MEMS Accelerometer Laboratory

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OUTLINE

INTRODUCTION

Acceleration (a) is the term given to the condition where and object experiences a change in velocity (v). Objects of mass (m) experience a force (F) equal to m times a. (F = ma) Earths gravity exerts an acceleration on objects creating a force. The acceleration due to gravity (g) has been found to be $9.8 m/s^2$. Acceleration, velocity and position (x) of objects are related by the following equation:

$$a = dv/dt = d^2x/dt^2$$

Acceleration

Earths Gravity	**1g**
Standing on the moon	**0.16g**
Passenger Car in a Turn	**2g**
Indy Car in a Turn	**3g**
Bobsled in a Turn	**5g**
Human Unconsciousness	**7g**
Human Death	**50g**
Car Crash Survival	**100g**
Mechanical Watch	**5,000g**
Electronics in Artillery	**15,000g**
Haldron Collider	**1.9E8g**

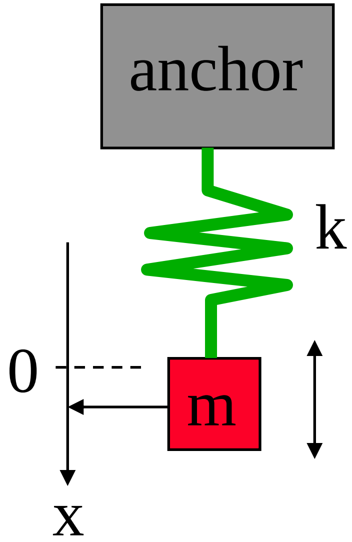
INTRODUCTION

An accelerometer is a sensor that can be used to measure acceleration. These sensors are used in systems for car air bag deployment, tilt sensing, and motion control. Most accelerometers are sensors that measure the force on a known mass (proof mass). The proof mass is supported by a spring, of spring constant (k), that will create a force equal and opposite to the force due to acceleration. The position is measured in response to changes in acceleration. There is also a friction or damping force.

$$F = ma$$

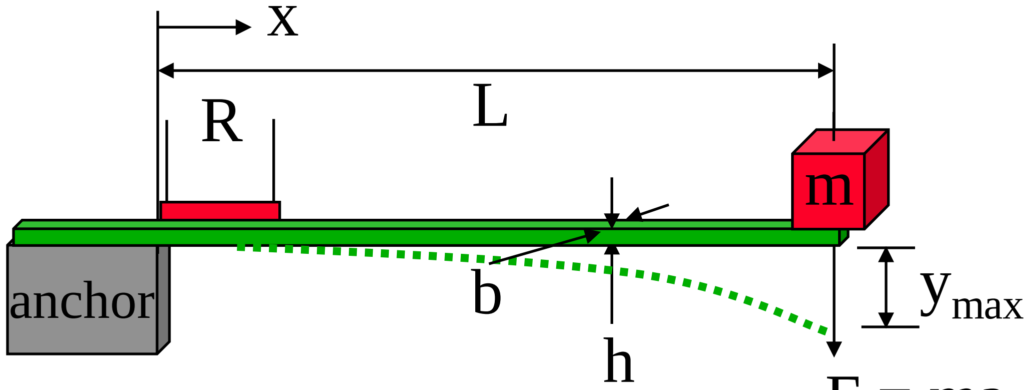
$$F = kx$$

$$m\, d^2x/dt^2 = kx$$



INTRODUCTION

One type of accelerometer is based on a cantilever beam (spring) with a mass (m) at the free end and integrated resistors (R) positioned to measure strain as the cantilever bends in response to acceleration.



L = length of beam
b = width of beam
h = thickness of beam
y_{max} = maximum deflection

EQUATIONS FOR CANTILEVER BEAM

The maximum deflection is at the free end of the cantilever

$$Ymax = F\,L^3/3EI$$

where E = Youngs Modulus

and I = $bh^3/12$, moment of inertia

The maximum stress ($\sigma_{x=0}$) is at the top surface of the cantilever beam at the anchor where x=0

$$\sigma_{x=0} = F\,Lh/2I$$

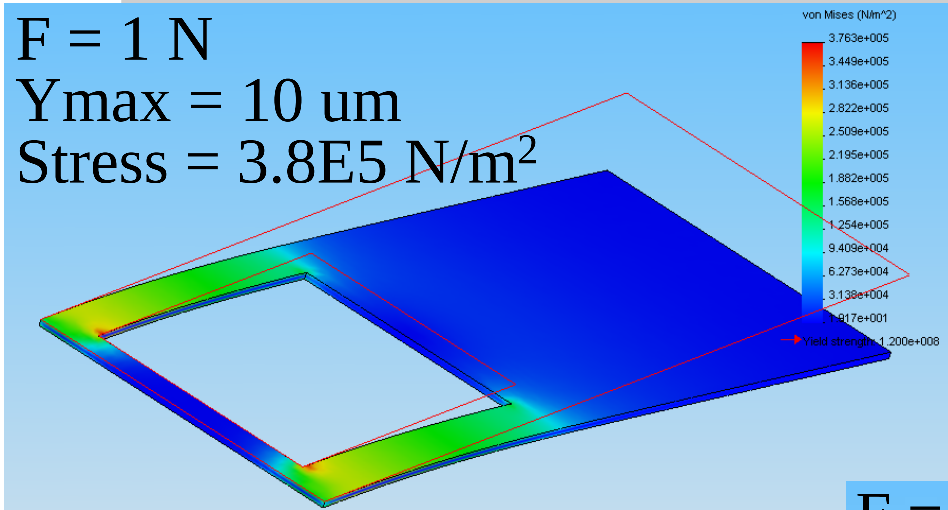
The resonant frequency (f_0) of the cantilever beam is

$$f_0 = 1/2\pi\ \{3EI\ /\ (L^3(m+0.236m_B))\}^{0.5}$$

where m_B is the beam mass and m is end mass and E is Young's Modulus for beam material

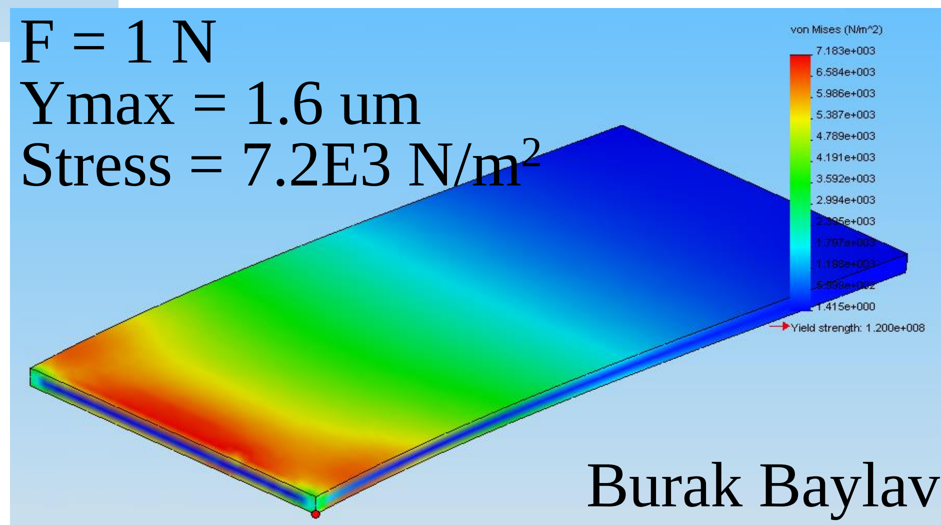
Mechanics of Materials, by Ferdinand P. Beer, E. Russell Johnston, Jr., McGraw-Hill Book Co.1981

FINITE ELEMENT ANALYSIS (FEA) OF CANTILEVER

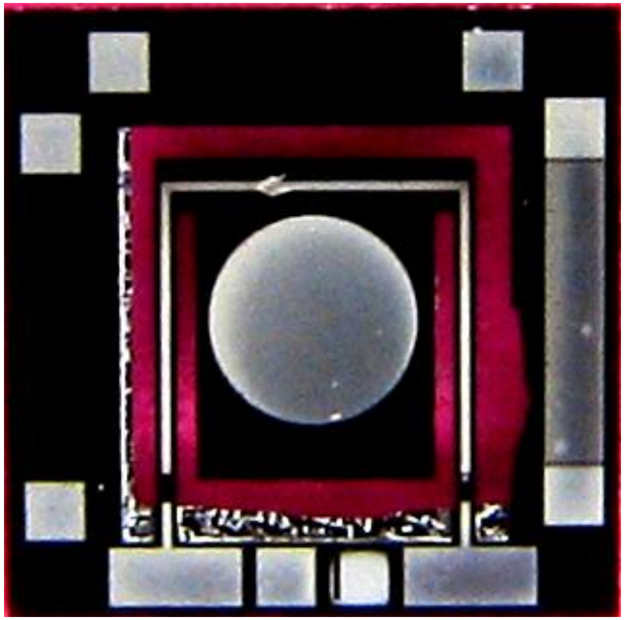


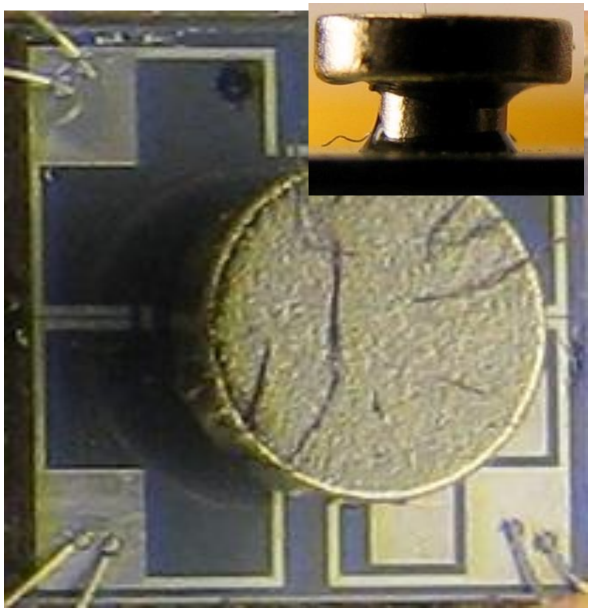
SolidWorks

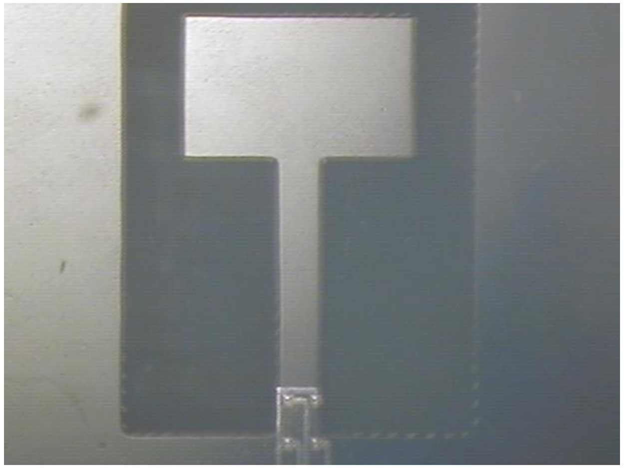
Length = 1500 µm
Width = 600 µm
Thickness = 20 µm
Window ~ 300 x 300 µm

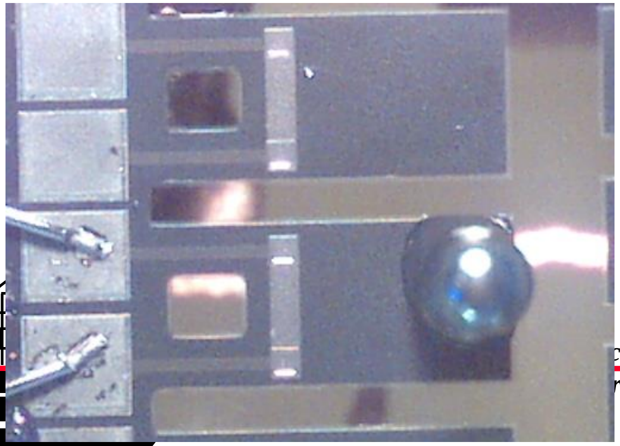


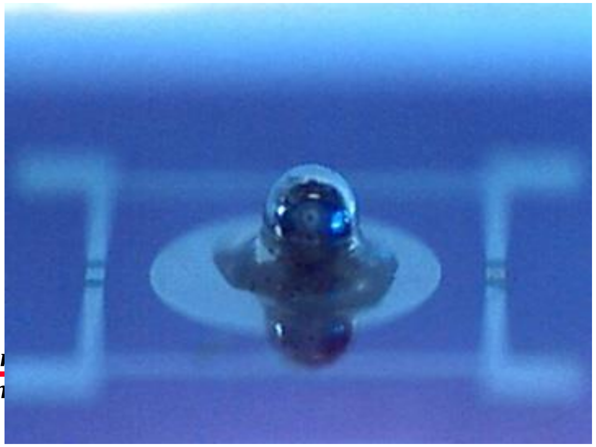
RIT ACCELEROMETERS

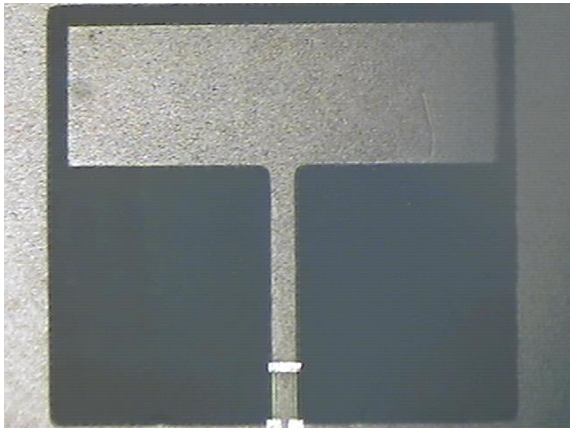




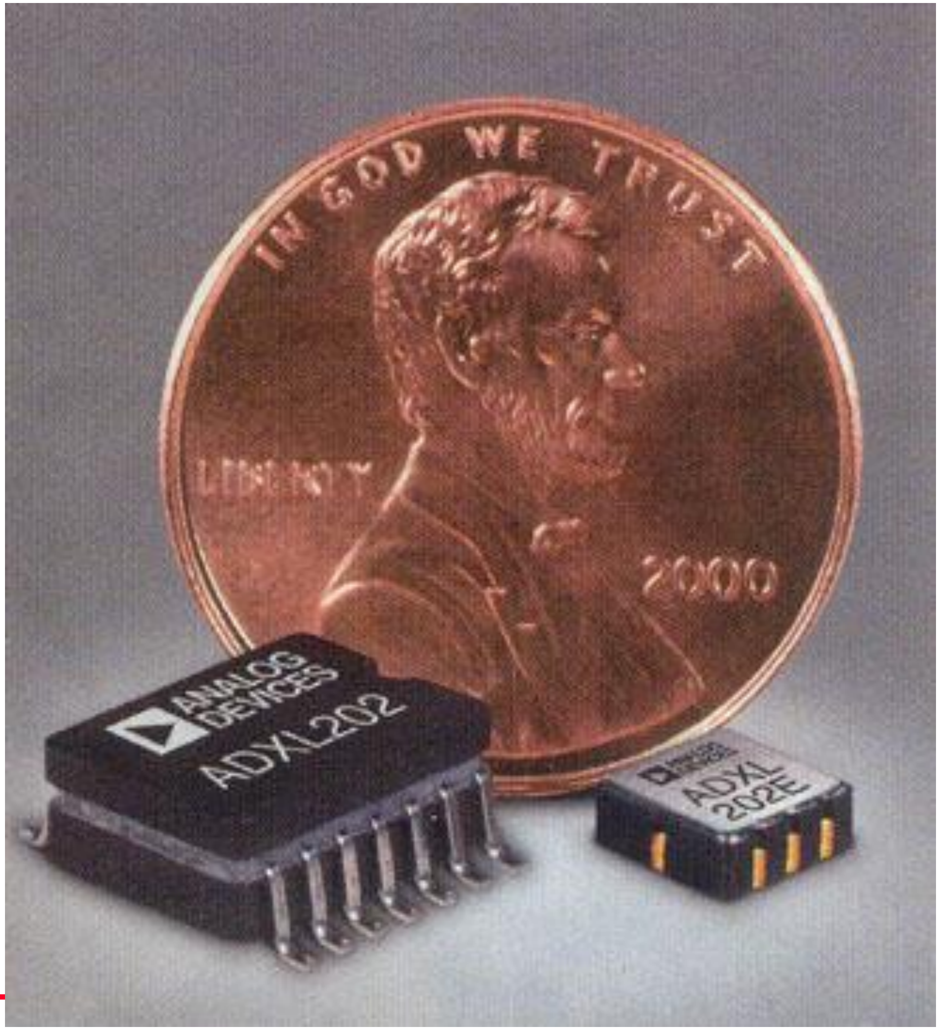




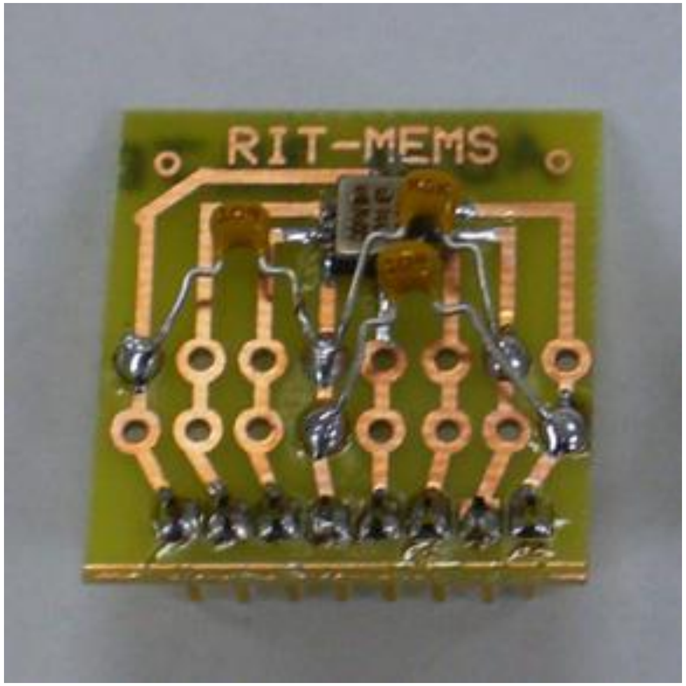




ADI ACCELEROMETERS

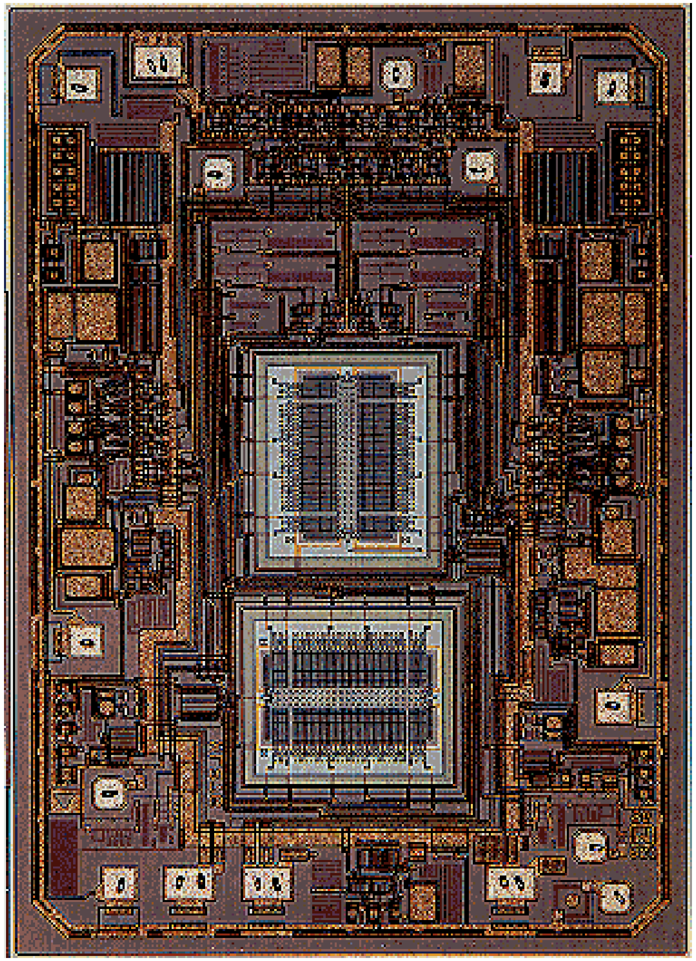


ADXL202
ADXL311
ADXL78



ANALOG DEVICES INC. (ADI) ACCELEROMETERS

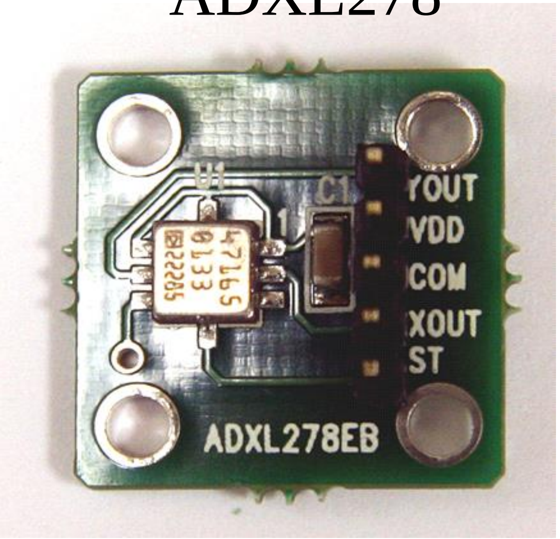
15 years ago, Analog Devices revolutionized automotive airbag systems with its unique *i*MEMS® (integrated Micro Electro Mechanical System) technology. *i*MEMS accelerometers were the first products in an array of MEMS inertial sensor solutions to use innovative design techniques to integrate small, robust sensors with advanced signal conditioning circuitry on a single chip. Today, ADI offers the industry's broadest accelerometer portfolio, with products addressing a range of user needs including high performance, low power consumption, integrated functionality, and small size.



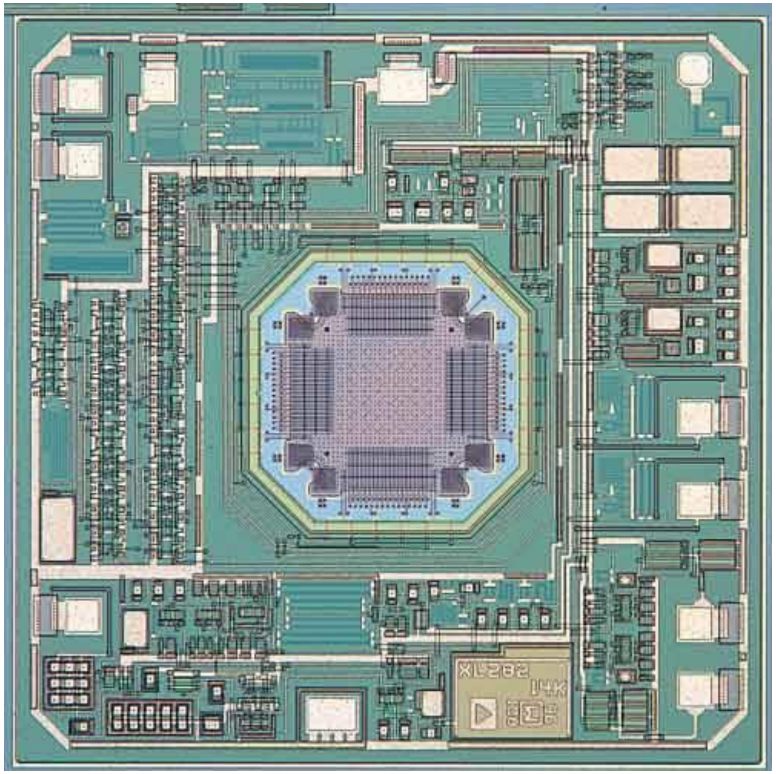
ADXL203 Dual Axis Analog Output

ANALOG DEVICES INC. (ADI) ACCELEROMETERS

ADXL278



Evaluation Board



http://www.analog.com

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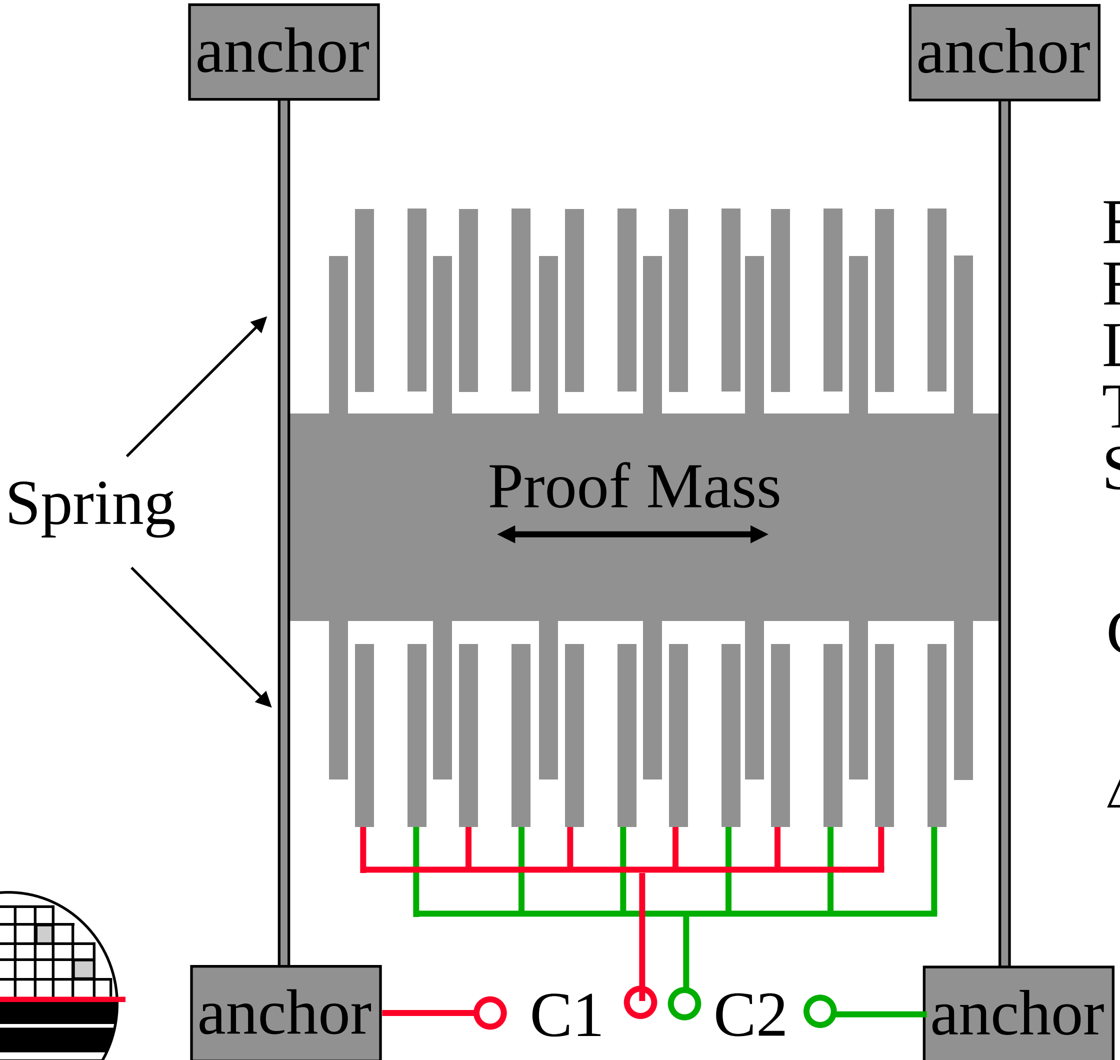
CAPACITIVE POSITION SENSING ACCELEROMETERS



Each of ~100 Fingers
Forms a Capacitor
Length ~125µm
Thickness ~2µm
Space ~1.3µm

C = eoer Area / space
= ~0.2pF total
ΔC = ~ +/- 0.1pF

ADXL203 ANALOG OUTPUT ACCELEROMETER

The ADXL103/ADXL203 are high precision, low power, complete single- and dual-axis accelerometers with signal conditioned voltage outputs, all on a single, monolithic IC. The ADXL103/ADXL203 measure...More

New! Tighter specifications on sensitivity, cross-axis sensitivity, and non-linearity.

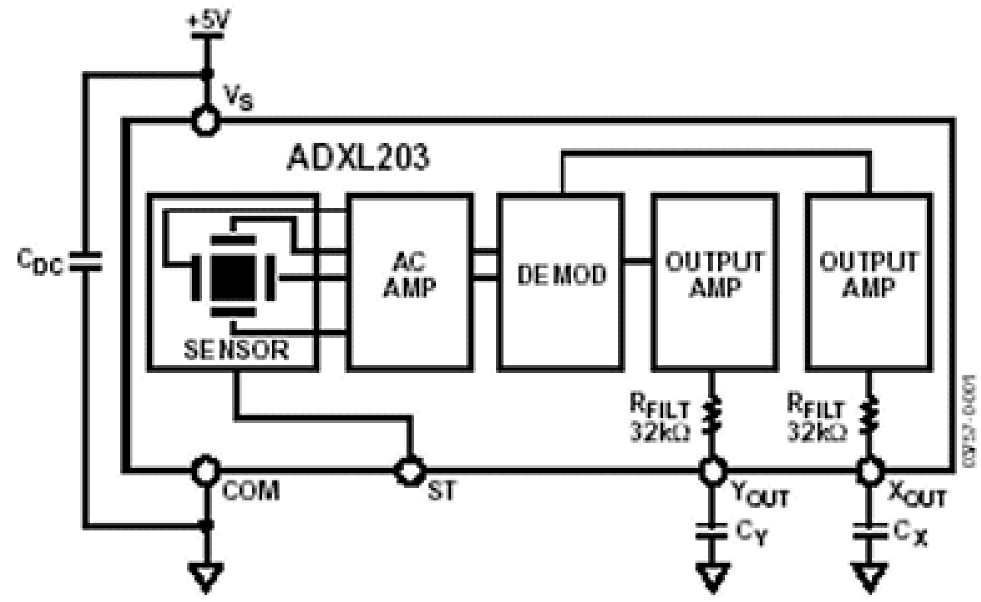
Specifications

Output Type	Analog
TypicalBand Width (kHz)	2.5kHz
Voltage Supply (V)	3 to 6
Range	+/- 1.7g
Sensitivity	1000 mV/g
# of Axes	2
Sensitivity Accuracy (%)	±4
Temp Range (°C)	-40 to 125°C
Package	E-8
Noise Density (µg/rtHz)	110

Find Similar Products

Functional Block Diagram

Enlarge



Symbols and Footprints

Other Diagrams: Pin Out Diagram

ADXL330 THREE AXIS ANALOG OUTPUT

Print this Page | Close this Window

ADXL330 Small, Low Power, 3-Axis ±3*g* *i*MEMS® Accelerometer

Product Description

The ADXL330 is a small, thin, low power, complete 3-axis accelerometer with signal conditioned voltage outputs, all on a single monolithic IC. The product measures acceleration with a minimum full-scale range of ±3 *g*. It can measure the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration resulting from motion, shock, or vibration.

The user selects the bandwidth of the accelerometer using the C_X, C_Y, and C_Z capacitors at the X_{OUT}, Y_{OUT}, and Z_{OUT} pins. Bandwidths can be selected to suit the application, with a range of 0.5 Hz to 1600 Hz for X and Y axes, and a range of 0.5 Hz to 550 Hz for the Z axis.

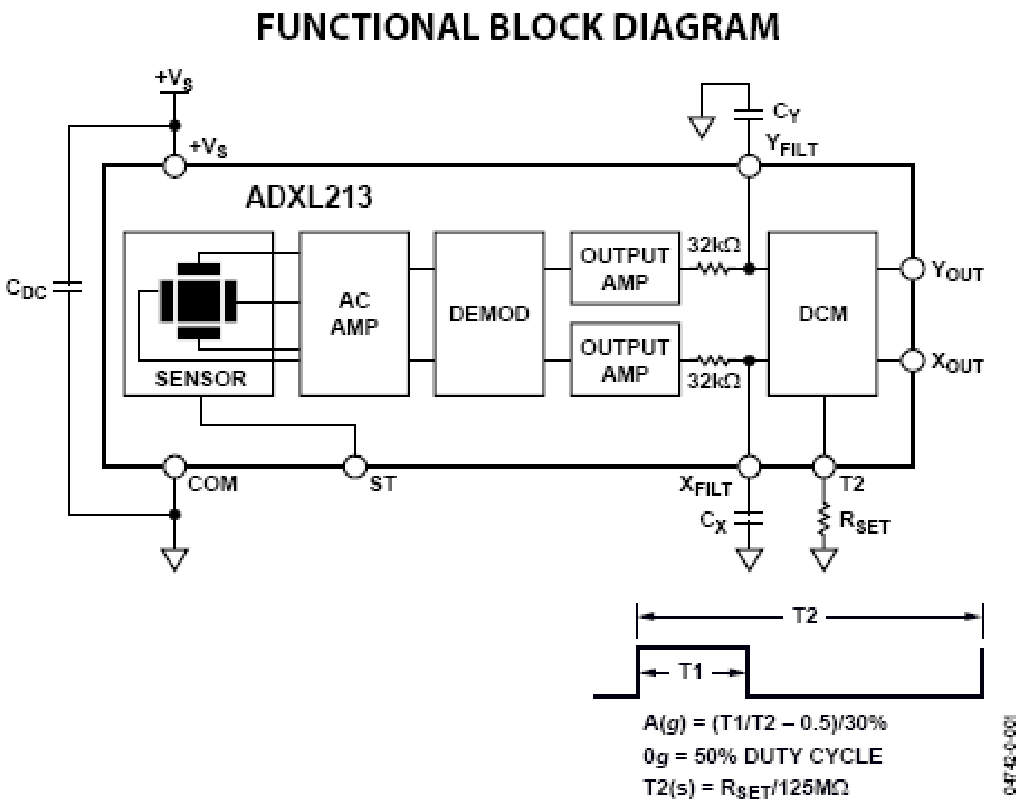
The ADXL330 is available in a small, low profile, 4 mm × 4 mm × 1.45 mm, 16-lead, plastic lead frame chip scale package (LFCSP_LQ).

Price ~ $5.50 ea

Applications:

Cost-sensitive, low-power, motion- and tilt-sensing applications
- Mobile devices
- Gaming system
- Disk drive protection

ADXL213 PULSE WIDTH OUTPUT ACCELEROMETER



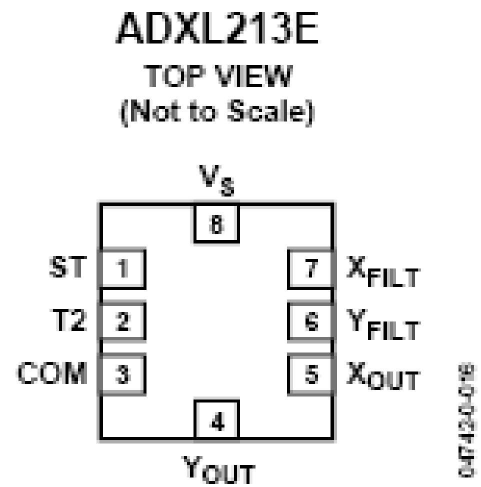


Figure 22. ADXL213 8-Lead CLCC

Functional block diagram of the ADXL213 accelerometer and PINs

TILT SENSING WITH ADXL213

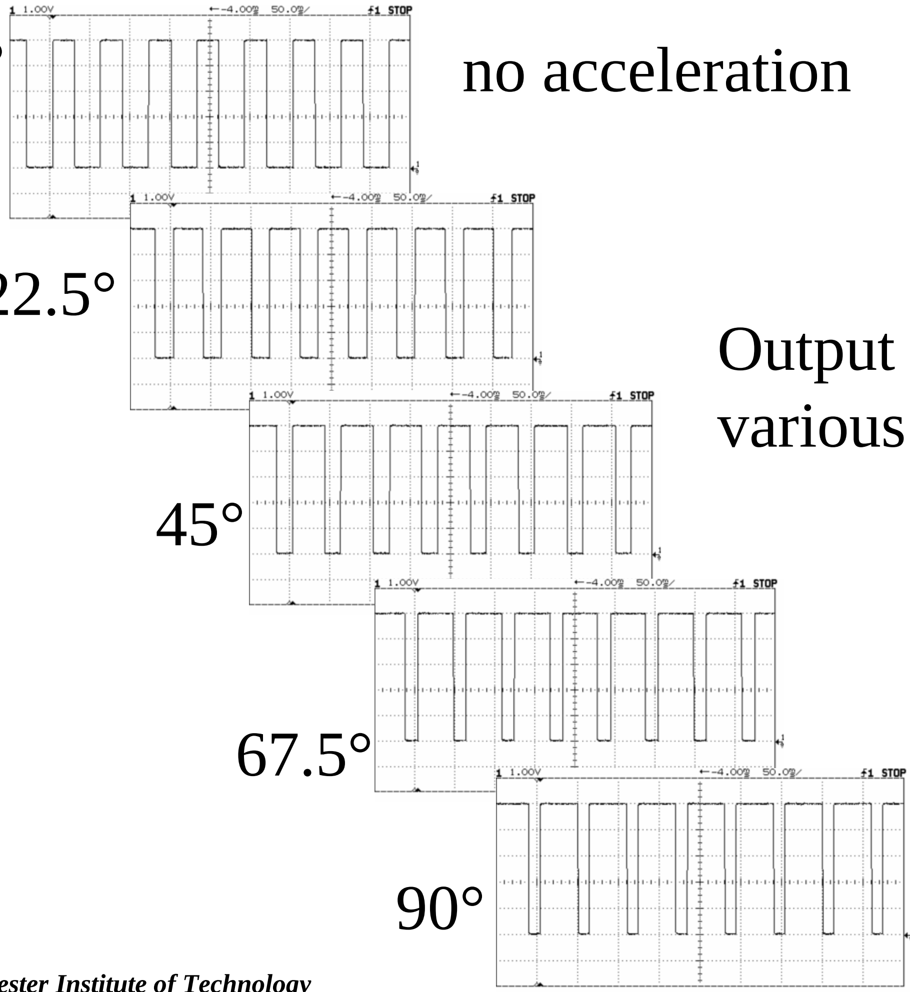
0 ° — no acceleration

22.5°

45°

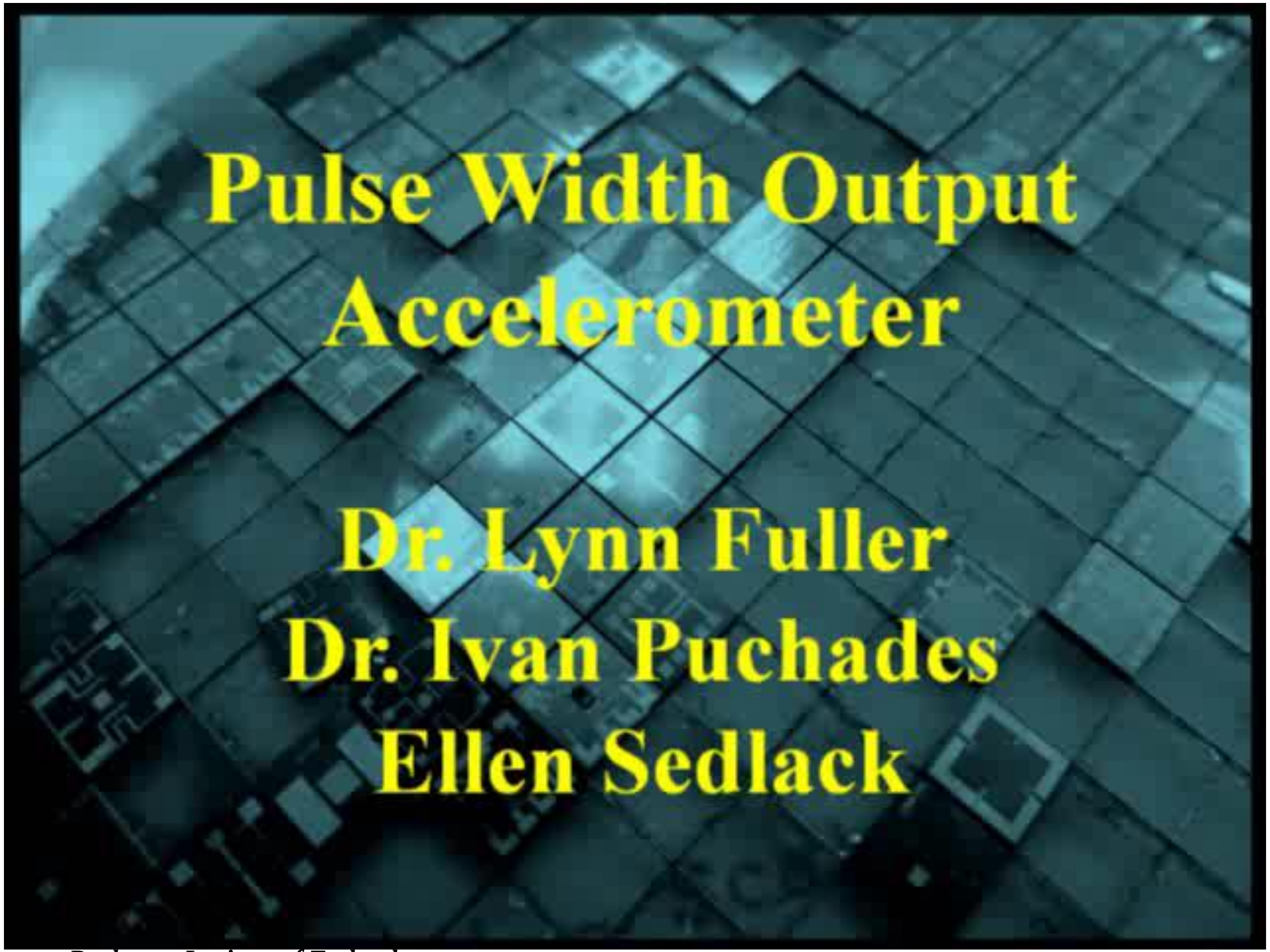
67.5°

90° — 1g acceleration due to gravity

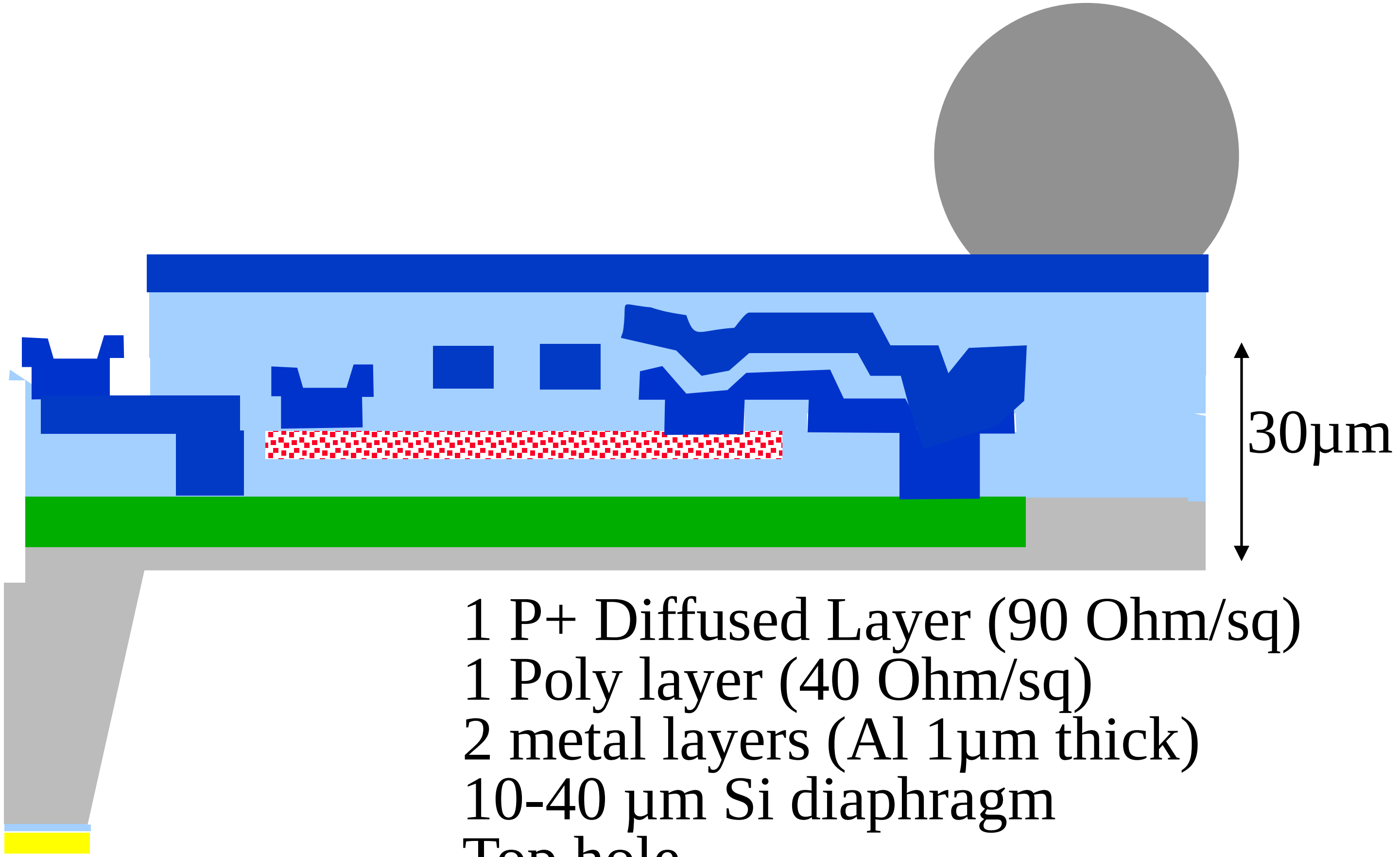


Output waveforms for various tilt angles

PULSE WIDTH ACCELEROMETER MOVIE

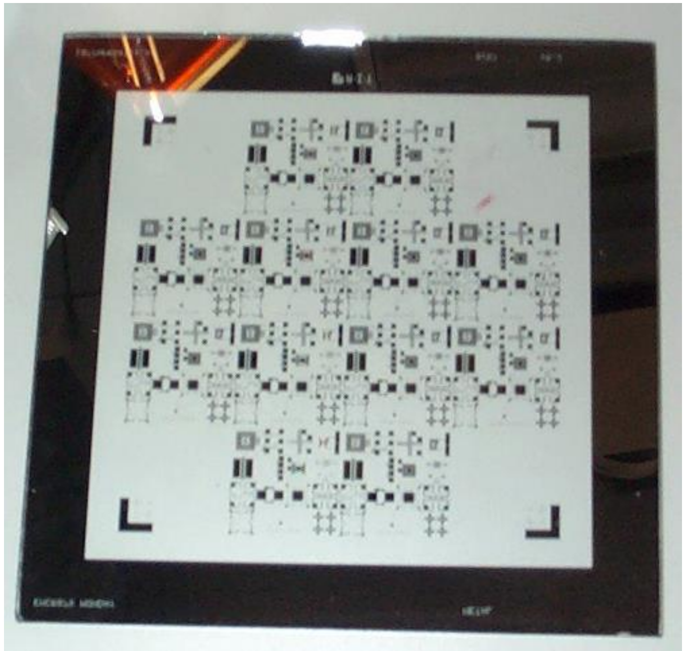


RIT MEMS TOP HOLE BULK PROCESS



1 P+ Diffused Layer (90 Ohm/sq)
1 Poly layer (40 Ohm/sq)
2 metal layers (Al 1µm thick)
10-40 µm Si diaphragm
Top hole

MASKS



TOP HOLE BULK MEMS PROCESS FLOW

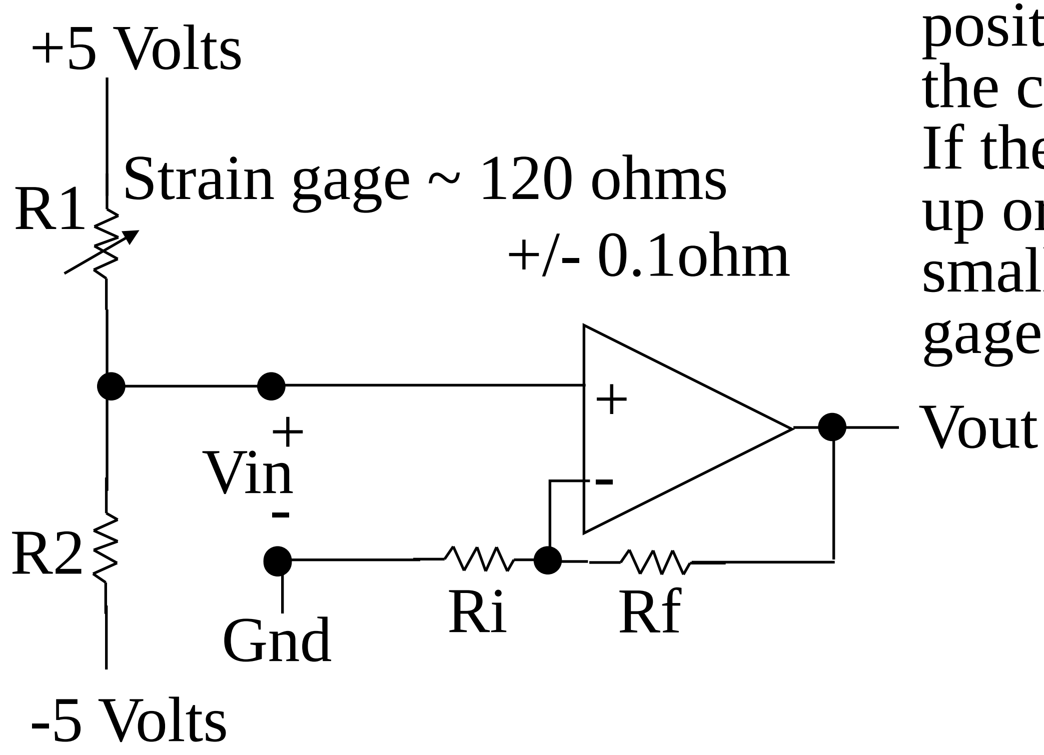
1. Obtain qty 10, 4" n-type wafers
2. CMP back side
3. CMP Clean
4. RCA Clean
5. Grow masking oxide 5000 Å, Recipe 350
6. Photo 1: P++ diffusion
7. Etch Oxide, 12 min. Rinse, SRD
8. Strip Resist
9. Spin-on Glass, Borofilm 100, include dummy
10. Dopant Diffusion Recipe 110
11. Etch SOG and Masking Oxide, 20min BOE
12. Four Point Probe Dummy Wafer
13. RCA Clean
14. Grow 500 Å pad oxide, Recipe 250
15. Deposit 1500 Å Nitride
16. Photo 2: for backside diaphragm
17. Spin coat Resist on front side of wafer
18. Etch oxynitride, 1 min. dip in BOE, Rinse, SRD
19. Plasma Etch Nitride on back of wafer, Lam-490
20. Wet etch of pad oxide, Rinse, SRD
21. Strip Resist both sides
22. Etch Diaphragm in KOH, ~8 hours
23. Decontamination Clean
24. RCA Clean
25. Hot Phosphoric Acid Etch of Nitride
26. BOE etch of pad oxide
27. Grow 5000Å oxide
28. Deposit 6000 Å poly LPCVD
29. Spin on Glass, N-250
30. Poly Diffusion, Recipe 120
31. Etch SOG
32. 4 pt Probe
33. Photo 3, Poly
34. Etch poly, LAM490
35. Strip resist
36. RCA Clean
37. Oxidize Poly Recipe 250
38. Deposit 1µm LTO
39. Photo 4, Contact Cut
40. Etch in BOE, Rinse, SRD
41. Strip Resist
42. RCA Clean, include extra HF
43. Deposit Aluminum, 10,000Å
44. Photo 5, Metal
45. Etch Aluminum, Wet Etch
46. Strip Resist
47. Deposit 1µm LTO
48. Photo 6, Via
49. Etch Oxide in BOE, Rinse, SRD
50. Strip Resist
51. Deposit Aluminum, 10,000Å
52. Photo 7, Metal
53. Etch Aluminum, Wet Etch
54. Strip Resist
55. Deposit 1µm LTO
56. Deposit Aluminum, 10,000Å
57. Photo 8, Top Hole
58. Top hole aluminum etch
59. Diaphragm thinning option
60. Top hole Silicon etch
61. Test

62. Package and add solder ball

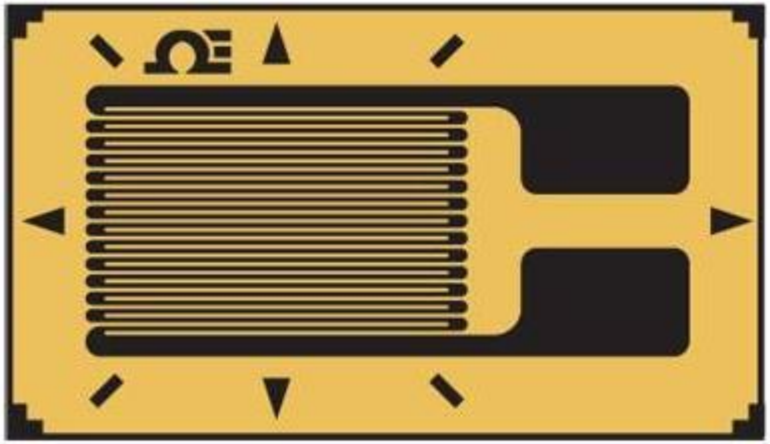
3-15-07

TEST FIXTURE MOVIE

STRAIN GAGE – POSITION SENSOR



A strain gage is used to measure position. It is a foil resistor glued on the cantilever beam near the anchor. If the tip of the cantilever is moved up or down the strain well cause a small change in the resistance of the gage and a change in Vout.

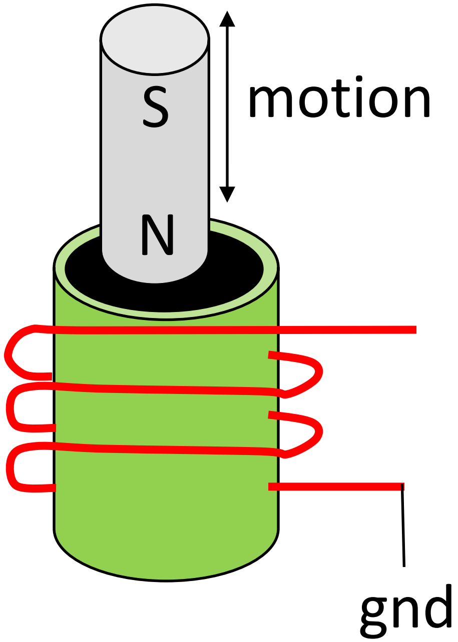


120 ohm

Vin near Zero so that it can be amplified

VELOCITY SENSOR

A coil in a changing magnetic field will generate a voltage.



Faraday's Law of Electromagnetic Induction

EMF = - Δ Φ/Δ t = - N Area Δ Φ/Δ t

http://micro.magnet.fsu.edu/electromag/java/faraday2/

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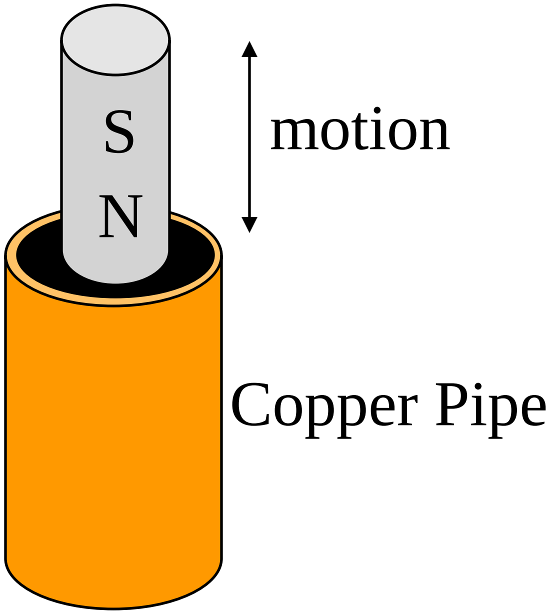
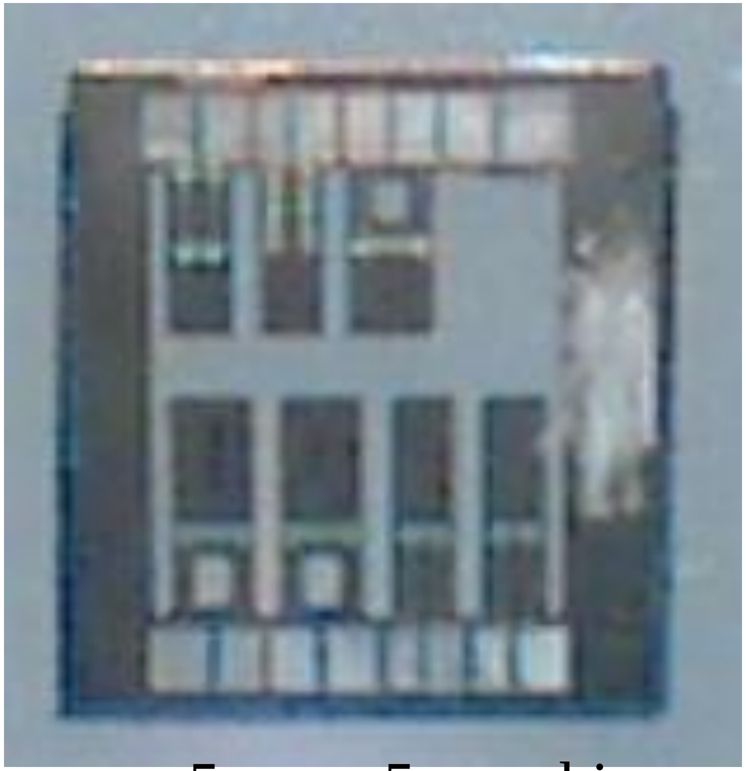
EDDY CURRENT DAMPER

The copper pipe is a coil (one turn) and if placed in a moving magnetic field will generate a voltage and since the coil is a closed loop there will be an electrical current (eddy current). The current moving in a loop will create a magnetic field and the field will oppose the magnetic field that created it. The opposing force dampens the oscillations of the vibrating beam.

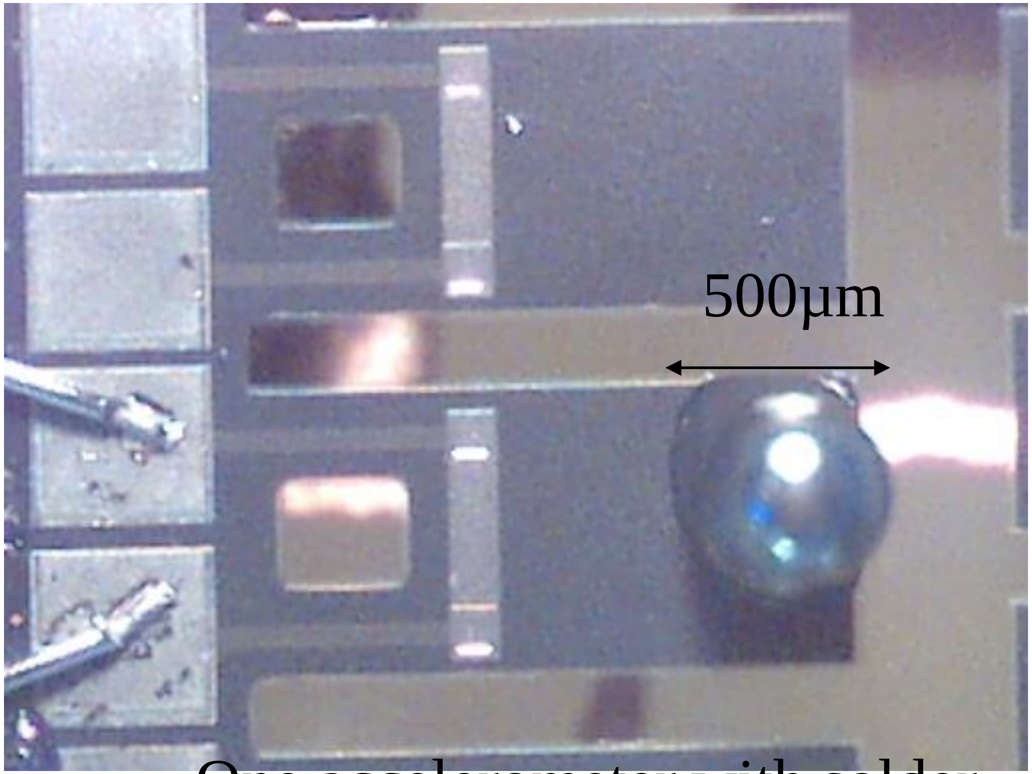


PICTURES OF RIT ACCELEROMETERS

RIT made Accelerometers Pictures



5mm x 5mm chip



One accelerometer with solder ball proof mass.

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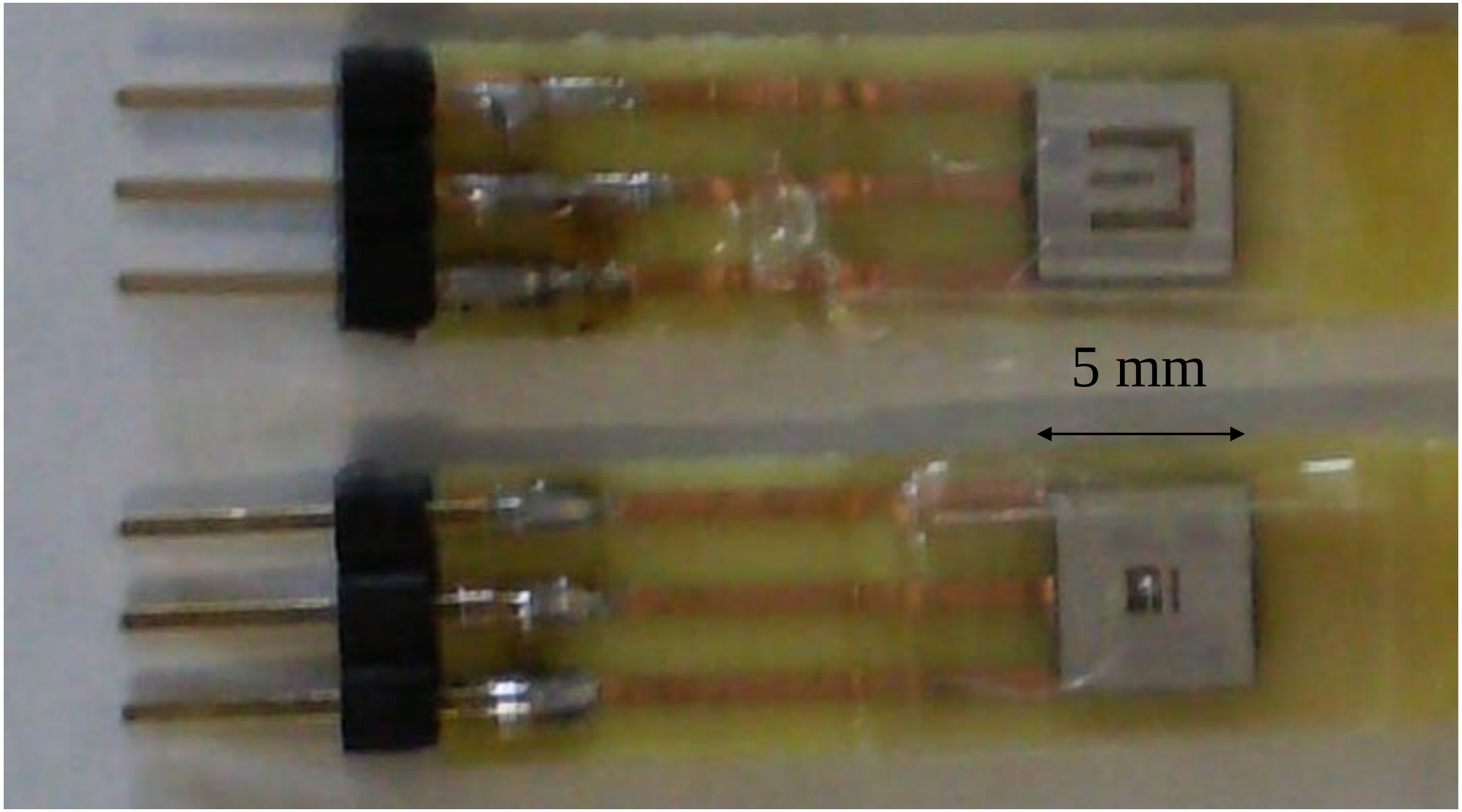
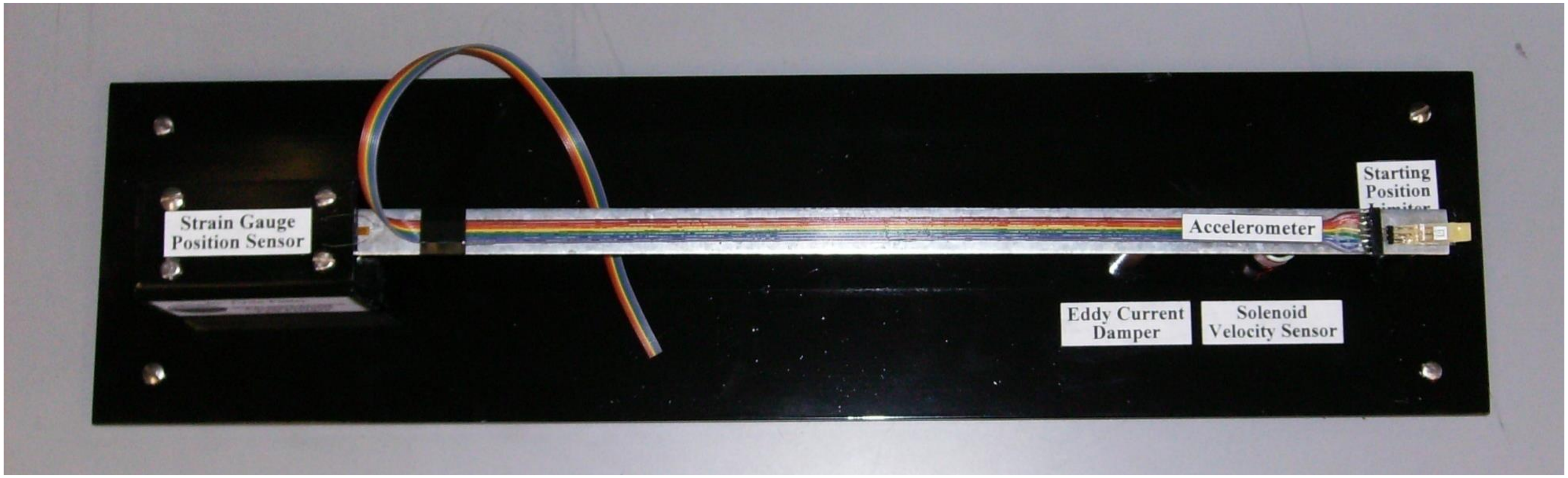
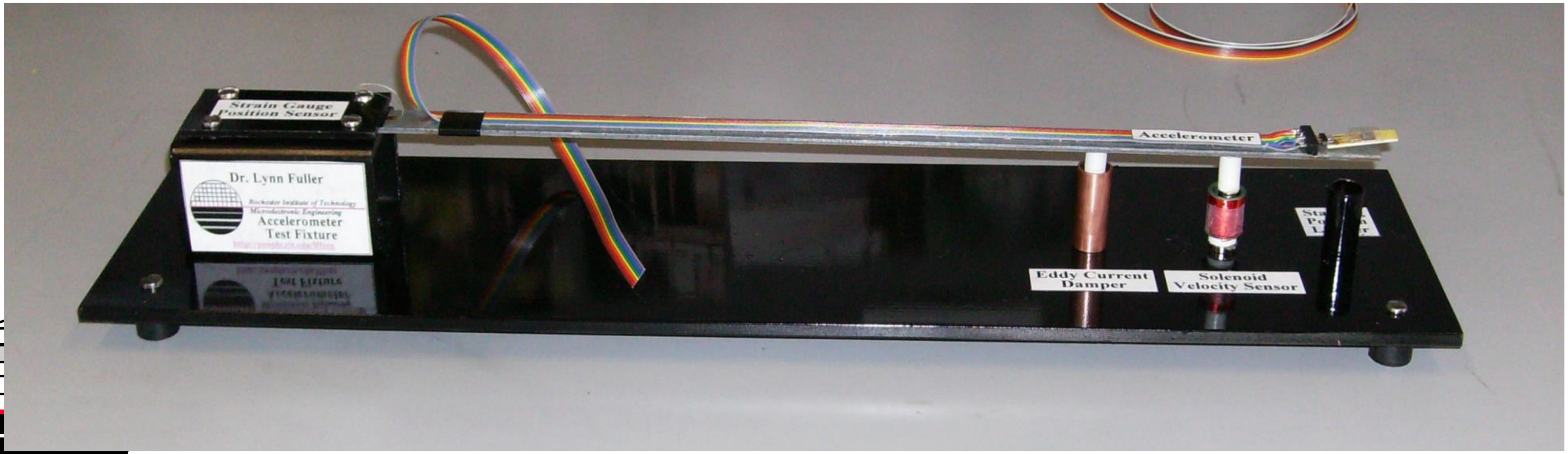
PACKAGED RIT ACCELEROMETERS



THE TEST FIXTURE





EXAMPLE CALCULATIONS FOR TEST FIXTURE

The resonant frequency (f_0) of the test fixture

$$f_0 = 1/2\pi \{3EI / (L^3(m+0.236m_B))\}^{0.5}$$

where m_B is the beam mass and m is end mass
and E is Young's Modulus for the beam material

$I = b\, h^3 /12$, moment of inertia

Then we write an expression for the position of the end of the beam on the test fixture after deflecting the beam by Ao and releasing.

$$X(t) = - Ao \cos (2\, \pi\, f_0\, t)$$

Taking the second derivative we write an expression for the acceleration experienced at the end of the beam on the test fixture.

$$a = d^2X(t)/dt^2 = Ao\, (2\, \pi\, f_0)^2 \cos (2\, \pi\, f_0\, t)$$

EXAMPLE CALCULATIONS FOR RIT ACCELEROMETER

The RIT accelerometer will experience a force at the end of the sensor cantilever beam equal to mass times acceleration.

$$F = ma = 4/3\ \pi\ r^3\ d\ Ao\ (2\ \pi\ f_0)^2 \cos\ (2\ \pi\ f_0\ t)$$

Using the maximum force we calculate the maximum stress

$$\sigma_{x=0} = F\ Lh/2I$$

Next we calculate the maximum strain using Hooke's Law.

$\varepsilon = \sigma_{x=0} / E$ where E is Young’s modulus for silicon

EXAMPLE CALCULATIONS FOR RIT ACCELEROMETER

The nominal resistance value is found to be:

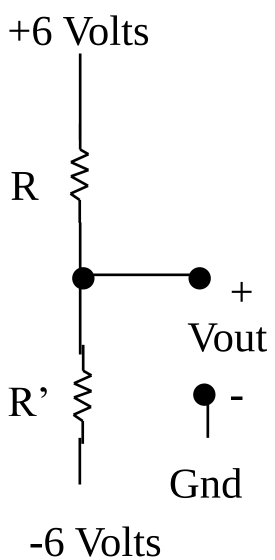
R = rhos L/W = 60 ohms 1000 µm/50µmm = 1200 ohms

The resistance value at maximum strain, R', is approximately:

R' = rhos L(1+ ε)/W

The accelerometer circuit output voltage is :

Vout = [12 R'/(R+R')] -6



Vout near Zero so that it can be amplified

SPREAD SHEET FOR ACCELEROMETER CALCULATIONS

ROCHESTER INSTITUTE OF TECHNOLOGY 6/13/07

MICROELECTROMECHANICAL SYSTEMS accelerometer.xls

Dr. Lynn Fuller, Burak Baylav

To use this spreadsheet change the values in the white boxes. The rest of the sheet is protected and should not be changed unless you are sure of the consequences. The calculated results are shown in the purple boxes.

Calculations for Cantilever Beam (Test Fixture)

Frequency of Oscillation:

f0 = 1/2π {3EI / (L^3(m+0.236mB))}0.5

I = b h^3

The resonant frequency f0 of the cantilever beam	13.48	hz
Beam Length, L	0.4	m
Beam Width, b	0.025	m
Beam thickness, h	0.003	m
End Mass, mB	0	Kg
Density for Material Selected Below	2.33	gm/cm3
Beam Mass = density x volume, m	69.9	gm
Young's Modulus for Material Selected Below	1.90E+11	N/m2

Acceleration versus time:

a = d2X(t)/dt2 = Ao (2 π f0)^2 cos (2 π f0 t)

Initial Deflection	2	cm
Maximum Acceleration	143.34	m/s2
Maximum Acceleration, in g's	14.63	g's

Calculations for RIT Accelerometer

Force:

F = Fmax cos(2*p*f0*t)

Maximum force due to proof mass, Fmax = ma	8.35E-05	N
end mass on RIT accelerometer, m = d V	5.82E-04	gm
volume, V = 4/3 π r^3	6.54E-05	cm^3
radius, r =	250	µm

SPREAD SHEET FOR ACCELEROMETER CALCULATIONS

Accelerometer, cantilever beam bending

Ymax = F L^3/3EI

I = b h^3

σ max = F L h / 2I

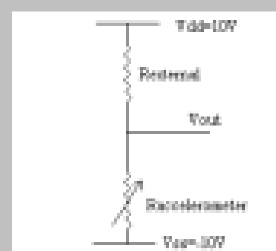
Ymax =	7.03E-01	µm
L =	2000	µm
b =	200	µm
h =	10	µm
Young's Modulus, E =	1.90E+11	N/m2
Max Stress, σ max =	5.01E+03	N/m2
Strain, ε = σ/E =	2.64E-08	µm/µm

Resistor Calculations

R = Rhos L/W

R' = R + Rhos (L+L*ε)/W

Nominal Resistance, R =	5400	ohms
Measured Sheet Resistance, Rhos =	60	ohms
Resistor Length, L =	900	µm
Resistor Width, W =	10	µm
Resistance under Max Stress, R' =	5400.0001	ohms
Delta R = R' - R =	0.000142375	ohms
Vdd = Vss =	10	volts
Rexternal =	5400	ohms
Nominal Vout =	0	volts
Vout Max =	1.31829E-07	volts

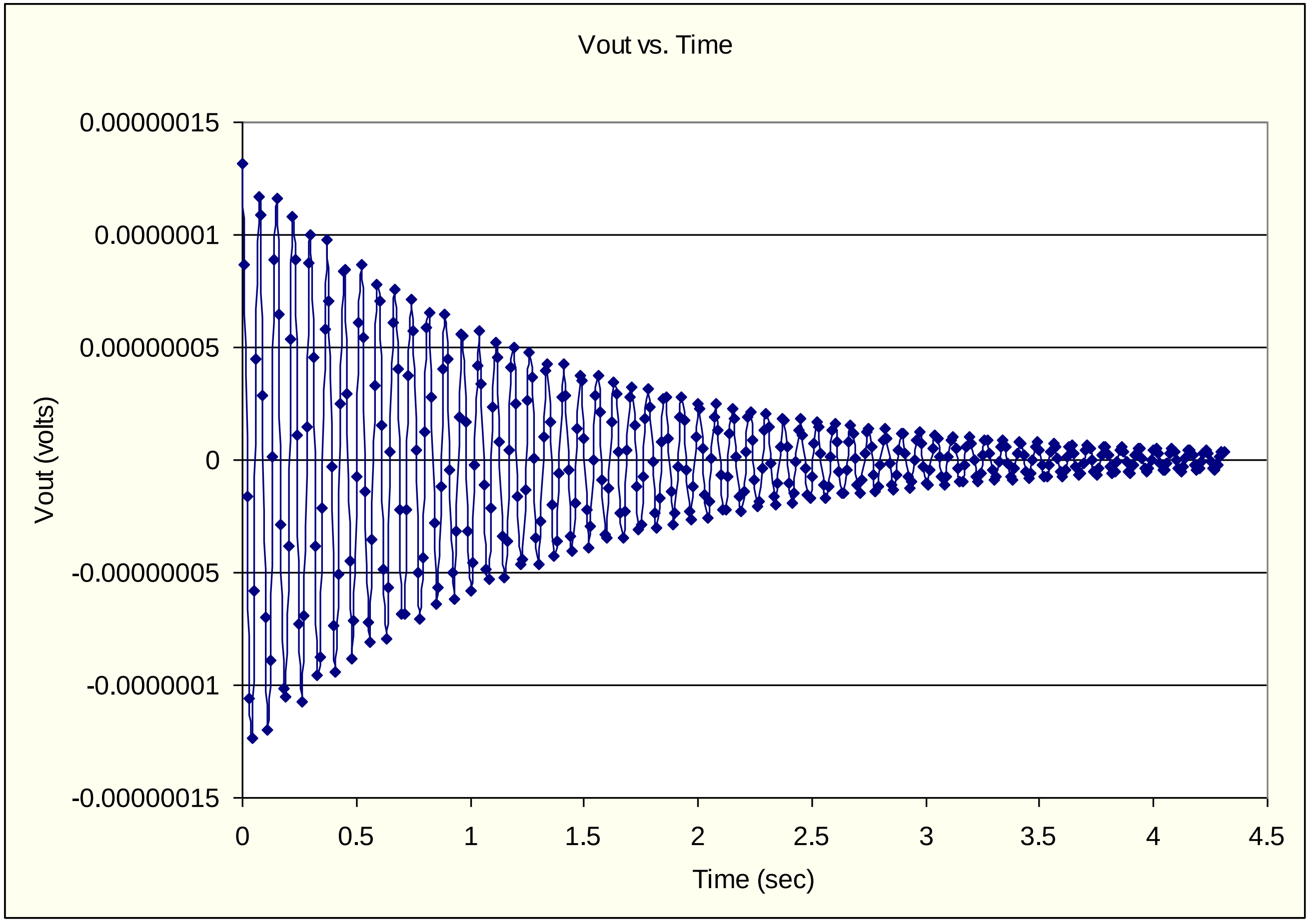


Constants:

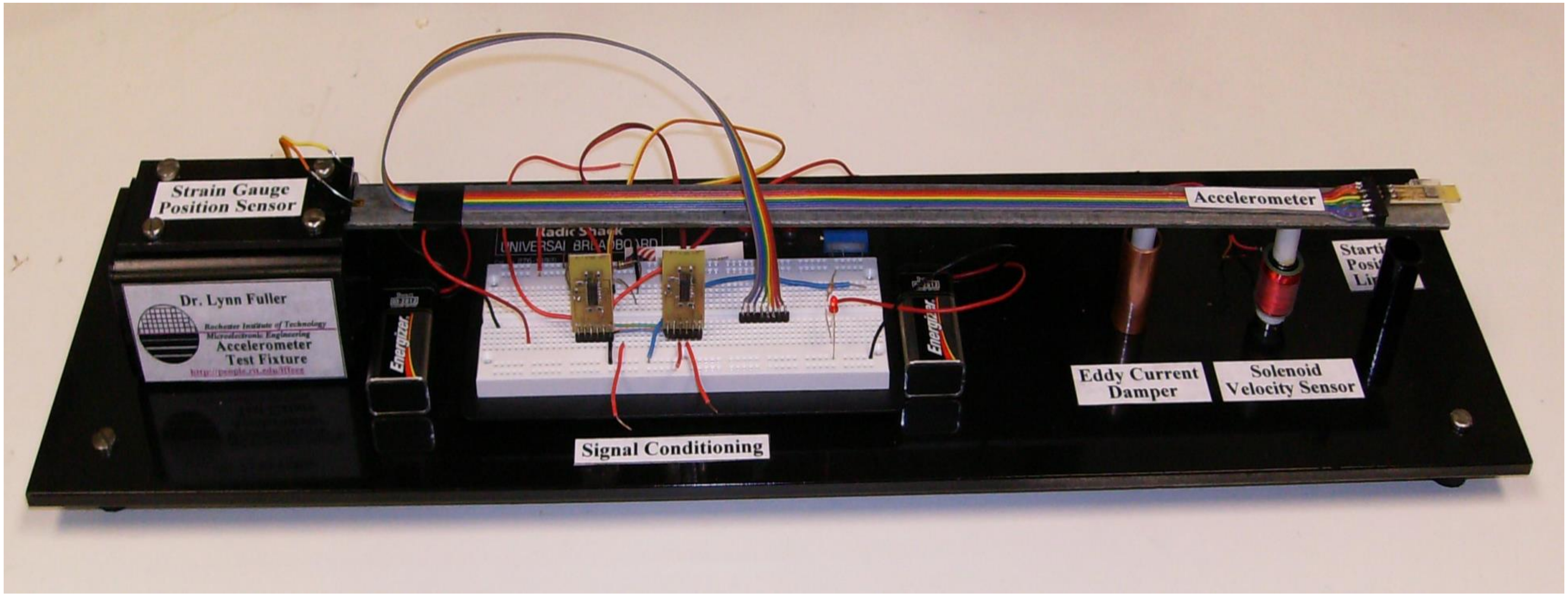
Select Material Using 1 or 0

	Youngs Modulus(N/m2)	**Density (gm/cm3)**	**Fixture**	**RIT Accerometer**
Silicon	1.9E+11	2.33	0	1
Silicondioxide	7.30E+10	2.19	0	0
Silicon Nitride	3.85E+11	3.44	0	0
Aluminum	6.80E+10	3.9	0	0
Steel	2.00E+11	7.8	1	0
Brass	1.10E+11	8.55	0	0
Lead		11.34		

CALCULATED PLOT OF VOUT VS. TIME

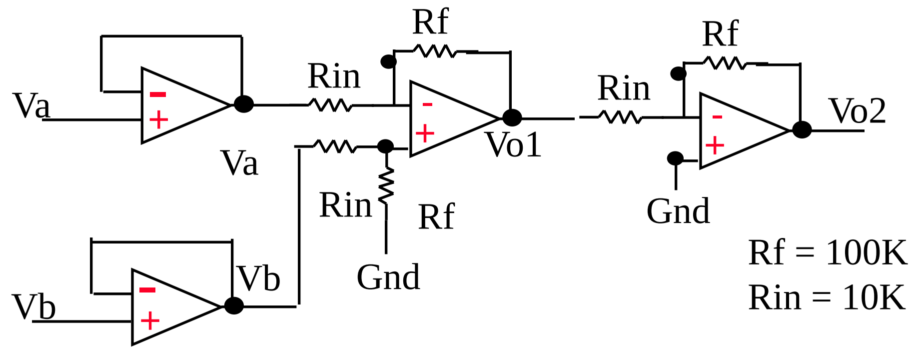


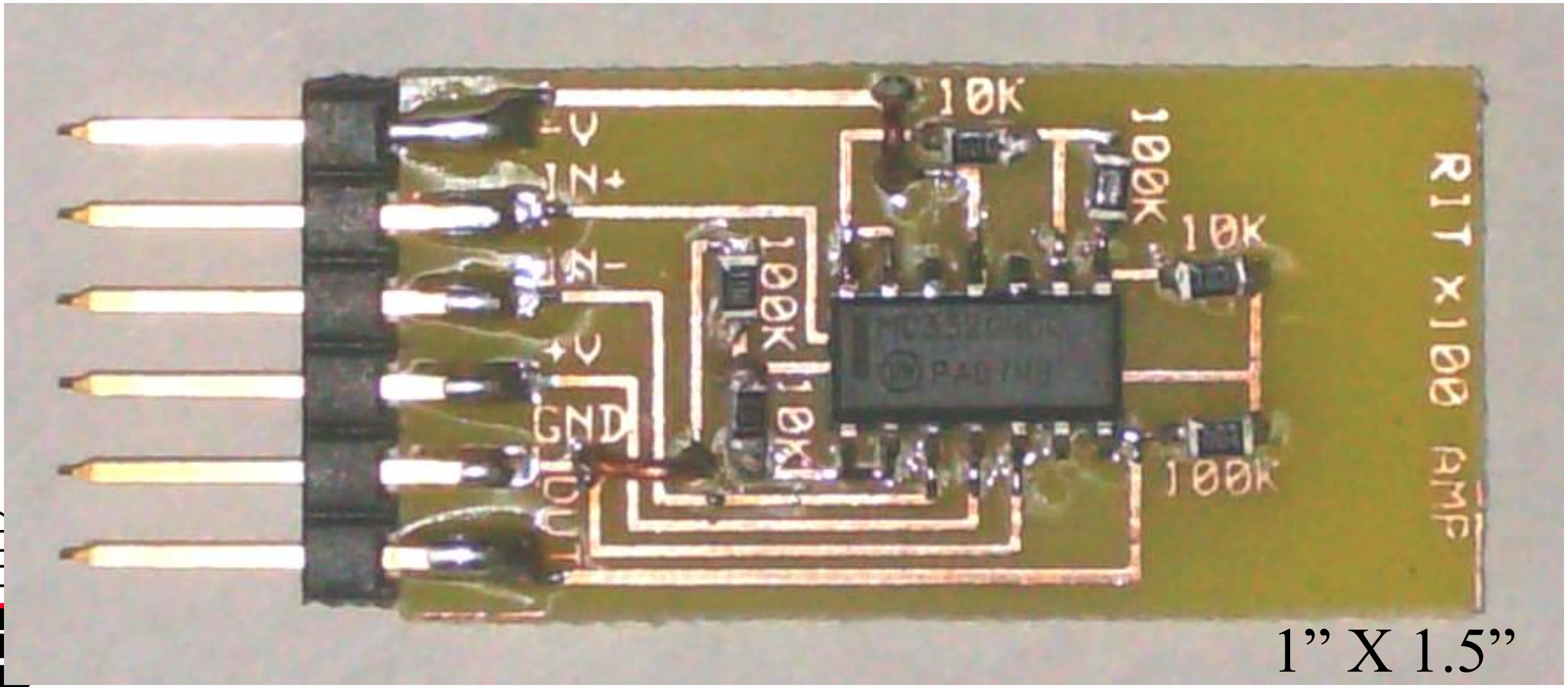
20 G ACCELEROMETER TEST SET UP



TESTING OF PRISM PROJECT ACCELEROMETERS

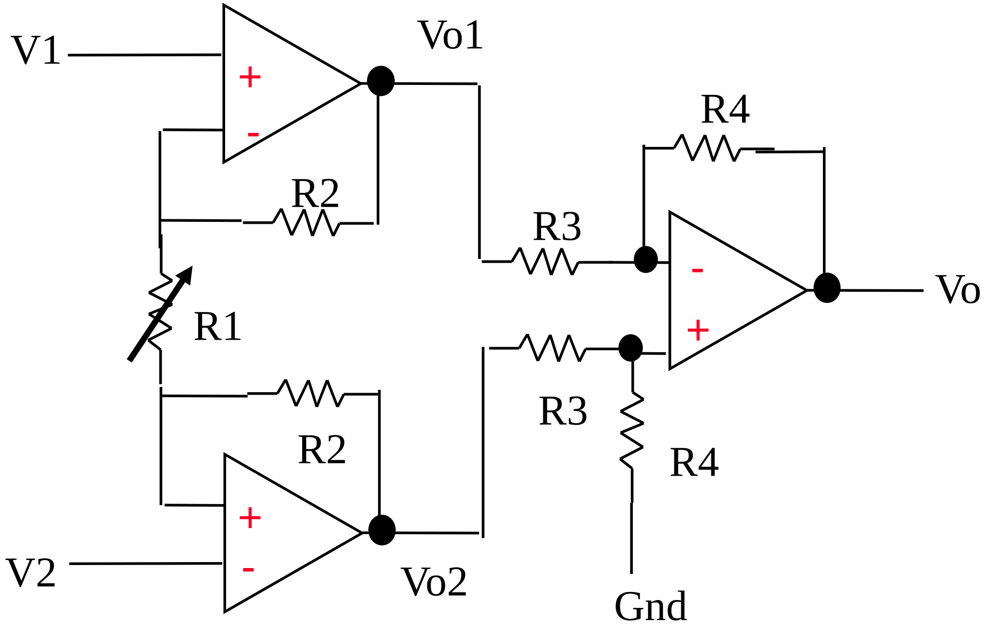
RIT 100X DIFFERENTIAL VOLTAGE AMPLIFIER





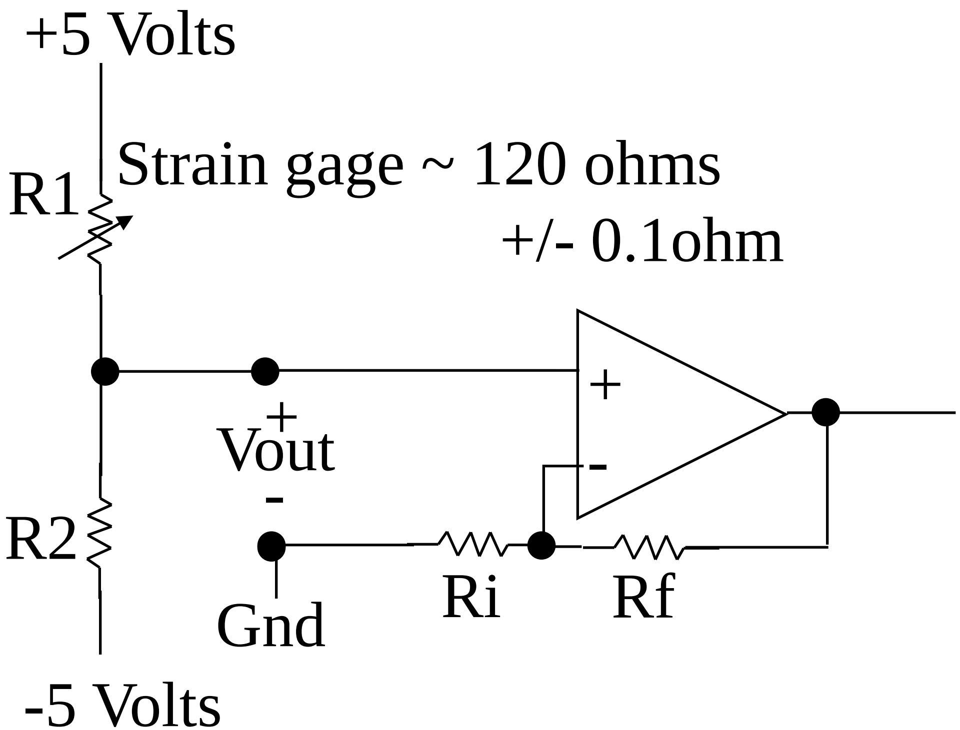
1" X 1.5"

INSTURMENTATION AMPLIFIER

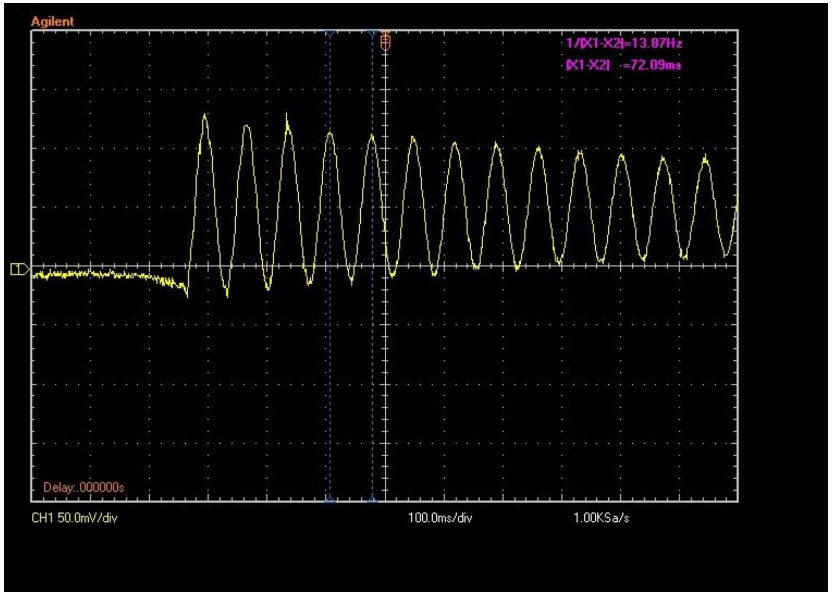


$$Vo = (V2\text{-}V1)\,\frac{R4}{R3}\left(1 + \frac{2R2}{R1}\right)$$

CONFIRMATION OF TEST FIXTURE RESONANT FREQUENCY



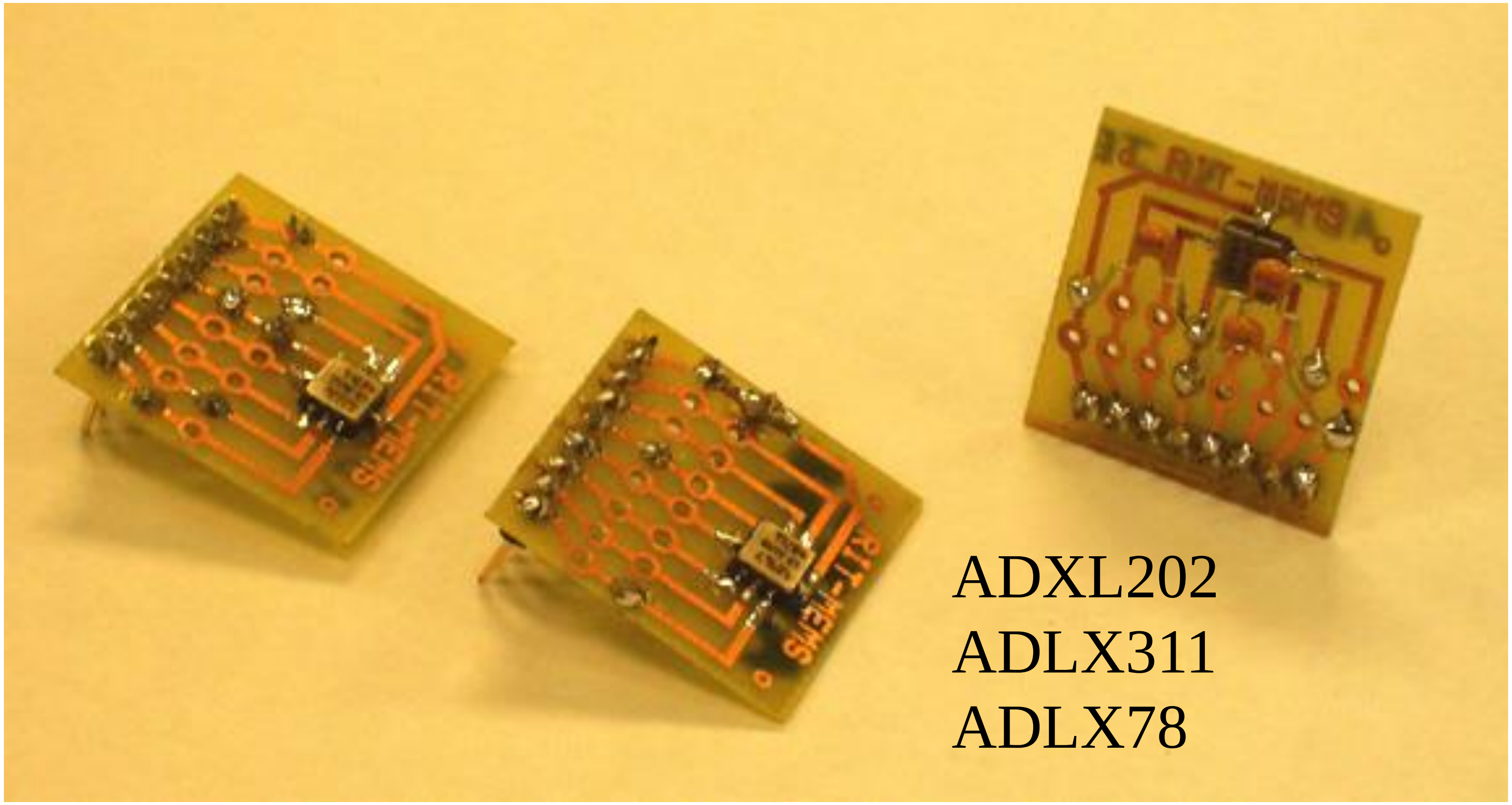
Vout near Zero so that
it can be amplified



Strain gage output signal

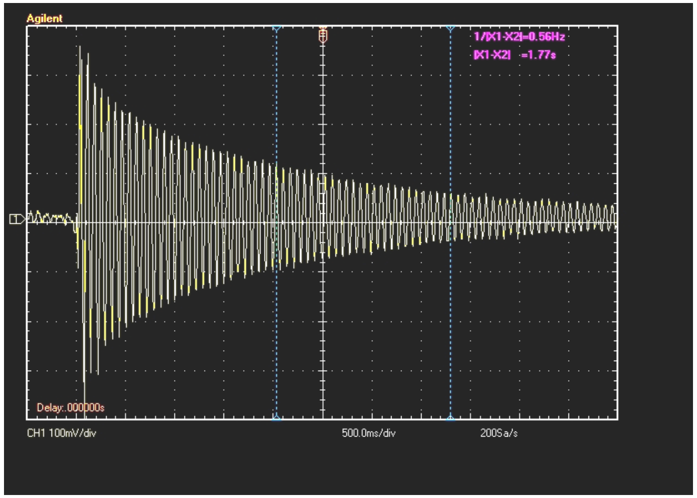
Period ~ 70msec
Thus frequency ~14.3 Hz

ADI ACCELEROMETER ON PCB WITH R,C AND PINS



ANALOG OUTPUT TYPE ACCELEROMETERS

Measured Output
No Damping

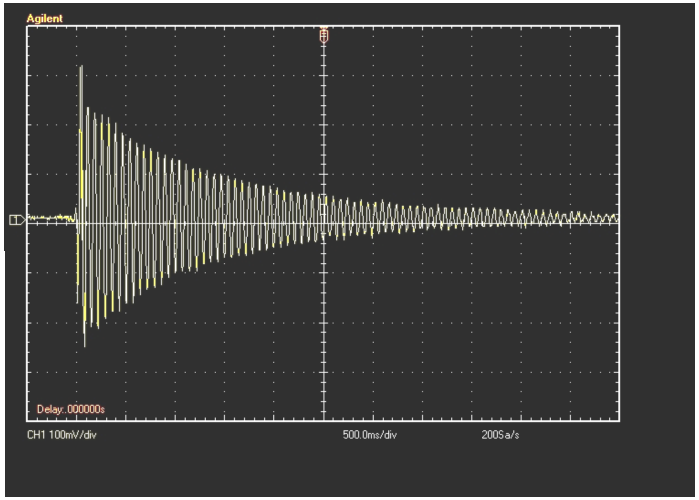


ADXL78

We can describe the envelope of the oscillations with the following eqn.

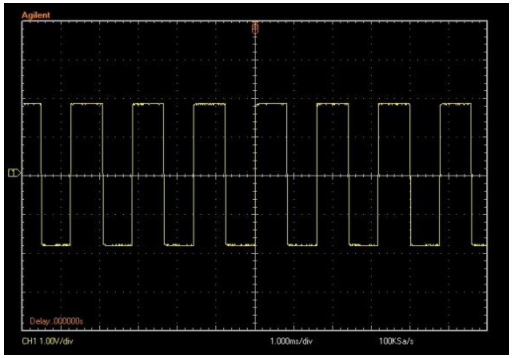
$$V_{out}=V_{max}\ e^{-\alpha t}$$

where α is the damping coefficient



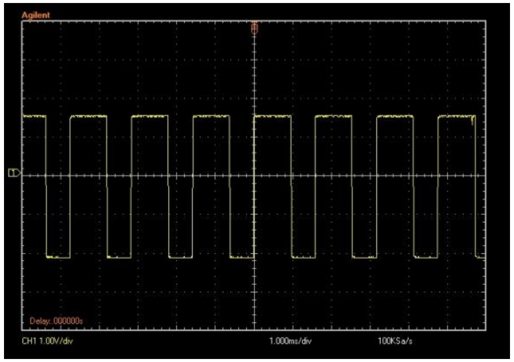
Measured Output
With eddy current
Damping

OUTPUT OF PULSE WIDTH TYPE ACCELEROMETER

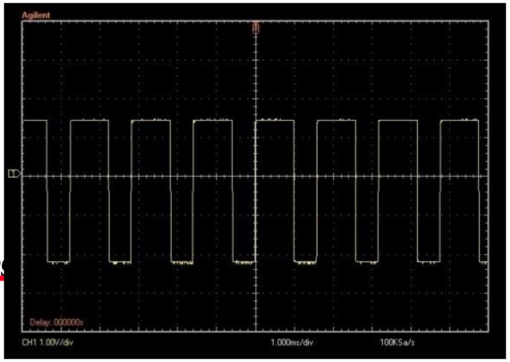


no acceleration

ADXL202

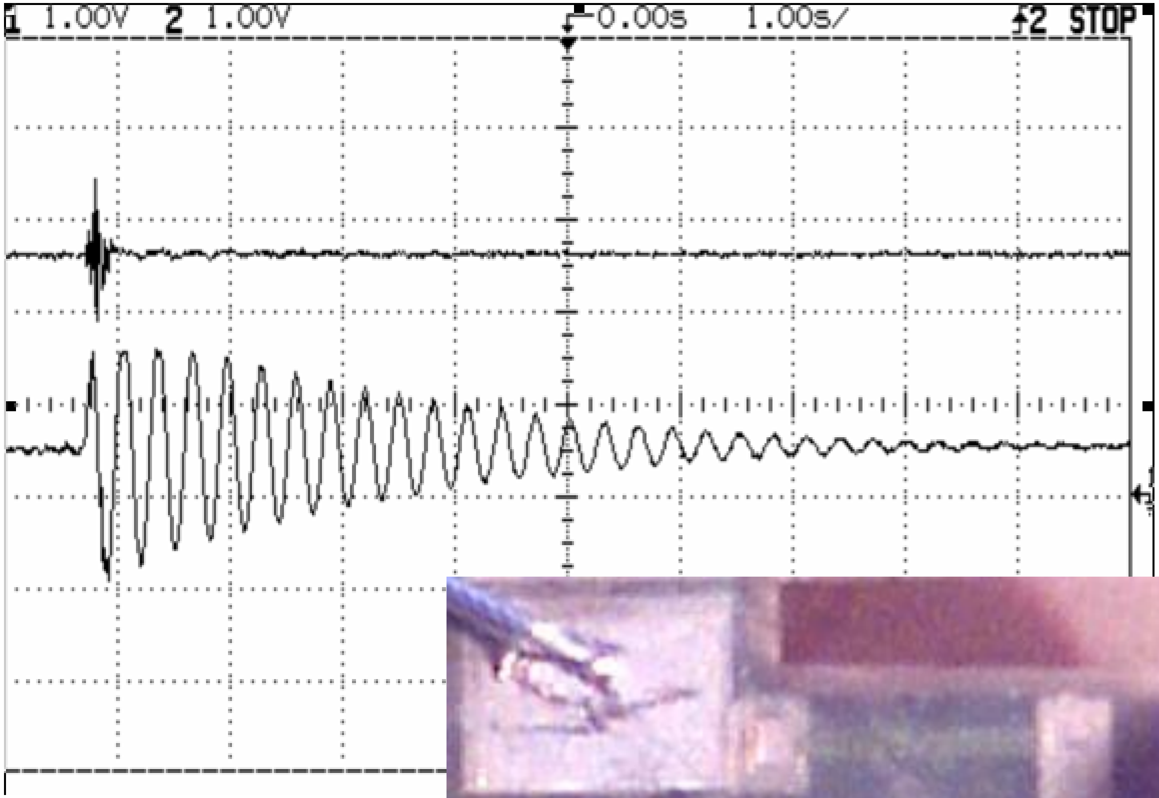


0.707g



1g acceleration
due to gravity

TEST RESULTS FOR RIT ACCELEROMETER

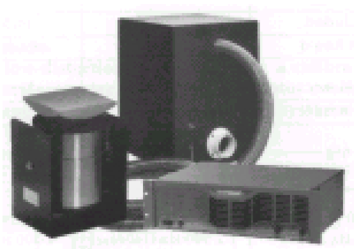


500µm

50 G ACCELEROMETER TESTER

SHAKER FOR TESTING SHOCK AND VIBRATION

Electro-Dynamic Shakers

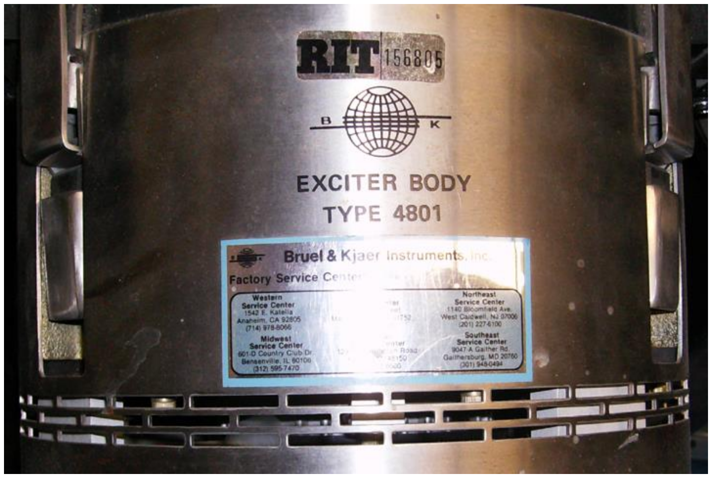


Dynamic Solutions LLC
Call Us Toll Free at 877-767-7077
mailto:aimmee@dynsolusa.com,steve@dynsolusa.com

PERMANENT MAGNET SHAKERS

Small Permanent Magnet Systems	VTS 40	VTS 65	VTS 80	VTS 100	VTS 150
LOW COST, LOW FORCE VIBRATION SYSTEMS					
Peak Sine	40 lbf	65 lbf	80 lbf	100 lbf	150 lbf
Amplifier Cooling Fan	INCLUDED				
Vibrator Cooling Fan	N/A	INCLUDED			
Stroke (p-p)	.75"	.75"	.75"	.75"	1.0"
Velocity	35 ips	70 ips	80 ips	100 ips	70 ips
Max. Acceleration (bare table)	60g	100g	115g	150g	210g
Armature Weight	.66 lbs	.66 lbs	.70 lbs	.66 lbs	.71 lbs
Suspension Stiffness	40 lbs./in (options available for larger payloads)				
First Major Resonance	4500 Hz	4500 Hz	7000 Hz	4500 Hz	5400 Hz
Frequency Range	2-6500 Hz				2-8500 Hz

RIT VIBRATIONS LAB – DR. MARCA LAM

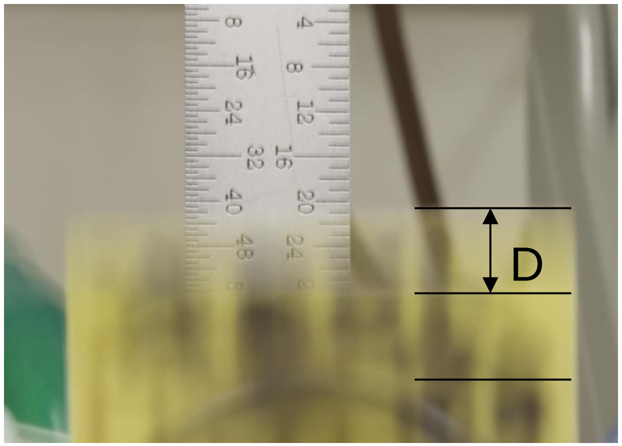


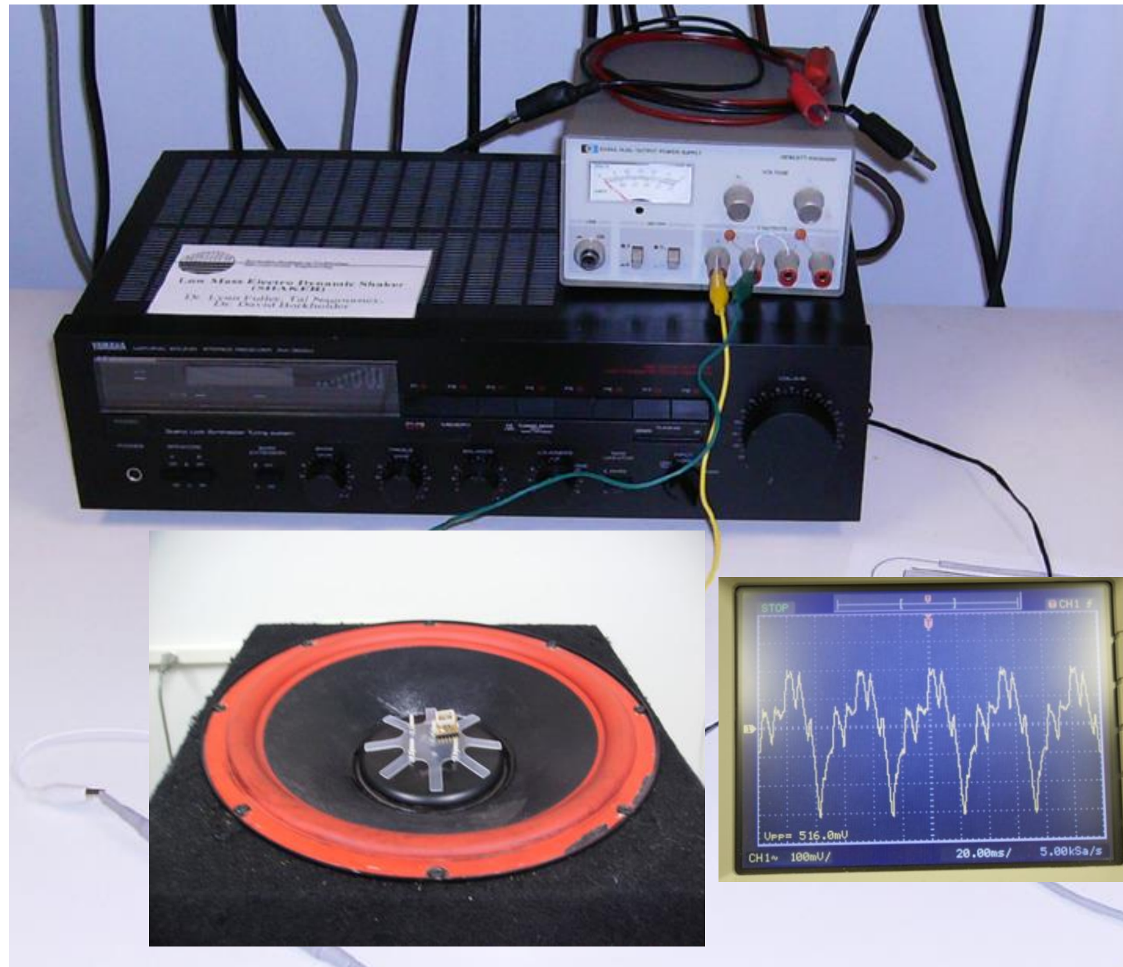
Power Amplifier 2707

Bruel & Kjaer Instruments Inc.
Big Table Head Type 4813
& Exciter Body Type 4801

Rochester Institute of Technology
Microelectronic Engineering

LOW MASS ELECTRO-DYNAMIC SHAKER





f = 20 Hz
Signal Generator = 2 Vpp
Gain = 40

D = 8/32”
A = $(2\pi f)^2 D$
A = 10.23 g

LOW MASS ELECTRODYNAMIC SHAKER

REFERENCES

1. Mechanics of Materials, by Ferdinand P. Beer, E. Russell Johnston, Jr., McGraw-Hill Book Co.1981, ISBN 0-07-004284-5

2. "Crystalline Semiconductor Micromachine", Seidel, Proceedings of the 4th Int. Conf. on Solid State Sensors and Actuators 1987, p 104

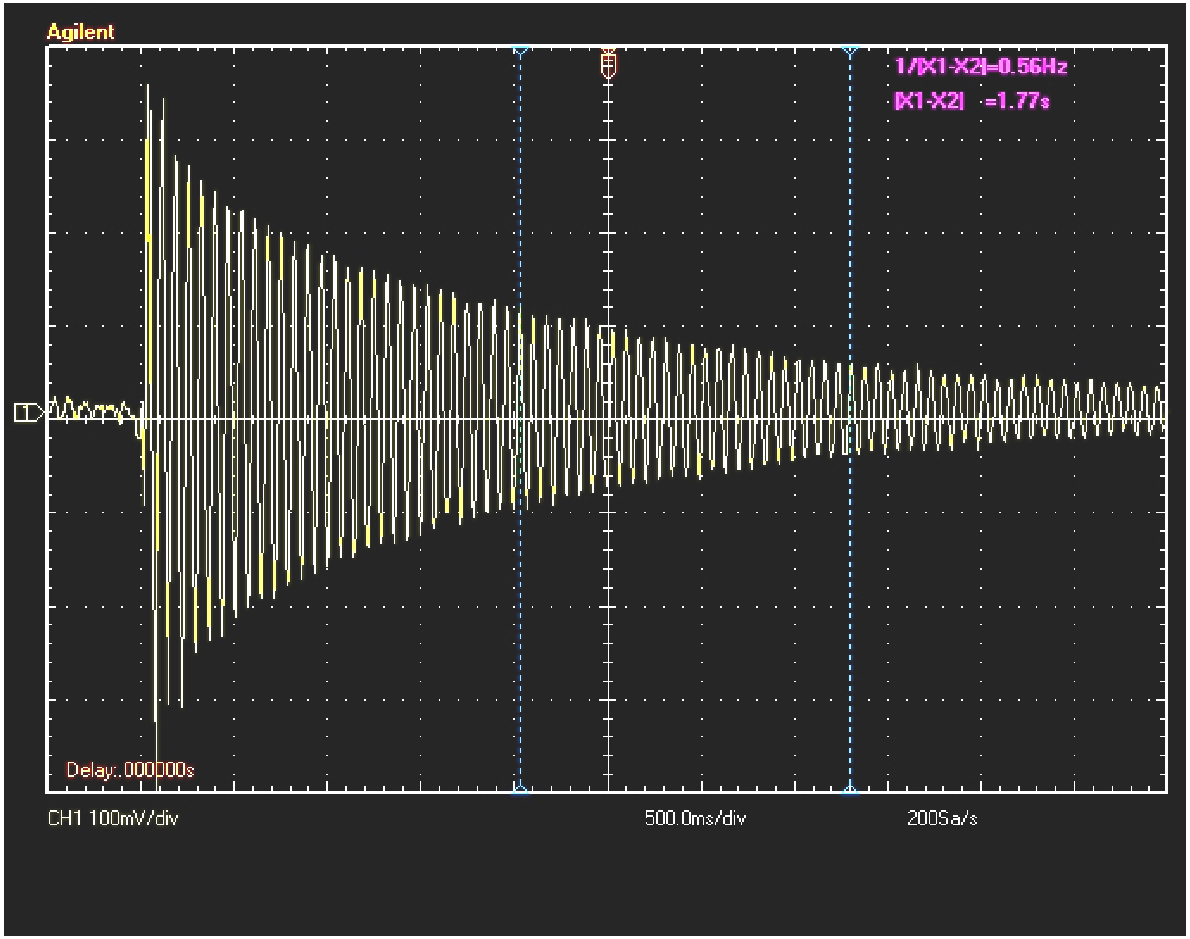
3. Analog Devices Inc., Accelerometers, www.Analog.com

HOMEWORK – ACCELEROMETER LAB

1. Determine the damping coefficient for the test fixture with no eddy current damping and with eddy current damping.
2. If the test fixture has an initial displacement of 3 cm, what is the maximum acceleration generated?
3. How can the test fixture cantilever beam resonant frequency be changed?
4. Under what conditions will the electrodynamic shaker generate 50 g's of acceleration?
5. What are the advantages of the pulse width output type of accelerometer compared to the analog output type of accelerometer?
6. Look up the price for some of Analog Devices accelerometers.
7. Describe the difference between the ADI Analog, digital, and PWM output accelerometers.

HW ACCEROMETER LAB: DAMPING

Measured Output
No Damping



We can describe the envelope of the oscillations with the following eqn.

$V_{out}=V_{max}\ e^{-\alpha t}$

where α is the damping coefficient

LABLES FOR TEST FIXTURE

Dr. Lynn Fuller

Rochester Institute of Technology
Microelectronic Engineering

Accelerometer
Test Fixture

http://people.rit.edu/lffeee

Eddy Current Damper

Solenoid Velocity Sensor

Accelerometer

Strain Gauge Position Sensor

Starting Position Limiter

Signal Conditioning