Metrology and Failure Analysis for 3D IC Integration

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New processes and new materials require new solutions for process development, process control and failure analysis.
3D TSV scheme

**Integrated Heterogeneous 2-Die Stack**

- **Tier 1**: CMOS Logic SoC
  - TSV (connect frontside to backside)
  - Very thin Wafer (manage TSV aspect ratio)
  - Active face down
- **Interface µ-Bump**
  - Backside RDL Metal (interface to µBump and/or routing to allow offset of µBump vs TSV)
  - µ-Bump (Tier to Tier interconnect)
  - Very thin underfill
- **Tier 2**: Commercial Die
  - Memory or Analog die, or…
  - Frontside Metal (interface to µBump)
  - Active face down & Pretty Thin
- **Flip Chip (C4) Bump**
  - Regular flip chip bump
  - Regular underfill
- **Package**
  - Regular PCB substrate
  - Regular plastic molding
  - Regular Package BGA Bump

Courtesy: R. Radojcic, Qualcomm
Contents

- Process control / Metrology
- Quality control / Failure analysis
- Stress engineering
Contents

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3D IC Integration: Process control/metrology needs (1)

TSV process
- TSV pitch and TSV CD (top & bottom)
- TSV depth: within wafer and wafer-to-wafer uniformity
- TSV etch profile: sidewall angle (top and bottom), via bottom profile (curvature)
- Sidewall oxide liner thickness
- Metal barrier dep: thickness uniformity, step coverage
- Cu ECD fill (filling defects: voids)
- Cu ECD overburden
- post-CMP topography

Microbump process
- Microbump quality
3D IC Integration: Process control/metrology needs (2)

Wafer bonding

- Wafer thickness
- Wafer bonding quality: bond strength, voids/micro-voids, hermeticity, ...
- Overlay metrology: wafer-to-wafer alignment, bond alignment

Defects

- Defects: critical vs. non-critical defects (etch defects, wafer edge defects, particles, scratches, ...)
- Delamination
- ...

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Analytical techniques for process control

Requirements

- Full-wafer (for wafer-level 3D IC)
- Nondestructive
- No particle generation
- High throughput
- High technique reliability and tool uptime
- Easy to use (operators, no physicists!)
- ...

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Analytical techniques for process control

In-line techniques (nondestructive)

- Scanning acoustic microscopy
- IR microscopy
- ...

Lab-based techniques

- X-sectioning of samples (e.g. FIB) + SEM imaging
- Scanning acoustic microscopy
Analytical techniques for process control

In-line techniques (nondestructive)

- Scanning acoustic microscopy
- IR microscopy
- …
- ➔ Talks Alain Diebold (Tue + Wed)

Lab-based techniques

- X-sectioning of samples (e.g. FIB) + SEM imaging
- Scanning acoustic microscopy
- ➔ Today
3D TSV process control: Target sample preparation

Focused Ion Beam is the method of choice for site specific preparation

Restrictions of standard FIB:
- large quantities of materials to be milled
- precise, but too slow (> 2…10 hours depending on geometry)
3D TSV process control: Fast sample preparation (work in progress)

Approaches for rapid X-sectioning:

1. increase of milling rate using chemical enhancement (for Si removal) and high current FIB
2. new plasma sources for FIB milling
3. laser ablation prior to high-rate FIB polishing

Reduction of preparation time (approaches 2 and 3):
~ 5 hours ➞ ~ 0.5 hours

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Selected TSV Process Control Requirements

Monitoring of via etch process (depth, taper, ...)

H 1 = 28.22 μm

V 1 = 2.457 μm
Selected TSV Process Control Requirements

Monitoring of sidewall and bottom oxide/barrier (thickness, uniformity,...)
Selected TSV Process Control Requirements

Monitoring of fill material (voids, grain structure, impurities ....)

FIB Channeling Contrast
Selected TSV Process Control Requirements

Monitoring of via-via-interconnections (IMC formation and distribution)
Contents

- Process control / Metrology
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- Stress engineering
3D IC Integration: Quality engineering / failure analysis needs

- Liner/barrier coverage/homogeneity (⇒ leakage)
- TSV incomplete fill / voids
- Adhesion/delamination
- Stress (⇒ CPI, Si cracks, Cu extrusion/„pop-up“)
Analytical techniques for failure analysis

Requirements

- Full-wafer or samples
- Non-destructive or destructive
- Reasonable throughput
- Reasonable technique reliability and tool uptime
- ...
Analytical technique for failure analysis

In-line techniques (nondestructive)

- Scanning acoustic microscopy
- IR microscopy (?)
- ...

Lab-based techniques

- Nano-XCT + subsequent X-sectioning (z. B. FIB) + SEM imaging
- ...

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Analytical technique for failure analysis

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Xradia NanoXCT: Lab based X-ray microscopy

- Laboratory X-ray Source
  - Cu target (8 keV) or
  - Cr target (5.4 keV)

- Energy Filter
- Condenser (light gathering optic)
- Sample
- Objective (zone plate)
- Zernike phase ring
- X-ray Camera

Courtesy: Xradia Inc.
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Xradia nanoXCT @ Fraunhofer IZFP Dresden

- X-ray tube
- Collimator
- specimen
- lens
- imaging system
- about 30 motors
Zone plate’s key parameters

Zone plate (X-ray lense) consists of concentric rings (zones) with zone width decreasing with radius

Interference principle of Huygens and Fresnel: Delay of the light in different regions, strong chromatic aberration.

Number of zones > 100 required for good focusing

Resolution is proportional to the width of the outermost (smallest) zone.

Outermost (smallest) zone width determines resolution and NA

(current limit: ~ 30nm, A/R ~ 30)

SEM image of a zone plate and its zone profile

Courtesy: Xradia Inc.

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Limits of zone plates: ~ 30 nm structures

Grating bar width: 100nm
Grating height: 1600nm

Zone plates are fabricated out of high-Z (typically gold) material using electron beam lithography, reactive ion etching and electroplating.

Focusing efficiencies 10-30% currently achievable (depends on A/R).

Courtesy: Xradia Inc.
TSV sample preparation for nano X-ray tomography

Preparation (e.g. with laser ablation) + Focused Ion Beam
Process development: nanoXCT analysis of TSVs

Failure localization in TSVs: Large filling defects

Cooperation with Lay Wai Kong, College of Nanoscale Science and Engineering at the University at Albany/NY
Flat samples: Laminography with tilted axis

- Johann Radon
  - Back projection possible based on projections of different angles
- Rotation of sample or X-ray source
- Reconstruction of 3D data, e.g. by filtered back projection
- Acquisition geometry depends on sample shape
  - cylindrical samples: normal CT
  - flat samples: Laminography, typical artifacts

NEW!

CT

Limited angle CL

CL with tilted axis

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X-ray microscope – setup

- Real optical imaging using the simplest microscope

Source | Condenser | dedicated sample stage (xyz-Θ) | X-ray lens | Detection system

1500 mm
Sample tilt
X-ray computed laminography study of TSVs

Comparison for equal measurement time

- Limited Angle CT
- CT with tilted rotational axis

- Better image quality (contrast)
- Less artifacts at the bottom of the TSV
Xray tomography at TSV sample: < 100nm voids visible

Cavity

Position of the surface

single void

Average over 10 Slices
FIB X-section of TSV after XCT study

- Cavity
- Void chain
- Curved bottom

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- Process control / Metrology
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TSV performance and reliability risks

- **Reliability**
  - Expansion
  - Contraction
  - $\Delta T > 0$
  - $\Delta T < 0$

- **Mobility change**
  - Radial tension
  - Circumferential compression

- **Via material, diameter**
- **Silicon crystal orientation, P/N**
- **Barrier layer material**
- **Insulation liner material and thickness**
- **TSV array pitch, height**

TSV extrusion and de-lamination
- P. Ho, RTI 3D Symposium 2009

Performance shifting after wafer thinning
- QCT/IMEC, DATE 2009

**Courtesy:** Xiaopeng Xu, Synopsys
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Cu TSV extrusions – Quantitative analysis

Both 4 and 5um TSV show Copper is extruded and with de-lamination at the wall

Cooperation with Lay Wai Kong, College of Nanoscale Science and Engineering at the University at Albany/NY

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Stress-induced reliability-limiting effects

Example: Cu extrusion / “pop-up”

- Reasons:
  - Shear stress (depends on geometry, process flow (thermal cycles) and materials (E, CTE values)
  - Adhesion (sidewall)

- Nano-XCT is a potential technique to study this effect nondestructively (region of interest not destroyed)
  ➔ Systematic quantitative analysis possible
Summary

3D TSV integration (new processes and materials) requires

- advanced techniques for **process control / metrology**
  - *Time-to-data* has to be reduced for X-sectioning techniques
    Plasma FIB, Laser ablation + FIB, ...

- advanced techniques for **quality control / failure analysis**
  - *Time-to-data* has to be reduced for nanoXCT
  Improved X-ray sources, optics and detectors
  Improved data analysis strategies (→ Discrete tomography)
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