1. a) For $V_C = +5V$ require $I_E = (10-5)/10k = 0.5mA$

$I_B = I_E/(1+\beta)$, so $I_B = 2.488\ \mu A$

But $I_B = (V_C - 0.7)/R_B$ assuming $V_{BE} \simeq 0.7V$

$\Rightarrow R_B = (5-0.7)/2.488\times10^{-6} = \underline{\underline{1.73\ M\Omega}}$ [6]

b) Circuit is MOSFET current mirror

Both (enh. mode) devices have $V_D \geq V_G \Rightarrow$ both active

Consider LHS, where $V_{DS} = V_{GS} = V_D$:

$$I_D = K(V_D - V_t)^2 = \frac{5 - V_D}{15k\Omega} \quad \bar{\omega}\ K = 0.2mA/V^2,\ V_t = 1V$$

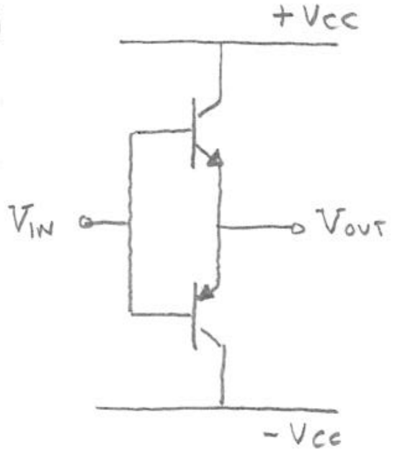
$$\Rightarrow \quad 3(V_D - 1)^2 = 5 - V_D$$

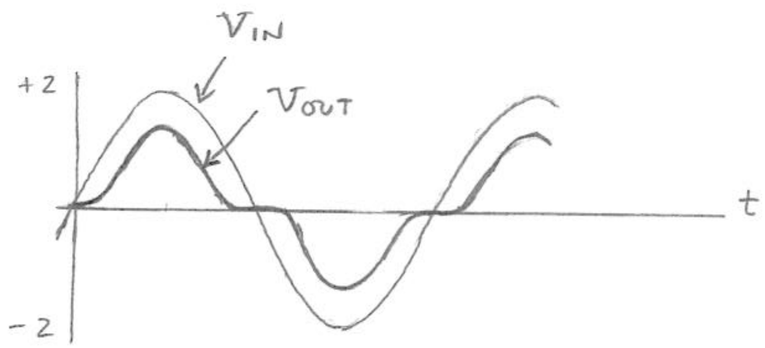
$$3V_D^2 - 5V_D - 2 = 0$$

$$V_D = \frac{5 \pm \sqrt{25+24}}{6} = \frac{5 \pm 7}{6} = \cancel{-\tfrac{1}{3}} \text{ or } +2V$$

MOSFETs matched, so $I = I_D = 0.2m \times (2-1)^2 = \underline{\underline{0.2\ mA}}$ [8]

c)





Circuit comprises two emitter followers, with NPN acting as follower when $V_{IN} \gtrsim 0.7V$ and PNP acting when $V_{IN} \lesssim -0.7V$. Problem is that for $|V_{IN}| \leq 0.7V$ both transistors are OFF and $V_{OUT} \simeq 0$

$\Rightarrow$ Cross-over distortion

Description and sketch assume load to ground. [8]

d) $I_{B2} = I_{E1} = (1+\beta_1)I_{IN}$ if Q1 active.

$I_{OUT} = I_{C1} + I_{C2} = \beta_1 I_{IN} + \beta_2 I_{B2} = [\beta_1 + \beta_2(1+\beta_1)]\,I_{IN}$ if both active

So $I_{OUT}/I_{IN} = \underline{\underline{\beta_1\beta_2 + \beta_1 + \beta_2}}$

d) cont'd

Saturation Voltage for Darlington is $\simeq 0 \cdot 9V$ (since $V_{E1} = V_{BE2} \simeq 0 \cdot 7$)

$\Rightarrow$ Max. I_{OUT} in $1k\Omega$ load is $(12 - 0 \cdot 9)/1k = \underline{\underline{11 \cdot 1 \text{ mA}}}$ [6]

e) Depl. Mode MOSFET has $V_{GS} = \phi \Rightarrow$ active if $V_{DS} \geq |V_t|$

Assume active initially. Then $I_D = K V_t^2 = 0 \cdot 4 \text{ mA}$

But this would imply $V = 0 \cdot 4m \times 10k = 4V$ and hence

$V_{DS} = 1V < |V_t| \Rightarrow$ mode must be $\underline{\underline{\text{TRIODE}}}$

For triode mode:

$$I_D = K \left[2(-V_t) V_{DS} - V_{DS}^2 \right] = (5 - V_{DS}) / 10k$$

With $K = 0 \cdot 1 \text{ mA}/V^2$, $V_t = -2V$ this becomes

$$4 V_{DS} - V_{DS}^2 = 5 - V_{DS}$$

$$V_{DS}^2 - 5 V_{DS} + 5 = 0$$

$>|V_t|$

$$V_{DS} = \frac{5 \pm \sqrt{25 - 20}}{2} = \cancel{3 \cdot 62} \text{ or } 1 \cdot 38 V$$

$$V = 5 - V_{DS} = \underline{\underline{3 \cdot 62V}}$$ [6]

f) For steady oscillation we require a solution to the characteristic equation with $s = j\omega$, substituting this form of s gives:

$$-j(1 + K)\omega^3 R^3 C^3 - 6\omega^2 R^2 C^2 + j5\omega RC + 1 = 0$$

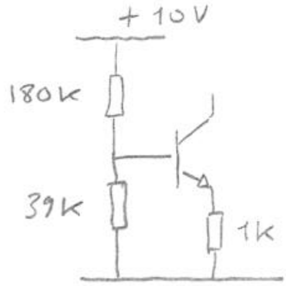
$Re\{LHS\} = 0 \Rightarrow \omega = \frac{1}{\sqrt{6} RC}$ (oscillation frequency)

$Im\{LHS\} = 0 \Rightarrow (1 + K)\omega^2 R^2 C^2 - 5 = 0$

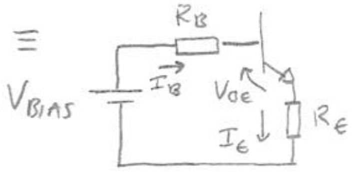
and with $\omega^2 R^2 C^2 = 1/6$ this becomes $1 + K - 30 = 0$

$$\underline{\underline{K = 29}}$$ [6]

2. a) Bias cct :



$\equiv$



$V_{BIAS} = \frac{39}{219} \times 10 = 1{\cdot}78$ V

$R_B = 39 // 180 = 32{\cdot}05$ k

KVL : $I_E R_E + V_{BE} + I_B R_B = V_{BIAS}$

$\Rightarrow I_E = \dfrac{V_{BIAS} - V_{BE}}{R_E + R_B/(1+\beta)}$

$= \dfrac{1{\cdot}78 - 0{\cdot}7}{1 + 32{\cdot}05/201}$

$= 0{\cdot}931$ mA

$I_c = \alpha I_E = \frac{200}{201} \times 0{\cdot}931 = \underline{\underline{0{\cdot}926 \text{ mA}}}$

$V_{OUT} = 10 - 4{\cdot}7 \times 0{\cdot}926 = \underline{\underline{5{\cdot}65 \text{ V}}}$

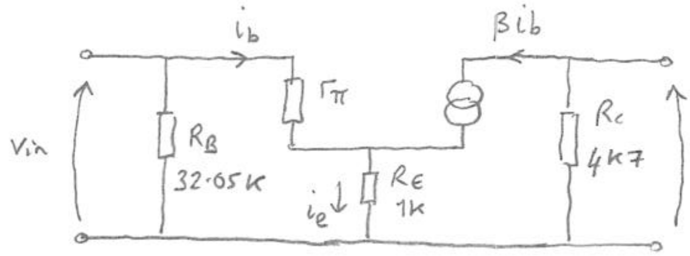
With $\beta = 150$, $I_E = (1{\cdot}78 - 0{\cdot}7)/[1 + 32{\cdot}05/151] = 0{\cdot}891$ mA

with $\beta = 250$, $I_E = (1{\cdot}78 - 0{\cdot}7)/[1 + 32{\cdot}05/251] = 0{\cdot}958$ mA

Corresponding I_c values are $\underline{\underline{0{\cdot}885 \text{ mA}}}$ and $\underline{\underline{0{\cdot}954 \text{ mA}}}$

β affects I_E only through $R_B/(1+\beta)$ term which is small cf R_E $\Rightarrow$ immunity to β variations [10]

b) SSEC :



$r_\pi = \beta V_T / I_c$

$= 5{\cdot}40$ kΩ

KVL : $V_{in} = i_b r_\pi + i_e R_E = i_b [r_\pi + (1+\beta) R_E]$ ... ①

Also $V_{out} = -\beta i_b R_c$ ... ②

② / ① $\Rightarrow$ $V_{out}/V_{in} = \dfrac{-\beta R_c}{r_\pi + (1+\beta)R_E} = \dfrac{-\alpha R_c}{r_\pi/(1+\beta) + R_E} = \dfrac{-\alpha R_c}{r_e + R_E}$

Putting $r_e = 5400/201$, $R_E = 1$k, $R_c = 4$k7, $\alpha = \frac{200}{201}$ $\Rightarrow$ $\frac{V_{out}}{V_{in}} = \underline{\underline{-4{\cdot}55}}$

$R_i = R_B // [V_{in}/i_b] = R_B // [r_\pi + (1+\beta)R_E] = 32{\cdot}05\text{k} // 206{\cdot}4\text{k} = \underline{\underline{27{\cdot}74 \text{ k}\Omega}}$

$R_o = \underline{\underline{4\text{k}7}}$ by inspection [14]

c) Gain with R_E bypassed is obtained by putting $R_E = 0$ in given equation. $A_v \to -\alpha R_c / r_e = -\dfrac{\beta R_c}{r_\pi} = \dfrac{-200 \times 4{\cdot}7}{5{\cdot}4} = -174$

So ratio $= \dfrac{174}{4{\cdot}55} = \underline{\underline{38}}$ [6]

3. a) Both MOSFETs carry the same drain current I_D, and $V_{G1} = V_{D1} = V_{OUT}$ for lower device

$$\Rightarrow \quad I_D = K_2 (V_G - V_{DD} - V_{t2})^2 = K_1 (V_{OUT} - V_{t1})^2$$

$$\sqrt{\ } \rightarrow \quad V_{OUT} - V_{t1} = \pm\sqrt{\frac{K_2}{K_1}} (V_G - V_{DD} - V_{t2})$$

Need to take -ve sign for both to be above threshold

$$\Rightarrow \quad V_{OUT} = V_{t1} + \sqrt{K_2/K_1} \cdot (V_{DD} + V_{t2} - V_G)$$

as req.

Putting $V_{t1} = 1V$, $\sqrt{\frac{K_2}{K_1}} = 0.5$, $V_{DD} = 10V$, $V_{t2} = -1V$, $V_G = 4V$

$$\Rightarrow \quad \underline{\underline{V_{OUT} = 3.5V}}$$

Check modes:

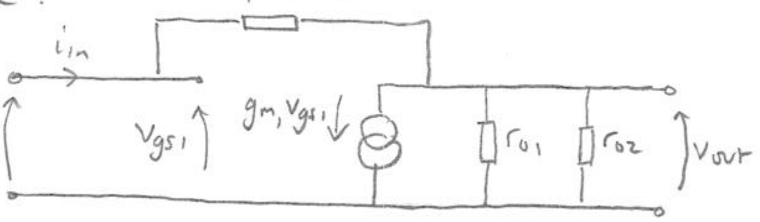
Upper FET req. $V_{DS} \leq V_{GS} - V_t$ $\quad V_{DS} = 3.5 - 10 = -6.5 \quad V_{GS} - V_t = 4 - 10 + 1 = -5$ $\quad \underline{\text{ok}}$

Lower FET req $V_{DS} \geq V_{GS} - V_t$ $\quad V_{DS} = 3.5 \quad V_{GS} - V_t = 3.5 - 1 = 2.5$ $\quad \underline{\text{ok}}$

$$I_D = K_1 (V_{out} - V_{t1})^2 = 1.25 \text{ mA}$$

[12]

b) SSEC:



$r_{o1} = r_{o2} = V_A / I_D$
$= 100V / 1.25 mA$
$= 80 k\Omega$

$$g_{m1} = 2\sqrt{K_1 I_D} = 2\sqrt{0.2m \times 1.25m} = 1 mA/V$$

KVL @ o/p $\Rightarrow$

$$g_{m1} V_{in} + \frac{V_{out}}{r_{o1}} + \frac{V_{out}}{r_{o2}} + \frac{V_{out} - V_{in}}{R_G} = 0$$

$$\Rightarrow \quad A_v = -\left(g_m - \frac{1}{R_G}\right) \cdot (r_{o1} \| r_{o2} \| R_G) = \underline{-39.8}$$

$$R_{in} = \frac{v_{in}}{i_{in}} = \frac{v_{in}}{(V_{in} - V_{out})/R_G} = \frac{R_G}{1 - A_v} = \underline{\underline{245 \ k\Omega}}$$

[14]

c) For the same bias conditions in lower MOSFET, would require a passive resistor of $(10 - 3.5)/1.2m = 5.4 k\Omega$ as load. Since this is $<< r_{o2}$, gain would be smaller.

[4]

4 a) When $V_{IN1} = V_{IN2} = 0$, common emitter voltage is $V_E \simeq -0.7V$

Tail current in this case is $I = (10-0.7)/20K = \underline{\underline{0.465\ mA}}$

Qs are matched and no differential i/p so

$$I_{C1} = I_{C2} = \frac{\alpha I}{2} = \frac{200}{201} \times \frac{0.465}{2} = 0.231\ mA = I_C$$

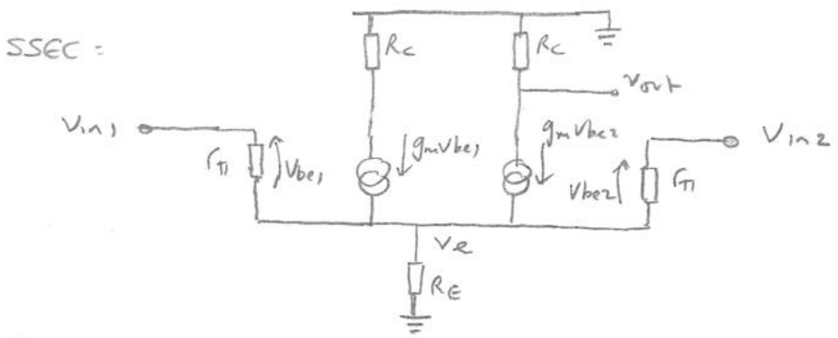
$$V_{OUT} = 10 - 0.231 \times 20 = \underline{\underline{5.37\ V}}$$

When $V_{IN1} = V_{IN2} = -2V$, $V_E \simeq -2.7V$

In this case $I = (10-2.7)/20K = \underline{\underline{0.365\ mA}}$

$\Rightarrow I_{C1} = I_{C2} = 0.182\ mA$ and $V_{OUT} = \underline{\underline{6.37\ V}}$ [10]

b) SSEC :



In case of purely differential i/p, where $V_{in1} = -V_{in2} = V_d/2$,

we know $V_e = 0$ from symmetry

$\Rightarrow V_{be2} = -V_d/2$ and $V_{out} = -R_C g_m V_{be2} = R_C g_m \frac{V_d}{2}$

Differential gain is then $A_d = \frac{V_{out}}{V_d} = \frac{R_C g_m}{2} = \frac{R_C I_C}{2V_T}$

If common mode voltage $V_{cm} = 0$, $I_C = 0.231\ mA$

$\Rightarrow \underline{\underline{A_d = 92.4}}$

Yes, A_d will vary with V_{cm} because it is proportional to I_C and, as shown in part a), I_C varies with V_{cm}. [12]

c) A_{cm} can be derived by splitting SSEC into two C.E. half-ccts

This gives $A_{cm} = -\frac{\alpha R_C}{r_e + 2R_E} \simeq -\frac{\alpha R_C}{2R_E}$

In this case we have $R_C = R_E = 20K$, $\alpha = \frac{200}{201}$ so $A_{cm} \simeq -0.5$

(exact formula gives -0.496)

A_{cm} could be reduced by replacing R_E with a current mirror; this would all the same bias condition to be achieved while having a much higher small-signal resistance in the tail. [8]