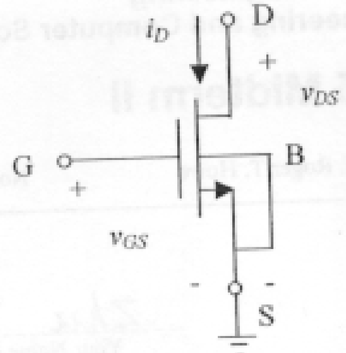
1. Short-Channel MOSFET Model [17 points].



Device parameters:

$C_{ox} = 4$ fF/ μm^2
$W = 2.5$ μm
$L = 0.1$ μm
$V_{Tn} = 1$ V
$V_{DS,sat} = 0.75$ V
$\lambda_n = 0.05$ V^{-1}
$v_{sat} = 10^7$ cm/s

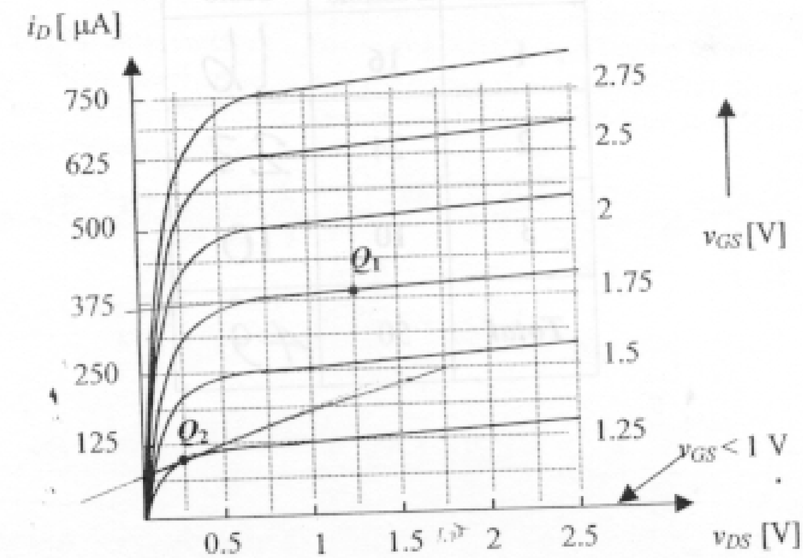
An improved model for the velocity-saturated MOSFET is:

$$i_D = C_{ox} W v_{sat} (v_{GS} - V_{Tn}) \left(\frac{v_{DS}}{V_{DS,sat}} \right) \left(1 - \frac{v_{DS}}{2V_{DS,sat}} \right) \text{ when } v_{DS} \le V_{DS,sat} = 0.75 \text{ V (triode region)}$$

$$= C_{ox} W v_{sat} (v_{GS} - V_{Tn}) \left(\frac{v_{DS}}{V_{DSsat}} - \frac{v_{DS}^2}{2 V_{DSsat}^2} \right)$$

$$i_D = \left(\frac{1}{2} \right) C_{ox} W v_{sat} (v_{GS} - V_{Tn}) \left[\frac{1 + \lambda_n v_{DS}}{1 + \lambda_n V_{DS,sat}} \right] \text{ when } v_{DS} > V_{DS,sat} = 0.75 \text{ V (saturation region)}$$

The drain characteristics for this short-channel MOSFET model are:



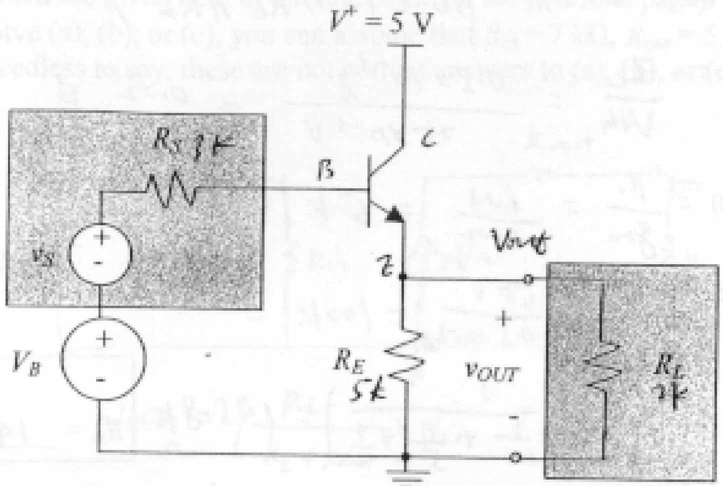
(a) [4 pts.] What is the small-signal transconductance g_m at the operating point Q_1 in μS? You can find the answer either from the drain current equations or graphically: in either case, be sure to explain your method clearly.

(b) [4 pts] What is the small-signal drain resistance r_o at the operating point Q_1 in kΩ? For this parameter at this operating point, graphical techniques don't give a sufficiently accurate answer.

(c) [4 pts.] What is the transconductance g_m at the operating point Q_2 in μS? You can find the answer either from the drain current equations or graphically: in either case, be sure to explain your method clearly.

(d) [4 pts] What is the small-signal drain resistance r_o at the operating point Q_2 in kΩ? You can find the answer either from the drain current equations or graphically: in either case, be sure to explain your method clearly.

2. BJT voltage buffer [18 pts.]



Given:
$\beta_o = 100$
$V_{th} = 25$ mV
$V_A = 50$ V
$V_{CEsat} = 0.1$V

$R_S = 3$ kΩ
$R_E = 5$ kΩ
$R_L = 2$ kΩ

(a) [3 pts.] Find the numerical value of V_B such that $V_{OUT} = 2.5$ V. Your answer should be accurate to +/- 5%. Notes: (i) the gray boxes indicate small-signal elements that can be neglected for the DC bias analysis and (ii) the DC base current I_B of the bipolar transistor can be neglected for the bias solution.

(b) [3 pts.] What is the numerical value of the DC collector current I_C for this amplifier?

(c) [4 pts.] Find the numerical value of the input resistance R_{in} of this amplifier in kΩ.

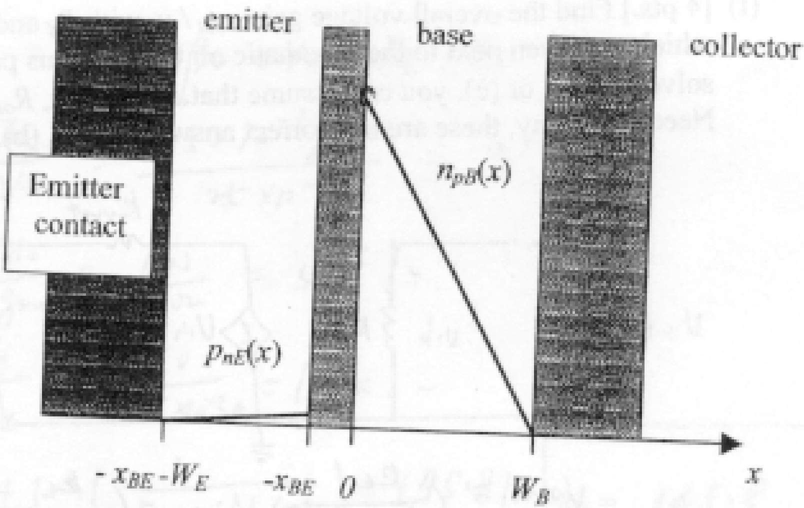
(d) [4 pts.] Find the numerical value of the output resistance R_{out} in kΩ.

(e) [3 pts.] Find the numerical value two-port parameter A_v, the open-circuit voltage gain, for this amplifier.

(f) [4 pts.] Find the overall voltage gain v_{out} / v_s with R_S and R_L present (values of which are given next to the schematic on the previous page). If you couldn't solve (a), (b), or (c), you can assume that $R_{in} = 7\ \mathrm{k}\Omega$, $R_{out} = 5\ \mathrm{k}\Omega$, and $A_v = 0.8$. Needless to say, these are not correct answers to (a), (b), or (c).

(g) [3 pts.] Suppose that the input voltage $v_s(t) = \hat{v}_s \cos(\omega t)$. What is the maximum amplitude $\hat{v}_s$ for which the small-signal, two-port model you've derived in parts (b)-(c) is reasonably accurate? You can assume that the frequency of $v_s(t)$ is low enough that capacitors can be neglected. *Justify your answer.*

3. npn bipolar transistors [10 pts.]



Given:
Base width = W_B = 150 nm = 0.15 μm
Emitter-base junction area = A_E = 25 μm²
Emitter width = W_E = 100 nm = 0.1 μm
Base-collector junction area = A_C = 50 μm²
Electron diffusion constant in base: D_n = 20 cm²/s
Hole diffusion constant in emitter: D_p = 7 cm²/s
Electron charge: q = -1.6 x 10⁻¹⁹ C
Intrinsic concentration: $n_i = 10^{10}$ cm⁻³

(a) [4 pts.] The collector current for this forward-active npn bipolar transistor is I_C = 25 μA. From the cross section of the device shown above, find the numerical value of the minority electron concentration at x = 0, at the base side of the emitter-base depletion region.

(b) [3 pts.] For the bias conditions in part (a), the base-emitter voltage V_{BE} = 697.5 mV. What is the doping concentration N_A in the base? If you couldn't solve part (a), you can use $n_{pB}(0) = 8 \times 10^{14}$ cm^{-3}, which is not the correct answer to part (a), of course.

(c) [3 pts.] The minority hole concentration in the emitter at the edge of the emitter-base depletion region is (0.04)*(your answer to part (a)). What is the forward-active DC current gain β_F for this transistor? Note that you don't need to have answered part (a) in order to answer this part!