IMPORTANT: Besides your calculator and the sheets you use for calculations you are only allowed to have an A4 sized "copy sheet" during this exam. Notes, problems and alike are not permitted. Please submit your "copy sheet" along with your solutions. You may get your "copy sheet" back after your solutions have been graded. *Do not forget to write down units and convert units carefully!*

ELE222E INTRODUCTION TO ELECTRONICS (21727)
Final Examination ✐ 29 May 2006 ⌚ 13.00-15.00
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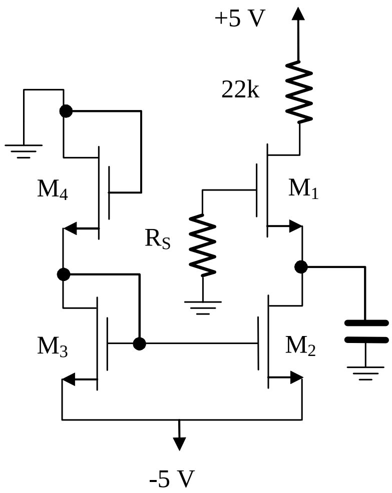
1. What is a semiconductor? How does a semiconductor differ from a conductor? Explain within two sentences. (5)

2. Explain the mechanisms by which charged carriers move through a silicon crystal. (2 sentences max, 5)

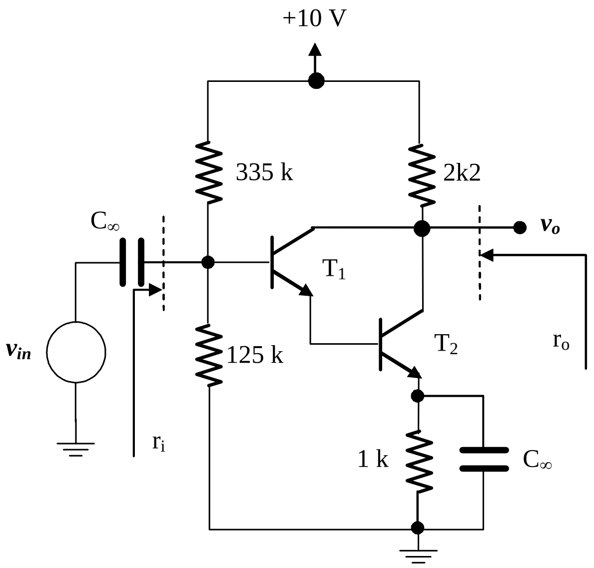


3. On the right you see a constant current source implemented by MOS transistors. The transistors M_2, M_3, and M_4 form the constant current source feeding the common source amplifier built with M_1.
   M_2, M_3, and M_4 are all identical with the following parameters:
   $\frac{1}{2}\mu_n C_{ox}\frac{W}{L} = 0{,}1 mA/V^2$, and V_{tn} = *1 V.*

   The parameters for M_1 are:
   $\frac{1}{2}\mu_n C_{ox}\frac{W}{L} = 0{,}2 mA/V^2$,
   $V_{A1} = \infty$, and V_{tn1} = *1 V.*

   a. Determine the currents and voltages in the constant current source. (15)

   b. Find the voltage gain from gate to drain with the AC signal source connected to the gate of M_1. (15)



4. For the circuit shown on the left, transistor parameters for identical T_1 and T_2 are $V_A = \infty$, V_T = 25 mV, $|V_{BE}|$ = 0,6 V, and $h_{fe} = h_{FE} = = \beta = 100$.

   a. Determine DC collector currents. (10)

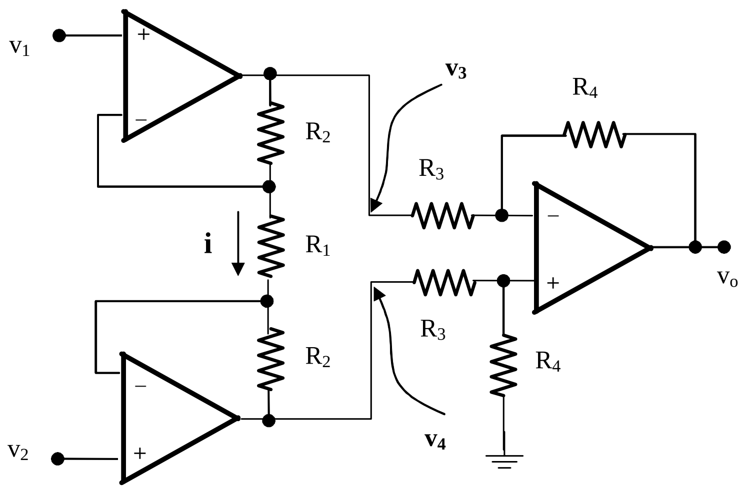
   b. Find the small signal voltage gain v_o/v_{in}. (15)

   c. Determine the input and output resistances. (10)

5. On the right you see an instrumentation amplifier made of 3 OPAMPs with resistors R_1 through R_4. Analyze the instrumentation amplifier in two stages:

   a. Find the voltages v_3 and v_4 as a function of the resistors and v_1 and v_2. HINT: First find the current **i** flowing through R_1. (15)

   b. Find v_o as a function of $(v_3 - v_4)$ and eventually find v_o as a function of all the 4 resistors and v_1 and v_2. (20)



GOOD LUCK!

SOLUTIONS:

1. The basic differences are
   a. There are two types of charged carriers in semiconductors, electrons and holes, respectively, whereas conductors only have electrons.
   b. Electrons can freely move within conductors whereas in semiconductors they have to pass an energy gap.

2. The mechanisms are
   a. Drift, and
   b. Diffusion.
   Check your textbook(s) for detailed explanation…

3. Since the reference current is the same in transistors M_3 and M_4,

$$\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS3}-V_{tn3})^2=\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS4}-V_{tn4})^2$$

Additionally, we see from the sketch that M_2 and M_3 operate in saturation because for each transistor, the gate is shorted to the drain.

a. $V_{GS3}+V_{GS4}=[0-(-5V)]=5V$, thus for identical transistors $\underline{\underline{V_{GS3}=V_{GS4}=2{,}5V}}$

Since M_2 and M_3 are identical transistors with $V_{GS3}=V_{GS2}$, the bias current is

$$\underline{\underline{I_4=I_3}}=\underline{\underline{I_{REF}=I_2=I_1=I_Q}}=\left[\frac{1}{2}\mu_n C_{ox}\frac{W}{L}\right]_2(V_{GS3}-V_{tn2})^2\underline{\underline{=0{,}225mA}}$$

To find V_{GS1} we use $I_Q=\left[\frac{1}{2}\mu_n C_{ox}\frac{W}{L}\right]_1(V_{GS1}-V_{tn1})^2=0{,}225mA$ and we obtain

$$V_{GS1}=\pm\sqrt{\frac{0{,}225mA}{0{,}2mA/V^2}}+1V=\begin{cases}2{,}06V\\0{,}06V\end{cases}.$$

From these two solutions only $\underline{\underline{V_{GS1}=2{,}06\text{ V}}}$ satisfies the condition for channel generation.

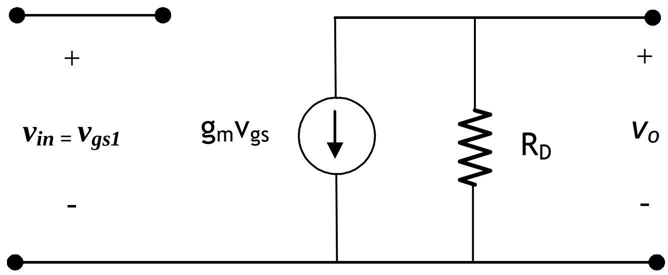
Since $\underline{\underline{V_{DS2}}}=-(-5V)-V_{GS1}=5-2{,}06\underline{\underline{=2{,}94V}}>V_{GS2}-V_{tn2}=2{,}5-1=1{,}5V$, M_2 is biased in saturation region.

For M1 to operate in saturation $V_{DS1}>V_{GS1}-V_{tn1}=2{,}06-1=1{,}06V$.

Since $V_{G1}=0$ V, $V_{S1}=-2{,}06$V, that is
$V_{DS1}=V_{D1}-V_{S1}=V_{D1}+2{,}06V>1{,}06V\Rightarrow\underline{\underline{V_{D1}>-1V}}$.
$V_{D1}=5V-I_Q R_D=0{,}05V\geq-1V$ Therefore M_1 operates in saturation.

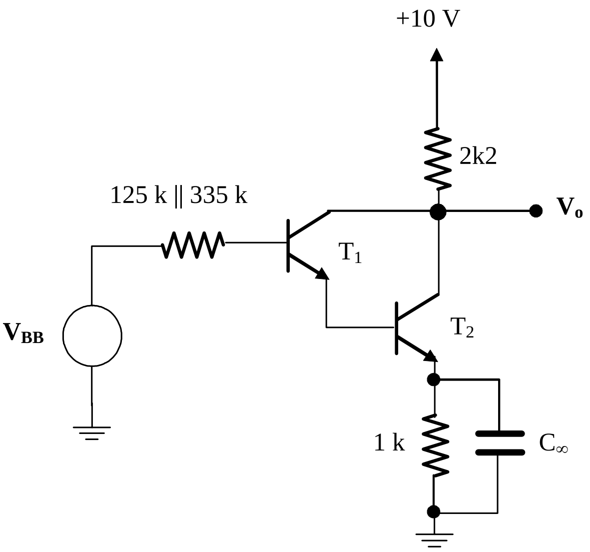
b. $A_v = \dfrac{v_o}{v_{in}} = -g_{m1} R_D$

$$\underline{\underline{g_{m1}}} = \sqrt{\left[2\mu_n C_{ox}\frac{W}{L}\right]_1 I_Q} = \underline{\underline{0{,}212 mA/}}$$



Thus

$$\underline{\underline{A_v = \frac{v_o}{v_{in}}}} = -g_{m1} R_D = \underline{\underline{-4{,}66 (V/V)}}$$



4. Transistor parameters are identical for T_1 and T_2: $V_A = \infty$, V_T = 25 mV, $|V_{BE}|$ = 0,6 V, and $h_{fe} = h_{FE}$ = = ß = 100.

   a. Using Thevenin equivalent circuit
   $\underline{\underline{R_{BB}}} = R_1 \parallel R_2 = \underline{\underline{91k}}$ and

   $$\underline{\underline{V_{BB}}} = \frac{125k}{125k + 335k} 10V = \underline{\underline{2{,}72V}}$$

   Thus,

   $$V_{BB} = R_{BB} I_{B1} + V_{BE1} + V_{BE2} + 1k \cdot I_{E2}$$

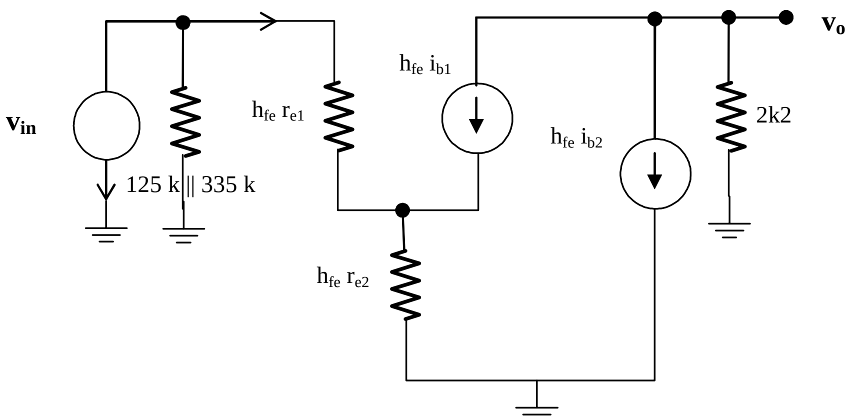
   where

   $$I_{E2} = (h_{FE} + 1) I_{B2} = (h_{FE} + 1) I_{E1} = (h_{FE} + 1)^2 I_{B1}$$

yielding $\underline{\underline{I_{C1}}} = h_{FE} \dfrac{V_{BB} - V_{BE1} - V_{BE2}}{R_{BB} + 1k \cdot (h_{FE} + 1)^2} = 100 \dfrac{2{,}72V - 0{,}6V - 0{,}6V}{91k + 1k \cdot (101)^2} \cong \underline{\underline{0{,}015mA}}$

$$\Rightarrow \underline{\underline{I_{C2}}} = h_{FE} \cdot (h_{FE} + 1) I_{B1} \cong \underline{\underline{1{,}50mA}}$$

b. After drawing the equivalent small signal circuit like on the right,



$$\underline{\underline{r_{e1}}} = \frac{V_T}{I_{C1}} = \underline{\underline{1k696}}$$

$$\underline{\underline{r_{e2}}} = \frac{V_T}{I_{C2}} = \frac{V_T}{h_{fe}(1 + h_{fe}) I_{B1}}$$

$$= \frac{r_{e1}}{(1 + h_{fe})} = \underline{\underline{16{,}8\Omega}}$$

$$v_o = -2k2 \cdot h_{fe}(i_{b1} + i_{b2}) = -2k2 \cdot h_{fe}\left(\left(h_{fe} + 1\right) + 1\right) i_{b1} = -2k2 \cdot h_{fe}\left(h_{fe} + 2\right) i_{b1}$$

$$v_{in} = i_{b1} h_{fe} r_{e1} + i_{b2} h_{fe} r_{e2} = i_{b1} h_{fe} r_{e1} + i_{b1}(h_{fe} + 1) h_{fe} \frac{r_{e1}}{h_{fe} + 1} = 2 h_{fe} r_{e1} i_{b1}$$

$$\underline{\underline{A_v}} = \frac{v_o}{v_{in}} = -\frac{2k2 \cdot h_{fe}\left(h_{fe}+2\right)i_{b1}}{2h_{fe}r_{e1}i_{b1}} = -\frac{2k2 \cdot \left(h_{fe}+2\right)}{2r_{e1}} = \underline{\underline{-66{,}2}}$$

c. $r_{in}^{'} = \frac{v_{in}}{i_{in}} = \frac{v_{in}}{i_{b1}} = 2h_{fe}r_{e1} \cong 339k$

$\underline{\underline{r_{in}}} = r_{in}^{'} \,||\, 125k \,||\, 335k = \underline{\underline{71k77}}$

To determine the output resistance study the circuit again. It very much resembles common emitter collector output circuit for which $r_o = R_C$. Therefore $\underline{\underline{r_o = 2k2}}$

5. Analyze the instrumentation amplifier:

a. Using the ideal properties of ideal OPAMP, the current I flowing through R_1 is found: $i = \frac{v_1 - v_2}{R_1}$. Since i flows also through both R_2, $v_3 = v_1 + iR_2$ and $v_4 = v_2 - iR_2$.

Thus $\underline{\underline{v_3 = \left(1+\frac{R_2}{R_1}\right)v_1 - \frac{R_2}{R_1}v_2}}$ and $\underline{\underline{v_4 = \left(1+\frac{R_2}{R_1}\right)v_2 - \frac{R_2}{R_1}v_1}}$.

b. From class we know that $\underline{\underline{v_o}} = \frac{\left(1+\frac{R_4}{R_3}\right)}{\left(1+\frac{R_3}{R_4}\right)}v_4 - \frac{R_4}{R_3}v_3 = \underline{\underline{\frac{R_4}{R_3}\left(v_4 - v_3\right)}}$. Inserting result found in (b) here yields $\underline{\underline{v_o}} = \frac{R_4}{R_3}\left(v_4 - v_3\right) = \underline{\underline{\frac{R_4}{R_3}\left(1+\frac{R_2}{R_1}\right)\left(v_2 - v_1\right)}}$