Photo-Imageable Dielectrics Enabling Structured MEMS and 2.5D / 3D Bonding Systems

IMAPS 2022

David Danza, Colin Hayes, Kevin Wang, Greg Prokopowicz, Paul Berry, Masaki Kondo, and Michael Gallagher
Agenda

• Introduction
• Dielectric Materials for Bonding Applications
• BCB Permeant Wafer Bonding
• Photo-patternable BCB Bonding
• Testing of Bonded Structures
• Future Work and Conclusion
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Photo-patternable Permanent Wafer Bonding

MEMS, HBM and Micro-optics (CMOS Image Sensors) are currently three of most important applications driving the need for permanent bonding materials.

Bonding Requirements for 2.5 / 3D-TSV Packaging

- High Bonding Strength
- High Throughput / High Accuracy
- High Yield / Low Cost

Types of Bonding Techniques

- Anodic / Si Direct / Eutectic / Adhesive / Hybrid

Advantages of Adhesive Bonding

- Low Bonding Temperature / High Bond Strength
- Low Cost / CMP / Reflow / Photo-patternable
## Dielectric Property Comparison

<table>
<thead>
<tr>
<th></th>
<th>CYCLOTENE™ 3022/402X Resin</th>
<th>CYCLOTENE™ 6505</th>
<th>XP-5G-006</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photo-patternable</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Target Film Thickness Range</strong></td>
<td>2.5-5 µm</td>
<td>3-10 µm</td>
<td>5-15 µm</td>
</tr>
<tr>
<td><strong>Tone</strong></td>
<td>Negative</td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td><strong>Viscosity cSt</strong></td>
<td>192</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td><strong>Via Resolution/Feature Size</strong></td>
<td>&lt;20 µm</td>
<td>≤5 µm</td>
<td>7.5 µm</td>
</tr>
<tr>
<td><strong>Aspect ratio</strong></td>
<td>1:4</td>
<td>&gt;1:1</td>
<td>&gt;1:1</td>
</tr>
<tr>
<td><strong>Wall slope</strong></td>
<td>45°</td>
<td>65-70°</td>
<td>&gt;80°</td>
</tr>
<tr>
<td><strong>Developer</strong></td>
<td>DS2100 solvent type</td>
<td>0.26N TMAH aqueous base</td>
<td>PGMEA solvent type</td>
</tr>
<tr>
<td><strong>Edge Bead / BSR Solvent</strong></td>
<td>T1100</td>
<td>MMP, PGME or PGME/PGMEA</td>
<td>Cyclopentanone</td>
</tr>
<tr>
<td><strong>Adhesion</strong></td>
<td>Not Tested</td>
<td>AP9000C → passes all tested</td>
<td>Self Priming → passes Si, Cu, Pt, SiN, self</td>
</tr>
<tr>
<td><strong>Process Condition</strong></td>
<td>Build-Up Cure Temperature</td>
<td>210°C / 40min</td>
<td>200°C/100min</td>
</tr>
<tr>
<td><strong>Material Properties</strong></td>
<td>Thermal Stability, &lt;1wt% loss/hr</td>
<td>&gt;300°C</td>
<td>290°C</td>
</tr>
<tr>
<td><strong>Shrinkage</strong></td>
<td>9%</td>
<td>9%</td>
<td>10%</td>
</tr>
<tr>
<td><strong>Residual Stress</strong></td>
<td>28 MPa</td>
<td>29 MPa</td>
<td>20 MPa</td>
</tr>
<tr>
<td><strong>Modulus</strong></td>
<td>2.8 GPa</td>
<td>2.9 GPa</td>
<td>2.4 GPa</td>
</tr>
<tr>
<td><strong>CTE</strong></td>
<td>42 ppm/°C</td>
<td>45 ppm/°C</td>
<td>95ppm/°C</td>
</tr>
<tr>
<td><strong>Tensile Strength at break</strong></td>
<td>90 MPa</td>
<td>121 MPa</td>
<td>84MPa</td>
</tr>
<tr>
<td><strong>Elongation</strong></td>
<td>8%</td>
<td>20%</td>
<td>28%</td>
</tr>
<tr>
<td><strong>Dielectric Constant @ 100MHz</strong></td>
<td>2.65</td>
<td>3.2</td>
<td>2.5→2.6 @ 20-60 GHz</td>
</tr>
<tr>
<td><strong>Dielectric Loss @ 100MHz</strong></td>
<td>0.0008</td>
<td>0.015</td>
<td>0.0028 → 0.0032 @ 20-60 GHz</td>
</tr>
<tr>
<td><strong>Breakdown Voltage</strong></td>
<td>5.3MV/cm</td>
<td>5.1MV/cm</td>
<td>TBD</td>
</tr>
<tr>
<td><strong>Moisture Uptake 23C/45% RH</strong></td>
<td>0.1%</td>
<td>1.1%</td>
<td>0.17%</td>
</tr>
</tbody>
</table>
Permanent Bonding Approaches with Polymer Adhesive

**BCB Permanent Wafer Bonding – Via Last Process (SONY BSI)**

1) Coating and bonding
2) Thin, Pattern, Etch
3) Cu Fill and CMP

**Non-Patterned BCB Process**

1) Coating
2) Alignment
3) Bonding

**Photo-patternable BCB Process**

1) Coating
2) Photopattern BCB
3) Plasma Clean
4) Align and Bond
Bonding Result – Cu Structured Si and Glass wafers

Bonded Wafer Pair

Cycotene™ 3022-57 Full Area Bonding Process

Temperature in C

2 Minutes wait Time

0.22 MPa Bond Pressure applied on Wafer Stack for 2 Minutes

Bonded Wafer Pair

Glass

Dry Etch BCB

Cu

Si

Cure Condition | Soft Cure Avg. Thickness | Soft Cure + Hard Cure Avg. Thickness
---|---|---
180°C / 8 hr | 4.67 ± 0.27 µm | 4.82 ± 0.39 µm
190°C / 8 hr | 5.10 ± 0.43 µm | 5.07 ± 0.42 µm
200°C / 90 min | 0.011 ± 0.46 µm | 0.19 ± 0.11 µm
210°C / 50 min | 5.09 ± 0.47 µm | 5.07 ± 0.40 µm

Hard Cure = 350°C/hr

Mag = 33x X
WD = 8.9 mm
Stage tilt = 8.9°
Aper. Size = 38.80 µm
TEM Cure = 1.0X
FIB Imaging = SEM
FIB Probe = 300K/50 pA
Spectroscopy = 0.060

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Permanent Bonding Approaches with Polymer Adhesive

### BCB Permanent Wafer Bonding – Via Last Process (SONY BSI)

1) Coating and Bonding  
2) Thin, Pattern, Etch  
3) Cu Fill and CMP

### Non-Patterned BCB Process

1) Coating  
2) Alignment  
3) Bonding

### Photo-patternable BCB Process

1) Coating  
2) Photopattern BCB  
3) Plasma Clean  
4) Align and Bond
Photo-Patternable Bonding – No Voiding After Bonding or Curing

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image of bonding" /></td>
<td><img src="image2.png" alt="Image of bonding" /></td>
<td><img src="image3.png" alt="Image of bonding" /></td>
</tr>
<tr>
<td>Images Courtesy of FhG IZM</td>
<td>Images Courtesy of FhG IZM</td>
<td>Void-free bonding and no outgassing after cure + 3X reflow</td>
</tr>
</tbody>
</table>

Passed Shear Test: Adhesion strength >30 MPa (identical to single layer BCB adhesive)

Material Flow After Cure

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Positive Tone Photo-patternable Bonding
**CYCLOTENE™ 6505 Process Conditions**

**Materials**
- Substrate: 200mm Silicon
- Adhesion Promoter: AP9000C
- Dielectric: CYCLOTENE™ 6505 Dielectric (positive tone)

**Bonding Evaluation**
1. Priming with AP9000C: 200mm Wafer Track
   - 2000rpm spin coat, 150˚C/60sec
2. Spin Coat: 200 mm Wafer Track
   - 1250 rpm/45 sec targeting 5.5 um after development
   - 90˚C/90 sec
3. Exposure tool: Mask Aligner
   - ABCD Mask Square Post (1-300 um features)
   - 20 um proximity gap
4. Post Exposure Delay: ~15 minutes
5. Development: 200mm Wafer Track
   - No prewet, MF CD-26 (0.26/N TMAH), single puddle 1x60 sec
   - DI water rinse for 60 sec
6. Bonding: Commercial 200mm Wafer Bonder
   - Temperature 80-120˚C
   - Force: 4-30kN
7. Hard Cure: Blue M Oven
   - Nitrogen-purged convection oven
   - 130 °C/15 min → 250˚C/60min

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**Lithographic Post Adhesion Test**

*Graph and images illustrating the test results.*

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Process Scheme for Patterned Permanent Bonding

Photopatternable 6505
Target opening to pillar size
Sidewall angle: 45-72°
Wall angle dependent on cure process
TMAH Develop: 60s SP

Cross section image showing side wall after development

After Cure
- ADI
  - CD: 8µm L/S Dose: 500 mJ/cm²

Alternate Cure
- ADI
  - CD: 5µm 1:2 Dose: 532 mJ/cm

Standard Cure
- ADI
  - CD: 10µm 1:2 Dose: 532 mJ/cm
    - Wall Angle 45°

- CD: 10µm 1:2 Dose: 532 mJ/cm
  - Wall Angle 72°
Patterned Wafer – 30µm double coat 6505 PID + 6X puddle
**Bonding Process – Impact on BCB Reflow**

**Bonding (no reflow)**
- Temperature: 80°C
- Force: 60 kN
- Time: 5 min
- Result: No pattern dimension change

**Bonding (reflow)**
- Temperature: 100°C
- Force: 60 kN
- Time: 3 min
- Result: Pattern reflow

Images Courtesy of Fraunhofer IZM
Bonding Process Flow

**Wafer to Wafer Bonding**
- **Spin Coat Dielectric**
- **PID**
- **Si Wafer**
- **Expose and Develop**
- **Si Wafer**
- **Wafer Contact**
- **Glass Wafer**
- **Bonding Platen**
- **Si Wafer**
- **Bonding Platen**

**Chip to Wafer Bonding**
- **Spin Coat Dielectric**
- **PID**
- **Glass Wafer**
- **Expose and Develop**
- **Glass Wafer**
- **Dice**
- **Flip Chip Bonding**
- **Si Wafer**
- **Bond Head**
CYCLOTENE™ 6505 Bonding Performance (Bonded)

Increased Bonding Temperature and Pressure
Large impact on feature shape
CYCLOTENE™ 6505 Bonding Performance (Cured)

20 µm pad as cured

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Force</th>
<th>Feature Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Bond</td>
<td></td>
<td>19 µm</td>
</tr>
<tr>
<td>80°C 4kN</td>
<td></td>
<td>19 µm</td>
</tr>
<tr>
<td>80°C 8kN</td>
<td></td>
<td>21 µm</td>
</tr>
<tr>
<td>110°C 6kN</td>
<td></td>
<td>21 µm</td>
</tr>
<tr>
<td>120°C 8kN</td>
<td></td>
<td>27 µm</td>
</tr>
</tbody>
</table>

50 µm pad as cured

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Force</th>
<th>Feature Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>48 µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48 µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>57 µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>61 µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>79 µm</td>
</tr>
</tbody>
</table>

Increased Bonding Temperature and Pressure
Large impact on feature shape
CYCLOTENE™ 6505 Cross Section After Bonding 20 um Pillar

80ºC 4kN

Glass

Silicon

Epoxy from sample prep

7.8 µm

11.3 µm

17.5 µm

120ºC 4kN

Glass

Silicon

Epoxy from sample prep

14.2 µm

4.3 µm

23 µm

Good Bond Joint
No Voiding

Good Bond Joint
No Voiding

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Negative Tone Photo-patternable Bonding
Process Scheme for Patterned Permanent Bonding

Photopatternable XP-5G-006
Target opening to pillar size
Sidewall angle: 85°
PGMEA Develop: 2x30 SP

Cross section image showing side wall after development

CD: 15.3 µm L/S Dose: 200 mj/cm²
CD: 11.88 µm - Dose: 117 mj/cm
CD: 10.16 µm - Dose: 150 mJ/cm

2.5 or 3D TSV
XP-5G-006 Process Conditions

Materials
- Substrate: 200mm Silicon
- Dielectric: XP-5G-006 Photoimageable Dielectric (negative tone)

Bonding Evaluation
1) Spin Coat: 200mm Wafer Track
   - 2500 rpm/45 sec at 5 um thickness as developed
   - 100˚C/180 sec
2) Exposure tool: i-line Mask Aligner
   - ABCD Mask Square Post (1-300 um features)
   - 20 um proximity gap
   - PEB 65˚C/90 sec
4) Development: 200mm Wafer Track
   - No prewet, PGMEA develop, double puddle 2x30 sec
   - PGMEA rinse for 30 sec
5) Bonding: Commercial Wafer Bonder
   - Temperature 80-120˚C
   - Force: 4-30kN
6) Hard Cure: Blue M Oven
   - Nitrogen-purged convection oven
   - 130 °C/15 min → 200°C/60min
Patterned Bonding of XP-5G-006

XP-5G-006 was exposed and developed
Bonded using W2W Bonder
Bonding Conditions: 120°C / 30kN / 5min
No voiding after cure or 3X solder reflow
XP-5G-006 Bonding Performance (Bonded)

Increased Bonding Temperature and Pressure
No Feature Reflow Seen
XP-5G-006 Bonding Performance (Cured)

Increased Bonding Temperature and Pressure
No Feature Reflow Seen
Adhesion to Bonded Surface (Silicon test) G1c Fracture Energy

Spin Coat, Expose/Process Adhesive

Vacuum Laminate

Cure, then test bond G1c

Adhesion Energy G1c of Materials

Fracture Energy G1c (J/m²)

XP006 Coated

XP006 Laminated

DVSBCB(AP3000)

XP006 Coated

XP006 Laminated

DVSBCB(AP3000)

Adhesion G1c vs Surface

Si, SiNx, SiO₂, Cu, PI, PI O₂

Plasma

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Cross-sectional SEM images of 20-µm pillars of XP-5G-006

Good Bond Joint
No Voiding

80ºC 8 kN

80-20µm x3.00k SE(L)

Good Bond Joint
No Voiding

120ºC 30 kN

6-120-20µm x3.00k SE(L)
Testing of Bonded Substrates
## Chemical Resistance of Photopatternable Dielectrics

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Solvent/Stripper/Plating Chemical</th>
<th>CYCLOTENE 6505 PID</th>
<th>XP-5G-006 PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT</td>
<td>Cu Plating Solution pH8.5</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>PGME</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>PGMEA</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>NMP</td>
<td>ΔFT &lt;3% *</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>DMSO</td>
<td>ΔFT &lt;3% *</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>2.38% TMAH</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>20% H₃PO₄ / 5% H₂O₂</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>Ni Plating Solution pH4</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>2%HF</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>Ni Plating Solution pH4</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>70°C</td>
<td>DMSO/KOH</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>90°C</td>
<td>DMSO/KOH / 60min</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Pass = no change in color, <1% change in film thickness. * For NMP & DMSO swelling occurs but can be removed by soft bake.
**Die Shear Results**

### Dielectric | Substrate | Temperature | Force | Shear Strength (N/mm²)
--- | --- | --- | --- | ---
**CYCLOTENE 6505** | Si + AP9000 | 90°C | 100N | 8.16
| | | 100°C | | 18.88
| | | 110°C | | 23.50
| | 90°C | | 15.03
| | 100°C | | 9.75
| | 110°C | | 8.44
| | 6505 | | Work in Progress

**XP-5G-006** | Si | 100°C | 150N | 20.25
| | 110°C | | 15.5
| | 120°C | | 13.75
| | 100°C | | Work in Progress

| Dielectric | Substrate | Temperature | Force | Shear Strength (N/mm²)
--- | --- | --- | --- | ---
**CYCLOTENE 6505** | Si + AP9000 | 90°C | 100N | 8.16
| | | 100°C | | 18.88
| | | 110°C | | 23.50
| | 90°C | | 15.03
| | 100°C | | 9.75
| | 110°C | | 8.44

| Test type | Destructive
| Max load | 100KG or 1000N
| Shear tool | 9 mm wide flat tip
| Shear speed | 75 µm/s
| Land speed | 500 µm/s
| Shear height | 20 µm
| Max shear distance | 4000 µm
Future Work on Flip Chip and Hybrid Bonding

**PID Flip Chip Sn/Ag/Cu Pillar**

1. Coating
2. Photopattern PID
3. Plasma Clean
4. Align and Bond

**PID Cu-Cu Hybrid Bonding**

1. Coating
2. Photopattern PID
3. Plasma Clean
4. Align and Bond

15μm φ Sn/Ag capped Cu pillar

37.5μm $C_L$ to $C_L$

18μm φ PID opening
Conclusions and Next Steps

Void free patterned bonding demonstrated for both positive and negative tone PID materials

<table>
<thead>
<tr>
<th></th>
<th>CYCLOTENE™ 6505 PID</th>
<th>XP-5G-006 PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photopatternable</td>
<td>Positive tone (TMAH)</td>
<td>Negative Tone (PGMEA)</td>
</tr>
<tr>
<td>Cure temperature</td>
<td>220°C/3hr</td>
<td>200°C/1hr</td>
</tr>
<tr>
<td>Adhesion promoter</td>
<td>AP9000C</td>
<td>Self Priming</td>
</tr>
<tr>
<td>Bonding temperature</td>
<td>80-110°C</td>
<td>80-110°C</td>
</tr>
<tr>
<td>Bonding force</td>
<td>4kN-8kN</td>
<td>4kN-12kN</td>
</tr>
<tr>
<td>Bonding time</td>
<td>≤10min</td>
<td>≤10min</td>
</tr>
<tr>
<td>Voiding or offgasing</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Reflow</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Sn/Ag capped copper pillars will be plated at a variety of pitches

C2W and W2W bonding are planned for Q2 with reliability testing to follow
Special thanks to Shekhar Subramoney, Keith Warrington, David Fleming, Christine Hatter, Paul Morganelli, Hua Dong, Peggy Wu, Monita Pau, Shashi Gupta, and Kirk Thompson