ROCHESTER INSTITUTE OF TEHNOLOGY
MICROELECTRONIC ENGINEERING

Microelectromechanical Systems (MEMs) Unit Processes for MEMs Deposition

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9-18-2012 mem_dep.ppt

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OUTLINE

Oxide Growth
Diffusion
Physical Vapor Deposition
LPCVD
Epitaxy
Spin Coating
Lift-Off
Copper Plating
Wafer Bonding
Anodic Bonding

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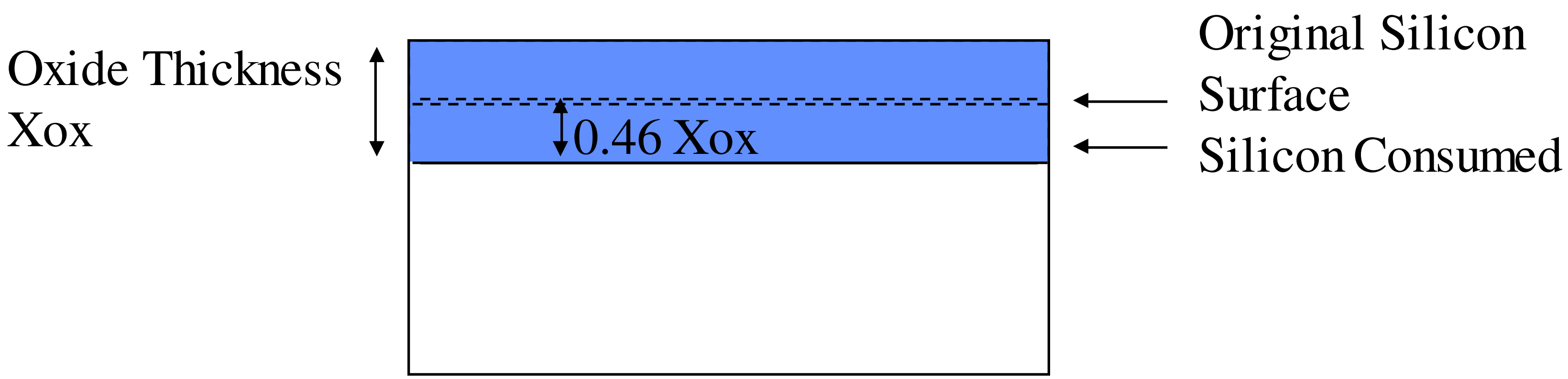
OXIDE GROWTH



Chemical Reactions:

Dry Oxidation: $Si + O_{2(g)} \longrightarrow SiO2$

Wet Oxidation: $Si + 2H_2O_{(g)} \longrightarrow SiO2 + 2H_{2(g)}$

Nox = 2.2E22 cm^{-3}
Ns = 5E22 cm^{-3}

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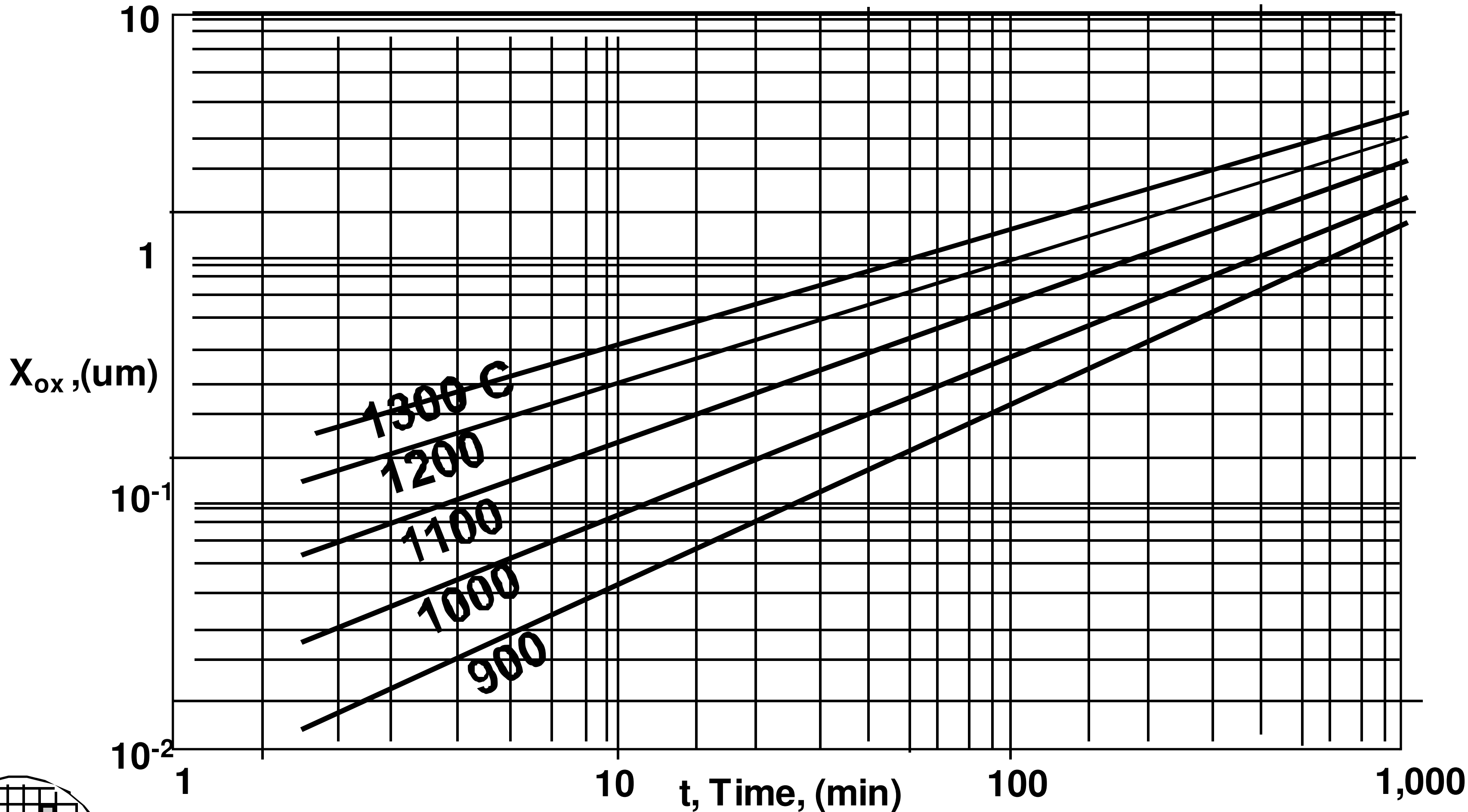
WET OXIDE GROWTH CHART



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PLAY BACK NEXT

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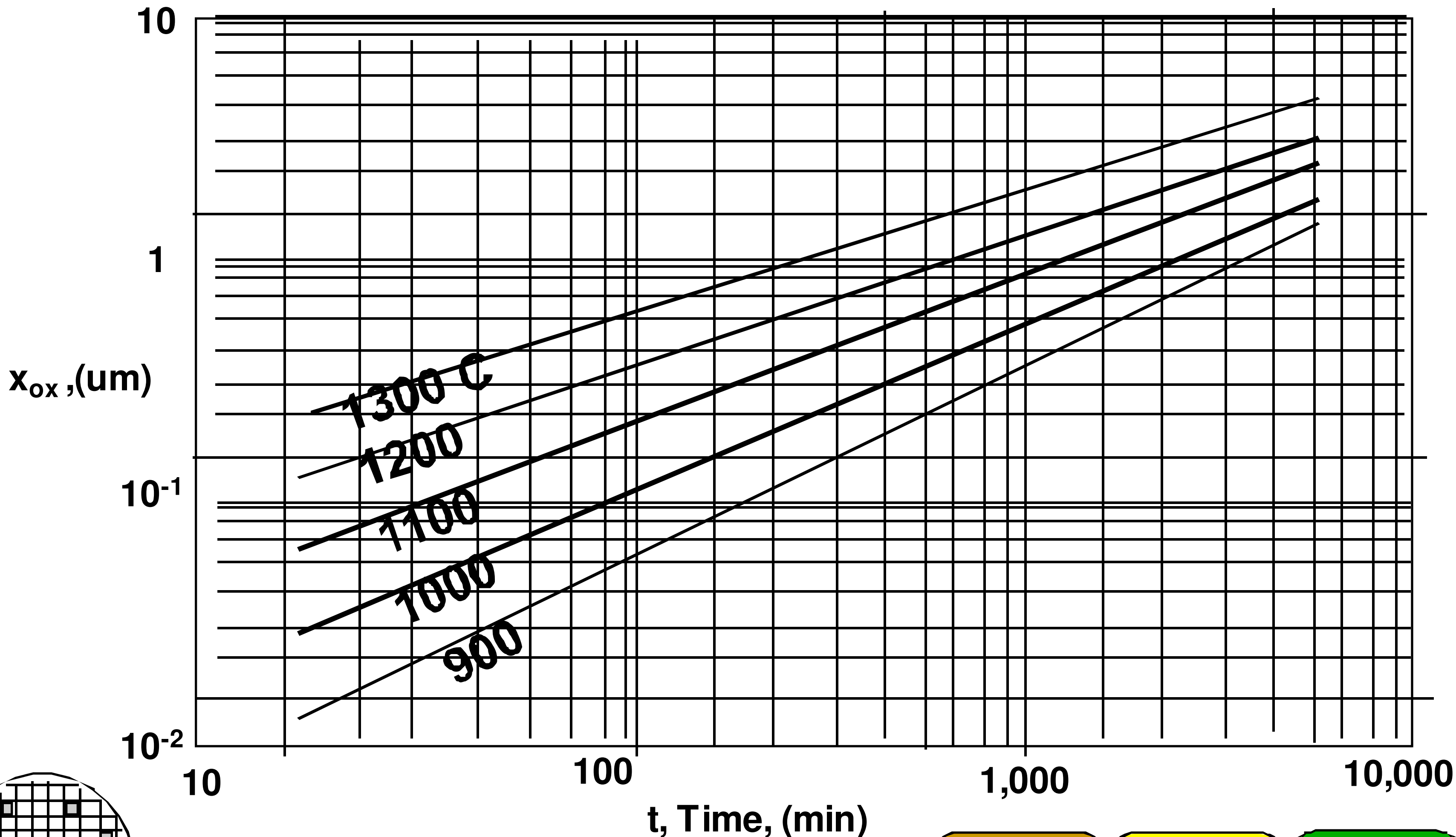
DRY OXIDE GROWTH CHART



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OXIDE GROWTH CALCULATOR

ROCHESTER INSTITUTE OF TECHNOLOGY — OXIDE.XLS — ZIP
MICROELECTRONIC ENGINEERING — 7/28/98

CALCULATION OF OXIDE THICKNESS — LYNN FULLER

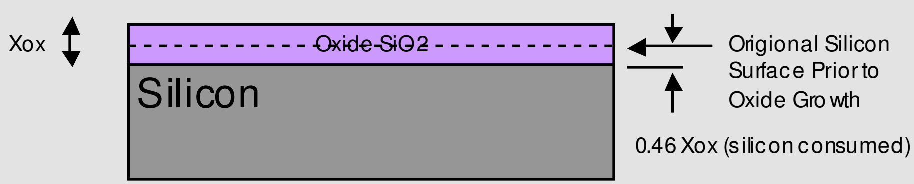
To use this spreadsheed change the values in the white boxes. The rest of the sheet is protected and should not be changed unless you are sure of the consequences. The calculated results are shown in the purple boxes.

CONSTANTS			VARIABLES			CHOICES	
K	1.38E-23	J/K					1=yes, 0=no
(Bo/Ao) dry	5760000	µm/hr	Temp=	1100	°C	wet	1
Ea (dry)	2	eV	time=	48	min	dry	0
(Bo/Ao) wet	71000000	µm/hr				<100>	
Ea (wet)	1.96	eV	Xint=	500	Å	<111>	
Bo dry	9.40E+02	µm2/hr					
Ea (dry)	1.24	eV					
Bo wet	250	µm2/hr					
Ea (wet)	0.74	eV					

CALCULATIONS:

Xox (Oxide thickness)=(A/2){[1+(t+Tau)4B/A^2]^0.5-1} = 5788 Å

B = Bo exp (-Ea/KTemp)	0.484600523	µm2/hr
B/A = (Bo/Ao) exp (-Ea/KTemp)	4.64E+00	µm/hr
A	0.104407971	µm
Tau = (Xi2+AXi)/B	0.01593147	hr



Roche
Micro

EXAMPLES

1. Estimate the oxide thickness resulting from 50 min. soak at 1100 °C in wet oxygen.

SOLUTION

2. Estimate the time needed to grow 2 µm of oxide at 1100 °C. in steam.

SOLUTION

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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

PLAY

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DIFFUSION MASKING

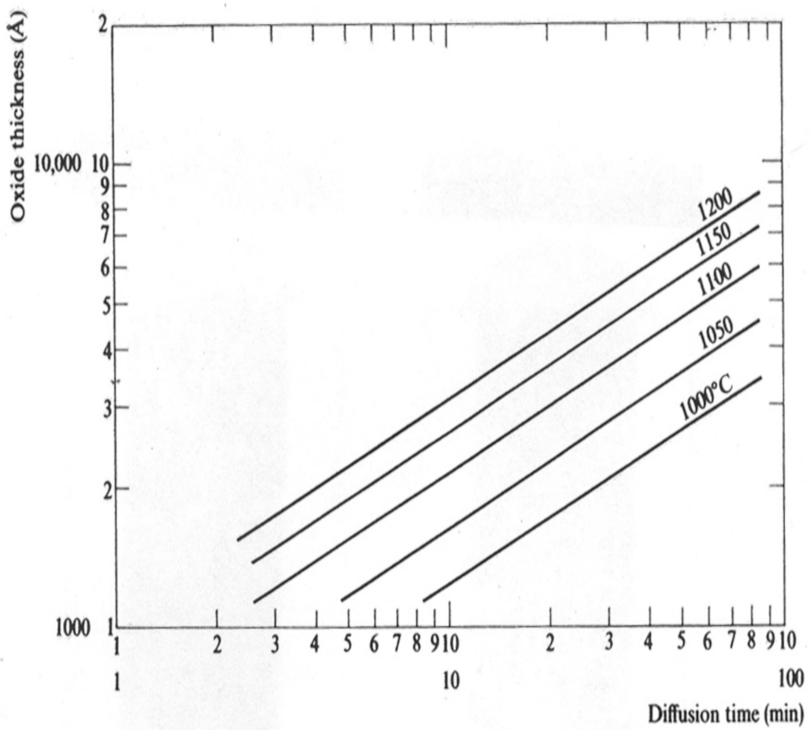

FIGURE 2-28
Minimum oxide thickness required for phosphorus diffusion masking as a function of time (after Burger and Donovan[4]).

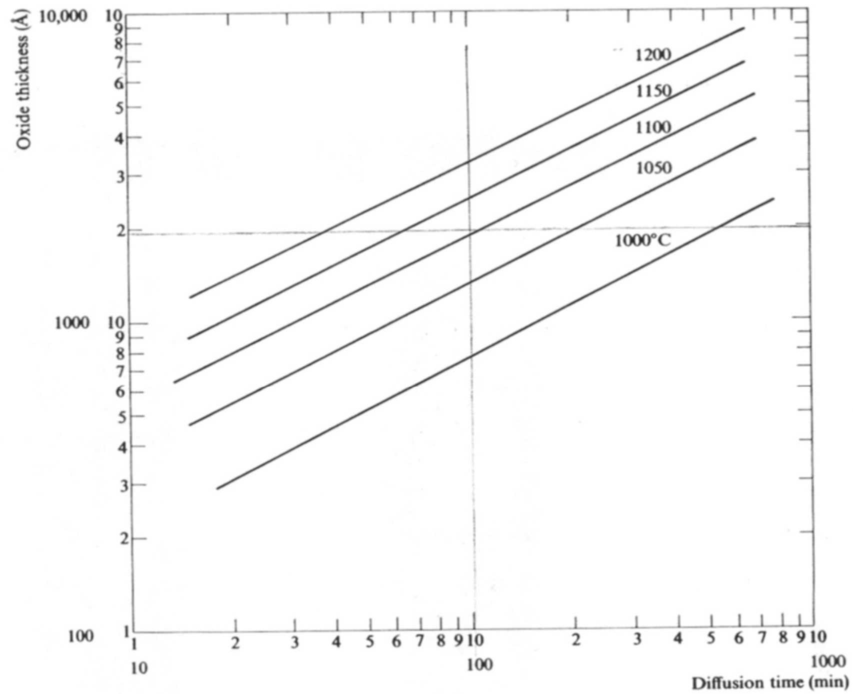

FIGURE 2-27
Minimum oxide thickness required to mask boron at various temperatures (after Burger and Donovan[4]).

From: Hamilton and Howard

DIFFUSION MASKING CALCULATOR

Select
  Boron or Phosphorous
Enter
  Temperature and Time

Ray Krom, 2007

Rochester Institute of Technology — Raymond Krom
Microelectronic Engineering — Dr. Lynn Fuller
9.5.07 — Raymond Krom

Diffusion Mask Calculator — **Enter 1-Yes 0-No in white boxes**

Temperatures must be between 1000C and 1200C or result will be in error.

Dopant		**Diffusion**		
Boron	0	Temp.	1100	°C
Phosphorous	1	Time	100	minutes

Boron 1867 Angstroms
Phosp 6399 Angstroms

Oxide
Fitted to data taken from Hamilton and Howard 6399 Angstroms

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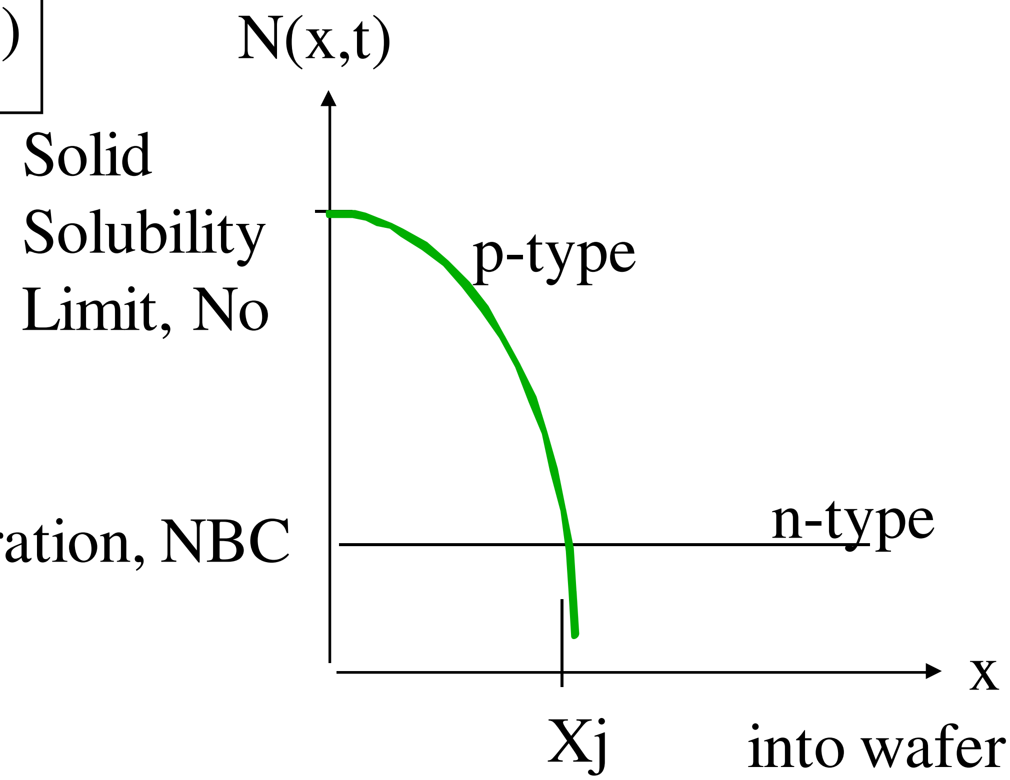
DIFFUSION FROM A CONSTANT SOURCE

PLAY STOP

$$N(x,t) = N_o \ \mathrm{erfc}\left(x/2\sqrt{Dt}\right)$$



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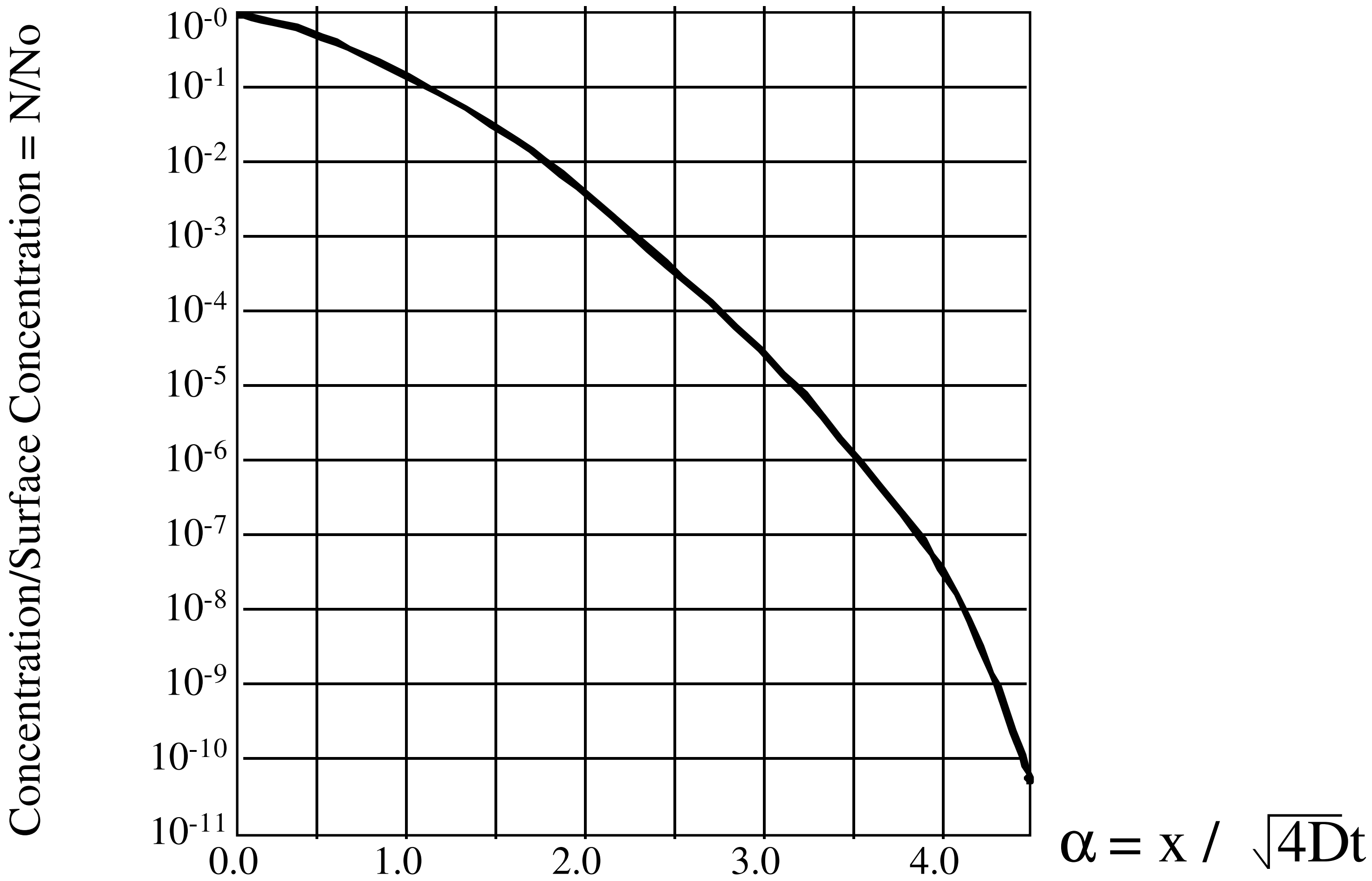
ERFC FUNCTION



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DIFFUSION CONSTANTS AND SOLID SOLUBILITY

DIFFUSION CONSTANTS

TEMP	BORON DRIVE-IN	PHOSPHOROUS PRE	PHOSPHOROUS DRIVE-IN	BORON SOLID SOLUBILITY NOB	PHOSPHOROUS SOLID SOLUBILITY NOP
900 °C	1.07E-15 cm2/s	2.09e-14 cm2/s	7.49E-16 cm2/s	4.75E20 cm-3	6.75E20 cm-3
950	4.32E-15	6.11E-14	3.29E-15	4.65E20	7.97E20
1000	1.57E-14	1.65E-13	1.28E-14	4.825E20	9.200E20
1050	5.15E-14	4.11E-13	4.52E-14	5.000E20	1.043E21
1100	1.55E-13	9.61E-13	1.46E-13	5.175E20	1.165E21
1150	4.34E-13	2.12E-12	4.31E-13	5.350E20	1.288E21
1200	1.13E-12	4.42E-12	1.19E-12	5.525E20	1.410E21
1250	2.76E-12	8.78E-12	3.65E-12	5.700E20	1.533E21

PLAY BACK NEXT

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TEMPERATURE DEPENDENCE OF DIFFUSION CONSTANTS

PLAY BACK NEXT

Temperature Dependence:

$D = D_0 \text{ Exp } (-E_A/kT) \text{ cm}^2/\text{sec}$ $k = 8.625E\text{-}5$ eV/°K T in Kelvins

Boron	$D_0 = 0.76$		Phosphorous	$D_0 = 3.85$
	$E_A = 3.46$			$E_A = 3.66$

Temperature Dependence of the Solid Solubility of Boron and Phosphorous in Silicon

$NOB = 3.5E17T + 1.325E20 \text{ cm}^{-3}$ T in Celsius

$NOP = 2.45E18T - 1.53E21 \text{ cm}^{-3}$ T in Celsius

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DIFFUSION FROM A LIMITED SOURCE

$$N(x,t) = \frac{Q'_A(tp)\ \mathrm{Exp}\ (-x^2/4Dt)}{\sqrt{\pi Dt}}$$

PLAY

for erfc predeposit

$$Q'_A\ (tp) = Q_A(tp)/\mathrm{Area} = 2\ No\ \sqrt{(Dptp)/\pi} = \mathrm{Dose}$$

PLAY

for ion implant predeposit

$$Q'_A(tp) = \mathrm{Dose}$$

Where D is the diffusion constant at the drive in temperature and t is the drive in diffusion time, Dp is the diffusion constant at the predeposit temperature and tp is the predeposit time

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DIFFUSION AND DRIVE IN CALCULATIONS

Starting Wafer Resistivity	Rho =	10	ohm-cm
Starting Wafer Type	n-type = 1	1	1 or 0
	p-type = 1	0	1 or 0
Pre Deposition Temperature		950	°C
Pre Deposition Time		15	min
Drive-in Temperature		1100	°C
Drive-in Time		480	min

CALCULATE	**VALUE**	**UNITS**
Solid Solubility at Temperature of Pre Deposition	4.65E+20	cm-3
Diffusion Constant at Temperature of Pre Deposition	3.93E-15	cm/sec
Diffusion Constant at Temperature of Drive-in	1.43E-13	cm/sec

CALCULATION OF DIFFUSION CONSTANTS

	D0 (cm2/s)	EA (eV)
Boron	0.76	3.46
Phosphorous	3.85	3.66

NOB = 3.5E17 (T) + 1.325E20

NOP = 2.45E18(T) - 1.53E21

CALCULATIONS	**VALUE**	**UNITS**
Substrate Doping = 1 / (q µmax Rho)	4.42E+14	cm-3
Ratio of Nsub/Ns =	9.51E-07	
Approximate inverse erfc from erfc(u)~=e^{-u^2}/(u(pi)^0.5)	3.47	

RESULTS	**VALUE**	**UNITS**
xj after pre deposition =((4Dp tp)^05)*(inv_erfc(Nsub/Ns))	0.13	µm
Pre deposition Dose, QA= 2No (Dp tp/π)^0.5	9.87E+14	atoms/cm2
xj after drive-in = ((4 Dd td/QA) ln (Nsub (π Ddtd)^0.5))^0.5	4.03	um
average doping Nave = Dose/xj	2.45E+18	atoms/cm3
mobility (µ) at Doping equal to Nave	109	cm2/V-s
Sheet Resistance = 1/(q (µ(Nave))Dose)	58	ohms
Surface Concentration After Drive-in = Dose/ (pDt)^0.5	8.68E+18	cm-3

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DIFFUSION FROM A LIMITED SOURCE

GIVEN		VALUE	UNITS
Starting Wafer Resistivity	Rho =	10	ohm-cm
Starting Wafer Type	n-type = 1	1	1 or 0
	p-type = 1	0	1 or 0
Pre Deposition Ion Implant Dose		4.00E+15	ions/cm2
Drive-in Temperature		1000	°C
Drive-in Time		360	min

CALCULATE	VALUE	UNITS
Diffusion Constant at Temperature of Drive-in	1.43E-14	cm/sec

CALCULATION OF DIFFUSION CONSTANTS

	D0 (cm2/s)	EA (eV)
Boron	0.76	3.46
Phosphorous	3.85	3.66

CALCULATIONS	VALUE	UNITS
Substrate Doping = 1 / (q umax Rho)	4.42E+14	cm-3

RESULTS	VALUE	UNITS
Pre deposition Dose	4.00E+15	atoms/cm2
xi after drive-in = ((4 Dd td/OA) ln (Nsub (π Ddtd)^0.5))^0.5	1.25	um
average doping Nave = Dose/xj	3.21E+19	atoms/cm3
mobility (µ) at Doping equal to Nave	57	cm2/V-s
Sheet Resistance = 1/(q (µ(Nave))Dose)	27.6	ohms
Surface Concentration = Dose/ (pDt)^0.5	1.28E+20	cm-3

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EXAMPLE

1. A predeposit from a p-type spin-on dopant into a 1E15 cm-3 wafer is done at 1100°C for 10 min. Calculate the resulting junction depth and dose.

SOLUTION

2. The spin-on dopant is removed and the Boron is driven in for 2 hours at 1100 °C. What is the new junction depth?

SOLUTION

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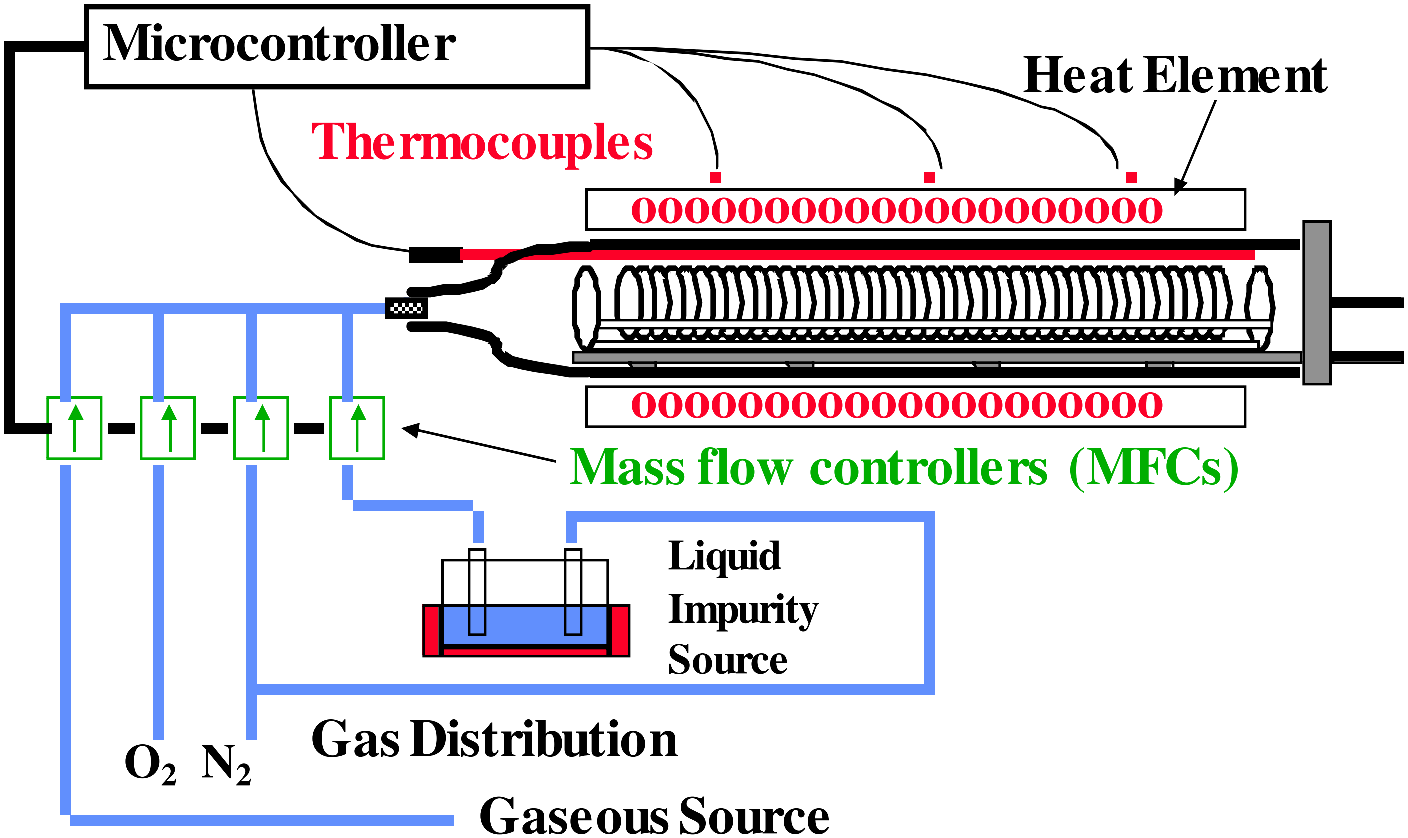
OXIDATION AND DIFFUSION FURNACE

Typical Diffusion System



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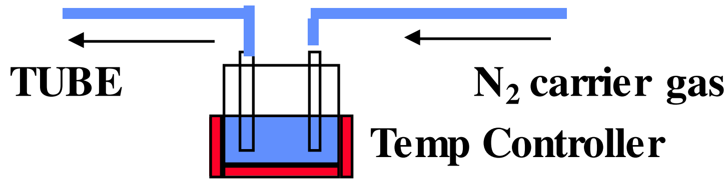
DIFFUSION SOURCES

- **Gaseous**
  - AsH_3 , PH_3 , PF_3 , B_2H_6 , BF_3
- **Liquid Source**
  - Bubbler



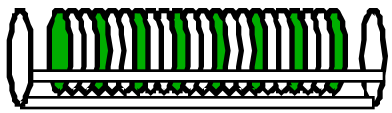
$POCl_3$: $4POCL_3 + 3O_2 \longrightarrow 2P_2O_5 + 6Cl_2$

BBr_3 : $4BBr_3 + 3O_2 \longrightarrow 2B_2O_3 + 12Br$

  - Spin-on glass (SOG)

Arsenosilica, Phosphosilica, Borosilica

- **Solid Source (disc)**
  - BN, $NH_4H_2PO_4$



Free atomic impurity formation:

2P2O5 + 5Si ⟶ 5SiO2 + 4P

2B2O3 + 3Si ⟶ 3SiO2 + 4B

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DIFFUSION EXAMPLE

Example: Single crystal silicon can be selectively etched. Regions with dopant concentration greater than 1e19 etch much slower than lighter doped regions. Design a process to create a 2 micrometer diaphragm.

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DOPING POLYSILICON

When using poly as a conductor in integrated circuits it is desirable to have low resistivity. Doping at 1000 °C for 20 min using Emulsitone Co., 19 Leslie Court, Whippany, NJ 07981 Tel (201)386-0053; Emitter Diffusion Source N250 spin-on dopant gives 10-15 ohm/sq sheet resistance for 0.75 um thick poly. (The Allied Signal Inc., 1090 South Milpitas Boulevard, Milpitas, CA 95035, Tel (408)946-2411, Accuspin P-854 dopant gives higher resistivity in the range of 100 ohm/sq.)

2 um Poly Doped n+ using N-250 for 30 min

@ 1100 C	rhos = 8 ohms
@ 950 C	rhos = 40 ohms
@ 800 C	rhos = 10,000 ohms

ION IMPLANT

See separate lecture notes on ion implant.
Important results are:

depth (range) vs energy
spread (straggle) vs energy
gaussian implant profile equation

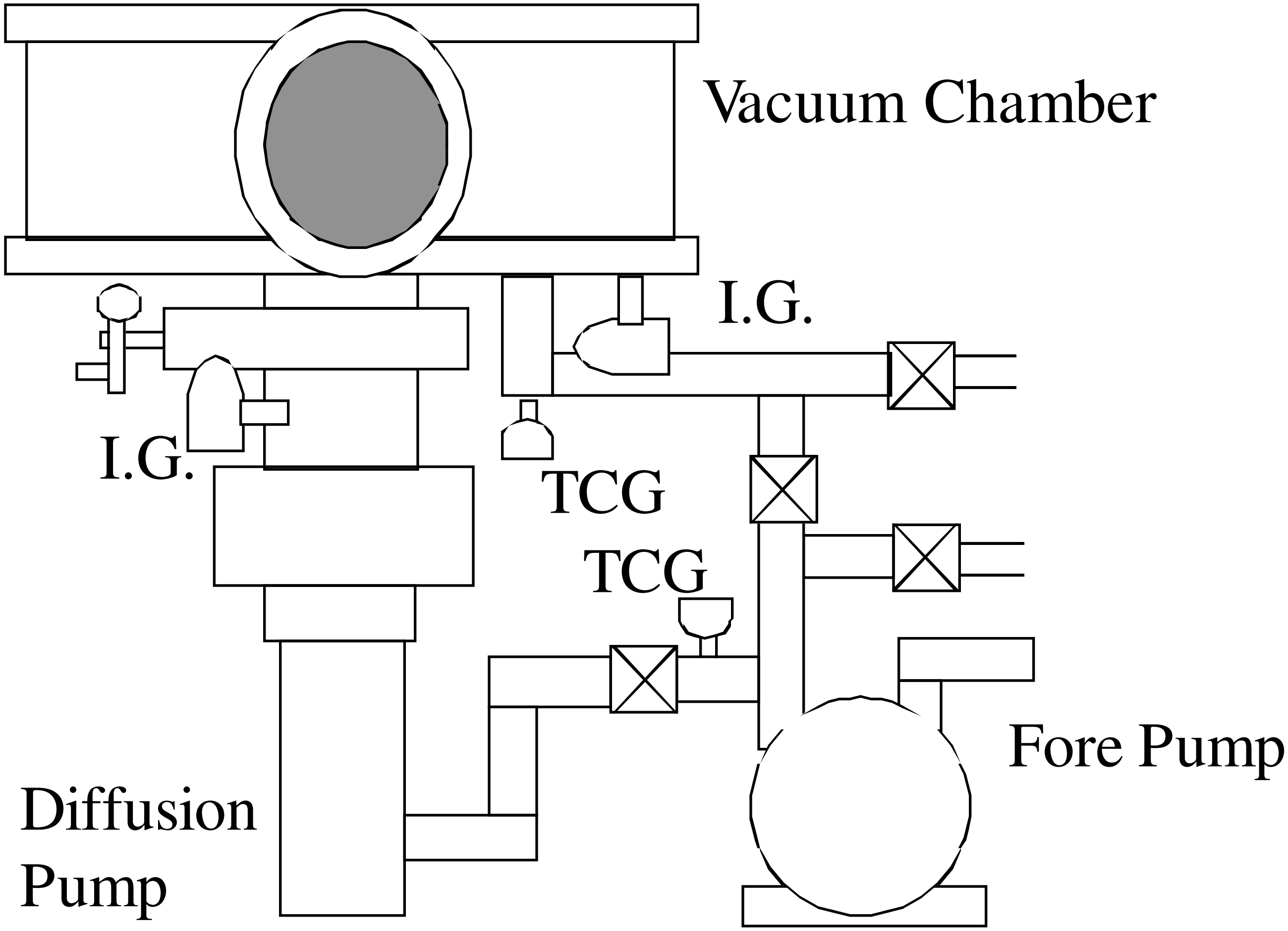
$$N(x)=\{Dose/(2\pi\ \Delta Rp^2)^{-0.5}\}EXP^{-[(x-Rp^\wedge 2)/2\Delta Rp^\wedge 2]}$$

Dose = It/qArea
masking for selective implantation
sheet resistance (ohms) = 1/ (qμDose)
MOSFET threshold voltage adjust = +/- qDose/Cox'

PHYSICAL VAPOR DEPOSITION (PVD)

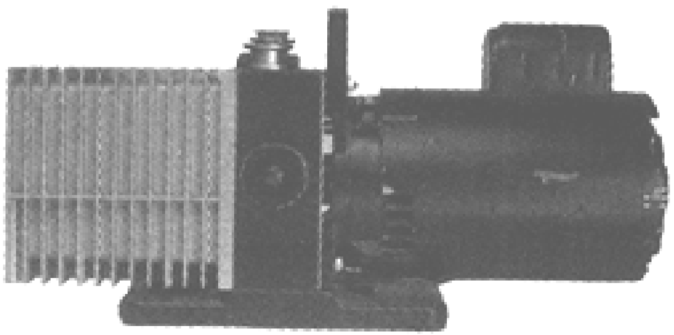
PVD:

- **Evaporation**
- **Sputtering**
  - DC
  - RF
  - Magnetron

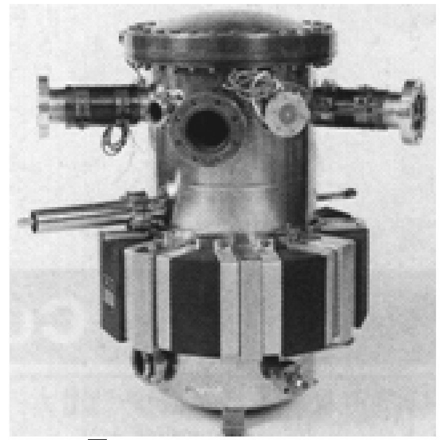


VACUUM PUMPS, GAUGES AND SYSTEMS

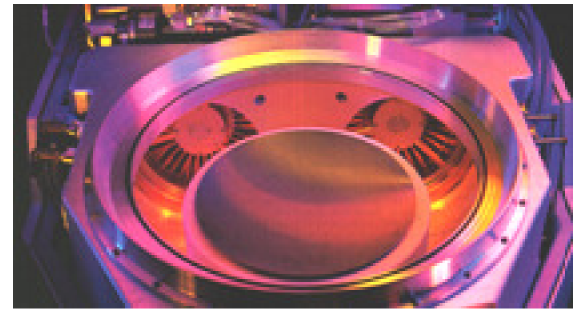
See separate lecture notes on Backend Wafer Processing (back_end.ppt) Pages 6-34



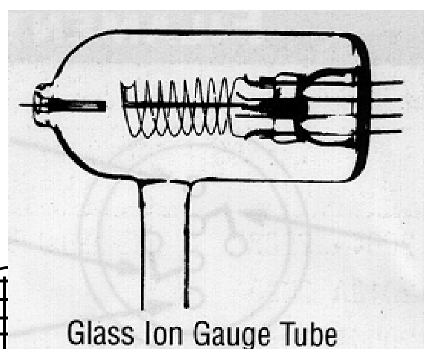
Rotary Vane Mechanical Pump



Ion pump



Magnetically levitated turbomolecular pumps on HDPCVD system



Glass Ion Gauge Tube

Thermocouple Gauge

Not shown:
- Diffusion Pump
- Cryo Pump
- Sublimation Pump
- Penning Gage

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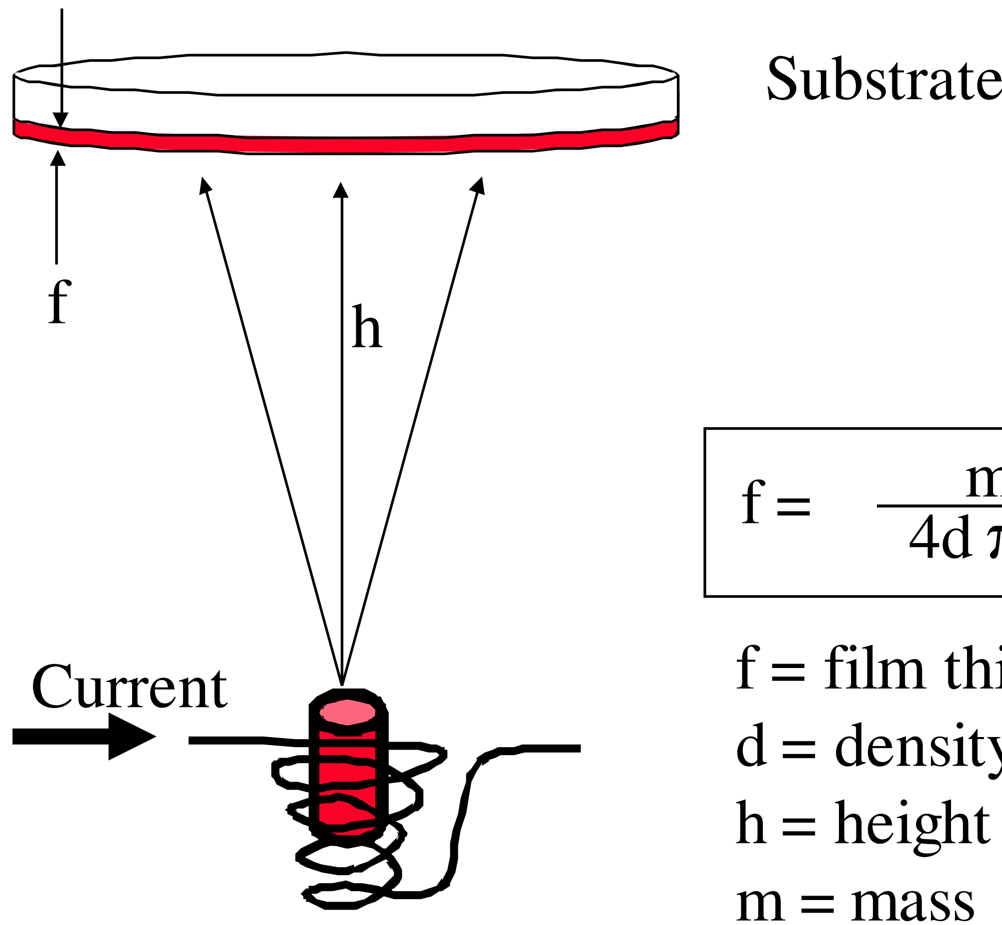
EVAPORATION



$$f = \frac{m}{4d\,\pi\,h^2}$$

f = film thickness

d = density

h = height

m = mass

EVAPORATION CALCULATION

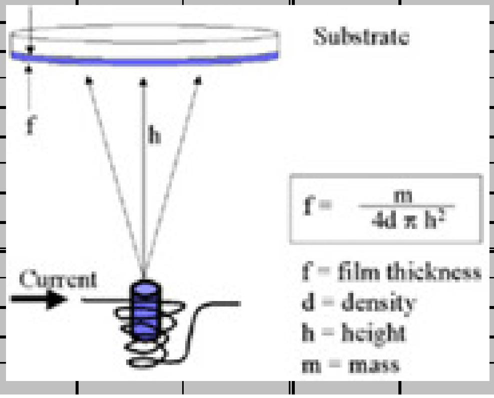
Rochester Institute of Technology		March 19, 2006
Microelectronic Engineering		Dr. Lynn Fuller

Evaporation in this model assumes that the mass evaporated is spread out over the inside surface of a sphere with radius equal to the distance from the evaporation source to the substrate. The surface area is 4 pi h^2 when multiplied by film thickness gives volume of material needed which is multiplied by the density to give the mass needed. Divide the mass by 2 if a dimpled boat is used allowing coating over a hemisphere instead of a sphere.

m = the mass that needs to be evaporated = 4 pi h^2 f d	m =	3.88	gm
f = the desired film thickness	f =	0.1	µm
d = the density of the material being evaporated	d =	19.3	
h = the height between the filament and the substrate	h =	40	cm
mass in troy oz is found = 0.3215 x mass (g)	m =	0.12	Troy Oz

Denisty of some materials — Select only one =1, others = 0

Aluminum	2.7	0
Gold	19.3	1
Copper	8.96	0
Tin	7.3	0
Lead	11.4	0



Dimpled Boat

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EVAPORATION TECHNIQUES

Aluminum - evaporate copper with tungsten wire basket. One pellet at 20 cm gives about 3000 A.

Copper - evaporate copper with tungsten wire basket. The basket needs to be crushed a little so the openings are small and the copper does not fall out of the basket once it is melted. One pellet at 20 cm gives about 3000 A. Dimpled Tungsten boats work great.

Chromium – use special Chromium coated tungsten wire filaments. Current through the filament heats the Cr which sublimes.

Gold - gold or gold/germanium can easily be evaporated from a basket with tightly spaced loops. The basket needs to be crushed a little so the openings are small and the gold does not fall out of the basket once it is melted. Dimpled Tantalum boats work great.

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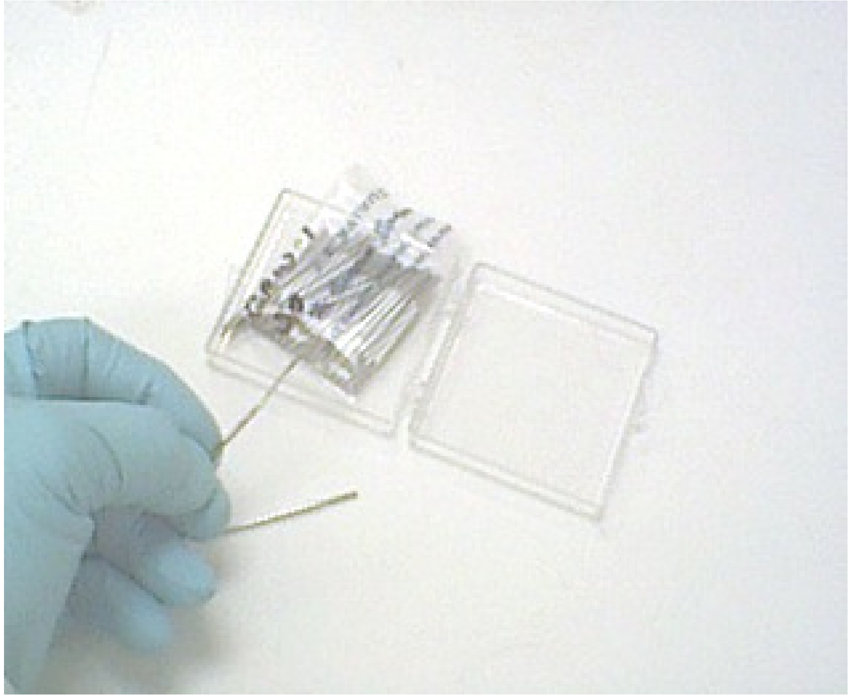
CHROME EVAPORATION

Deposit chrome by evaporation (actually sublimation) from special chrome coated tungsten rods. Using the CVC evaporator. Heat rods to red hot by setting filament voltage to 190 on the dial. Then open the shutter for the desired time calculated from rate of 35 Å/sec. (at a distance of 40 cm from source to substrate)



R.D.Mathis
P.O. Box 92916
Long Beach, CA 90809-2916
www.rdmathis.com

Part No. ??
Cost $250/50 qty

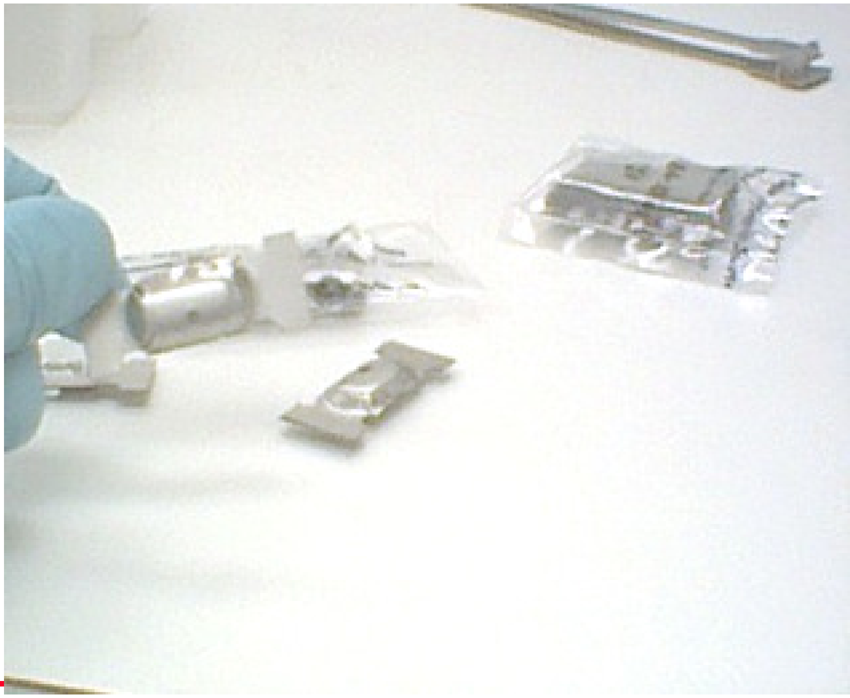
DEPOSITION OF SILICON MONOXIDE (SiO)

Evaporate SiO with Ta boat and cover with hole. The material sublimes and a film will be deposited. It looks like glass and can be measured on the ellipsometer. The ellipsometer gave an index of refraction of 1.88

Using the CVC evaporator X mg at 40 cm gives about 300 Å. Set to 250 on the dial.

R.D.Mathis
P.O. Box 92916
Long Beach, CA 90809-2916
www.rdmathis.com

Part No.
Cost



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EVAPORATION DATA

Material	Formula	Melt pt. °C	Temp °C @ Vapor Pressure 1E-8	1E-6	1E-4
Aluminum	Al	660	677	812	1010
Alumina	Al2O3	2045	1045	1210	1325
Antimony	Sb	630	279	345	425
Arsenic	As	814	107	152	210
Beryllium	Be	1278	710	878	1000
Boron	B	2100	1278	1548	1797
Cadmium	Cd	321	64	120	180
Cadmium Sulfide	CdS	1750			550
Chromium	Cr	1890	837	977	1177
Cobalt	Co	1495	850	990	1200
Gallium	Ga	30	619	742	907
Germanium	Ge	937	812	957	1167

MRC Co., "Evaporation and Sputtering Data Book," Orangeburg, NY
http://www.epimbe.com/pages/vp

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EVAPORATION DATA

Material	Formula		Melt pt. °C		Temp °C @ Vapor Pressure 1E-8	1E-6	1E-4
Gold	Au		1062		807	947	1132
Hafnium Oxide	HfO2		2812				2500
Nickel	Ni		1453		927	987	1262
Palladium	Pd		1550		842	992	1192
Platinum	Pt		1769		1292	1492	1747
Selenium	Se		217		89	125	170
Silicon	Si		1410		992	1147	1337
Silicon Dioxide	SiO2		1800				1025
Silicon Nitride	Si3N4						800
Silver	Ag		961		574	617	684
Tantalum	Ta		2966		1960	2240	2590
Titanium Ti		1668		1067	1235	1453	
Tungsten W		3410		2117	2407	2757	
Zirconium	Zr		1852		1477	1702	1987

MRC Co., "Evaporation and Sputtering Data Book," Orangeburg, NY
http://www.epimbe.com/pages/vp

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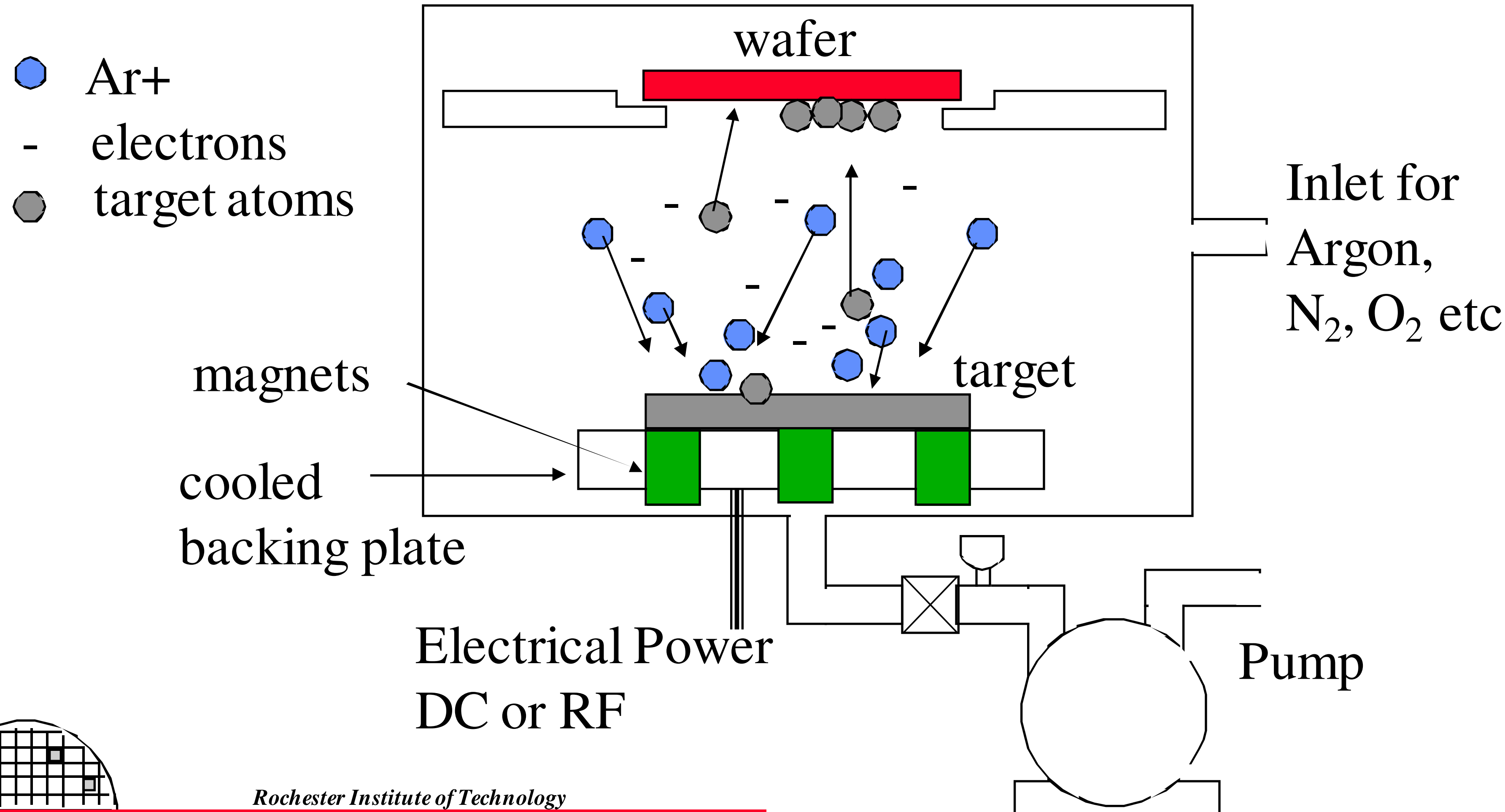
SPUTTERING



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SPUTTERING

DC Sputtering - Sputtering can be achieved by applying large (~2000) DC voltages to the target (cathode). A plasma discharge will be established and the Ar+ ions will be attracted to and impact the target sputtering off target atoms. In DC sputtering the target must be electrically conductive otherwise the target surface will charge up with the collection of Ar+ ions and repel other argon ions, halting the process.

RF Sputtering - Radio Frequency (RF) sputtering will allow the sputtering of targets that are electrical insulators (SiO_2, etc). The target attracts Argon ions during one half of the cycle and electrons during the other half cycle. The electrons are more mobile and build up a negative charge called self bias that aids in attracting the Argon ions which does the sputtering.

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SPUTTERING

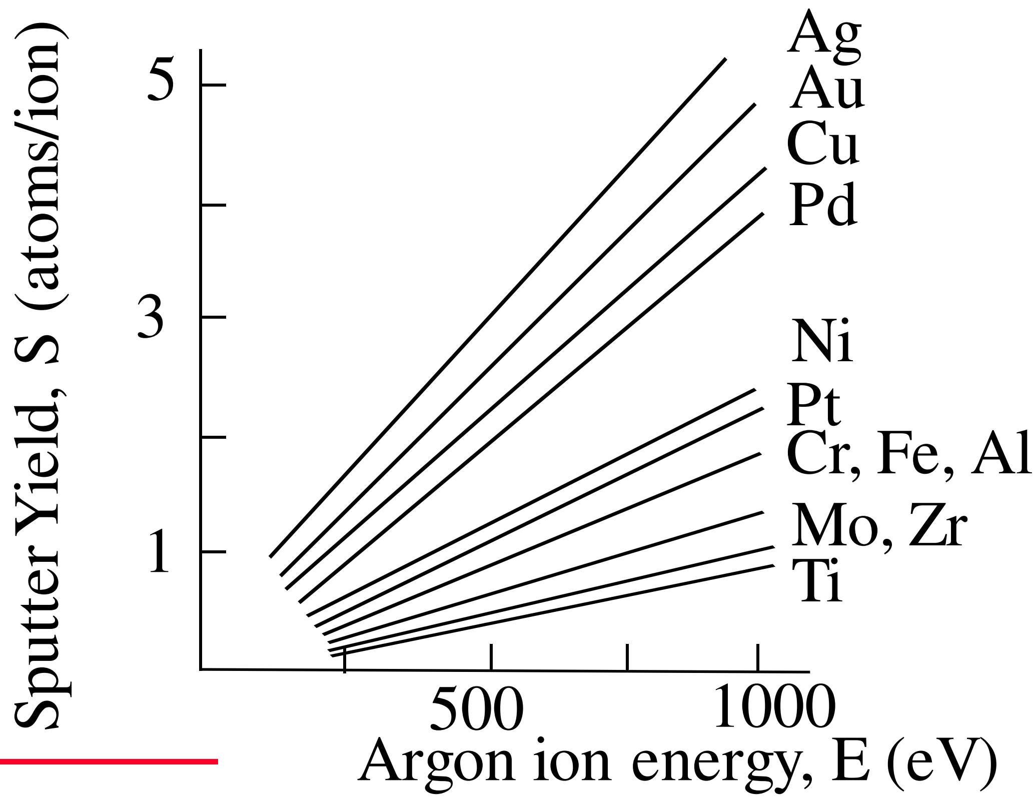
Magnetron Sputtering - Magnets buried in the baseplate under the target material cause the argon ions and electrons to concentrate in certain regions near the surface of the target. This increases the sputtering rate.

Deposition Rate ~ JSE

J is current density

S is sputter yield

E is ion energy



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SPUTTER TARGETS

PE 2400 Targets

Au
Zr
SiO2 Qty2
Si Qty2
TiO2
Nb2O5
In2O5 Qty2
Permalloy
Fe
AlNi
NiFeMg
Ni
Co

Ta2O5
Cr
Ta
Mg
NiFe
CrSiO
Nb
SnO2
Al2O3
MgF2
MgO
Target Insulators 3
Backing Plates6

2" Unbonded for Denton

Gold
Palladium

CVC 601

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SPUTTER TARGETS

8" Bonded for CVC-601
Aluminum 100%
Aluminum Oxide
Aluminum/1% Silicon
Chrome
Chrome Oxide
Copper
Molybdenum
Tantalum
Titanium
Titanium10%/Tungsten 90%
Silicon Dioxide
Silicon
Indium Tin Oxide

8"Unbonded for CVC-601
Molybdenum/Titanium
Titanium/Al 1%/Silicon 2%

4" Unbonded for CVC 601
Chrome
Indium 90%/Tin 10%
Nickel
Tantalum
Tin
Nickel-Chromium 80%/20%
108E-6 ohm cm, TCR 110 E-6/°C
$450- 4"x1/4" Mel Hollander, Research and PVD Materials Corp. (973) 575-4245

RIT SPUTTERING DATA

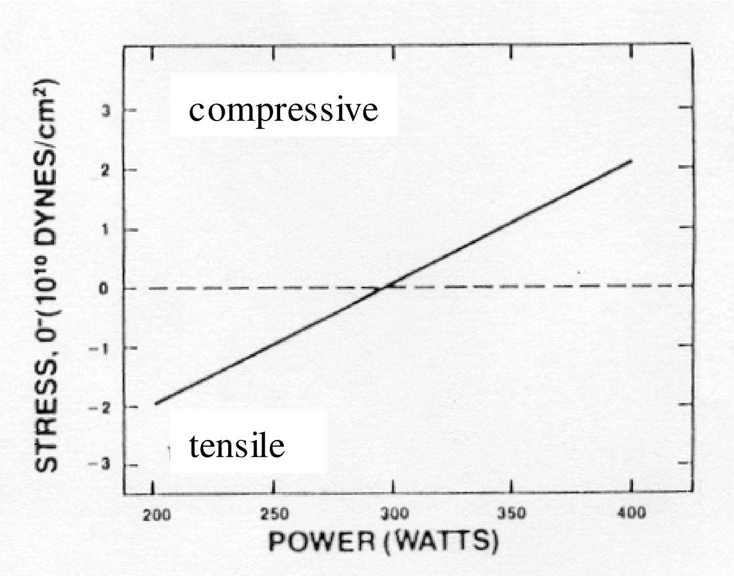
Material	Head	Power (watts)	Rate
Aluminum	8”	2000	240 Å/min.
Nickel	4”	500	170
Chromium	8”	1350	350
InSn + O2	4”	100	80
Copper	8”	325	110
Gold*	2”	40 mA,50mTorr	250
Tantalum	4”	500	190
Titanium	8”	1350	220
Tungsten	4”	500	100
Tungsten	8”	1000	115
Palladium#	2”	10mA, 90 mTorr	100

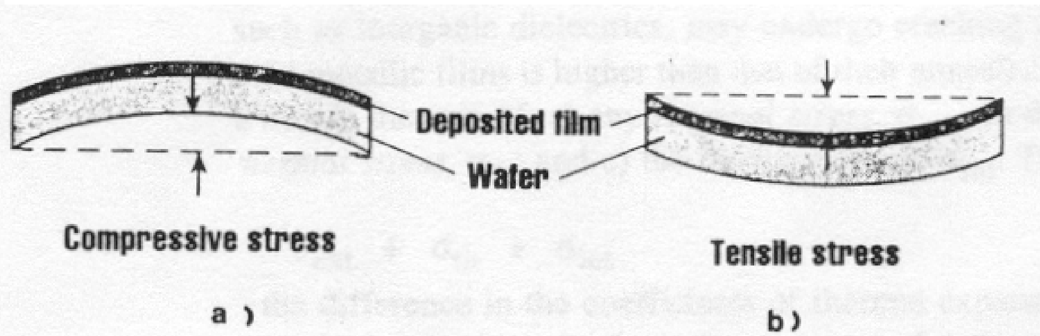
This data is for the CVC 601 Sputter System at 5 mTorr Argon Pressure, Base Pressure Prior to Sputter <1E-5

*Denton Sputter Machine

STRESS IN SPUTTERED FILMS

Compressively stressed films would like to expand parallel to the substrate surface, and in the extreme, films in compressive stress will buckle up on the substrate. Films in tensile stress, on the other hand, would like to contract parallel to the substrate, and may crack if their elastic limits are exceeded. In general stresses in films range from 1E8 to 5E10 dynes/cm2.



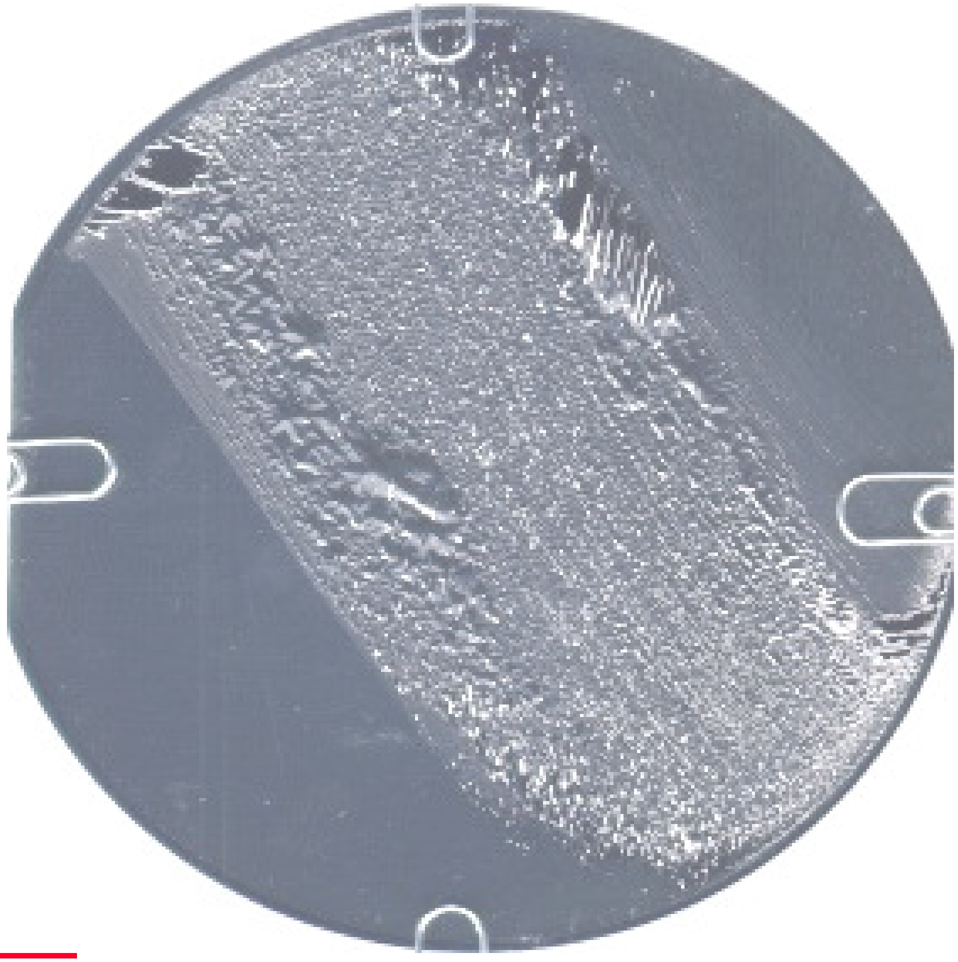


For AVT sputtered oxide films Dr. Grande found Compressive 18MPa stress, 1-29-2000

10 dyne/cm² = 1 newton/m² = 1 Pascal

STRESS IN SPUTTERED TUNGSTEN FILMS

Tungsten
- CVC 601
- 4" Target
- 500 Watts
- 50 minutes
- 5 mTorr Argon
- Thickness ~ 0.8 µm



Picture from scanner in gowning

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REACTIVE SPUTTERING

Reactive Sputtering - introducing gases such as oxygen and nitrogen during sputtering can result in the deposition of films such as indium tin oxide (ITO) or titanium nitride TiN (other examples include AlN, Al_2O_3, AnO Ta_2O_5)

Unwanted Background Gases in Sputtering - Most Films are very reactive when deposited. Water and oxygen cause rougher films, poorer step coverage, discoloration (brown aluminum), poorer electrical properties, etc.

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REACTIVE SPUTTERING PROCESSES

Deposition of Reactive Sputtered Ta2O5

CVC 601, 25% Oxygen, 75% Argon, 90 min, 500 watts, 4 inch target resulting in ~5000 Å, nanospec should use index of refraction of 2.2

Deposition of Reactive Sputtered TaN

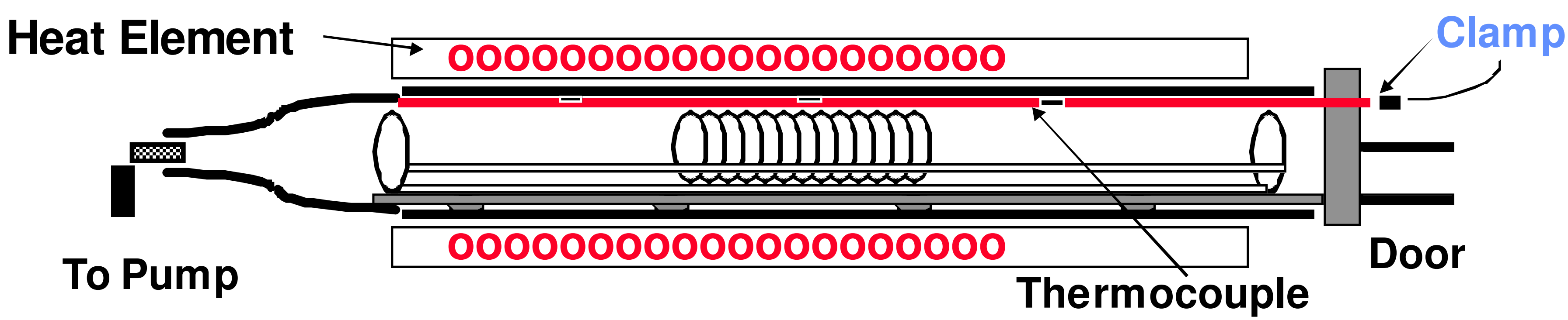
CVC 601, 8" Target of Ta, Ar 170 sccm, N2 34 sccm, Pressure = 4 mTorr, 2000 W, Rate ~900 Å/15 min

Deposition of Reactive Sputtered TaN

CVC 601, 4" Target of Ta, Ar 62 sccm, N2 34 sccm, Pressure = 6 mTorr, 500 W, Rate=157 Å/min, Rhos=228 ohms

CHEMICAL VAPOR DEPOSITION (CVD)

APCVD Atmospheric Pressure CVD
LPCVD Low Pressure CVD
PECVD Plasma Enhanced LPCVD
MOCVD Metal Organic CVD



CVD CHEMISTRY

Epi	$SiCl_4 + 2H_2 \rightarrow Si + 4HCl$
Polysilicon	SiH_4 (gas) $\rightarrow$ Si (solid) $+ 2H_2$
Silicon Nitride	$SiCl_2H_2 + NH_4 \rightarrow Si_3N_4 + HCl$
Low Temperature Oxide	$SiH_4 + O_2 \rightarrow SiO_2 + H_2$
Tungsten (Selective on Si not on SiO2)	$WF_6 + 3H_2 \rightarrow W + 6HF$
TEOS (tetraethyl orthosilicate)	$Si(C_2H_5O)_4 \rightarrow SiO_2 + 4C_2H_4 + 2H_20$
TiN (TDMAT)	reduction of $Ti[N(CH_2CH_3)_2]_4$
Copper CVD	reduction of ???

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RIT LPCVD TOOLS

6" LPCVD
Top Tube for LTO
Bottom Tube for Poly and Nitride

4" LPCVD

DETAILS FOR RIT 4" LPCVD SYSTEM

Polysilicon Deposition:

Temperature = 610 °C $SiH_4 = Si + 2H_2$
Pressure = 300 mTorr
Gas = Silane (SiH_4) Flow = 90 sccm
Rate = 77 Å/min

Low Temperature Silicon Oxide: (Not recommended, poor uniformity)

Temperature = 400 °C $SiH_4 + O_2 = SiO_2 + 2H_2$
Pressure = 250 mTorr
Silane (SiH_4) Flow = 40 sccm
Oxygen (O_2) Flow 48 sccm
Rate = 70 Å/min +/- 10 Å/min

Silicon Nitride (Si_3N_4) (normal - stociometric):

Temperature = 790-800-810 °C Ramp from (door to pump)
Pressure = 375 mTorr $3SiH_2Cl_2 + 4NH_3 = Si_3N_4 + 9H_2 + 3Cl_2$
Dichlorosilane (SiH_2Cl_2) Flow = 60 sccm
Ammonia (NH_3) Flow = 150 sccm
Rate = 60 Å/min +/- 10 Å/min

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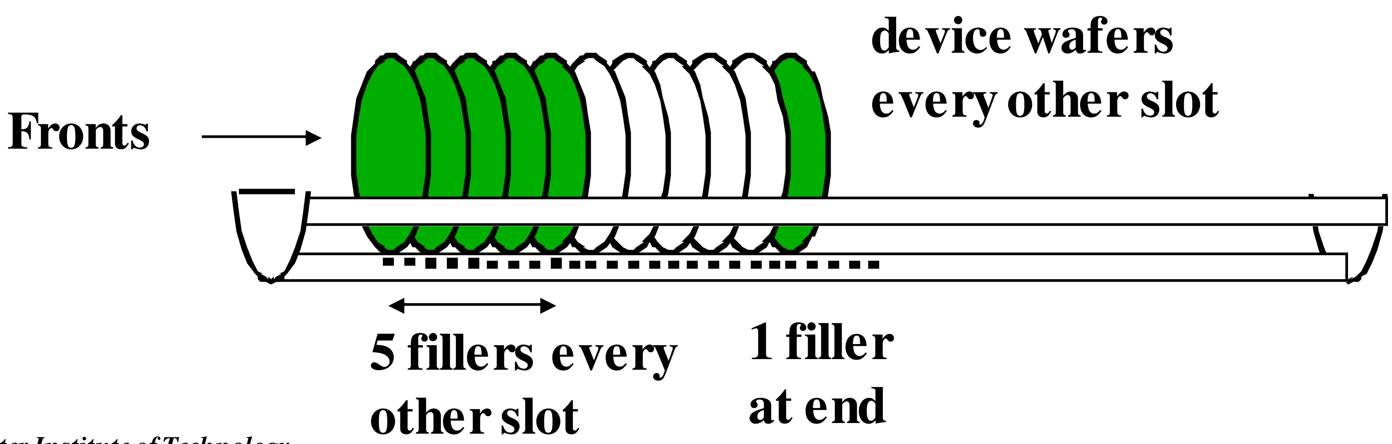
DETAILS FOR RIT 4" LPCVD SYSTEM

High Dep. Rate Polysilicon Deposition:

Temperature = 650 °C $SiH_4 = Si + 2H_2$
Pressure = 300 mTorr
Gas = Silane (SiH_4)
Flow = 90 sccm
Rate = 235 Å/min (~ 3 times the normal dep. rate at 610 °C)

Thicker films have larger grain size (grain size ~ equal to film thickness) and thus a rougher appearance.



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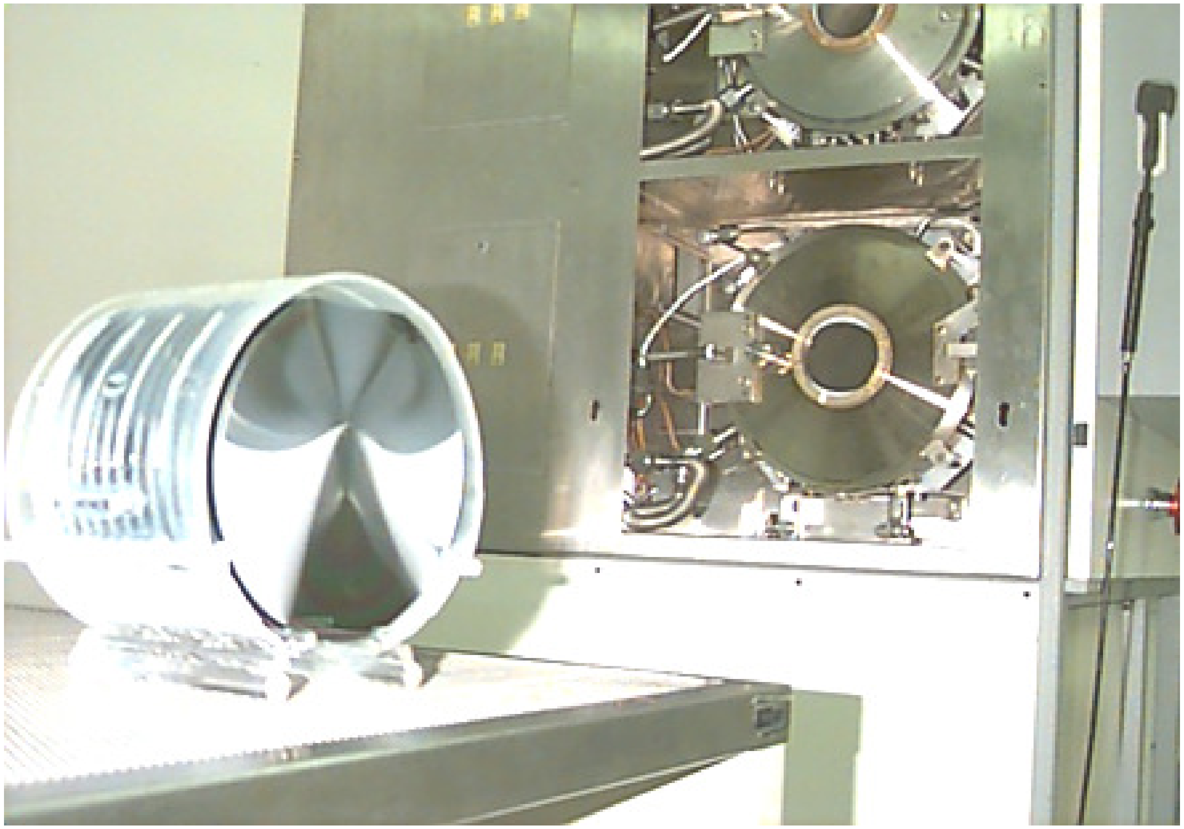
LTO

Wafers are loaded back to back in caged boat. The boat is filled with dummy wafer to total 25 wafers. Monitor wafer is placed in the middle.



Caged Boat

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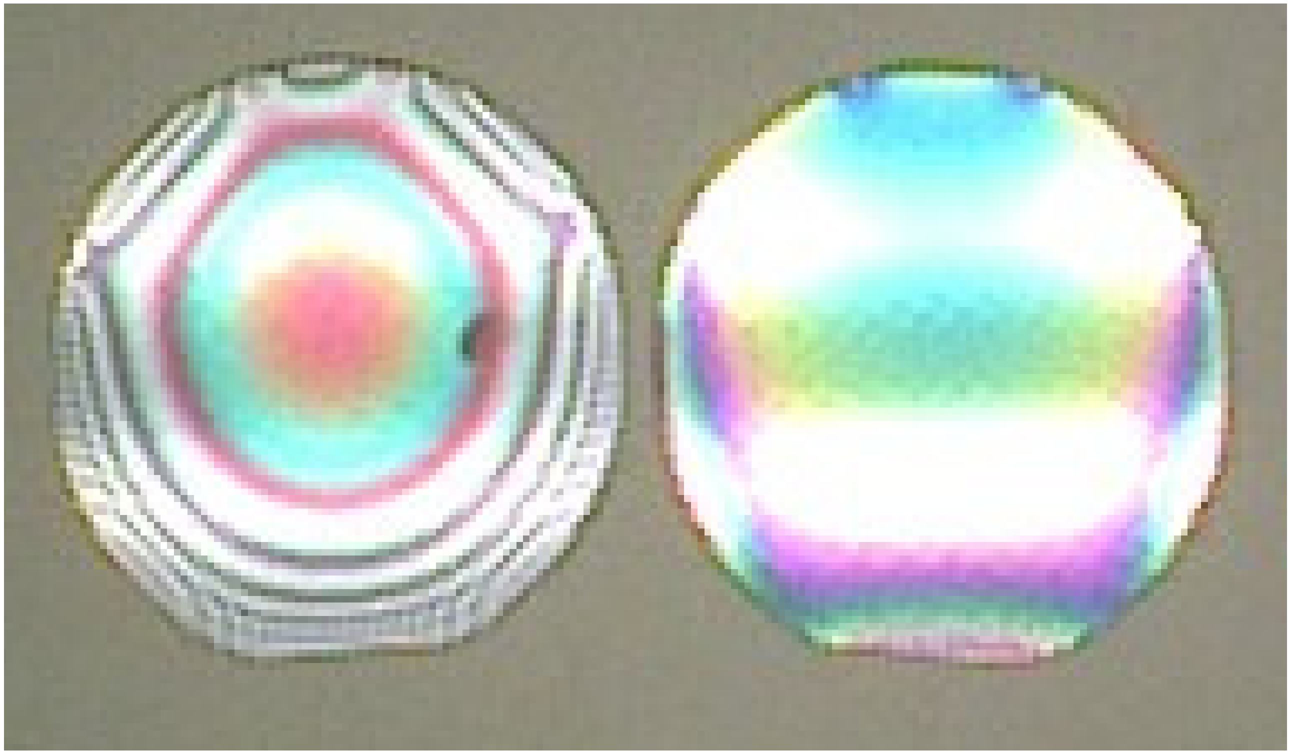
LTO



In 4" LPCVD

Using 6" LPCVD
Caged Boat and Injectors

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PECVD OXIDE FROM TEOS

TEOS Program: (Chamber A)

Step 1

- Setup Time = 15 sec
- Pressure = 9 Torr
- Susceptor Temperature= 390 C
- Susceptor Spacing= 220 mils
- RF Power = 0 watts
- TEOS Flow = 400 scc
- O2 Flow = 285 scc

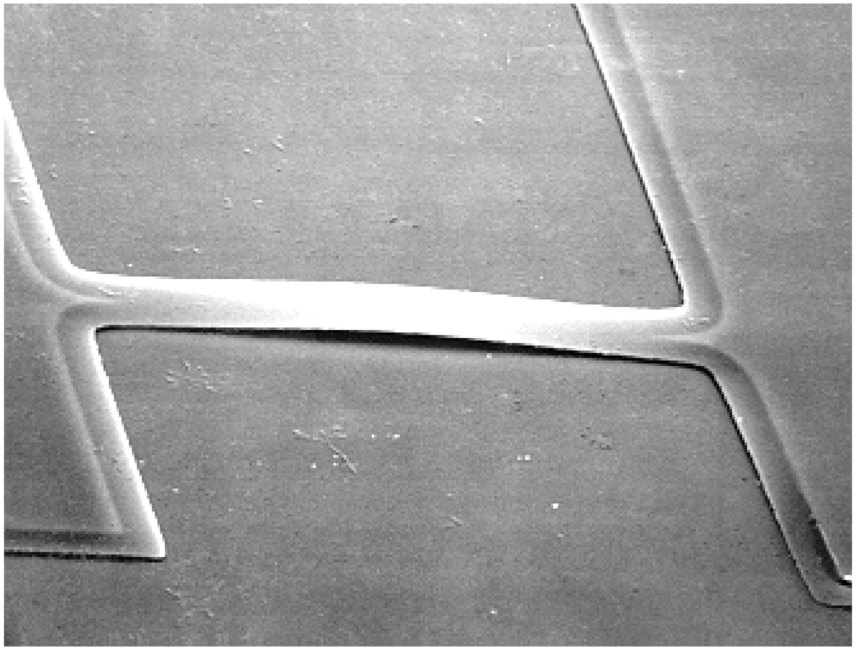
Step 2 – Deposition

- Dep Time = 55 sec (5000 Å)
- Pressure = 9 Torr
- Susceptor Temperature= 390 C
- Susceptor Spacing= 220 mils
- RF Power = 205 watts
- TEOS Flow = 400 scc
- O2 Flow = 285 scc

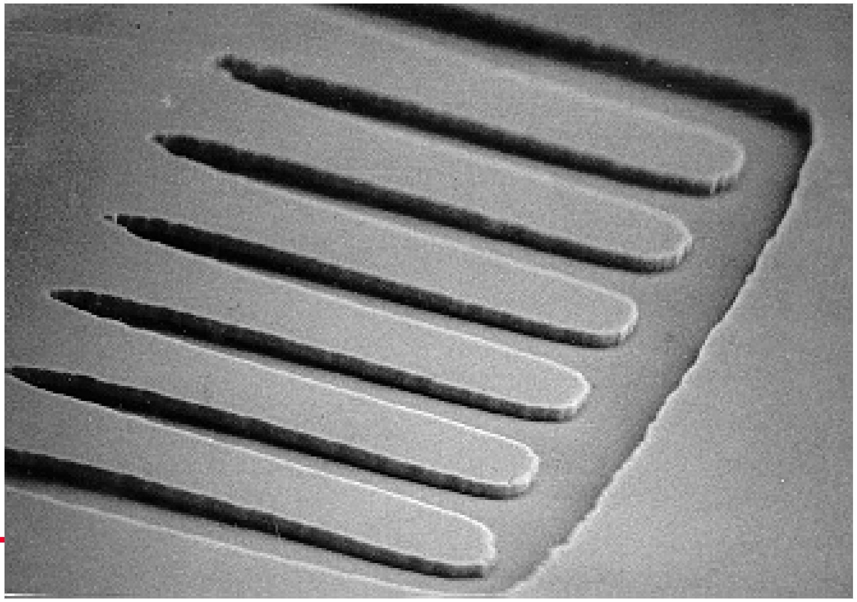
Step 3 – Clean

- Time = 10 sec
- Pressure = Fully Open
- Susceptor Temperature= 390 C
- Susceptor Spacing= 999 mils
- RF Power = 50 watts
- TEOS Flow = 0 scc
- O2 Flow = 285 scc

STRESS IN POLY AND NITRIDE FILMS



Stress in poly films can cause buckling and bending of beams and cantilever structures. When doping poly after deposition the high temperatures (1000 C) anneal stress. Undoped poly structures require an anneal.



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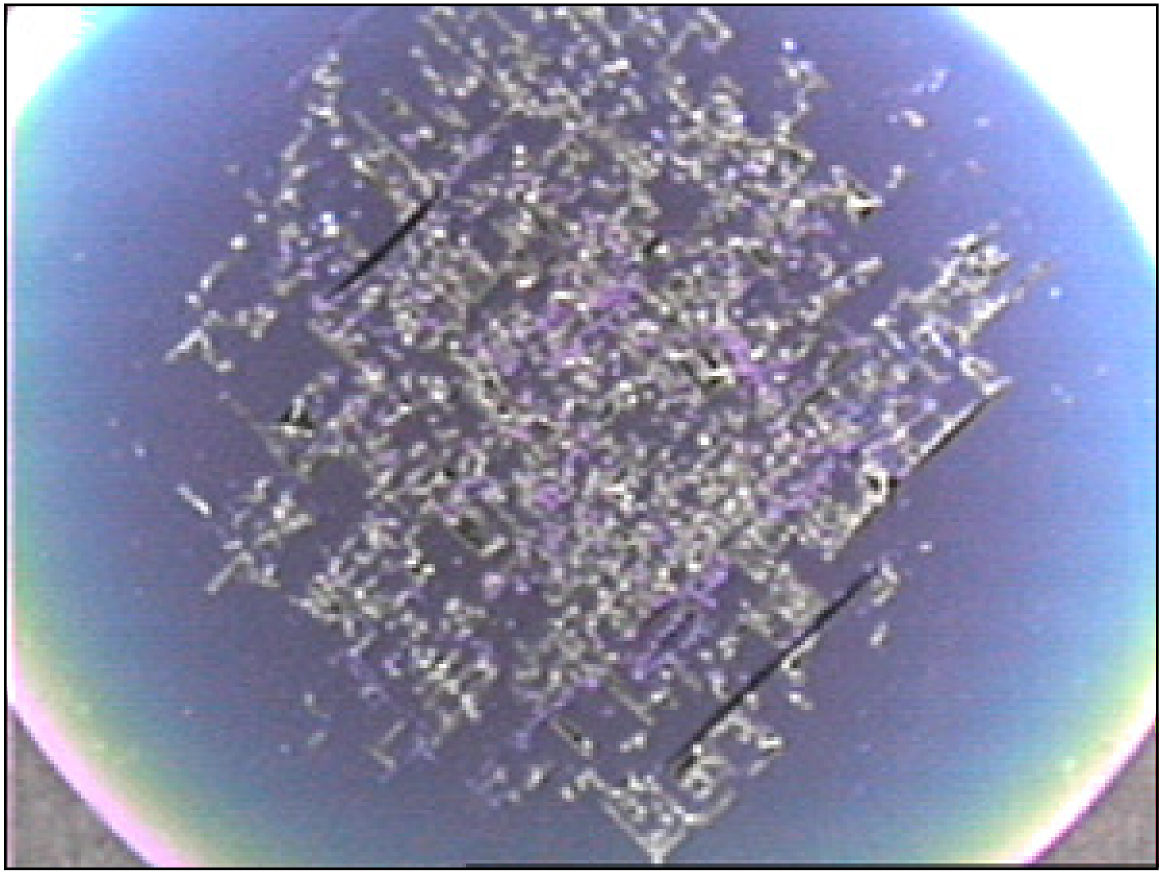
STRESS IN NITRIDE FILMS

Stress in an 8000 A Nitride Film causing fracture



LOW STRESS SILICON RICH Si_3N_4

ADE Measured stress for various Dichlorosilane:Ammonia Flow Ratios

Flow	Stress x E 9 dynes/cm2
10:1	+14.63
5:1	+14.81
2.5:1	+12.47
1:1	+10.13
1:2.5	+7.79*
1:5	+3
1:10	0

*standard recipe

Stress; $\sigma = (E/(6(1-v)))*(D^2/(rt))$

where E is Youngs modulus,
v is Poissons ratio,
D and t are substrate and film thickness
r is radius of curvature (+ for tensile)

T.H Wu, "Stress in PSG and Nitride Films as Related to Film Properties and Annealing", Solid State Technology, p 65-71,May '92

10 dyne/cm^2 = 1 newton/m^2 = 1 Pascal

MEASUREMENT OF STRESS IN Si3N4

Kenneth L. Way, Jr. did his senior project on stress in silicon nitride films as a function of the ratio of ammonia to dichlorosilane. Samples were coated with various flows and stress was measured at ADE corporation. The silicon nitride was etched off of the backside of the wafer so that the stress curvature was due to the layer on the front side only. Dr. Lane said the nitride runs at 1:10 (ammonia:dichlorosilane) ratios are rough on the pumping system.

Dr. Grande sent samples to Kodak for stress measurement. He found stress of +900 MPa Tensile for the standard Nitride recipe for 1500 A thickness, 1-29-2000

10 dyne/cm^2 = 1 newton/m^2 = 1 Pascal

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DEPOSITION OF LOW STRESS SILICON NITRIDE

Si_3N_4 is deposited at 800 C in the LPCVD system, a temperature ramp of 790-800-810 is desired from front to pump. Wafers are loaded with five blank spots then one filler wafer then one to ten device wafers then a bare silicon wafer for thickness measurement.

Films can be deposited up to about 5000 Å directly on silicon before the stress is so large that the film fractures (Dr. Lane, Dr. Fuller). Pad oxide under the nitride film and special silicon rich nitride films may allow nitride film thickness over 5000 Å. The process details for low stress silicon nitride are NH_3 flow of 4% to give 20 sccm and Dicholorosilane flow of 97% to give 200 sccm and a Deposition Pressure of 650 mTorr. Knob settings are 620 at Load, 393 at center and 470 at pump. to get 790-800-810 temperature ramp. The deposition rate is about 80 A/min.

9-6-96 Dr. Fuller did a 100 min deposition giving 8100Å (center) to 8800Å (edge) nitride thickness which did not fracture due to stress. It is a definite improvement.

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NITRIDE THICKNESS COLOR CHART

Thickness	Color
200	Silver
400	Brown
550	Yellow-brown
730	Red Violet
770	Deep Blue
930	Blue
1000	Pale Blue
1100	Very Pale Blue
1200	Silver
1300	Light Yellow
1500	Yellow
1800	Orangfe-Red
1900	Red Violet
2100	Dark Red
2300	Blue
2500	Blue-Green
2800	Light Green
3000	Orange-Yellow
3300	Red Violet

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APPLY PARYLENE

Approximately 1 gm of Parylene C gives ~3000Å film thickness, Deposit 5 wafers per run.

Adhesion Promotor (gammamethacryloxypropyltrimethoxysilane) spin coat 3000 rpm 1 min. Bake 110 C for 2 min. Then load into Parylene Deposition Tool.

See: http://www.scscookson.com/parylene/properties.cfm

PECVD OF CARBON FILM (DIAMOND LIKE FILM)

Drytech Quad Tool
CH_4 flow 45 sccm
50 mTorr
200 Watt
Deposition Rate ~ 320 Å/min
Index of Refraction = 2.0

APCVD TEOS

Oxide from TEOS {tetraethoxysilane, $Si(C_2H_5O)_4$} at Atmospheric Pressure:

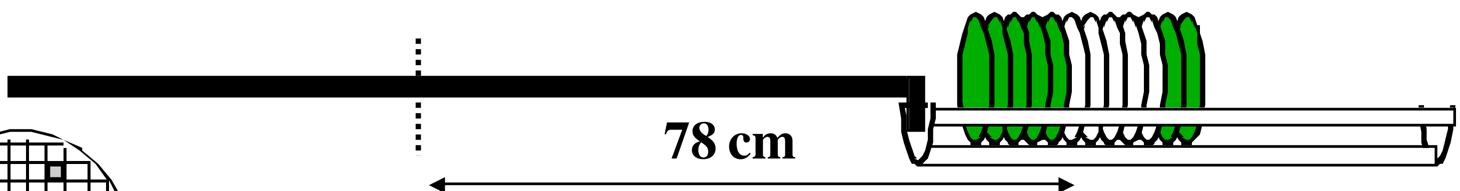
TEOS Bubbler Temperature = 68°C (2 hr warm up)
Furnace Temperature = 640 °C all zones (Tube #15)
Nitrogen Flow = 4.5 L/min
Oxygen Flow = 3 L/min (9 marking)
Nitrogen Carrier Gas Through TEOS Bubbler = 2.6 L/min
(45 marking)
Pressure = atmospheric
Rate = 160 Å/min

$Si(C_2H_5O)_4 > SiO_2 + 4C_2H_4 + 2 H_20$

Dan Ma
June 7, 1998

LPCVD

The placement of the wafers in the boat and the placement of the boat in the furnace and the temperature of the furnace all affect the deposition rate. Rates from 35 A/min to 100 A/min have been observed with basically the same LPCVD recipe. 80 A/min was obtained by simply spacing the dummy wafers and the device wafers in every other slot in the boat. Starting in the 5th slot place 5 dummy wafers in every other slot followed by 5 device wafers and two dummies all spaced every other slot. Place the boat such that the 1st device wafer is slightly closer to the door so that all device wafers are forward with respect to the center of the furnace. 5 or 10 degrees hotter will also give a higher deposition rate. For thick layers do the deposition in two runs and switch the order to give more uniform deposition. Flats up and all wafers pretty much vertical also helps uniformity. These films are not as dense as thermal oxide. They etch faster in BHF and KOH etches.



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EPITAXY

Epitaxial Layer Growth is the formation of single crystal material on a single crystal substrate.

$$SiCl_4 + 2H_2 \rightleftarrows Si + 4\,HCl$$

Allows lightly doped layers to be grown on top of heavily doped material, which is impossible through diffusion. Thickness from 1 to 20 micrometers and doping from 1E15 cm-3 to 1E17 cm-3

Deposition rate of 0.4 to 1.5 microns/minute at 1150-1230 °C

SPIN COATING

N-Type Spin-on diffusion Source
- Allied Diffusion Technology P854
- Emulsitone N250
- Emulsitone Arsenocilica Film

P-Type Spin-on Diffusion Source
- Allied Accuspin B-150
- Emulsitone Borofilm 100

Spin-on Glass
- Allied-Accuspin 211, 311, 512
- Emulsitone 4%Boron/4%Phosphorous Glass

Prices ~$150 for 125ml Bottle
Allied Signal Inc.
1090 S. Milpitas Blvd
Milpitas, CA 95035
Tel (408) 946-4211

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POLYIMIDE

Polyimide has a melting point of 450 C, can be spin coated and imaged with lithographic processes making it useful for many applications.

Using DuPont Corporations PI-2555 we can get film thickness between 2.5 µm @ 5000 rpm and 5.0 µm @ 1500 rpm. It is cured by placing on 120 °C hot plate for 30 min. and then on a 350 °C hot plate for 30 min. Multilayer coatings can give thickness greater than 10 µm. (a 500 gm bottle costs ~$250) Du Pont Co., Electronic Materials Division, Barley Mill Plaza, Reynolds Mill Building, Wilmington, DE 19898 (800)441-7543

OCG Microelectronic Materials, Belgium, makes a polyimide "Proimide 114A" which we have used.

These film are easily imaged using an aluminum barrier layer and conventional photoresist (such as Shipley System-8) followed by Oxygen Reactive Ion Etch.

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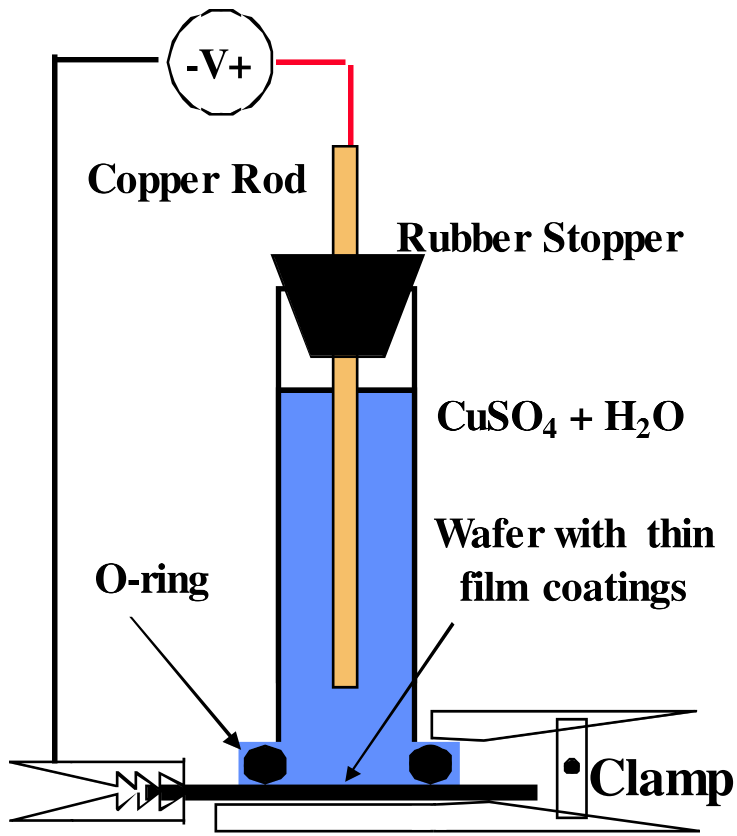
COPPER PLATING

Mix about 65g of Copper Sulfate ($CuSO_4$) crystals to 200 ml of water plus water. Make sure there are no undissolved solids in the mixture. When done, the solution should look dark blue. To increase the conductivity of the solution, add about 5 ml of Sulfuric acid using a pipette.

Wet the O-ring to make a better seal.

Set the DC voltage supply to get a current density of about 3 mA/cm2. (15 mA for 1 inch diameter circular area of exposed copper) Plate copper for about 45 min.

$CuSO_4 + H_2O \Rightarrow Cu^{2+} + SO^{2-}_4 + H_2O$



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COPPER PLATING

Copper Sulfate ($CuSO_4$) + water- $CuSO_4 + H_2O => Cu^{2+} + SO^{2-}{}_4 + H_2O$

When a voltage is applied and a current flows, the copper ions (Cu^{2+}) will move towards the negative electrode (cathode), where it gains an electron and becomes a copper molecule (2Cu). At the same time the sulfate ion ($SO^{2-}{}_4$) will be attracted to the anode where it becomes a sulfate molecule.

Adhesion and uniformity of the plating is a function of the rate of deposition and the substrate material. It was found that Cu will not plate on aluminum or chrome but will plate on nickel but nickel will not stick to aluminum so the following film stack was used to plate onto silicon (for solder bump contacts). Plated Copper (2 to 10 µm) on evaporated Copper (2500 A) on Nickel (2400 A) on Chrome (1000 A) on Aluminum (7000 A) on Silicon.

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COPPER PLATING APPARATUS

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GOLD PLATING

Electroless gold solution can be used on copper or nickel films. This chemically replace copper atoms with gold atoms. Can only plate up to the original copper film thickness. Immerse copper in heated 80 C gold plating bath for 10 min.

Electroplating of gold is also common.

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NICKEL PLATING

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EVALUATION OF FILM PROPERTIES

Thickness
Stress
Morphology
Stociometery
Grain Size
Contact Angle
More

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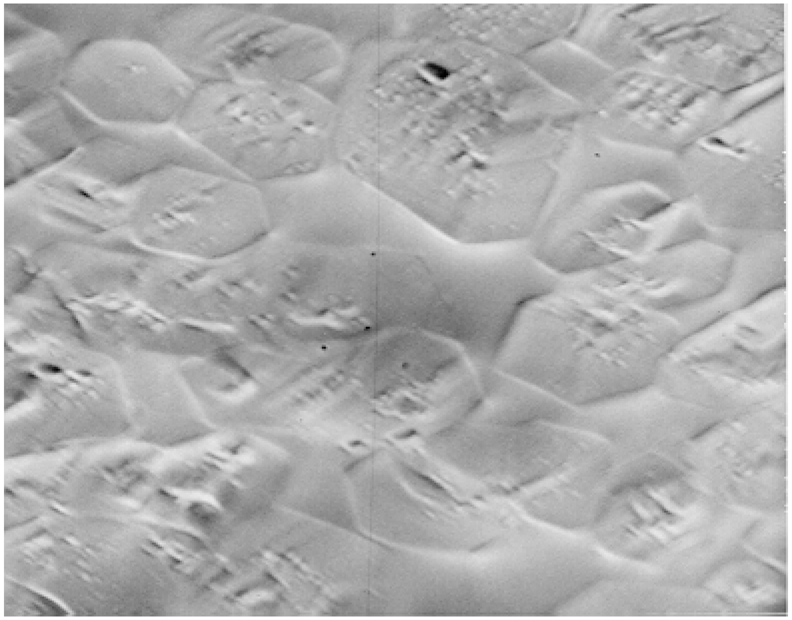
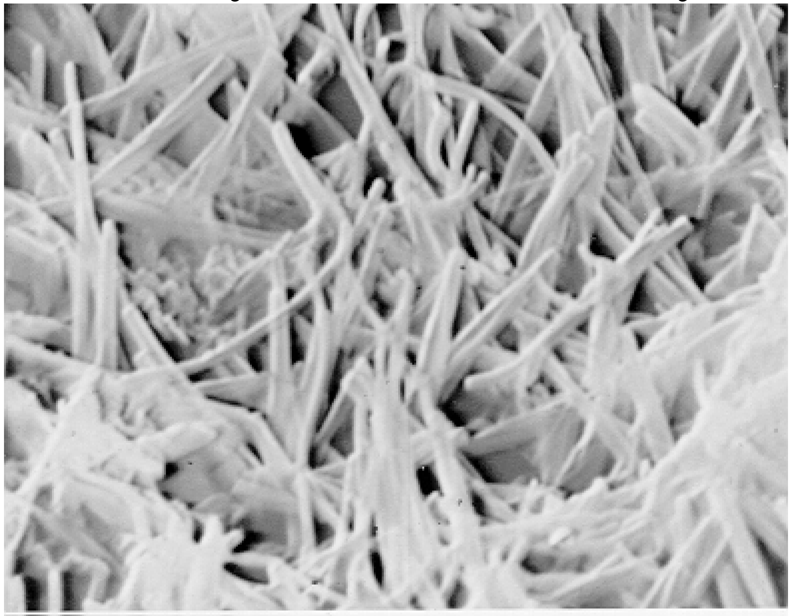
SEM OF FILM MORPHOLOGY



Polysilicon Substrate

Polymer Film on Poly



6-7-99

WAFER BONDING

Wafer Bonding

- With Intermediate Layer
  - Sodium-Silicate
  - Sputtered Pyrex
  - Adhesive
  - Eutectic
  - Thermal Oxide
  - Glass
- Without Intermediate Layer
  - Direct
  - Anodic
  - Field Assisted
  - Electrostatic

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WAFER BONDING

Silicon Direct: No Voltage, Temp 800 to 1100 C,
No Intermediate Layer, Very Clean Surface, Very Flat Surface

Anodic (Glass to Silicon): Voltage 300 to 2000, Temp 300 to 500 C,
No Intermediate Layer, Special Glass Required (7740)

Sputtered Pyrex: Voltage 20 to 200, Temp 300 to 500, Layer 1 to 5 µm

Thermal Oxide: Voltage 10 to 30, Temp 1100 C, Layer 1 to 3 µm

Spin On Glass: No Voltage, Temp 200 to 500 C, Layer 30 to 100 nm,
borosilicate or phosphoro/borosilicate spin on glass.

Eutectic: No Voltage, Temp just below Eutectic Point, Scrubbing
Action and Pressure Needed,

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DIRECT Si-Si FUSION BONDING

Direct fusion bonding - two wafers with or without SiO2 can be directly bonded by placing them together and heating to 800 C and followed by anneal at temperatures up to 1100 C in oxygen or nitrogen. The two surfaces can be hydrophilic or hydrophobic. (The RCA clean makes the surface of bare silicon wafers hydrophilic. An HF dip makes the surface hydrophobic.)

See Karl Suss tools for wafer bonding www.suss.com

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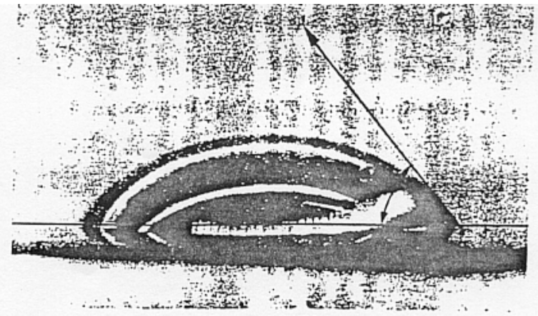
SURFACE PREPARATION

RCA clean followed by 10 min HF gives contact angle of 52°, Hydrophobic Surface

RCA clean gives contact angle of 4.5°, Hydrophilic Surface



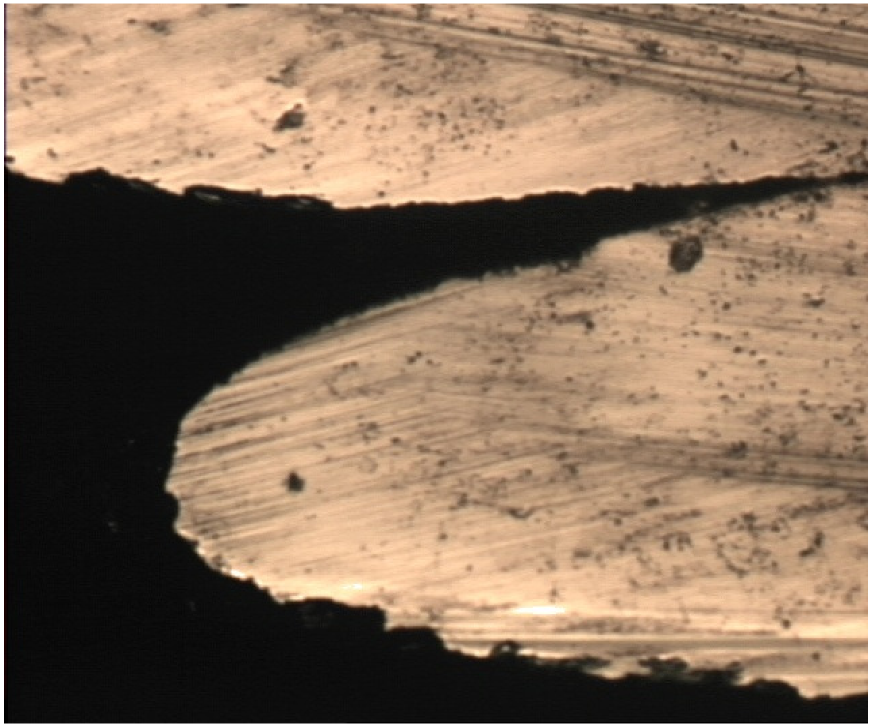
Contact angle measurement of a water drop on a silicon surface

(A) RCA clean
$NH_4OH:H_2O_2:H_2O = 1:1:6$ for 10 min at 75 °C,
$HCl:H_2O_2:H_2O = 1:1:6$ for 10 min at 75 °C,
(B) $H_2O:H_2O_2:NH_4OH = 6:1:4$ for 10 min at 55 °C
(C) RCA clean and 65% HNO_3 for 10 min
(D) RCA clean and 2% HF for 10 min
(E) $H_2SO_4:H_2O_2 = 5:1$ for 10 min
(F) 30% H_2SO_4 for 10 min

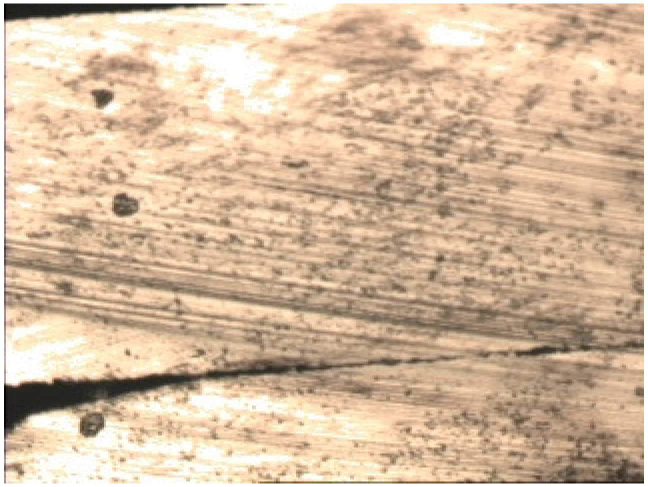
At the end of the pretreatments the wafers were always rinsed in deionized water.

pretreatment	direct after pretreatment	5 h	27 h	3 d	6 d
A	4.5°	5.5°	9°	16°	20°
B	5.5°	4°	5.5°	7.5°	12°
C	1°	4°	4°	12.5°	16.5°
D	52°	61°	63.5°	59.5°	57°
E	1.5°	4°	6°	17°	22°
F	51°	46°	45°	47.5°	45°

WAFER BONDING RESULTS



Shiny surfaces against each other,
- 1100 C in Furnace14
- time = 30 minutes
- dry O2 (5 lpm)



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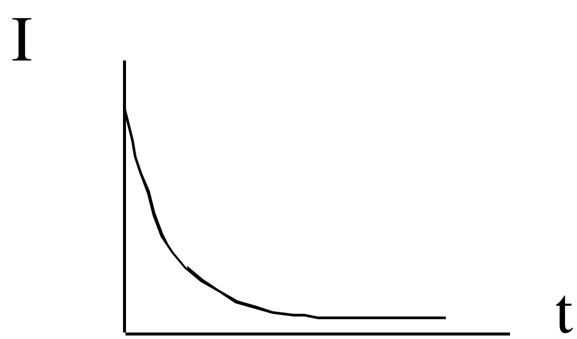
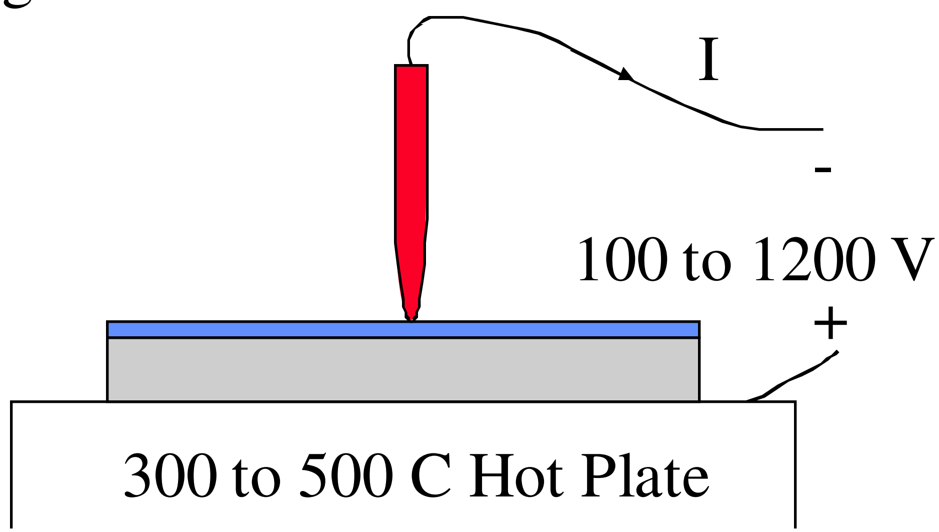
ANODIC BONDING

Anodic bonding is used to permanently bond a glass sheet to a silicon wafer at low temperature (~400C) using a combination of heat and high electric field.

1. Place glass (e.g. Corning 7740) sheet on silicon wafer.
2. Heat to ~400 C
3. Apply positive voltage to silicon wafer (up to 1200V)





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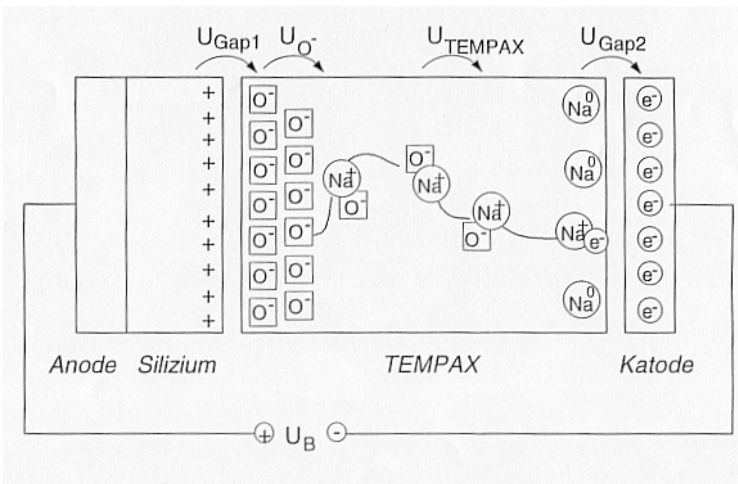
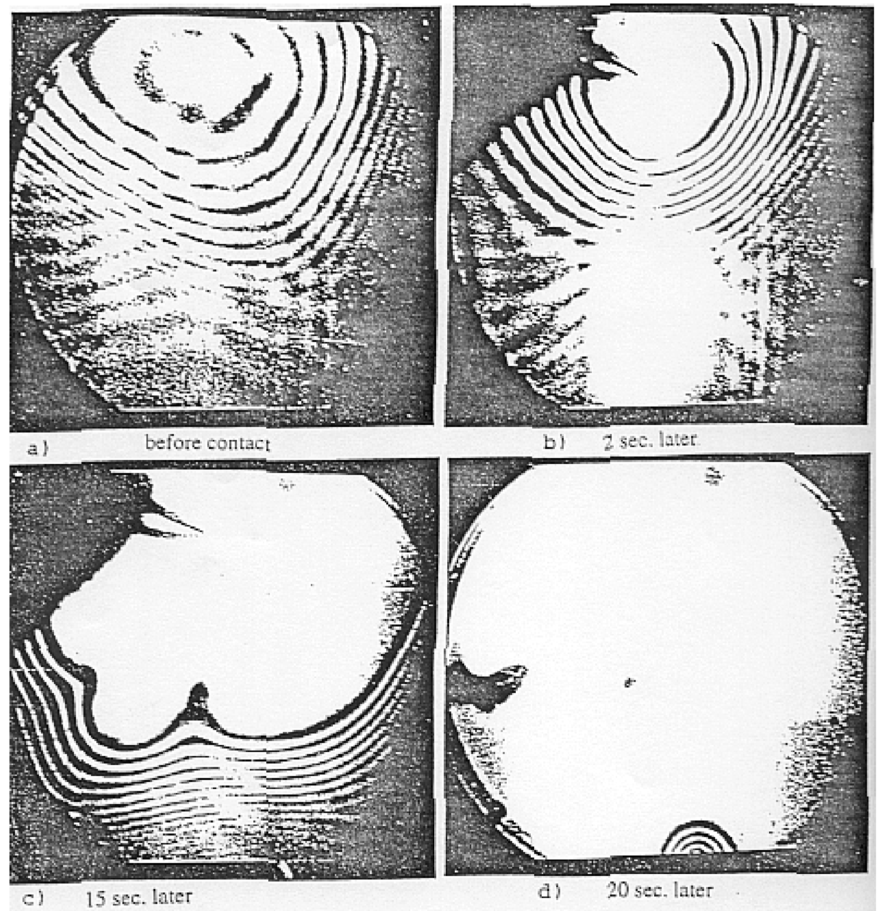
INFRARED TIME LAPSE OF ANODIC BONDING

Left to right, before contact 2 seconds later, 15 seconds later, 20 seconds later.



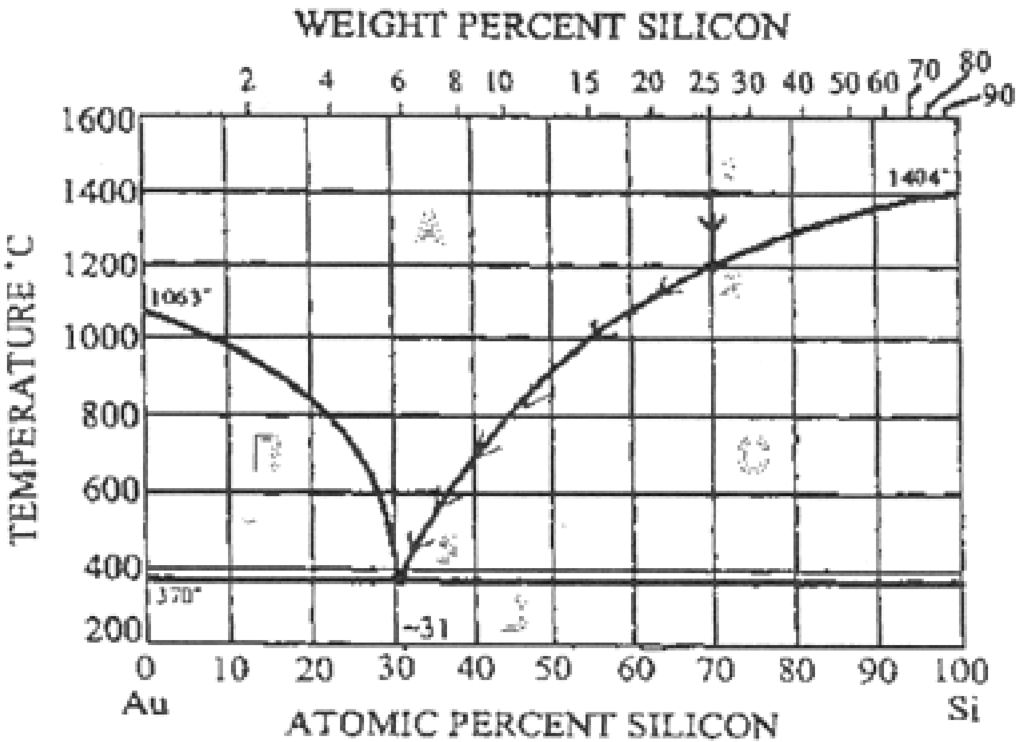


EUTECTIC BONDING

Gold and Silicon form a eutectic at 370 C

Aluminum Silicon at 570 C

Bonding occurs as metal diffuses into the Silicon and Silicon diffuses into the metal



METHOD OF TESTING BOND

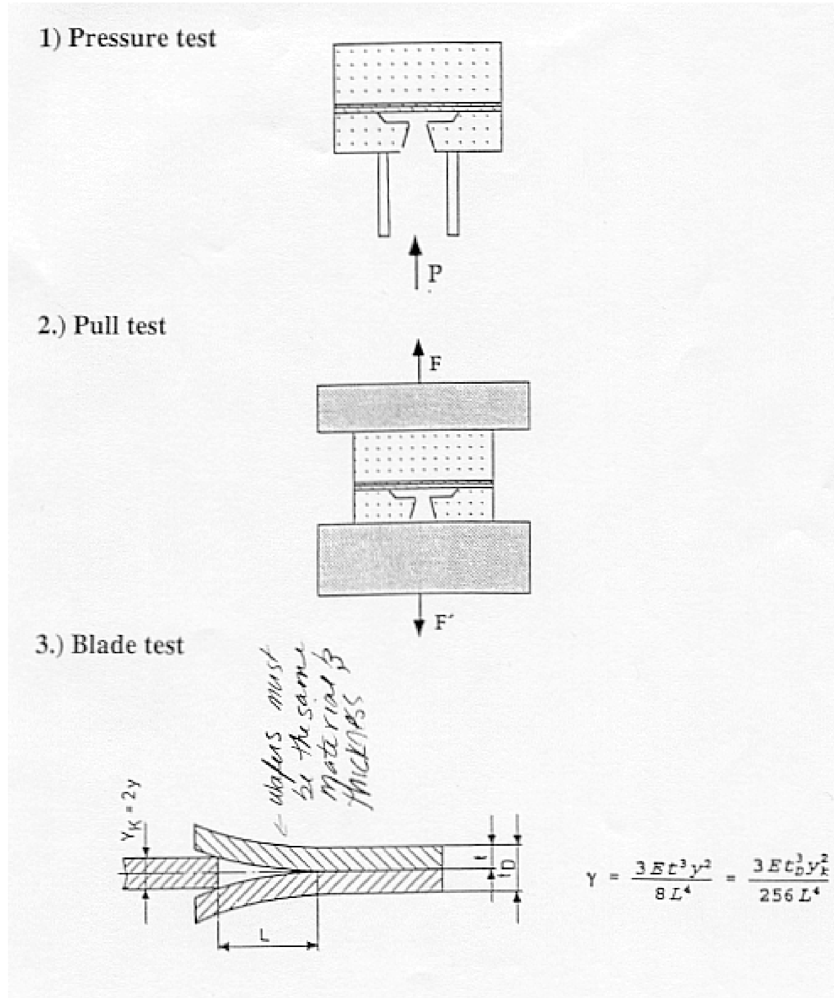
Measure the bond strength in force per unit area, N/m²

Silicon fusion bonds have strengths ~2E7 N/ m²

Low Temperature Glass Bonds ~2E7 N/m²

Anodic bonds ~2E6 N/m²

Polymer bonds ~1N/m²



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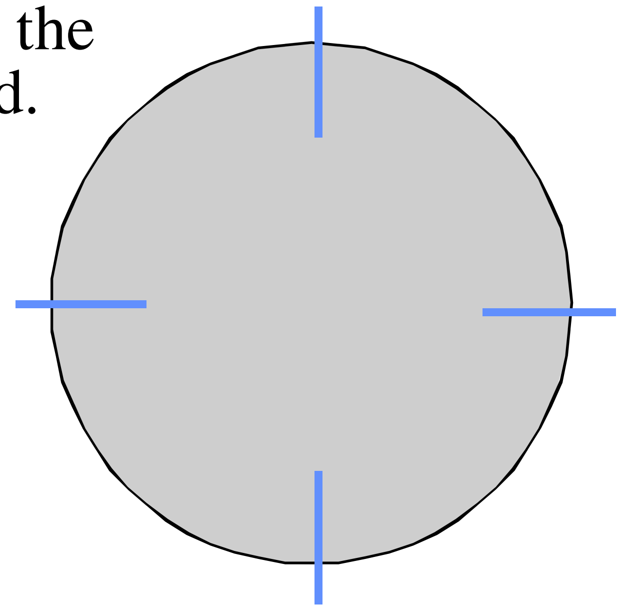
METHOD FOR ALIGNMENT

Two (or four) cylindrical optical fibers or wires are placed in V groves etched near the edge of each wafer. The two wafers are brought together, the wires are removed and the wafers are bonded.



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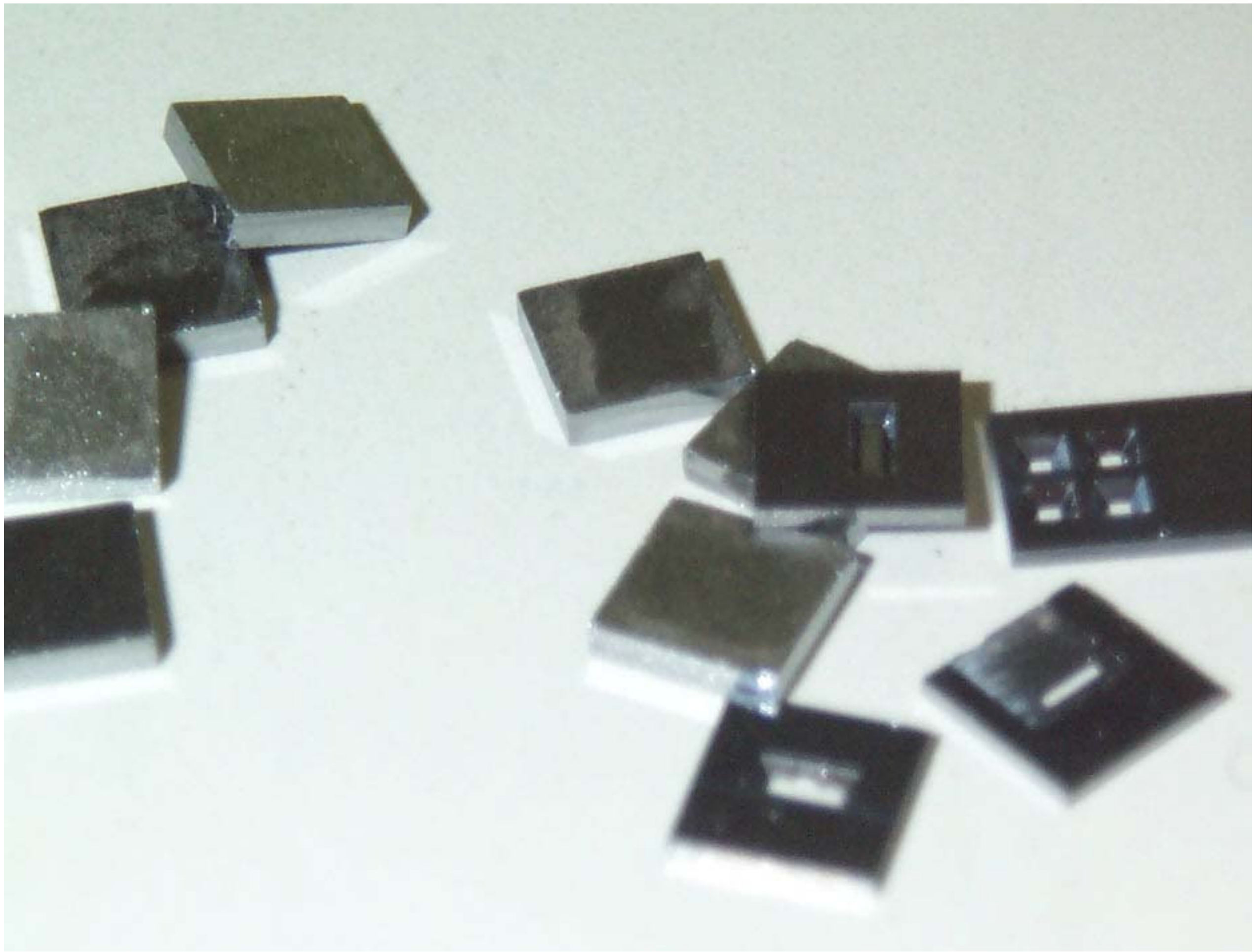
FUEL INJECTOR PROJECT



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3. Supplier of evaporation and sputtering supplies, R.D.Mathis, P.O. Box 92916 Long Beach, CA 90809-2916, www.rdmathis.com

4. Silicon Wafer Bonding Technology for VLSI and MEMs Applications, S.S. Iyer and A.J. Auberton-Herve editors, 170pp., ISBN 0 85296 039 5, January 2002, £49 / US $79 http://www.iee.org/Publish/Books/Emisp/

HOMEWORK - MEMS DEPOSITION

1. Design a process to deposit a 1000 Å nitride layer on a silicon wafer followed by a 0.5 µm polysilicon layer followed by a 1000 Å nitride layer followed by a 1.6µm sacrificial oxide layer followed by a 2.0 µm Poly layer.
2. Read Wikipedia description of silicon wafer bonding – Direct Bonding.

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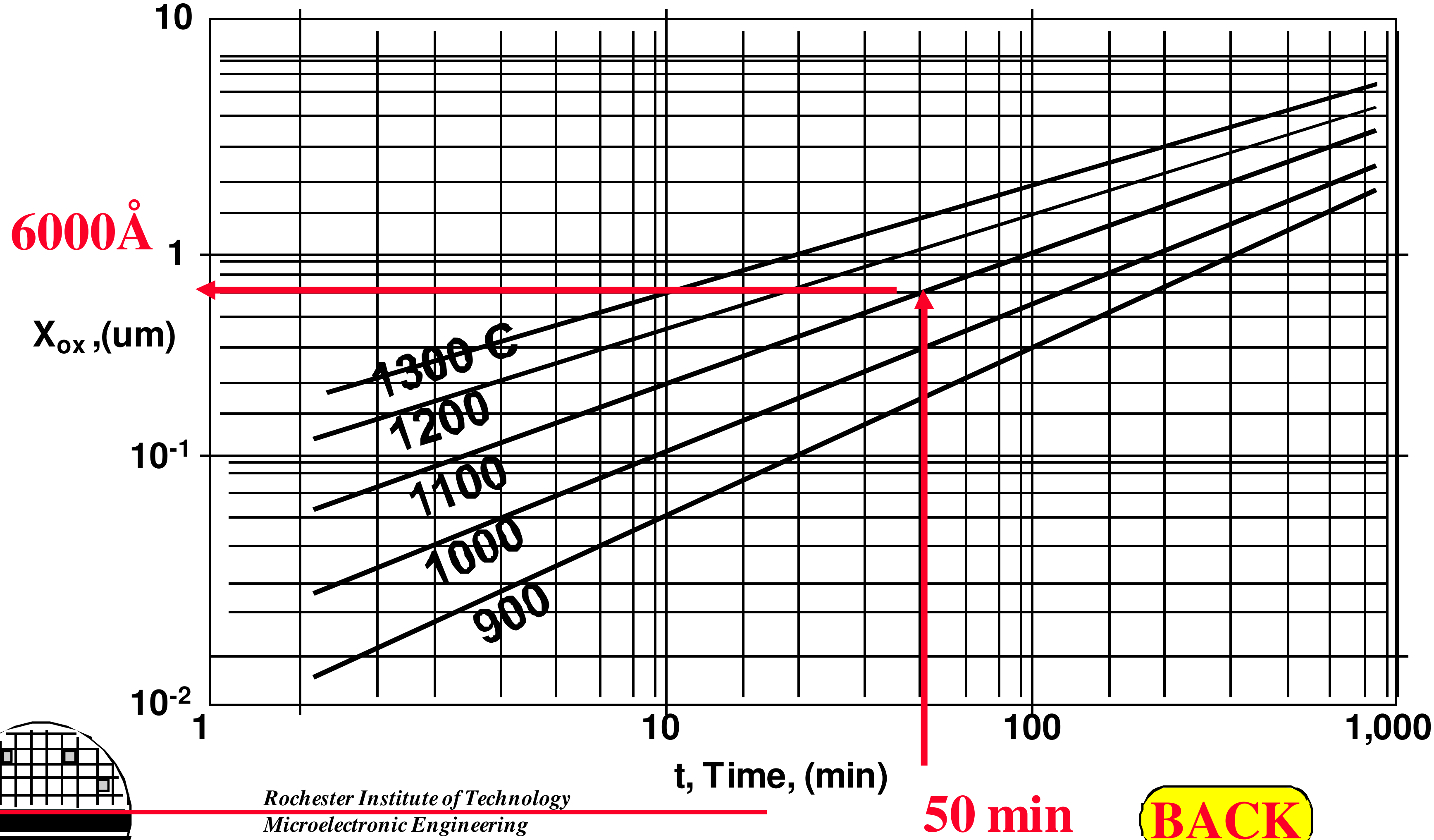
WET OXIDE GROWTH CHART EXAMPLE 1



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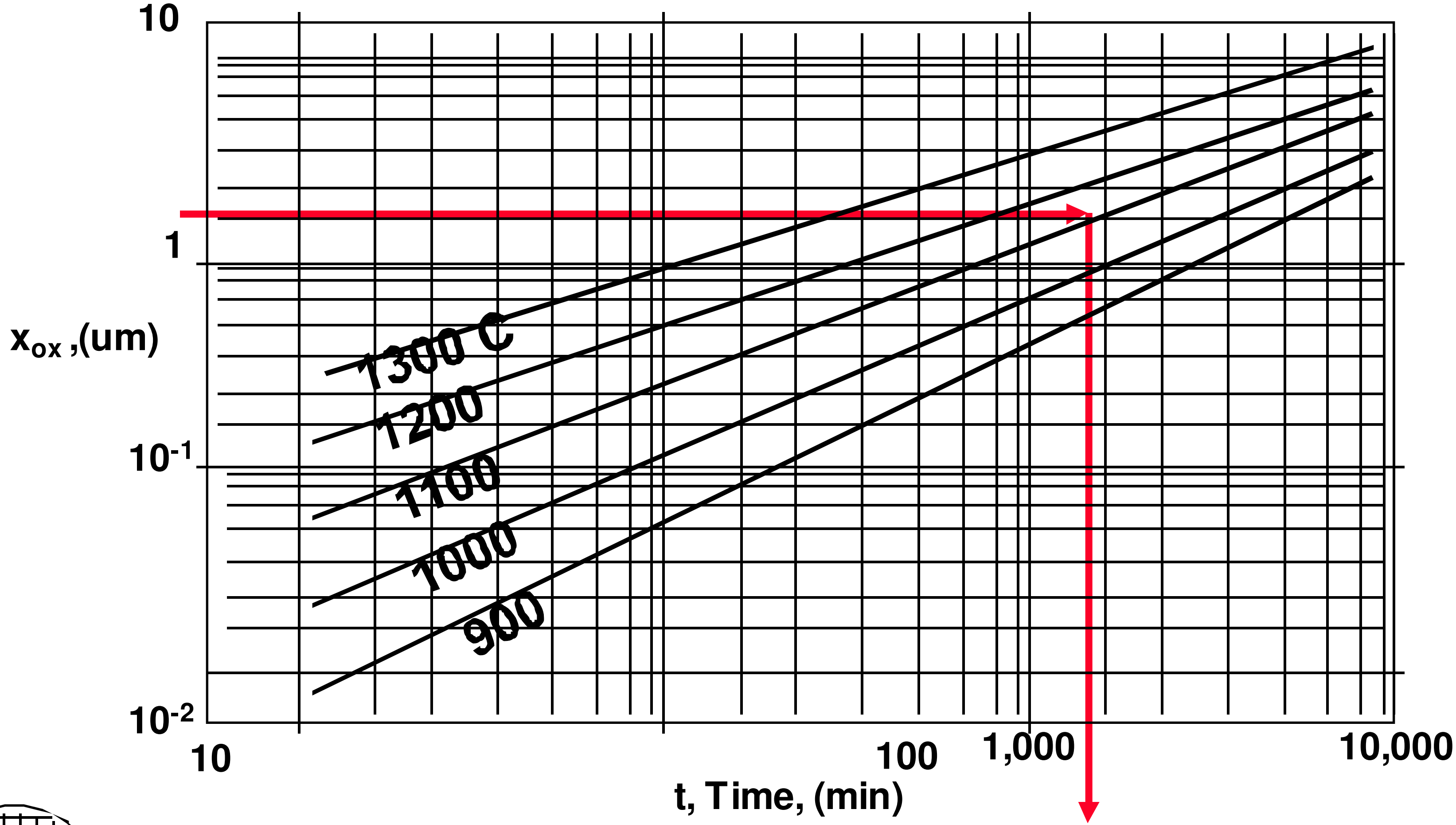
DRY OXIDE GROWTH CHART EXAMPLE 2



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BACK

EXAMPLE

1. A predeposit from a p-type spin-on dopant into a 1E15 cm-3 wafer is done at 1100°C for 10 min. Calculate the resulting junction depth and dose.

No = 5.175E20 cm-3, D = 1.55E-13 cm2/s

$3.4 = xj/2\sqrt{Dt}$

xj = 0.656 µm

Dose = 5.633E15 cm-2

2. The spin-on dopant is removed and the Boron is driven in for 2 hours at 1100 °C. What is the new junction depth?

xj = 2.26 µm