1. (30 pts) Consider the instrumentation amplifier where $R_{1x} = R_1$ and $R_{2x} = R_2(1+\alpha)$. First, assume all op amps are ideal:

(a) (6 pts) Express V_o in terms of V_{I1}, V_{I2}, R_1, R_2, R_3 , R_4, and α.

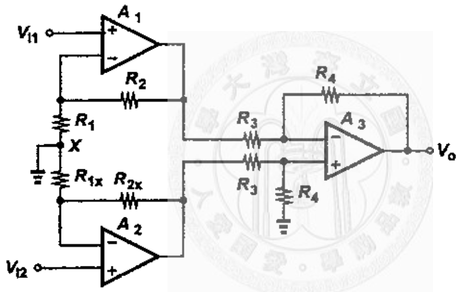
(b) (8 pts) Repeat (a) if node X is disconnected from ground.

(c) (8 pts) Derive CMRR for part (a) and part (b).

Now, assume α equal to 0. And, R_2=$2R_1$ and R_4=$2R_3$.

(d) (4 pts) If all of the op amps have output range from 0 V to 10 V, what is the output voltage for (a) (node X is connected to ground) if $V_{I1} = 5.5V$ and $V_{I2} = 5.6V$?

(e) (4 pts) Repeat (d) if node X is disconnected from ground.

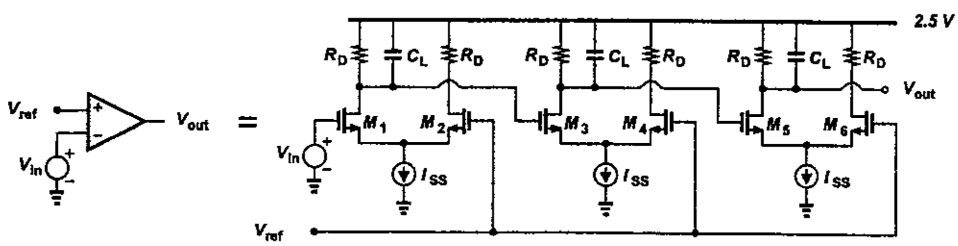


2. (20 pts) Shown in the following figure is a multi-stage amplifier, in which $I_{ss} = 1mA$, $R_D = 1K$, $\frac{W}{L} = 50$, $\mu_n C_{ox} = 0.5mA/V^2$, and $V_{ref} = 2V$. Note that V_{in} contains a 2-V DC voltage and a small signal voltage source. Note that all NMOS are identical and have $V_{TH} = 0.5V$

(a) (7 pts) What is low-frequency small-signal gain of this amplifier ($\frac{V_{out}}{V_{in}}$)?

(b) (7 pts) If only $C_L = 1pF$ is needed to calculate frequency response , estimate 3-dB frequency.

(c) (6 pts) If this amplifier operates without any extra circuitry, do we need to do any frequency compensation? Please explain.



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3. Fig. 3 shows the intrinsic carrier concentration (n_i), electron concentration (n), and conductivity (σ) of a semiconductor material. T is the absolute temperature, and the typical operation temperature of most semiconductor devices is around 300~400K.
   (a) This semiconductor material is doped. What are the doping type and doping level? Please explain. (5 pts)
   (b) In the temperature range of 300~400K, the conductivity decreases with rising temperature while the carrier concentration has no significant change, so apparently the reduction in conductivity is caused by decreasing mobility. Please explain why the mobility decreases with temperature in this range. (5 pts)
   (c) Fig. 3 shows that the intrinsic carrier concentration in the log scale has nearly linear dependence on the inverse temperature. At a specific temperature point the relationship can be approximately expressed as $\Delta(\ln n_i)/\Delta(1/T) \cong -C$. Consider that $n_i^2 = N_C N_V \exp(-E_g/kT)$, and the values of N_C, N_V, and E_g do not change as significantly as n_i in this temperature range. Please estimate the band gap energy of this semiconductor material at this temperature point. (10pts)

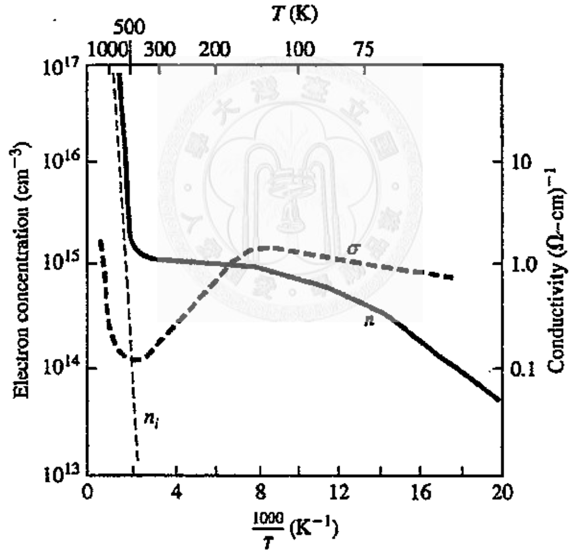

Fig. 3

4. Consider a pn junction diode made of a semiconductor material with atom density N_o, intrinsic carrier concentration n_i, band gap energy E_g, and electrical permittivity ε_s. The active doping levels are N_1 and N_2 ($N_2 << N_1$) for its two doped regions, and most voltage drops in the p-region. The excess minority carrier lifetime is τ in both regions. The minority carrier diffusivity and mobility are D_1 and μ_1 for the n-region and D_2 and μ_2 for the p-region. The electron charge is q, and the thermal voltage is $V_T = kT/q$.
   (a) Please use the appropriate symbols and parameters provided above to express the reverse saturation current density (J_s). (10 pts)
   (b) Please express the depletion width (W_{dep}) and maximum electric field (E_{max}) when a reverse bias V_r is applied on this p-n diode. (10 pts)
   (c) Now consider that an intrinsic region with thickness $W = 3W_{dep}$ is inserted into the junction to form a p-i-n diode. What is the junction built-in voltage V_o of this p-i-n diode? (10 pts)

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