CHALLENGES OF ADVANCED PACKAGING FAILURE ANALYSIS

BERNICE ZEE & JIANN MIN CHIN
FOUNDRY TECHNOLOGY AND PRODUCT ENGINEERING, AMD
OUTLINE

• Introduction – Heterogenous Integration
• Emerging Next Generation Packaging Technologies
• Importance of Failure Analysis (FA)
• Failure Mechanisms in Next Generation Packaging Technologies
• Requirements for Next Generation Package FA
• FA Capabilities Development
• Case Studies
• Conclusion
INTRODUCTION - HETEROGENEOUS INTEGRATION

• Advance packaging innovations to enable functionality diversification at lower cost.
• The trend for next generation packaging: (1) stacking (2) “dis-integration”.

EMERGING NEXT GENERATION PACKAGING TECHNOLOGIES

• High-density organic substrate:
  – Low cost alternative to Si interposer.
  – Enable high density, fine pitch interconnects.


• 3D Wafer-on-Wafer Stacking:
  – High aspect ratio TSV, fine pitch bonding for true 3D packaging.


• Embedded interconnect bridge
  – Improved electrical performance between chiplets.

Robust & efficient Failure Analysis is essential to having the highest possible die quality to make any KGD / advanced packaging approach work.

**IMPORTANCE OF FAILURE ANALYSIS (FA)**

- Failure analysis is key to the product time-to-market cycle.
- Needed at every step of the market cycle → Iterative!
- Robust & efficient Failure Analysis is essential to having the highest possible die quality to make any KGD / advanced packaging approach work.

FAILURE MECHANISMS IN NEXT GENERATION PACKAGING TECHNOLOGIES

μ-bump
- Delamination
- Cracks
- Misalignment
- Shorts
- Damage in underlying MEOL
- Warpage

MCM Organic Package
- Copper trace damage
- Cracks

Interposer/TSV
- Delamination
- Pin holes/ breakdown in liner
- Voids
- Cracks
- Electro migration

C4 Bump
- Delamination
- Cracks
- Misalignment
- Shorts

Chip 1
- CPU
- GPU
- IO

Chip 2
- CPU
- GPU

Organic Package

• If there are defects, need to find them all.
REQUIREMENTS FOR NEXT GEN PACKAGE FA

• Nondestructive Testing and Fault Isolation:
  → High Spatial / Axial Resolution; Improved Electrical Sensitivity.
• Nondestructive Defect Visualization Capabilities:
  → High Spatial / Axial Resolution; Acquisition Speed.
• New Sample Preparation and Materials Characterization Methodologies:
  → High Precision and Throughput; Improved Analytical Sensitivity.
• Time to results / resolution limitations / sensitivity limitations / cost of ownership?
LOCK-IN THERMOGRAPHY (IR-LIT)

Defect Z-depth Determination Using Lock-in Thermography for Stacked Devices:

\[ \phi = \frac{z}{\mu} \]  
\( z = \text{defect depth} \)
\( \mu = \text{thermal diff. length} \)

- Phase Shift (\( \phi \)) is used to calculate defect depth.
- Challenge: how to improve phase data acquisition consistency, accuracy, and time to results?

Source: Zee, B. et al., ISTFA 2018. "Improved Phase Data Acquisition for Thermal Emissions Analysis of 2.5D IC"
LOCK-IN THERMOGRAPHY (IR-LIT)

- Real-time 3D parabolic curve fitting automatically extracts the lowest calculated phase value.
- Auto-stop lock-in measurements when a pre-defined goodness of fit is reached.

Source: Zee, B. et al., ISTFA 2018. “Improved Phase Data Acquisition for Thermal Emissions Analysis of 2.5D IC”
ELECTRO OPTICAL TERAHERTZ PULSE REFLECTOMETRY (EOTPR)

- Fault location is determined by measuring the time of flight to a suspect peak in the waveform.
- Challenge: how to find references for comparison?
EOTPR – WAVEFORM SIMULATION TO ESTIMATE DEFECT LOCATION

Simulation workflow overview

- **Good Device Workflow**
  - Generate new circuit model
  - Import waveform of Good Device
  - Construct circuit: Model
  - Input trace lengths
  - Run simulation

- **Failed Device Workflow**
  - Duplicate circuit model
  - Import Waveform of Failed Device
  - Modify circuit model, as required
  - Allow only fault location to vary
  - Run simulation
  - Extract fault location

**Waveform comparison**

- Model waveform
- Measured waveform

**EOTPR signal intensity (a.u.) vs Optical Delay /ps**

- Known good device (KGD) used to generate model using lumped circuit elements → trace length inputted to generate simulated waveform to match KGD waveform.
- Waveform of failed device is measured, and software runs simulation to fit and extract fault location after waveform optimization.
MAGNETIC FIELD IMAGING

Magnetic Field Imaging (MFI) 3D Path Solver:

XY Defect Localization:

Z Defect Localization:

Physical Failure Analysis:


- Using a current path extracted from the current density image as a starting point, the 3D solver adjusts that path in a way that matches the observed magnetic field in the acquired scans.
- From these adjustments, a true 3D current path can be constructed.
SPACE DOMAIN REFLECTOMETRY (SDR)

- Space-domain reflectometry (SDR) utilizing SQUID sensor is a FA technique for open fault isolation that directly displays a physical 2D image of an open failures.
- A continuous wave RF signal is injected into the defective trace and the sensor acquires a 2D image of the induced RF magnetic field.
- At RF frequencies the open impedance, $Z_{\text{open}}$ (typically in MΩ range), is much greater than the trace characteristic impedance, $Z_0$ (~50Ω), thus, the open boundary reflects back nearly all the incident power while no RF power is transmitted past the open.


[Image of SDR diagram and examples of results]
ACOUSTIC IMAGING

Optimization of Acoustic Imaging for High Resolution imaging:

- High speed data processing.
- Mid high-\( f \) broadband transducer.
- Minimize water path between transducer and sample.
- Constant TOF during scan.
- Challenge: how to image through a memory stack to the \( \mu \)-bump interface?


![Image of acoustic imaging diagram with labels for top Si die, \( \mu \)-bump, interposer, and C4 bump interfaces.]
3D X-RAY MICROSCOPY

Nondestructive High Resolution Imaging with 3D X-Ray Microscopy:

- Nondestructive high resolution image of internal structures and defects.
- Locate and isolate defects difficult to find with traditional FA techniques.
- Challenge: how to get faster time to results and better resolution for smaller features?

CASE STUDY 1 - SHORT FAILURE (CSAM/LIT)

- No significant anomaly was observed in the unit under CSAM.
CASE STUDY 1 – SHORT FAILURE (CSAM/LIT)

Thermal Emission (LIT) Site in XY space detected in full camera frame:

Reject unit:

Good unit:

Phase shift measurement results for Z depth localization:

- Solid Line – Reference
- Pink Diamond – Experimental Data

• Phase shift measurement results: defect was possibly located in the die metal and/or active circuitry.
CASE STUDY 1 – SHORT FAILURE (CSAM/LIT)

TIVA:

PFA results:

- Root cause: M3 metal damage.
CASE STUDY 2 – SHORT FAILURE (CSAM/LIT/3D X-RAY)

- Delamination was observed under CSAM inspection.
CASE STUDY 2 – SHORT FAILURE (CSAM/LIT/3D X-RAY)

Thermal Emission Site (LIT) in XY space detected in full camera frame:

Phase shift measurement results for Z depth localization:

- Phase shift measurement results: defect was possibly located at C4 bump interface.
CASE STUDY 2 – SHORT FAILURE (CSAM/LIT/3D X-RAY)

- Possible to do further isolation without having to create a theoretical phase shift model in LIT.
- Do iterative Si thinning at region of interest (ROI) and LIT was done until a more distinct thermal hotspot size was observable.
CASE STUDY 2 – SHORT FAILURE (CSAM/LIT/3D X-RAY)

3D X-ray results:

- ASIC Die
- μbump
- Interposer
- C4 bump

PFA results:

- Suspected solder like material shorting the failure signal pin to VSS

- Root cause: Solder flow into passivation/UF delamination.
CASE STUDY 3 – OPEN FAILURE (CSAM/EOTPR/3D X-RAY)

- No anomaly observed in CSAM and 2D RTX at associated failure bumps.
CASE STUDY 3 – OPEN FAILURE (CSAM/EOTPR/3D X-RAY)

- EOTPR found defect to be mid-way between the substrate termination and interposerer termination putting it near the bottom of the TSV.
CASE STUDY 3 – OPEN FAILURE (CSAM/EOTPR/3D X-RAY)

- 3D X-ray Microscopy performed to verify NDT – crack was observed.

- XRM provides visual knowledge of the location to focus on and the nature of defect in order to carry out accurate PFA.
CASE STUDY 4 – POWER SUPPLY SHORT FAILURE (LIT/CSAM)

- Root cause: aluminium FM bridged μ-bumps (defect visible in CSAM).
CASE STUDY 5 – POWER SUPPLY SHORT FAILURE (LIT/CSAM)

• Root cause: metal shorts.
SUMMARY

- Failure analysis field continue to be very challenging with progress of packaging technology.
- Early involvement of FA in the technology/product cycle is KEY.
- Innovations in FA techniques and tools need to occur in tandem with packaging technology advances.
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