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Heterogeneous Integration Systems: Ensuring Reliability

HIR Symposium, Feb 22-24, 2023

HI for Market Applications
- Mobile
- IoT
- Medical, Health & Wearables
- Automotive
- High Performance Computing & Data Center
- Aerospace & Defense

Heterogeneous Integration Components
- Single Chip and Multi Chip Packaging (including Substrates)
- Integrated Photonics
- Integrated Power Electronics
- MEMS & Sensor integration
- RF and Analog Mixed Signal

Cross Cutting topics
- Materials & Emerging Research Materials
- Emerging Research Devices
- Interconnect
- Test
- Supply Chain
- Security
- Thermal Management

Integration Processes
- SiP
- 3D +2.5D
- WLP (fan in and fan out)

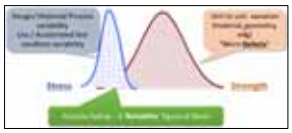
Design & Reliability
- Co-Design
- Modeling and Simulation
- Reliability

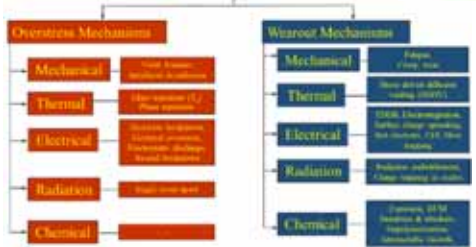
Acknowledgment:
Richard Rao (Marvell), Shubhada Sahasrabudhe (Intel)

HI system reliability

Prognostics and Health Management

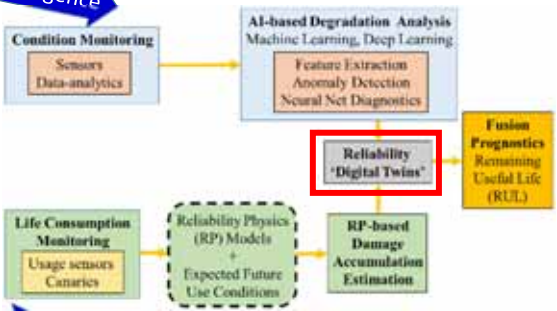
Degradation and Failure Mechanisms





Fusion of bottom-up physics and top-down AI approaches

Machine Learning & Artificial Intelligence



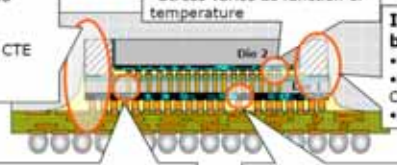
Reliability Physics

HI systems reliability: CBPI in HPC Applications

Impact of Flip Chip Package on 3D chip-stack (CPI)
- Stress induced by Cu-pillars on low-K
- Stress induced by overmold, laminates CTE mismatch
- …

Impact of TSV/uBump on top die
- Built-in stress
- Stress varies as function of temperature

Impact of 3D-SIC bonding on dies
- Stress during bonding
- Stress due to underfill CTE mismatch
- …

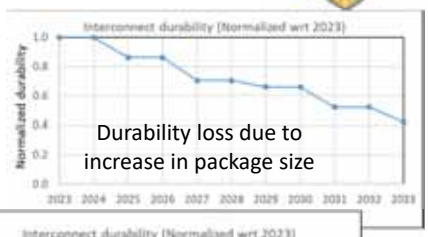


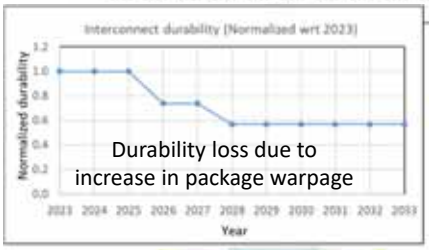
Impact of die thinning
- Releases stress
- Strength of die
- …

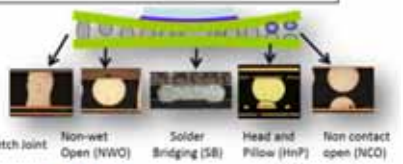
Impact of TSV on bottom die
- Built-in stress
- Stress varies as function of temperature
- …

Stress/strain can lead to
- mechanical failures due to delamination, peel, fatigue, …
- electrical impact due to parameter shifts, increased variability, EM,…

Multi-scale



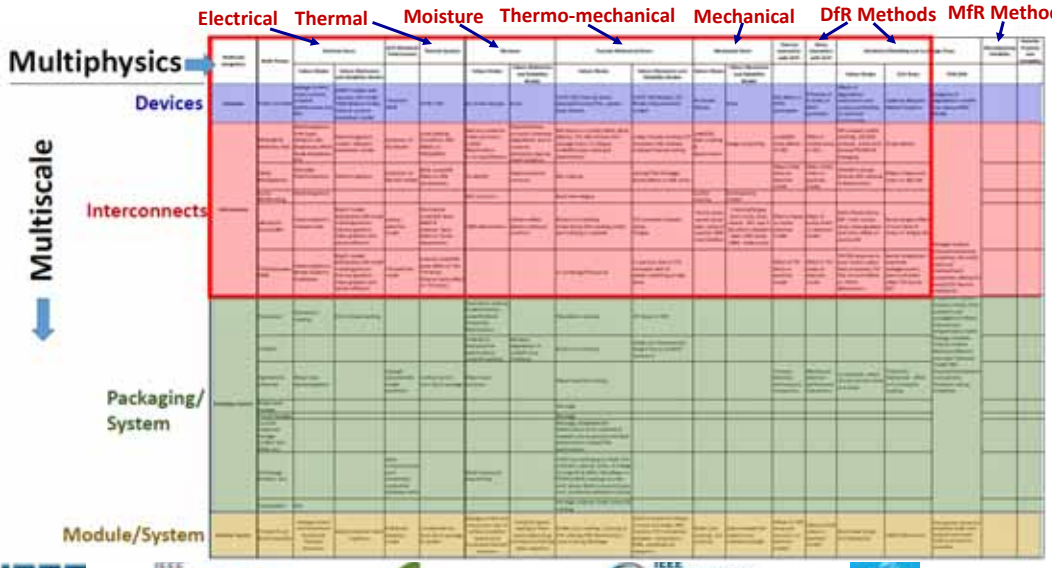




Warpage induced defects and failures

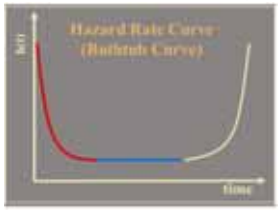
Source: IMEC

Modes/Mechanisms/Models for degradation & failure

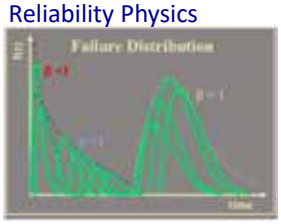


Reliable HI systems: Approach

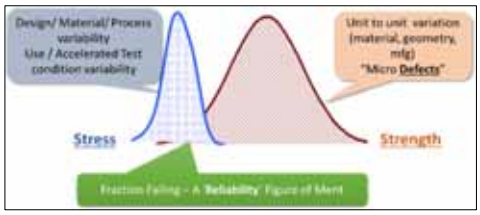
Top down:
Artificial Intelligence
and Machine Learning



Bottom up:
Reliability Physics



Reliability Assurance Activities



Multi-physics/multi-scale HI systems require holistic cradle-to-grave methodology

- Reliability Targets
- Life Cycle Conditions
- Design for Reliability
- Manufacturing for Reliability
- Knowledge based Testing for Qualification
- Product Health Management
- Supply chain Integration
- Affordability of Reliable HI Systems

Chapter 24 Table of contents – 2022 Plans

1. Executive Summary
2. HI System Reliability:
   - Introduction and Scope
   - Top Down (Data-Based) vs Bottom-up (Reliability Physics) Approaches for Reliable HI Systems

   Compact Models and Digital Twins
3. Reliability Assurance Activities for HI Systems Digital Twins
   - Life Cycle Conditions & Reliability Targets
     - Automotive
     - Aerospace & Defense
     - HPC & Data Centers
     - IoT
     - Mobile
     - Medical Health and Wearables
   - Design for Reliability (DfR)
   - Manufacturing for Reliability (MfR)
   - Qualification for reliability (QfR)
   - Sustainment for Reliability (SfR) via Prognostics and Health Management (PHM)
   - Role of the Supply Chain in Assuring Reliable HI systems
   - Affordability of Reliable HI systems

   Degradation Physics in new technologies & Photonics

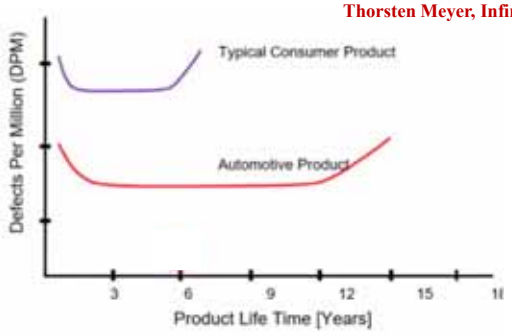
   Process quality and metrology
4. System Reliability – Software Reliability, Operator Reliability, Interactive factors
5. Difficult Challenges and Disruptive Opportunities
6. Approach and Roadmap for Addressing Difficult Challenges

Reliability Targets and Life-cycle conditions

Example - Automotive Quality/Reliability Requirements

Thorsten Meyer, Infineon

- Product lifetime and quality/ reliability are differing between Consumer and Automotive
- Typical consumer electronic components generally manufactured with
  - a different quality/ reliability mindset
  - a shorter useful life span
- One factor in consumer space: tradeoff between time to market and quality;
  - Faster access to higher performance (or new features) invariably requires taking higher risk
- Die and package traceability required in ATV
- Cost issues, especially for zero defects target in the traditional automotive market
- Differences will have to be carefully considered for
  - new package platforms
  - utilization of commercially available (consumer) systems



	Consumer	Automotive
Ambient temperature range	0 to 85 °C	-30 to 150 °C
Expected Operating Life	2-3 years	>10 years
Acceptable Failure Rates	300 ppm	"ZERO" (!!)
Supply Lifetime	2-3 years	15-20 years

Designing for reliability: Reliability-physics process

INPUTS

Hardware configuration
materials, geometry, architecture

Life Cycle Loading

Operational Loads
Power dissipation, voltage, current, frequency, duty cycle

Environmental Loads
Temperature, relative humidity, pressure, shock. The life cycle includes transportation, storage, handling and Application environments

ANALYSIS

Modeling & Simulation TWG ⟷ Reliability TWG

Multiphysics "Stress" Analysis
Stresses at failure sites
- Electrical
- Thermal
- Mechanical – Vibration & shock
- Diffusion
- Thermo-hygro-mechanical
- Electromagnetic & Quantum fields

Reliability Margins
Design margins for relevant failure mechanisms due to stresses at each failure site:
- stress margins for overstress mechanisms
- life margins for wearout mechanisms

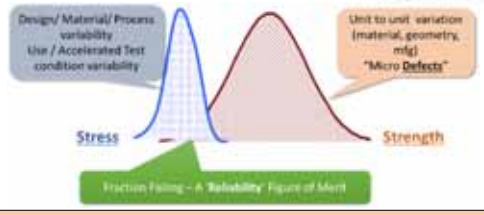
Aggregation to the System Level
Reliability block diagrams
Monte Carlo simulations
Bayesian updates with field/test data (if any)

Sensitivity Analysis
Sensitivity of the product durability to changes in: application, design, manufacturing window, life-cycle support methodologies

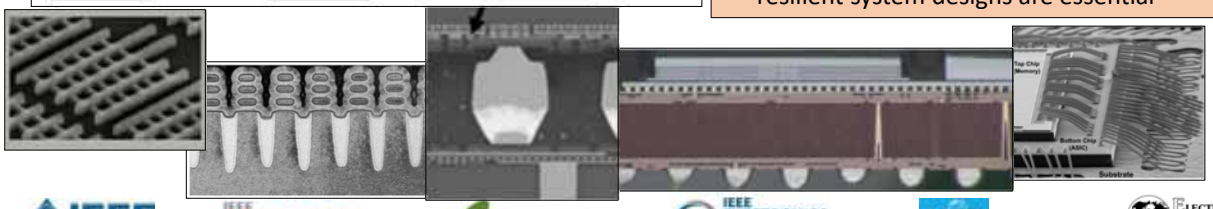
OUTPUTS

- Ranking of potential failure mechanisms and sites
- Design tradeoffs
- Risk mitigation solutions
- Accelerated test conditions
- Reliability Assessment
- Health Prognostics

Influence of manufacturing quality on reliability



- Process modeling and process metrology pose significant challenge for HI Systems development
- 'Zero defects' are no longer realistic and resilient system designs are essential



Qualification and testing: Reliability validation/verification

The changing and challenging landscape

Need for dynamic, flexible models and methods

Extreme environments | Extreme usages/ lifetime | Latest tech nodes

Diverse components | New failure modes | Wide range of Rel tests | Innovative FA/FI | Stochastic modeling

Field Telemetry | Reliability Physics | Test time optimizations | Digital Twin feedback loop

Multi-physics methods to quantify 'stress' and 'strength' distributions at potential sites of failure	Qualification testing needs to be Customized, Knowledge-based and Innovative	Data feedback loop with Digital Twins to validate failure characteristics and run virtual experiments	Integrated PHM - Self-cognizant, intelligent, bio-mimetic hardware to 'age with grace'

Source: Sahasrabudhe (Intel)

Reliability challenges: Future outlook

Digital Twins

		Reliability Targets	Life Cycle Conditions	Design for Reliability	Manufacturing for Reliability	Qualification for Reliability	Sustainment for Reliability	Supply Chain
Applications	Mobile IoT Medical, Health and wearables Automotive HPC & Data Centers Aerospace and Defense							
Package Integration	WLP (FO/FI) 2.5D and 3D integration Wafer Singulation and Thinning Chip-package interactions (CPI) Interconnects (TSVBs, µbumps, wirebonds, Flip Chip solder joints) Substrates/Interposers Board Assembly SOC/SIP/SOP[3] formats							
Technologies	Microelectronics > 10 nm Microelectronics <10 nm Photonics & optics MEMS and sensors Power electronics Energy souces (Batteries/PV[6]/FC[7]) RF/Analog Devices							

1-5 Years:
Multi-physics fusion approaches for reliability assurance
- Bottom-up *Reliability Physics* based approaches, tools, infrastructure
- Top-down *Machine Learning & AI* based approaches, tools, infrastructure

5-10 Years:
Fusion approaches for co-design (based on 'digital twins') and life-cycle PHM of next-gen robust HI systems
- Fault-tolerant systems
- Resilient systems

10-15 Years:
Fusion approaches for intelligent, adaptive, reconfigurable products with integrated autonomous life-cycle management capability
- Intelligent, self-cognizant systems
- Self-healing systems

Current members of reliability TWG:

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