Polishing and bonding

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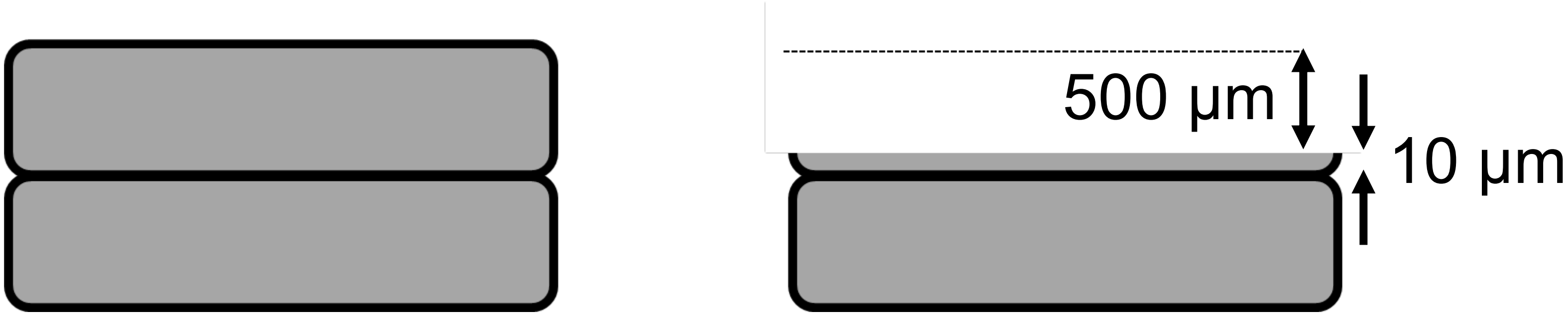
Grinding vs. polishing

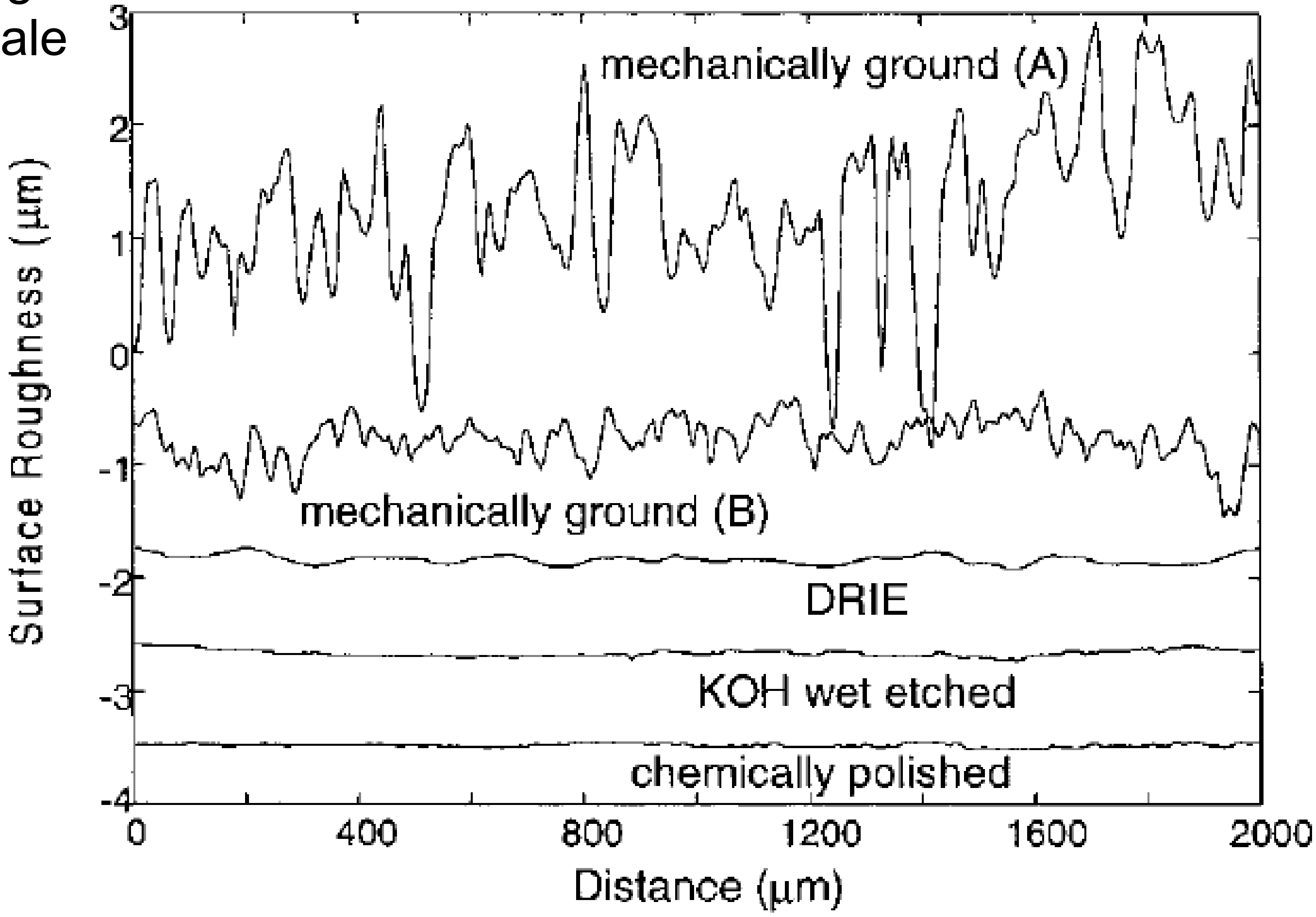


Both use abrasive particles, but:

Grinding removes 10 µm/min in large chunks because large particles
Grinding results in very rough surface because very large chunks
Grinding leaves mechanical damage due to large chunks being torn off

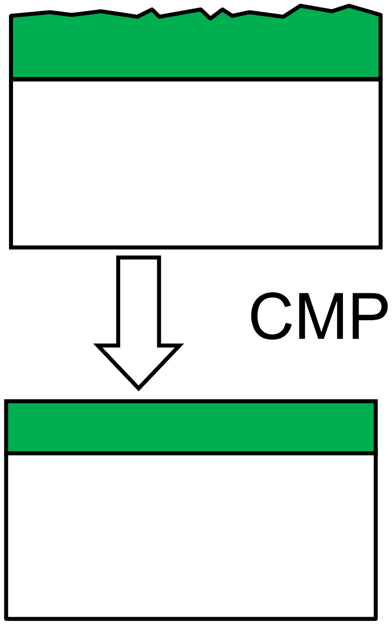
Polishing uses nanoparticles to achieve smooth surfaces
Polishing removes 0.1 µm/min because small particles, small forces
Mechanism of removal is chemical and mechanical (CMP !)

Log scale



J. Am. Ceram. Soc., **83** [6] 1476–84 (2000)

Polishing needed after grinding !

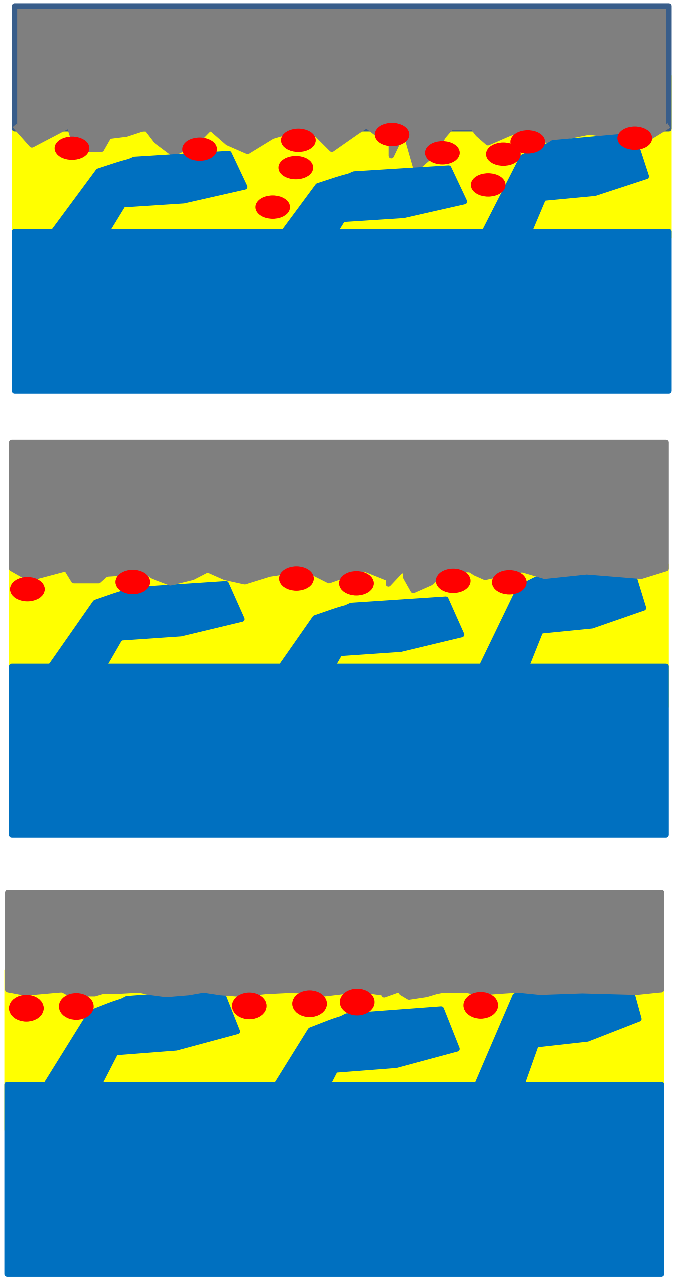


CMP

Surface roughness after grinding with µm-particles is micrometers.

Surface roughness after polishing with nanometer particles is nanometers.

CMP: chemical-mechanical polishing



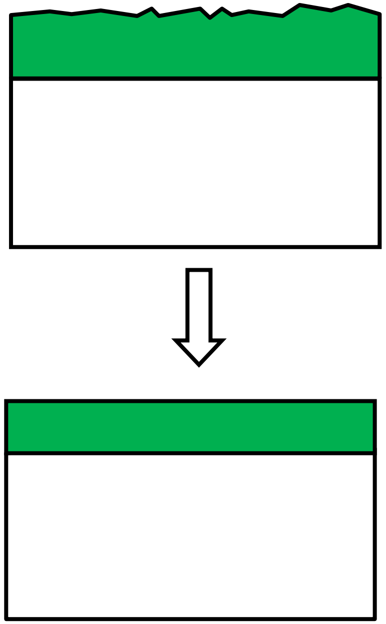
Ceramic particles in acidic (or alkaline) solution abrade surface. Acid(base) etches surface.

Soft polishing pad presses particles against surface.

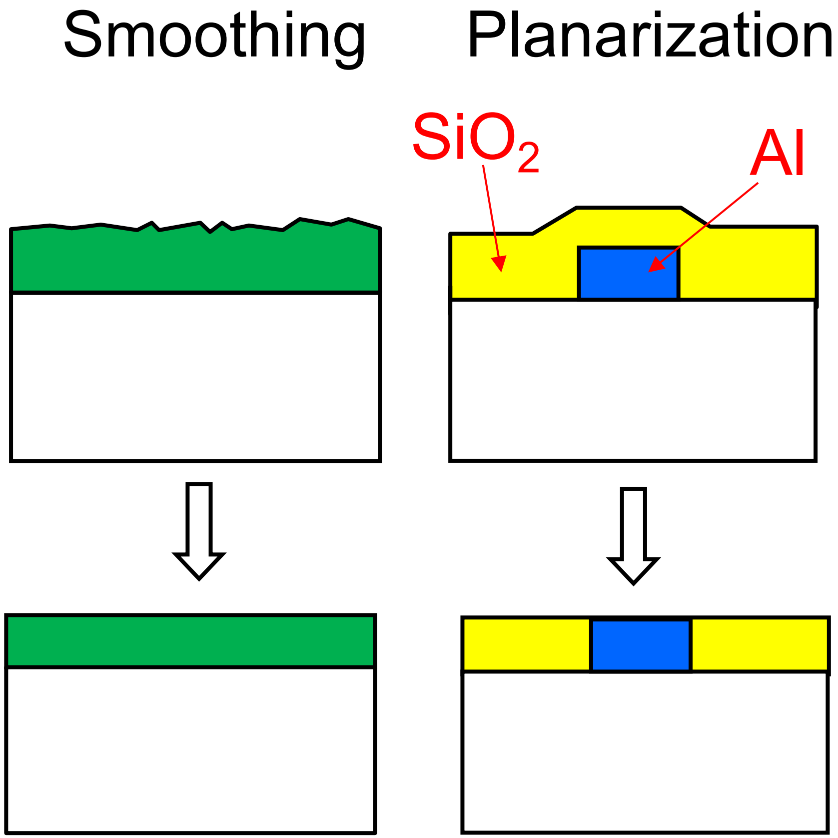
Polishing rate e.g. 100-1000 nm/min.

Applications of polishing

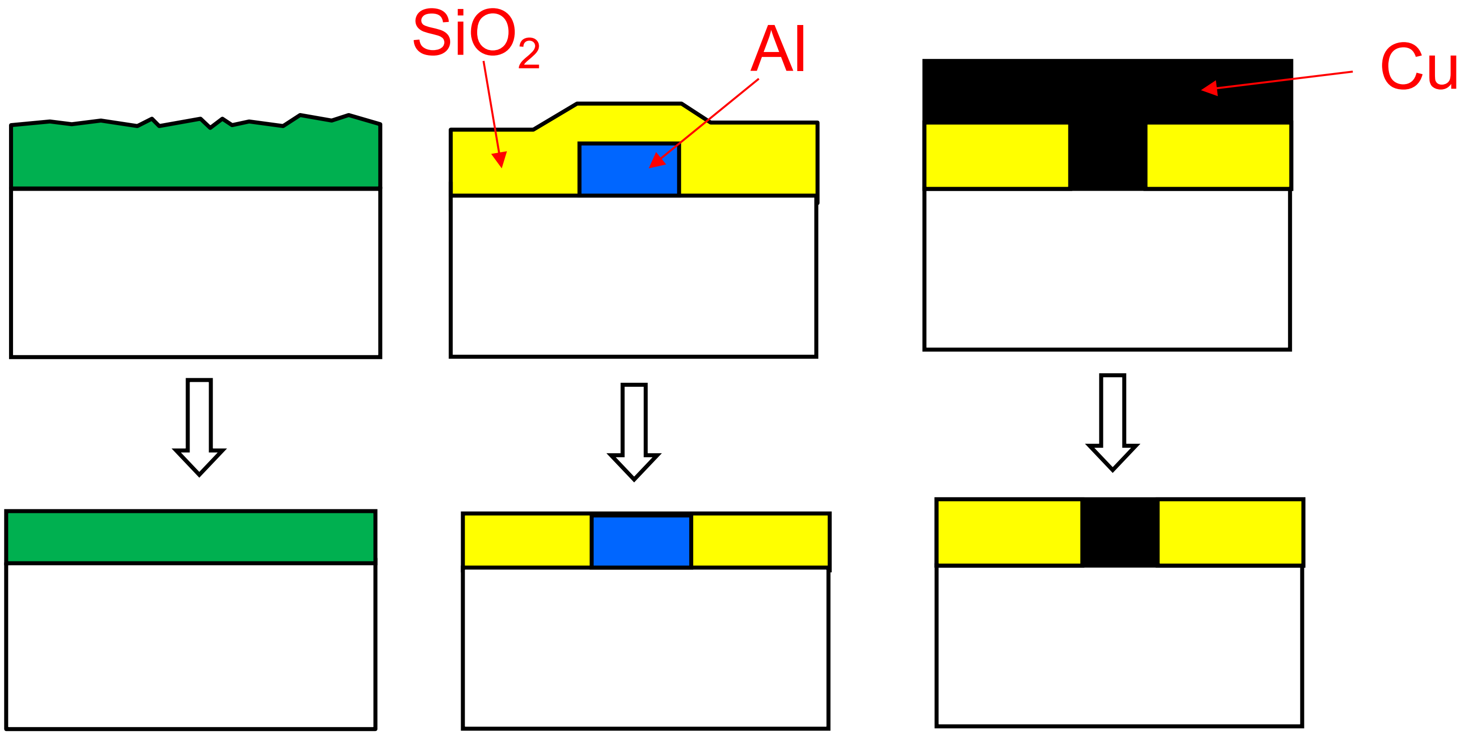
Smoothing



Applications of polishing



Applications of polishing

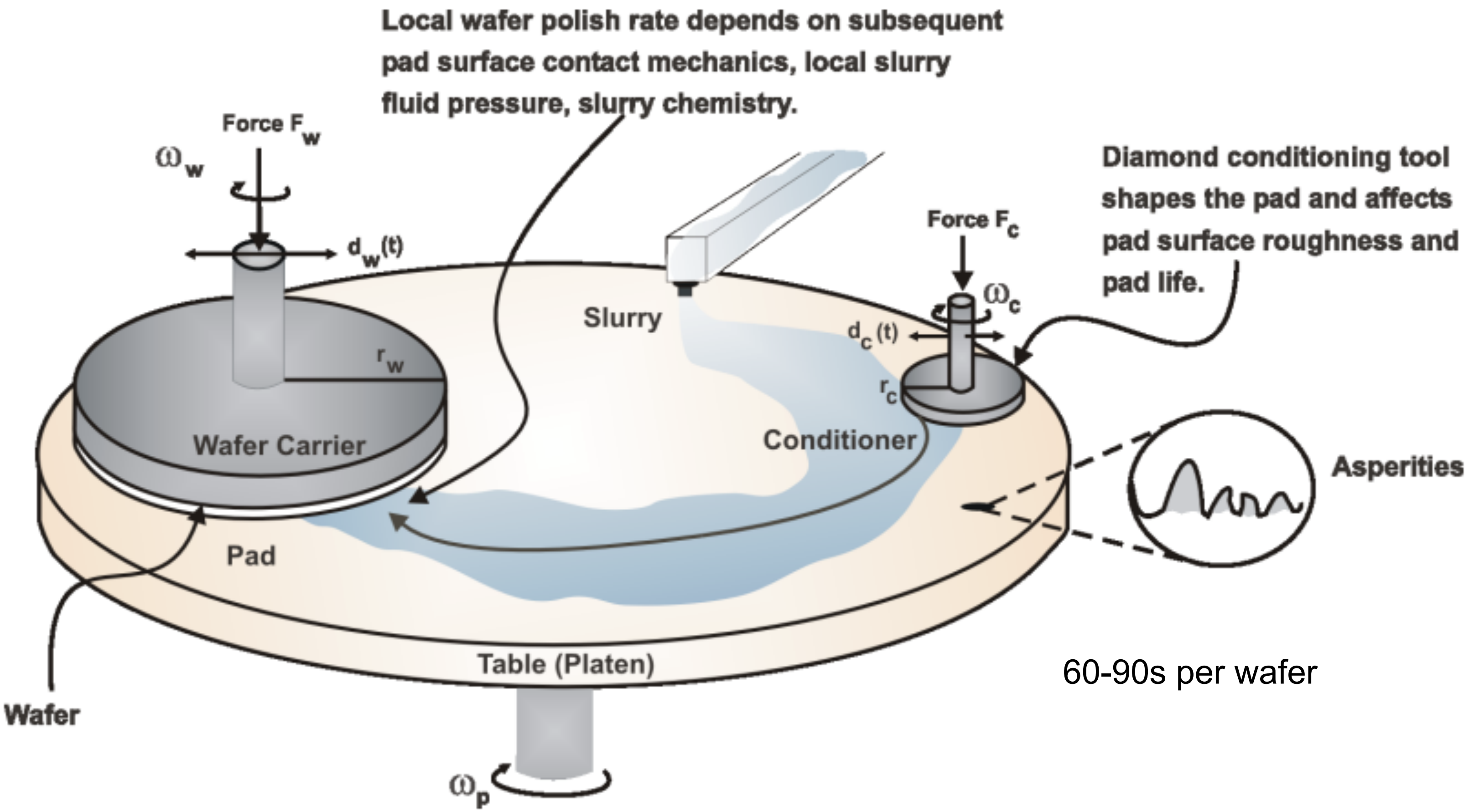


Smoothing

Planarization

Damascene

Rotary CMP tool

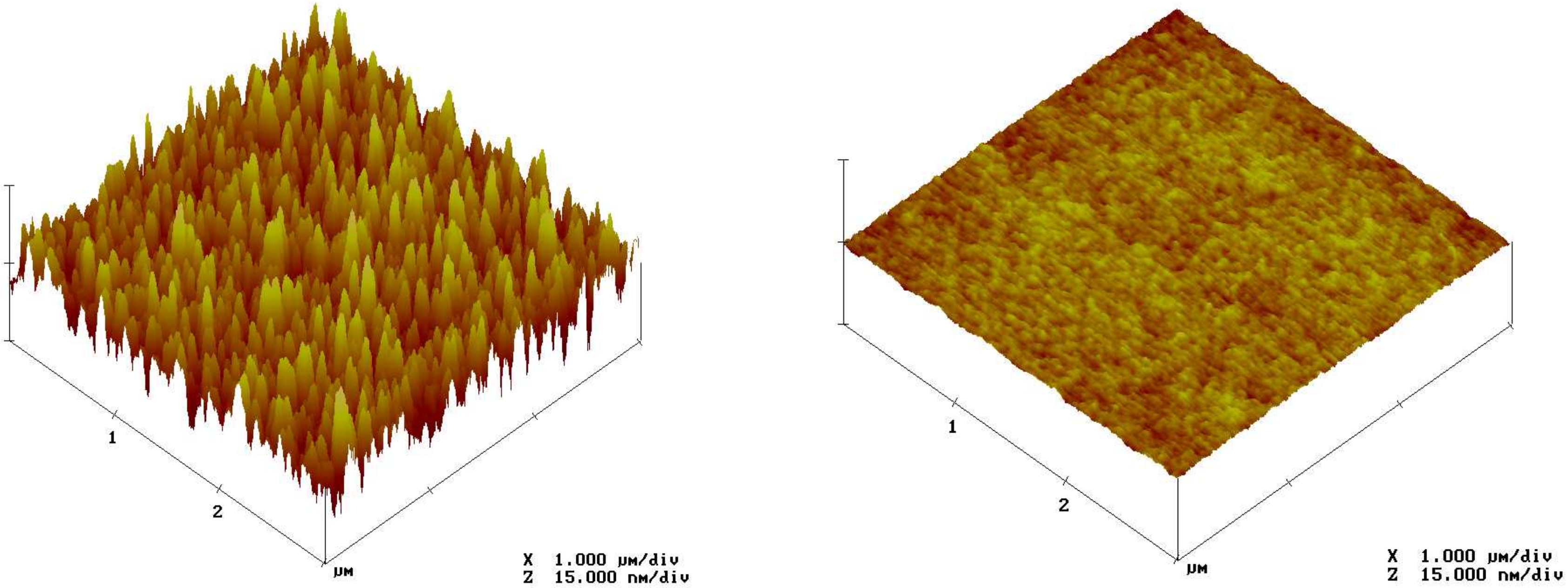


Local wafer polish rate depends on subsequent pad surface contact mechanics, local slurry fluid pressure, slurry chemistry.

Diamond conditioning tool shapes the pad and affects pad surface roughness and pad life.

60-90s per wafer

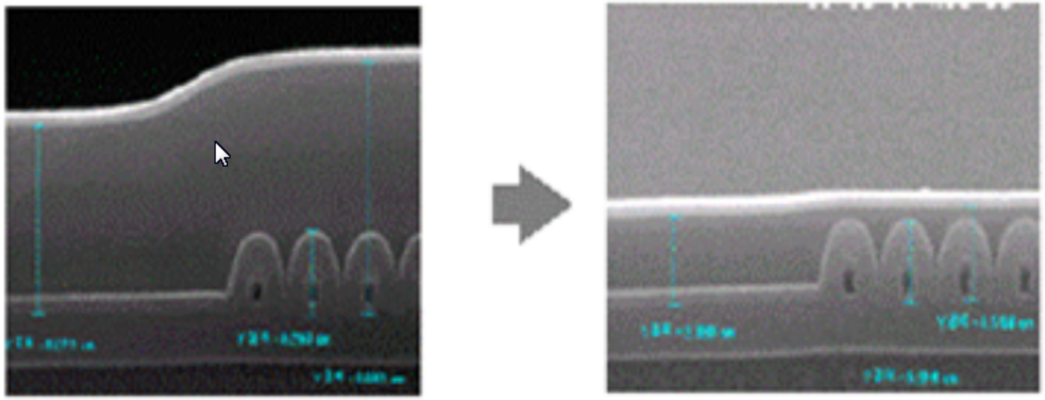
CVD oxide roughness



AFM scans of PECVD oxide: a) as deposited film peak-to-valley height is 26 nm, with RMS roughness of 3.3 nm; b) after CMP peak-to-valley is 2 nm and RMS roughness is 0.2 nm. Figure courtesy Kimmo Henttinen, VTT.

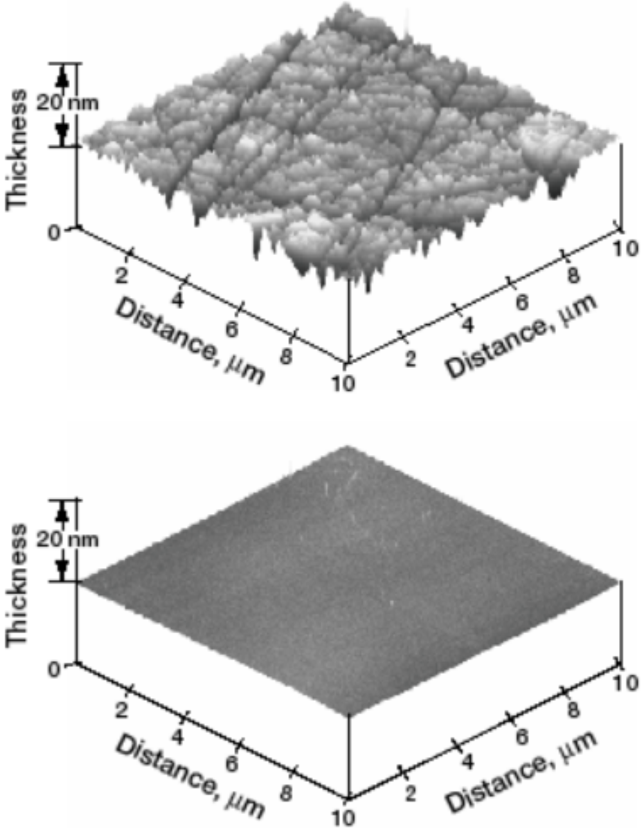
Results of CMP

CMP of SiO_2



Planarization

SiC wafer before and after CMP



Polishing

Polish selectivity & polish stop

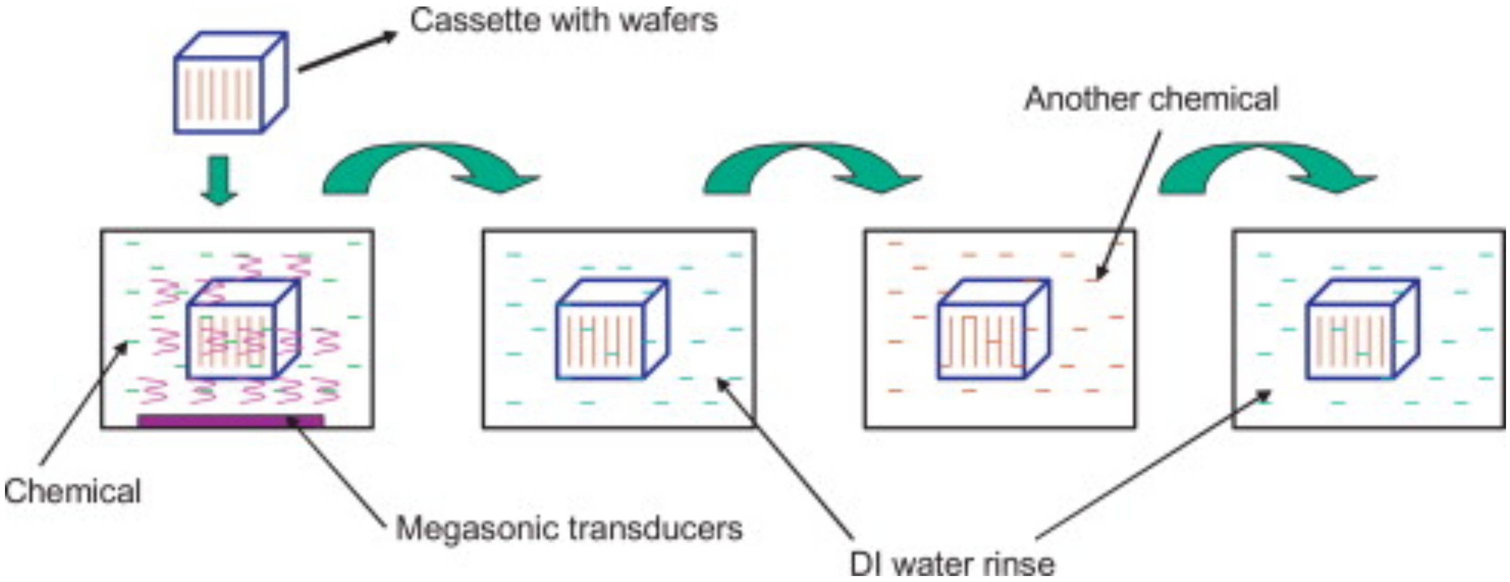
Polish selectivity:

Polishing rate of material 1/polishing rate of material 2

e.g. Copper 400 nm/min Oxide 40 nm/min ➔ 10:1
e.g. Copper 400 nm/min TaN 10 nm/min ➔ 40:1

Polish stop: if selectivity is very high, we call it polish stop (even though some underlying material is removed)

Cleaning after polishing

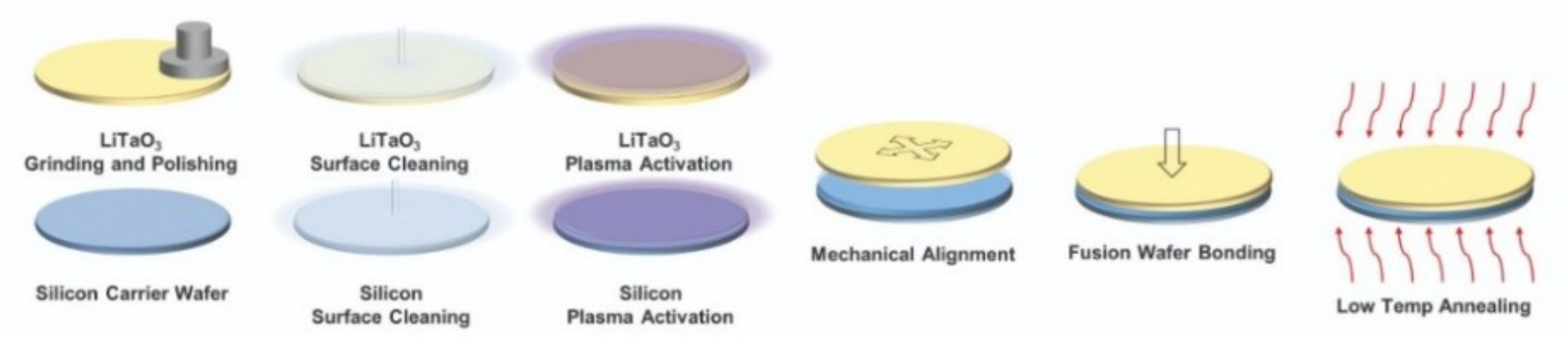


Zillions of particles.
Multiple step cleaning required.
First rinsing water has to be discarded, too many particles.

Keswani et al:Developments in Surface Contamination and Cleaning Wet and Dry Cleaning Methods 2015, Pages 145-183

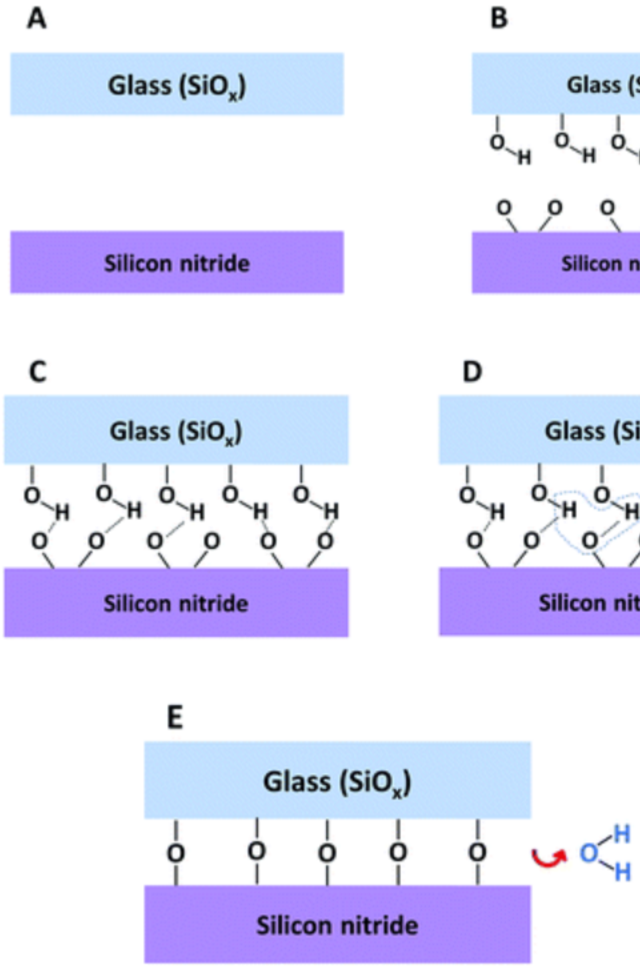
Bonding

Joining two pieces
Permanently or temporarily



https://siliconsemiconductor.net/article/108622/Wafer_Bonding_Enables_Future_RF_Filter_Manufacturing/feature

Activation can lower bonding temperature



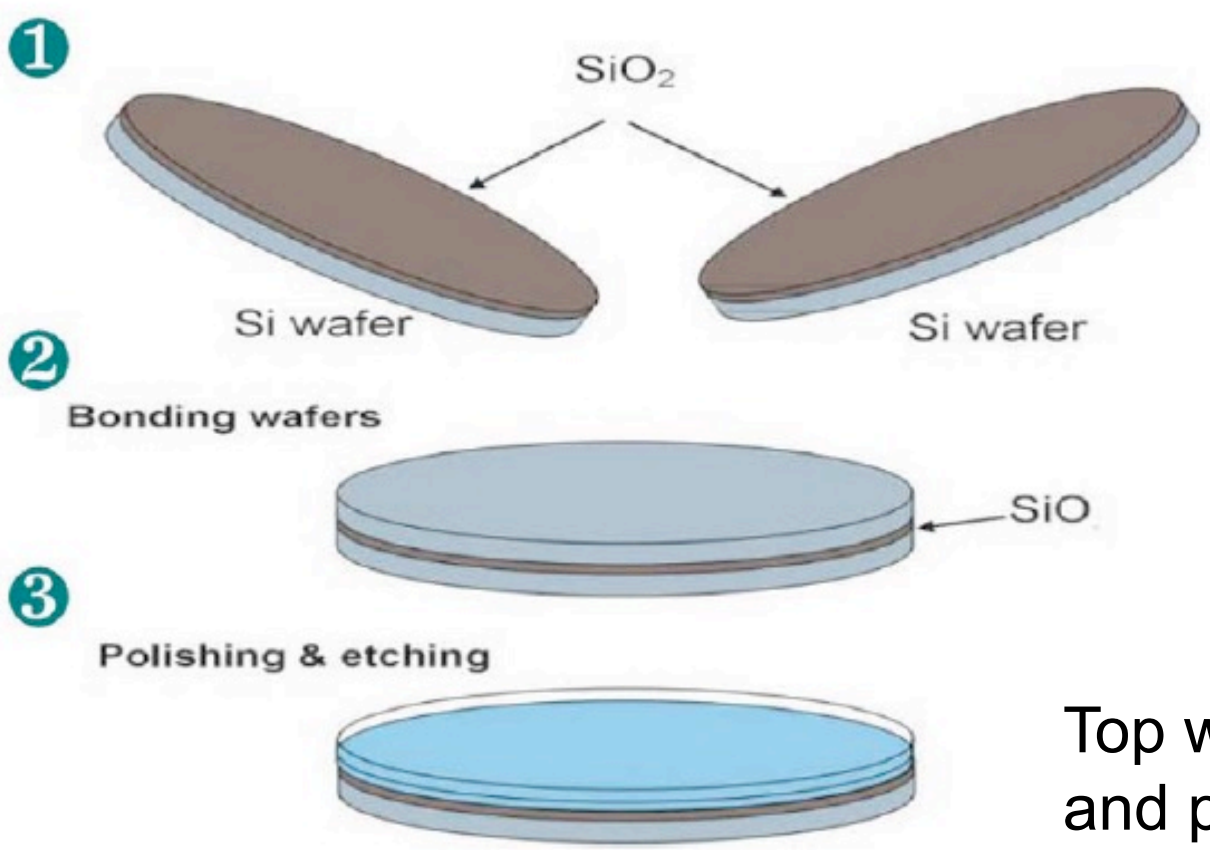
Reactive bonds from activation enable bonding at lower temperature (if flatness and smoothness are good enough).

One or both wafers may need to be activated.

At least we need to start from known condition.

Pasternak et al: RSC Adv., 2018, **8**, 2161-2172

SOI: silicon-on-insulator



Cleaning ➔ particle removal and hydroxyl bonds

RT joining and high temperature anneal

Top wafer grinding and polishing to desired thickness

Bonding considerations

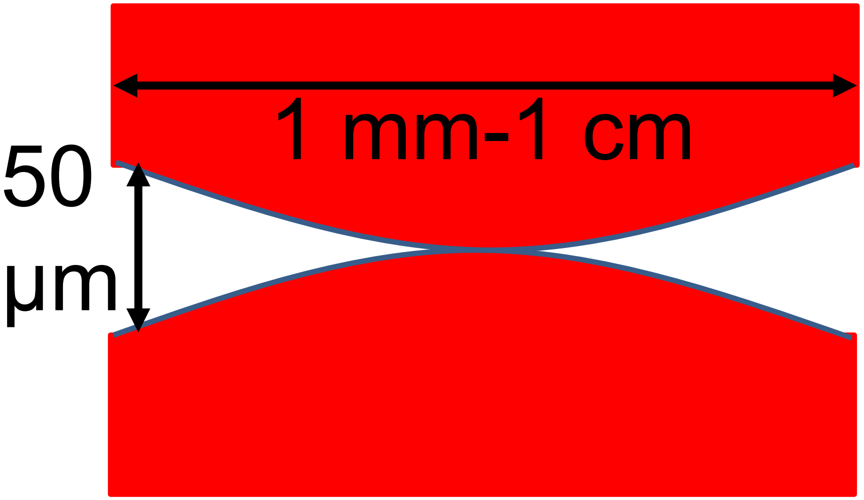
- Bond properties

  - What are the chemical bonds that will form ?
  - Do they exist naturally or formed by treatment?
  - Bond strength ?
  - Permanent vs. temporary ?

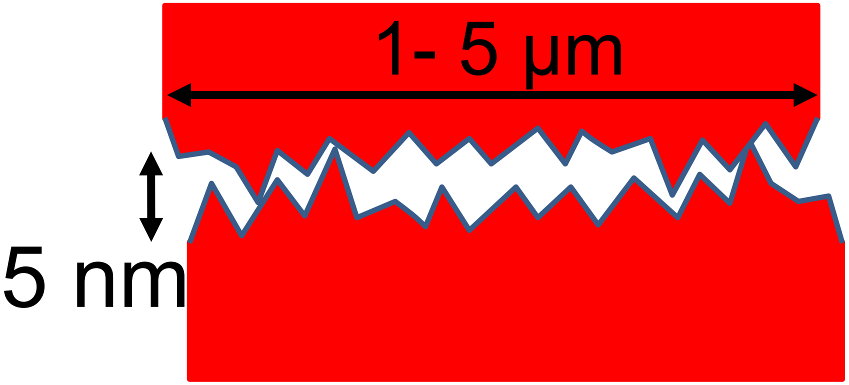
Bonding: materials

- Chemical compatibility (e.g. interdiffusion)
- Temperature tolerance
  - Bond formation temperature
  - Operational temperature of final product
- CTE (coefficient of thermal expansion) mismatch between materials
- Surface quality (roughness; waviness)
- Surface particles

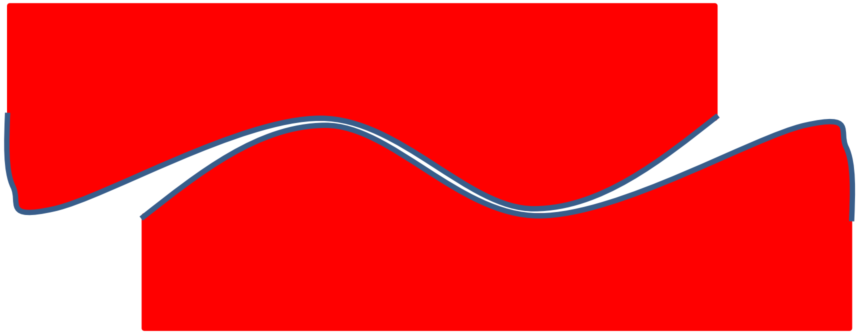
Flatness vs. smoothness

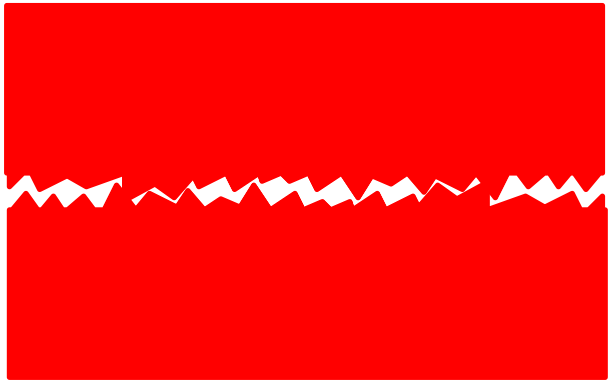


macroscopic



atomic/nanoscale

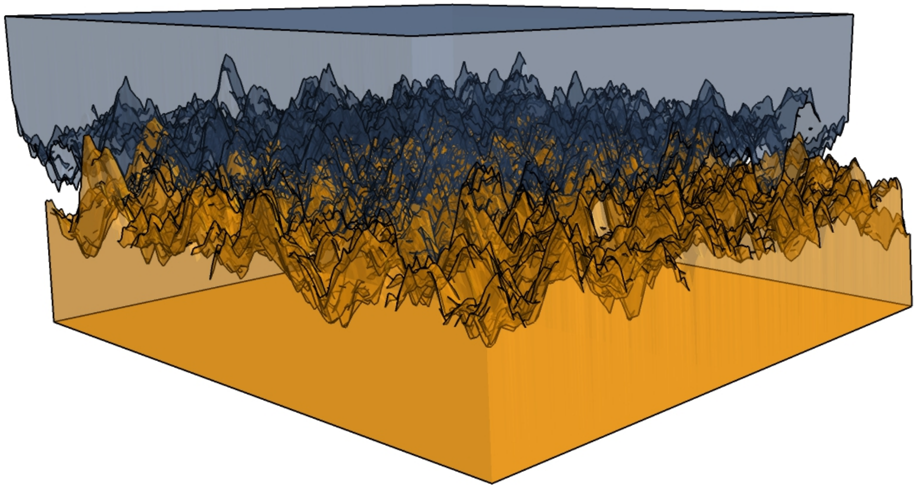




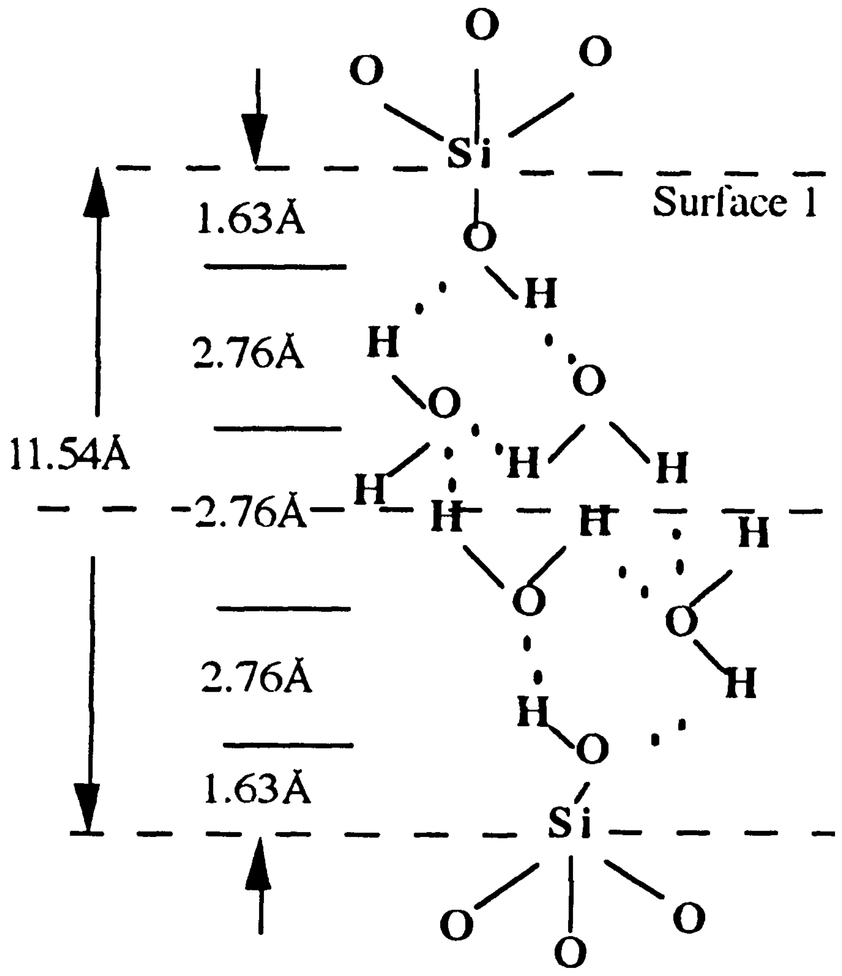
Mechanics of joining

- Even polished surfaces have roughness $R_{\text{peak-to-valley}}$ 3-10 nm ➔ not perfect contact
- Heat to 1000^{o}C ➔ viscous flow

➔ Intimate contact



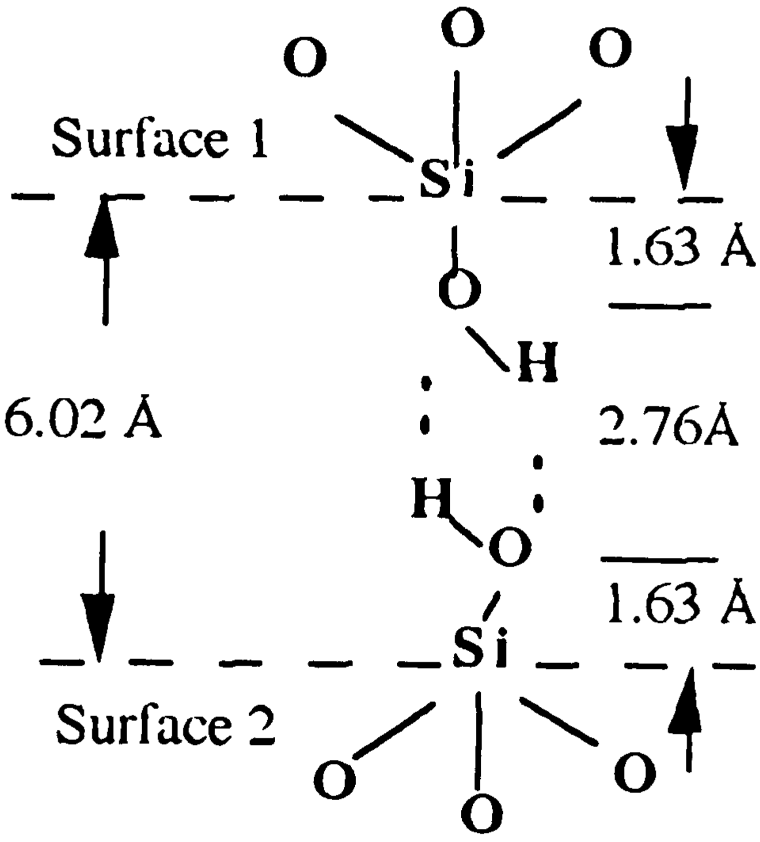
Surface water & hydrogen bonds



At room temperature, bonding happens via physisorbed water, i.e. hydrogen bonds.

Tong & Gösele: Semiconductor wafer bonding

Heating to remove water



250°C removes physisorbed water, but chemisorbed water still remains.

Surface energy 250 mJ/m^2 pretty close to theoretical value.

High temperature➔ Si-O-Si bonds

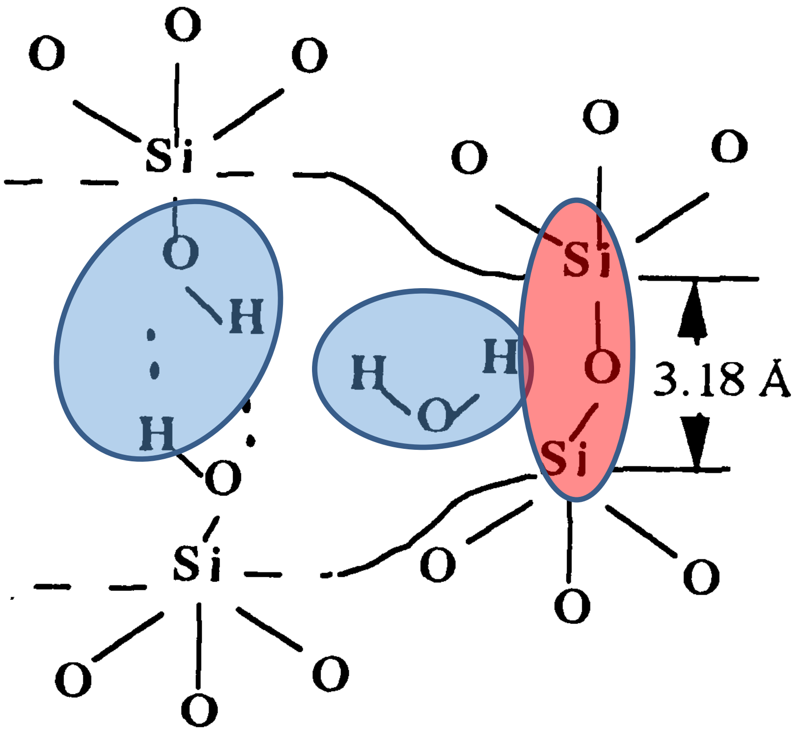
Si-O-Si bond 400 kJ/mol.

Measured surface energy

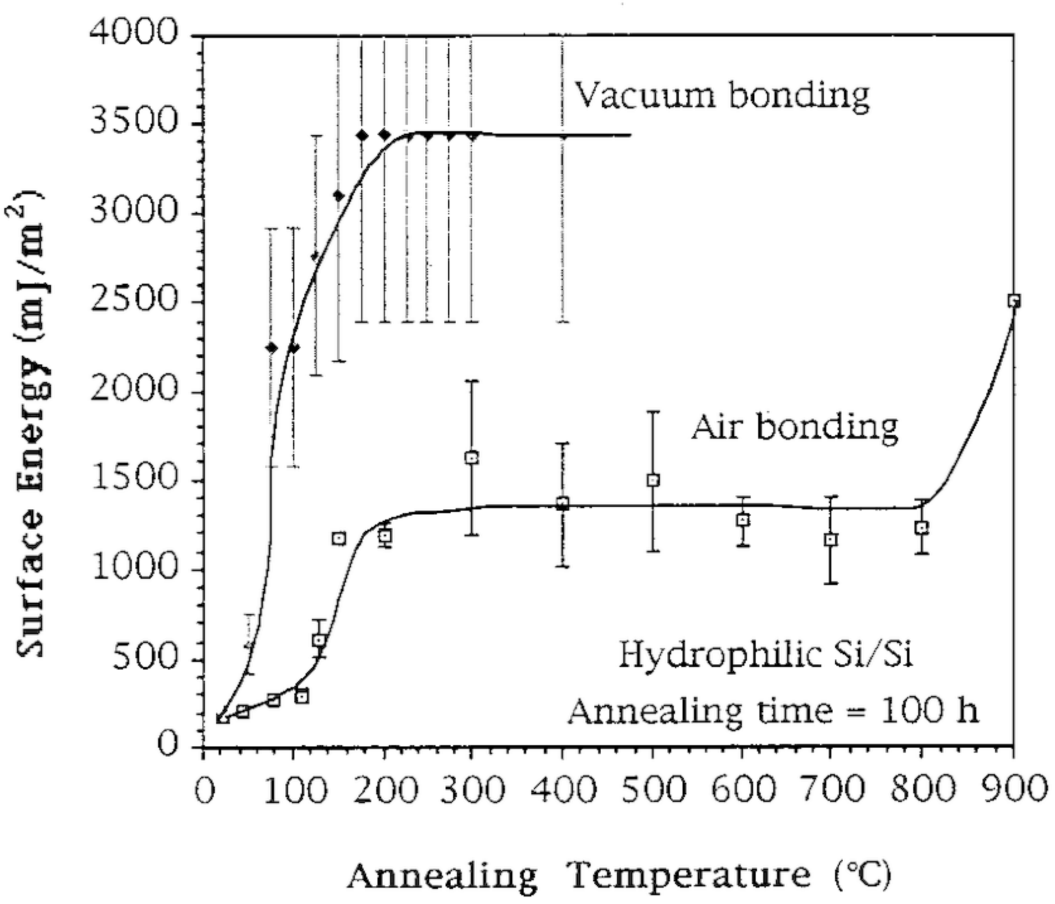
3000 mJ/m^2

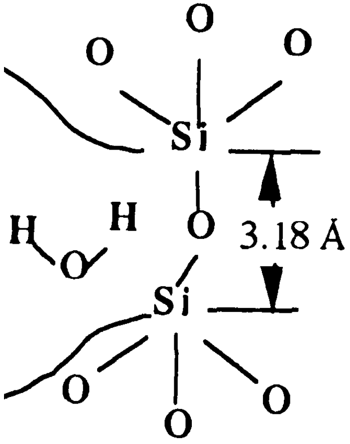
Theoretically:

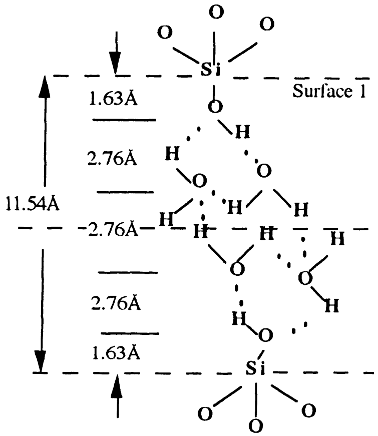
10^{15}cm^{-2} * 400 kJ/mol ➔ 3500 mJ/m^2



Bond strength = f(T)

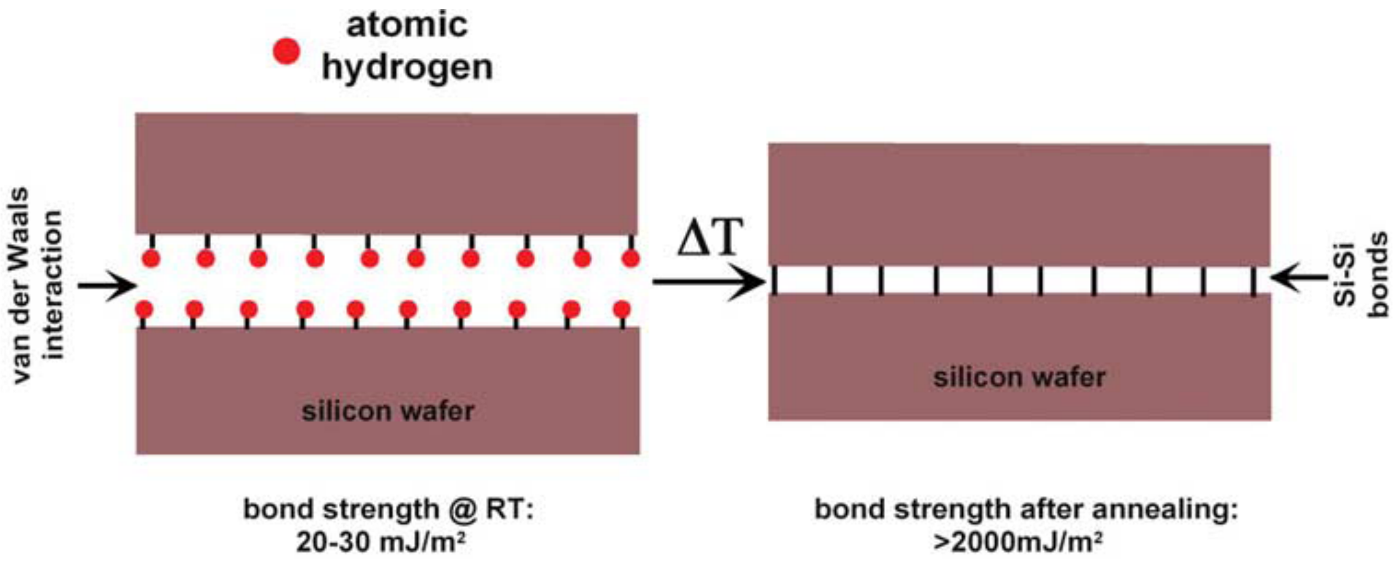






Gösele et al: JVST A 17(4):1145-1152 · July 1999

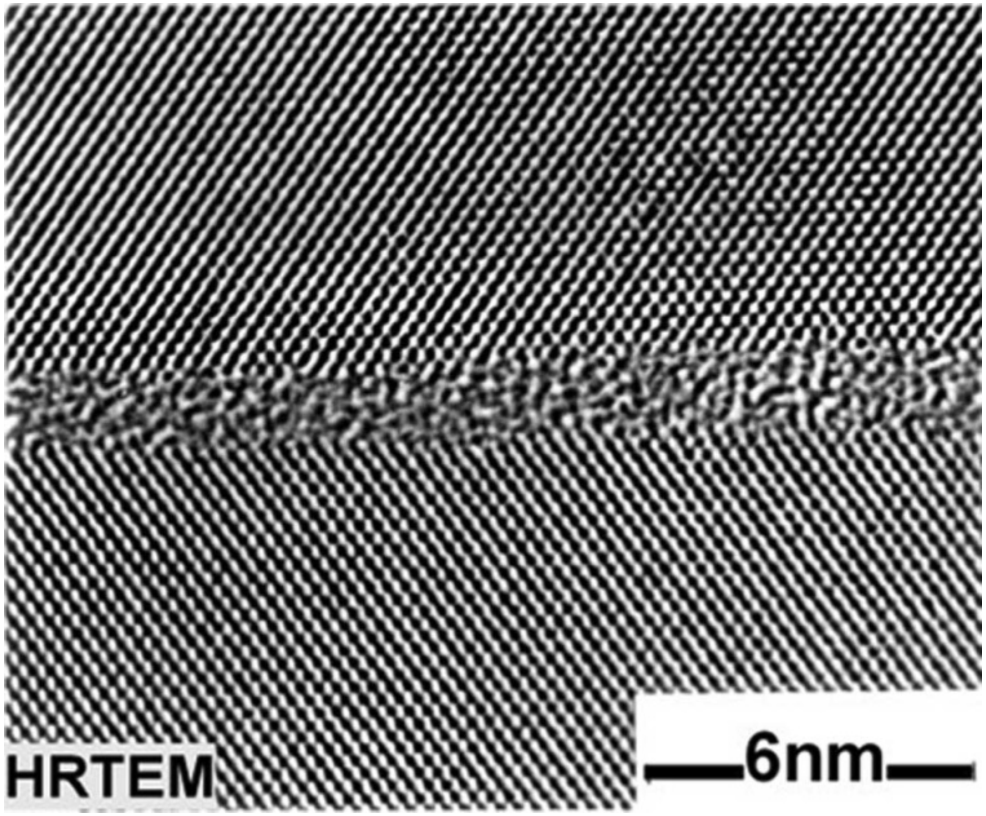
Hydrophobic Si-Si bonding



- Silicon native oxide removed in HF ➔ H-termination
- H-terminated surface adsorbs hydrocarbon contamination ➔ quick !
- Initially, hydrogen bonds are very weak ➔ more sensitive to defects
- Bonding and annealing will result in direct Si-Si covalent bond
- H_2 has no place to go ➔ H_2 bubbles form at interface

(Christiansen *et al.* 2006)

Bond interface



HRTEM showing thin amorphous oxide between two single crystal silicon layers

Practical bonding process steps

-particle removal
-surface chemistry modification
-(optional) vacuum pumping
-(optional) wafer alignment
-room temperature joining
-application of **force/heat/voltage**
-(optional) wafer thinning

Bonding methods

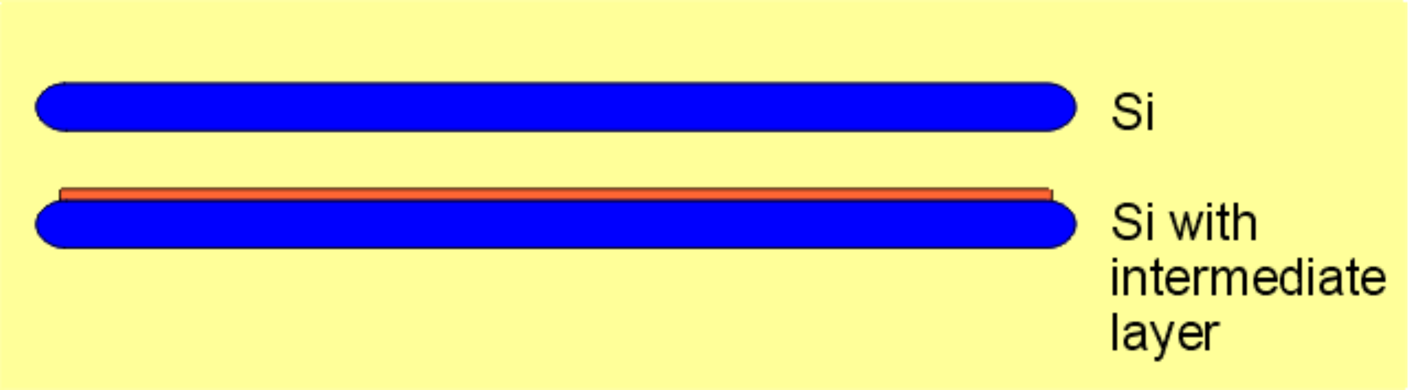
• direct bonding = fusion bonding (Si/Si; glass/glass; SiO_2/Si) • anodic bonding (AB) Si/glass, glass/Si/glass	No intermediate layer
• thermo-compression bonding (TCB) • Eutectic/TLP bonding	Metallic intermediate layer
• Si/glass frit bonding • adhesive bonding limited by “glue” properties	Insulating intermediate layer

Fusion/direct/thermal bonding

- Identical materials bonded
- No CTE problems
- Bonds naturally available
- Apply heat/pressure to enhance bonding

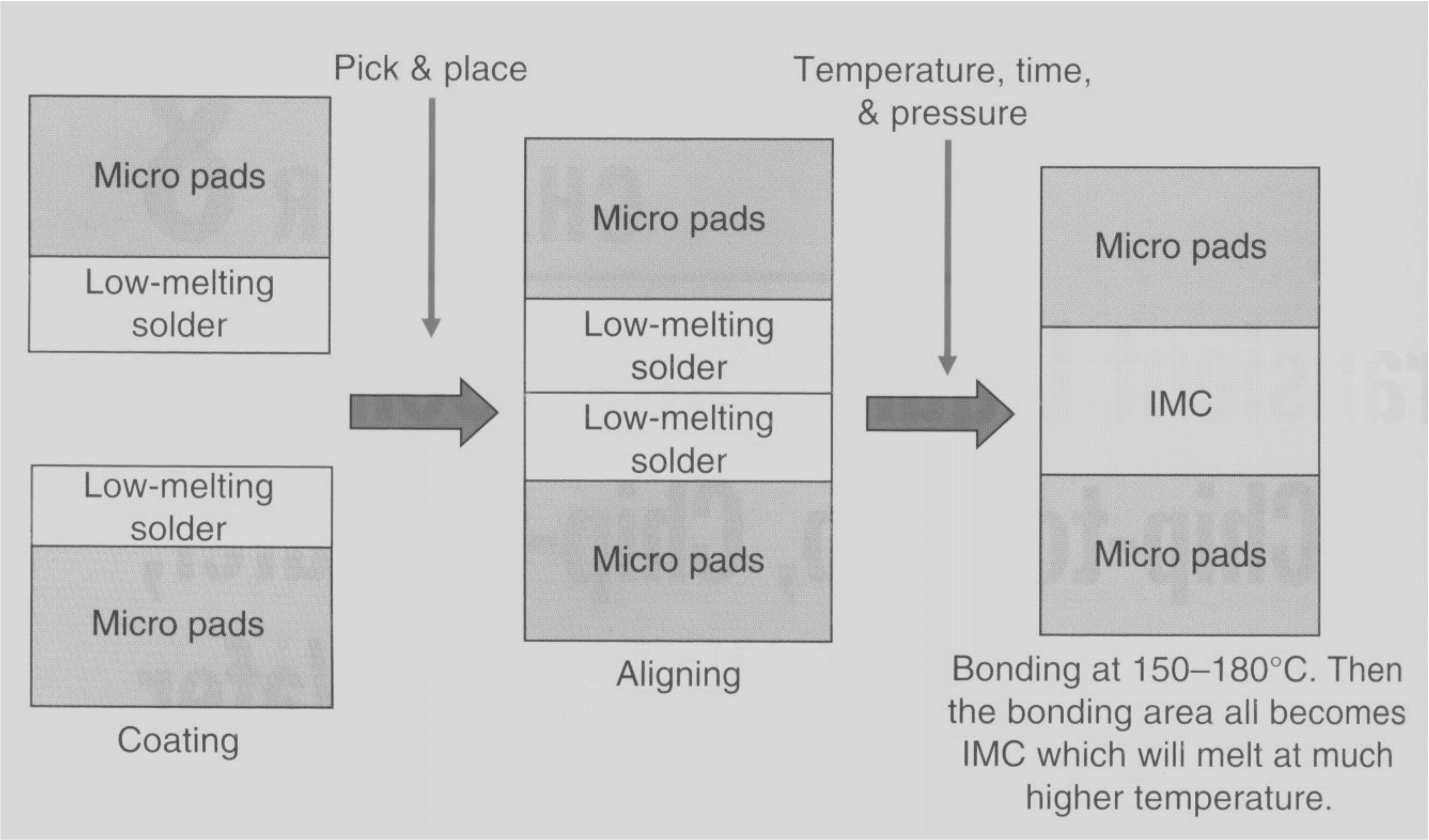
- Si-Si
- Glass-glass
- Polymer-polymer

Thermo-Compression Bonding
≈ apply enough heat & pressure



Double Sided Heating:	**up to 550°C**
Contact Force:	**100 - 40000N**
Bonding Atmosphere:	**1E-5 - 3000mbar**

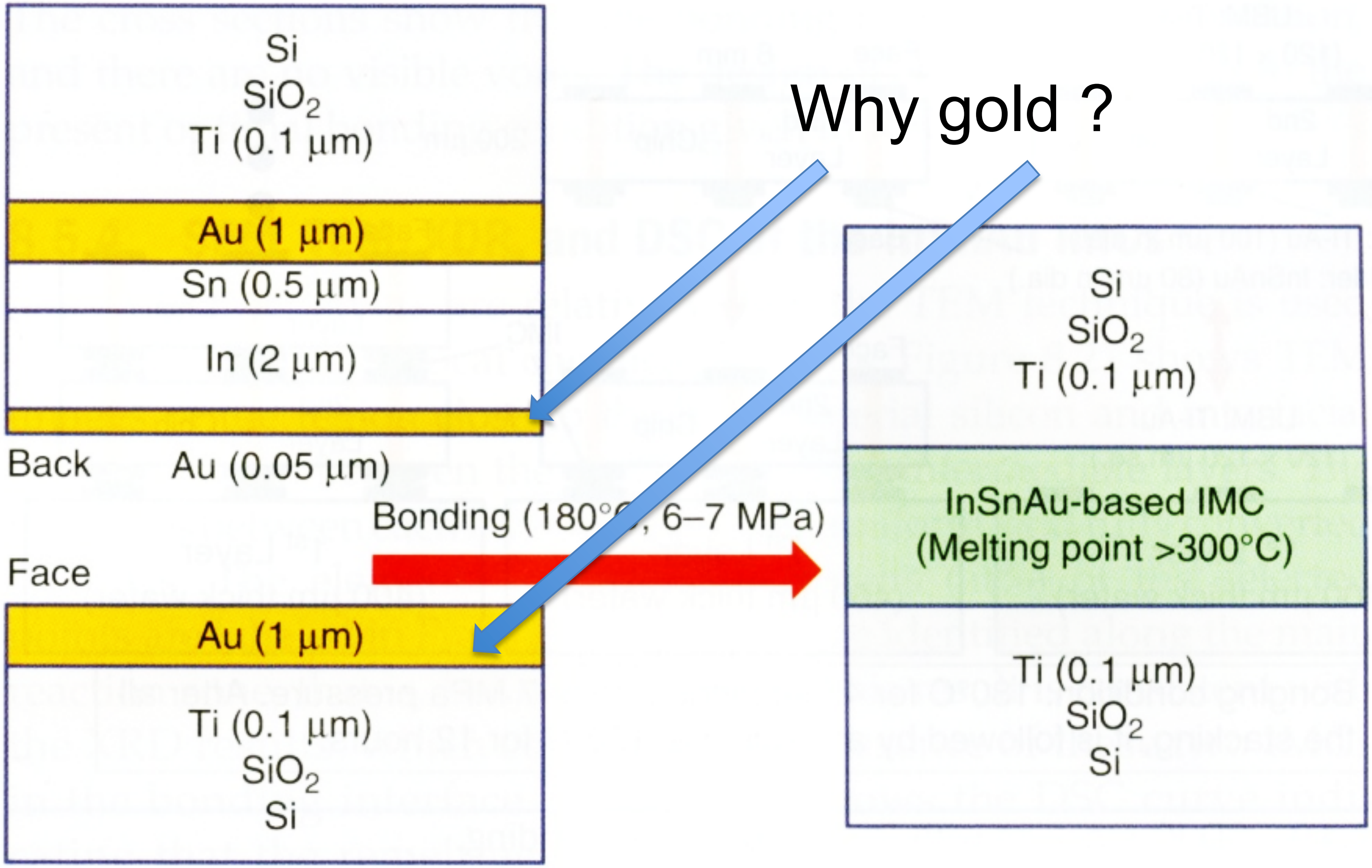
TLP: Transient Liquid Phase
≈SLID: Solid-Liquid Interdiffusion



Bonding at 150–180°C. Then the bonding area all becomes IMC which will melt at much higher temperature.

John H. Lau: Through-silicon vias

TLP/SLID, example



Why gold ?

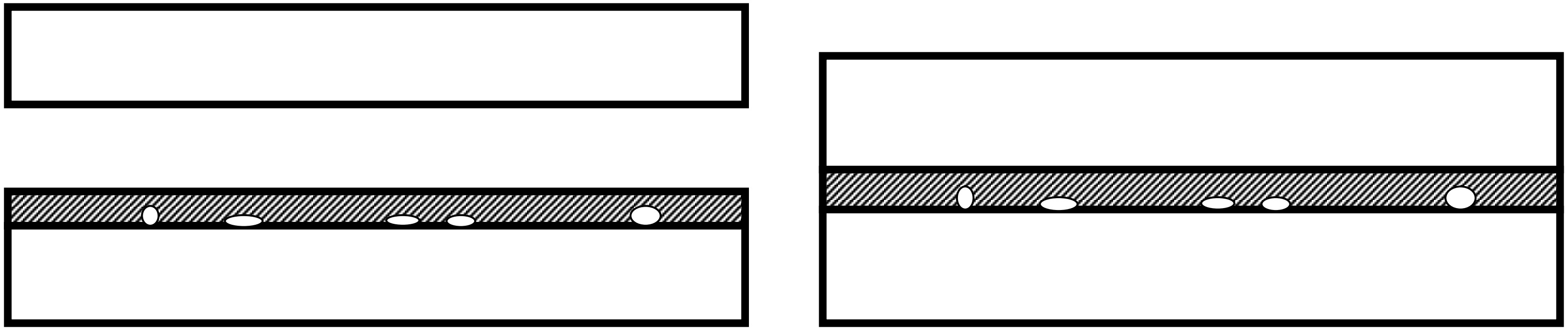
John H. Lau: Through-silicon vias

Adhesive bonding $\approx$ gluing

- surface cleaning
- spin coating of polymer
- initial curing (solvent removal bake)
- evacuate vacuum (optional)
- join the wafers
- final curing with pressure and/or heat

Adhesive bonding benefits

- temperatures around 100°C (>T_g)
- tolerant to (some) particle contamination
- structured wafers can be bonded
- low cost, simple process

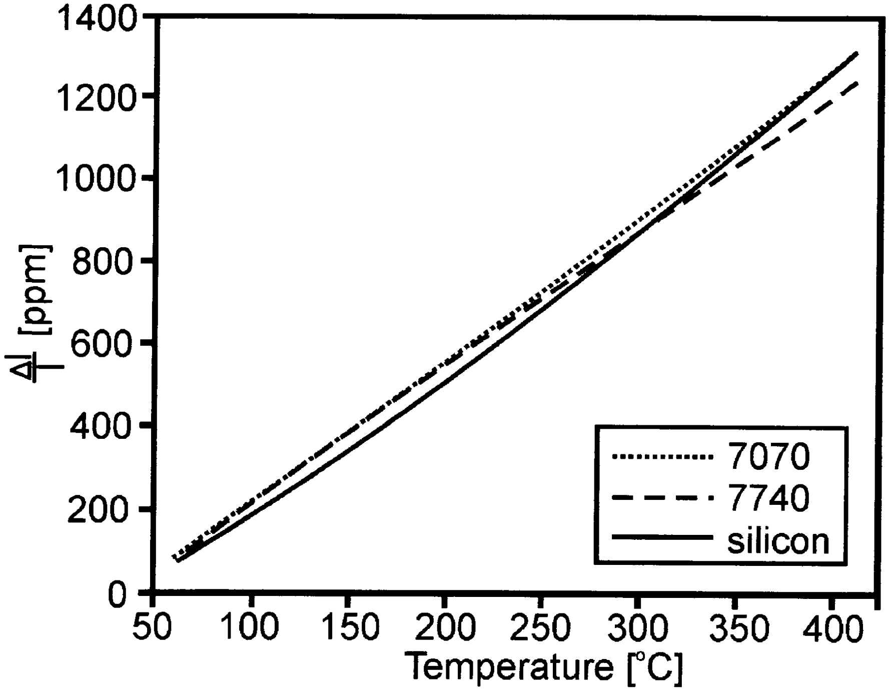


Anodic bonding
= Field-assisted thermal bonding

- Glass/silicon bonded
- Glass/metal bonded

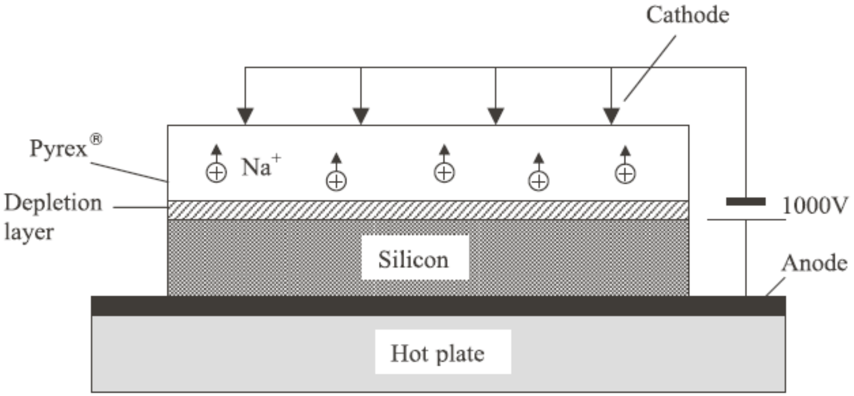
- Coefficients of thermal expansion of silicon and glass must be matching, otherwise cracking upon cooling

➔ only certain glasses suitable for anodic bonding: Pyrex, Borofloat



Pyrex 7070 and 7740 thermal expansion match with silicon

Anodic bonding



Relies on mobile Na^+ and oxygen ions in glass.

Temperature raises ion mobility in glass.

Voltage attracts oxygen ions to interface.

$Si + 2\ O_2^- \rightarrow SiO_2 + 4\ e^-$ reaction at glass-silicon interface.

Double Sided Heating: **up to 550°C**

Contact Force: **1 - 1000N**

High Voltage Supply: **0 - 2000V / 0 - 50mA**

Bonding Atmosphere: **1E-5 - 3000mbar**

Polymer thermal bonding

- Raise temperature above Tg

➔softening

➔intimate contact

Hold long enough

➔cool down below T_g

➔Bond interface indistinguishable from bulk materials (because same bonds !)

Polymer bonding (2)

Softening by solvent surface treatment

➔Intimate contact

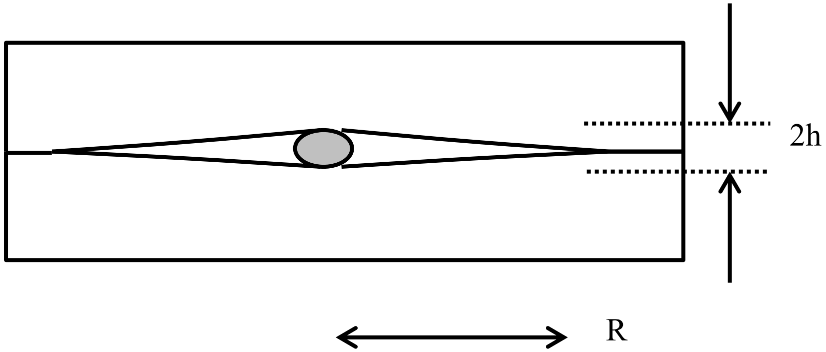
Hold long enough

Bonding of different polymers, too!

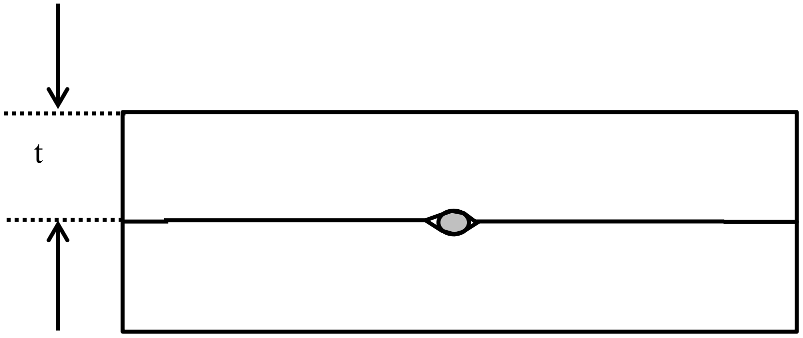
In theory a room temperature process

In practise difficult to control the thickness of the softened layer

Problems with particles

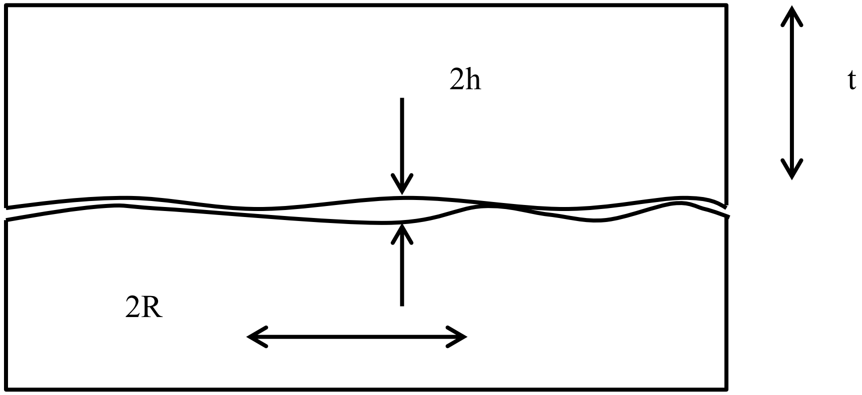


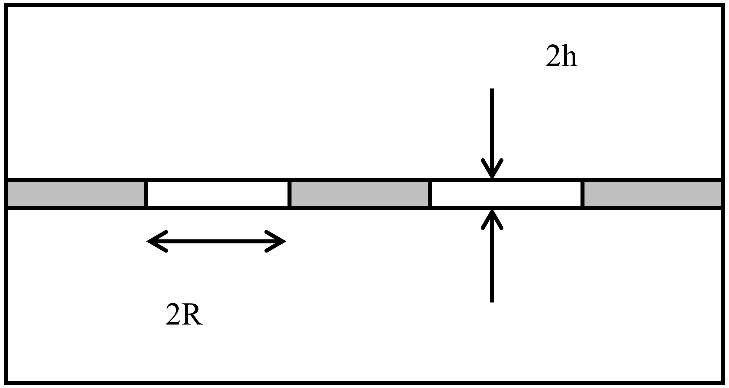
Voids created by particles are very large compared to particles themselves because silicon is rigid material



Silicon can conform only to very small particles, < 100 nm

Flatness & microstructures





Only flat wafers can be bonded (=no long wavelength undulation)

Shallow channels will be bonded if they are too wide

Note: flatness is macroscopic measure; smoothness is local/atomic measure