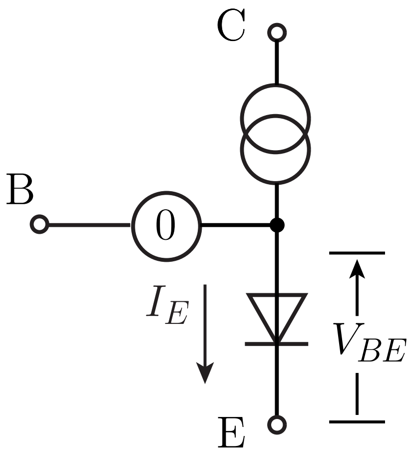
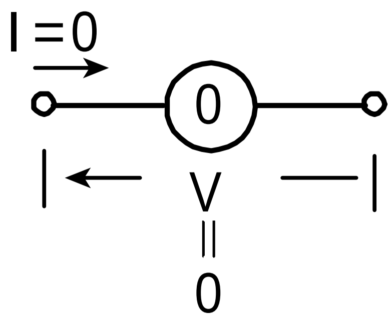
差動増幅回路の大信号特性と OTA(電圧制御電流源回路)

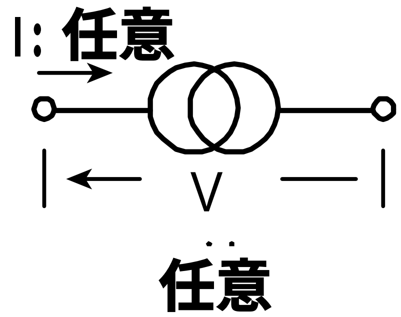
バイポーラ差動増幅回路の大信号特性

バイポーラトランジスタのモデル (大信号モデル)





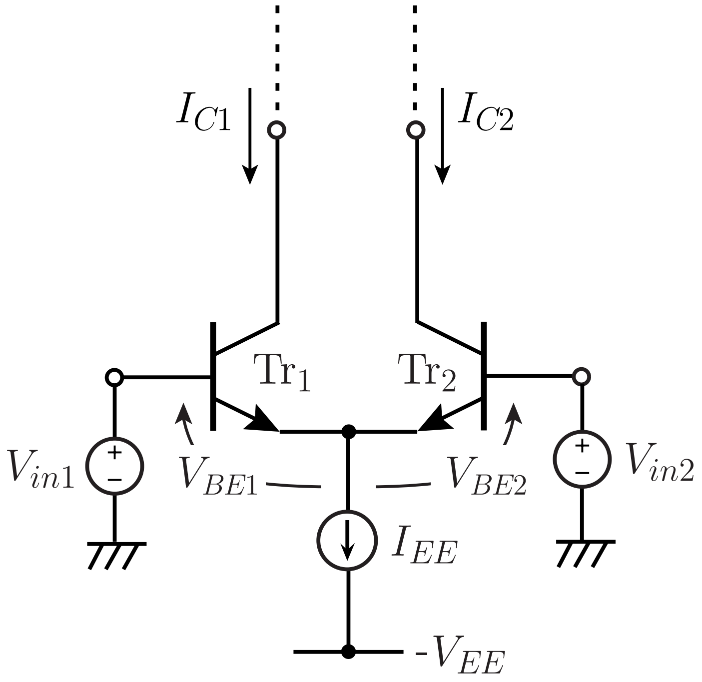
(a) ナレータ



(b) ノレータ

$$I_E = I_{ES}\exp\left(\frac{qV_{BE}}{kT}\right) \qquad I_C = I_E$$

バイポーラ差動増幅回路



$$V_{in1} - V_{BE1} + V_{BE2} - V_{in2} = 0$$

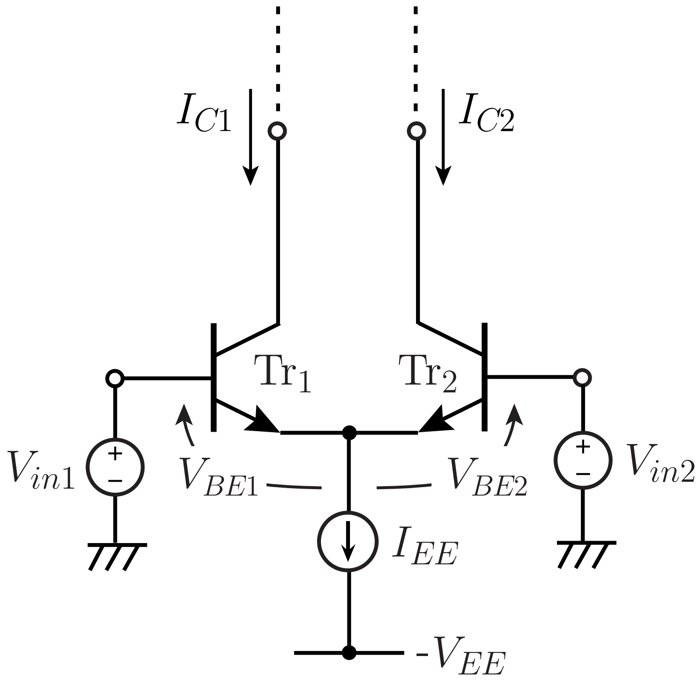
$$\Delta V_{in} = V_{in1} - V_{in2} = V_{BE1} - V_{BE2}$$

$$V_{BEi} = \frac{kT}{q} \ln\left(\frac{I_{Ei}}{I_{ES}}\right)$$

$$I_{Ci} = I_{Ei}$$

$$\Delta V_{in} = \frac{kT}{q} \ln\left(\frac{I_{E1}}{I_{ES}}\right) - \frac{kT}{q} \ln\left(\frac{I_{E2}}{I_{ES}}\right)$$

$$= \frac{kT}{q} \ln\left(\frac{I_{E1}}{I_{E2}}\right)$$



$$\frac{I_{E1}}{I_{E2}}=\exp\left(\frac{q\Delta V_{in}}{kT}\right)$$

$$I_{E1}+I_{E2}=I_{EE}$$

$$I_{E1}=\frac{I_{EE}}{1+\exp\left(\frac{-q\Delta V_{in}}{kT}\right)}$$

$$I_{E2}=\frac{I_{EE}}{1+\exp\left(\frac{+q\Delta V_{in}}{kT}\right)}$$

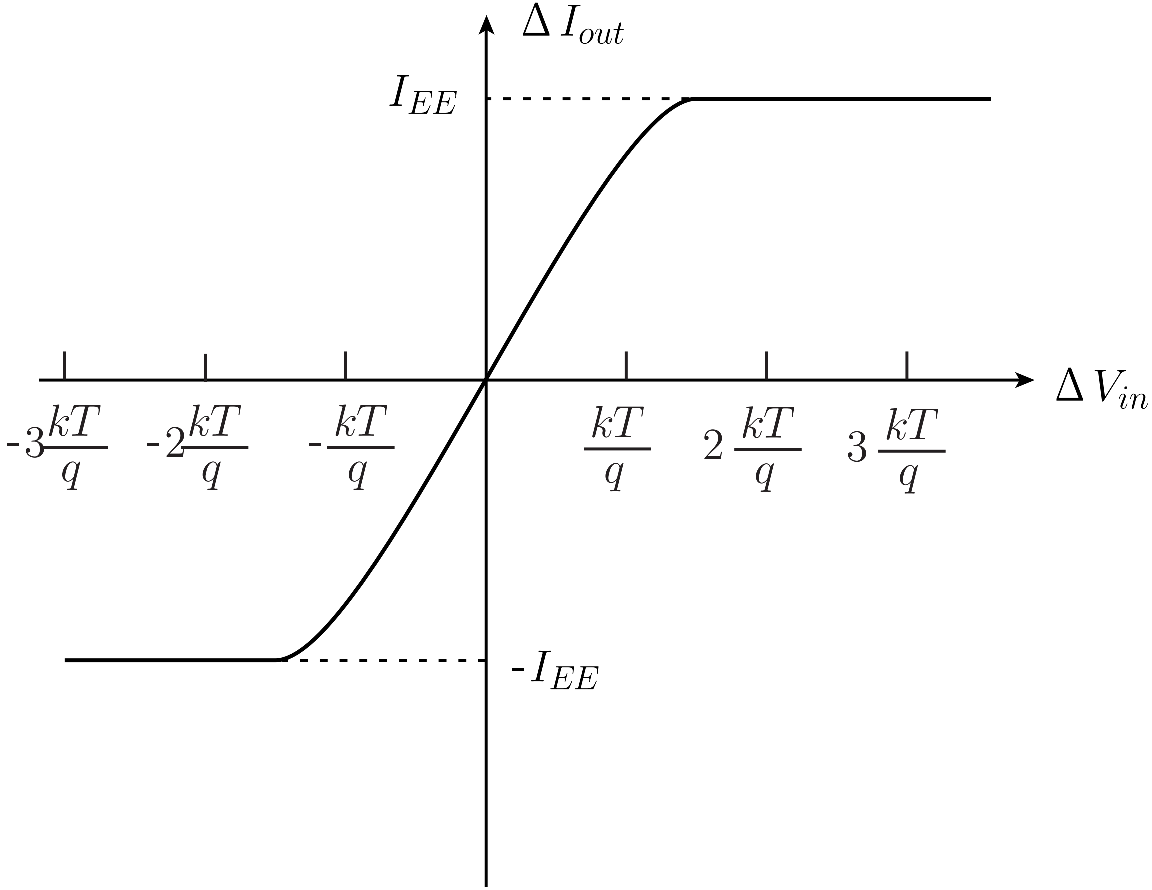
$$I_{E1} = \frac{I_{EE}}{1+\exp\left(\frac{-q\Delta V_{in}}{kT}\right)} \qquad I_{E2} = \frac{I_{EE}}{1+\exp\left(\frac{+q\Delta V_{in}}{kT}\right)}$$

$$\Delta I_{out} = I_{C1} - I_{C2} = I_{E1} - I_{E2}$$

$$= I_{EE}\left(\frac{1-\exp\left(\frac{-q\Delta V_{in}}{kT}\right)}{1+\exp\left(\frac{-q\Delta V_{in}}{kT}\right)}\right)$$

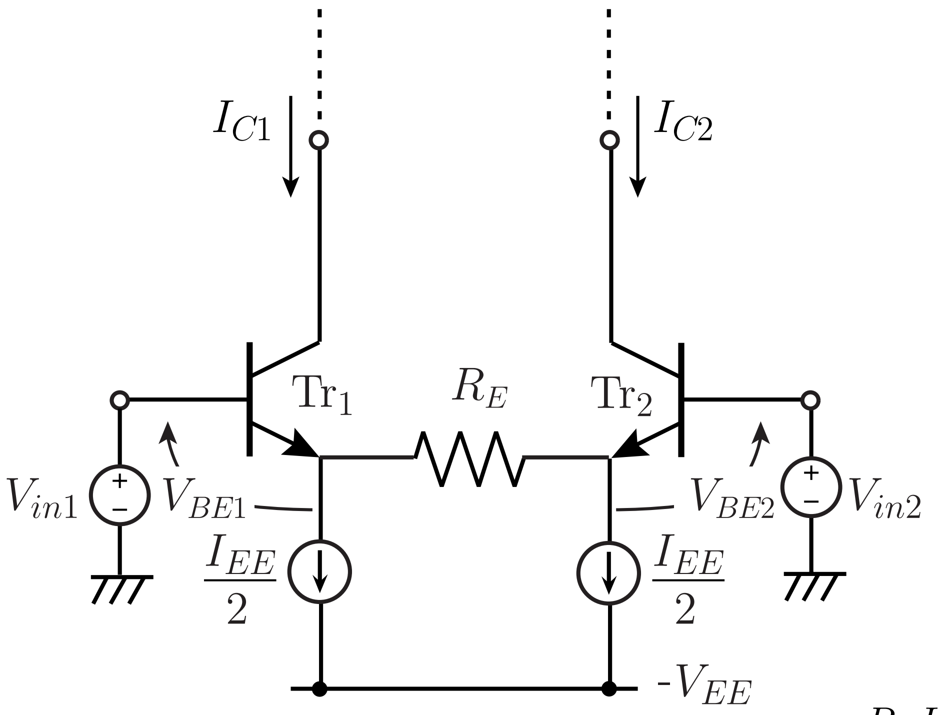
$$= I_{EE}\left(\frac{\exp\left(\frac{q\Delta V_{in}}{2kT}\right)-\exp\left(\frac{-q\Delta V_{in}}{2kT}\right)}{\exp\left(\frac{q\Delta V_{in}}{2kT}\right)+\exp\left(\frac{-q\Delta V_{in}}{2kT}\right)}\right) = I_{EE}\tanh\left(\frac{q\Delta V_{in}}{2kT}\right)$$

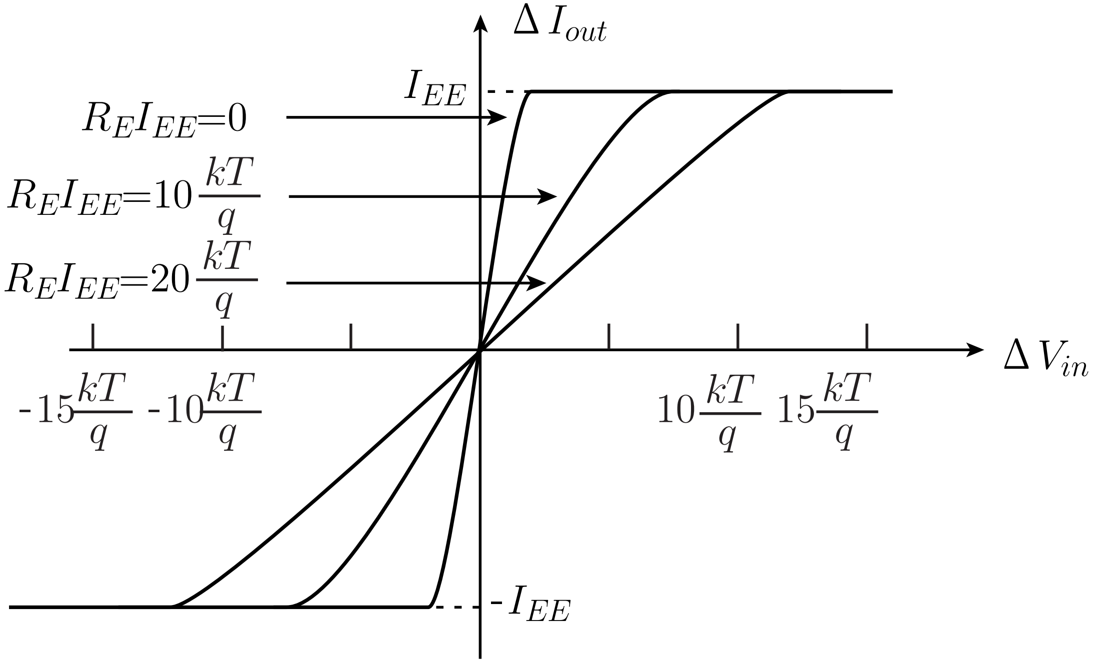
バイポーラ差動増幅回路の大信号特性



線形範囲：数十mV程度

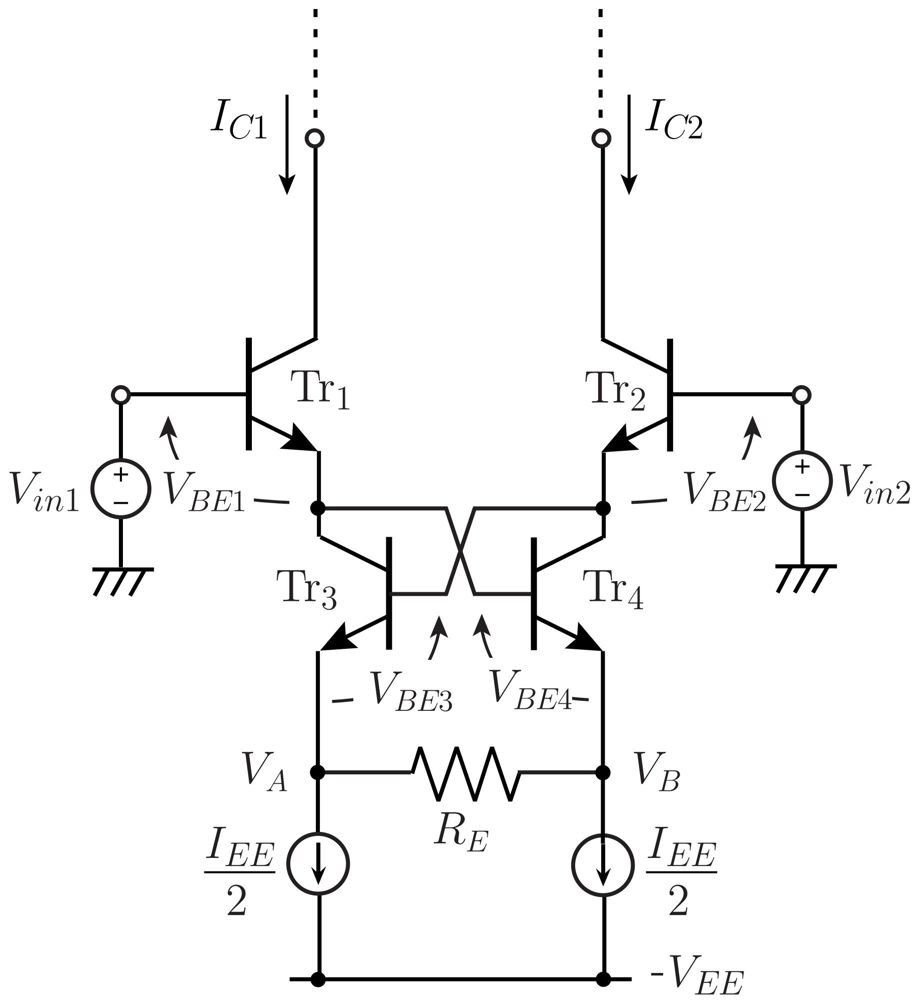
線形入力範囲の拡大





伝達コンダクタンスの低減

Caprio's Quad



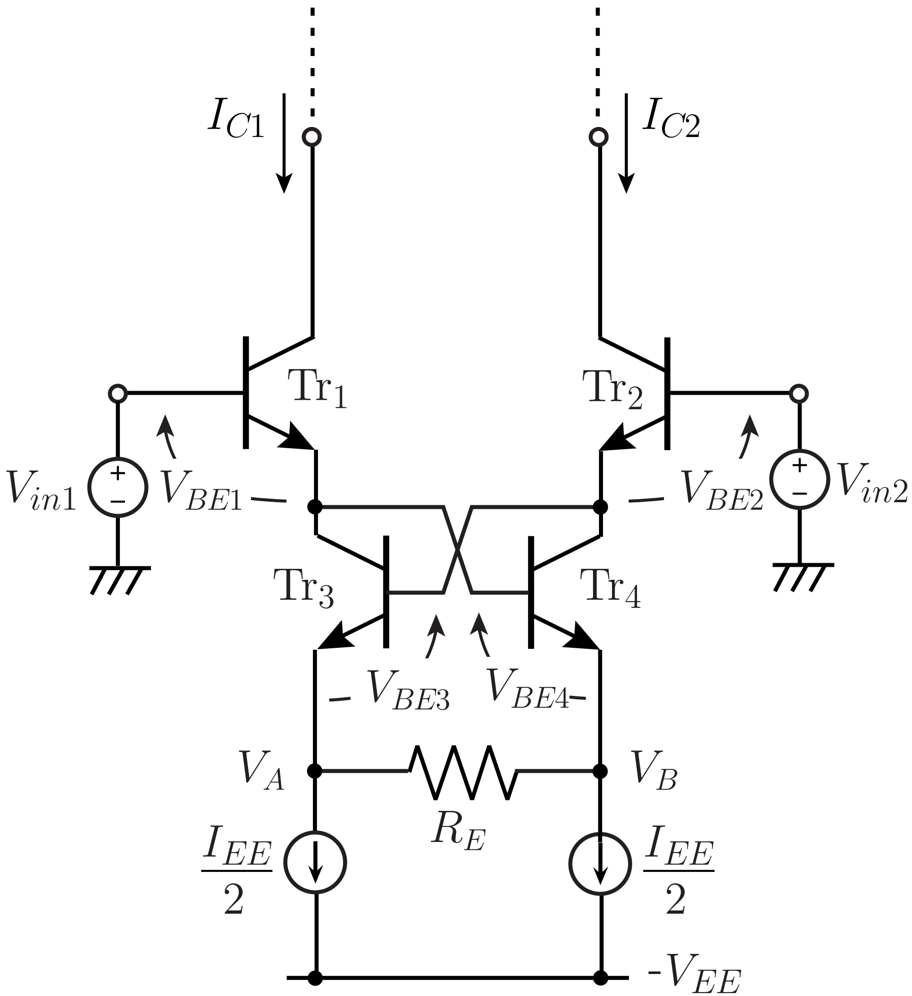
$$V_{BE} = \frac{kT}{q} \ln\left(\frac{I_E}{I_{ES}}\right)$$

$$I_{E1} = I_{E3} \qquad I_{E2} = I_{E4} \rightarrow V_{BE1} = V_{BE3} \qquad V_{BE2} = V_{BE4}$$

$$V_A = V_{in2} - V_{BE2} - V_{BE3}$$

$$V_B = V_{in1} - V_{BE1} - V_{BE4}$$

$$\boxed{V_A - V_B = V_{in2} - V_{in1}}$$



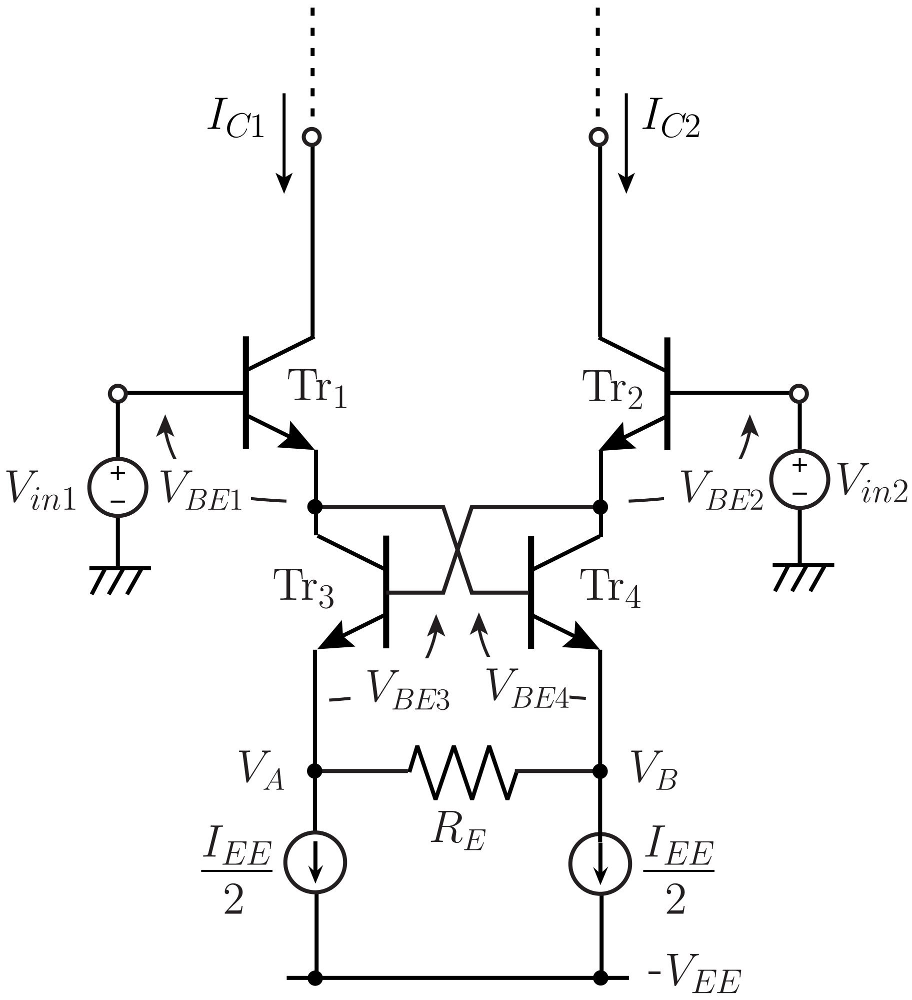
$$V_A - V_B = V_{in2} - V_{in1}$$

$$I_{RE} = \frac{V_{in2} - V_{in1}}{R_E} = \frac{-\Delta V_{in}}{R_E}$$

$$I_{C1} = \frac{I_{EE}}{2} + I_{RE}$$

$$I_{C2} = \frac{I_{EE}}{2} - I_{RE}$$

$$\Delta I_{out} = I_{C1} - I_{C2} = 2 I_{RE} = \frac{-2}{R_E} \Delta V_{in}$$



Tr3について

$V_{C3}=V_{in1}-V_{BE1}$

$V_{B3}=V_{in2}-V_{BE2}$

$V_{C3}>V_{B3}\rightarrow$

$V_{in1}-V_{BE1}>V_{in2}-V_{BE2}$

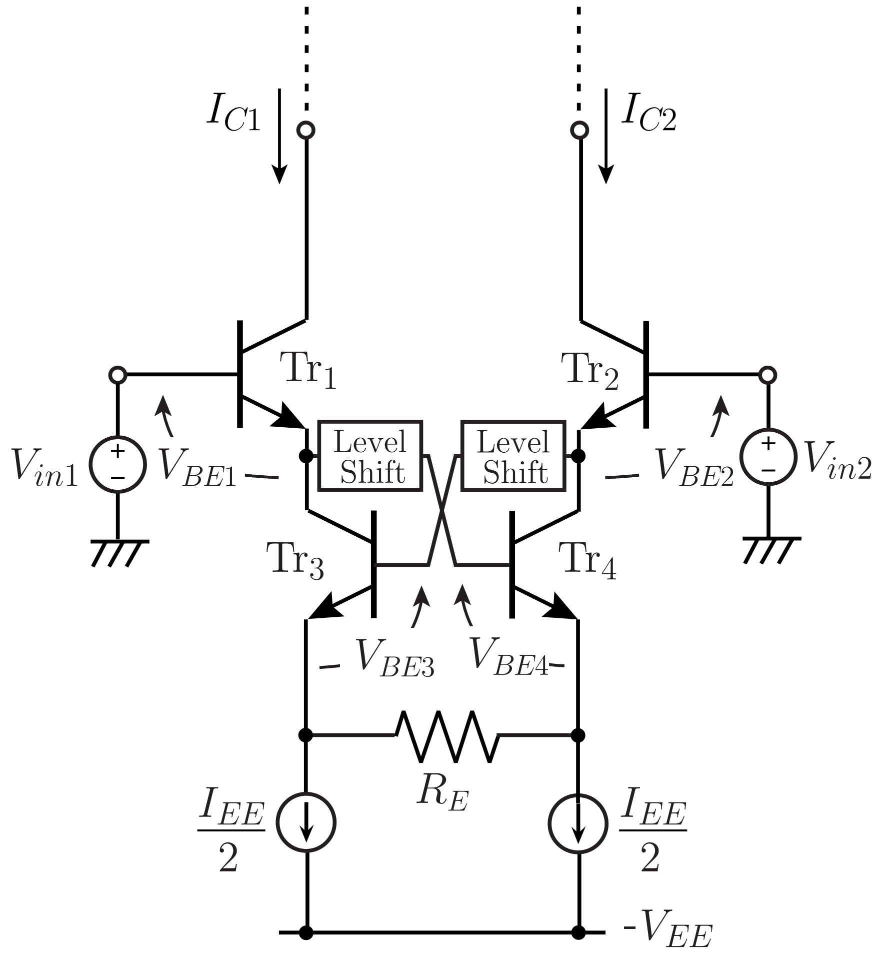
Tr4について

$V_{C4}=V_{in2}-V_{BE2}$

$V_{B4}=V_{in1}-V_{BE1}$

$V_{C4}>V_{B4}\rightarrow$

$V_{in1}-V_{BE1}<V_{in2}-V_{BE2}$



$$V_{C3}=V_{in1}-V_{BE1}$$

$$V_{B3}=V_{in2}-V_{BE2}-V_{shift}$$

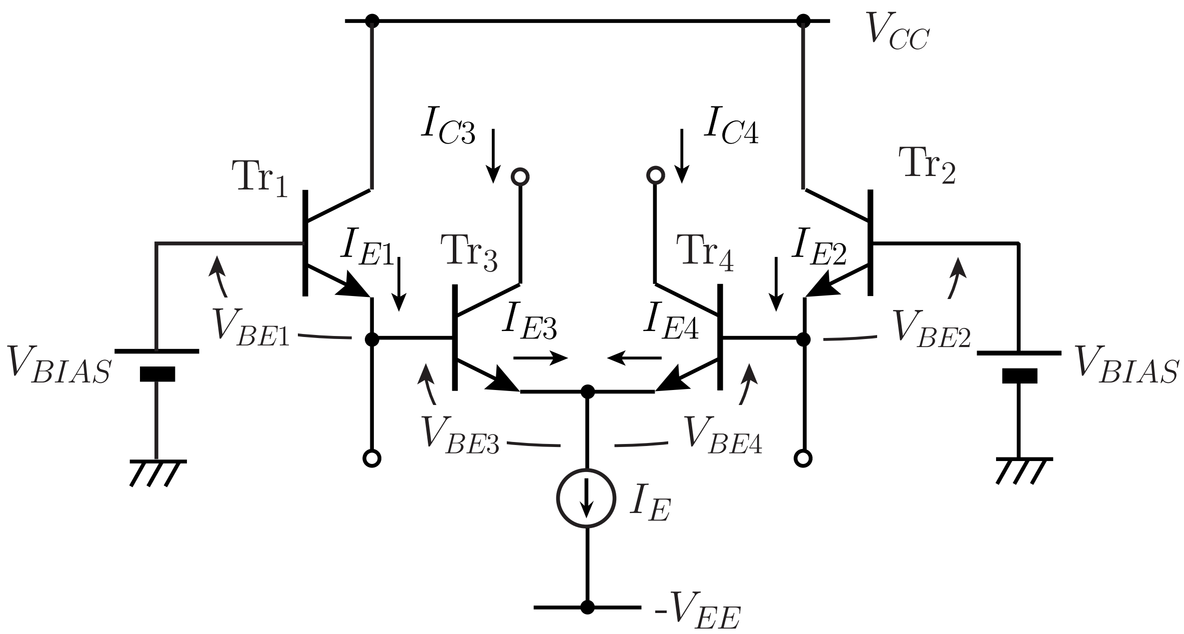
$$\boxed{V_{in1}-V_{BE1}>V_{in2}-V_{BE2}-V_{shift}}$$

$$V_{C4}=V_{in2}-V_{BE2}$$

$$V_{B4}=V_{in1}-V_{BE1}-V_{shift}$$

$$\boxed{V_{in1}-V_{BE1}-V_{shift}<V_{in2}-V_{BE2}}$$

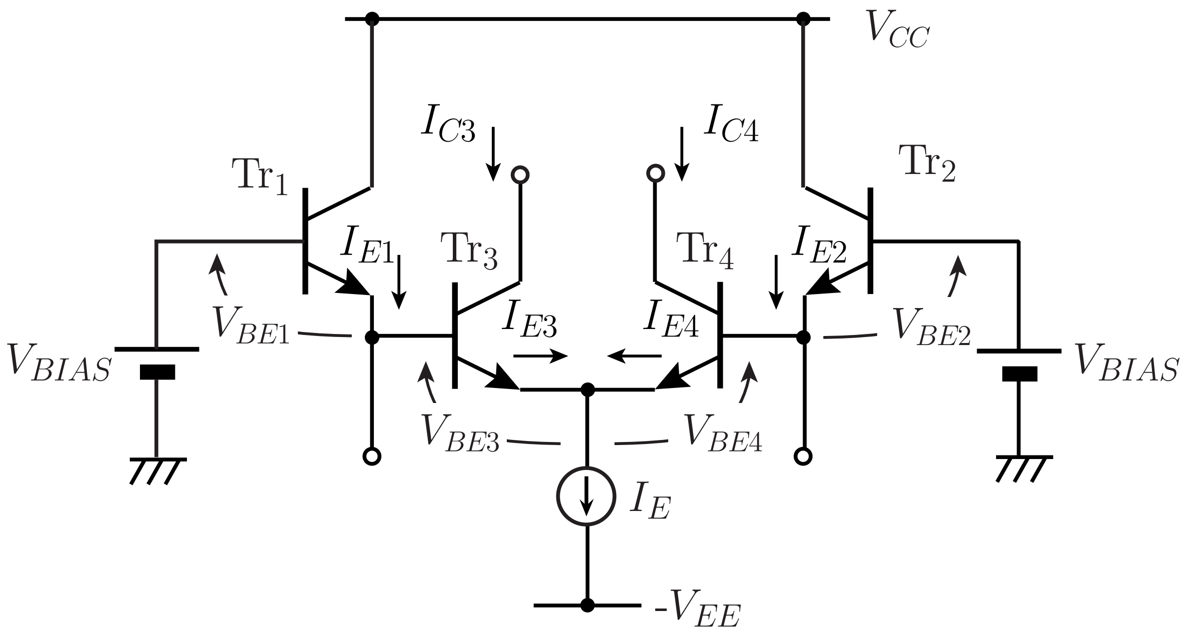
伝達コンダクタンスの電子的制御



$$V_{BE1}+V_{BE3}=V_{BE2}+V_{BE4}$$

$$\frac{kT}{q}\ln\left(\frac{I_{E1}}{I_{ES}}\right)+\frac{kT}{q}\ln\left(\frac{I_{E3}}{I_{ES}}\right)=\frac{kT}{q}\ln\left(\frac{I_{E2}}{I_{ES}}\right)+\frac{kT}{q}\ln\left(\frac{I_{E4}}{I_{ES}}\right)$$

$$I_{E1}I_{E3}=I_{E2}I_{E4}$$



$$I_{E3}+I_{E4}=I_E$$

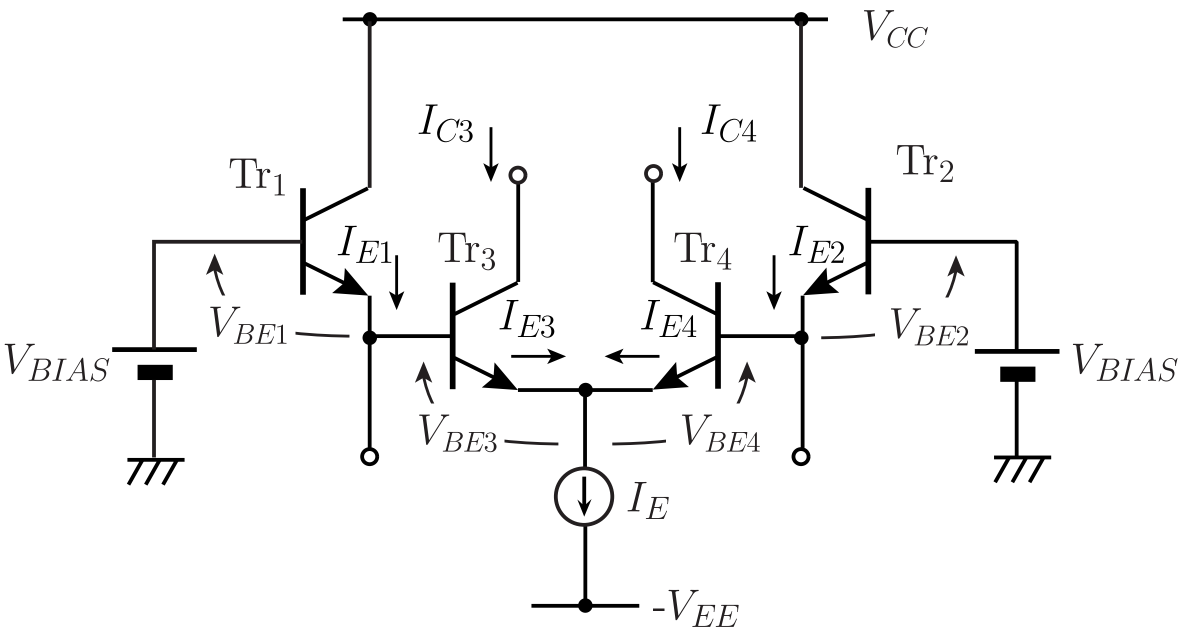
$$I_{E1}+I_{E2}=I_D$$

$$\rightarrow I_{E1}I_{E3}=I_{E2}I_{E4}$$

$$I_{E1}I_{E3}=(I_D-I_{E1})(I_E-I_{E3})$$

$$I_{E1}I_E+I_{E3}I_D=I_E I_D$$

$$\boxed{\frac{I_{E1}}{I_D}+\frac{I_{E3}}{I_E}=1}$$



$$I_{E3}+I_{E4}=I_E$$

$$I_{E1}+I_{E2}=I_D$$

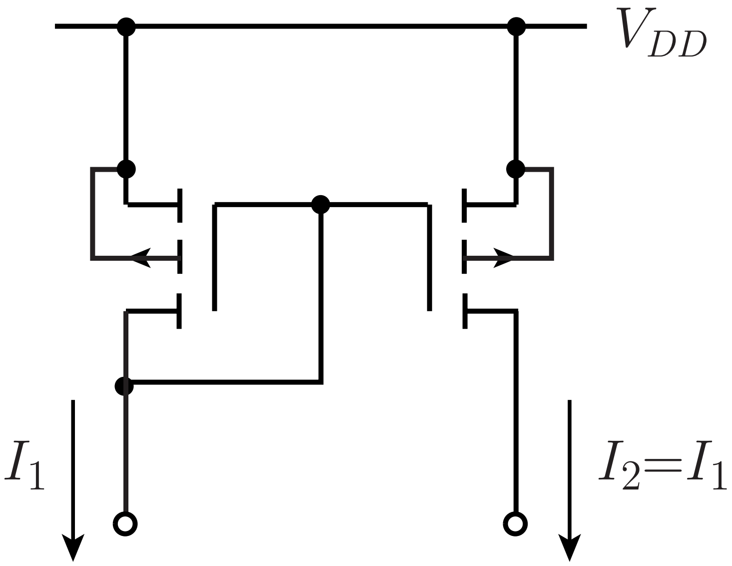
$$\frac{I_{E1}}{I_D}+\frac{I_{E3}}{I_E}=1$$

$$A_I=\frac{I_{C3}-I_{C4}}{I_{E1}-I_{E2}}=\frac{I_{E3}-I_{E4}}{I_{E1}-I_{E2}}=\frac{2I_{E3}-I_E}{2I_{E1}-I_D}=\frac{I_E}{I_D}\frac{2\frac{I_{E3}}{I_E}-1}{2\frac{I_{E1}}{I_D}-1}$$

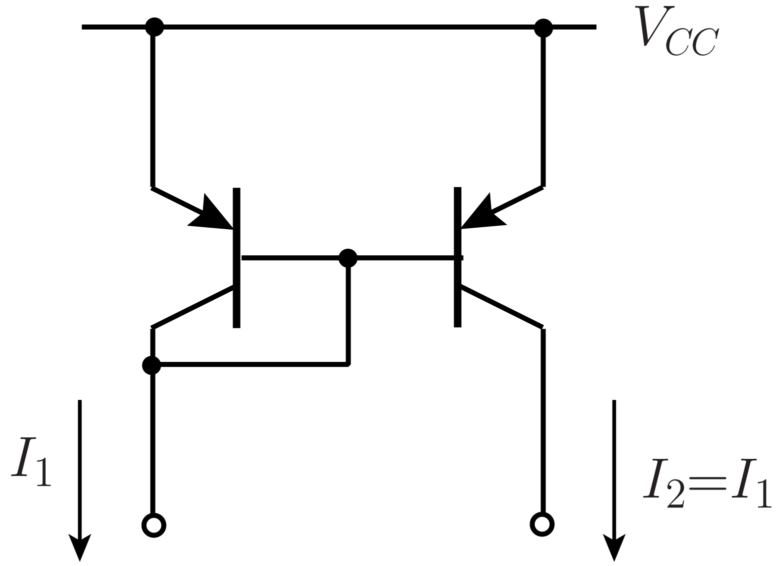
$$A_I=\frac{I_E}{I_D}\frac{2\frac{I_{E3}}{I_E}-1}{2\left(1-\frac{I_{E3}}{I_E}\right)-1}=-\frac{I_E}{I_D}$$

電流の減算

カレントミラー回路



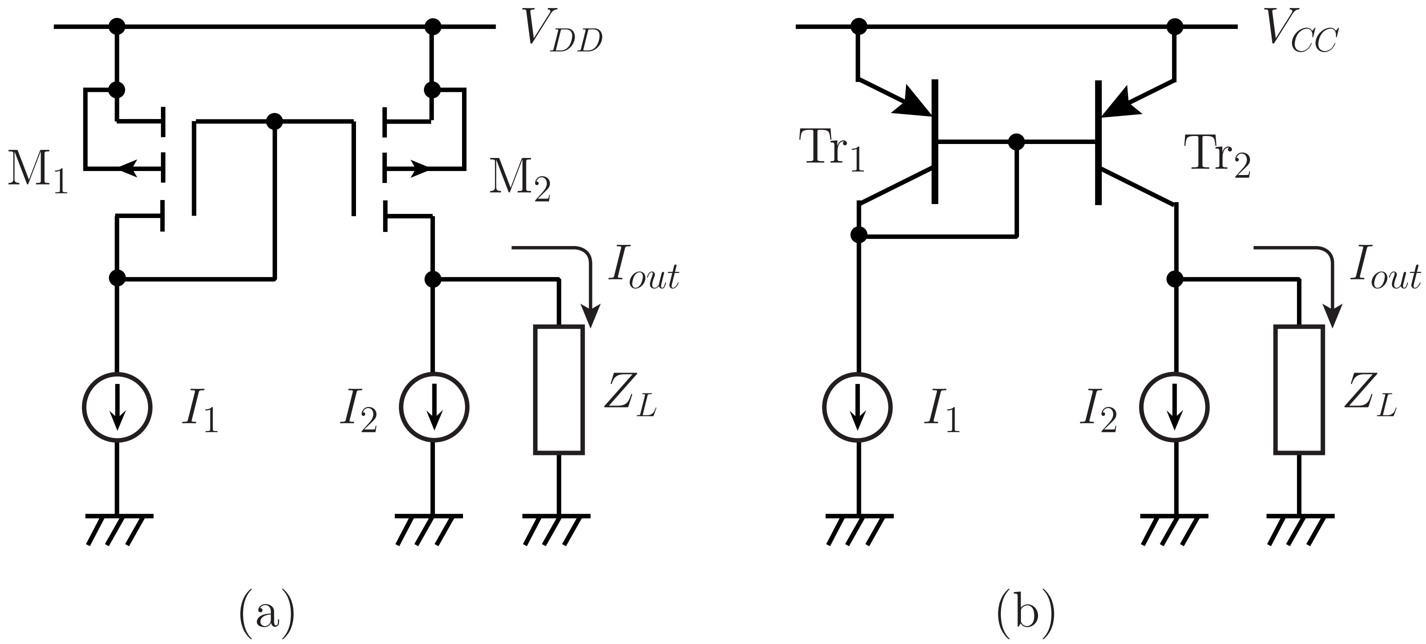
(a)



(b)

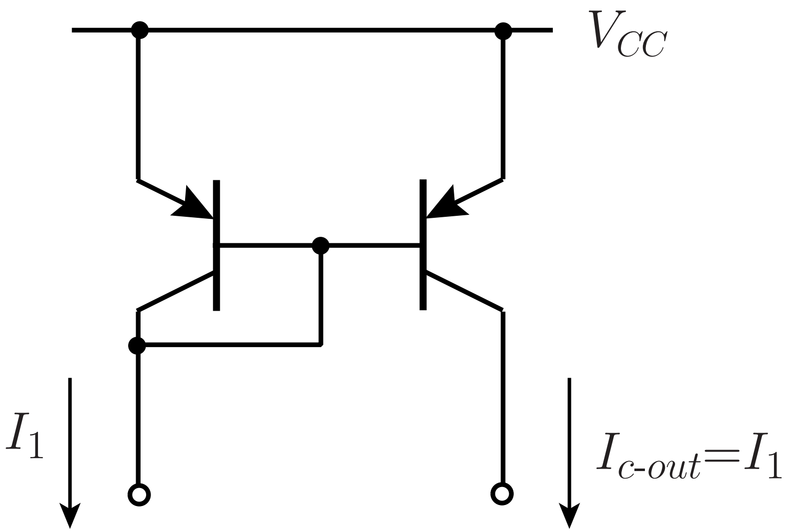
飽和領域で動作

能動活性領域で動作



$$I_{out}=I_1-I_2$$

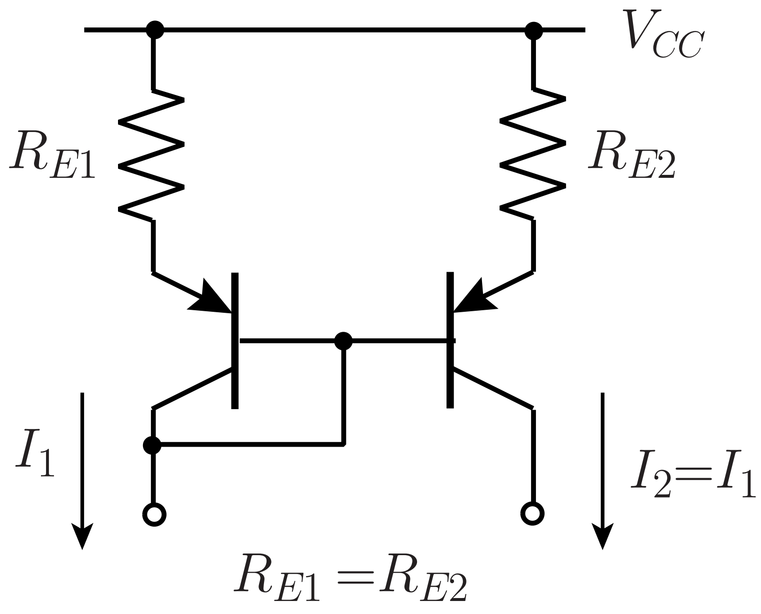
バイポーラ・カレントミラー回路の問題点



ベース・エミッタ間電圧が等しいので$I_{c-out} = I_1$

$$V_{BE}=\frac{kT}{q}\ln(\frac{I_1}{I_{S1}}+1)=\frac{kT}{q}\ln(\frac{I_{c-out}}{I_{S2}}+1)$$ より $$I_{c-out}=\frac{I_{S2}}{I_{S1}}I_1$$

I_{S1}とI_{S2}が等しくないと$I_{c-out} \neq I_1$



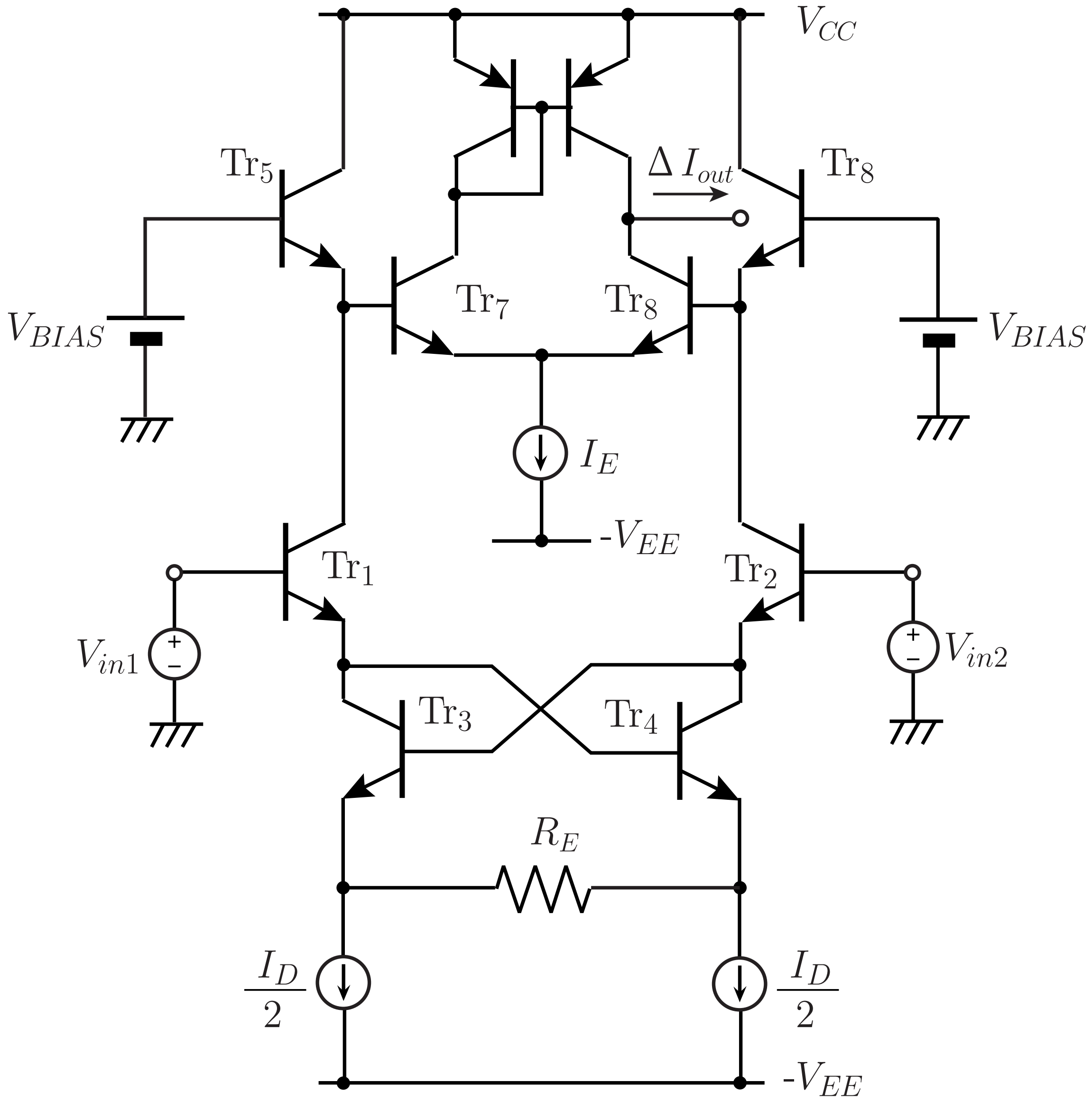
I_{S1}とI_{S2}の差の影響をR_Eにより吸収

$$R_{E1}I_1+\frac{kT}{q}\ln\left(\frac{I_1}{I_{S1}}+1\right)=R_{E2}I_2+\frac{kT}{q}\ln\left(\frac{I_2}{I_{S2}}+1\right)$$

$$R_{E1}I_1 \approx R_{E2}I_2$$

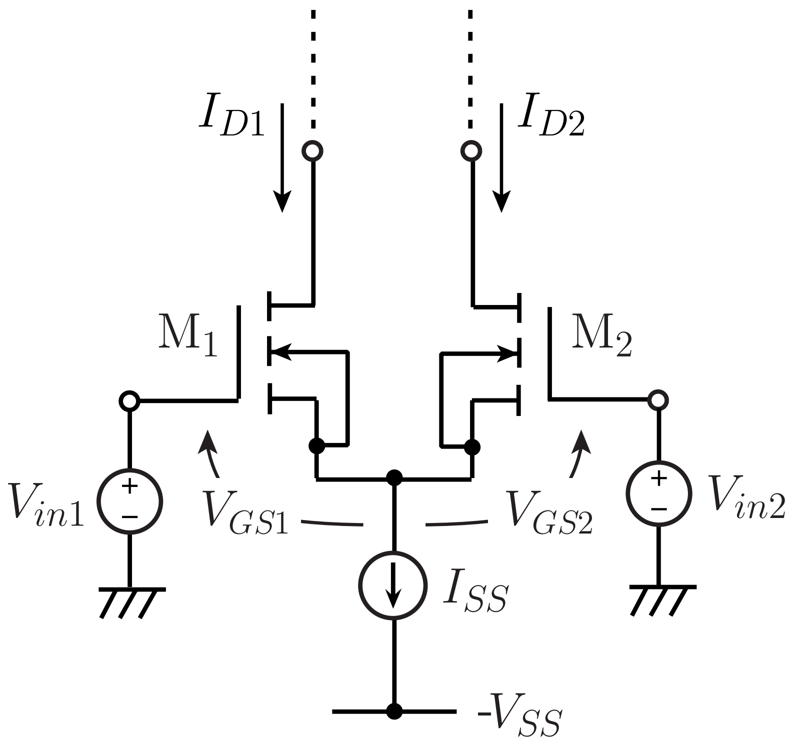
$R_{E1}=R_{E2}$のとき$I_1 \approx I_2$

バイポーラトランジスタによる電子的に特性可変のOTA



MOS差動増幅回路の大信号特性

MOS差動増幅回路



飽和領域： $V_{DS} \geq V_{GS} - V_T > 0$

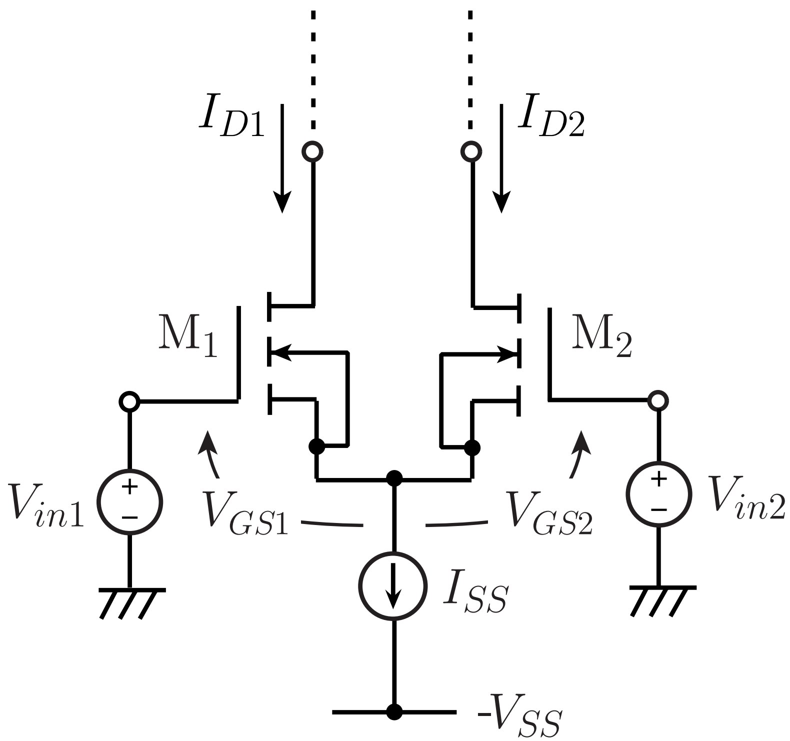
（$V_{SB}=0$と仮定）

2乗則：$I_D = K(V_{GS} - V_T)^2$

$$V_{in1} = \sqrt{\frac{I_{D1}}{K}} + V_S + V_T$$

$$V_{in2} = \sqrt{\frac{I_{D2}}{K}} + V_S + V_T$$

$$\Delta V_{in} = V_{in1} - V_{in2} = \sqrt{\frac{I_{D1}}{K}} - \sqrt{\frac{I_{D2}}{K}}$$



$$\Delta V_{in} = V_{in1} - V_{in2} = \sqrt{\frac{I_{D1}}{K}} - \sqrt{\frac{I_{D2}}{K}}$$

$$\Delta V_{in}^2 = \frac{I_{D1} + I_{D2}}{K} - 2\sqrt{\frac{I_{D1} I_{D2}}{K^2}} = \frac{I_{SS}}{K} - 2\sqrt{\frac{I_{D1}(I_{SS} - I_{D1})}{K^2}}$$

$$I_{D1}^2 - I_{SS} I_{D1} + \frac{K^2}{4}\left(\frac{I_{SS}}{K} - \Delta V_{in}^2\right)^2 = 0$$

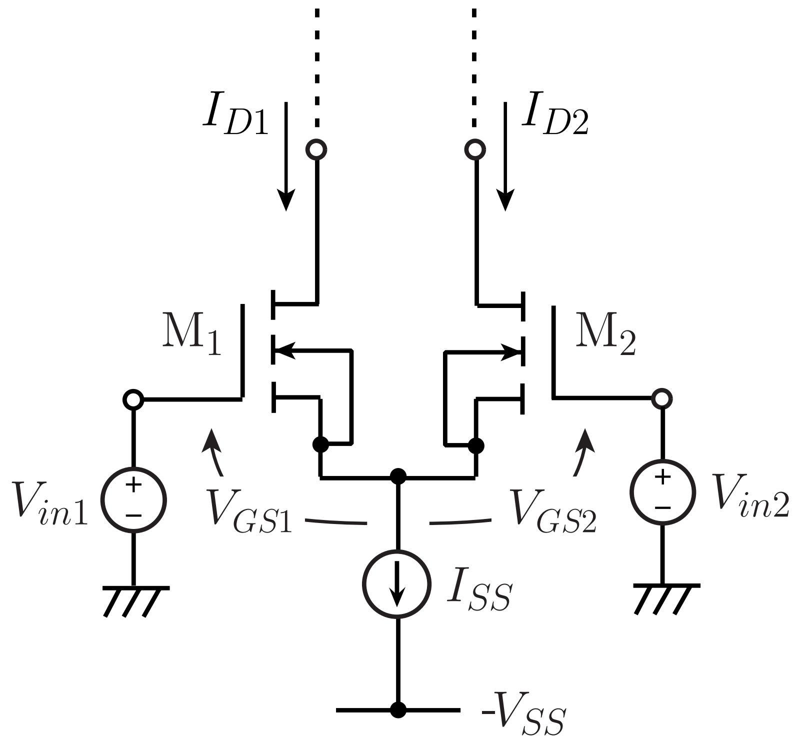
$$I_{D1}^2 - I_{SS} I_{D1} + \frac{K^2}{4}\left(\frac{I_{SS}}{K} - \Delta V_{in}^2\right)^2 = 0$$

$$I_{D1} = \frac{I_{SS} \pm \sqrt{2K I_{SS} \Delta V_{in}^2 - K^2 \Delta V_{in}^4}}{2}$$

$\Delta V_{in} > 0$のとき$I_{D1} > I_{SS}/2$より

$$I_{D1} = \frac{I_{SS} + \Delta V_{in}\sqrt{2K I_{SS} - K^2 \Delta V_{in}^2}}{2}$$

$$I_{D2} = \frac{I_{SS} - \Delta V_{in}\sqrt{2K I_{SS} - K^2 \Delta V_{in}^2}}{2}$$



$$I_{D1} = \frac{I_{SS} + \Delta V_{in}\sqrt{2KI_{SS} - K^2 \Delta V_{in}^2}}{2}$$

$$I_{D2} = \frac{I_{SS} - \Delta V_{in}\sqrt{2KI_{SS} - K^2 \Delta V_{in}^2}}{2}$$

$$\Delta I_{out} = I_{D1} - I_{D2} = \Delta V_{in}\sqrt{2KI_{SS} - K^2 \Delta V_{in}^2}$$

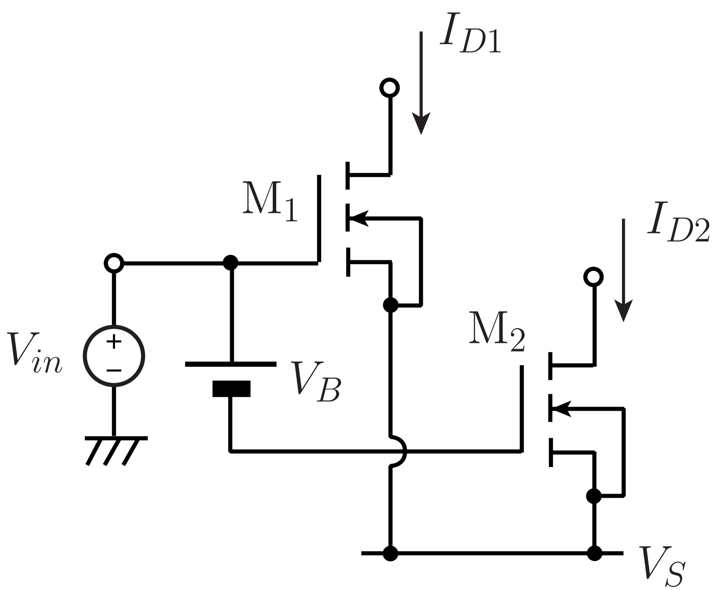
$$|\Delta V_{in}|^2 << \sqrt{2I_{SS}/K}$$ ならば

$$\Delta I_{out} = \Delta V_{in}\sqrt{2KI_{SS} - K^2 \Delta V_{in}^2} \approx \sqrt{2KI_{SS}}\,\Delta V_{in}$$

I_{SS}やKによって線形範囲を拡大可能

I_{SS}やKの値に実質的な制限

バイアスオフセット技術



2乗則：$I_D=K(V_{GS}-V_T)^2$

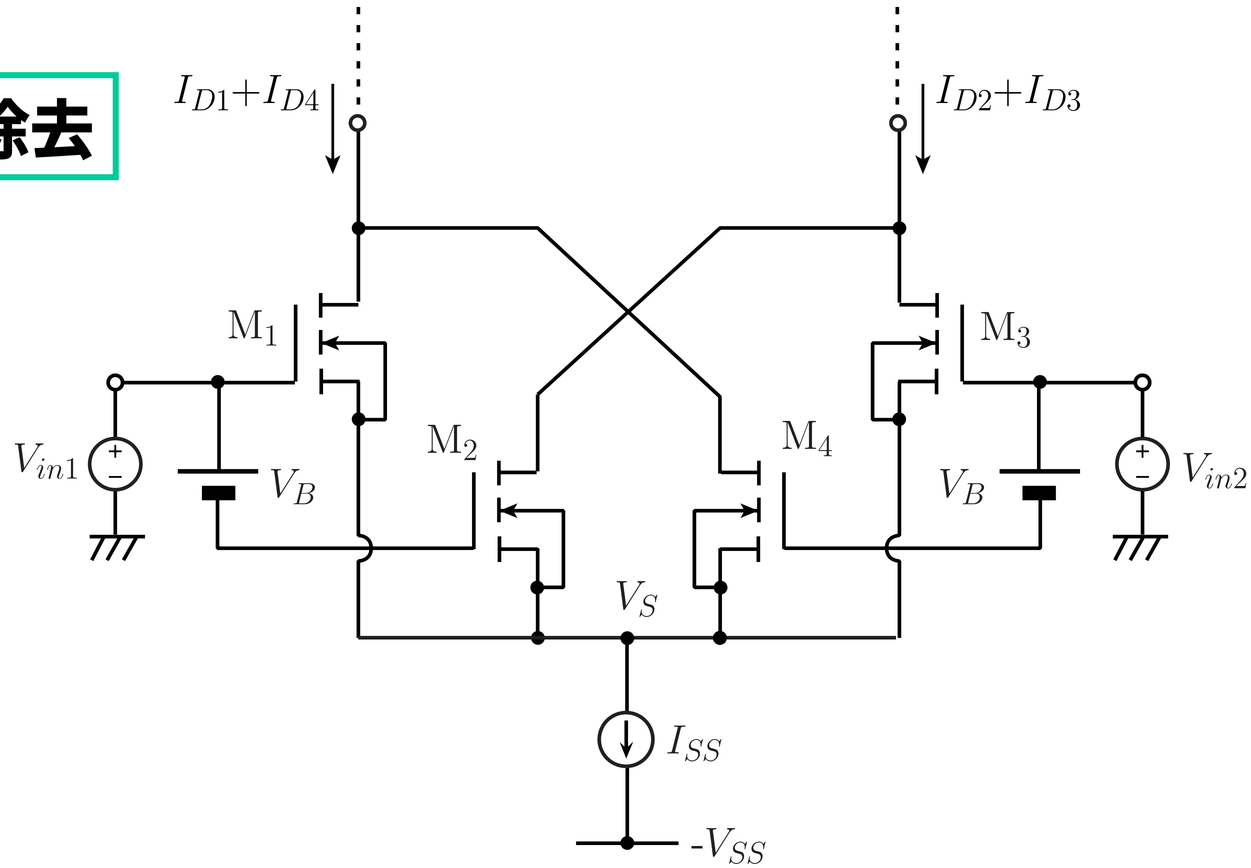
$$I_{D1}=K(V_{in}-V_S-V_T)^2$$

$$I_{D2}=K(V_{in}-V_B-V_S-V_T)^2$$

$$I_{D1}-I_{D2}=K(2V_{in}-V_B-2V_S-2V_T)V_B$$

$$=2KV_BV_{in}-K(V_B+2V_S+2V_T)V_B$$

オフセット電流の除去

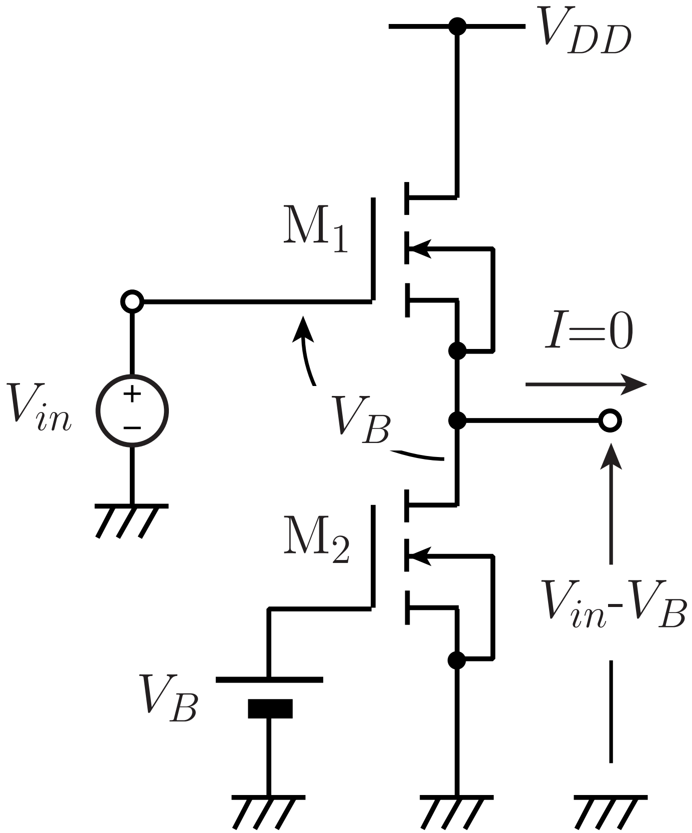


$$I_{D1}-I_{D2}=2KV_BV_{in1}-K(V_B+2V_S+2V_T)V_B$$

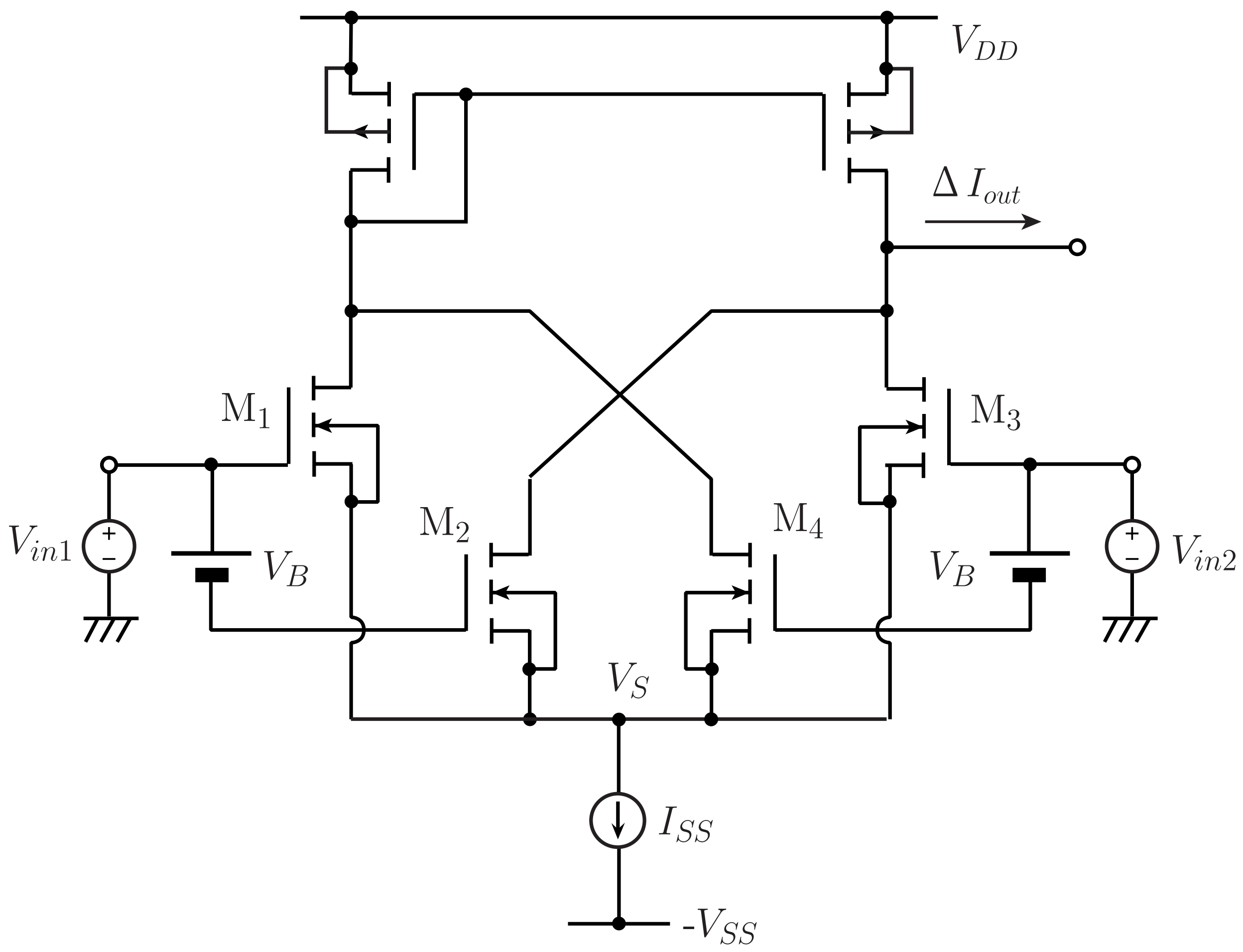
$$I_{D3}-I_{D4}=2KV_BV_{in2}-K(V_B+2V_S+2V_T)V_B$$

$$\Delta I_{out}=(I_{D1}-I_{D2})-(I_{D3}-I_{D4})=2KV_B(V_{in1}-V_{in2})$$

非接地直流電圧源の実現



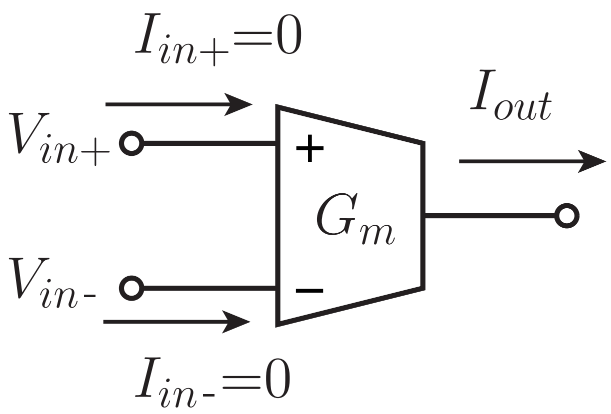
MOSトランジスタによる電子的に特性可変のOTA



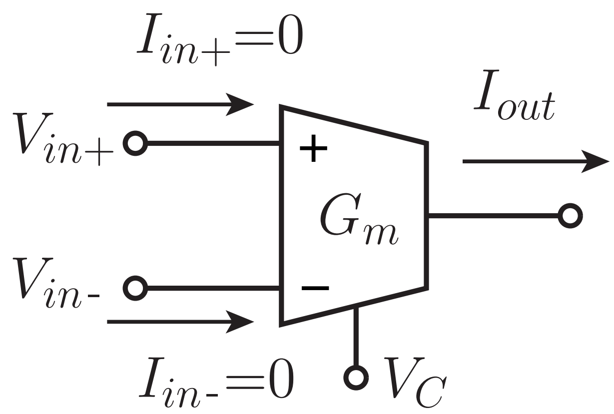
$$\Delta I_{out} = (I_{D1} - I_{D2}) - (I_{D3} - I_{D4}) = 2KV_B(V_{in1} - V_{in2})$$

OTAの応用

OTAの記号



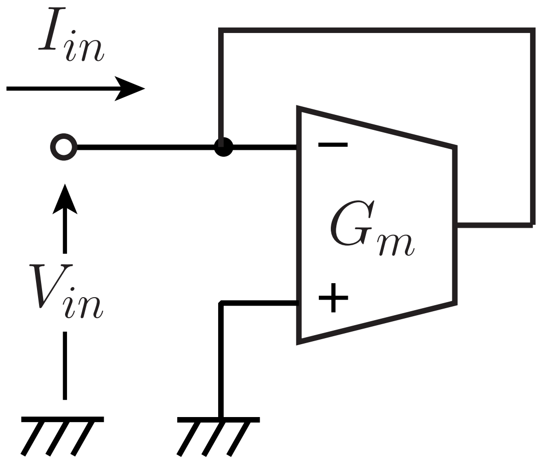
(a)



(b)

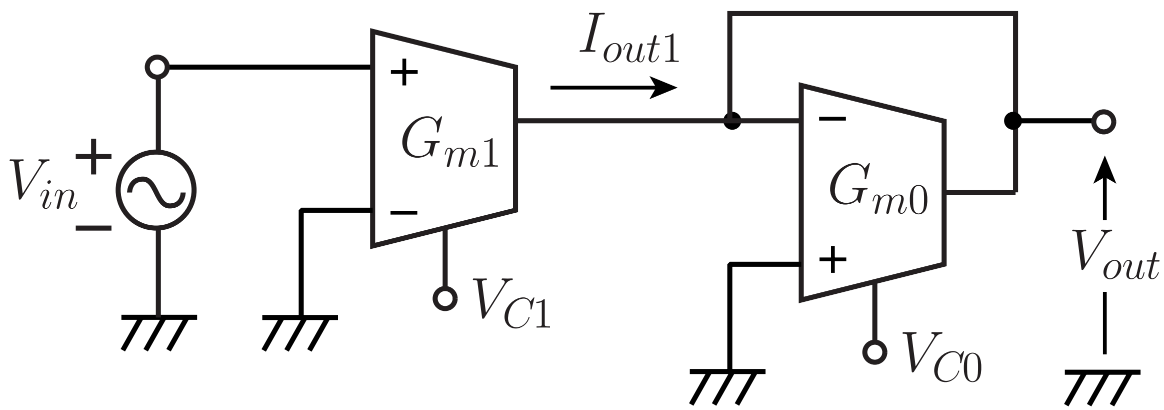
$$I_{out} = G_m (V_{in+} - V_{in-})$$

OTAによる抵抗の構成



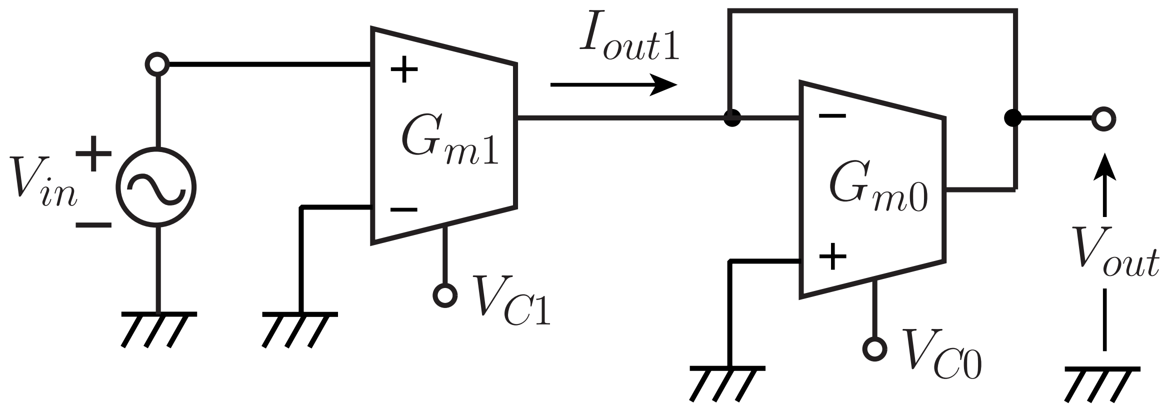
$$I_{in} = G_m V_{in} \rightarrow R_{in} = \frac{V_{in}}{I_{in}} = \frac{1}{G_m}$$

OTAによる増幅回路の構成



$$V_{out}=\frac{1}{G_{m0}}I_{out1}=\frac{G_{m1}}{G_{m0}}V_{in}$$

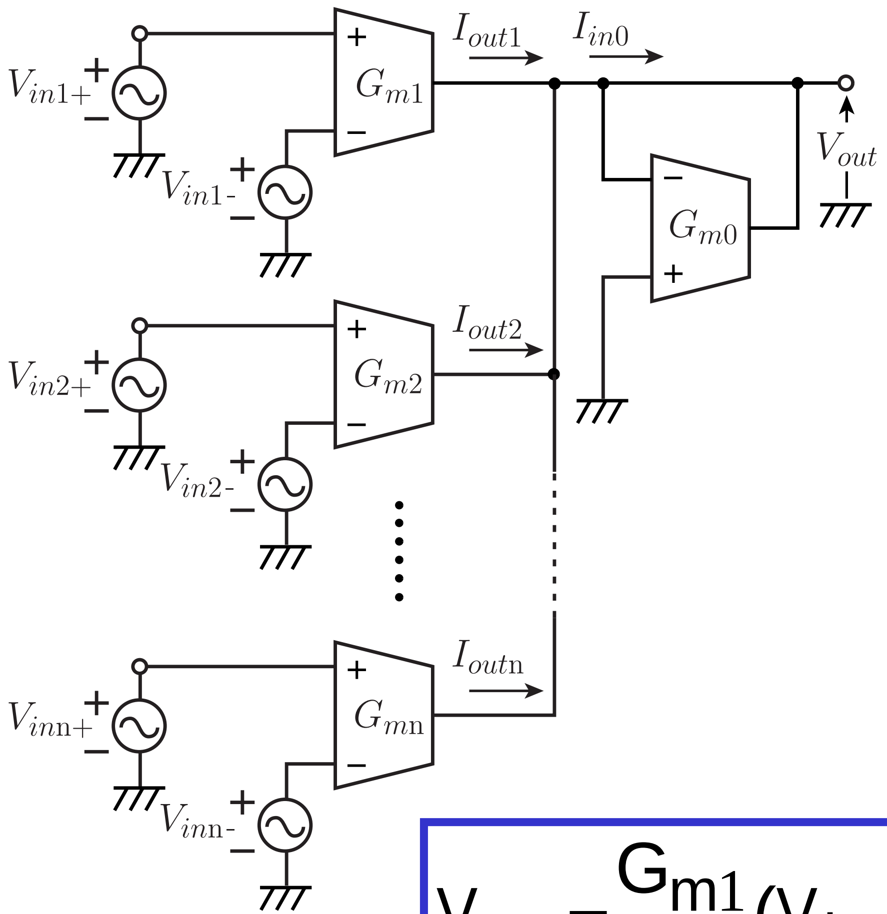
OTAによる乗除算回路の構成



$$G_{m0} = K_{m0} V_{C0}, \quad G_{m1} = K_{m1} V_{C1}$$

$$V_{out} = \frac{G_{m1}}{G_{m0}} V_{in} = \frac{K_{m1}}{K_{m0}} \cdot \frac{V_{C1} V_{in}}{V_{C0}}$$

OTAによる加減算回路の構成

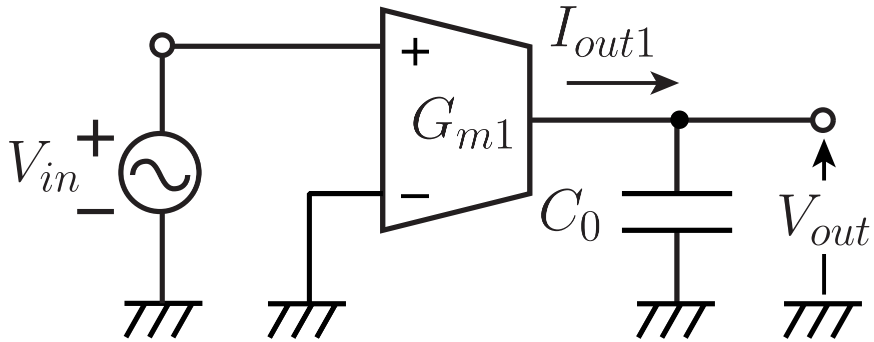


$$I_{in0} = I_{out1} + I_{out2} + \cdots + I_{outn}$$

$$I_{outi} = G_{mi}(V_{ini+} - V_{ini-})$$

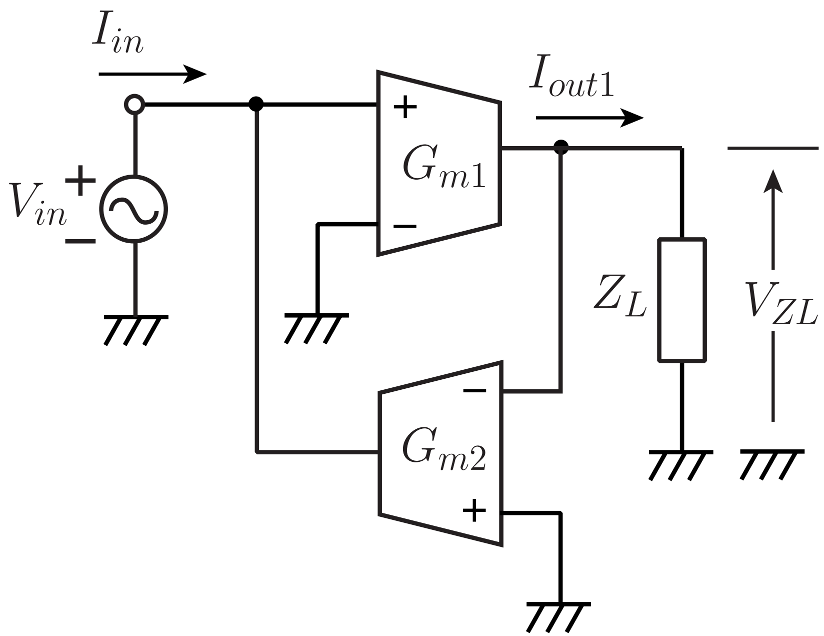
$$V_{out} = \frac{G_{m1}}{G_{m0}}(V_{in1+} - V_{in1-}) + \frac{G_{m2}}{G_{m0}}(V_{in2+} - V_{in2-}) + \cdots$$
$$\cdots + \frac{G_{mn}}{G_{m0}}(V_{inn+} - V_{inn-})$$

OTAによる積分回路の構成



$$V_{out} = \frac{1}{sC_0} I_{out1} = \frac{G_{m1}}{sC_0} V_{in}$$

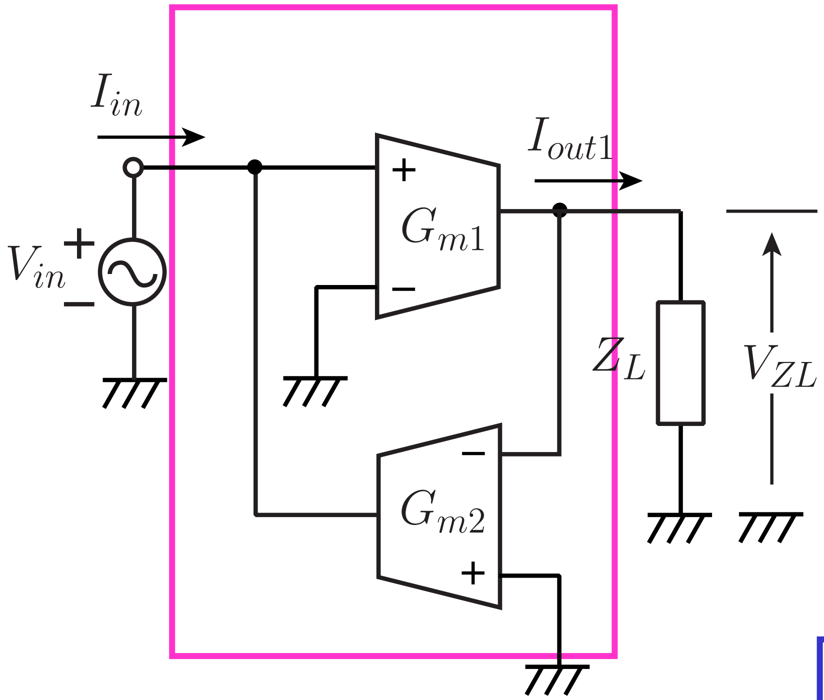
OTAによるインピーダンスの実現



$$V_{ZL} = Z_L I_{out1} = Z_L G_{m1} V_{in}$$

$$I_{in} = G_{m2} V_{ZL}$$

$$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{V_{in}}{G_{m2} V_{ZL}} = \frac{V_{in}}{G_{m2} Z_L G_{m1} V_{in}} = \frac{1}{G_{m2} Z_L G_{m1}}$$



ジャイレータ

$$Z_L = \frac{1}{sC_L}$$

$$Z_{in} = \frac{1}{G_{m2} Z_L G_{m1}} = s\frac{C_L}{G_{m1} G_{m2}}$$