Bulk Micromachined Pressure Sensor

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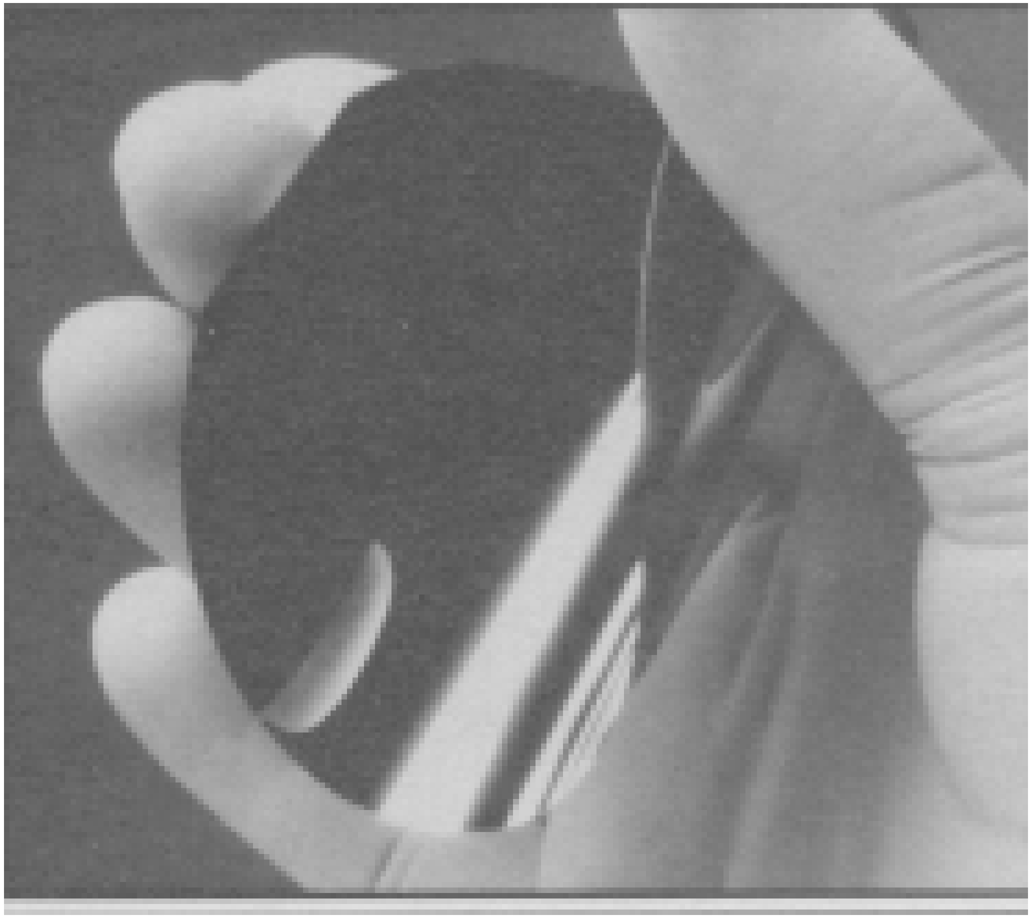
OUTLINE

Piezoresistive Pressure Sensor
Resistor Layout
Maskmaking
Alignment Details
Process Details
Packaging
Testing Approach
Test Results

SINGLE CRYSTAL SILICON



Thickness
10 µm

Wafer
Diameter
75 mm

DESIGN GUIDELINES

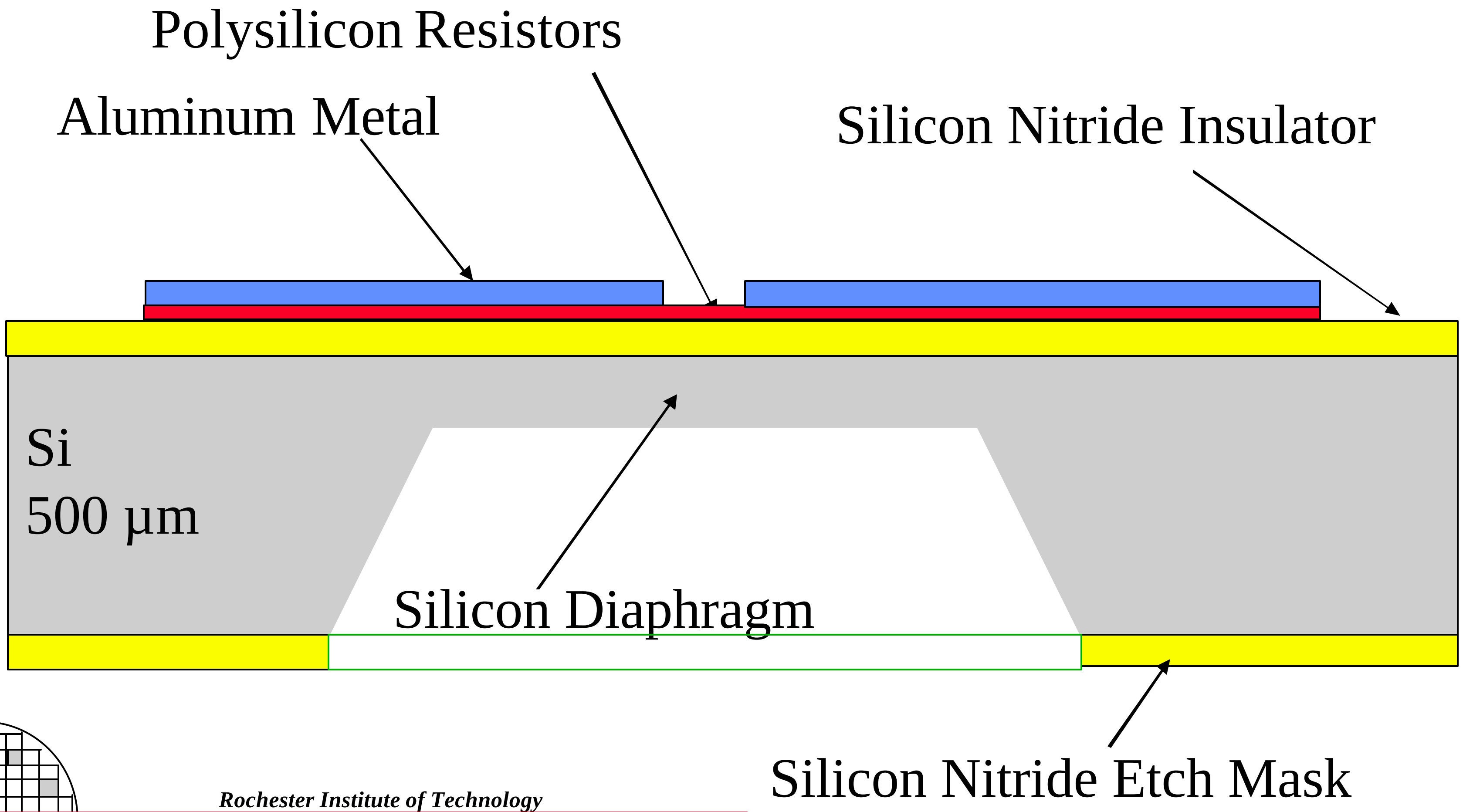
Each student has 5mm x 5mm area

Diaphragm size up to 3mm

Three Layer Design

- **Diaphragm (Green)**
- **Resistor (Red)**
- **Metal (Blue)**

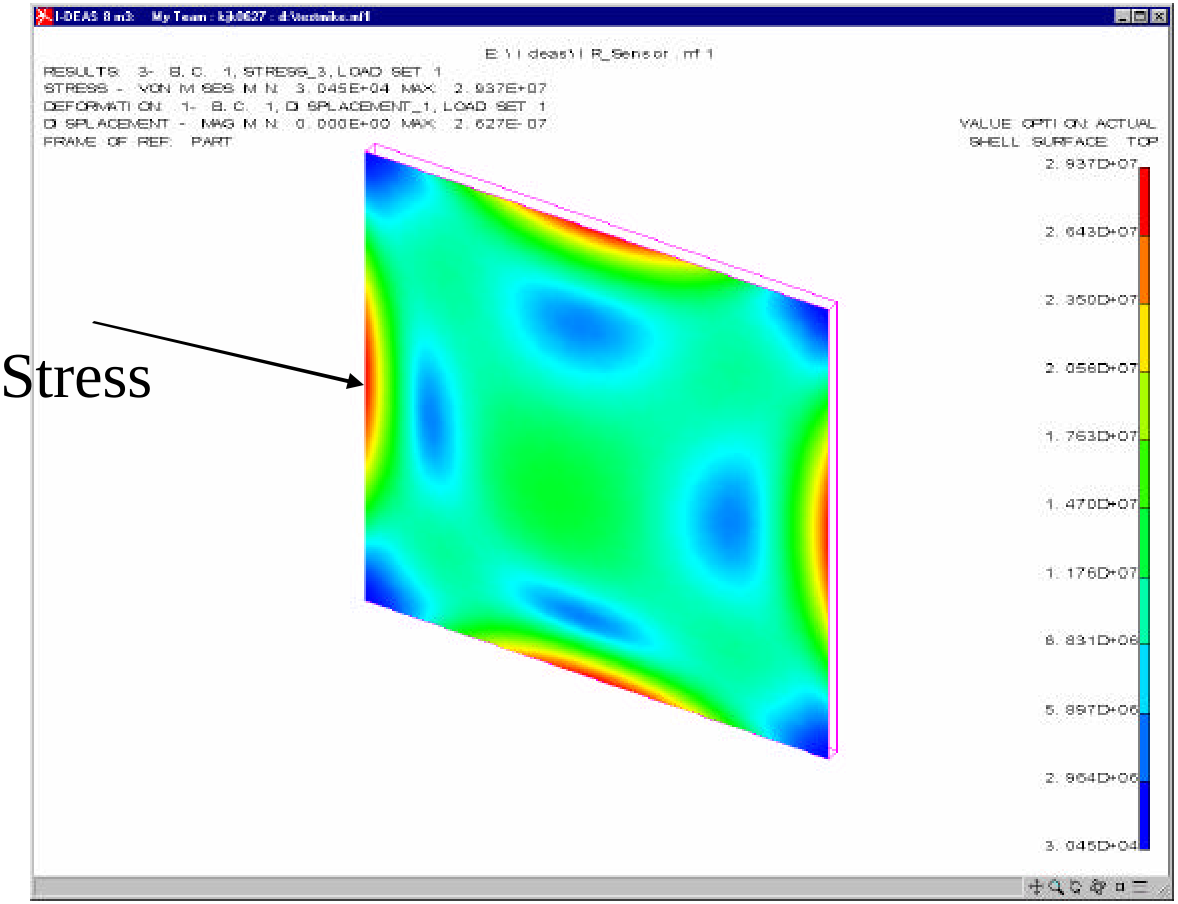
BACKSIDE ETCHED BULK MICROMACHINED POLYSILICON RESISTOR PRESSURE SENSOR



Bulk Micromachined Pressure Sensor

FINITE ELEMENT ANALYSIS

Points of
Maximum Stress



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                                                    E:\ideas\R_Sensor.mf1
RESULTS: 3- B.C. 1,STRESS_3,LOAD SET 1
STRESS - VON MISES MIN: 3.045E+04 MAX: 2.937E+07
DEFORMATION: 1- B.C. 1,DISPLACEMENT_1,LOAD SET 1
DISPLACEMENT - MAG MIN: 0.000E+00 MAX: 2.627E-07
FRAME OF REF: PART
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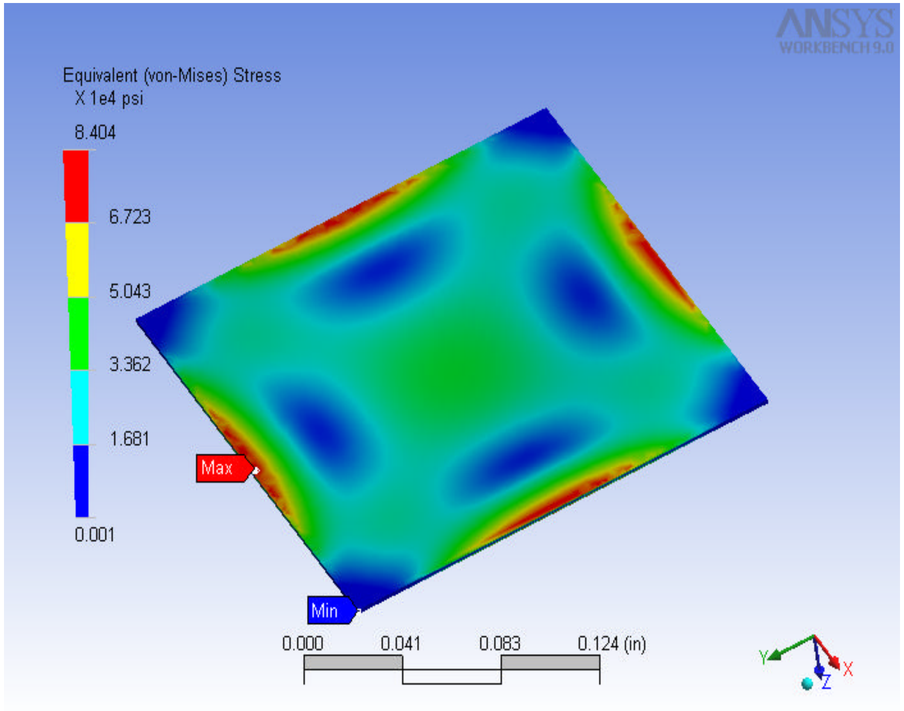
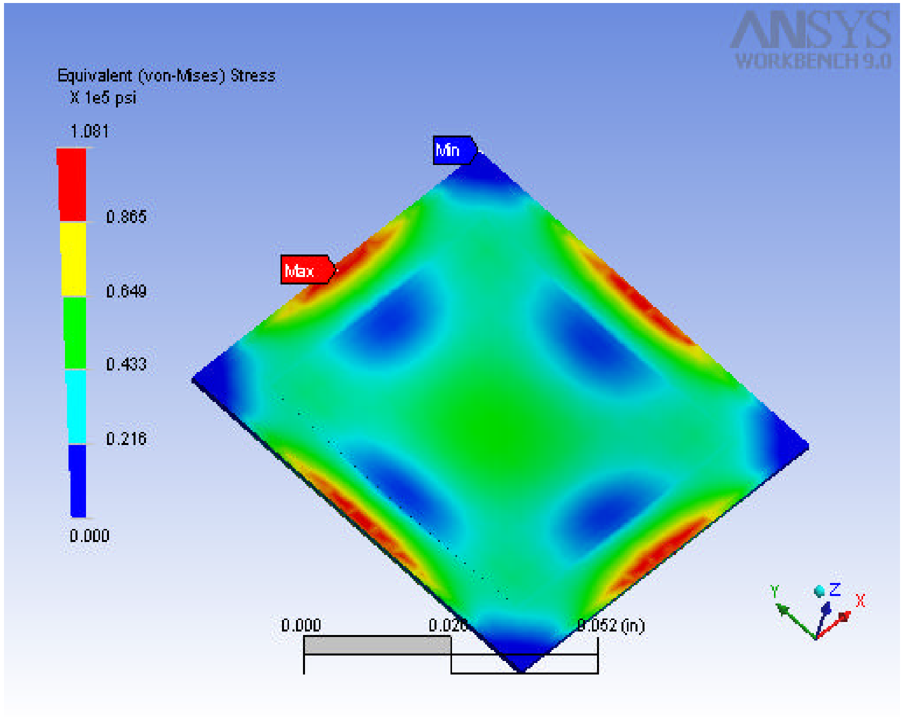
ANSYS FINITE ELEMENT ANALYSIS

Regular Si Diaphragm



Corrugated Diaphragm

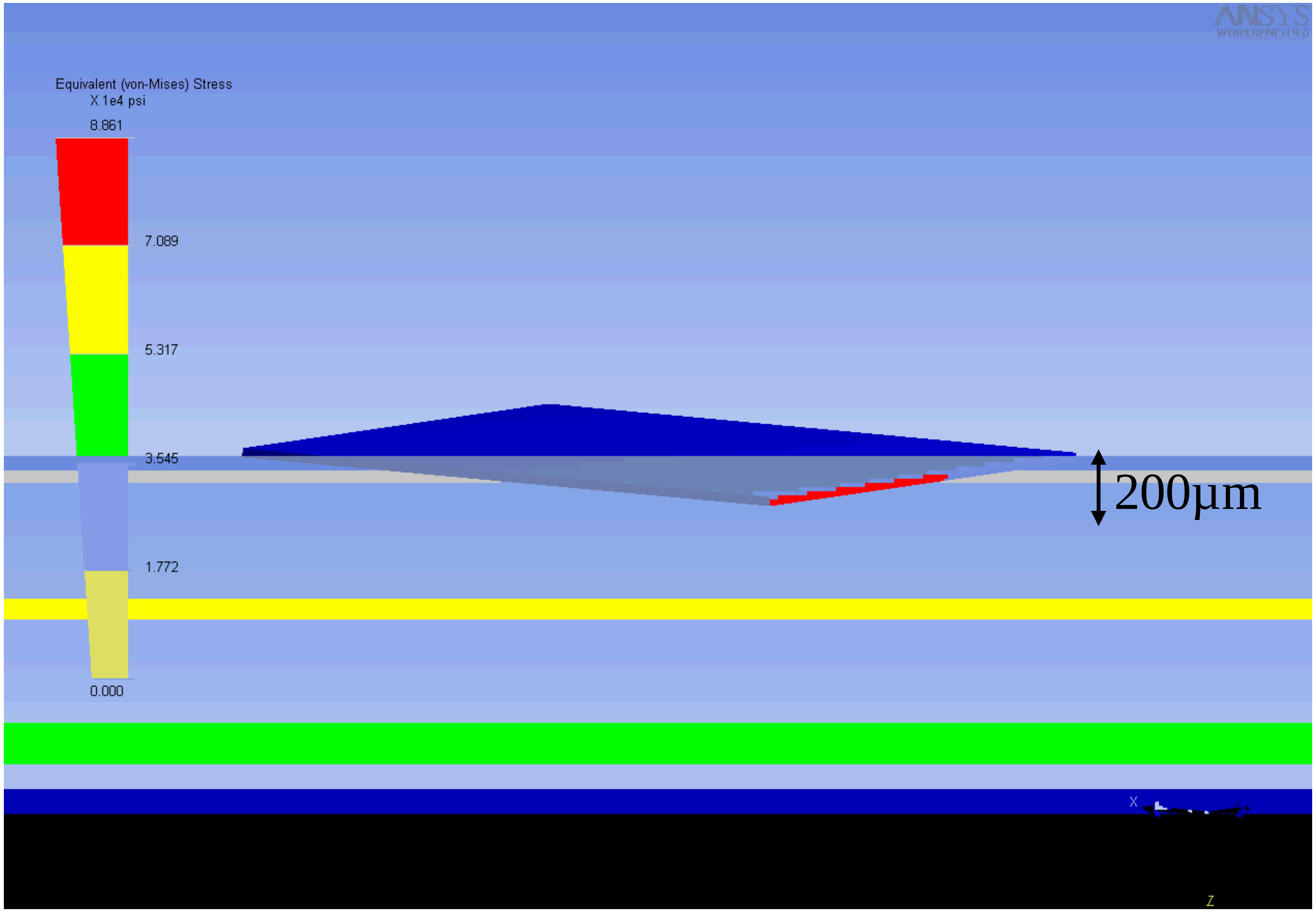
Layer 2: 1.5mm x 1.5mm Polysilicon 1µm thick



2mm x 2mm diaphragm 30µm thick, 50 psi applied

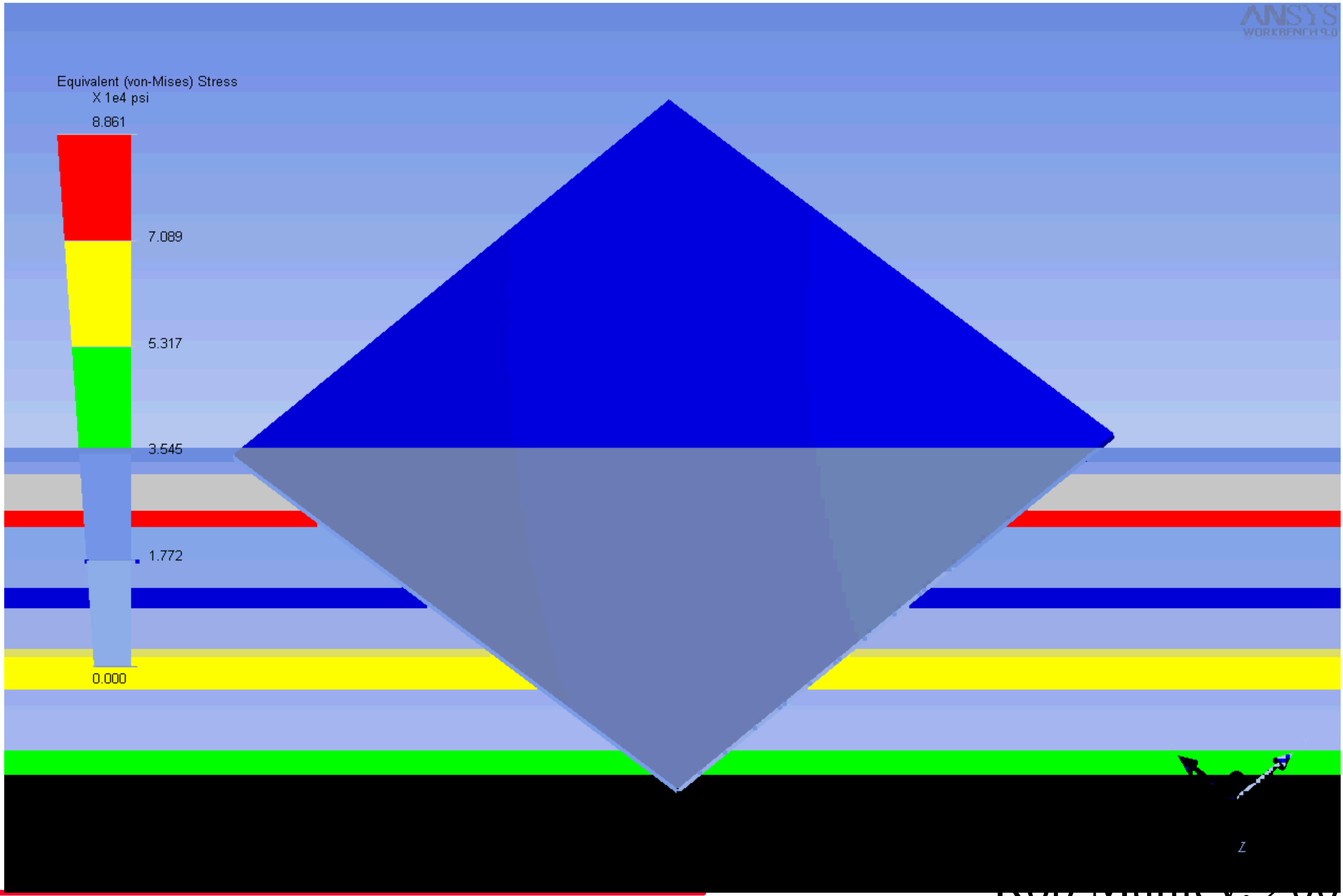
Rob Manley, 2005

DIAPHRAGM DEFORMATION MOVIE



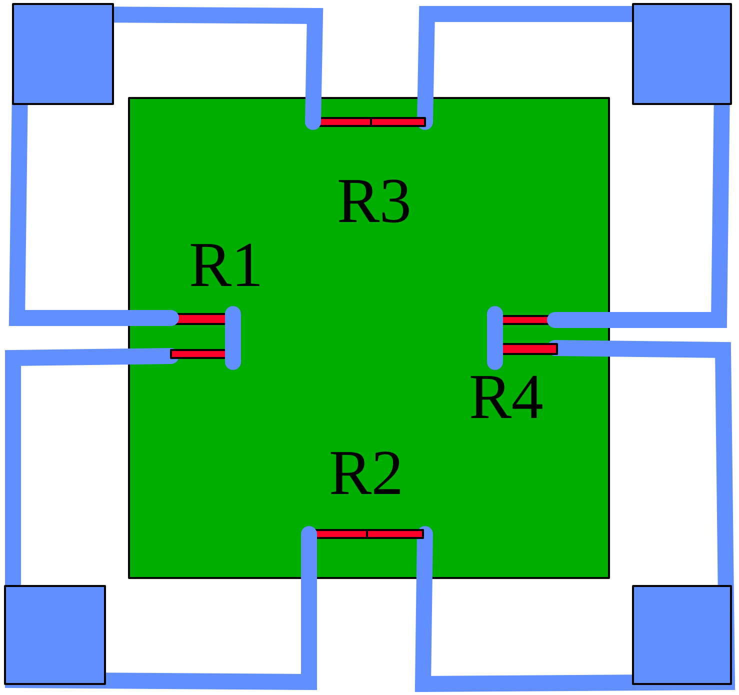
Rob Manley, 2005

DIAPHRAGM STRESS MOVIE



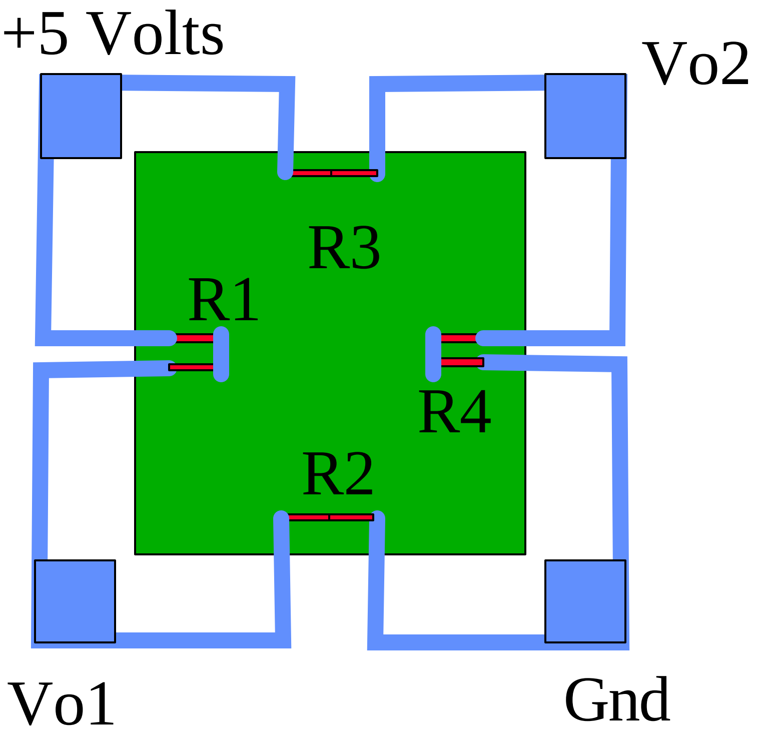
Rob Manley, 2005

RESISTOR LAYOUT



Two resistors parallel to edge near region of maximum stress and two resistors perpendicular to the edge arranged in a full bridge ciruit. If all resistors are of equal value then Vout = Vo1-Vo2 = zero with no pressure applied.

CALCULATION OF EXPECTED OUTPUT VOLTAGE



The equation for stress at the center edge of a square diaphragm (S.K. Clark and K.Wise, 1979)

Stress = 0.3 $P(L/H)^2$ where P is pressure, L is length of diaphragm edge, H is diaphragm thickness

For a 3000µm opening on the back of the wafer the diaphragm edge length L is 3000 – 2 (500/Tan 53°) = 2246 µm

CALCULATION OF EXPECTED OUTPUT VOLTAGE (Cont.)

Stress = 0.3 P $(L/H)^2$

If we apply vacuum to the back of the wafer that is equivalent to and applied pressure of 14.7 psi or 103 N/m^2

P = 103 N/m^2

L= 2246 µm

H= 25 µm

Stress = 2.49E8 N/m^2

Hooke's Law: Stress = E Strain where E is Young's Modulus

$$\sigma = E\,\varepsilon$$

Young's Modulus ofr silicon is 1.9E11 N/m^2

Thus the strain = 1.31E-3 or .131%

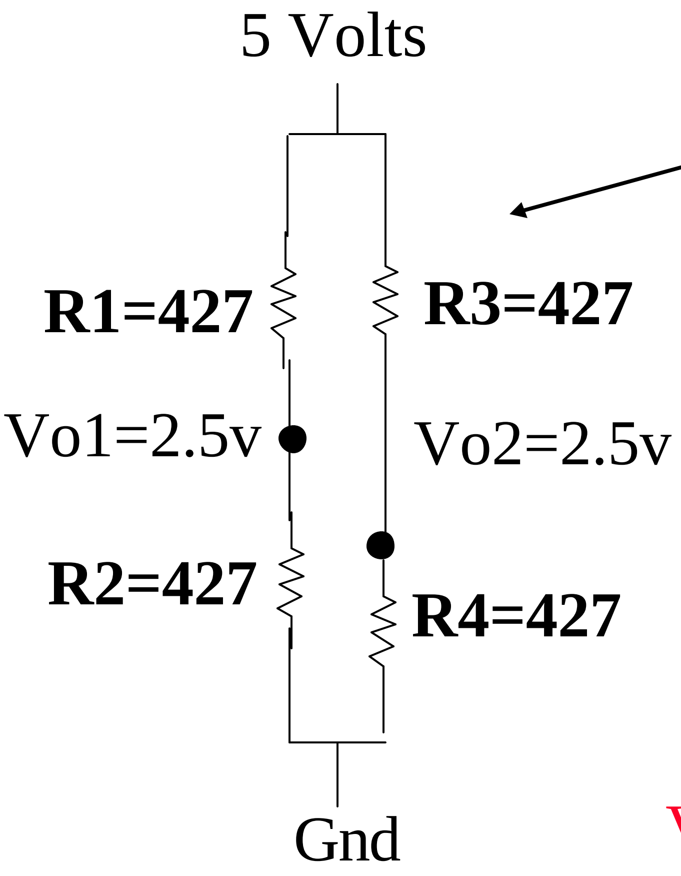
CALCULATION OF EXPECTED OUTPUT VOLTAGE (Cont.)

The sheet resistance (Rhos) from 4 point probe is 61 ohms/sq
The resistance is R = Rhos L/W
For a resistor R3 of L=350 µm and W=50 µm we find:
R3 = 61 (350/50) = 427.0 ohms

R3 and R2 decrease as W increases due to the strain
assume L is does not change, W’ becomes 50+50x0.131%
W’ = 50.0655 µm
R3’ = Rhos L/W’ = 61 (350/50.0655) = 426.4 ohms

R1 and R4 increase as L increases due to the strain
assume W does not change, L’ becomes 350 + 350x0.131%
R1’ = Rhos L’/W = 61 (350.459/50) = 427.6 ohms

CALCULATION OF EXPECTED OUTPUT VOLTAGE (Cont.)



5 Volts

R1=427

R3=427

Vo1=2.5v

Vo2=2.5v

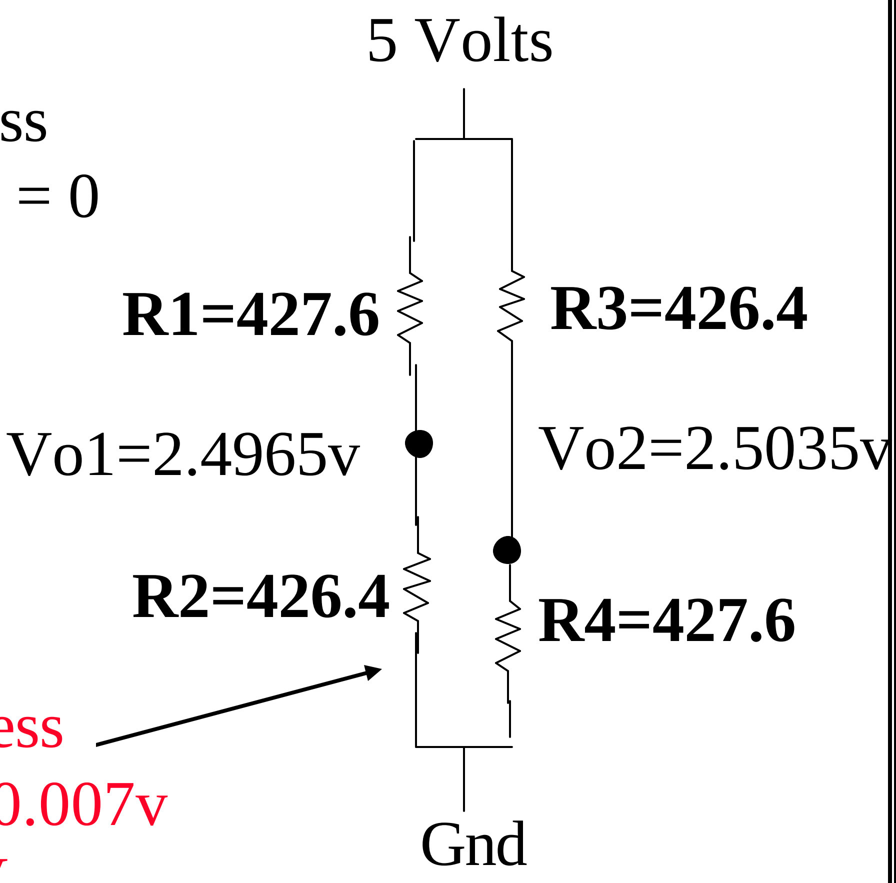
R2=427

R4=427

Gnd

No stress

Vo2-Vo1 = 0



5 Volts

R1=427.6

R3=426.4

Vo1=2.4965v

Vo2=2.5035v

R2=426.4

R4=427.6

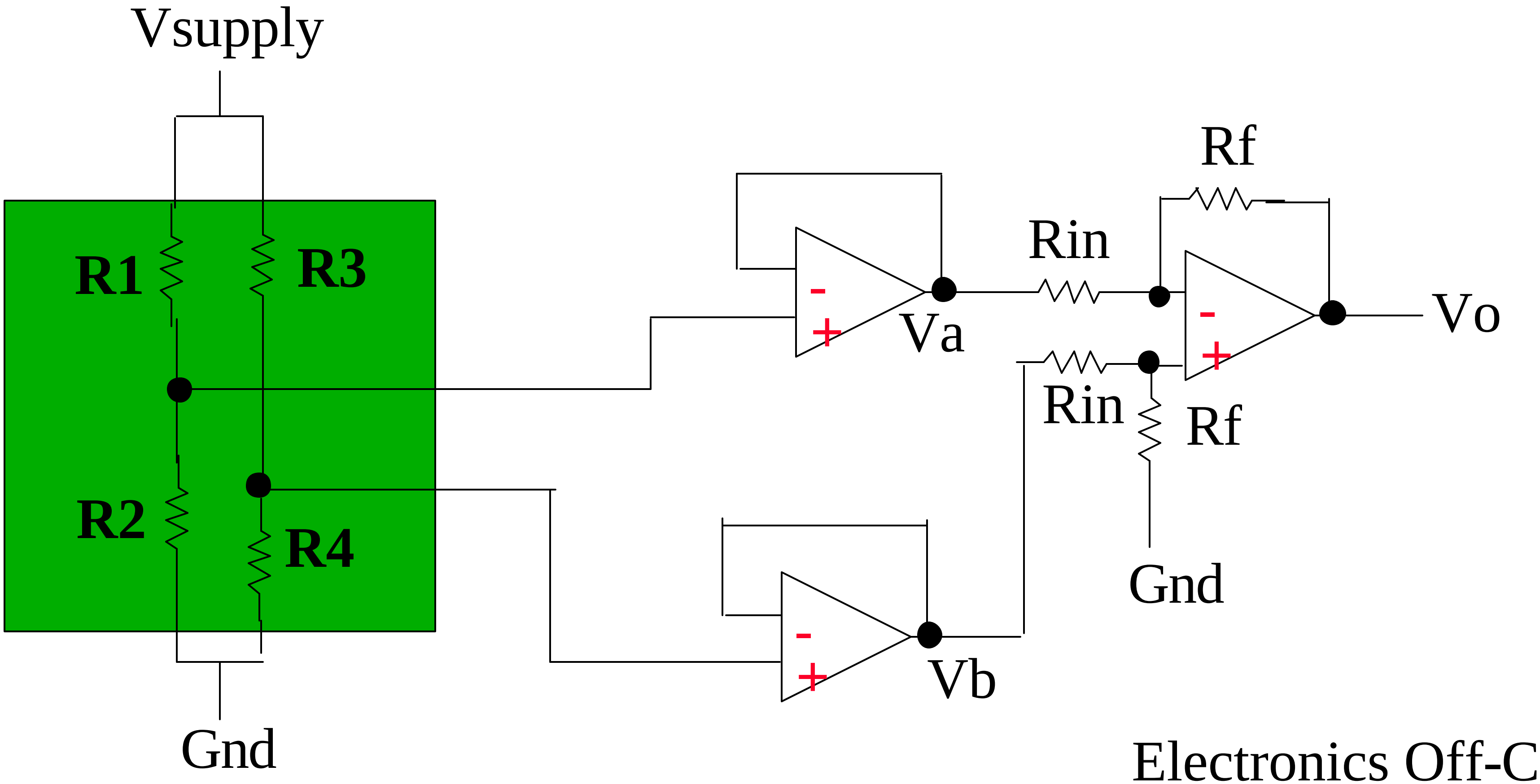
Gnd

With stress

Vo2-Vo1 = 0.007v

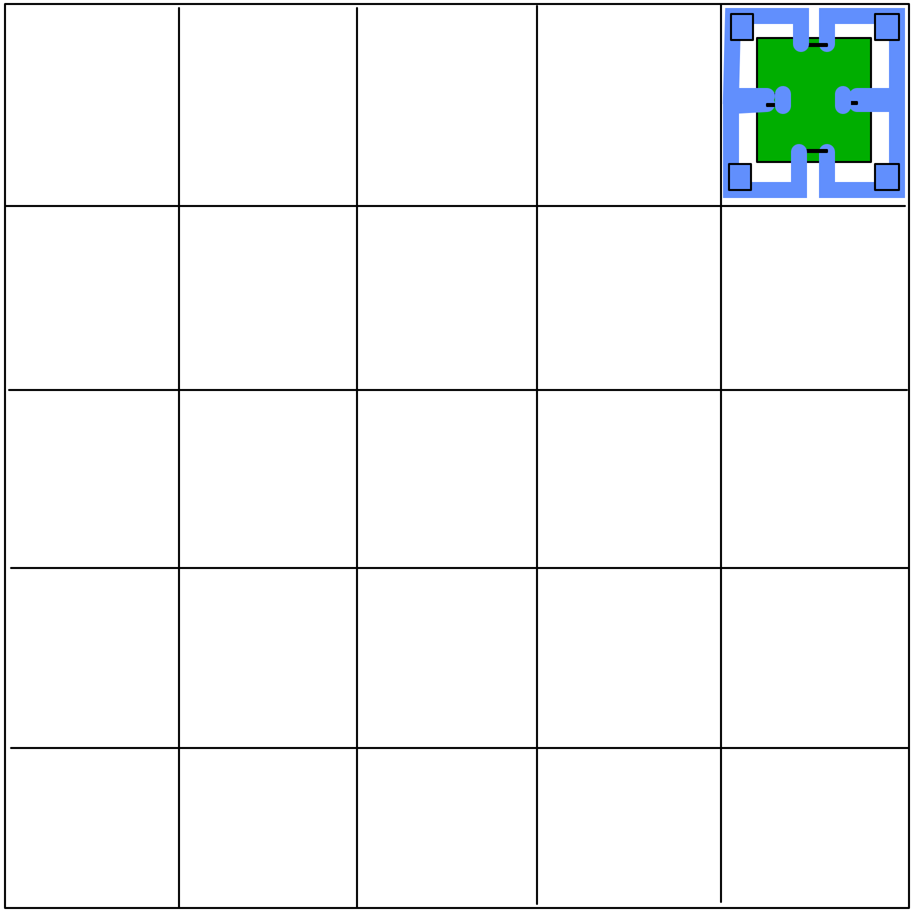
=7 mV

BUFFER / DIFFERENTIAL AMPLIFIER / FILTER



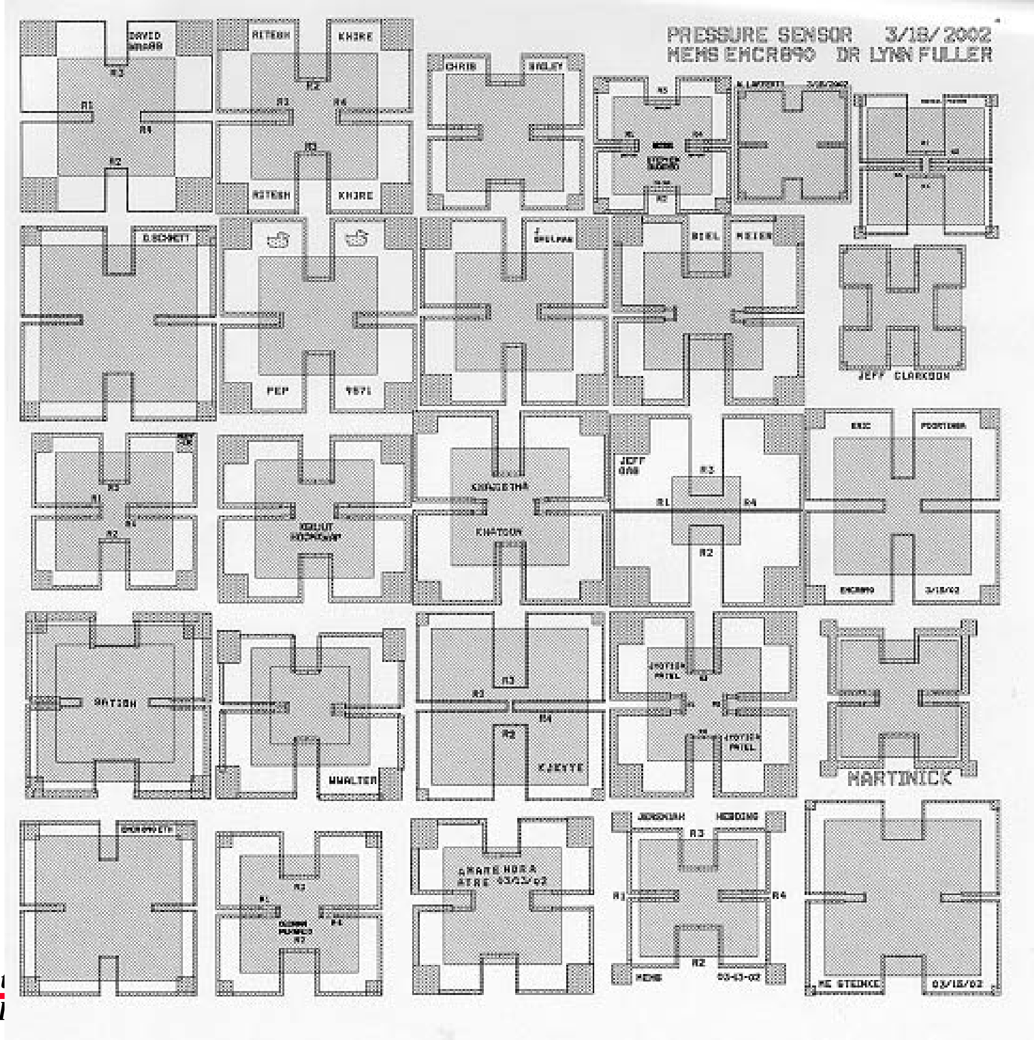
Electronics Off-Chip
May not be needed

5 X 5 ARRAY FOR 25 STUDENT DESIGNS

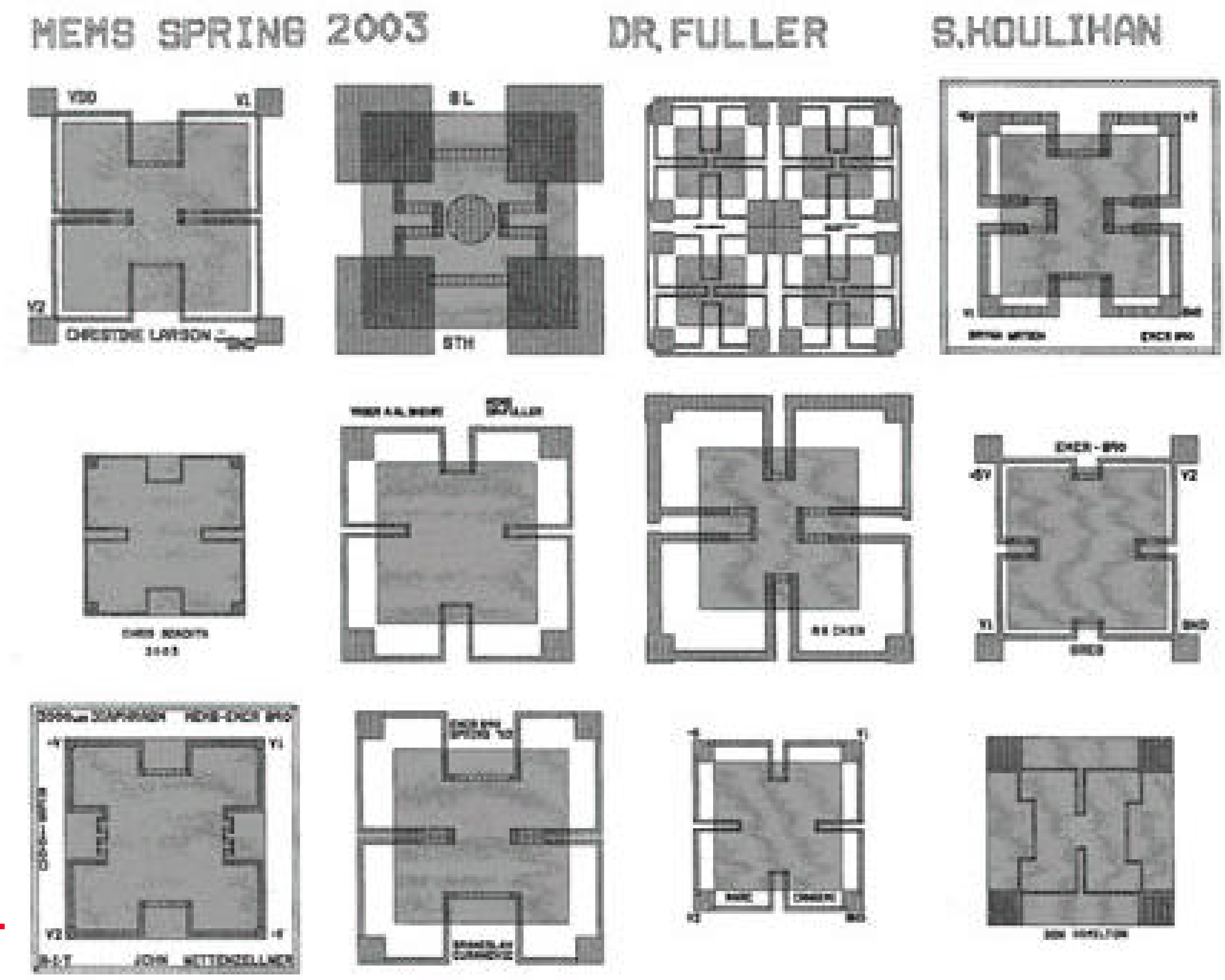


Each Design
5mmx5mm

26 STUDENT DESIGNS 2002

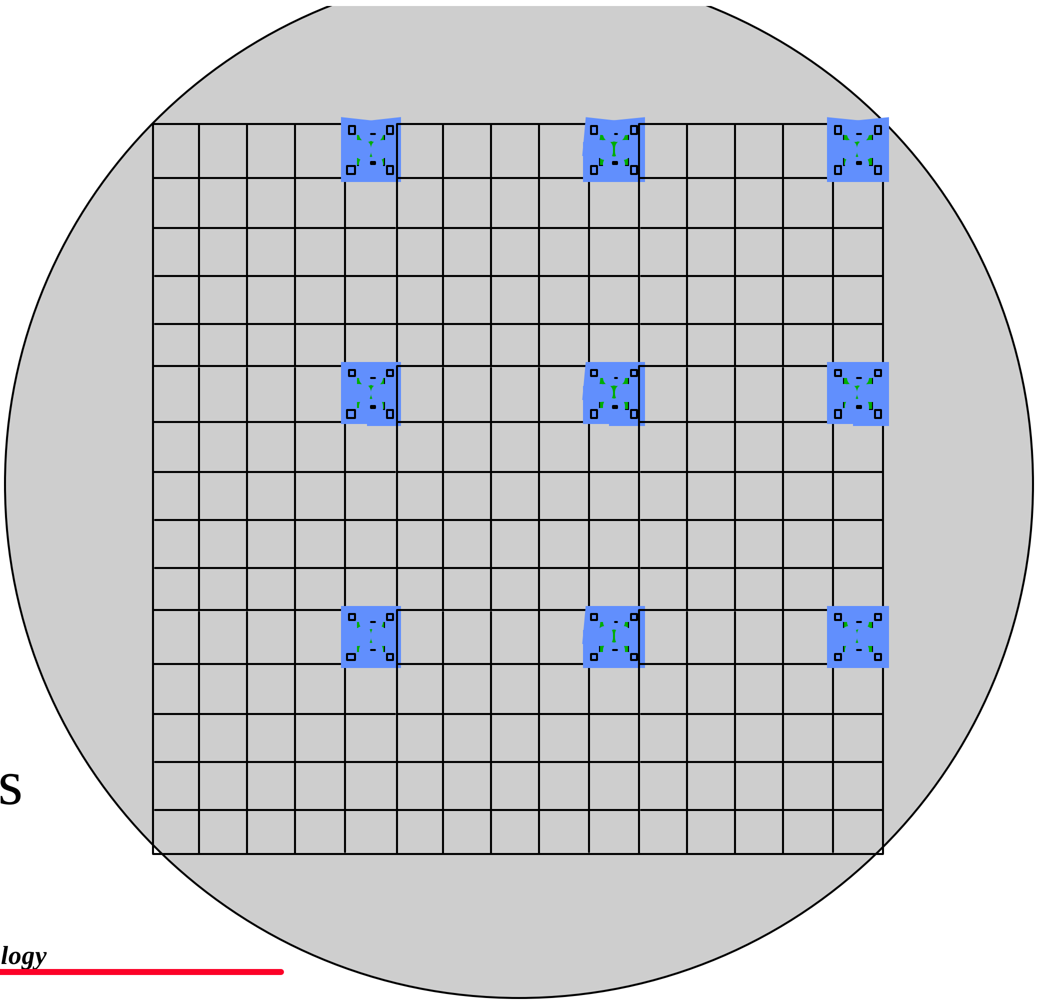


12 STUDENT DESIGNS 2003



4” WAFER AND ARRAY

3 LAYERS
- Diaphragm
- Resistor
- Metal

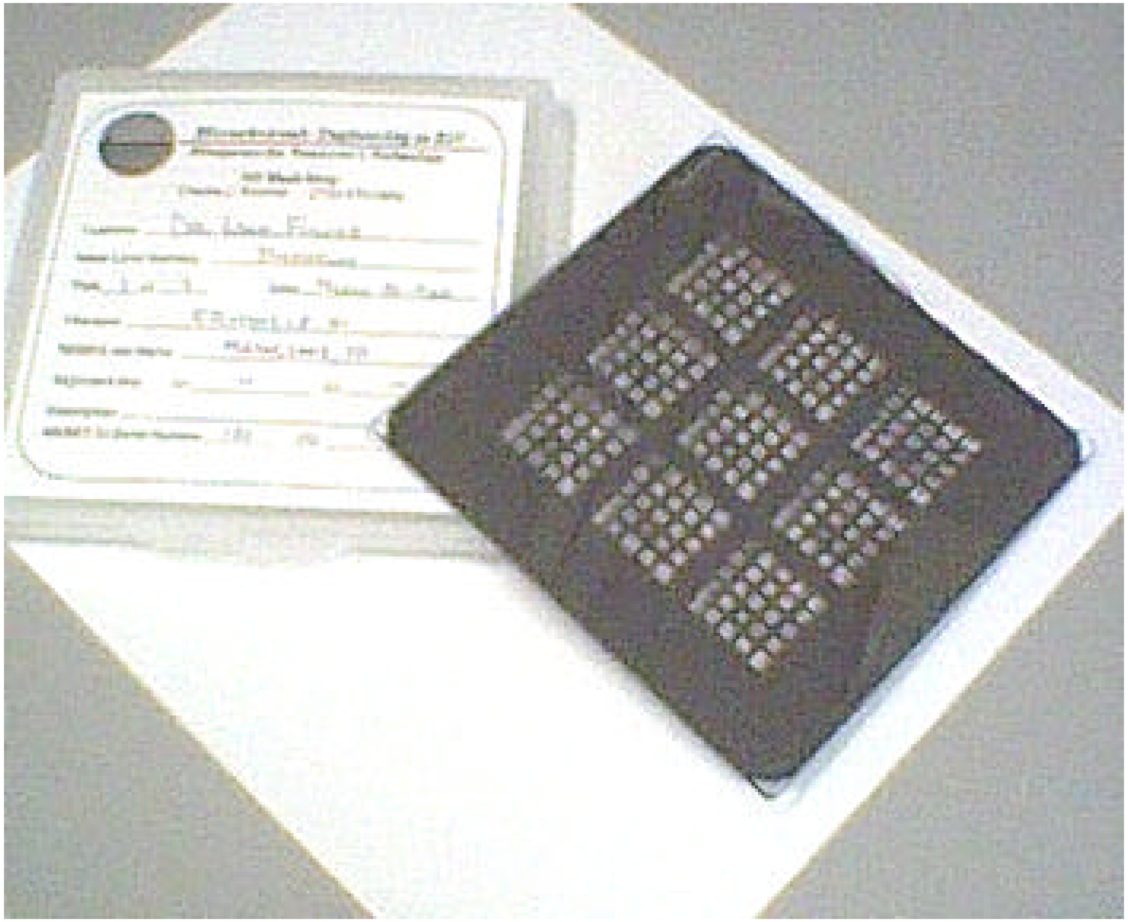


3x3 array of 25 Designs
For a total of 225 Sensors

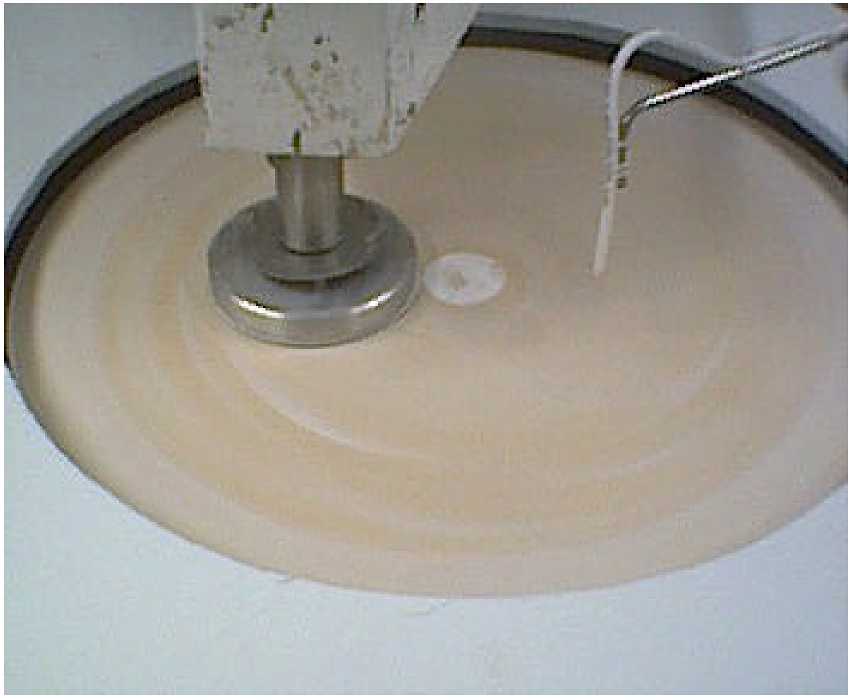
ORDER MASK

1x Mask with pattern repeated 3x3 array for total of 9
Mirror Layers 2 (red – poly) and 3 (blue – metal)
Do not mirror Layer 1 (green-diaphram)
No alignment marks (we will align to the pattern)

MASK



CMP BACKSIDE OF WAFERS



Strassbaugh CMP Tool

CMP DETAILS

Strassbaugh CMP Tool

Slurry: Lavisil-50-054, with pH=12, 15 min per wafer Slurry drip rate: ~1 drop/second

Down Pressure = 8 psi

Quill Speed = 70 rpm

Oscillation Speed = 6 per min

Table Speed = 50 rpm (~10 Hz)

The quality of this polish must be very good. If after polish you can not visually tell the front from the back then it is good. Otherwise the subsequent nitride coating will not be good enough to act as an etch mask to KOH

RCA CLEAN WAFERS

APM

H_2O – 4500ml
NH_4OH–300ml
H_2O_2 – 900ml
75 °C, 10 min.

DI water
rinse, 5 min.

H_20 - 50
HF - 1
60 sec.

DI water
rinse, 5 min.

HPM

H_2O–4500ml
HCL-300ml
H_2O_2 – 900ml
75 °C, 10 min.

DI water
rinse, 5 min.

SPIN/RINSE
DRY

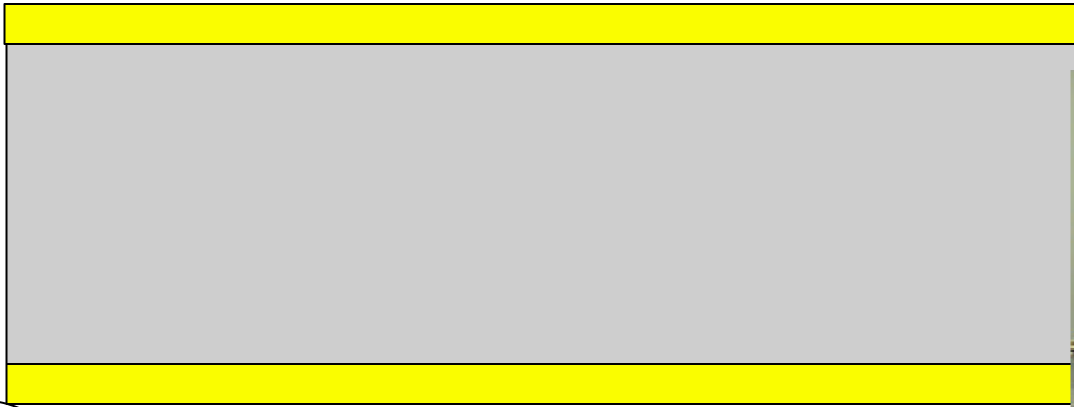
What does RCA
stand for?

ANSWER

PLAY

DEPOSIT PROTECTIVE SILICON NITRIDE LAYER

Silicon Nitride (Si3N4) (normal - stociometric):
Temperature = 790-800-810 °C Ramp from (door to pump)
Pressure = 375 mTorr 3SiH2Cl2 + 4NH3 = Si3N4 + 9H2 + 3Cl2
Dichlorosilane (SiH2Cl2) Flow = 60 sccm
Ammonia (NH3) Flow = 150 sccm
Rate = 60 Å/min +/- 10 Å/min
Time ~25 min for 1500 Å

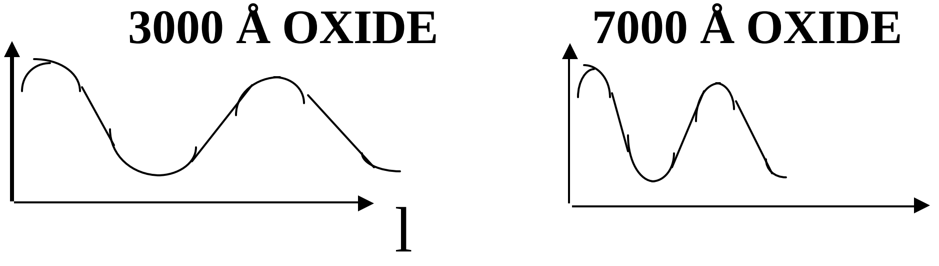


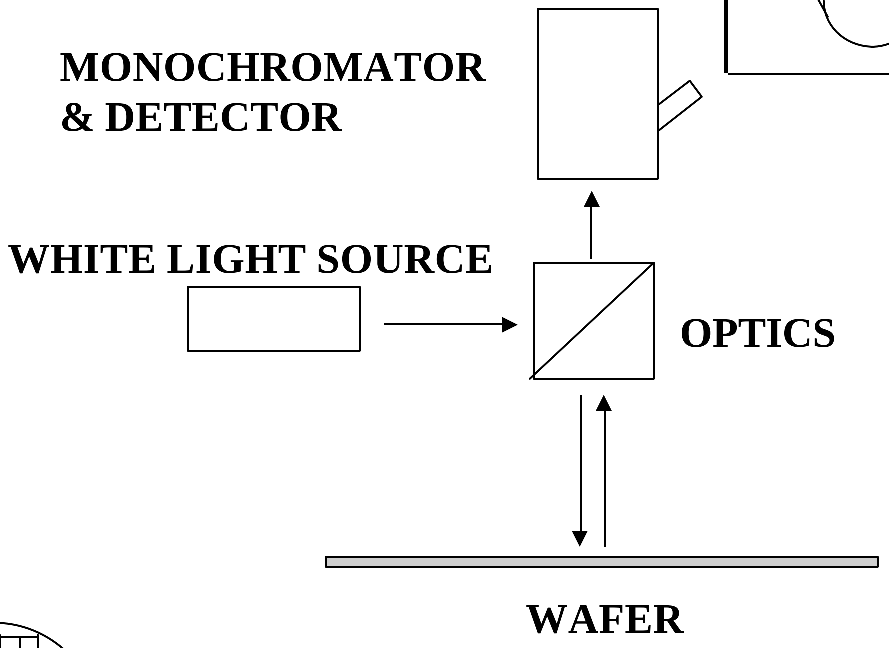
PICTURE OF WAFER AFTER NITRIDE DEPOSITION

This nitride is about 3500 Å thick.   A thinner layer may have less stress and be less sensitive to microcracks and pinholes. Nitride does not etch in KOH so even a very thin layer will mask. Try ~1500 Å

(REFLECTANCE SPECTROMETER) NANOSPEC THICKNESS MEASUREMENT

INCIDENT WHITE LIGHT, THE INTENSITY OF THE REFLECTED LIGHT IS MEASURED VS WAVELENGTH





Oxide on Silicon	400-30,000 Å
Nitride	400-30,000
Neg Resist	500-40,000
Poly on 300-1200 Ox	400-10,000
Neg Resist on Ox 300-350	300-3500
Nitride on Oxide 300-3500	300-3500
Thin Oxide	100-500
Thin Nitride	100-500
Polyimide	500-10,000
Positive Resist	500-40,000
Pos Resist on Ox 500-15,000	4,000-30,000

NANOSPEC FILM THICKNESS MEASUREMENT TOOL

OXIDE THICKNESS COLOR CHART

Thickness	Color
500	Tan
700	Brown
1000	Dark Violet - Red Violet
1200	Royal Blue Blue
1500	Light Blue - Metallic Blue
1700	Metallic - very light Yellow Green
2000	LIght Gold or Yellow - Slightly Metallic
2200	Gold with slight Yellow Orange
2500	Orange - Melon
2700	Red Violet
3000	Blue - Violet Blue
3100	Blue Blue
3200	Blue - Blue Green
3400	Light Green
3500	Green - Yellow Green
3600	Yellow Green
3700	Yellow
3900	Light Orange
4100	Carnation Pink
4200	Violet Red
4400	Red Violet
4600	Violet
4700	Blue Violet

Thickness	Color
4900	Blue Blue
5000	Blue Green
5200	Green
5400	Yellow Green
5600	GreenYellow
5700	Yellow -"Yellowish"(at times appears to be Lt gray or matel
5800	Light Orange or Yellow - Pink
6000	Carnation Pink
6300	Violet Red
6800	"Bluish"(appears violet red, Blue Green, looks Blue
7200	Blue Green - Green
7700	"Yellowish"
8000	Orange
8200	Salmon
8500	Dull, LIght Red Violet
8600	Violet
8700	Blue Violet
8900	Blue Blue
9200	Blue Green
9500	Dull Yellow Green
9700	Yellow - "Yellowish"
9900	Orange
10000	Carnation Pink

Nitride Thickness = (Oxide Thickness)(Oxide Index/Nitride Index)

Eg. Yellow Nitride Thickness = (2000)(1.46/2.00) = 1460

1^{st} LAYER LITHOGRAPHY

The objective is to protect the nitride using photoresist on one side of the wafer prior to etching the pattern for the diaphragm holes in the nitride on the back of the wafers. The plasma etch will only etch from one side so the nitride on the other side of the wafer will remain after the nitride etch for the diaphragm holes.

COAT AND DEVELOP TRACK

COAT

DEHYDRATE BAKE

200 °C, 120 sec.
Optional

COAT

HMDS
Vapor Prime
S-8 RESIST
4500 rpm, 60 sec.

SOFT BAKE

90 °C
60 sec.

DEVELOP

POST EXPOSURE BAKE

115 °C, 60 sec.
Optional

DEVELOP

DI Wet
CD-26 Developer
50 sec., Puddle
Rinse, Spin Dry

HARD BAKE

125 °C, 60 sec.

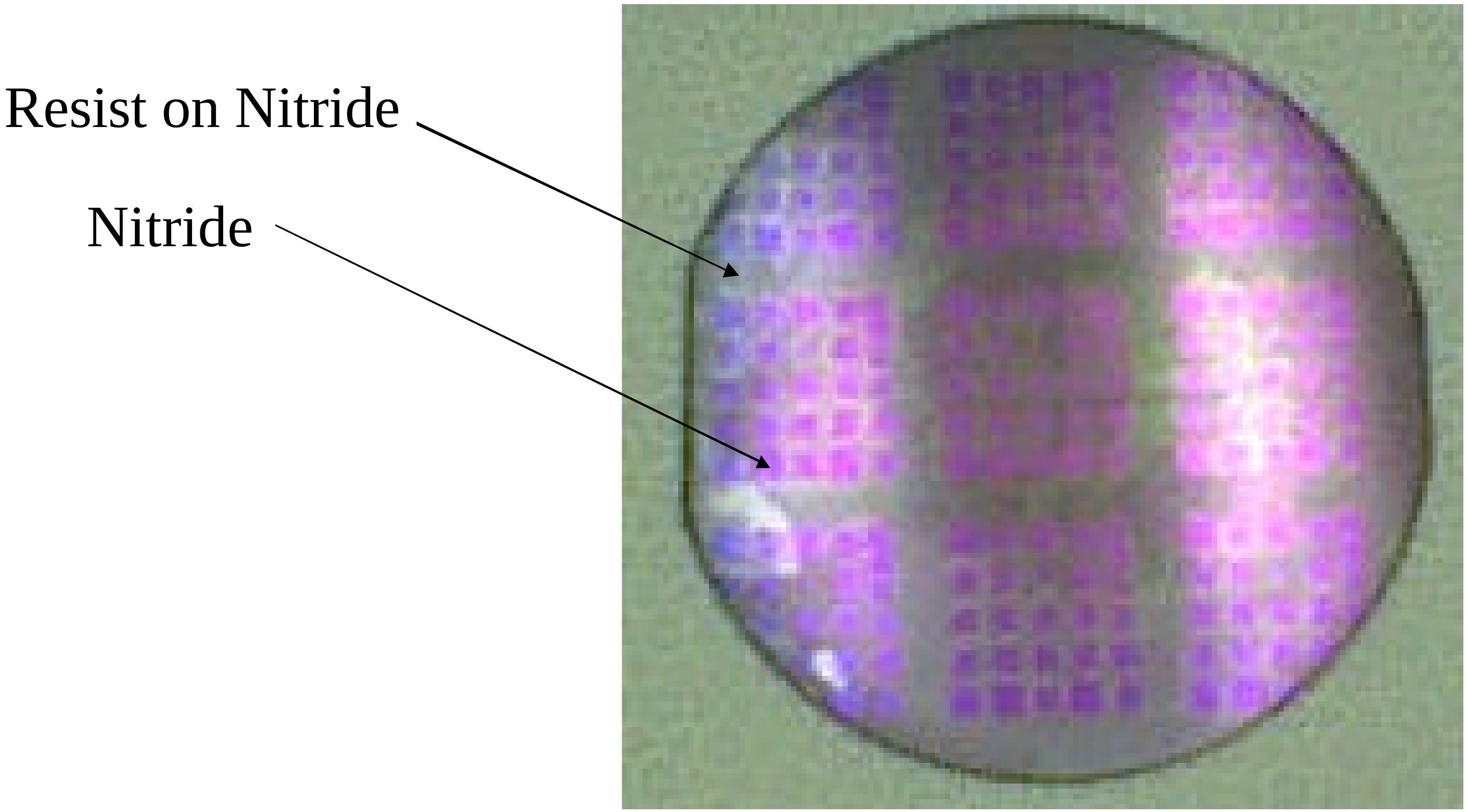
AUTOMATED COAT AND DEVELOP TRACK

EXPOSURE TOOLS

The resist needs and exposure dose (E) of about 50 mj/cm2. The intensity (I) is measured and found to be ~5 mw/cm2 so using the equation E=It we find exposure time of 10 seconds.

SEE www.suss.com
contact printers
with back side alignment

IMAGES AFTER LITHOGRAPHY

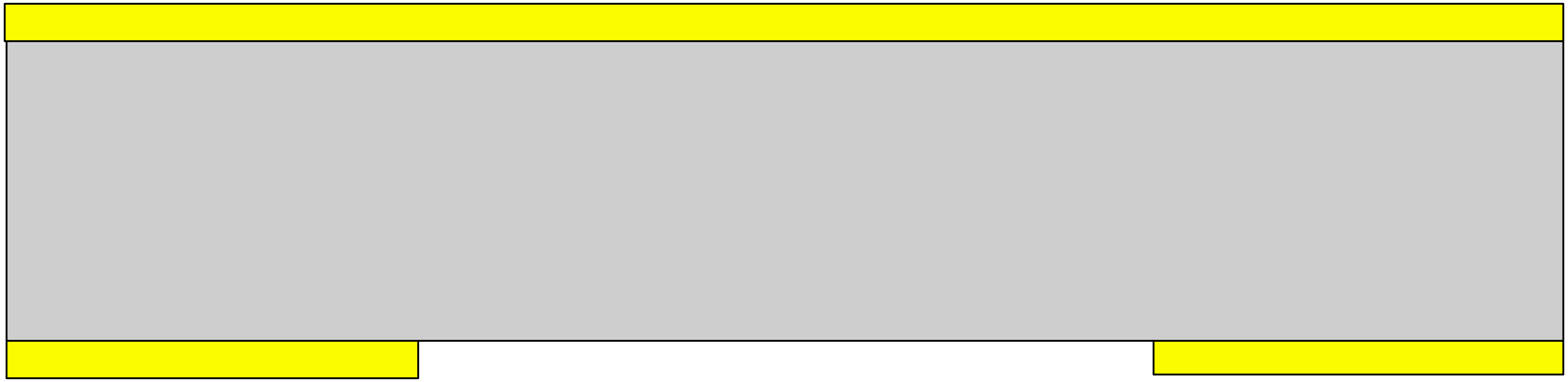


SILICON NITRIDE ETCH

The objective is to plasma etch the nitride down to the bare silicon on the back of the wafer in the areas where the holes to form the diaphragm will be etched. Since we intend to etch almost all the way through the silicon wafer it is not critical to stop the etch exactly after etching through the nitride.

OPEN DIAPHRAGM ETCH HOLES

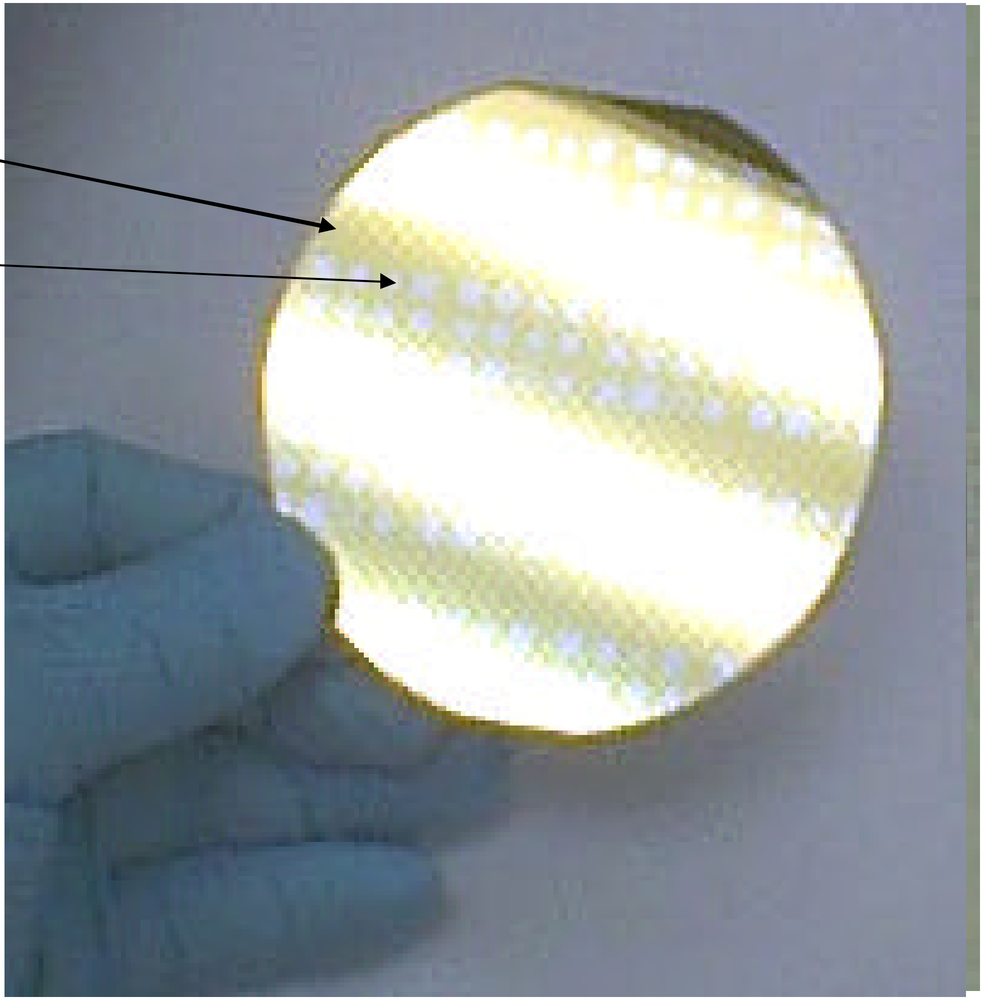
Lam 490 Etch Tool
Plasma Etch Nitride (~ 1500 Å/min)
SF6 flow = 200 sccm, He flow = 0 sccm
Pressure= 260 mTorr
Power = 125 watts
Time=thickness/rate or use end point detection ~2.5 min



PLASMA ETCH TOOL

Lam 490 Etch Tool
Plasma Etch Nitride (~ 3500 Å/min)
SF_6 flow = 30 sccm
He flow = 150 sccm
Pressure= 340 mTorr
Power = 175 watts
Time=thickness/rate
or
use end point detection capability
This system has filters at 520 nm and 470 nm. In any case the color of the plasma goes from pink/blue to white/blue once the nitride is removed.

PICTURE OF WAFER AFTER NITRIDE ETCH



Resist on Nitride

Silicon

PLASMA ASHER TOOL

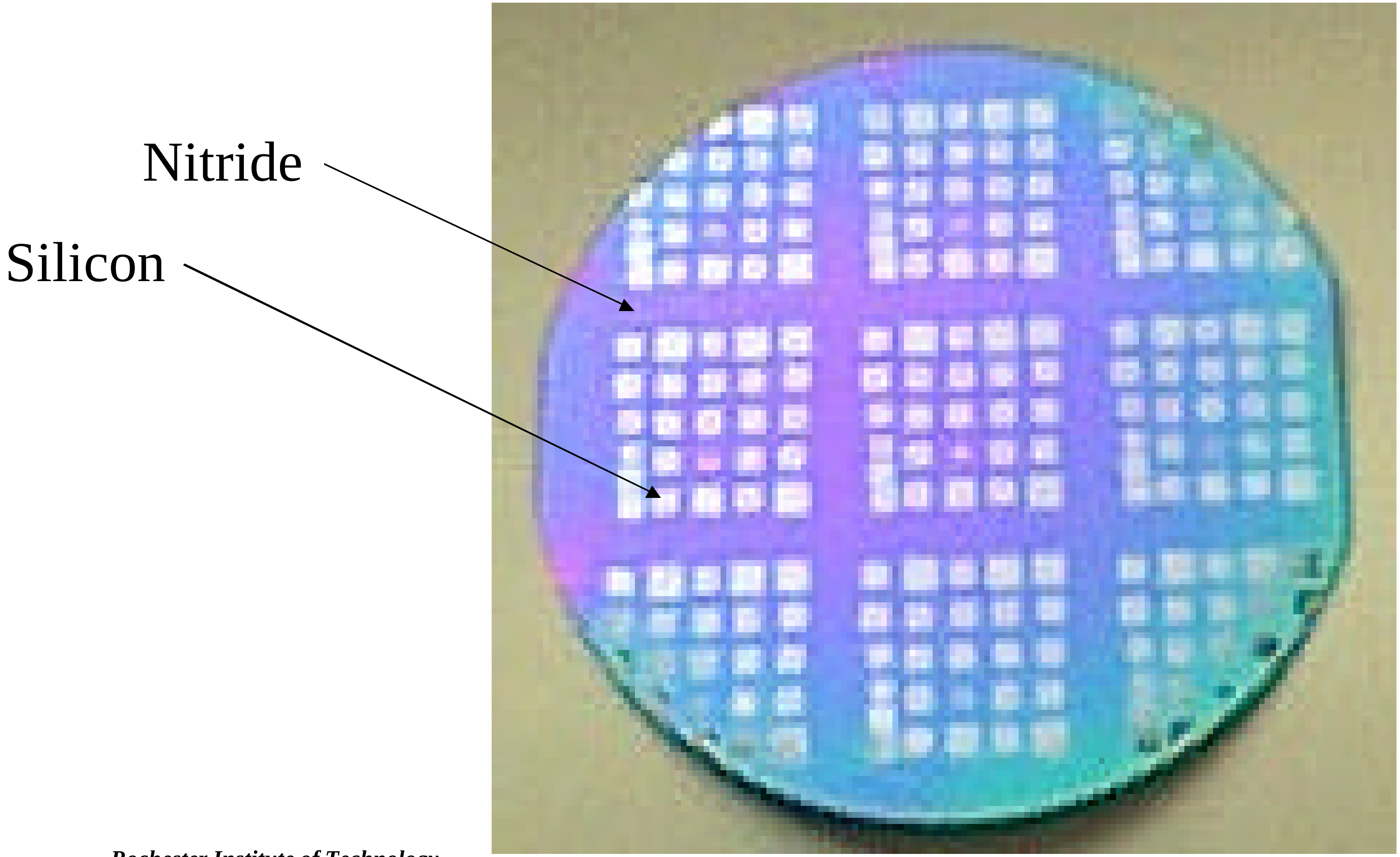
O_2 + Energy = 2 O

O is reactive and will combine with plastics, wood, carbon, photoresist, etc.

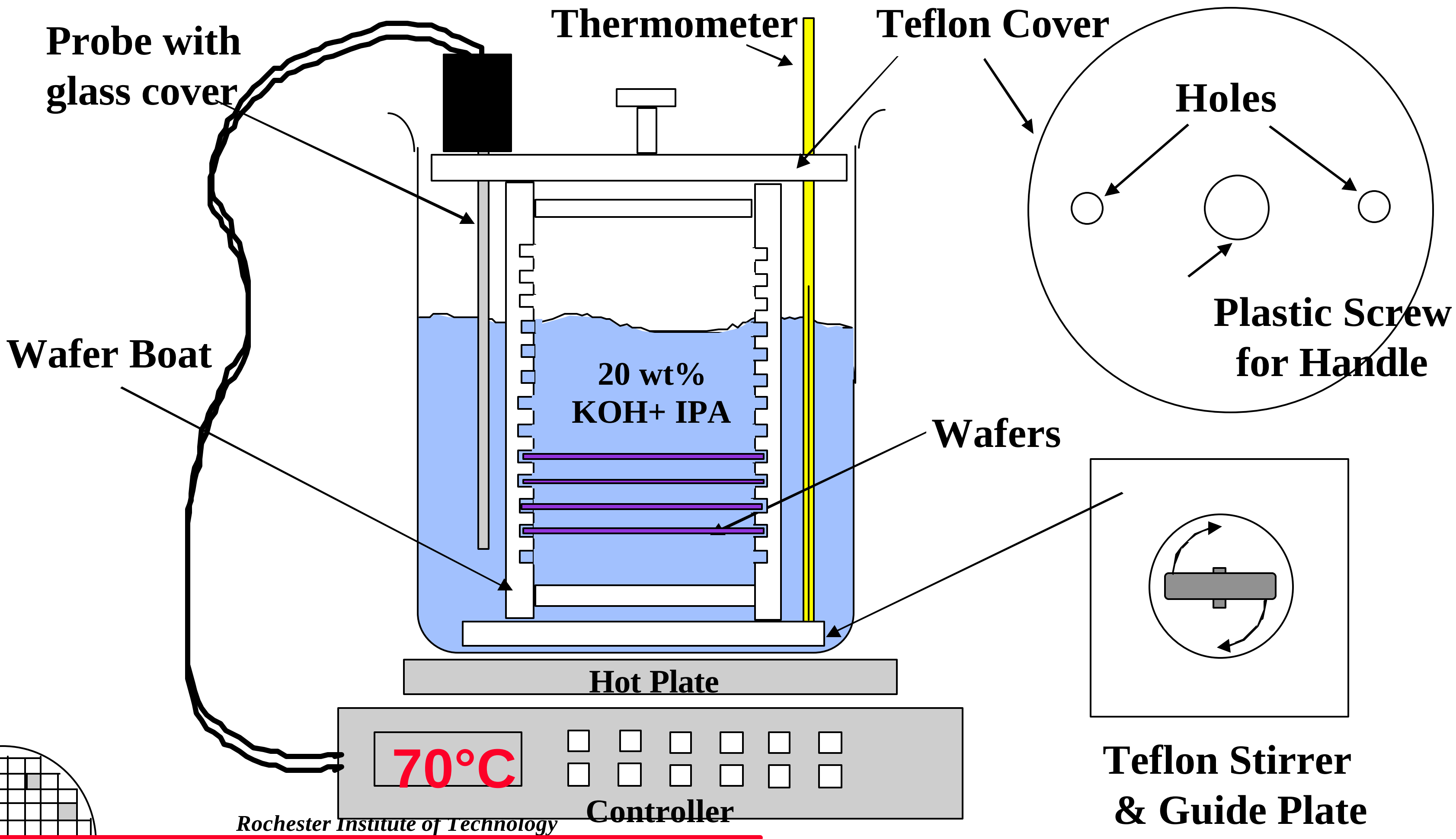
RF Power = 500 watts
Heat Lamp = 500 watts for 10 sec.
O_2 Flow = 4500 sccm
Pressure = 4000 mTorr
Time ~ 2 min./wafer

Asher

PICTURE OF WAFER AFTER RESIST STRIP

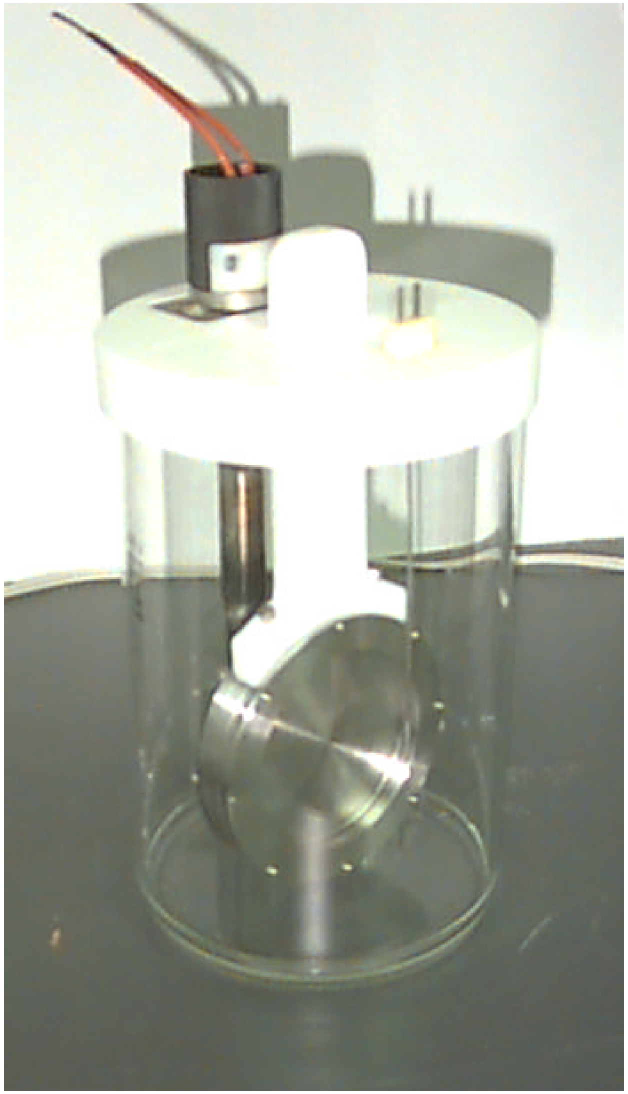


ETCH WAFERS IN KOH



SINGLE SIDED KOH ETCH APPARATUS

Dual 4 inch wafer holder with "O" ring seal to protect outer ½ " edge of the wafer. Integral heater and temperature probe for feedback control system. Stainless steel metal parts do not etch in KOH.

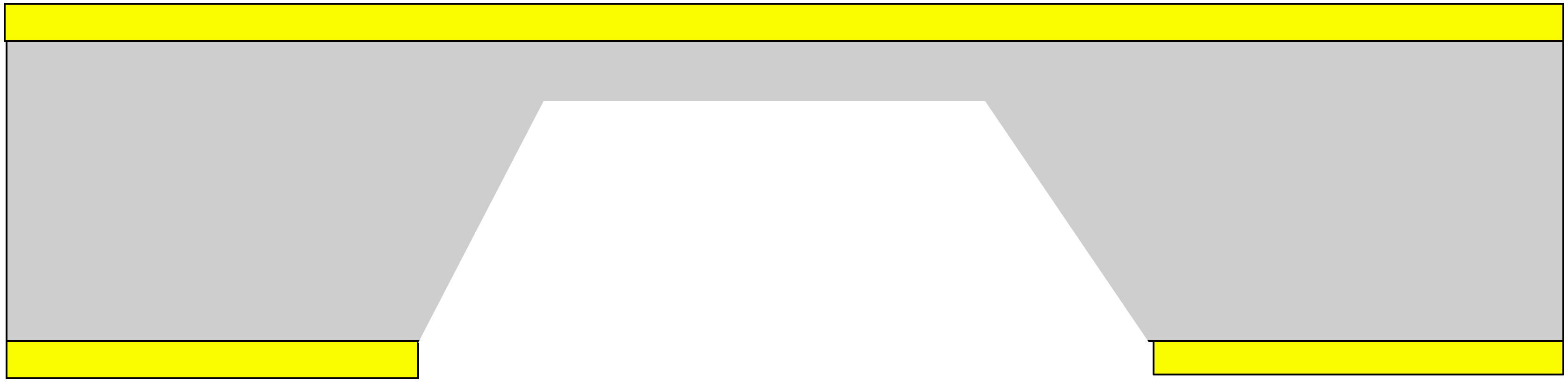


SINGLE SIDED KOH ETCH APPARATUS

Mounting the wafers in the etch apparatus.

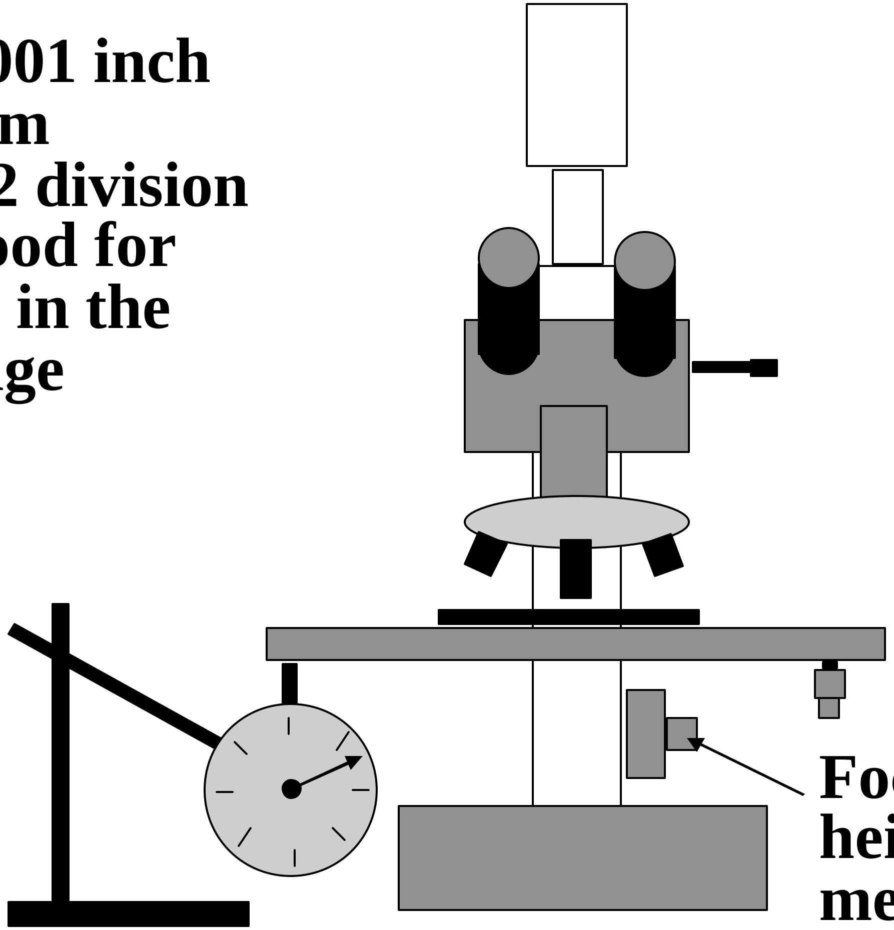
AFTER KOH ETCH

Etch for 8 hours and measure the etch depth. Calculate an etch rate. Calculate the remaining etch time to leave a 20 µm diaphragm. (Starting wafers 500 µm thick) Etch remaining time. Rinse in DI water. Spin dry.



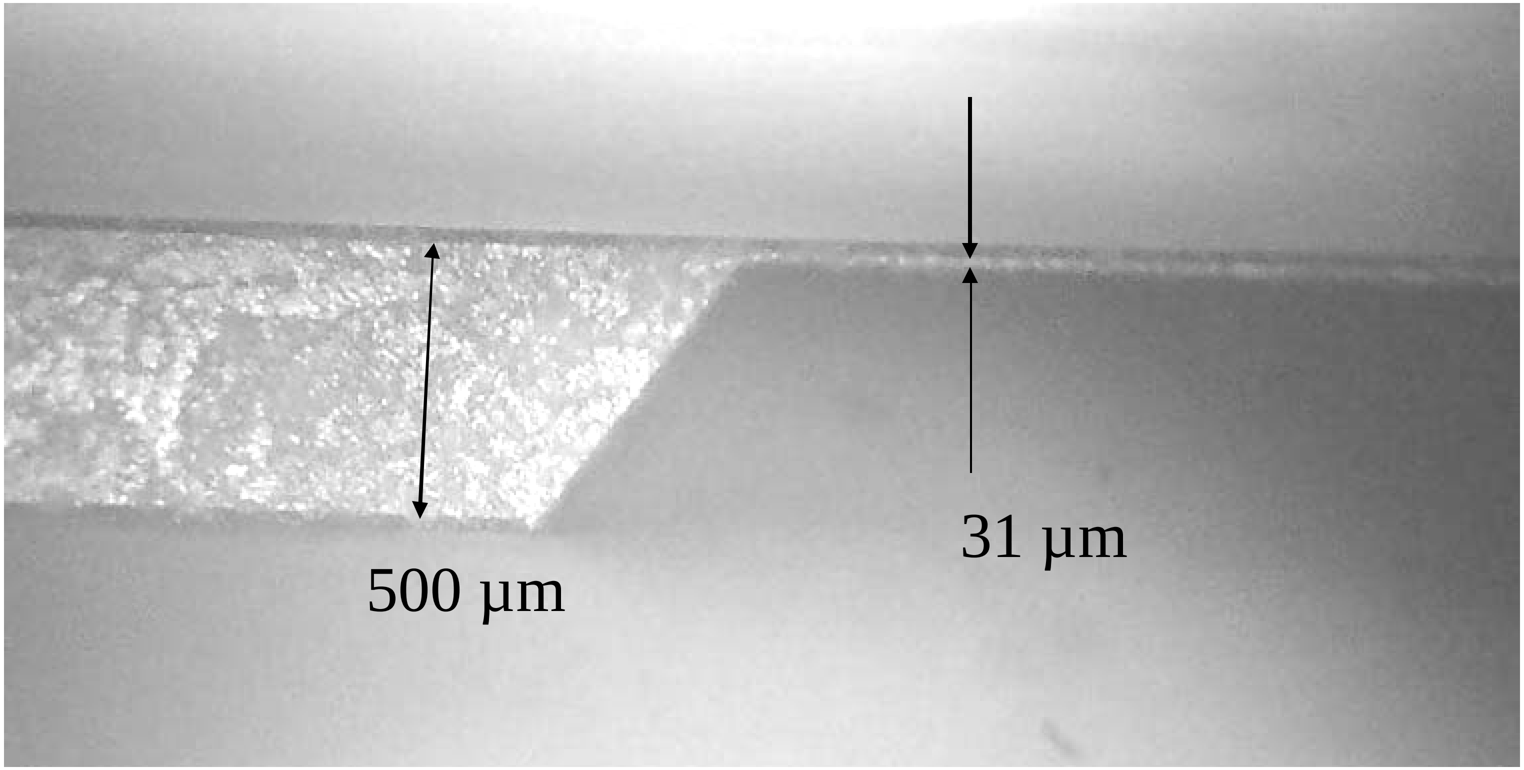
HEIGHT MEASUREMENT USING OPTICAL MICROSCOPE

Dial divisions are 0.001 inch units equal to 25.4 µm accuracy is about 1/2 division or 12.5 µm, this is good for measuring thickness in the 100's of microns range



Focus and height measurement each division is 1 µm

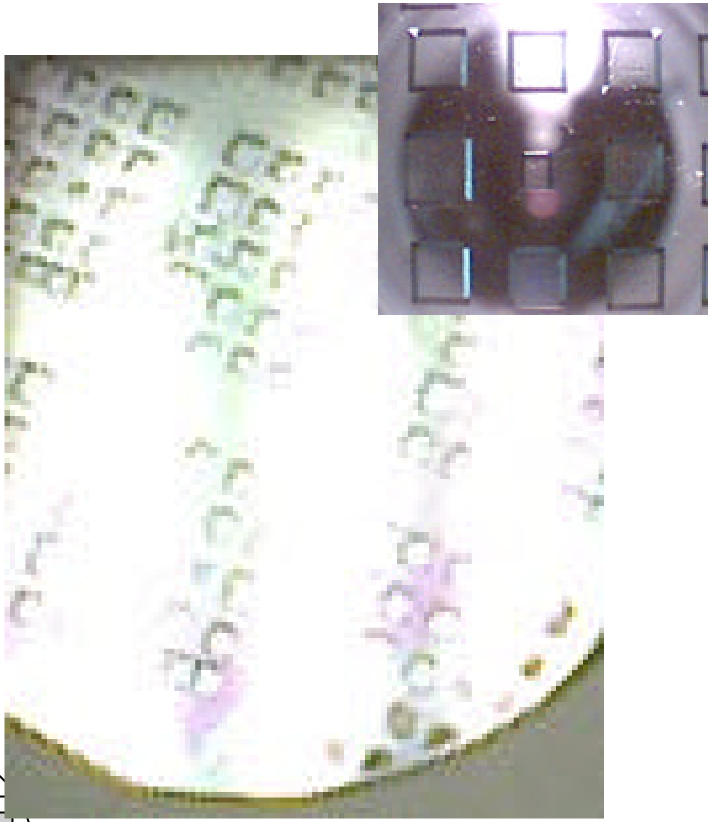
HEIGHT MEASUREMENT USING OPTICAL MICROSCOPE

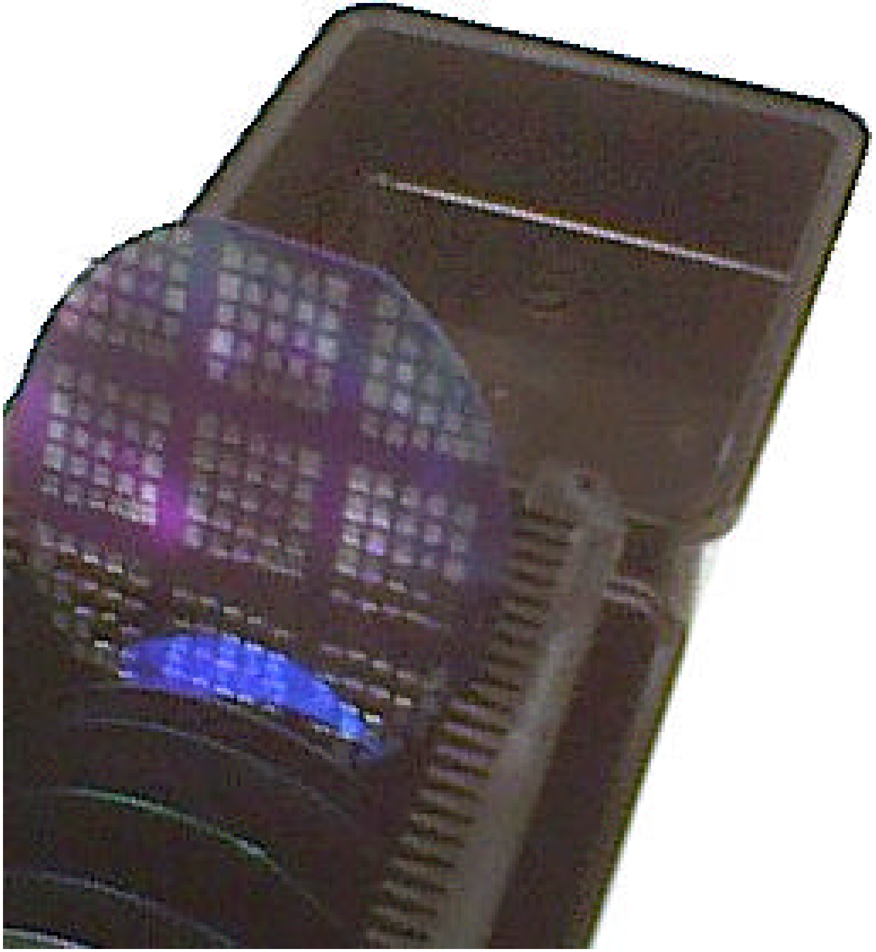


20% KOH Etch, @ 72 C, 10 Hrs.

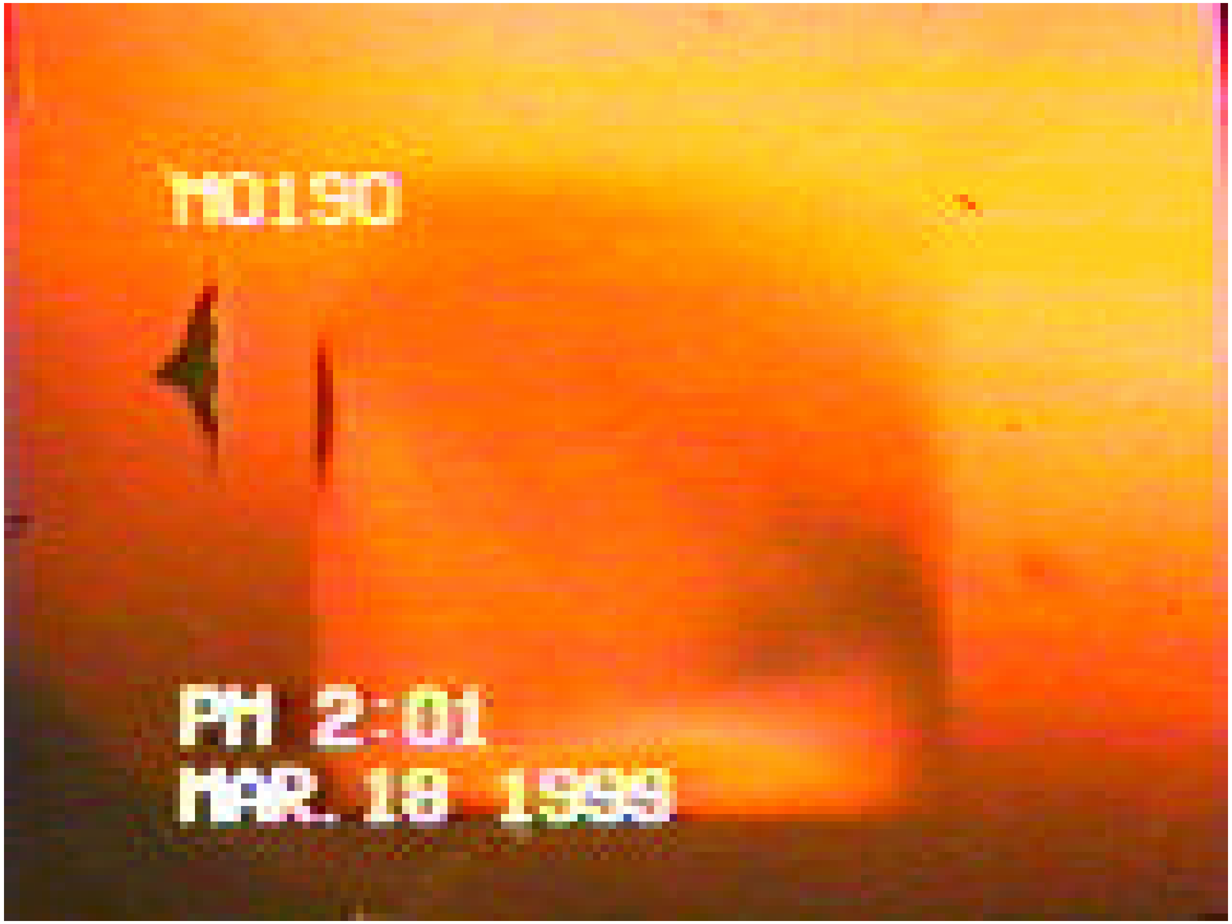
PICTURES OF WAFER AFTER KOH ETCH

50 µm in 57 min ~.877 µm/min



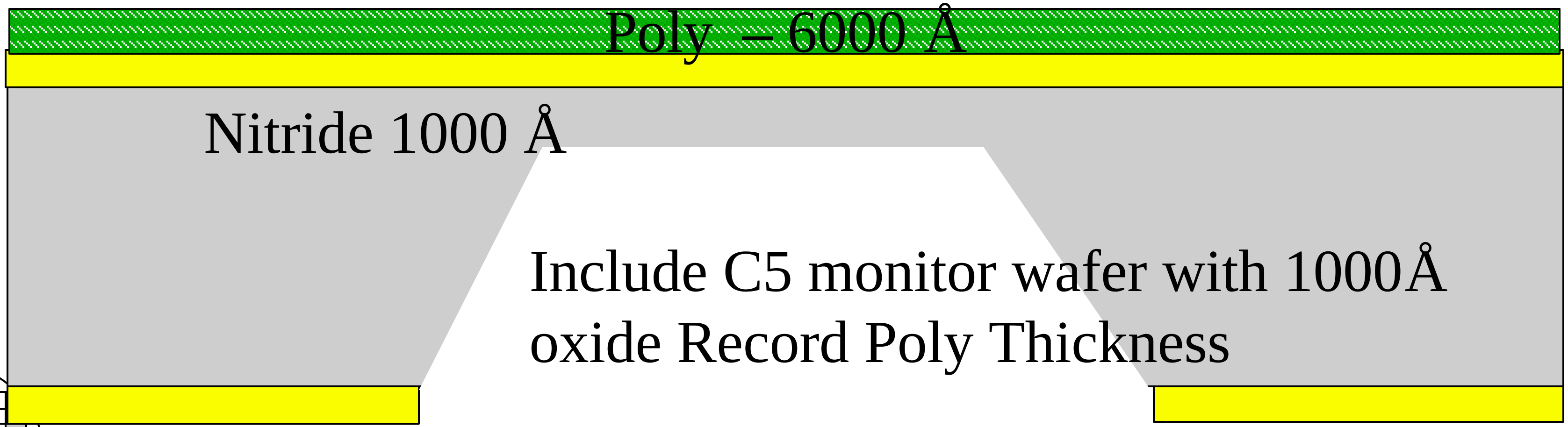


VACUUM WAND CAUSES DIAPHRAGM TO DEFLECT



DEPOSIT POLYSILICON

4” LPCVD Tool (or 6” Tool)
5000 Å Poly Silicon
Temp = 610 °C
Pressure = 330 mTorr
Silane Flow 45%
Time = 60 min.
Include Monitor Wafer with
1000 Å Oxide

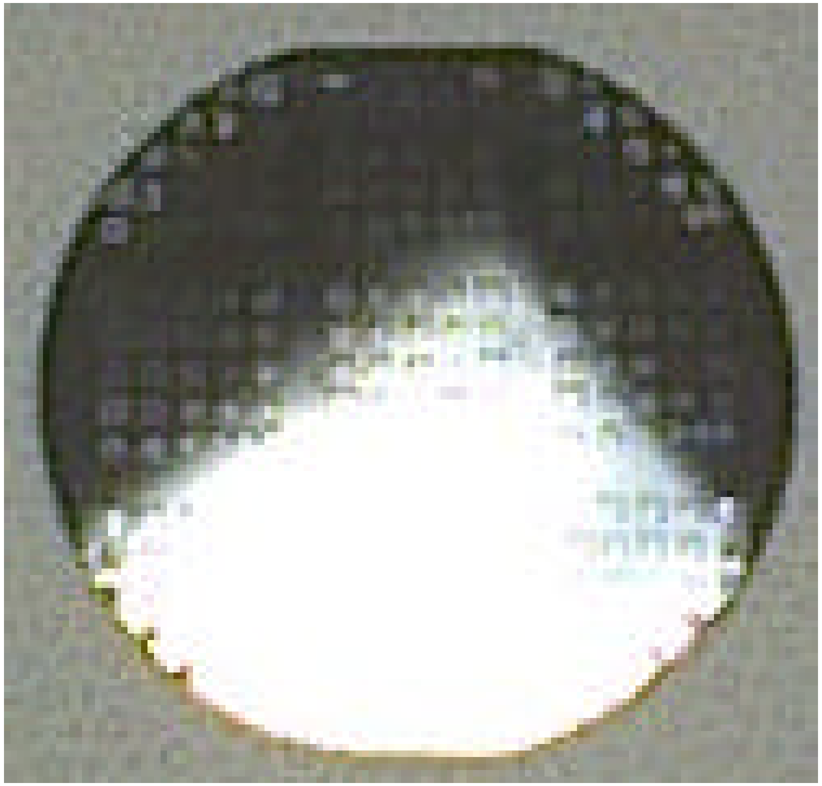


Include C5 monitor wafer with 1000Å oxide Record Poly Thickness

PICTURES OF WAFER AFTER POLY DEP

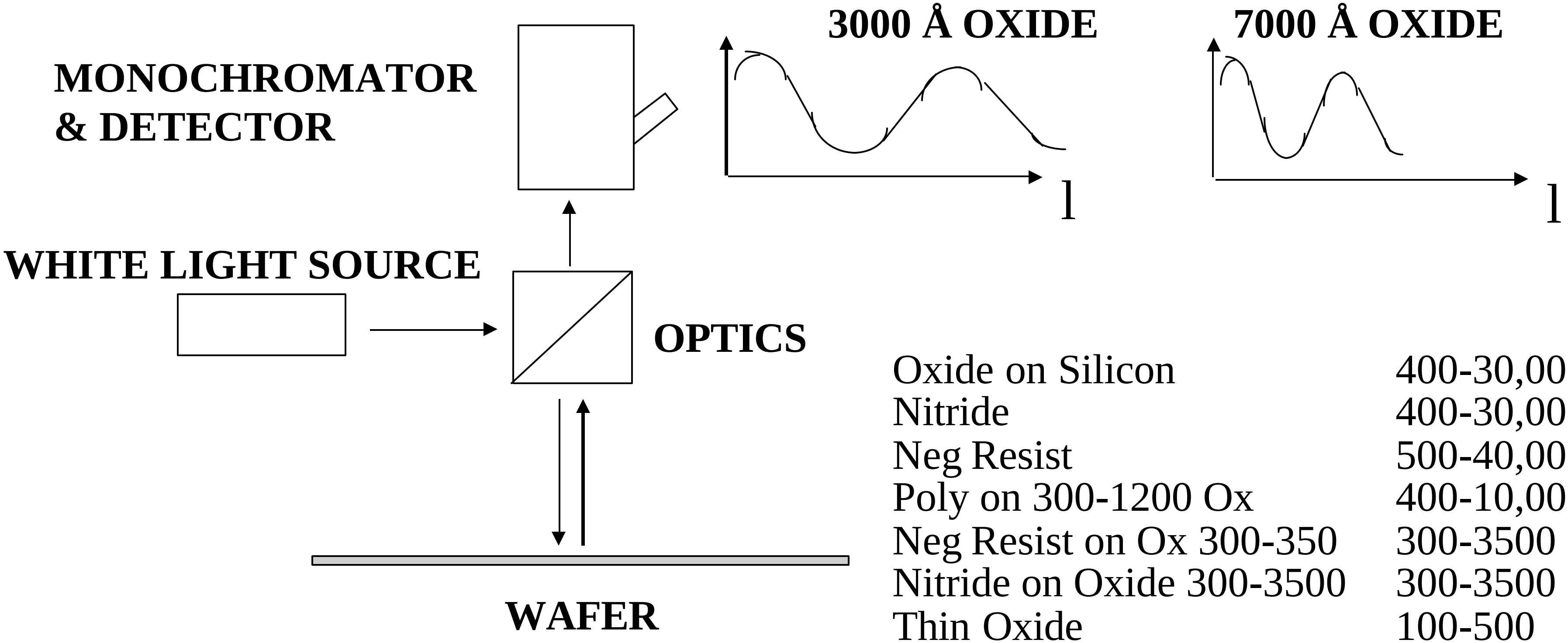
Both sides look shinny silver

Measure thickness on C5



REFLECTANCE SPECTROMETER (NANOSPEC - THICKNESS MEASUREMENT)

INCIDENT WHITE LIGHT, THE INTENSITY OF THE REFLECTED LIGHT IS MEASURED VS WAVELENGTH



3000 Å OXIDE

7000 Å OXIDE

MONOCHROMATOR & DETECTOR

WHITE LIGHT SOURCE

OPTICS

WAFER

Oxide on Silicon	400-30,000 Å
Nitride	400-30,000
Neg Resist	500-40,000
Poly on 300-1200 Ox	400-10,000
Neg Resist on Ox 300-350	300-3500
Nitride on Oxide 300-3500	300-3500
Thin Oxide	100-500
Thin Nitride	100-500
Polyimide	500-10,000
Positive Resist	500-40,000
Pos Resist on Ox 500-15,000	4,000-30,000

N+ POLY DOPING OBJECTIVE

The objective is to dope the polysilicon n+ so it will be conductive. We will use a spin-on glass dopant source and high temperature diffusion process to allow dopant atoms to diffuse from the spin-on glass into the polysilicon. The spin-on glass will be etched off and the sheet resistance will be measured using a four point probe technique. Measured sheet resistance should be less than 25 ohms/square.

Spinner

Spin-on glass
N-250

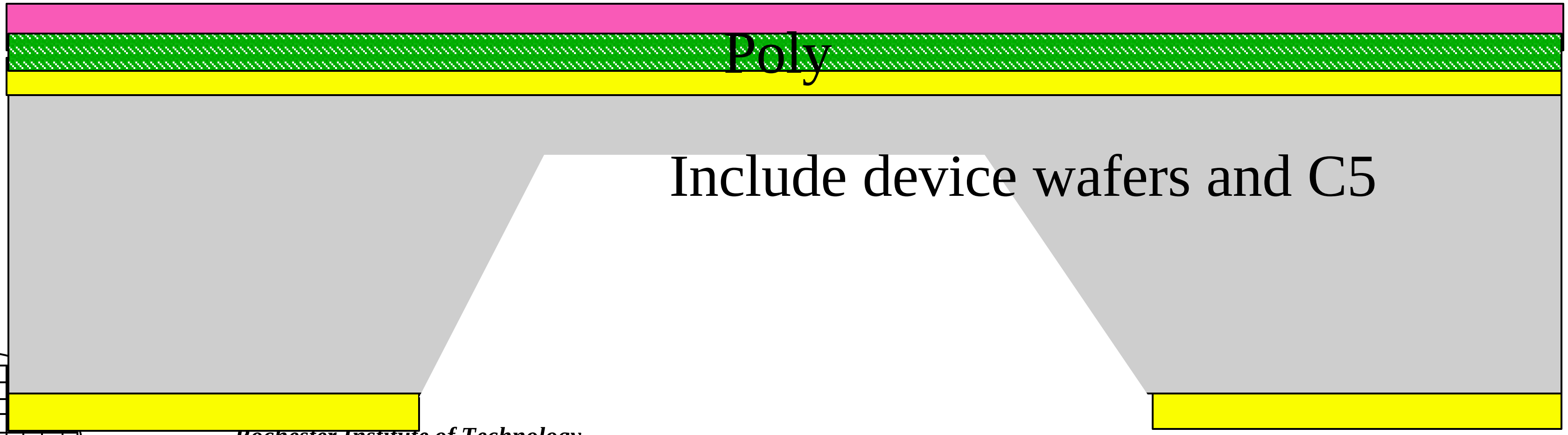
DOPE POLYSILICON

1) Spin coat with Emulsitone
N-250, 3000 rpm, 30 sec
Bake 200 C, 15 min, oven in photo1

2) Use Bruce Furnace Recipe 120
Tube 03 or Use Tube 12 and the
following manual sequence.

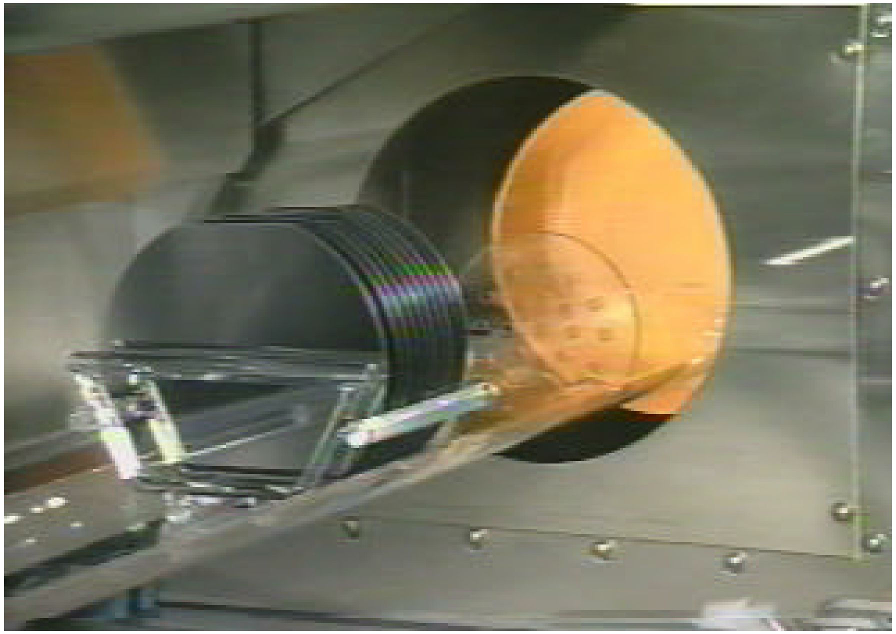
2.1) Push at 900 C in N2
Ramp to 1000 C in N2
Start soak at 990 C
Time = 15 min. in N2
Pull at 1000 C in N2

2.2) Etch Phosphorous Doped
Glass in BHF wet etch, 2 min.
Rinse and spin Dry



Include device wafers and C5

BRUCE FURNACE AND SRD TOOLS

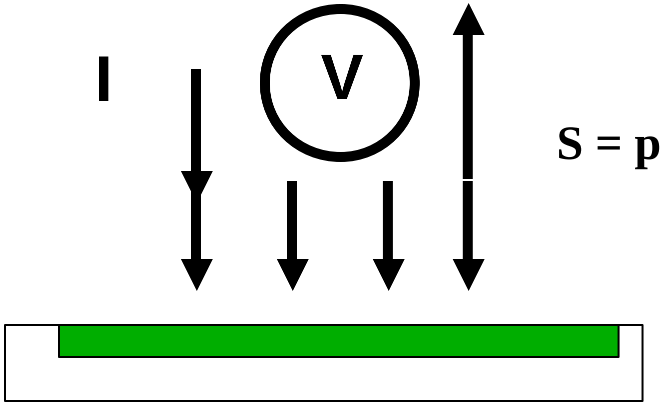


Bruce Furnace

Spin Rinse Dry (SRD) Tool

ETCH DOPED GLASS AND 4 PT PROBE

1) Etched Doped Glass in Buffered HF acid 3 min.
2) Rinse in DI water bath 5 min.
3) Spin Dry
4) Measure and Record Sheet Resistance



S = probe spacing

xj = Diffusion Layer Thickness

Rhos = p/ln2 x V / I = 4.532 V/I ohms/sq ,if S>xj

V=0.63 volts
I=0.047 amps
Rhos = 61 ohms/sq

Rochester Institute of Technology
Microelectronic Engineering

PHOTO 2

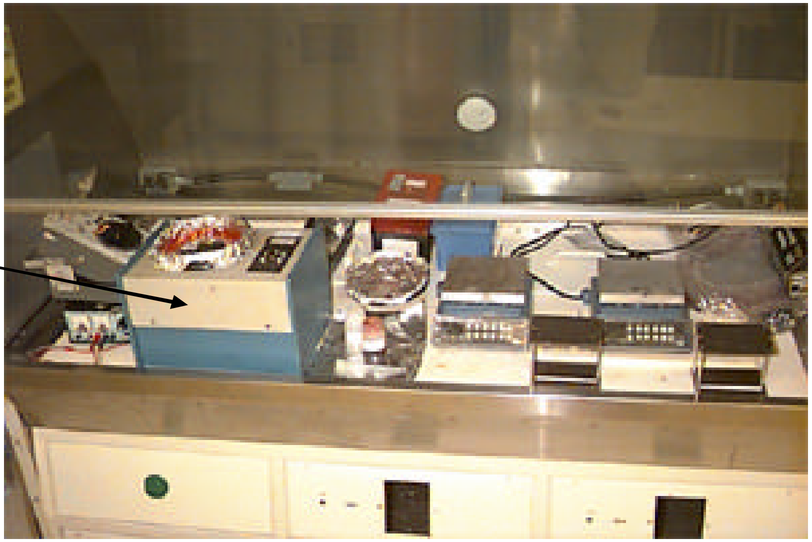
The objective is to protect the poly using photoresist on the front of the wafer prior to etching the pattern for the resistors in the poly. This photostep requires alignment of the resistor pattern on the front of the wafer to the holes on the back of the wafer. Because the wafer has holes on the backside it is better not to use the robotic automatic wafer track system. Do all the steps by hand and reduce the spin speeds to 3000 rpm. The resist will be thicker so increase the exposure dose by 50% to 75 mj/cm^2 (15 seconds)

HAND SPINNER COAT

Spin coat by hand at 3000 rpm

HMDS (few drops)

Shipley 812 Resist →



Spinner

SOFT BAKE

90 °C
60 sec.

EXPOSURE TOOLS

The aligner is used in the test mode to provide UV light but no alignment or automatic wafer handling is used. 1st and 2nd masks are taped together the wafer is inserted between the masks and the mask is aligned to the back side wafer pattern.

The resist needs an exposure dose (E) of about 75 mj/cm^2. The intensity (I) is measured and found to be ~5 mw/cm2 so using the equation E=It we find exposure time of 15 sec.

HAND DEVELOP

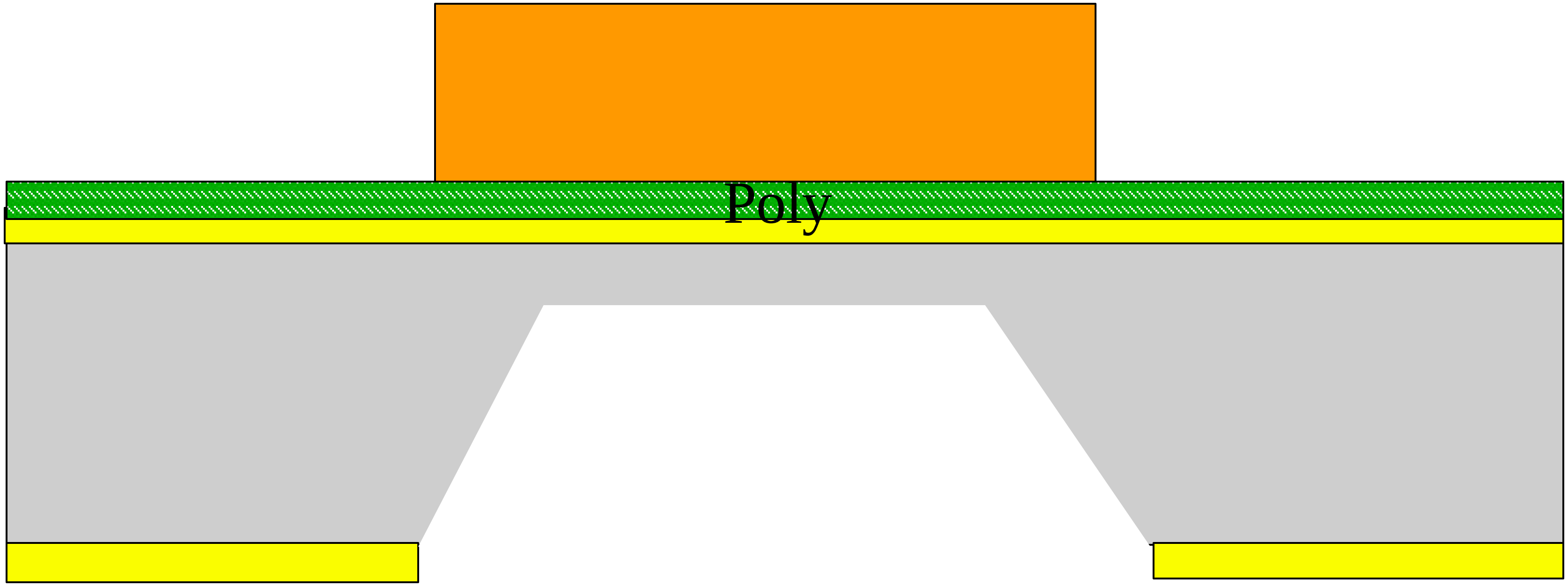
DEVELOP

DI Wet
CD-26 Developer
50 sec., Puddle
Rinse, Blow Dry

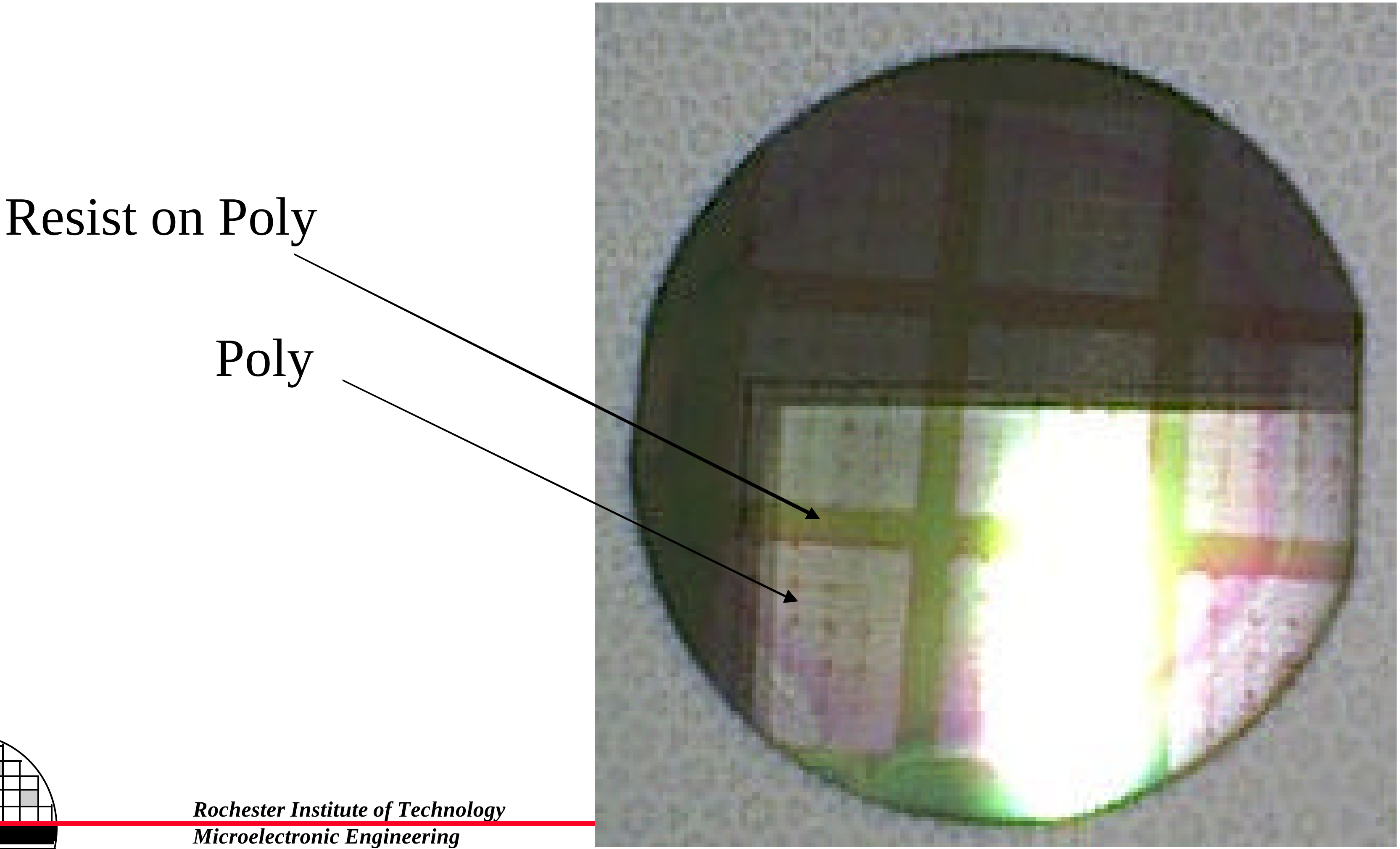
HARD BAKE

125 °C, 60 sec.

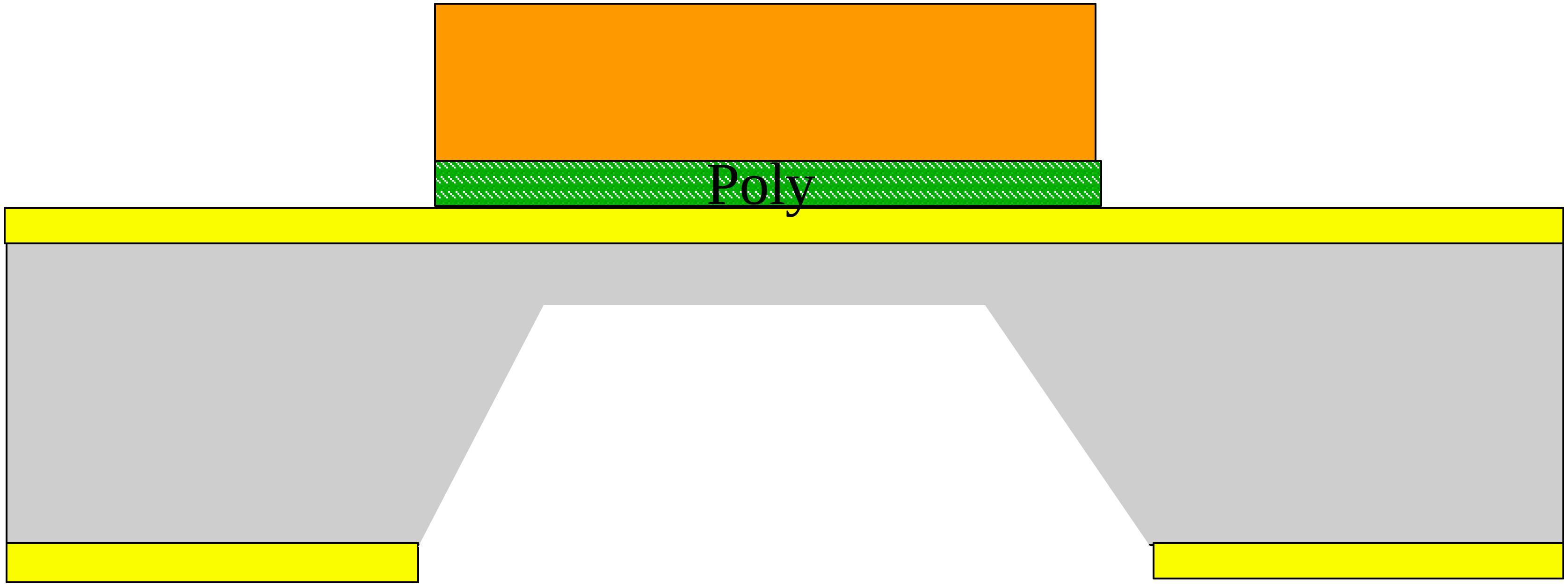
AFTER COAT, EXPOSE AND DEVELOP



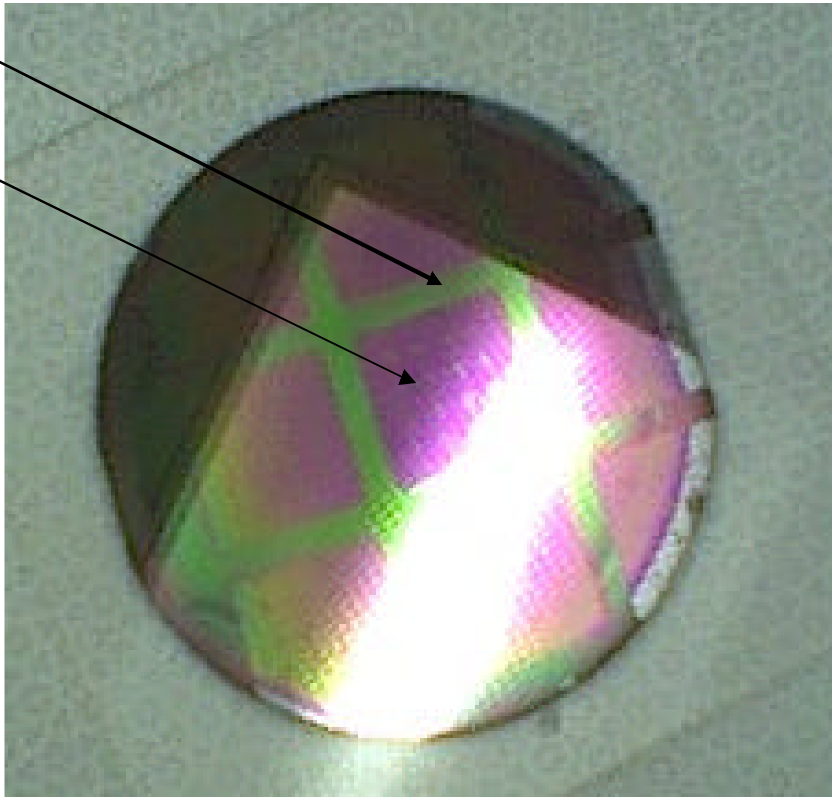
PICTURES OF WAFER AFTER PHOTO 2



POLY ETCH



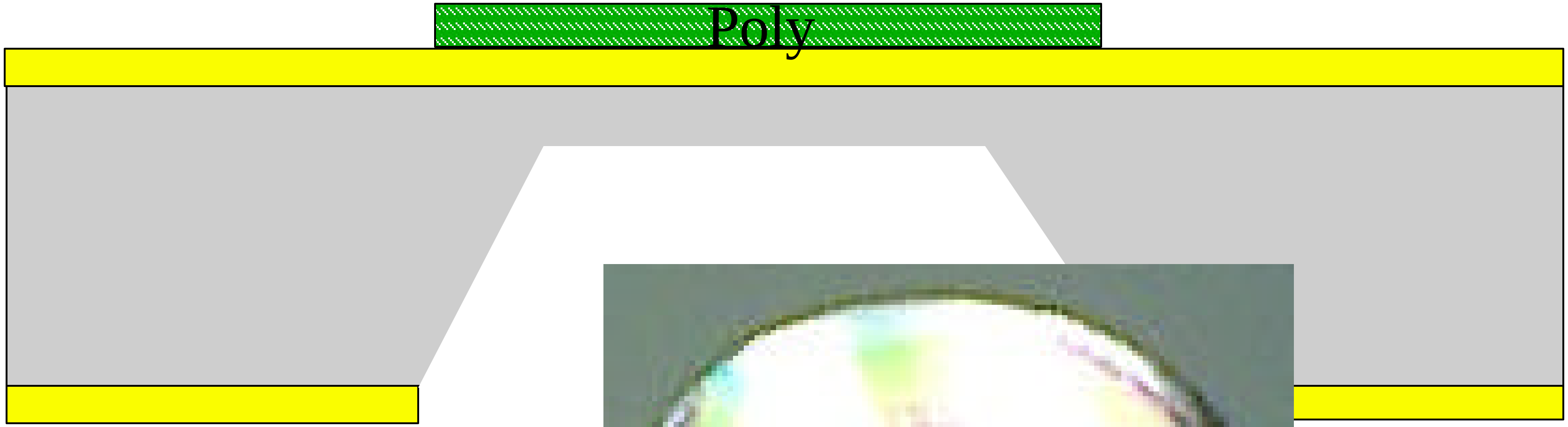
PICTURES OF WAFER AFTER POLY ETCH



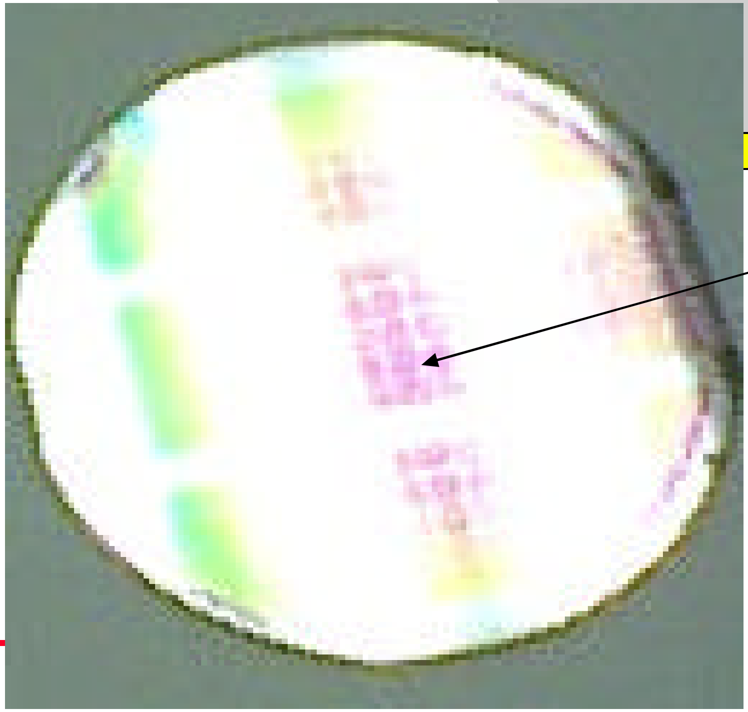
Resist on Poly

Nitride

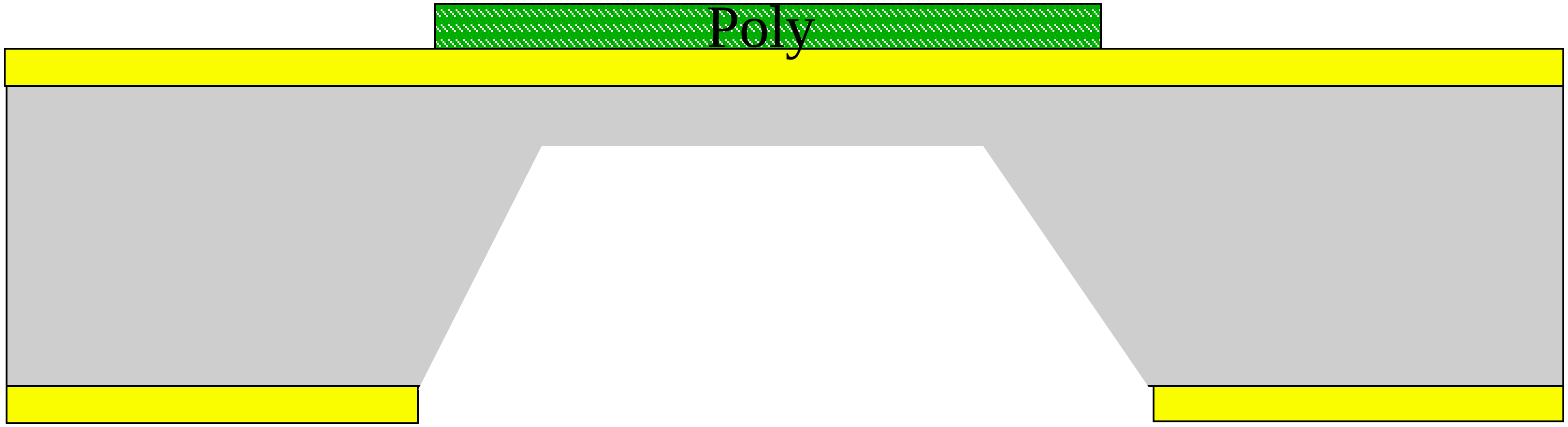
STRIP PHOTORESIST



Strip Resist in Acetone
Rinse in DI Water
Blow Dry



RCA CLEAN



SPUTTER ALUMINUM

20 min Bake at 300 C
during pump down
Base Pressure 2E-5
2000 watts
5 mTorr Argon
5 min presputter
30 min sputter
Al/1%Si
Thickness ~0.75 µM

CVC 601 Sputter Tool

AFTER ALUMINUM DEPOSITION

Al Thickness ~0.75 µM

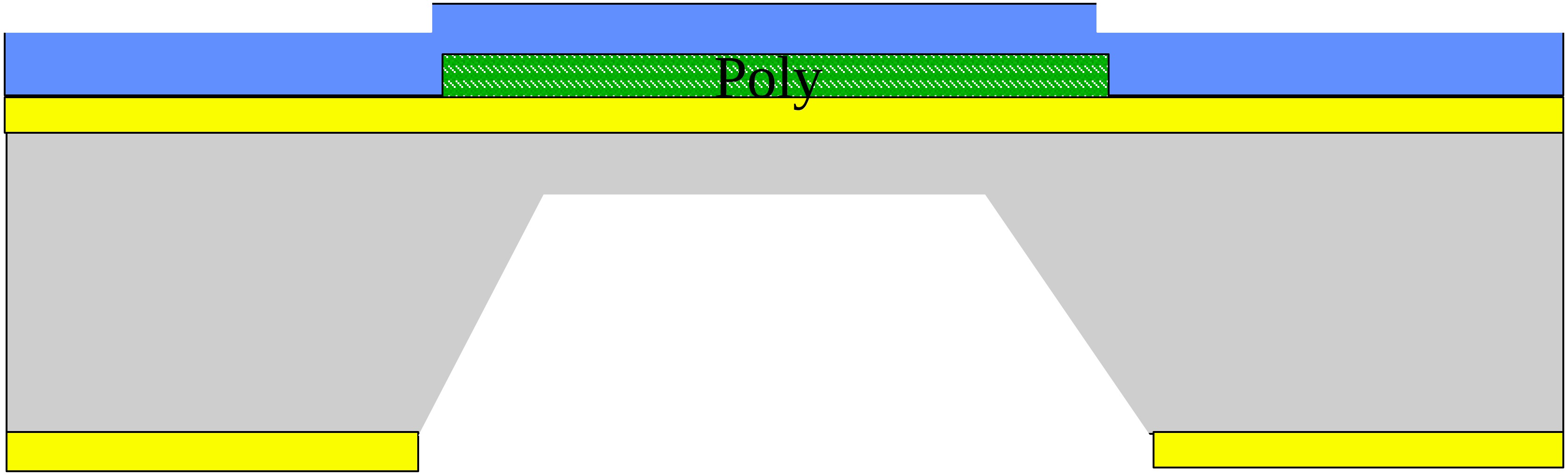


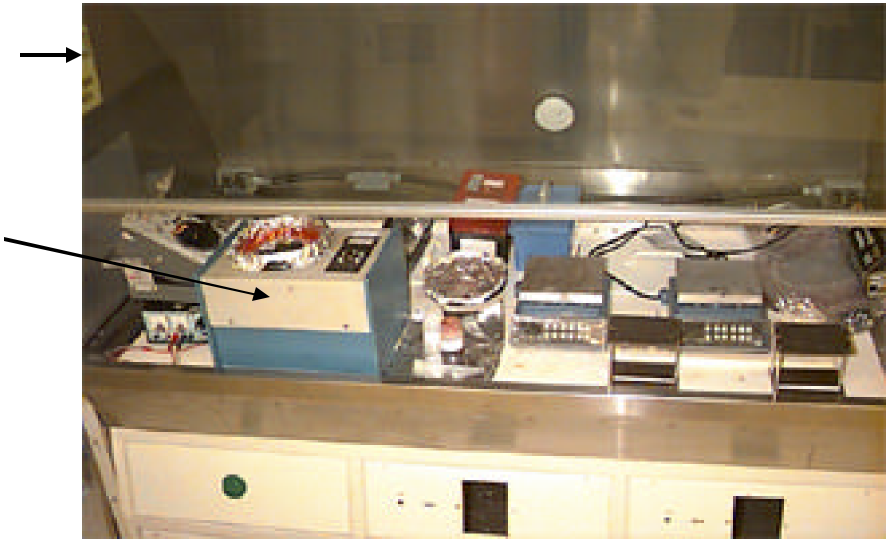
PHOTO 3

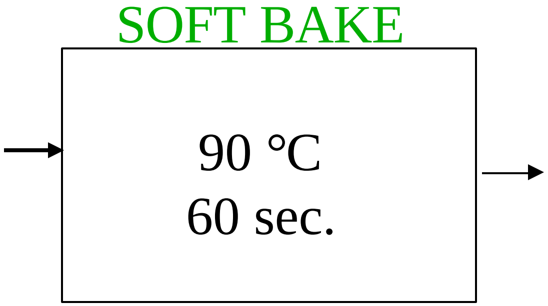
The objective is to protect the aluminum using photoresist on the front of the wafer prior to etching to create the pattern in the aluminum. This photostep requires alignment of the metal pattern mask to the resistor pattern on the front of the wafer.

Because the wafer has holes on the backside it is better not to use the robotic automatic wafer track system. Do all the steps by hand and reduce the spin speeds to 3000 rpm. The resist will be thicker so increase the exposure dose by 50% to 75 mj/cm^2 (15 seconds)

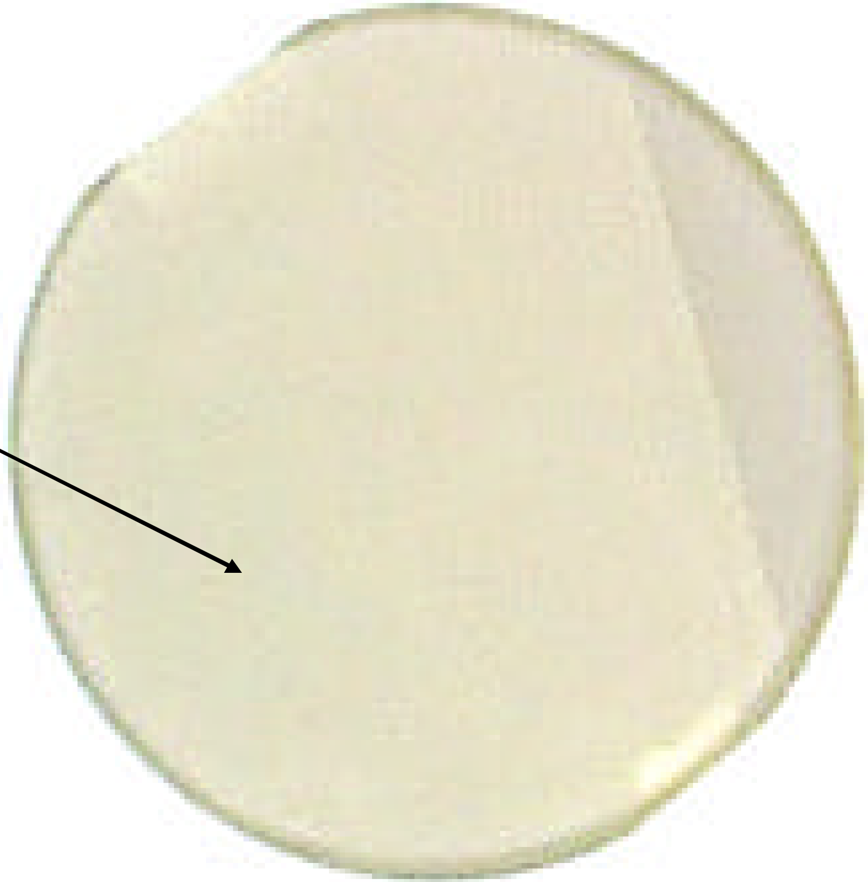
HAND SPINNER COAT

Spin coat by hand at 3000 rpm
HMDS (few drops)
Shipley 812 Resist





PICTURES OF WAFER AFTER PHOTO 3



Resist on Al

EXPOSURE TOOLS

The aligner is used in the test mode to provide UV light. No automatic wafer handling is used. Alignment is done using capability of the tool.

The resist needs an exposure dose (E) of about 75 mj/cm^2. The intensity (I) is measured and found to be ~5 mw/cm2 so using the equation E=It we find exposure time of 15 sec.

HAND DEVELOP

DEVELOP

DI Wet
CD-26 Developer
50 sec., Puddle
Rinse, Blow Dry

Air Gun
Blow Dry

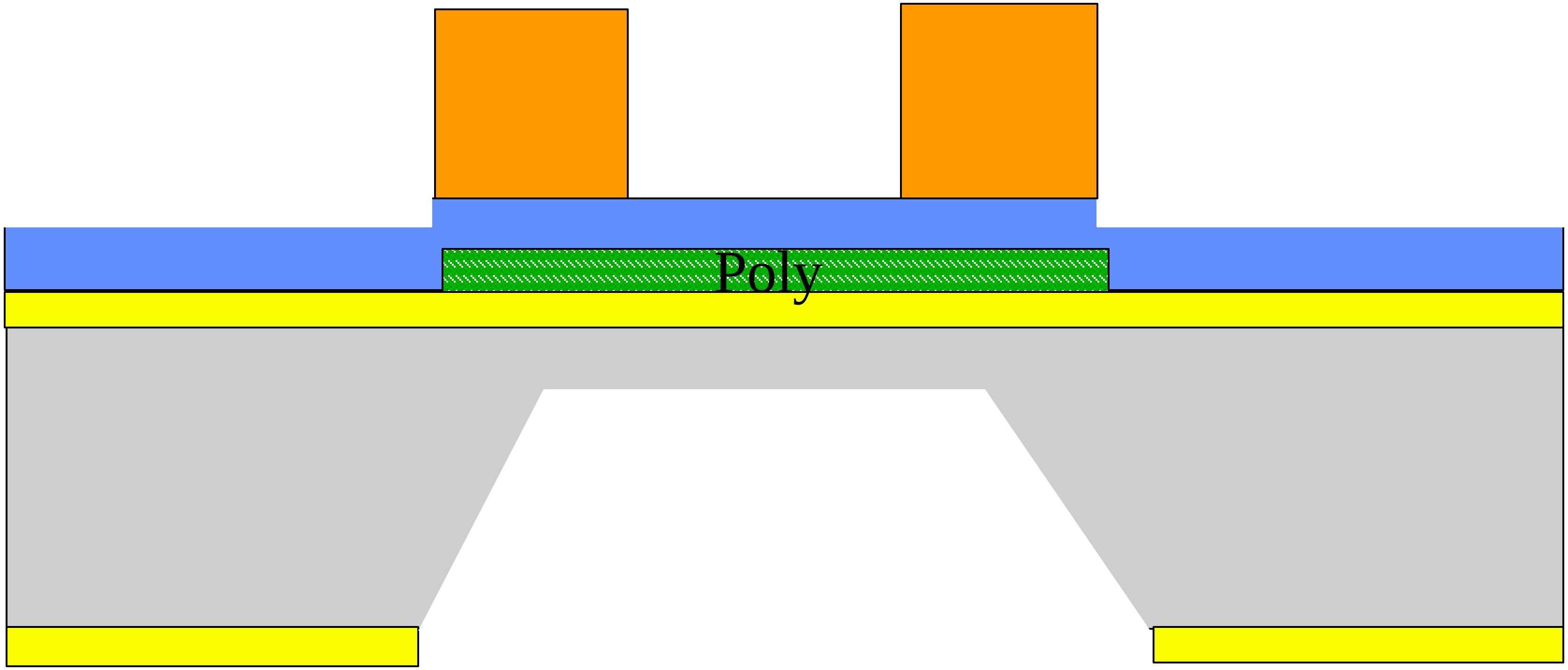
CD-26

DI water

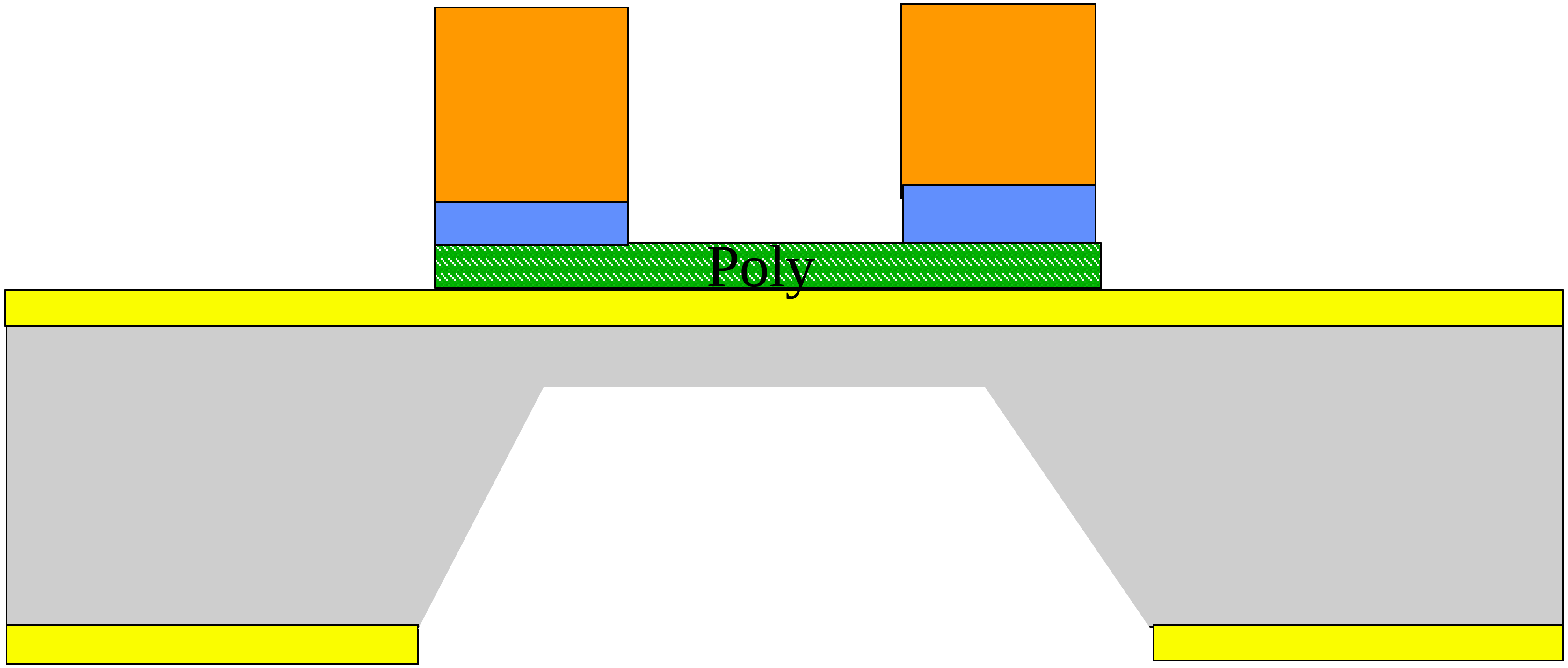
HARD BAKE

125 °C, 60 sec.

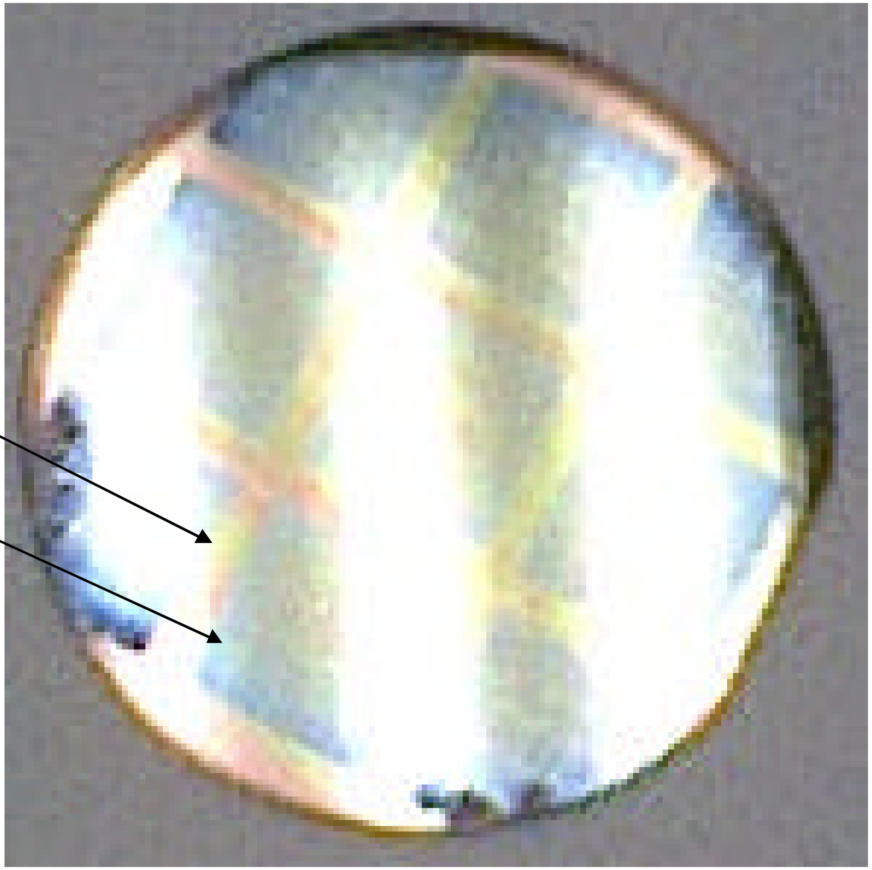
AFTER COAT, EXPOSE AND DEVELOP



ALUMINUM ETCH



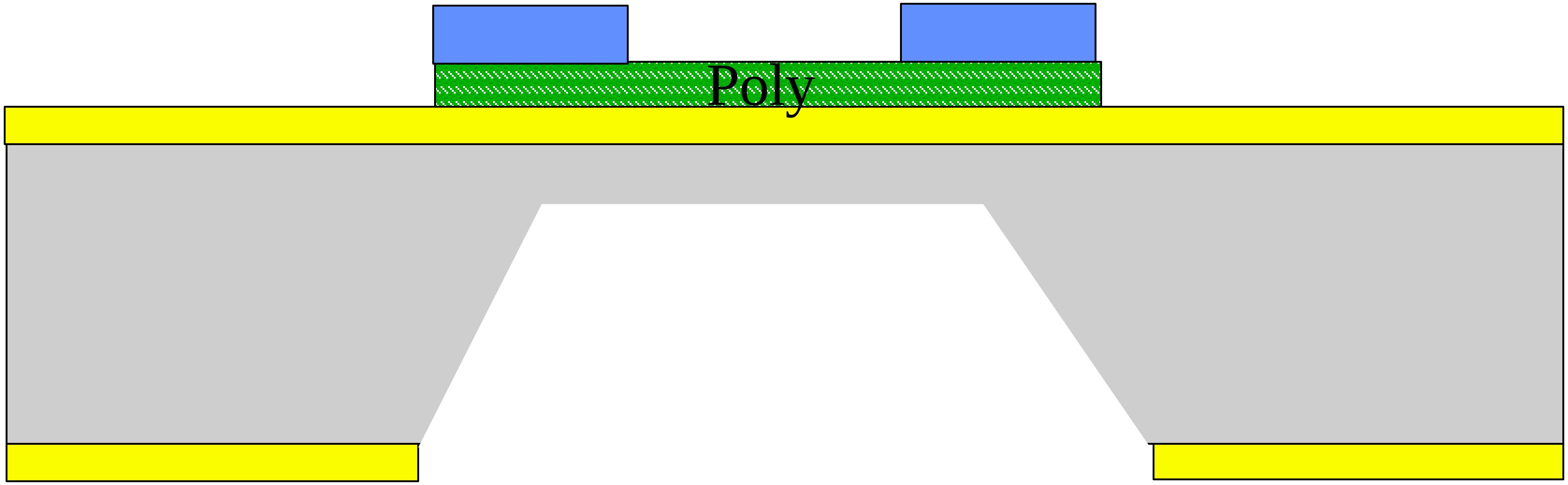
PICTURES OF WAFER AFTER AL ETCH



Resist on Al

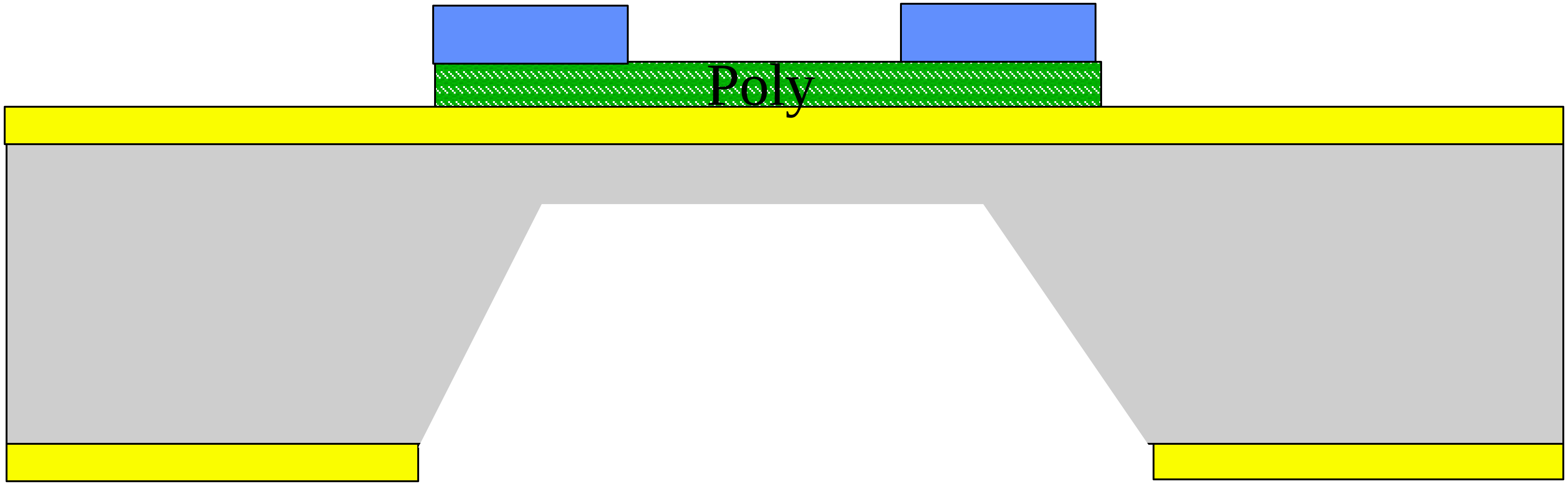
Al patterns
On Nitride

STRIP PHOTORESIST



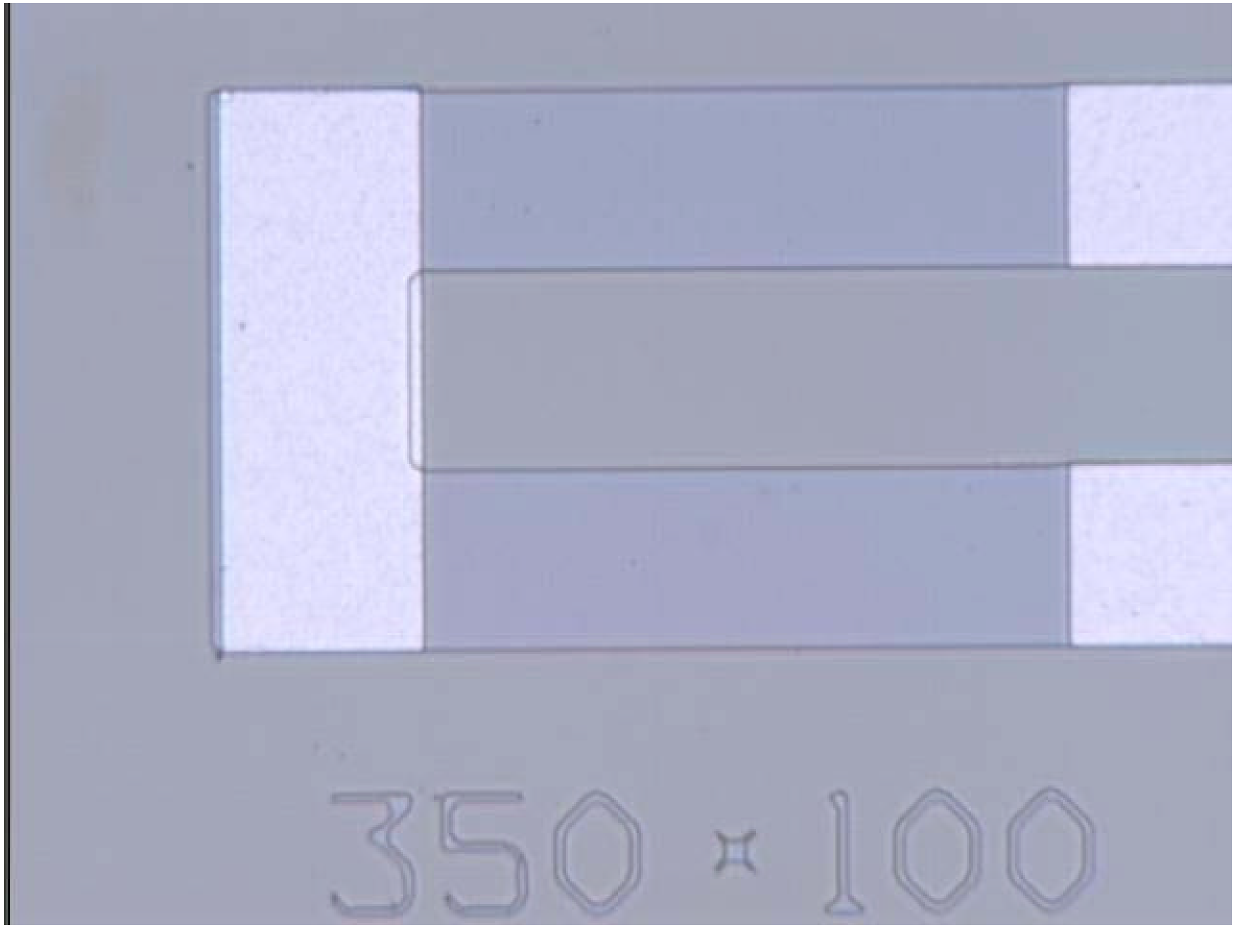
Strip Resist in Acetone
Rinse in DI Water
Blow Dry

SINTER

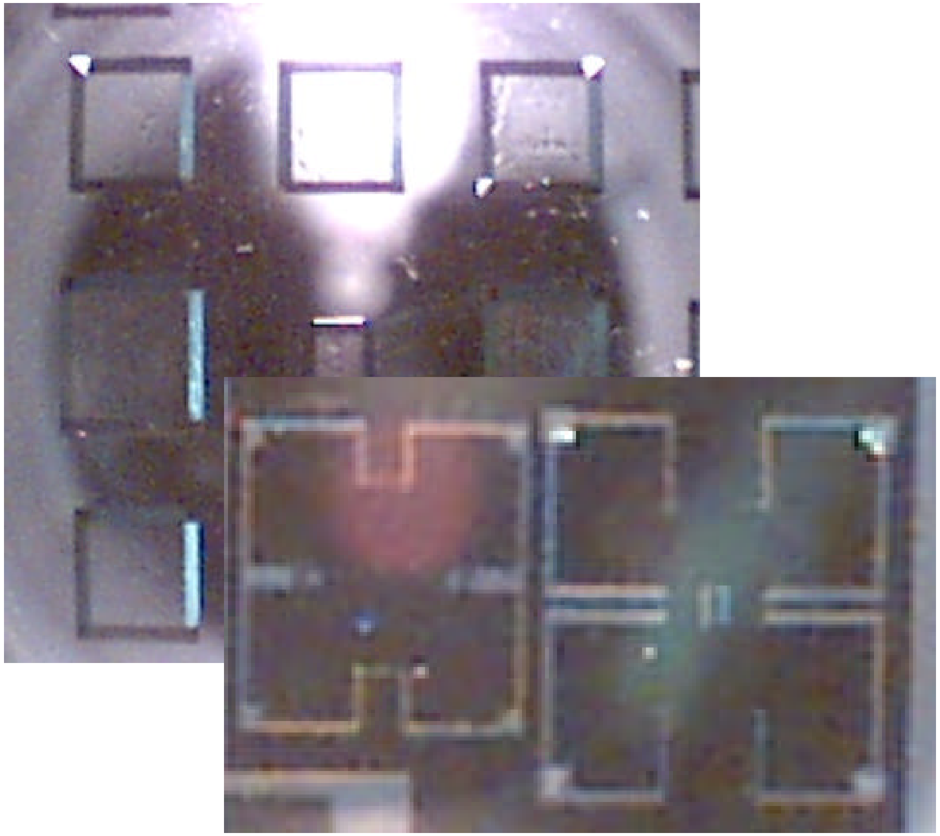


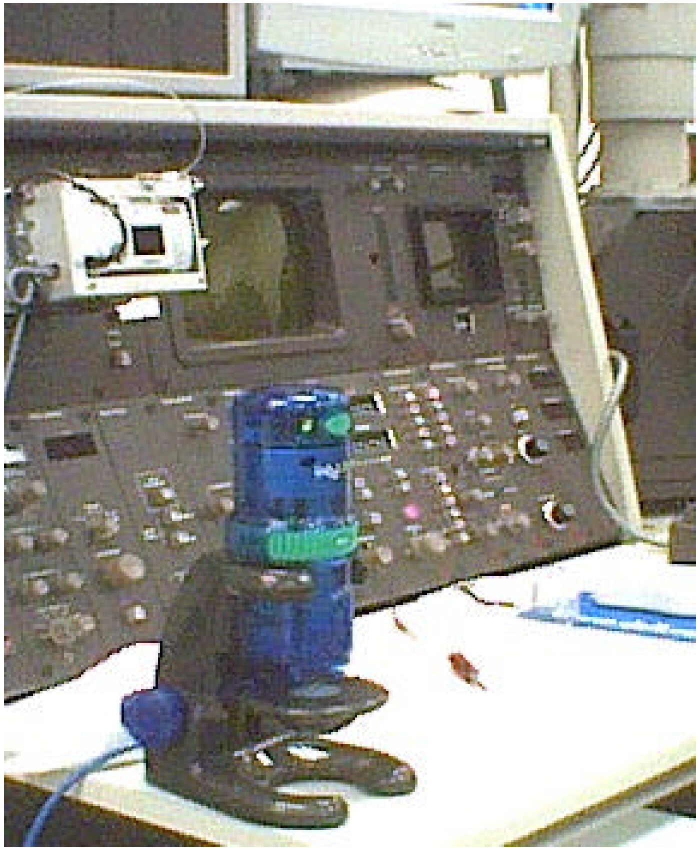
450 C
N2/H2
30 min.

PICTURES OF RESISTOR SENSOR

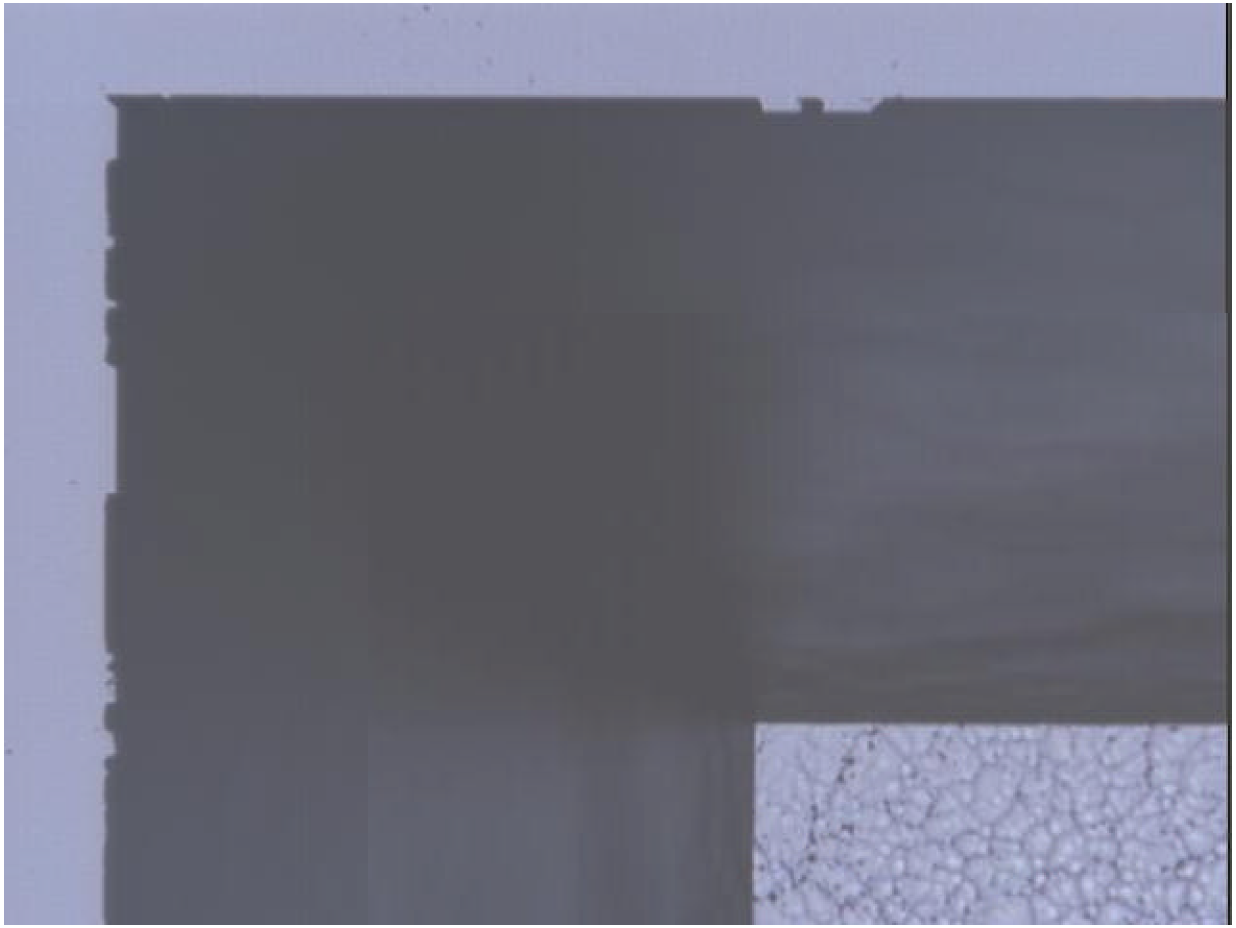


PICTURES

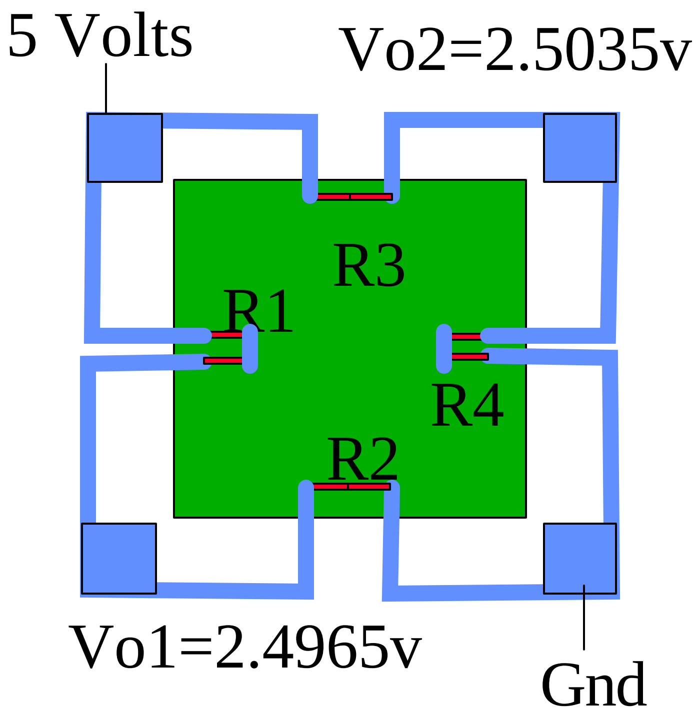


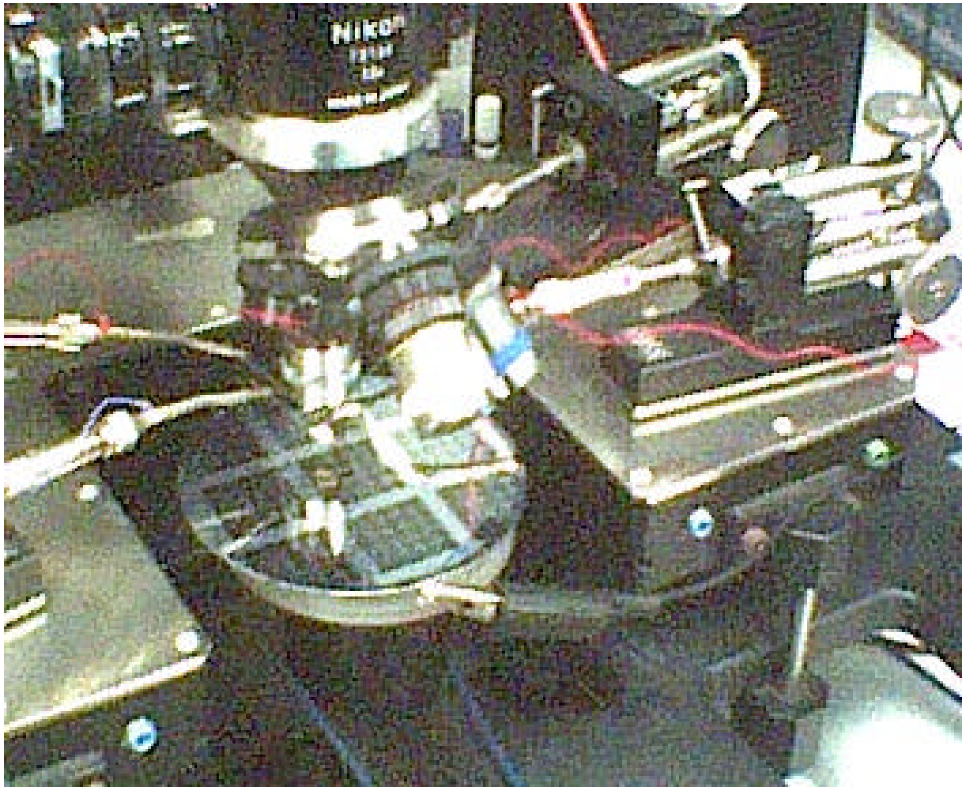


PICTURES OF DIAPHRAGM HOLE



PROBE STATION TEST SETUP

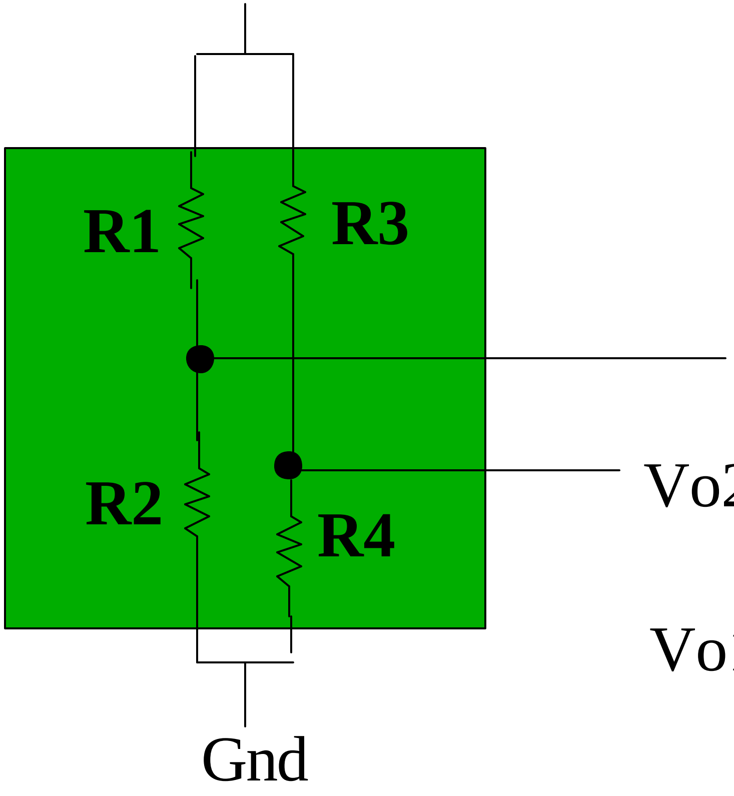




Apply and release chuck vacuum to observe change in output voltage

PROBE STATION TESTING

Vsupply = 5 Volts



Turn on Vacuum Chuck (~14.7 psi)

Vo1 Should be 2.5000 volts to ground

2.5075

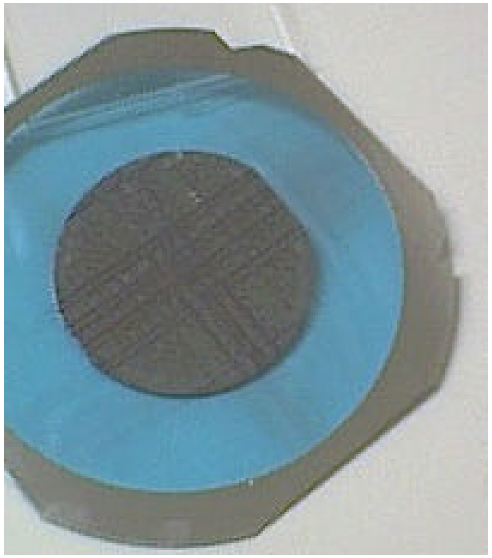
Vo2 Should be 2.5000 volts to ground

2.4925

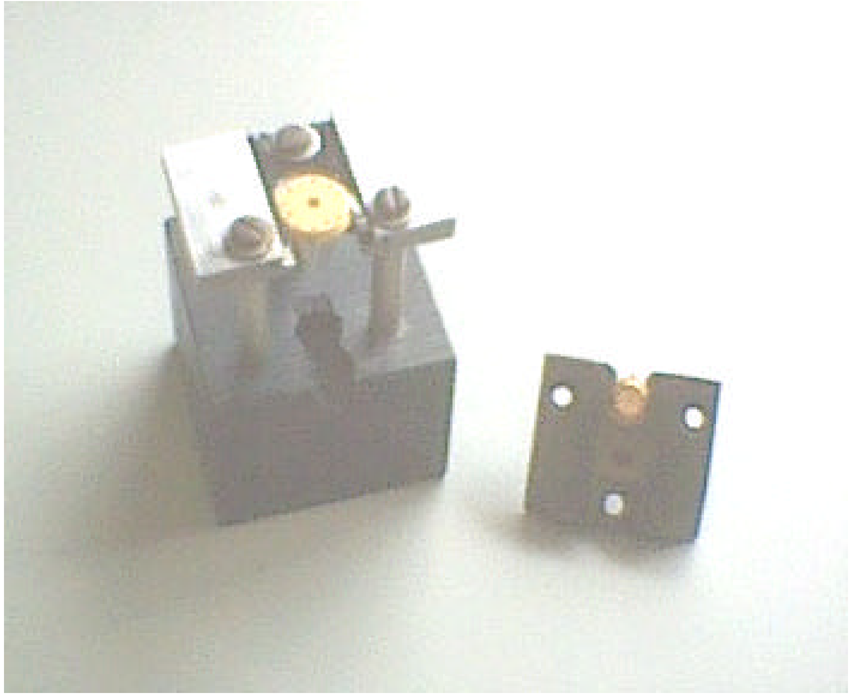
Vo1-Vo2 = 0.0000

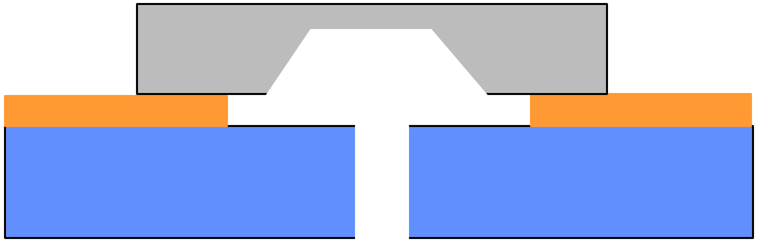
0.0150 or 15 mVolts

K&S WAFER SAW



MOUNT CHIP ON TO-8 PACKAGE



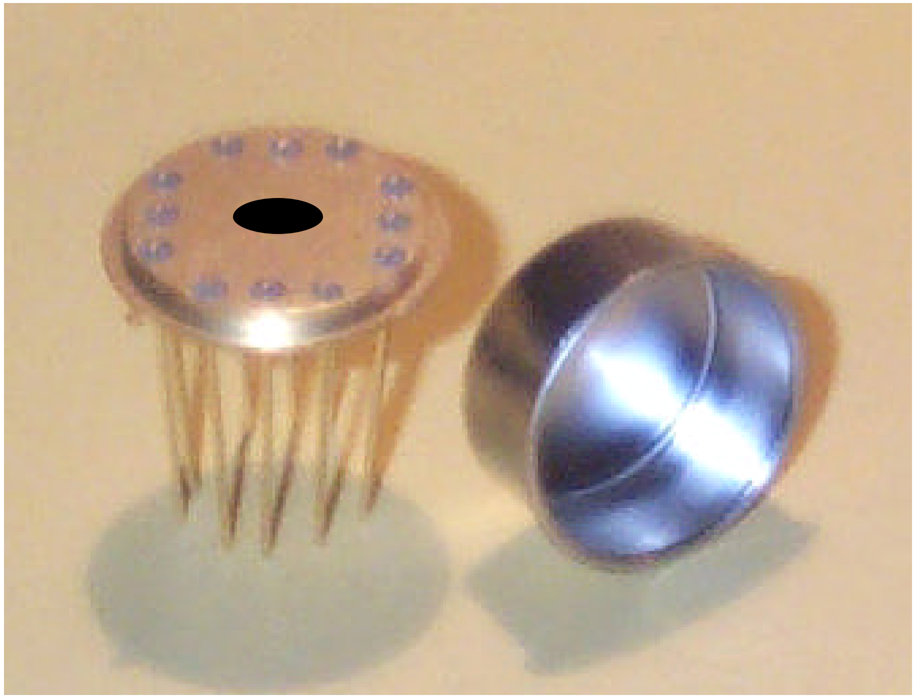


Fixture to hold TO-8 and TO-39 packages for wire bonding.

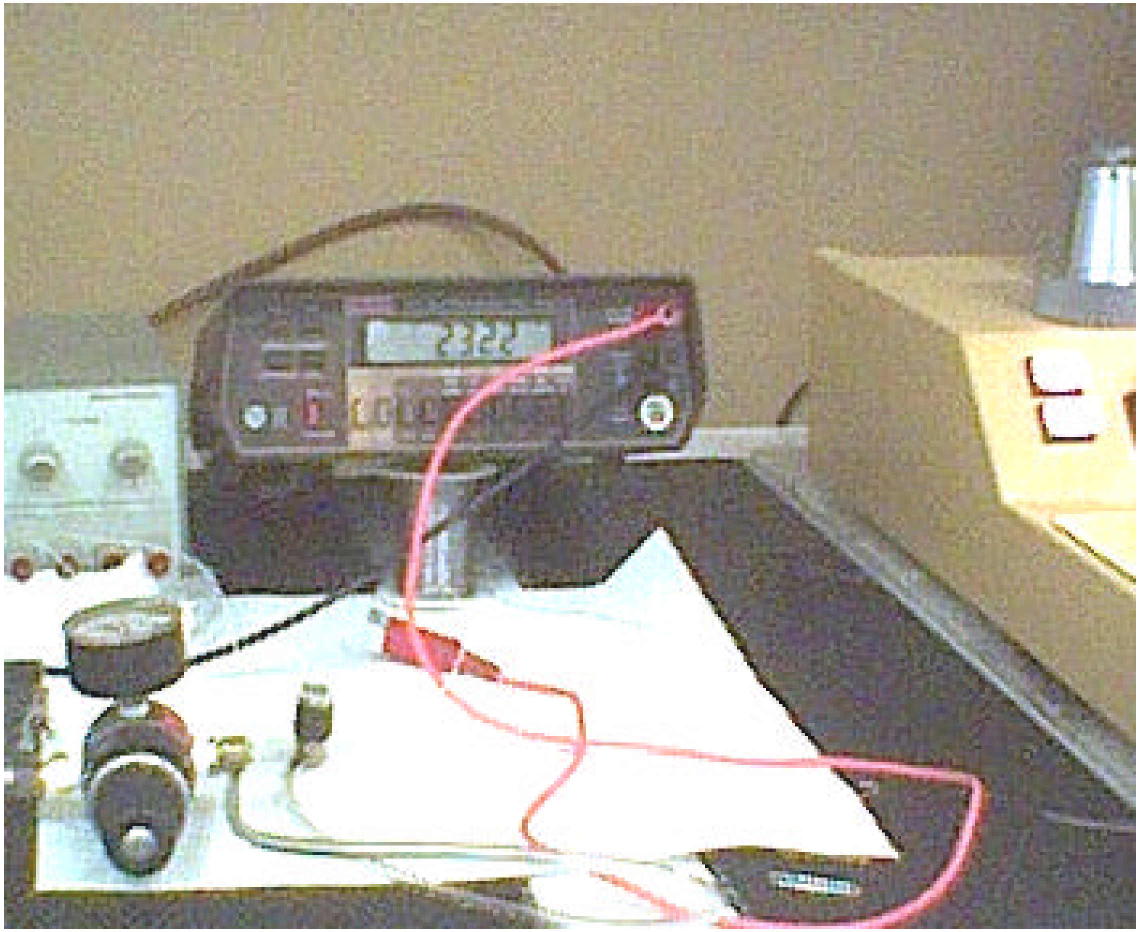
WIRE BOND

ATTACH PNEUMATIC FITTING

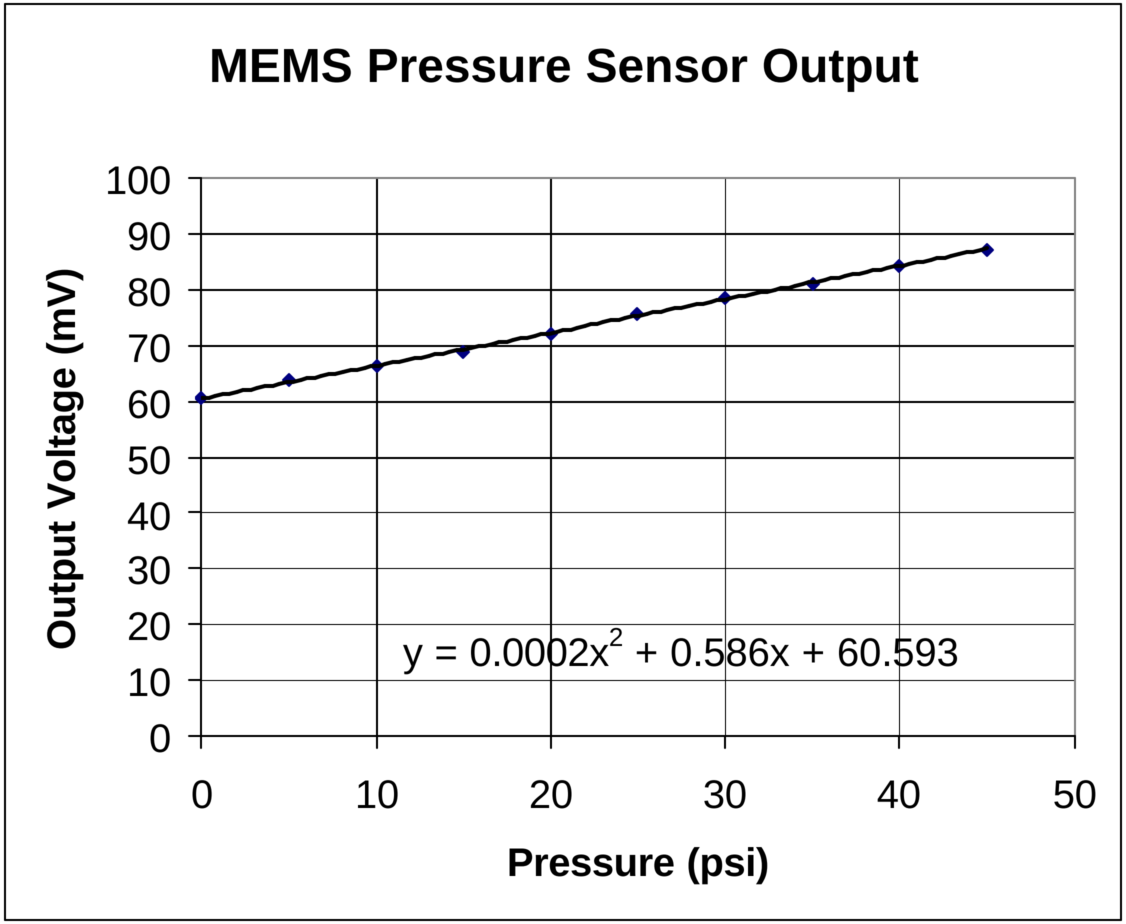
Attach interconnect wires
Epoxy to pneumatic fitting
Add protective cover



PNEUMATIC TEST SET UP



OUTPUT VOLTAGE VERSUS PRESSURE



0	60.6
5	63.84
10	66.32
15	68.95
20	72.28
25	75.62
30	78.68
35	81.25
40	84.39
45	87.21

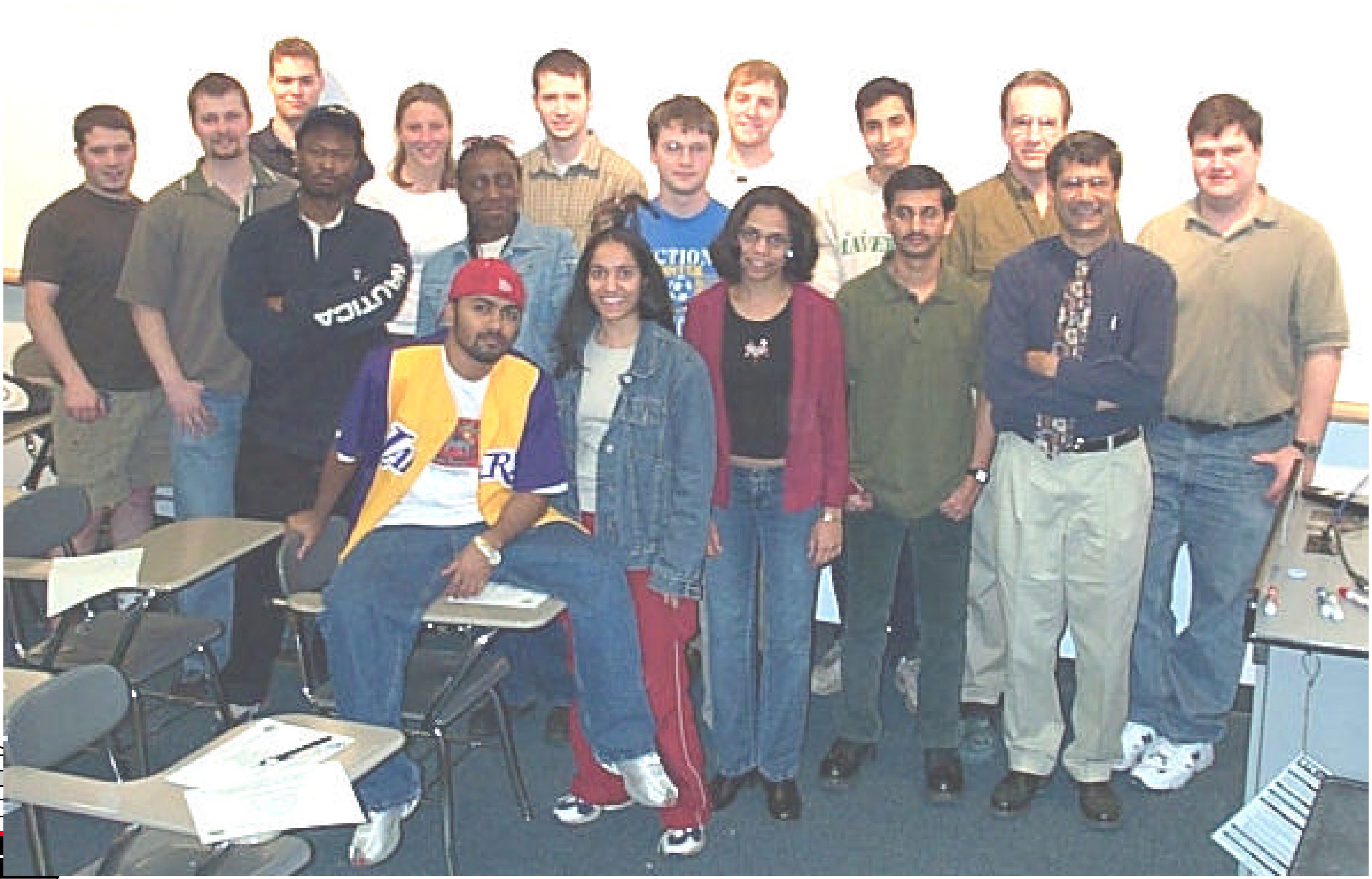
5-15-03

RESULTS AND CONCLUSION

MEMs devices were designed, including
Analytical Analysis, Mask Layout
Photomasks were made
Fabrication process was designed
Wafers were processed
Completed wafers were tested
Chips were packaged
Packaged chips were tested

Successful Project!!!

ACKNOWLEDGMENTS



REFERENCES

1. Process Development for 3 D Silicon Microstructures, with Application to Mechanical Sensor Devices, Eric Peeters, Katholieke Universiteit Leuven, March 1994.]
2. United States Patent 5,357,803
3. S.K. Clark and K.D. Wise, “Pressure Sensitivity in Anisotropically Etched Thin-Diaphragm Pressure Sensors”, IEEE Transactions on Electron Devices, Vol. ED-26, pp 1887-1896, 1979.