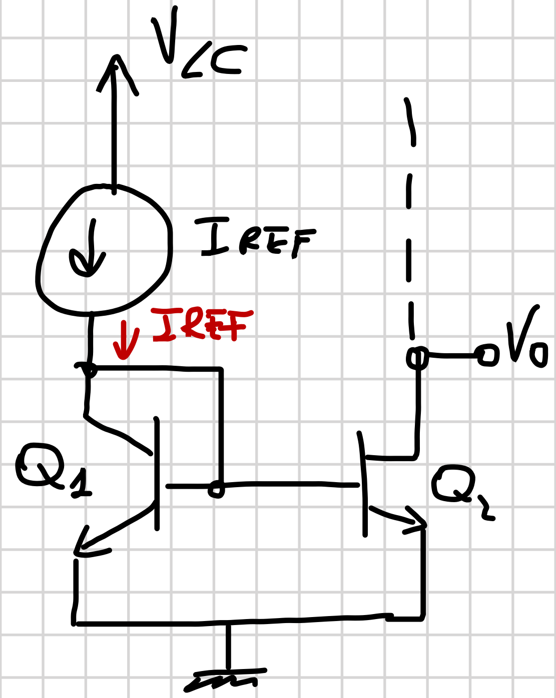
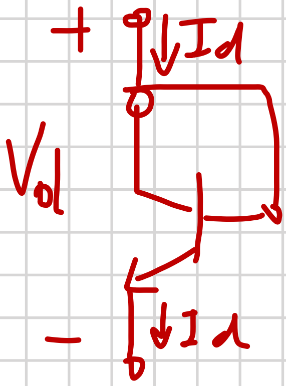


$$I_C = I_S\left(e^{+\frac{V_{BE}}{V_T}}-1\right)$$

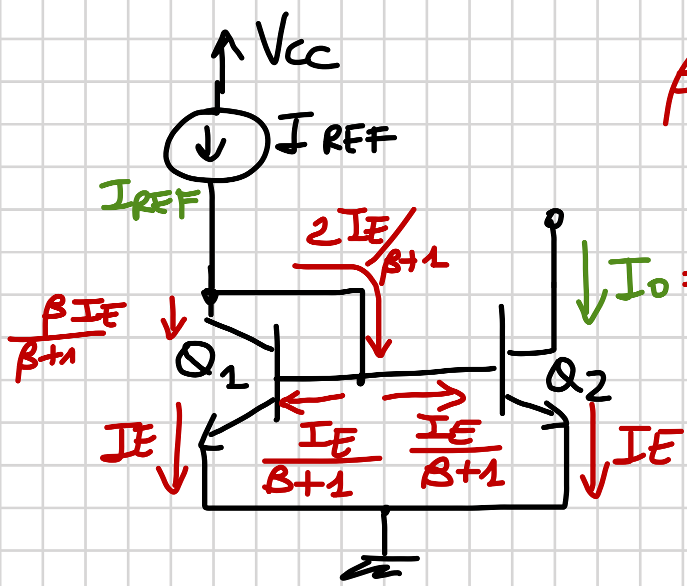


$$I_d = I_S\left(e^{\frac{V_d}{V_T}}-1\right)$$

$$I_{C1} = I_S\left(e^{\frac{V_{BE1}}{V_T}}-1\right)$$

$$I_{C2} = I_S\left(e^{\frac{V_{BE2}}{V_T}}-1\right)$$

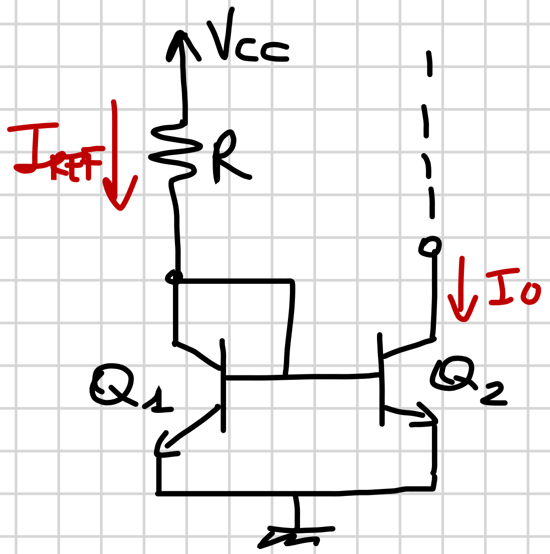
$$\beta = \frac{I_C}{I_B}$$



$$I_o = \frac{\beta I_E}{\beta+1}$$

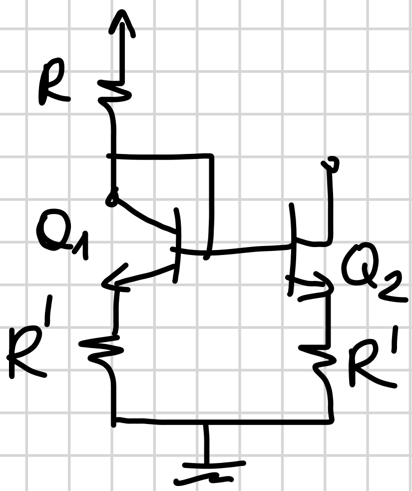
$$I_{REF} = \frac{\beta I_E}{\beta+1} + \frac{2 I_E}{\beta+1} = \frac{\beta+2}{\beta+1} I_E = \frac{\beta+2}{\beta} I_o$$

$$\boxed{\frac{I_o}{I_{REF}} = \frac{\beta}{\beta+2}}$$

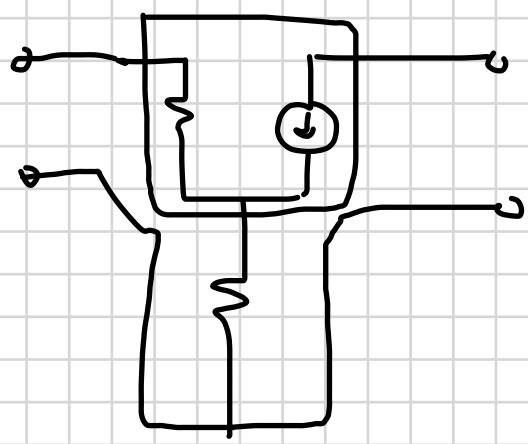


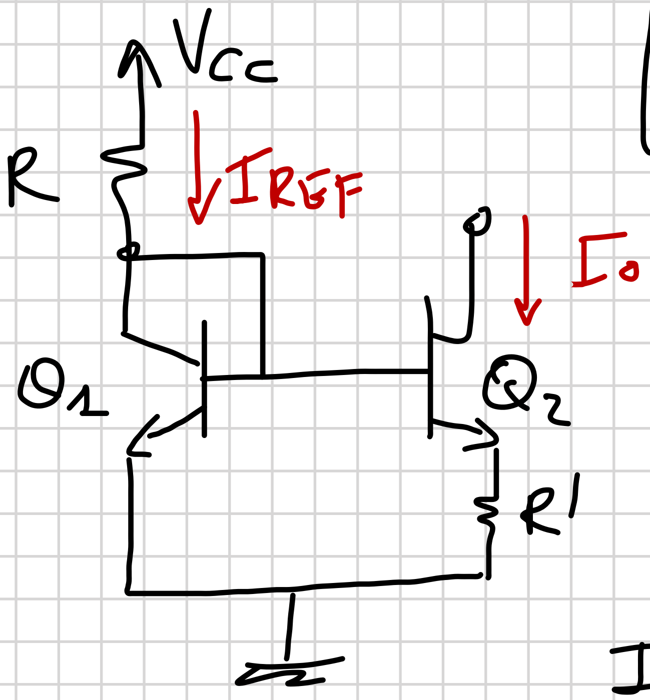
$$I_o \simeq I_{REF}$$

$$I_{REF} = \frac{V_{CC} - V_{BE}}{R}$$



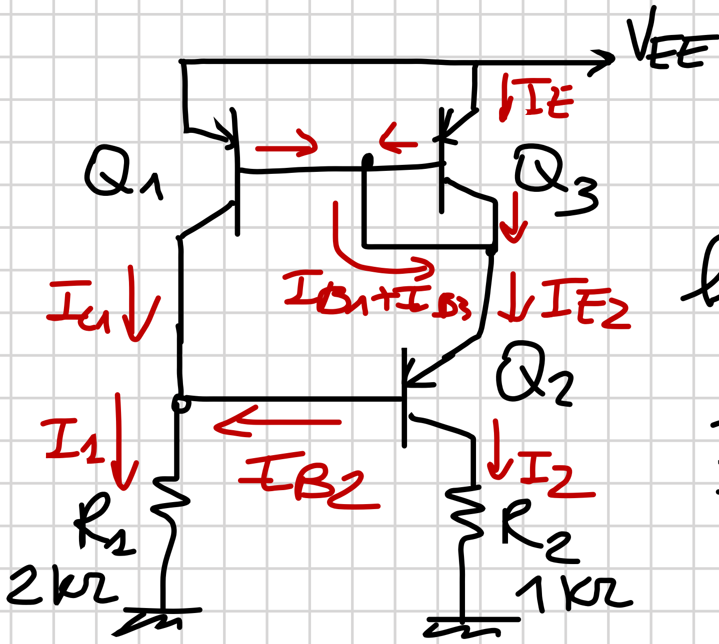
$$R' I_{C1} + V_{BE1} =$$
$$R' I_{C2} + V_{BE2}$$





$$V_{BE1} = V_{BE2} + \underbrace{R' I_{C2}}_{>0}$$
$$\Downarrow$$
$$V_{BE1} > V_{BE2}$$
$$\Downarrow$$
$$I_{C1} > I_{C2}$$
$$\equiv$$
$$I_{REF} > I_O$$

WIDLAR



$V_{EE} = 12V$

$h_{FE} = 100 = \beta$

$\dfrac{I_1}{I_2} = ?$

$I_{B3} = \dfrac{I_E}{\beta+1}$ $\quad I_{E3} = I_{E2} = I_E$

$I_{B1} = \dfrac{I_E}{\beta+1}$ $\quad I_{C1} = \dfrac{\beta}{\beta+1} I_E = I_{C3}$

$$I_{E2} = I_{C3} + I_{B1} + I_{B3} = \frac{\beta}{\beta+1} I_E + \frac{2 I_E}{\beta+1} =$$

$$= \frac{\beta+2}{\beta+1} I_E$$

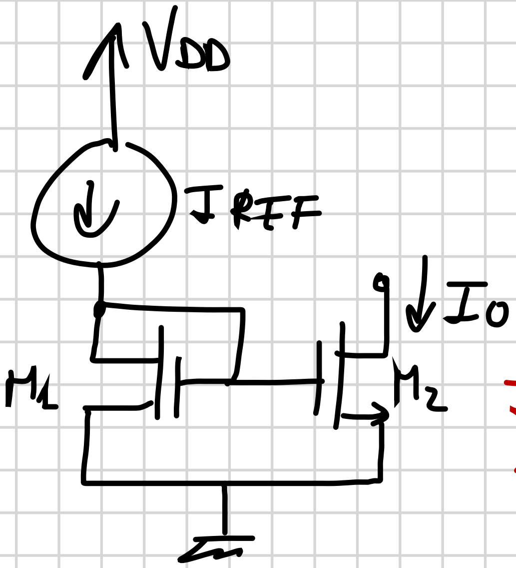
$$I_1 = I_{C1} + I_{B2} = \frac{\beta}{\beta+1} I_E + \frac{\beta+2}{(\beta+1)^2} I_E$$

$$I_1 = \frac{\beta^2+2\beta+2}{(\beta+1)^2} I_E$$

$$I_2 = \frac{\beta}{\beta+1} I_{E2} = \frac{\beta(\beta+2)}{(\beta+1)^2} I_E$$

$$\frac{I_1}{I_2} = \frac{\beta^2+2\beta+2}{\beta(\beta+2)} = 1,000196$$

$$I_1 = \frac{V_{EE}-2V_{EB}}{R_1} = 5,3\,mA$$



$I_1 = K_1 (V_{GS1} - V_{T1})^2$

$I_2 = K_2 (V_{GS2} - V_{T2})^2$

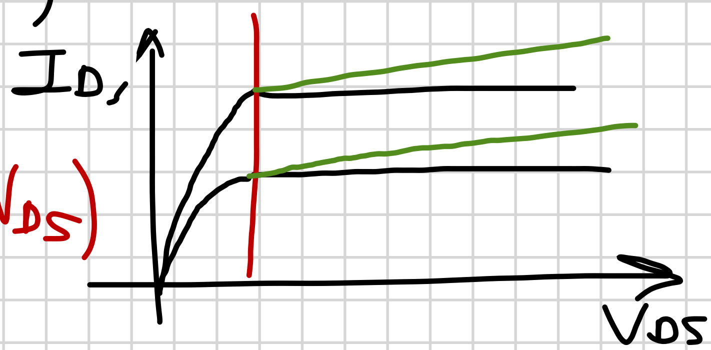
$V_{T1} = V_{T2} = V_T$

$I_1 = I_{REF}$

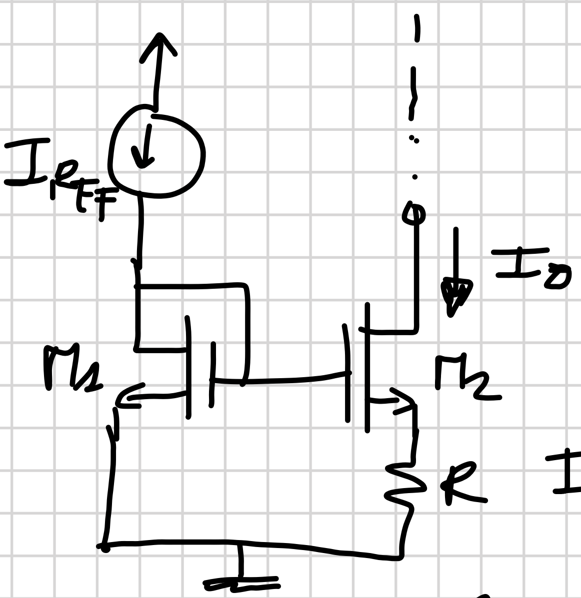
$$\frac{I_1}{I_2} = \frac{K_1}{K_2} \frac{\cancel{(V_{GS1} - V_T)^2}}{\cancel{(V_{GS2} - V_T)^2}} =$$

$$= \frac{K_1}{K_2} = \frac{\left(\frac{W}{L}\right)_1}{\left(\frac{W}{L}\right)_2} = \frac{I_{REF}}{I_O}$$

$I = K (V_{GS} - V_T)^2$



$I = K (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$



$I_1 = K_1 (V_{GS1} - V_T)^2 = I_{REF}$

$I_2 = K_2 (V_{GS2} - V_T)^2$

$V_{GS2} = V_{GS1} - R I_2$

$$I_2 = K_2 \left[(V_{GS1} - V_T) - R I_2 \right]^2 =$$

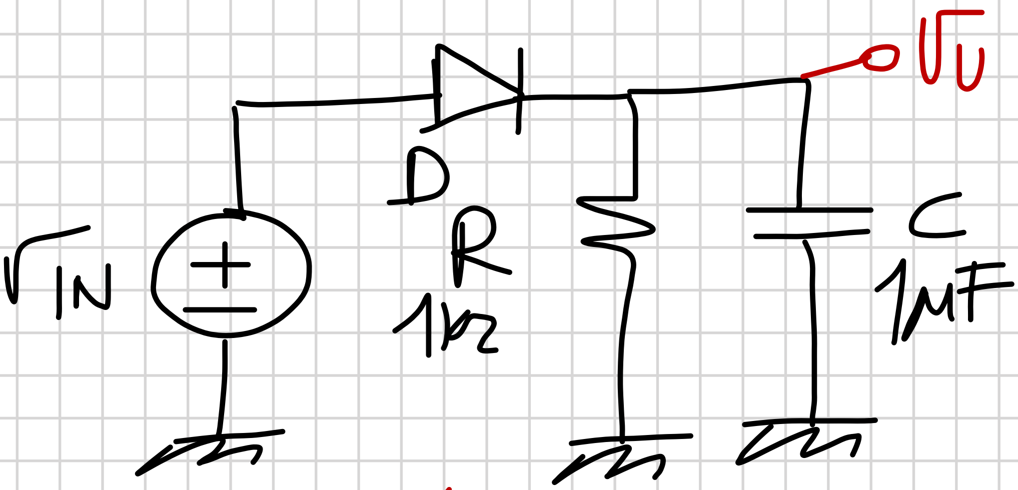
$$= K_2 (V_{GS1} - V_T)^2 - 2 K_2 R (V_{GS1} - V_T) I_2 + K_2 R^2 I_2^2$$

$$k_2(V_{GS1}-V_T)^2 = \frac{k_2}{k_1} I_1$$

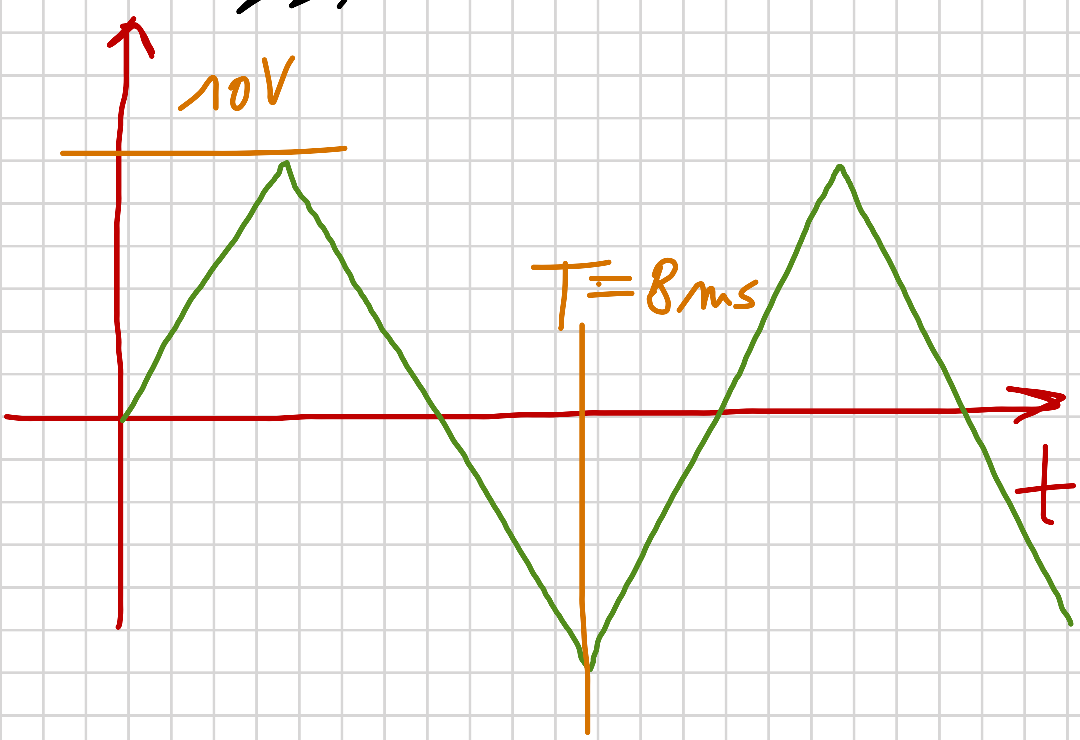
$$(V_{GS1}-V_T) = \sqrt{\frac{I_1}{k_1}}$$

$$k_2 R^2 I_2^2 - \left[1+2k_2R\sqrt{\frac{I_1}{k_1}}\right] I_2 + \frac{k_2}{k_1} I_1 = 0$$

$$I_2 = \frac{\underbrace{\left[1+2k_2R\sqrt{\frac{I_1}{k_1}}\right]}_{A} \mp \sqrt{A^2 - 4\frac{R^2k_2^2 I_1}{k_1}}}{2k_2R^2}$$

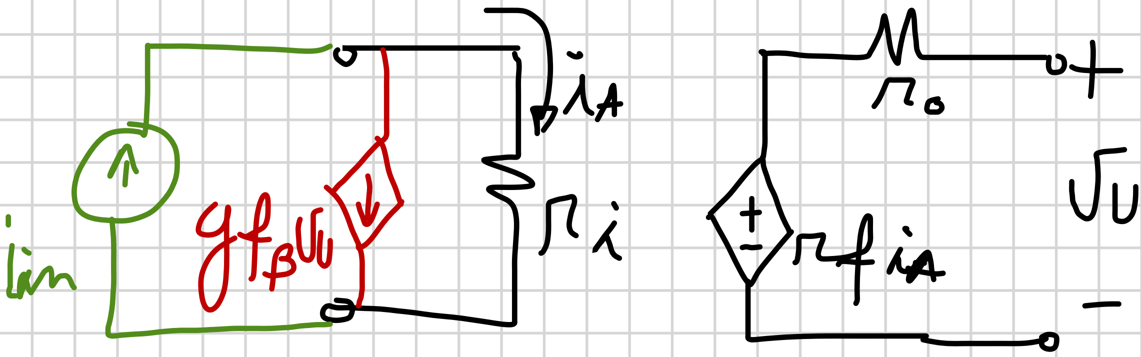


T = 8ms



$r_i = 1\,k\Omega \qquad r_f = 100\,\Omega \qquad r_o = 100\,\Omega$

$r_f' = 1\,\Omega$



$$r_f' = \left.\frac{v_u}{i_{in}}\right|_{i_u=0} = \frac{r_f\,(i_{in} - g_{f\beta} v_u)}{i_{in}} =$$

$$\Rightarrow \frac{r_f}{1 + r_f g_{f\beta}}\, i_{in} = v_u$$

$$1 + r_f g_{f\beta} = \frac{r_f}{r_f'} = 1000 \Rightarrow \underline{\underline{g_{f\beta} = 0{,}999}}$$

$$r_i' = \frac{v_{in}}{i_{in}} = \frac{i_A r_i}{i_{in}} = \frac{r_i}{1 + r_f g_{f\beta}} = 0{,}1\,\Omega$$

$$r_o' = \left.\frac{v_u}{i_u}\right|_{i_{in}=0} = \frac{r_o i_u + r_f(-g_{f\beta} v_u)}{i_u} = 0{,}1\,\Omega$$