UE4002 Autumn 2006

Each part of each question carries equal marks.
The body effect may be ignored in each question.
The following equation is given for the drain current of an NMOS in saturation:

$$I_D = \frac{K_n' W}{2 L}(V_{GS} - V_{tn})^2(1 + \lambda_n V_{DS})$$

For dc biasing calculations take $\lambda_n = \lambda_p = 0$.
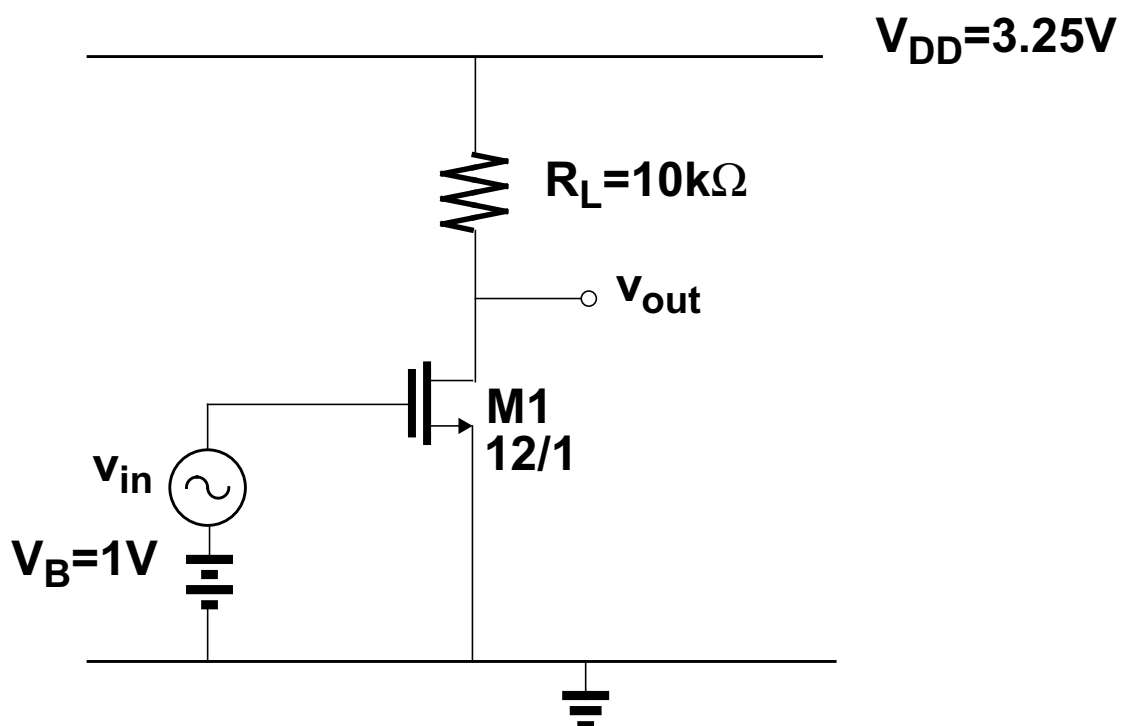In each question, capacitances other than those mentioned may be ignored.

Question 1

Figure 1

Figure 1 shows a common-source stage with a resistive load.
Biasing and component values are as shown in Figure 1.
Take $K_n' = 200\mu A/V^2$, $V_{tn} = 0.75V$.
  (i)   Draw the small-signal equivalent circuit for the circuit shown in Figure 1.
  (ii) Derive an expression for the small-signal voltage gain (v_{out}/v_{in}) in terms of R_L and the small-signal transistor parameters of M1.
  (iii) Show that M1 is in saturation.
        What is the headroom of M1 (i.e. the amount by which V_{DS} of M1 exceeds the minimum value of V_{DS} required by M1 to be in saturation)?
        Calculate the small-signal voltage gain in dB.
        Assume $g_{ds1} \ll 1/R_L$.
  (iv) The gain of the circuit is increased by changing only the W/L ratio of M1.
        What is the maximum value of W/L such that M1 is still in saturation?
        What is the small-signal voltage gain in dB with this value of W/L?
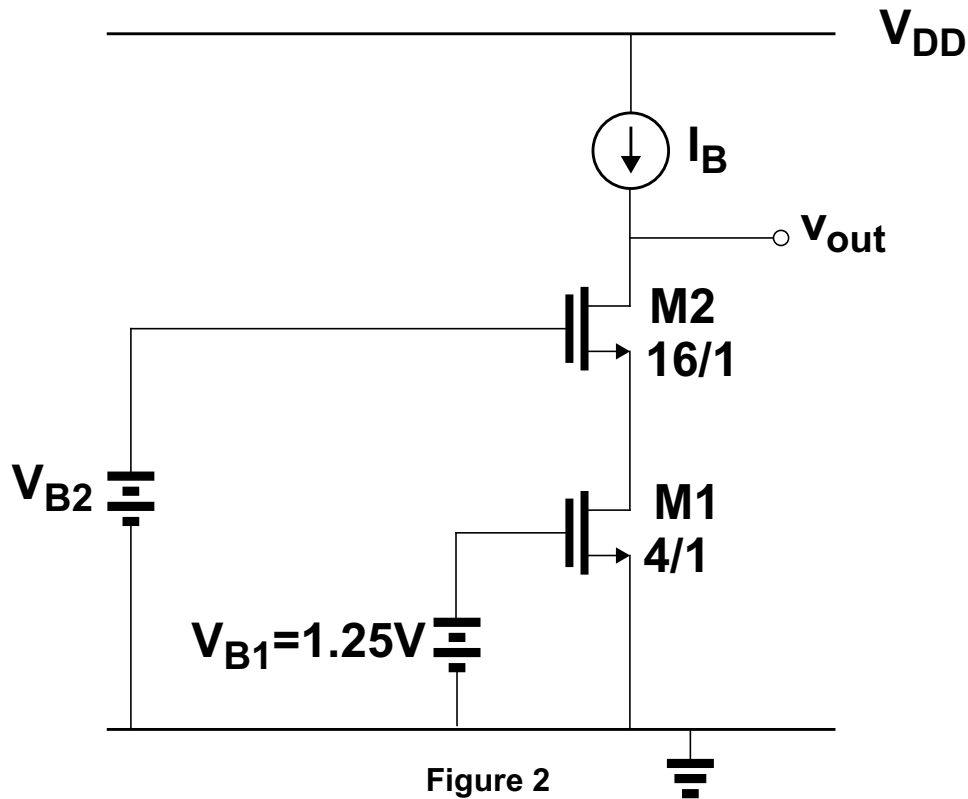
Figure 2

Figure 2 shows a cascode stage with a current source load.
Biasing and transistor dimensions are as shown in Figure 2.
Take $K_n^{'}$=200µA/V^2, V_{tn}= 0.75V.

    (i)   What is the minimum value of V_{B2} such that M1 is in saturation? (Assume M2 is in saturation for this calculation). What is then the minimum voltage at the output node (v_{out}) such that M2 is in saturation?

    (ii)   Draw a small-signal equivalent circuit of the cascode stage, showing how to measure the small-signal output resistance i.e. the resistance looking into the node v_{out}.

    (iii)   Derive an expression for the small-signal output resistance in terms of the small-signal parameters of M1 and M2. Simplify the expression assuming $g_{m1}, g_{m2}, >> g_{ds1}, g_{ds2}$.

    (iv)   Calculate the small-signal output resistance assuming all transistors are in saturation. Take λ_n=0.04/L V^{-1} with L in microns.
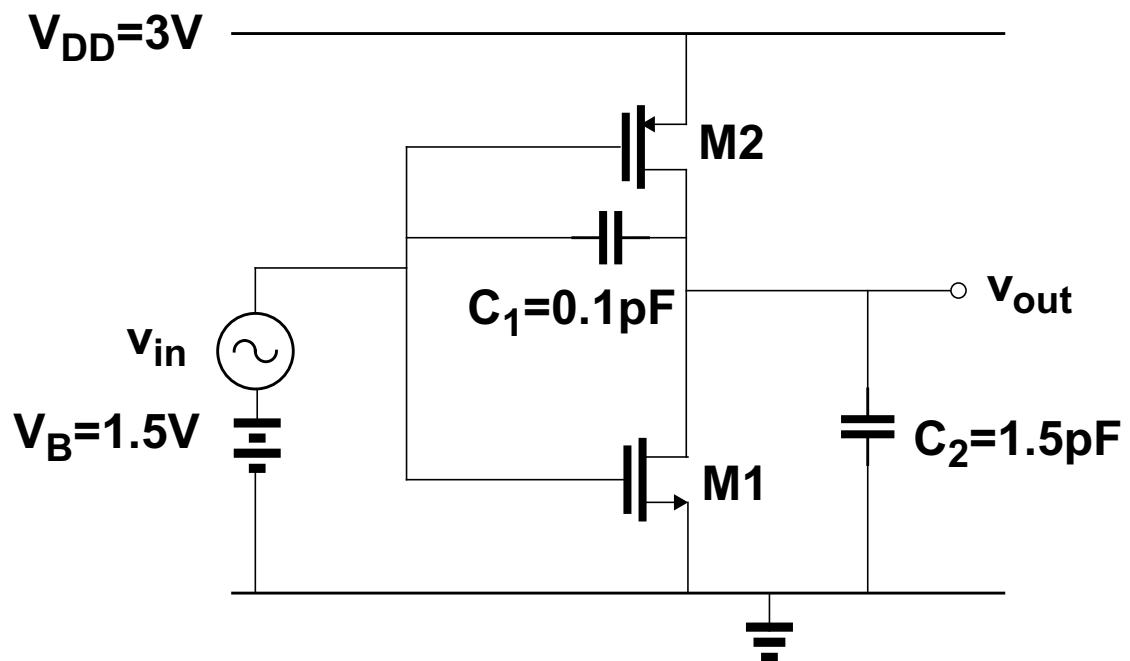
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Figure 3

Figure 3 shows a CMOS inverter stage.
Biasing and component values are as shown in Figure 3.
Take V_{tn}=0.7V, V_{tp}=-0.7V, λ_n=λ_p=0.04V^{-1}.

  (i)   Draw the small-signal equivalent circuit for the CMOS inverter stage shown in Figure 3.
  (ii) Derive an expression for the high-frequency transfer function.
  (iii) Calculate the dc gain in dB, and the break frequencies (i.e. pole and/or zero frequencies).
        Assume both transistors are in saturation with a drain current of 200μA.
  (iv) Draw a Bode diagram of the gain response.
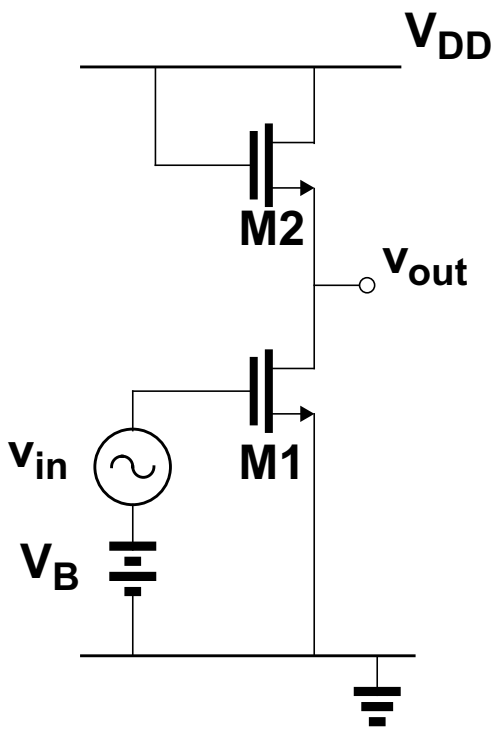   What is the value of gain at frequencies well above the break frequencies?
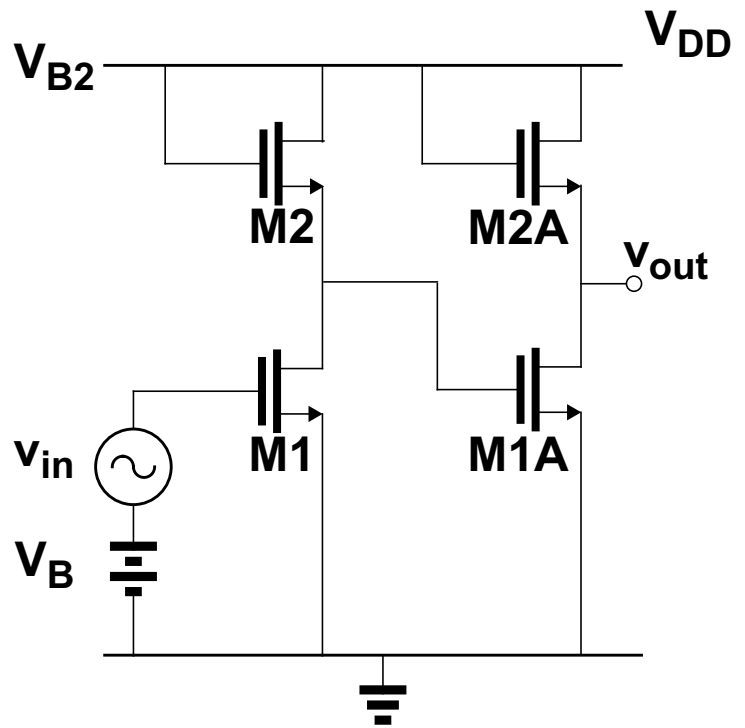
Figure 4a

Figure 4b

For the circuits shown in Figure 4a and 4b, assume all transistors are operating in saturation and $g_{m1}, g_{m2} \gg g_{ds1}, g_{ds2}$.
Only thermal noise sources need be considered.

Take Boltzmann's constant $k = 13.8 \times 10^{-24} \text{J/}^\circ\text{K}$, temperature $T = 300^\circ\text{K}$.

(i)   Draw the small-signal model for the circuit shown in Figure 4a.
        What is the small-signal voltage gain (v_{out}/v_{in}) in terms of the small-signal parameters of M1 and M2?

(ii)   What is the input-referred noise voltage density in terms of the small-signal parameters of M1 and M2, Boltzmann's constant k and temperature T?

(iii) Calculate the input-referred noise voltage density if $g_{m1} = 400\mu\text{A/V}$, $g_{m2} = 100\mu\text{A/V}$.
        What is the noise voltage density at the output?
        (Note: the units $\mu\text{A/V}$ are equivalent to μS).

(iv)   The gain stage shown in Figure 4a is cascaded with an identical gain stage, with identical transistor dimensions, as shown in Figure 4b. Assume also that M1A has the same biasing conditions as M1.
        Calculate the input-referred noise voltage density of the circuit shown in Figure 4b.
        What is the total input-referred noise in a bandwidth of 1MHz to 10MHz?