TOKYO ELECTRON

A Novel, Automated Measurement and Analysis Technique for Bonding Energy of Fusion and Hybrid Wafer to Wafer Bonding

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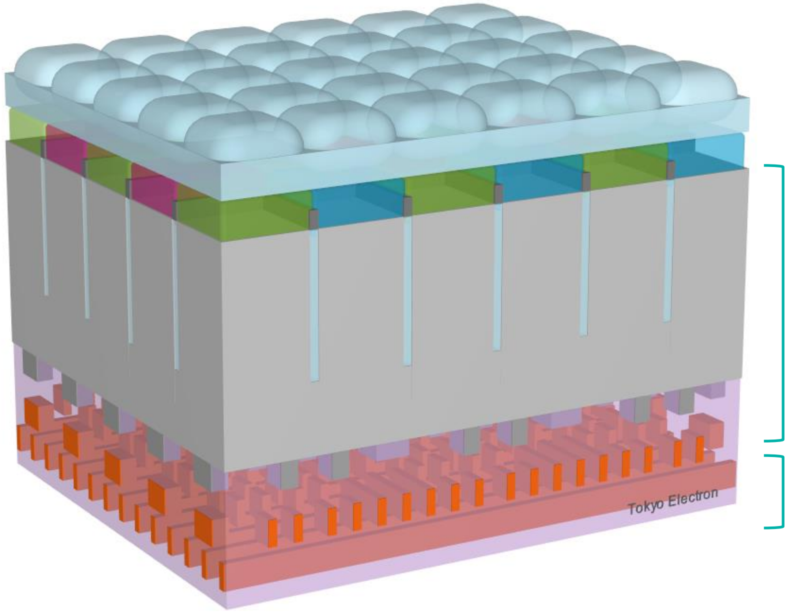
Outline

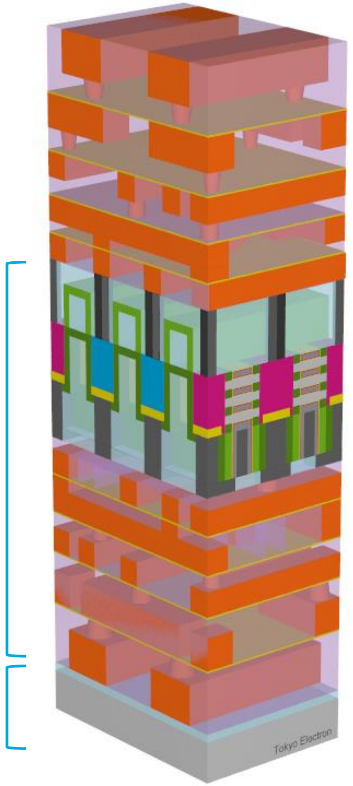
- Wafer-to-wafer bonding background and process flow
- Bonding strength measurement (dual cantilever beam)
- Removing DCB error in ambient environment
- Fusion bonding strength experiments
- Hybrid bonding strength demonstration

Wafer-to-Wafer Bonding Enabling 3D Integration

- Hybrid Bonding
- Fusion Bonding

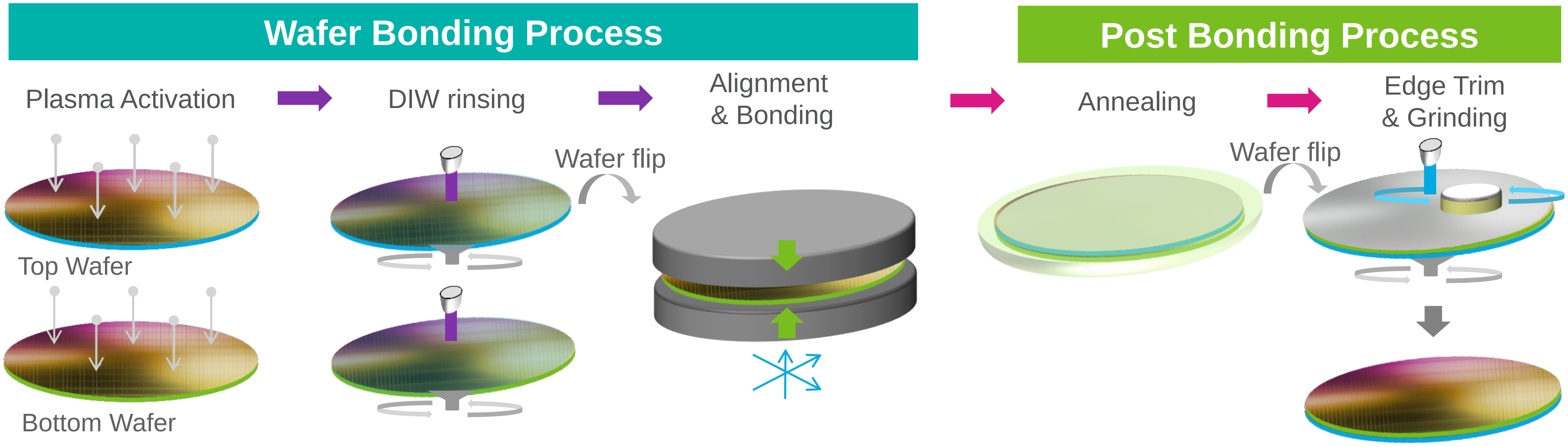


Bonding Interface

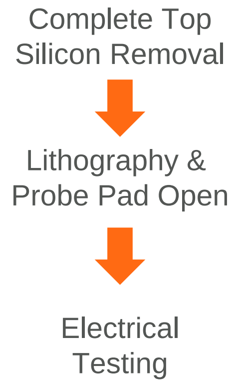


Source: TEL

Wafer-to-Wafer Bonding Process Flow



- Surface activation plasma (SAP) and rinse is used to form Si-OH groups on the wafer
- A post-bond anneal is used to condense these groups into permanent Si-O-Si bonds and any copper pads will expand to form Cu-Cu bonds across the interface
- Bonding quality before thinning is determined by bonding strength and void detection

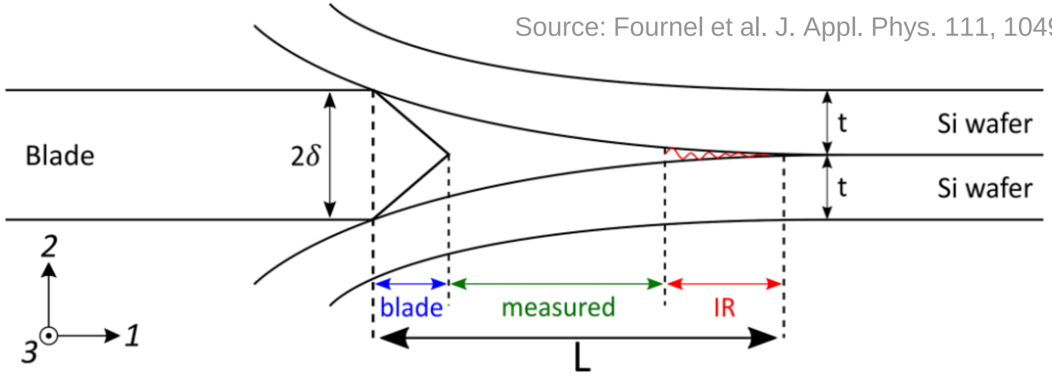


Dual Cantilever Beam Bonding Energy (BE) Measurement

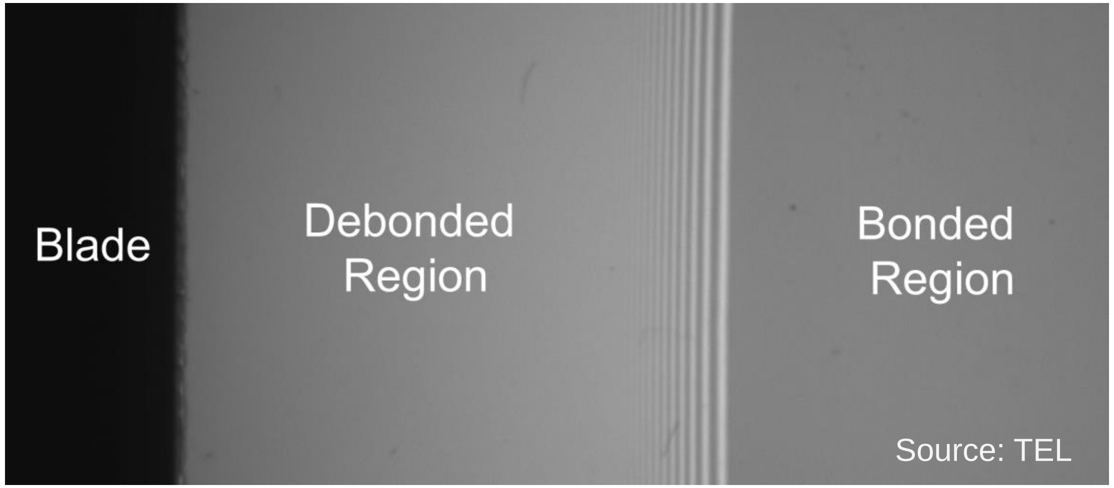
- Bonding energy is typically measured by DCB
- Blade is inserted between bonded wafers along a given Si crystal plane
- BE is calculated from the resulting crack length using Maszara's formula (1)-(3):
- $G_{IC} = 2\gamma$ (1)
- $\gamma = \frac{3(t_{blade})^2 E_1 (t_{beam1})^3 E_2 (t_{beam2})^3}{16(L_{crack})^4 [E_1 (t_{beam1})^3 + E_2 (t_{beam2})^3]}$ (2)
- $BE = \gamma = \frac{3E(t_{blade})^2 (t_{beam})^3}{32((L_{crack})^4}$ (3)

Source: Maszara, W.P., et al.,J. Appl. Phys. 64(10): p. 4943-4950 (1988).

Source: Fournel et al. J. Appl. Phys. 111, 104907 (2012).

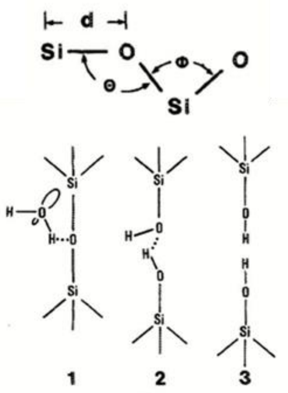


Top-Down View (IR Camera)



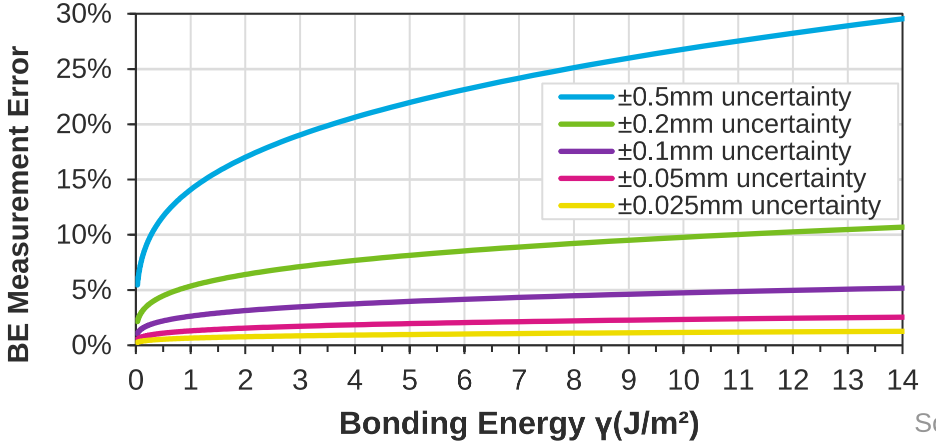
Measurement Errors in DCB Testing

- Operator measurement error:
  - Measuring crack length accurately by eye
  - Timing when to capture image/measure BE
  - Operator bias
- Environmental error:
  - Stress corrosion – humidity decreases bonding energy over time:
  - Stressed Si-O-Si + H_2O → Si-OH + Si-OH



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

$$BE = \frac{3E_{Si}(t_{blade})^2(t_{wafer})^3}{32(L_{crack})^4}$$



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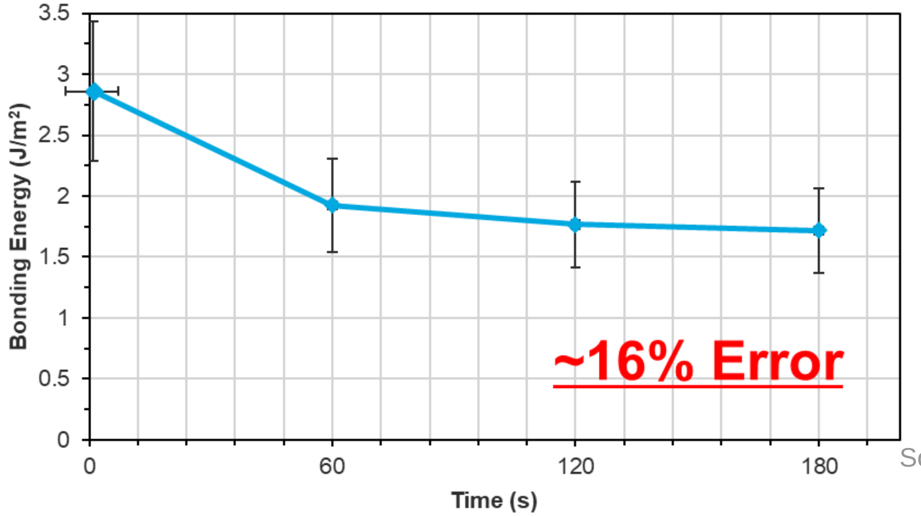
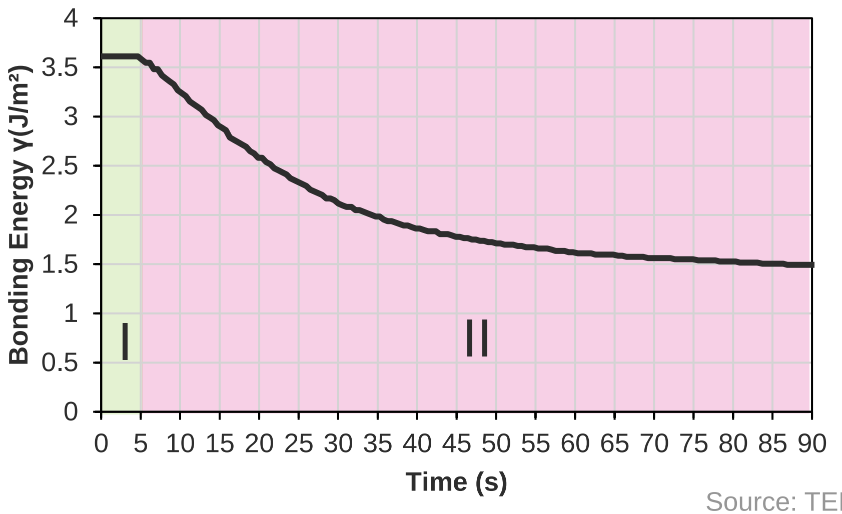


Source: TEL

Removing Error using New DCB Method

- Manual error is removed by automation:
  – Custom algorithm determines when the blade is inserted and measures crack length to ±50um every 0.5s
- By measuring BE multiple times per second, it is found that initially, BE is stable and not affected by stress corrosion
- Measuring BE in this initial plateau removes environmental effects without a glovebox

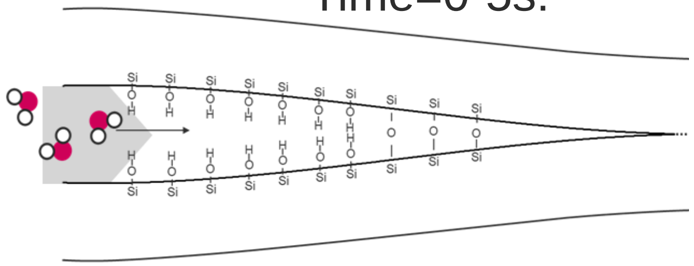
ThOx (N_2 SAP, 350C PBA)



Source: TEL

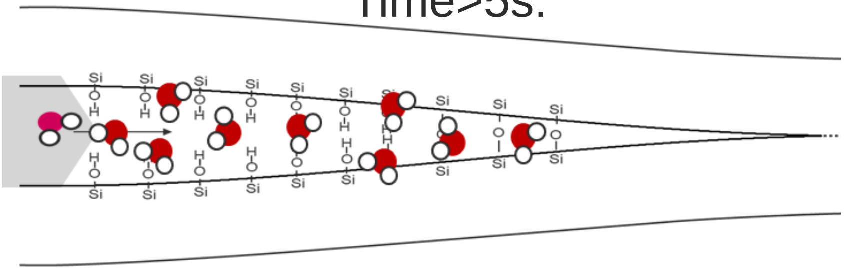
Regime I

Time=0-5s:



Regime II

Time>5s:

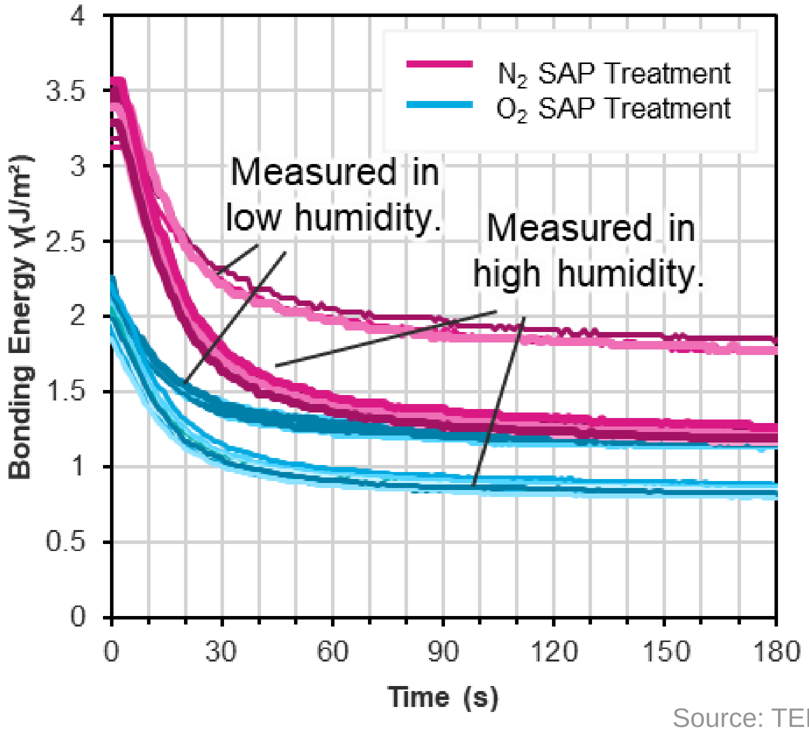


Source: TEL

- **Stable BE w/o stress corrosion**
- **BE decreases over time based on the relative humidity**

Removing Environmental Effects Without a Glovebox

- Thermal Oxide SiO_2 (ThOx) wafers were bonded and treated by 350C 1hr post-bond anneal (PBA)
- BE was measured in ambient environment on two days with high/low humidity
- The new DCB method clearly distinguishes between the two SAP conditions regardless of humidity



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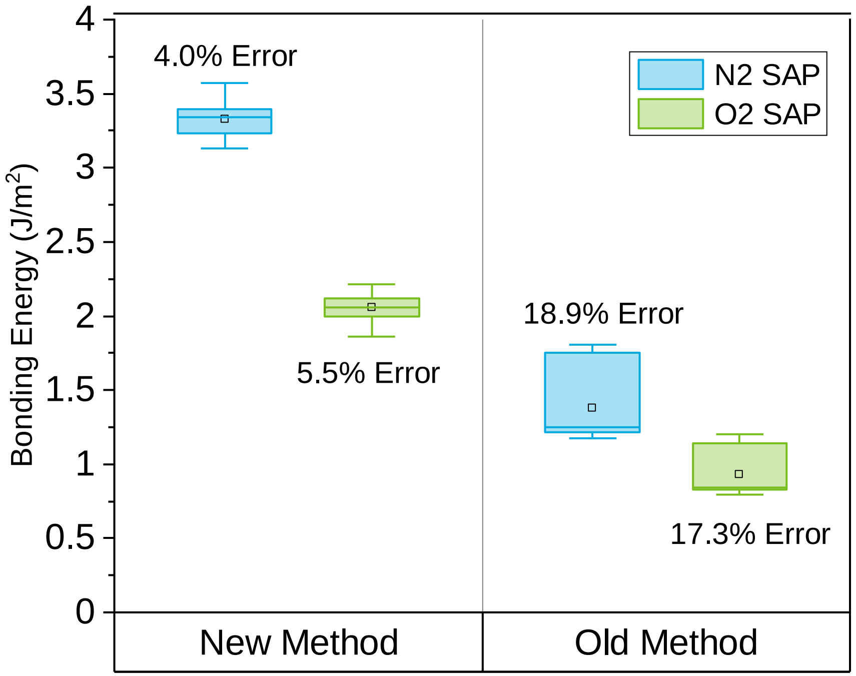
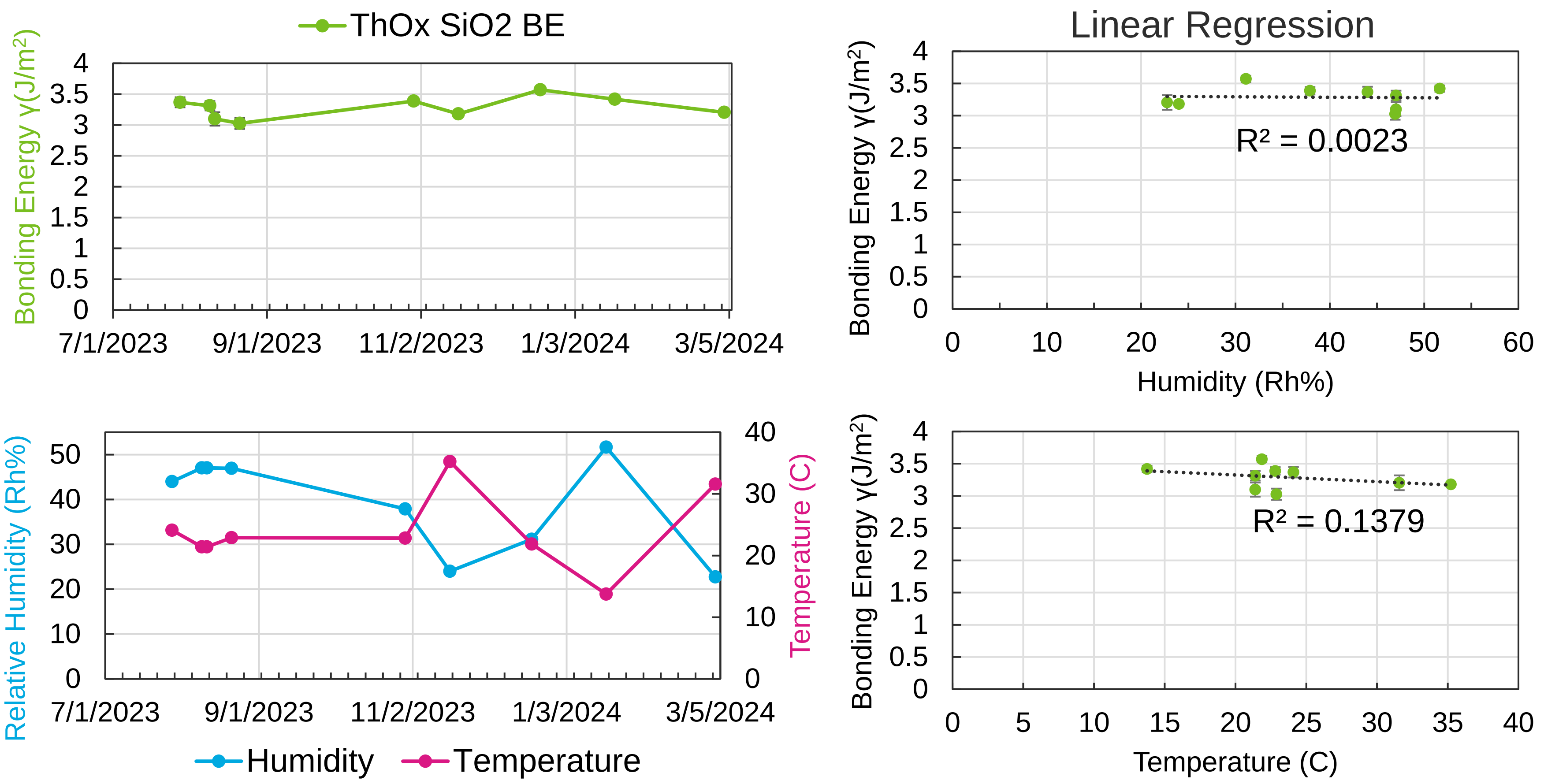


Source: TEL

Measurement Reliability and Repeatability

- Standard thermal oxide (ThOx SiO_2) bonded pair BE tested over 8 months
- All measurements taken out of cleanroom and without glovebox
- Mean BE is 3.31 J/m^2
- Total error of 5.6%
- No correlation between BE and temperature or humidity

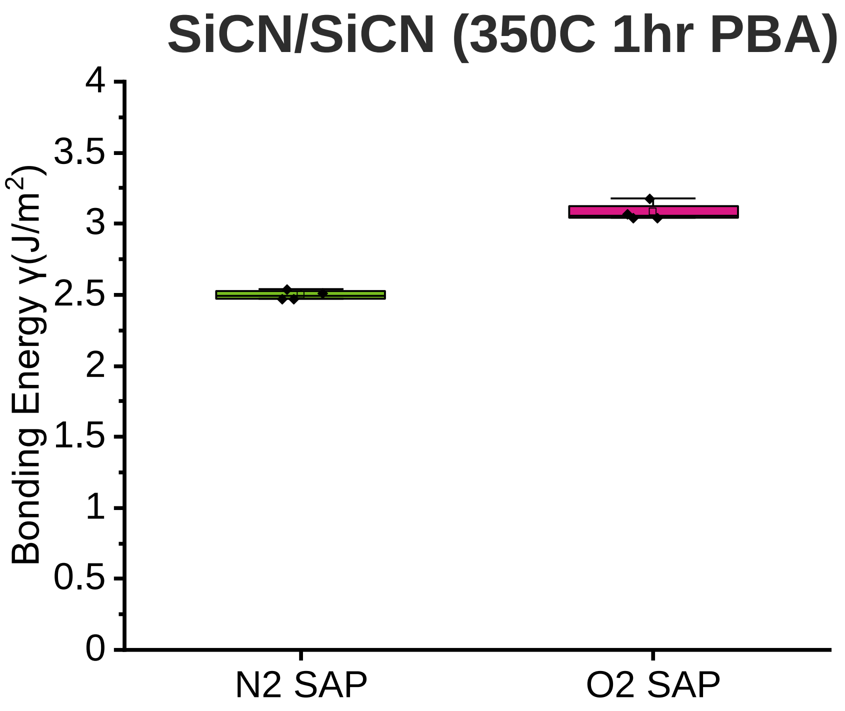
Bonding energy of ThOx (SiO_2) bonded pairs (N_2 SAP, 350C PBA)

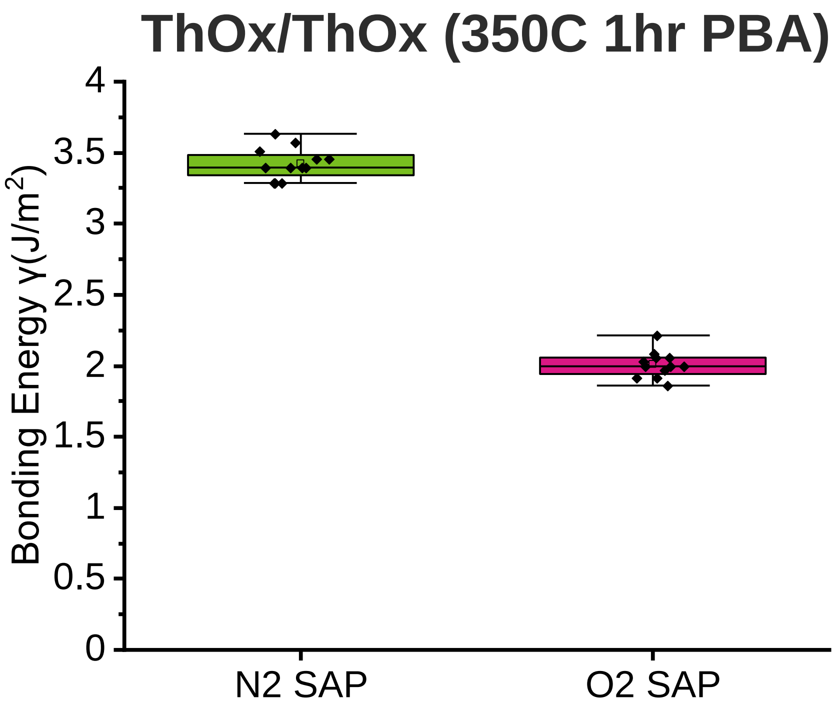


Source: TEL

Fusion Bonding Strength Results

- For SiCN, O_2 SAP provides highest BE, but N_2 SAP is still comparable
- For SiO_2, N_2 SAP provides the highest BE

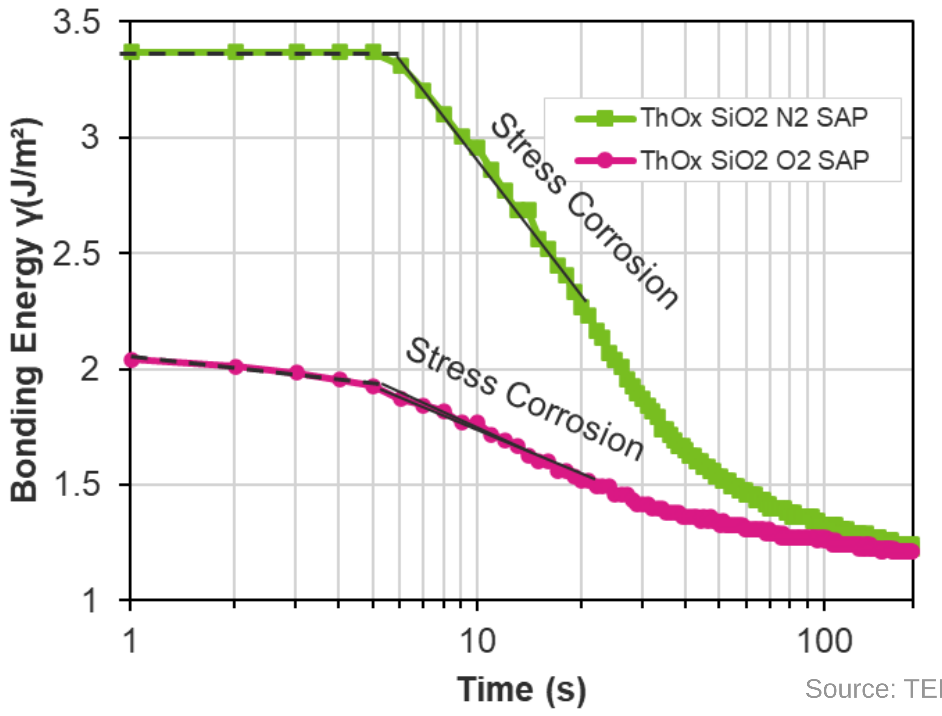




Source: TEL

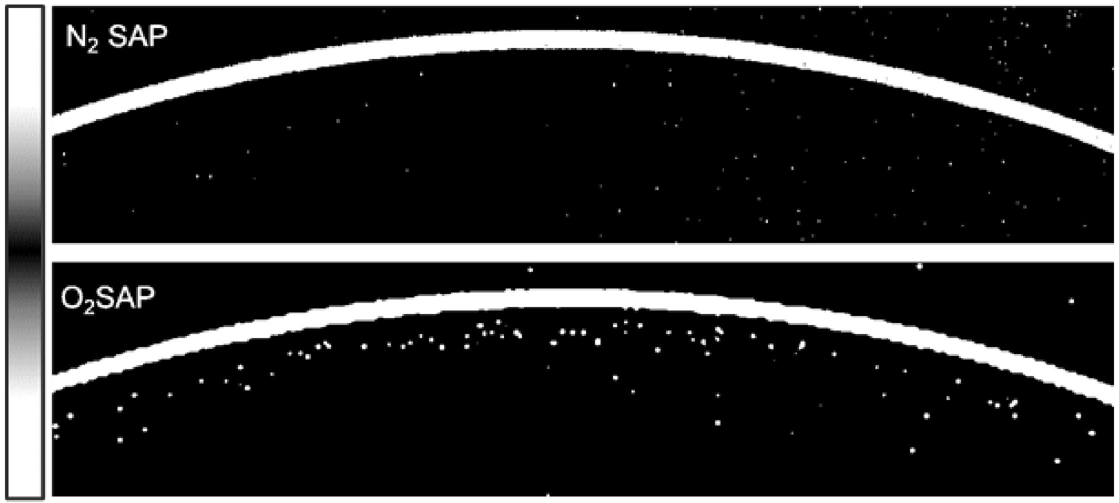
Detecting Water in Bonding Interface

- DCB is highly sensitive to water through stress corrosion reaction
- Stress corrosion in the initial stable region means there is residual water in the bonding interface



Source: TEL

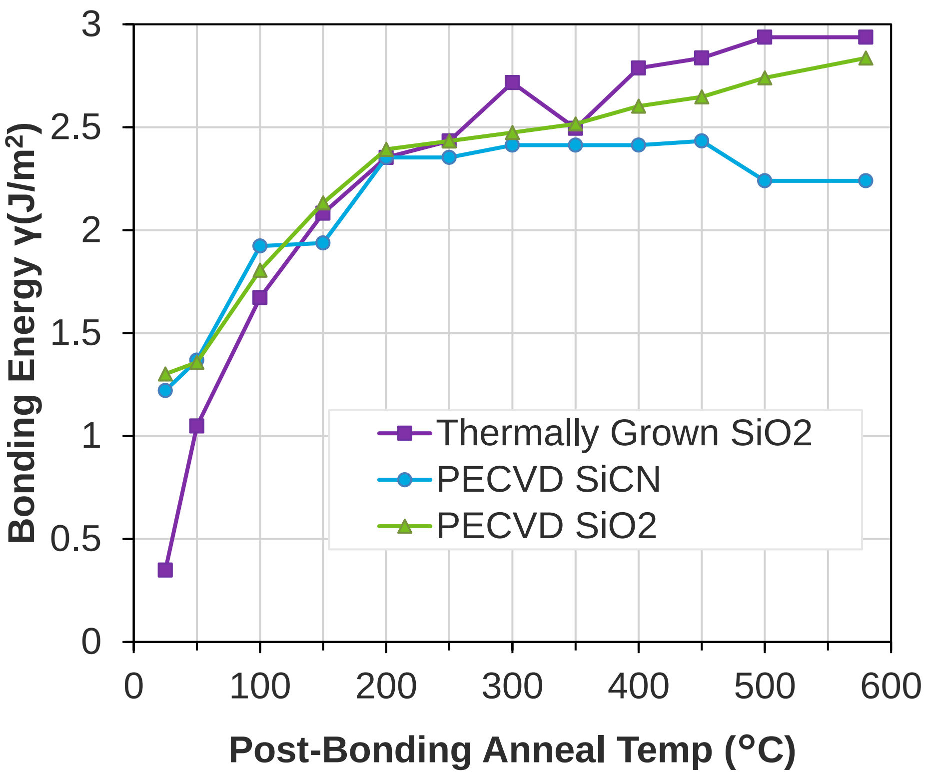
100MHz CSAM

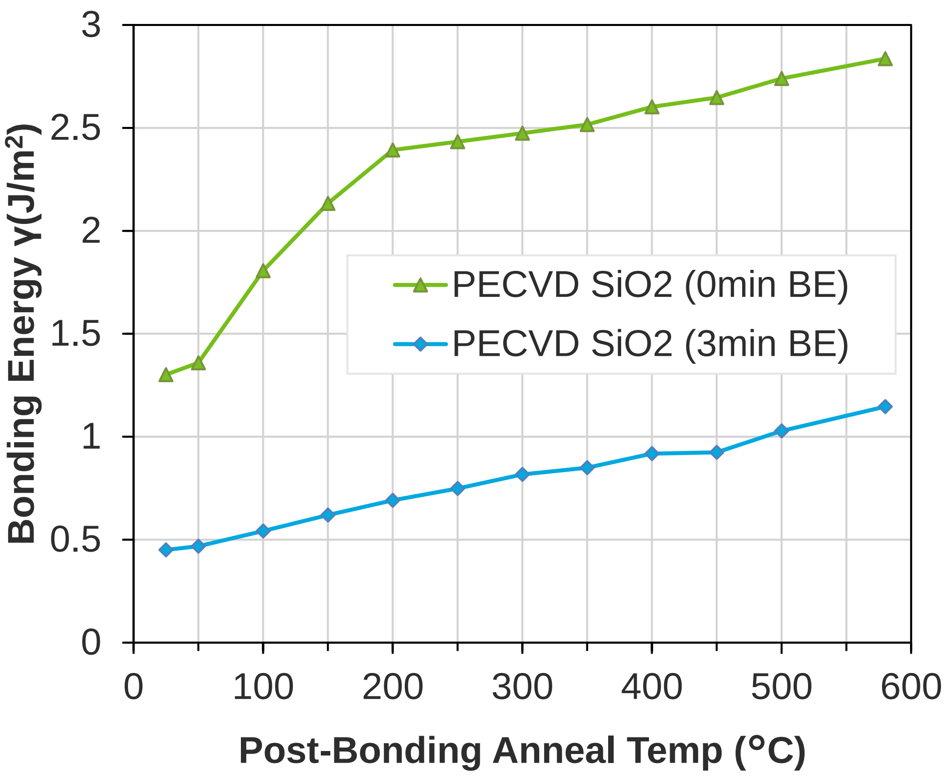


Source: TEL

Clearly Identifying Trends using New DCB

- All wafers were bonded at the same time and annealed for 2hr over the course of two weeks
- 200C 2hr was found the be the minimum anneal conditions for stable BE

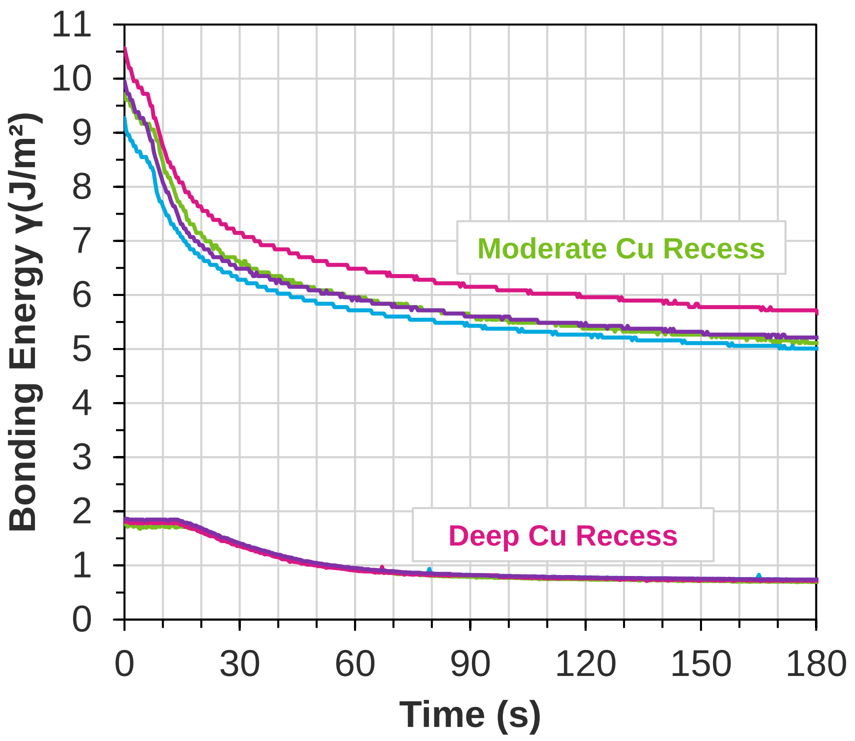




Source: TEL

Hybrid Bonding Strength Results

- 1um pitch Tokyo Electron (TEL) test vehicle was prepared with 500nm diameter Cu pads uniformly distributed across the bonding layer
- Different CMP conditions were used to achieve a deep and moderate Cu recess before bonding



Source: TEL

Conclusions

New DCB Method:

- Industry leading accuracy (<5% error) and throughput without glovebox
- Can be used to detect residual water in bonding interface
- Powerful diagnostic tool for evaluating wafer bonding quality

Fusion/hybrid bonding experiments:

- N_2 SAP has higher BE for oxides, while O_2 SAP has higher BE for nitrides
- Below 200C post-bond anneal, fusion bonding energy rapidly deteriorates
- Demonstrated BE measurement of Cu hybrid bonding test vehicle

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