DE LA RECHERCHE À L'INDUSTRIE

DIRECT BONDING MECHANISM : FROM ADHESION TO ADHERENCE.

Frank Fournel

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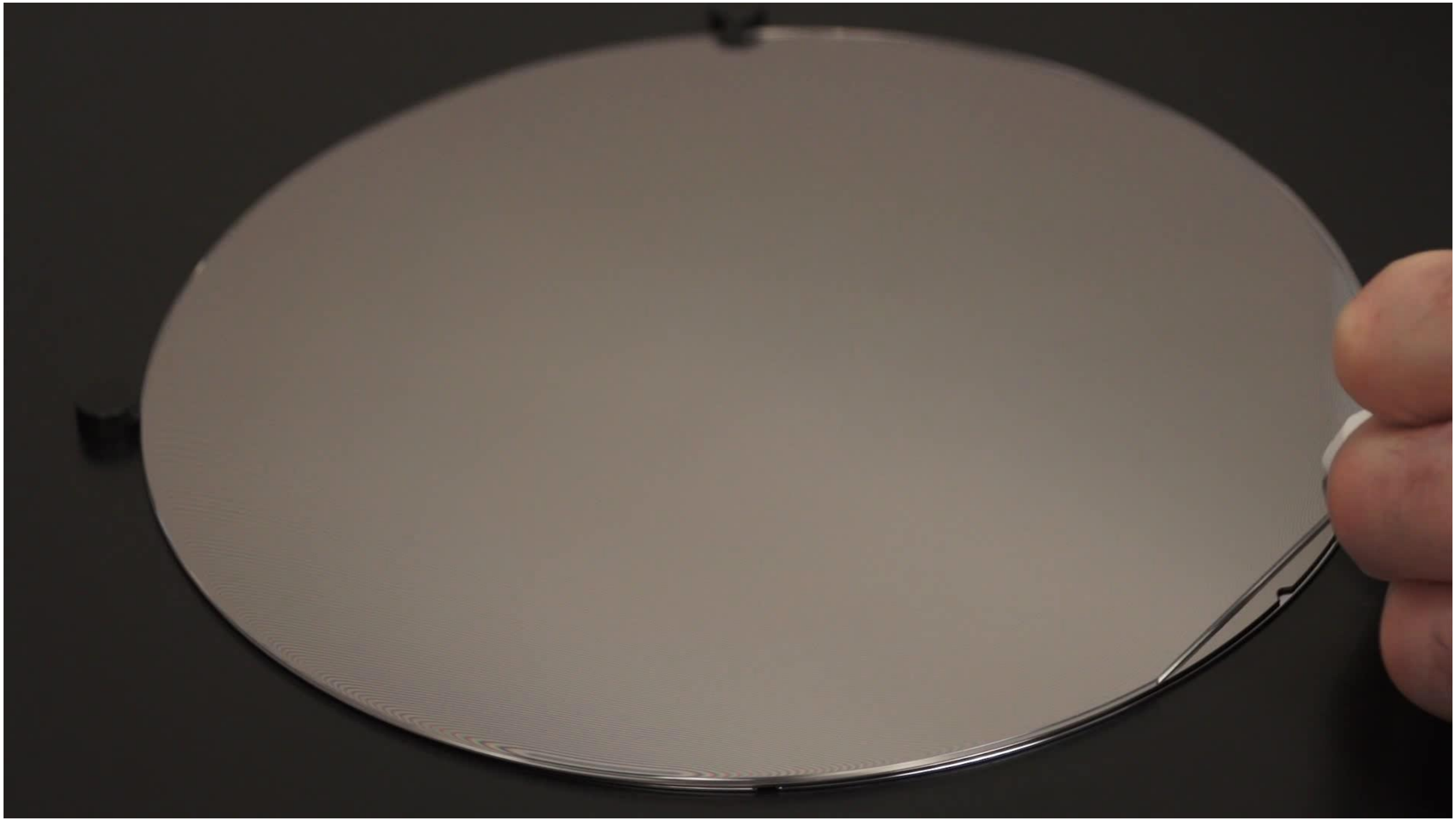
DIRECT BONDING

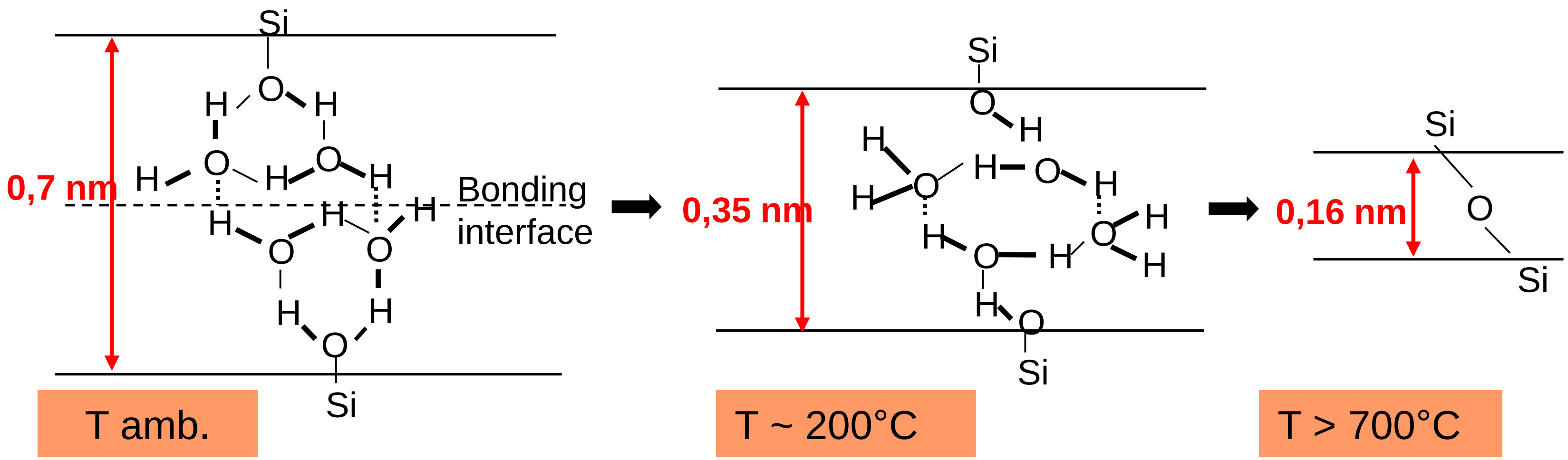
Spontaneous bonding without "thick" liquid material

(usualy at room temperature and ambient pressure)

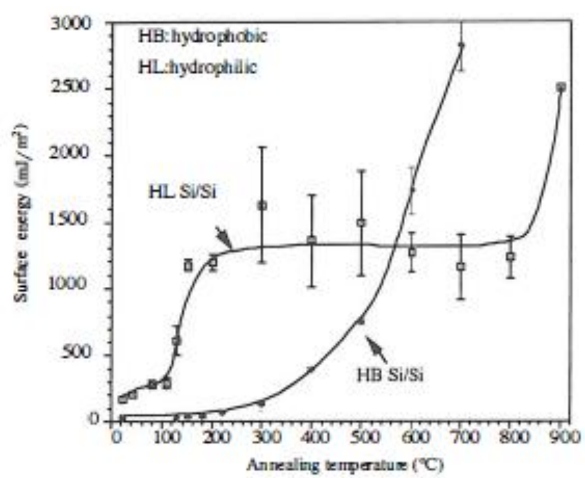


Stengl Model : hydrophilic Si bonding

Based on infrared spectroscopy and bonding energy measurement..

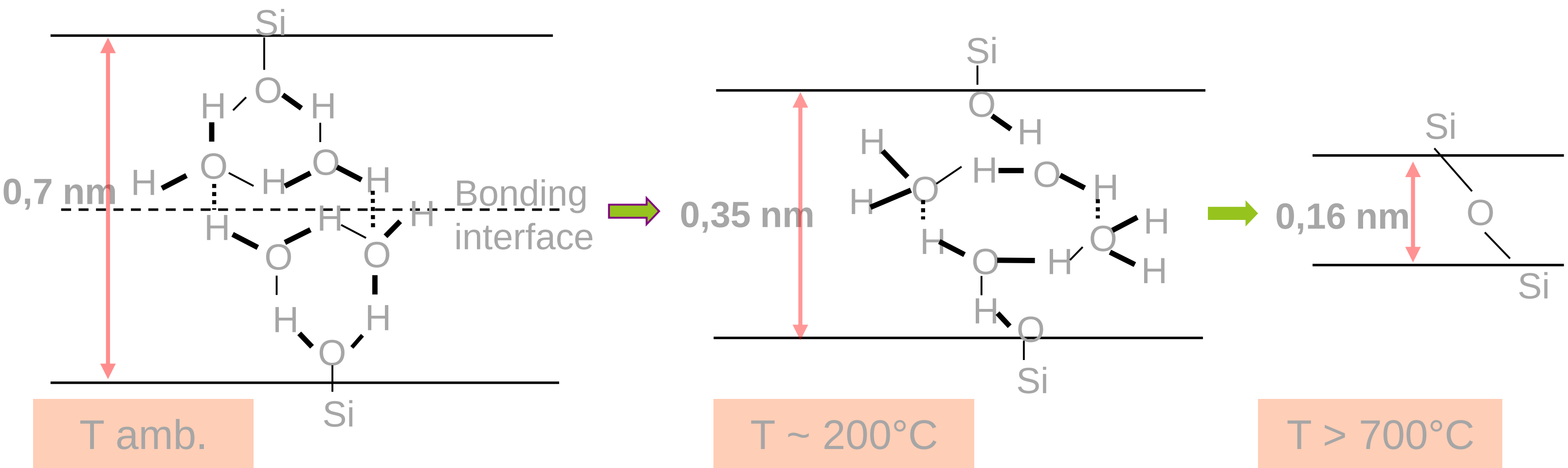


R. Stengl et al., J. J. Appl. Phys. Lett. (1989)

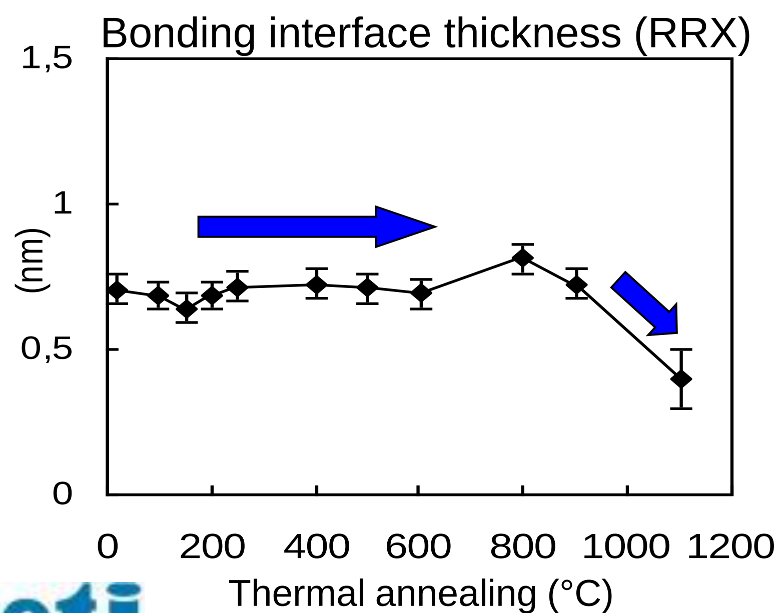


Q.Y. Tong, U. Gosele,"SemiConductor Wafer Bonding: Science and Technology", John Wiley Sons Inc (1998)

PHYSICAL MECHANISM



R. Stengl et al., J. J. Appl. Phys. Lett. (1989)



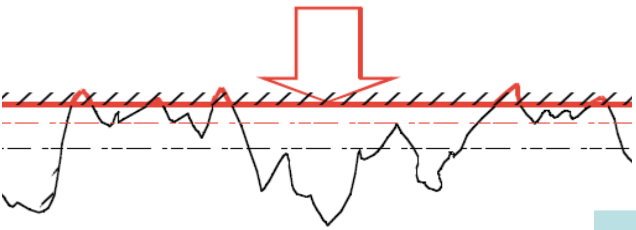
RRX=> Constant interface thickness

→ **Model has to be optimized**

Hertz model (RT Bonding)

$$\sigma^{*2} = \sigma_1^2 + \sigma_2^2$$

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$



Greenwood et al., Proc. Roy. Soc., A295, 300 (1966).

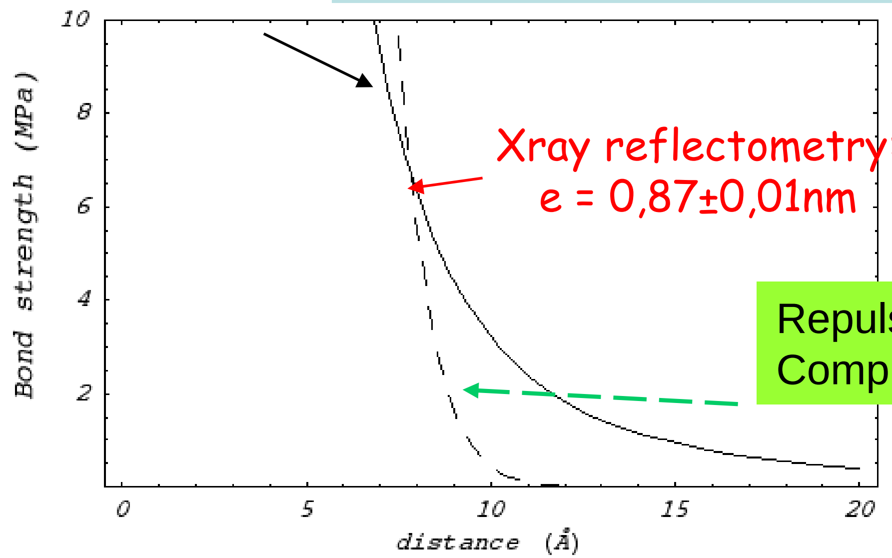
Number of asperities in contact $N = N_0\ F_0(d/\sigma^*)$

Surface area in contact $A = A_0\ (N_0 R \sigma^*)\, \pi F_1(d/\sigma^*)$

Total repulsive force $P = N_0 R^{1/2} \sigma^{*3/2}\ 4/3 E^* F_{3/2}(d/\sigma^*)$

$$F = \frac{A}{6\pi d^3}$$

Attractive forces: Van der Waals
(Hydrophobic Si Bonding: A= 20.10^{-20}J)



Xray reflectometry:
e = 0,87±0,01nm

~1% of contacted surface

Repulsive forces:
Compressed asperities

*Fr. Rieutord et al., ECS 2006

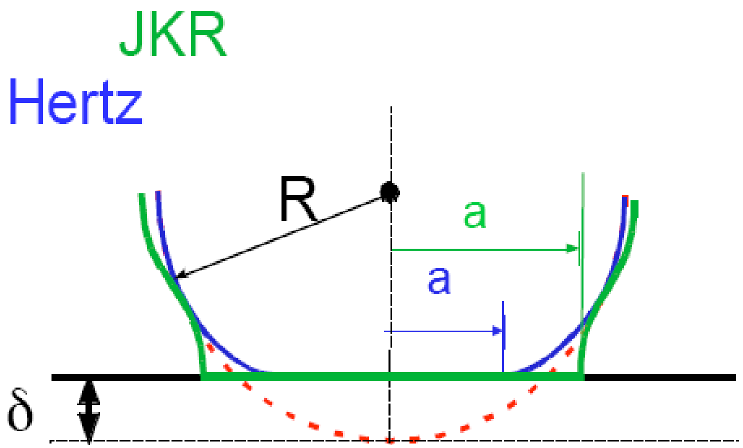
JKR Model during annealing

Johnson-Kendall-Roberts

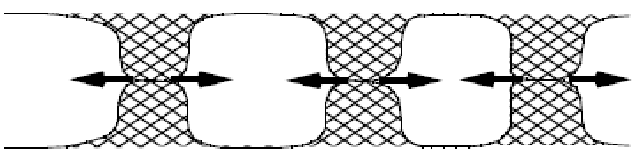
$$E_{tot}(z) = \int_z^{\infty} P(u)du - (wA(z) \quad + vdW(z))$$

Elastic energy
(Asperity compression)

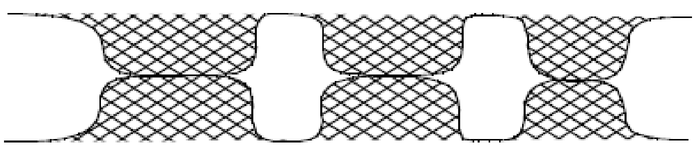
Surface energy
(Adhesion)



➢ Ziplock model



RT, low T



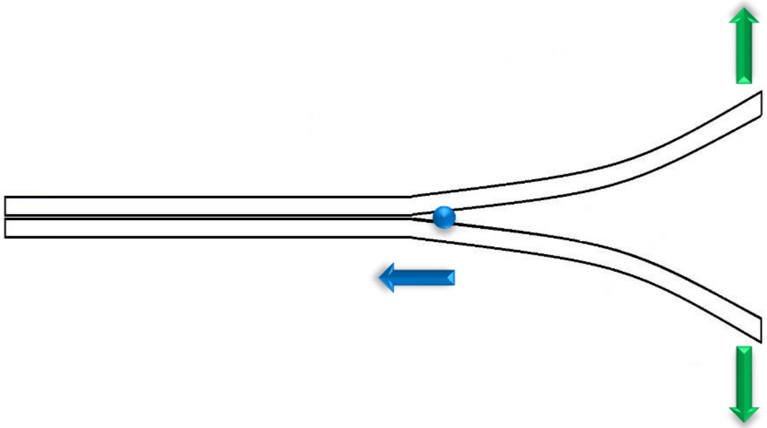
Medium T (<~400°C)

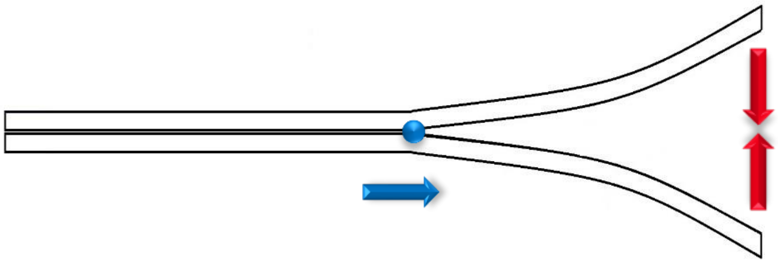
high T

*Fr. Rieutord et al., ECS 2006

ADHESION

Adherence vs adhesion





Adherence Energy

(=Bonding / Fracture energy, Fracture toughness, Criticazl strain energy release rate…)

- Energy needed to open the bonding

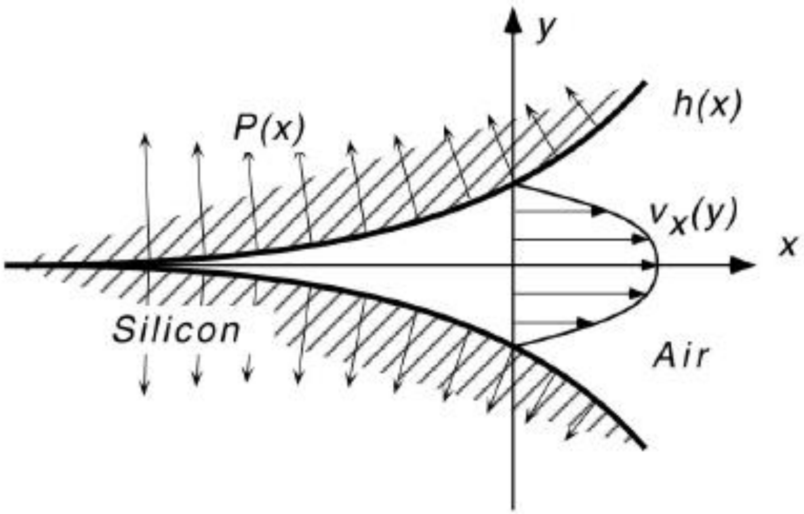
  Chemical bonds breaking

- Measured after bonding
- Double Cantilever Beam (DCB) measurement

Adhesion Energy

- Energy needed to realize the bonding
  - Mechanical deformation
  - Hydrodynamic flow
- Measured during the bonding
- Lack of experimental data

Adhesion energy => Bonding Wave



$$U = \frac{(2\gamma)^{5/4}}{\eta t^{3/4}} \frac{\Lambda^{1/2}}{\left(\frac{E}{1-\nu^2}\right)^{1/4}} \frac{A^{3/4}}{9}$$

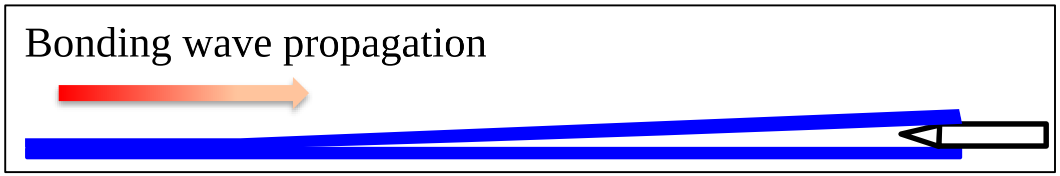
With $2\gamma = E_{adhesion}$

With Λ=mean free path, A=Numerical constant

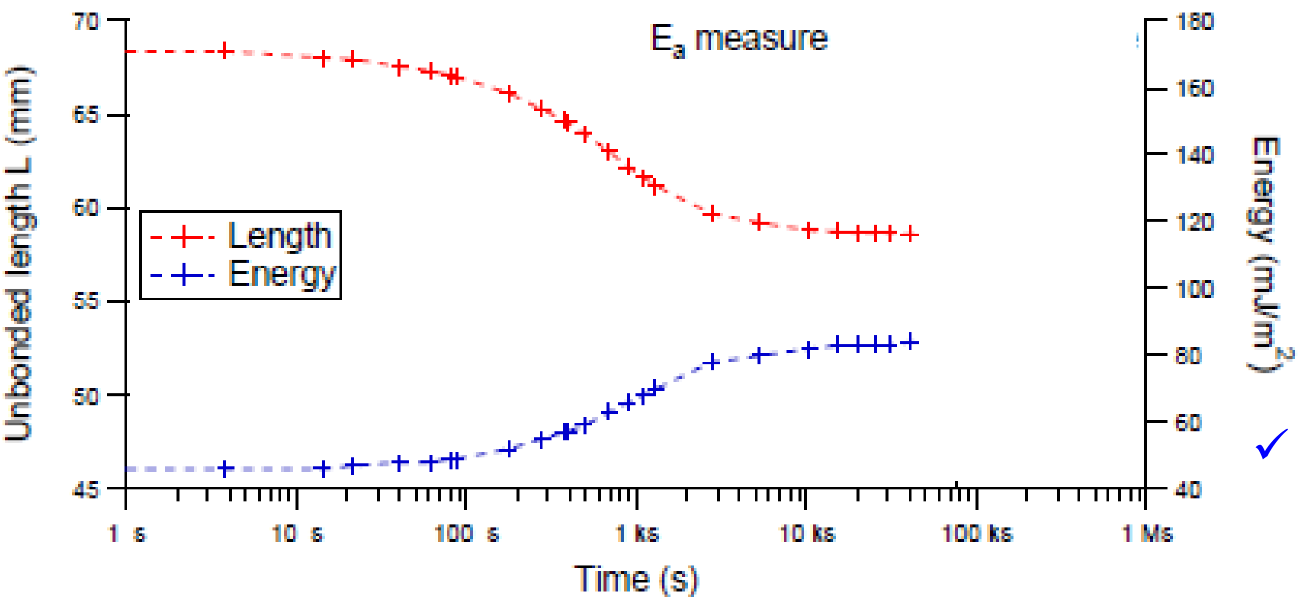
*F. Rieutord, et al., Physical Review Letters 94, (2005).

Adhesion energy measurement:

Modified DCB technique can measure the adhesion energy of chemical Si/Si direct bonding:



- ✓ Unbounded length
- ✓ El-Zein => Adhesion energy

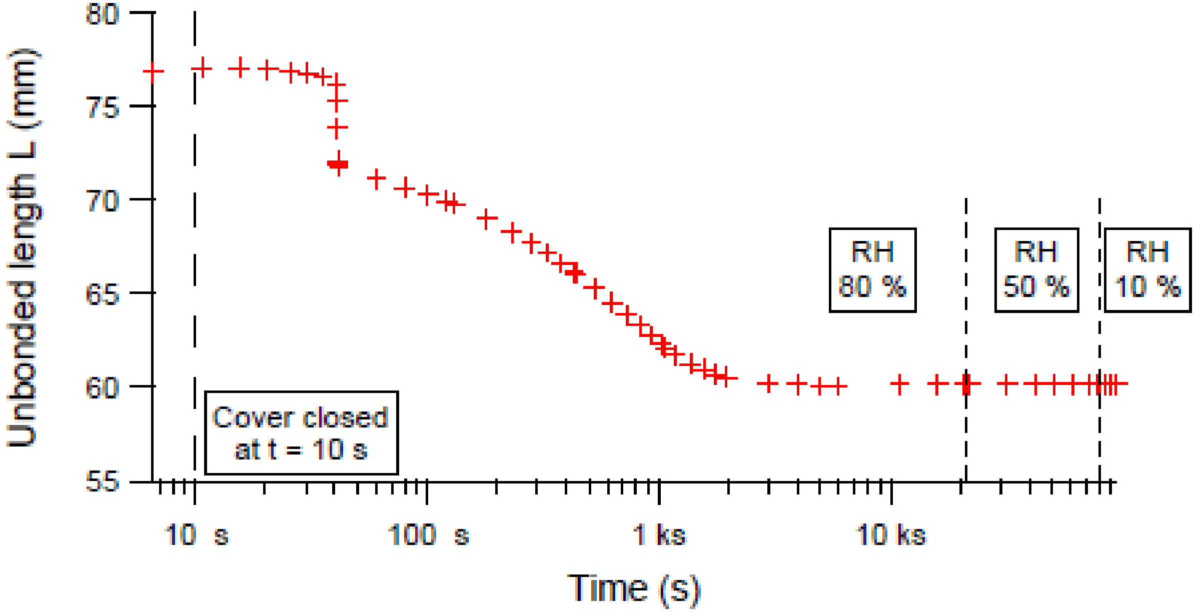


- ✓ Small evolution during 4 hours!

  ? Capillarity effect ? (meniscus)

**D. Radisson, phd, Université Grenoble Alpes, 2014.*

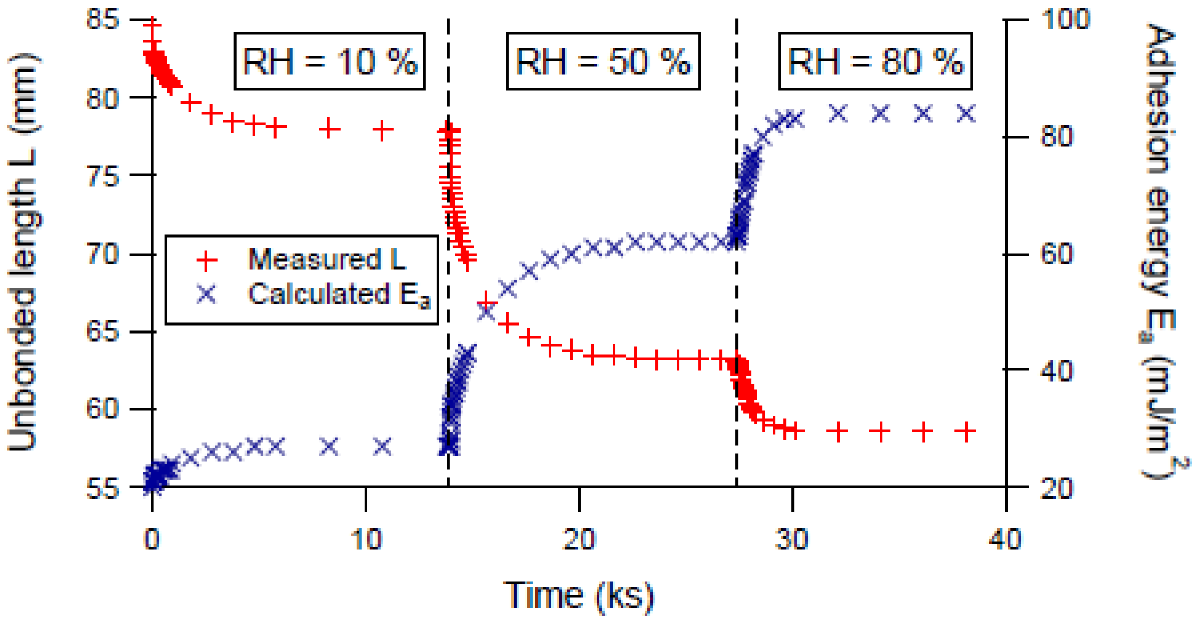
Adhesion energy measurement / Time evolution:



Time evolution is not driven by meniscus!!

**D. Radisson, phd, Université Grenoble Alpes, 2014.*

Adhesion energy measurement / Time evolution:

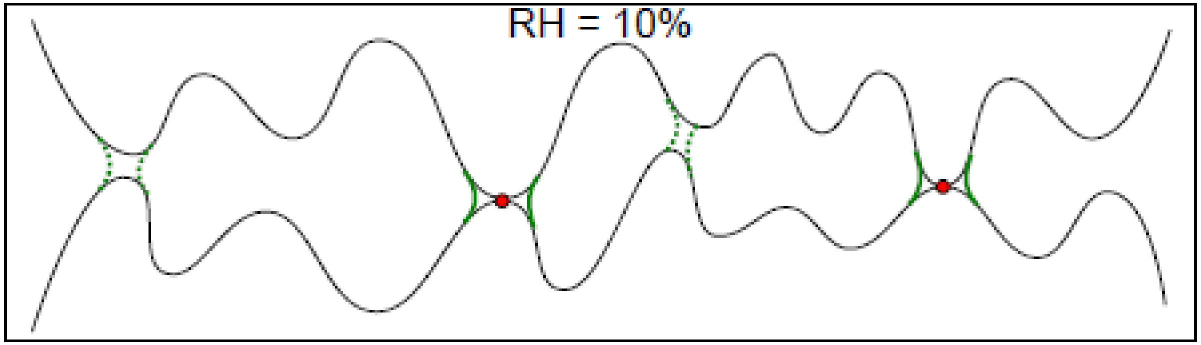


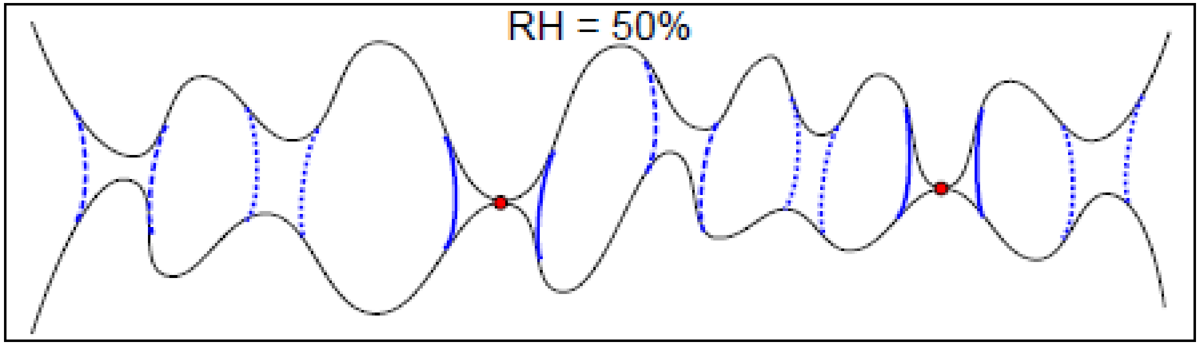
=> Time evolution depends of the amount of water.
=> Fast and slow evolution.

=> It is easier to bond in humid atmosphere!! ☺

**D. Radisson, phd, Université Grenoble Alpes, 2014.*

Adhesion energy measurement / Time evolution:





=> Already existing bridge => fast evolution.
=> New bridge formation => slow evolution
(depends on the amount of adsorbed water)

**D. Radisson, phd, Université Grenoble Alpes, 2014.*

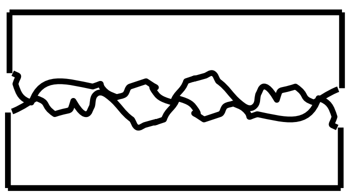
Bonding "engines" : chemistry & roughness

Attractive force:

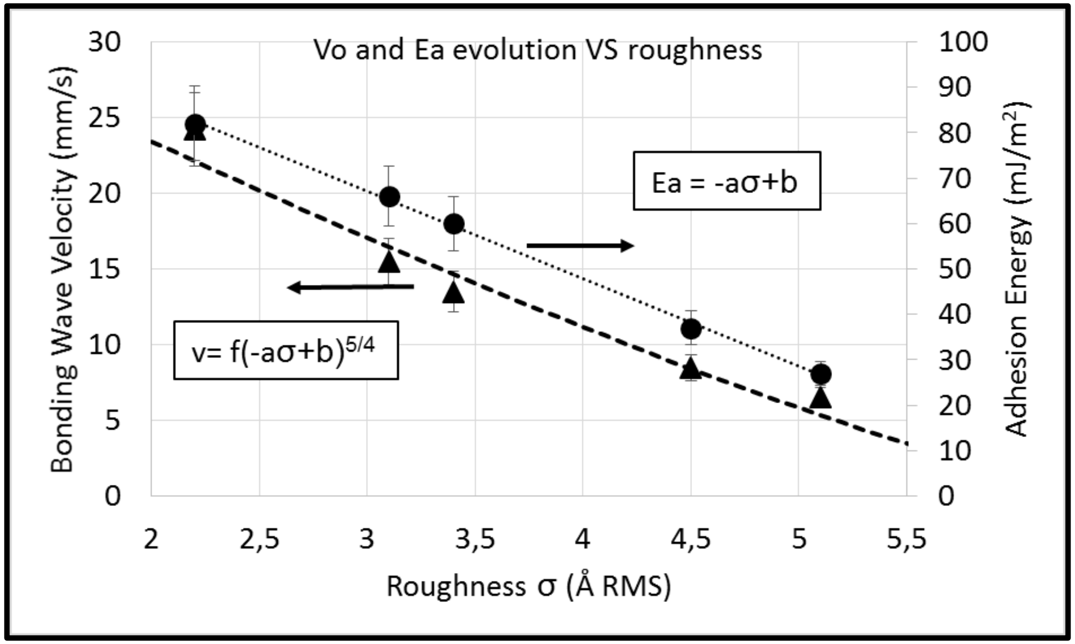
- *Van der Waals (+hydrogen bonds) + capillarity*

Repulsive force

- *Non adhesive contact on rough surface => Roughness acts as "accelerator pedal"*



Adhesion energy versus roughness (Si/SiO_2 bonding)



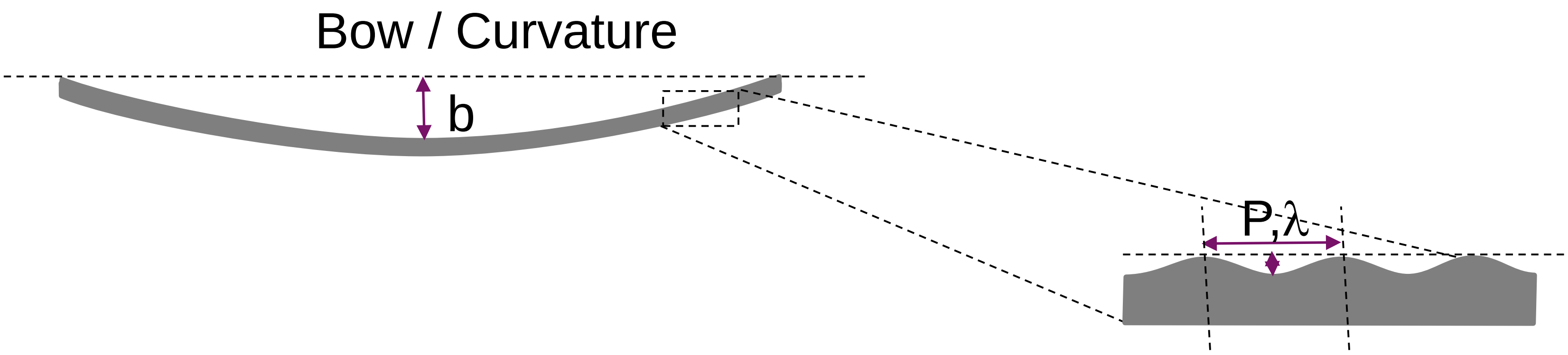
✓ **Roughness specification : <0.6nm RMS**

leti

*V. Larrey, et al., ECS Trans. 75, 145 (2016).

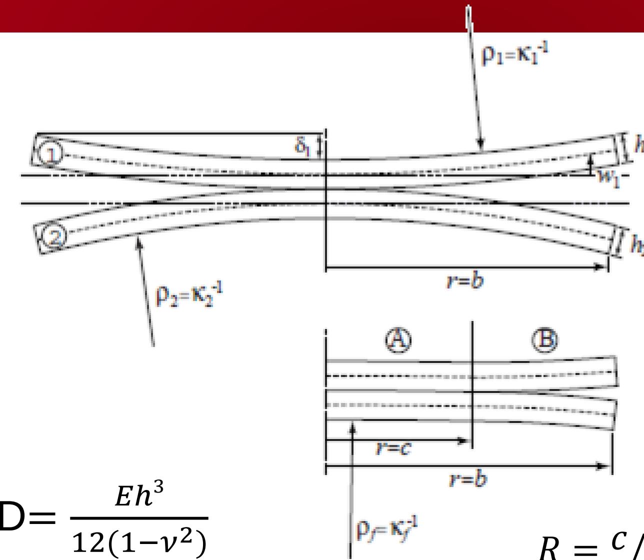
Bonding "breaks"

➢ *Surface mechanical adaptation ("all atoms bonding")*



?Which criteria?

Thin plate theory



$$k_i = -\frac{\frac{\partial^2(w)}{\partial i^2}}{\left(1+\frac{\partial(w)}{\partial i}\right)^{3/2}} \qquad \varepsilon_i = \frac{z}{k_i} \qquad M_i dj = \int_{-h/2}^{h/2} \sigma_i \, z dj dz$$

Cylindrical geometry $M_r = -D\left(\frac{\partial^2 w}{\partial r^2} + \frac{\nu}{r}\frac{\partial w}{\partial r}\right)$ D= $\frac{Eh^3}{12(1-\nu^2)}$ $R = {}^{c}/_{b}$

For bonded part A : $w_A = \frac{1}{2}(kf - ki)^2$

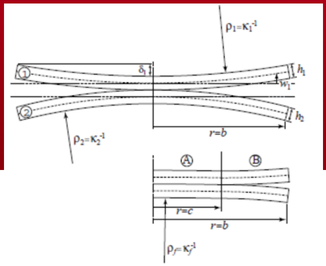
For non bonded part : Moment equilibrium without shearing force : $\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w_B}{\partial r}\right)\right] = 0$

$$dU_E = -\frac{1}{2}\left(Mx\frac{\partial^2 w}{\partial x^2} + My\frac{\partial^2 w}{\partial y^2}\right)dxdy \qquad U_E(c) = \pi D \int_0^b \left[\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r}\right)^2 - \frac{2(1-\nu)}{r}\frac{\partial w}{\partial r}\frac{\partial^2 w}{\partial r^2}\right] r dr$$

$$G = \frac{dU_E}{dA(c)} = \frac{1}{6}\frac{E_1 h_1^3}{1+\frac{E_1}{E_2}\frac{h_1^3}{h_2^3}}(k_1-k_2)^2 \frac{1+\nu}{1-\nu}\frac{1}{[(1+\nu)+R^2(1-\nu)]^2}$$

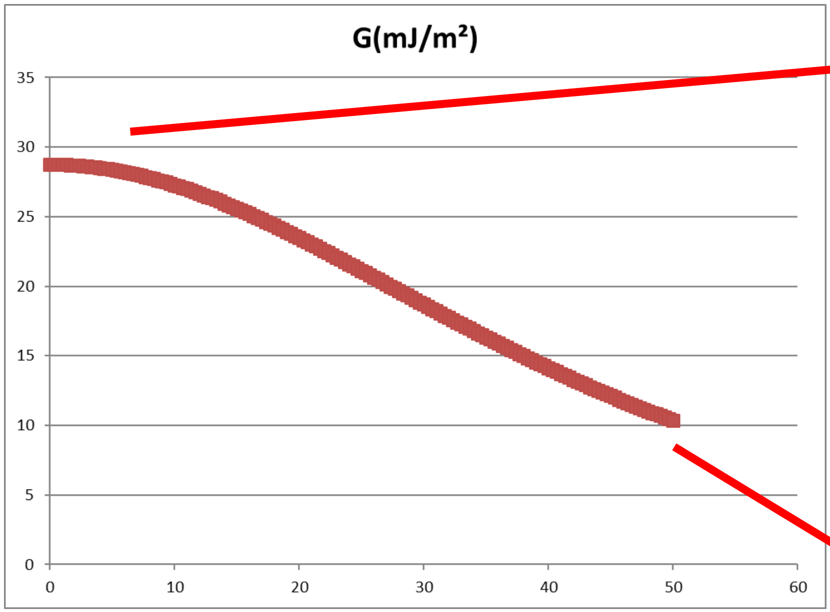
*K.T. Turner, Wafer Bonding: Mechanics-Based Models and Experiments, Massachusetts Institute of Technology, 2004.

ADHESION

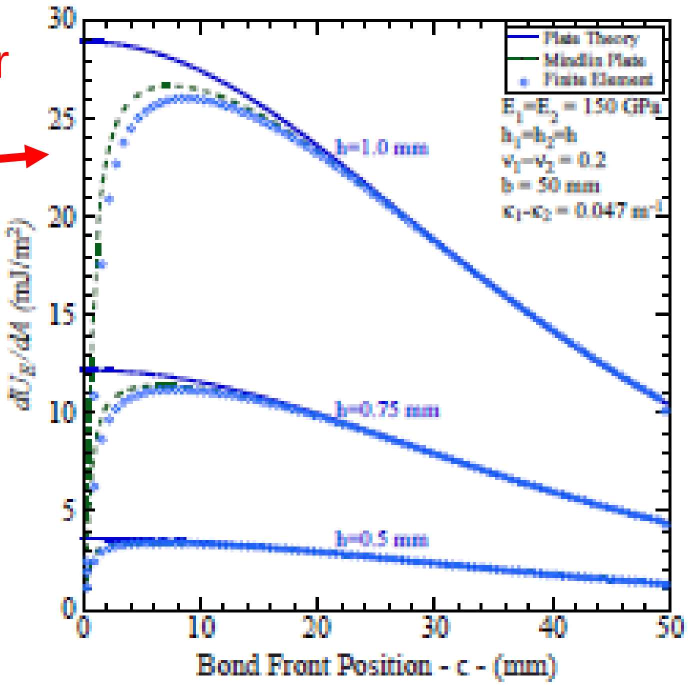


Thin plate theory :

Not well accurate at the center

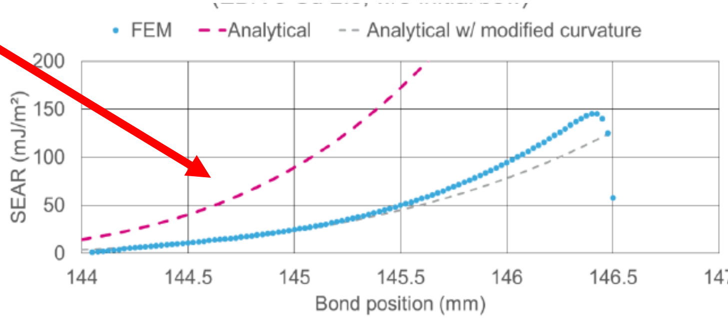


Bond front position (mm)



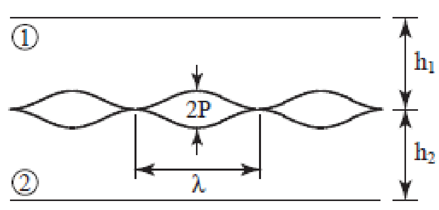
Neither at the edge

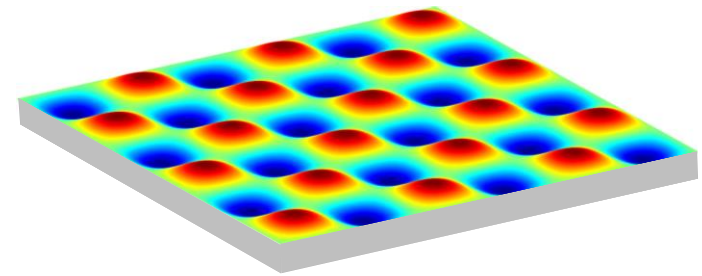
(with specific edge roll down)



K.T. Turner, Wafer Bonding: Mechanics-Based Models and Experiments, Massachusetts Institute of Technology, 2004.

Thin plate theory



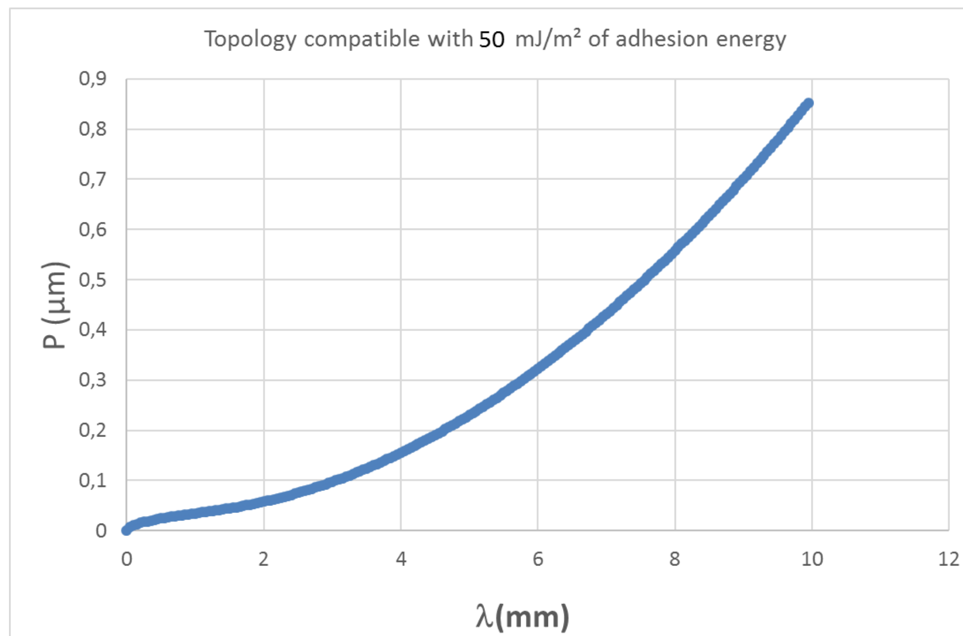


$$\text{Gap} = 2P\left[1 + \cos\left(2\pi\frac{x}{\lambda}\right)\cos\left(2\pi\frac{y}{\lambda}\right)\right]$$

$$\frac{\Delta U}{\Delta A} = \frac{\pi}{4\sqrt{2}}\frac{P^2}{\lambda}\left[\frac{1}{\overline{E_1}I(2\pi\frac{h_1}{\lambda})} + \frac{1}{\overline{E_2}I(2\pi\frac{h_2}{\lambda})}\right]$$

$$\bar{E} = \frac{\mathrm{E}}{(1-\nu^2)}$$

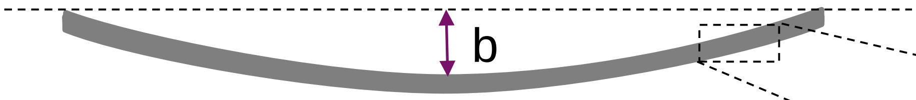
$$I(x) = \frac{e^{2\sqrt{2}x} + e^{-2\sqrt{2}x} - 2 - 8x^2}{e^{2\sqrt{2}x} - e^{-2\sqrt{2}x} + 4\sqrt{2}x}$$

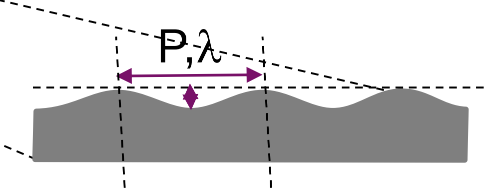


K.T. Turner, Wafer Bonding: Mechanics-Based Models and Experiments, Massachusetts Institute of Technology, 2004.

Bonding "breaks"

Bow / Curvature





For 200mm wafer (725µm) and **50 mJ/m²** of adhesion energy

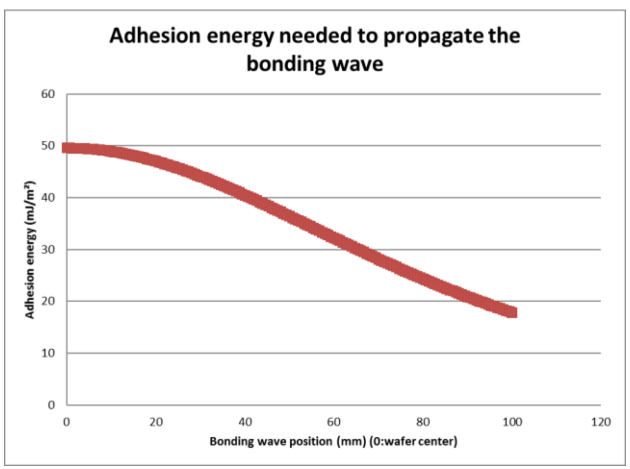
⇒ b < 250 µm

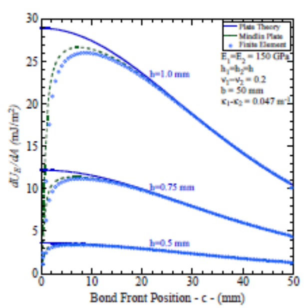
⇒ Curvature < 0,05 m^{-1}

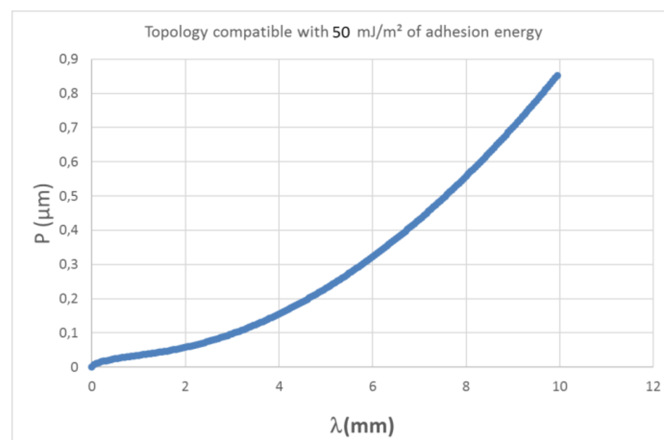
⇒ Curvature radius > 20 m

For 200mm wafer (725µm), **50 mJ/m²** of adhesion energy, λ=1cm

=> P<1µm

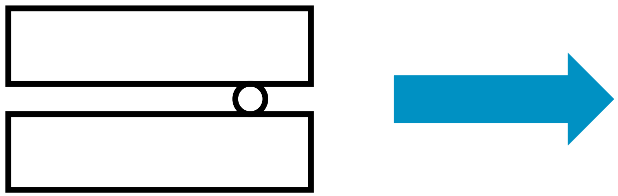


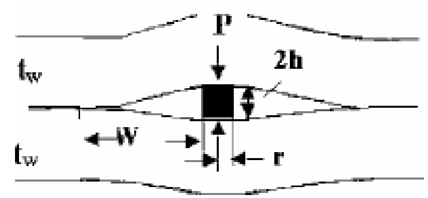


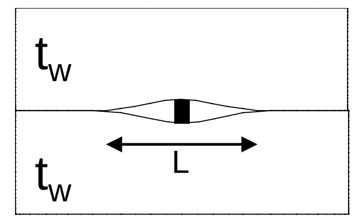


ADHESION

Low particle contamination

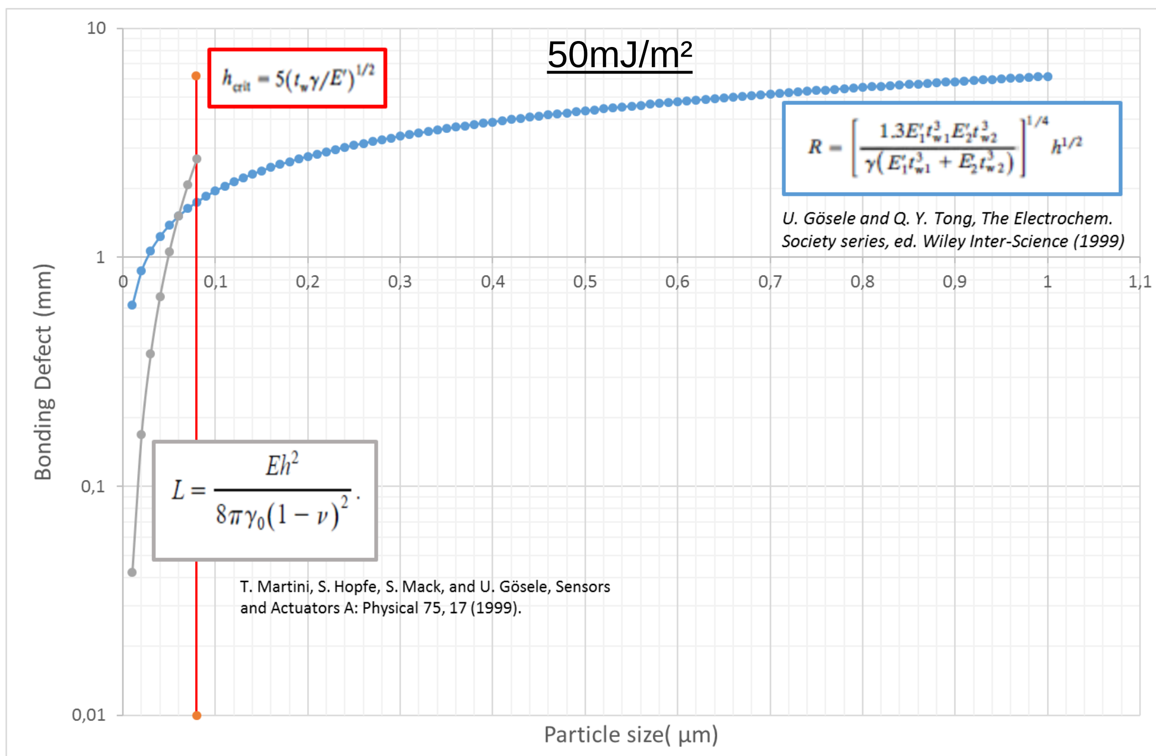






Height	500nm	1µm
Adhesion Energy mJ/m²	80	90
Average radius	3,4mm	5,4mm

LETI 2010



ADHESION

Physical preparation

1. Bow, planarity (250µm sur 200mm & 1µm/1cm)
2. Micro Roughness => Adhesion energy
   (hydrophilic 5Å RMS, hydrophobic 2.5Å RMS)
3. Particle contamination

Chemical preparation

4. Organic contamination
5. Surface bonds (Si-OH, Si-H…) => Adhesion energy

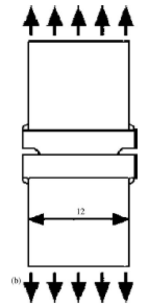
(6. Surface / sub-surface modification)

⇒The right chemistry
⇒Particle removing
⇒"Cleaning just before bonding"

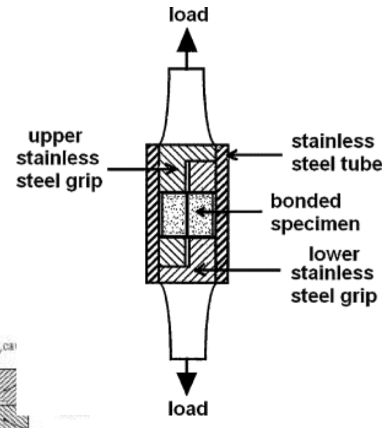
ADHERENCE

For thick substrates:

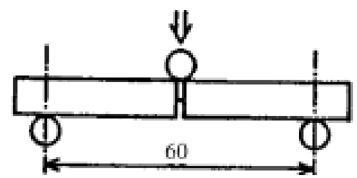
Tensile test



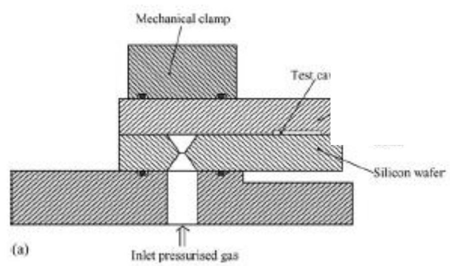
Shearing test



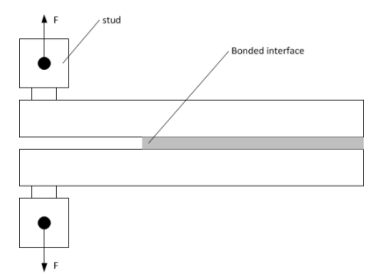
3 ou 4 bending points



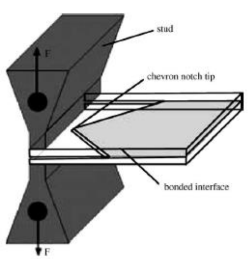
« Blister » test



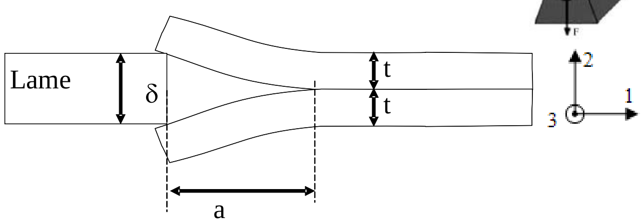
Double cantilever beam test under prescribed load control



Chevron test



Double cantilever beam test under prescribed displacement control

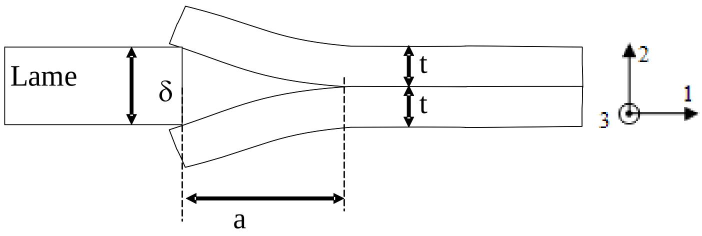


*O. Vallin, K. Jonsson, and U. Lindberg, Mat. Sci. and Eng. R 50, p.109–165 (2005)

M. S. El-Zein et al., J. of Composites Technology and Research 10(4) pp.151-155 (1988).

Mathematic Models:

Maszara, El-Zein, Gillis, Williams, Srawley, Kanninnen…



El-Zein : S_{ij} for anisotropy => β_{ij} for plan strain assumption

$$\beta_{ij} = S_{ij} - \frac{S_{i3}S_{j3}}{S_{33}}$$

$$C_0 = \frac{24}{wt^3}\left(\frac{\beta_{11}a^3}{3} - \frac{\beta_{26}t^3}{24}\right)$$

$$G = \frac{3}{8}\frac{\delta^2}{a^4}\frac{\dfrac{\beta_{1_{11}}}{t_1^3} + \dfrac{\beta_{2_{11}}}{t_2^3}}{\left[\dfrac{\beta_{1_{11}}}{t_1^3}\left(1 - \dfrac{\beta_{1_{26}}t_1^3}{8\beta_{1_{11}}a^3}\right) + \dfrac{\beta_{2_{11}}}{t_2^3}\left(1 - \dfrac{\beta_{2_{26}}t_2^3}{8\beta_{2_{11}}a^3}\right)\right]^2}$$

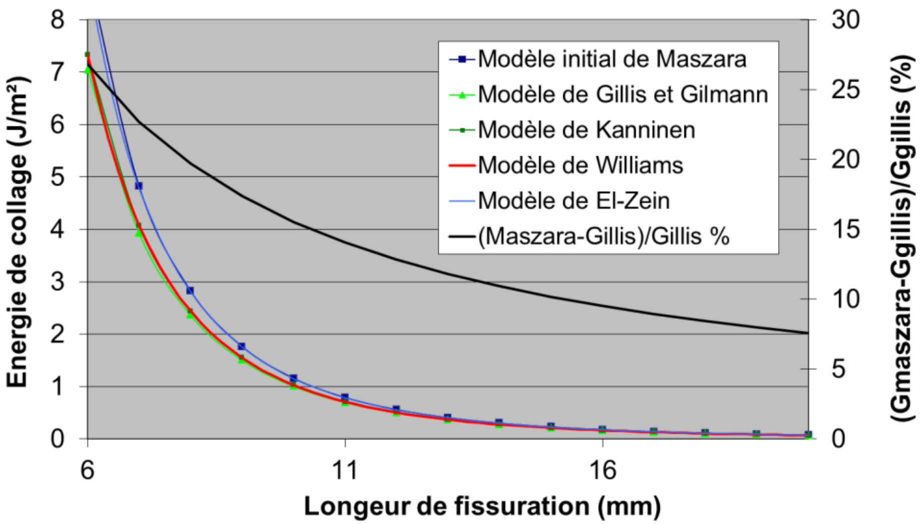
For orthotropic materials (Si beam <001>/<110>) : $\beta_{26}=0$ => ~Maszara:

$$\frac{1}{\beta_{11}} = \frac{1}{S_{11} - \dfrac{S_{13}S_{13}}{S_{33}}} = \frac{1}{S_{11} - \dfrac{S_{13}S_{31}}{S_{33}}} = \frac{1}{\dfrac{1}{S_{11}}\left(1 - \dfrac{S_{13}}{S_{11}}\dfrac{S_{31}}{S_{33}}\right)} = \frac{1}{\dfrac{1}{E_{11}}\left(1 - \nu_{13}\nu_{31}\right)} = \frac{E_{11}}{\left(1 - \nu_{13}^2\right)}$$

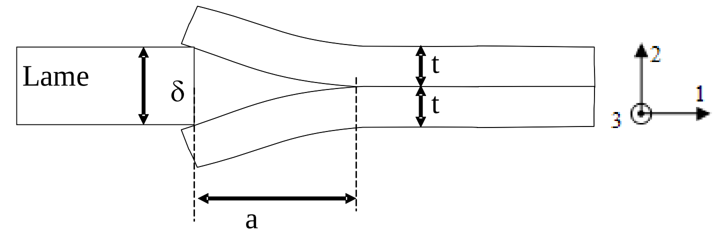
$$G = \frac{3\delta^2}{8a^4}\frac{E_1^* t_1^3 E_2^* t_2^3}{E_1^* t_1^3 + E_2^* t_2^3} \qquad E_i^* = \frac{E_{i,11}}{1 - \upsilon_{13}^2}$$

*F. Fournel, et al., Journal of Applied Physics 111, 104907 (2012).

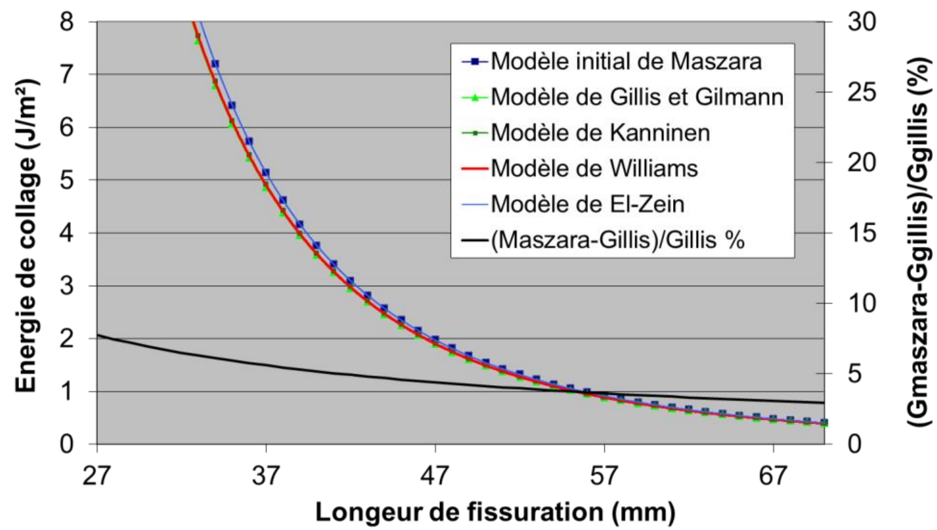
Mathematic models:



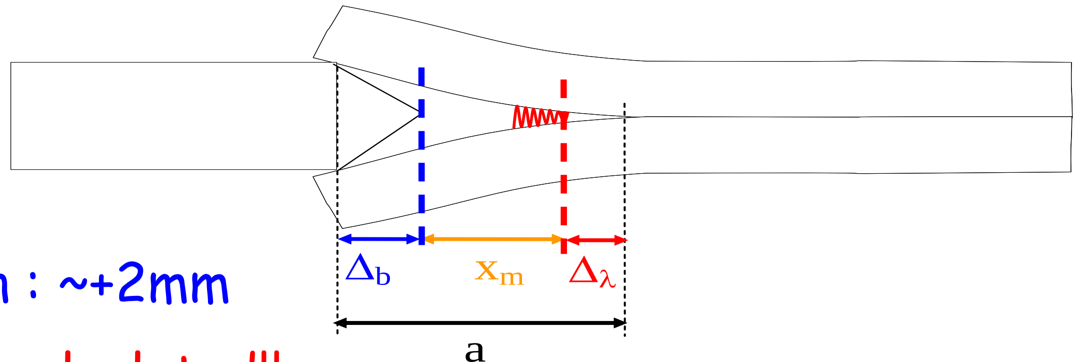
Thin blade : 50µm
Thin wafers : 525µm



Thick blade : 640µm
200mm Si wafers: 725µm



Measurement protocol:



Δ_b: known : ~+2mm

Δ_λ: to be calculated!!

Timoshenko beam equation:

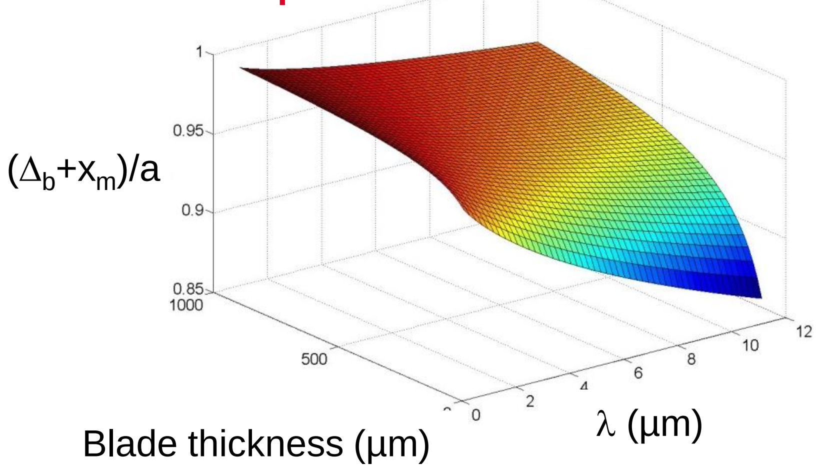
$$d_m = \frac{\delta}{4}\left[2 - \frac{3x_m}{a} + \left(\frac{x_m}{a}\right)^3\right] = \frac{\lambda}{8}$$

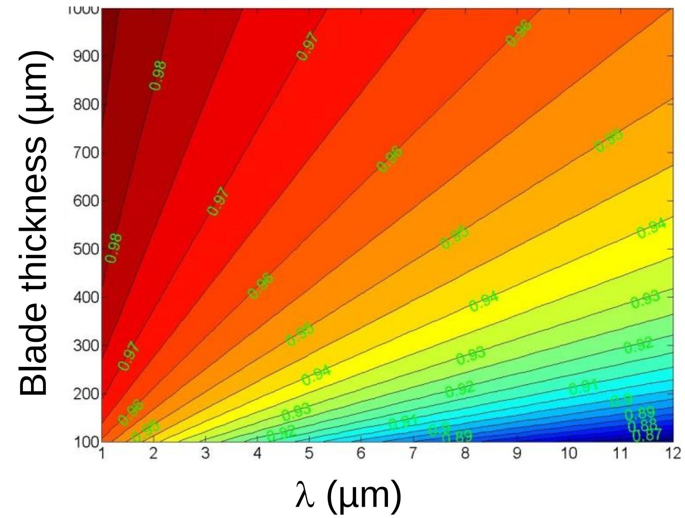
El-Zein beam equation (two different anisotropic beams):

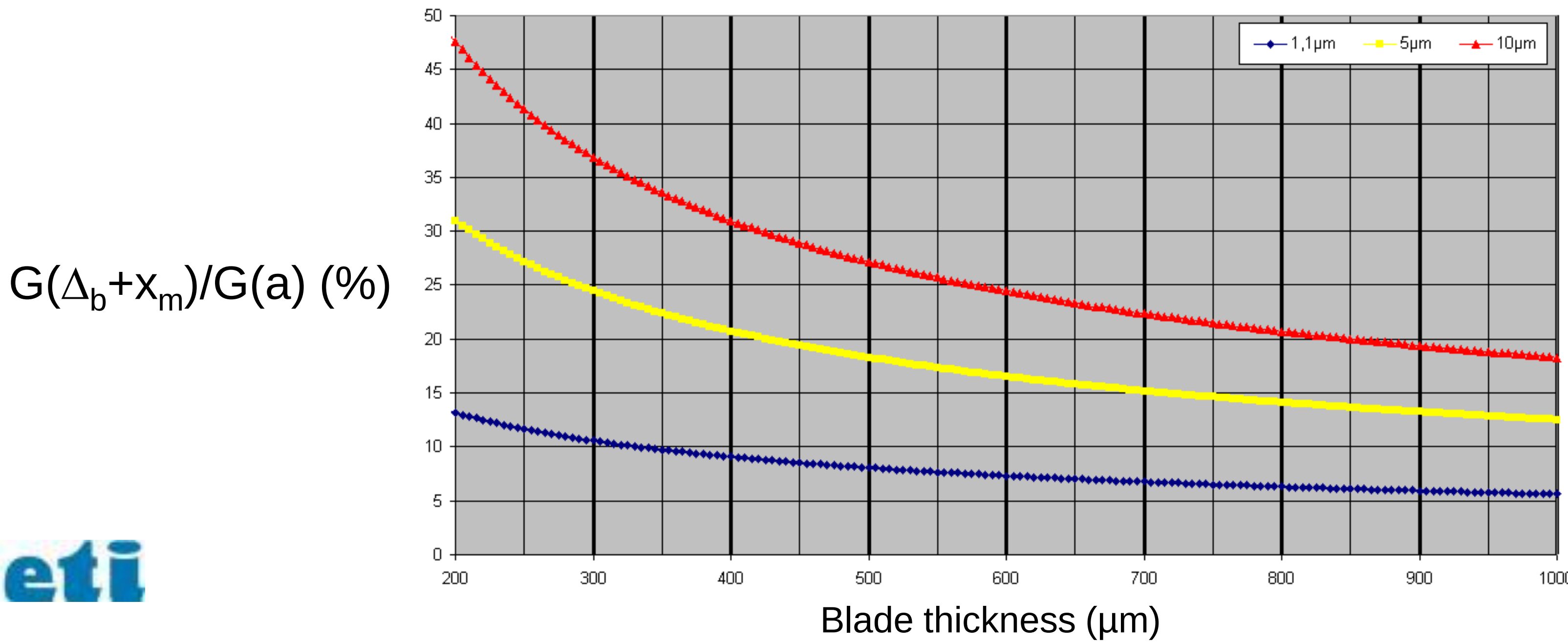
$$z^3 - \frac{3x_m^2}{4\left(1-\frac{\lambda}{4\delta}\right)^2} z - \frac{x_m^3}{4\left(1-\frac{\lambda}{4\delta}\right)^3} + \frac{x_m^3}{2\left(1-\frac{\lambda}{4\delta}\right)} - \frac{3x_m}{8\left(1-\frac{\lambda}{4\delta}\right)} \frac{\left(\frac{(\beta_{12})_1}{t_1} + \frac{(\beta_{12})_2}{t_2}\right)}{\left(\frac{(\beta_{11})_1}{t_1^3} + \frac{(\beta_{11})_2}{t_2^3}\right)} - \frac{1}{8}\frac{(\beta_{26})_1 + (\beta_{26})_2}{\left(\frac{(\beta_{11})_1}{t_1^3} + \frac{(\beta_{11})_2}{t_2^3}\right)} = 0$$

F. Fournel, et al., Journal of Applied Physics 111, 104907 (2012).

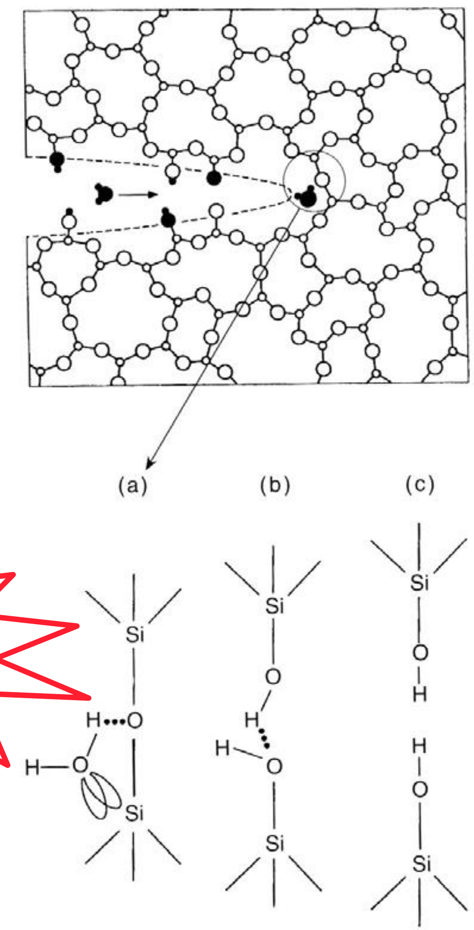
Measurement protocol:







“Stress corrosion cracking (SCC) is the growth of cracks under tensile stress in a corrosive environment.”

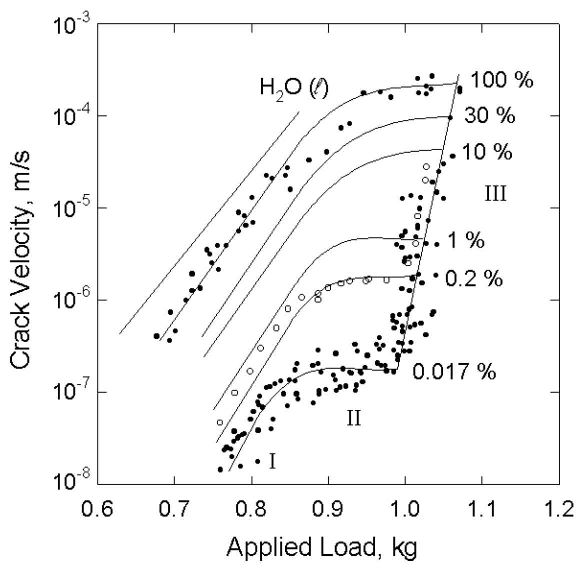


For SiO_2 (glass, silica…) :

1. Stress => Si-O-Si angle modification => Ionization
2. Specific chemical molecules:

- Lewis basis (electron pair donor)
- Brönsted acid (proton donor)
- Acid-Basis distance =~ Si-O distance (0,163nm)

Example : Soda lime crack growth



Water is the best

T.A. Michalske and B.C. Bunker, J. Appl. Phys. 56(10) p.2666 (1984)

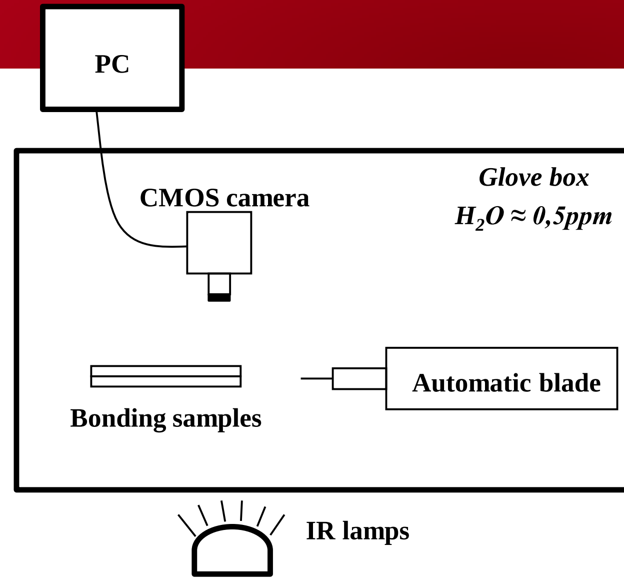
S.M. Wiederhorn et al., J. Mater. Sci. 17 pp.3460-3478 (1982).

ADHERENCE

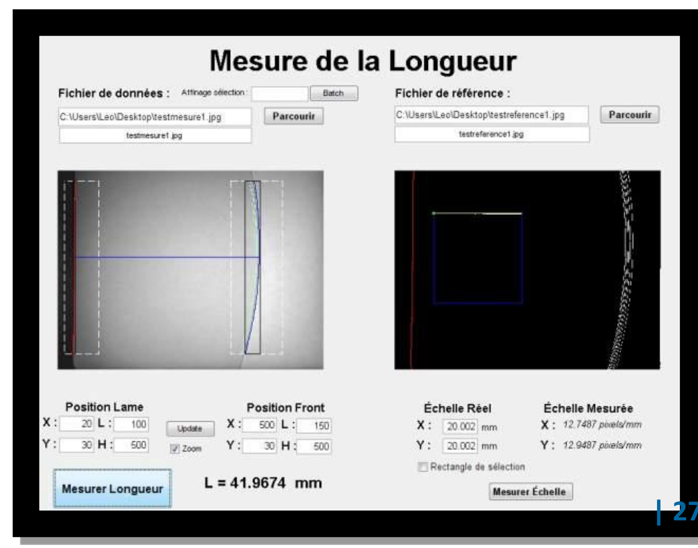
Setup:

Glove box with dessicator

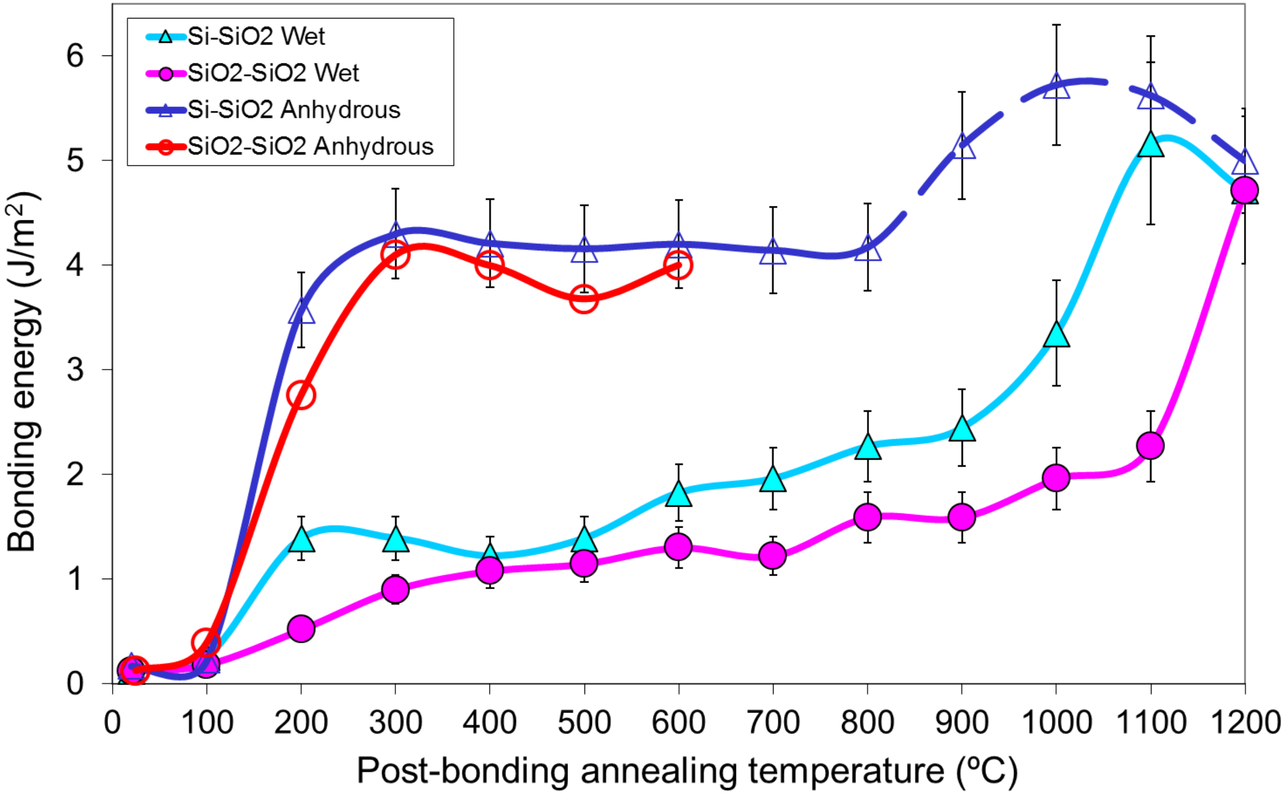
Automatic blade insertion



Video recording / processing homemade software



Standard hydrophilic bonding



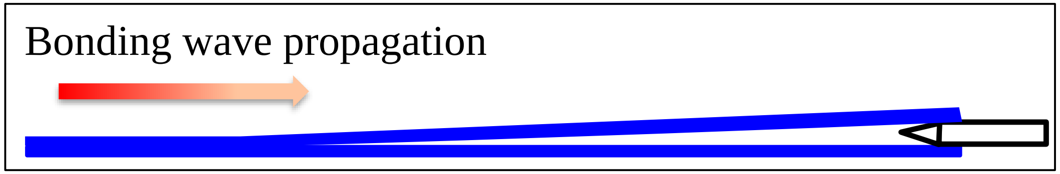
=> Anhydrous bonding energy is:

more «realistic»

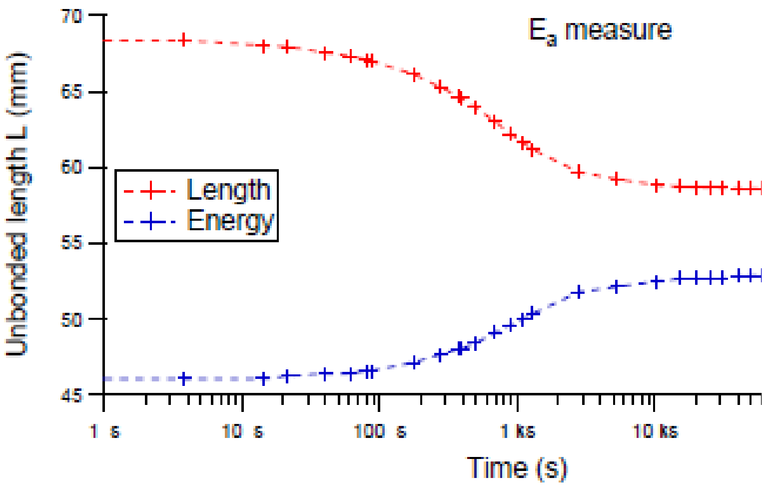
more «discriminating» for mechanism understanding

Adhesion energy measurement:

Modified DCB technique can measure the adhesion energy of chemical Si/Si direct bonding:



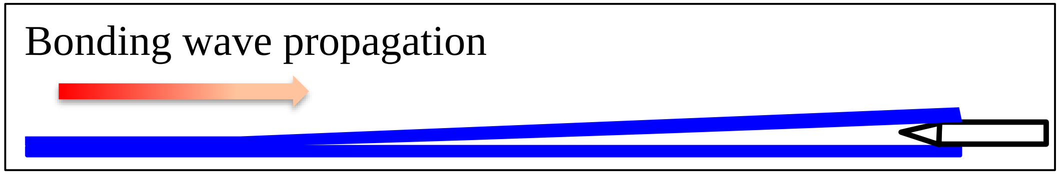
- ✓ Unbounded length
- ✓ El-Zein equation => Adhesion energy



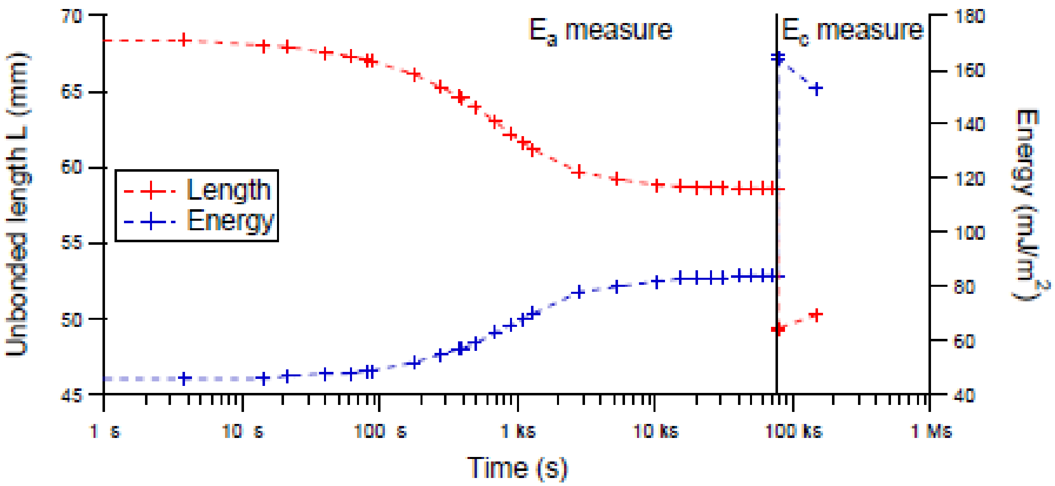
D. Radisson, phd, Université Grenoble Alpes, 2014.

Adhesion energy measurement:

Modified DCB technique can measure the adhesion energy of chemical Si/Si direct bonding:



- ✓ Unbounded length
- ✓ El-Zein equation => Adhesion energy



- ✓ After 4 hours : bonding energy is measured by entering the blade

=> Bonding energy > Adhesion energy

Siloxane bonds presence @RT for chemical bonding

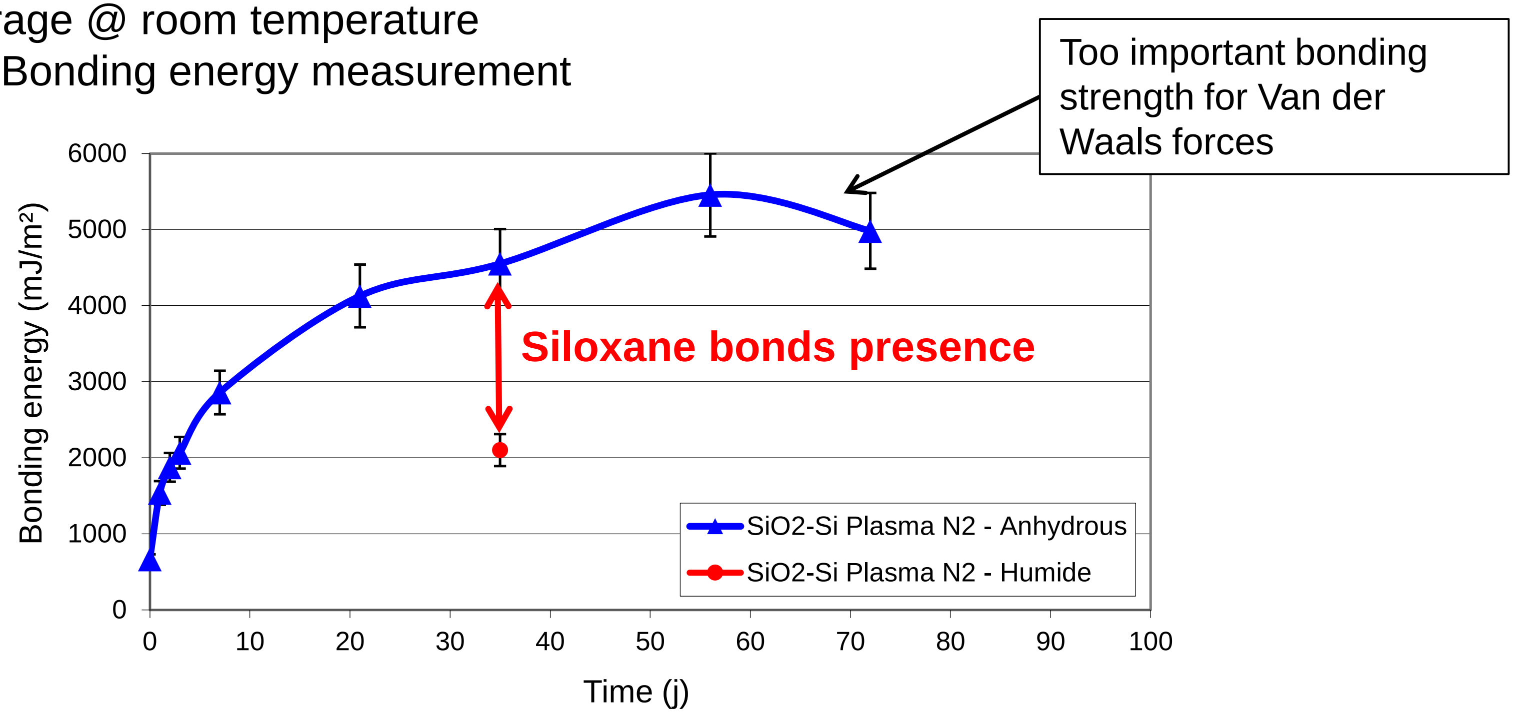
D. Radisson, phd, Université Grenoble Alpes, 2014.

WSC and covalent bonding at room temperature:

N2 plasma Si/SiO2 direct bonding

Storage @ room temperature

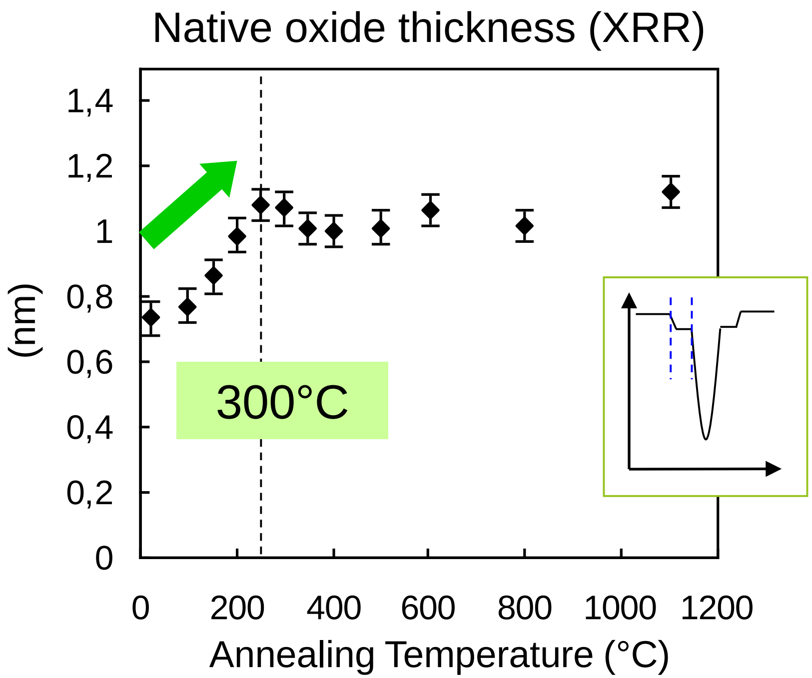
Bonding energy measurement

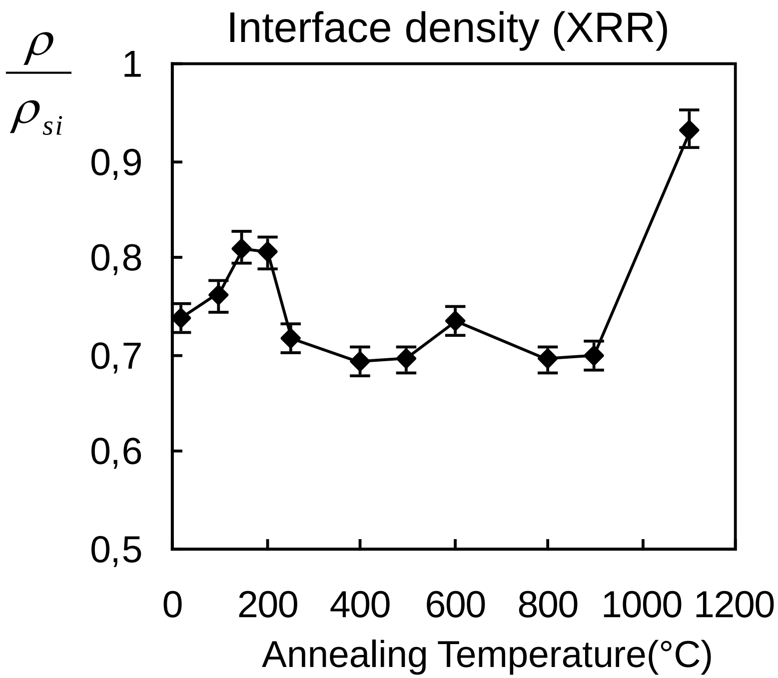


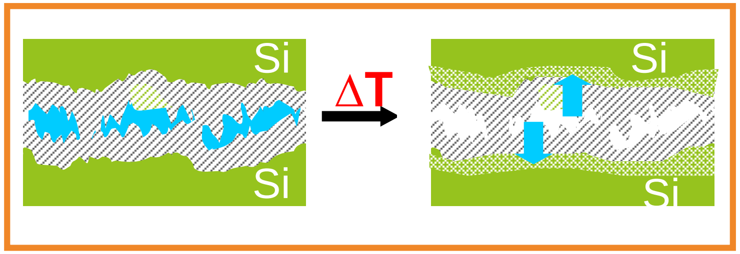
- **Siloxane bonds can thermodynamically appear at room temperature**
- **Mixt of Van Der Waals and Siloxane @RT but Siloxane hardly visible!**
  - **Too few contact point?**
  - **Trapped water which induce internal WSC?**

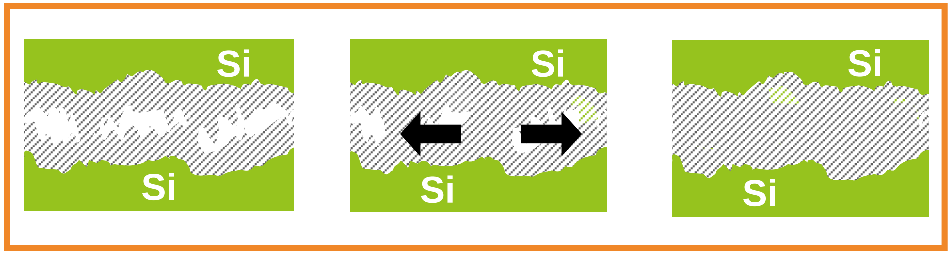
**F. Fournel, et al., ECS Trans. 64, 121 (2014).*

Si-Si hydrophilic bonding





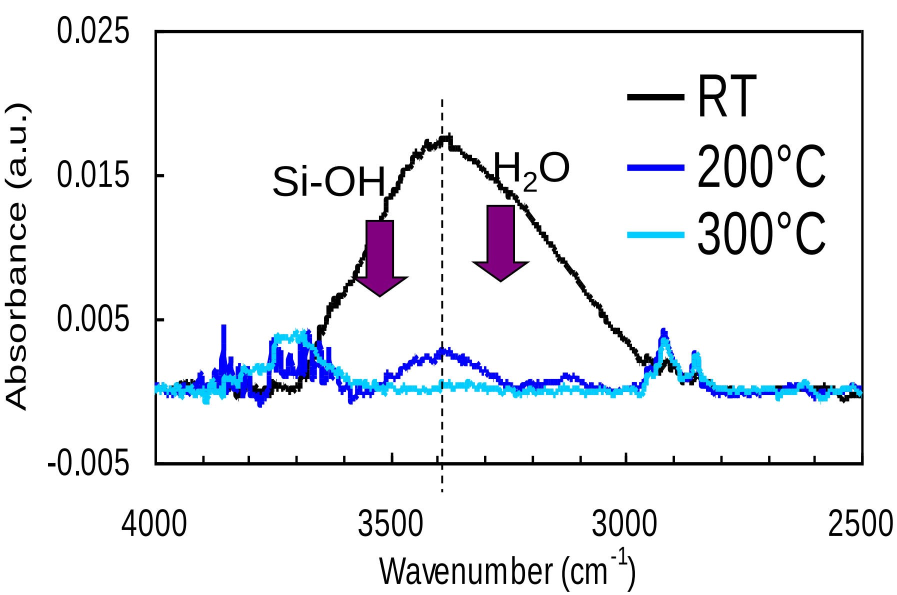




C. Ventosa et al., J. Appl. Phys. 104, 123524 (2008)
C. Ventosa PhD, Collaboration with DSM-INAC

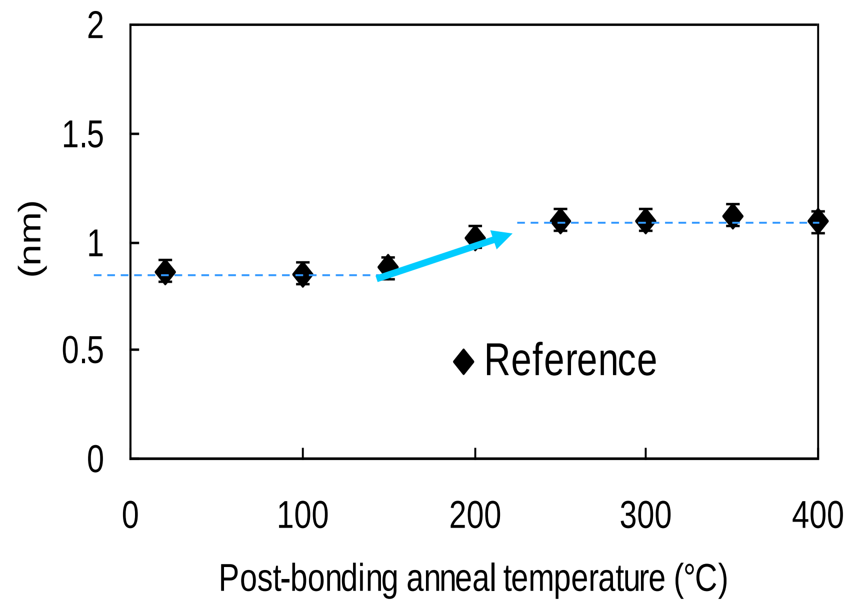
Si-Si hydrophilic bonding

FTIR-MIR: O-H absorption band

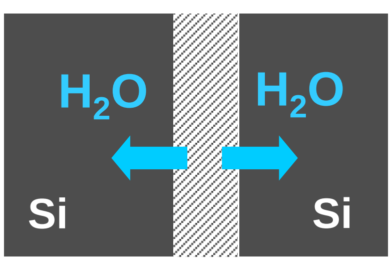


✓ Disappearing of the O-H band at 200°C and 300°C post-bonding anneal

XRR: oxide film thickness



✓Increase of oxide film thickness



Si-Si

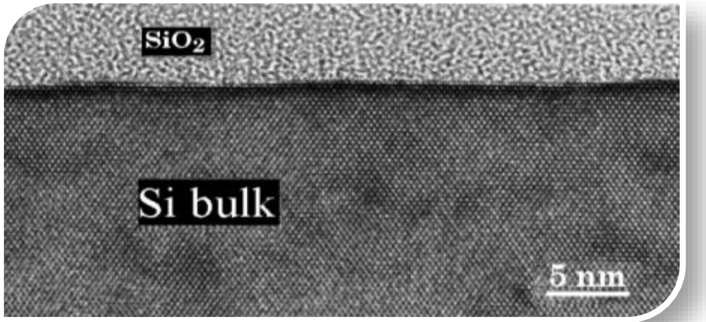
Silicon oxidation through the reaction Si + $2H_2O$ → SiO_2 + $2H_2$

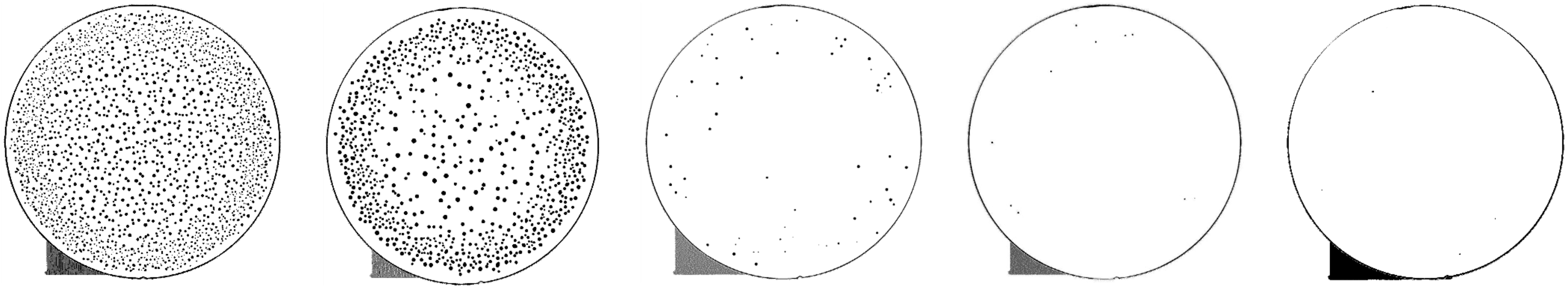
Main source of voids at the bonding interface

C. Ventosa PhD, Collaboration with DSM-INAC

Si-SiO_2 hydrophilic bonding

⇒ SiO_2 layer can store the hydrogen
… if the layer is thick enough!

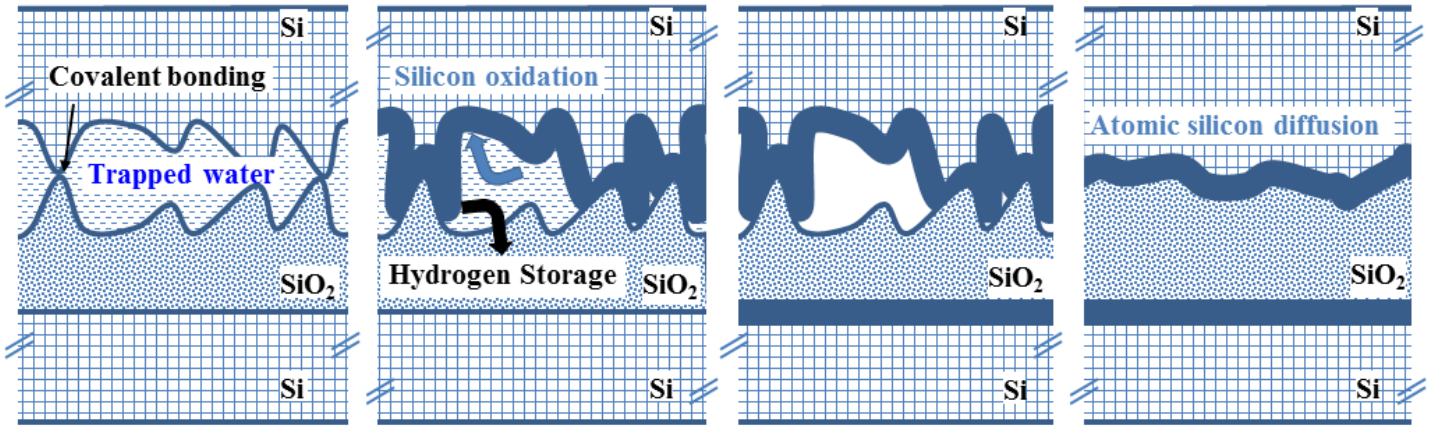




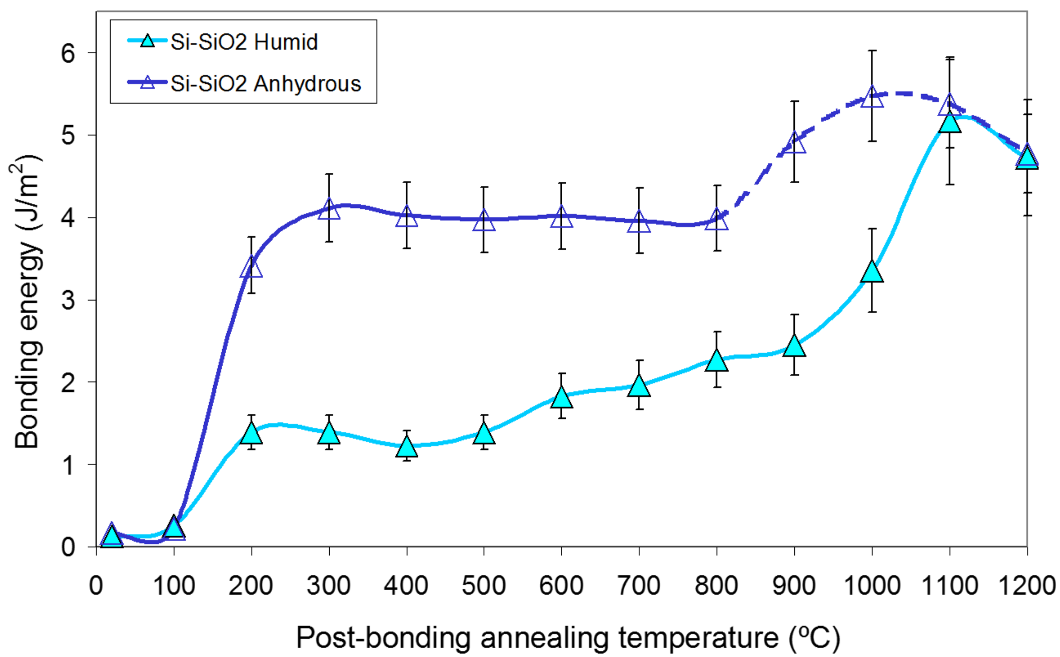
This bonding type is really depending of the last cleaning step

F. Fournel, et al., ECS Trans. 16, 475 (2008).

SI/SIO2 BONDING MECHANISM

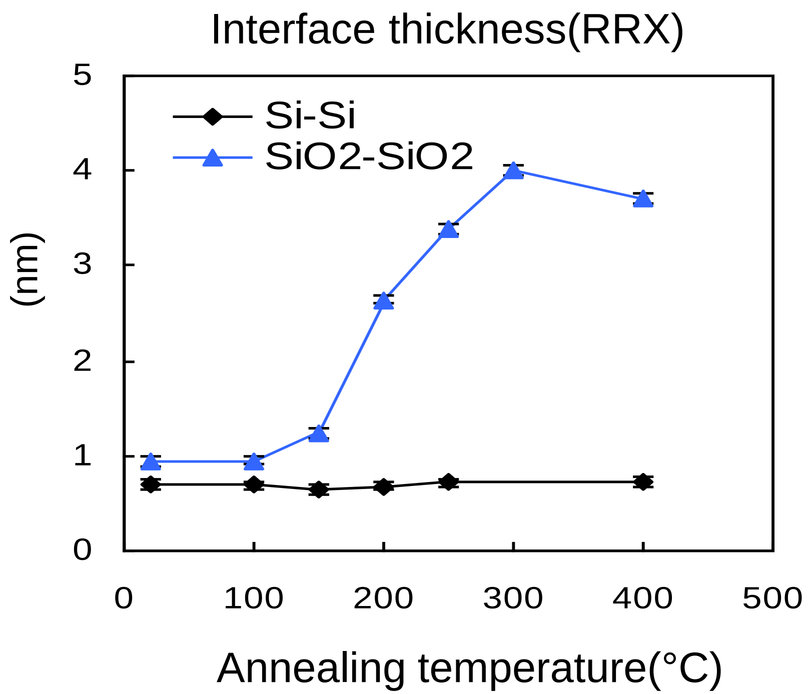


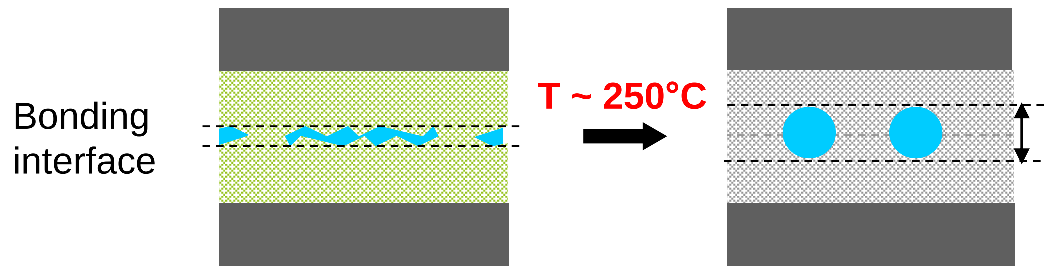
a) RT b) [RT – 200°C] c) [200°C-800°C] d) above 800°C



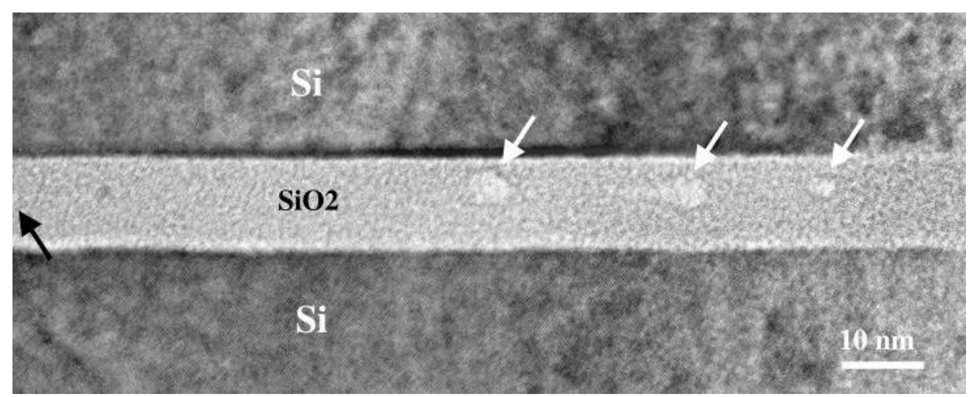
*F. Fournel, el al., ECS J. Solid State Sci. Technol. 4, P124 (2015).

SiO_2-SiO_2 hydrophilic bonding





TEM : LETI/DPTS



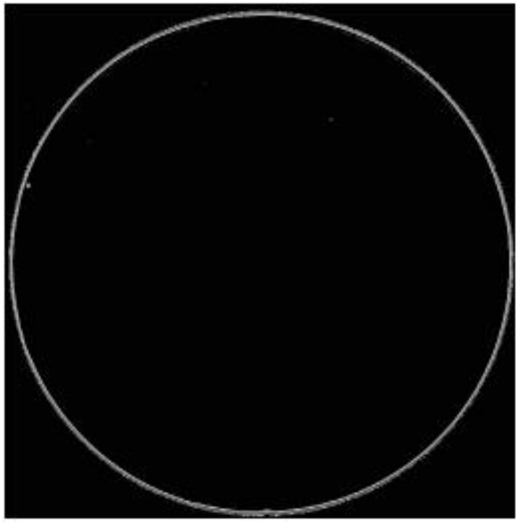
➢ **Oxyde layer is a water barrier layer**

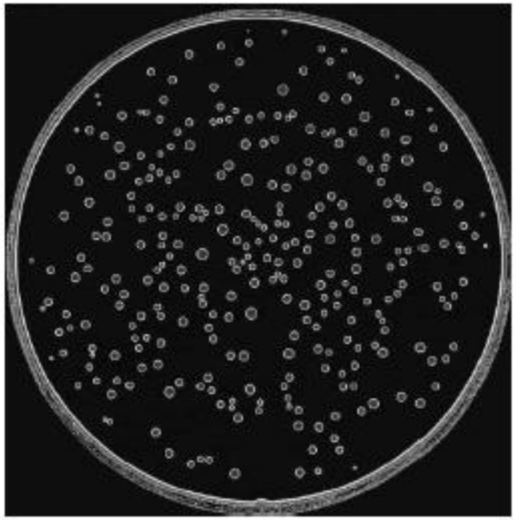
C. Ventosa et al., Electrochemical and Solid State Letters, 12 (10) H373-H375 (2009)

C. Ventosa PhD, Collaboration with DSM-INAC

SiO_2-SiO_2 hydrophilic bonding

Thin oxide bonding : 5nm SiO_2- 5nm SiO_2





Annealing temperature(°C) : 400°C 600°C

Thermal oxide is a water barrier until 600°C.

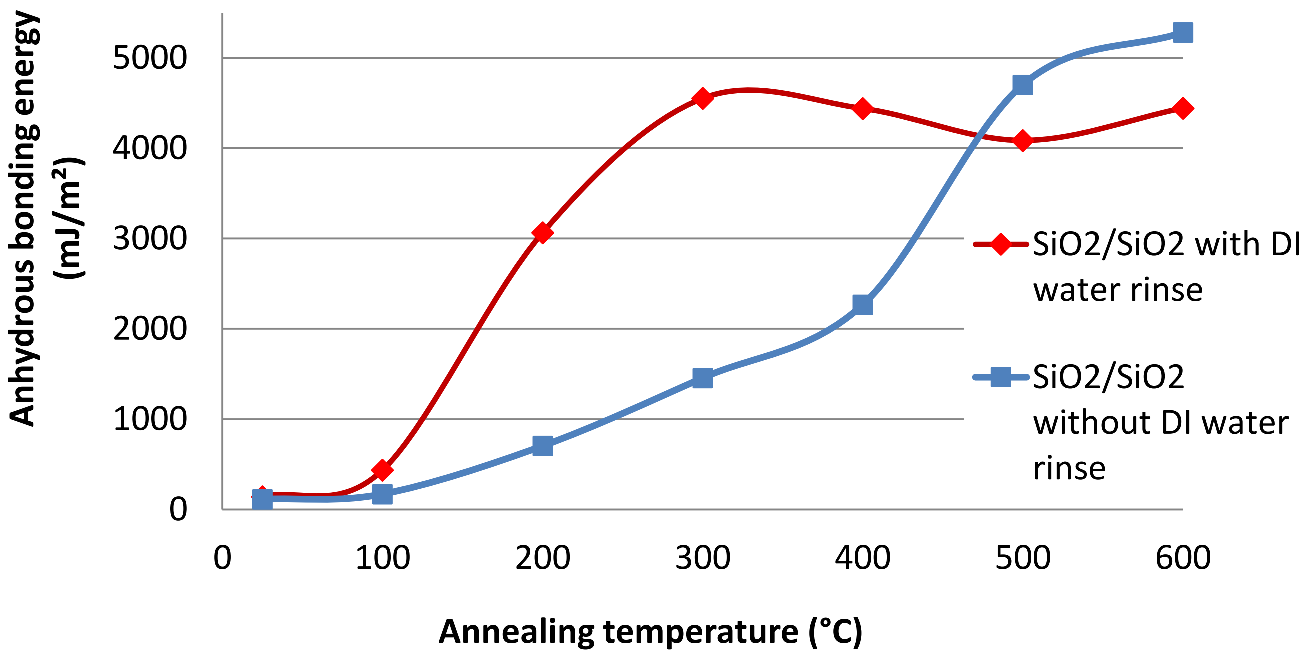
MECHANISM

SiO_2 surface cleaning with N_2 dryer

=>"dry" SiO_2 surface

Adding Di-water rinse

=>"wet" SiO2 surface



⇒***Water is an adherence promoter***

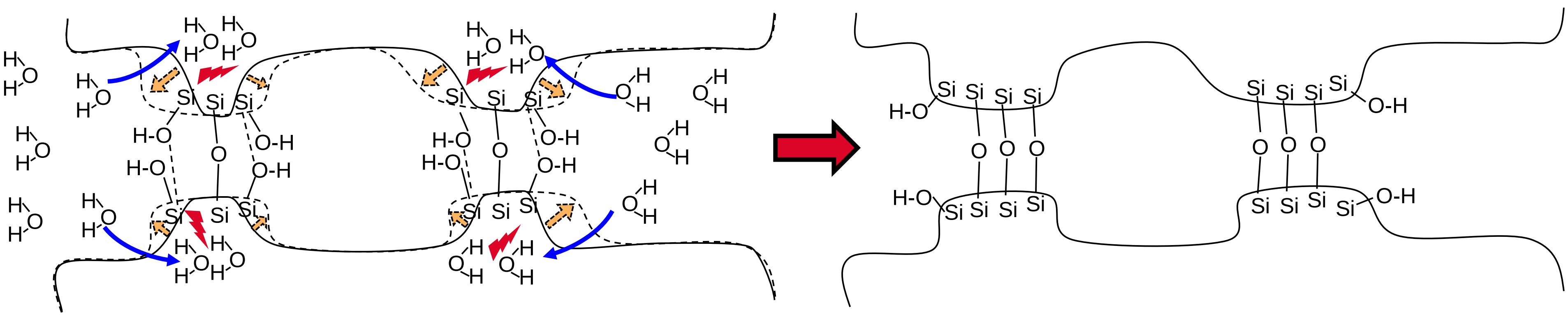
F. Fournel et al., WaferBond'15 (2015)

❑ ***Water stress corrosion during annealing:***

- @ RT few silanol bonds
- **With temperature** : water penetration inside SiO_2 asperity (→)
- SiO_2 Hydrolysation Si-O-Si + H2O => Si-OH (⚡)
- Asperity broadening (⇨)
- New covalent bonds formation (---)

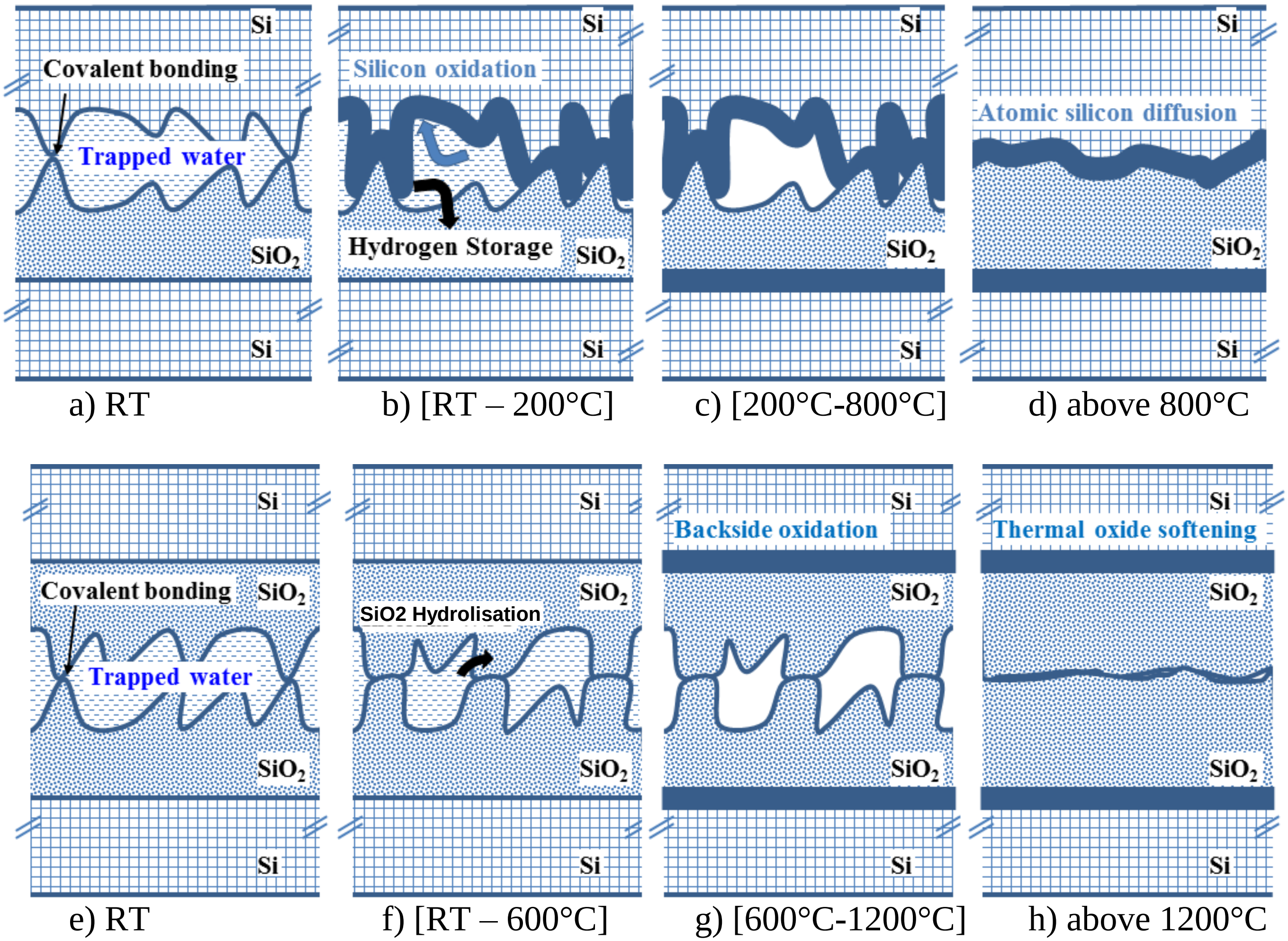
⇒ More important contact area with covalent bonds

=> More important bonding energy



*F. Fournel et al., WaferBond'15 (2015)

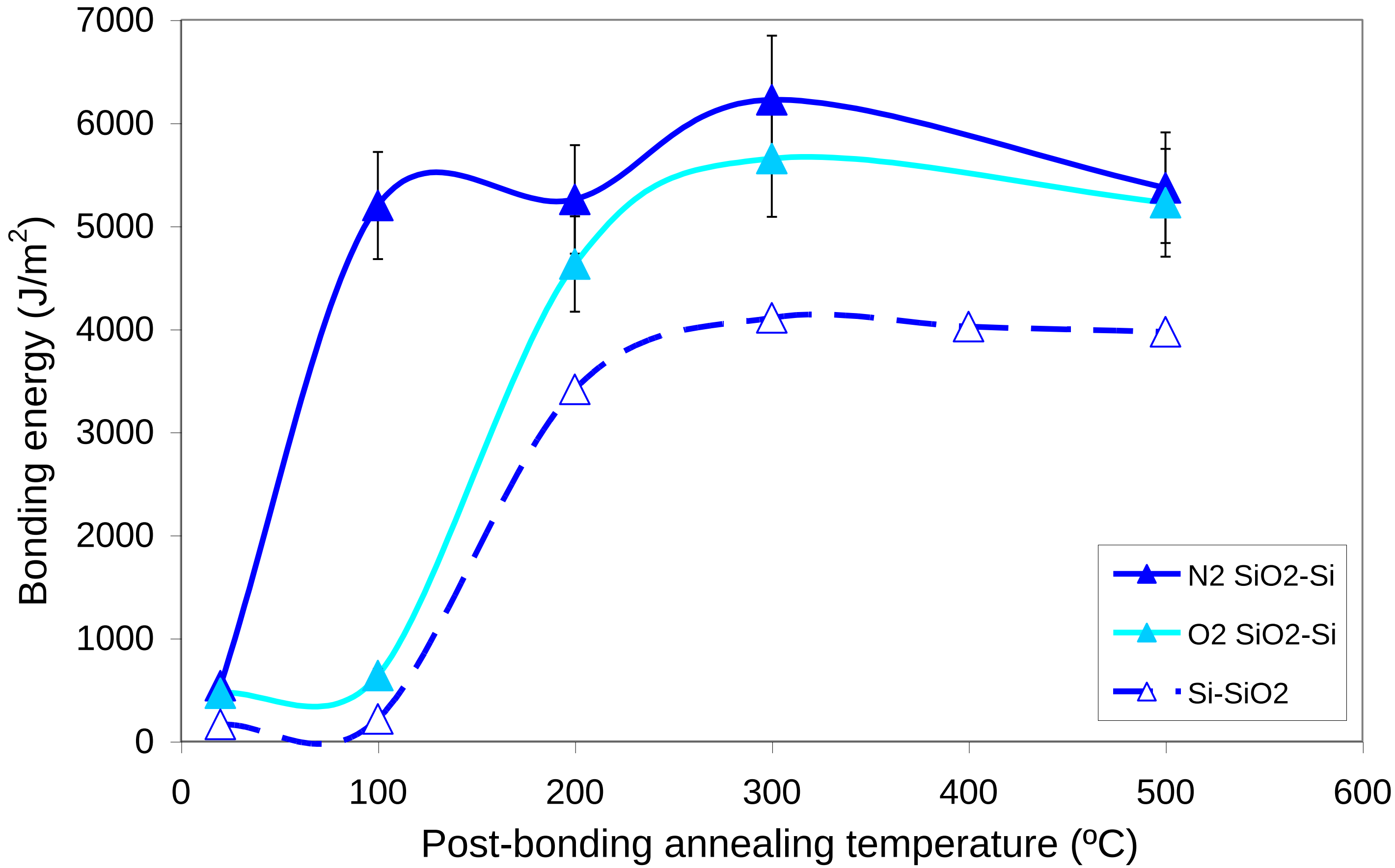
SI/SIO2 AND SIO2/SIO2 BONDING MECHANISM



⇒ **Water is an adherence promoter**

**F. Fournel, el al., ECS J. Solid State Sci. Technol. 4, P124 (2015).*

Plasma bonding Si-SiO_2:

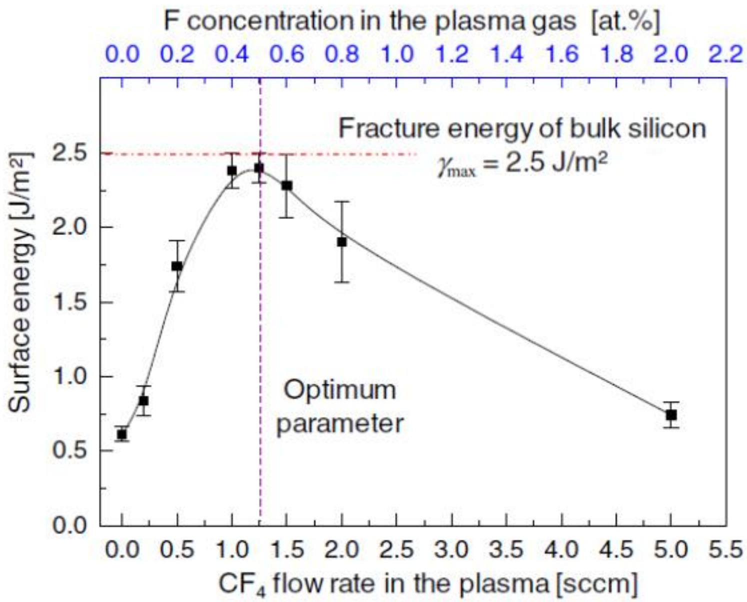


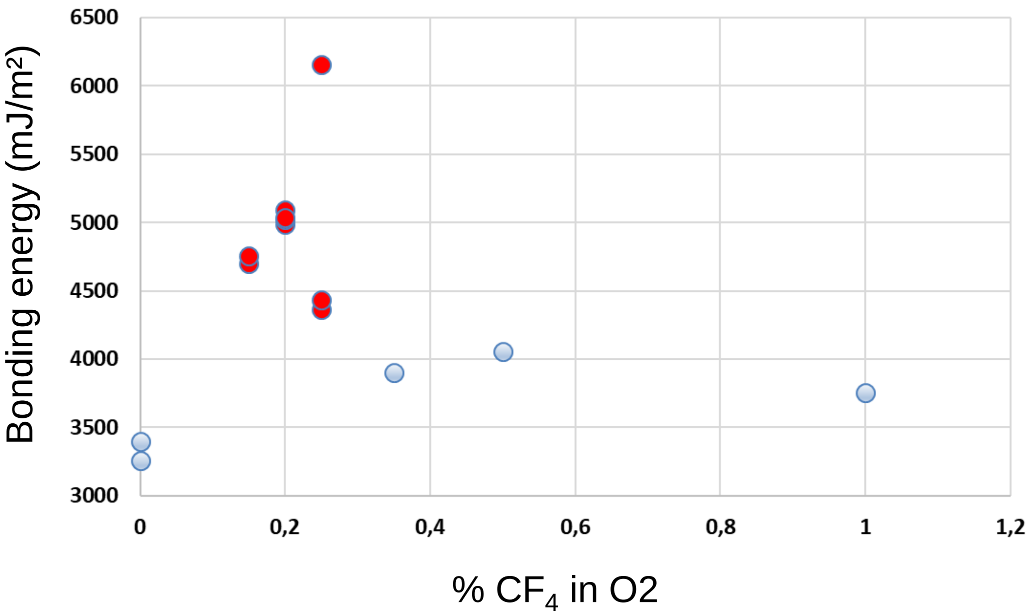
=> Si-SiO_2 Plasma N_2 : 5J/m²@100°C

=> Plasma N_2 > Plasma O_2

Fluorine plasma

Annealing temperature : 190°C / 1h

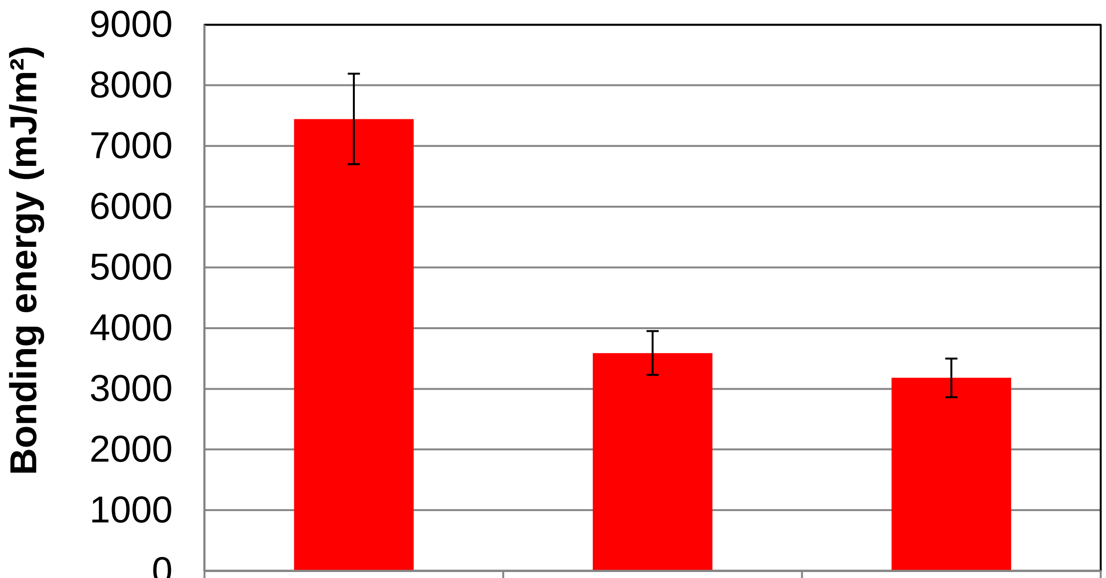




*Wang, C, et al. « Low-Temperature Direct Bonding of Silicon to Quartz Glass Wafer via Sequential Wet Chemical Surface Activation. », *5th LTB-3D conference,* IEEE, Tokyo, Japan, 2017; pp 21–21. https://doi.org/10.23919/LTB-3D.2017.7947417.

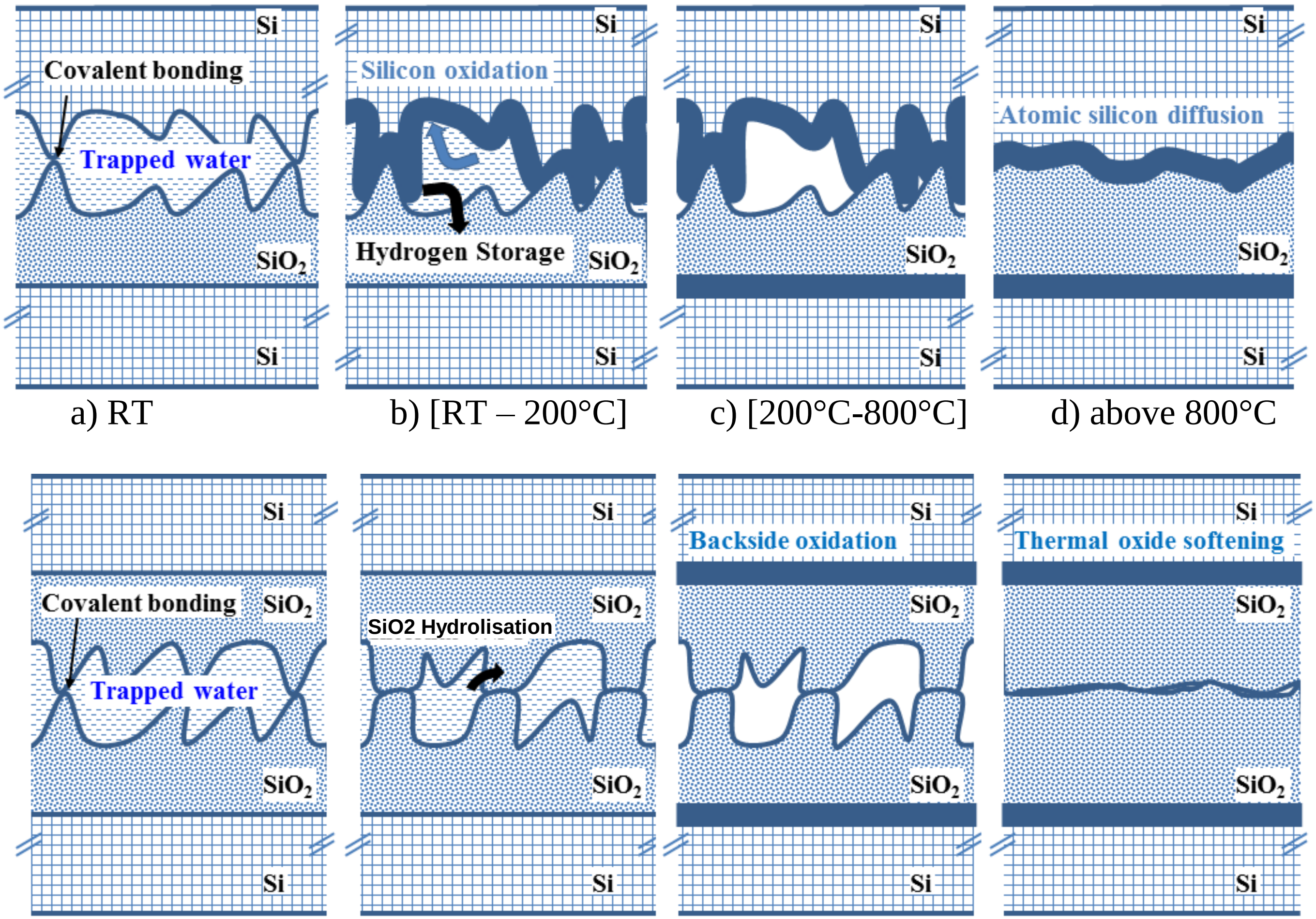
=> HUGE adherence at low temperature

CMP SiO2//SiO2:



	VP500 Buffing	VP500 pas Buffing	IC1010 pas Buffing
Mesure Anhydre	7445	3590	3181

SI/SIO2 AND SIO2/SIO2 BONDING MECHANISM



a) RT b) [RT – 200°C] c) [200°C-800°C] d) above 800°C

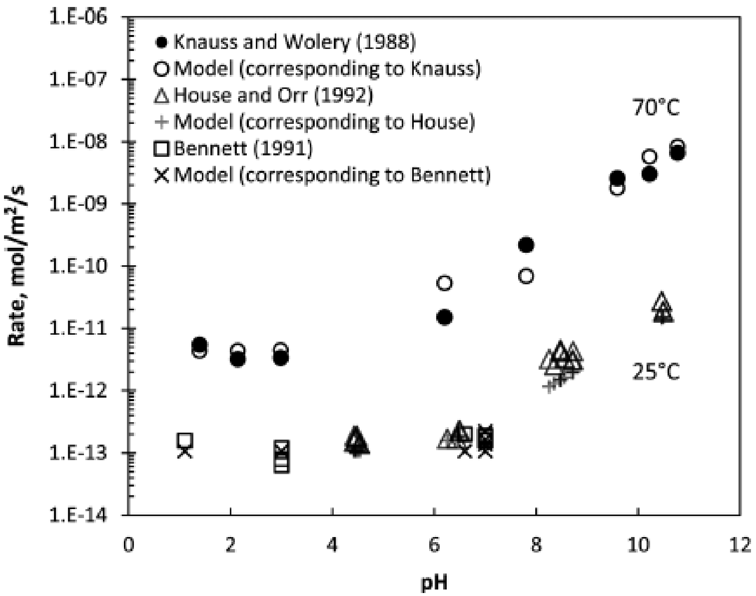
e) RT f) [RT – 600°C] g) [600°C-1200°C] h) above 1200°C

⇒ **Water is an adherence promoter**

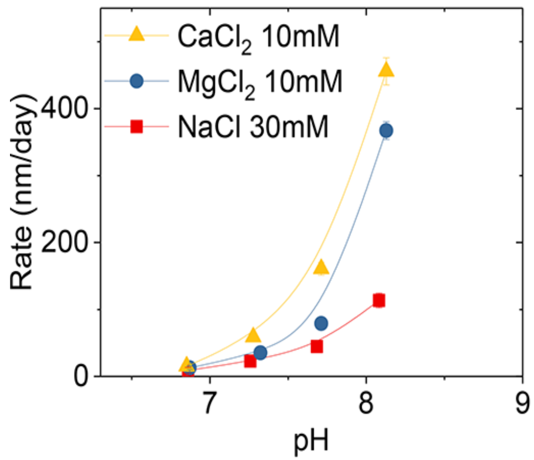
*F. Fournel, el al., ECS J. Solid State Sci. Technol. 4, P124 (2015).

ADHERENCE BOOSTER MOLECULE

Silica dissolution in basic solution

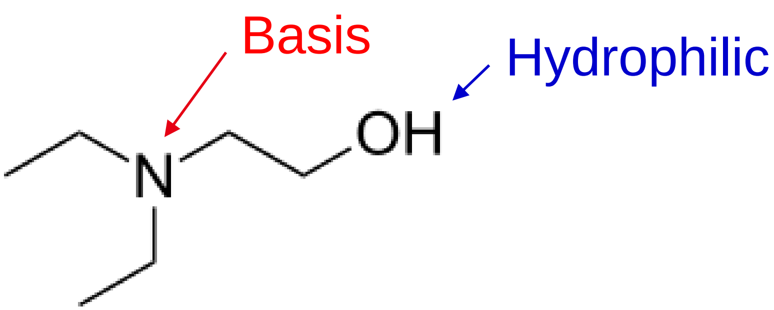


F.K. Crundwell et al., ACS Omega 2, 1116 (2017).



Yoon Kyeung Lee, et al. *ACS* (9), 49 42633-38 (2017).

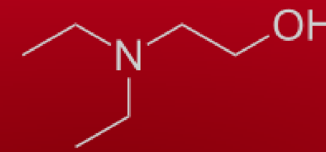
N,N-diethylethanolamine (DEAE)



Dissolution is enhance @ high pH

=> Hydrolisation is enhanced @ high pH

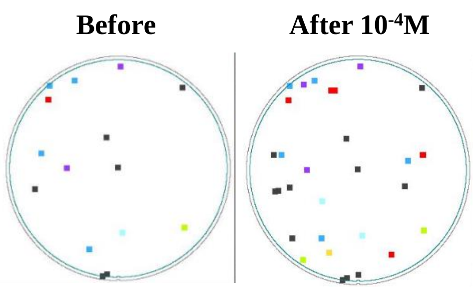
ADHERENCE BOOSTER MOLECULE



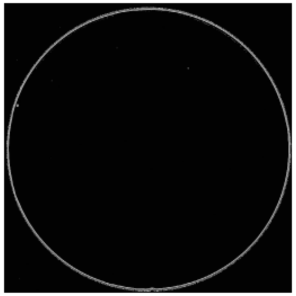
Basic molecule (DEAE):

Deposition on silicon surface

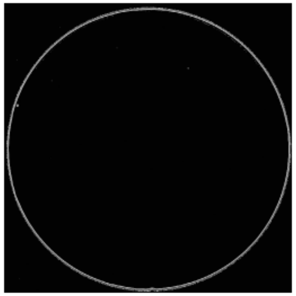
SP2 surfscan @90nm



After annealing

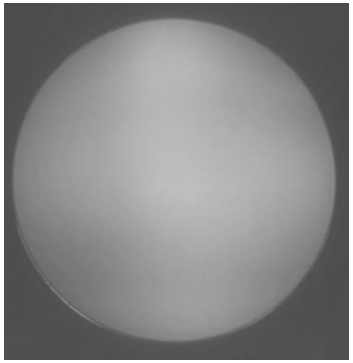


Si//SiO2 @400°C



Si//SiO2 @1100°C

No adhesion impact

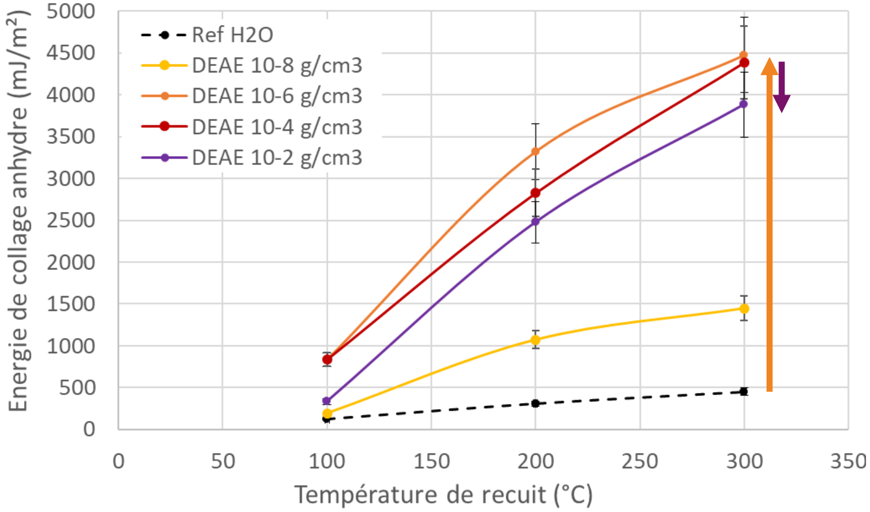


leti

⇒No impact on defectivity

(small amount of molecule)

Adherence with DEAE in $SiO_2//SiO_2$



Huge impact on Adherence

=> 10^{-5} (g/cm^3) (~10^{-4} M) seems to be a save optimal concentration

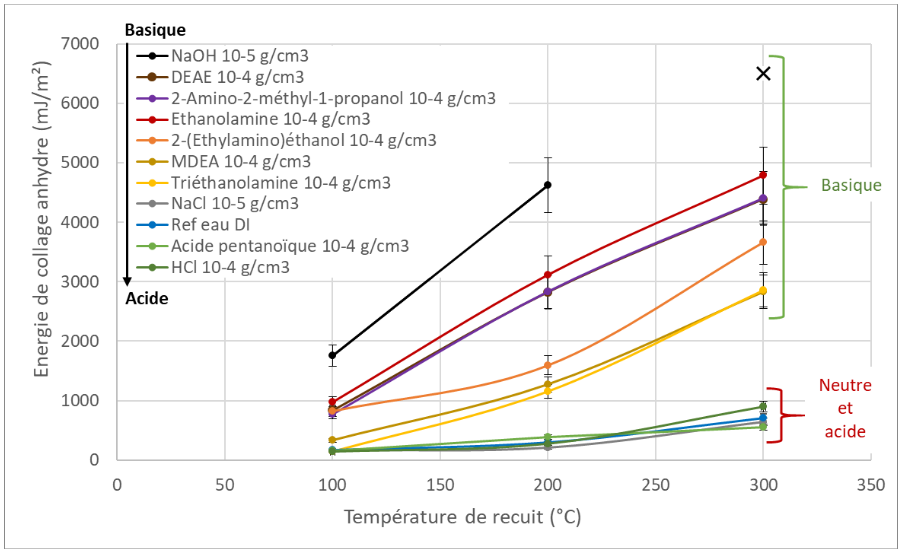
*Fournel, F, et al., *ECS Trans.* **2020**, *98* (4), 3. https://doi.org/10.1149/09804.0003ecst.

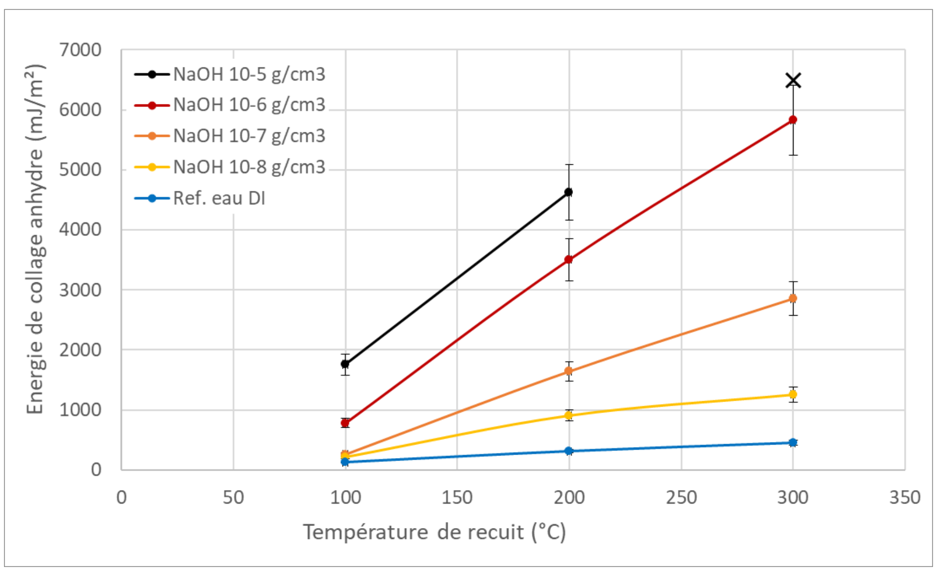
*Calvez, A., et al., ECS *J. Solid State Sci. Technol.* **2021**, *10* (6), 064005. https://doi.org/10.1149/2162-8777/ac08d7,

*Calvez, A., « Gestion de l’eau Dans Le Collage Direct. », Phd, Université Grenoble Alpes, 2022

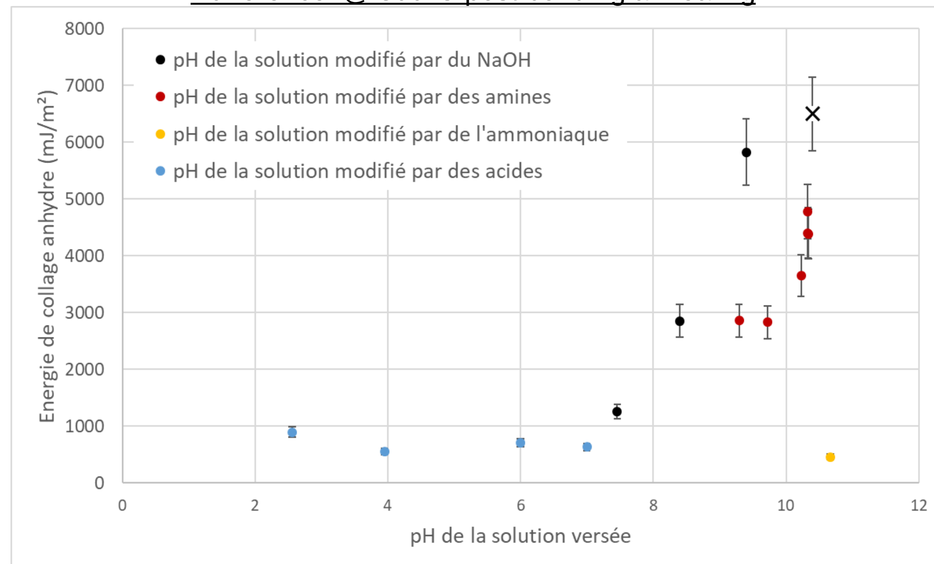
ADHERENCE BOOSTER MOLECULE

Different molecule ($SiO_2//SiO_2$)

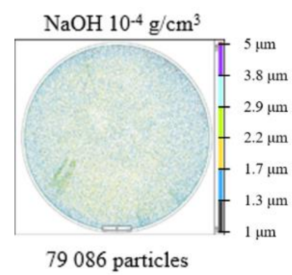




Adherence @ 300°C post bonding annealing



pH seems to be the key parameter



Not anymore bondable

NaOH is the best one… for the moment ☺

Deposition model

Double electrostatic layer

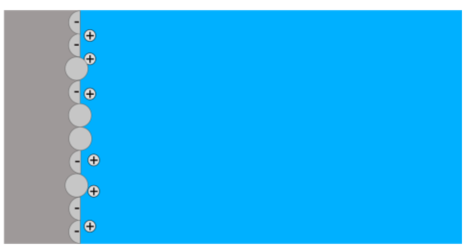
- Poisson-Boltzman equation : surface charges, surface potential and ionic volume concentration

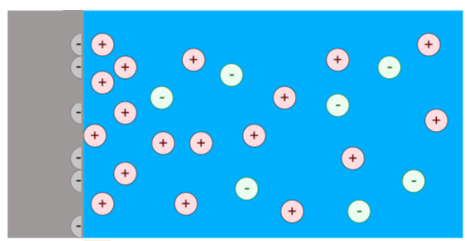
$$[Na^+]_0 = [Na^+]_\infty \ exp\left(\frac{e\psi_0}{k_B T}\right)$$

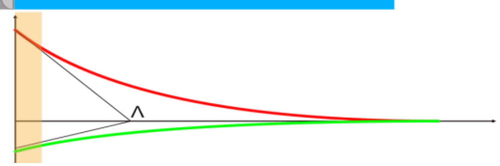
- Integration over Debye length :
  Dry surface :

~0,883

$$\frac{[Na^+]_0}{K} = \frac{1}{e}\left(e\, n_{SiOH}\frac{K_d}{K_e}\right)^{2/3} (2\varepsilon\varepsilon_0 k_B T)^{1/6}\ \rho^{\ 5/6}$$





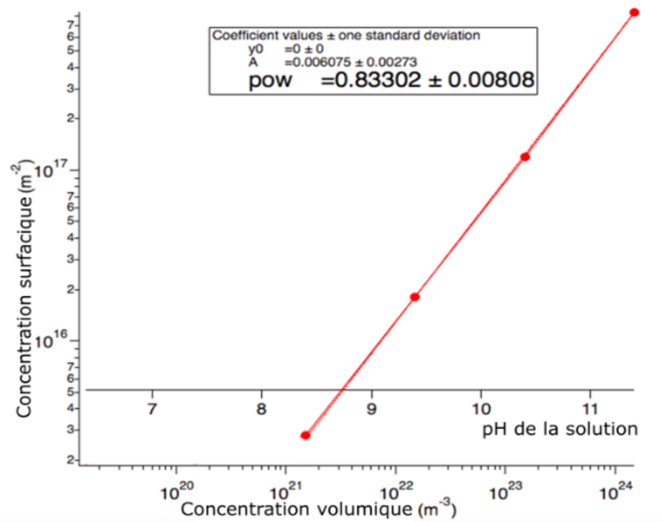


Partially ionized Silica surface

TXRF

Dispensed solution	Na^+ concentration on wafer surface (at/cm²)
H_2O	< 2x10^{11}
NaOH 10^{-8} g/cm³	< 2x10^{11}
NaOH 10^{-7} g/cm³	2.8x10^{11}
NaOH 10^{-6} g/cm³	1.8x10^{12}
NaOH 10^{-5} g/cm³	1.2x10^{13}
NaOH 10^{-4} g/cm³	8.4x10^{13}

< 1/100 ML



TAKE AWAY MESSAGES

- Direct bonding mechanism based on Rough Surface model

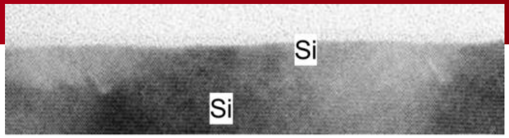
- Adhesion energy to perform the bonding
  (not only van der Waals but also capillarity bridges)
- Adherence energy for the bonding strength
  (covalent bonding are already @ RT)

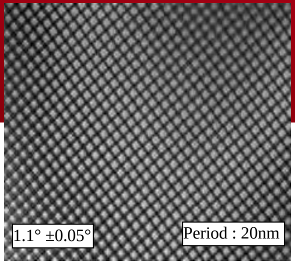
- Adherence measurement impacted by WSC
  => DCB in Anhydrous atmosphere

- SiO_2 adherence mechanism based on silica hydrolisation

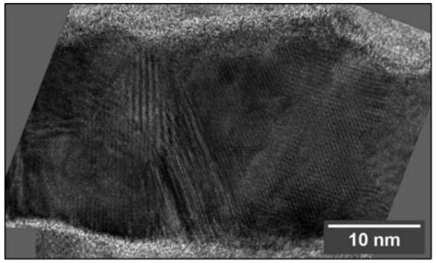
- CMP or Plasma are adherence booster (fluorine plasma)
- Chemical molecule can be as good as plasma (NaOH)

OTHER DIRECT BONDING TYPE





- Hydrophobic bonding (Si/Si…)
- Polymer bonding (even with direct bonding ☺)
- Metallic bonding : Au/Au



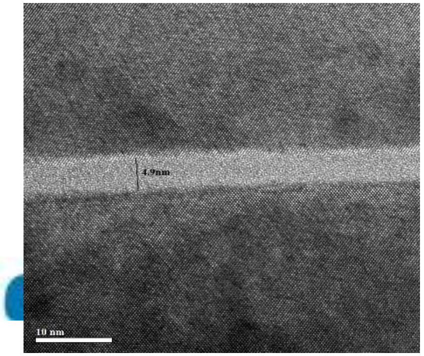
TEM cross section of RT Gold:Gold interface

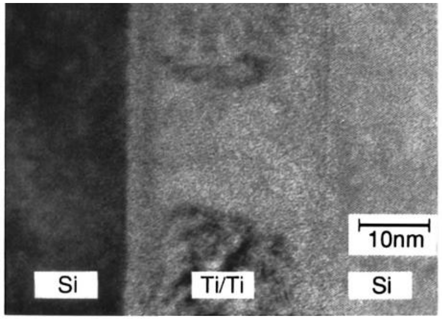
- Ultra high vacuum bonding technic

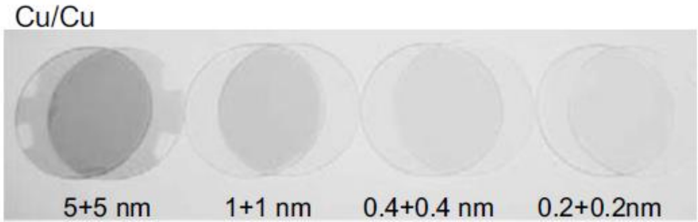
Generate dangling bonds and to bond with them!

  - SAB (surface activation bonding) => "etching"
  - ADB (atomic diffusion bonding) => "deposition"

SAB Si bonding Without annealing – 4,9nm amorphous layer







Shimatsu, T et al.,*Journal of Vacuum Science & Technology A* **1998**, *16* (4), 2125–2131.

Merci pour votre attention