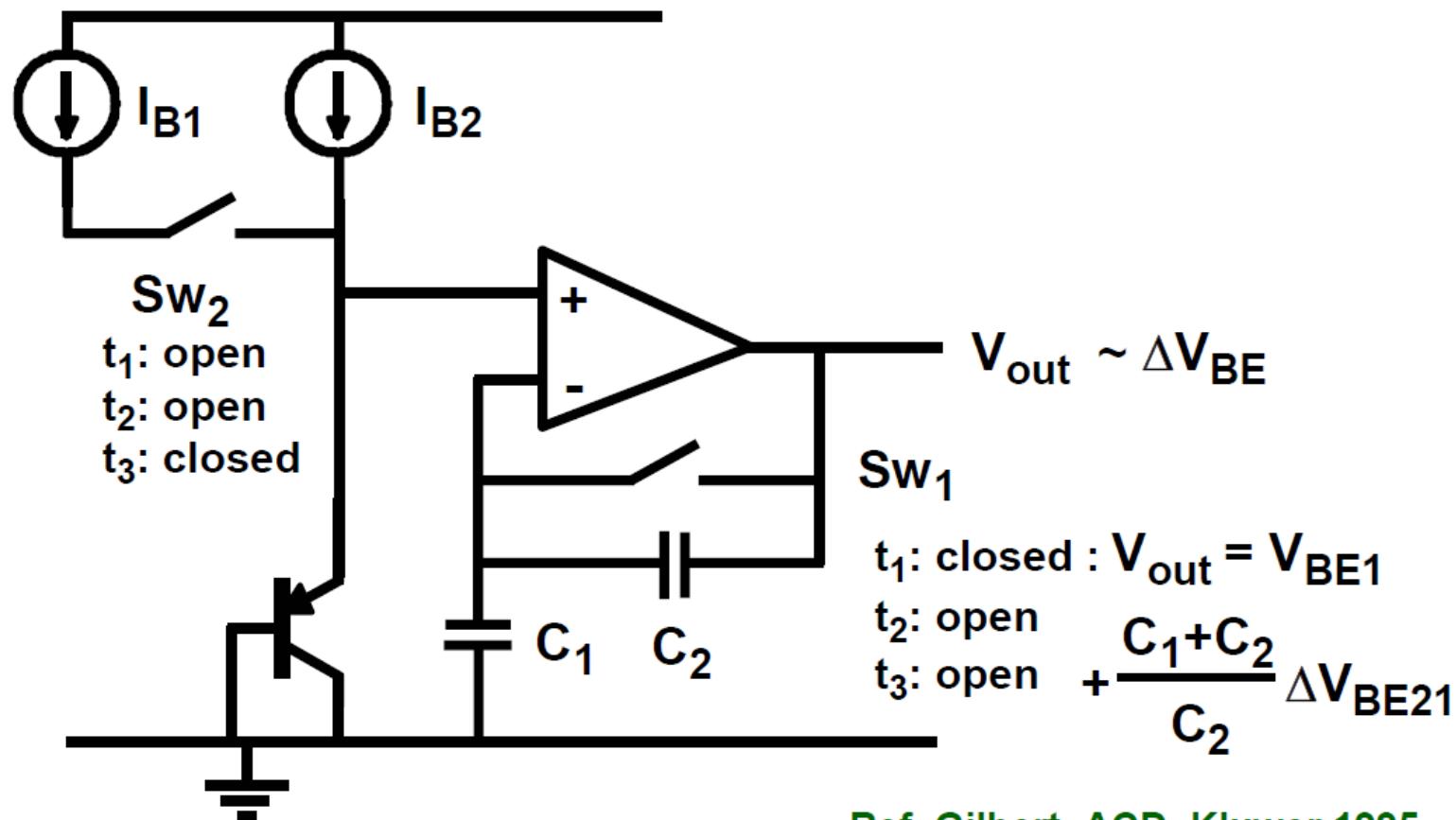
$$B = 4$$

$$G = 6$$

$$AD1/AD2 = 8$$

带隙基准设计实例

● 例5 单结基准源



作业

- 12.7 12.10 12.19

本章结束