DE LA RECHERCHE À L'INDUSTRIE

FROM DIRECT BONDING MECHANISMS TO APPLICATIONS

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2019

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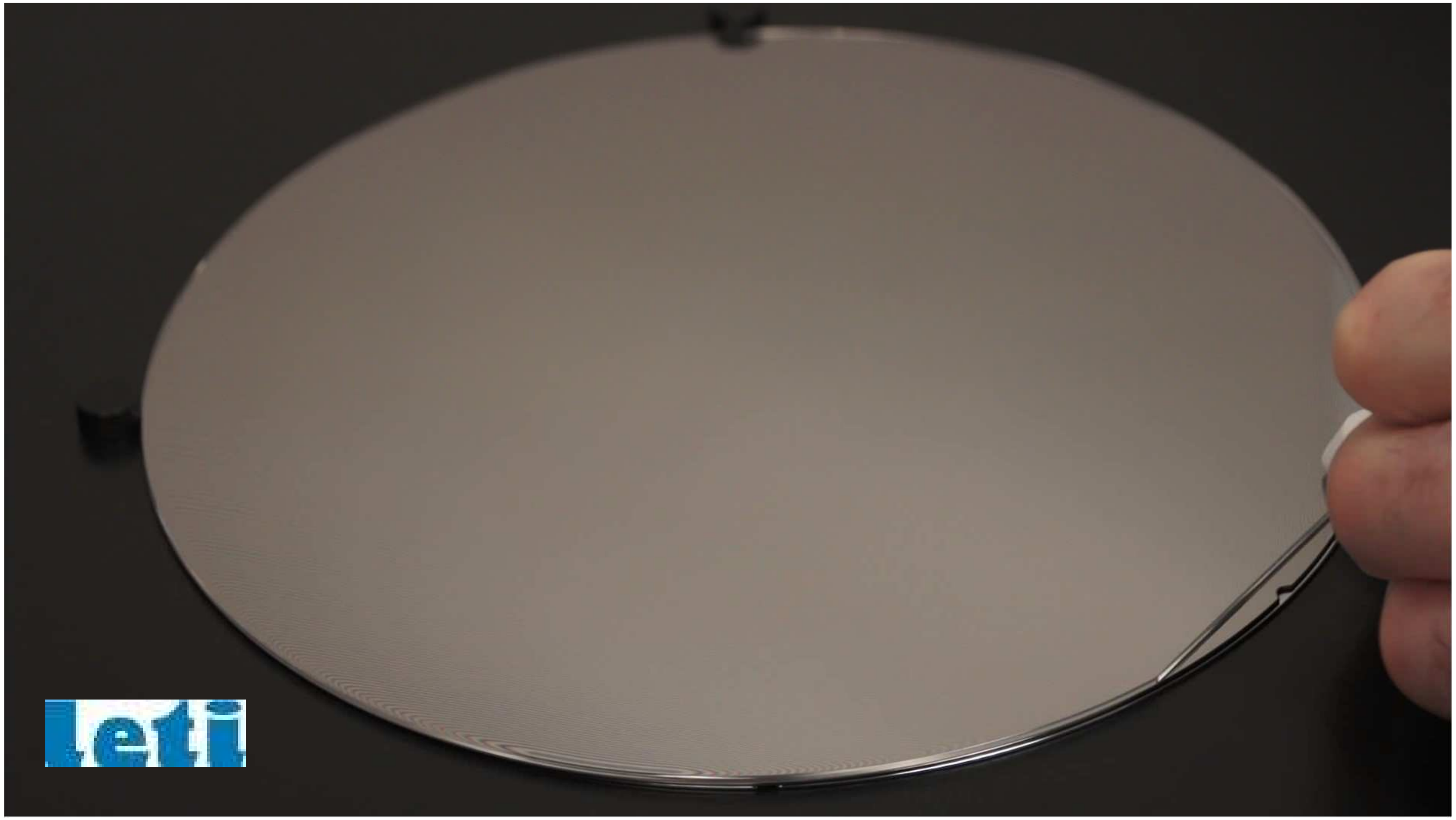
Spontaneous bonding without "thick" liquid material

(usualy at room temperature and ambient pressure)

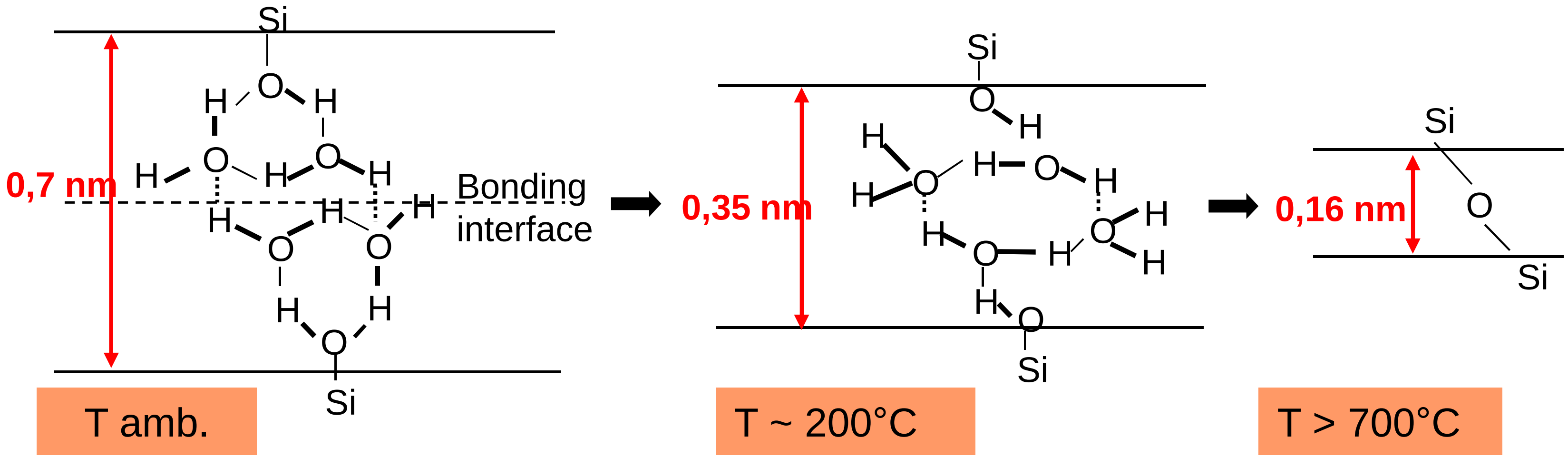


Direct bonding

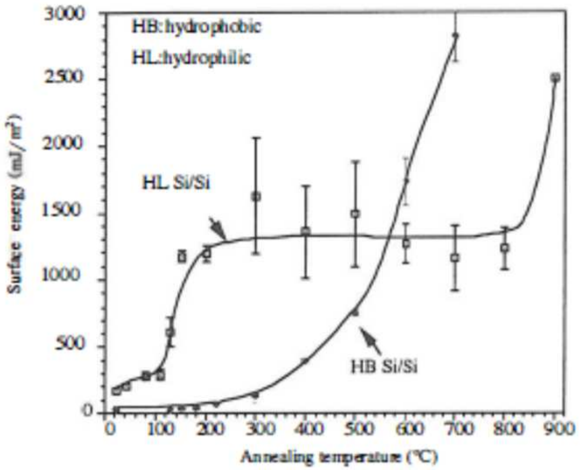
- Silicon & Silicon dioxide
  - Small digest of static mechanism
  - Adhesion and Adherence
  - Physicochemical Mechanism
  - Interface water edge diffusion
- Direct bonding of others materials
  - Copper/Copper
  - Hybrid Copper/Silicon dioxide
- Direct bonding LETI applications

Stengl Model : hydrophilic Si bonding

Based on infrared spectroscopy and bonding energy measurement..

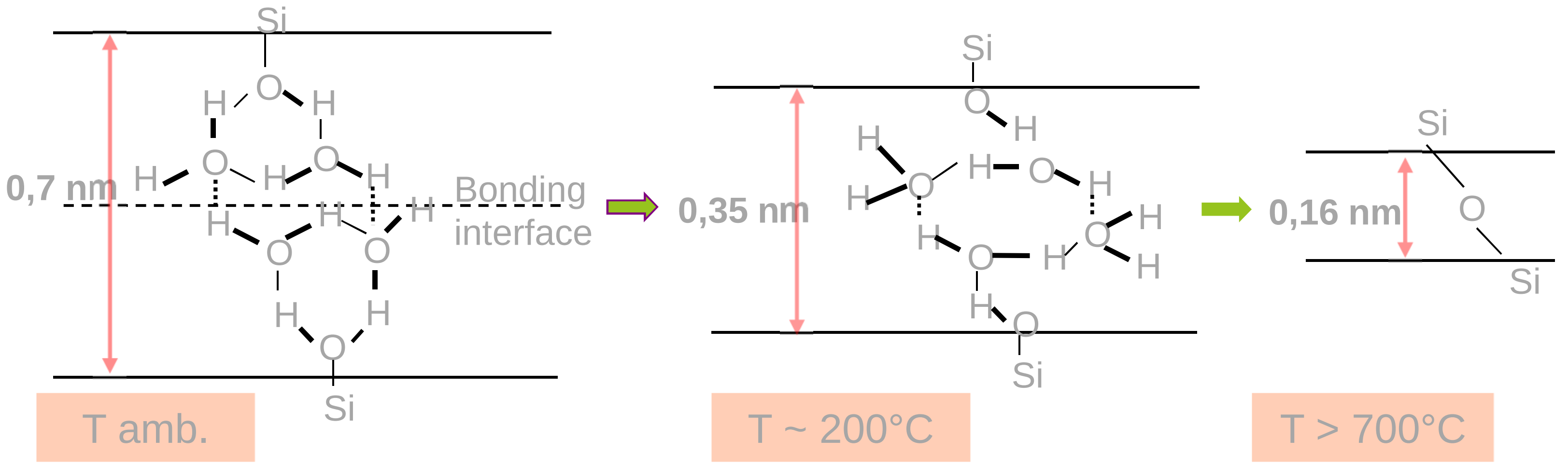


R. Stengl et al., J. J. Appl. Phys. Lett. (1989)

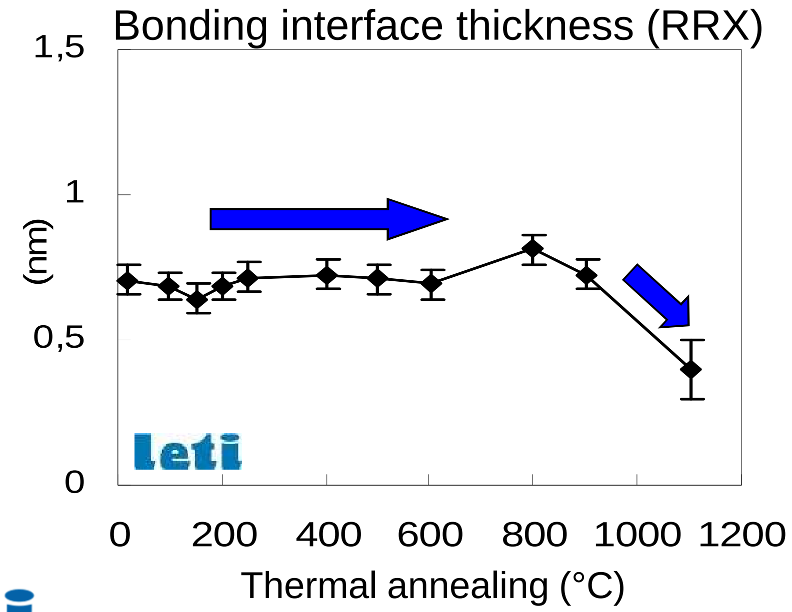


Q.Y. Tong, U. Gosele,"SemiConductor Wafer Bonding: Science and Technology", John Wiley Sons Inc (1998)

PHYSICAL MECHANISM



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



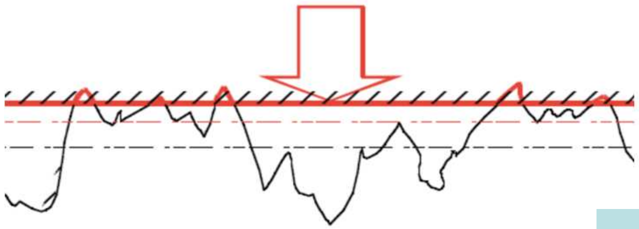
RRX=> Constant interface thickness

→ **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).

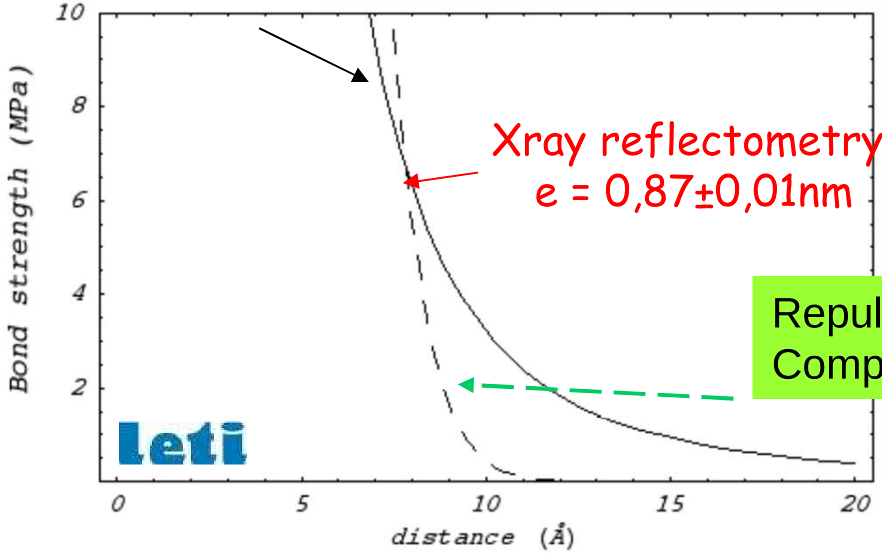
Number of asperities in contact $N = N_0\ F_0(d/\sigma^*)$

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

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

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

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



~1% of contacted surface

Repulsive forces:
Compressed asperities

*Fr. Rieutord et al., ECS 2006

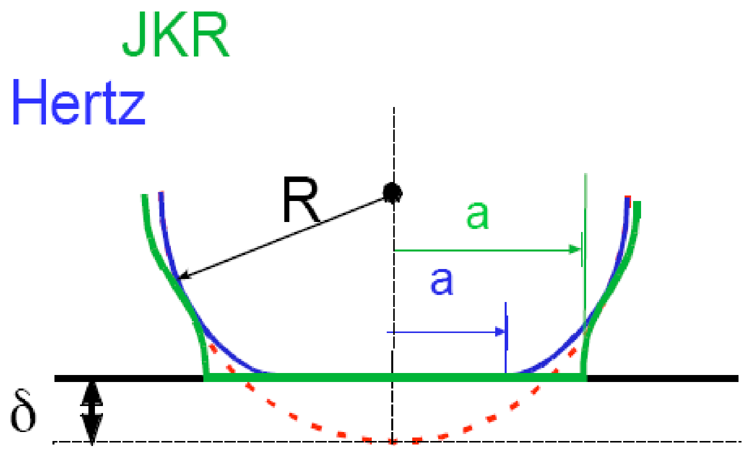
JKR Model during annealing

Johnson-Kendall-Roberts

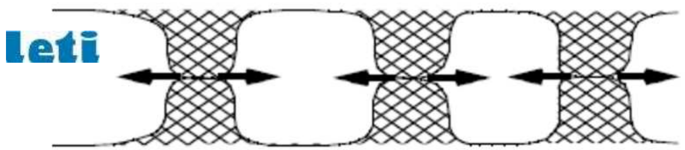
$$E_{tot}(z) = \int_z^{\infty} P(u)du - (wA(z) + vdW(z))$$

Elastic energy
(Asperity compression)

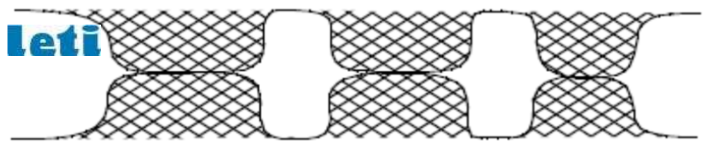
Surface energy
(Adhesion)



➢ Ziplock model



RT, low T



Medium T (<~400°C)

high T

*Fr. Rieutord et al., ECS 2006

Direct bonding

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  - Small digest of static mechanism
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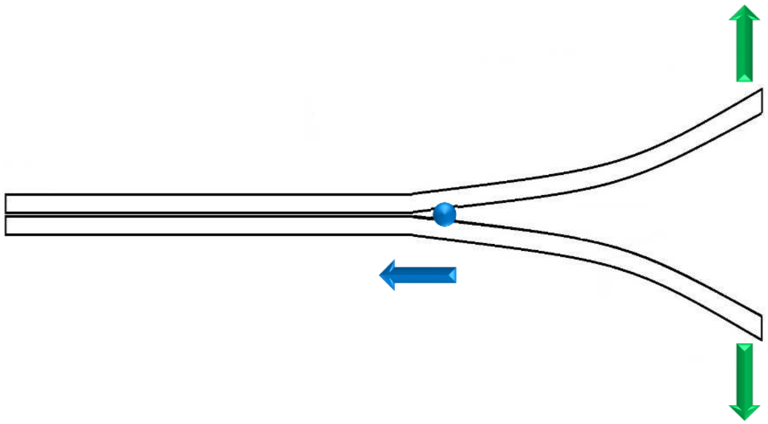
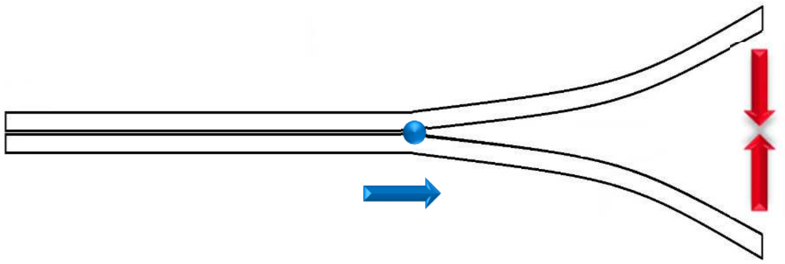
Adherence vs adhesion





Adherence Energy

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

- Energy needed to open the bonding

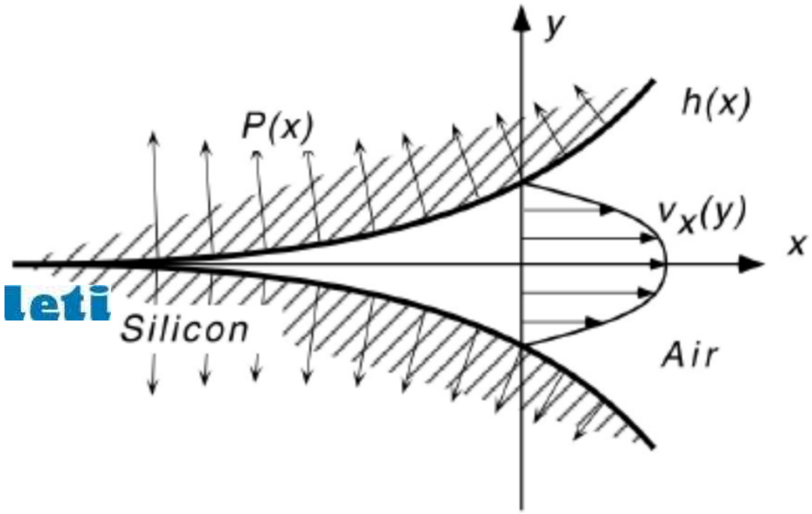
  Chemical bonds breaking

- 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



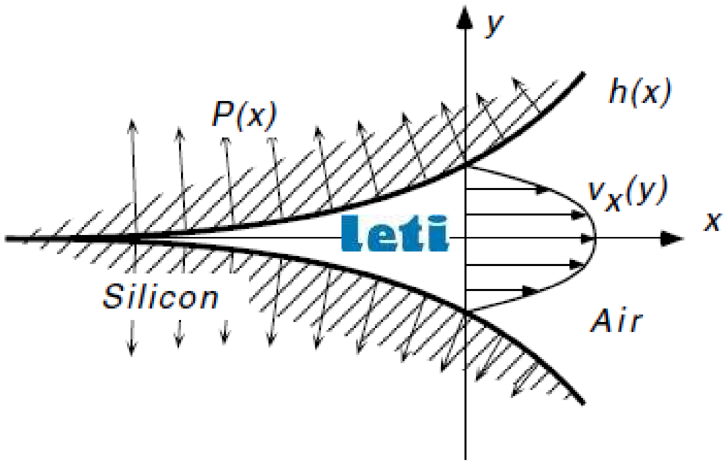
$$U = \frac{(2\gamma)^{5/4}}{\eta t^{3/4}} \frac{\Lambda^{1/2}}{\left(\frac{E}{1-\nu^2}\right)^{1/4}} \frac{A^{3/4}}{9}$$

With $2\gamma = E_{adhesion}$

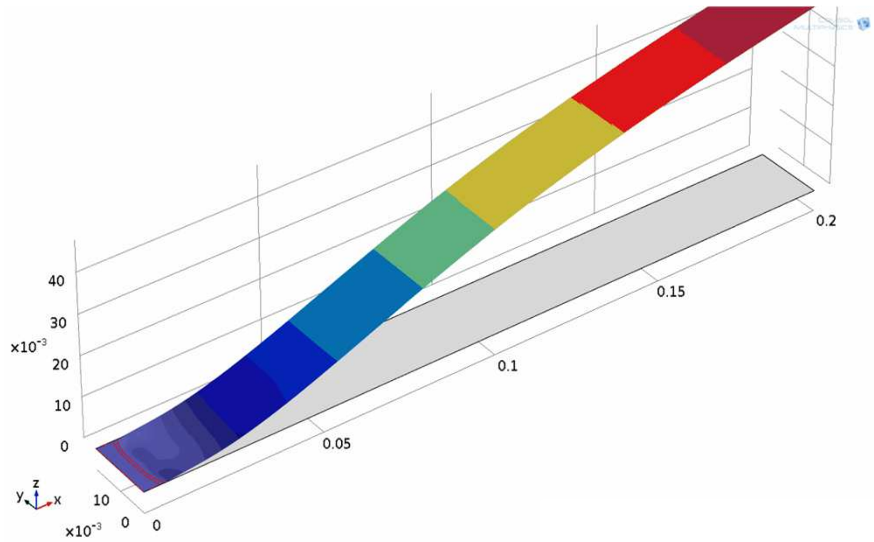
With Λ=mean free path, A=Numerical constant

ADHESION

- <u>Edge less model*</u>
- Symmetrical geometry
- Constant speed
- 1D :Poiseuille flow
- Engine : adhesion energy
- Break : fluid flow



- <u>Edge model**</u>
- Non symmetrical geometry
- Radial speed
- 2D : FEM
- Engine : adhesion energy
- Break : fluid flow



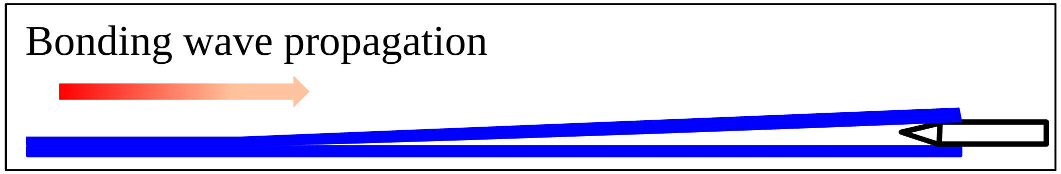
*F. Rieutord, et al., Physical Review Letters 94, (2005).

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

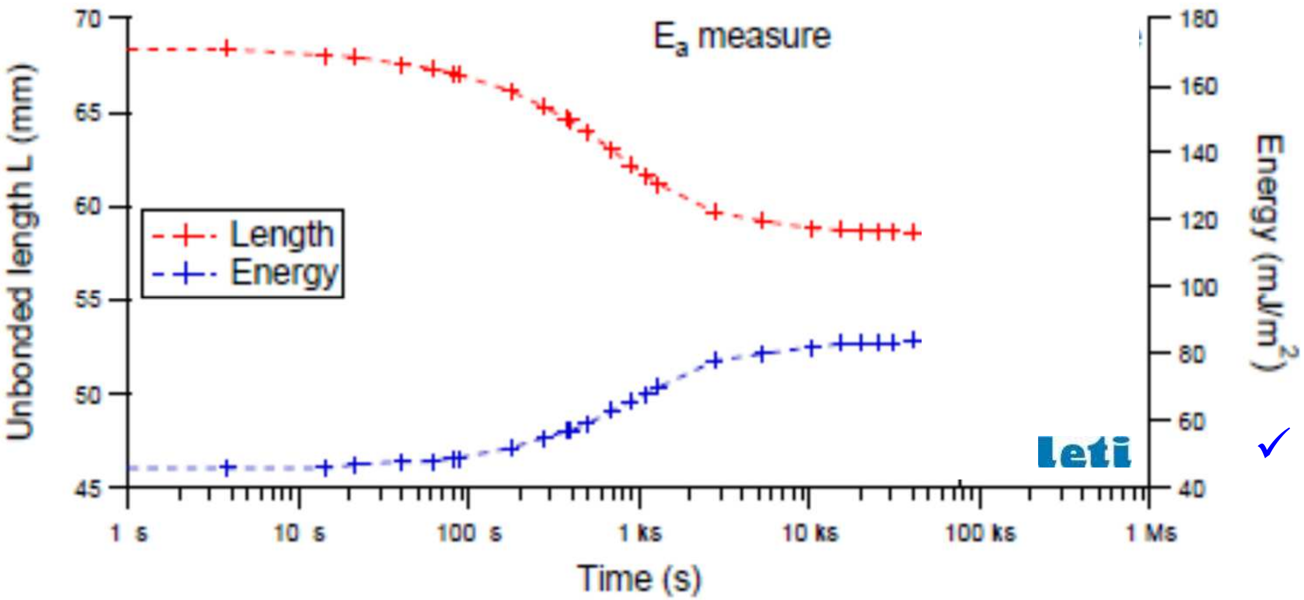
ADHESION

Adhesion energy measurement:

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



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

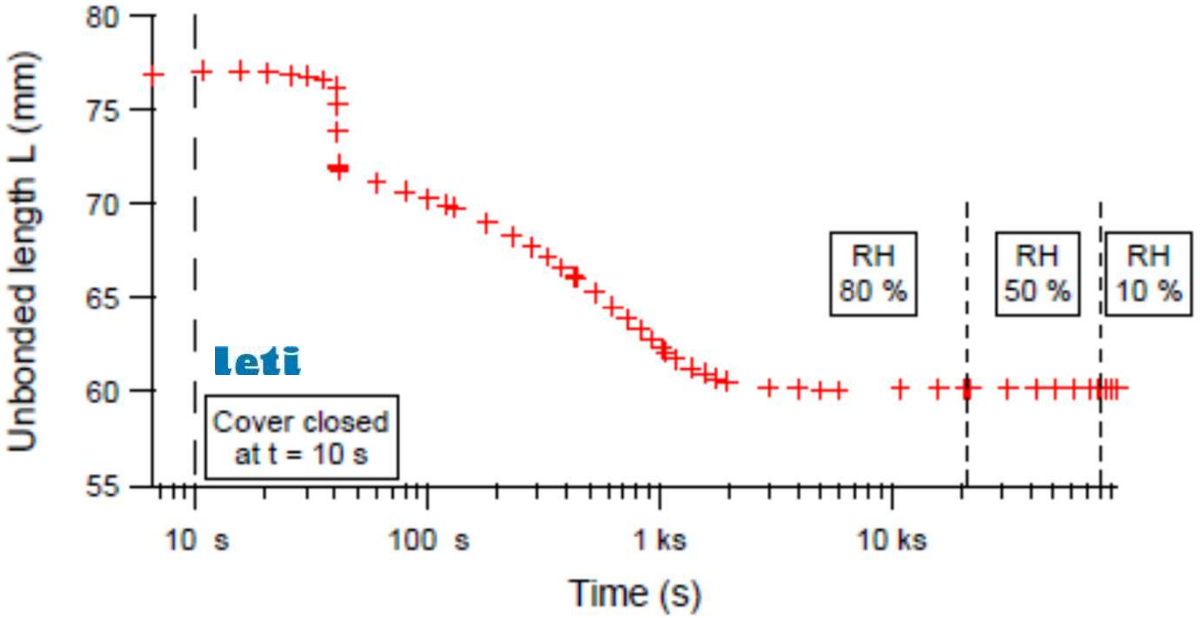


- ✓ Small evolution during 4 hours!

  ? Capillarity effect ? (meniscus)

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

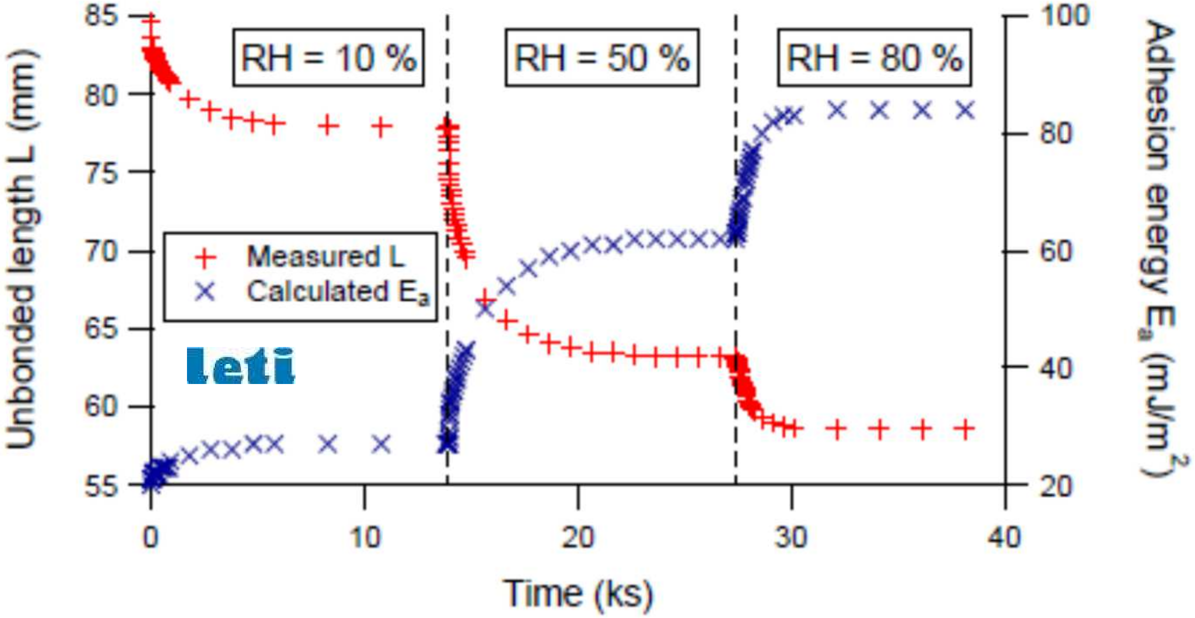
Adhesion energy measurement / Time evolution:



Time evolution is not driven by meniscus!!

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

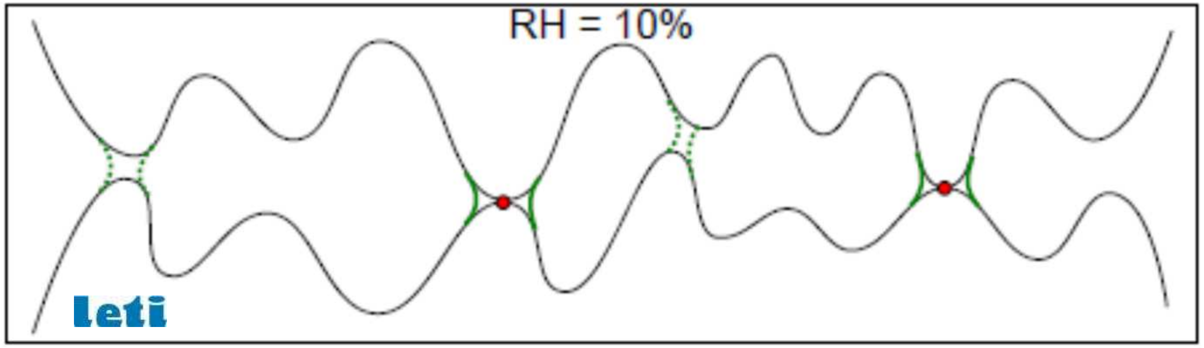
Adhesion energy measurement / Time evolution:

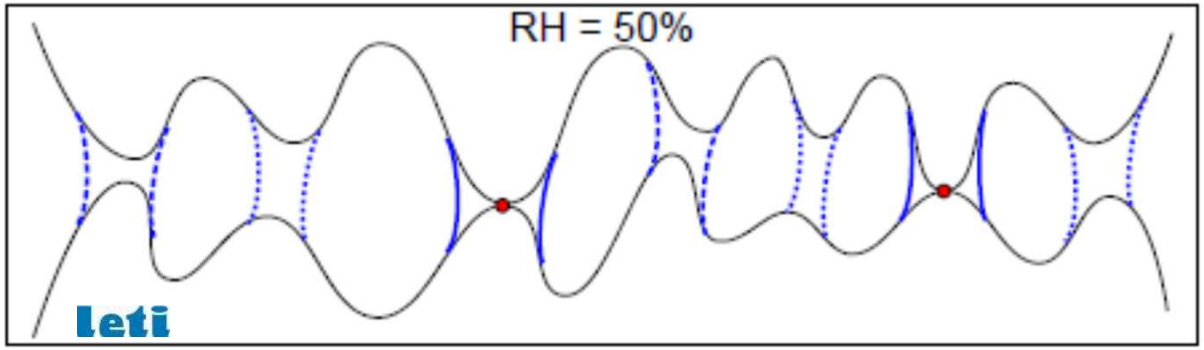


=> Time evolution depends of the amount of water.
=> Fast and slow evolution.

*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.*

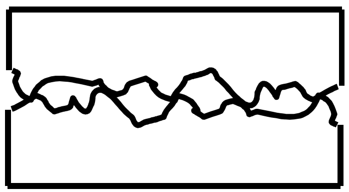
Bonding "engines" : chemistry & roughness

Attractive force:

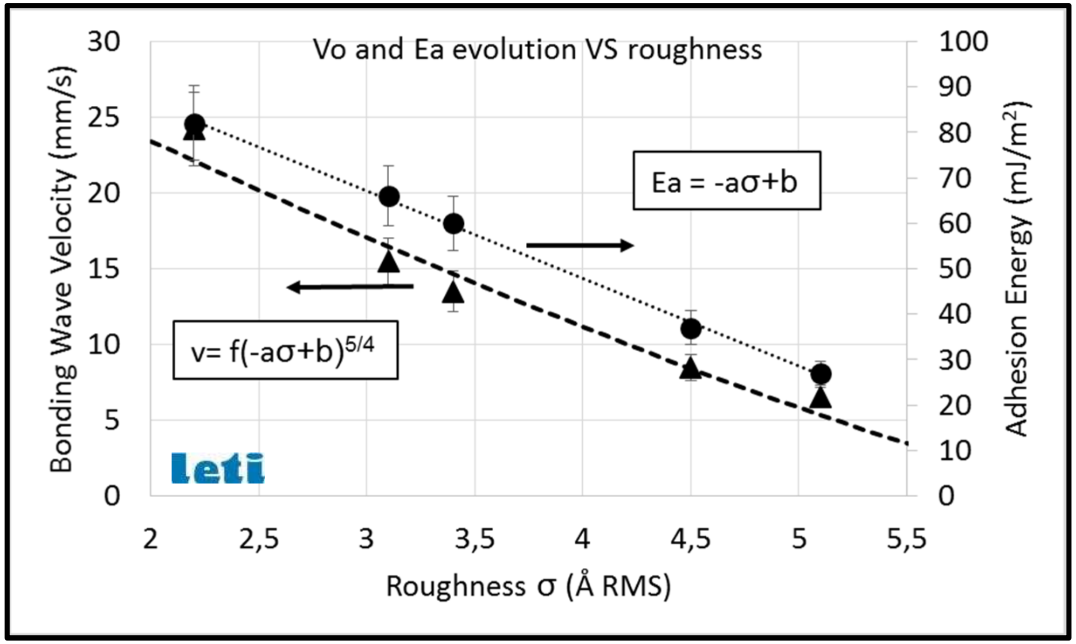
- *Van der Waals (+hydrogen bonds) + capillarity*

Repulsive force

- *Non adhesive contact on rough surface*



Adhesion energy versus roughness (Si/SiO_2 bonding)



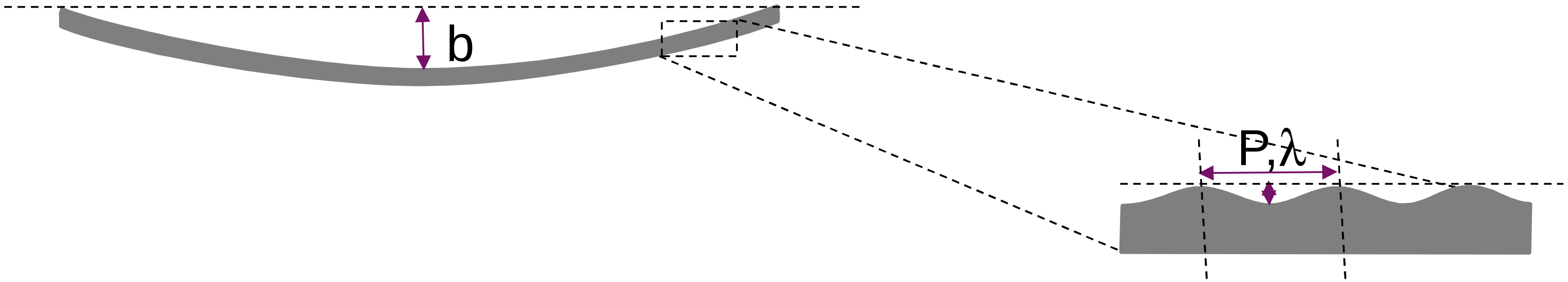
✓ **Roughness specification : <0.6nm RMS**

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

Bonding "breaks"

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

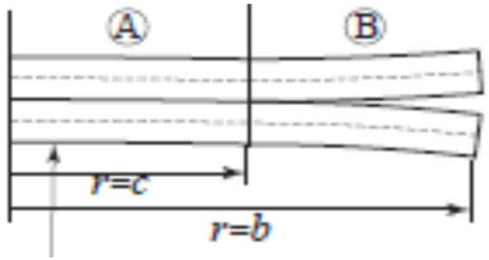
Bow / Curvature



?Which criteria?

Mindlin theory

Higher-order plate theory (bending / transverse shear…)



- $\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w_B}{\partial r}\right)\right] = 0 \qquad \Phi_B(r\beta) = w_B'(r\beta)$
- $\Phi''(r\beta) + \frac{1}{r}\Phi'(r\beta) - \left(\frac{1}{r^2} + \beta^2\right)\Phi(r\beta) = -\beta^2 {W_a}'(r\beta)$

$$\beta^2 = \frac{k_p G h}{D}$$

Modified Bessel differential equation solved with even polynomial solution (instead of the use of the Sturve function:

$$w_A(r\beta) = b_{2p}r^{2p} + \cdots + b_6 r^6 + b_4 r^4 + b_2 r^2 + b_0$$

$$\Phi_A(r\beta) = \sum_{i=1}^{p} U_{2p-2i+1} r^{2p-2i+1} + C_3 I_1(r\beta)$$

$I_1(r\beta)$ is the modified Bessel function of first order

$$U_{2p-2i+1} = (2p-2i+2)b_{2p-2i+2} + \frac{U_{2p-2i+3}}{\beta^2}\left[(2p-2i+3)^2 - 1\right] \; and \; U_{2p+1} = 0$$

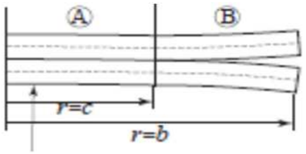
$$w_B(r\beta) = \frac{1}{4}C_5 r^2 + C_6 ln\left(\frac{r}{c}\right) + C_7$$

$$C_3, C_5, C_6, C_7 \quad \begin{cases} w_{A|r=c} = w_{B|r=c} \\ \Phi_{A|r=c} = \Phi_{B|r=c} \\ M_{rA|r=c} = M_{rB|r=c} \\ M_{rB|r=b} = 0 \end{cases}$$

$$if\ h = f(x), k = \frac{f''}{\left(1 + f'^2\right)^{3/2}}$$

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

Mindlin theory

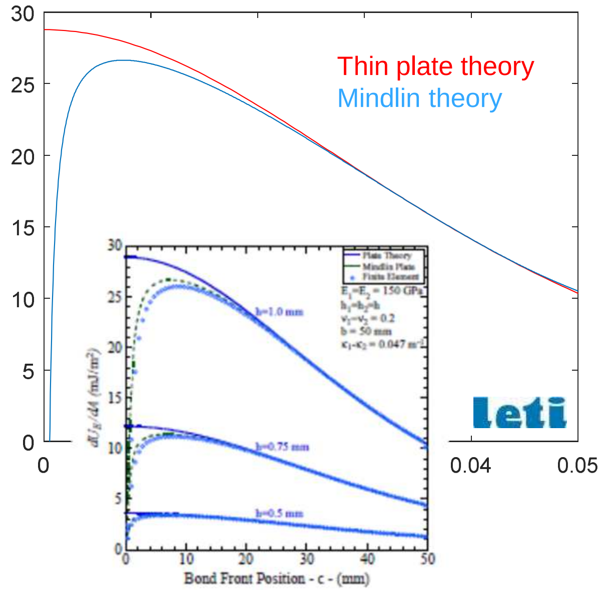


$$U(c) = \pi \int_0^b D\left\{\left[(\Phi')^2 + 2\frac{\nu}{r}\Phi\Phi' + \left(\frac{\Phi}{r}\right)^2\right] + \beta^2 (w' - \Phi)^2\right\} r dr$$

$$\beta^2 = \frac{k_p G h}{D}$$

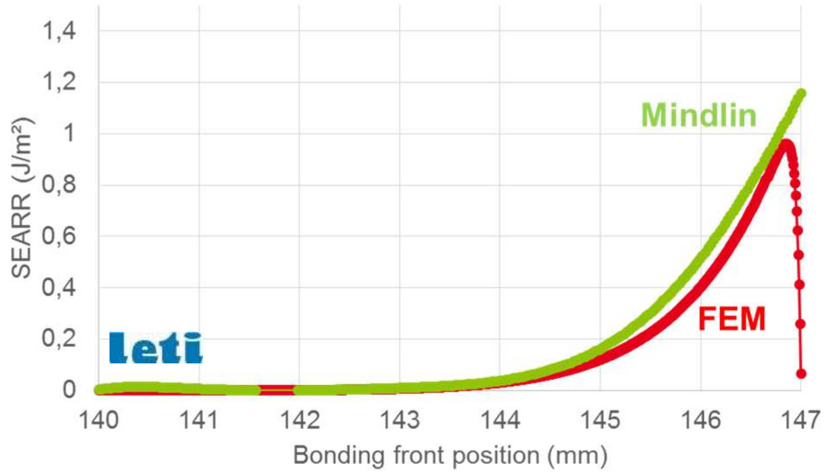
$$G = \frac{\partial U(c)}{\partial (c)}$$

Center simulation



Edge simulation

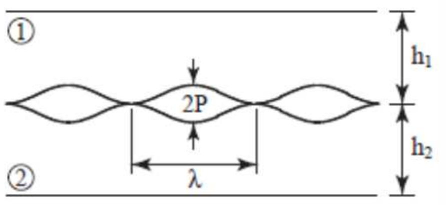
(with specific edge roll down)

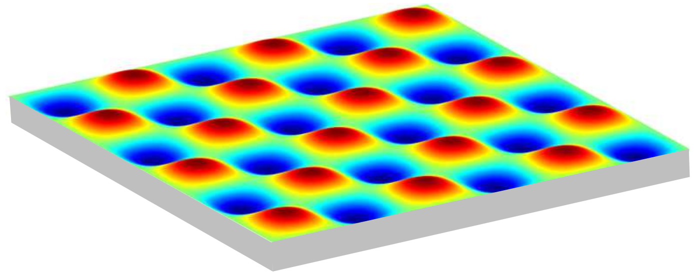


K.T. Turner, Wafer Bonding: Mechanics-Based Models and Experiments, Massachusetts Institute of Technology, 2004.

ADHESION

Thin plate theory



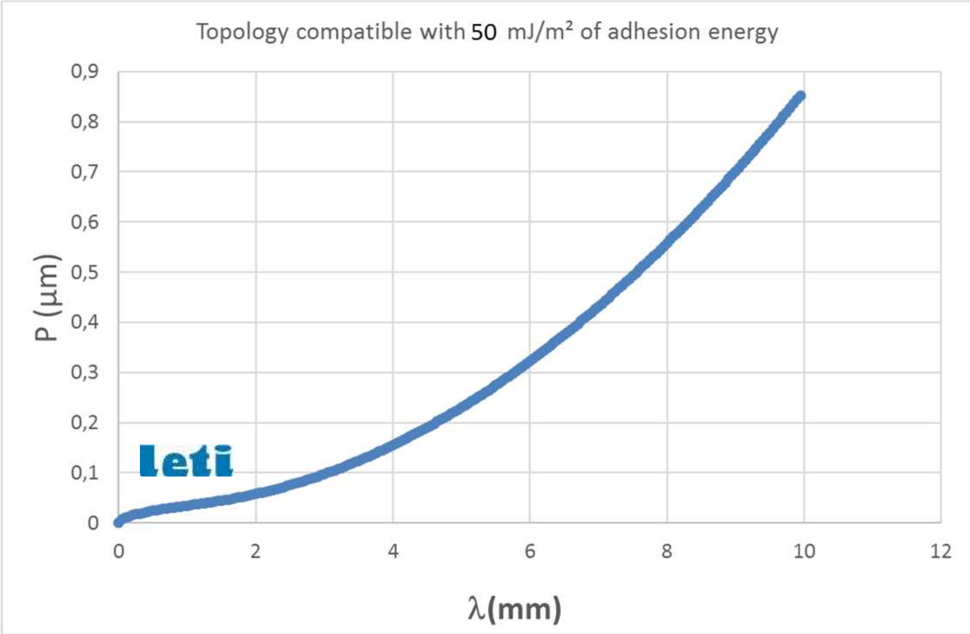


$$\text{Gap} = 2P\left[1 + cos\left(2\pi\frac{x}{\lambda}\right) cos\left(2\pi\frac{y}{\lambda}\right)\right]$$

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

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

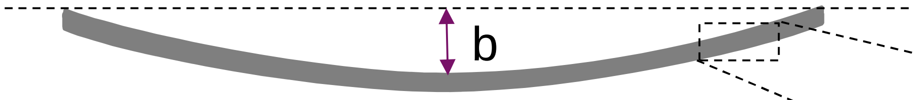
$$I(x) = \frac{e^{2\sqrt{2}x} + e^{-2\sqrt{2}x} - 2 - 8x^2}{e^{2\sqrt{2}x} - e^{-2\sqrt{2}x} + 4\sqrt{2}x}$$

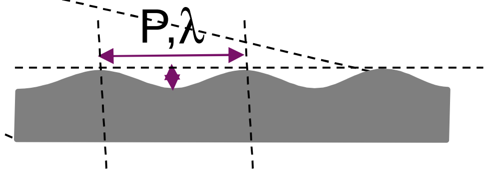


*K.T. Turner, Wafer Bonding: Mechanics-Based Models and Experiments, Massachusetts Institute of Technology, 2004.

Bonding "breaks"

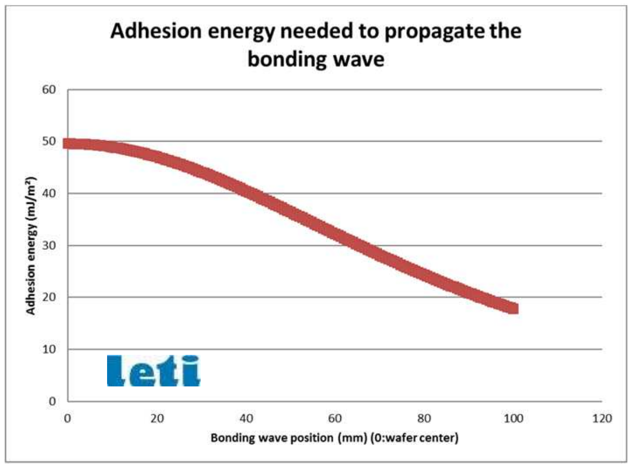
Bow / Curvature

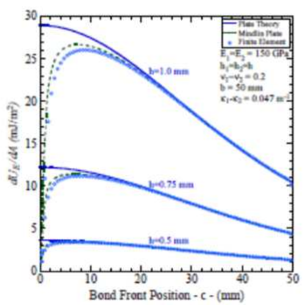


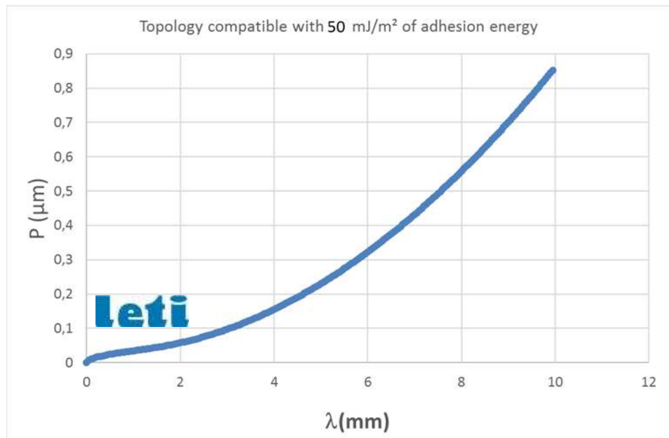


For 200mm wafer (725µm) and
50 mJ/m² of adhesion energy
⇒ $b < 250$ µm
⇒ Curvature < 0,05 m^{-1}
⇒ Curvature radius > 20 m

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







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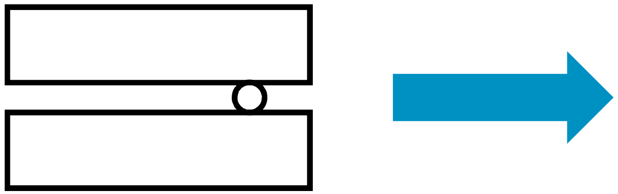
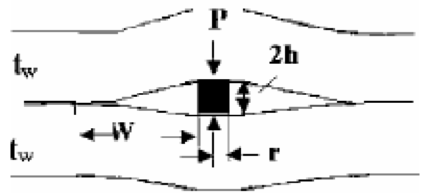
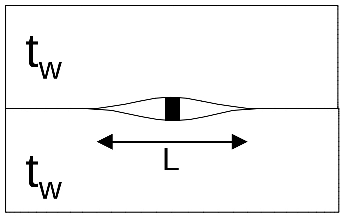
ADHESION

Low particle contamination

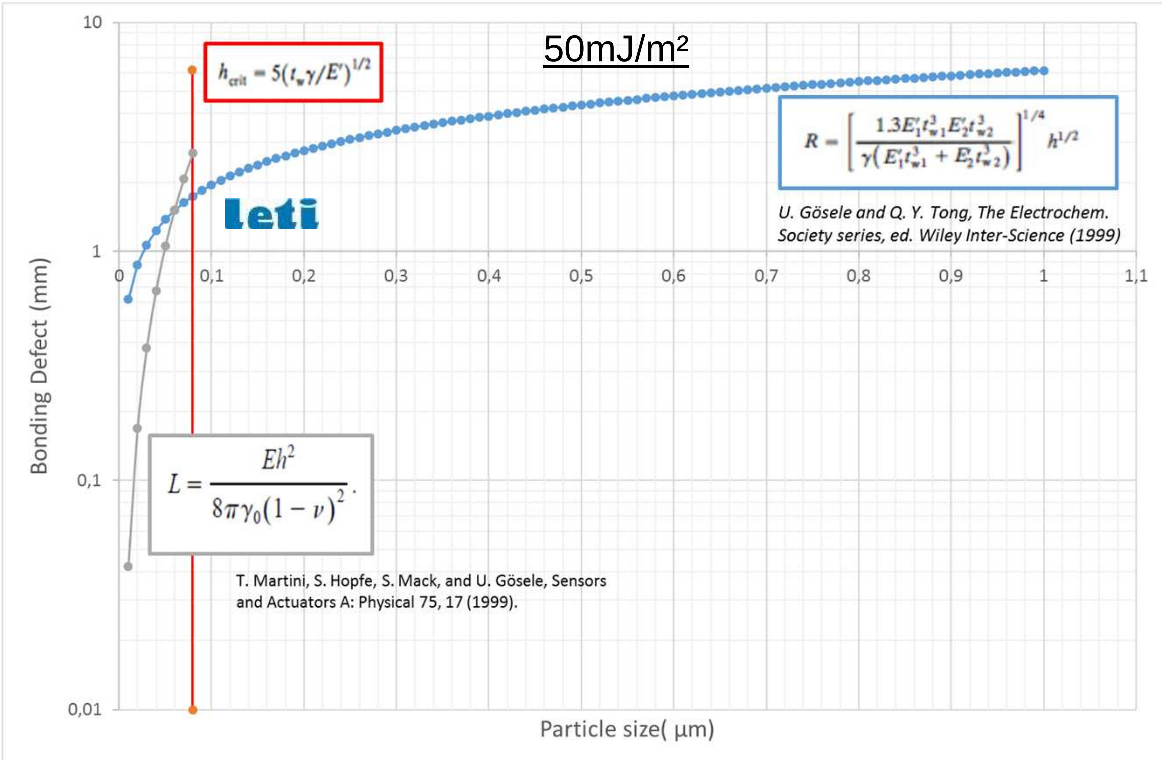






Height	500nm	1µm
Adhesion Energy mJ/m²	80	90
Average radius	3,4mm	5,4mm

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"

Direct bonding

- Silicon & Silicon dioxide
  - Small digest of static mechanism
  - Adhesion and Adherence
  - Physicochemical Mechanism
  - Interface water edge diffusion

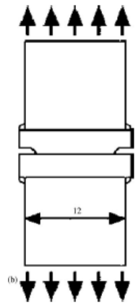
- Direct bonding of others materials
  - Copper/Copper
  - Hybrid Copper/Silicon dioxide

- Direct bonding LETI applications

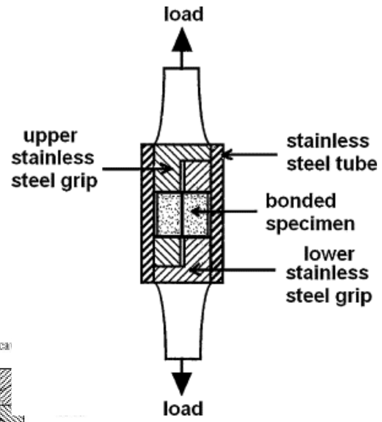
ADHERENCE

For thick substrates:

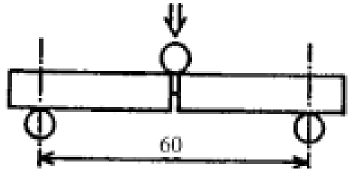
Tensile test



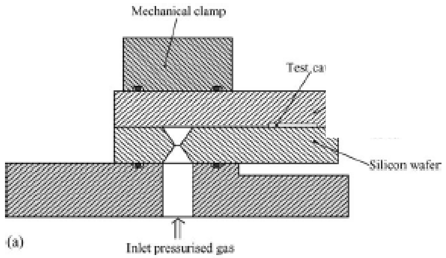
Shearing test



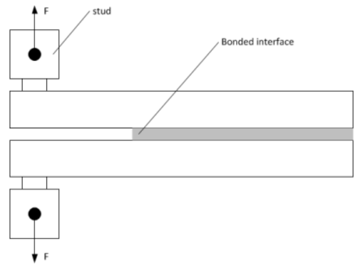
3 ou 4 bending points



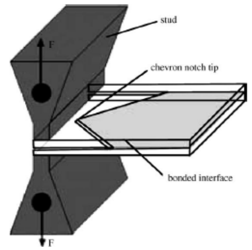
« Blister » test



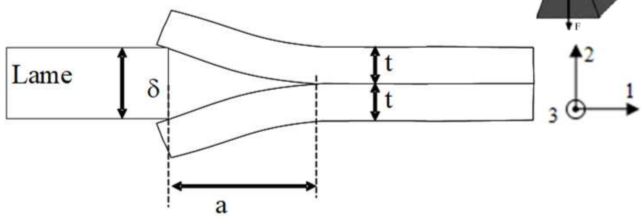
Double cantilever beam test under prescribed load control



Chevron test



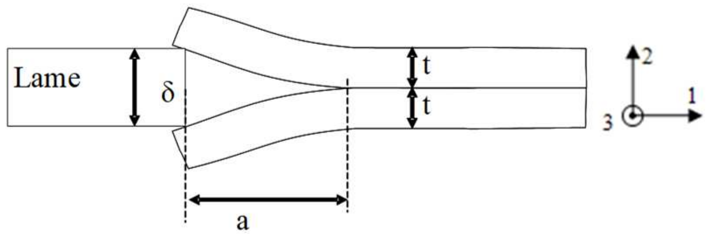
Double cantilever beam test under prescribed displacement control



*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

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

$$C_0 = \frac{24}{wt^3}\left(\frac{\beta_{11}a^3}{3} - \frac{\beta_{26}t^3}{24}\right) \qquad G = \frac{3}{8}\frac{\delta^2}{a^4}\frac{\frac{\beta_{1_{11}}}{t_1^3}+\frac{\beta_{2_{11}}}{t_2^3}}{\left[\frac{\beta_{1_{11}}}{t_1^3}\left(1-\frac{\beta_{1_{26}}t_1^3}{8\beta_{1_{11}}a^3}\right)+\frac{\beta_{2_{11}}}{t_2^3}\left(1-\frac{\beta_{2_{26}}t_2^3}{8\beta_{2_{11}}a^3}\right)\right]^2}$$

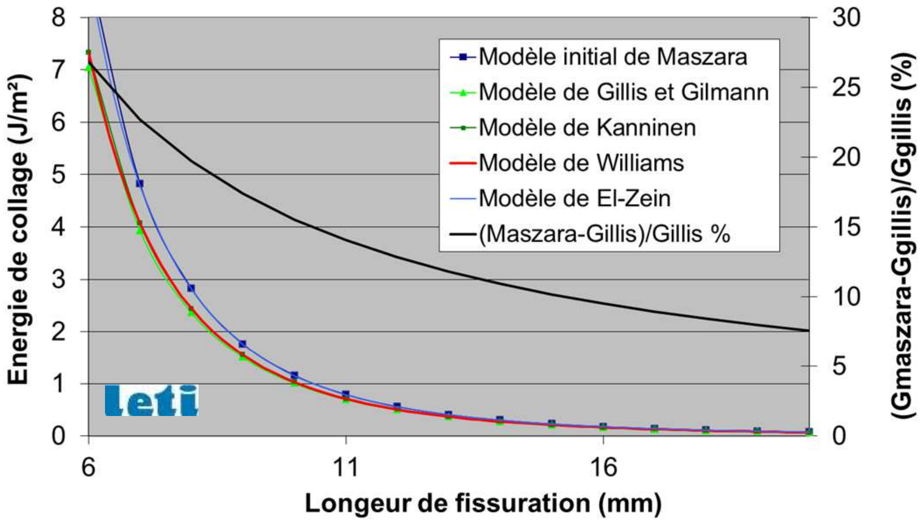
For orthotropic materials (Si beam <001>/<110>) : β_{26}=0 => ~Maszara:

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

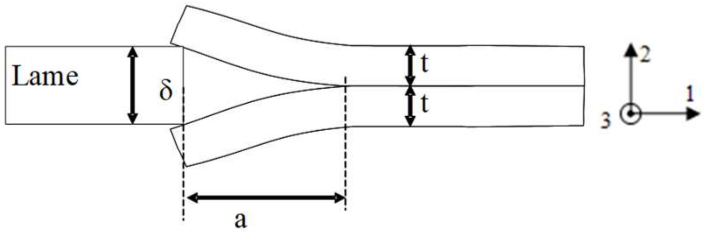
$$G = \frac{3\delta^2}{8a^4}\frac{E_1^*t_1^3E_2^*t_2^3}{E_1^*t_1^3+E_2^*t_2^3} \qquad E_i^* = \frac{E_{i,11}}{1-\upsilon_{13}^2}$$

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

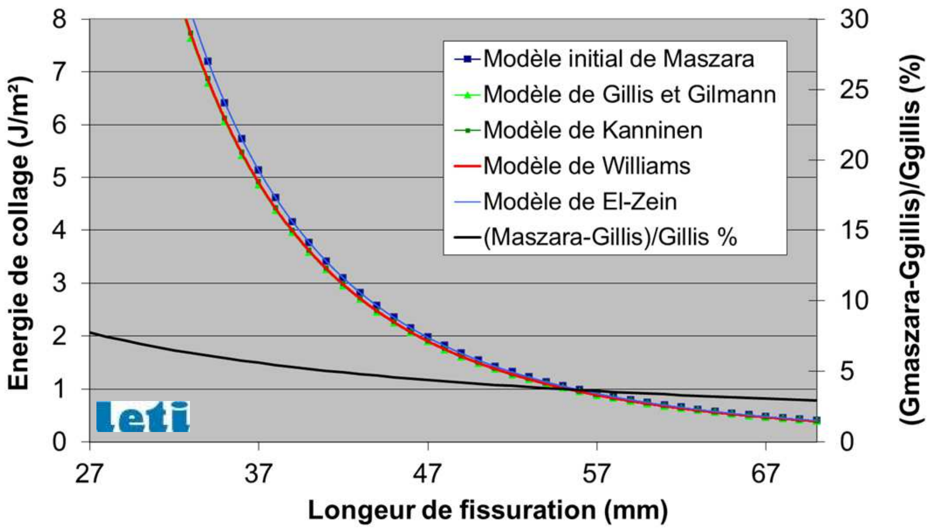
Mathematic models:



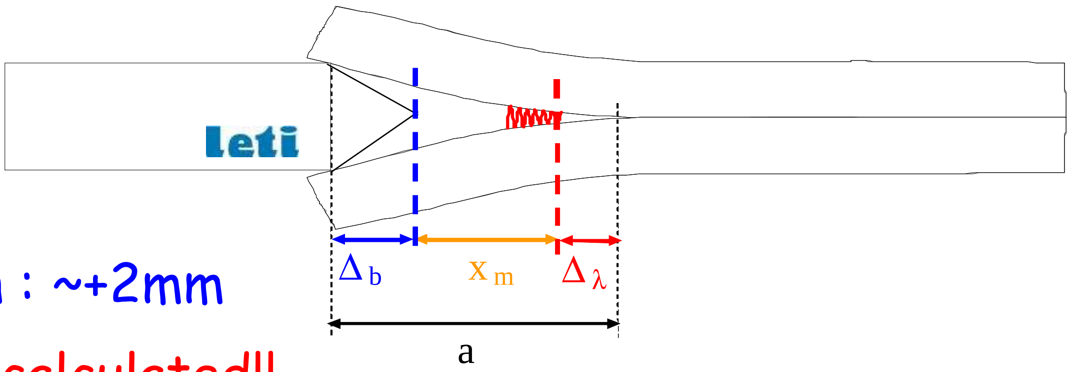
Thin blade : 50µm
Thin wafers : 525µm



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



Measurement protocol:



Δ_b: known : ~+2mm

Δ_λ: to be calculated!!

Timoshenko beam equation:

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

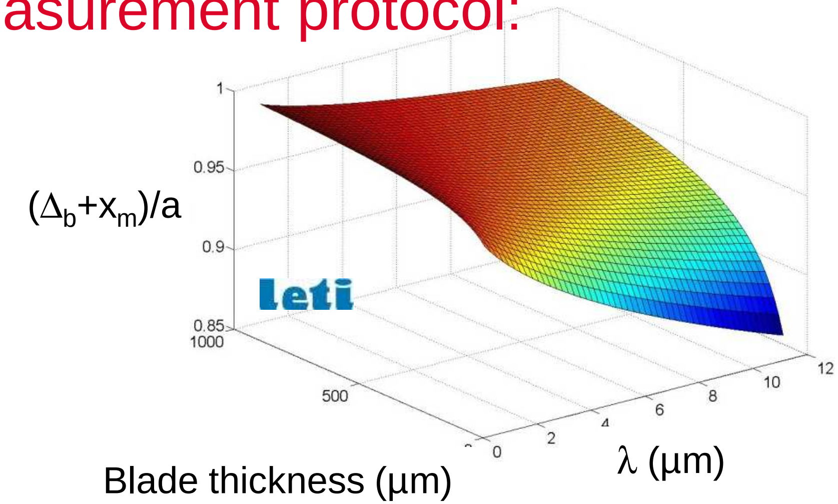
El-Zein beam equation (two different anisotropic beams):

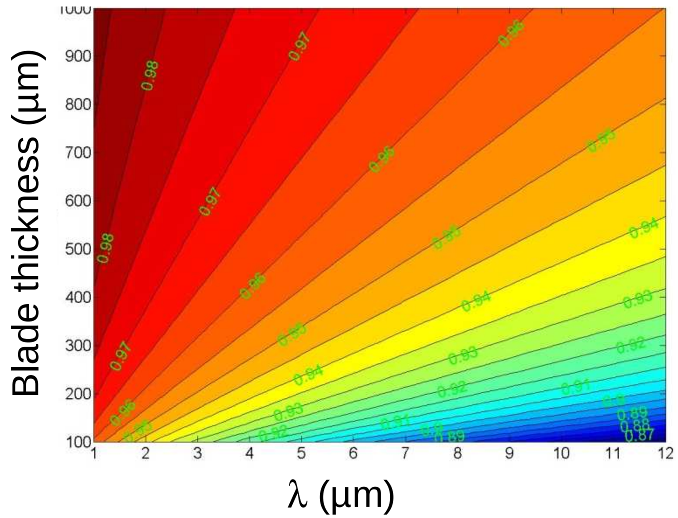
$$z^3 - \frac{3x_m^2}{4\left(1-\frac{\lambda}{4\delta}\right)^2} z - \frac{x_m^3}{4\left(1-\frac{\lambda}{4\delta}\right)^3} + \frac{x_m^3}{2\left(1-\frac{\lambda}{4\delta}\right)} - \frac{3x_m}{8\left(1-\frac{\lambda}{4\delta}\right)} \frac{\left(\frac{(\beta_{12})_1}{t_1} + \frac{(\beta_{12})_2}{t_2}\right)}{\left(\frac{(\beta_{11})_1}{t_1^3}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

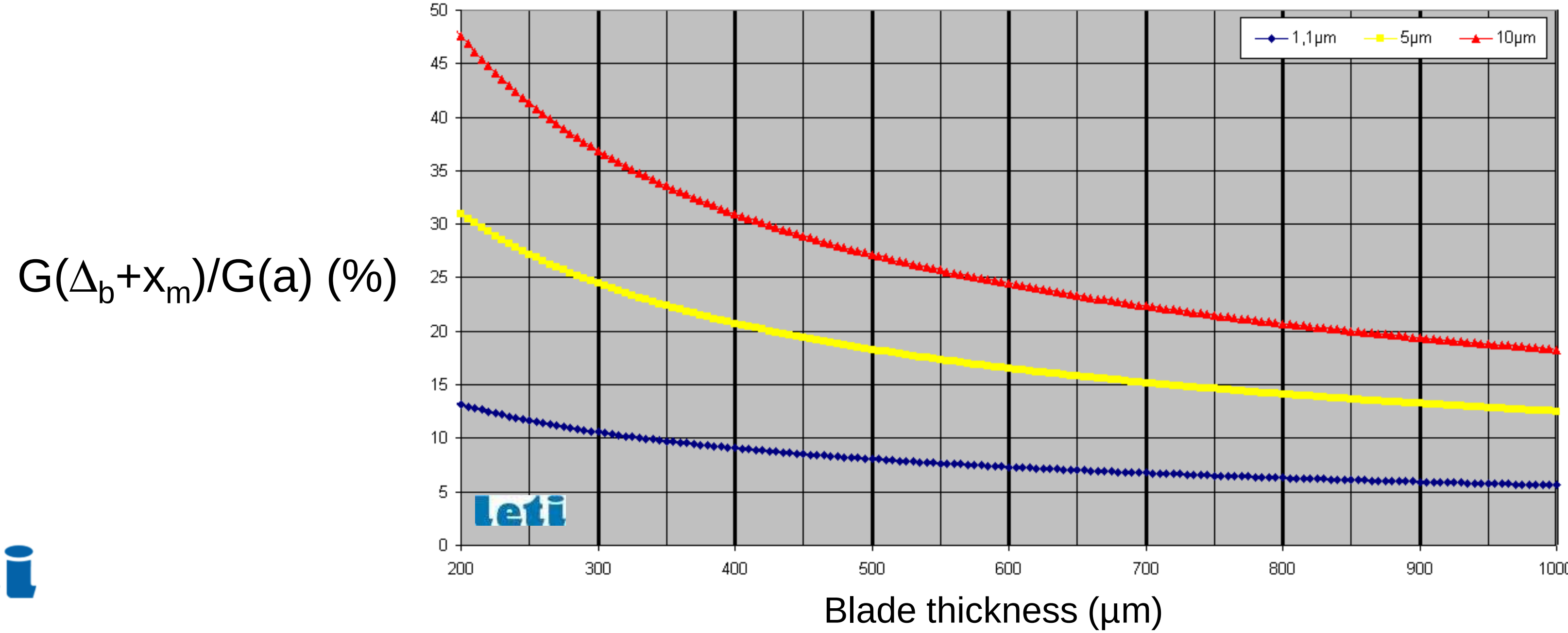
*F. Fournel, et al., Journal of Applied Physics 111, 104907 (2012).

ADHERENCE

Measurement protocol:





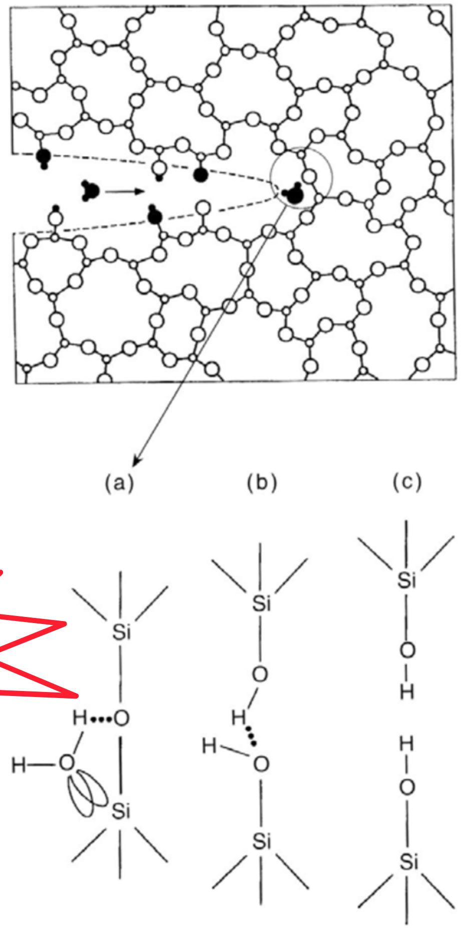


leti

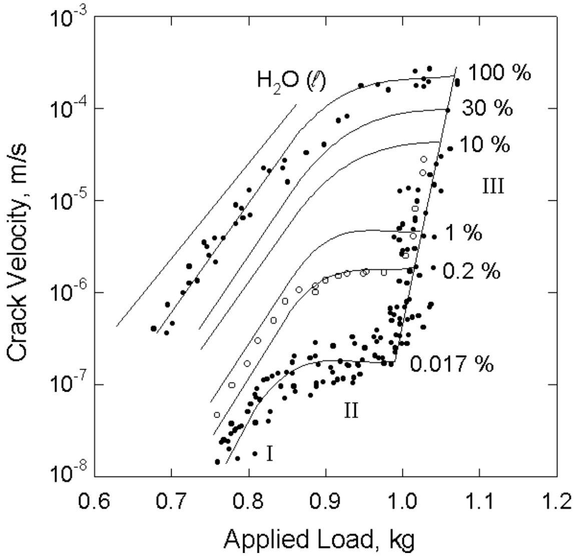
"Stress corrosion cracking (SCC) is the growth of cracks under tensile stress in a corrosive environment."

For SiO2 (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

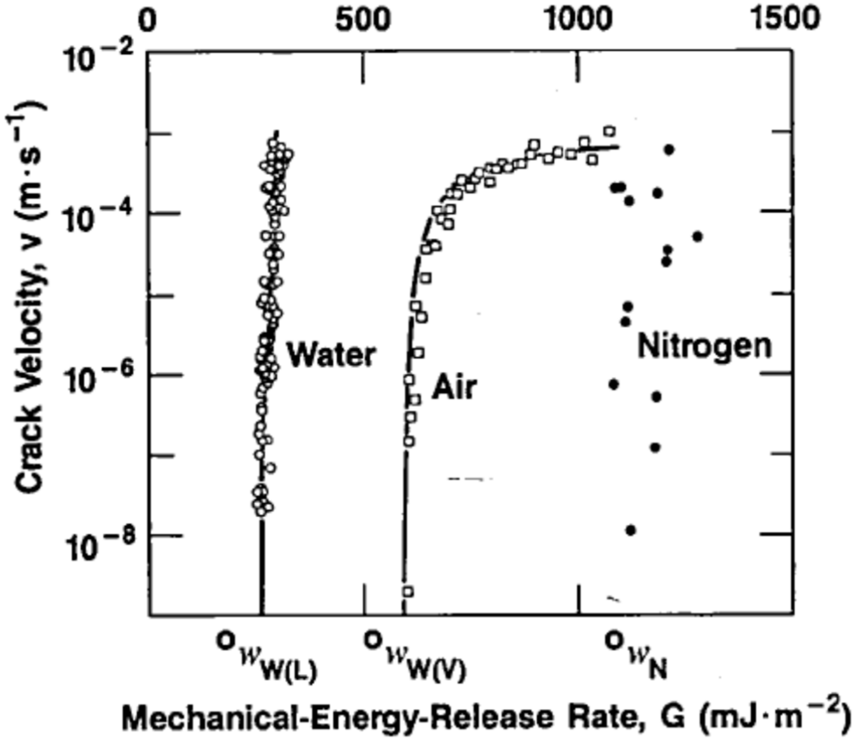


S.M. Wiederhorn et al., J. Mater. Sci. 17 pp.3460-3478 (1982).

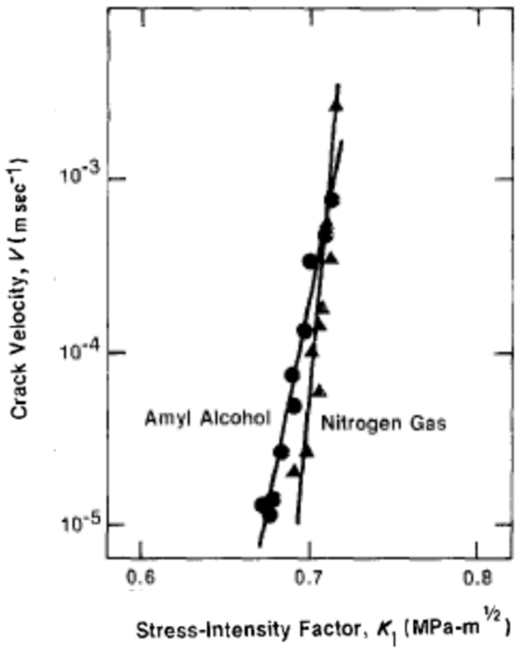
Water is the best

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

ADHERENCE



K.T. Wan et al.,J. Mater. Res. 5(1) (1990) 172



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

For bulk study:

Anhydrous atmosphere

=> Real fracture toughness

=> For bonding study:

Anhydrous atmosphere

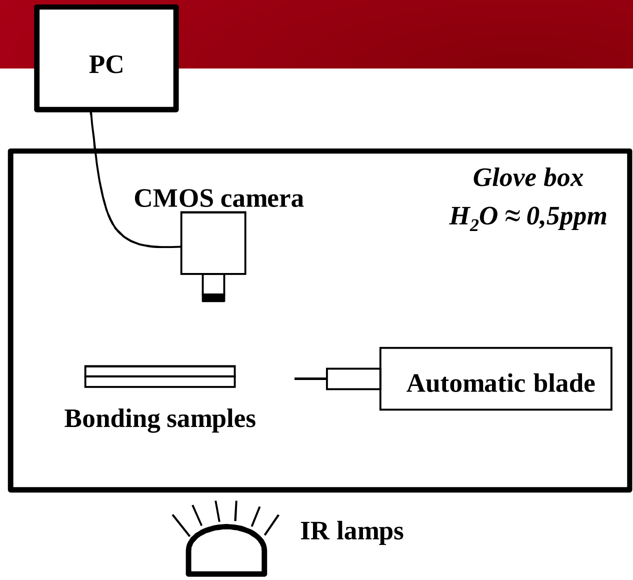
=> Real bonding energy.

ADHERENCE

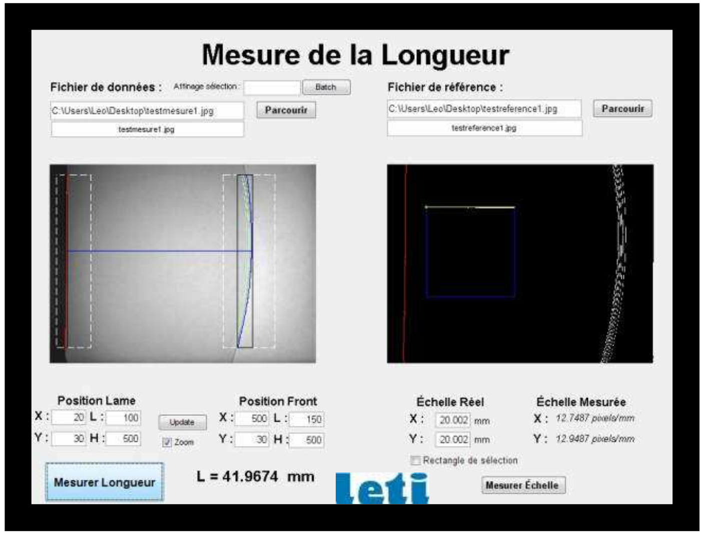
Setup:

Glove box with dessicator

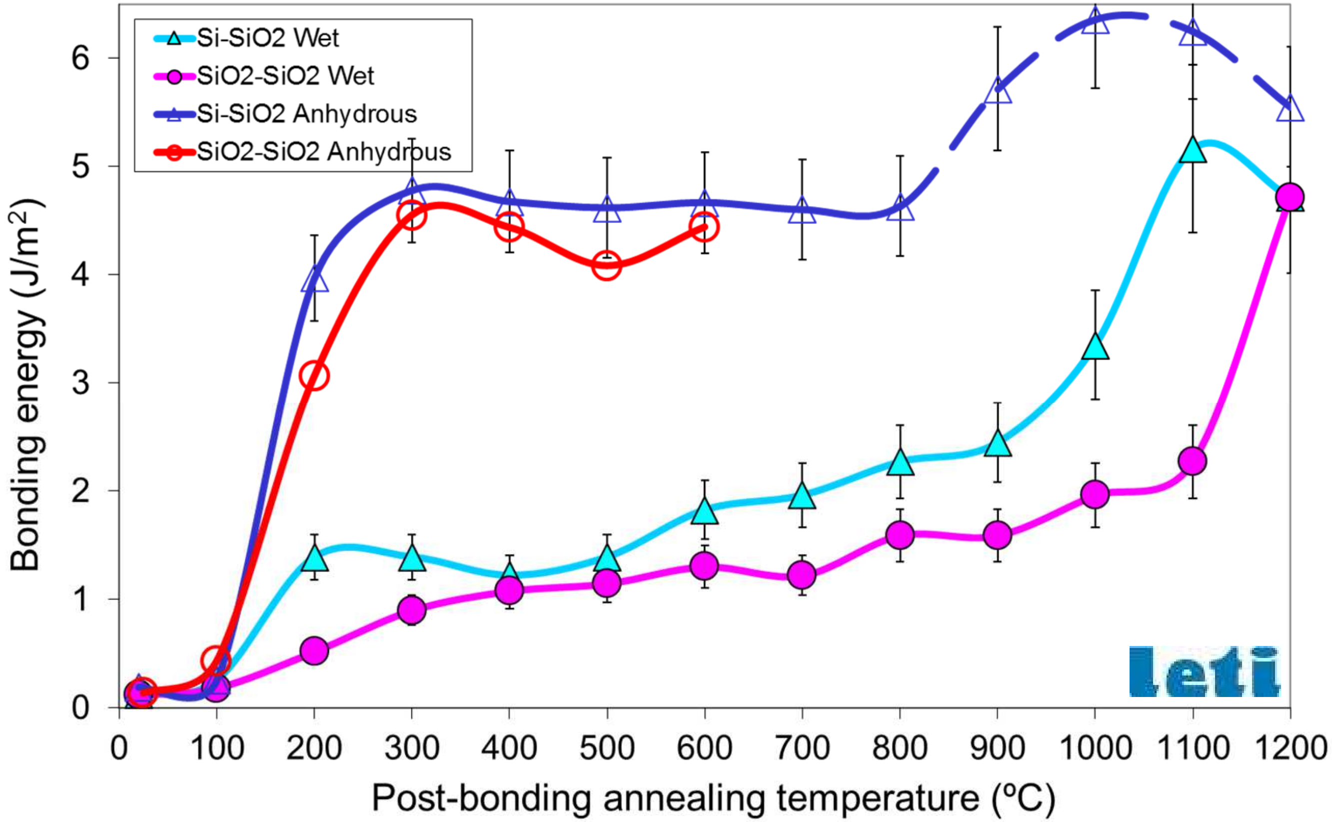
Automatic blade insertion



Video recording / processing homemade software



Standard hydrophilic bonding

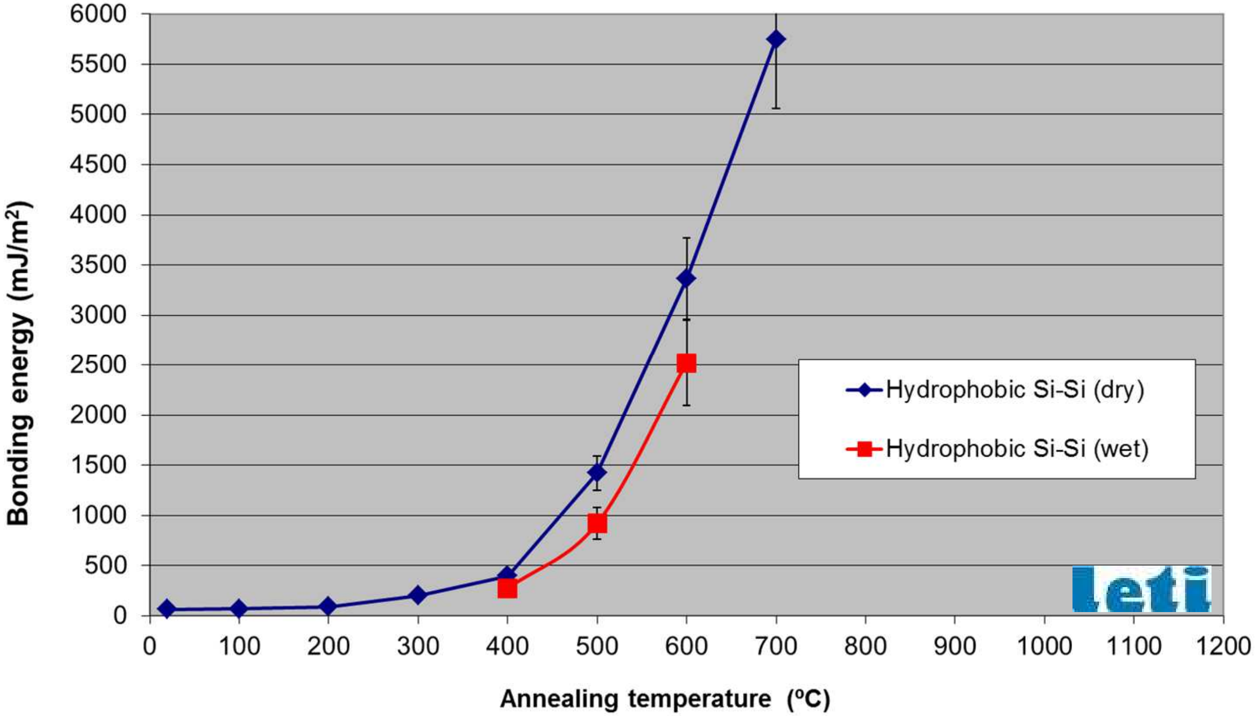


=> Anhydrous bonding energy is:

more «realistic»

more «discriminating» for mechanism understanding

Hydrophobic bonding:



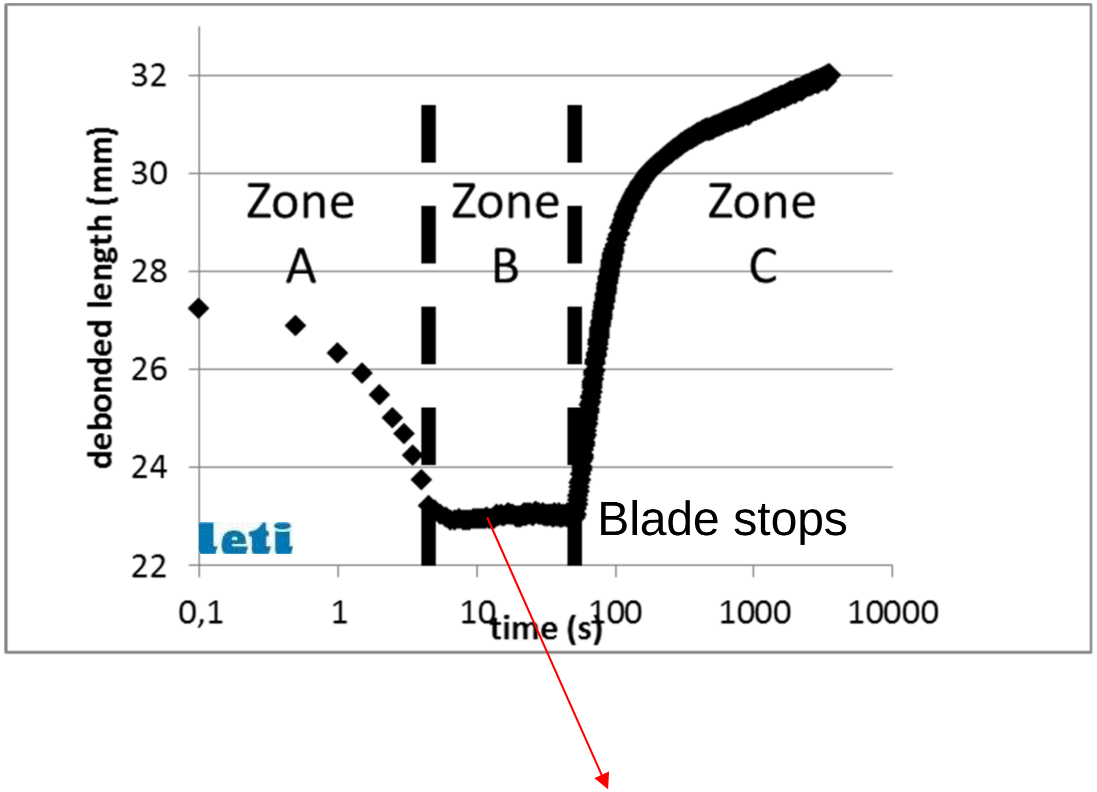
Si/Si Hydrophobic bonding is not sensitive to humidity

=> Comparison with hydrophilic bonding only with anhydrous measurement

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

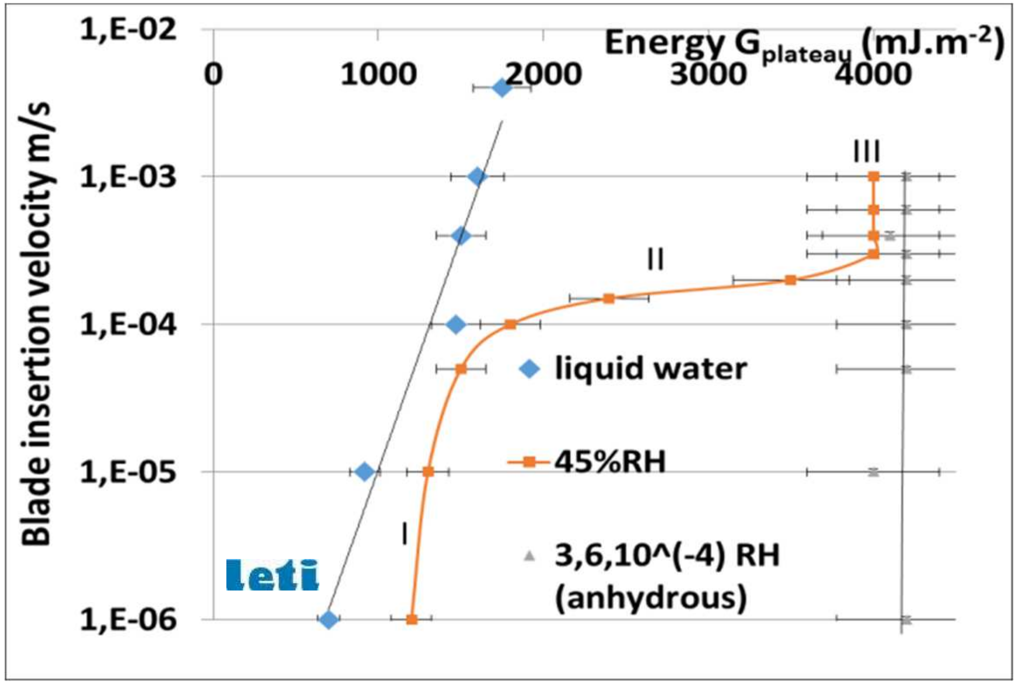
Dynamic bonding energy:

During constant blade movement (A and B) :



G”plateau”

Dynamic bonding energy:

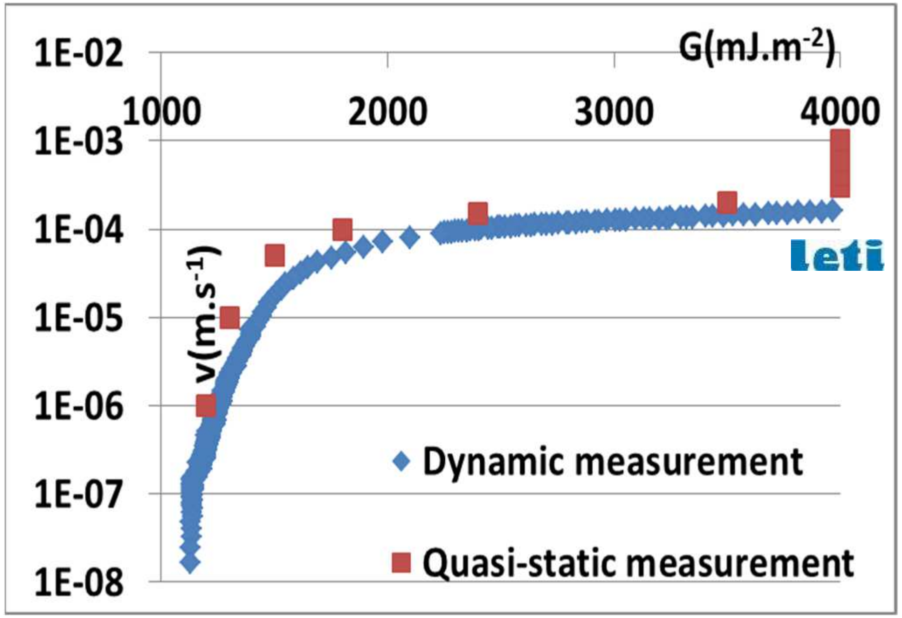


⇒ "Widerhorn" graphics

⇒ WSC is involve in DCB direct bonding mresurement

DIRECT BONDING ENERGY

Dynamic bonding energy:



⇒ Quasi-static is very interesting to have the WSC threshold

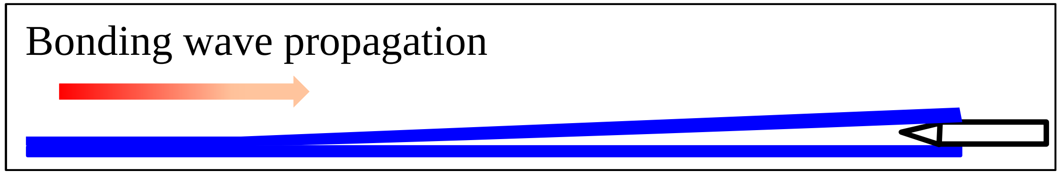
Direct bonding

- Silicon & Silicon dioxide
  - Small digest of static mechanism
  - Adhesion and Adherence
  - Physicochemical Mechanism
  - Interface water edge diffusion
- Direct bonding of others materials
  - Copper/Copper
  - Hybrid Copper/Silicon dioxide
- Direct bonding LETI applications

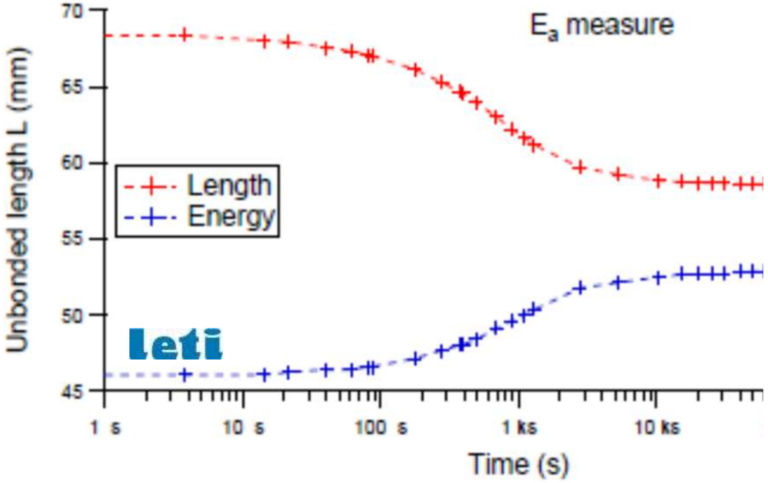
MECHANISM

Adhesion energy measurement:

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



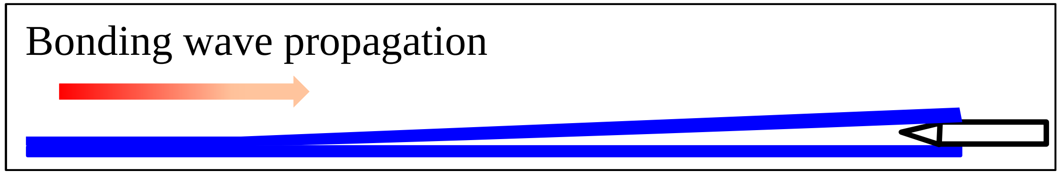
- ✓ Unbounded length
- ✓ El-Zein equation => Adhesion energy



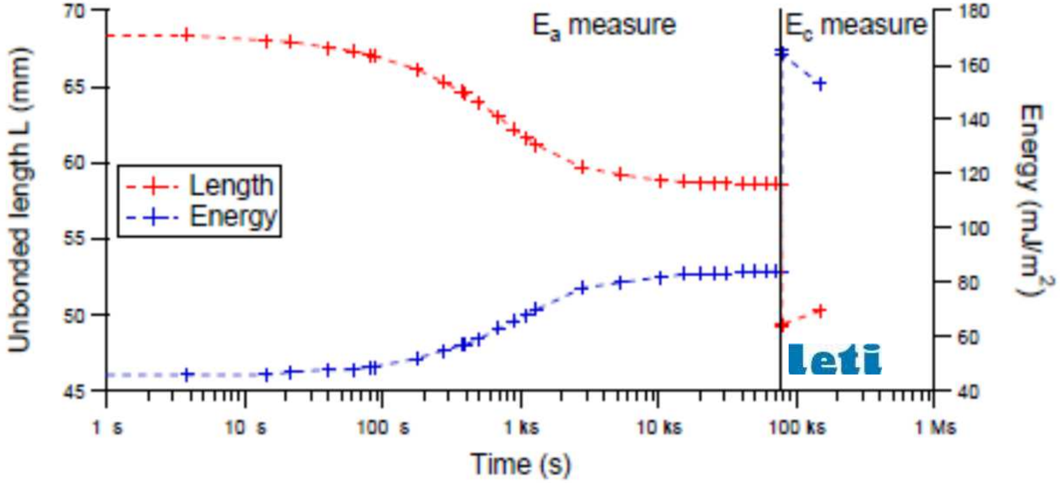
D. Radisson, phd, Université Grenoble Alpes, 2014.

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

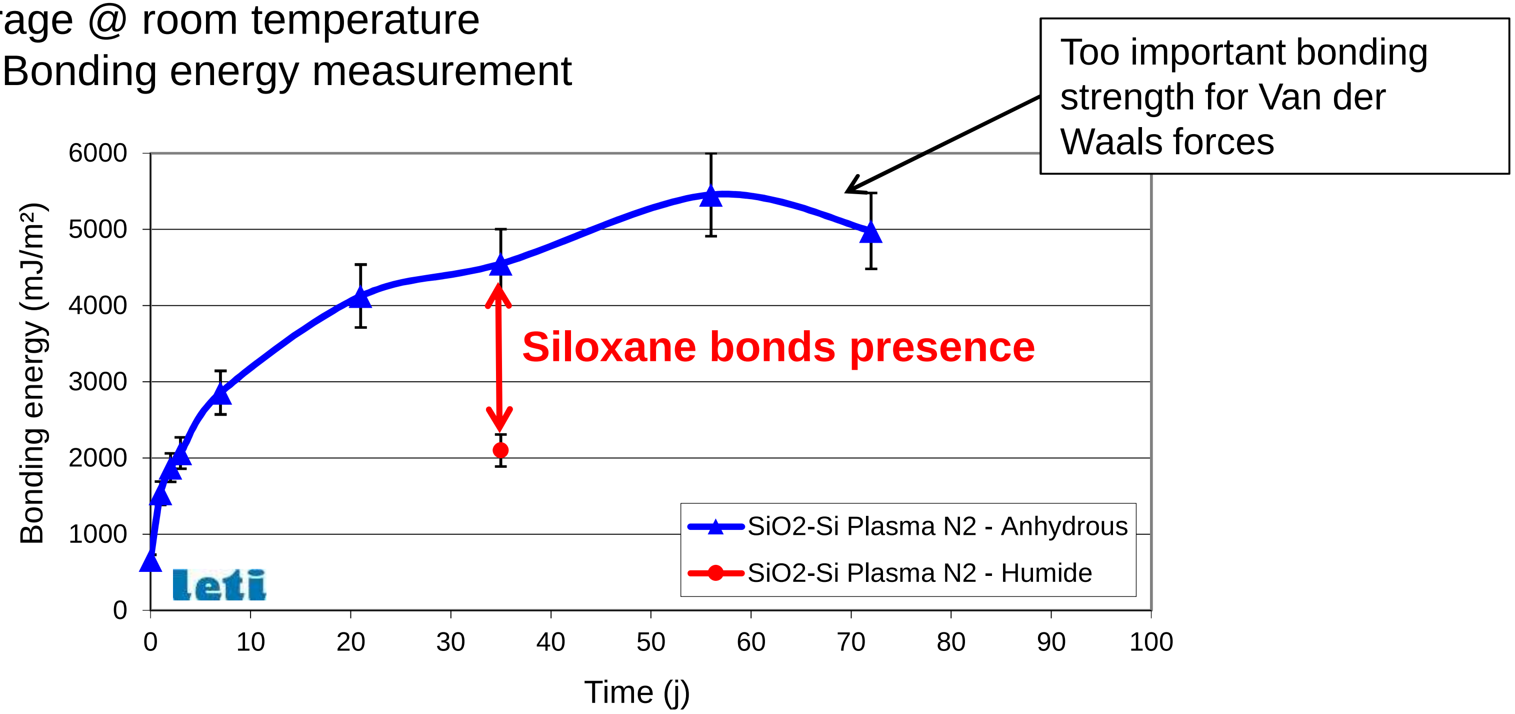
=> Bonding energy > Adhesion energy

Siloxane bonds presence @RT for chemical bonding

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

WSC and covalent bonding at room temperature:

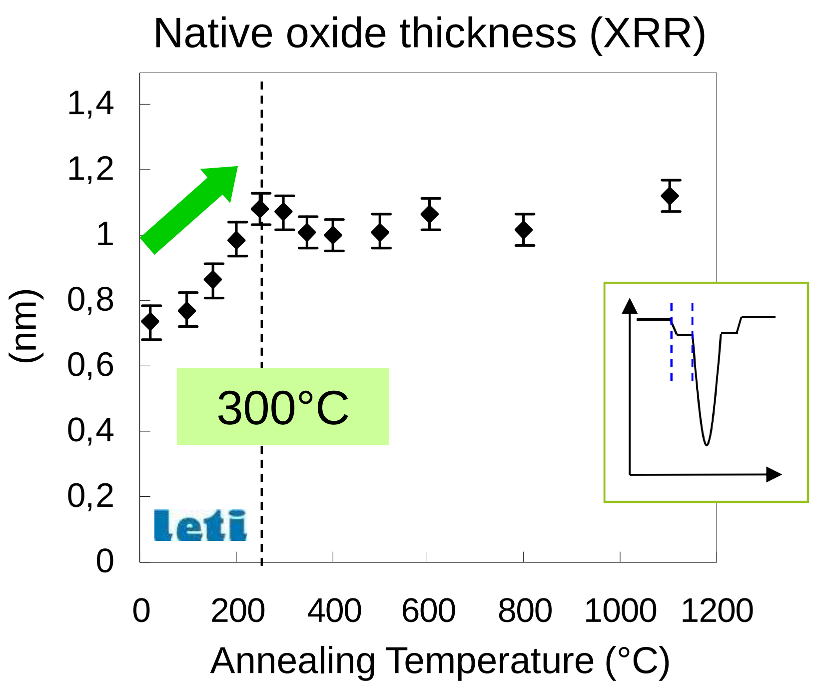
N2 plasma Si/SiO2 direct bonding
Storage @ room temperature
Bonding energy measurement

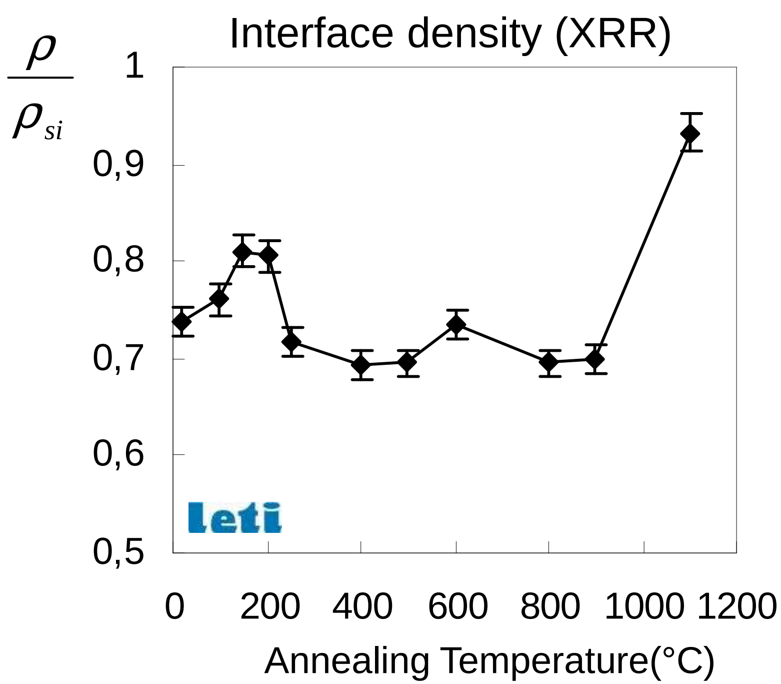


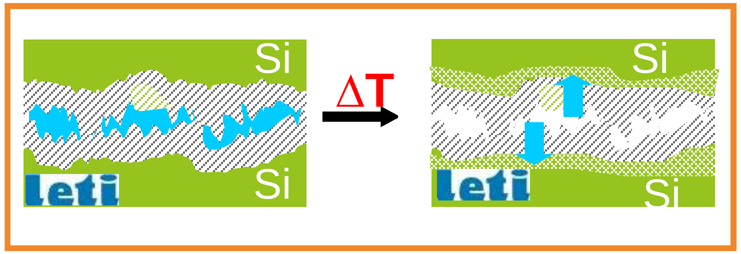
- **Siloxane bonds can thermodynamically appear at room temperature**
- **Mixt of Van Der Waals and Siloxane @RT but Siloxane hardly visible!**
  - ***Too few contact point?***
  - ***Trapped water which induce internal WSC?***

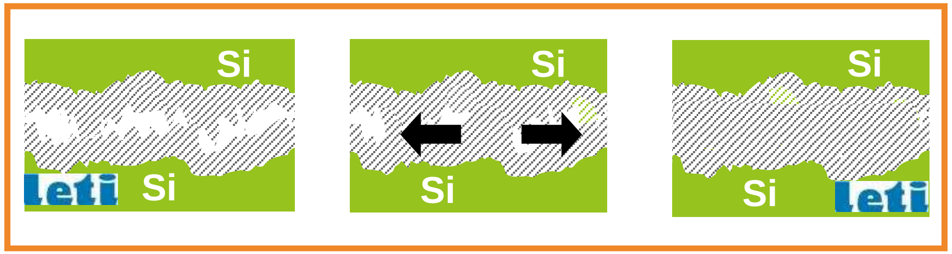
**F. Fournel, et al., ECS Trans. 64, 121 (2014).*

Si-Si hydrophilic bonding







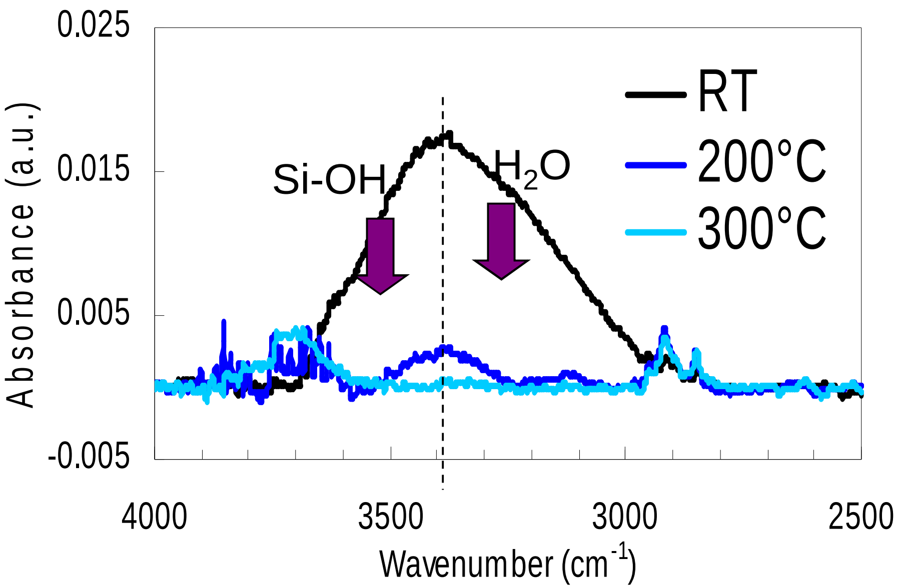


C. Ventosa et al., J. Appl. Phys. 104, 123524 (2008)
C. Ventosa PhD, Collaboration with DSM-INAC

MECHANISM

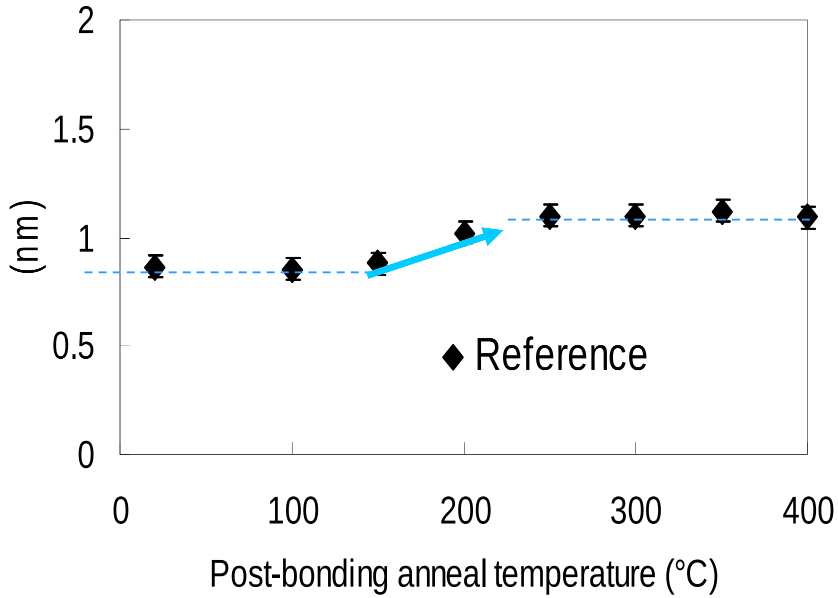
Si-Si hydrophilic bonding

FTIR-MIR: O-H absorption band

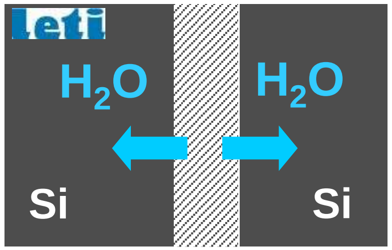


✓ Disappearing of the O-H band at 200°C and 300°C post-bonding anneal

XRR: oxide film thickness



✓Increase of oxide film thickness



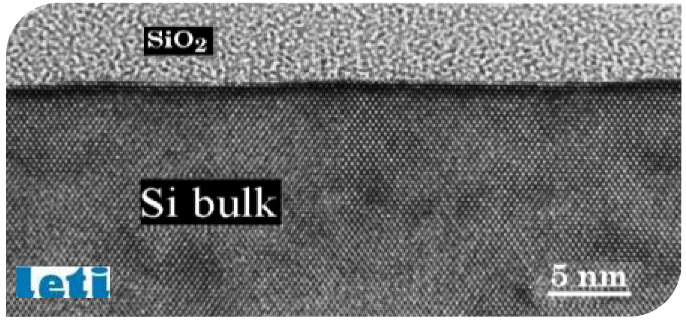
Si-Si

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

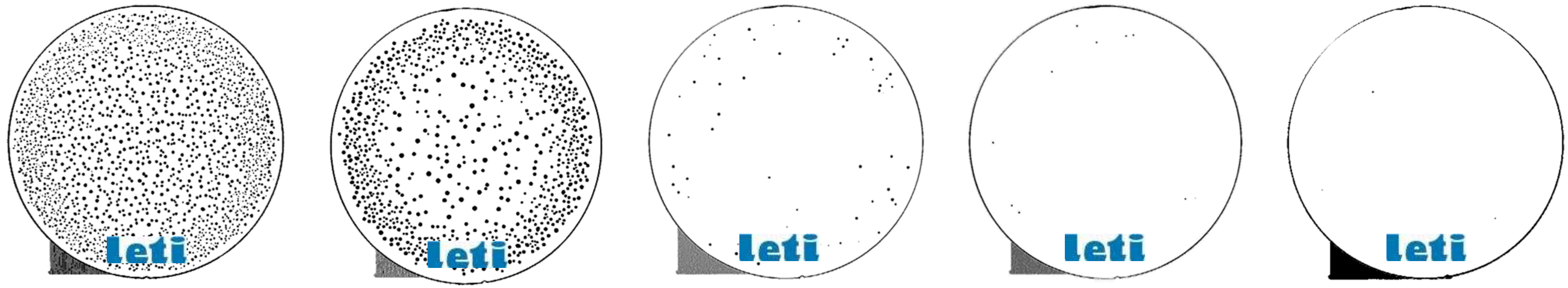
Main source of voids at the bonding interface

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!

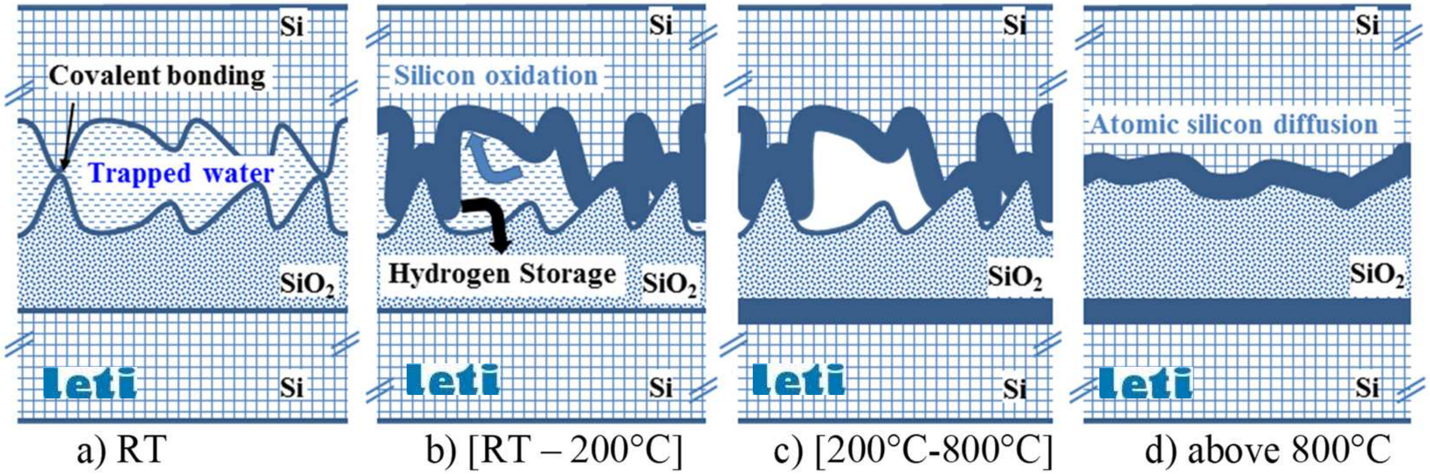


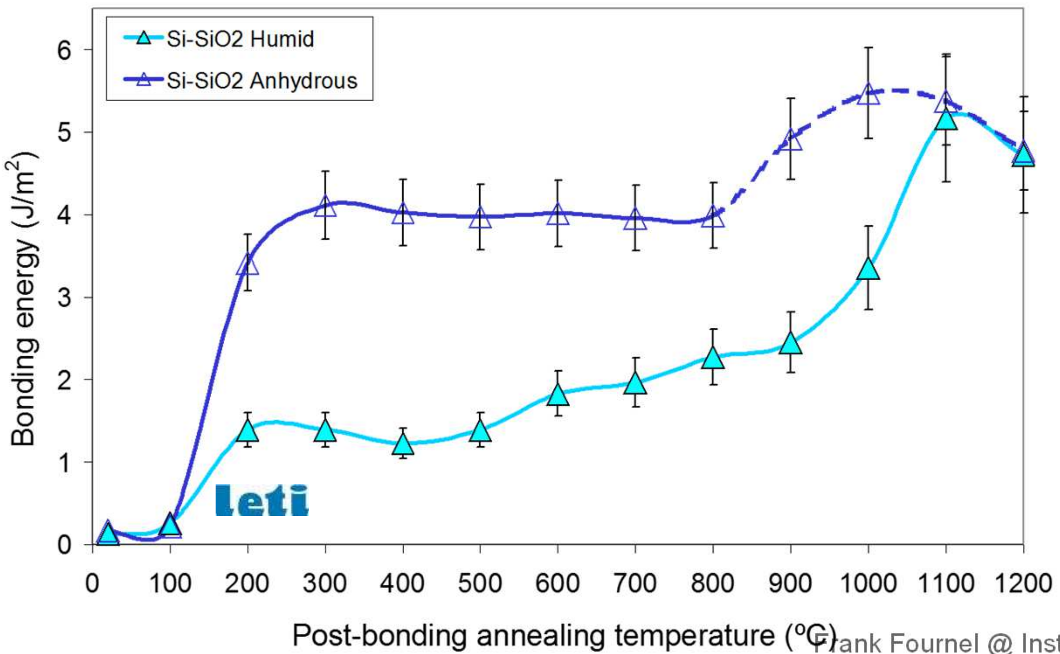
Si/Si | Si/SiO_2 12nm | Si/SiO_2 25nm | Si/SiO_2 **50nm** | Si/SiO_2 100nm

This bonding type is really depending of the last cleaning step

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

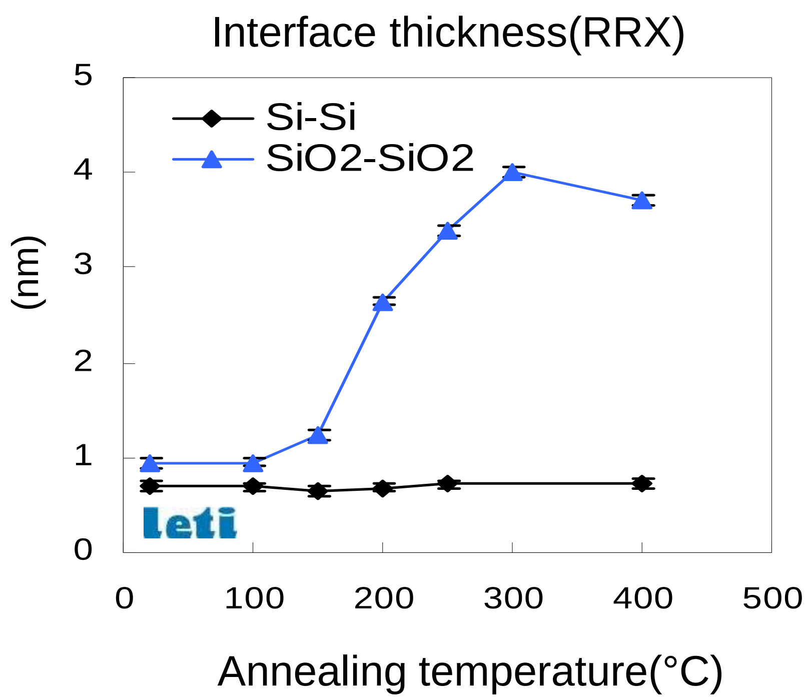
SI/SIO2 BONDING MECHANISM

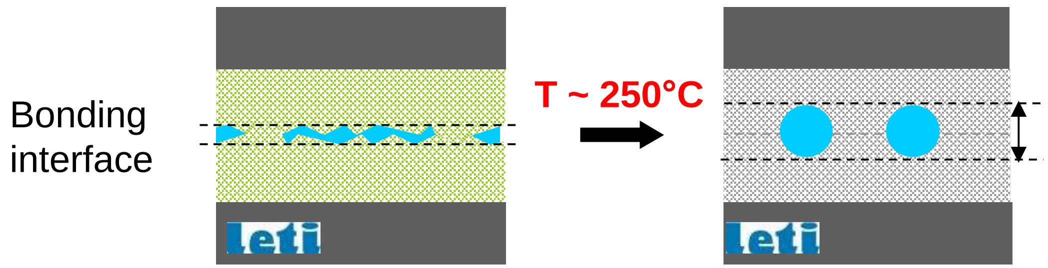




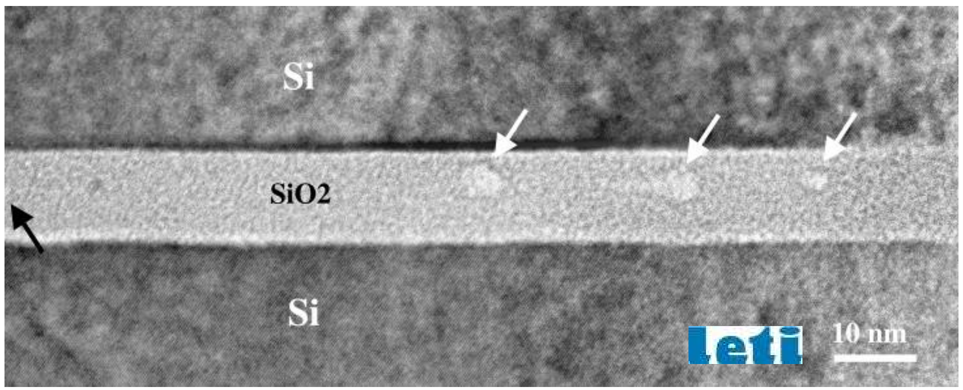
*F. Fournel, el al., ECS J. Solid State Sci. Technol. 4, P124 (2015).

SiO_2-SiO_2 hydrophilic bonding





TEM : LETI/DPTS



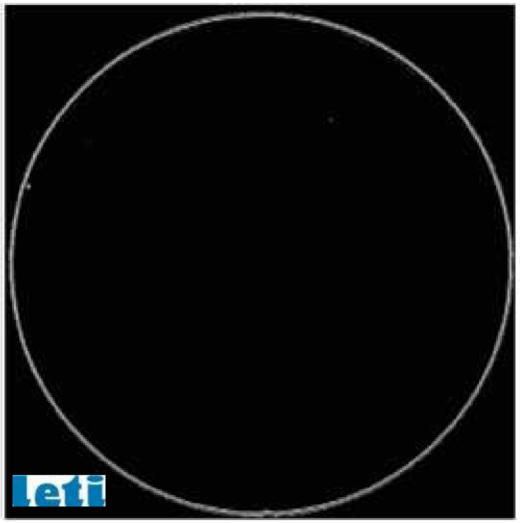
➢ **Oxyde layer is a water barrier layer**

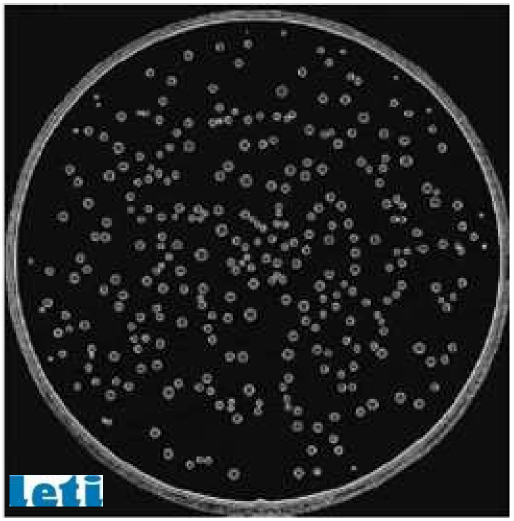
C. Ventosa et al., Electrochemical and Solid State Letters, 12 (10) H373-H375 (2009)

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.

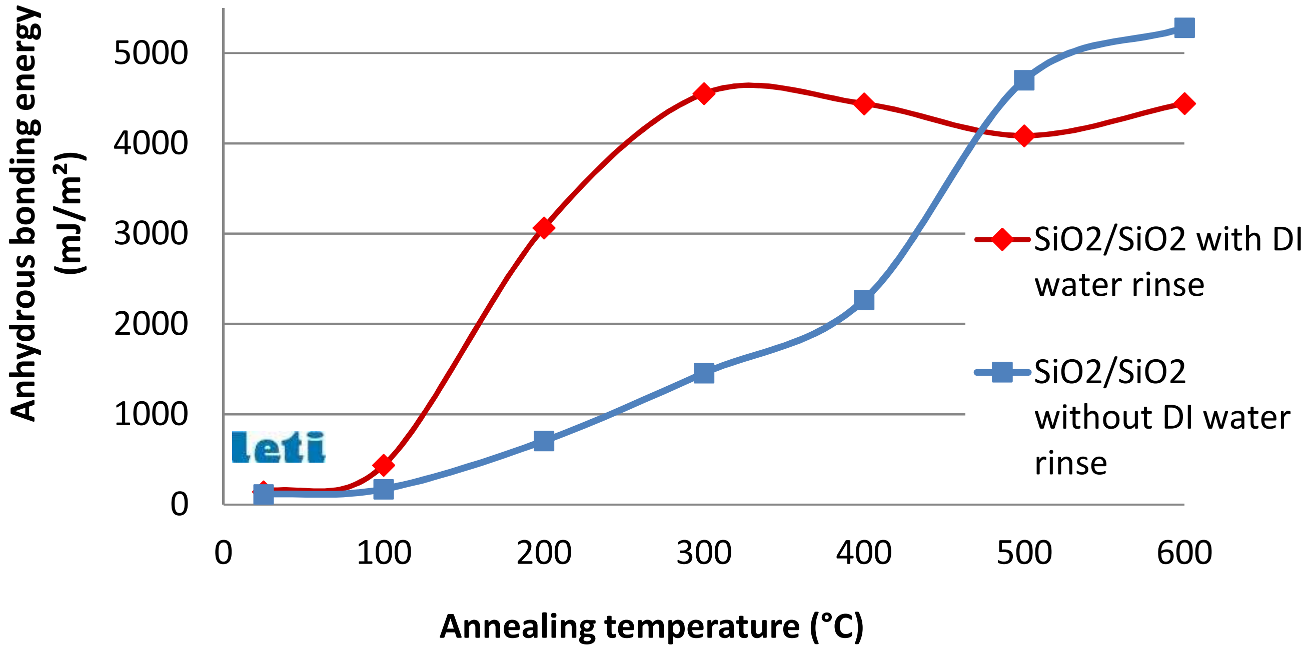
MECHANISM

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)

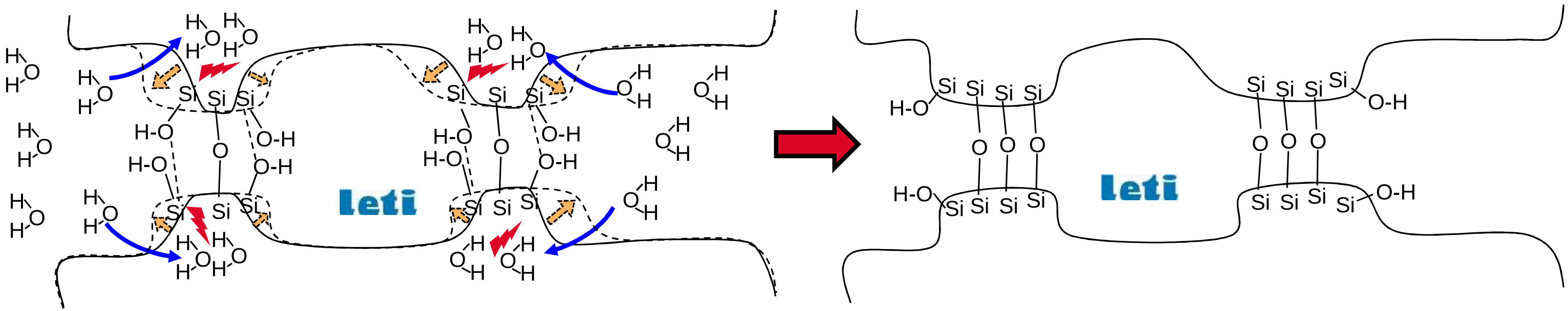
❑ ***Silica hydrolysation during annealing:***

$t_{bonding}$ $t_{annealing}$
Bonding => annealing => DCB

- @ RT few silanol bonds
- **With temperature** : water penetration inside SiO_2 asperity ( )
- Silica hydrolysation inside asperity ( )
- Asperity broadening ( )
- New covalent bonds formation (---)

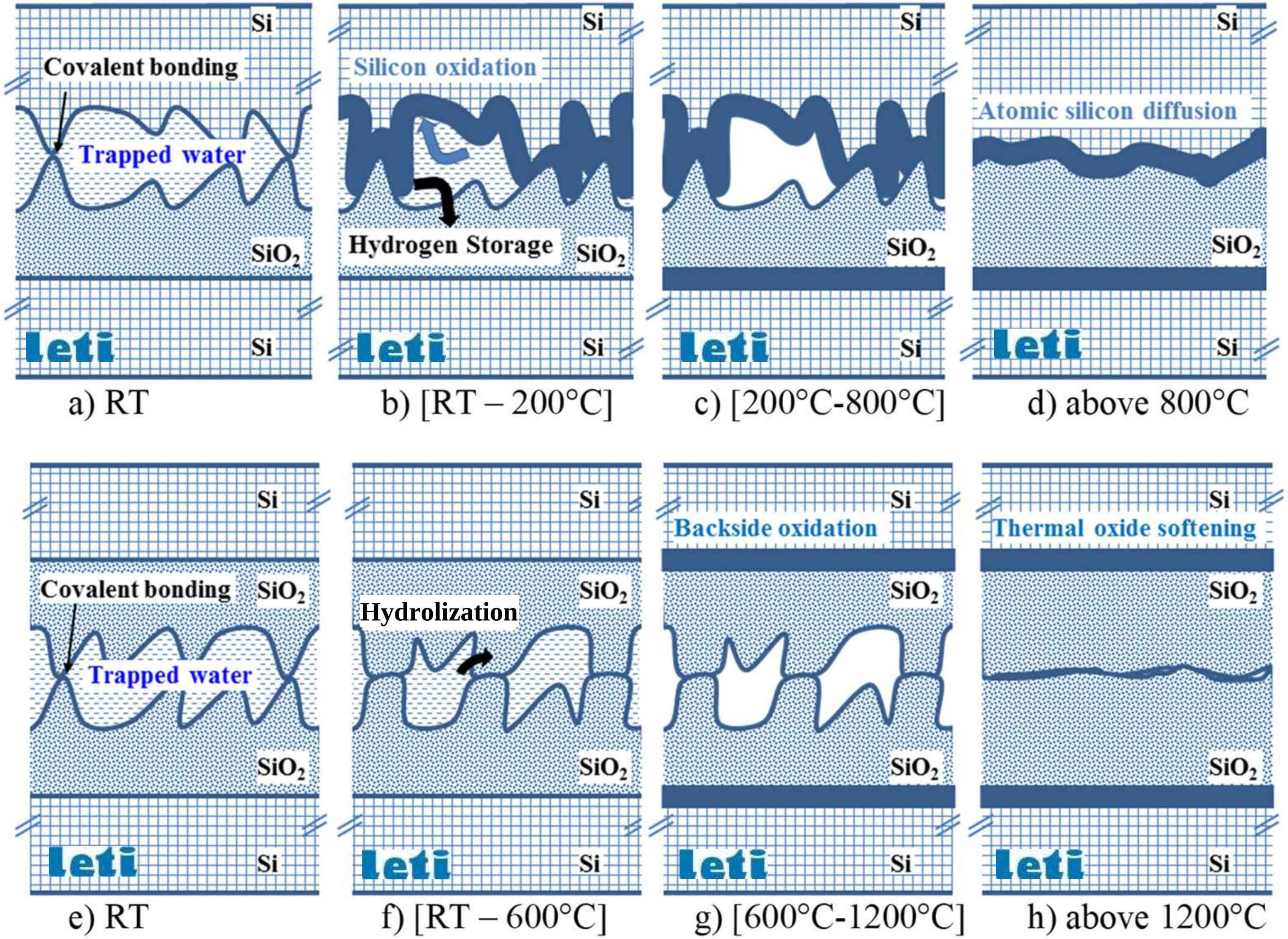
⇒ More important contact area with covalent bonds

=> More important bonding energy



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

SI/SIO2 AND SIO2/SIO2 BONDING MECHANISM



⇒ Water is an adherence promoter.

⇒ Water is important but… not too much (deposited oxide drying)

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

Direct bonding

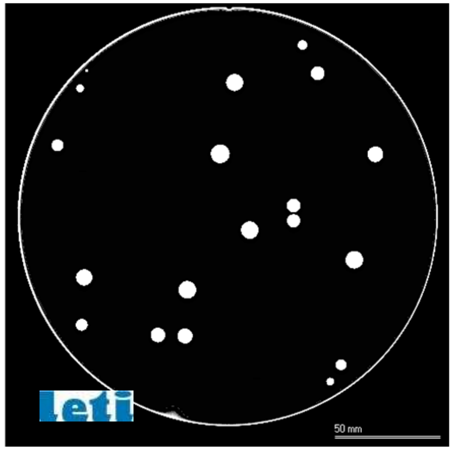
- Silicon & Silicon dioxide
  - Small digest of static mechanism
  - Some Characterization technics
  - Adhesion and Adherence
  - Physicochemical Mechanism
  - Interface water edge diffusion
- Heterostructure
- Direct bonding of others materials
  - Copper/Copper
  - Hybrid Copper/Silicon dioxide

INTERFACE WATER EDGE DIFFUSION

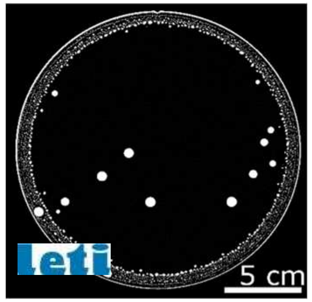
Evidence of water diffusion at direct bonding interface* :

Si/Si direct bonding → Storage (x hours) → Annealing (300°C) → SAM

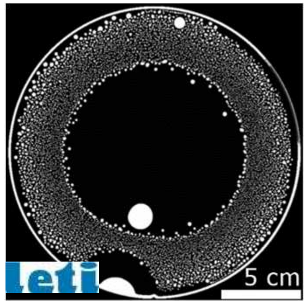
Si/Si direct bonding → Annealing (300°C) → SAM



x=4h

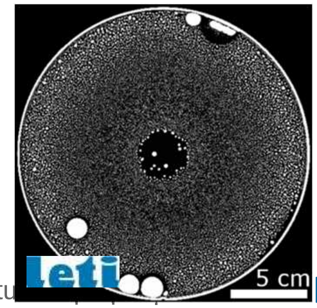


x=72h



⇒ **Water can diffuse at the bonding interface**

x=260h



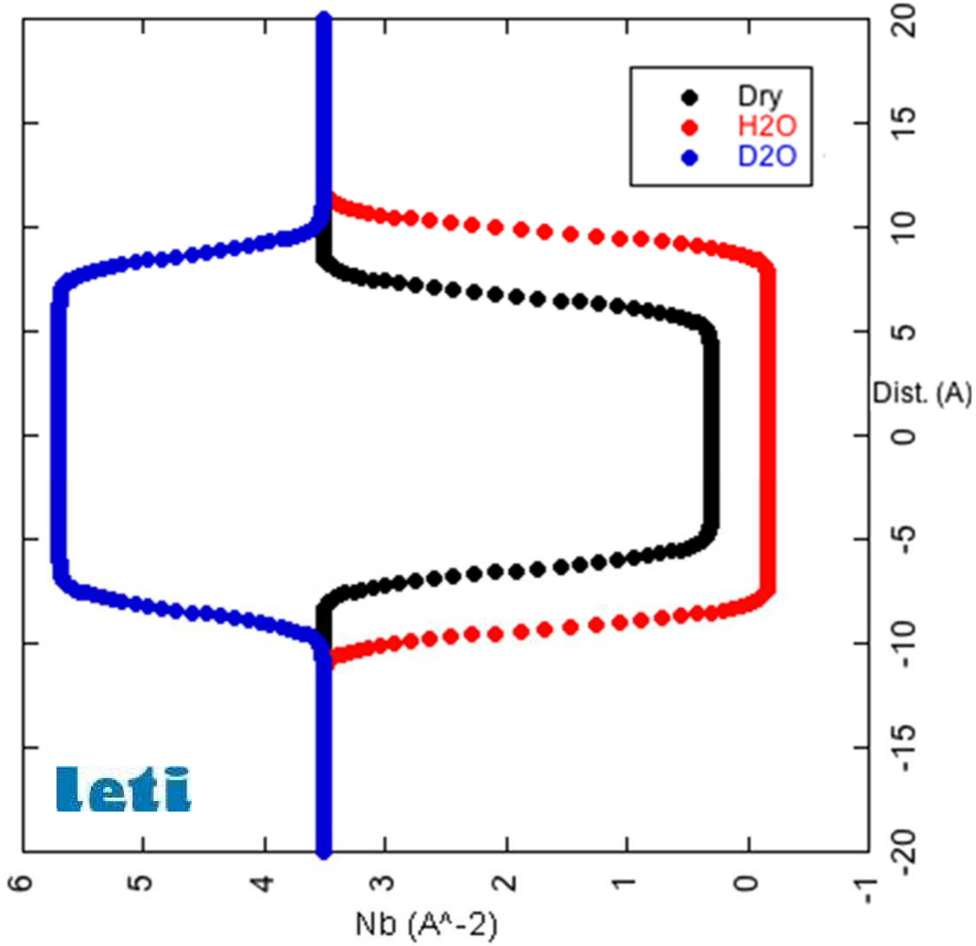
**M. Tedjini et al., Applied Physics Letters 109, 111603 (2016).*

INTERFACE WATER EDGE DIFFUSION

Three non annealed structure:

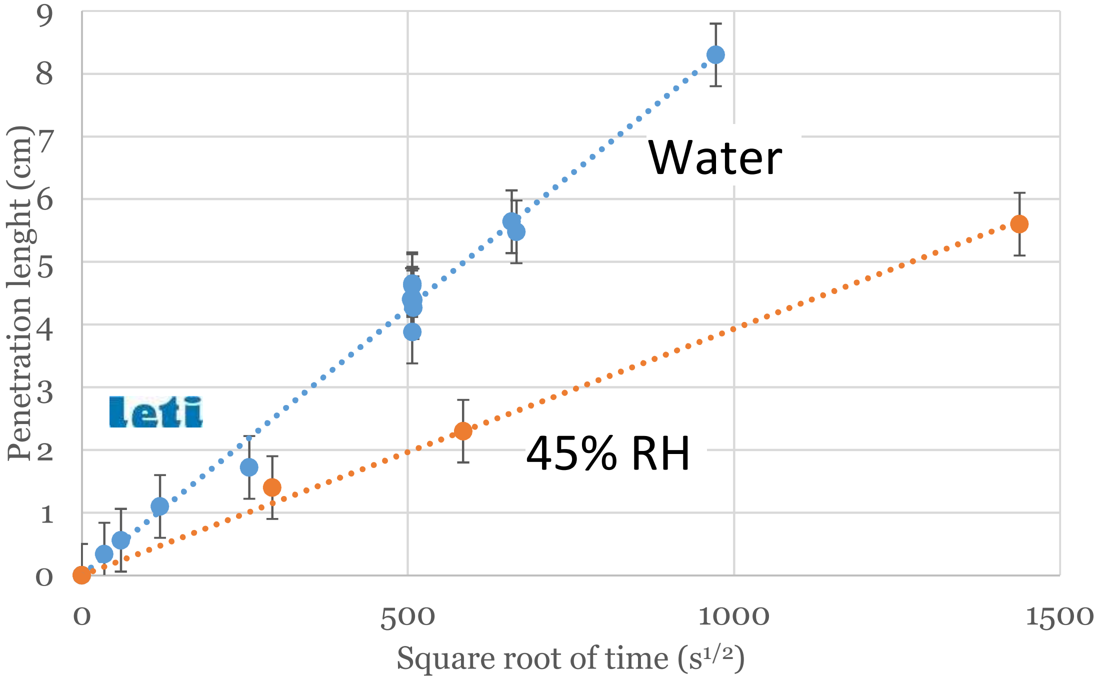
- Dry
- H_2O imbibition
- D_2O imbibition

Neutron reflectivity is very sensitive to the H2O and D2O difference



M. Tedjini Phd, Université de Grenoble (2017).

INTERFACE WATER EDGE DIFFUSION



Square law :

$$l^2 = A\,t$$

$$A_{eau} = 7,2\ 10^{-9} \pm 10^{-9}\ \ m^2.s^{-1}$$

$$A_{45\%RH} = 3,9\ 10^{-9} \pm 10^{-9}\ \ m^2.s^{-1}$$

$$A_{eau} \approx 2\ A_{45\%RH}$$

1 days :

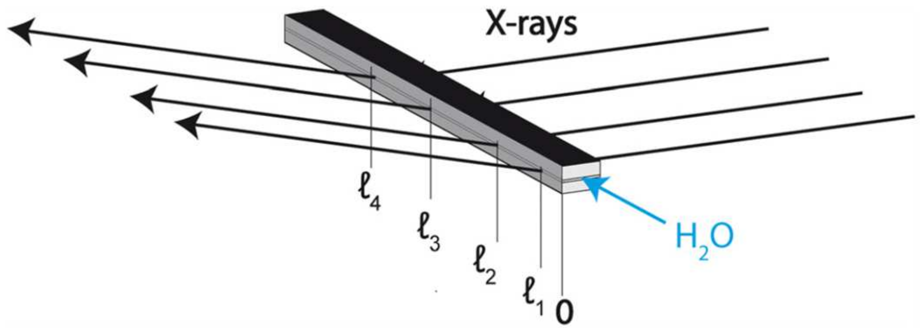
- 1cm in air (45%RH)
- 2.5 cm in water

10 cm (full 200mm wafer):

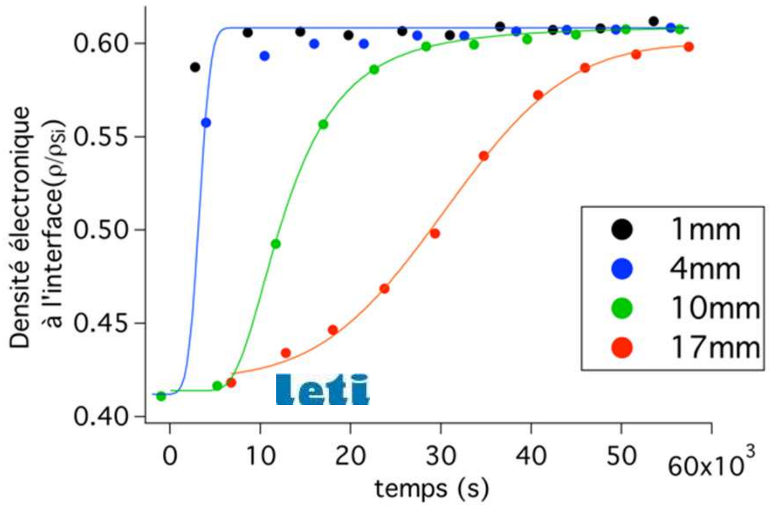
- 30 days in air (45%RH)
- 16 days in water

**M. Tedjini Phd, Université de Grenoble (2017).*

INTERFACE WATER EDGE DIFFUSION



- **Dry isolated beam**
- **Isolatation removal (t=0)**
- **Measurement along the beam and regarding the time**



$$l^2 = A\,t$$

$$A_{ESRF} = 9\;10^{-9} \pm 10^{-9}\;m^2.s^{-1}$$

$$A_{SAM} = 7,2\;10^{-9} \pm 10^{-9}\;m^2.s^{-1}$$

Water before imbibition:

- 1.6 ML in « dry » bonding (0.8 ML on each side)
- Imbibition add 1.8 ML

M. Tedjini Phd, Université de Grenoble (2017).

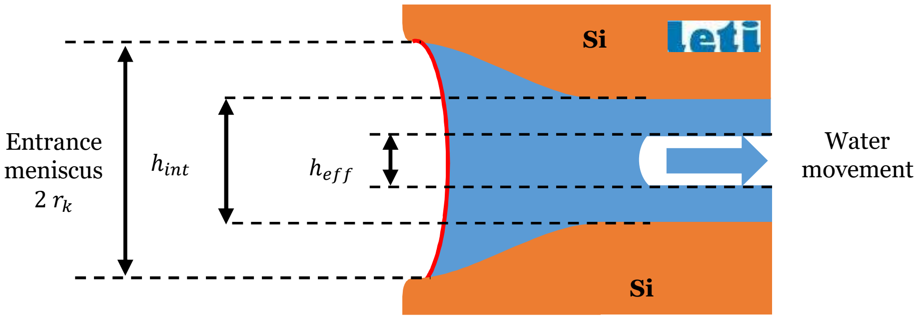
In total : water 3.4 ML ⇔ 1 nm of thickness ☺

INTERFACE WATER EDGE DIFFUSION

Capillarity

Hydrophilicity is the key parameter

Water front well defined



$$r_k = \frac{\gamma}{ln(RH)\rho k_B T}$$

$$l^2 = A\,t$$

$$A = \frac{1}{3}\gamma\,cos(\theta)\left(\frac{1}{h_{int}} - \frac{1}{2|r_k|}\right)\frac{{h_{eff}}^2}{\mu}$$

*M. Tedjini Phd, Université de Grenoble (2017).

Diffusion

- **Concentration gradient is the key parameter**
- **No well defined water front**

$$\frac{\partial N}{\partial t} = \frac{\gamma \cos(\theta)}{3\mu} r \frac{1}{N_0}\frac{\partial}{\partial x}\left(N\frac{\partial N}{\partial x}\right)$$

=> Porous diffusion equation

Numerical simulation are needed

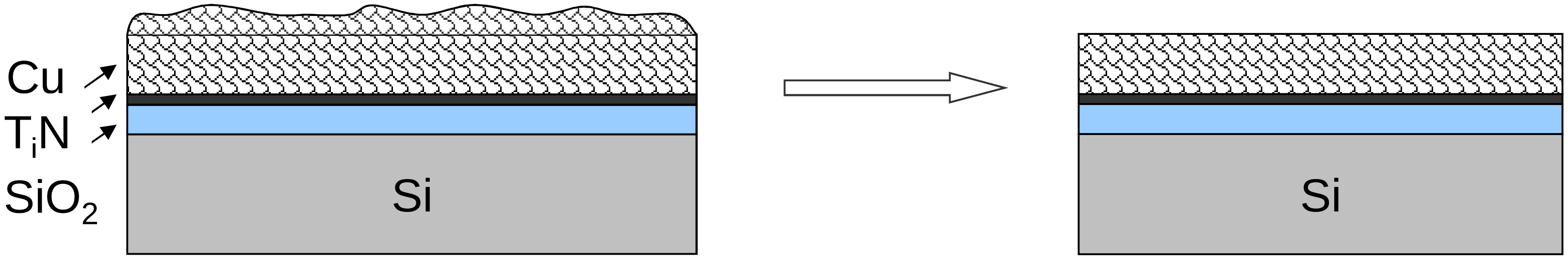
Direct bonding

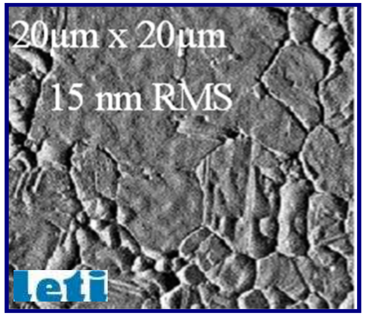
- Silicon & Silicon dioxide
  - Small digest of static mechanism
  - Adhesion and Adherence
  - Physicochemical Mechanism
  - Interface water edge diffusion
- Direct bonding of others materials
  - Copper/Copper
  - Hybrid Copper/Silicon dioxide
- Direct bonding LETI applications

COPPER METAL DIRECT BONDING

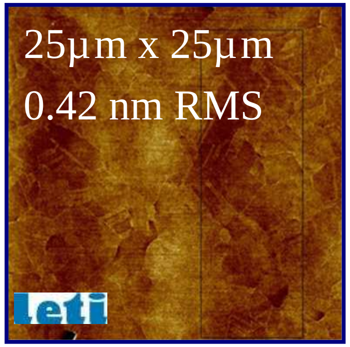
Cu/Cu direct bonding

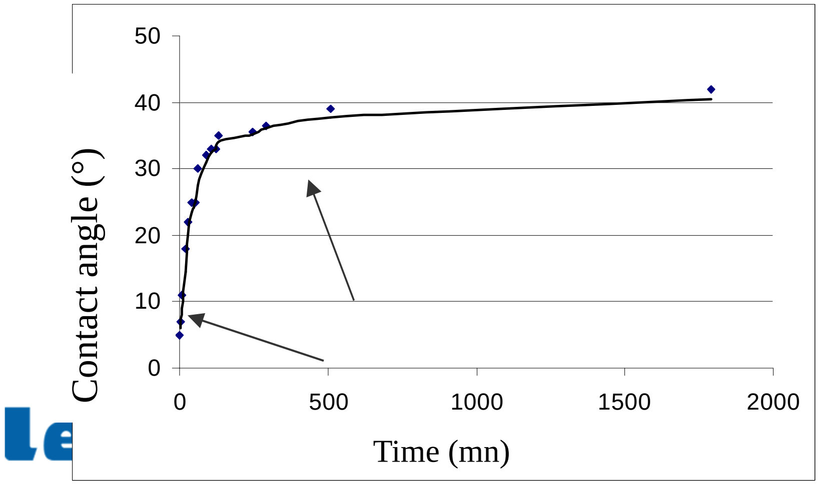
L. Di Cioccio et al. *ECS (2010)*

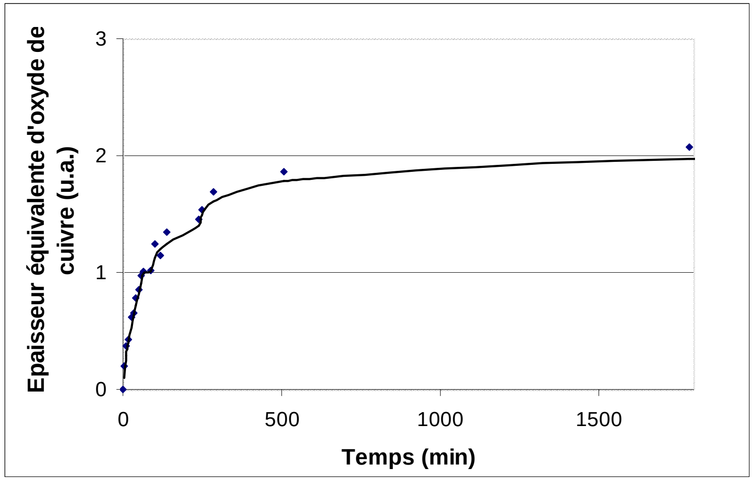




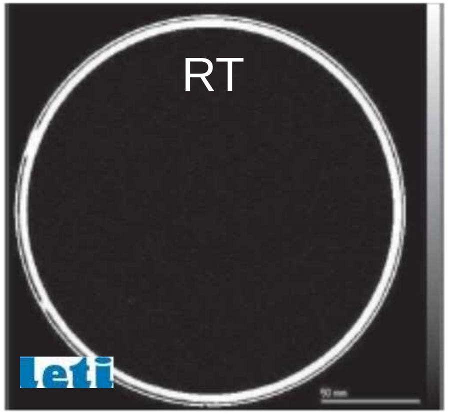
- **Bonding within 1 hour after the surface preparation**
  - **Contact angle < 20°**
  - **Reduced oxide thickness**

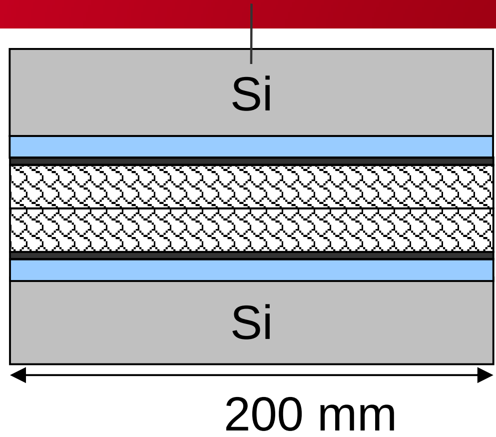


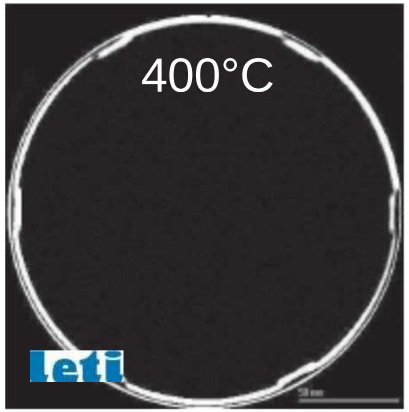




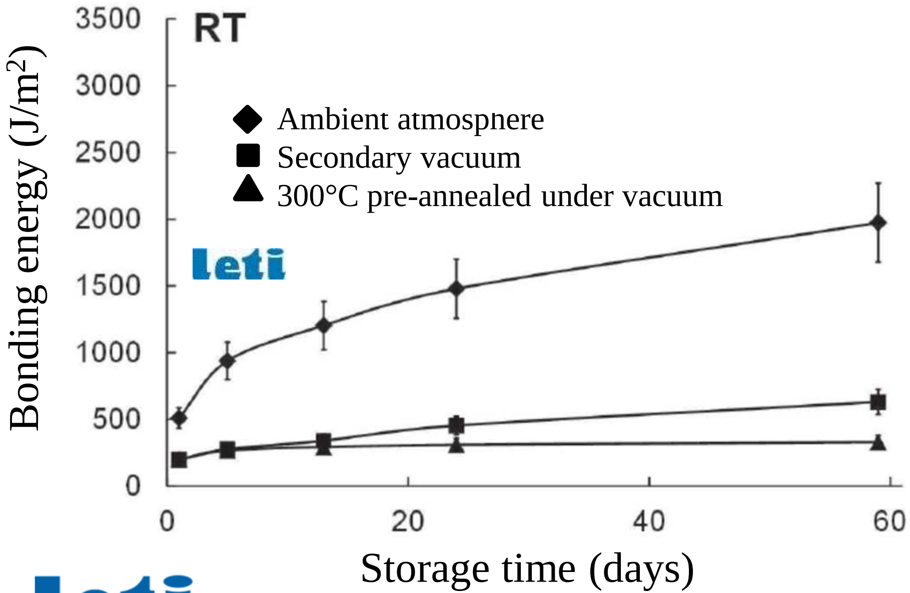
COPPER METAL DIRECT BONDING



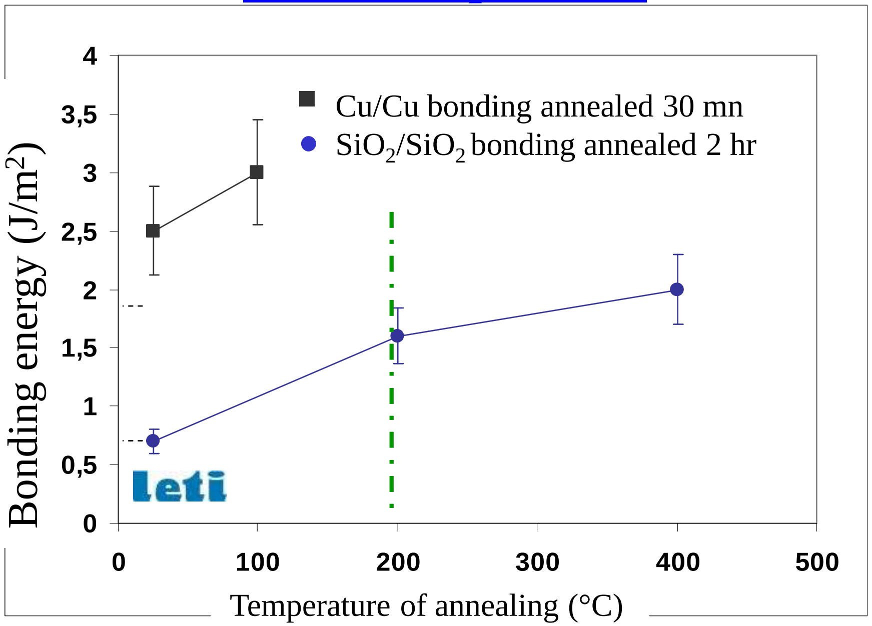




Evolution of bonding energy with storage time

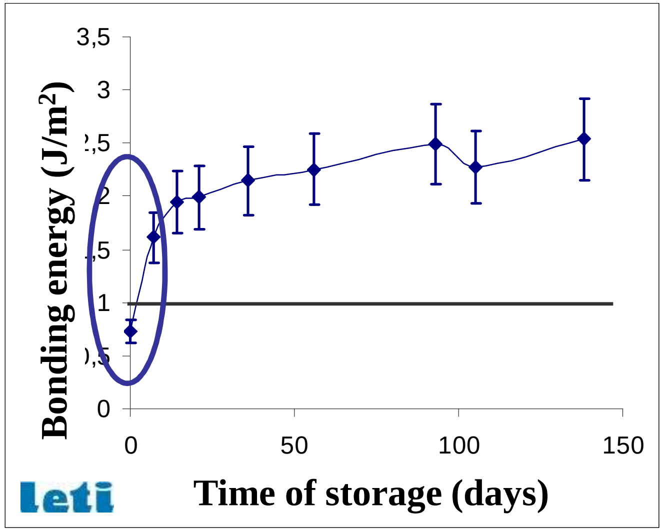


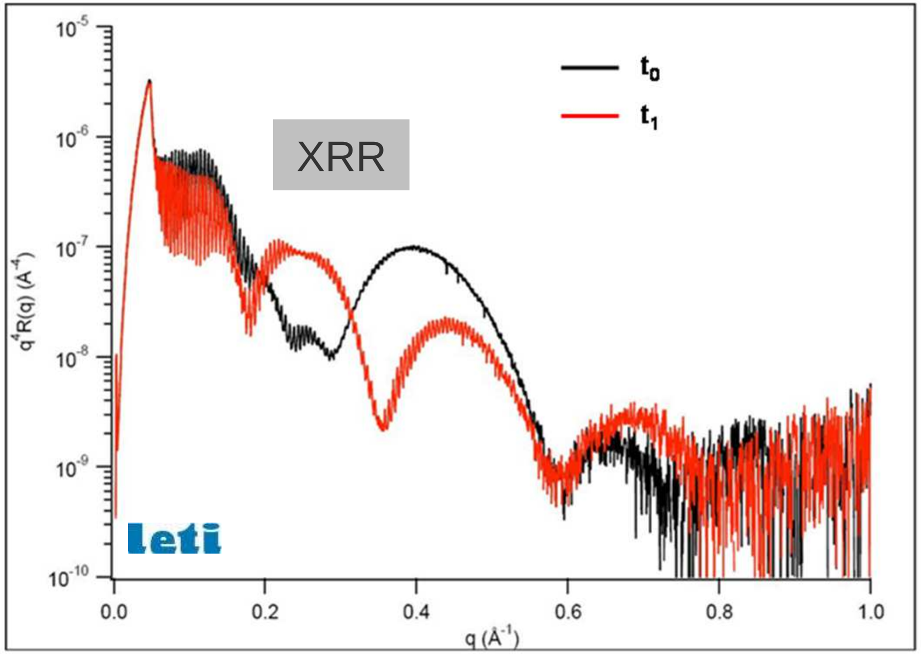
Evolution of bonding energy with anneal temperature

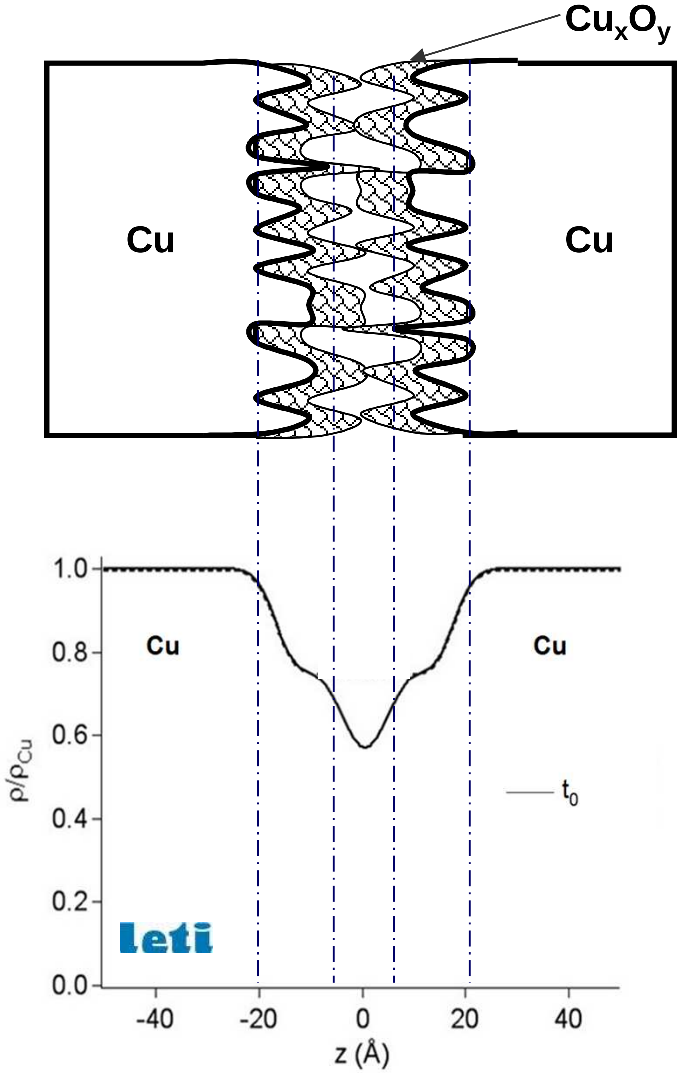


P. Gueguen et al IITC , Proc. p 61 (2008)

COPPER METAL DIRECT BONDING

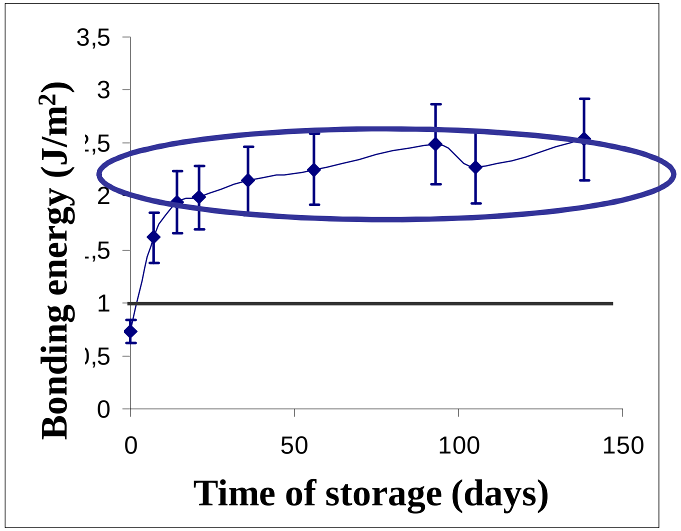


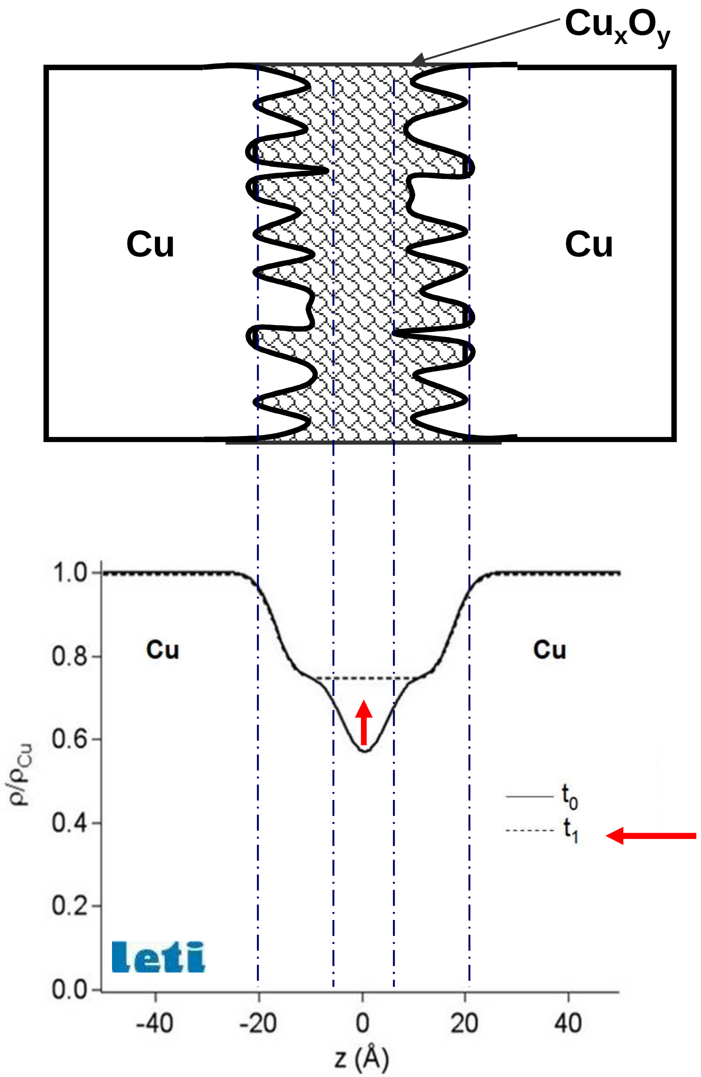




P. Gueguen et al IITC , Proc. p 61 (2008)

COPPER METAL DIRECT BONDING

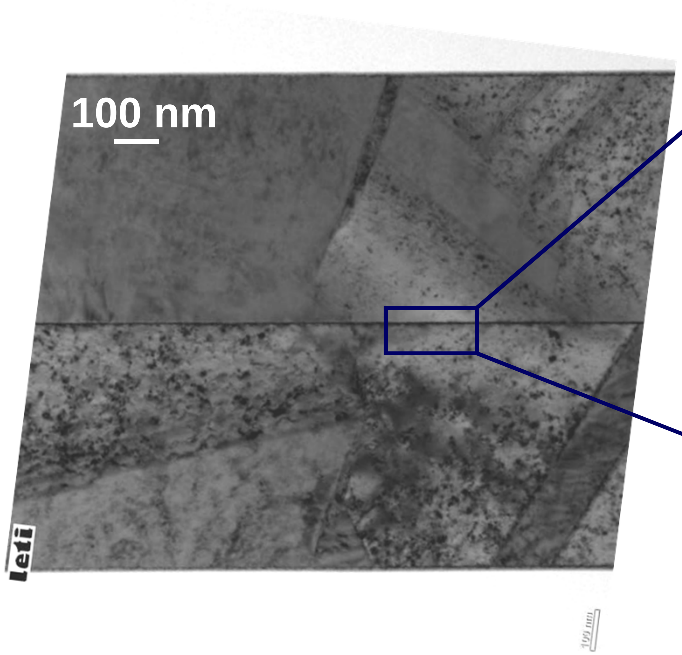


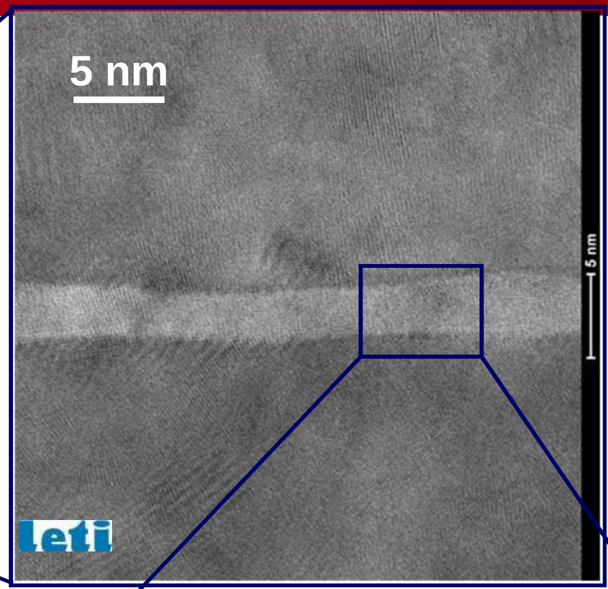


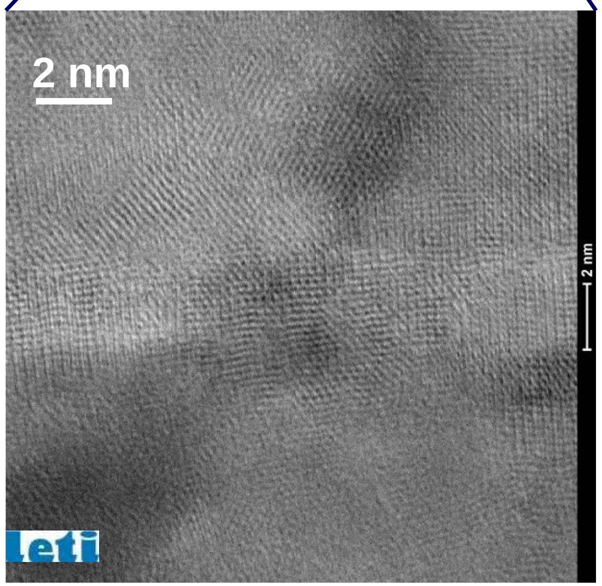
- **Bonding is filled with a material with an electronic density lower than the one of copper**
- **Interface width of 4 nm**

P. Gueguen et al IITC , Proc. p 61 (2008)

COPPER METAL DIRECT BONDING



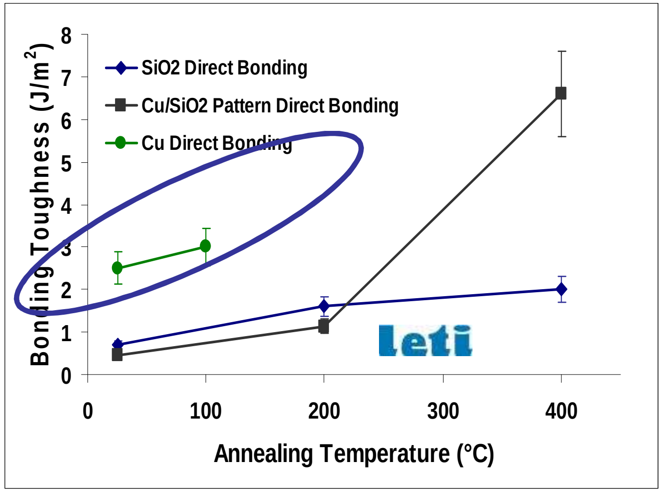


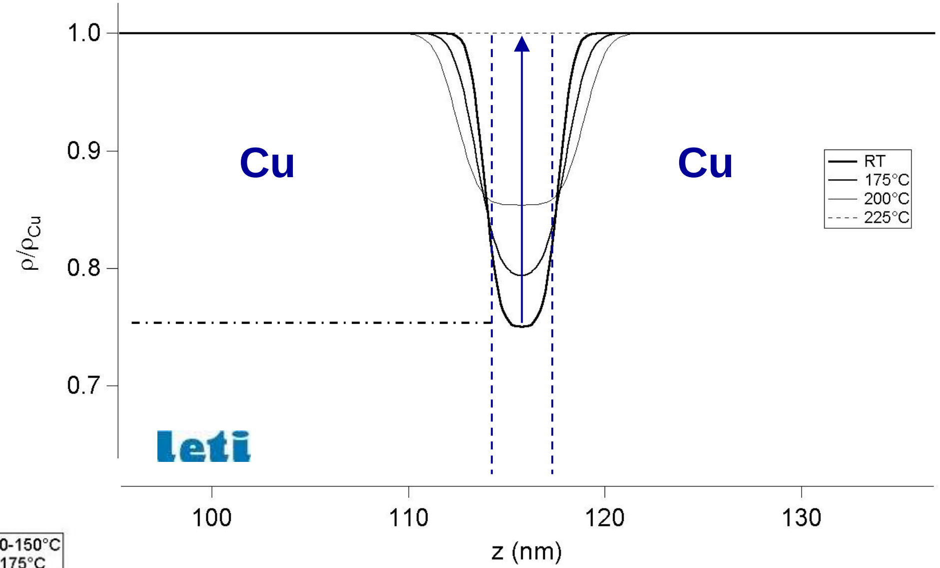


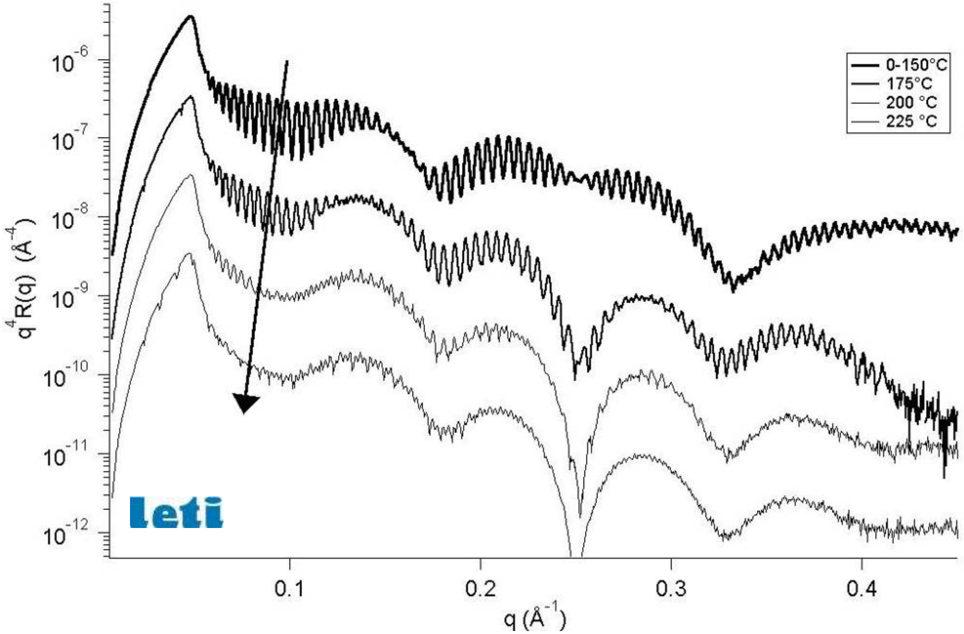
- **Homogeneous layer at the bonding interface**
- **Thickness of 4 nm**
- **Correlation with XRR**

P. Gueguen et al, Wafer Bonding conf proc., (2009)

COPPER METAL DIRECT BONDING





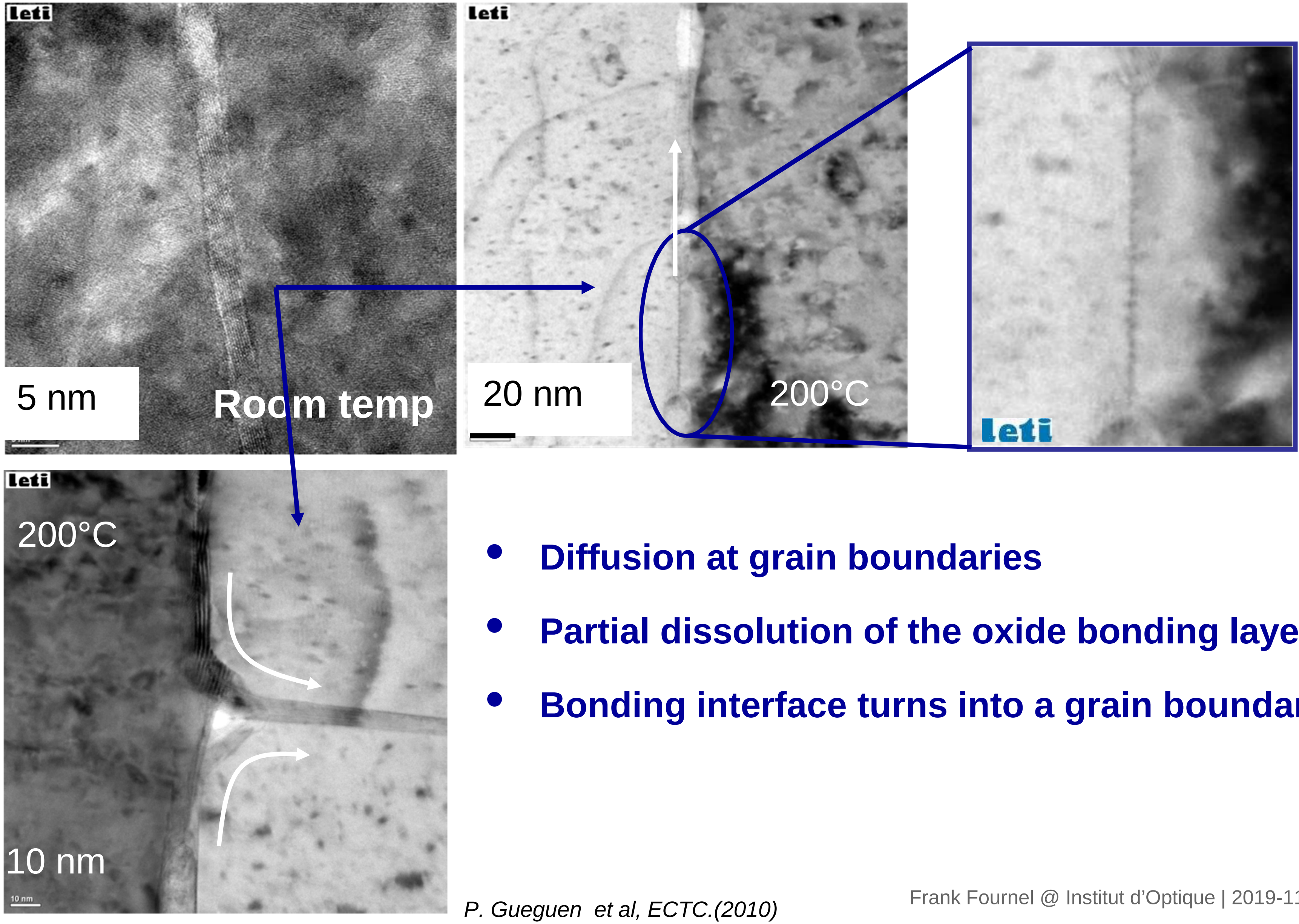


Evolution of electronic density profile with temperature

Bonding interface is closed around 200°C

P. Gueguen et al, JES, 156(10) H772-H776 (2009)

COPPER METAL DIRECT BONDING



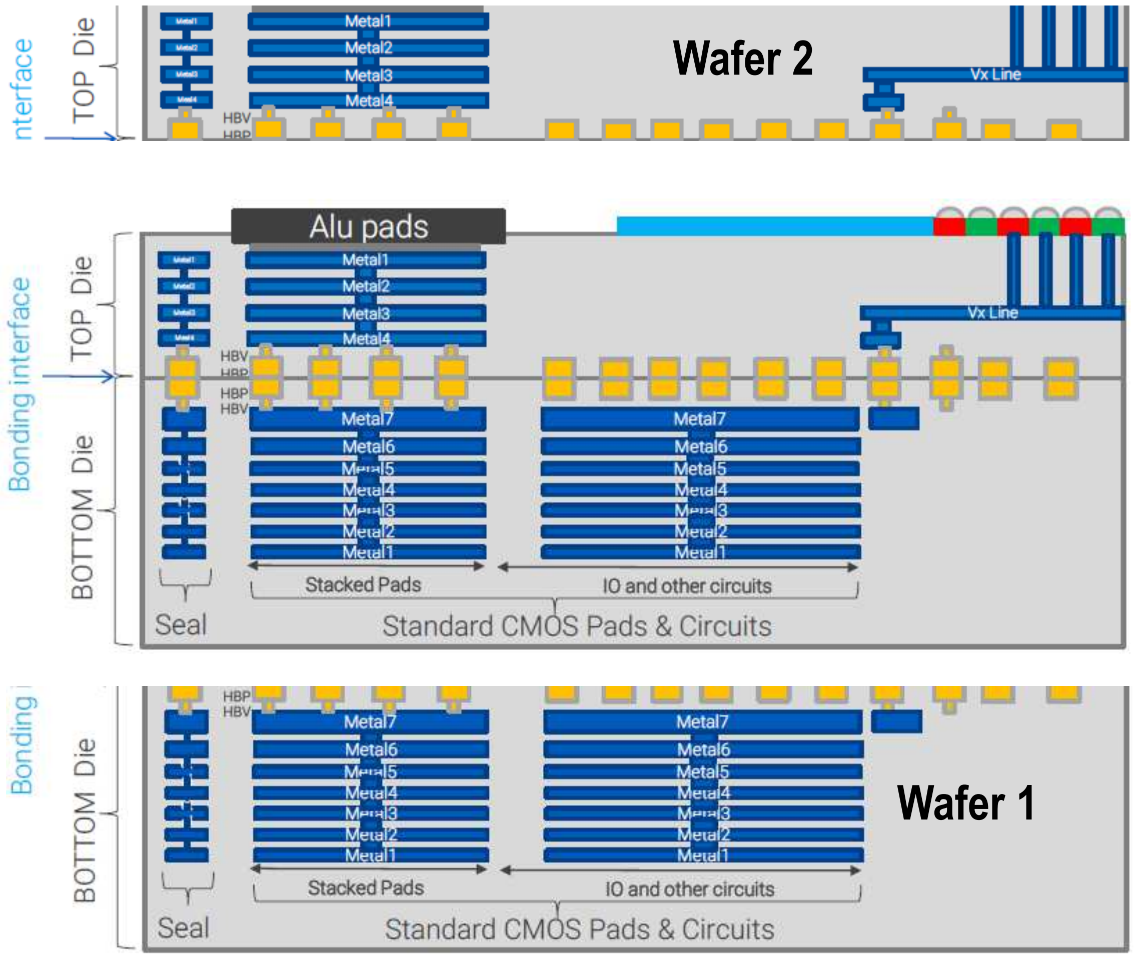
- **Diffusion at grain boundaries**
- **Partial dissolution of the oxide bonding layer**
- **Bonding interface turns into a grain boundary**

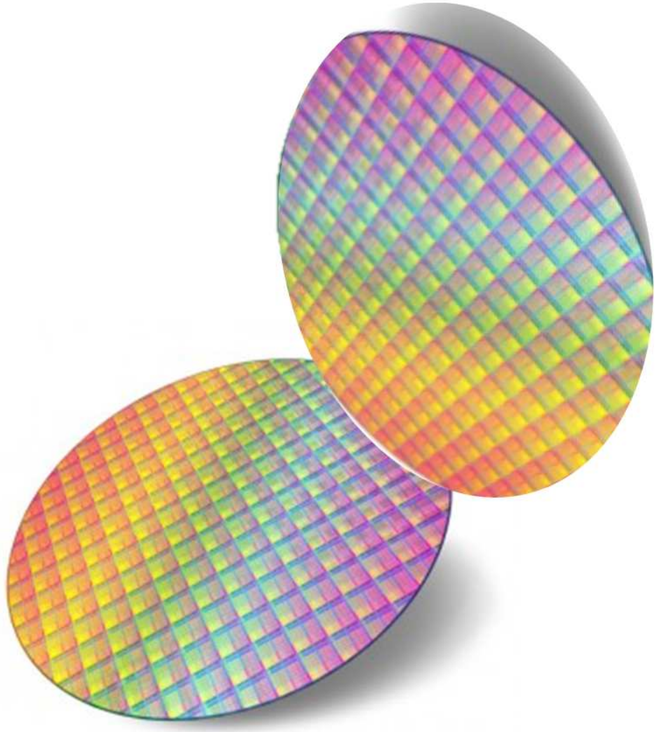
P. Gueguen et al, ECTC.(2010)

Direct bonding

- ❑ Silicon & Silicon dioxide
  - ➢ Small digest of static mechanism
  - ➢ Adhesion and Adherence
  - ➢ Physicochemical Mechanism
  - ➢ Interface water edge diffusion
- ❑ Direct bonding of others materials
  - ➢ Copper/Copper
  - ➢ Hybrid Copper/Silicon dioxide
- ❑ Direct bonding LETI applications

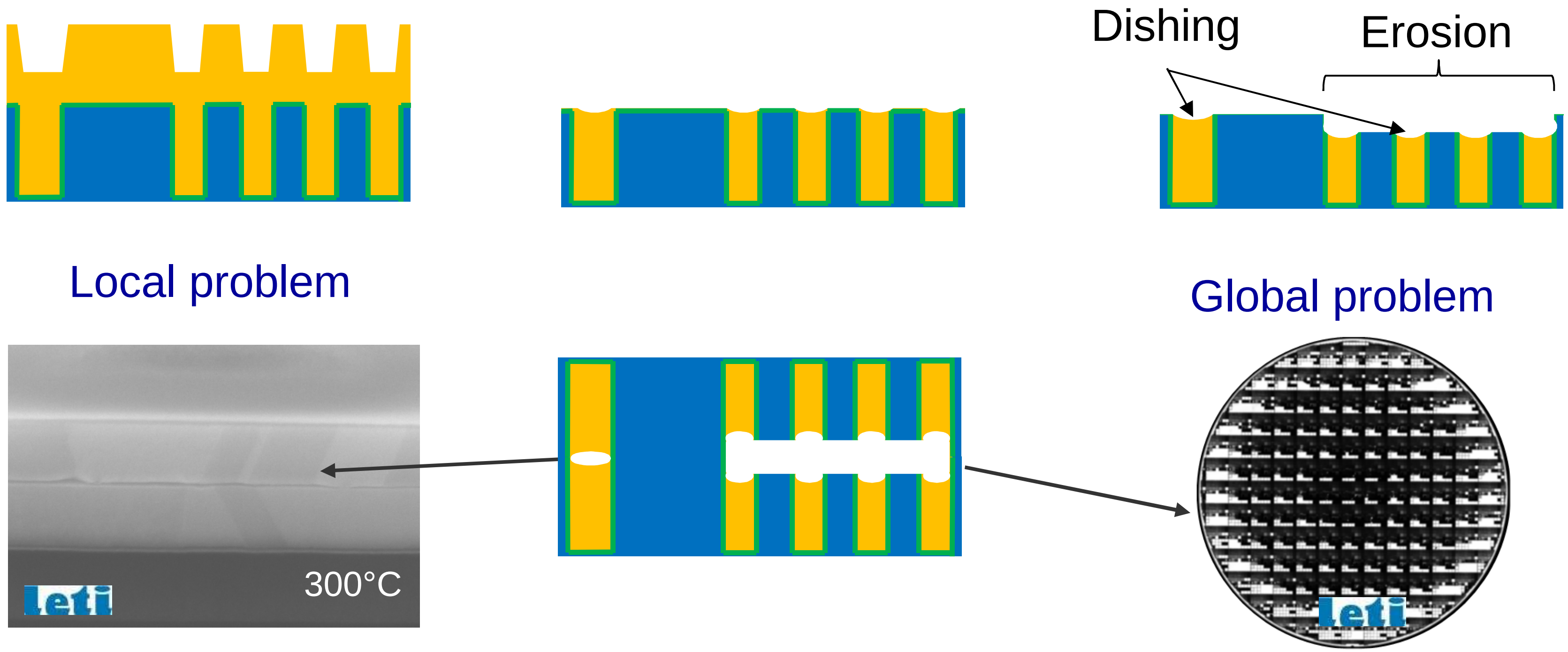
Hybrid direct bonding

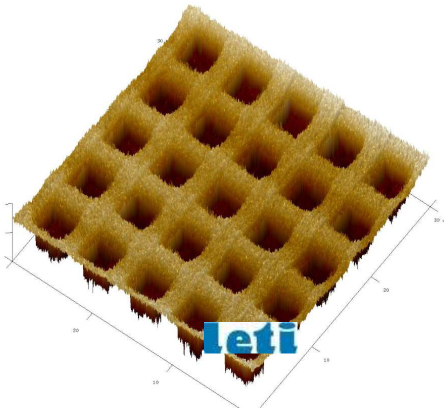


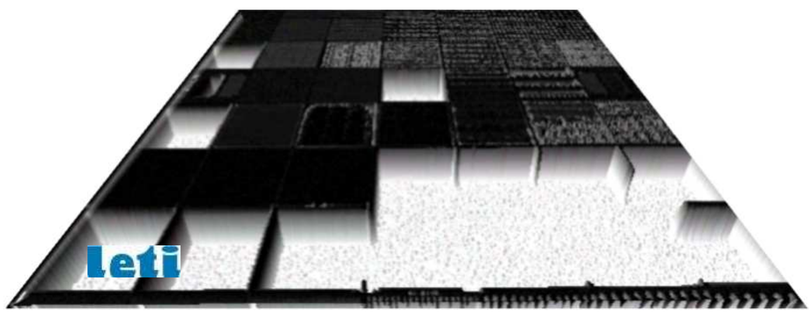


J. Chossat 3D Summit Grenoble 2016

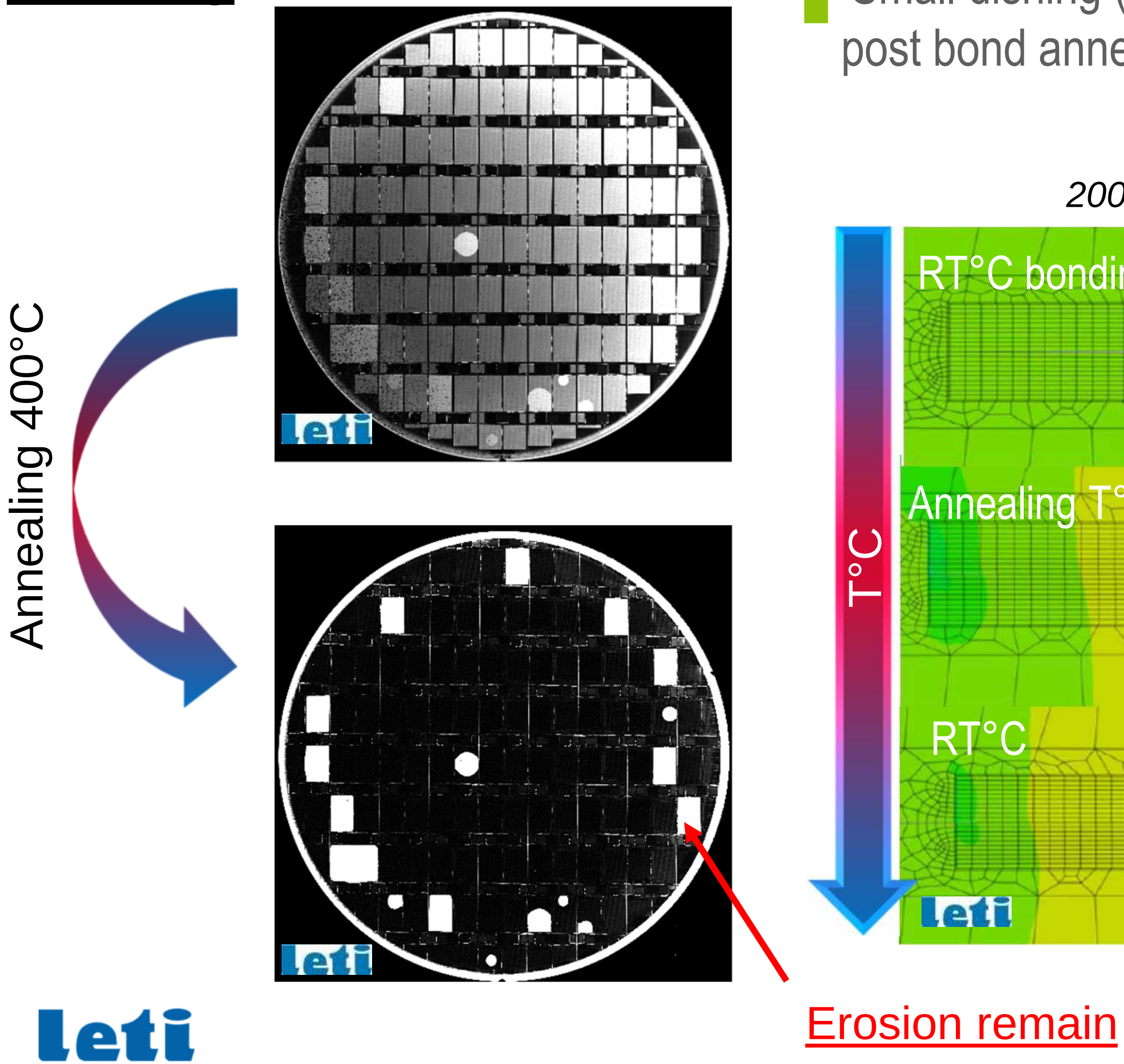
Hybrid direct bonding



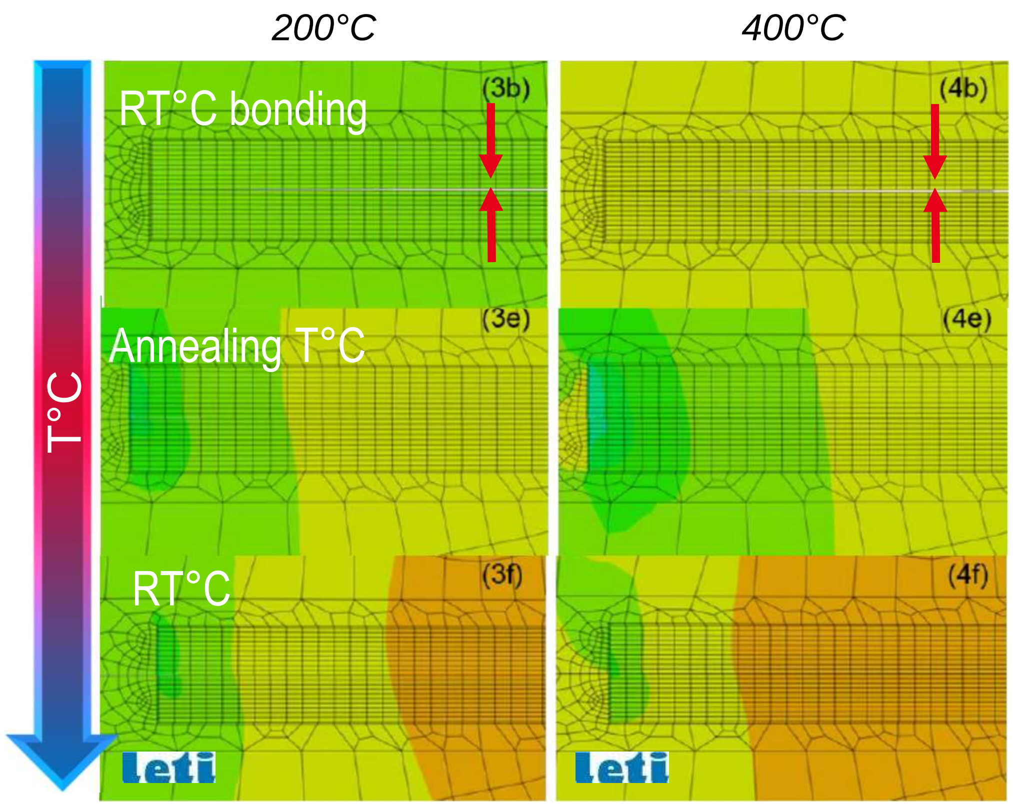




Dishing



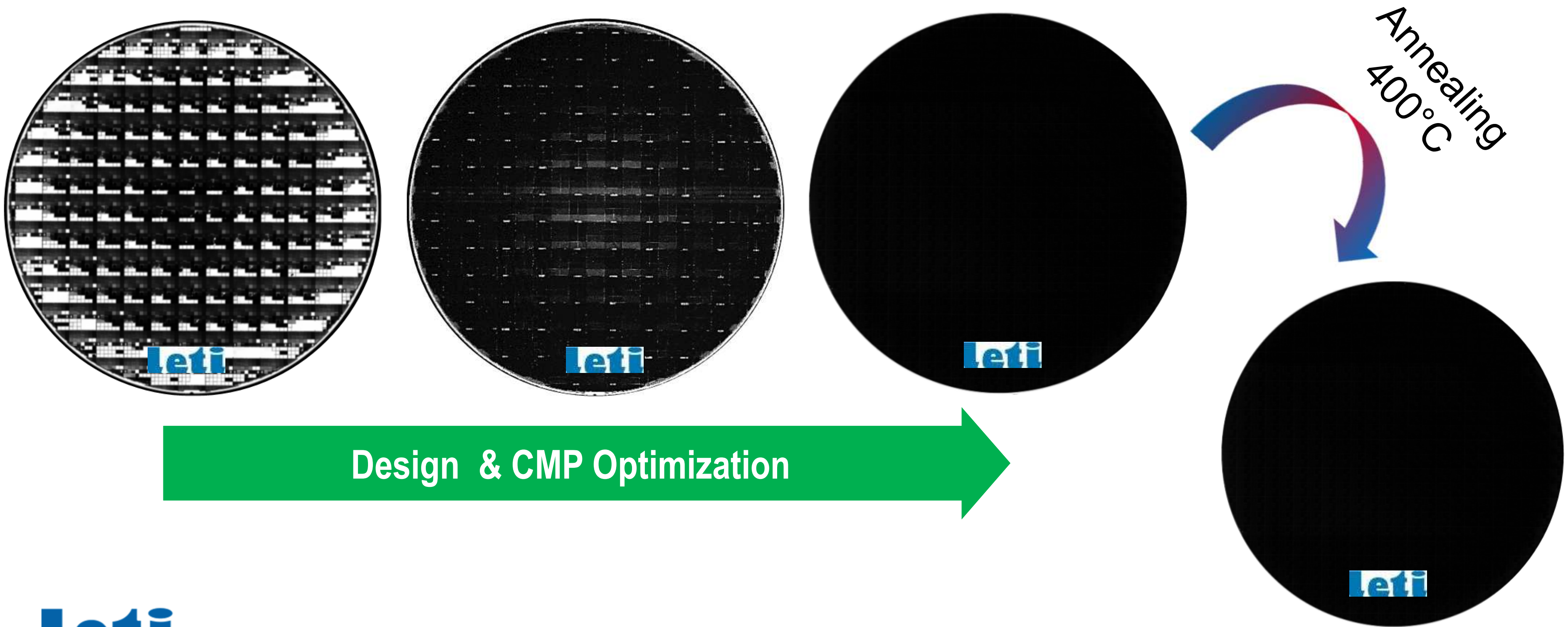
Small dishing (~10nm) of Cu pads overcome during post bond annealing even @ low T°C: 200°C



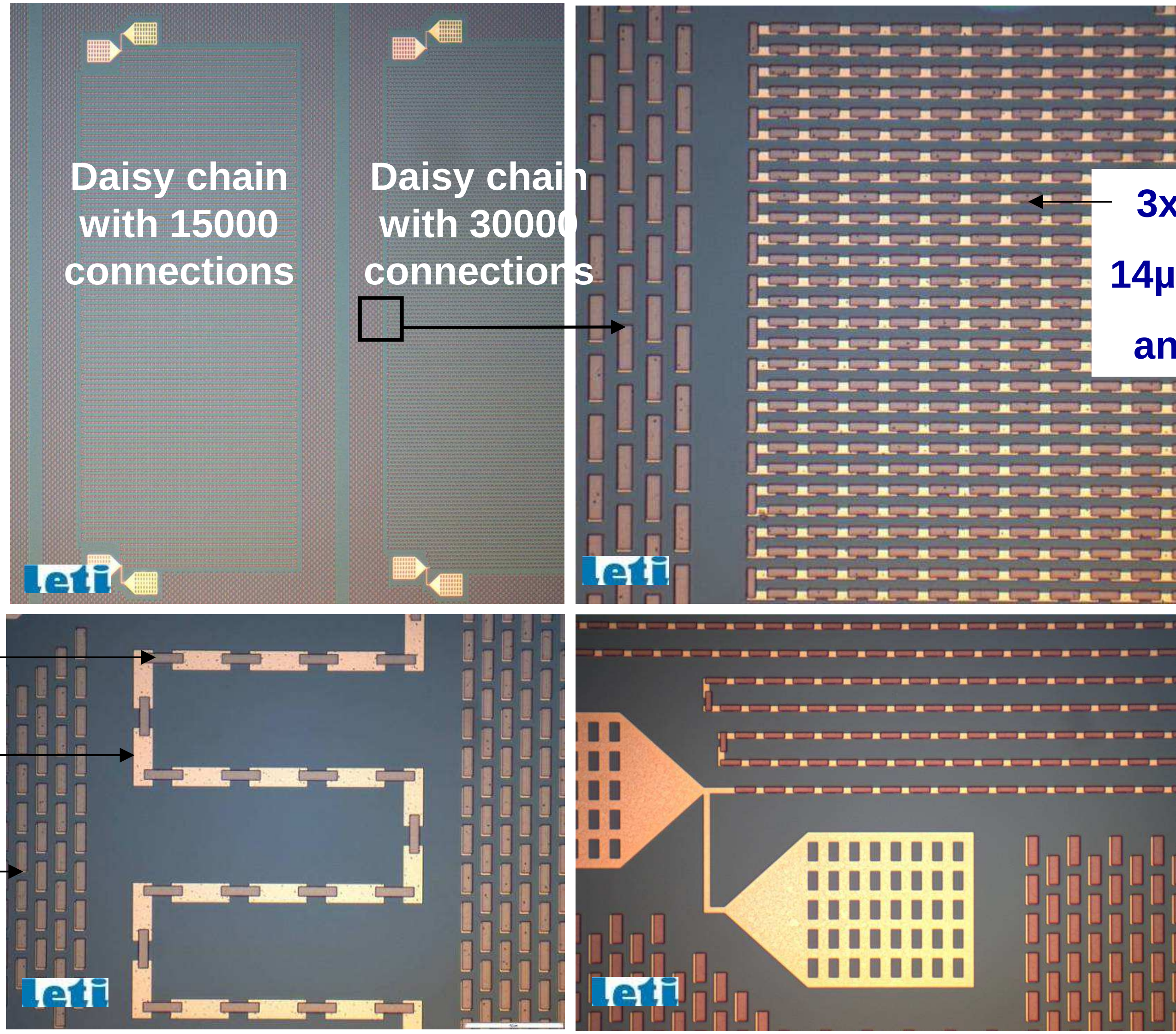
*Y. Beilliard et al. International Journal of Solids and Structures, 2016

COPPER METAL DIRECT BONDING

Erosion



COPPER METAL DIRECT BONDING



Y. Beillard Phd University of Grenoble (2015)

COPPER METAL DIRECT BONDING

Resistance of daisy chains (400°C post bonding anneal):

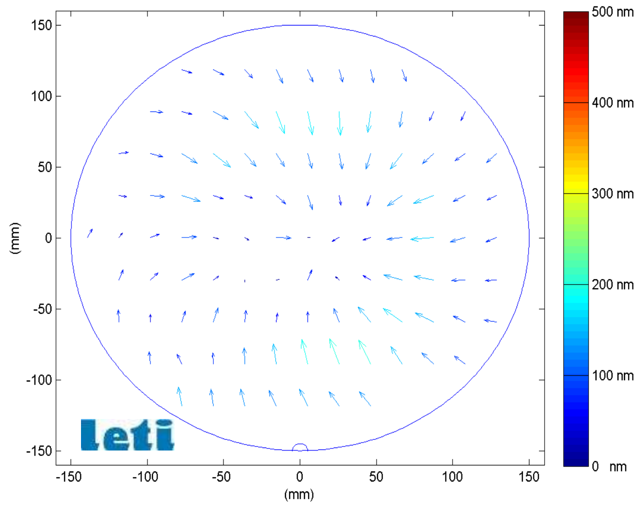
Daisy chains	1	2	3	4
Contact area (µm²)	5x5	3x3	3x3	3x3
Number of connection	4872	10136	14934	29422
Global resistance (Ω)	310	801	1180	2340
Bonding interface resistance ΔR (m Ω)	1.2	2	2	2.5

Reproducible measurement for each type of daisy chain
Bonding interface resistance "negligible"

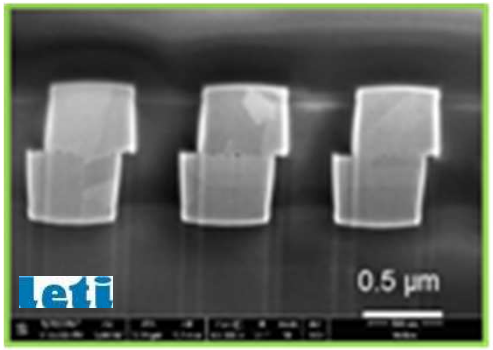
Y. Beillard Phd University of Grenoble (2015)

Hybrid direct bonding : Ultra-fine pitch

Alignment using an EVG Gemini FB XT and a SmartView®NT bonder



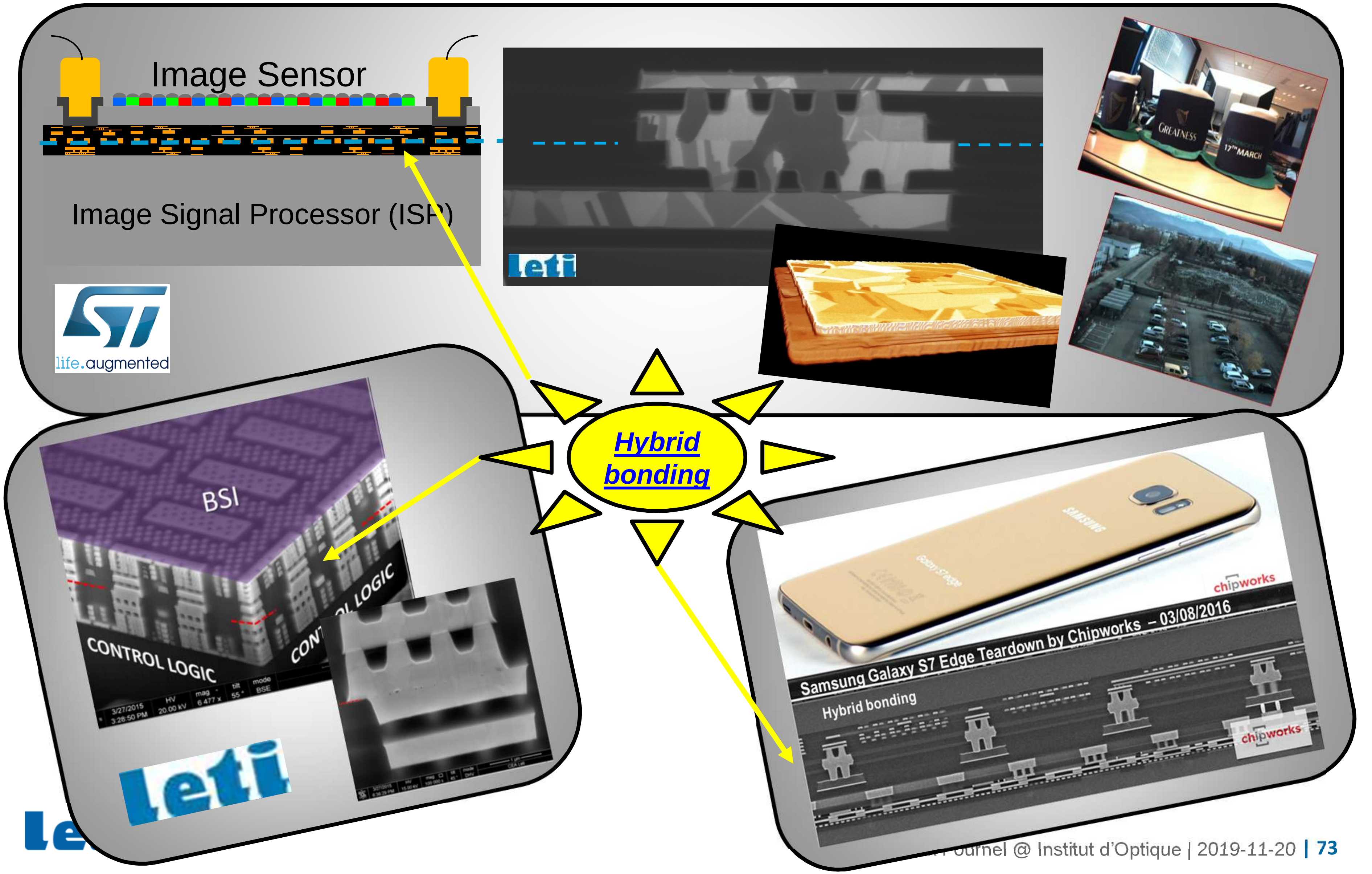
Alignment <200nm 3σ on 300mm wafers
(measured with AVM inside the Gemini)



Pitch ~1µm

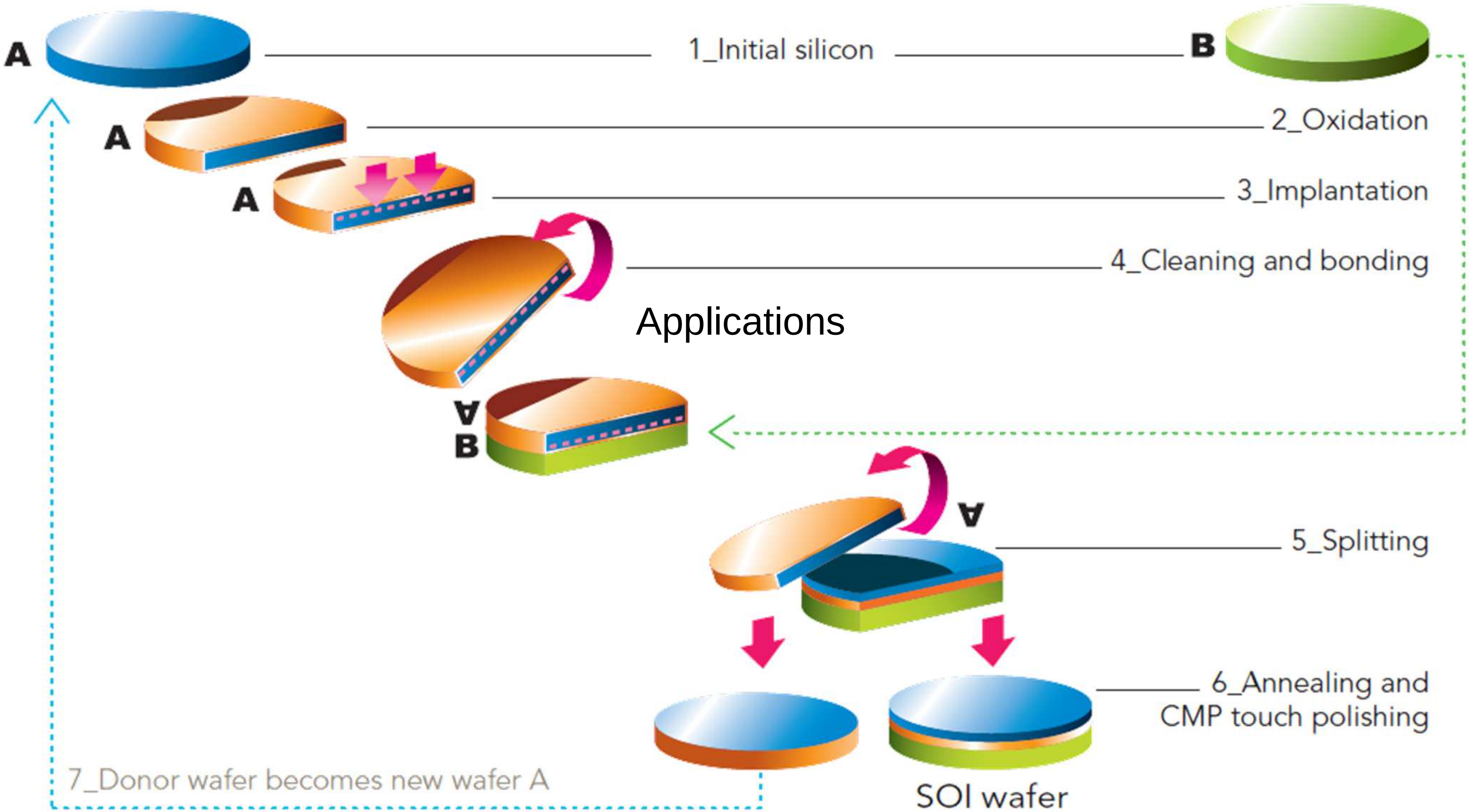
A. Jouve et al, IEEE S3S (2017)

COPPER METAL DIRECT BONDING



WAFER BONDING APPLICATIONS IN LETI

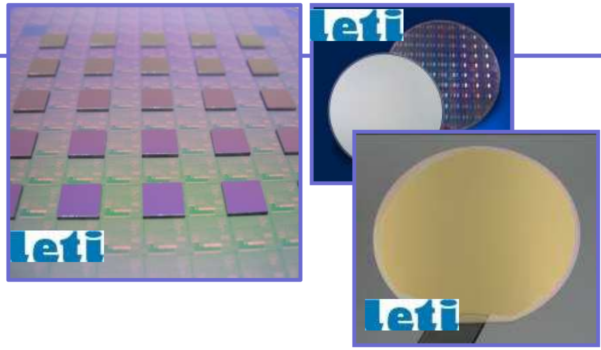
THE SMART-CUT™ TECHNOLOGY



Applications

ADVANCED SUBSTRATES : A NEW PATH FOR INNOVATION

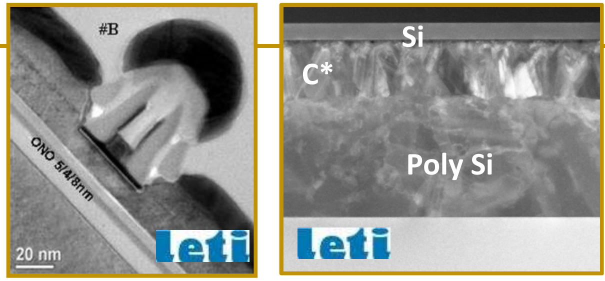
Superficial layer



Disruptive active layers

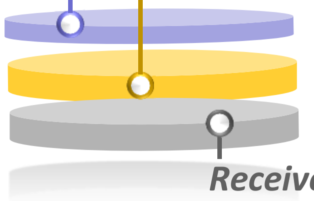
Strained Silicon (sSOI),
Germanium, Graphen
Piezoelectrics (LNO, LTO, Qz)
III-V materials (GaAs, InP, etc.)

Buried layer(s)

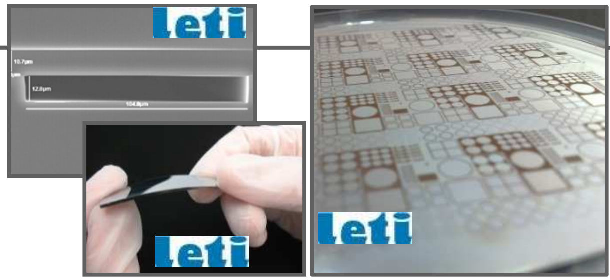


Functionalized buried layer(s)

Dielectrics (Al_2O_3, Si_3N_4, Diamond)
Debondable layer (polymer, Si_3N_4)
Conductive layer (metal, ITO
Patterned inter- layer



Receiver

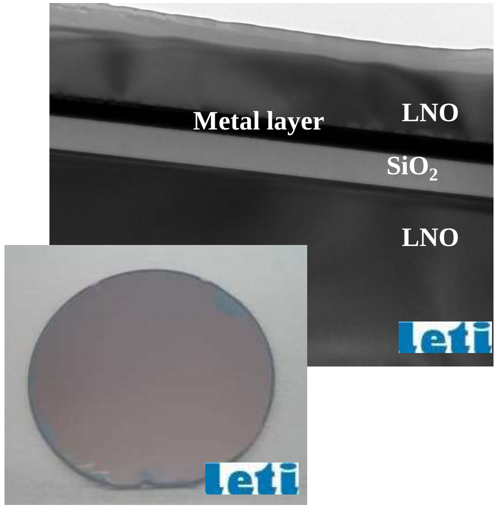


Optimized substrates

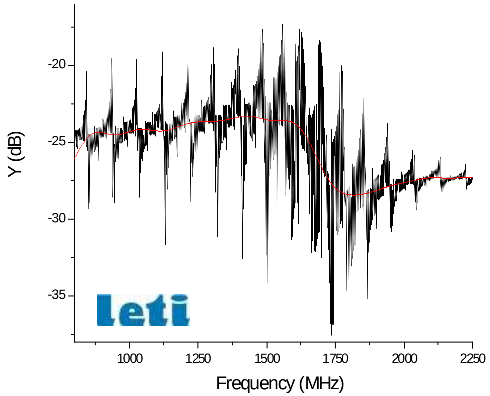
High Resistivity (HR)
Transparent substrates (Sa, Glass)
Metal substrates (Cu, Mo, W)
Patterned or flexible substrates

APPLICATIONS

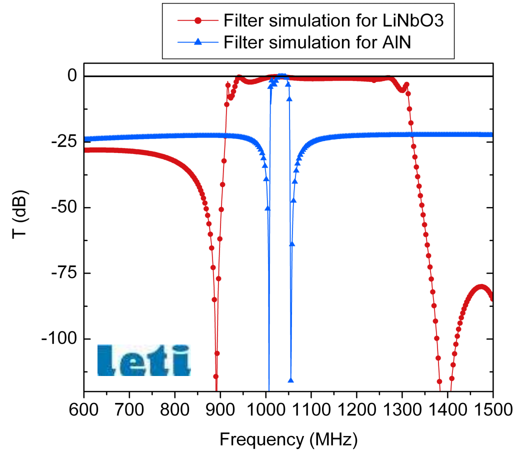
LiNbO3 thin layer transfered by Smart Cut™ on a metal electrode



HBAR (Hugh overtone Bulk Acoustic Resonator)



RF Filters simulation



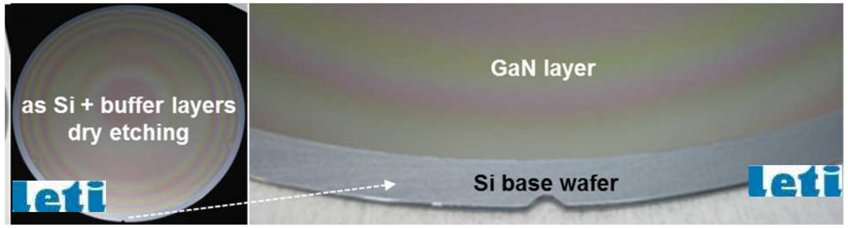
→ **The highest kt² electromechanical coupling factor ever reported**

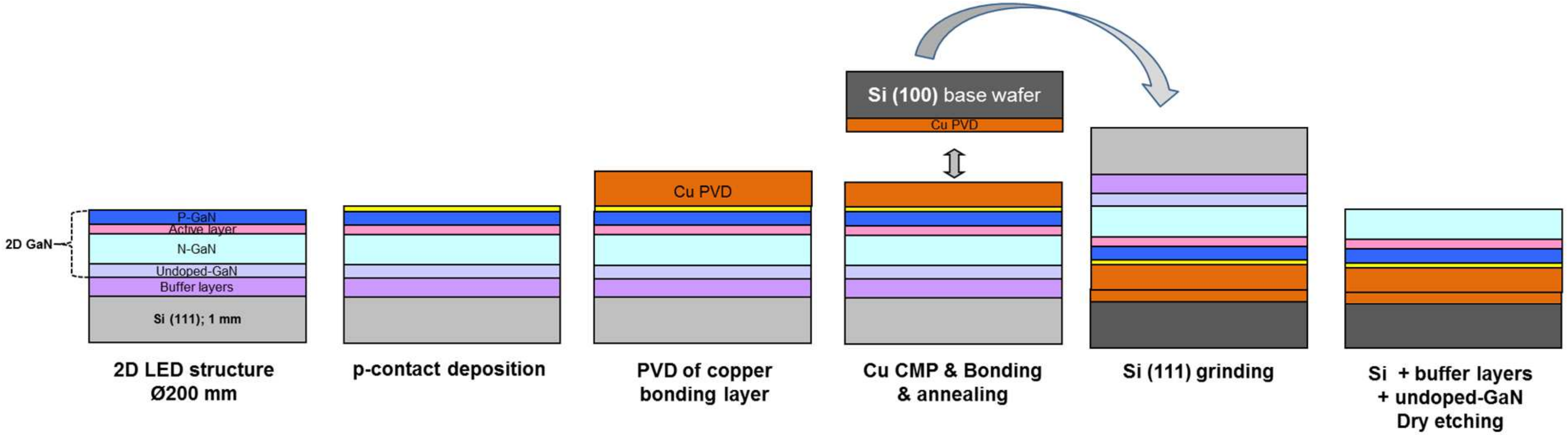
30% < Kt² < 40%
Theoretical value for X-Cut ~ 45%

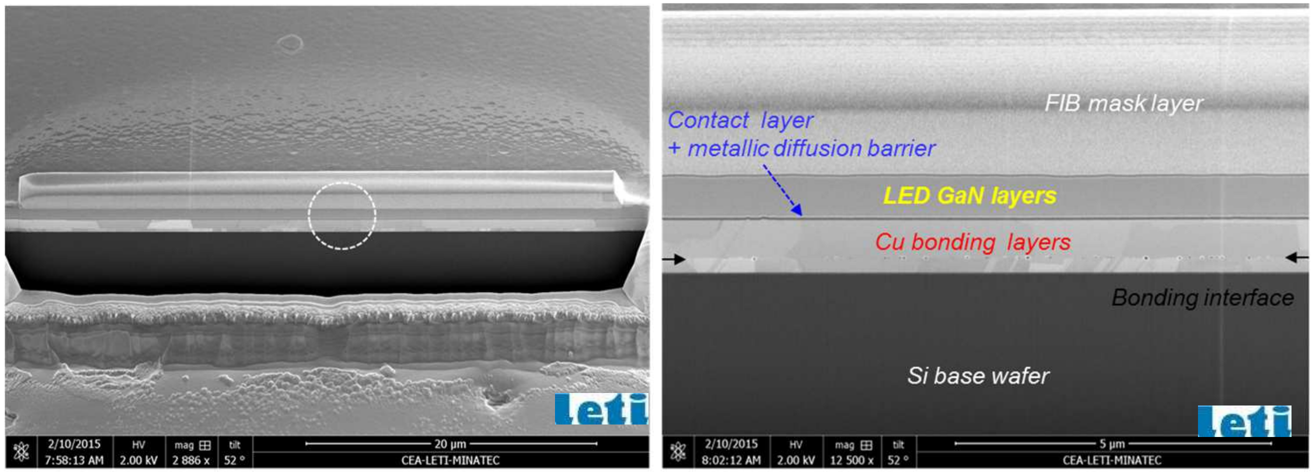
World record for thin films layers
→ State of the art deposited AlN ~7%

- Pijolat et al., *IEEE Ultrasonics (2008)*
- Moulet et al., *IEEE IEDM (2008)*

GaN LED Structure on 200mm Si
by Cu//Cu bonding



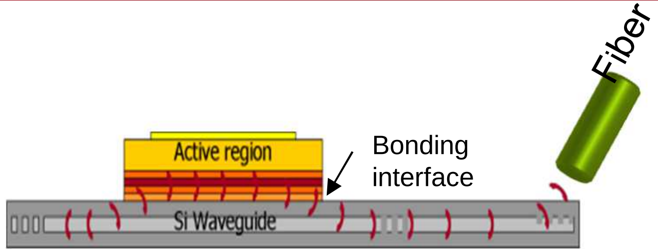




APPLICATION : SILICON PHOTONIC

Si Photonic requirements

- **heterogeneous structure**
- **Optical coupling**

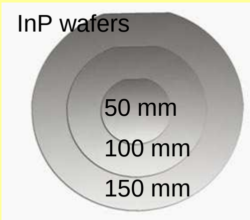


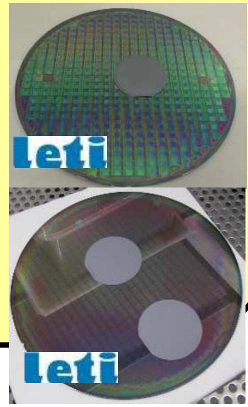
Direct bonding

✔ Layer quality

Si/SiO_2 100 nm compatible with optical coupling

✘ Transferred surface limited by donor wafer size

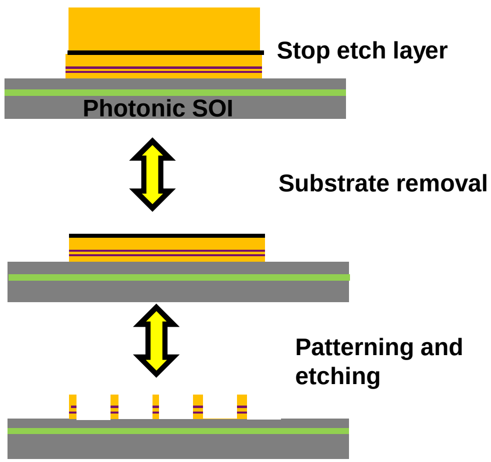




Direct growth

✔ 200/300 mm full surface

✘ III-V Layer quality (dislocations)

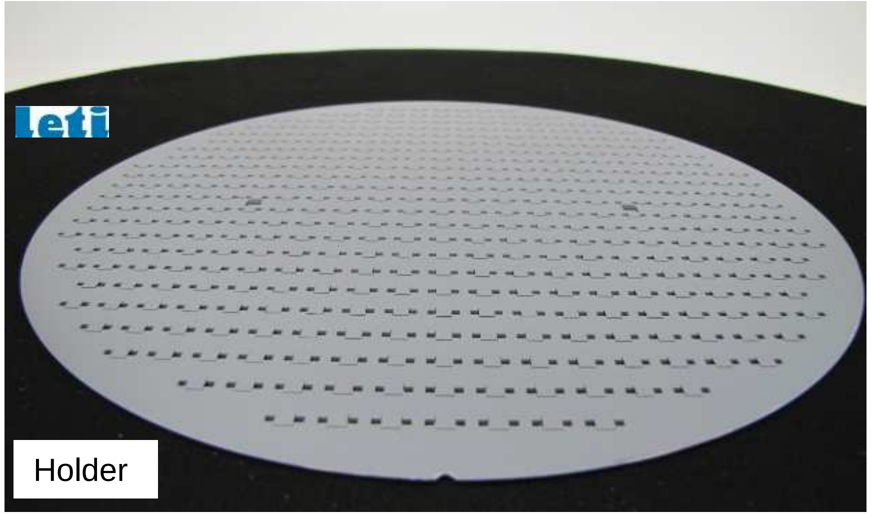


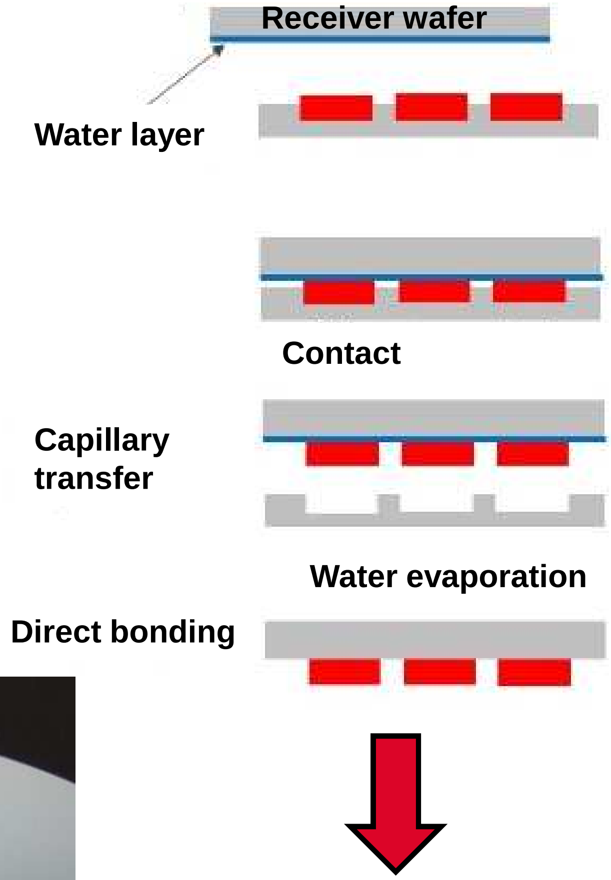
Dies to wafer direct bonding

Mains challenges = die handling and cleaning

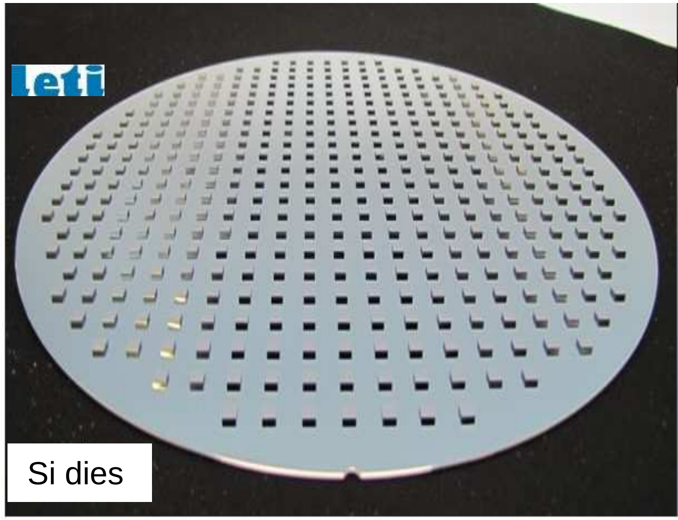
APPLICATION : SILICON PHOTONIC

LETI collective bonding: Capillary transfer





2 hours 200°C annealing



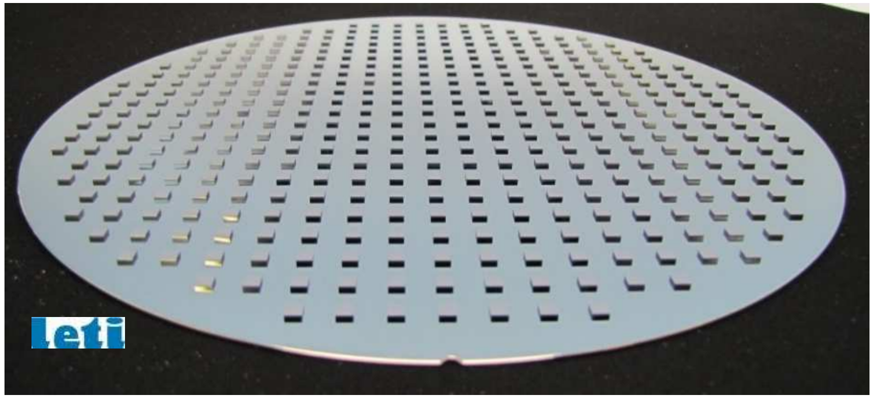
APPLICATION : SILICON PHOTONIC

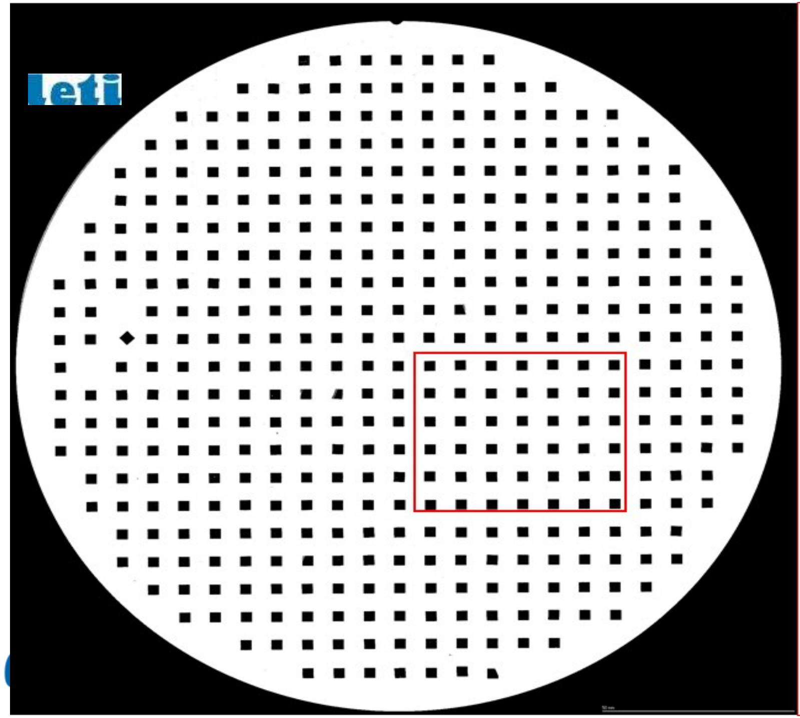
LETI collective bonding: Capillary transfer

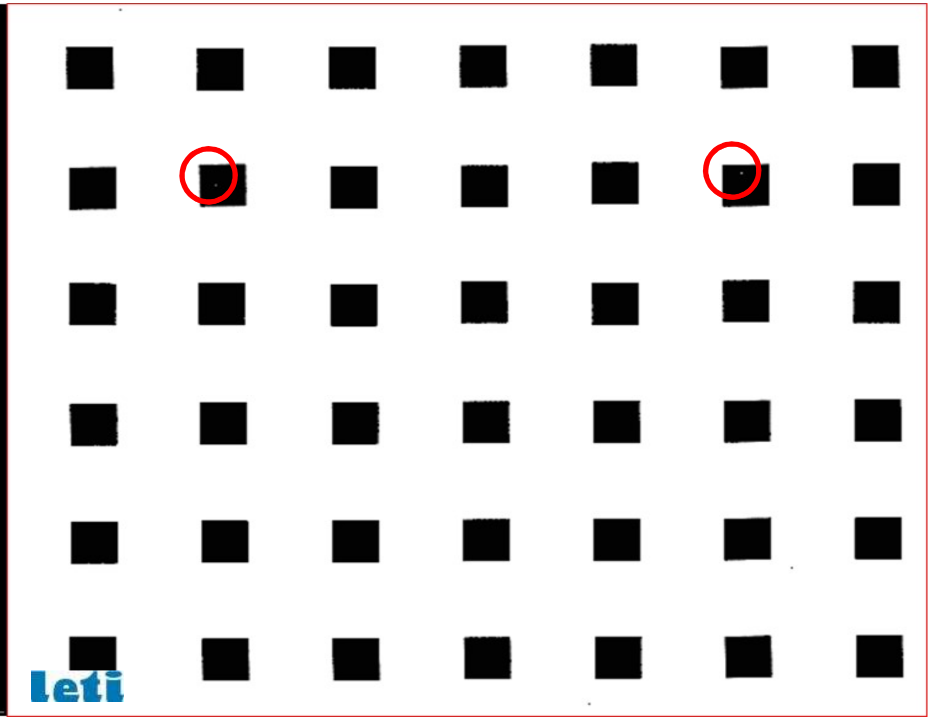
3x3mm silicon chips reported on a receiver wafer by collective direct bonding

⇒ Bonding Yield >95%

⇒ Defect free >80%

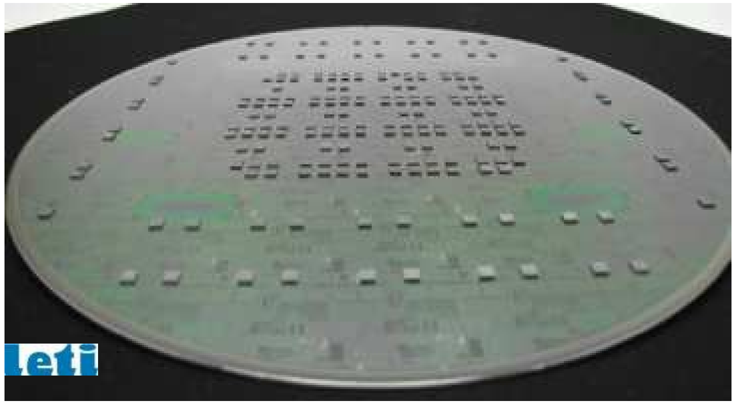


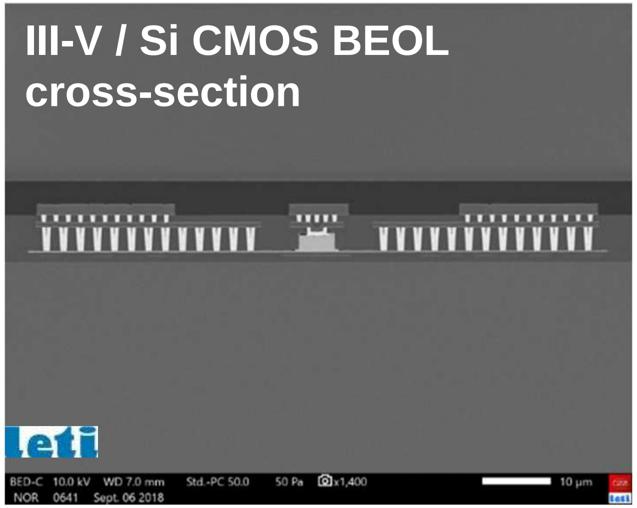


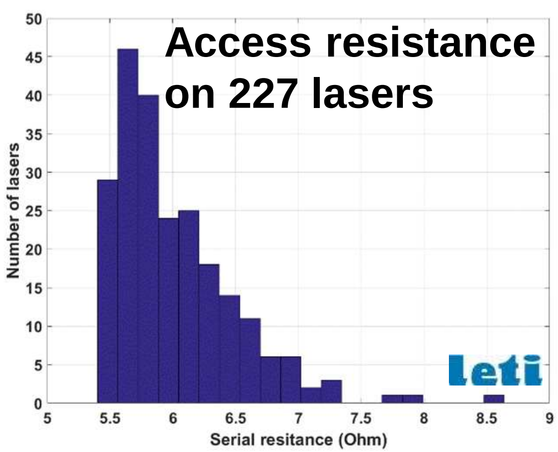


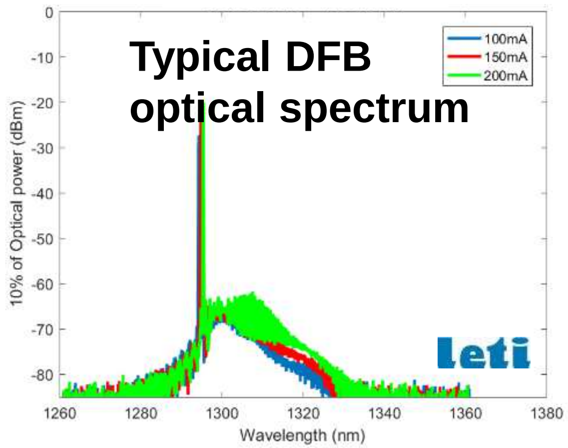
APPLICATION : SILICON PHOTONIC

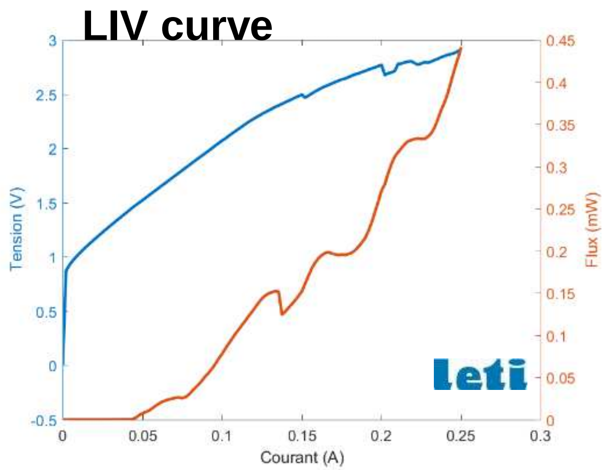
CMOS friendly Hybrid III-V on silicon Lasers





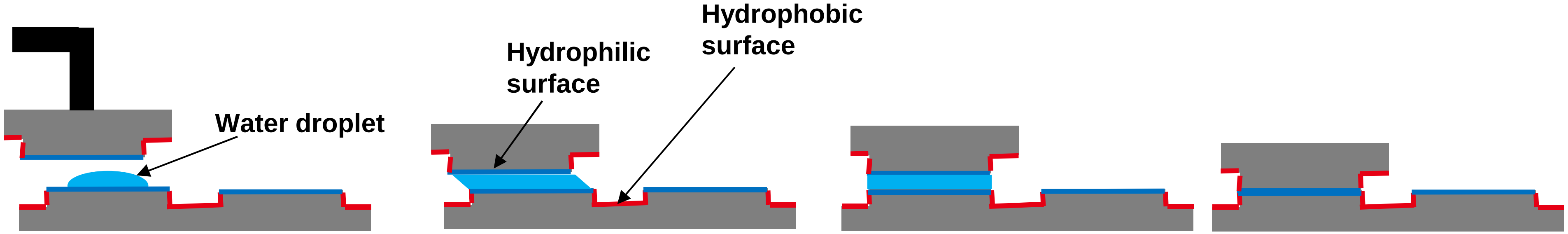






B. Szelag et al., Hybrid III-V/Silicon technology for laser integration on a 200 mm fully CMOS-compatible silicon photonics platform, IEEE J. Sel. Top. Quantum Electron., In Press (2019)
B. Szelag et al., Advances on large-scale integration CMOS compatible hybrid III-V/Si laser on 200mm platform, In Proc. of SPIE, Smart Photonic and Optoelectronic Integrated Circuits XXI, 10922-61 (2019)
K. Hassan et al., Technological advances on CMOS compatible hybrid III-V/Si lasers in 200mm platform, In Proc. of SSDM, H-3-01 (2019)

APPLICATION : HYBRID BONDING SELF-ASSEMBLY



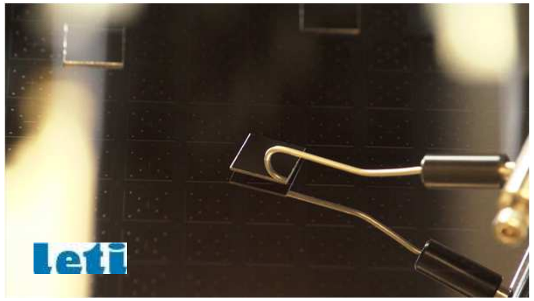
Die release

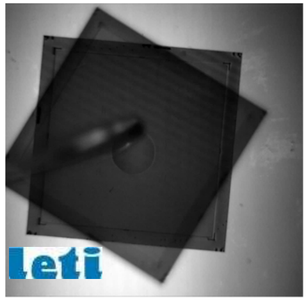
Water spreading and self alignment

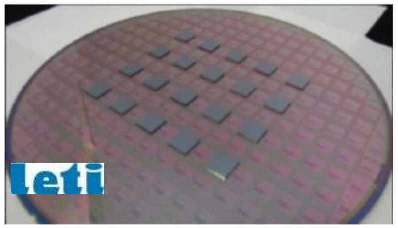
Water spreading and self alignment

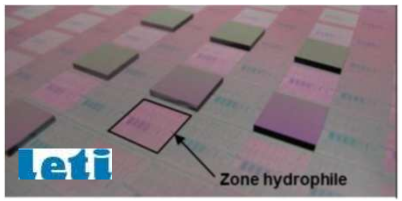
Water evaporation and direct bonding

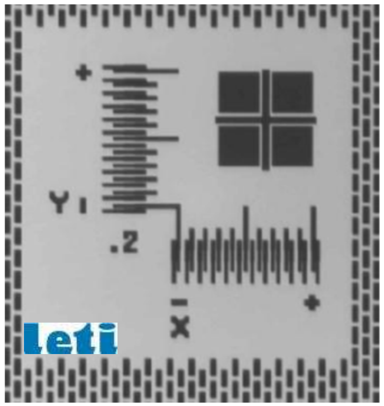
self assembly observation :



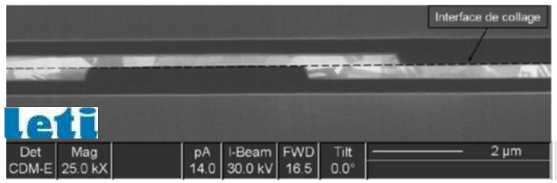


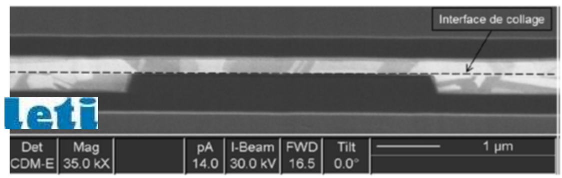






Alignment: <0,5µm
(die miss alignment during die release ~100-200µm)



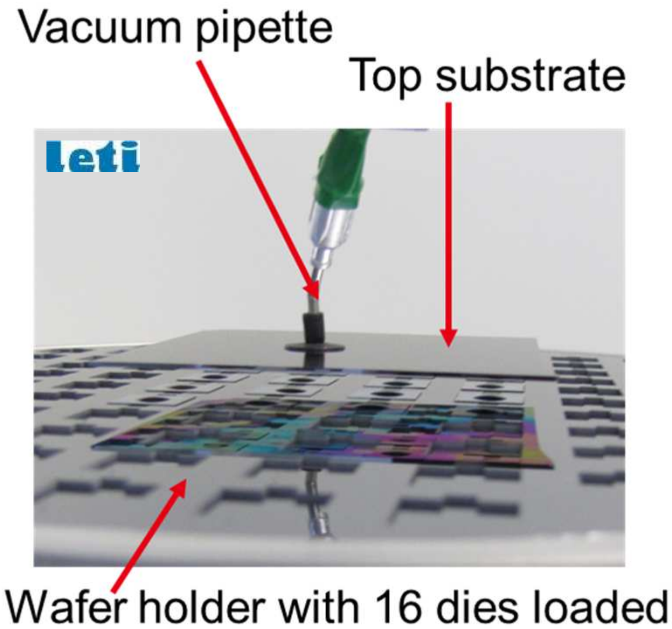


Hybrid bonding compatible.

APPLICATION : HYBRID BONDING SELF-ASSEMBLY

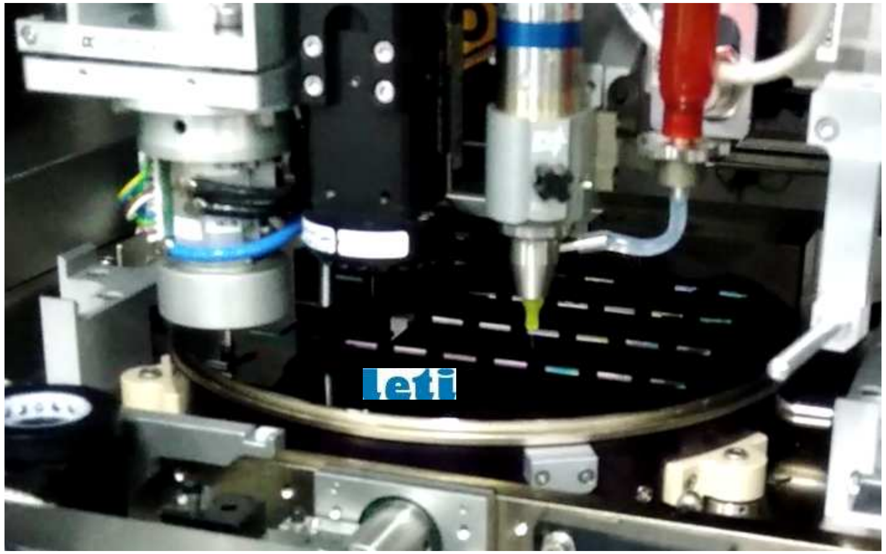
Die hybrid bonding self-assembly

Collective process



⇒ Throughput
⇒ Low first placement precision

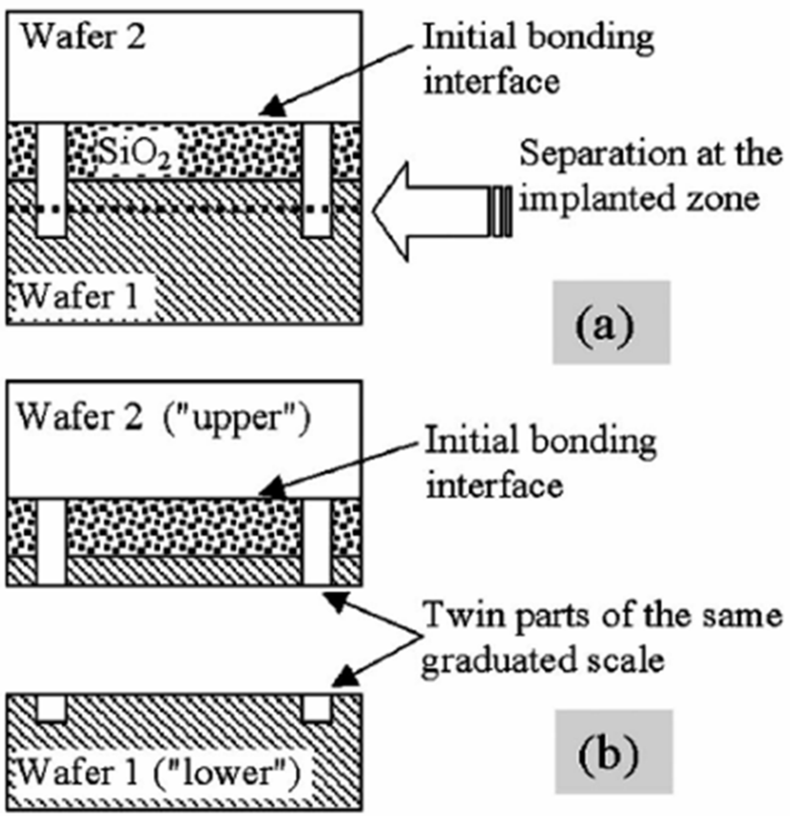
Peak&Place tool

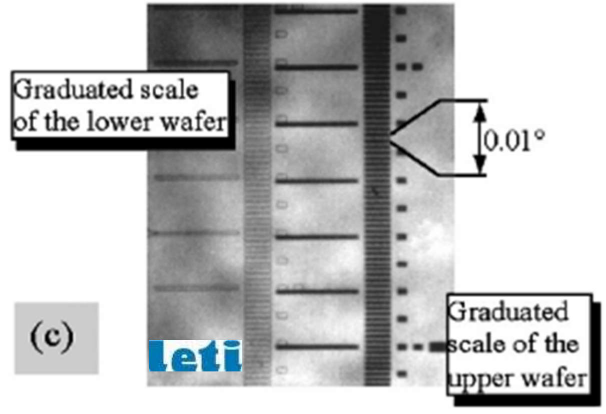


⇒ Medium Throughput ?
⇒ "Precise" first placement

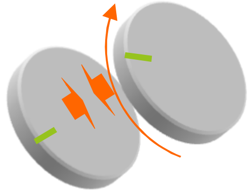
Self-Assembly process for 3D Die-to-Wafer using direct bonding: A step forward toward process automatisation, A. Jouve et al., ECTC (2019)

APPLICATIONS



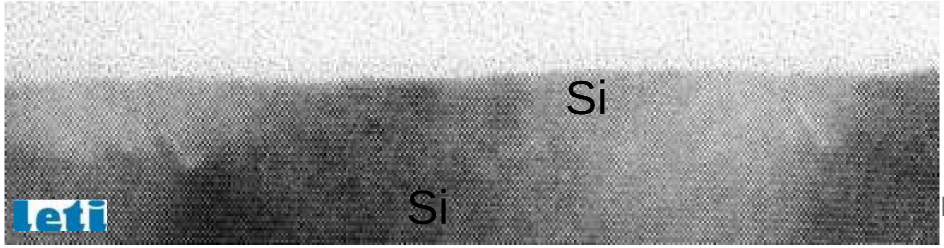


Controlled misalignment before molecular bonding



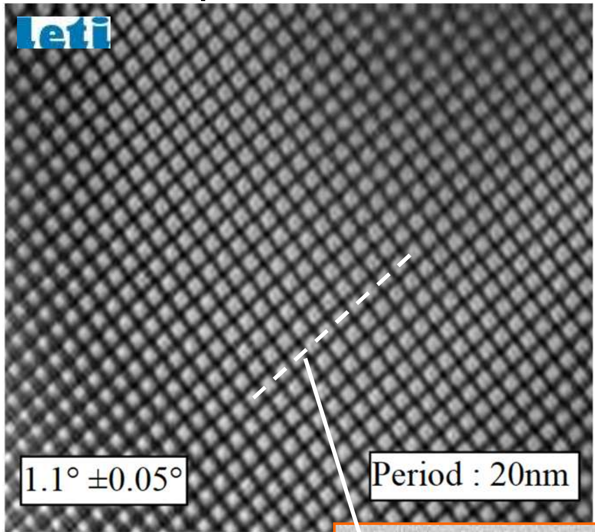
Controlled angle down to 0,005°

(F. Fournel et al. APL 2002)

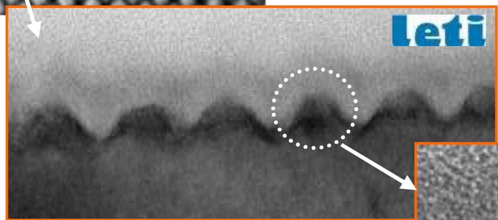


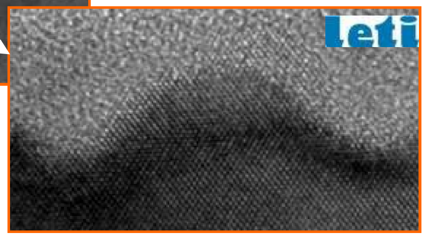
APPLICATIONS

TEM plane view



AFM scan (pitch = 20nm)





Organized Ge nanodots

Self-assembly for inorganic or organic nanostructures, electronic, magnetic and optical nanosystems

Merci pour votre attention