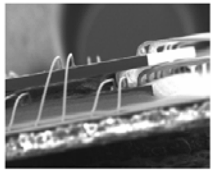
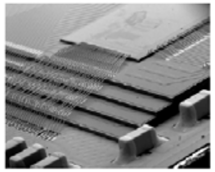
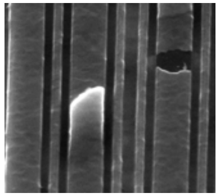
Micro and Nano- Electronics Reliability
Classical approach and new trends

Part 2.5: Electro-Thermo and Stress Migration effects

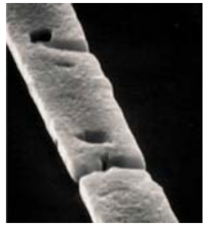


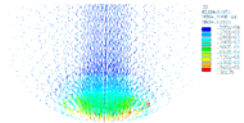


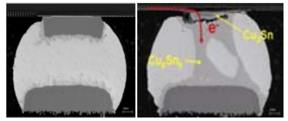
Electro-Thermo and Stress Migration effects



A void and a hillock generated by electromigration







SEM image of a solder bump before and after current stressing
Chao, B.; Chae, S.-H.; Acta Met., 55, 2007

Chapter layout

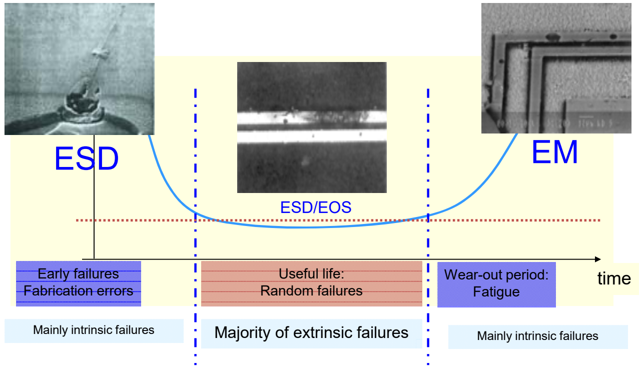
- **1. Introduction**
- **2. Electromigration physics**
- **3. Induced failure modes**
- **4. Reliability statistical models**
- **5. PoF approach: FEM simulations of mass flux migrations**
- **6. Case of study: Package on Package**

Introduction

- Few reliability problems have attracted as much attention in the scientific literature as electromigration.
- First identified as a failure mechanism over 50 years ago, when it surprised and briefly threatened the existence of the integrated circuit industry.
- Subject of intensive research and development ever since
- Wear-out failure
  - ➢ caused by the degradation of the component materials,
  - ➢ associated with some operational parameters,
    - ✓ the amount of heat,
    - ✓ current or voltage applied during use.

To effectively produce design rules for whatever material choice is made, failure mechanisms must be well understood

Electromigration



Electromigration physics

- Electromigration is the biased mass transport of metal atoms due to the momentum transfer from collisions between conducting electrons and diffusing metal atoms.
- Two forces affect ionized atoms in a conductor.
  - The direct electrostatic force Fe as a result from the electric field therefore having the same direction.
  - The force from the exchange of momentum with other charge carriers Fp showing toward the flow of charge carriers. In metallic conductors Fp is caused by a so-called "electron wind" or "Ion wind".
- The resulting force Fres on an activated ion in the electrical field is:

$$F_{res} = F_e - F_p = q \cdot Z^* \cdot E = q \cdot Z^* \cdot j \cdot \rho$$

Electromigration physics

- Electromigration is due to the momentum exchange between conducting electrons and diffusing metal atoms.

> ➢ Simply stated, perhaps, but how does it happen?

Electromigration physics

- In a perfect lattice, there is no resistance. Electrons move about in a periodic potential with no other interaction with the metal atoms.
  - A perfect lattice cannot exist above absolute zero
    - ✓ Missing atoms: "vacancies",
    - ✓ Impurities
    - ✓ Boundaries between crystals of different orientation: "grain boundaries"
    - ✓ Regions of imperfection: "dislocations"

Electromigration physics

- At any temperature above 0K, atomic vibrations, "phonons", occur:
  - ✓ A metal atom is put out its of perfect position about 10^{13} times each second
  - ✓ disturbance of the periodic potential,
  - ✓ electron scattering.
  - ✓ the electron changes direction
  - ✓ any change in direction is accompanied by an acceleration; and for every acceleration there is a force.

→ After many collisions (another word for the scattering event), the force averages out in the direction of electron flow

Flux of metal atoms due to electromigration

$$J = DC \frac{Z^* e \rho j}{kT}$$

- J : atomic flux,
- D: diffusion coefficient for the appropriate mass transport mechanism, Z*: "effective charge", represents the sign and the magnitude of the momentum exchange
- ρ: resistivity
- j: current density.
- kT: average thermal energy per atom.

The electromigration induced mass flux is directly proportional to
- the current density,
- the diffusion coefficient
- the concentration of diffusing atoms.

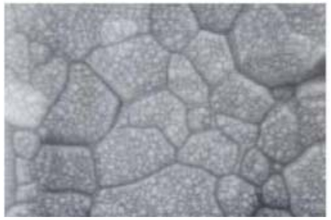
Appears for current densities above 10^5 A/cm²

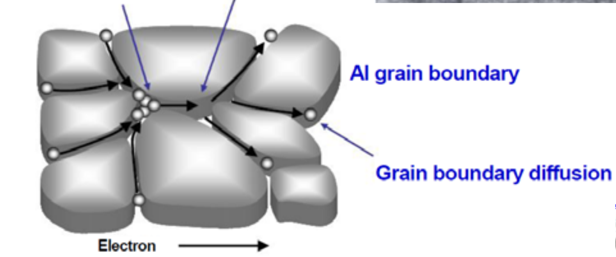
Induced failure Modes

- Electromigration occurs when some of the momentum of a moving electron is transferred to a nearby activated ion. This causes the ion to move from its original position.
- Over time this force knocks a significant number of atoms far from their original positions
  - void or internal failure open circuit.
- Electromigration can also cause the atoms of a conductor to pile up and drift toward other nearby conductors
  - unintended electrical connection known as a hillock failure or whisker failure: short circuit

Electromigration mechanism in Al

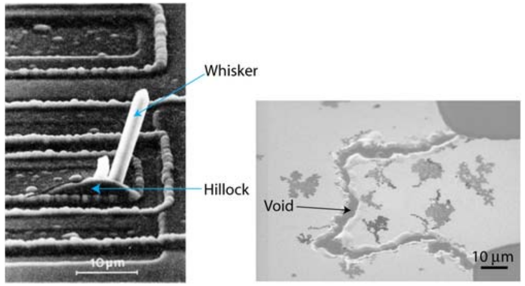
Aluminum grain structure



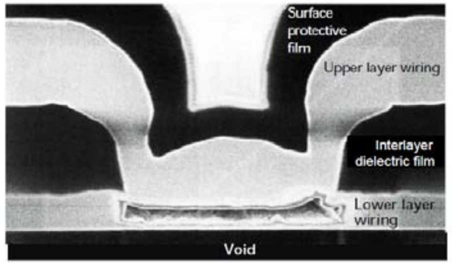


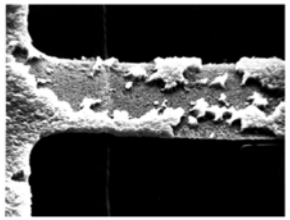
Induced failure Modes

- When atomic flux into a region is greater than the flux leaving it, the matter accumulates in the form of a hillock or a whisker.
- If the flux leaving the region is greater than the flux entering, the depletion of matter ultimately leads to a void.

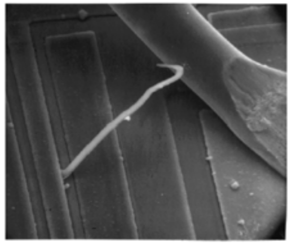


Failure induced by electromigration





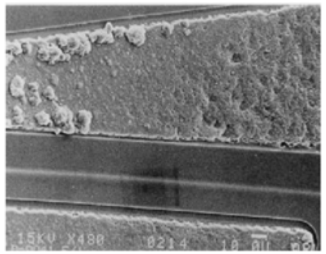
Electromigration damage in an Al conductor line with a thick refractory (TiW) redundant barrier layer.



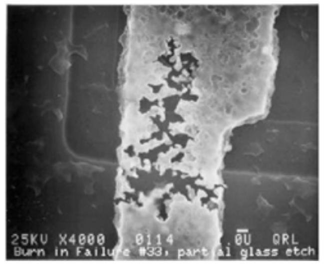
Extrusion to a bond wire causing a short circuit.

Typical failure at an interlevel via for an integrated circuit incorporating redundant barrier and anti-reflective coating

J R Lloyd *Electromigration in integrated circuit conductors* J. Phys. D: Appl. Phys. 32 (1999) .



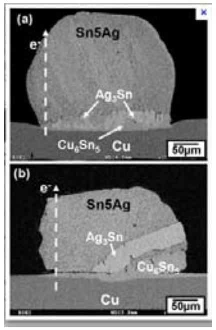
Electromigration in the aluminum conductor of a power transistor has built up aluminum at the left and depleted it on the right.



Electromigration in an aluminum integrated circuit track with preferential migration at grain boundaries.

Case Studies of Metallurgical Failure Mechanisms in Microelectronics
Ray Haythornthwaite Chipworks Inc

EM in SnAg



Electromigration live

- The movie corresponds to the in-situ TEM recording of grain growth and the electromigration process at low temperature (~100K) in a thin Pt bridge under passing of electrical current.
- http://www.dailymotion.com/video/x2kdzc6

http://nchrem.nl/movies/electromigration-at-100-k/

Reliability statistical models

- The electromigration driving force is proportional to the current density.
- It could be assumed that electromigration failure would scale in the same way—linearly with the current—but that is not always the case. Traditionally, it has been observed that electromigration failure followed a $1/j^2$ law rather than 1/j.

$$t_{50} = Aj^{-2}\exp\left(\frac{\Delta H}{kT}\right)$$

j: current density
ΔH: activation energy for failure
A: constant
kT: average atomic thermal energy

Black's Law

Reliability statistical models

- Observations of failure times were not always agreeing with Black's equation

$$t_{50} = Aj^{-n}\exp\left(\frac{\Delta H}{kT}\right)$$

Modified Black's Law

- The current exponent, n, was found to lie commonly "between 1 and 3", but was noticed to vary from experiment to experiment. This led to an adoption of an earlier modification of Black's Law that allowed the current exponent to vary and thus accommodate some of these disparate experimental results

Reliability statistical models

$$t_{50} = A j^{-n} \exp\left(\frac{\Delta H}{kT}\right)$$

- Δ H : activation energy for EM failure depends
  - on the material
    - ✓ ΔH ~1.4 eV for bulk Al
    - ✓ but ΔH reduced to 0.5 to 1 eV by 0.3 to 0.5 % Cu addition
  - on grain size pattern
    - ✓ ΔH ~ 1 to 2 eV for thin films with large grain sizes
    - ✓ ΔH reduced down to 0.4 / 0.6 eV form very fine grained samples
- The "constant" A depends on the geometry, structure, grain size, …
- n is highly dependant on residual stress and ..current density…

First summary

- Without an electrical field the movement of electrical charges in the metallization is without any preferred direction.
- Only free surfaces, grain boundaries and dislocations lead to a directed movement. In the neighborhood of such locations this leads to diffusion.
- With an applied electrical field a directed movement of the electrical charge occurs and out of this material flux or mass flux results. This effect is called electrotransport or electromigration.

First summary

- If the mass flux is homogenous no defects will occur. Only the existence of divergences in the mass flux leads to migration effects. Such divergences can be caused
  - By non-homogeneities in the microstructure (grain boundaries for instance)
  - At surfaces or interfaces
  - Temperature gradients and non-homogeneities in the chemical composition

Reliability at system level

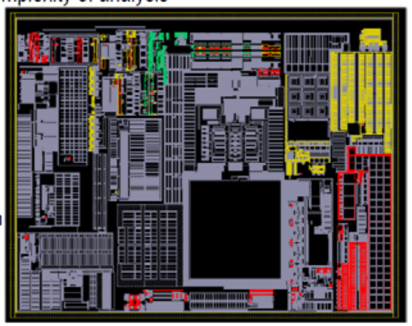
Reliability-aware power integrity

- Electromigration is characterized by maximum current limit
- Constant scaling pushes the current limit
- At SoC level, increased complexity of analysis

What is the current density?

What is the metal width to take into account?

What is the metal length to consider?



➔ **Automated flow mandatory**

Source: Z. Liu, DAC 2006

Physics of Failure approach

- Electromigration is due to high temperatures and high current densities
  - High current densities induce joule heating
  - Different CTE's lead to mechanical stress
- Electromigration but also thermomigration and stress migration mass flux divergences lead to void or hillock growth
- With the calculation of the mass flux divergence the weakest link in trace and bump may be determined

⇨ Use of Finite Element Model

Migration effects: modeling

1. Electromigration

- Electromigration is the mass transport phenomenon in metallization which occurs after applying current densities above a threshold depending on the short-length effect. The mass flux which is responsible for the migration depends on the atomic density N, the Boltzmann constant k_B, the local temperature T, the current density j, the specific resistance ρ, the activation energy E_A associated with the diffusion process, the diffusion coefficient D_0 as well as the effective charge Z*.

$$\overrightarrow{J_{EM}} = \frac{N}{k_B T} e Z^* \left(\vec{j} - \vec{j}_{th}\right) \rho \ D_0 \exp\left(-\frac{E_A}{k_B T}\right)$$

Migration effects: modeling

2. Thermomigration

- With decreasing geometrical dimensions the current densities are increasing. This leads to joule heating in the metallization. Depending on the geometry of the metallization structure temperature gradients can occur.
- The thermo-transport induces a mass flux called thermomigration and is depending on the temperature gradient gradT, the atomic density N, Boltzmann's constant k_B, the square of the temperature T, the activation energy E_A associated with the diffusion process, the diffusion coefficient D_0 and the heat of transport Q.

$$\overrightarrow{J_{TM}} = -\frac{N Q}{k_B T^2} D_0 \exp\left(-\frac{E_A}{k_B T}\right) grad\, T$$

Migration effects: modeling

3. Stress Migration

- Stress migration is a failure mechanism where stress applied to metal lines causes the metal atoms to creep, forming voids in metal lines : increased metal line resistance and disconnection.
- Stress is generated in the metal lines (Al, Cu) used in LSI due to temperature differences between the heat treatment process in the manufacturing process and the operating environment temperature.
- This stress can cause composition deformation in metal lines, resulting in short-circuits between metal lines, or vacancies in the metal lines can creep and converge in a single location, forming a void.
- Stress migration occurs due to the interaction between the metal line stress and the metal atom creep speed. Whereas the metal atom creep speed increases at high temperatures, the stress acting on the metal lines decreases at high temperatures, so there is known to be a peak to the temperatures at which stress migration occurs.

Migration effects: modeling

3. Stress Migration

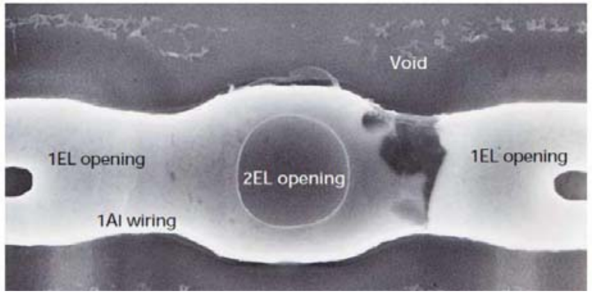
- Multilevel metallization up to ten and more levels are standard in IC applications.
- Due to the different processing temperatures thermo-mechanical stress may be induced. This residual stress is induced by different thermo-mechanical material properties.
- The stress in the copper can reach values from 200 to 500 MPa at room temperature.
- Joule heating also induces thermo-mechanical stress. Both mechanisms will overlay and influence the reliability of the metallization.

$$\overrightarrow{J_{SM}} = -\frac{N\Omega}{k_B T} D_0 \exp\left(-\frac{E_A}{k_B T}\right) grad\, \sigma_H$$

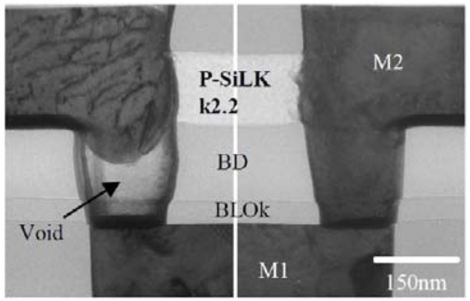
Ω atomic volume
σ_H hydrostatic stress

$$\sigma_H = \frac{1}{3}(\sigma_x + \sigma_y + \sigma_z)$$

Disconnection defects due to Al stress migration



Void Caused by Stress Migration in a Copper Wiring Via Hole



Physics of Failure approach: Mass Flux Divergences

Electromigration

$$\vec{J}_A = \frac{N}{k_B T} eZ^* \vec{j} \rho D_0 \exp\left(-\frac{E_A}{k_B T}\right)$$

Thermomigration

$$\vec{J}_{th} = -\frac{NQ^*}{k_B T^2} D_0 \exp\left(-\frac{E_A}{k_B T}\right) gradT$$

Continuity Equation

$$div(\vec{J}_{tot}) + \frac{\partial N}{\partial t} = 0$$

Stress Migration

$$\vec{J}_S = -\frac{N\Omega}{k_B T} D_0 \exp\left(-\frac{E_A}{k_B T}\right) grad\sigma_H$$

Concentration Distr.

$$\vec{J}_C = D_0 \exp\left(-\frac{E_A}{k_B T}\right) gradN$$

Physics of Failure approach: Simulation Flow

ANSYS program
External program

Geometry modelling
↓
Thermoelectrical simulation
↓
Storage of thermal and electrical solutions
↓
-Thermomechanical simulation
- Storage of mechanical solutions
↓
Mass Flux and Mass Flux Divergences calculation
↓
- Reload of the Results into ANSYS
↓
Static results of (Mass Flux, Divergences and Stress Gradient)

Case study: Package on Package

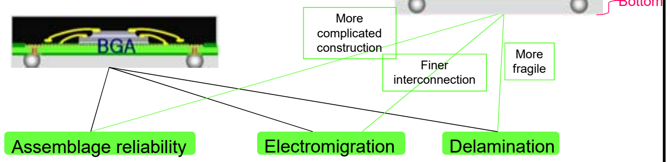
- Simulation of Migration Effects in PoP
  K. Weide-Zaage*, H. Fremont, L. Wang*
  ✓ Eurosime 2008
- Electrically driven matter transport effects in PoP interconnections
  W. Feng, K. Weide-Zaage*, F. Verdier, B. Plano, A. Guédon-Gracia, H. Frémont
  ✓ Eurosime 2009

IMS, Université Bordeaux 1 ENSEIRB-UMR 5218
351 Cours de la Libération, 33405 TALENCE Cedex FRANCE

***Information Technology Laboratory, Leibniz University of Hannover**
Schneiderberg 32, 30167 Hannover GERMANY

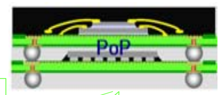
Case study: Package on Package

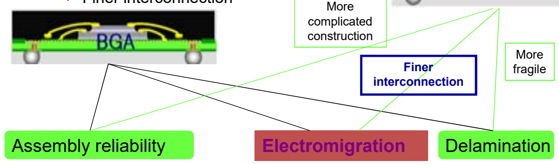
- PoP: Package-on-Package
  - Lead free bump (SAC : SnAgCu alloy)
- Potential degradation mechanisms
  - Delamination
  - Thermomechanical fatigue of solder joints
  - Electromigration



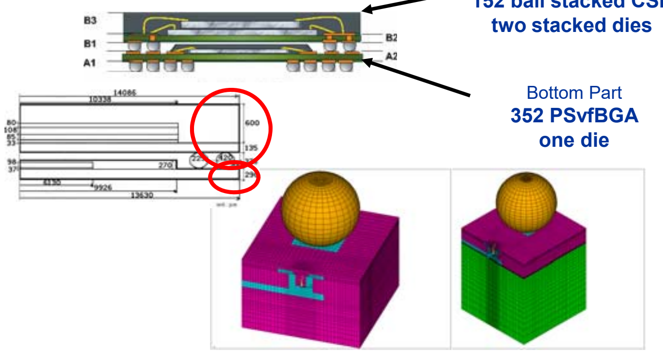
Case study: Package on Package

- Electromigration
  - Current induced mass transport
    - ✓ Current density
    - ✓ Temperature
  - PoP
    - ✓ Increasing electic current
    - ✓ Finer interconnection

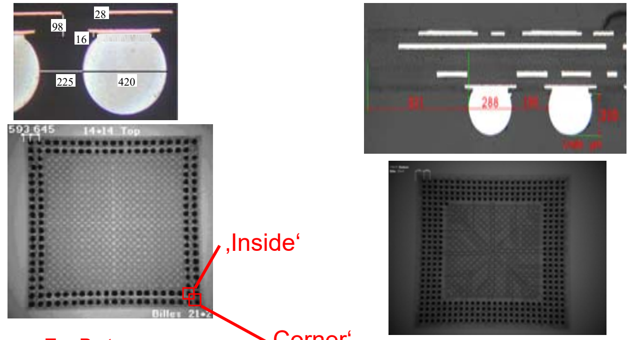




PoP Dimensions



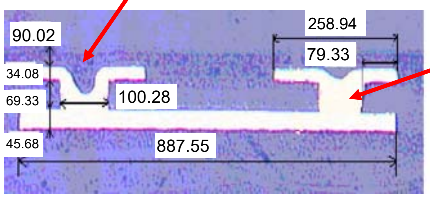
SEM and X-Ray Pictures Bump

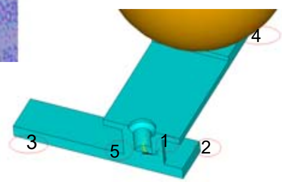


SEM Pictures and FE-Model Cu

Bump location

Via Fill in

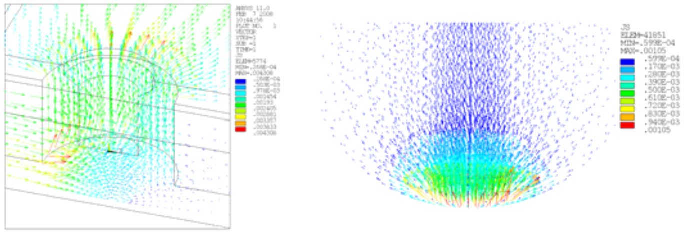




Material Properties

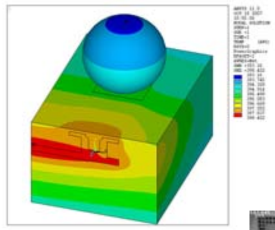
Property	FR-4	Cu	SnAgCu
ρ μΩcm	1e18	1.91	13.3
α_T 1/K	x,y:1.05 z:0.34	3.95	53.5
Young GPa	x,y:26 z:13	117	450
Poisson	x-y,z:0.42 x,y:0.11	0.35	0.3392
CTE 10^{-6}/K	x,y:15 z:58	17.1	20
Z*	--	-4	-23
Q eV	--	-0.0867	-0.0084
E_a eV	--	0.9	0.8

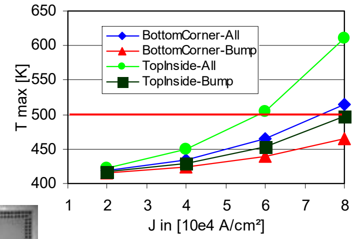
Current Crowding

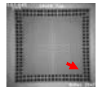


CC in the bump is only one quarter of the CC in trace

Temperature Distribution

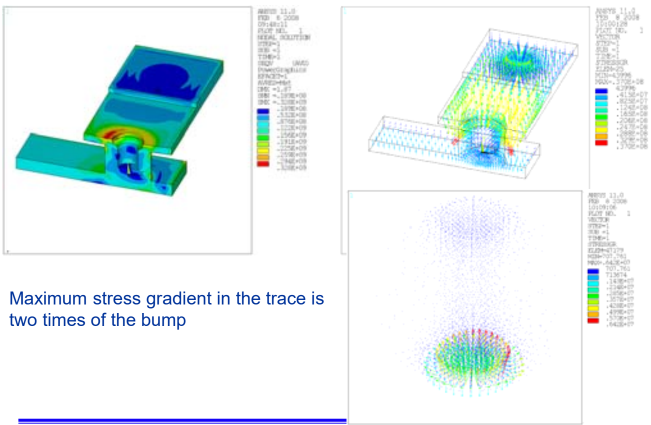






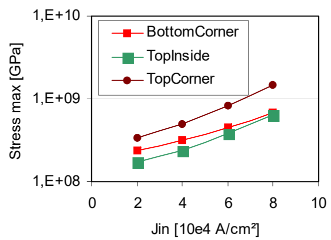
Maximum T in the middle of the trace (Top Part Inside)

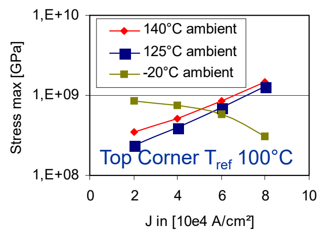
Stress and Stress Gradient

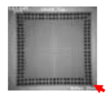


Maximum stress gradient in the trace is two times of the bump

Stress and Ambient Temperature

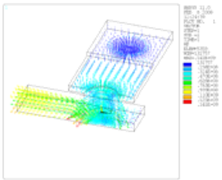


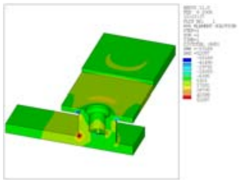


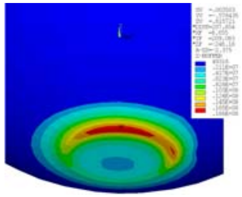


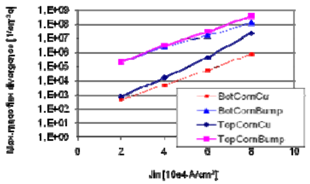
Maximum stress in Top Part Corner

Mass Flux and Mass Flux Divergence



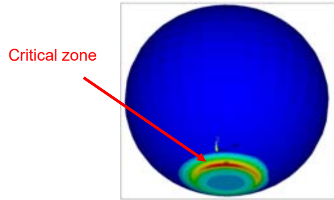






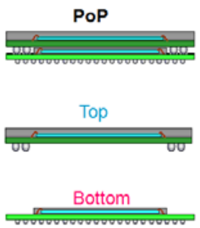
Simulation results

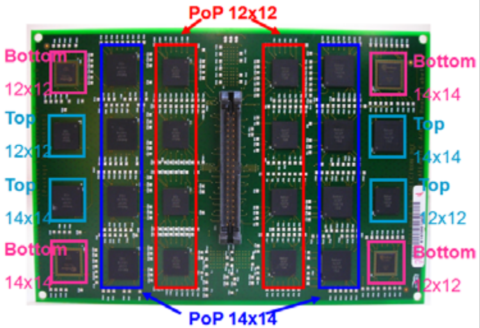
Critical zone: bottom of the bump



Experimental study

- Assembly card
  - Daisy chains

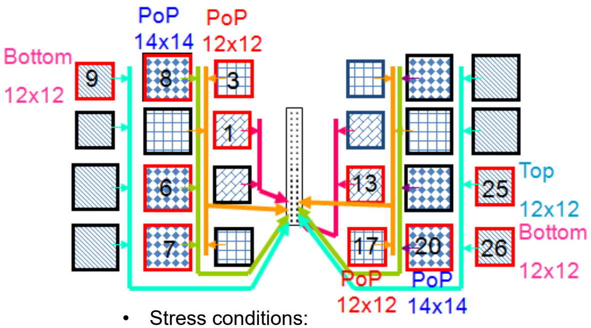




Experimental study

- Temperature-controlled chamber
  - ✓ 120° C
  - ✓ 100° C
- Current generator
  - ✓ 1 A
- 4-wires resistance measurement
  - ✓ Locate failed chain
- EDX (Energy Dispersive X-ray Analysis)
  - ✓ IMC

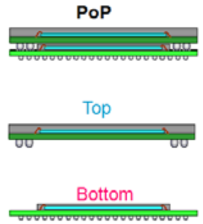
Experimental study



- Stress conditions:
  - ➢ 120 ° C /1A
  - ➢ 100 ° C / 1A

Results and discussion

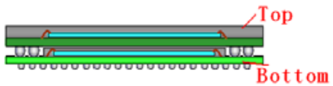
First failed components: PoP
- – Higher temperature
- – Temperature affects mass flux



Card	Experiment		type
1	120° C 1A	1st	PoP 14x14
		2nd	PoP 12x12
		3rd	PoP 14x14
2	100° C 1A	1st	PoP 14x14
		2nd	PoP 14x14
		3rd	PoP 14x14
		4th	PoP 14x14

Results and discussion

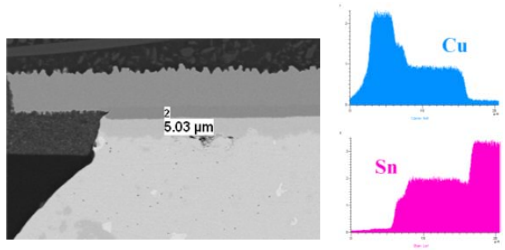
Open chain



Card	Experiment		Failure: Location of open chain
1	120° C 1A	1st	« bottom »
		2nd	« top »
		3rd	« bottom »
2	100° C 1A	1st	« bottom »
		2nd	« top »
		3rd	« bottom »
		4th	« bottom »

Results and discussion

- Failure analysis
  - ➢ Cross section, polishing and EDX
  - ➢ Brittle IMC: Cu_3Sn and Cu_6Sn_5

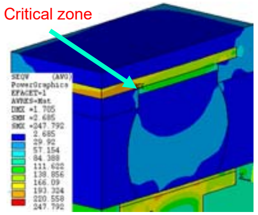


EDX image of Bump SAC
after 136h 1A/120°C

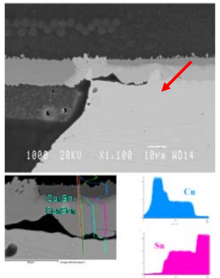
Results and discussion

- Failure analysis

Critical zone



Von Misses stress for 1A/120°C

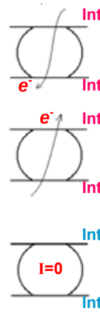


EDX image of Bump SAC after 136h 1A/120°C

Results and discussion

- Failure analysis: IMC measurements
  - Comparison between the components
    - **Biased**
    - Non-biased

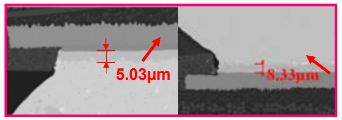
Interface	Average (µm)	Min (µm)	Max (µm)
1 (cathode)	4.28	4.15	5.63
2 (anode)	6.83	4.74	10.40
3 (cathode)	3.12	2.37	4.15
4 (anode)	8.71	7.12	10.30
5	1.01	0.99	1.04
6	0.97	0.65	1.03



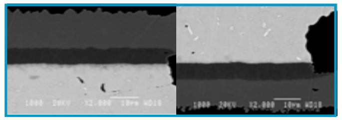
Results and discussion

- Failure analysis
  - Comparison between the components
    - Chemical potential gradient J_{chem}
    - Electromigration flux J_{em}
  - Joule heating for biased components
    - Worse thermal dissipation for PoP

$$J = J_{chem} + J_{em}$$



Biased component

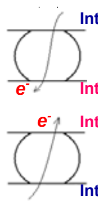


Non-biased component

Results and discussion

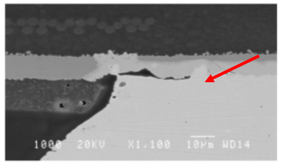
- Failure analysis
  - Influence of the electron flux J_{em}
    - IMC(anode) > IMC(cathode)

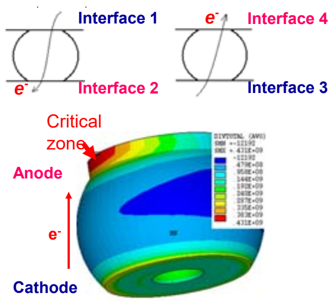
Interface	Average (µm)	Min (µm)	Max (µm)
1 (cathode)	4.28	4.15	5.63
2 (anode)	6.83	4.74	10.4
3 (cathode)	3.12	2.37	4.15
4 (anode)	8.71	7.12	10.3



Results and discussion

- Failure analysis
  - Influence of the electron flux J_{em}
    - IMC(anode) > IMC(cathode)





Mass flux divergences

Conclusion of case study

- Electromigration effects
  - ➢ Critical assembly
    - ✓ PoP
  - ➢ IMC thickness
    - ✓ **Biased component >** Non-biased component
    - ✓ **Anode side >** Cathode side
  - ➢ Critical zone
    - ✓ Cathode (UBM/bump interface) on the “bottom”
    - ✓ Agreements with simulation results

Bibliographic references

- Electromigration in integrated circuit conductors *J. Phys. D: Appl. Phys. 32 (1999)* **J R Lloyd**
- Electromigration for Designers: An Introduction for the Non-Specialist **J R Lloyd** *(2002)* *http://www.edadesignline.com/192200480*
- *http://www.doitpoms.ac.uk/tlplib/electromigration/damage.php*
- Simulation of Migration Effects in PoP *Proc. of the Eurosime* **K. Weide-Zaage, H. Fremont, L. Wang** (2008)
- Finite element simulation in metallization for reliability prediction **K. Weide-Zaage** *Chapter 12 in Chemical Mineralogy, Smelting and Metallization ISBN: 978-1-60692-853-0*
- Sony reliability handbook http://www.sony.net/Products/SC-HP/tec/catalog/pdf/chapter2e_201108.pdf