Hybrid Bonding Based on Polyimide for Low Temperature Process

Hitoshi Araki, Masaya Jukei, Kota Nomura,
Yugo Tanigaki, Takenori Fujiwara, Yu Shoji.
Toray Industries, Inc.

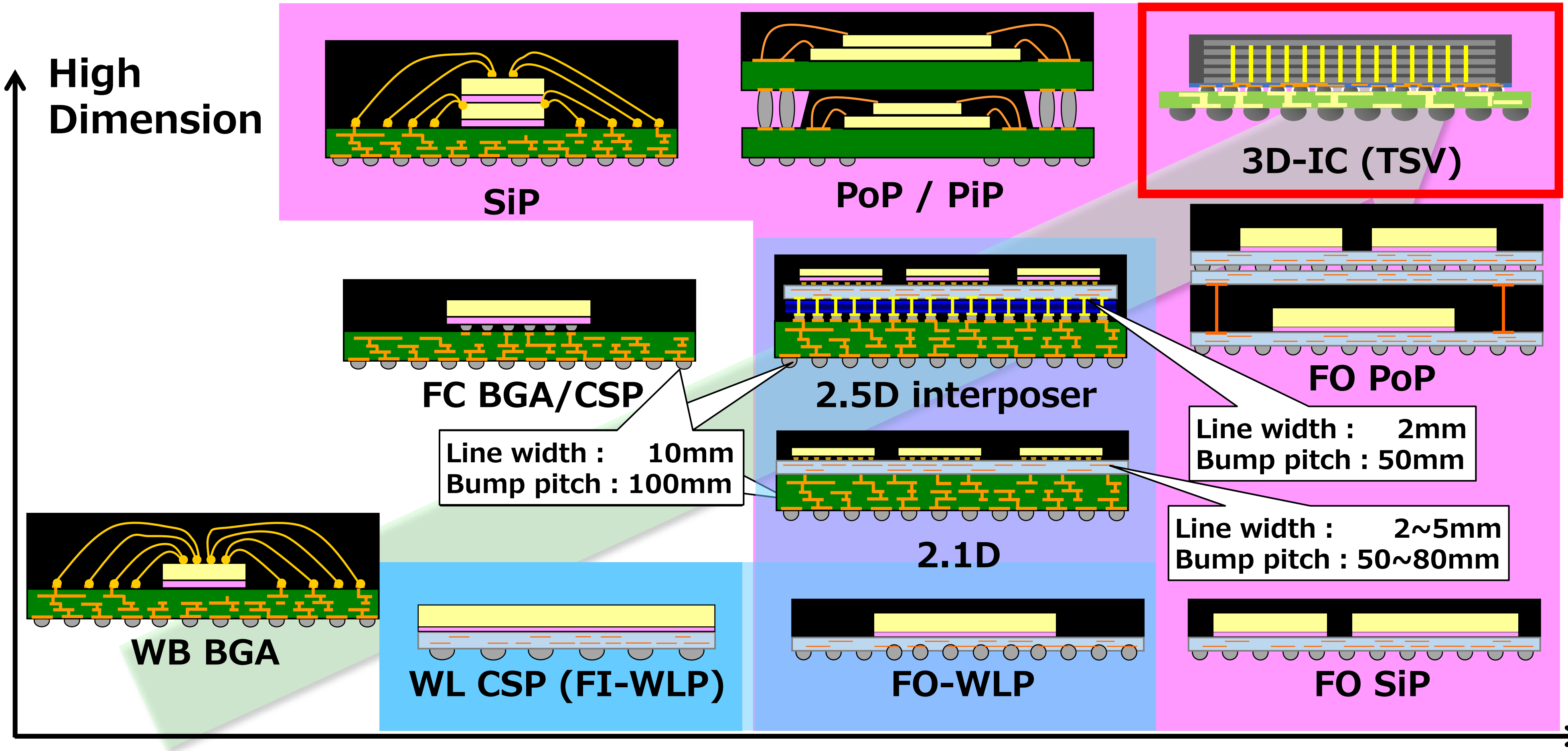
Outline

1. Introduction and Background
2. Polymer Bonding Test
3. Polyimide-to-Polyimide (PI-PI) Bonding Mechanism
4. Hybrid Bonding Demonstration
5. Summary

Outline

1. **Introduction and Background**
2. Polymer Bonding Test
3. Polyimide-to-Polyimide (PI-PI) Bonding Mechanism
4. Hybrid Bonding Demonstration
5. Summary

Semiconductor Chip Packaging Technology

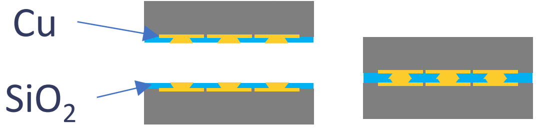


Improvement
- ✓ High-density
- ✓ Performance
- ✓ Power efficiency
- ✓ Various functionalities

3D-IC technology stacking multiple chips vertically ⇨ **High-density and Highly integrated devices**

Hybrid Bonding Technology (=HB)

Hybrid Bonding(HB) Technology

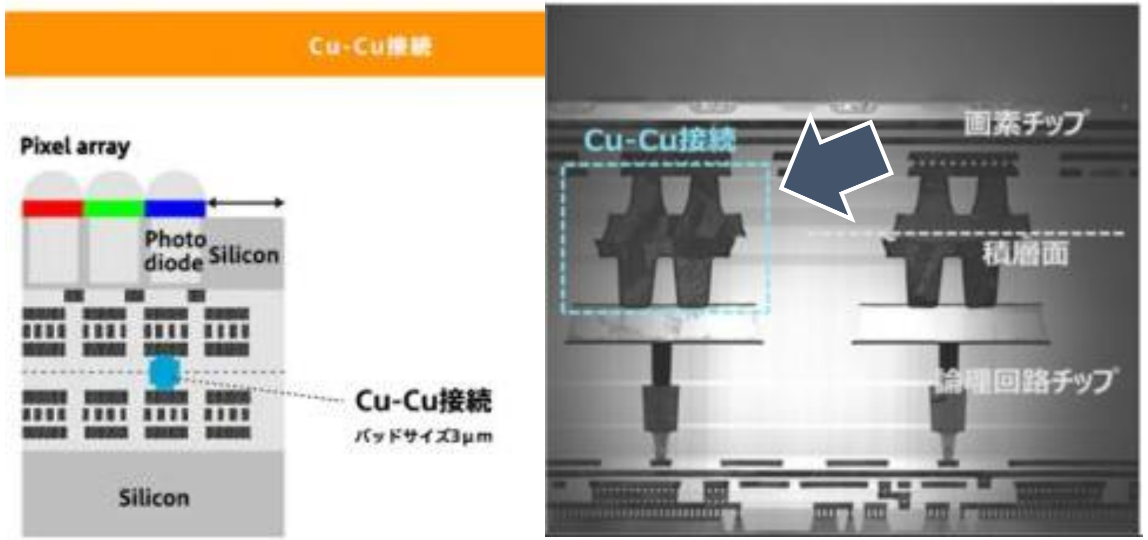


Hybrid Bonding is bumpless interconnect technology.

Interconnect	μ-bump	HB
Bump Density	1.0X	16.0X
Speed	1.0X	11.9X
Bandwidth	1.0X	191.0X
Power Efficiency	1.0X	0.05X

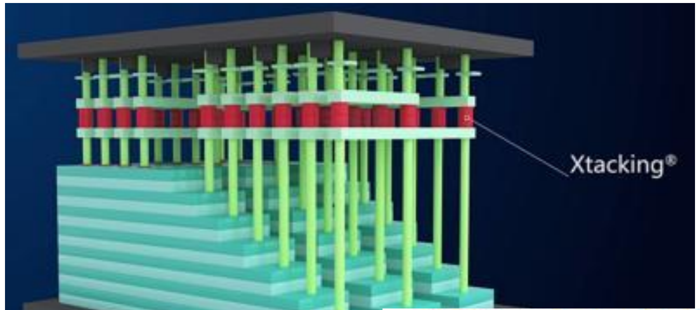
Published in 2019 Symposium on VLSI Technology by TSMC.

Sony : CMOS-Image Sensor

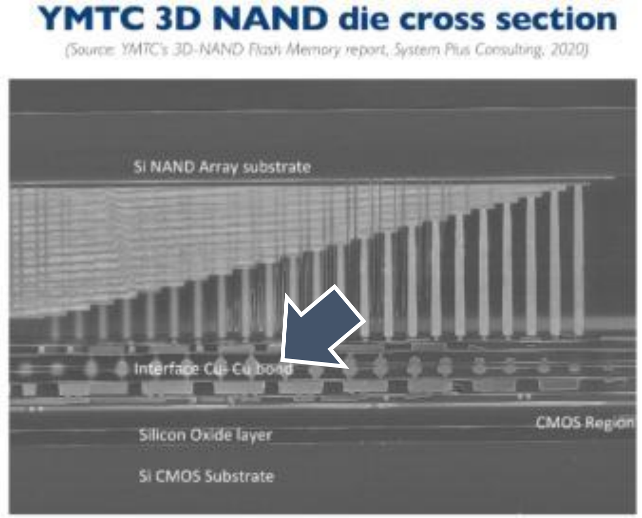


Source : Sony

YMTC : NAND Memory



Source : YMTC

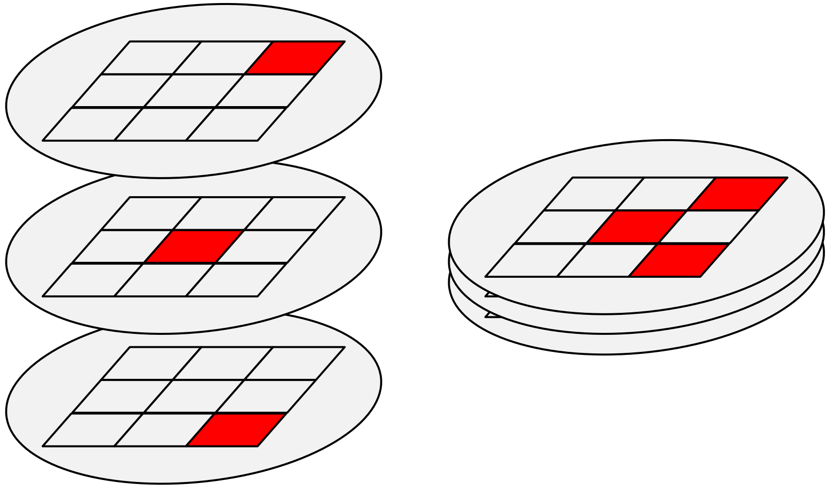


Wafer to Wafer (W2W) process has already POR

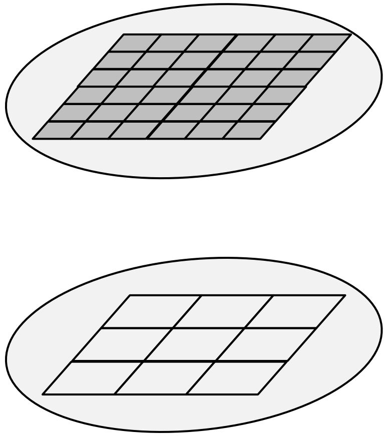
Dielectrics = SiO_2 (Inorganic)

Issue of the Wafer to Wafer bonding

W2W

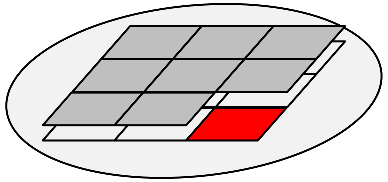


The more stacking wafers,
the more defects

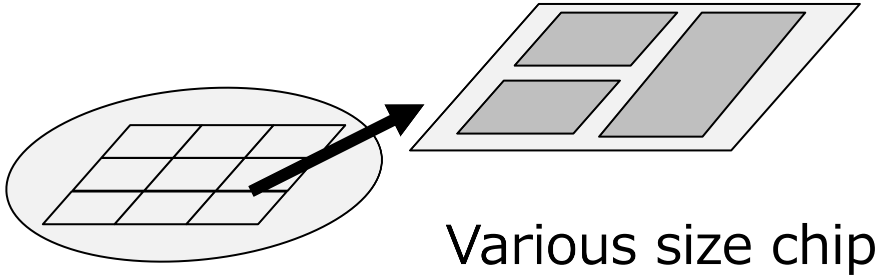


Cannot bond difference size chip

Chip to Wafer(C2W)



Bonding with
only known good die



Various size chip
available

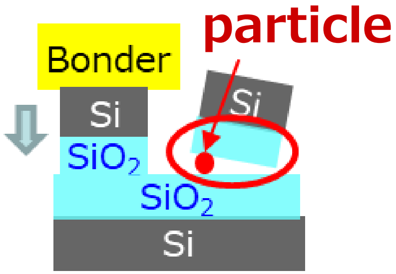
Benefits of C2W HB : Free combination of design with high yield.

Issues for C2W Inorganic HB

Issue

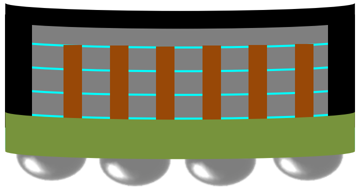
Voids problem due to particle from dicing

⇨ **Bonding failure and Defective insulation**



Warpage due to multiple stacking of thinned chips

⇨ **Crack, mis-alignment and bonding failure**



Low yield **Low reliability**

Solution

Inorganic Hybrid Bonding

▼

Polymer Hybrid Bonding

Low temperature processable (<250℃)

Polymer dielectric materials

Wide range CTE control (5～100ppm/K)

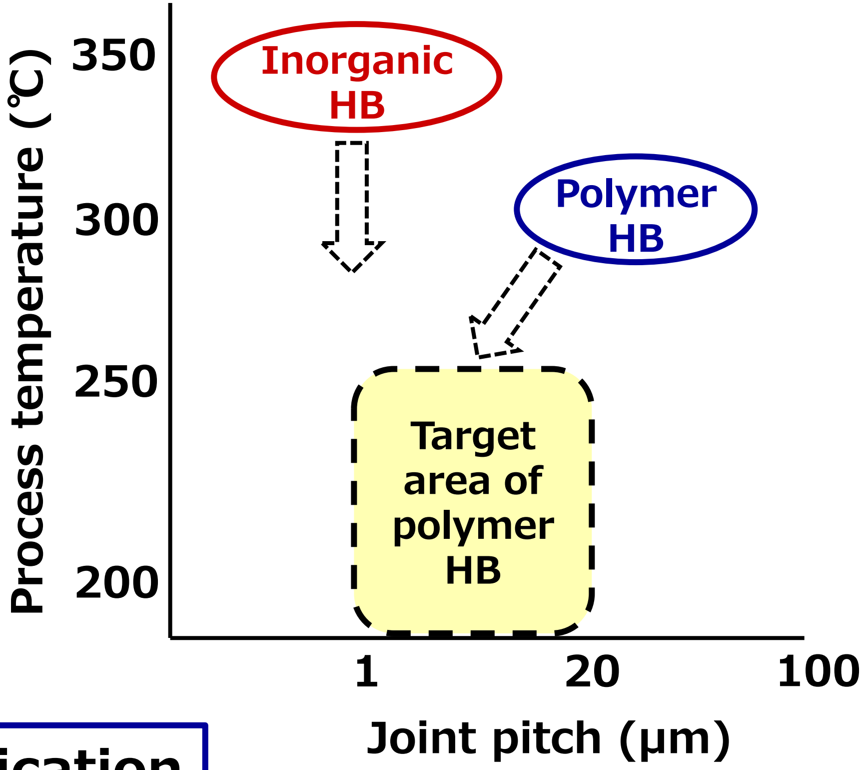
Low modulus (<5GPa)

Polymer hybrid bonding could be the solution for C2W HB issues.

Process Capability and Target

	Inorganic HB (SiO_2)	Polymer HB
Bump pitch	1µm	3~10µm
Max. Process temp.	≧300℃ (Annealing)	250℃ (Annealing)
Bonding yield *particle influence	Low	High
Thermal conductivity	High	Low
Application	Logic/SRAM	HBM die stack

■Status/Development Target



Advantages

SiO_2 : Fine pitch and thermal conductivity

Polymer : Low temp. process with higher yield

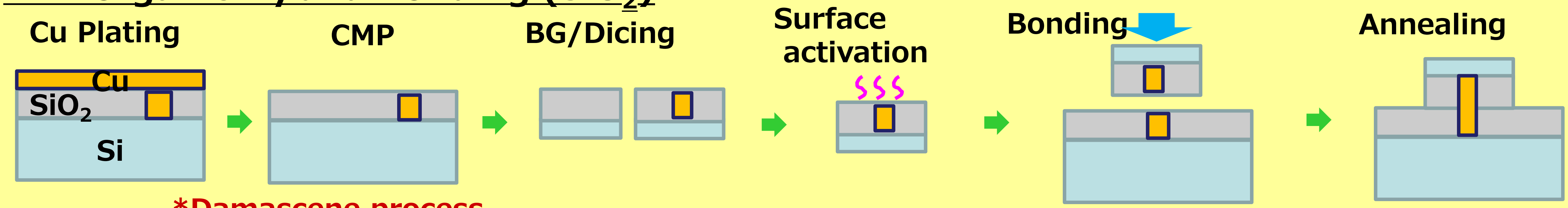
Application

Logic / SRAM with ≦1µm pitch

HBM die stack with 1~20µm pitch

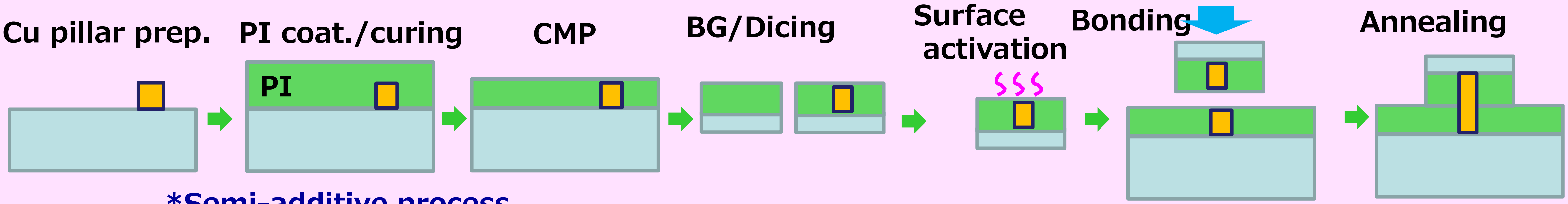
Process of Inorganic and Polymer HB

1. Inorganic Hybrid Bonding (SiO_2)



*Damascene process

2. Polymer Hybrid Bonding



*Semi-additive process

Establishing polymer CMP process could be a challenge.

Mechanism of polymer bonding with surface activation is still at an immature stage.

Polymer HB Challenges

Low Temperature & Low Pressure Bonding

Investigation about criteria of bonding process conditions.
***Optimization for each polymers**

Bonding Mechanism

Estimation of the polymer-to-polymer bonding mechanism.
***Analysis of surface after plasma activation**

Polymer CMP Process

Control of Cu topology and Cu height after CMP process.
***Optimization of CMP conditions**

Outline

1. Introduction and Background
2. **Polymer Bonding Test**
3. Polyimide-to-Polyimide (PI-PI) Bonding Mechanism
4. Hybrid Bonding Demonstration
5. Summary

Material Properties and Design for HB

✓ Low temp. curable feature

	Target	Polyimide-A (PI-A)	Polyimide-B (PI-B)
Curing condition	≦250℃	230℃×60min	200℃×60min
Tg [℃]	>200℃	150, 280	283
Td_5 [℃]	High	350	440
CTE [ppm/K]	Low	55	23
Elongation [%]	–	100	62
Modulus [GPa]	–	1.7	3.2
Design	–	High elongation/toughness & Low modulus type	Low CTE type *close to Cu (=18ppm/K)

*Suppression of stress and warpage

PI-A (Low modulus) and PI-B (Low CTE) were designed for polymer HB study.

Polymer HB Challenges

Low Temperature & Low Pressure Bonding

Investigation about criteria of bonding process conditions.
*Optimization for each polymers

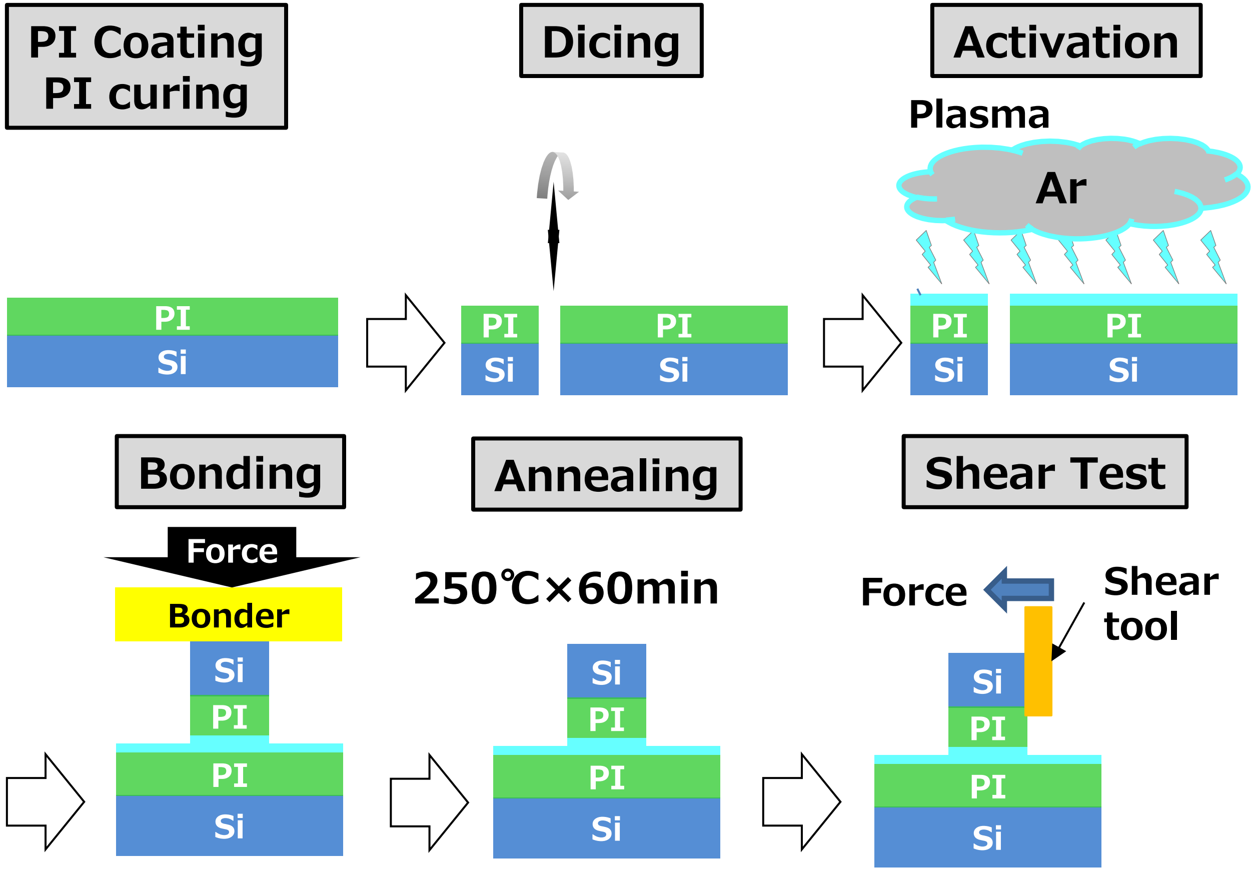
Bonding Mechanism

Estimation of the polymer-to-polymer bonding mechanism
*Analysis of surface after plasma activation

Polymer CMP Process

Control of Cu topology and Cu height after CMP process.
*Optimization of CMP conditions

Test Method of General PI-PI Bonding



PI Coating
PI curing

Dicing

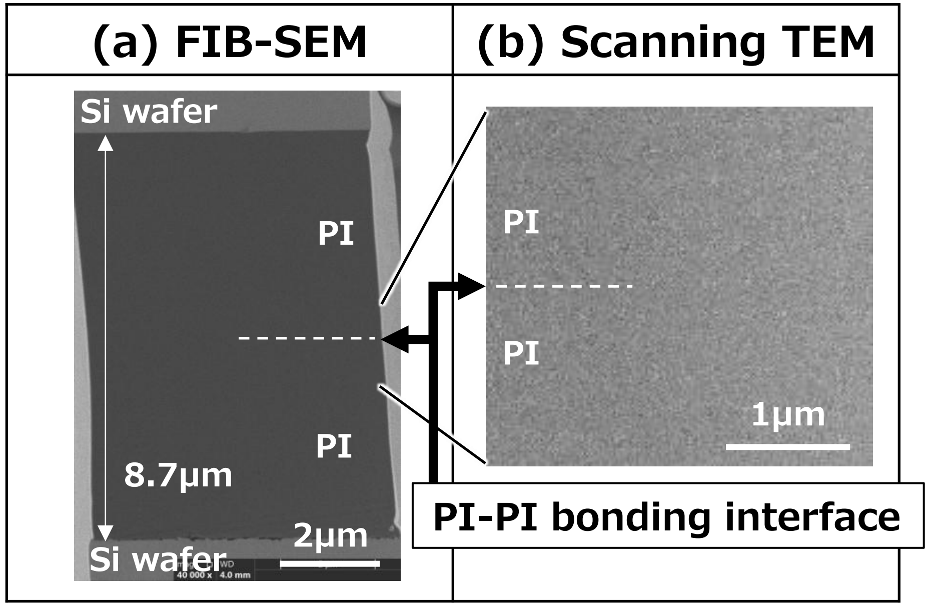
Activation

Bonding

Annealing

Shear Test

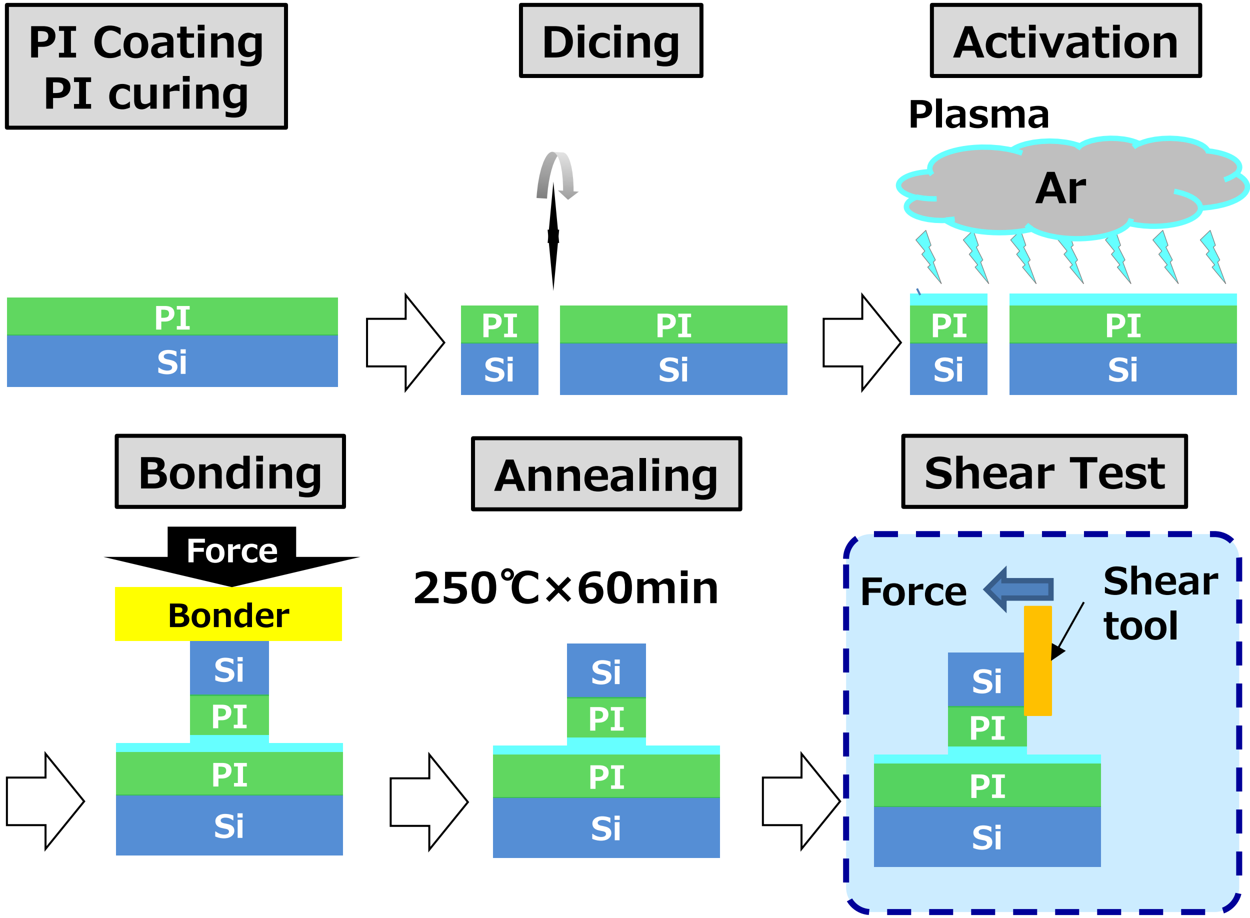
*Cross-section image of
PI-PI bonded interface
(Die shear strength >25MPa)



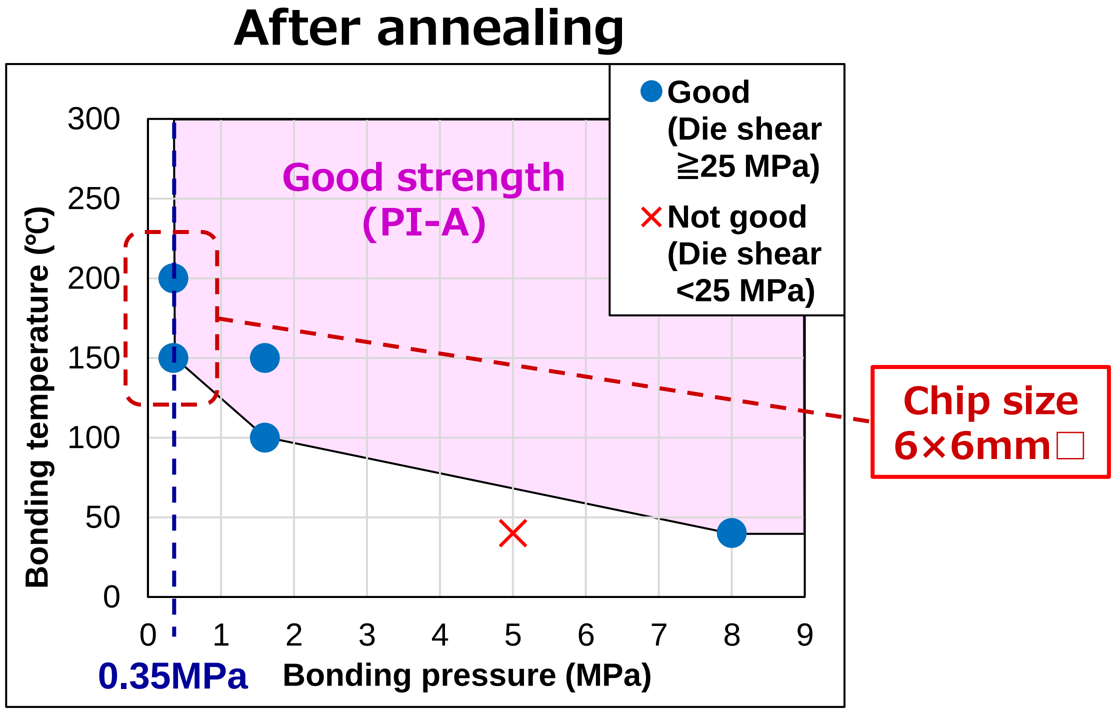
✓ No voids in submicron-scale

PI-PI bonding strength was evaluated by die shear test
Die shear strength of >25MPa was sufficient (*FIB-SEM, STEM)

Result of PI-PI Bonding Test (PI-A)



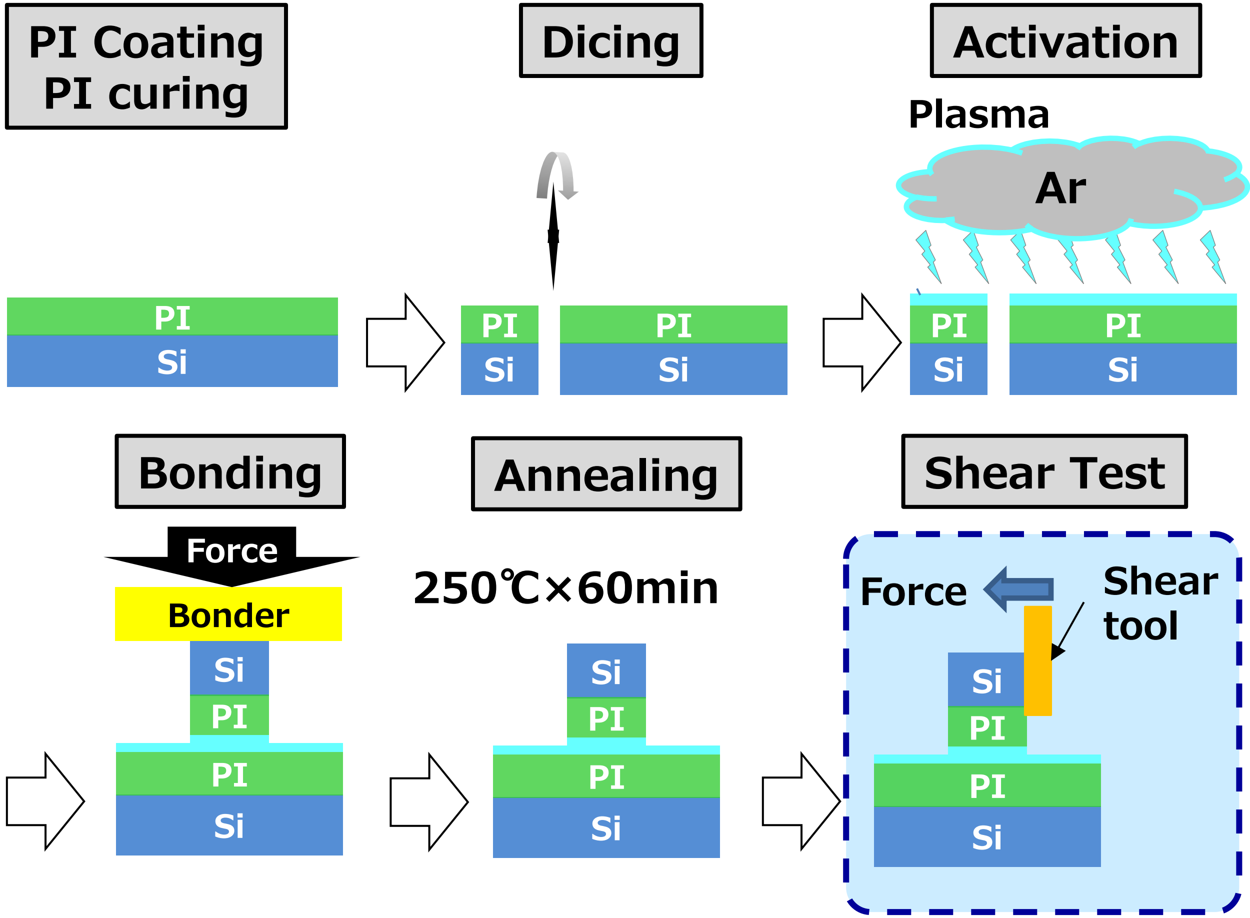
PI-A *Low modulus



*Plasma condition : 20Pa, 20sccm, 20s, RF power=150W
*Chip size : 2.5×2.5mm□ (except for 0.35MPa)

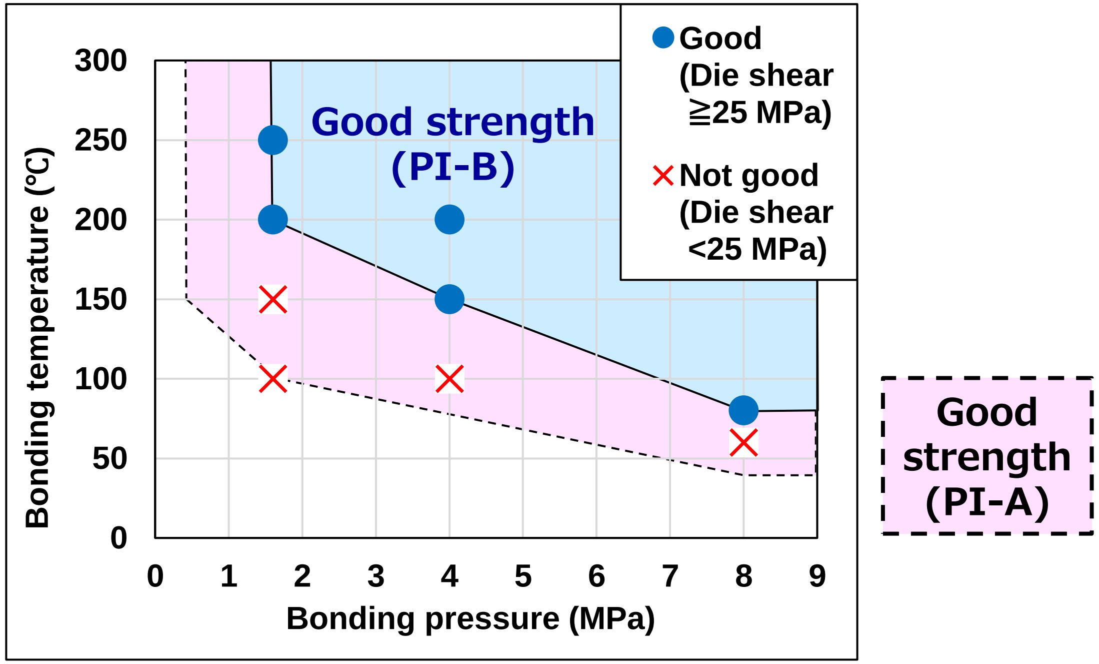
PI-A : Low pressure & Low temp. bonding property.
Trade-off relationship between temp. and pressure.

Result of PI-PI Bonding Test (PI-B)



PI-B *Low CTE

After annealing



*Plasma condition : 20Pa, 20sccm, 20s, RF power=150W
*Chip size : 2.5×2.5mm□

PI-B : Relatively high pressure & high temp. bonding.
PI-A/PI-B : Different criteria of bonding process.

→ **Mechanical properties were contributed**

Outline

1. Introduction and Background
2. Polymer Bonding Test
3. **Polyimide-to-Polyimide (PI-PI) Bonding Mechanism**
4. Hybrid Bonding Demonstration
5. Summary

Polymer HB Challenges

Low Temperature & Low Pressure Bonding

Investigation about criteria of bonding process conditions.
*Optimization for each polymers

Bonding Mechanism

Estimation of the polymer-to-polymer bonding mechanism.
*Analysis of surface after plasma activation

Polymer CMP Process

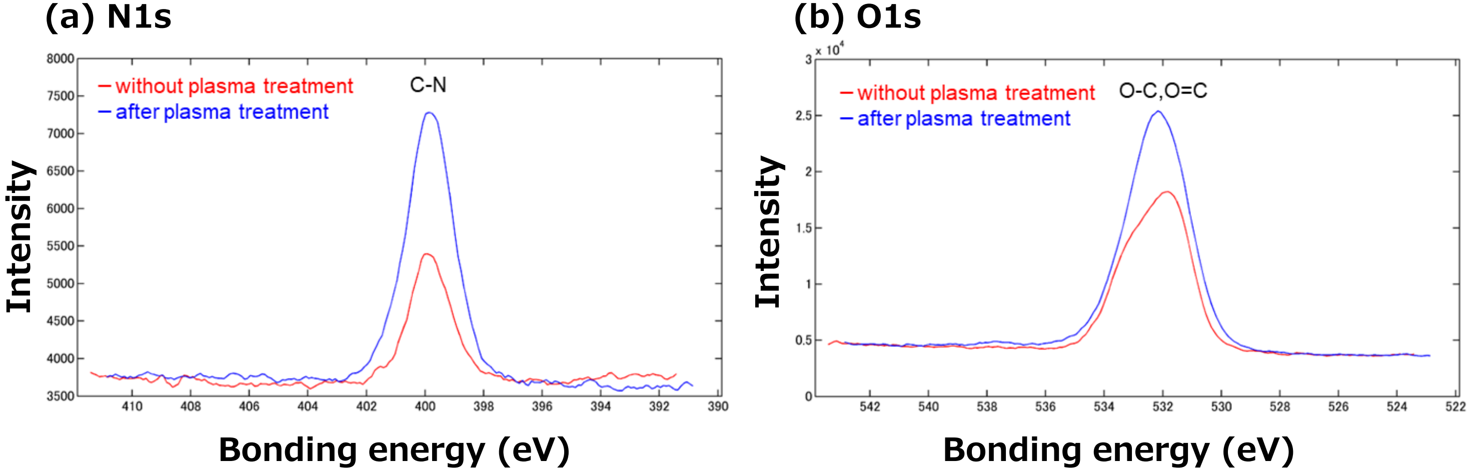
Control of Cu topology and Cu height after CMP process.
*Optimization of CMP conditions

3. Polyimide-to-Polyimide Bonding Mechanisms

Effect of Plasma Activation

＊Plasma condition :
20Pa, 20sccm, 20s, RF power=150W

■X-ray Photoelectron Spectroscopy Analysis (XPS)


(a) N1s

(b) O1s

PI-B
＊Low CTE

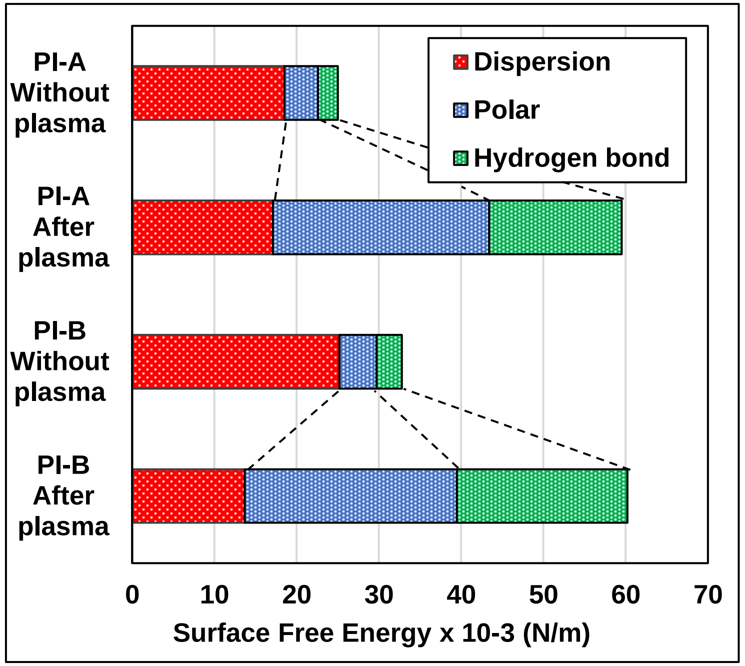
Plasma	C	N	O	-COOH
Before	1.00	0.03	0.29	0.001
After	1.00	0.09	0.49	0.013

✓ COOH group : Increased
✓ C-N bonding : Increased

■Surface Free Energy Analysis (SFE)

PI-A
＊Low modulus

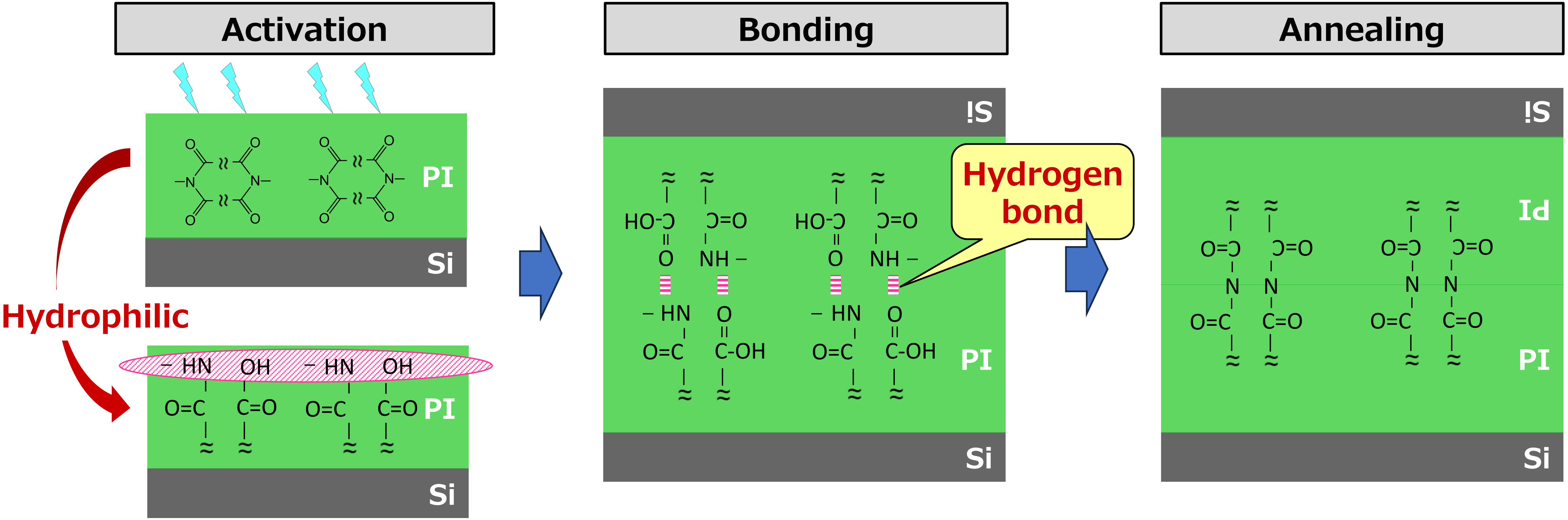
PI-B
＊Low CTE



✓ Polar and hydrogen bond : Increased
✓ PI-A/PI-B : No significant difference

Plasma activation : Increasing of polar and hydrogen bond component

Assumed Bonding Mechanism



***Increasing of COOH and amide groups**

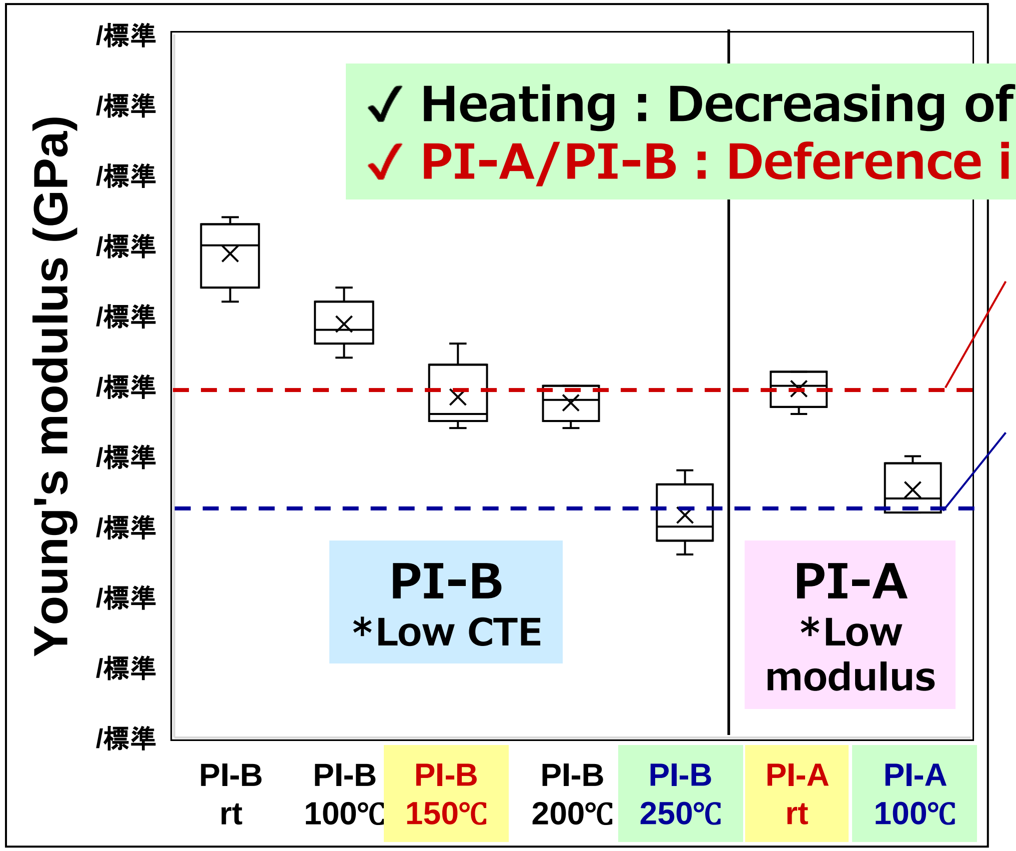
***Generation of interaction (ex. hydrogen bond)**

***Formation of covalent bond (ex. intermolecular imidization)**

Bonding driving force :
①Interaction by hydrogen bond ②Covalent bond by imidization

Influence of mechanical Properties

■Young's Modulus vs. Temperature (Nano-indentation)



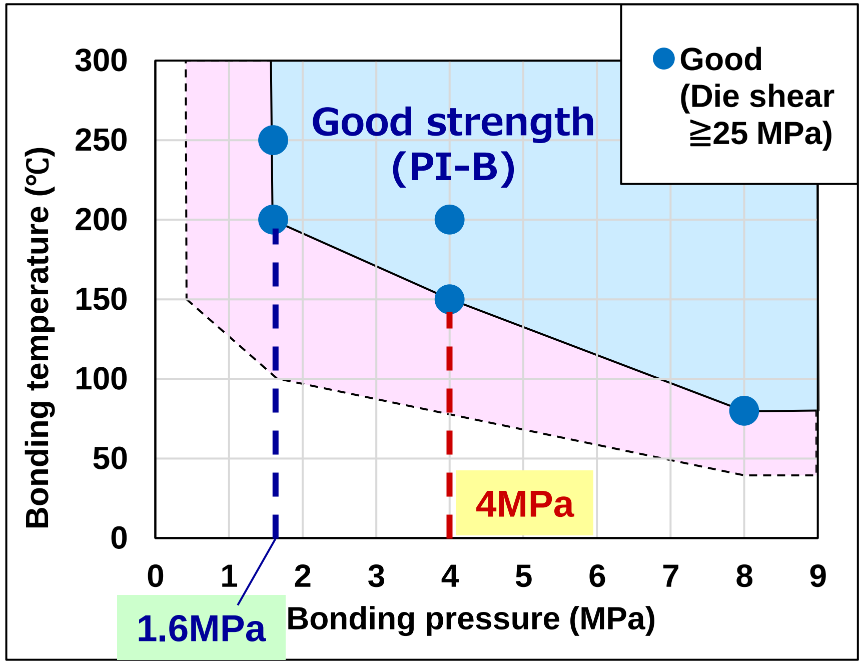
✓ Heating : Decreasing of modulus
✓ PI-A/PI-B : Deference in modulus changing

Assumed criterion of 4MPa bonding condition

Assumed criterion of 1.6MPa bonding condition

(After annealing)

Good strength (PI-A)



Heating at specific temp. → Leading towards to certain modulus → Provide PI-PI bonding with good strength

Outline

1. Introduction and Background
2. Polymer Bonding Test
3. Polyimide-to-Polyimide (PI-PI) Bonding Mechanism
4. **Hybrid Bonding Demonstration**
5. Summary

Polymer HB Challenges

Low Temperature & Low Pressure Bonding

Investigation about criteria of bonding process conditions.
*Optimization for each polymers

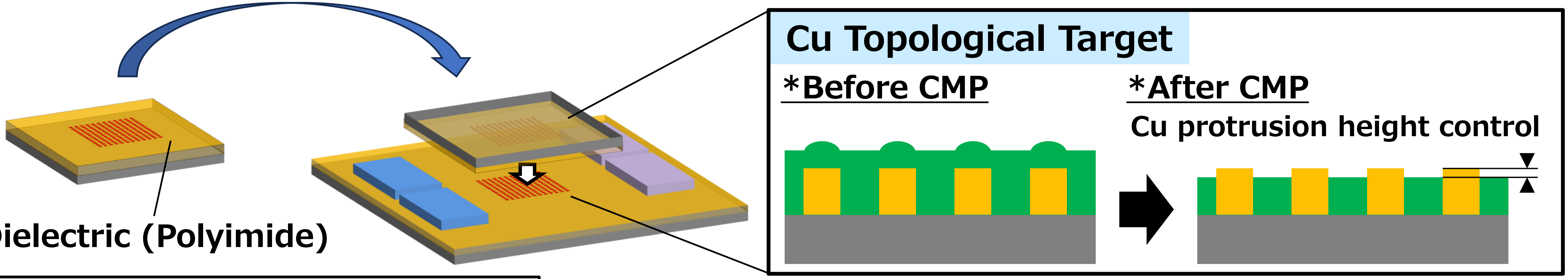
Bonding Mechanism

Estimation of the polymer-to-polymer bonding mechanism.
*Analysis of surface after plasma activation

Polymer CMP Process

Control of Cu topology and Cu height after CMP process.
*Optimization of CMP conditions

Control of Cu Topology for HB



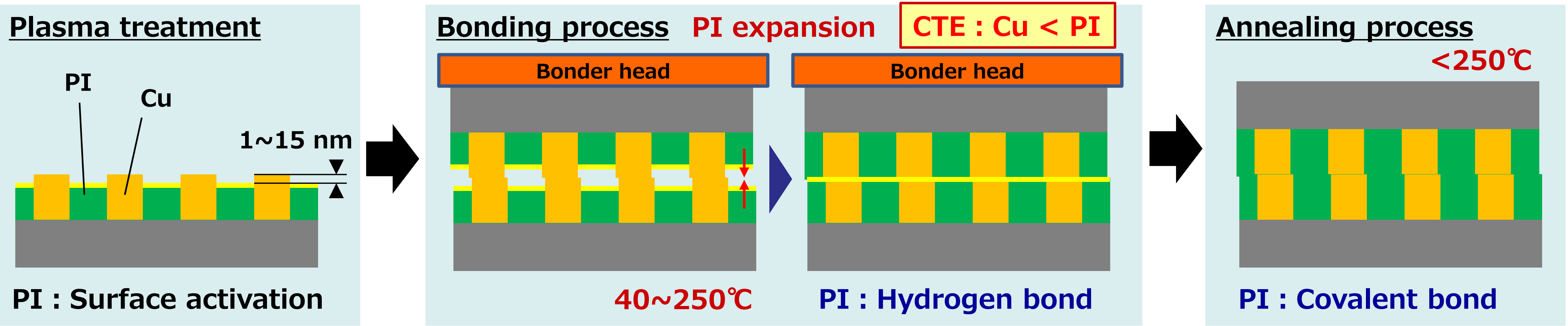
Cu Topological Target

***Before CMP**

***After CMP**

Cu protrusion height control

Bonding Scheme (Current Target)



Plasma treatment

PI : Surface activation

Bonding process PI expansion **CTE : Cu < PI**

40~250℃

PI : Hydrogen bond

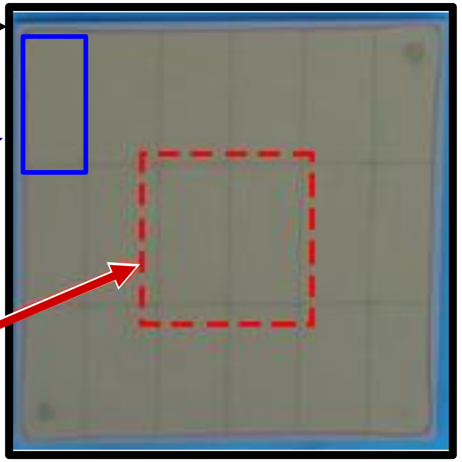
Annealing process

PI : Covalent bond

Toray's Target : Suitable Cu protrusion for HB is PI dependent (*CTE : Cu < PI).

Conditions of HB Test

■Coupon Sample Detail



Coupon size : 36mm×36mm
18chips in a coupon

Small chip
6mm×13mm

central small 2chips

Cu pillar : 5μmΦ, 10μm pitch

*Courtesy of Institute of Microelectronics, Singapore's Agency for Science

■CMP conditions

Equipment :
NF-300 (NANO FACTOR Inc.)
Slurry :
Alkaline type slurry
Pad :
Hard type pad
Table speed :
120 rpm
Pad temp. :
<40℃

*Courtesy of D-process inc., Japan

<Test method>

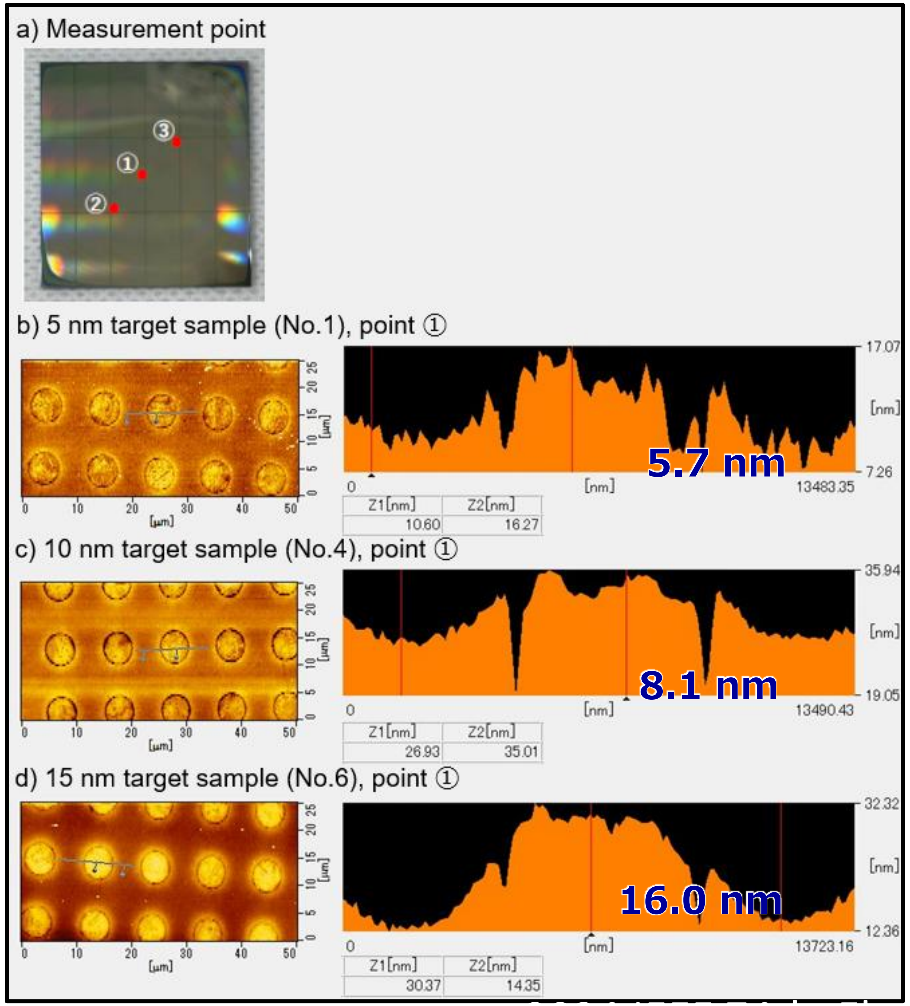
Step 1 : PI coating and PI curing of PI-A (*Low modulus)
Step 2 : CMP treatment of PI surface and Cu surface
Step 3 : Measurement of surface profile of PI/Cu with central small 2chips

PI-A (Low modulus) was applied to hybrid bonding test.

4. Hybrid Bonding Demonstration

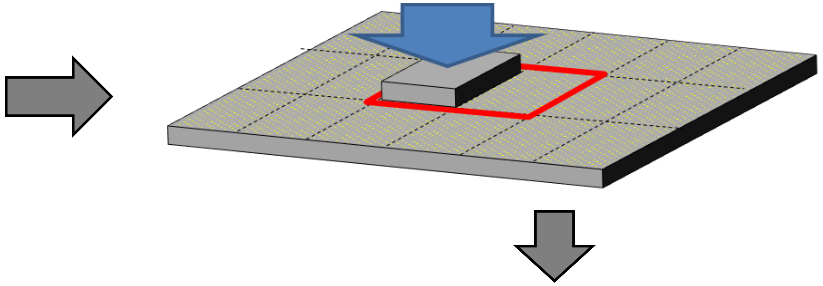
Result of HB Test

■AFM Analysis



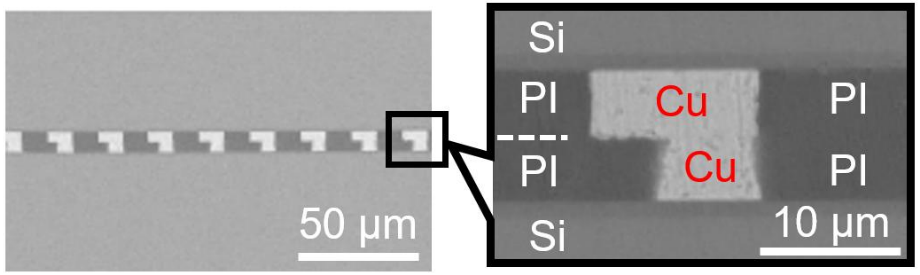
Dicing

Bonding + Annealing



Bonding Condition :
Temp.=200℃
Force=25N (=0.35MPa)
Time=3s
Annealing :
250℃×3h

■Cross-section SEM Image of Bonded Chips



*5nm Cu protrusion

✓ Good PI-PI and Cu-Cu joints (No void)

*Courtesy of Institute of Microelectronics, Singapore's Agency for Science

Cu protrusion was controlled at target range of 5~15nm.
PI-PI/Cu-Cu hybrid bonding was successfully demonstrated.

Process Procedure for Daisy Chain Test

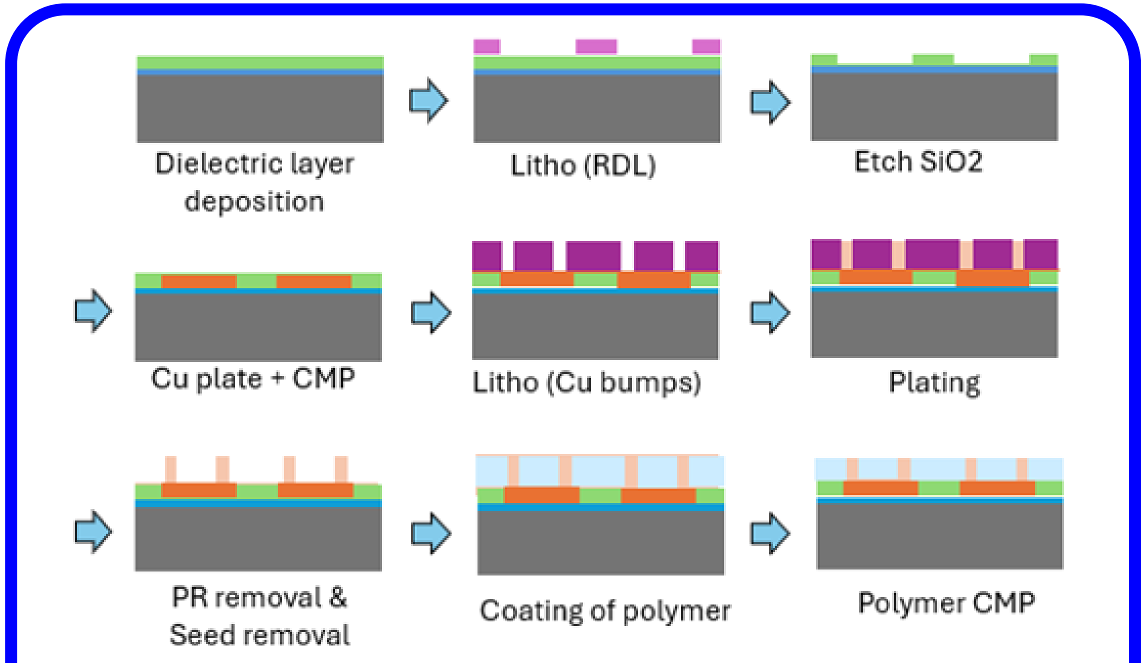


Figure 1: Fabrication process of top chips

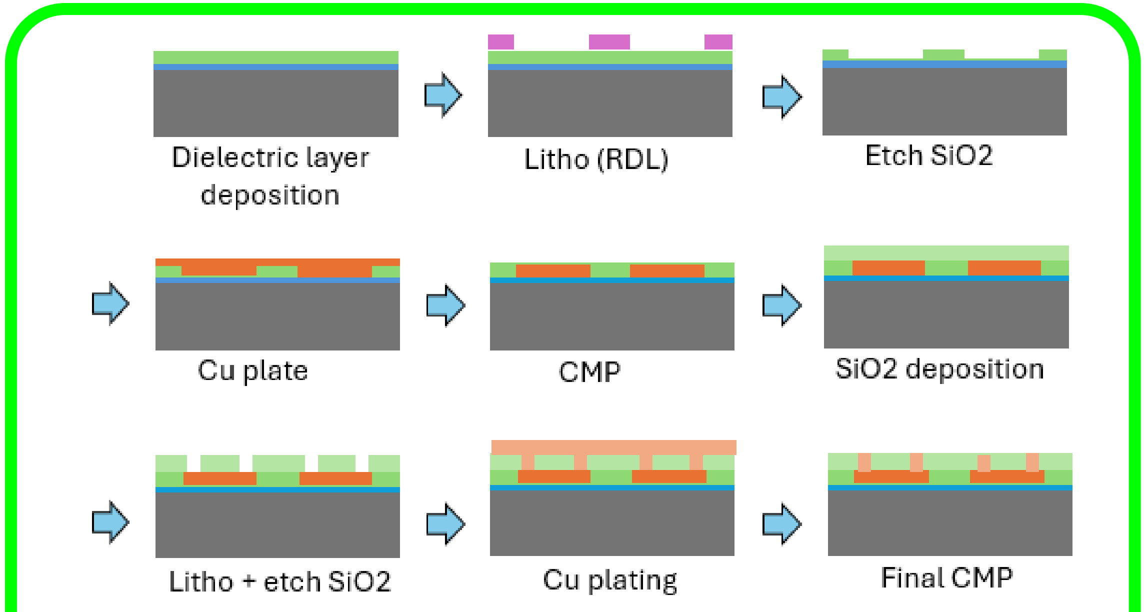


Figure 2: Fabrication process of interposer

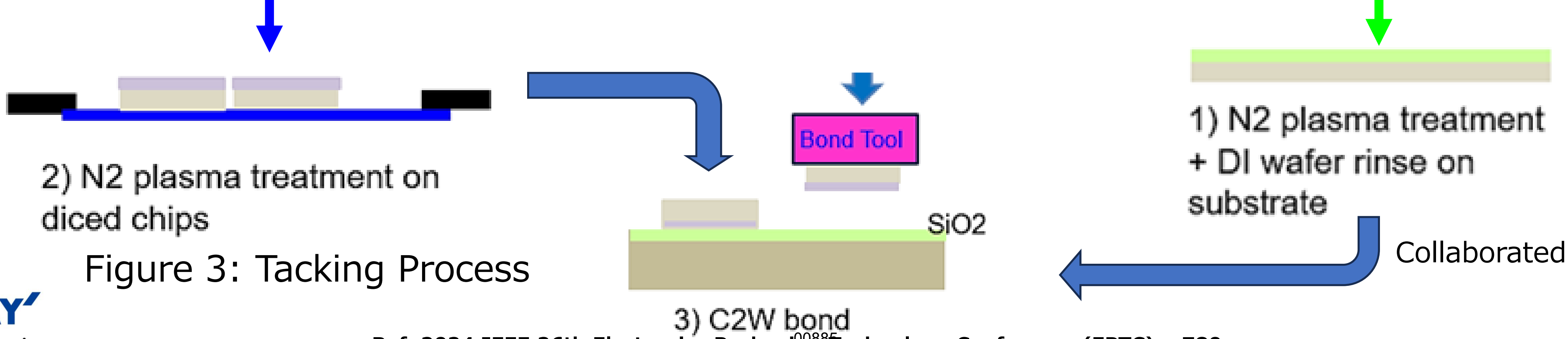


Figure 3: Tacking Process

Collaborated with A*STAR IME

Ref. 2024 IEEE 26th Electronics Packaging Technology Conference (EPTC), p780

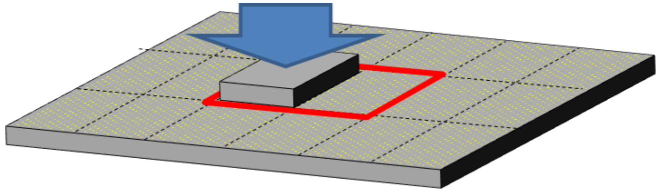
Daisy Chain Results with SiO2 and Polymer

Test Condition

- Bonding Chuck : 200℃
- Substrate: r.t.
- Bonding Pressure : 1.3MPa
- Bonding time : 30s
- Annealing : 250℃×5h

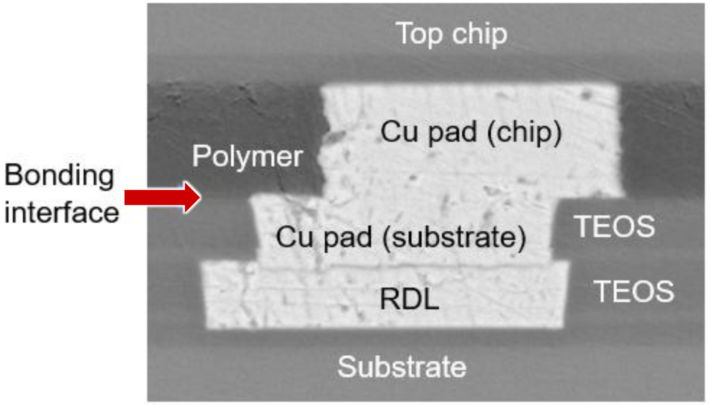
"IME's C2W HB consortium"

Bonding



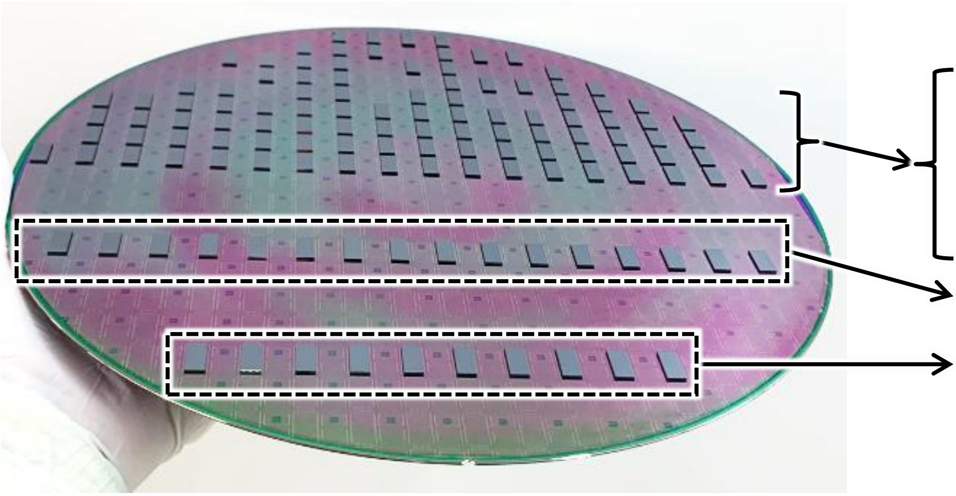
Alignment accuracy <2μm

<X-sectional View>

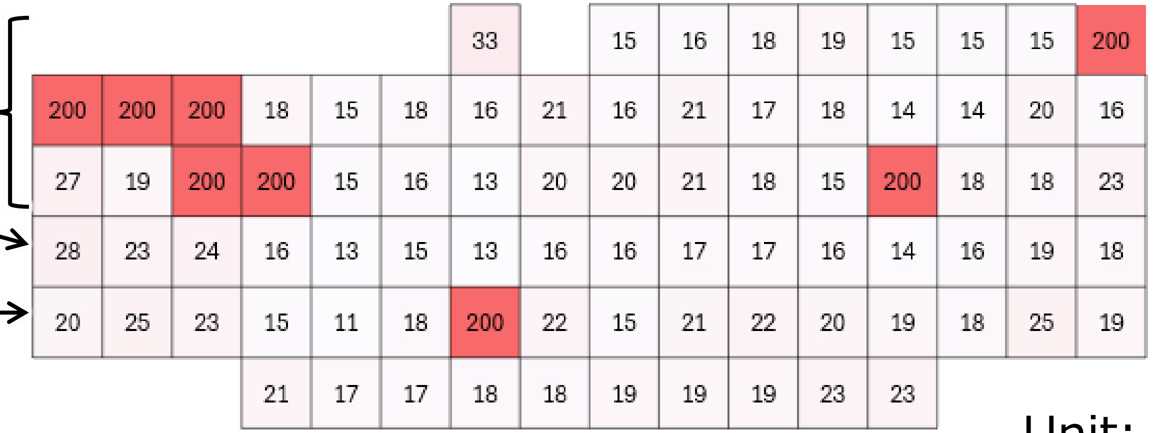


Collaborated with IME A*STAR

■Image after C2W-HB



<Electric resistance of each die after annealing>



						33		15	16	18	19	15	15	15	200
200	200	200	18	15	18	16	21	16	21	17	18	14	14	20	16
27	19	200	200	15	16	13	20	20	21	18	15	200	18	18	23
28	23	24	16	13	15	13	16	16	17	17	16	14	16	19	18
20	25	23	15	11	18	200	22	15	21	22	20	19	18	25	19
			21	17	17	18	18	19	19	19	23	23			

☐ : OK
🟥 : NG

Unit: Ω

Ref. 2024 IEEE 26th Electronics Packaging Technology Conference (EPTC), p780

Yield 90%, we have to optimize Cu protrusion.

Summary

1. Low temperature curable polyimides for hybrid bonding has been developed.
2. Relationship between bonding conditions and material modulus was revealed.
3. PI-PI bonding mechanism was proposed by analysis of PI surface after plasma activation.
4. An amount of Cu protrusion was precisely controlled by PI/Cu CMP, and hybrid bonding with low temperature curable polyimide was successfully demonstrated.

Thank you !