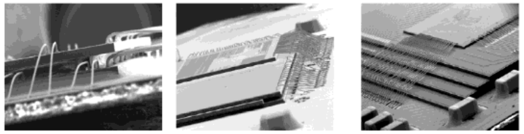
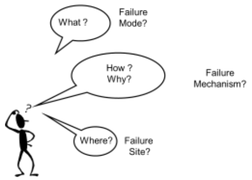
Micro and Nano- Electronics Reliability
Classical approach and new trends

Part 4: Physics of Failure approach



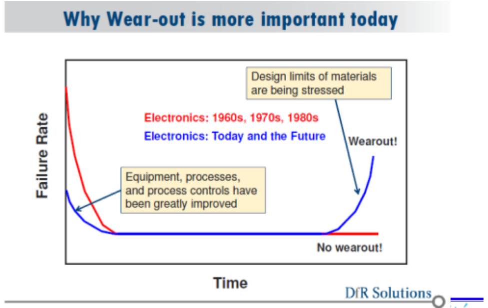
Physics of Failure

- Addresses the wear-out part of the bathtub curve
- Does not consider the random “usual life” part



Predict life times
Propose corrective action

Physics of failure



Introduction to the physics-of-failure methodology

- Identify potential failure mechanisms, e.g., chemical, electrical, physical, mechanical, structural, or thermal processes leading to failure, and the failure sites on each device.
- Expose the product to highly accelerated stresses to find the dominant root-cause of failure.
- Identify the dominant failure mechanism as the weakest link.
- Model the dominant mechanism (what and why the failure takes place) : define a failure criterion
- Combine the data gathered from acceleration tests and statistical distributions, e.g., Weibull distribution, Lognormal distribution.
- Develop an equation for the dominant failure mechanism at the site and its mean time-to failure (MTTF).

Physics-of-failure modeling and simulation tools are the key elements in this approach

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Steps in the PoF approach (1/2)

- **Identify use environment and product hardware configuration:**
  - ➢ Review field history data and similar product performance
  - ➢ If a new product category, evaluate comparable products
- **Design & conduct a suite of accelerated stress tests on a *representative design:***
  - ➢ Failure-limited step-stress tests, to identify overstress limits
  - ➢ Failure-limited long-term accelerated stress tests, to identify durability
- **Identify failure modes and perform root-cause assessment of failure mechanism(s):**
  - ➢ Identify failure modes and mechanisms through failure analysis
  - ➢ PoF model constants at field & test conditions

Steps in the PoF approach (2/2)

- **Conduct stress analysis for field and test environments:**
  - ➢ Modeling and simulation (FEA, etc)
  - ➢ Experiments
  - ➢ Statistical tools (Weibull) for confidence limits

- **Input stress levels into PoF model(s) to estimate product durability**

Defining accelerated test conditions

- For a known or suspected failure mechanism,
  - ➢ Identify all stimuli affecting the mechanism based on anticipated application conditions and material capabilities:
    - ✓ temperature
    - ✓ electric field
    - ✓ humidity,
    - ✓ thermomechanical stresses,
    - ✓ vibration,
    - ✓ corrosive environments.

Defining accelerated test conditions

- Choice of accelerated test conditions based on
  - ➢ material properties
  - ➢ application requirements (“mission profile”).

- Need to conduct accelerated tests over a reasonable time interval.

BUT avoid

- ➢ generating fails that are not pertinent to the experiment,
  - ✓ due to stress equipment problems
  - ✓ due to materials problems,
  - ✓ “false failures” caused by product overstress conditions that will never occur during actual product use

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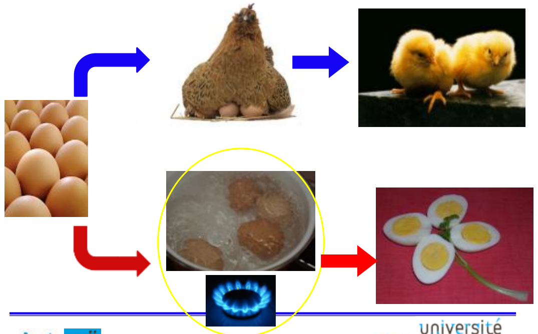
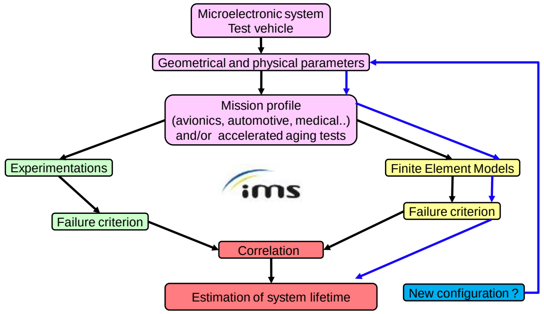
Bad accelerating conditions



PoF: Methodological approach



Microelectronic system
Test vehicle

Geometrical and physical parameters

Mission profile
(avionics, automotive, medical..)
and/or accelerated aging tests

Experimentations

Finite Element Models

Failure criterion

Failure criterion

Correlation

Estimation of system lifetime

New configuration ?

Modeling and simulation are the key elements in this approach

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Wearout Examples

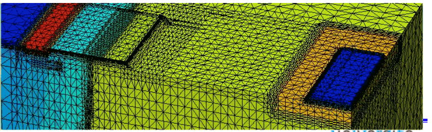
- What is susceptible to wearout in electronic designs?
  - Ceramic Capacitors (oxygen vacancy migration and dielectric breakdown)
  - Electrolytic Capacitors (electrolyte evaporation, dielectric dissolution)
  - Corrosion failures (silver platings on PCBs or resistors/capacitors, conductive anodic filament formation)
  - Relays and other Electromechanical Components
  - Integrated Circuits (EM, TDDB, HCI, NBTI)
  - PCB Assemblies
    - Plated through hole fracture (Z-axis expansion)
    - Solder joint fracture (thermal cycle, mechanical vibration/shock)

DfR Solutions

Device simulation

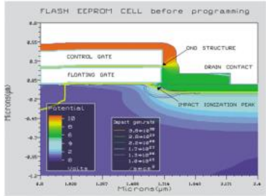
Device simulation

- Device simulation tools simulate the electrical characteristics of semiconductor devices:
    - ➢ response to external boundary conditions imposed on the structure:
        - ▪ electrical,
        - ▪ thermal
        - ▪ optical
- The input device structure typically comes from process simulation steps



Reliability Modeling and Prediction

- Reliability device simulators aim to model the most significant physical failure mechanisms in the electronic devices:
    - ➢ time-dependent dielectric breakdown (TDDB)
    - ➢ negative bias temperature instability (NBTI),
    - ➢ electromigration (EM),
    - ➢ hot carrier injection (HCI).
- These mechanisms are modeled throughout the circuit design process so that the system will operate for a minimum expected useful life.
- Only wearout mechanisms can be linked to life times



S-Pisces includes models to support simulation of EPROMs, EEPROMs and FLASH EEPROM cells. Hot carrier injection and Fowler-Nordheim tunneling are used to charge and discharge the floating gate. The figure (above) illustrates potentials and ionization rate in a FLASH EEPROM cell prior to programming. The complex geometry is imported automatically from ATHENA.

http://www.silvaco.com/products/vwf/atlas/spisces/spisces_datasheet.html

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Reliability simulation methodology

- Most state-of-the-art reliability simulation methods try to emulate the degradation process of aged devices in a repetitive scheme. They are based on the physical failure mechanisms and contain the major wearout models for EM, HCI, NBTI and TDDB.
- A set of parameters for each of these failure mechanisms are identified and the algorithms of extracting these parameters for a given technology are developed by accelerated tests on test structures.
- A circuit simulator, such as SPICE, is employed to calculate the electrical parameters of fresh and degraded devices to predict their degradation or failure from these parameters.

Reliability Modeling and Prediction

- Integrated circuit are composed of tens or hundreds of millions of transistors:
    - ➢ chip-level reliability prediction methods are mostly statistical.
    - ➢ calculation of failure probability of the chips at the end of life, when a given wearout mechanism is expected to dominate.
- However, modern prediction tools do not predict the random, post burn-in failure rate that can be seen in the field.
- The reliability simulation methods can help designers understand how the devices degrade over time, identify the reliability bottlenecks within the circuits and make design tradeoffs between performance and reliability in the product design stage.
- It can also help manufacturers build their circuits such that no known wearout mechanism will dominate over the life of an operating device and assure adequate reliability for the product.

Finite element simulation

Finite Element Modeling: Principles

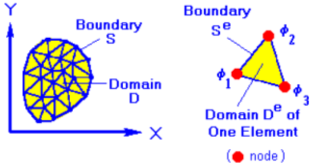
- Computer-based numerical technique for calculating the strength and behavior of engineering structures.
- Calculation of physical phenomena described by partial differential equations
    - ➢ Thermal dissipation
    - ➢ Mechanical deflection, stress, vibration, buckling behavior
- Physical problems diversity
    - ➢ Solid
    - ➢ Fluid and soil mechanics
    - ➢ Electromagnetism
    - ➢ Dynamics
    - ➢ …

Finite Element Modeling: Principles

- Discretization
- Continuous world → Discrete world
- Irresolvable mathematical problem → System of equations
  - ➢ Simplifying assumptions
  - ➢ Boundary conditions
  - ➢ Results to be carefully interpreted
- Approximate solutions of
  - ➢ Partial differential equations
  - ➢ Integral equations

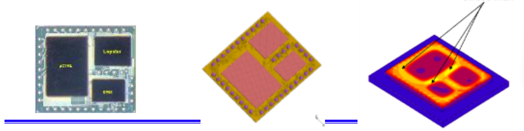
Finite element simulation

- Structure broken down into many small simple blocks or elements (meshing)
- Behavior of an individual element described with a relatively simple set of equations.
- Solution domain discretized into smaller regions called elements
- Solution determined in terms of discrete values of some primary field variables φ (e.g. displacements in x, y z directions) at the nodes



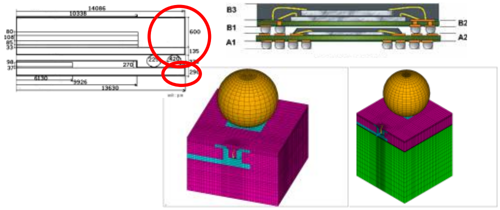
Finite element simulation

- Just as the set of elements would be joined together to build the whole structure, the equations describing the behaviors of the individual elements are joined into an extremely large set of equations that describe the behavior of the whole structure.
- Elements are connected at specific points, called nodes, and the assembly process requires that the solution be continuous along common boundaries of adjacent elements.
- The computer can solve this large set of simultaneous equations. From the solution, the computer extracts the behavior of the individual elements.



Finite element simulation: key points

- Geometry
- Meshing
- Boundary conditions
- Material properties



Finite element simulation: related tools

- Material characterization


Profilometer


Traction


Traction - shear - pull

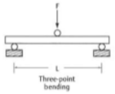
- Simulation tools


- Accurate weight measurement

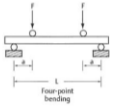

Thermal resistance

Mechanical tests

- Bending tests



Three-point bending



Four-point bending

https://www.youtube.com/watch?v=zeyqcPiUFPs
https://www.youtube.com/watch?v=1mFEQNE64lI

Mechanical tests

- https://www.youtube.com/watch?v=bG340h6hsaY

Shear test

- https://www.youtube.com/watch?v=6i380FE3ZQo

Pull test

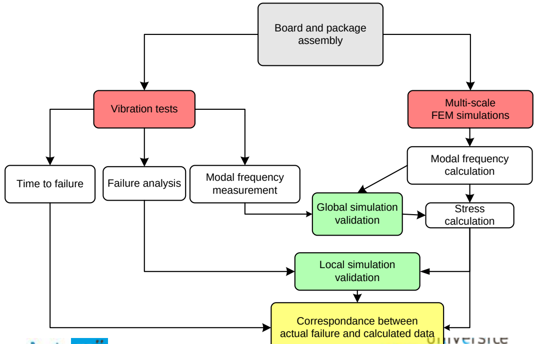
Case study

Case study 3: Technological choice for mechanical stresses in military applications

- Context
  - ➢ New solder materials : SnAgCu replaces the “well known” SnPb
  - ➢ Military applications : vibration tests to detect assembly weaknesses
  - ➢ Empirical damage laws to predict SnPb assembly life-times
  - ➢ SAC: large dispersion in experimental published Time To Fails

➡
- Evaluation of technological choices to increase the lifetimes of large BGA assembled with SAC
- Comparison with SnPb assemblies

Case study 3: Technological choice ; methodological study



Board and package assembly

Vibration tests

Multi-scale FEM simulations

Time to failure

Failure analysis

Modal frequency measurement

Modal frequency calculation

Global simulation validation

Stress calculation

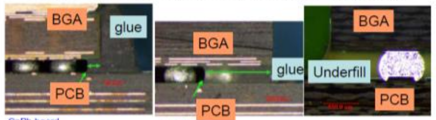
Local simulation validation

Correspondance between actual failure and calculated data

Experimental part

- 10 FR4 boards
- SnPb or SAC
- Different kinds of underfilling
  - ➢ pell-off joint,
  - ➢ underfill,
  - ➢ no glue
- Random vibrations at 4 levels
- Failure criterion: open circuit

Unexpected difference on gluing width in the periphery of the packages:



SnPb board
Little penetration of glue (normal)

SAC board
large penetration of glue (abnormal)

M.Berthou, H.Lu, P.Retailleau, H.Frémont, A.Guédon-Gracia, C.Jéphos-Davennel, C. Bailey
Vibration test durability on large BGA assemblies: Evaluation of reinforcement techniques,
proceedings of IEEE CPMT Symposium Japan, paper 11-3 (2010)

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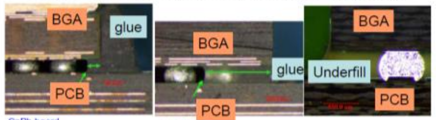

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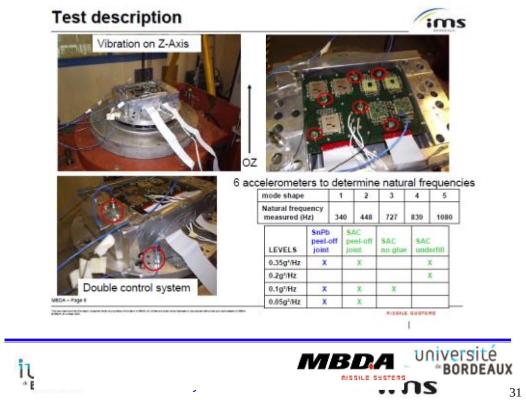


Test description

Vibration on Z-Axis

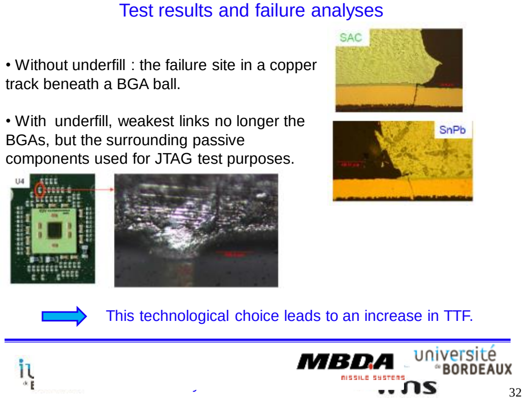
OZ

6 accelerometers to determine natural frequencies

mode shape	1	2	3	4	5
Natural frequency measured (Hz)	340	448	727	839	1080

LEVELS	SnPb peel-off joint	SAC peel-off joint	SAC no glue	SAC underfill
0.35g²/Hz	X	X		X
0.2g²/Hz				X
0.1g²/Hz	X	X	X	
0.05g²/Hz	X	X		

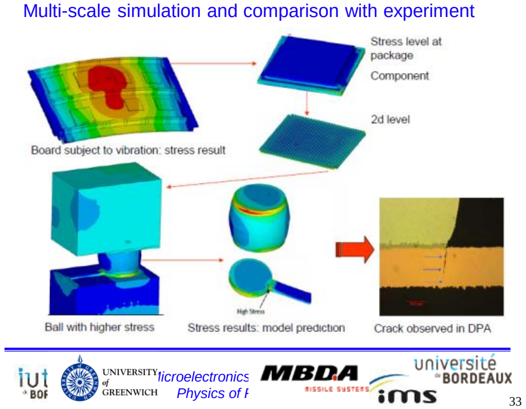
Double control system



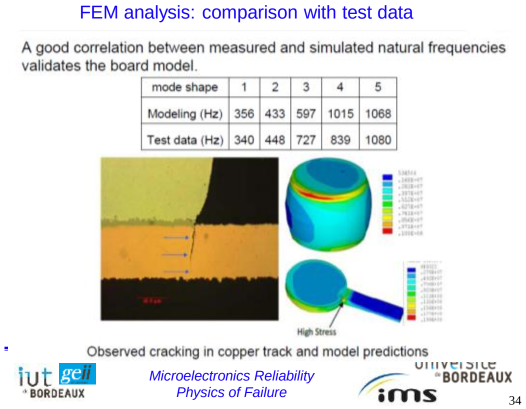
Test results and failure analyses

- Without underfill : the failure site in a copper track beneath a BGA ball.
- With underfill, weakest links no longer the BGAs, but the surrounding passive components used for JTAG test purposes.

➡ This technological choice leads to an increase in TTF.



Multi-scale simulation and comparison with experiment



FEM analysis: comparison with test data

A good correlation between measured and simulated natural frequencies validates the board model.

mode shape	1	2	3	4	5
Modeling (Hz)	356	433	597	1015	1068
Test data (Hz)	340	448	727	839	1080

Observed cracking in copper track and model predictions

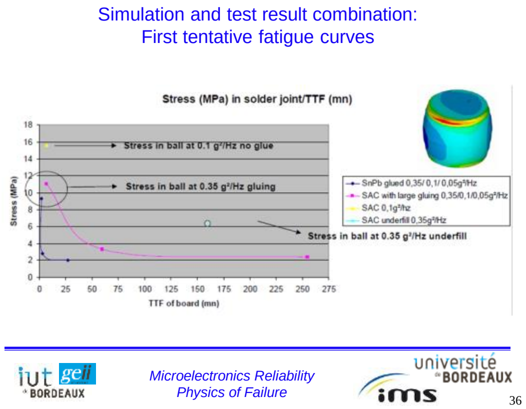
Synthesis: Test and simulation results comparison

For a given BGA,

- Simulations
  - ➢ Stress calculated in copper tracks without gluing at 0.1g²/Hz
  - ➢ Stress calculated in copper tracks with glue at 0.35g²/Hz.

  } Same magnitude
- Tests
  - ➢ TTF of both structures for these two vibration levels also similar

➡ First tentative fatigue curves



Simulation and test result combination: First tentative fatigue curves

Case study: technological choices

- Technological choices are critical
  - ➢ Increased role of simulations
  - ➢ Experimental trials still necessary