FINITE ELEMENT ANALYSIS OF MEMS SQUARE PIEZORESISTIVE ACCELEROMETER DESIGNS WITH LOW CROSSTALK

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B.E. Hons Electronics and Instrumentation BITS-Pliani India (Class of 2010)

Overview

- Designs of 3 Accelerometers, Specifications, Application, Introduction.
  - COMSOL Simulations for
    - Mechanical Stress, Voltage distribution, frequency Analysis
  - Verification of Results by Governing laws
  - Method of Fabrication
  - Read out circuit Design
  - Future and Conclusions
- Tools Used: COMSOL 3.4 , Cadence- Virtuso, Calibre-(Verification Tool), TSMC 0.35u Kit.

Introduction

- Acceleration is the time rate of change of velocity. measured in (ft/s)/s or (m/s)/s
- A “g” is a unit of acceleration equal to Earth’s gravity at sea level 32.2 ft/s sq. or 9.81 m/s sq.

Acceleration in Human Terms

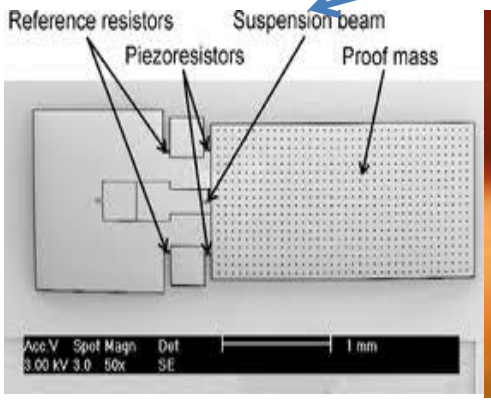
Description	**“g” level**
Earth’s gravity	1g
Passenger car	2g
Bumps in road	2g
Indy car driver	3g
Bobsled rider	5g
Human unconsciousness	7g
Space Shuttle	10g
Golf Stick	500g
Gun Recoil	10000g
Biomedical Instruments (Centrifugal machines	>50000g

Accelerometer

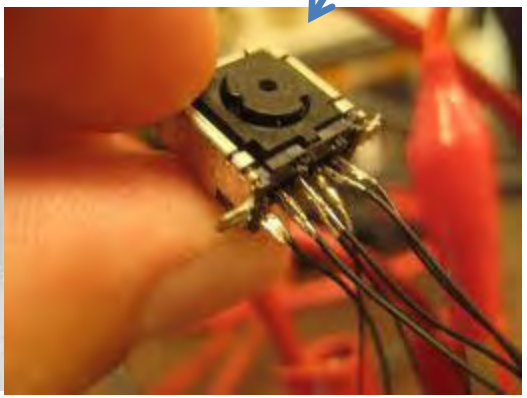
- Measures Static and gravitation force: Tilt and Inclination
- Measurement of Dynamic acceleration: Vibration and Shock

Major World Wide players: VTI technologies with 35% of market share, Denso, Delphi Delco, Analog Devices, Infineon/Sensonor, STM, Colibrys and Tronic's Microsystems mainly

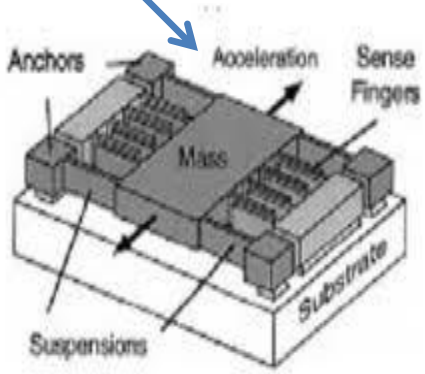
Major Types



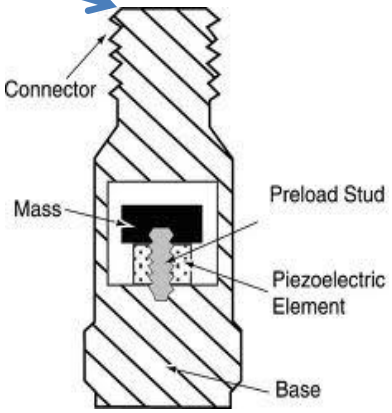
Piezoresistive



Infra Red



Capacitive



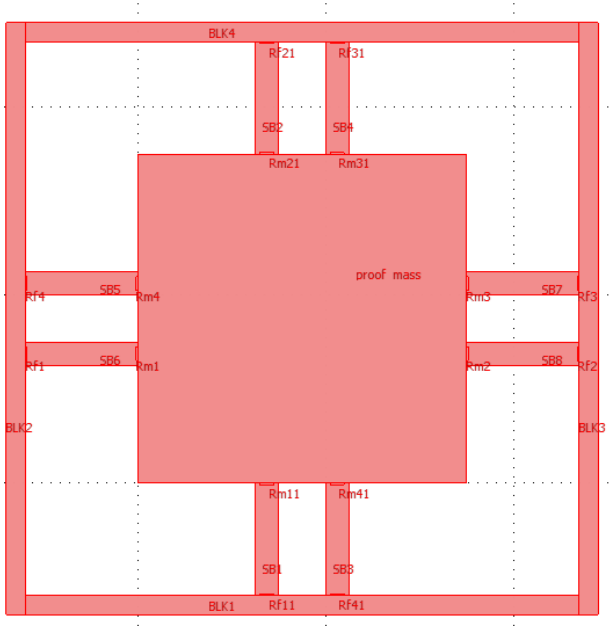
Piezoelectric

Piezoresistive Accelerometer

- Principle : External Acceleration displaces frame relative to the proof mass, which in turn changes the inertial stress in the suspension beam. Piezoresistors placed on the stress areas along the suspension beam will measure the acceleration.
- Square based Configuration have been considered for Finite Element Analysis (FEA)

3-Configurations:- Draw using COMSOL

1



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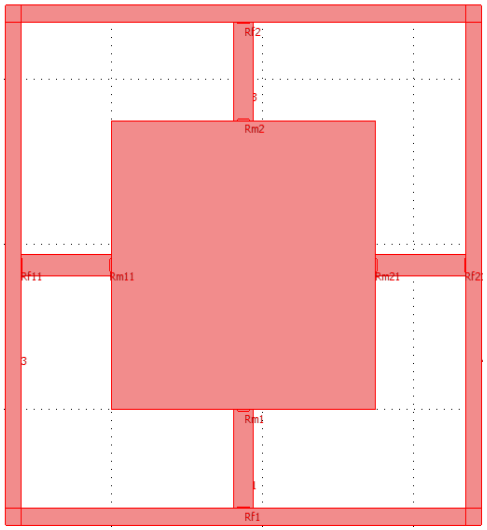

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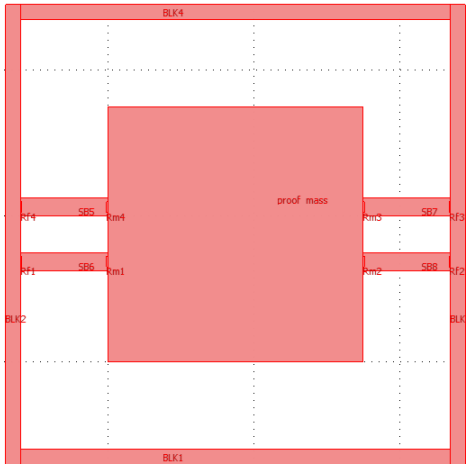
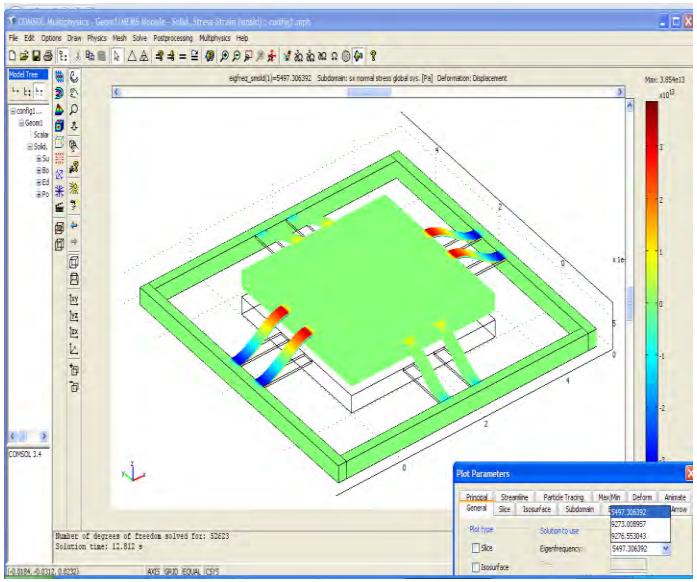


Dimensions
Proof Mass: (3500×3500×300)um
Flexures : ((1200×250×50) um
Frame : (6300*200*280) um (4 in number)
Resistors : (150*20*2.5) um

Material Used: Single Crystal Silicon Substrate p-type (100)

Piezoresistors aligned with [110] direction of the silicon wafer

COMSOL Simulations



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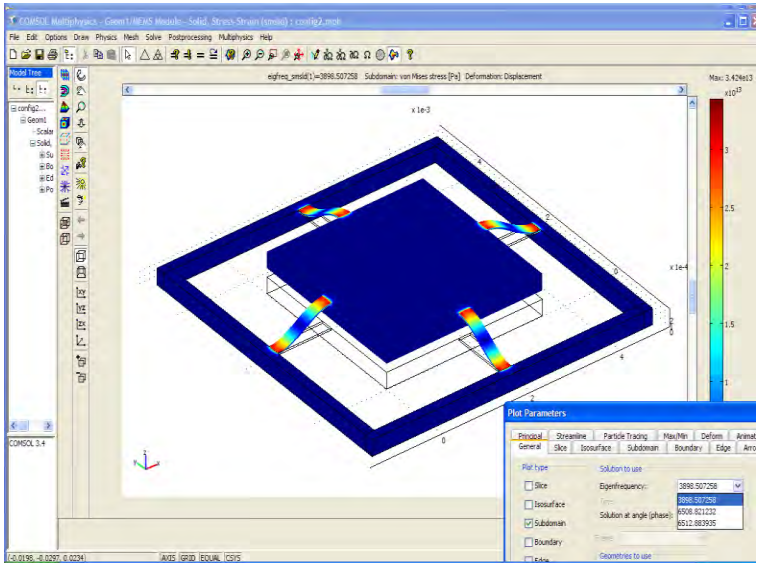

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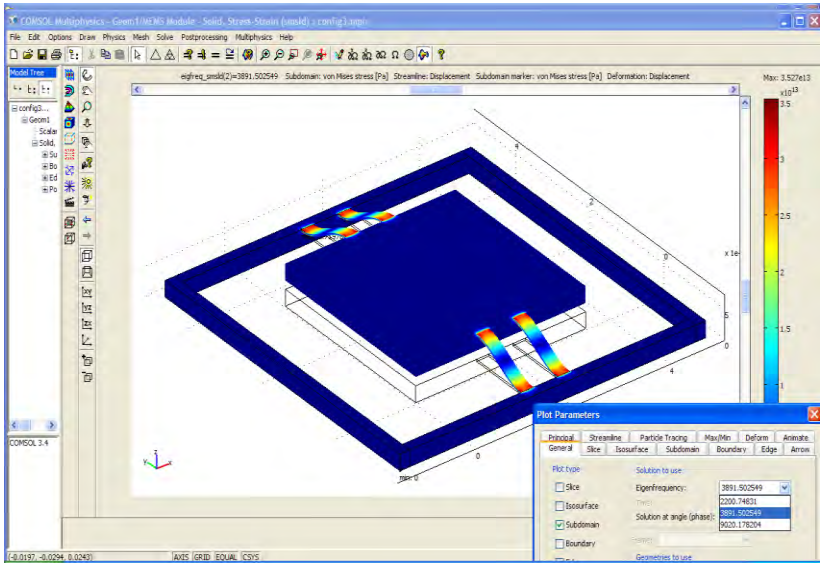
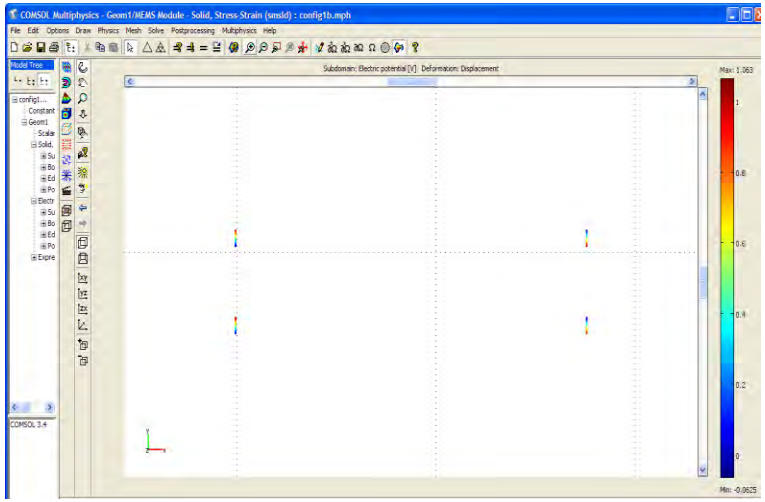
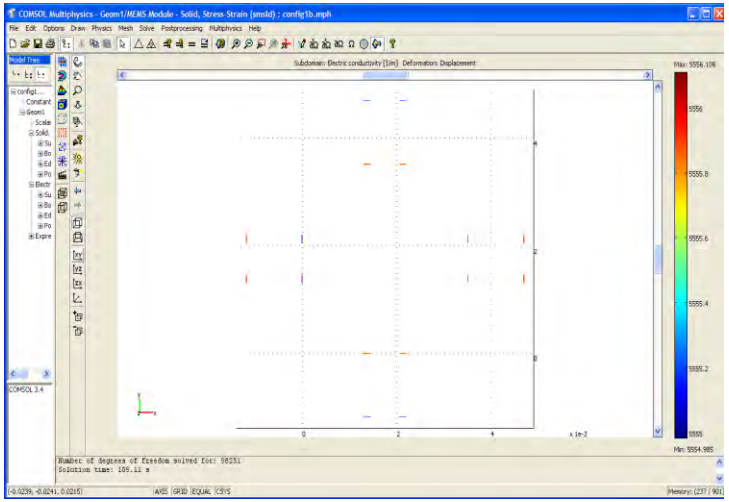
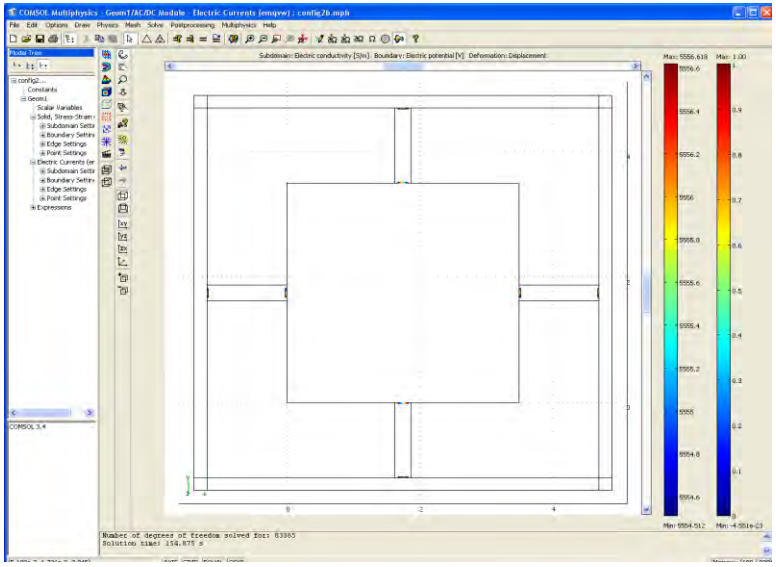


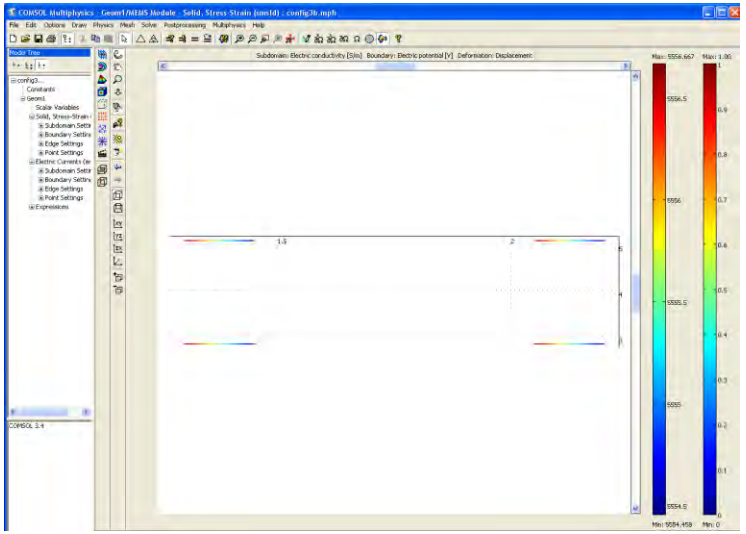
3

Voltage Distribution



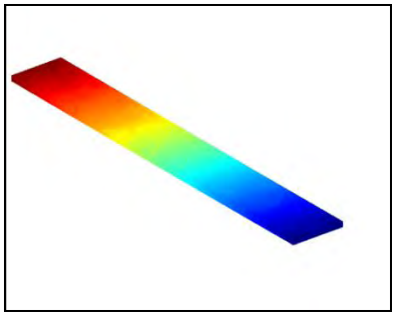






Quantitative analysis change in Resistance

Configuration 1	ΔR	ΔR	ΔR
Piezoresistors	Mode-1 (Desired Axis)	Mode-2	Mode-3
R1f	⇩	⇧	⇧
R1m	⇧	⇩	⇩
R2f	⇩	⇧	⇧
R2m	⇧	⇧	⇩
R3f	⇩	⇩	⇩
R3m	⇧	⇧	⇧
R4f	⇩	⇧	⇩
R4m	⇧	⇩	⇧
R11f	⇩	⇧	⇧
R11m	⇧	⇩	⇩
R21f	⇩	⇧	⇩
R21m	⇧	⇩	⇧
R31f	⇩	⇩	⇩
R31m	⇧	⇧	⇧
R41f	⇩	⇩	⇧
R41m	⇧	⇧	⇩
Configuration 2	ΔR	ΔR	ΔR
Piezoresistors	Mode-1 (Desired Axis)	Mode-2	Mode-3
R1f	⇩	0	⇧
R1m	⇧	0	⇩
R2f	⇩	⇩	0
R2m	⇧	⇧	0
R3f	⇩	0	⇩
R3m	⇧	0	⇧
R4f	⇩	⇧	0
R4m	⇧	⇩	0
Configuration 3	ΔR	ΔR	ΔR
Piezoresistors	Mode-1 (Desired Axis)	Mode-2	Mode-3
R1f	⇩	⇧	⇧
R1m	⇧	⇩	⇩
R2f	⇩	⇩	⇧
R2m	⇧	⇧	⇩
R3f	⇩	⇩	⇩
R3m	⇧	⇧	⇧
R4f	⇩	⇧	⇩
R4m	⇧	⇩	⇧



Change in the conductivity along the piezoresistor

Mathematical Analysis

- **Sensitivity**

Vout=Δ R×Vin/R

S=Vout/ (Δg×Vin)

S=Δ R/(R×Δg)

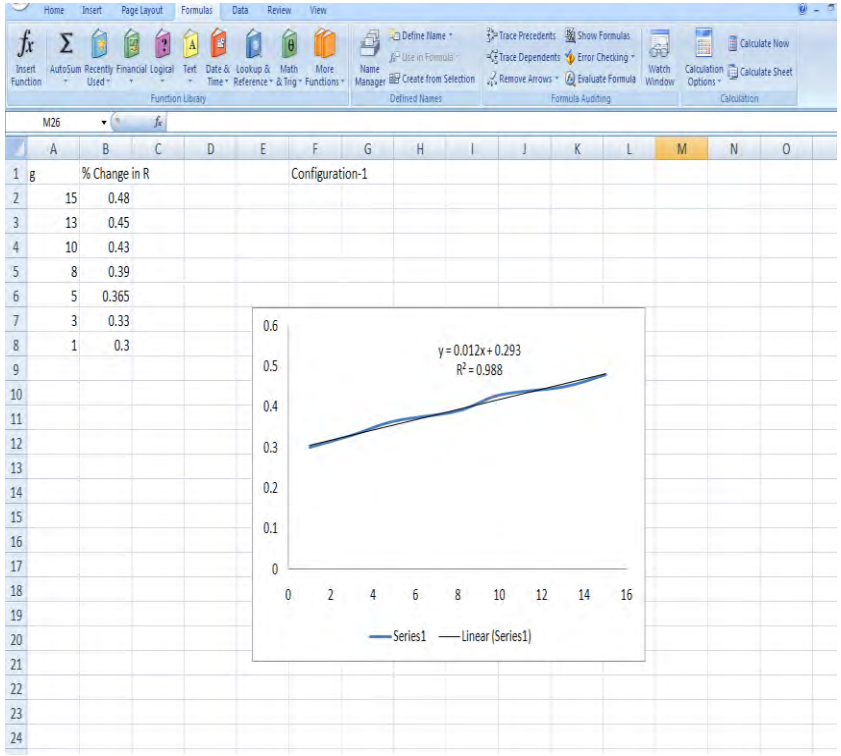
- **Stress Analysis**
  - Simulation Results match with following equations

Deformation Equation

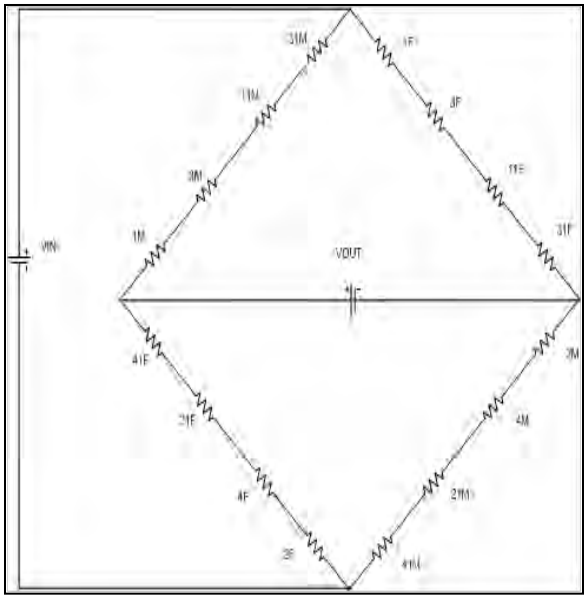
$$y(x) = \frac{Fx(3x - 4x^2)}{48EI}$$

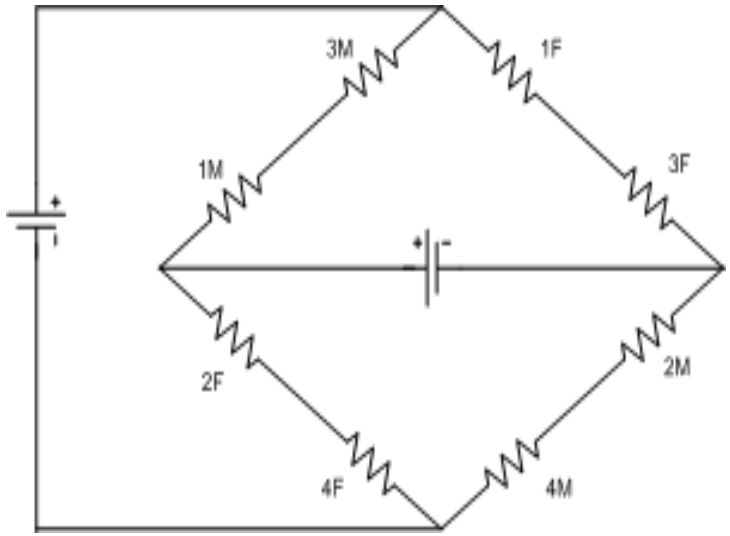
Maximum Stress Equation

$$\sigma_{max} = \frac{FLt}{8I}$$

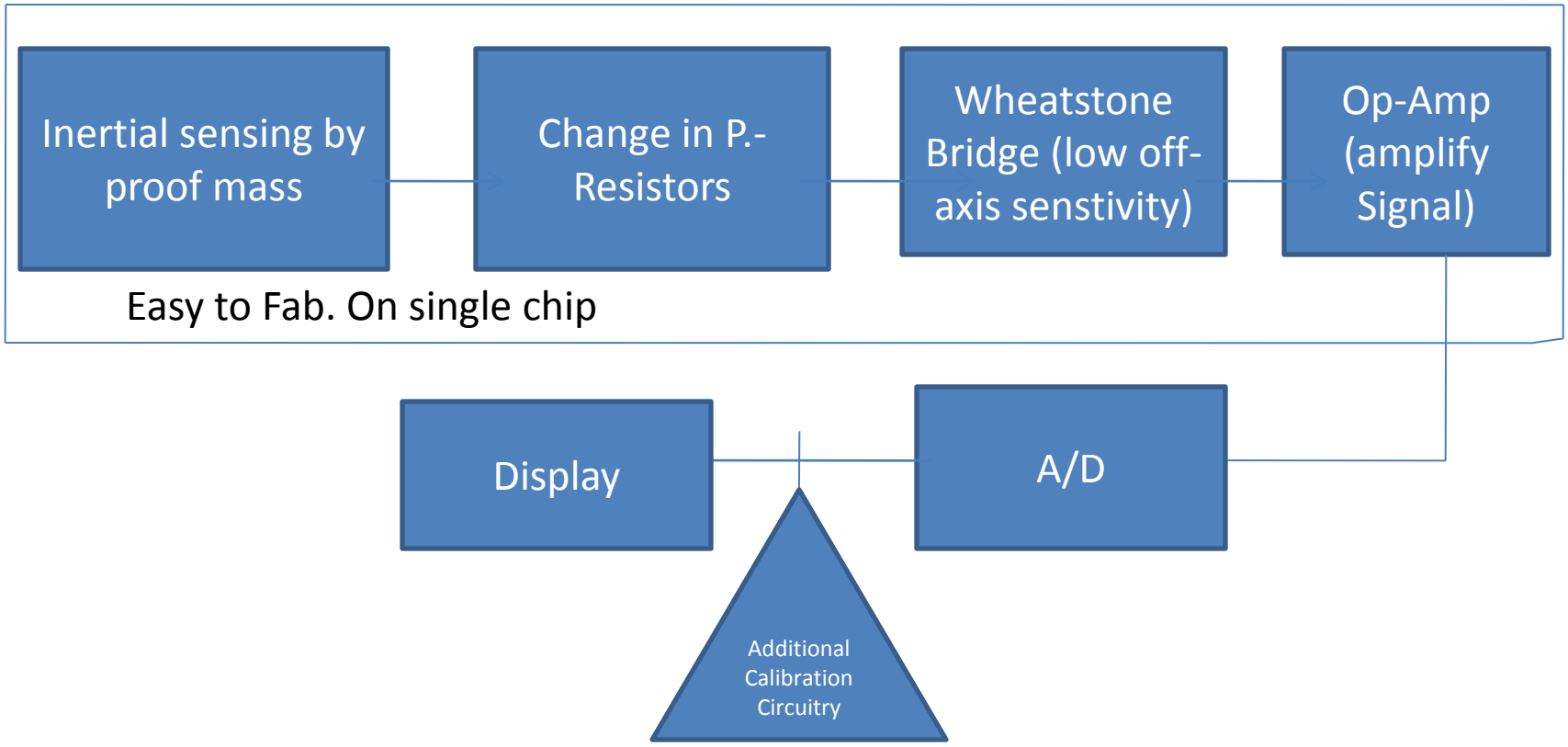


Wheatstone Bridge Connections

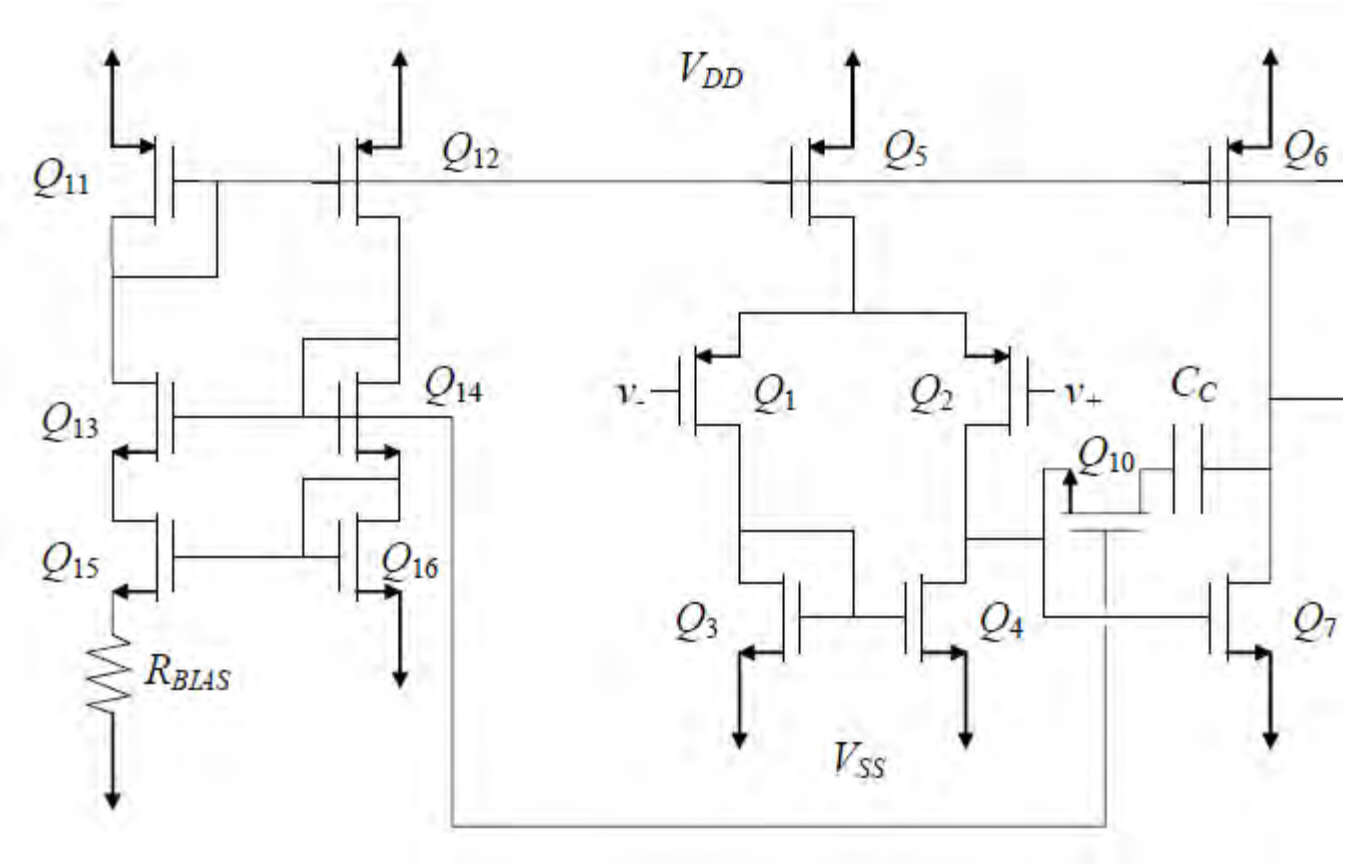




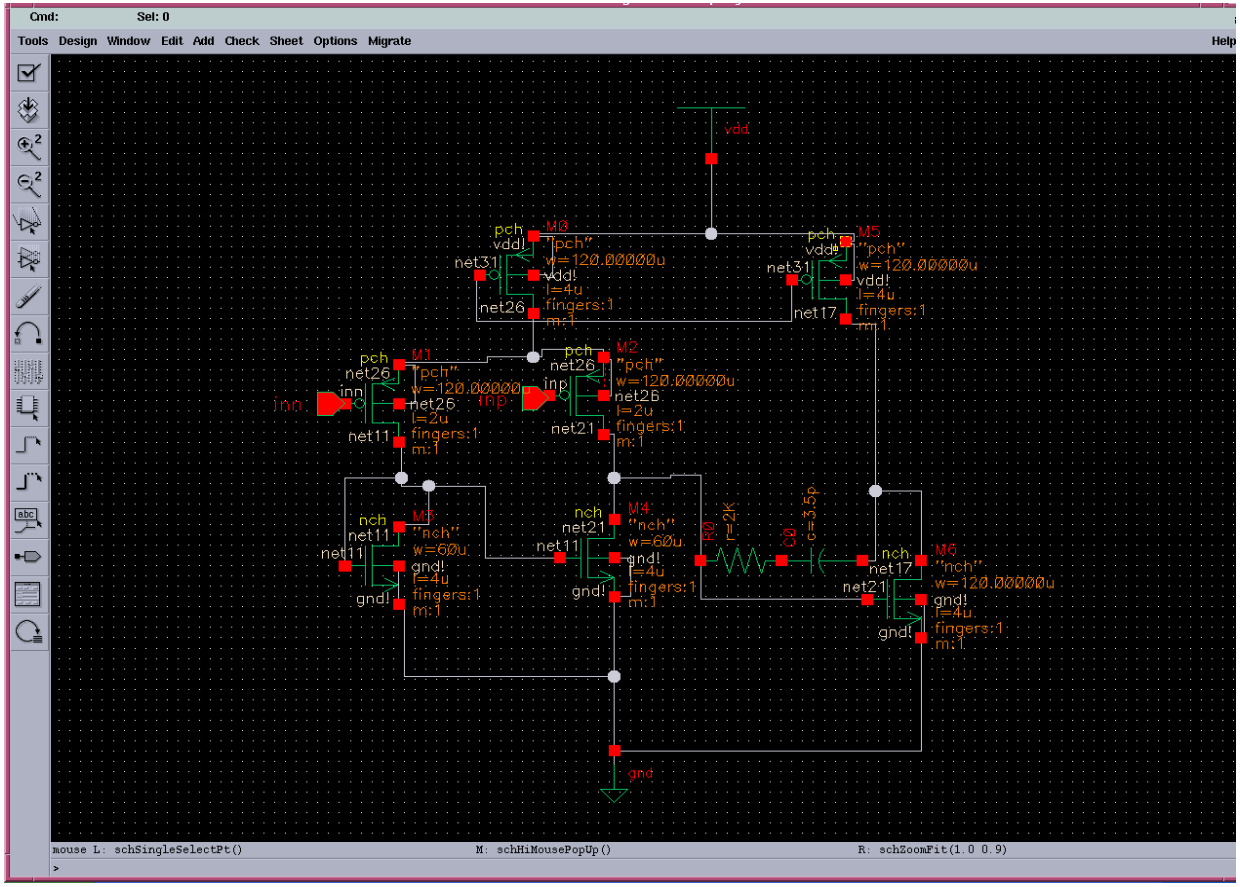
Block Diagram of System



Op-Amp Circuit



Schematic


Cmd:
Sel: 0
Tools Design Window Edit Add Check Sheet Options Migrate
Help
vdd
M0
"pch"
w=120.00000u
l=4u
fingers:1
m:1
M5
"pch"
w=120.00000u
l=4u
fingers:1
m:1
M1
"pch"
w=120.00000u
l=2u
fingers:1
m:1
M2
"pch"
w=120.00000u
l=2u
fingers:1
m:1
inn
inp
M3
"nch"
w=60u
l=4u
fingers:1
m:1
M4
"nch"
w=60u
l=4u
fingers:1
m:1
R0
r=2K
C0
c=3.5p
M6
"nch"
w=120.00000u
l=4u
fingers:1
m:1
gnd
mouse L: schSingleSelectPt()
M: schHiMousePopUp()
R: schZoomFit(1.0 0.9)

Pre-Simulation

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File Edit Format View Help

```
*two stage operational amplifeir

.lib "C:\Documents and Settings\ASIC04\My Documents\SEM2\analog electron'

.option post=2
.op

v1      gnd     0       0v
v2      vdd     0       3.3

*       d       g       s       b
m1      1       inn     2       vdd     pch     w=15u   l=2u     m=8
m2      3       inp     2       vdd     pch     w=15u   l=2u     m=8
m3      1       1       gnd     gnd     nch     w=15u   l=4u    m=4
m4      3       3       1       gnd     gnd     nch     w=15u   l=4u    m=4
m5      2       4       vdd     vdd     pch     w=15u   l=4u    m=8

m6      out     4       vdd     vdd     pch     w=15u   l=4u     m=8
m7      out     3       gnd     gnd     nch     w=15u   l=4u     m=8


m8      4       4       vdd     vdd     pch     w=15u   l=4u   m=8
m9      6       4       vdd     vdd     pch     w=15u   l=4u     m=8
m10     4       6       7       gnd     nch     w=15u   l=4u   m=4
m11     6       6       8       gnd     nch     w=15u   l=4u     m=1
m12     7       8       a       gnd     nch     w=15u   l=4u   m=4
m13     8       8       gnd     gnd     nch     w=15u   l=4u   m=1

rb      a       gnd     3k
r1      3       b       2k
c1      b       out     3.5p

vina    inn     gnd     dc      0       ac      1
vinb    inp     gnd     dc      0

c2      out     gnd     1p


.ac     dec     10      10      1g

.print ac       vdb(out)  vp(out)
```

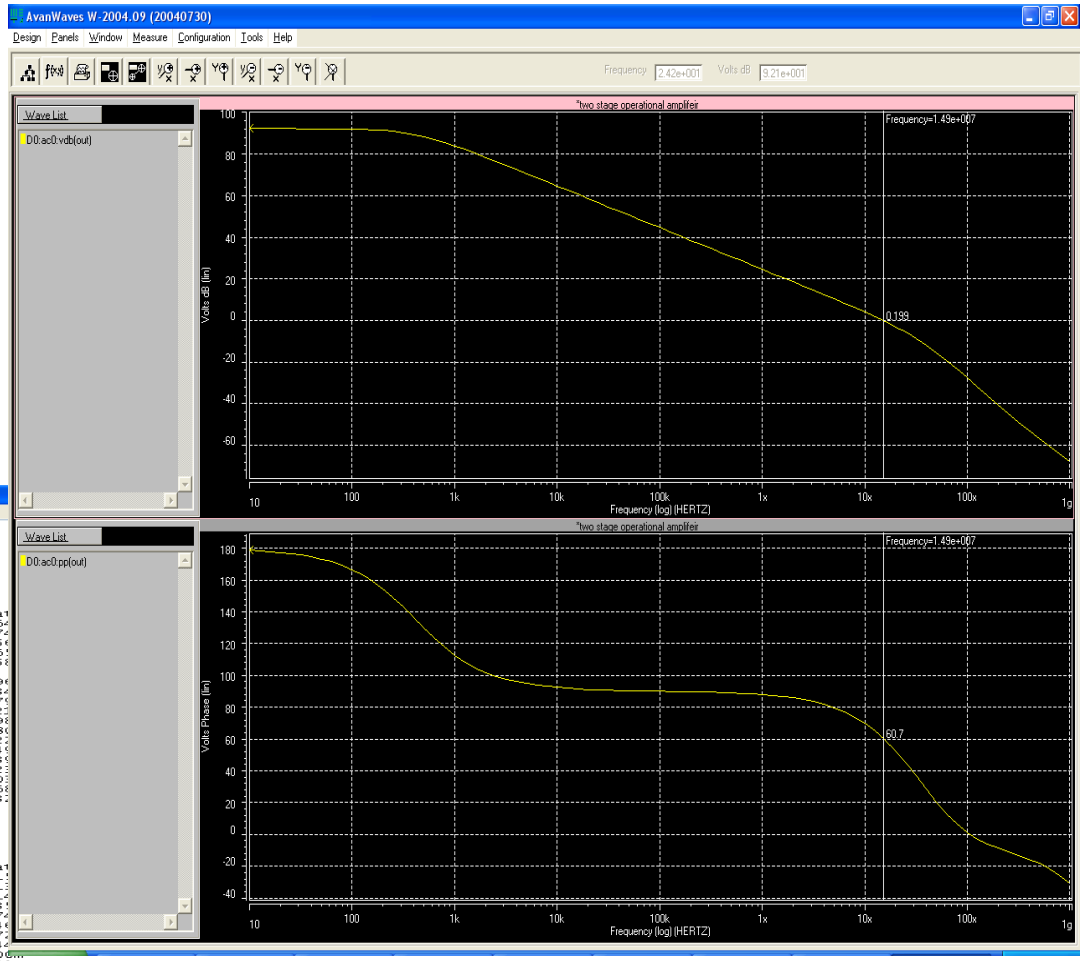
opamp.lis - Notepad

File Edit Format View Help

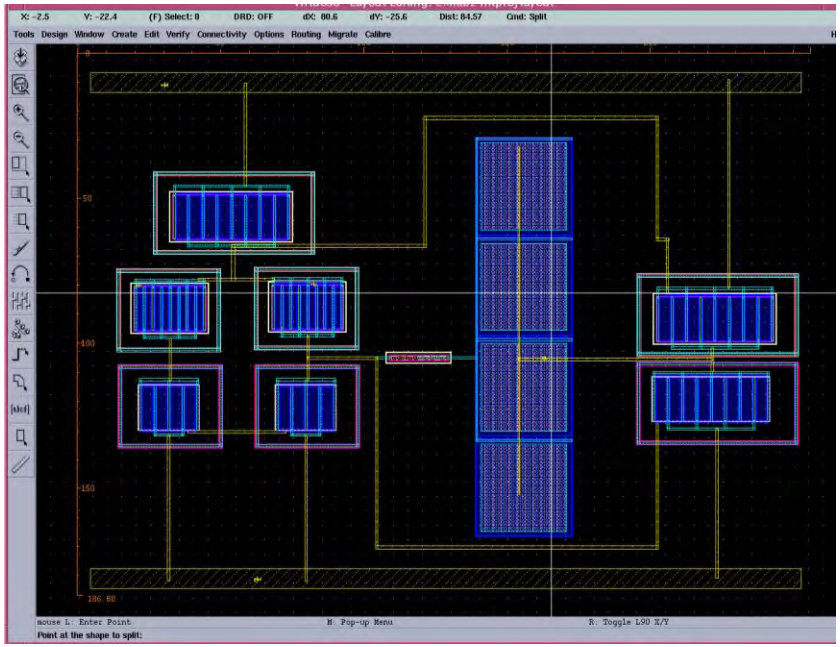
```
**** mosfets

subckt
element   0:m1          0:m2          0:m3          0:m4          0:m5          0:m6
model     0:pch.1       0:pch.1       0:nch.1       0:nch.1       0:pch.1       0:pch.1
region     Saturati      Saturati      Saturati      Saturati      Saturati      Saturati
 id       -28.7898u     -28.7898u      28.7899u      28.7899u     -57.5796u     -57.8664
 ibs       11.0073f      11.0073f     -42.3970a     -42.3970a      11.3609a      11.4174
 ibd       11.0073f      11.0073f     -76.4397f     -76.4397f      14.8776p      56.5256
 vgs       -1.1719       -1.1719       659.8443m     659.8443m    -966.5265m    -966.5265
 vds     -512.0376m    -512.0376m      659.8443m     659.8443m      -2.1281       -2.3958
 vbs        2.1281        2.1281          0.            0.            0.            0.
 vth       -1.0750       -1.0750       542.9784m     542.9784m    -742.0344m    -741.5296
 vdsat   -155.6151m    -155.6151m      147.8861m     147.8861m    -254.6309m    -255.0734
 beta       3.4378m       3.4378m       3.1188m       3.1188m       1.9477m       1.9471
 gam eff  414.9439m     414.9439m      469.5089m     469.5089m     417.8721m     417.8723
 gm       381.8366u     381.8366u      342.3773u     342.3773u     433.3306u     434.7298
 gds        2.3241u       2.3241u      610.1337n     610.1337n       1.0865u       1.0958
 gmb       45.4154u      45.4154u      103.1985u     103.1985u     101.3887u     101.7222
 cdtot    113.4278f     113.4278f       73.6349f      73.6349f     121.1111f     116.8748
 cgtot    671.8951f     671.8951f      760.2447f     760.2447f       1.5439p       1.5438
 cstot    768.1108f     768.1108f      927.5474f     927.5474f       1.9223p       1.9223
 cbtot    315.4949f     315.4949f      423.4274f     423.4274f     757.0466f     752.8103
 cgs      593.3047f     593.3047f      641.3849f     641.3849f       1.3668p       1.3668
 cgd       22.0332f      22.0332f       12.4358f      12.4358f      22.0332f      22.0332


subckt
element   0:m7          0:m8          0:m9          0:m10         0:m11         0:m12
model     0:nch.1       0:pch.1       0:pch.1       0:nch.1       0:nch.1       0:nch.1
region     Saturati      Saturati      Saturati      Saturati      Saturati      Saturati
 id        57.8664u     -56.1615u     -56.4628u      56.1615u      56.4628u      56.1615
 ibs      -85.2160a      11.0812a      11.1406a     -76.4397f     -19.1099f     -76.3315
 ibd     -152.9177f      11.0083f      11.4443f     -121.2056f    -19.2267f     -76.4714
 vgs       659.8443m   -966.5265m    -966.5265m      998.8856m       1.1773      771.9735
 vds       904.1894m   -966.5265m      -1.1823         1.2146        1.1773      950.3774
 vbs          0.           0.            0.          -1.1189      -940.4581m    -168.4845
 vth       542.7342m   -744.2247m    -743.8179m      819.3397m     781.1946m     591.9277
 vdsat     148.0651m   -252.7121m    -253.0683m      206.9389m     392.2116m     199.1244
 beta        6.2377m       1.9470m       1.9471m       2.9716m       1.7285m       3.0808
 gam eff   469.5089m     417.8721m     417.8721m     444.7204m     448.0759m     465.0221m
 gm        687.1001u     425.6147u     427.4096u     516.6021u     258.3803u     514.4526u
 gds         1.1488u       1.4727u       1.3323u     790.7684n     464.6783n     865.6443n
 gmb       207.1138u      99.5620u      99.9854u     108.8384u      56.9389u     143.0712u
 cdtot     142.5027f     148.6934f     141.9367f      63.0370f      15.9788f      69.5135f
 cgtot       1.5205p       1.5439p       1.5439p     793.9906f     201.1192f     796.9332f
 cstot       1.8551p       1.9223p       1.9223p     921.0562f     235.6173f     974.4926f
 cbtot     842.0877f     784.6291f     777.8724f     305.8468f      79.0549f     394.7010f
 cgs         1.2828p       1.3668p       1.3668p     715.6450f     181.6527f     696.7209f
 cgd        24.8715f      22.0332f      22.0332f      12.4358f       3.1089f      12.4358f
```

AvanWaves W-2004.09 (20040730)

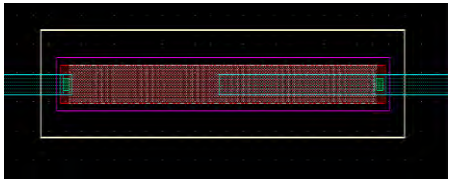
Design Panels Window Measure Configuration Tools Help



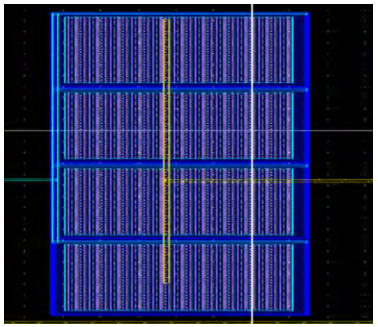
Layout



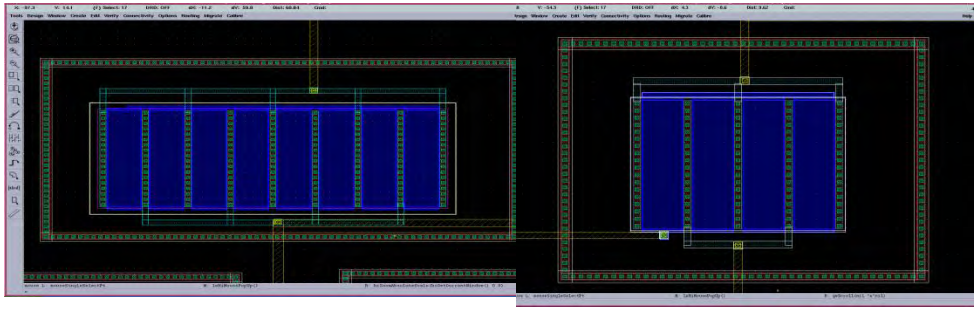
resistor



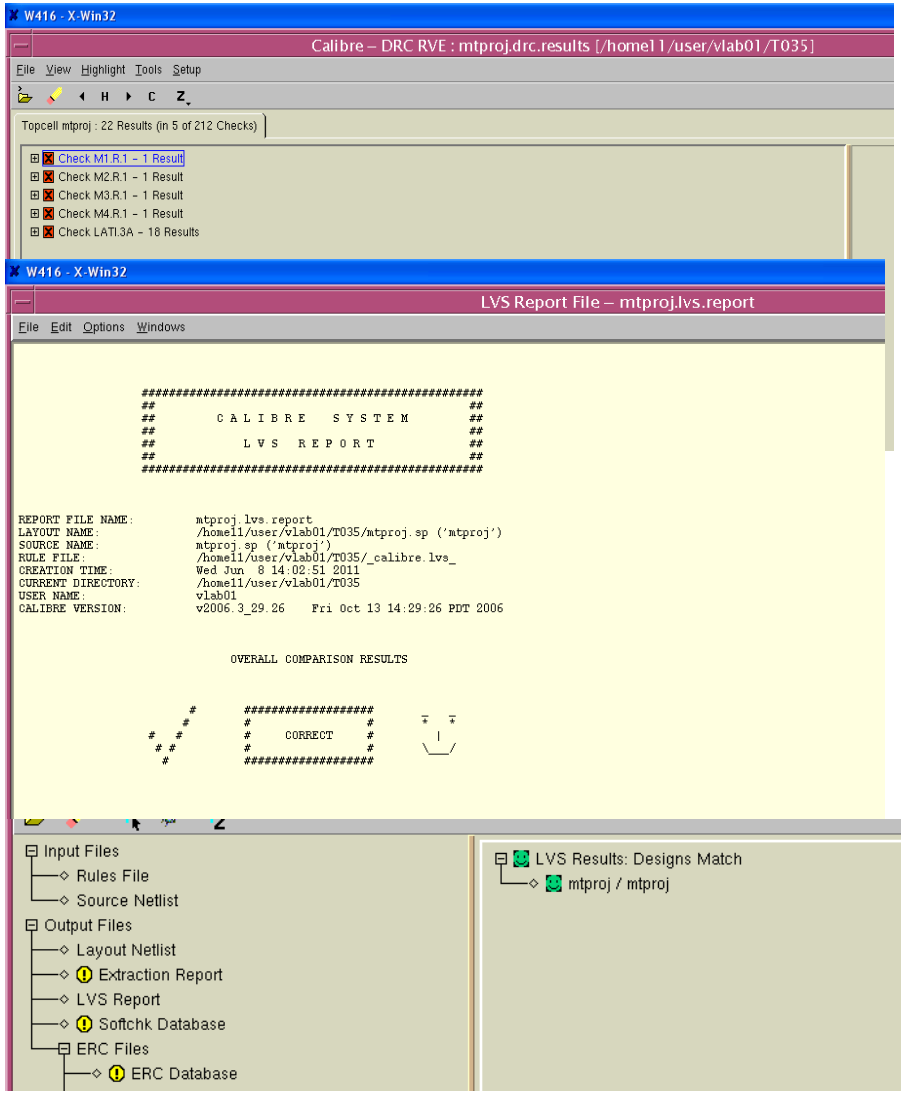
Capacitor

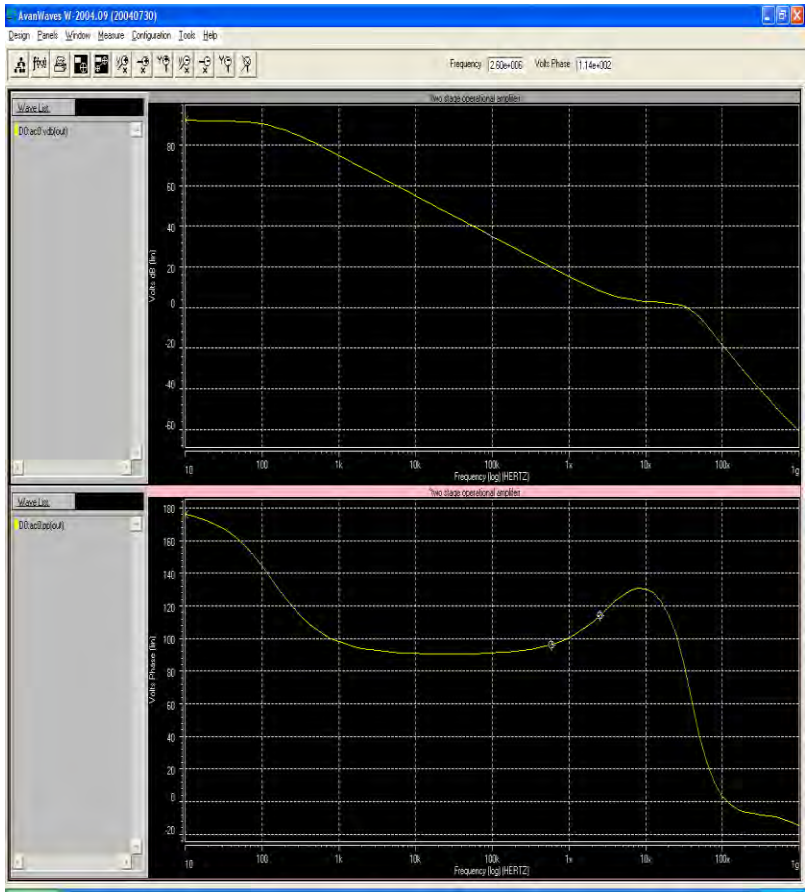


Transistors

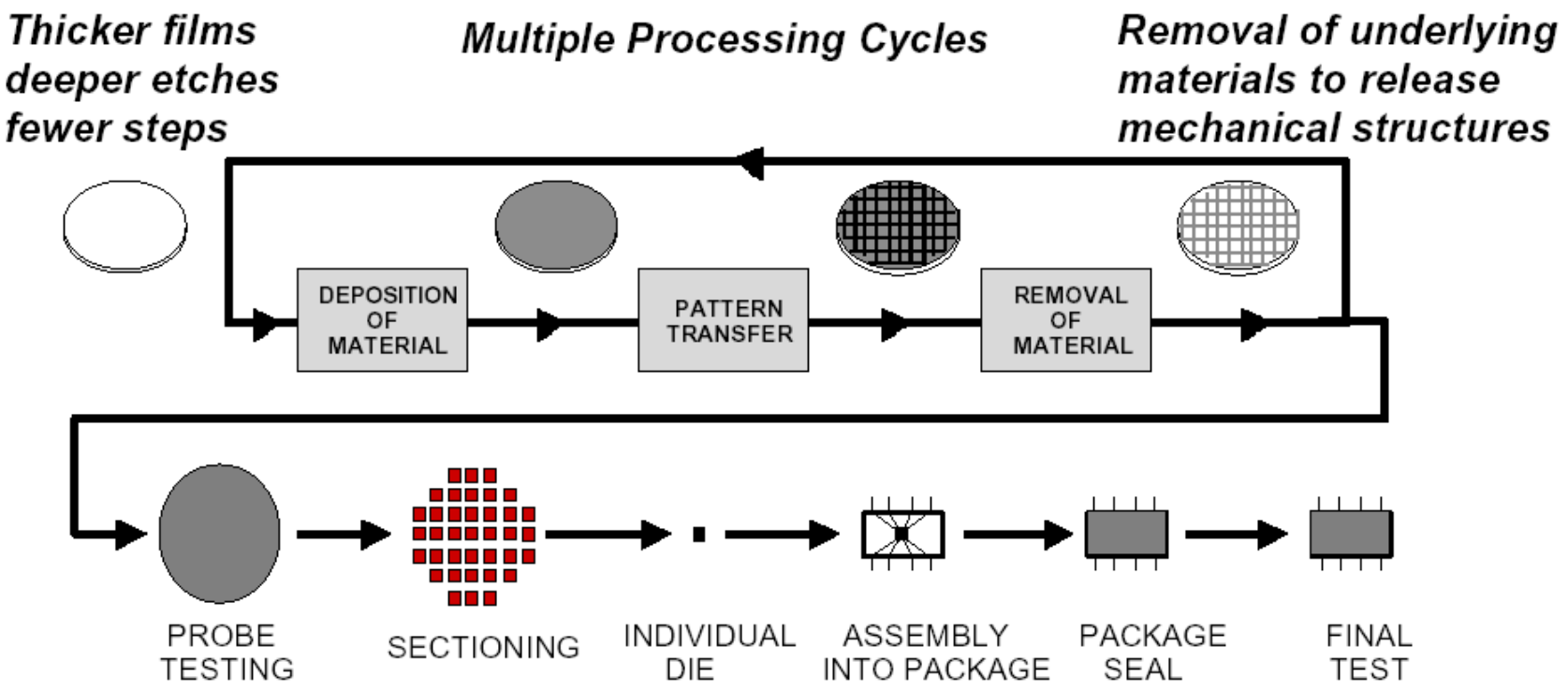


Layout Check, Post Simulation



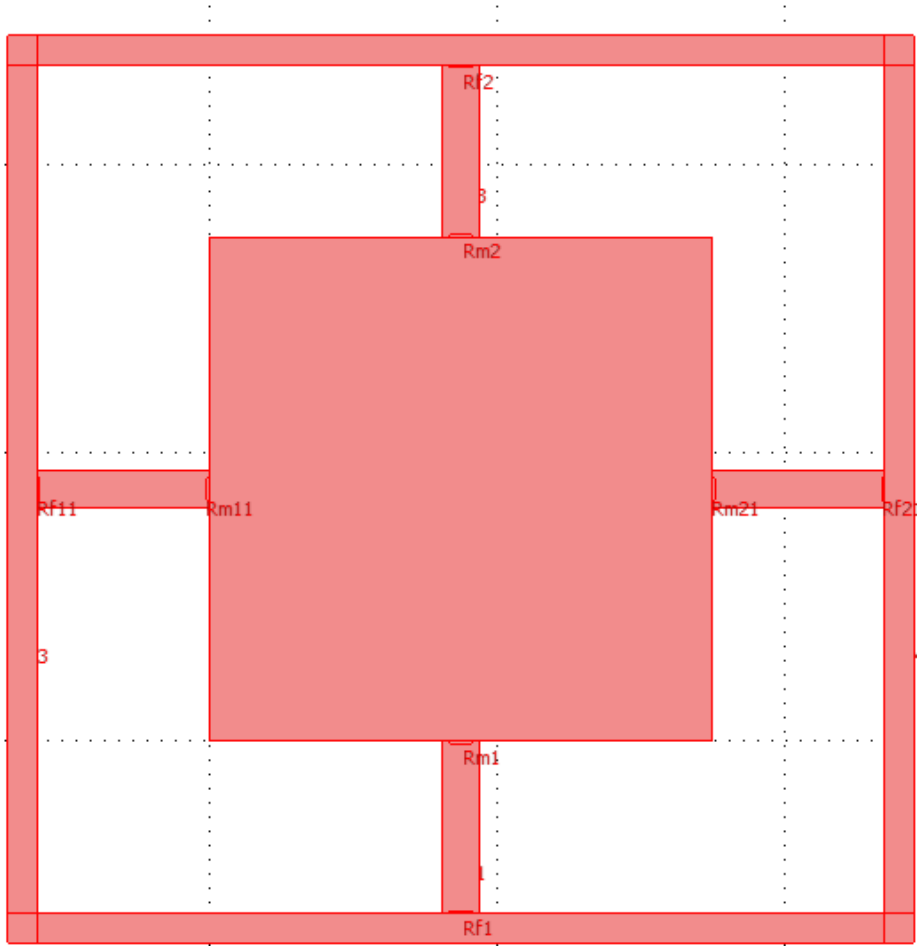


Fabrication



Connections

in



Connections for other two configuration would be made on similar basis

Conclusions

Advantages

- Simple in structure
- Simple in fabrication process
- Easy to make read circuitary
- Less susceptible to parasitic capacitance or electromagnetic interference(EMI)
- Can also be used for accelerations upto 70,000 g

Disadvantages

- Large temperature sensitivity therefore it might need a compensation circuit
- Small sensitivity compared with other sensors

References

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Thank You