MEMS Capacitor Sensors and Signal Conditioning

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4-2-11 capacitor_sensors.ppt

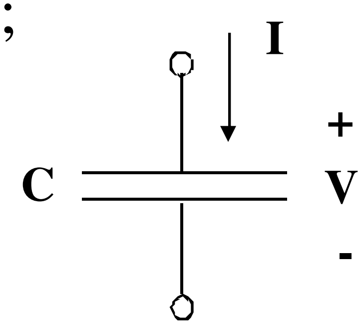
OUTLINE

Capacitors
Capacitors as Sensors
Chemicapacitor
Diaphragm Pressure Sensor
Condenser Microphone
Capacitors as Electrostatic Actuators
Signal Conditioning
References
Homework

CAPACITORS

Capacitor - a two terminal device whose current is proportional to the time rate of change of the applied voltage;

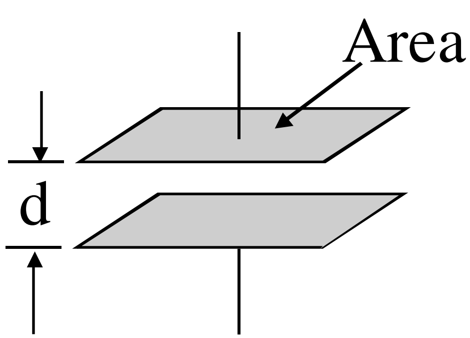
$$I = C\, dV/dt$$



a capacitor C is constructed of any two conductors separated by an insulator. The capacitance of such a structure is:

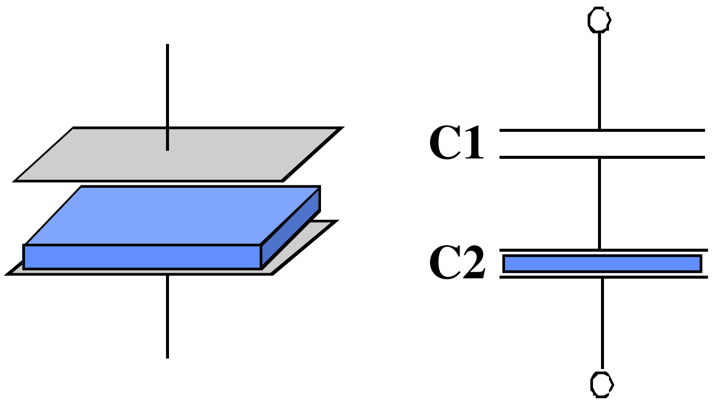
$$C = \varepsilon o\ \varepsilon r\ Area/d$$

where
εo is the permitivitty of free space
εr is the relative permitivitty
Area is the overlap area of the two conductor separated by distance d
$\varepsilon o = 8.85E\text{-}14$ F/cm
εr air = 1
$\varepsilon r\ SiO_2 = 3.9$



OTHER CAPACITOR CONFIGURATIONS

Two Dielectric Materials between Parallel Plates



$$C_{Total} = C1C2/(C1+C2)$$

Example: A condenser microphone is made from a polysilicon plate 100 µm square with 1000Å silicon nitride on it and a second plate of aluminum with a 1µm air gap. Calculate C and C' if the aluminum plate moves 0.1 µm.

DIELECTRIC CONSTANT OF SELECTED MATERIALS

Vacuum	1
Air	1.00059
Acetone	20
Barium strontium titanate	500
Benzene	2.284
Conjugated Polymers	6 to 100,000
Ethanol	24.3
Glycerin	42.5
Glass	5-10

Methanol	30
Photoresist	3
Plexiglass	3.4
Polyimide	2.8
Rubber	3
Silicon	11.7
Silicon dioxide	3.9
Silicon Nitride	7.5
Teflon	2.1
Water	80-88

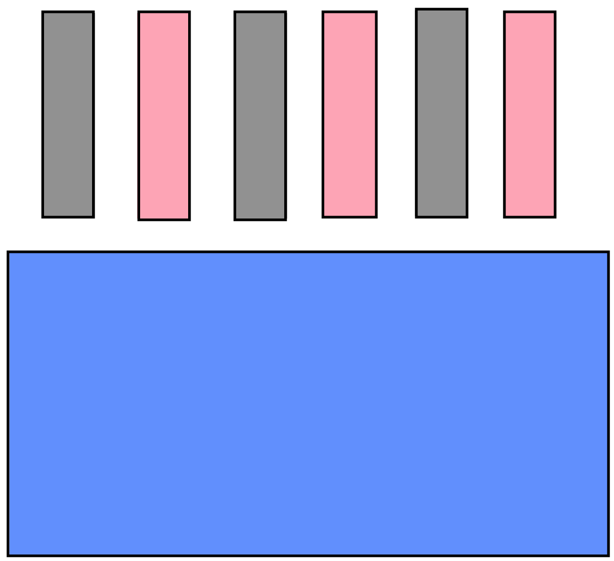
http://www.asiinstruments.com/technical/Dielectric%20Constants.htm

CALCULATIONS

	A	B	C	D	E	F	G	H	I
1	**Rochester Institute of Technology**								8-Apr-08
2	Dr. Lynn Fuller		Microelectronic Engineering, 82 Lomb Memorial Dr., Rochester, NY 14623						
3									
4	To use this spread sheet enter values in the white boxes. The rest of the sheet is protected and should not be								
5	changed unless you are sure of the consequences. The results are displayed in the purple boxes.								
6									
7	**Capacitance of Two Parallel Plates**								
8	**Capacitance = eoer Area/d**					C =	8.85E-12	F	
9						eo = Permitivitty of free space	8.85E-14	F/cm	
10						er = relative permitivitty =	1		
11						Area =	1.00E-02	cm2	
12						number of pairs of plates, N =	1		
13						distance between plates, d =	1	µm	
14						If round plates, Diameter =	0	µm	
15						If rectangular plates, length =	1000	µm	
16						If rectangular plates, width =	1000	µm	
17	**Force Between Two Parallel Plates**					Force =	4.43E-04	N	
18	**Electrostatic Force= eoer Area $V^2/2d^2$**				Applied Voltage, V =		10	volts	
19									
20	**Capacitance for very Thick Interdigitated Fingers**								
21		**C = (N-1) eoer L h/s**				Capacitance, C =	1.77E-13	F	
22						Number of Fingers, N =	101		

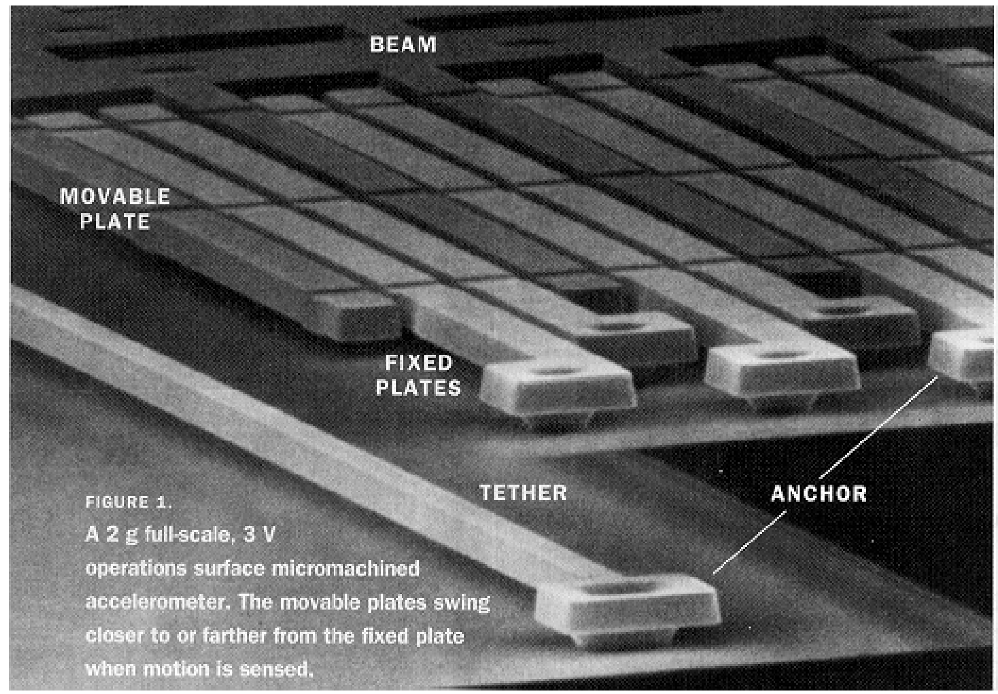
OTHER CAPACITOR CONFIGURATIONS

Interdigitated Fingers with Thickness > Space between Fingers



$$C = (N\text{-}1)\ \varepsilon_o \varepsilon_r\ L\ h\ /s$$

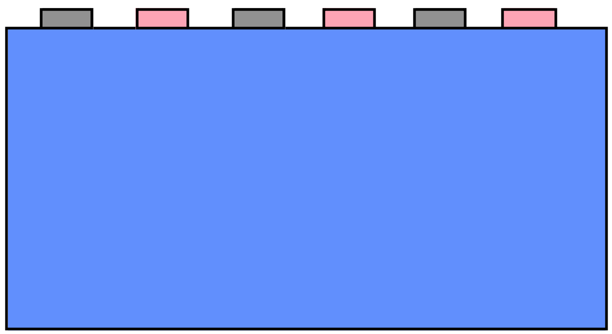
h = height of fingers
s = space between fingers
N = number of fingers
L = length of finger overlap

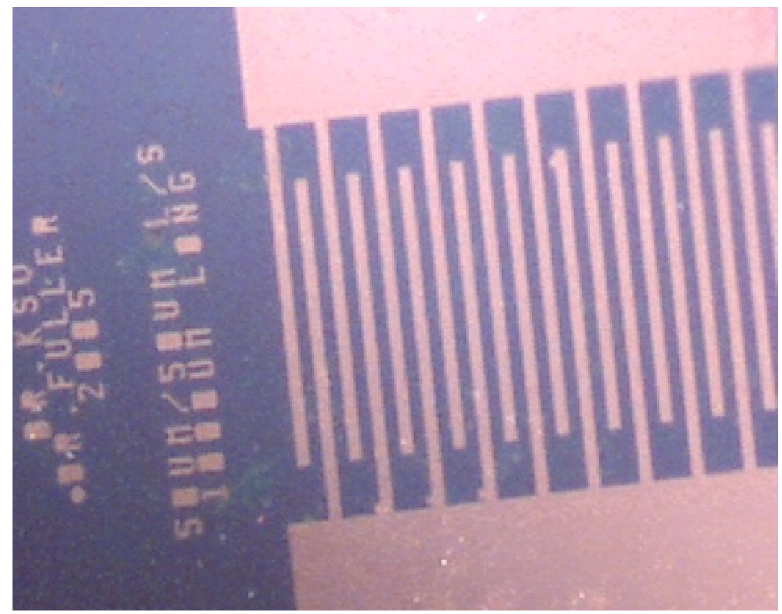


Example:

OTHER CAPACITOR CONFIGURATIONS

Interdigitated Fingers with Thickness << Space between Fingers





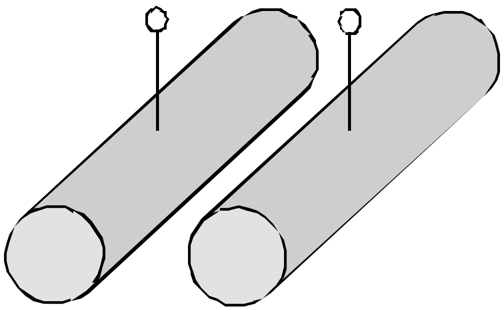
$$C = LN\left(\frac{4\,\varepsilon_o\varepsilon_r}{\pi}\right)\sum_{n=1}^{\infty}\frac{1}{2n-1}\;Jo^2\left(\frac{(2n-1)\pi s}{2(s+w)}\right)$$

Jo = zero order Bessel function
w = width of fingers
s = space between fingers
N = number of fingers
L = length of finger overlap

Reference:
Lvovich, Liu and Smiechowski,

OTHER CAPACITOR CONFIGURATIONS

Two Long Parallel Wires Surrounded by Dielectric Material



Capacitance per unit length C/L

$$C/L = 12.1\ \varepsilon_r / (\log [(h/r) + ((h/r)^2 - 1)^{1/2}]$$

h = half center to center space
r = conductor radius (same units as h)

Reference: Kraus and Carver

Example: Calculate the capacitance of a meter long connection of parallel wires.

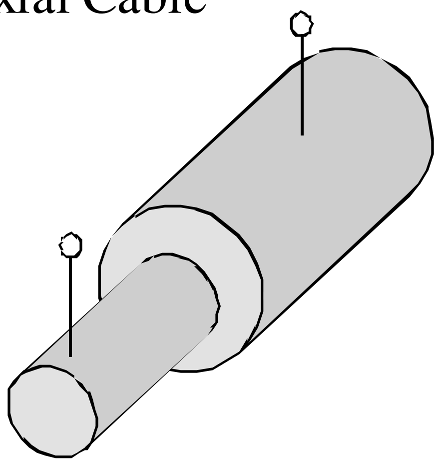
Solution: let, h = 1 mm, r = 0.5mm, plastic er = 3 the equation above gives

C/L = 63.5 pF/m

C = 63.5 pF

OTHER CAPACITOR CONFIGURATIONS

Coaxial Cable



Capacitance per unit length C/L

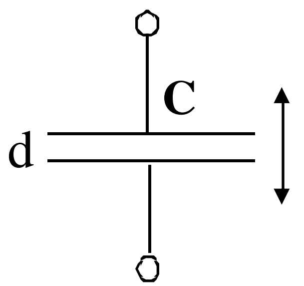
$$C/L = 2\,\pi\,\varepsilon_o\,\varepsilon_r / \ln(b/a)$$

b = inside radius of outside conductor
a = radius of inside conductor
Reference: Kraus and Carver

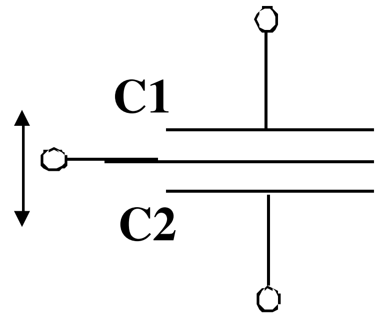
Example: Calculate the capacitance of a meter long coaxial cable.

Solution: let b = 5 mm, a = 0.2mm, plastic er = 3 the equation above gives
C/L = 51.8 pF/m
C = 51.8 pF

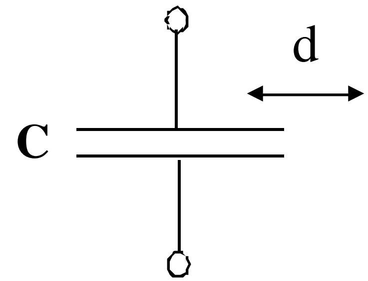
CAPACITORS AS SENSORS



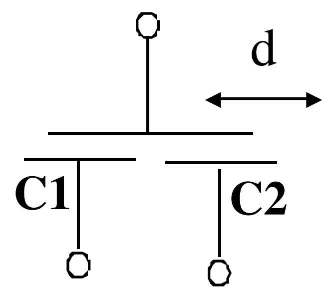
One plate moves relative to other changing gap (d)



Center plate moves relative to the two fixed plates



One plate moves relative to other changing overlap area (A)



CAPACITORS AS SENSORS

Change in Space Between Plates (d)

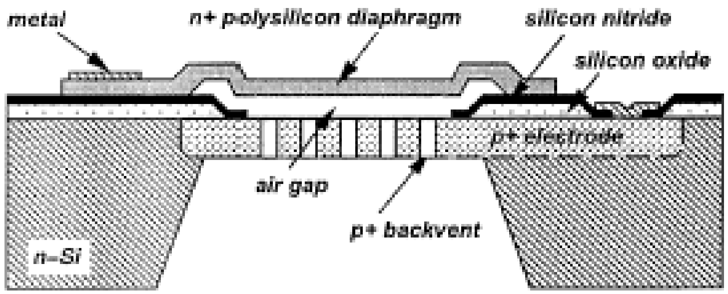
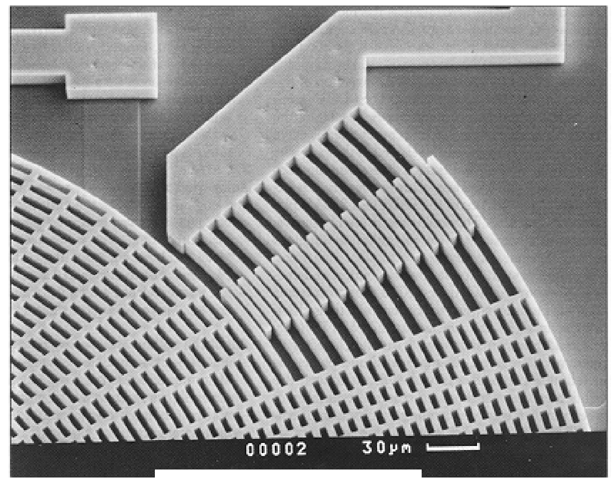


Figure 1: Cross section of the polysilicon diaphragm condenser microphone

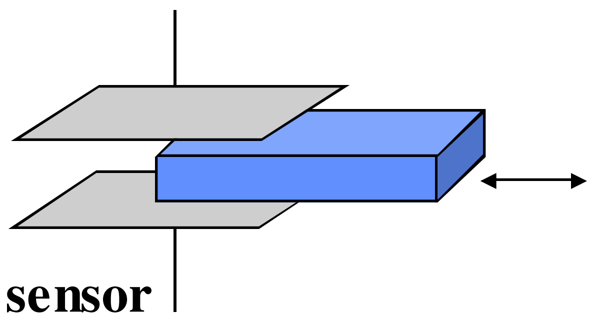
microphone

Change in Area (A)



gyroscope

Change in Dielectric Constant (er)

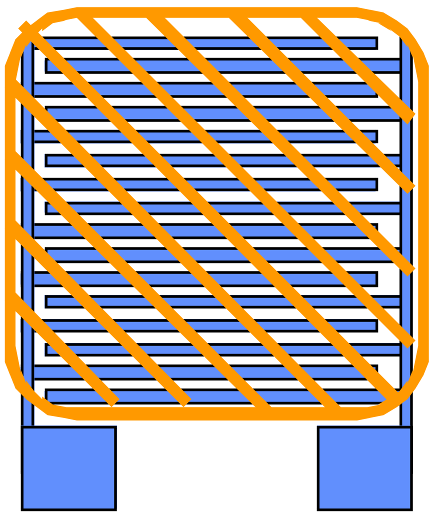


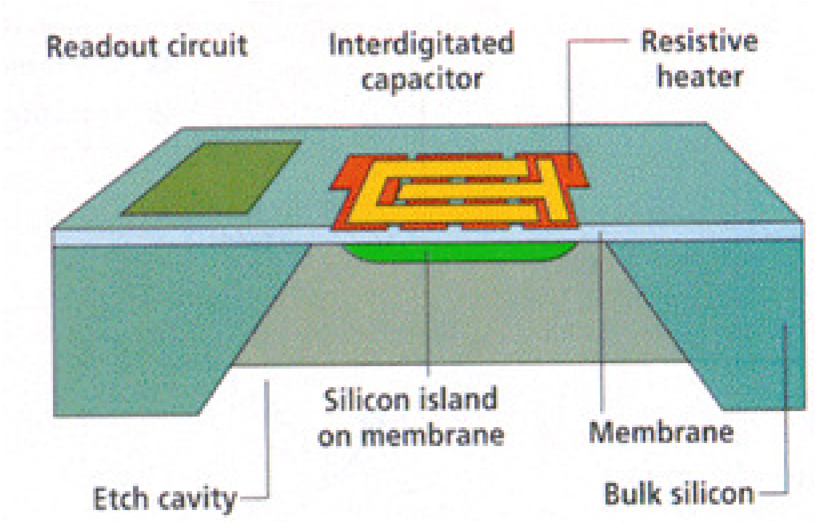
position sensor

CHEMICAL SENSOR

Two conductors separated by a material that changes its dielectric constant as it selectively absorbs one or more chemicals. Some humidity sensors are made using a polymer layer as a dielectric material.

Change in Dielectric Constant (er)

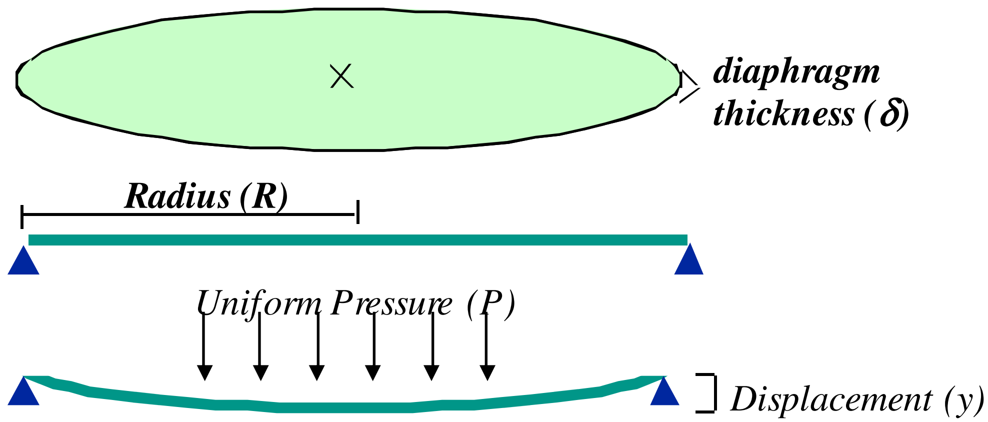




chemical sensor

DIAPHRAGM PRESSURE SENSOR

Diaphragm: Displacement



Equation for deflection at center of diaphragm

$$y = \frac{3PR^4[(1/\nu)^2-1]}{16E(1/\nu)^2\delta^3} = \frac{(249.979)PR^4[(1/\nu)^2-1]}{E(1/\nu)^2\delta^3}$$

E = Young's Modulus, **ν** = Poisson's Ratio

for Aluminum **ν** =0.35

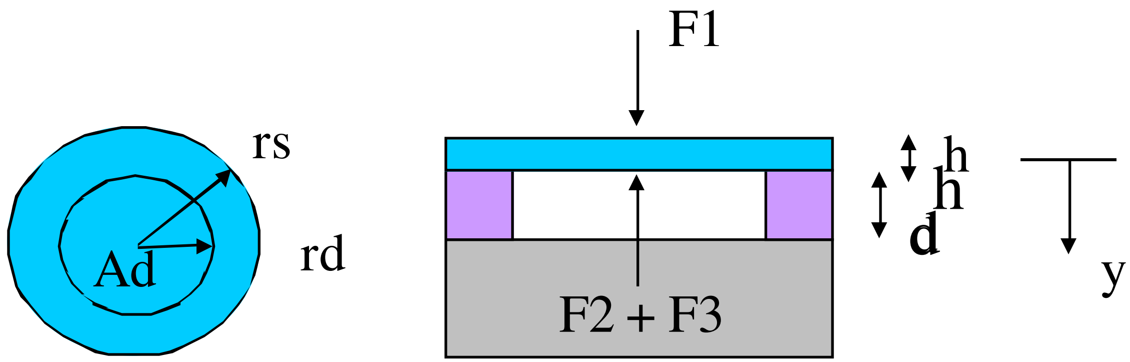
*The second equation corrects all units assuming that pressure is mmHg, radius and diaphragm is μm, Young's Modulus is dynes/cm^2, and the calculated displacement found is μm.

Mechanics of Materials, by Ferdinand P. Beer

DIAPHRGM WITH CAPTURED VOLUME

PV = nRT

F1 = force on diaphragm = external pressure times area of diaphragm
F2 = force due to captured volume of air under the diaphragm
F3 = force to mechanically deform the diaphragm



F1= F2 + F3 F1 = P x Ad F2 = nRT Ad / (Vd + Vs)

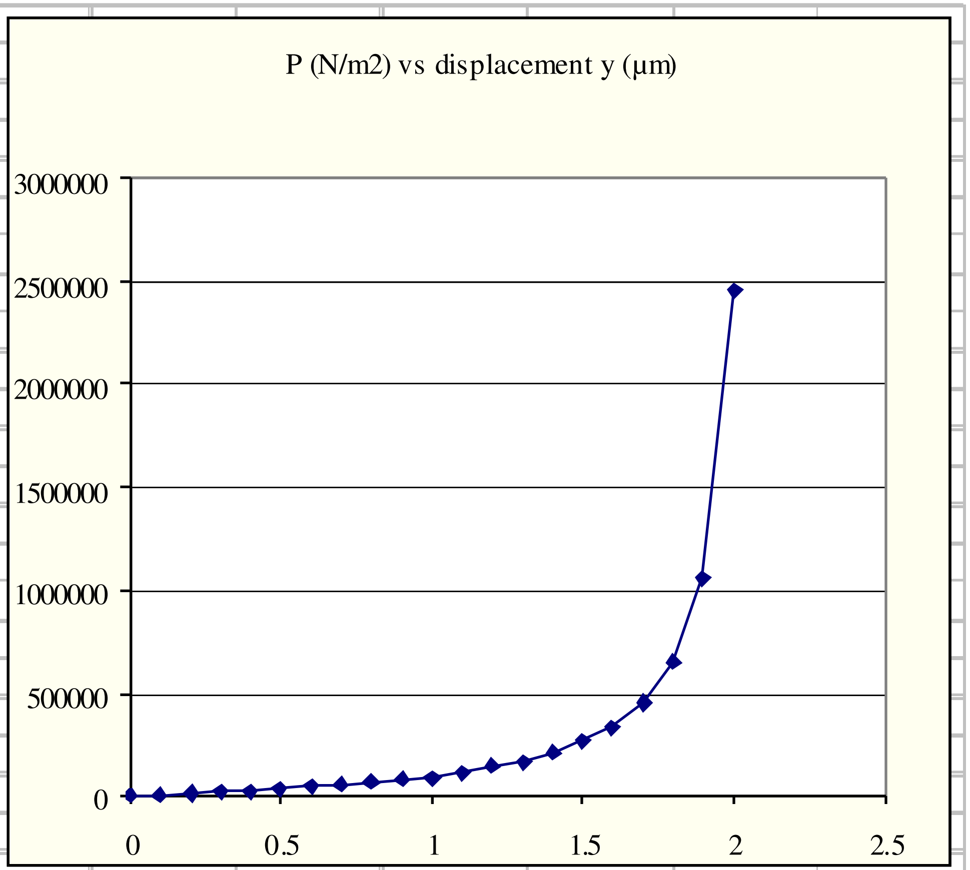
where Vd = Ad (d-y) and Vs = G1 Pi ($rs^2 - rd^2$)(d) where

G1 is the % of spacer that is not oxide

$F3 = (16\ E\ (1/\nu)^2\ h^3\ y)/(3\ rd^4[(1/\nu)^2-1])$

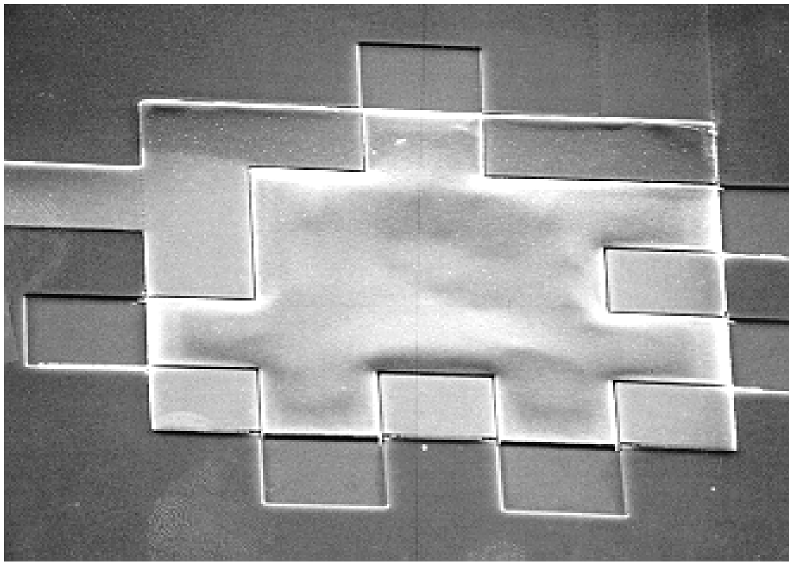
DIAPHRAGM WITH CAPTURED VOLUME

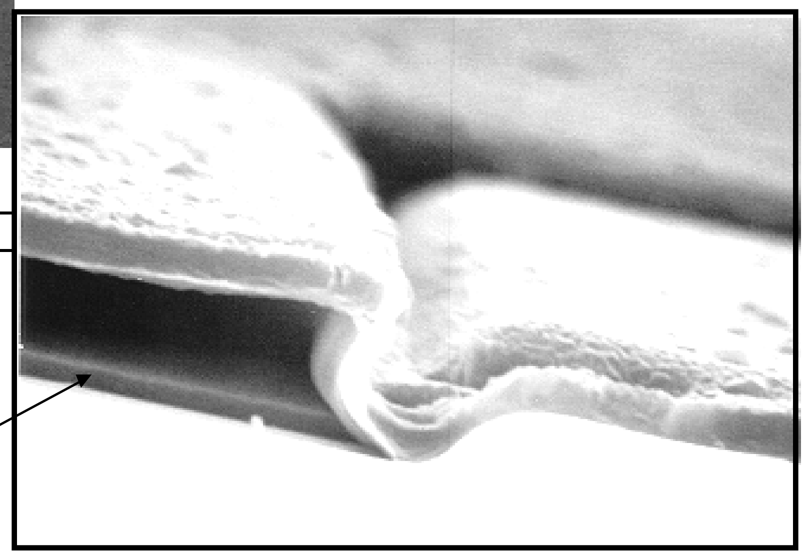
y (µm)	P (N/m2)
0	0
0.1	5103.44
0.2	10748.09
0.3	17025.03
0.4	24047
0.5	31955.23
0.6	40929.06
0.7	51199.69
0.8	63070.47
0.9	76947.31
1	93386.12
1.1	113169.1
1.2	137433.1
1.3	167895.7
1.4	207281.3
1.5	260184.8
1.6	335009.7
1.7	448945.4
1.8	643513.4
1.9	1051199
2	2446196



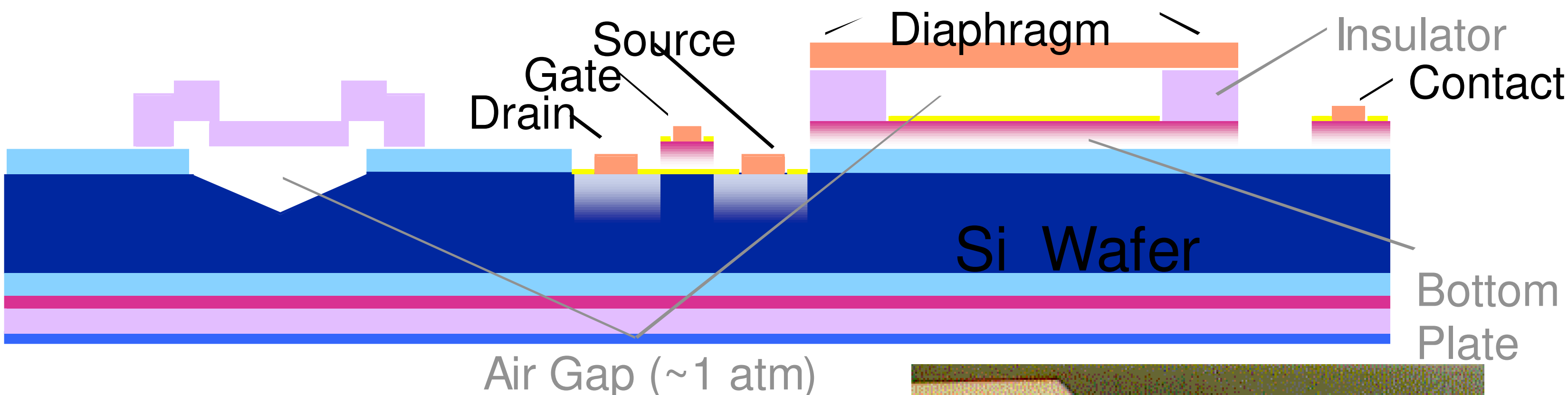
CONDENSER MICROPHONE

ALUMINUM DIAPHRAGM

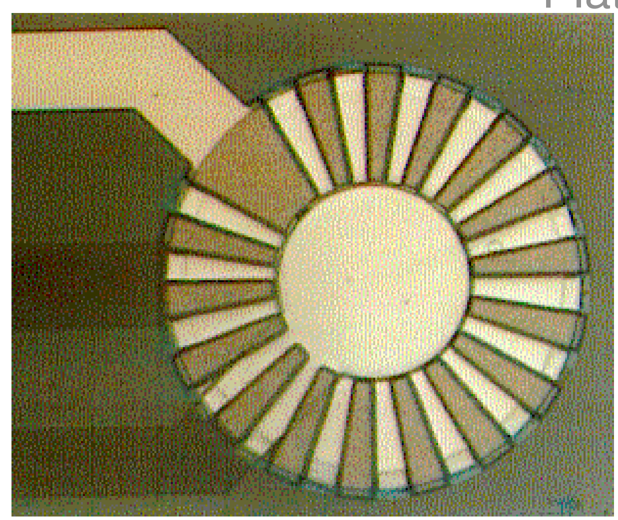




ALUMINUM DIAPHRAGM PRESSURE SENSOR



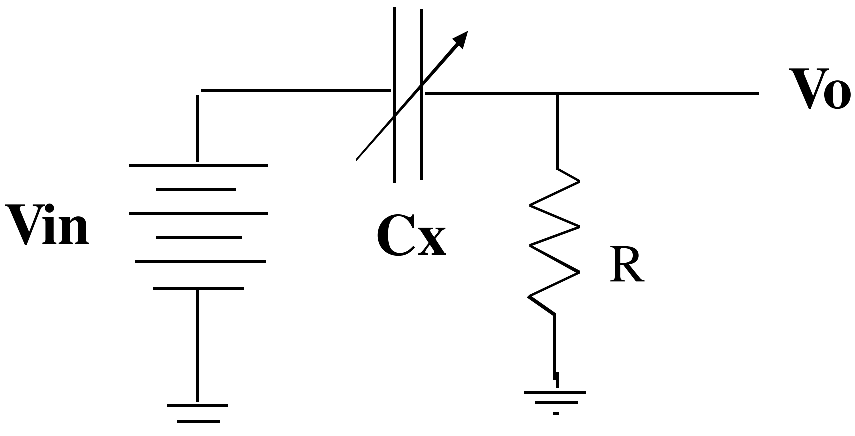
Kerstin Babbitt **-** University of Rochester
Stephanie Bennett **-** Clarkson University
Sheila Kahwati **-** Syracuse University
An Pham **-** Rochester Institute of Technology



SIGNAL CONDITIONING FOR CAPACITOR SENSORS

Delta Capacitance to AC Voltage
Static Capacitance to DC Voltage
Capacitance to Current
Ring Oscillator Capacitance to Frequency
RC Oscillator Capacitance to Frequency
Frequency to Digital
Capacitance to Analog Voltage to Digital
Other
Wireless

DELTA CAPACITANCE TO AC VOLTAGE

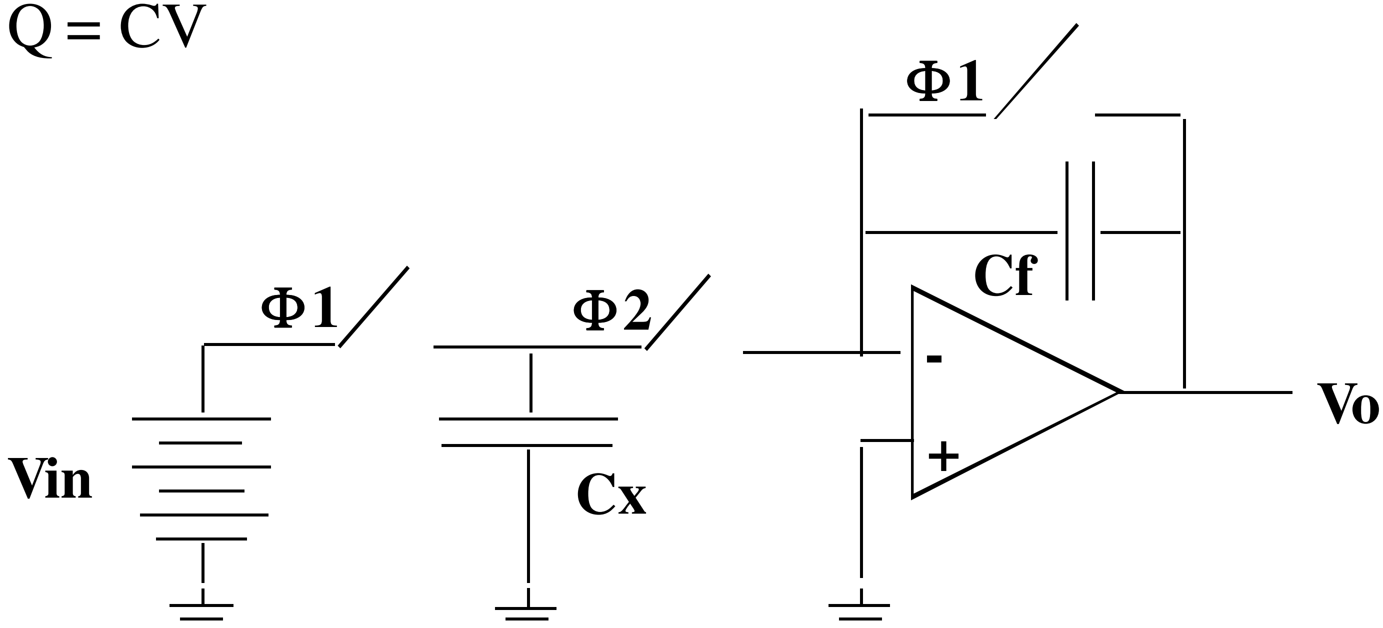


If Cx is fixed Vo is zero. If Cx changes there will be a change in current and a corresponding change in Vo

Example: Let Vin = 3 volts, C = 10 pF, microphone action causes C to change by 0.1pF at 1000 Hz. Calculate the output voltage.

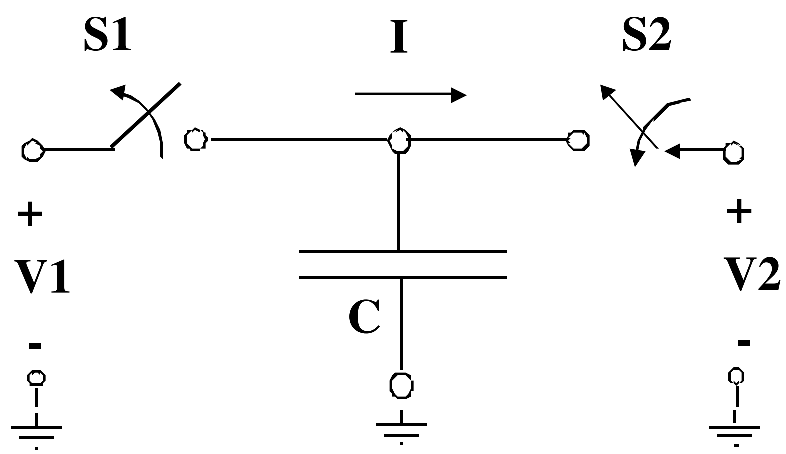
STATIC CAPACITANCE TO DC VOLTAGE

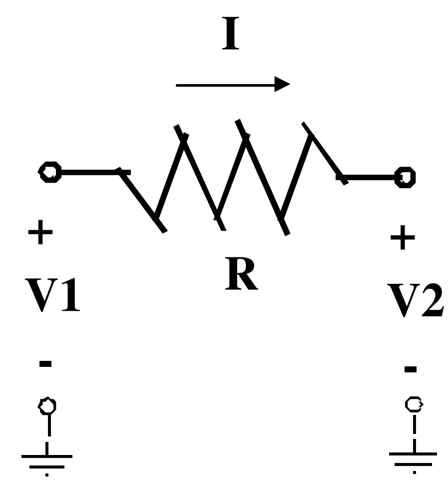
Q = CV



Vo = - Vin Cx/Cf

SWITCHED CAPACITOR EQUIVALENT RESISTOR





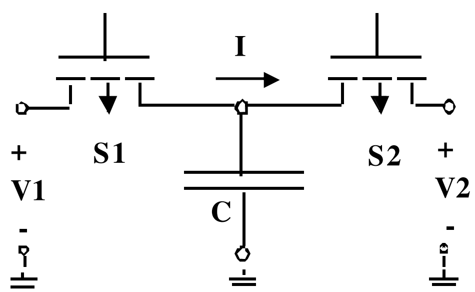
I = Cfs (V1-V2)

I = (1/R) (V1-V2)

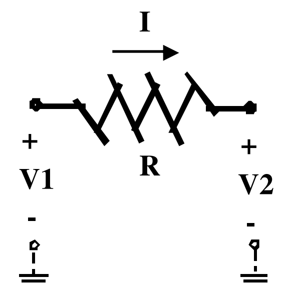
S1 closed C charges to V1, charge transferred is Q = CV1
S1 is opened
S2 is closed C charges to V2, charge transferred is Q = CV2
if the switches operate at a switching frequency fs, then I = Qfs = Cfs(V1-V2)
and Req = 1/(Cfs)

SC EXAMPLE

1. The sampling frequency fs must be much higher than the signal frequencies
2. The voltages at node 1 and 2 must be unaffected by switch closures.
3. The switches are ideal.
4. S1 and S2 are not both on at same time. (use non overlapping clocks)



Req = 1/(Cfs)

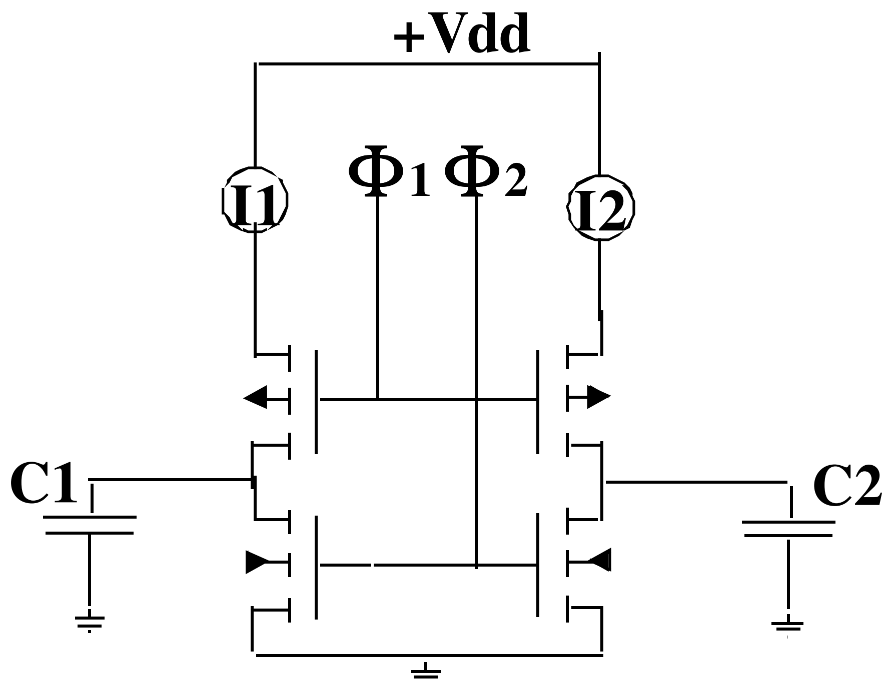


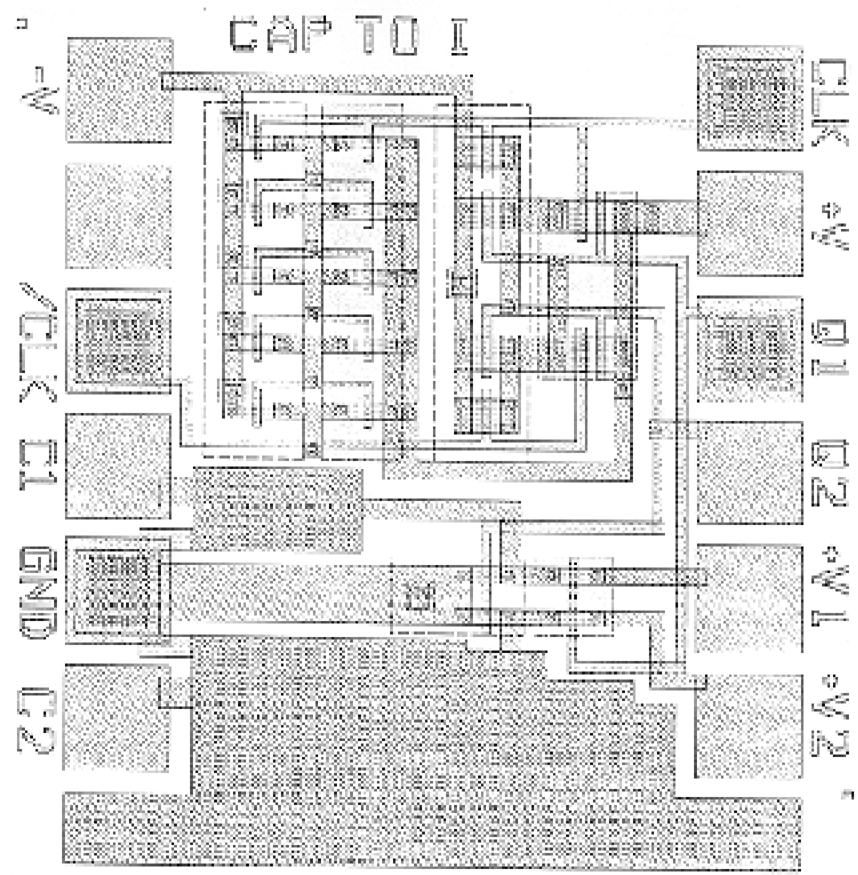
Example: for audio applications with frequencies up to 10KHz, we select switch frequency of 500KHz, for a 1 MEG ohm resistor we find that

C = 1/ (500K 1MEG) = 2 p/F

If Xox = 500 Å, then the capacitor will be about 30 µm by 30 µm

CAPACITANCE TO CURRENT

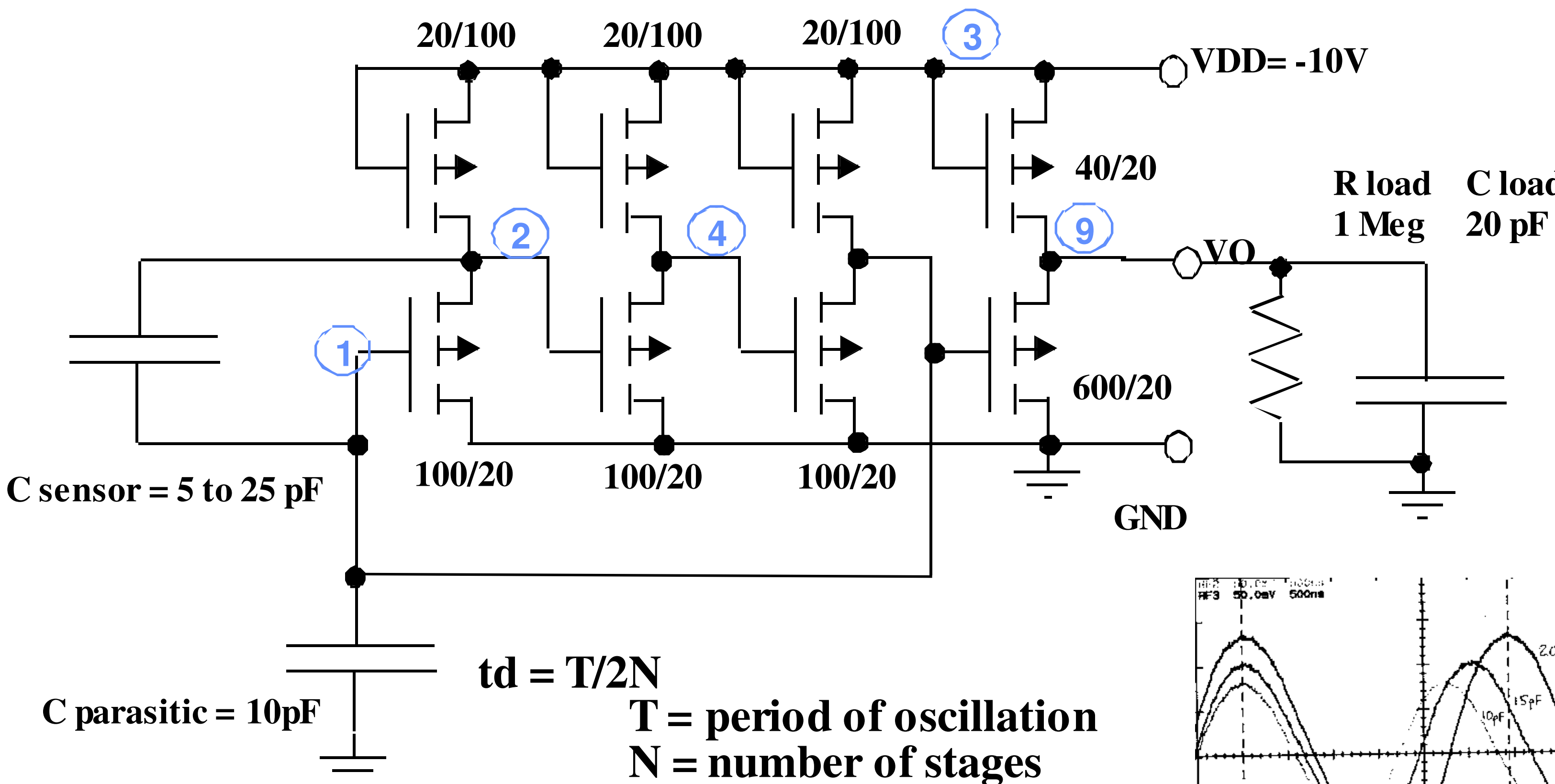




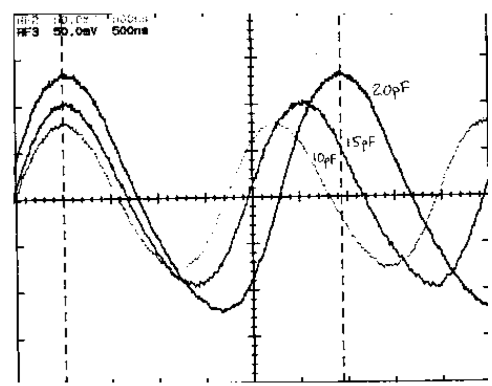
I2-I1= Vdd f (C2-C1)

where f is the clock frequency

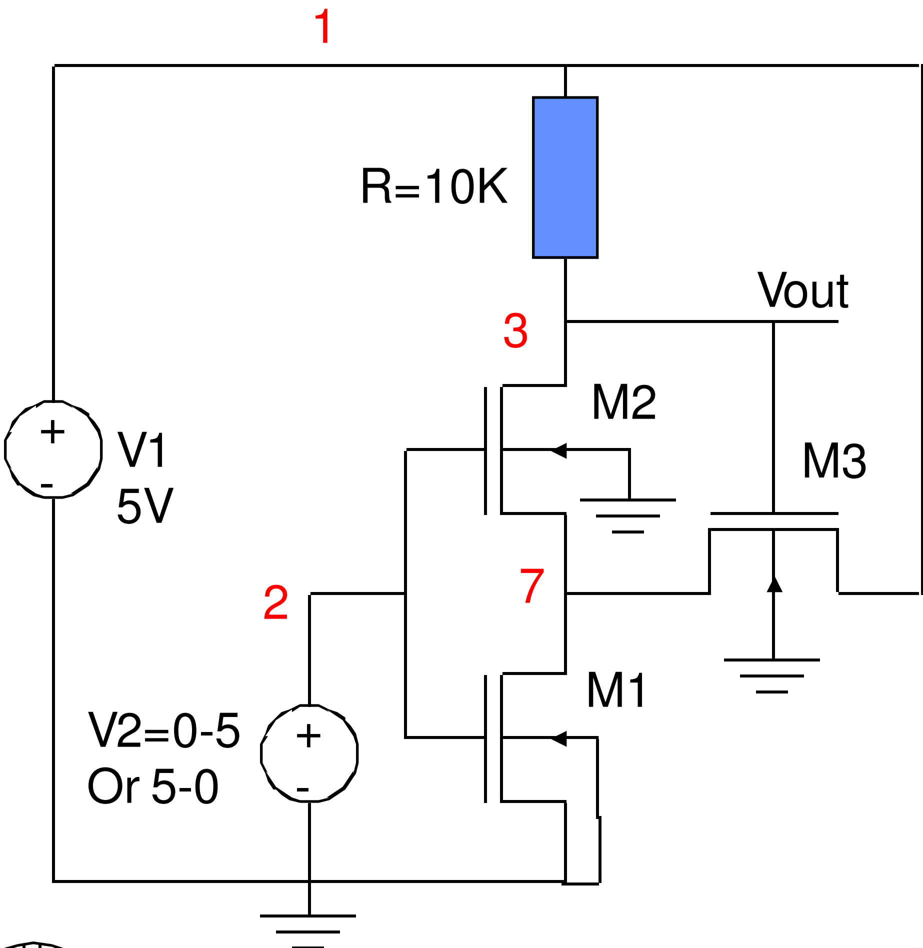
RING OSCILLATOR, C TO FREQUENCY

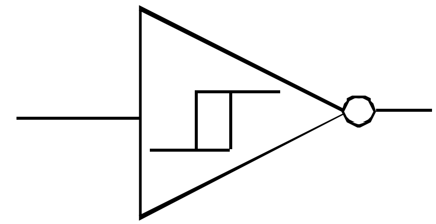


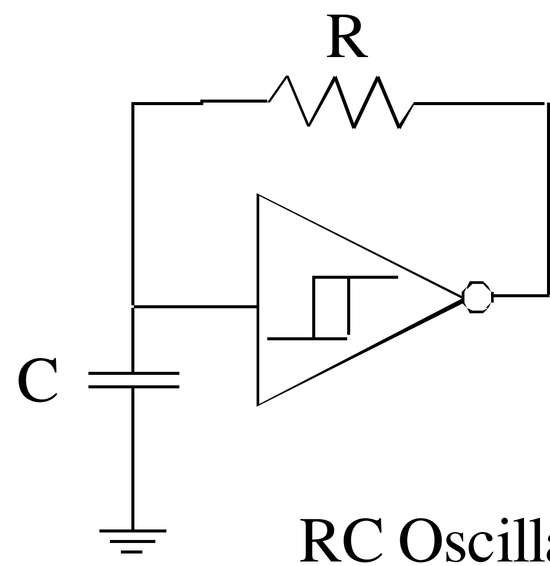
td = T/2N
T = period of oscillation
N = number of stages



RC OSCILLATOR USING INVERTER WITH HYSTERESIS

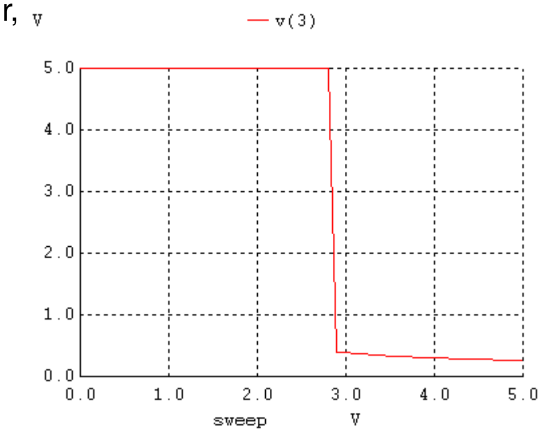


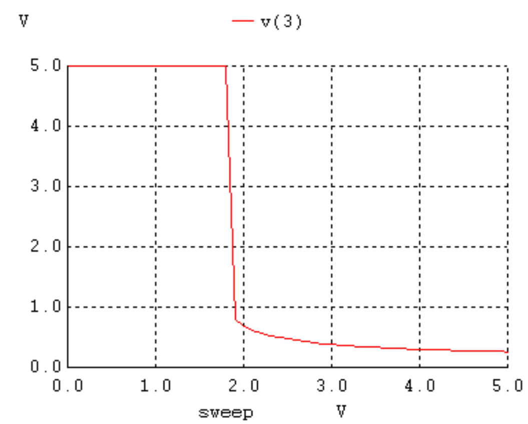




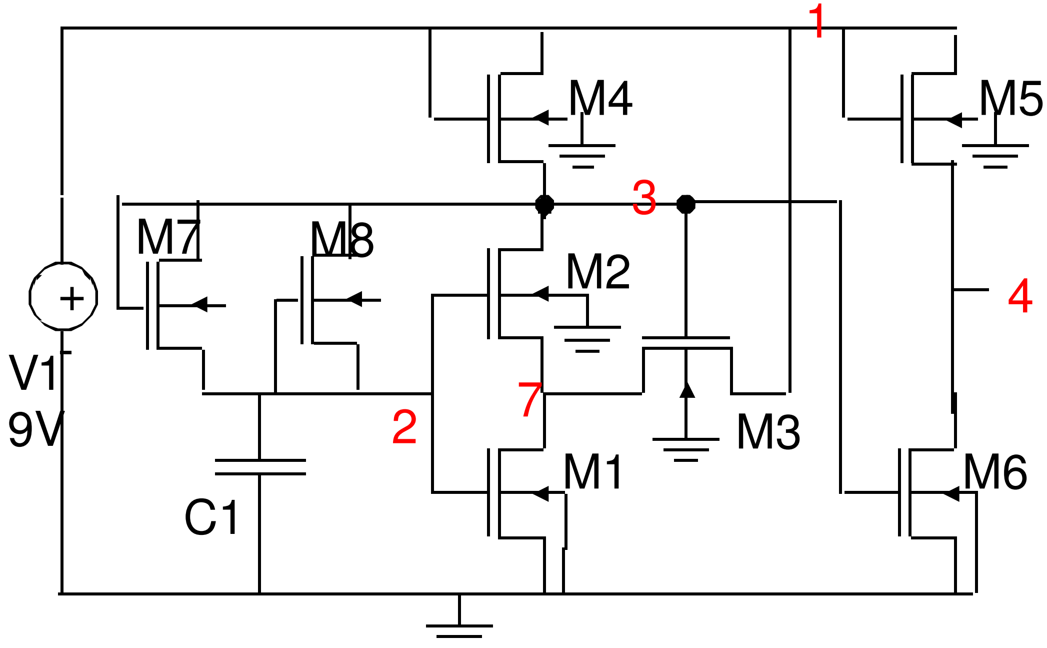
INVERTER WITH HYSTERESIS

```
INVERTER WITH HYSTERESIS USING FOR RIT SUB-CMOS NMOSFET, Dr. Lynn Fuller,
*LINE ABOVE IS TITLE
*START WIN SPICE AND ENTER LOCATION AND NAME OF INPUT FILE
*THIS FILE IS HYSTERESIS.TXT
*EXAMPLE: winspice> source c:/spice/Hysteresis.txt
*THE TRANSISTOR MODELS ARE IN THE FILE NAMED BELOW
.INCLUDE E:\SPICE\WINSPICE\RIT_MICROE_MODELS.TXT
*CIRCUIT DESCRIPTION
*VOLTAGE SOURCES
V1 1 0 DC 5
V2 2 0 DC 0
*TRANSISTORS
M1 7 2 0 0 RITSUBN49 L=2U W=16U ad=96e-12 as=96e-12 pd=44e-6 ps=44e-6 nrd=0.025 nrs=0.025
M2 3 2 7 0 RITSUBN49 L=2U W=16U ad=96e-12 as=96e-12 pd=44e-6 ps=44e-6 nrd=0.025 nrs=0.025
M3 1 3 7 0 RITSUBN49 L=2U W=16U ad=96e-12 as=96e-12 pd=44e-6 ps=44e-6 nrd=0.025 nrs=0.025
*RESISTORS
R1 1 3 10000
*REQUESTED ANALYSIS
.OP
.DC V2  5  0  -.1
*.DC V2 0 5 .1
.PLOT DC V(3)
.END
```

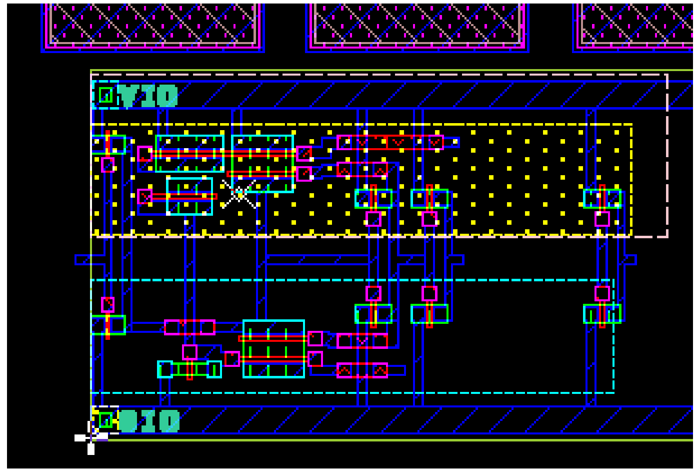


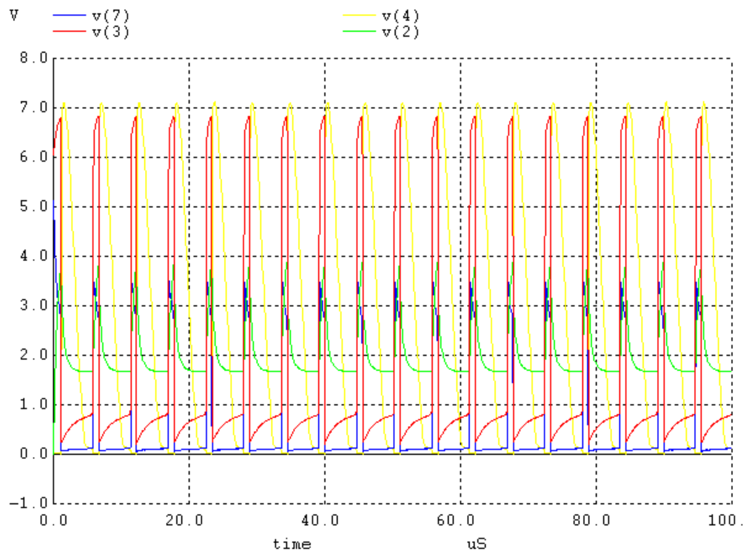


RC OSCILLATOR, INVERTER WITH HYSTERESIS



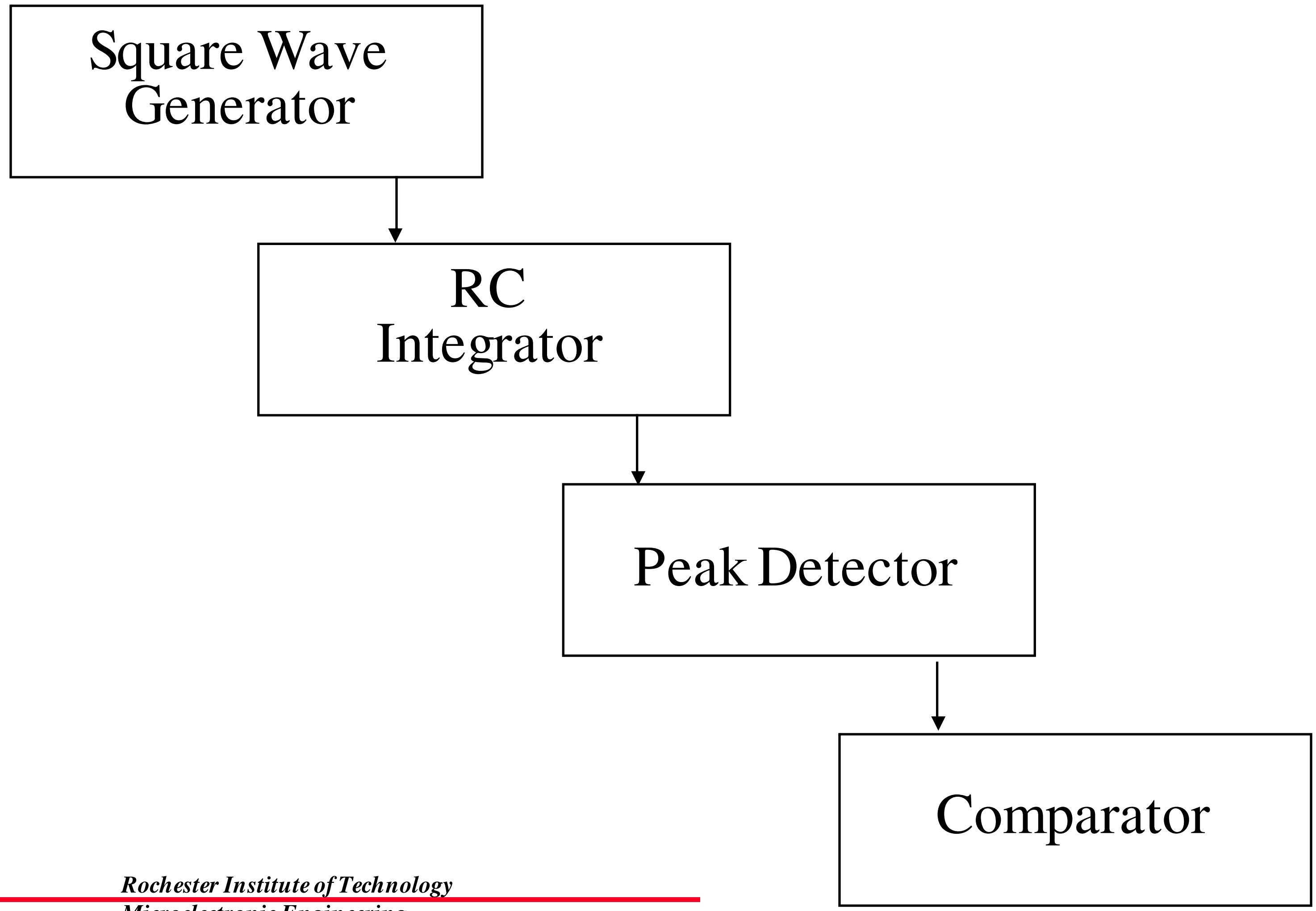
All PMOS Realization



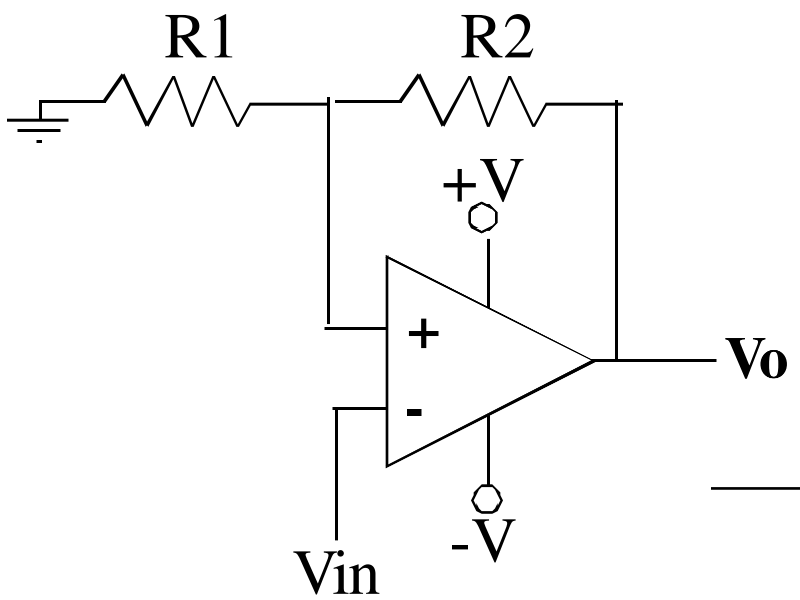


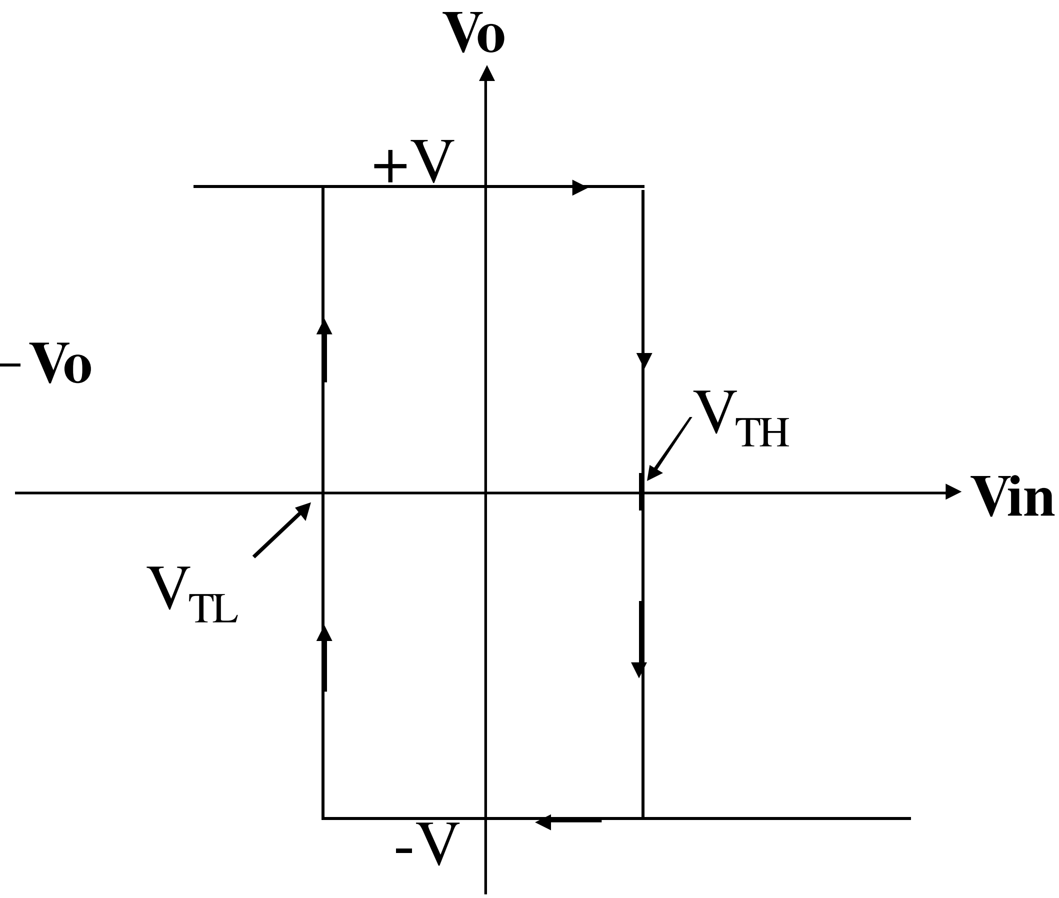
3.0pF

DESIGN EXAMPLE



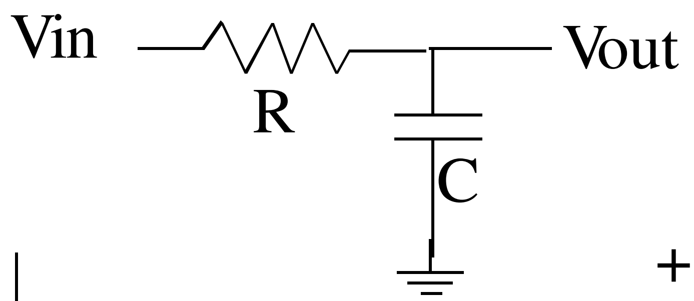
BISTABLE MULTIVIBRATOR

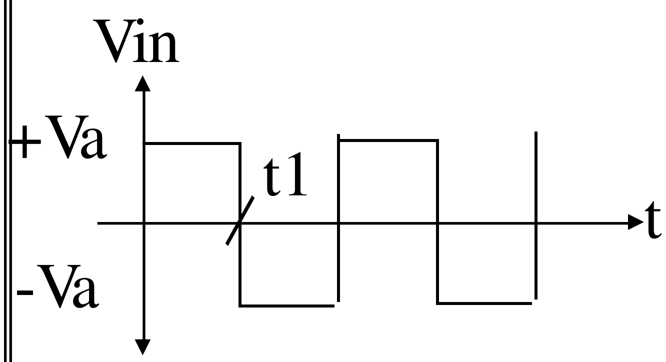


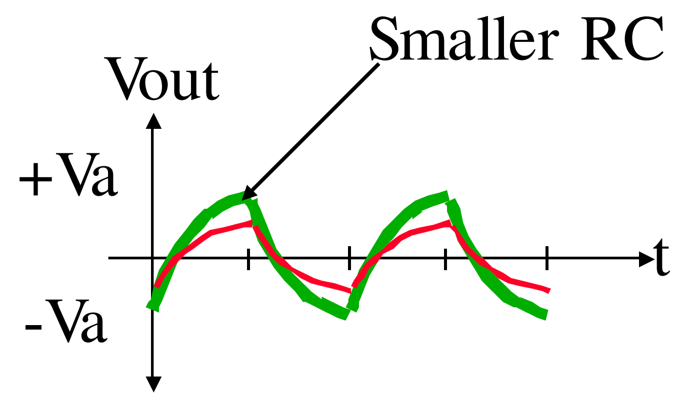


Sedra and Smith pg 1187

RC INTEGRATOR



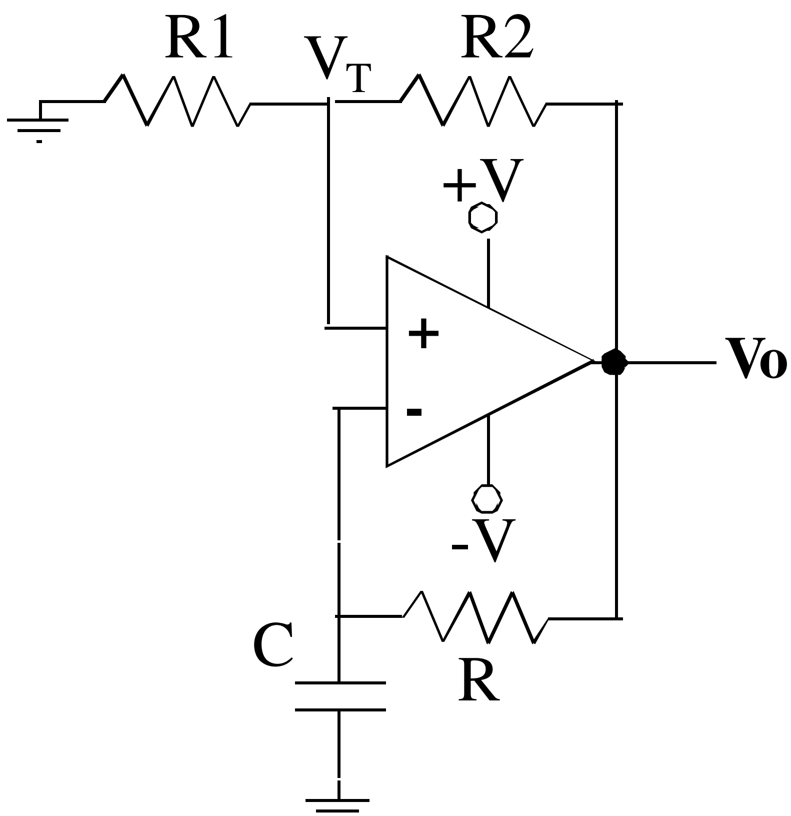


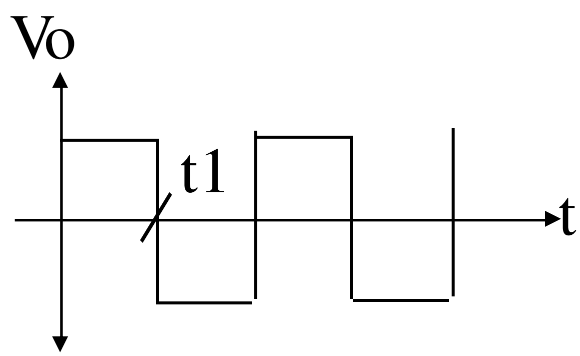


$$Vout = (-Va) + [2Va(1-e^{-t/RC})] \qquad \text{for } 0<t<t1$$

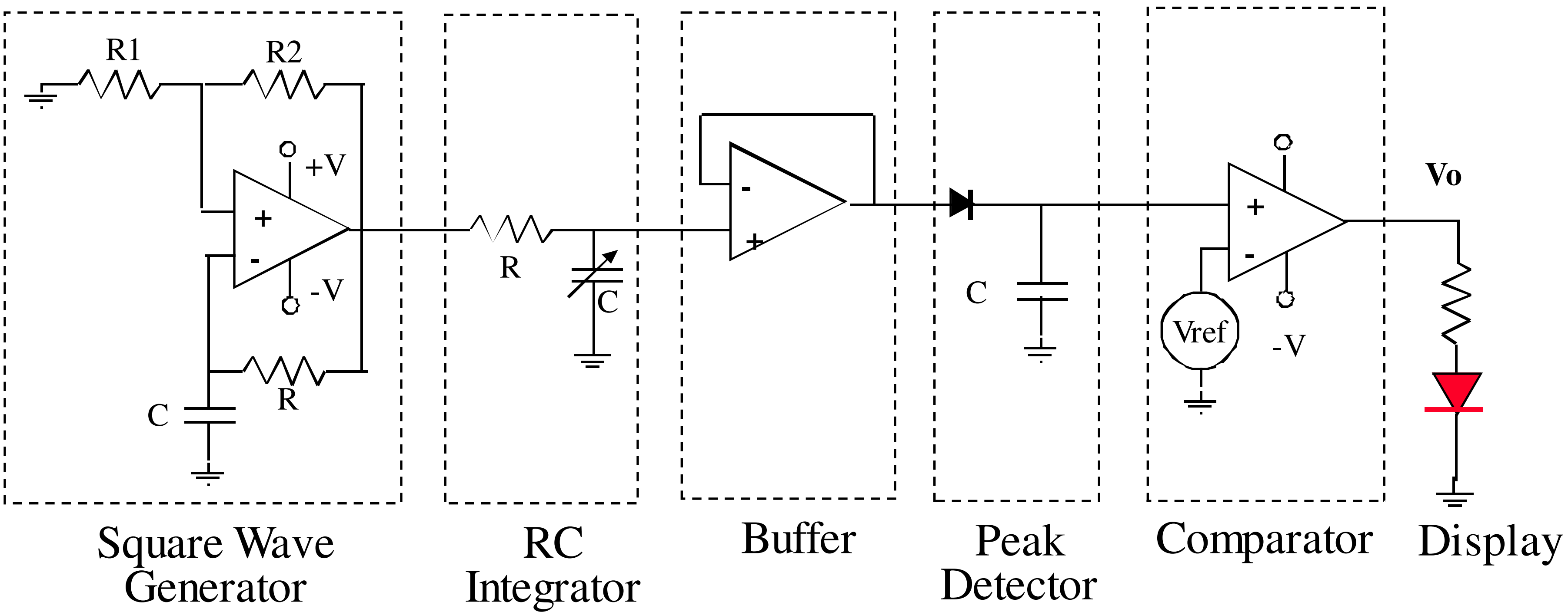
If R=1MEG and C=10pF find RC=10us

OSCILLATOR USING BISTABLE MULTIVIBRIATOR



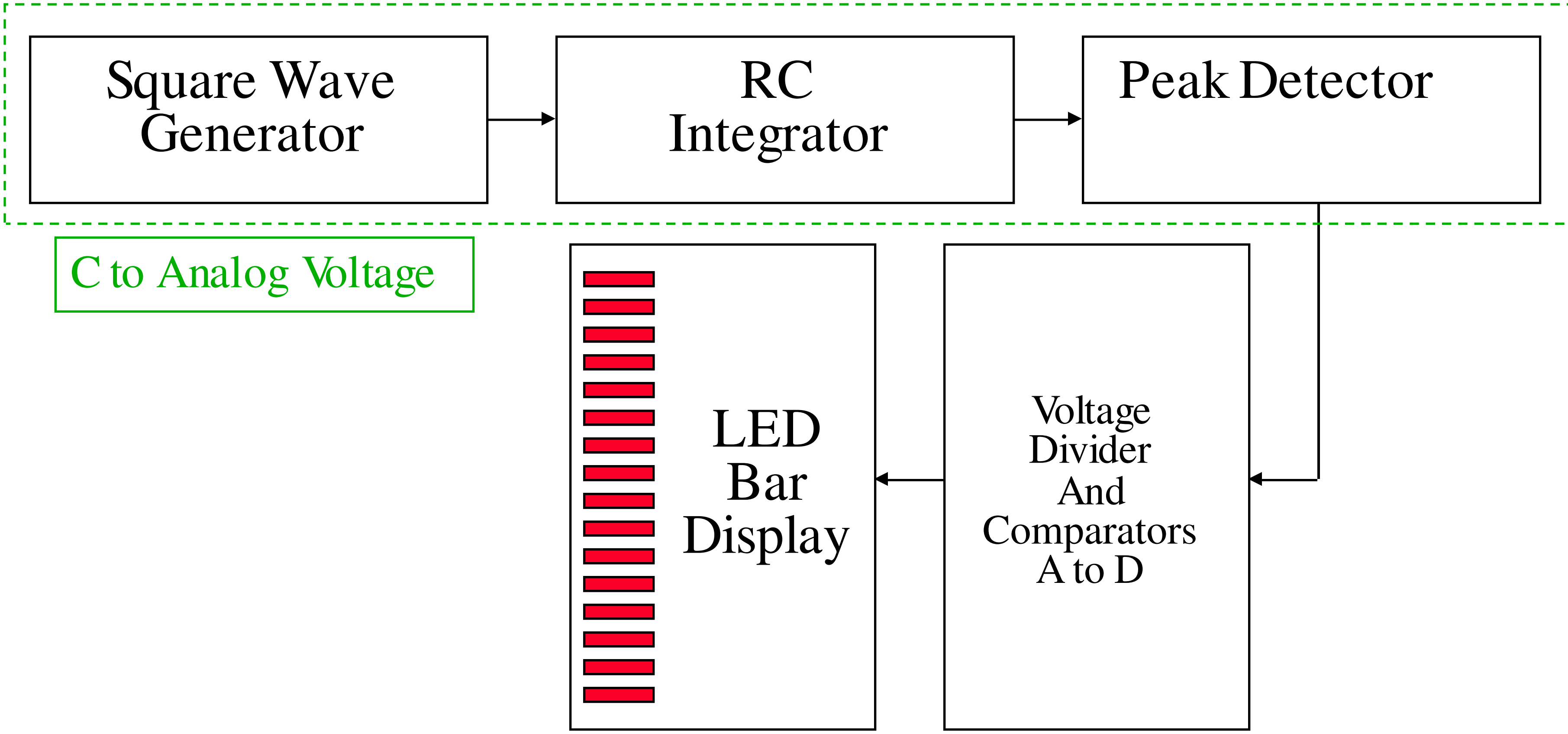


LIQUID LEVEL DETECTOR



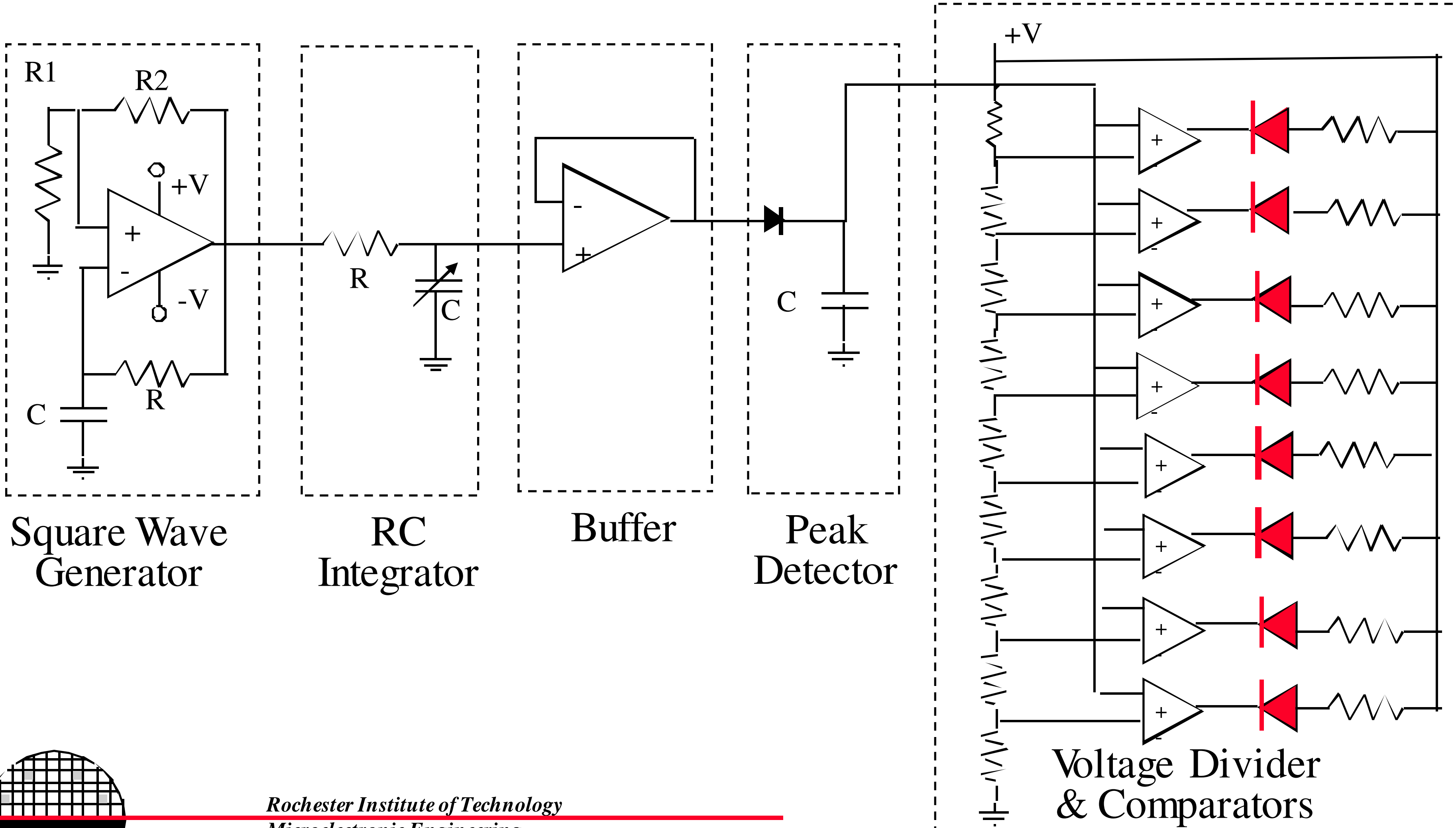
Rochester Institute of Technology
Microelectronic Engineering

CAPACITANCE TO ANALOG VOLTAGE TO DIGITAL

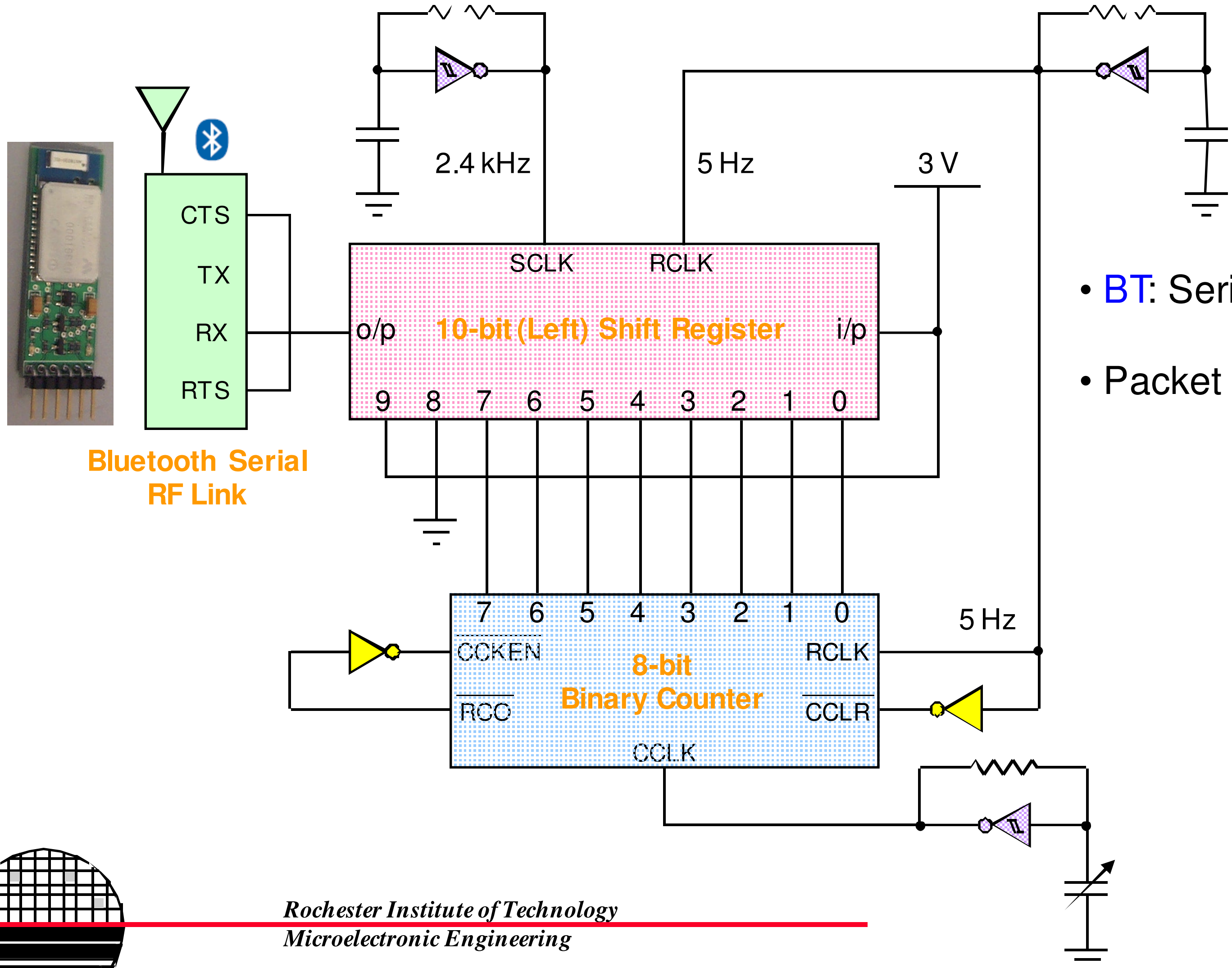


Rochester Institute of Technology
Microelectronic Engineering

CAPACITOR SENSOR ELECTRONICS



BLUETOOTH WIRELESS CAPACITOR SENSOR



- BT: Serial Port Profile (RS232)
- Packet Specification :

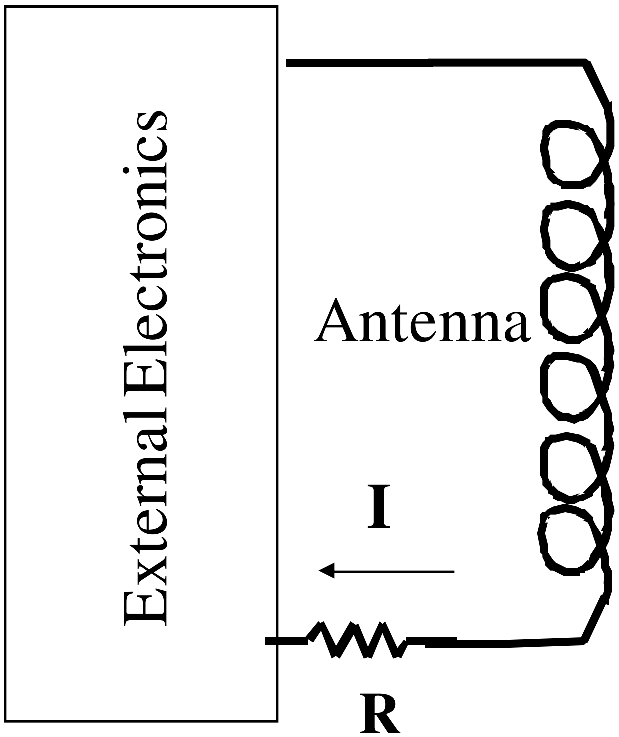
  Baud rate: 2400

  Data bits: 8

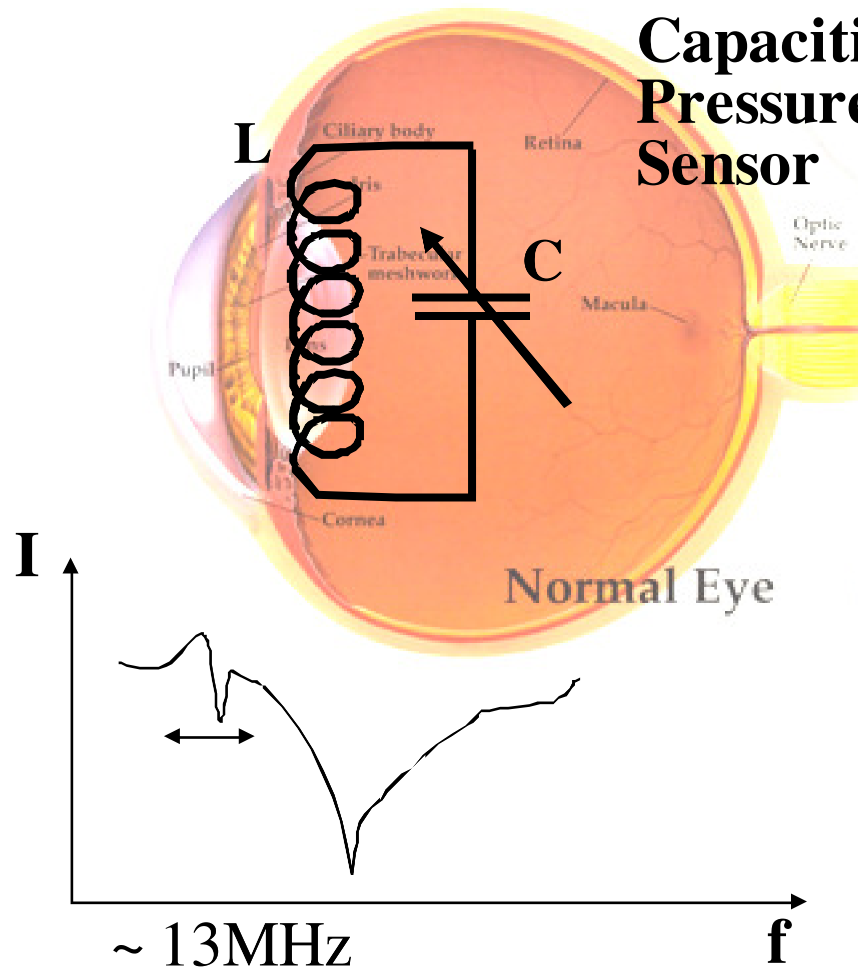
  Parity: None

  Stop bits: 1

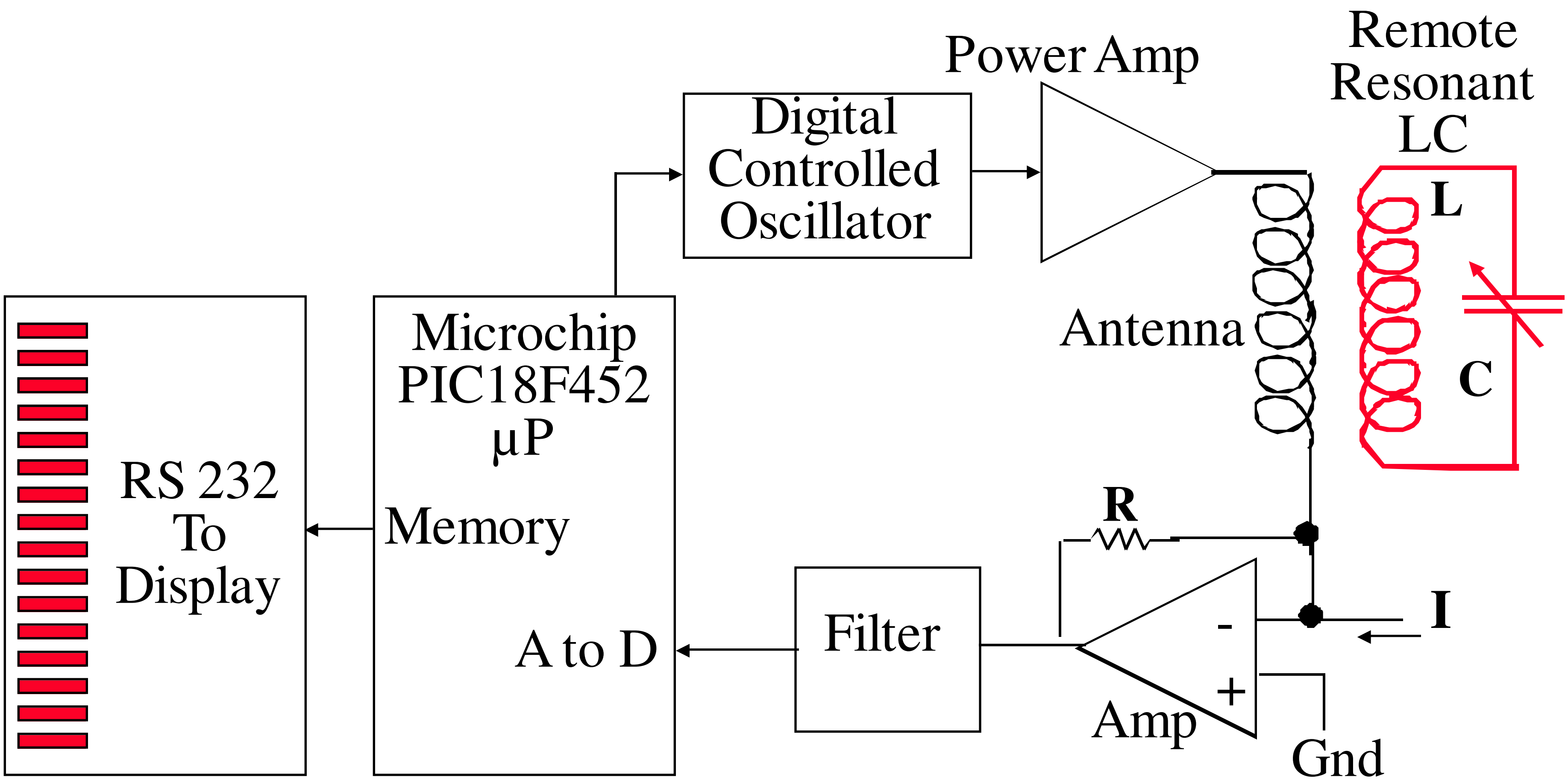
WIRELESS REMOTE SENSING OF L OR C



Capacitive Pressure Sensor



BLOCK DIAGRAM FOR REMOTE SENSING ELECTRONICS

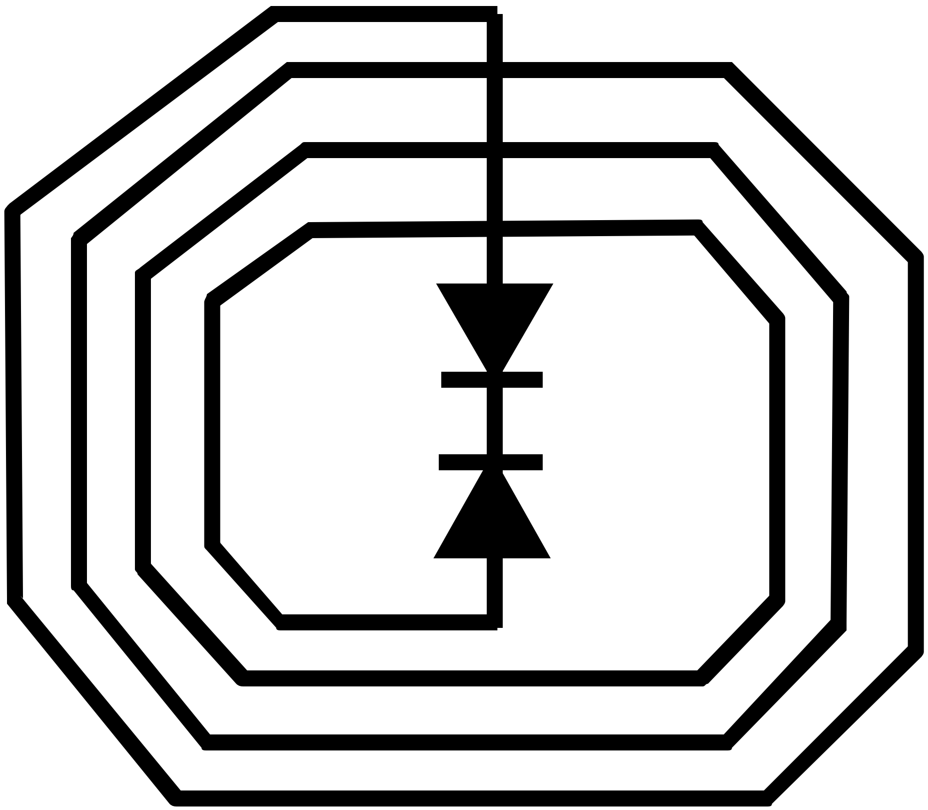


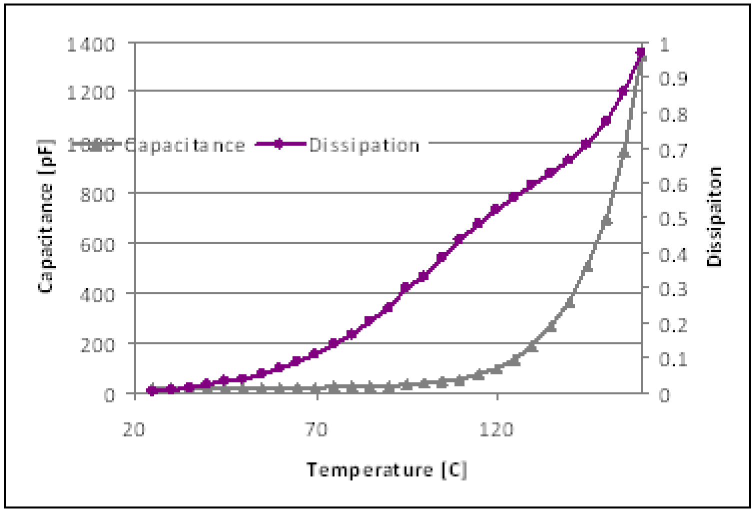
SIMILAR IDEA FOR WIRELESS TEMPERATURE

Network Analyzer

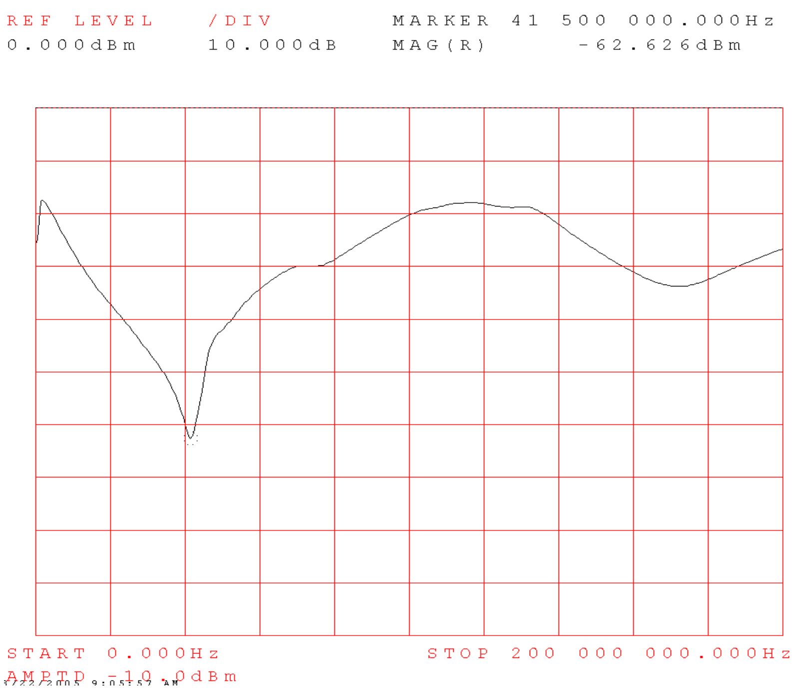
I vs. Frequency

TEMPERATURE SENSING WITH COIL AND DIODES

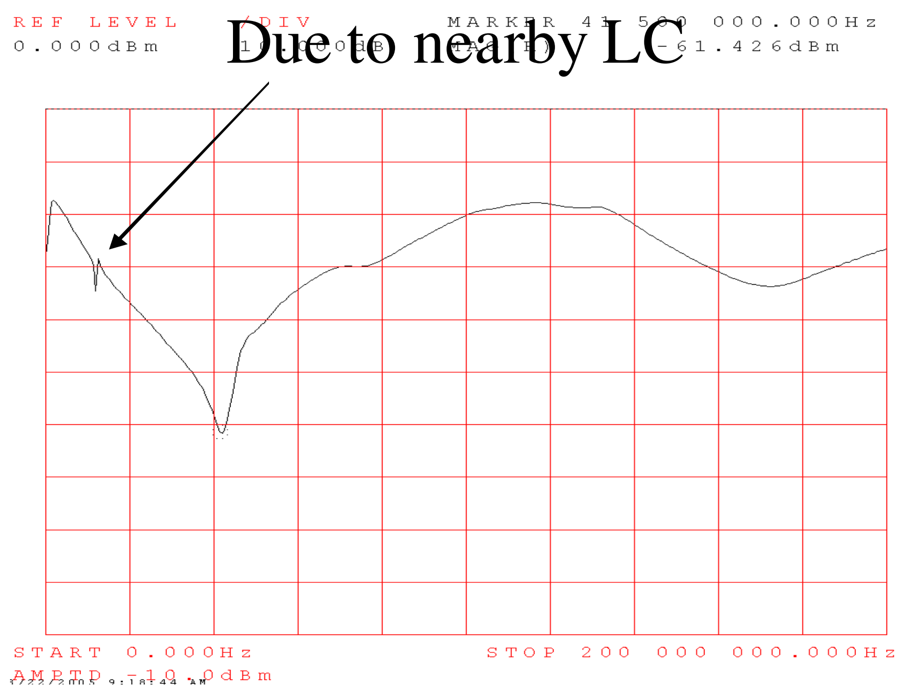




PICKUP COIL CURRENT



No Resonant Circuit Present



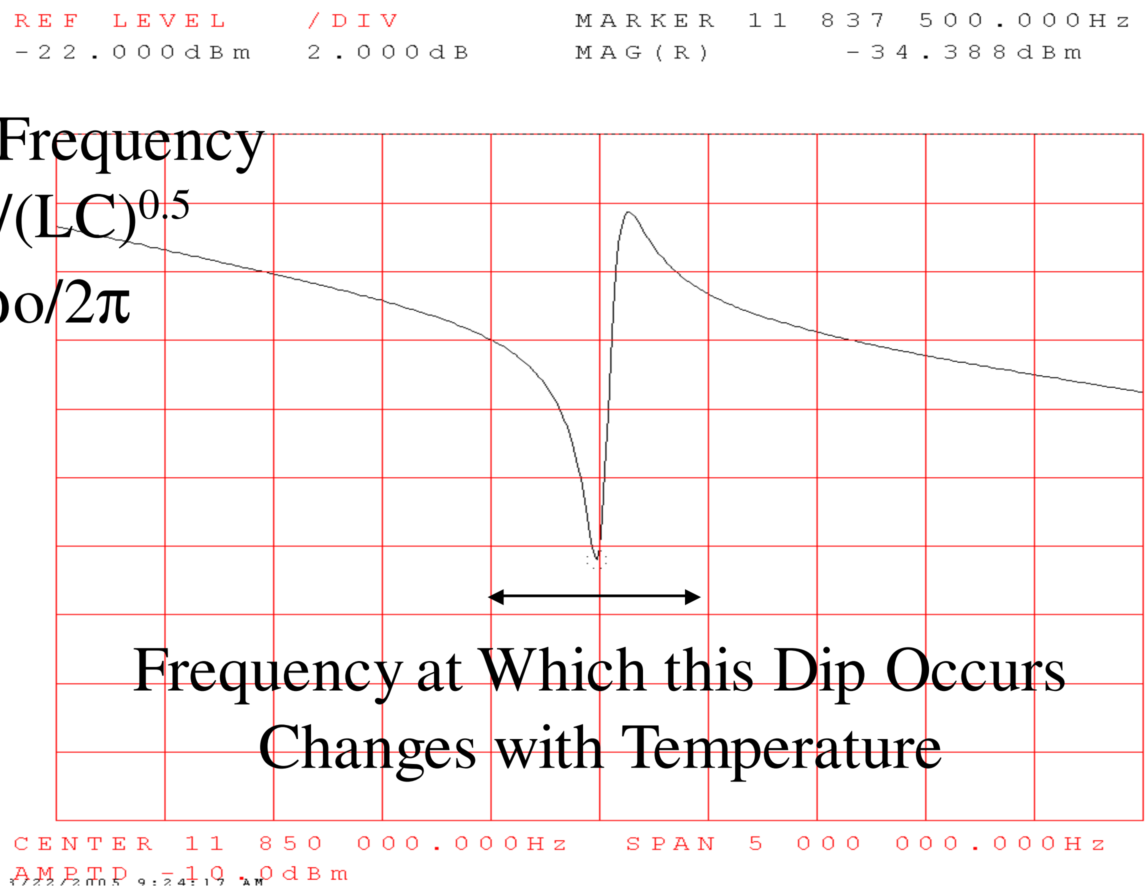
Resonant LC Circuit Present

ZOOM IN ON RESONANCE DUE TO LC

Resonant Frequency

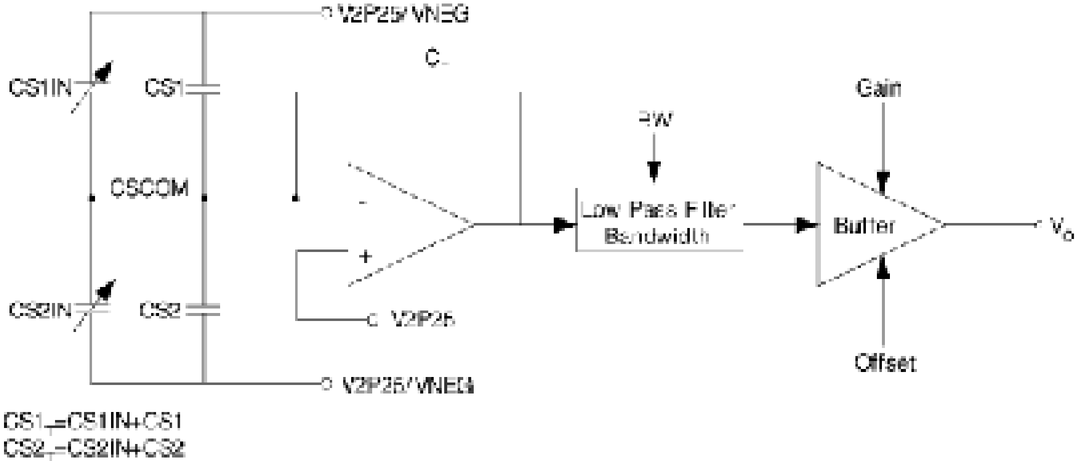
$\omega o = 1/(LC)^{0.5}$

$fo = \omega o/2\pi$



Frequency at Which this Dip Occurs Changes with Temperature

COMMERCIAL CHIPS

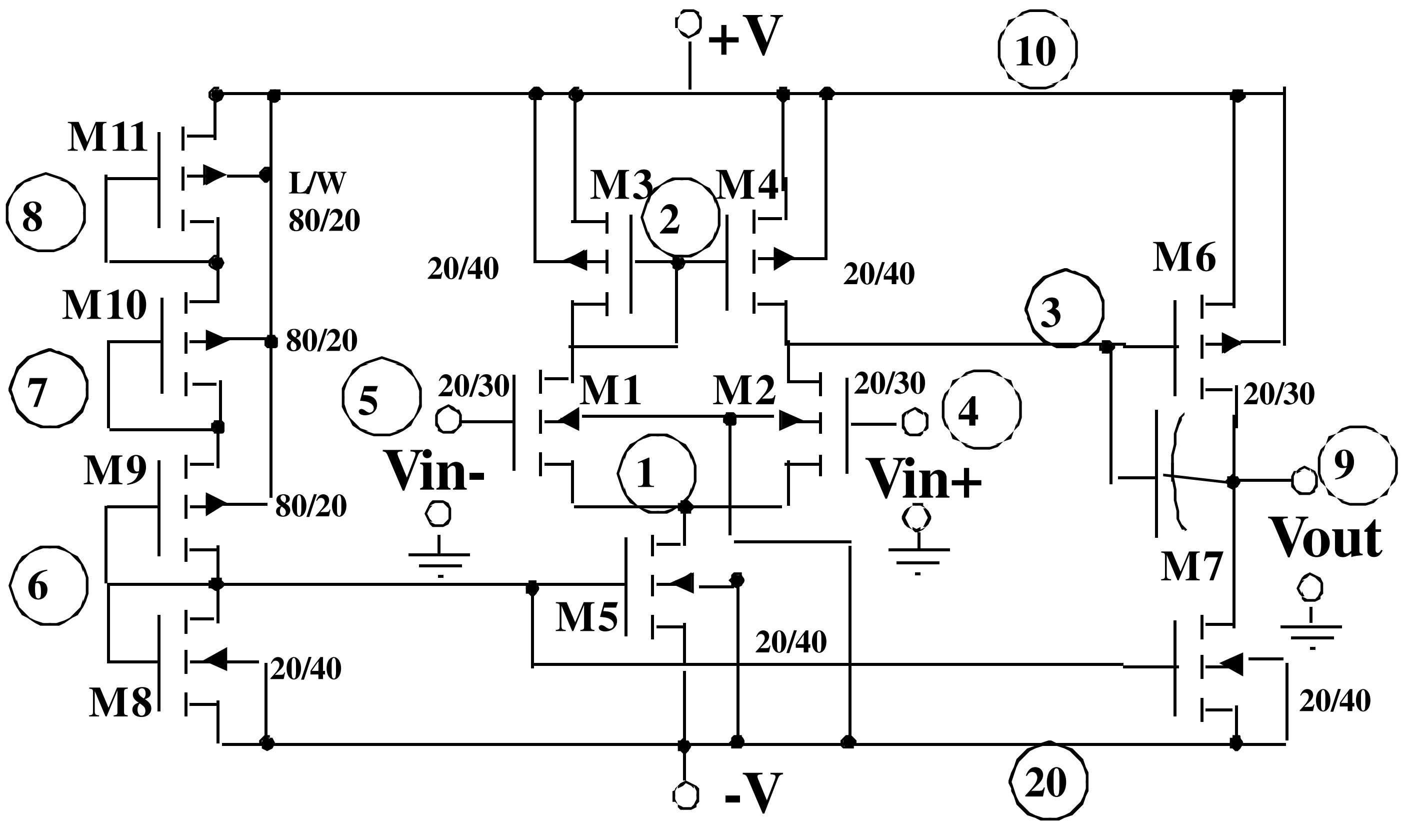


MS3110 Universal Capacitive Read-out IC (left) and its block diagram (right).

SIGNAL CONDITIONING BUILDING BLOCKS

Operational Amplifier
Analog Switches
Non-Overlapping Clock

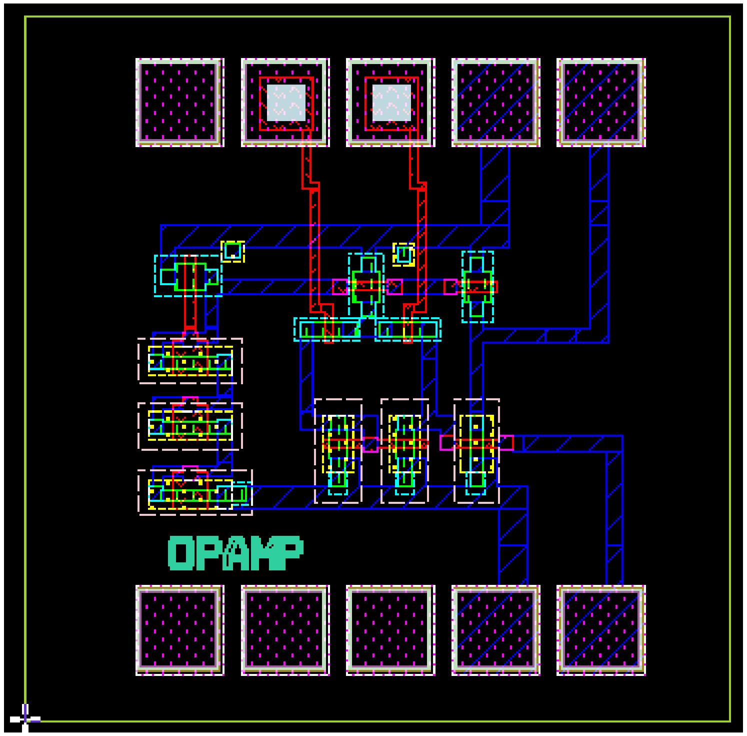
CMOS OPERATIONAL AMPLIFIER

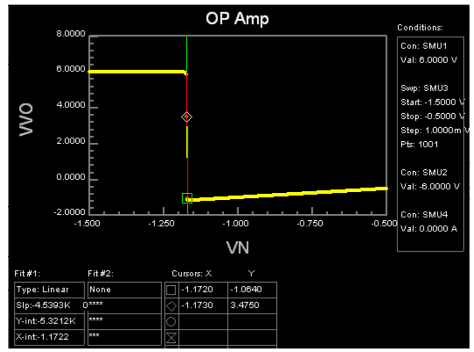


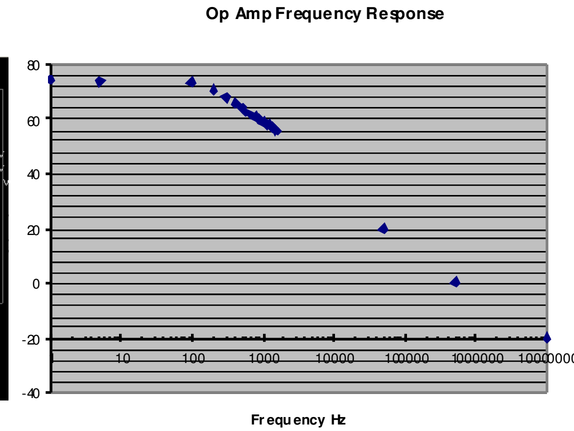
p-well CMOS

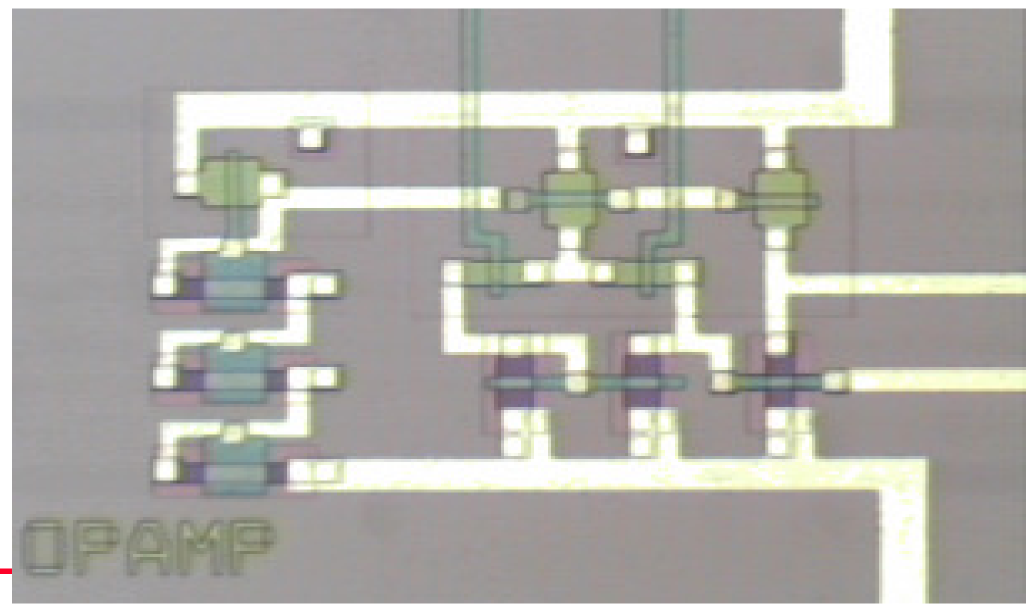
dimensions
L/W
(µm/µm)

VERSION 1 OP AMP



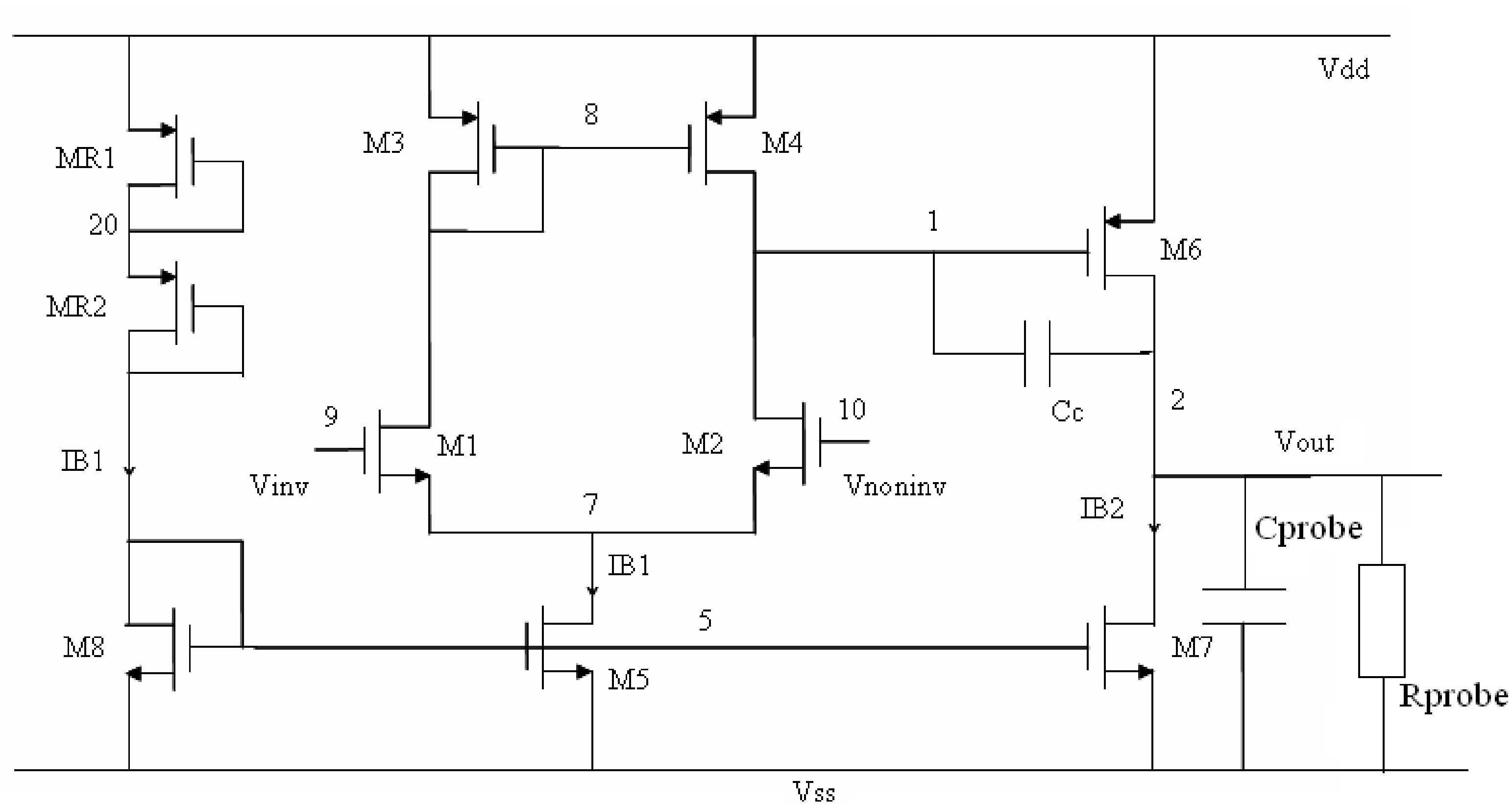






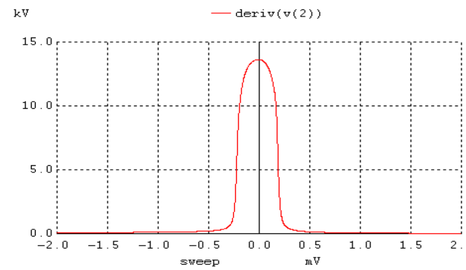
Gain ~5000
Offset 1.17 mV
GBW = 500KHz

BASIC TWO STAGE OPERATIONAL AMPLIFIER



SPICE ANALYSIS OF OP AMP VERSION 2

```
.incl rit_sub_param.txt
m1 8 9 7 6 cmosn w=9u l=5u nrd=1 nrs=1 ad=45p pd=28u as=45p ps=28u
m2 1 10 7 6 cmosn w=9u l=5u nrd=1 nrs=1 ad=45p pd=28u as=45p ps=28u
m3 8 8 4 4 cmosp w=21u l=5u nrd=1 nrs=1 ad=102p pd=50u as=102p
    ps=50u
m4 1 8 4 4 cmosp w=21u l=5u nrd=1 nrs=1 ad=102p pd=50u as=102p
    ps=50u
m5 7 5 6 6 cmosn w=40u l=5u nrd=1 nrs=1 ad=205p pd=90u as=205p
    ps=90u
m6 2 1 4 4 cmosp w=190u l=5u nrd=1 nrs=1 ad=950p pd=400u as=950p
    ps=400u
m7 2 5 6 6 cmosn w=190u l=5u nrd=1 nrs=1 ad=950p pd=400u as=950p
    ps=400u
m8 5 5 6 6 cmosn w=40u l=5u nrd=1 nrs=1 ad=205p pd=90u as=205p
    ps=90u
vdd 4 0 3
vss 6 0 -3
cprobe 2 0 30p
Rprobe 2 0 1meg
cc 1 2 0.6p
mr1 20 20 4 4 cmosp w=6u l=10u nrd=1 nrs=1 ad=200p pd=60u as=200p
    ps=60u
mr2 5 5 20 4 cmosp w=6u l=10u nrd=1 nrs=1 ad=200p pd=60u as=200p
    ps=60u
**************
************
```

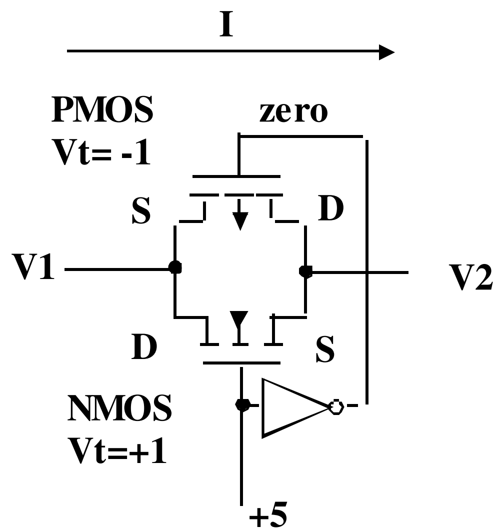


13.5kV/V gain

```
***dc open loop gain*********
vi1 9 0 0
vi2 10 0 0
*.dc vi2 -0.002 0.002 1u
.dc vi2 -1 1 0.1m
*****open loop frequency
    characteristics*****
*vi1 9 0 0
*vi2 10 0 dc 0 ac 1u
*.ac dec 100 10 1g
.end
```

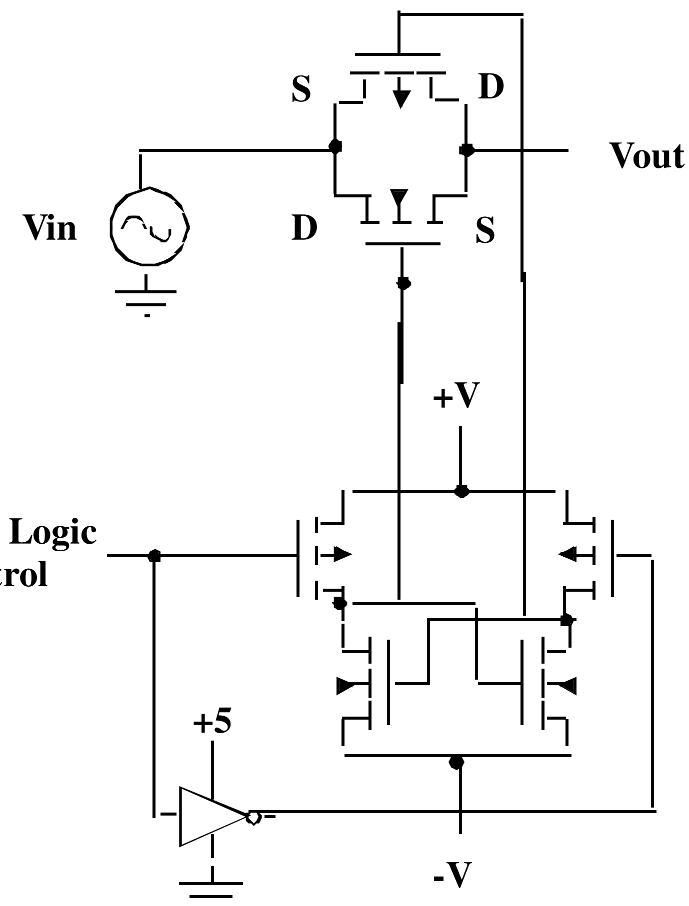
OPERATIONAL AMPLIFIER

ANALOG SWITCHES



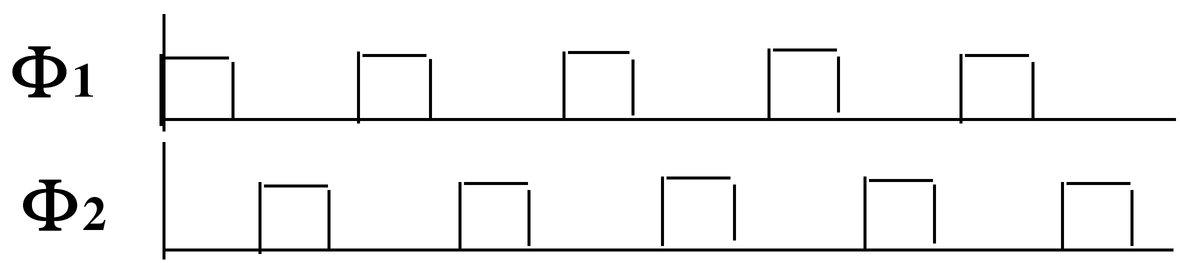
For current flowing to the right (ie V1>V2) the PMOS transistor will be on if V1 is greater than the threshold voltage, the NMOS transistor will be on if V2 is <4 volts. If we are charging up a capacitor load at node 2 to 5 volts, initially current will flow through NMOS and PMOS but once V2 gets above 4 volts the NMOS will be off. If we are trying to charge up V2 to V1 = +1 volt the PMOS will never be on. A complementary situation occurs for current flow to the left. Single transistor switches can be used if we are sure the Vgs will be more than the threshold voltage for the specific circuit application. (or use larger voltages on the gates)

(+V to -V) ANALOG SWITCH WITH (0 to 5 V) CONTROL



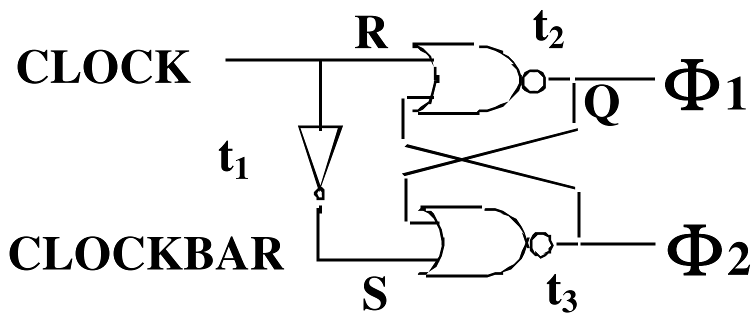
TWO PHASE NON OVERLAPPING CLOCK

Synchronous circuits that use the two phase non overlapping clock can separate input quantities from output quantities used to calculate the results in feedback systems such as the finite state machine.

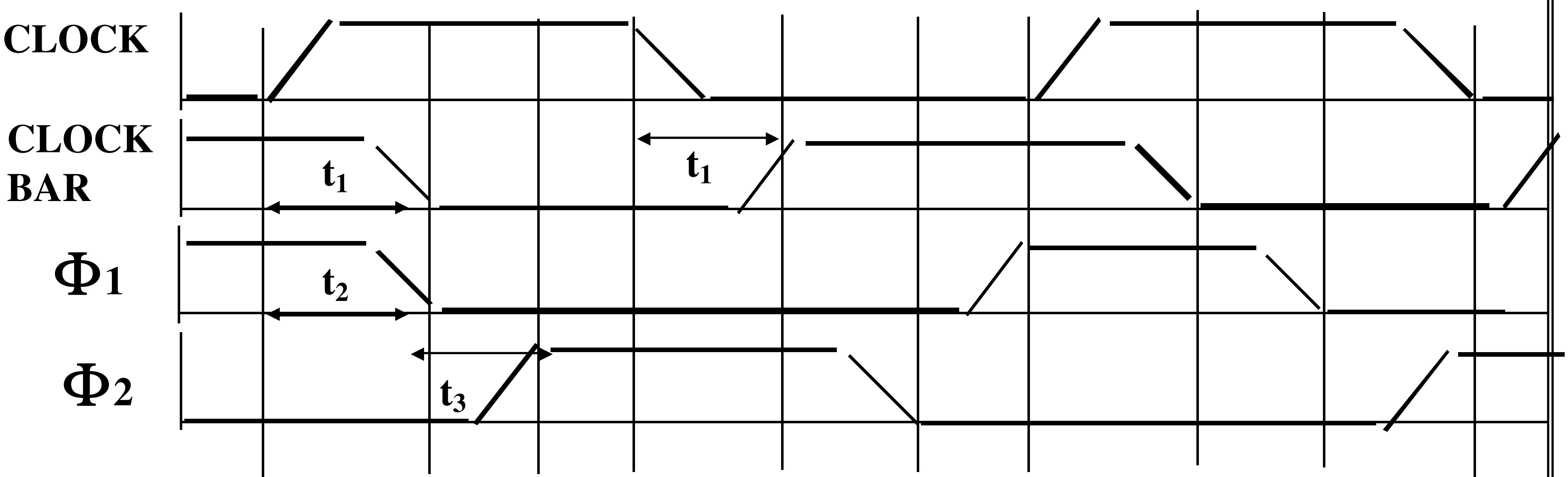


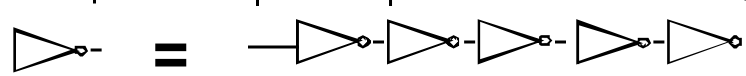
TWO-PHASE CLOCK GENERATORS

A	B	C
0	0	1
0	1	0
1	0	0
1	1	0

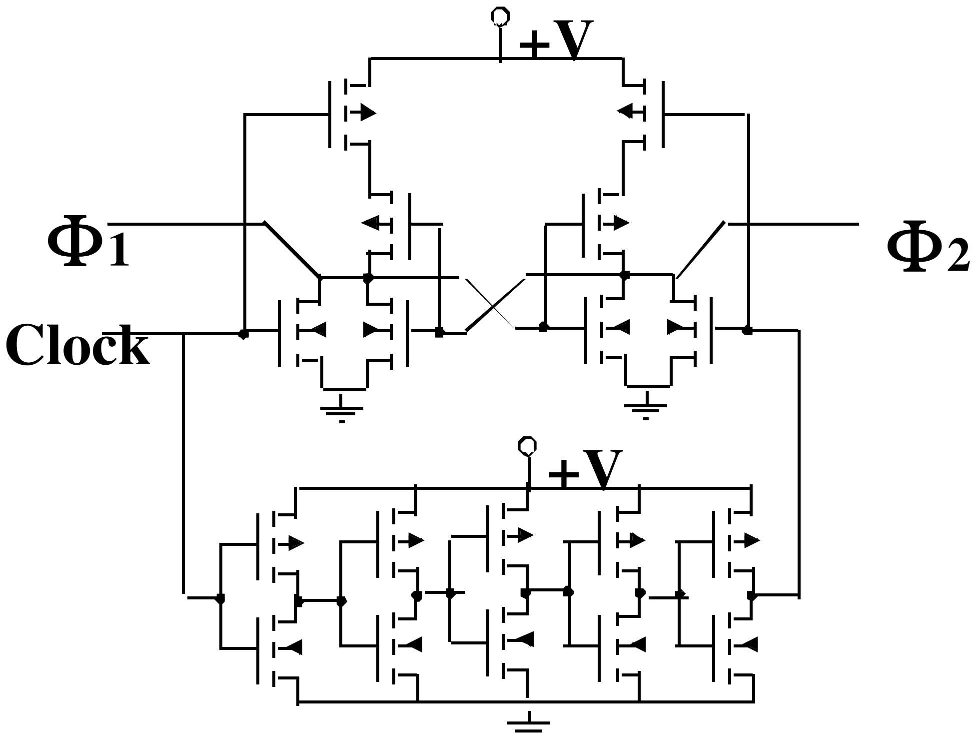


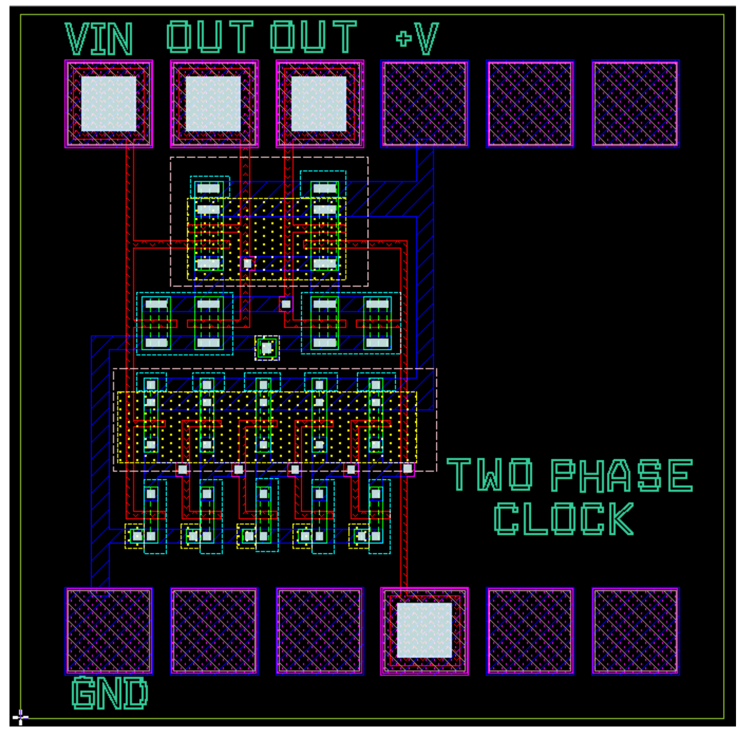
R	S	Q
0	0	Qn-1
0	1	1
1	0	0
1	1	INDETERMINATE





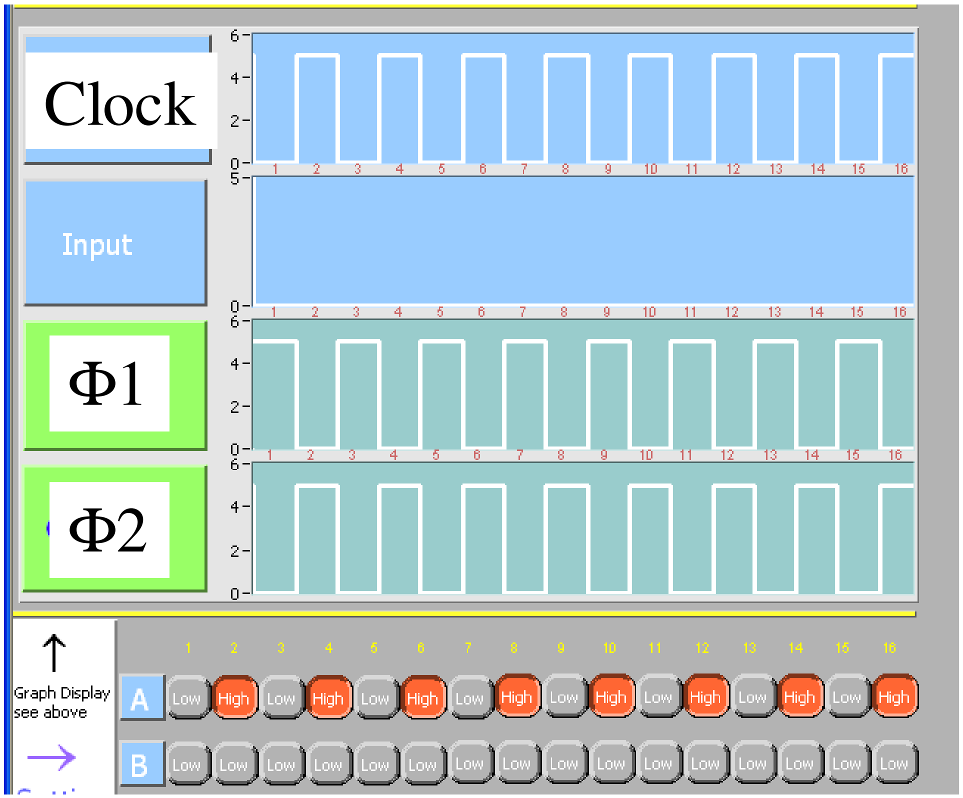
TRANSISTOR LEVEL SCHEMATIC OF 2 PHASE CLOCK

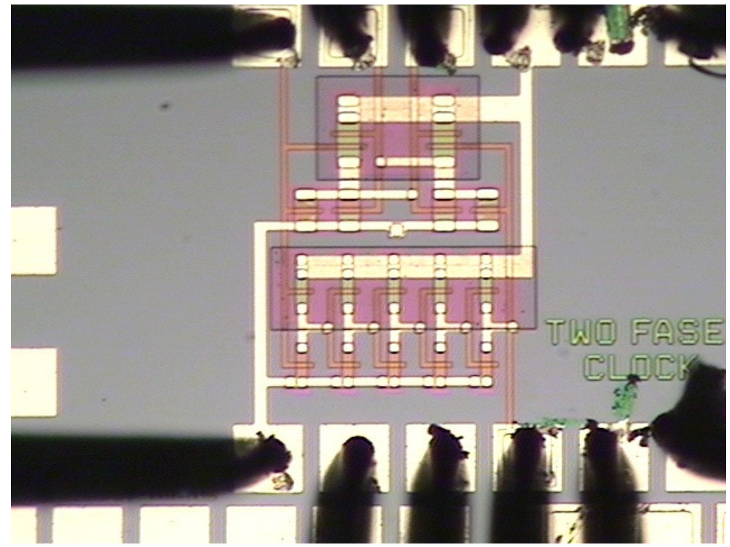


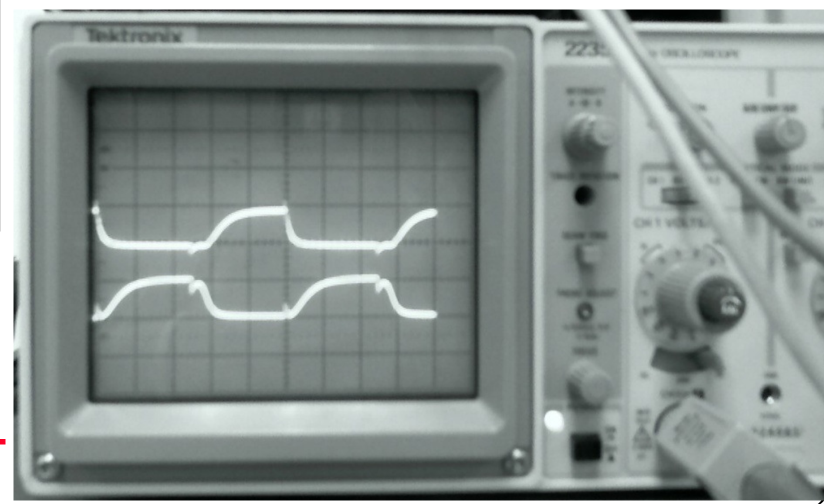


Layout

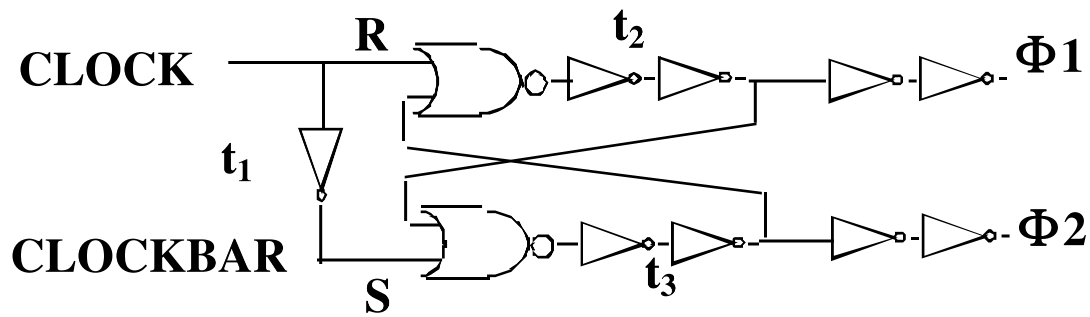
TWO PHASE NON OVERLAPPING CLOCK

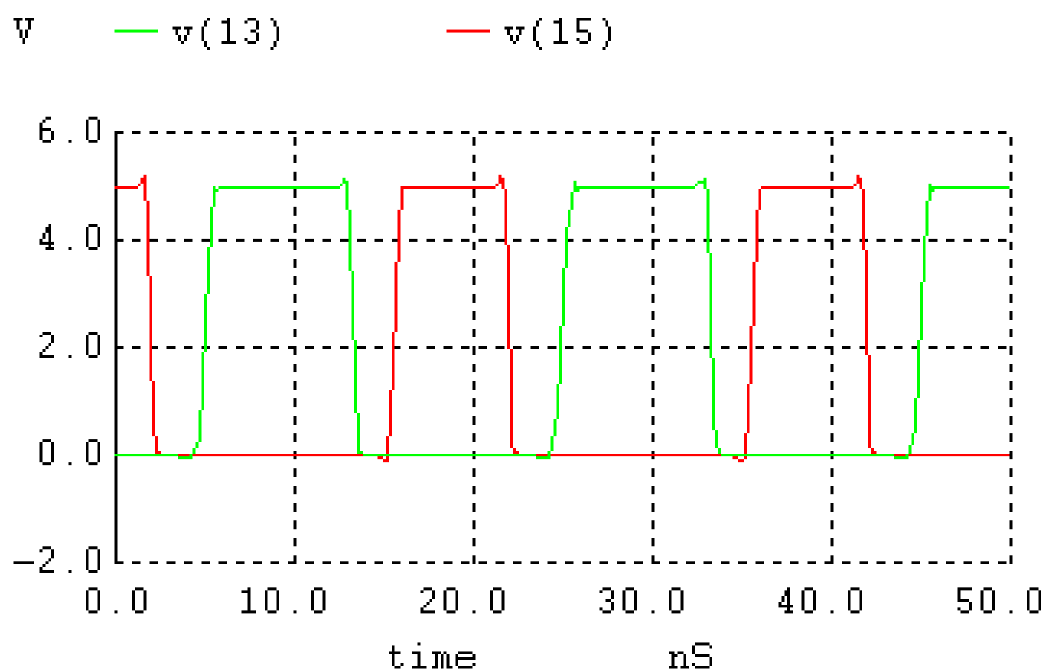






WINSPICE SIMULATION FOR VERSION TWO + BUFFERS





REFERENCES

1. Mechanics of Materials, by Ferdinand P. Beer, E. Russell Johnston, Jr., McGraw-Hill Book Co.1981, ISBN 0-07-004284-5
2. Electromagnetics, by John D Kraus, Keith R. Carver, McGraw-Hill Book Co.1981, ISBN 0-07-035396-4
3. Fundamentals of Microfabrication, M. Madou, CRC Press, New York, 1997
4. Switched Capacitor Circuits, Phillip E. Allen and Edgar Sanchez-Sinencio, Van Nostrand Reinhold Publishers, 1984.
5. "Optimization and fabrication of planar interdigitated impedance sensors for highly resistive non-aqueous industrial fluids", Lvovich, liu and Smiechowski, Sensors and Actuators B:Chemical, Volume 119, Issue 2, 7 Dec. 2006, pgs 490-496.

HOMEWORK – MEMS CAPACITOR SENSORS

1. Calculate the capacitance for a round plate of 100µm diameter with an air gap space of 2.0 µm.
2. If the capacitor in 1 above has the air gap replaced by water what will the capacitance be?
3. Design an apparatus that can be used to illustrate the attractive force between two parallel plates when a voltage is applied.
4. Design an electronic circuit that can measure the capacitance of two metal plates (the size of a quarter) separated by a thin foam insulator for various applied forces.