Outline

1 Introduction

2 Basic IC fabrication processes

3 Fabrication techniques for MEMS

4 Applications

5 Mechanics issues on MEMS

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2. Basic IC fabrication processes

2.1 Deposition and growth

2.2 Photolithography

2.3 Etching

2.4 Bonding

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2.4 Bonding

- Bonding is the process to assemble individual components in micromachining
- In order to construct a complete micromachined device, micromachining of individual components as well as assembly of these components is required
- Bonding process can be achieved by several techniques

  + Silicon fusion bonding (SFB)

  + Anodic bonding (silicon - glass)

  + Silicon - silicon anodic bonding

  + Others

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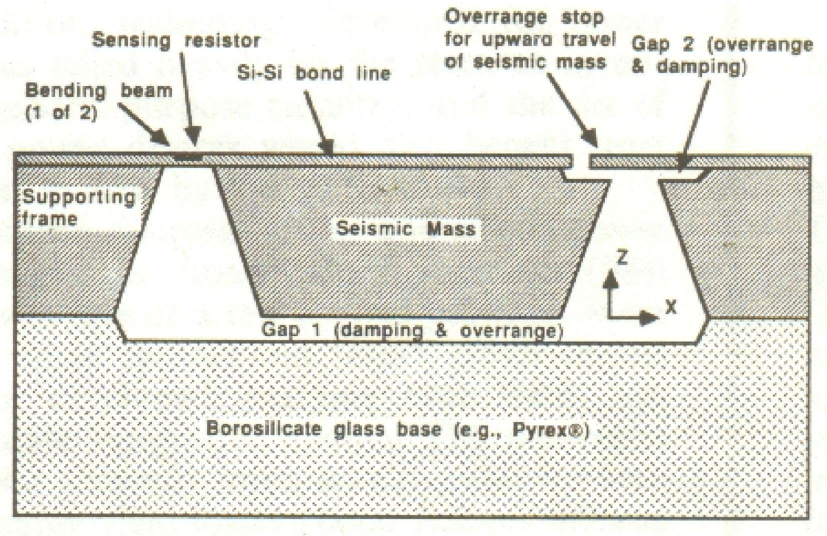
- **Bonding applied to improve reliability**



P.W. Barth, Sensors and Actuators A, 1990.

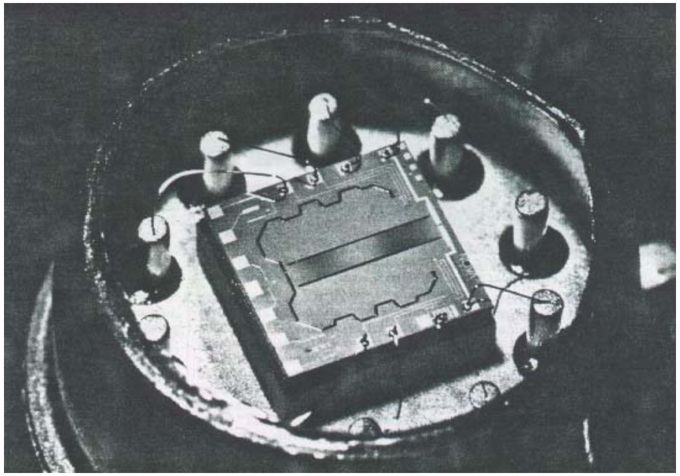


Figure source: L. O'Connor, Mechanical Engineering, 1992

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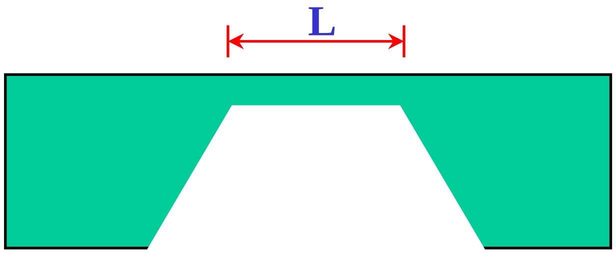
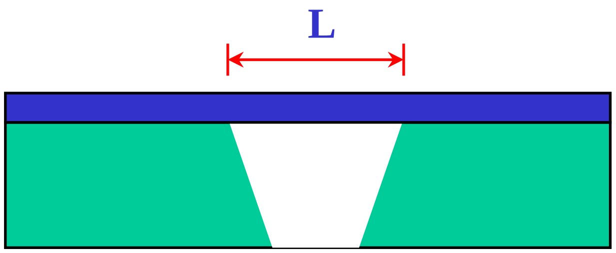
- Bonding applied to reduce space and cost, for example, micromachined membrane for pressure sensor

+ Bulk micromachining through backside etching



+ Bonding



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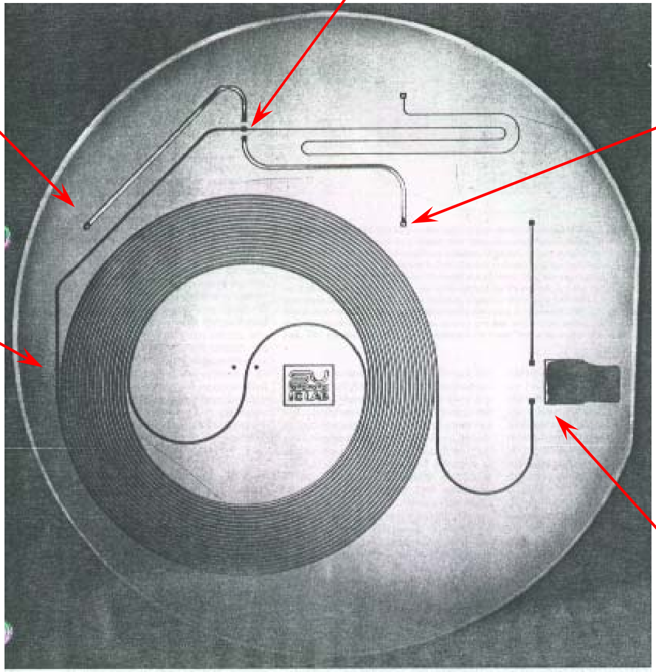
- **Bonding is required to construct the devices**

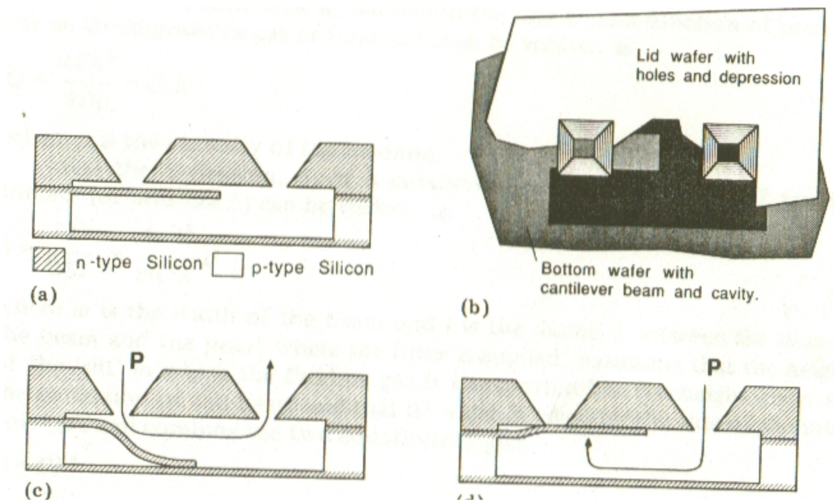
  + **Gas chromatograph**



S.C. Terry, Ph.D. thesis, 1975.
S.C. Terry, J.H. Jerman and J.B. Angell, IEEE Transaction on ED, 1979.

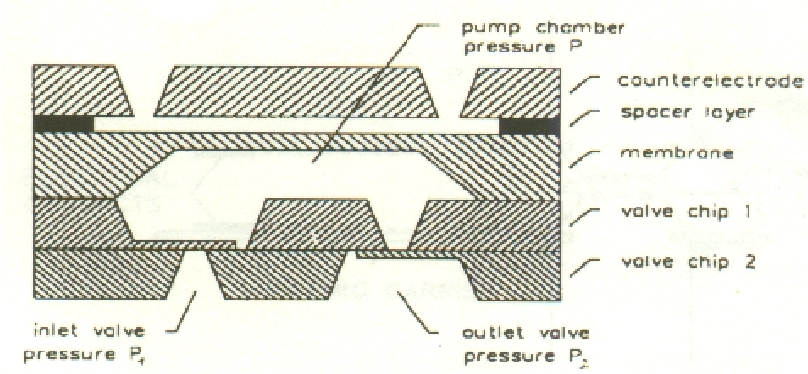
+ Microfluid devices

1. Valve



J. Tiren, L. Tenerz, and B. Hok,
Sensors and Actuators, 1989.

2. Pump



S. Shoji and M. Esashi, J.
Micromechanics and Microeng., 1994

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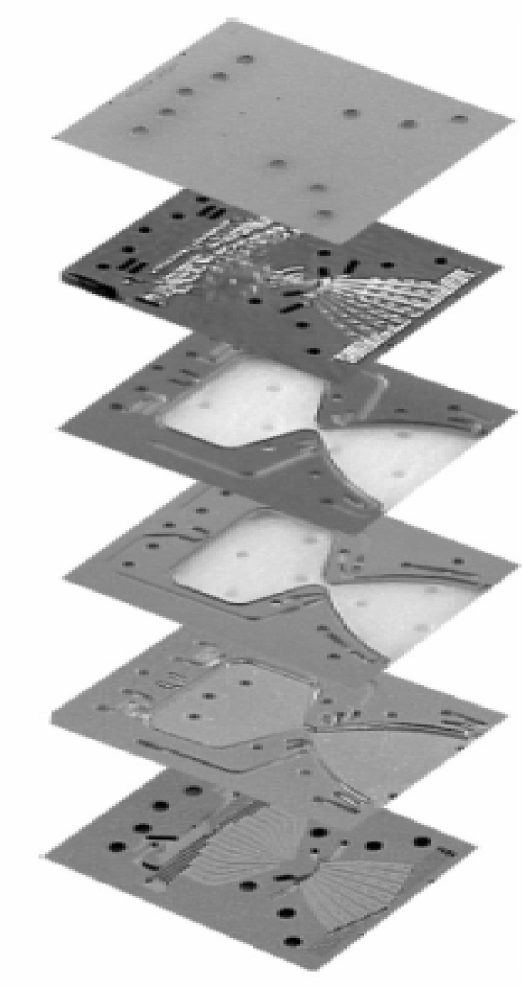
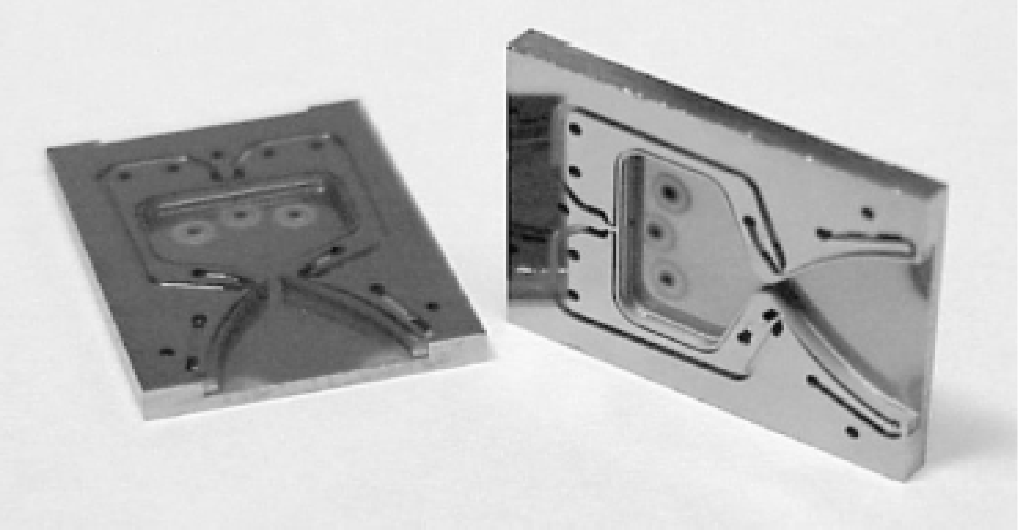
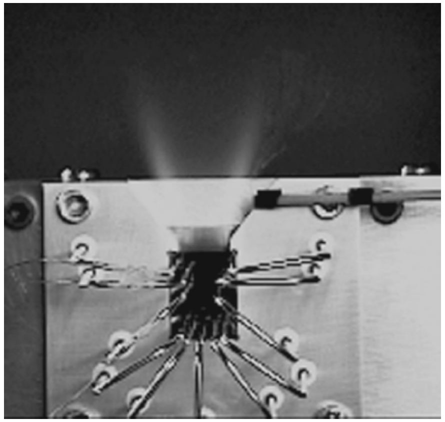
+ Microfluid system







A.P. London, A.A. Ayon, A.H. Epstein, S.M. Speating,T. Harrison, Y. Peles, J.L. Kerrebrock, 2001

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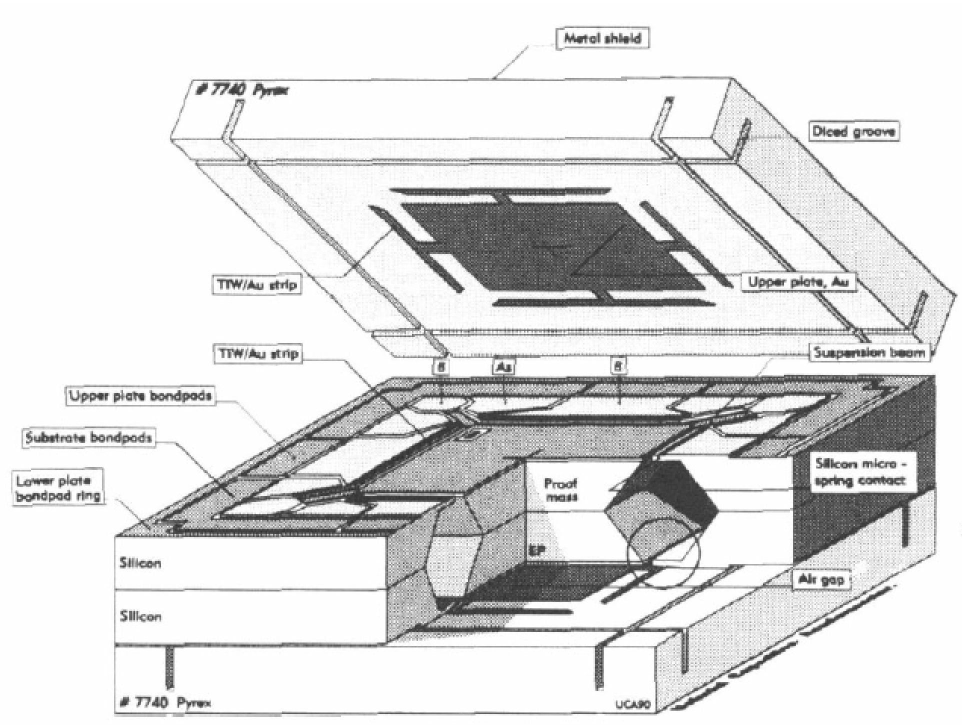
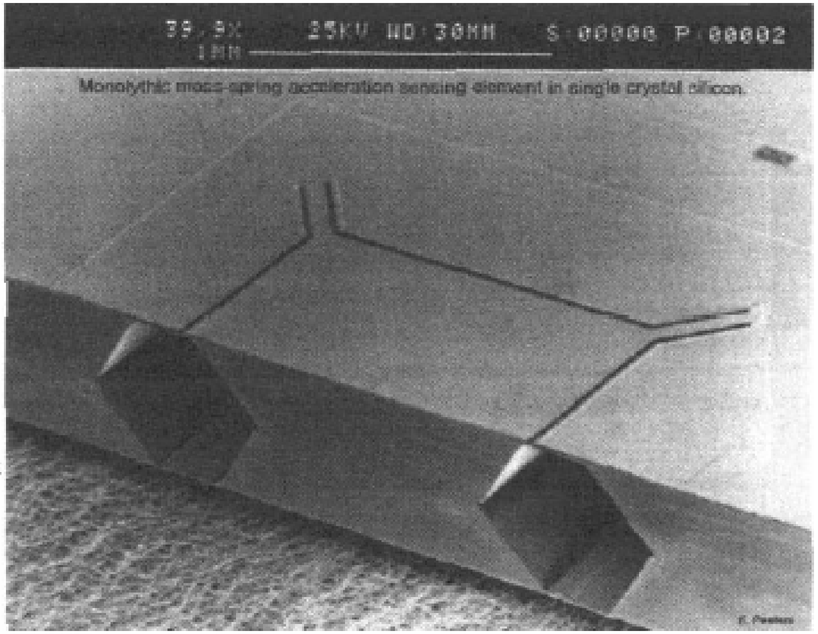
+ Capacitive accelerometer





E. Peeters, S. Vergote, B. Puers and W. Sansen, 1992

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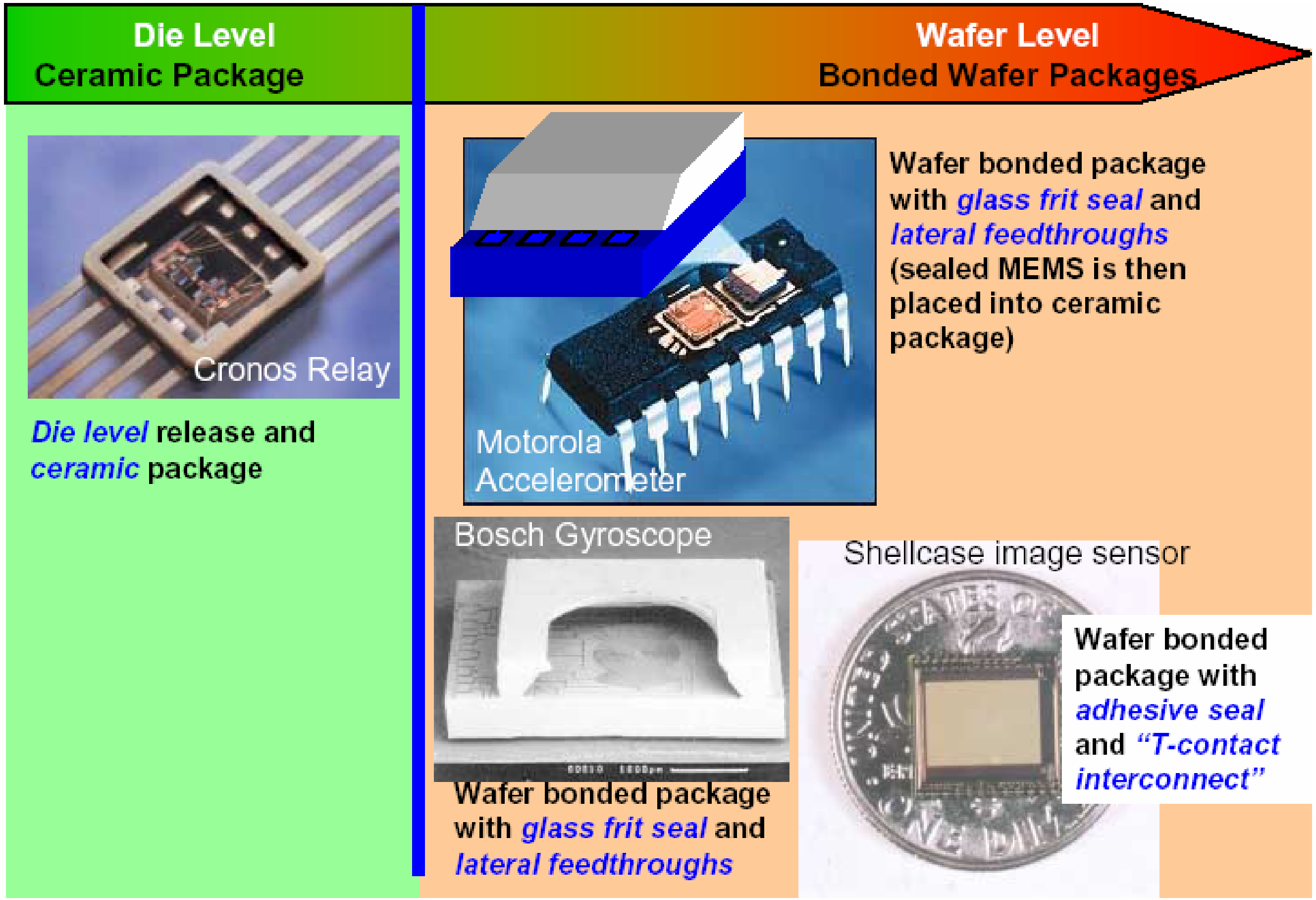
- **MEMS packaging**



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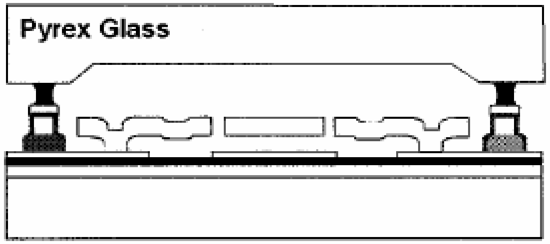
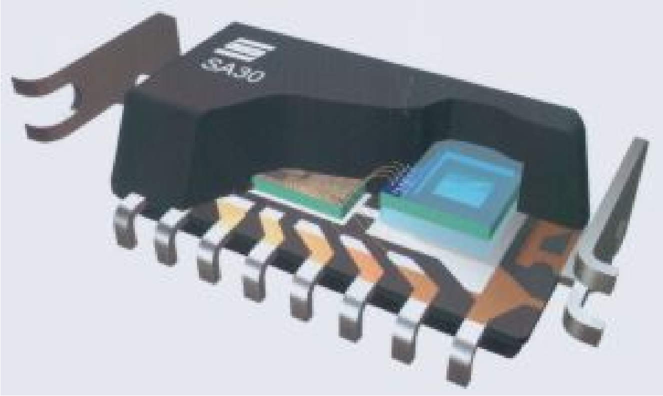
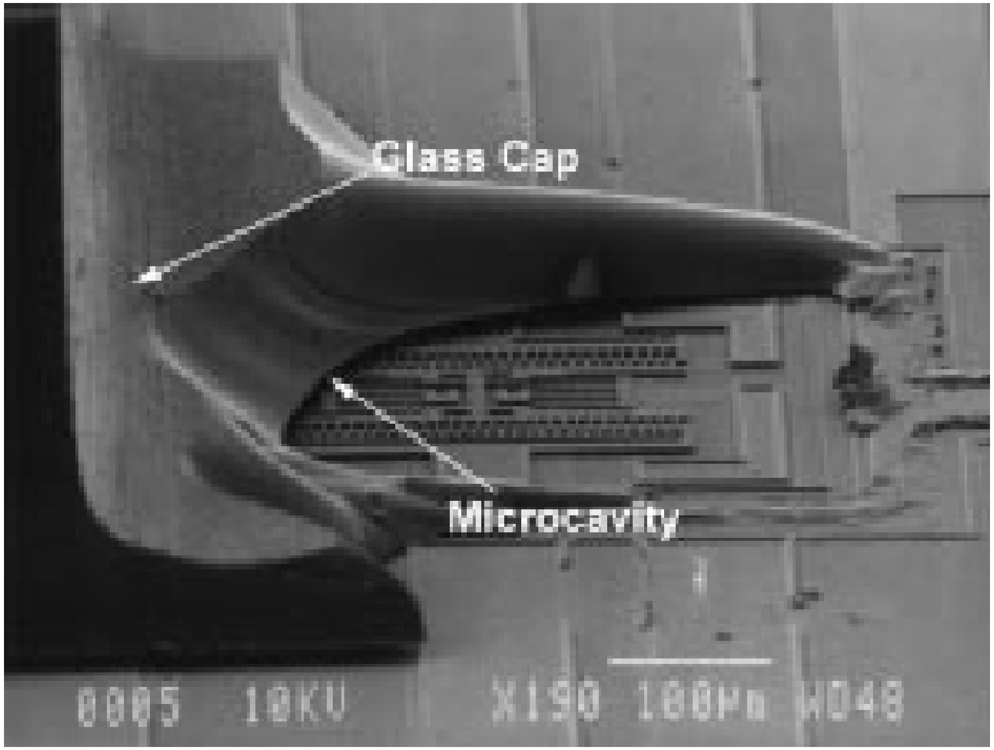
- **Wafer bonding - MEMS packaging**



Resonator





Y.T. Cheng, L. Lin, and K. Najafi, 2001

Approaches

- **Non-intermediate**
- Fusion Bonding
- Anodic Bonding

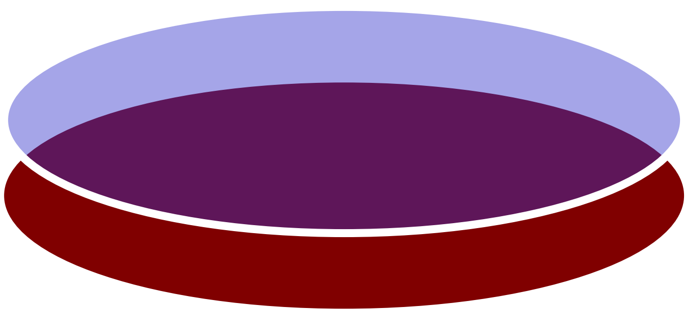
- **Intermediate**

  - Adhesive Bonding
- Organic

  Epoxy Bonding

  PR Bonding

- Inorganic
- Eutectic Bonding
- Glass Frit Bonding
- Solder Bonding



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2.4.1 Silicon Fusion Bonding

- **Silicon fusion bonding (SFB) or silicon direct bonding (SDB) - let the polished sides of two silicon substrates contact, and then annealed them at high temperature. A bond which is as strong as bulk silicon is formed between the substrates during annealing.**

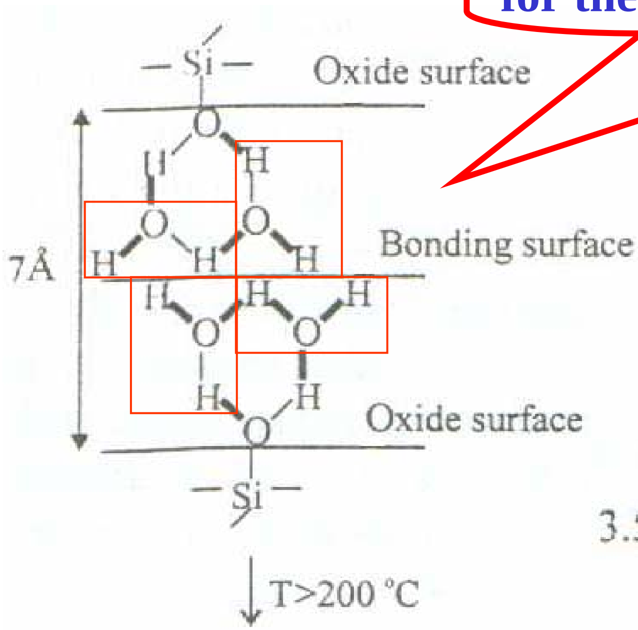
- **There are three steps in the process**

  + First, the substrates are cleaned in a strong oxidizing solution to form a hydrophilic surface on substrate (i.e. surface with a high density of hydroxyl groups)

  + The substrates are then squeezed together and these two substrates will stick firmly together due to hydrogen bonds

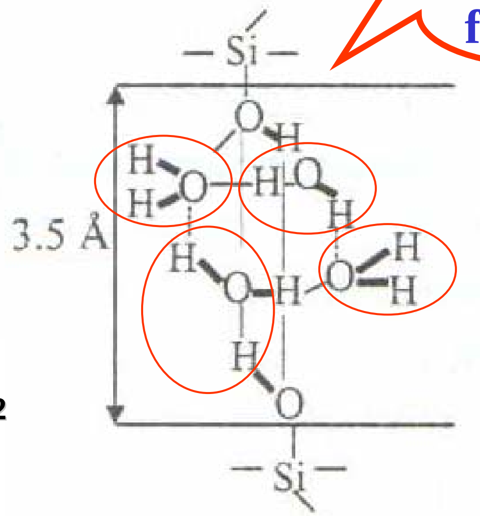
  + Finally the substrates are annealed at high temperature and strong bonds (Si-O) are developed during annealing.

Below 200°C, hydrogen seems to be responsible for the bonding of hydrophilic surface



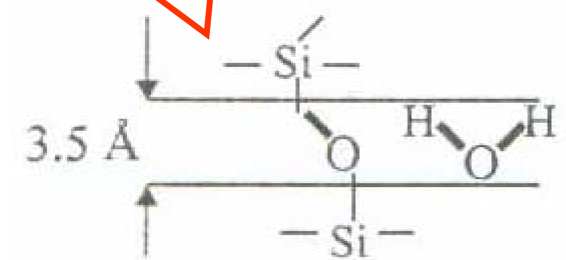
SiOH : $(OH_2)_2$:HOSi : $(OH_2)_2$

T>700 °C, chemical reactions occur and a bond between the hydroxyl groups probably form directly which is responsible for the bond strength



SiOH : SiOH+$(H_2O)_4$

T>1000 °C , covalent bond between SiO unit



Si-O-Si+H_2O

I.A. Maia, J.R. Senna, 1998

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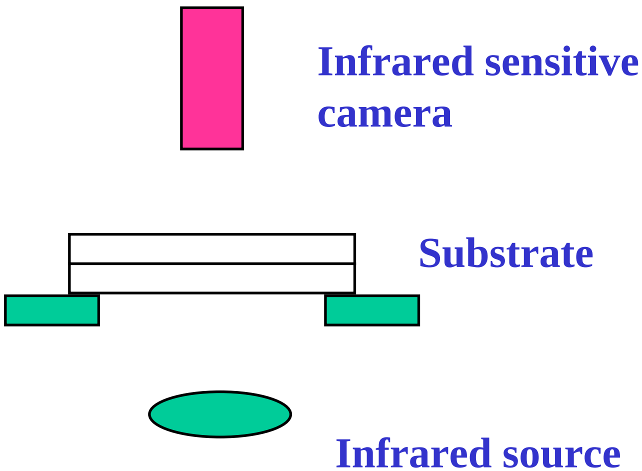
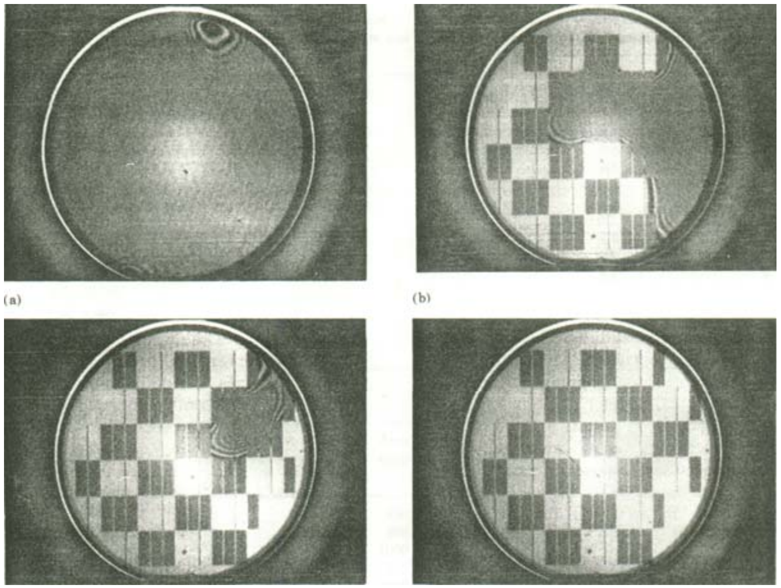
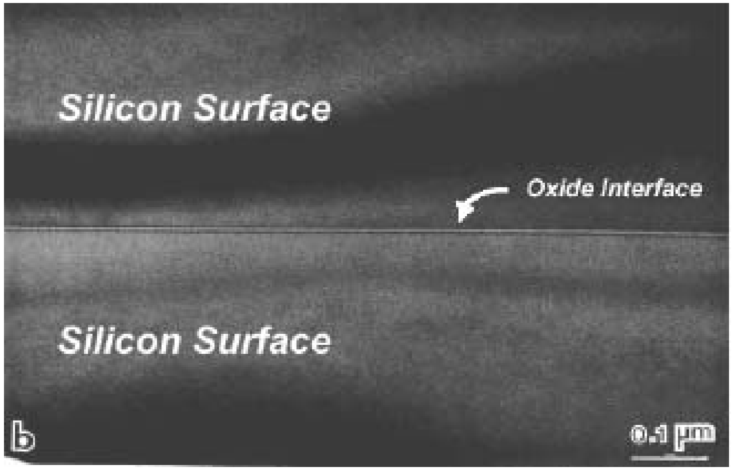
- **The bonding quality can be inspected by infrared imaging system**

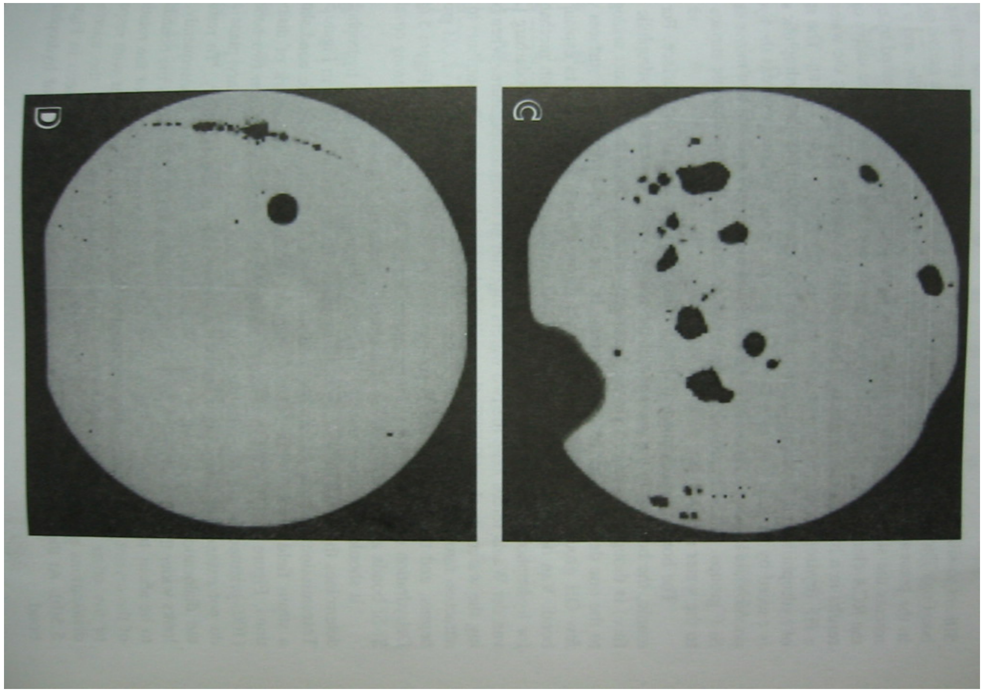




C. Harendt, et. Al., Sensors and Actuators, 1991

- **Bonding quality – the existing of voids**





Void Formation

- **Insufficient wafer flatness**
- **Surface contamination**
- **Particulates**
- **Trapped air**

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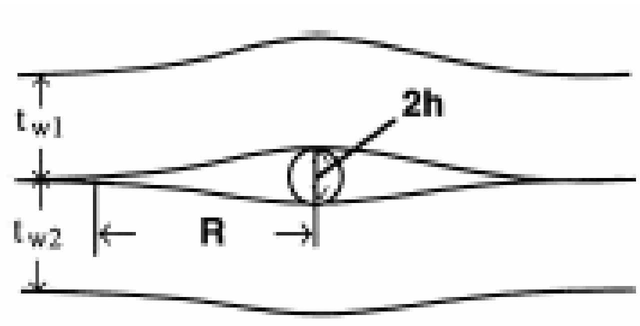
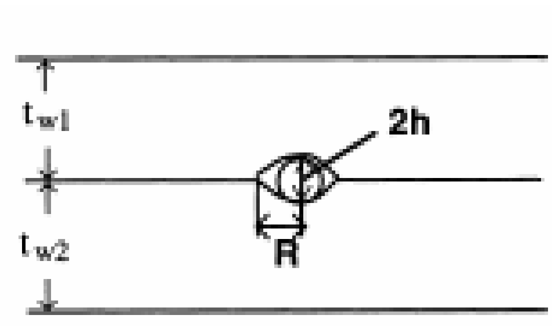
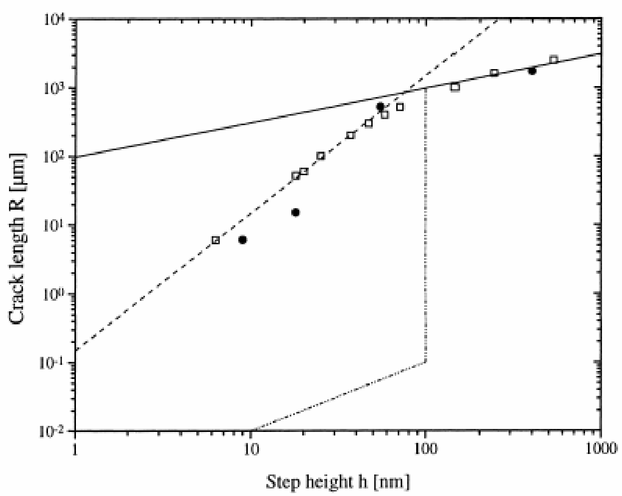
- **Interface bubbles**





$$R = [2/3E' t_w^3/\gamma]^{1/4} h^{1/2} \qquad E' = E/(1-\nu^2)$$



r : Surface energy of each wafer

E: Young' modulus

ν : Poisson's ratio

Diameter of 1μm→unbonded area with A diameter of 1 cm

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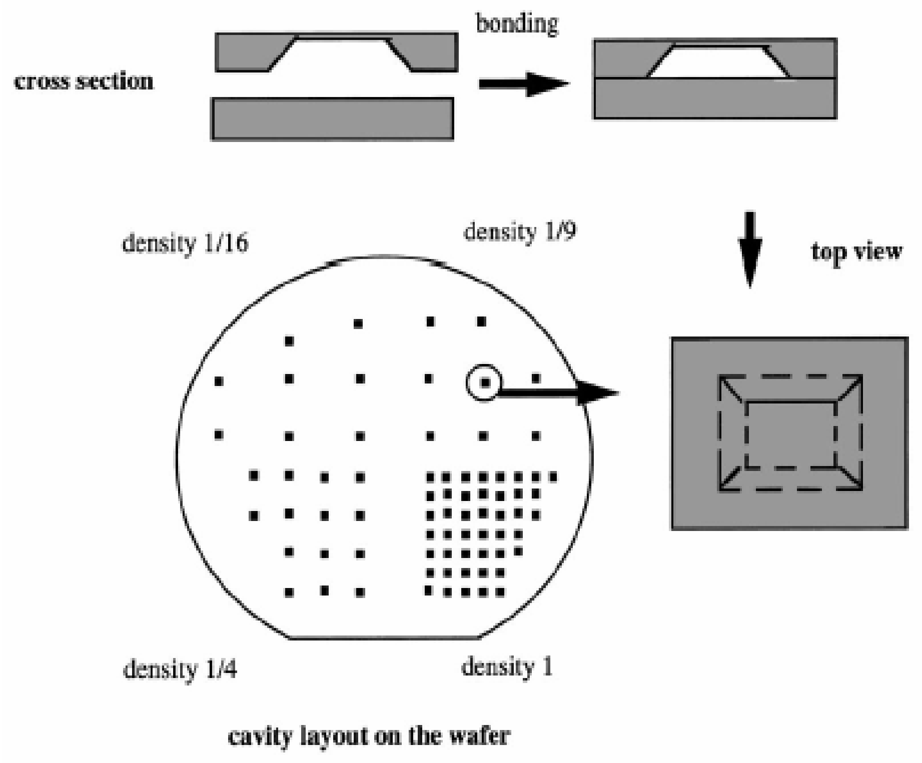
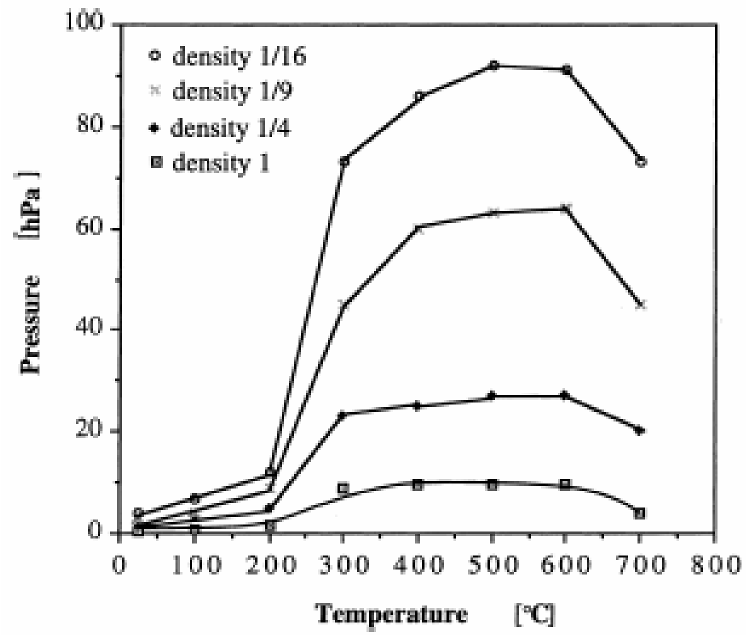
- **Interface bubbles – density test**





S. Mack, H. Baumann, and U. Gosele. 1996

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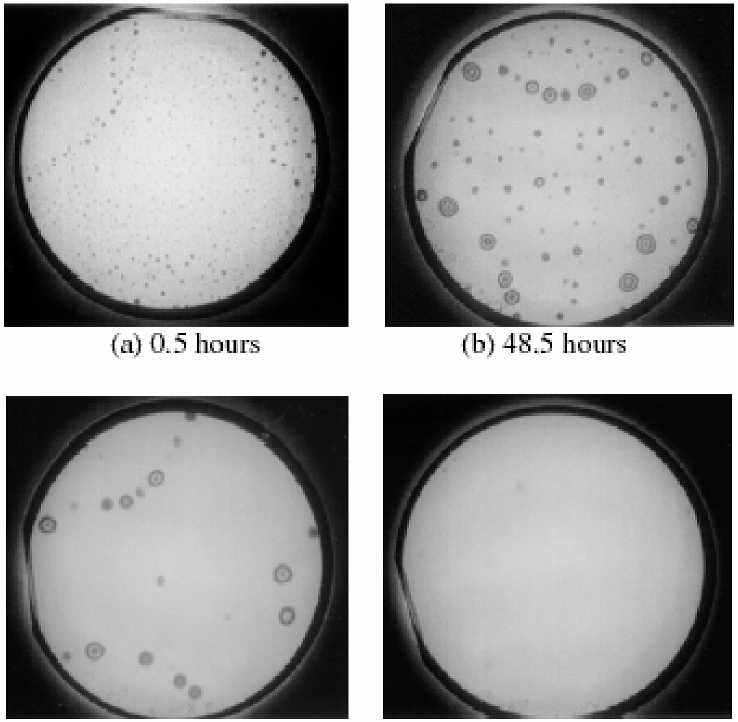
- **Interface bubbles - temperature dependent**



(a) 0.5 hours (b) 48.5 hours

(c) 138 hours (d) 274 hours

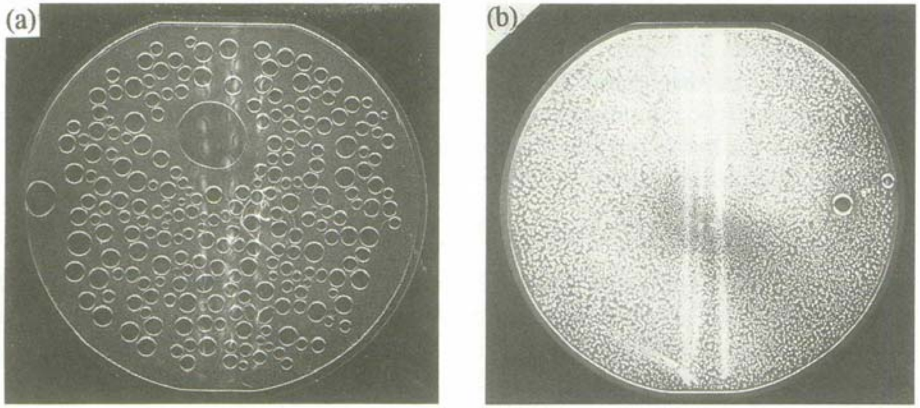


Fig. 5.14 (*a*) X-ray topographic image of large bubbles and (*b*) of tiny bubbles at the interface of bonded hydrophilic Si/Si pairs after annealing at 800°C for 30 min.

The interface bubbles in bonded silicon pairs usually disappear after annealing at temperature over 1000℃

The samples were then annealed at 600℃

A. A. Ayón1, et. al.

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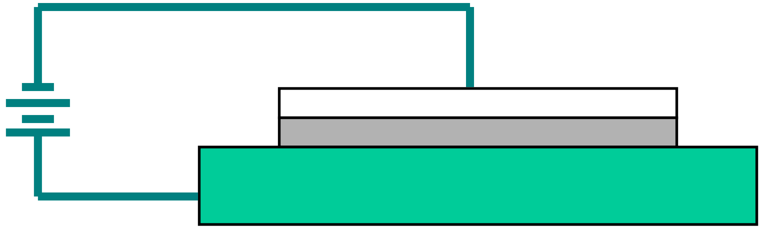
2.4.2 Anodic Bonding

- Anodic bonding - this is the process used to bond silicon to glass. The glass can be in the form of a plate or substrate, or a thin film between two silicon substrate.

- There are two steps in the process

  + Place a glass substrate and a Si substrate on a heating plate (under 450˚C). At the elevated temperature, the ions in the glass is allowed to move

  + Apply high negative voltage to the glass, the ions become mobile and drift to the cathode. When the glass and the Si substrate is pulled by the electrostatic force, the oxygen ions left on the glass surface will bond with the silicon atoms



Glass
Silicon
Hot plate

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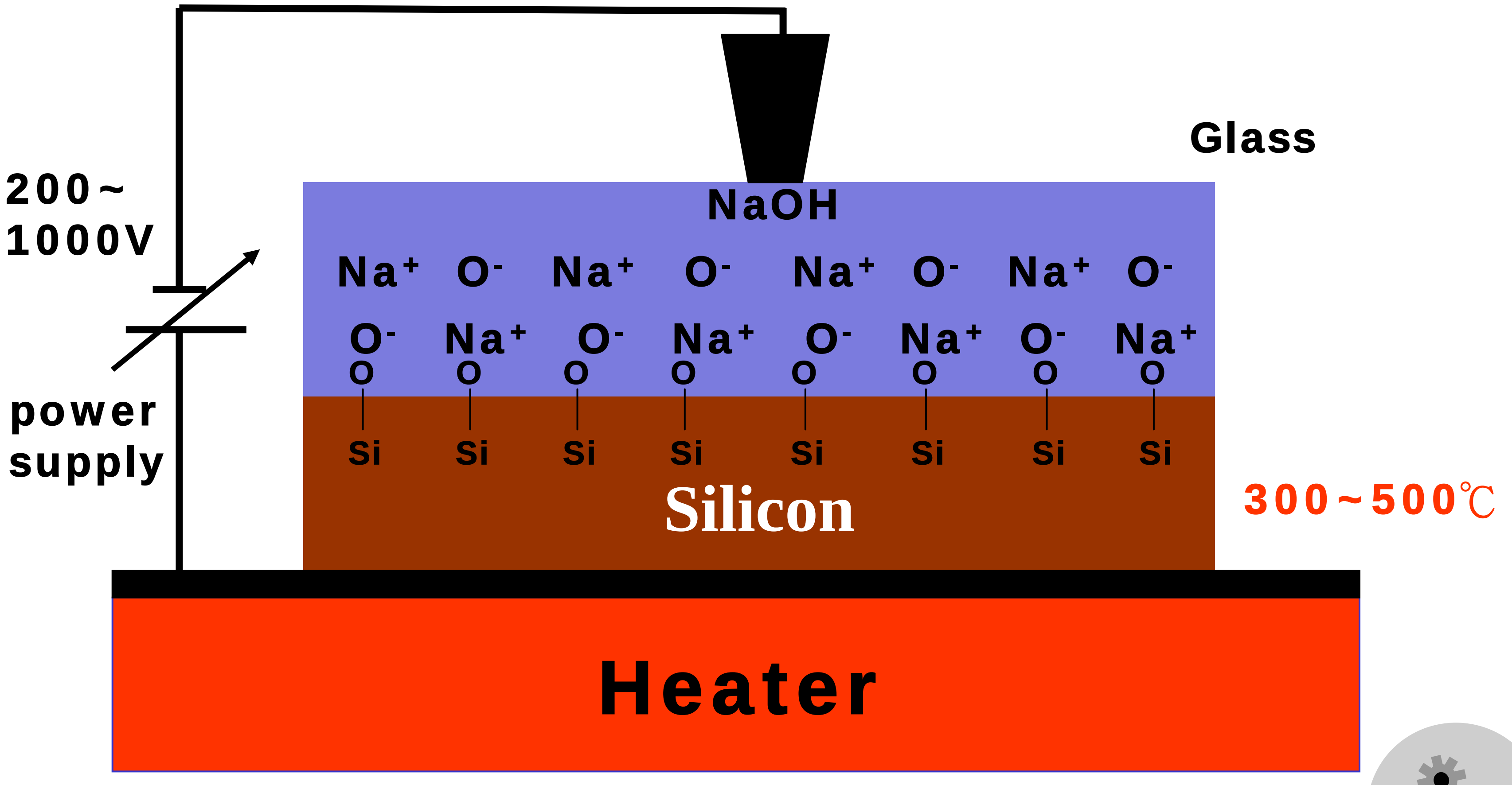
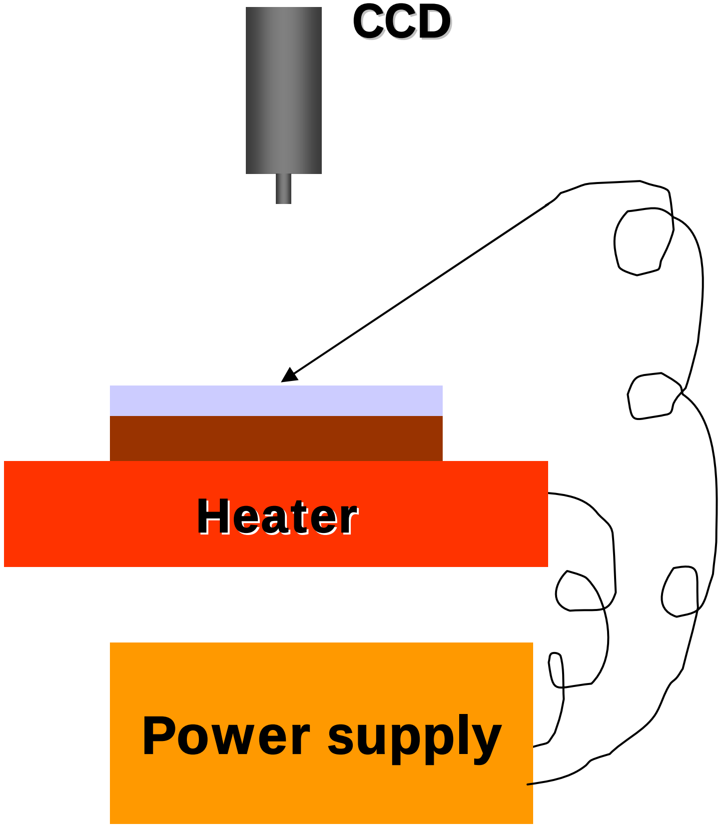
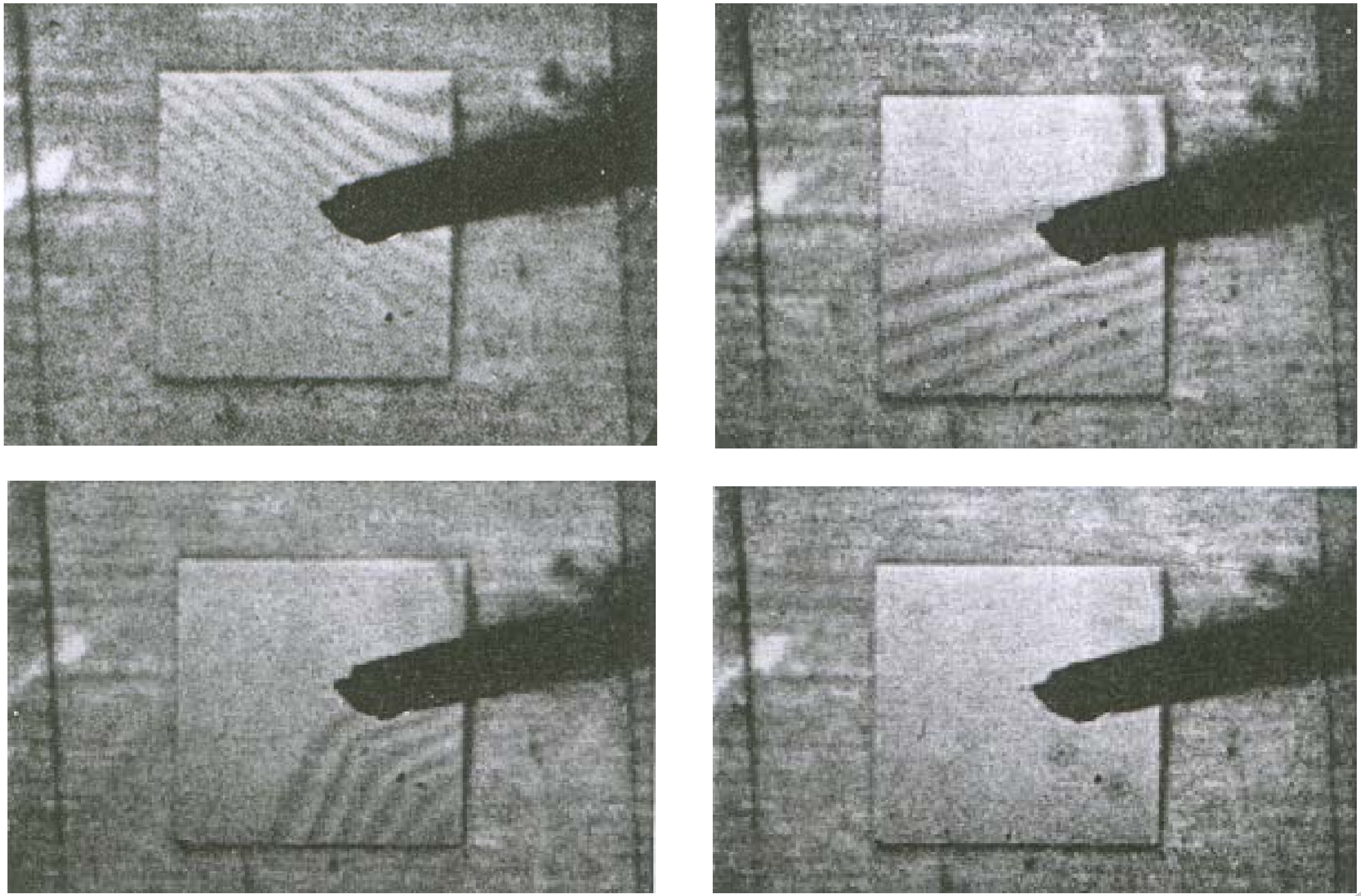

Glass
200~
1000V
power
supply
NaOH
Na+ O- Na+ O- Na+ O- Na+ O-
O- Na+ O- Na+ O- Na+ O- Na+
O O O O O O O O
Si Si Si Si Si Si Si Si
Silicon
300~500℃
Heater
MDL
NTHU

MDL
NTHU


CCD
Heater
Power supply


MPEG-1



Wallis, G and Pomerantz, D I, 1969

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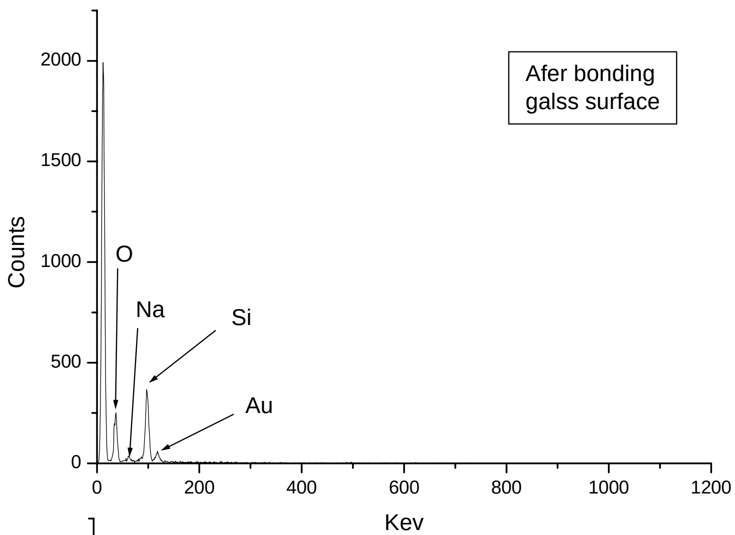

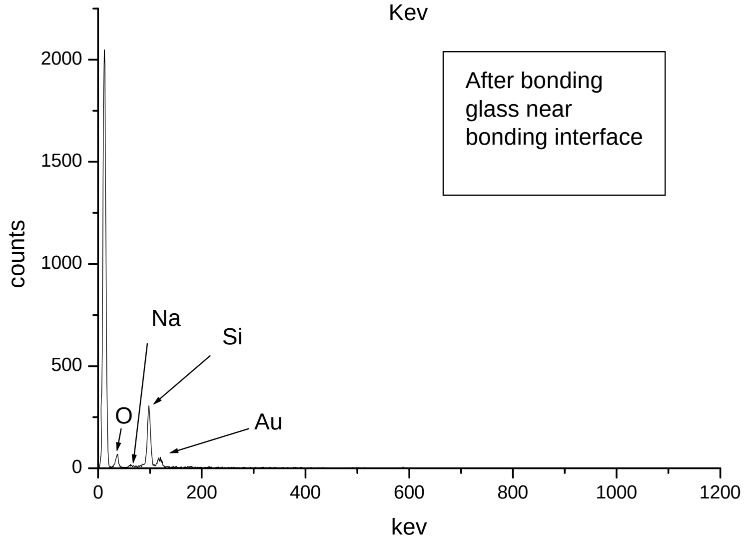

H. A. Yang, master thesis, 2002

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- **Several important issues during bonding**

  + **The glass must be slightly conductive when heated to the temperature well below its softening point**

  + **The thermal expansion coefficients of the two materials should be as close as possible.**

  + **Temperature and voltage are two major parameters need to be controlled to obtain better bonding**

  + **The surface has to be smooth, although this requirement is not as critical as in the fusion bonding process**

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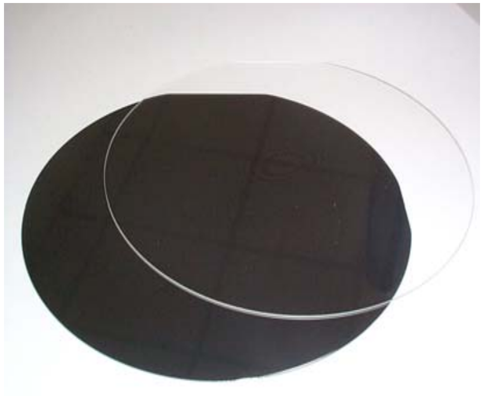
- **Thermal expansion coefficient**

	Thermal expansion coefficient
PYREX 7740	**32.5×10^{-7}/℃**
Silicon	**30.9×10^{-7}/℃**



- When two different materials are combined, for example during a bonding process, a problem due to the mismatch of their thermal expansion coefficients may arise. This may lead to thermal stress as the temperature changes and break the bonded wafers. Using materials having sufficiently close thermal expansion coefficient can reduce thermal stress.

- **Bonding strength**

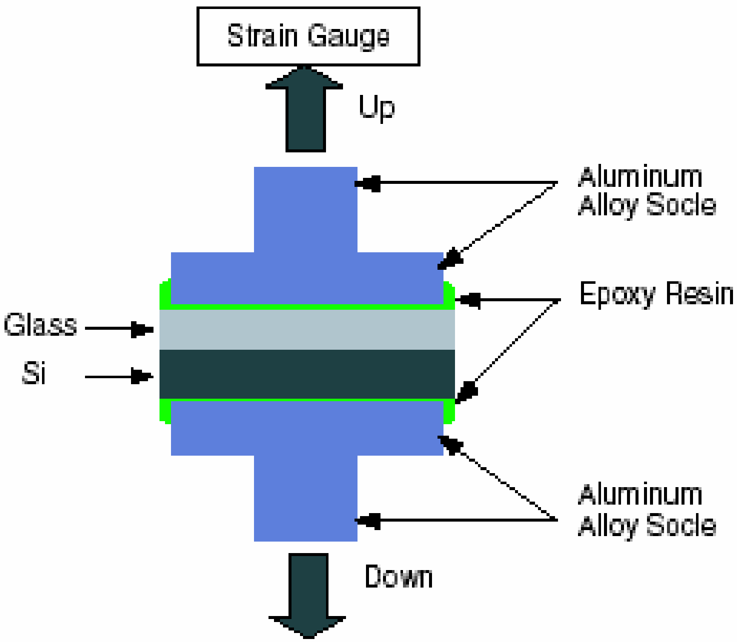


Table 1. Bond-no bond matrix with 1.5 mm thick glass at 1 atm in air.

DC VOLTAGE	TEMPERATURE					
	300 °C	350 °C	375 °C	400 °C	425 °C	450 °C
175 V	-	-		1.1 MPa	3.3 MPa	3.4 MPa
350 V	-	1.0 MPa	1.8 MPa	2.0 MPa	3.5 MPa	3.6 MPa
530 V	1.2 MPa	1.95 MPa	2.4 MPa	2.8 MPa	3.65 MPa	3.8 MPa
700 V	1.5 MPa	2.2 MPa	2.75 MPa	2.8 MPa	3.5 MPa	3.75 MPa
880 V					3.3 MPa	
1050 V					3.75 MPa	

Table 2. Bond-no bond matrix with 1.5 mm thick glass at 3.5×10^{-5} mbar in air.

DC VOLTAGE	TEMPERATURE					
	300 °C	350 °C	375 °C	400 °C	425 °C	450 °C
175 V	-	-	-	-	1.2 MPa	1.4 MPa
350 V	-	-	0.9 MPa	1.2 MPa	2.45 MPa	2.4 MPa
530 V	-	-	1.9 MPa	2.1 MPa	2.4 MPa	2.6 MPa
700 V	-	1.8 MPa	2.0 MPa	2.2 MPa	2.3 MPa	2.5 MPa
880 V	-				2.4 MPa	
1050 V					2.5 MPa	

A Coma and B Puers, 1995

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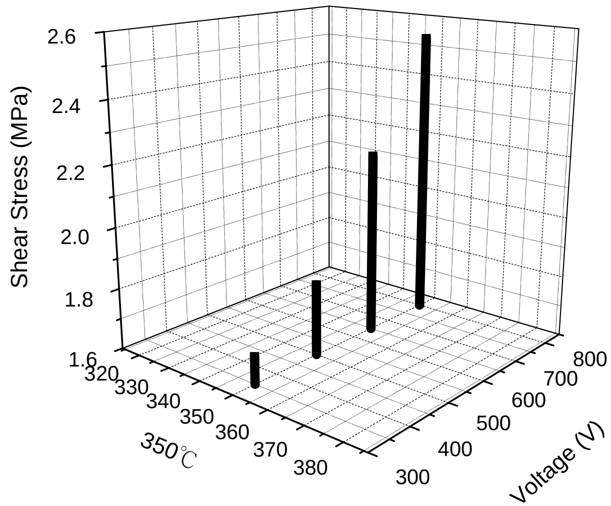
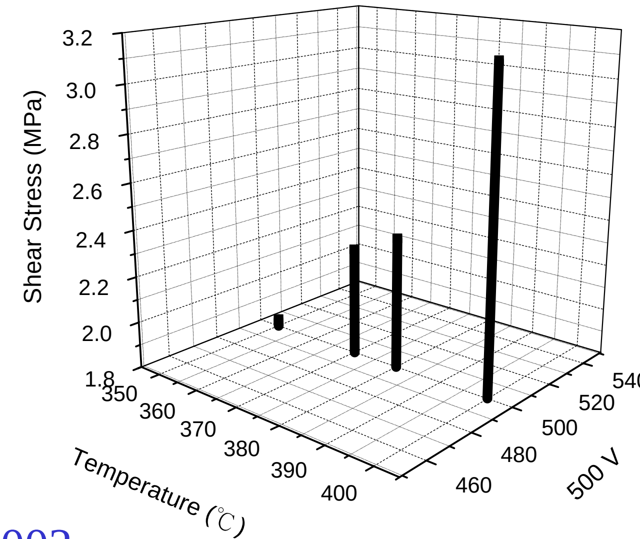
- **Bonding strength**

Voltage & Temperature	Bonding Strength （MPa）
350℃ ；350V	1.6879 MPa
350℃ ；500V	1.8330 MPa
350℃ ；650V	2.1899 MPa
350℃ ；800V	2.5351 MPa

Voltage & Temperature	Bonding Strength （MPa）
350℃ ；500V	1.8330 MPa
370℃ ；500V	2.2701 MPa
380℃ ；500V	2.3677 MPa
400℃ ；500V	3.1425 MPa





H. A. Yang master thesis, 2002

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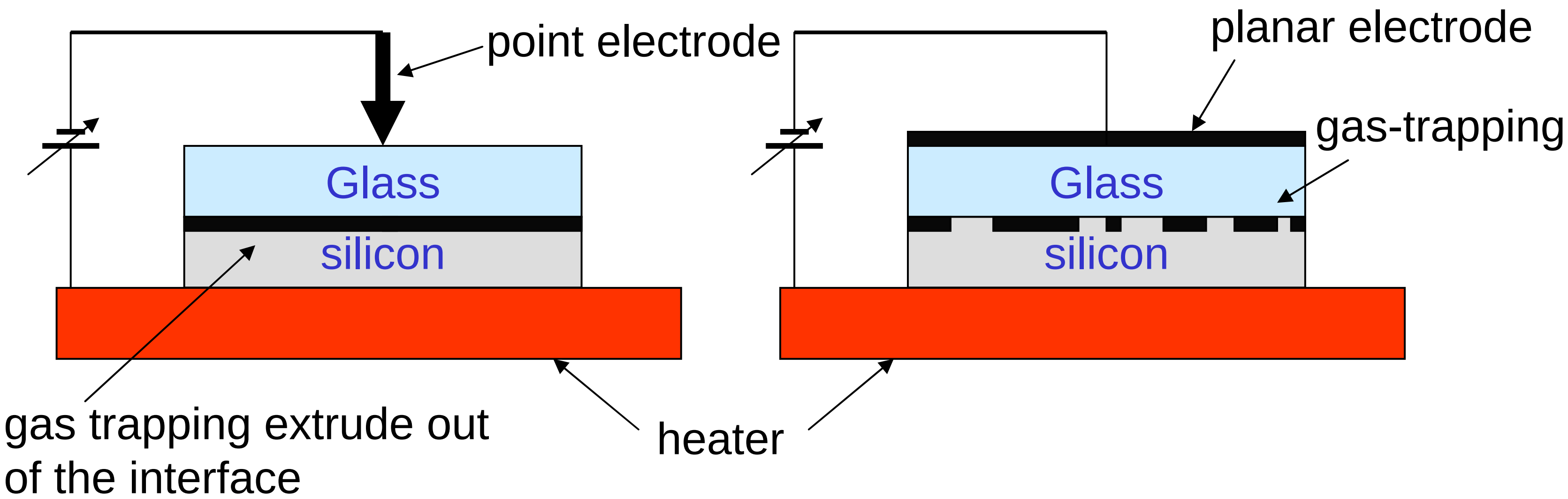
- **Bonding mechanism – point vs planar electrodes**



- Point electrode: starts from the spot below the point cathode electrode, and this bonding phenomenon can prevent gas trapped inside the interface.

- Planar cathode: short bonding time, but has gas-trapping problem.

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- **Special electrode design – radial type**

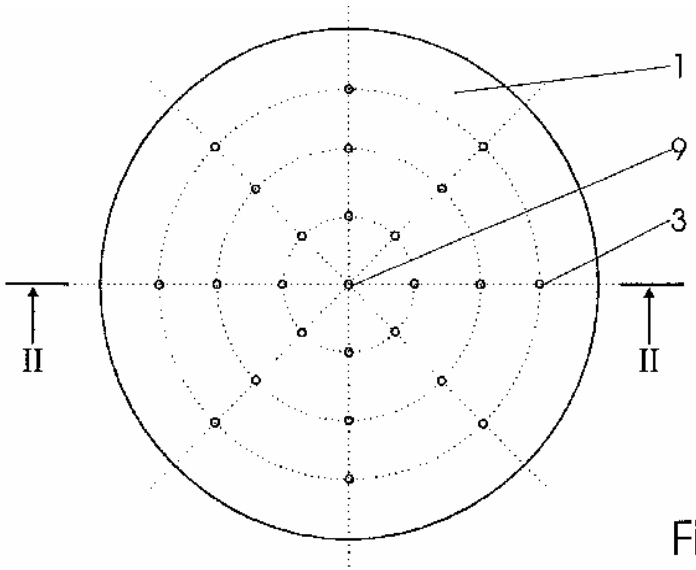
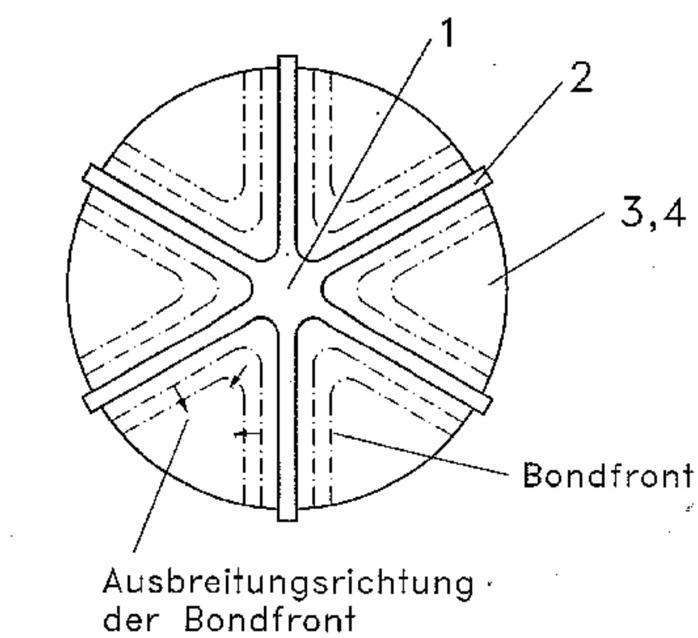


Fig. 1



- Both of Germany patents DE4423164 and DE4426288 was used radiate to Improvement of bonding time and quality of Anodic bonding, but the free oxygen from air helps the anodic bonding to occur, it make the bonding time of the wafer edge is faster than other position of the wafer.

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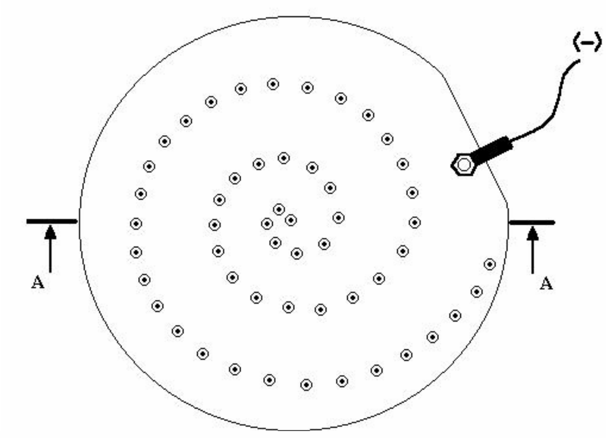
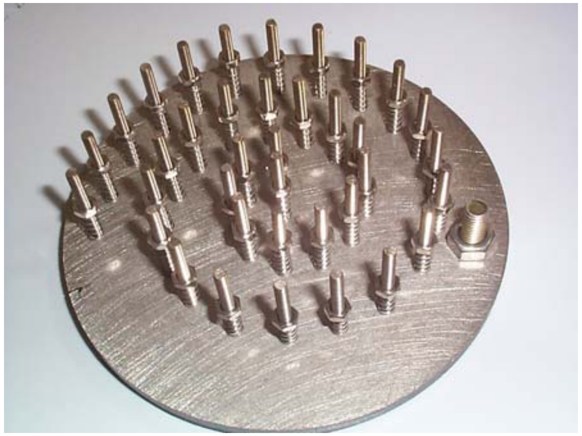
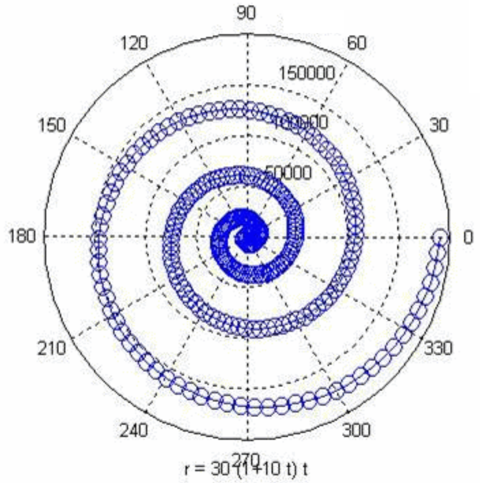
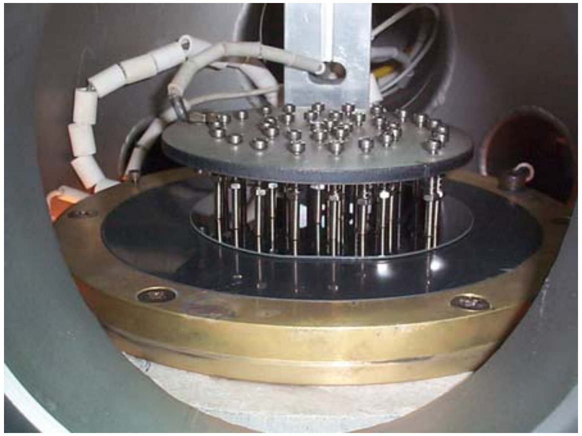
- **Special electrode design – spiral type**









H. A. Yang, master thesis, 2002

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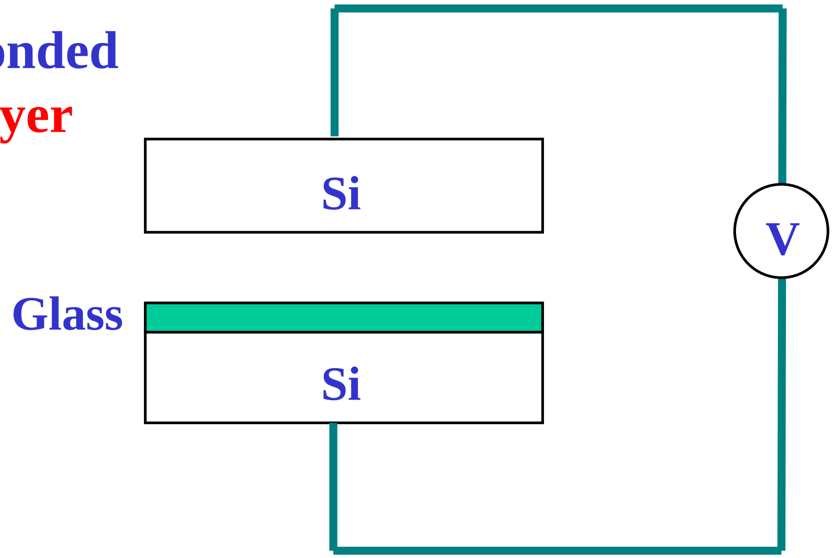
2.4.3 Silicon-Silicon Anodic Bonding

- Silicon-silicon anodic bonding - this technique adopts the idea of silicon-glass anodic bonding

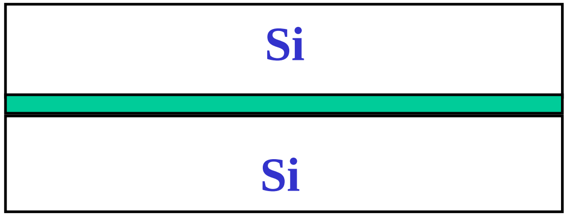
  Silicon and silicon is electrostatic bonded together by a thin deposited glass layer



- The surface of the silicon to be bonded should be **polished**

- The minimum deposited glass film thickness is about **3 μm** and the voltage applied is from ~50 volts to ~ 200 volts

- The **thermal residual stress** effect can be reduced since the silicon substrates have the same thermal expansion coefficients, and the only thermal stress comes from the very thin glass film.



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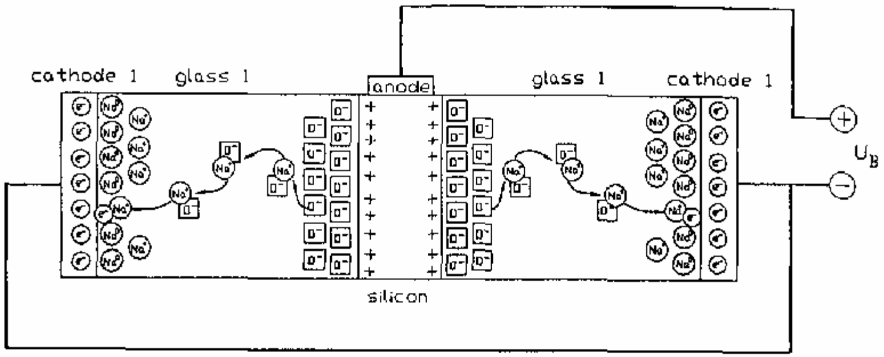
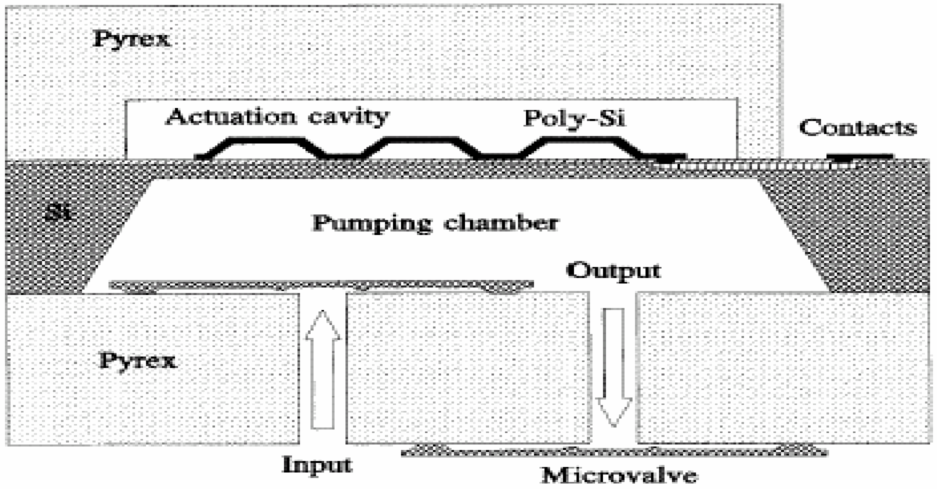
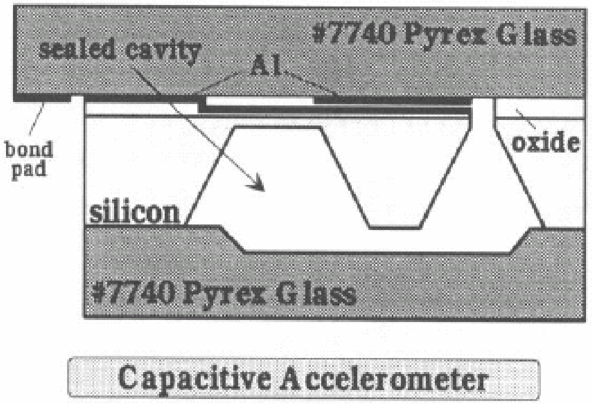
- **Bonding for three layers**







Michael Harz, 1992

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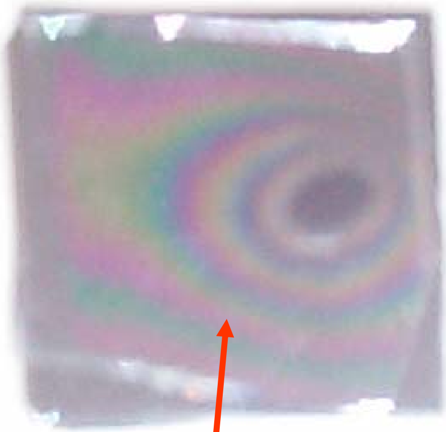
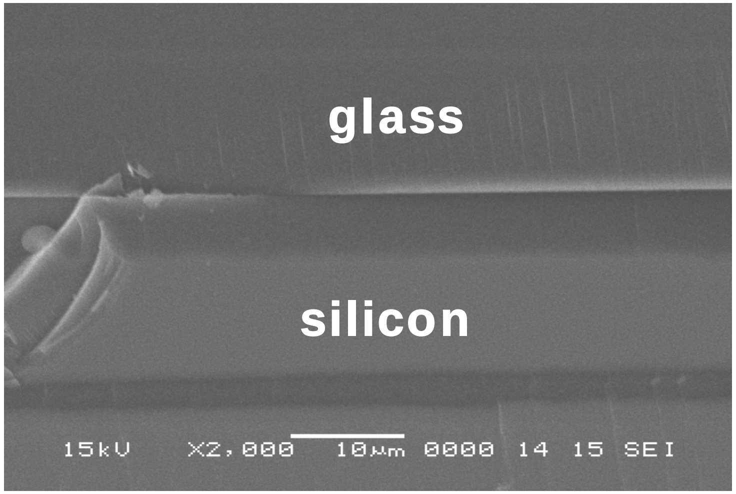
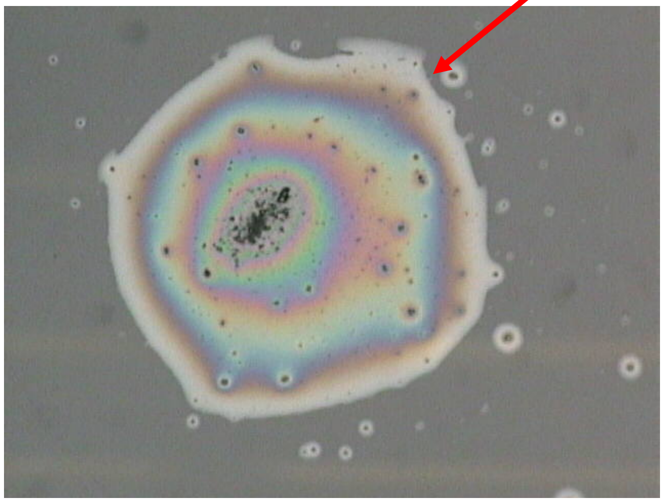
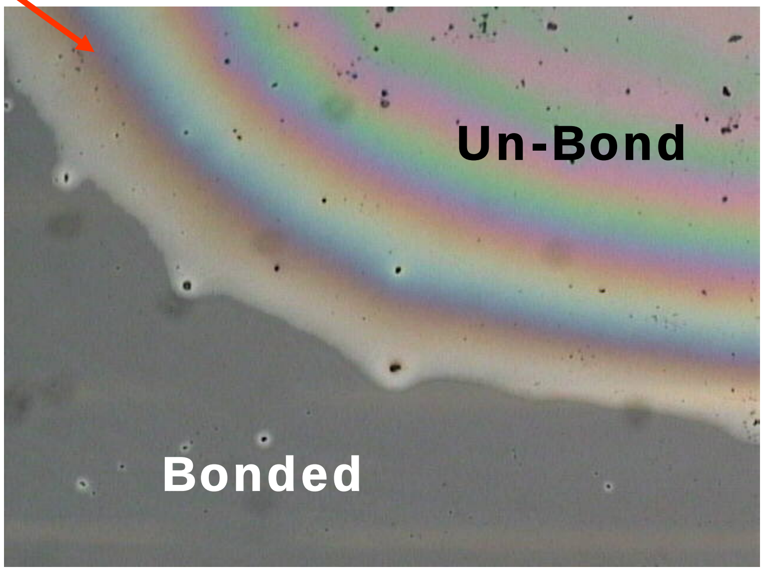
Before bonding





Newton Ring





H. A. Yang master thesis,2002

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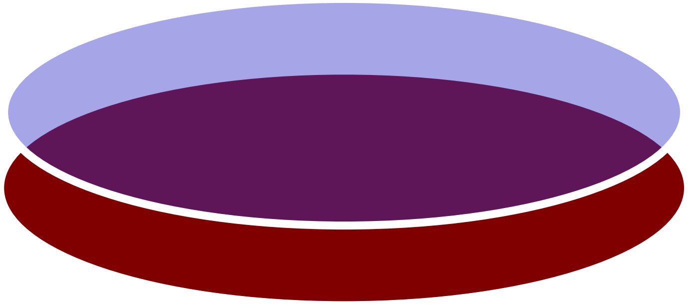
Approaches

- **Non-intermediate**
- Fusion Bonding
- Anodic Bonding

- **Intermediate**

- Adhesive Bonding

- Organic
  - Epoxy Bonding
  - PR Bonding
- Inorganic
  - Eutectic Bonding
  - Glass Frit Bonding
  - Solder Bonding



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2.4.4 Others

- **Low temperature glass bonding – The silicon substrates are bonded by a deposited (sputtered) low melting point glass. Thus the applied electric field is not necessary**

  + The sealing temperature may down to 200ºC

- **Polymer bonding**

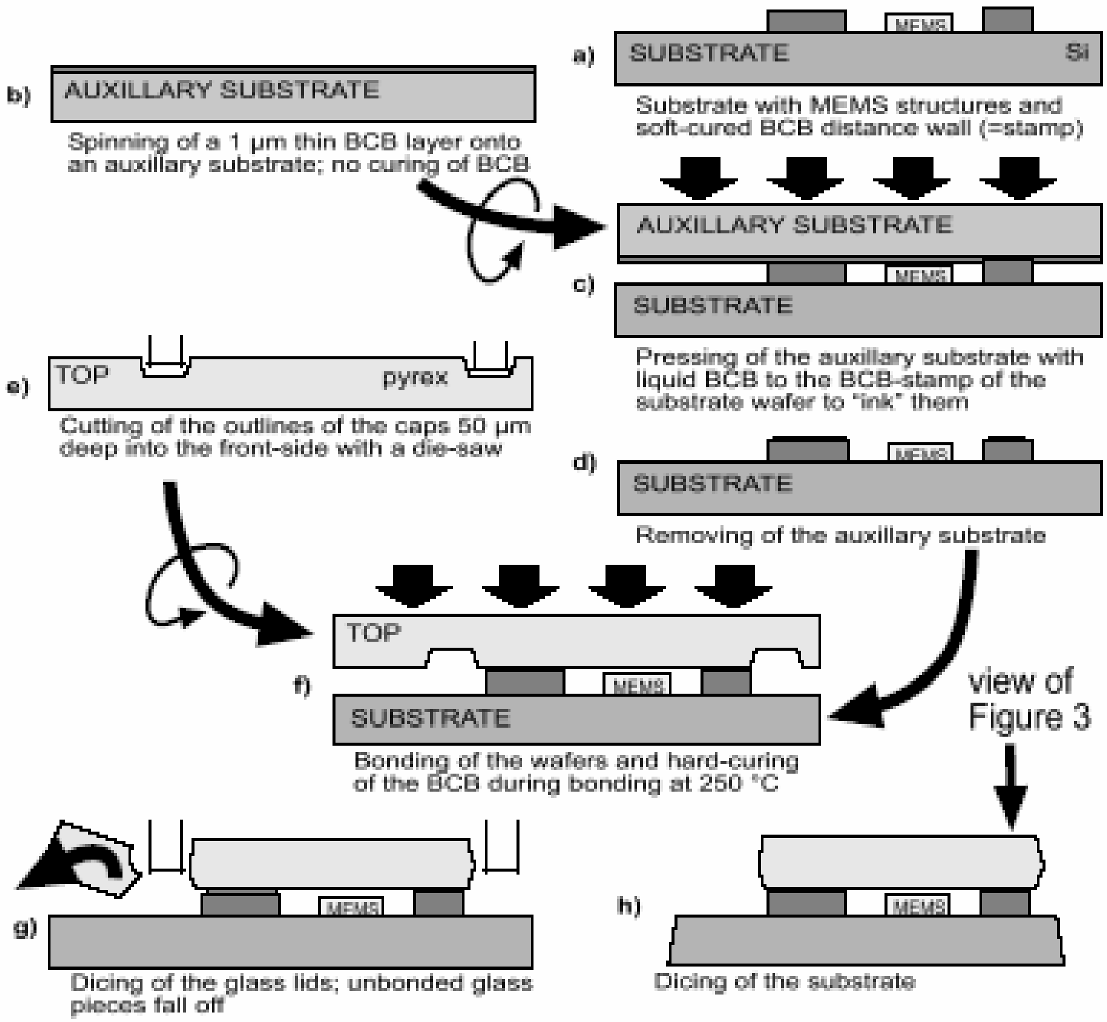
  + Photoresist, polyimide, epoxy

  + Not hermetic seal

  + Aging

Organic Wafer Bonding - Polymer

- **BCB Bonding**



J. Oberhammer and G. Strmme, Sweden, 2004

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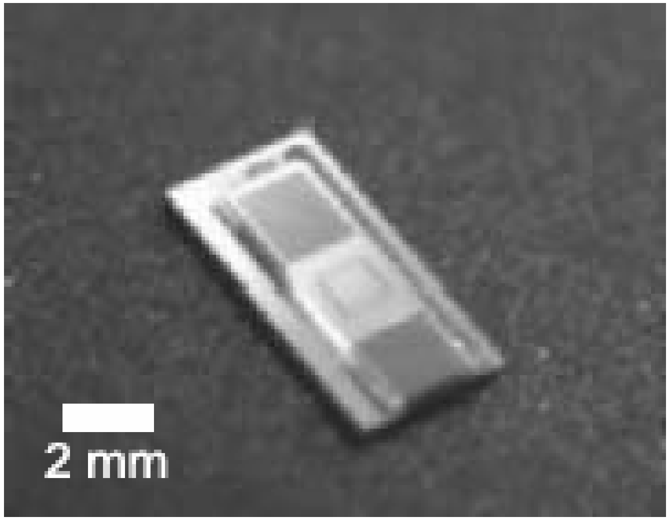
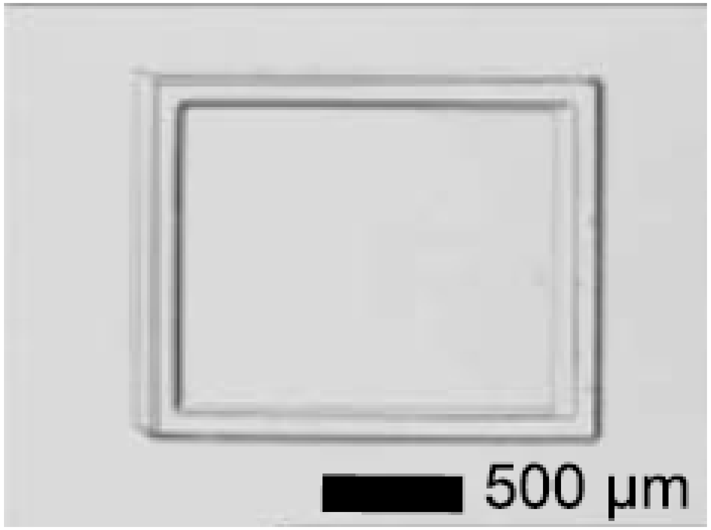
- **BCB Bonding Results**

  + **BCB thickness of 18 μm**

  + **Hard-curing at 250℃**

  + **Tensile strength 9.52 MPa**





J. Oberhammer and G. Strmme, Sweden, 2004

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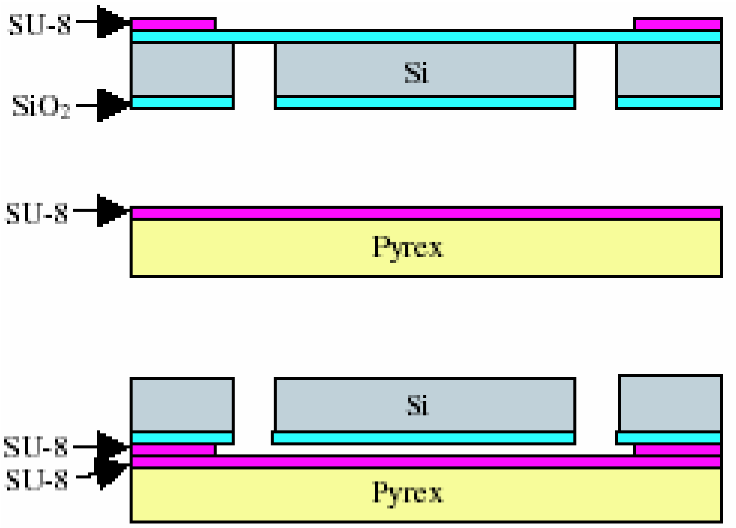
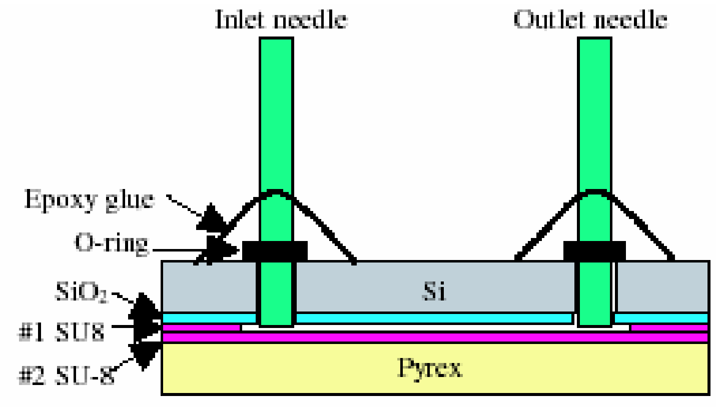
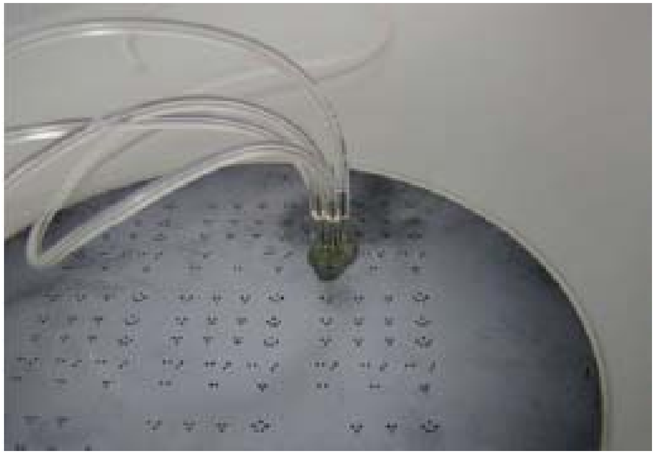
- **SU-8 Bonding**





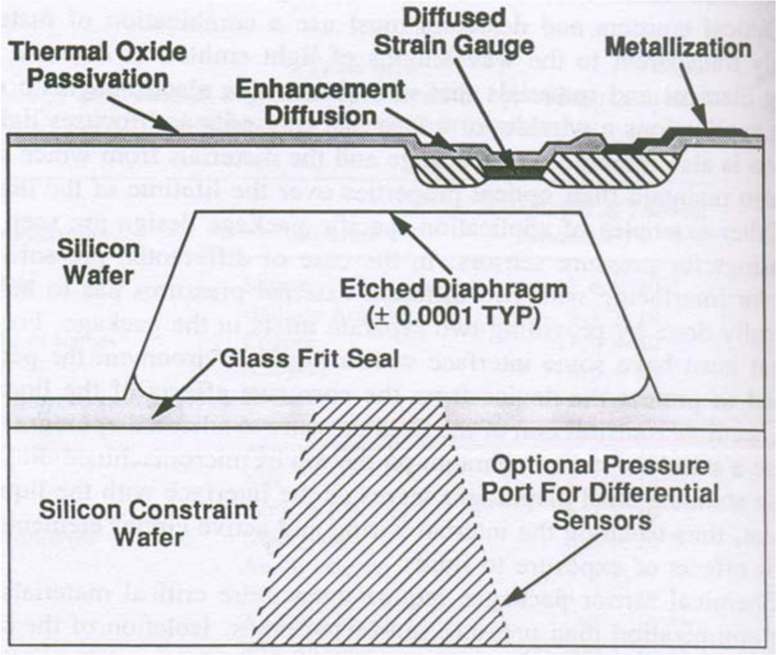


S. Li, C. Freidhoff, R. M Young and R. Ghodssi, 2003

Inorganic Wafer Bonding – Glass Frit

- Inorganic glass frits require high temperature, but achieve better sealing properties

75°C for 15 min to evaporate organic solvent, then heat up to 375°C to burn out grease.



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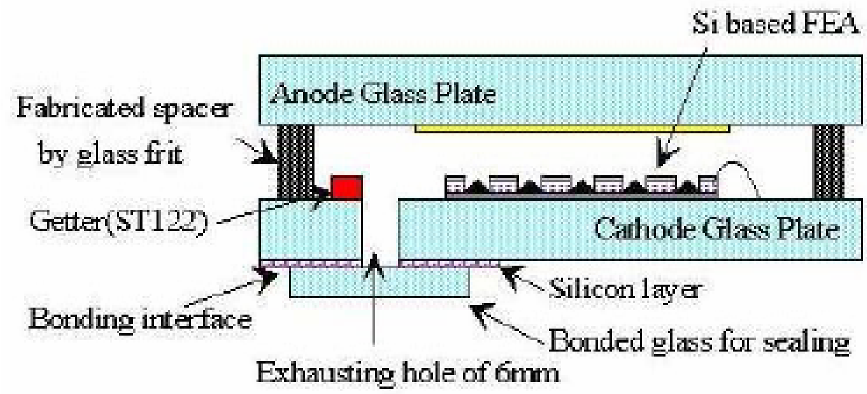
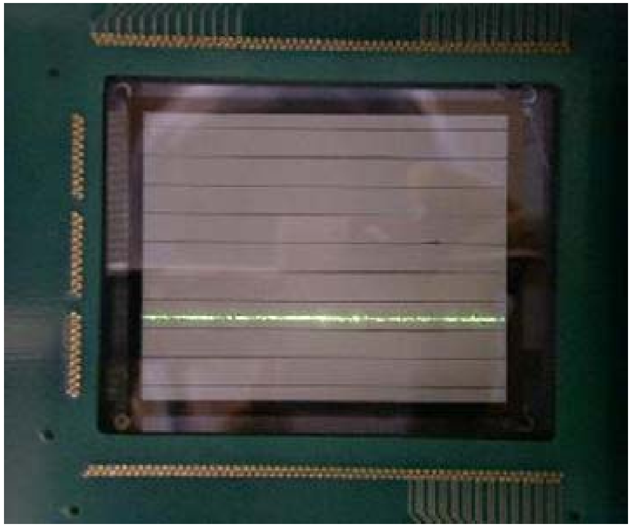
- Glass frit layer can be patterned to achieve localized or selective bonding
- Slight curvature, roughness, and even topology can be compensated by reflowing glass
- Sealing can be hermetic





S. Park and M. Kim, 2000

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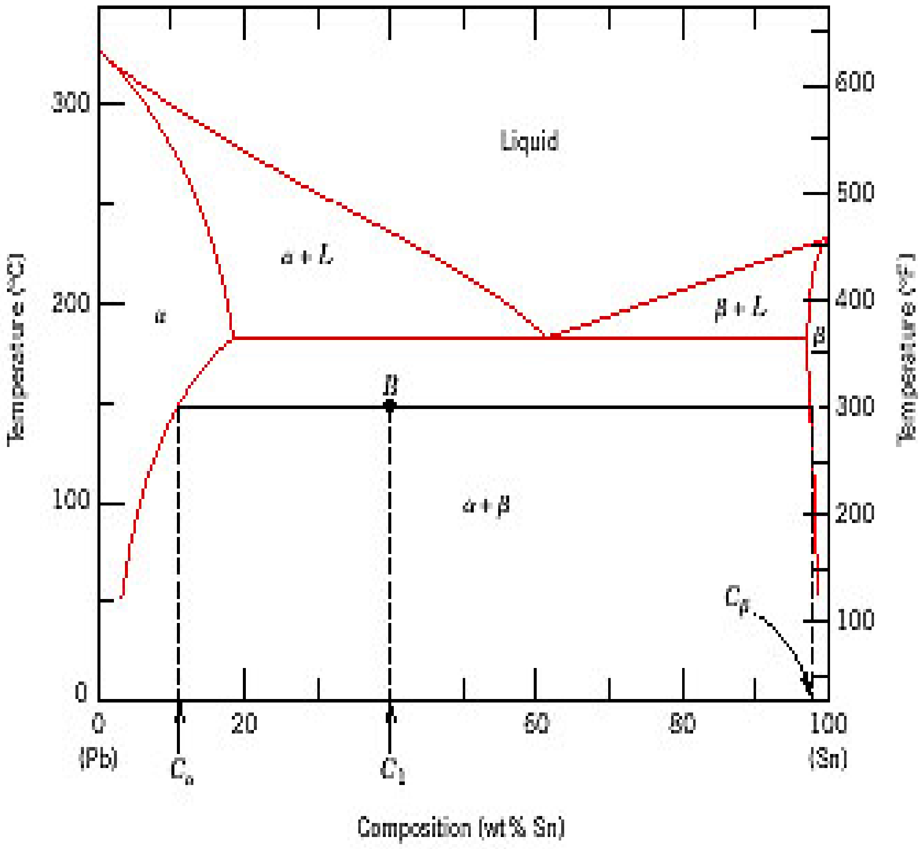
Inorganic Wafer Bonding – Eutectic Bonding

- Eutectic:

  In a 2-component phase diagram where there is either partial or no solid solubility between the components, there is a eutectic point, corresponding to the composition of the lowest melting temperature
- In the Sn/Pb system, the temperature of the eutectic point is 183℃ and the composition is 61.9% Sn and 38.1% Pb by weight



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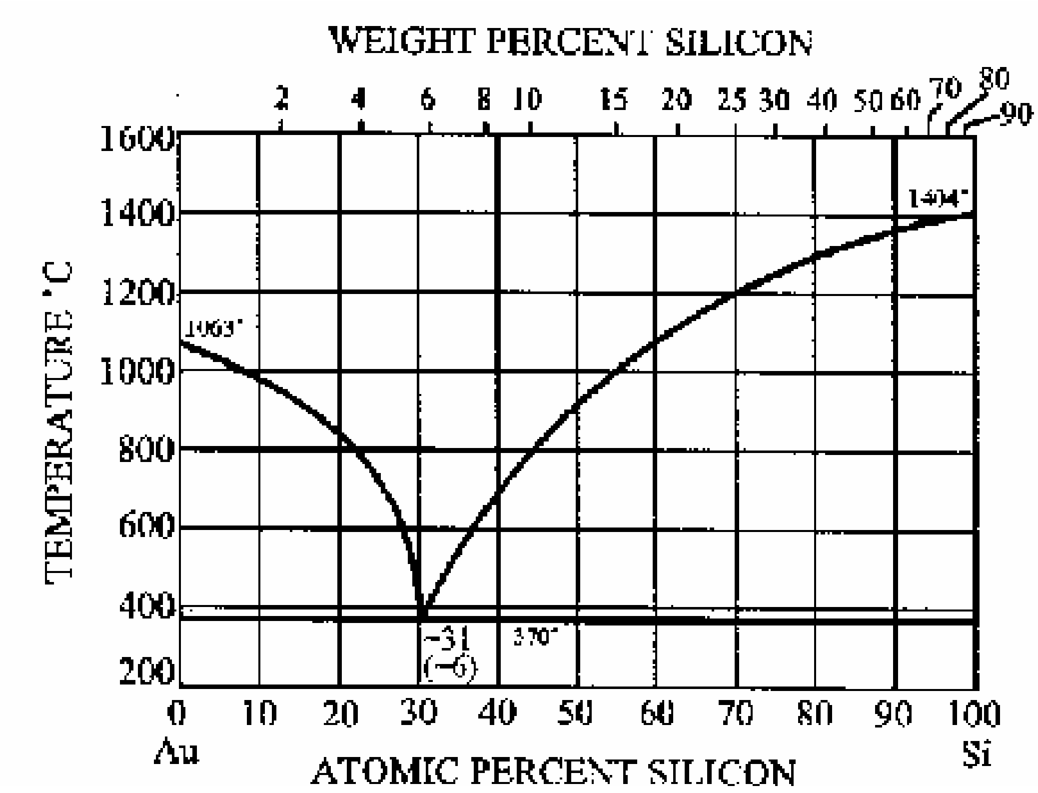
- **Au-Si eutectic**

  + Au – Si eutectic temperature about 370℃ at 31% Au/Si
  + Bonding temperature is below Al interconnect melting point



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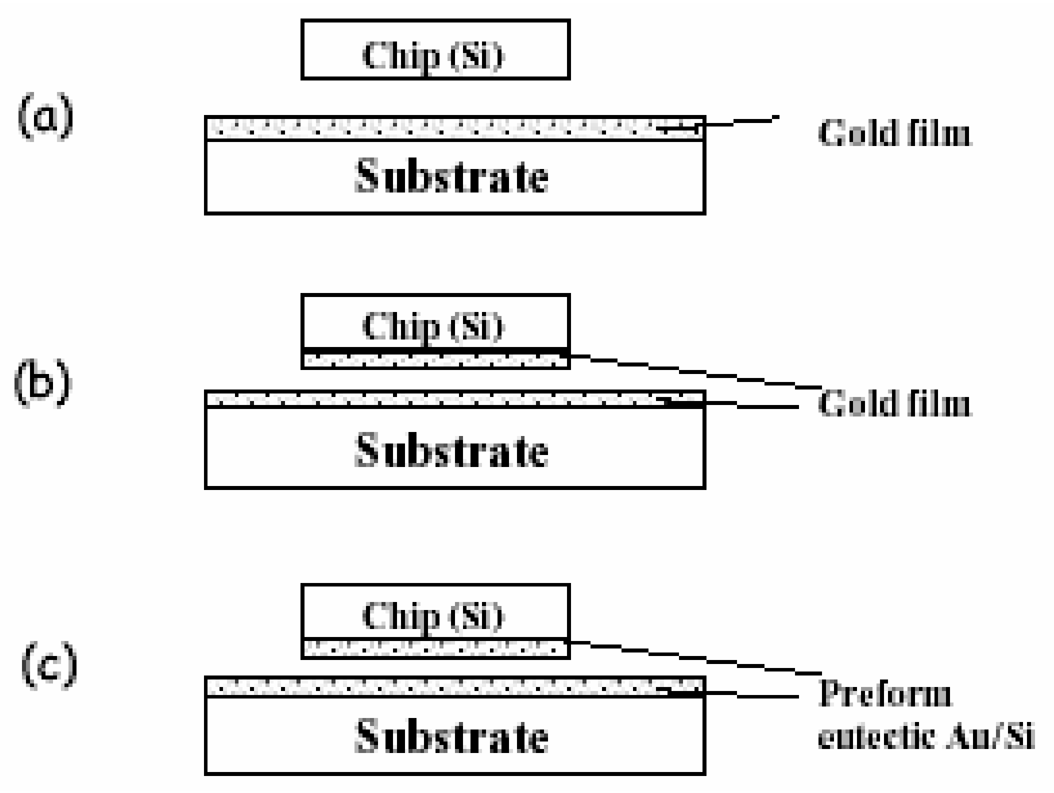
- Deposit 150A Cr/1500A Pt 1500~5000A Au film on substrate.
- Heat up to 425-500 in N_2 ambient.



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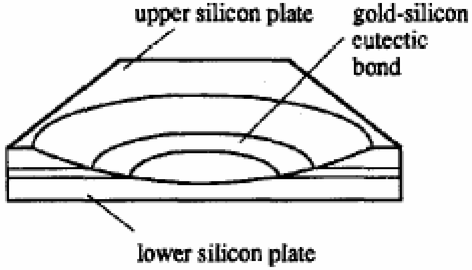
Assembling three-dimensional microstructures using gold-silicon.eutectic bonding



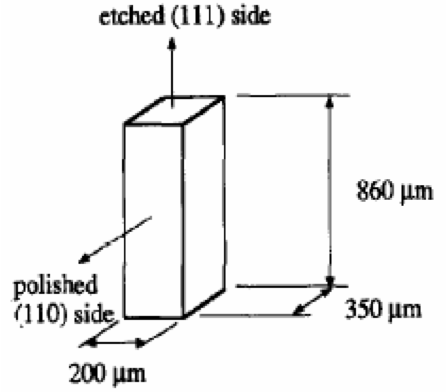


Table 2
Results of the macrobonding experiments

Temperature (°C)	Deposited material	
	Au (150 nm)	Cr + Au (≈5 + 150 nm)
375	partially bonded	locally bonded
455	partially bonded	completely bonded
520	partially bonded	completely bonded

Samples from the bonding at 455℃ and 520℃ with Cr and Au layers could not be separated by a wedge anywhere along the edge of the bonded silicon plates.

A.L. Tiensuu, M. Bexell, J.A. Schweitz, L. Smith, S. Johansson, 1994

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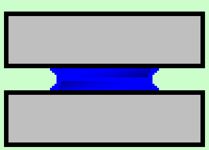
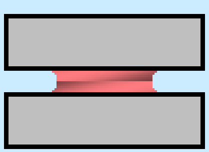
Wafer Bonding Methods

Techniques		Advantages	Drawbacks
"Surface" bonding		Hermetic	Flat surface required
	Anodic	strong bond	high-voltage
	Fusion (Direct)	strong bond	high temp
	Surface-activated	varies	varies
Metallic interlayer		Hermetic Non-flat surface ok	Specific metals required
	Eutectic	strong bond	flat surface req'd
	Thermocompression	non-flat surface ok	high force
	Solder	self-aligning	solder flow possible
Insulating interlayer		Non-flat surface ok	Varies
	Glass frit	hermetic common in MEMS	large area medium-hi temp
	Adhesive	versatile	non-hermetic