Thermo-compression Bonding Assembly Technology

IMAPs March 2023
Agenda

• Packaging Technology Roadmap
• Fluxless TCB
• Compare TCB to Hybrid Bonding
  • Process steps
  • Cost Model
• Cu to Cu TCB
Introduction

• **Moore’s Law** has driven performance for the SEMI industry for decades. However, in recent years, Moore’s law has ground to a halt:
  • Rising wafer manufacturing cost & increased chip design complexity outweigh the benefits of die shrinks
  • This results in lower pace of new Si nodes with fewer and fewer state-of-the art fab’s being constructed

• **Where does increased performance come from**
  • The answer is packaging technology
  • Increasing 2D and 3D I/O and chip packaging density through Heterogeneous Integration

• **Heterogeneous 2.5D/3D re-integration of dissimilar chips (“More than Moore”):**
  • Combining different functions, from different wafers, with different feature sizes...

• **Heterogeneous Integration** requires high bandwidth and low power communication between chiplets,
  • This drives an aggressive roadmap for Advanced Packaging technologies and fine-pitch interconnects
Example Interconnect Pitch Scaling – Intel AP Roadmap

**Embedded Multi-die Interconnect (EMIB)**
- bump pitch **50-40 microns**
  - leads industry
  - first 2.5D embedded bridge solution
  - products shipping since 2017

**Foveros Technology**
- bump pitch **50-36 microns**
  - wafer-level packaging capabilities
  - first-of-its-kind 3D stacking solution

**Foveros Omni**
- bump pitch **~25 microns**
  - next gen Foveros technology
  - unbounded flexibility with performance 3D stacking technology for die-to-die interconnect and modular designs

**Foveros Direct**
- bump pitch **< 10 microns**
  - direct copper-to-copper bonding for low resistance interconnects
  - blurs the boundary between where the water ends and the package begins

Source: Electronic Design Magazine
Interconnect Roadmap for Advanced Packages

- C4 Flip Chip
- Fluxless TCB (Solder)
- Thermo-Compression Bonding
- Cu to Cu TCB
- Hybrid Bonding bumpless
- Cu-Cu Interconnect
- Sn-Based Solder Interconnect

I/O Density [I/Os / mm²]

I/O Pitch [μm]
Interconnect Pitch Scaling for Heterogeneous Integration

- **I/O Density [I/Os/mm²]**
  - 10^1
  - 10^2
  - 10^3
  - 10^4
  - 10^5

- **C4 Flip Chip**
  - Mass reflow

- **Chip-to-Substrate (C2S) & Chip-to-Wafer (C2W) solution for TC-CUF/NCP/NCF**

- **Thermo-Compression Bonding**
  - Local reflow

- **Thermo-Compression Bonding (local reflow)**

- **Hybrid Bonding**
  - Bumpless

- **Fluxless TCB**
  - Inert bonding environment & large die capability.
  - Flux-less oxide reduction bonding with formic acid

- **Cu-to-Cu TCB**

- **WCC# Accuracy**
  - > 1.0
  - 0.5
  - 0.3

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*Refers to the Upper Control Limit for Worst Case Corner Cpk_wcc > 1. Includes repeatability and mean offset!*

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Challenges with Flux Based TCB Process

- Fluxing adds TCB process complexity
- Pre-bonding fluxing step is required:
  - Flux pre-applied to the substrate has a limited activation time and imposes limits on maximum substrate temperature
  - Dipping large die in flux can be challenging and extended flux activations times may be required to fully clean the substrate
- Post-bonding flux cleaning step is required even for ‘no-clean’ materials:
  - Flux residual clean-up required for high package reliability after underfilling
  - Thorough cleaning of large chip areas with small chip gap and/or high density interconnects can be challenging and time consuming
Advantages of Fluxless TCB Process

- No pre-applied flux or flux cleaning steps
- No flux vapor contamination of equipment, tooling, or sensitive components such as optical/photonic devices
- Possible to run higher substrate and/or die contact temperatures for higher quality interconnects as there is no flux burn off time needed
- Higher accuracy/more consistent alignment possible as there is no flux for the vision to see features through
Oxide Reduction via Formic Acid Vapor

Formic acid molecular formula: HCOOH

- Step 1: Sn (II) formate creation ($100^\circ C < T < 150^\circ C$)
  \[ SnO(s) + 2HCOOH(g) \rightarrow Sn(COOH)_{2(s)} + H_2O(g) \]
  - surface oxide on solder
  - FA vapor
  - organic tin formate layer replaces oxide
  - water vapor byproduct

- Step 2: Sn (II) formate decomposition ($T > 150^\circ C$)
  \[ Sn(COOH)_{2(s)} \rightarrow Sn(s) + 2CO_2(g) + H_2(g) \]
  - tin layer remains on solder surface
  - carbon dioxide and hydrogen byproducts
Example In-Situ Formic Acid TCB Process Flow

FA trigger and reduction

- Bondhead, 180 °C
- Silicone chip
- Solder cap
- Cu-pads
- Laminate substrate
- Chuck, 180 °C

Thermo-Compression Bonding

- Bondhead, 320 °C
- Silicone chip
- Laminate substrate
- Chuck, 180 °C

final assembly after bonding

- Bondhead, 160 °C
- Silicone chip
- Laminate substrate
- Chuck, 180 °C
Schematic of a Formic Acid Delivery System

- **Nitrogen Supply**
- **Nitrogen** shielding gas
- **Bubbler**
- **Formic Acid**
- **Exhaust**
- **Upper Bondhead**
- **Lower Bondhead / TCB heater**
- **Vacuum**

**Bondhead Shroud**
- The bondhead mounted shroud creates a mini formic acid rich environment prior to and during chip placement

**Nitrogen saturated with formic acid vapor**

**Chip**
- Cu/Sn pillars
- Cu/Sn pads

**Substrate**
- Substrate & heater
- Nitrogen saturated with formic acid vapor
Formic Acid Delivery System Overview

- Formic acid vapor is delivered to the bonding area using a bondhead mounted delivery shroud.
Animation of the Fluxless Bond Process
APTURA – 3rd Generation TCB Tool

• Specifically designed for the most demanding TCB processes
  • Large die, ultra-fine pitch 10um, multi-die

• High throughput dual head bonding

• Up to 70 mm die size

• Accuracy < 1.0 um 3S

• Active co-planarity control with non-contact measurement

• Advanced TCB process options
  • Inert environment bond chamber < 100 ppm O2
  • K&S patented flux-less bonding
Future Accuracy Needs

- Heterogeneous integration and packaging are replacing Moore’s law in driving semiconductor performance. This trend is driving interconnect pitch scaling requirements

<table>
<thead>
<tr>
<th>Pitch (um)</th>
<th>Bump Dia (um)</th>
<th>Bump gap (um)</th>
<th>Accuracy requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>24.5 (70%)</td>
<td>10.5</td>
<td>2.0 um</td>
<td>Aptura → 1.0 µm</td>
</tr>
<tr>
<td>25</td>
<td>17.5 (70%)</td>
<td>7.5</td>
<td>1.5 um</td>
<td>Aptura → 1.0 µm</td>
</tr>
<tr>
<td>10</td>
<td>5.5 (55%)</td>
<td>4.5</td>
<td>0.8 um</td>
<td>Aptura Next → 0.8 µm</td>
</tr>
</tbody>
</table>

Source: Intel, ECTC 2022

Intel 10um Test Vehicle
Bump dia = 55% pitch

Source: Intel, ECTC 2022

Intel 20um Test Vehicle
Bump dia = 70% pitch

Source: Intel, ECTC 2022
Fluxless Bonding Productivity

- The fluxless process delivers about the same productivity as a conventional TCB flux based TCB processes

- The formic acid process requires a short pre-bonding cleaning step for formic acid vapor to remove oxides from the chip and substrate

- No time required for flux dipping and flux activation during bonding
Formic Acid vs. Flux Based Example Bond Cycle

- The FA process delivers nearly the same productivity as a conventional flux based TCB process:
Copper-to-Solder Fluxless Bonding in Inert Environment

- 30 mm X 30 mm die-to-die assembly
- Top die: Solder capped copper pillar
- Bottom die: Cu pillar
- Interconnect: Cu-to-Solder
Cu-Solder Bonding in Inert Environment after 45min Heat Exposure

- Cu surface was held at 150 C in nitrogen for 45 min before bonding process
- Oxygen concentration in nitrogen chamber was less than 100 ppm
- Localized FA supply get rid of any natural or existing copper oxides prior to bonding step

• Pre-bond FA vapor cleaning time 1 sec
Fluxless TCB vs Hybrid Bonding – C2W Process Flows

Fluxless TCB

Component Wafer

Substrate Wafer

Cu Pillar • Solder (µBumps)

Dicing

Underfill & Cure

Hybrid Bonding

Component Wafer

Substrate Wafer

Si

ILD

via layer & metal pads

CMP

Plasma Dicing

Surface Treatment

Batch Anneal

Hybrid Bonding

• added process complexity
• inspections for process control

- CMP – nm-scale roughness
- Plasma Dicing – minimized particle generation
- Surface Treatment – clean, plasma activation, hydration, oxide removal
## Fluxless TCB vs Hybrid Bonding – Pro’s & Con’s

<table>
<thead>
<tr>
<th>Packaging Considerations</th>
<th>Fluxless TCB</th>
<th>Hybrid Bonding</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Finest Pitch</td>
<td>20µm, extendable to 10µm or below</td>
<td>&lt; 10µm</td>
</tr>
<tr>
<td>• Productivity</td>
<td>up to 1200 units per hour</td>
<td>1000 – 2000 units per hour</td>
</tr>
<tr>
<td>• Process Sensitivity to Debris</td>
<td>not sensitive to small debris</td>
<td>super critical – small debris = yield loss</td>
</tr>
<tr>
<td>• Assembly Cleanliness Req’s</td>
<td>use existing facilities</td>
<td>similar to Front-End</td>
</tr>
<tr>
<td>• Die Surface Roughness</td>
<td>no change from current practice</td>
<td>special CMP, &lt; 0.5nm Ra, Cu dishing critical</td>
</tr>
<tr>
<td>• Die Surface Preparation</td>
<td>no change from current practice</td>
<td>wet clean, plasma activation, hydration, oxide removal</td>
</tr>
<tr>
<td>• Special Dicing Requirements</td>
<td>no change from current practice</td>
<td>plasma dicing</td>
</tr>
<tr>
<td>• Cu Area vs Dielectric Layout</td>
<td>no special requirements</td>
<td>Needs carefully control – Cu distribution and %</td>
</tr>
<tr>
<td>• P&amp;P Accuracy Requirements</td>
<td>proven 1µm @ 3σ</td>
<td>&lt; 200nm @ 3σ</td>
</tr>
<tr>
<td>• Bonding Process</td>
<td>large temperature cycle</td>
<td>room temperature bonding, very low force</td>
</tr>
<tr>
<td>• Interconnect</td>
<td>liquidous</td>
<td>non-liquidous – special (1,1,1) plating R&amp;D</td>
</tr>
<tr>
<td>• Underfill</td>
<td>ultra fine pitch challenges – exploring new methods</td>
<td>no underfill required</td>
</tr>
<tr>
<td>• Start Up Cost</td>
<td>natural extension of TCB</td>
<td>huge investment required</td>
</tr>
<tr>
<td>• Cost of Ownership</td>
<td>lower cost</td>
<td>higher cost</td>
</tr>
</tbody>
</table>
Fluxless TCB vs Hybrid – Process Cost Comparison

- Bottoms-up «activity-based» cost modeling, allocating cost to each process step:
  - Cost categories: labor, capital, material/tooling, yield loss# and indirect/OH cost

Assumptions:
- Process cost comparison assumes 100% yield for both processes.
- Package cost includes Si cost (~9300$ per 7nm node wafer)
- Assumes Large Die.
Fluxless TCB vs Hybrid – Yield & Package Cost Comparison

- TCB much less sensitive to particles, Hybrid Bonding requires front-end cleanliness
- Small particles covered in underfill or solder – no effect for TCB

- Hybrid Bonding yield drastically dropping as die size increases:
  - 10 good die out of 16 total
  - 63% yield
  - 1 good die out of 4 total
  - 25% yield
  - 0 good die out of 1 total
  - 0% yield

- Hybrid Bonding package cost vs defect density:
  - TCB typically @ ≥ 99.8% yield
  - Large Die stacking further multiplier of single-layer yield loss

Assuming particles as the only source of yield loss, i.e. perfect alignment, perfect Cu pad dishing, etc.
High Density Cu-Cu Interconnects: K&S-UCLA Partnership

- Cu Pillar pitch: 10 µm
- Total contacts per chip: 36,000
- Roughness on both pillar & pad: < 2 nm
- Test vehicles fabricated by UCLA
- TCB Tool: K&S with FA delivery system

S. Jangam et al., ECTC 2019
K&S-UCLA Paper

Chip with bond pads
Substrate with Cu-pillars

Bonded Interface

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Improving throughput of conventional TCB

- Conventional TCB has challenges
  - Single step TCB is time consuming (30s – 40s/die)

- To overcome these challenges, we propose a two-stage TCB.
  - **Stage 1:** die tacking process (< 10s).
  - **Stage 2:** batch annealing process
    - Annealing several wafers at once eliminates anneal time as a throughput concern.
    - Current process > 320 UPH (~11.2s/die)

Throughput improvement

- 90 UPH \(\rightarrow\) 320 UPH \(\rightarrow\) 1100 UPH
Executive summary

• We have developed a high throughput (up to 1000 UPH) thermal compression bonding scheme using a novel two-stage bonding approach.

• We have achieved 2x MIL-SPEC bonding strength (> 100N for 2x2mm² dielets) post anneal with specific contact resistance ~ 1.2x10⁻⁹ ohm-cm².

• We have demonstrated MIL-SPEC reliability using UHAST 96 hours testing.

• We believe that TCB using this scheme is a viable and potentially more manufacturable assembly process down to ~7 µm bump pitches, with further scaling possible with tool alignment improvements.
Hybrid-like Cu-Cu Formic Acid Process on the Aptura

- We’ve developed a Cu to Cu interconnect for customers as an alternative to Hybrid bonding
- Process uses very short pads on the die and substrate prepared with low roughness
- The Formic acid TCB process uses < 5 sec total cleaning and bonding time which results in well attached chips, in a class 10k cleanroom
- The CMP like finish helps to enables reduces bonding pressures to <10 MPa (applied for 2 sec.)
- Process is capable of fine pitches < 10 um
- No additional equipment upgrade needed beyond the normal formic acid
- 2 step process: Cross section image shows an example bond before annealing
Summary

- Heterogeneous integration and packaging are replacing Moore’s law in driving semiconductor performance. This trend is driving interconnect pitch scaling requirements.

- Flux contamination and residue limits the pitch of thermo-compression flip chip and is a serious problem for ultra fine pitch interconnect.

- K&S has developed a fluxless TCB process for chip to substrate and chip to wafer bonders which solves problems with flux.

- The process is capable and being used for Sn to Sn, Sn to Cu, and Cu to Cu interconnect.

- Formic acid vapor fluxless TCB can extend the pitch capability for flip chip packages down to 10 – 20µm and possibly beyond.

- Fluxless TCB bonding is an extension of standard semiconductor assembly practices and does not require massive process and infrastructure changes that Hybrid bonding does.

- The process and equipment have been matured and are in high volume manufacturing.
Questions?

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Fluxless High Volume Manufacturing Readiness

- Chemical safety has been designed into the formic acid (FA) bonder system from the early design stages
- Machine conforms to multiple chemical safety standards including SEMI S2, S6, and EN 1127-1
- Machine features redundant sensors/valves on safety critical functions and safety systems are monitored/controlled by a safety rated PLC
- FA is only flammable under a limited set of conditions, however all electronics that could be exposed to formic acid under normal and failure condition are protected by intrinsically safe barriers
- Additionally multiple environmental monitor sensors are present to monitor FA vapor concentration at various points in the machine
**Thermal compression bonding is NOT demanding**

<table>
<thead>
<tr>
<th></th>
<th>Hybrid Bonding</th>
<th>Direct thermal compression bonding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Process Development</strong></td>
<td>• Necessitates meticulous control over 1) dielectric flatness (6σ roughness ≤ 1 nm) and 2) metal recess</td>
<td>• Simpler process development: only optimizing the metal-metal bonding</td>
</tr>
<tr>
<td></td>
<td>• Extensive CMP optimization</td>
<td>• Relaxed CMP requirements</td>
</tr>
<tr>
<td><strong>Dicing process</strong></td>
<td>• Mandatory particle-free dicing.</td>
<td>• Cu pads/pillars are recessed so, blade dicing with standard wet cleaning is feasible.</td>
</tr>
<tr>
<td><strong>Bonding environment &amp; activation</strong></td>
<td>• ISO-4 or below (Literature suggests ISO-2)</td>
<td>• ISO-8 and above, even outside cleanroom.</td>
</tr>
<tr>
<td></td>
<td>• Plasma activation and particulate removal prior to bonding is crucial.</td>
<td>• Requires in-situ reducing environment during bonding – studied extensively [1].</td>
</tr>
<tr>
<td><strong>Dielet size</strong></td>
<td>• Almost any size due to less tacking pressure requirements.</td>
<td>• Limited by max. bond-head pressure during tacking.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Works well for dielet sizes within dielet golden regime.</td>
</tr>
<tr>
<td><strong>Throughput</strong></td>
<td>• 1000+ units-per-hour (UPH) due to fast dielectric bonding during tacking phase.</td>
<td>• 1000+ UPH possible with <strong>optimized tack and anneal process</strong>.</td>
</tr>
<tr>
<td><strong>Conclusion</strong></td>
<td>• TCB has low process development cost as well as low operation cost compared to HB.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• TCB is less sensitive to particles during dicing and bonding.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Therefore, we believe TCB should be used for bonding pitches up-to 7 µm.</td>
<td></td>
</tr>
</tbody>
</table>
