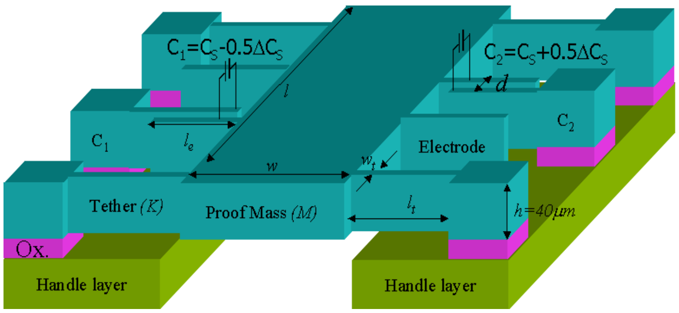
ECE6422 *Interface IC Design for MEMS & Sensors* **Fall 2015**

HOMEWORK #2
(DUE: 09/24/2015 IN CLASS)

1. **Design of a differential capacitive micro-accelerometer on silicon-on-insulator (SOI) substrate**:

Part I. Physical design of the micromechanical element:
The figure below shows the schematic of a differential capacitive accelerometer. The design specifications are provided in the table.



ρ : Volume density of silicon =2.3gr/cm^3
E_x : Young's modulus of silicon =166GPa <110>
μ_{eff} : Effective viscosity of air =1.8×10^{-5} P.s
n : Total number of the electrodes
D : Air damping
M : Proof mass
le : Electrode length
C_S : Rest capacitor of the sense electrodes

$$D = n\mu_{eff}\, l_e \left(\frac{h}{d}\right)^3$$

Brownian Noise Equivalent Acceleration (*BNEA)*	< 20μg/√Hz
Mechanical Sensitivity *(S)*	0.2pF/g
$V_{PULL\text{-}IN}$	>2.0V
Quality factor *(Q)*	0.7
Capacitive Gap *(d)*	2μm
Device layer thickness *(h)*	40μm
Overall size	<6×6mm^2
Sensor Bandwidth *(BW)*	500Hz

a. Calculate the dimensions of the proof mass, tethers, and sense electrodes and also the number of required sense electrodes at each side of the proof mass to satisfy the desired specifications. Explain your design flow. You can ignore the mass of electrodes and tethers in comparison with the proof mass.

b. Implement your accelerometer design in COMSOL and perform the simulations listed below. The values calculated in part (a) provide a good starting point for your design, but you may need to change some of them to meet all the design requirements. (Hint: you should use the Electromechanics Interface (emi) which is part of the Structural Mechanics module. Check model "Biased resonator" under MEMS module in the model libraries for exemplary setups.)

   i. Eigenfrequency study to find the fundamental resonant frequency of the accelerometer. Show that the resonant frequency changes as the polarization voltage varies. Also you need to make sure that the second resonant frequency of the structure is at least two to three times larger than the fundamental frequency.

   ii. Frequency-Domain study to obtain the frequency response and the 3-dB bandwidth of the accelerometer (~500 Hz).

   iii. Stationary study to find the mechanical sensitivity of the accelerometer in terms of the change in capacitance due to input acceleration (~200 fF/g).

   iv. Finally, your simulated design should meet the BNEA and overall size specifications.

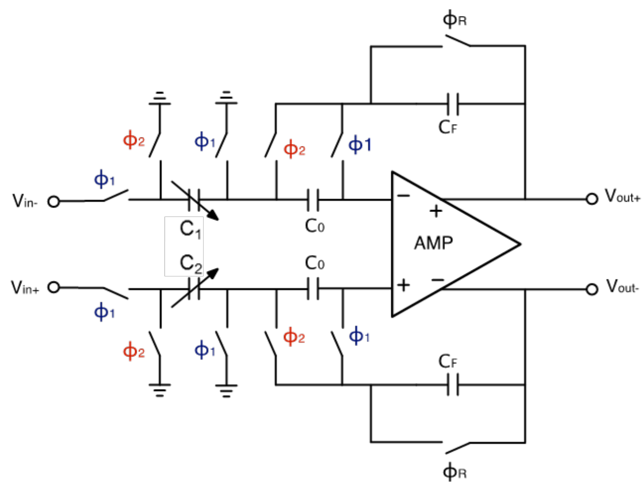
Part II. Switched Capacitor Charge Amplifier interface:

The accelerometer is interfaced with the fully-differential switched-capacitor circuit shown below, $\Phi 1$ and $\Phi 2$ are non-overlapping clock phases and ΦR is a reset clock that is in-phase with $\Phi 1$ (closes with $\Phi 1$ but opens up slightly before $\Phi 1$). C_1 and C_2 are differential capacitances of the micro-accelerometer ($C_1=C_0-0.5\Delta C_S$ and $C_2=C_0+0.5\Delta C_S$). Assume that the Op-Amp has an open loop gain of A_0, infinite input resistance, and an input offset voltage of V_{OS} at each of its inputs (with opposite polarities).

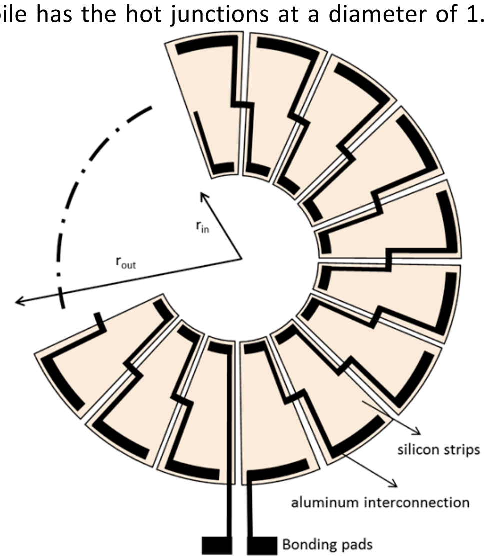
a. Draw the simplified diagrams of the circuit for each clock phase (i.e., $\Phi 1$ high - $\Phi 2$ low, and, $\Phi 1$ low - $\Phi 2$ high).

b. What is the function of capacitance C_o and why is it used? What is a better choice of value for C_0: 2pF or 0.2pF, and why?

c. Derive an expression for the differential output ($\Delta V_{out}=V_{out+}-V_{out-}$) in terms of the two input voltages (V_{in+} and V_{in-}). Under what condition the overall transfer function ($\Delta V_{out}/\Delta V_{in}$ when $C_1=C_2$) will become independent of the op-amp gain ($\Delta V_{in}=V_{in+}-V_{in-}$)? You must show your work to receive full credit.



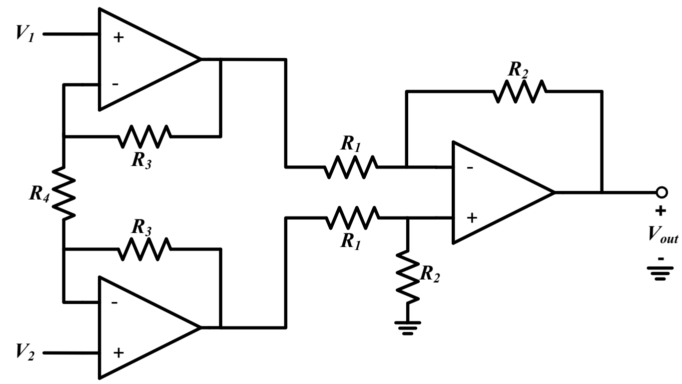
2. **Circular Thermopile Design**: A thermopile is integrated in a closed silicon membrane. The membrane is monocrystalline silicon with a diameter of 3.6 mm and a thickness of 5 μm (κ_{Si}=150 W/K-m). The integrated silicon-aluminum thermopile has the hot junctions at a diameter of 1.8 mm, and the cold junctions are at the edge of the rim at 3.6 mm as shown in the figure below. The Seebeck coefficient of the silicon, α_{Si} is 0.6 mV/K (that of aluminum is negligible at approximately -1.7 μV/K). The sheet resistance of the silicon, R_S, is 50 Ω/square (again that of the aluminum can be ignored). What is the sensitivity of the thermopile (V_{out}/P_{in}), if its electrical resistance is 80 kΩ (if no separation between the silicon strips is required, and the aluminum does not require extra space)? For more information, refer to the following paper.



"Thermal Sensors Based on the Seebeck Effect", AW Van Herwaarden, PM Sarro, Sensors and Actuators, 1986

3. For **the instrumentation amplifier** shown below, assuming that the op amps are ideal:

   a) Derive the relationship between the output voltage V_{out} and the input voltages V_1 and V_2.



   b) This circuit is used for the readout of the voltage of a differential resistive Wheatstone bridge of a micromachined pressure sensor. If the available supply voltage is 3.0V (no negative supply available) and the maximum fractional change in each resistance of the pressure sensor is 5%, give values for the resistances of the circuit to have a full-scale output swing. Comment on how you would choose your values to increase the dynamic range of the circuit. Draw the Wheatstone bridge to show how it is interfaced with the circuit.

4. A two-stage MOS amplifier is shown below. Note that the first stage incorporates diode-connected rather than current source loads.

   a. Assuming that all transistors are operating in saturation and $(W/L)_{1,2}$ =50/0.6, $(W/L)_{3,4}$=10/0.6, $(W/L)_{5,6}$ =20/0.6 and $(W/L)_{7,8}$=56/0.6, calculate the input referred noise voltage if μ_nC_{ox} = 75μA/V^2 and μ_pC_{ox} = 30 μA/V^2. (I_{SS}=0.5mA)

   b. How would this value change if the transistor flicker noise is considered? (Use K_{fp}=0.3×10^{-25} V^{2}F and K_{fn} = 1 x 10^{-25} V^{2}F).

   c. Calculate the flicker noise corner frequency of the op-amp.