IEEE ELECTRONICS PACKAGING SOCIETY

EPTC 2019

EPTC Professional Development Course

Reliability Mechanics and Modeling for IC Packaging

– *Theory, Implementation and Practices*

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Outline

- Introduction
- Temperature Loading
- Mechanical Loading
- Moisture Loading
- Electrical Current Loading - Multi-Physics Modeling
- Summary

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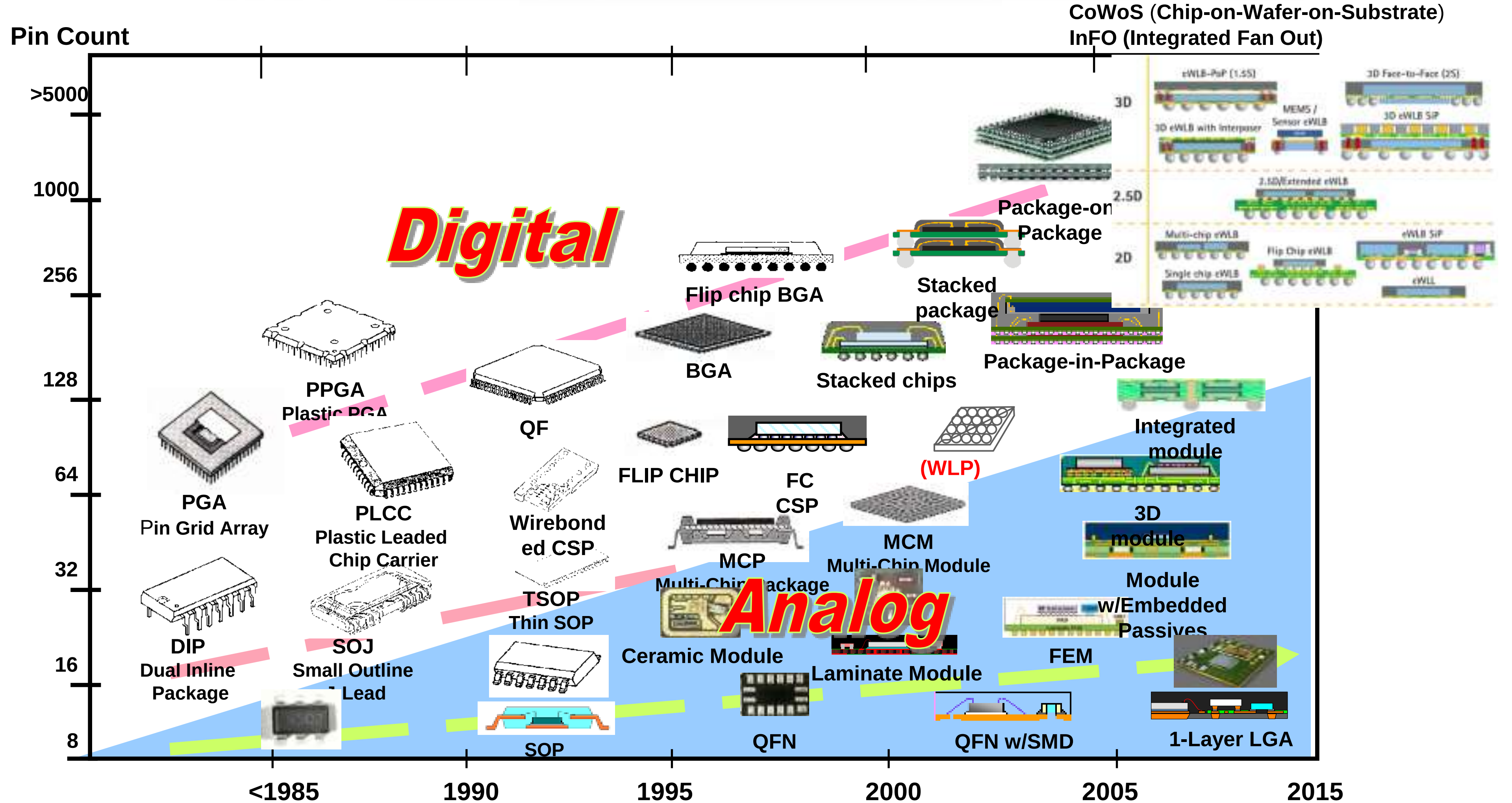
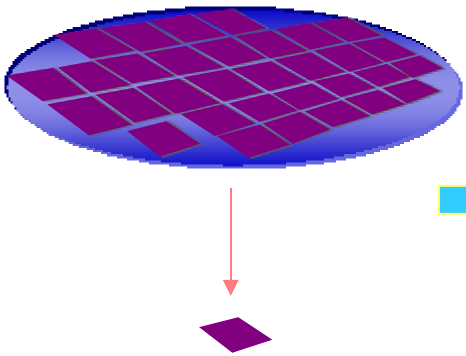
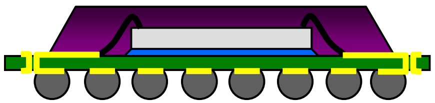
Electronic Packaging Evolution

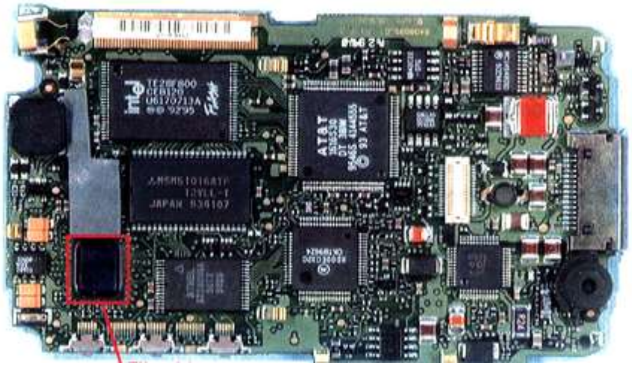


Through Hole → *Surface Mount* → *Fine Pitch/Thin* → *Area Array* → *Modules/System* → *3D/integration*

Wafer, Package, and Board Levels



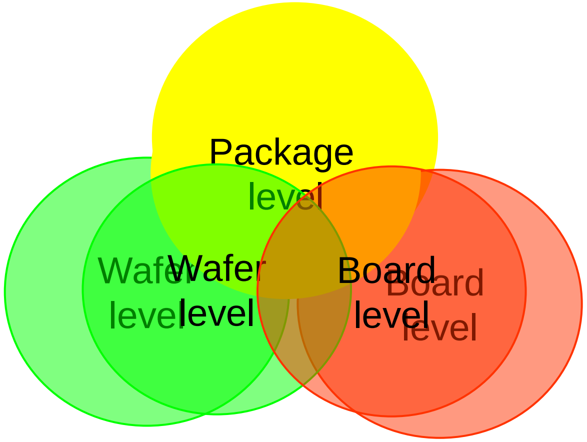




Wafer Fabrication & Backend Process

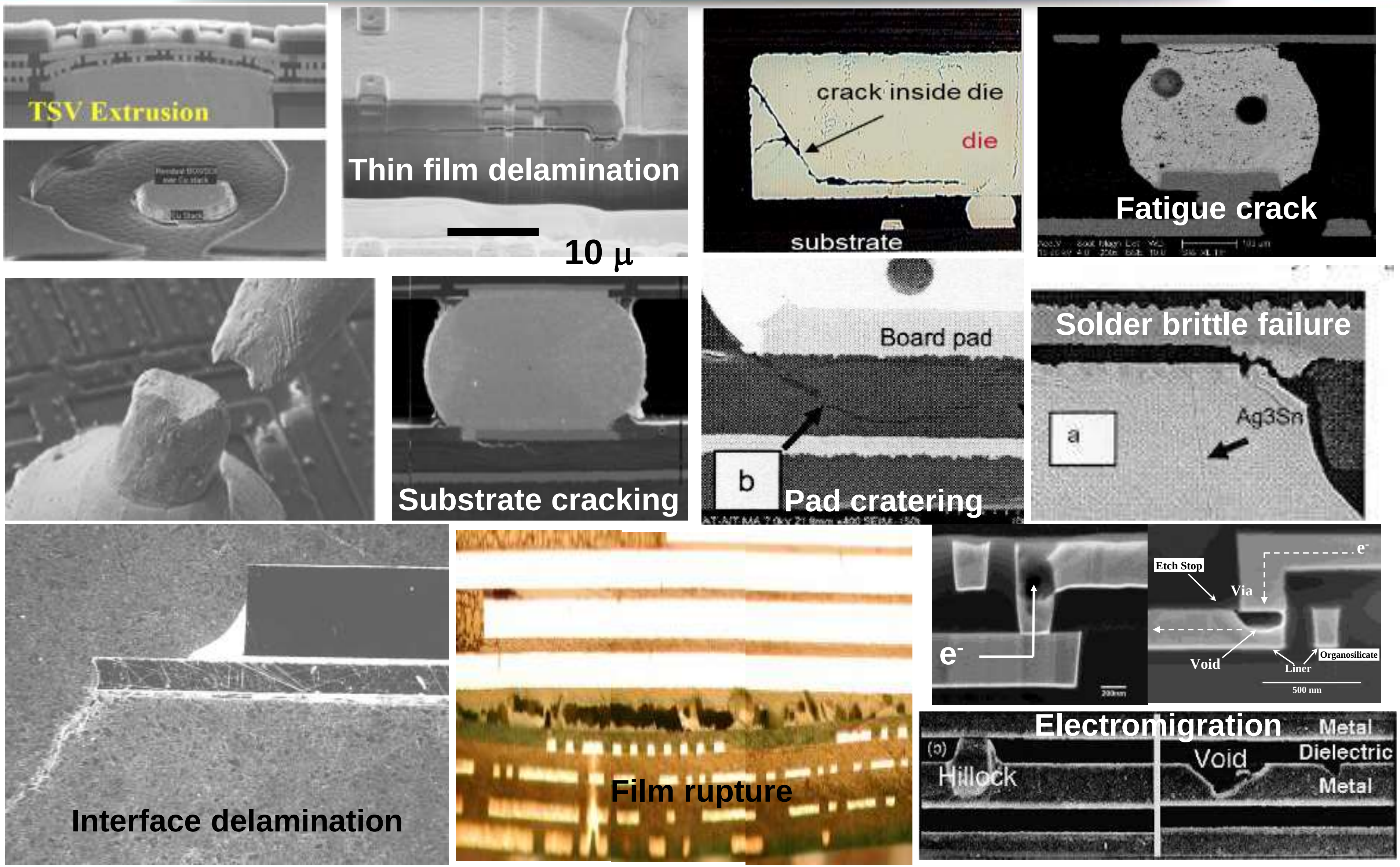
Electronic Packaging

Surface Mounting

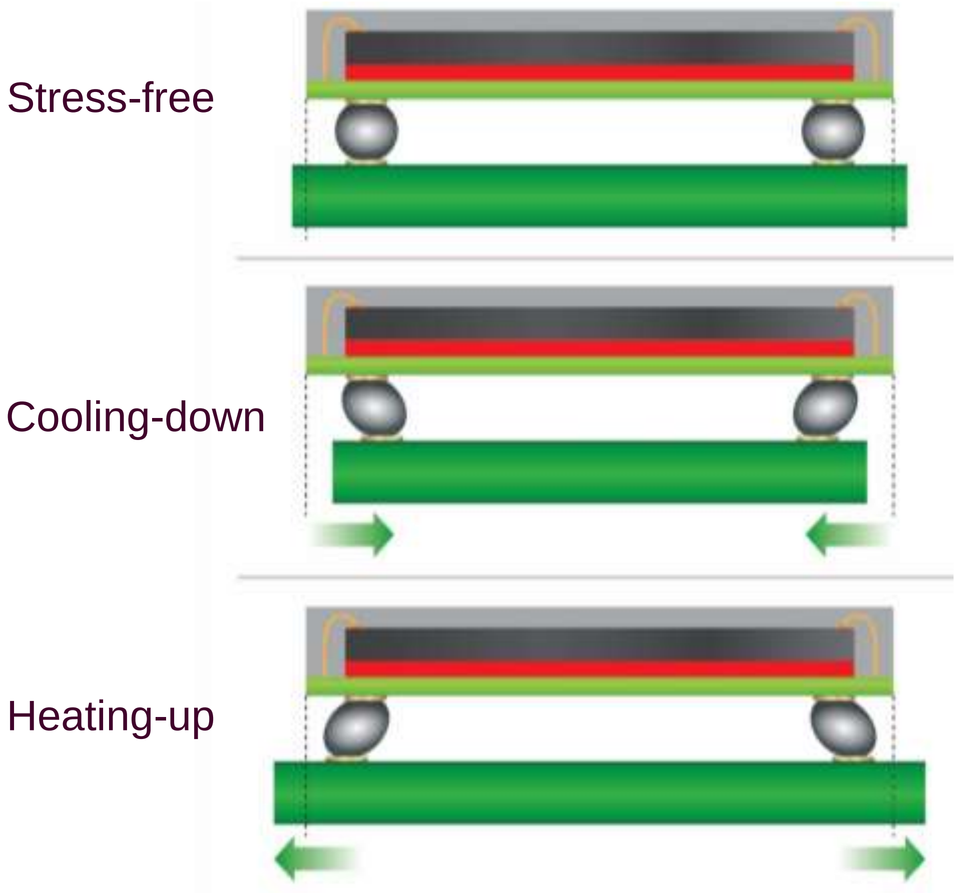


- Design of a package must consider the interactions among wafer, package, and board (e.g. CPI – chip-package-interaction).

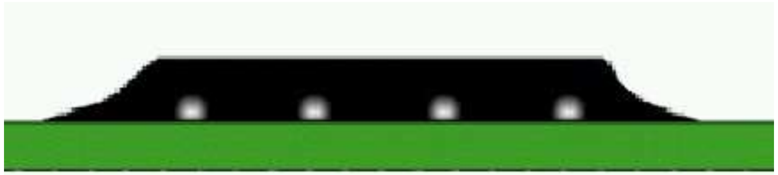
Examples of Failures



Thermal-mechanical Stress



Thermal stress in solder



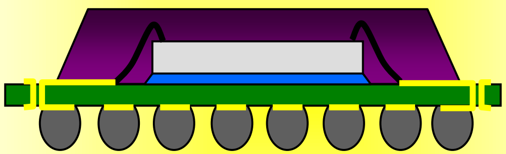
Cooling-down

Package warpage

Mechanical Load

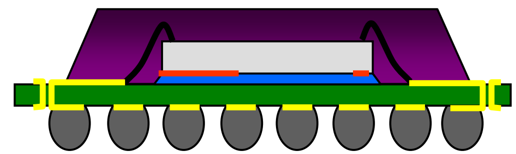
- Handheld electronic products are susceptible to drop impact failure.

Moisture-induced Failure

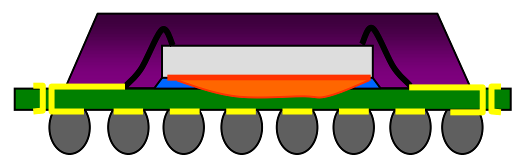


Stage 1: Moisture absorption

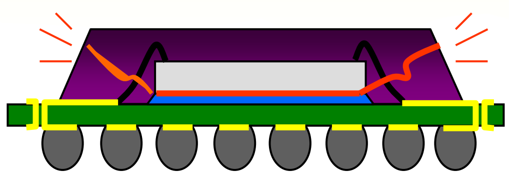
Device exposed to reflow temperature, typically 260°C



Stage 2: Initiation of delamination

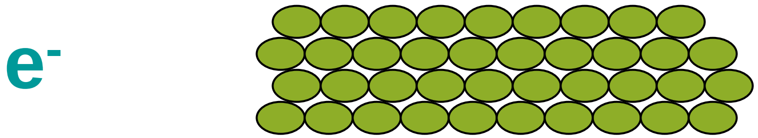


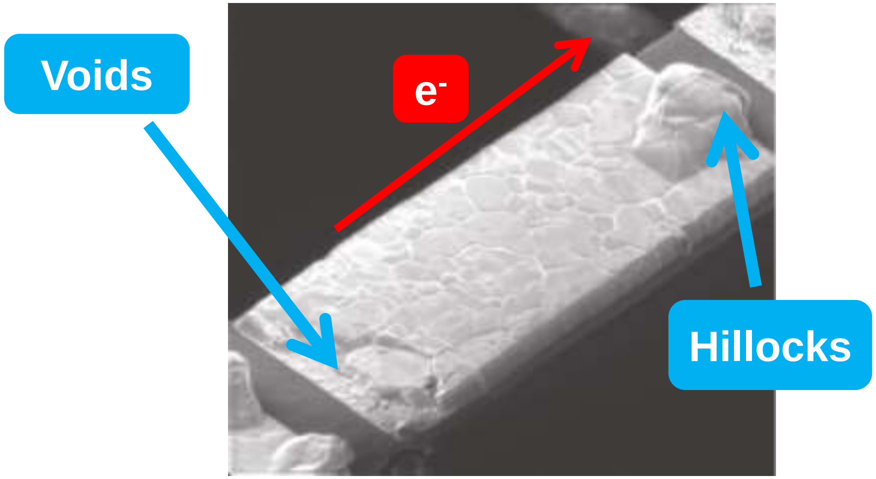
Stage 3: Delamination propagation

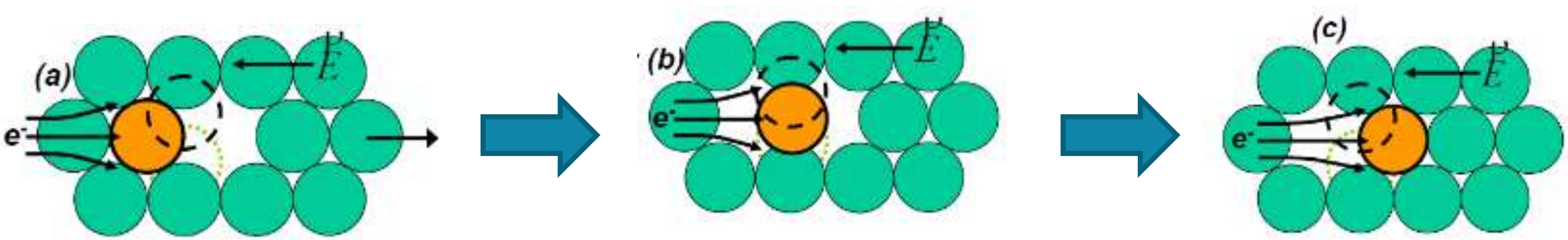


Stage 4: Package cracking and vapor release

Electrical Current Stressing







Electron wind

Organization of Course

- **Four modules**
  - Temperature loading
    - Thermal mismatch, temperature gradient, etc.
  - Mechanical loading
    - Drop and impact, bend, etc.
  - Moisture loading
    - Moisture diffusion, vapor pressure, swelling.
  - Electrical current loading - combined loading
    - Electrical-thermal, electrical-thermal-mechanical, and electromigration (electrical-thermal-mechanical-mass transport)

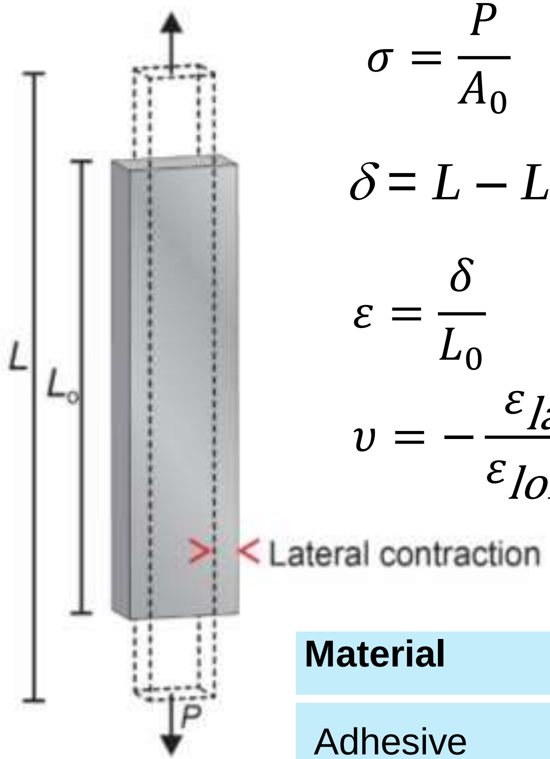
- **Theory, implementation, and best practices.**

- Introduction
- Temperature Loading
- Mechanical Loading
- Moisture Loading
- Electrical Current Loading - Multi-Physics Modeling
- Summary

Outline

- **Basic concepts and analytical solutions**
- **Applications**
  - Die-level thermal stress – thermal stress in TSV
  - Package-level thermal stress problem – warpage
  - Chip-package interaction (CPI) – sub-modeling technique
  - Board level thermal stress problems
    - Solder ball thermal cycling
    - Creep equations
- **Best practices**
  - Initial stress free condition
  - Full model vs. global/local model
  - Volume averaging
  - Stress singularity

Stress, Strain, and Basic Elastic Material Properties

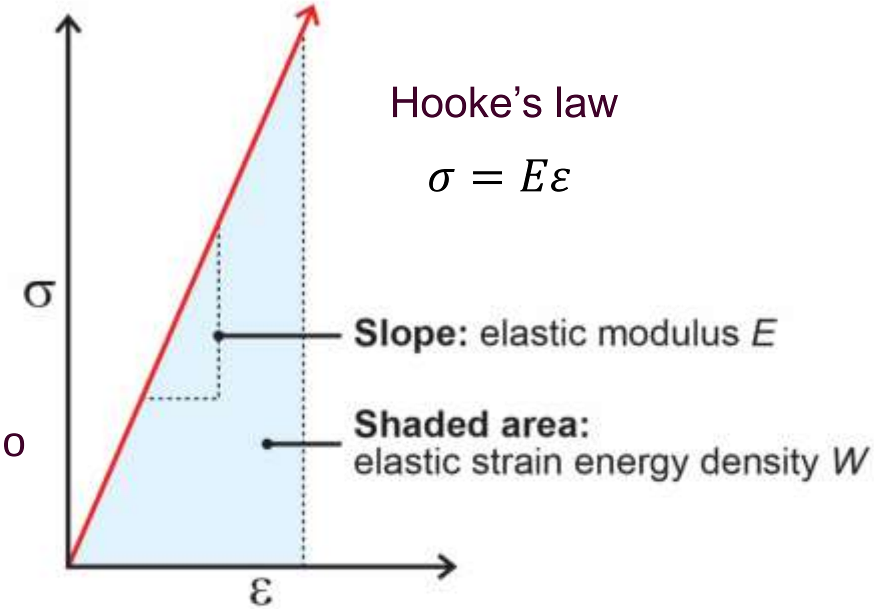


$$\sigma = \frac{P}{A_0}$$

$$\delta = L - L_0$$

$$\varepsilon = \frac{\delta}{L_0}$$

$$\upsilon = -\frac{\varepsilon_{lat}}{\varepsilon_{long}}$$ Poisson ratio

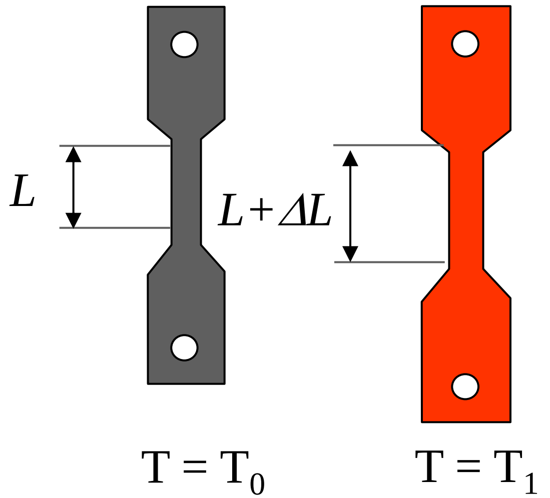


Hooke's law

$$\sigma = E\varepsilon$$

Material	Elastic Modulus (GPa)	Poisson Ratio
Adhesive	0.01 – 10	0.4 – 0.49
Epoxy	10 –30	0.35 – 0.48
Copper	120	0.35
Silicon	131	0.28
Solder	25 – 51	0.35
Substrate/PCB	11 – 26	various

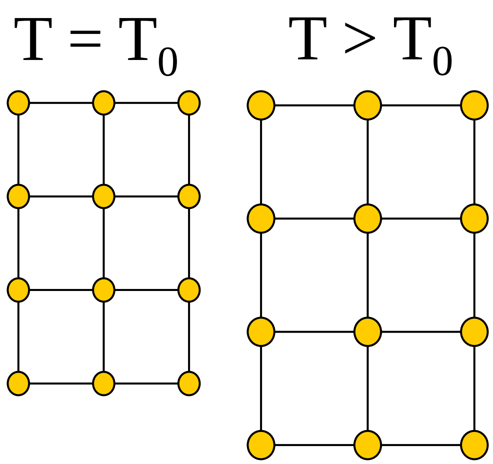
Coefficient of Thermal Expansion (CTE)



$$\varepsilon^{th} = \frac{\Delta L}{L}$$

$$\alpha = \frac{\varepsilon^{th}}{\Delta T}$$

- Material dimensions change with temperature.
- The rate of dimensional change with temperature is called CTE.
- Primary driver of thermo-mechanical stress in electronic packages.

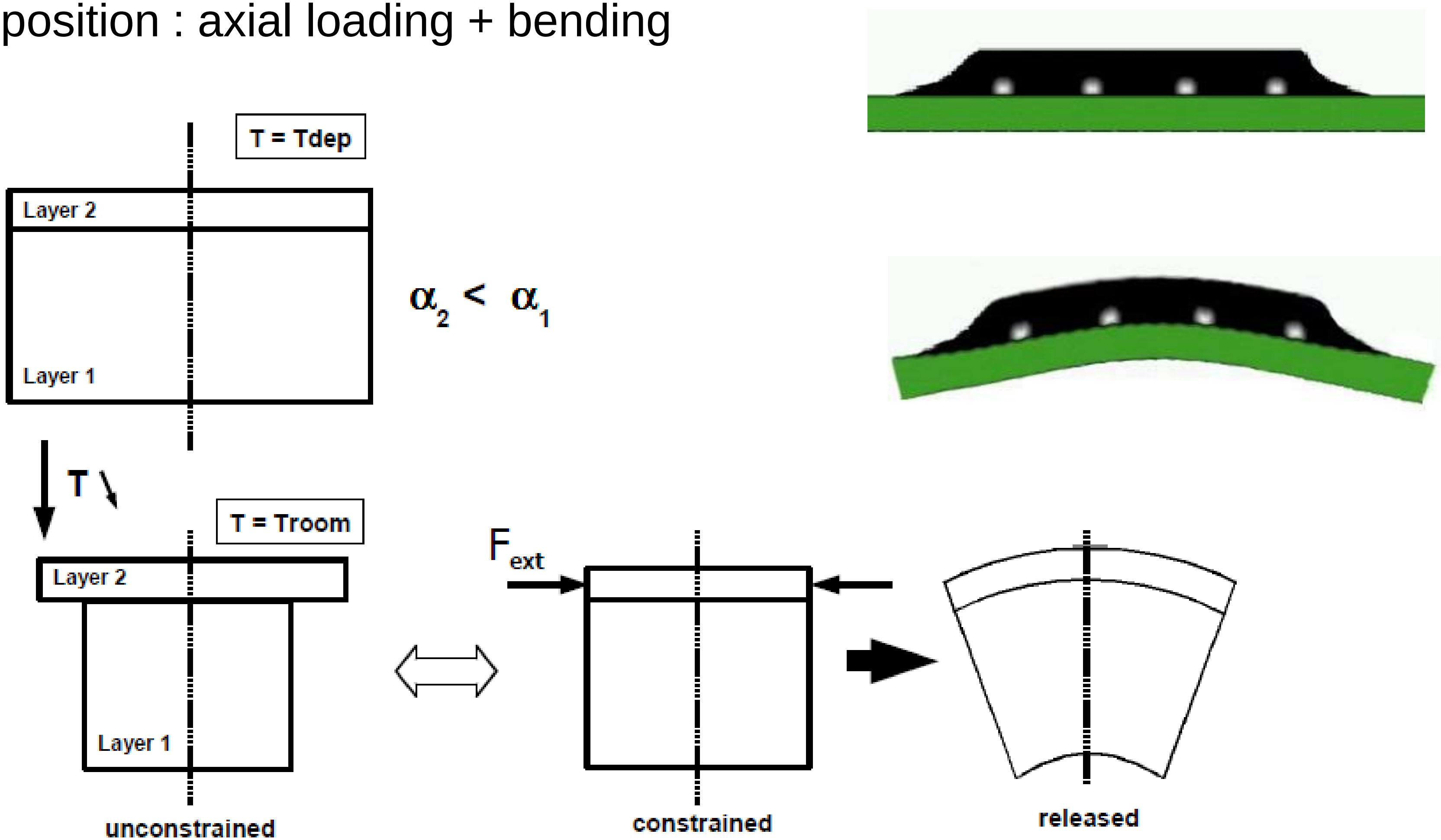


Increase internal energy (heat) causes atomic bond lengths to increase

Material	α (ppm/°C)
Aluminum	23
Stainless Steel	12
Silicon	2.6
Copper	17
Underfill Epoxy	20, 70
FR4 (in plane)	15, 10
FR4 (z-axis)	65, 180

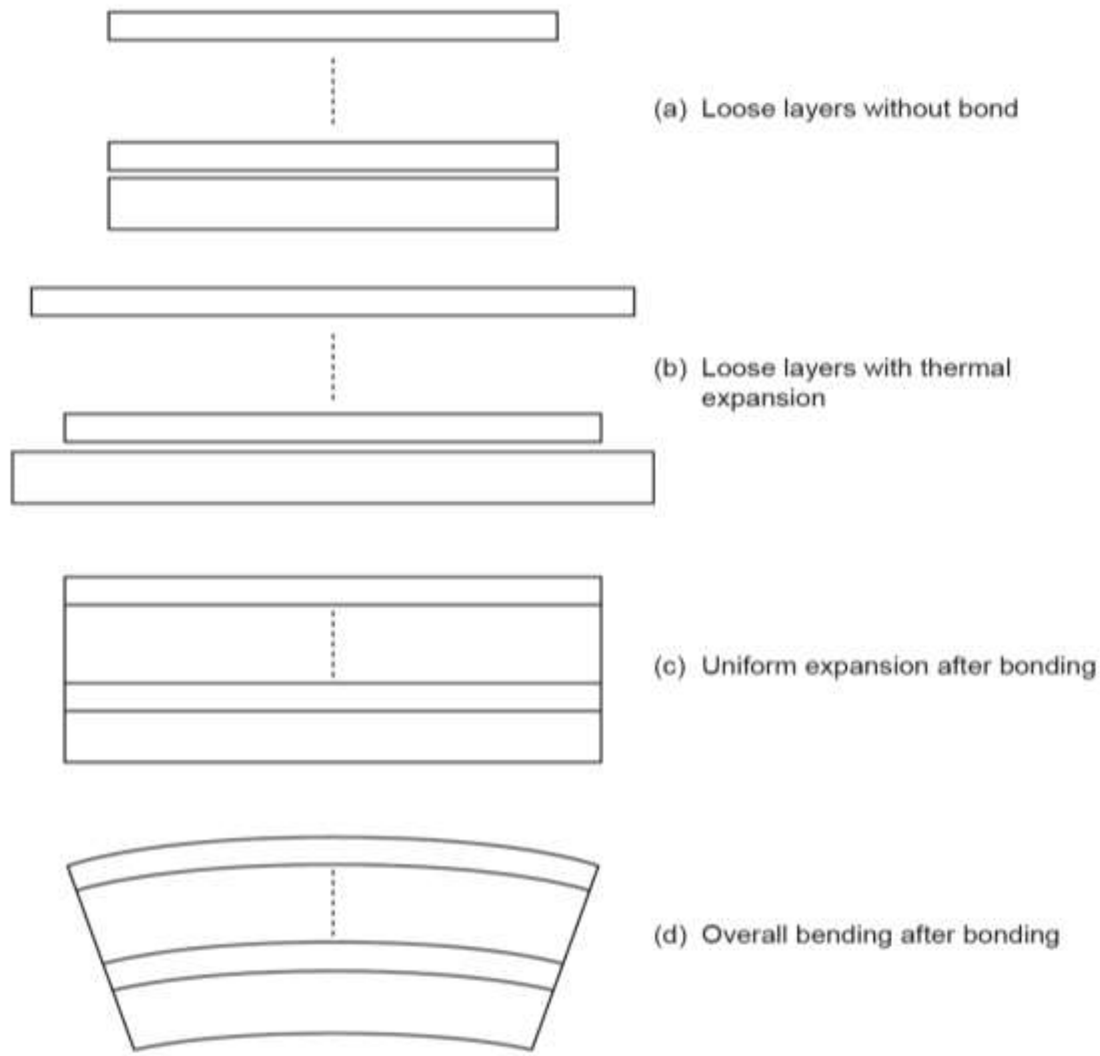
Thermal Mismatch – Two-Layer Structure

Superposition : axial loading + bending



Thermal-Mismatch – Multi-Layer Structure

Superposition : axial loading + bending



Thermal-Mismatch : Analytical Solution

Multi-layer structure

$$\varepsilon_{xi}(y) = (y - h_b)K + C, \text{ with } h_{i-1} \leqslant y \leqslant h_i$$

$$\sigma_{xi}(y) = \bar{Y}_i\left[(y - h_b)K + C + \nu_i A - \eta_i \varepsilon_i^0\right], \text{ with } h_{i-1} \leqslant y \leqslant h_i$$

(stress in each layer)

$$h_b = \frac{\sum_{i=1}^{n} \bar{Y}_i D_i h_{mi}}{\sum_{i=1}^{n} \bar{Y}_i D_i}$$

$$C = \frac{\sum_{i=1}^{n} \bar{Y}_i D_i \left[\eta_i \varepsilon_i^0 - \nu_i A\right]}{\sum_{i=1}^{n} \bar{Y}_i D_i}$$

- h_b is the Bending Axis of the composite device;
- C is the Uniform Strain of the composite device; (effective CTE)
- A is the Axial constant Strain of the composite device;
- K is the Curvature of the composite device; (warpage)
- K_{nat} is the component due to Natural bending of the curvature of the composite device;
- K_{app} is the Applied curvature of the composite device;
- ε_i^0 is the Stress-free Strain of layer i;

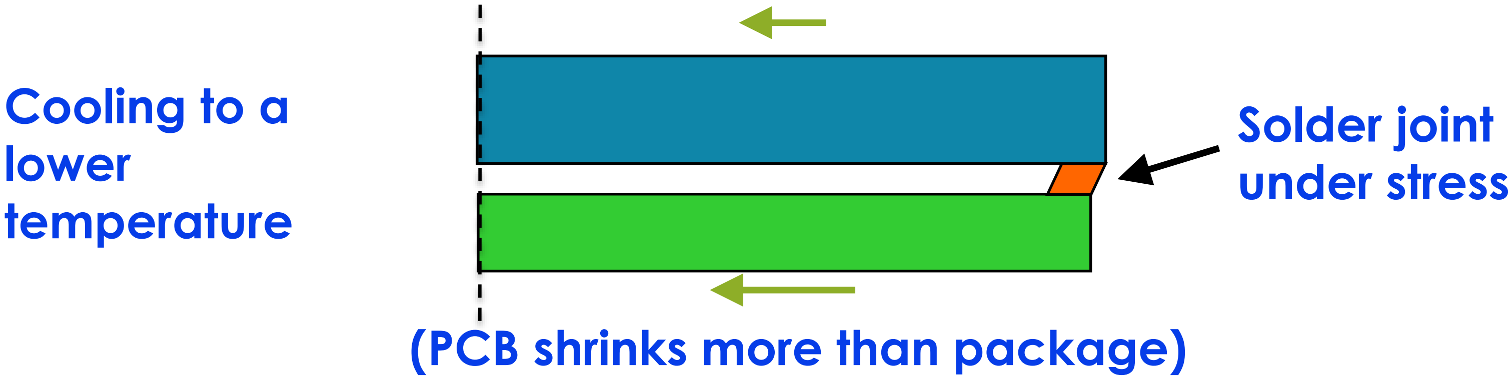
$$K = K_{nat} + K_{app} = \frac{\sum_{i=1}^{n} \bar{Y}_i D_i \left[h_{mi} - h_b\right]\left(\eta_i \varepsilon_i^0 - C - \nu_i A\right)}{\sum_{i=1}^{n} \bar{Y}_i D_i \left[h_i^2 + \frac{D_i^2}{3} - h_i D_i + h_b\left(h_b - 2h_{mi}\right)\right]} + K_{app}$$

$$\varepsilon_i^0 = \alpha_i\left(T_{room} - T_{depi}\right) + \varepsilon_i^{Btin}$$

Ana Neves Vieira da Silva. Analytical Modeling of the Stress-Strain Distribution in a Multilayer Structure with Applied Bending. PhD Dissertation. Instituto Superior Tecnico of Universidade Tecnica de Lisboa, Portugal.

Thermal Mismatch - Shear Stress and Strain on Solder Joint

A simplified and approximate solution

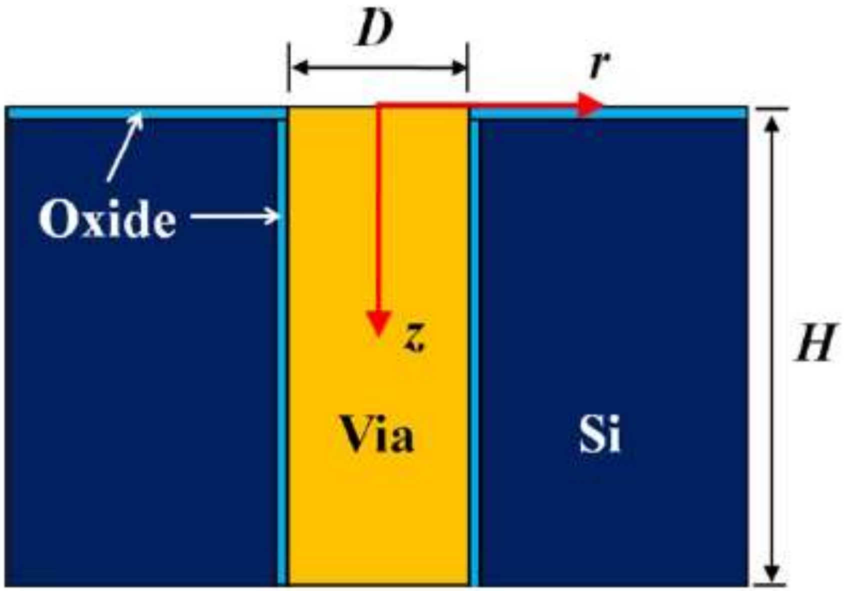


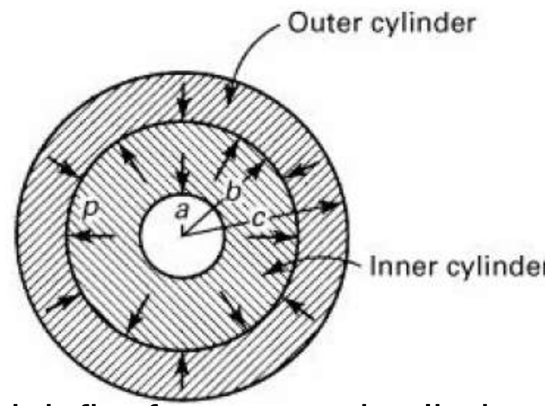
$$\gamma = \frac{L(\alpha_{PCB} - \alpha_{chip})\Delta T}{h}$$

$$\tau = G \cdot \gamma$$

τ : shear stress in solder
γ: solder ball shear strain
G: elastic shear modulus
L: distance of netural point (half-die size, diagnoal)
h: solder ball stand-off
α: CTE

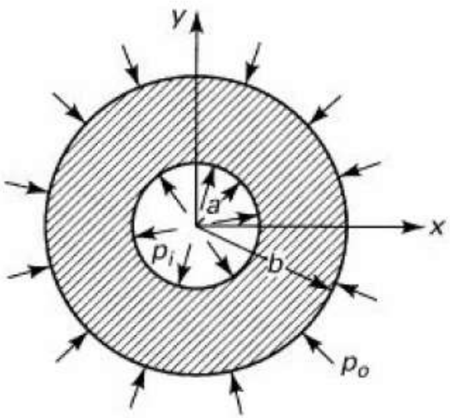
Thermal Mismatch – TSV Structure





Shrink fit of compound cylinder

$$\delta = \frac{bp}{E_o}\left(\frac{b^2 + c^2}{c^2 - b^2} + \nu_o\right) + \frac{bp}{E_i}\left(\frac{a^2 + b^2}{b^2 - a^2} - \nu_i\right)$$



$$\sigma_r = \frac{a^2 p_i - b^2 p_o}{b^2 - a^2} - \frac{(p_i - p_o)a^2 b^2}{(b^2 - a^2)r^2}$$

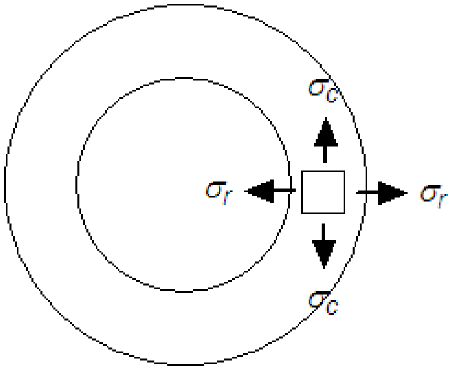
$$\sigma_\theta = \frac{a^2 p_i - b^2 p_o}{b^2 - a^2} + \frac{(p_i - p_o)a^2 b^2}{(b^2 - a^2)r^2}$$

$$u = \frac{1 - \nu}{E}\frac{(a^2 p_i - b^2 p_o)r}{b^2 - a^2} + \frac{1 + \nu}{E}\frac{(p_i - p_o)a^2 b^2}{(b^2 - a^2)r}$$

Single cylinder under external and internal pressure

Advanced Mechanics of Materials and Applied Elasticity, 5th Edition, by Saul K. Fenster, Ansel C. Ugural.

Thermal Stress due to Temperature Gradient



$$\sigma_r = \alpha E\left[-\frac{1}{r^2}\int_a^r Tr\,dr + \frac{r^2 - a^2}{r^2(b^2 - a^2)}\int_a^b Tr\,dr\right]$$

$$\sigma_\theta = \alpha E\left[-T + \frac{1}{r^2}\int_a^r Tr\,dr + \frac{r^2 + a^2}{r^2(b^2 - a^2)}\int_a^b Tr\,dr\right]$$

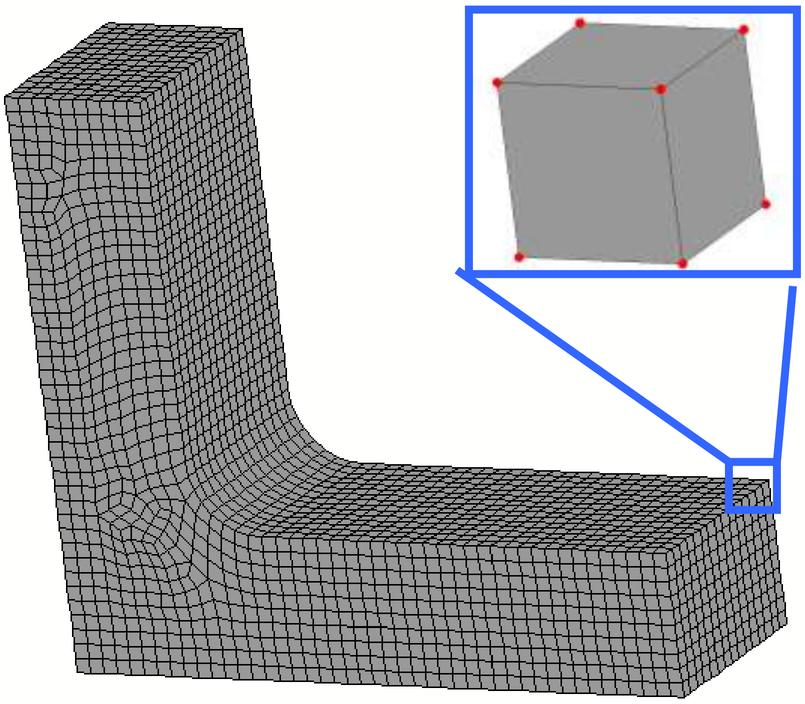
$$\sigma_r = \alpha E\left[\frac{1}{b^2}\int_0^b Tr\,dr - \frac{1}{r^2}\int_0^r Tr\,dr\right]$$

$$\sigma_\theta = \alpha E\left[-T + \frac{1}{b^2}\int_0^b Tr\,dr + \frac{1}{r^2}\int_0^r Tr\,dr\right]$$

Advanced Mechanics of Materials and Applied Elasticity, 5th Edition, by Saul K. Fenster, Ansel C. Ugural.

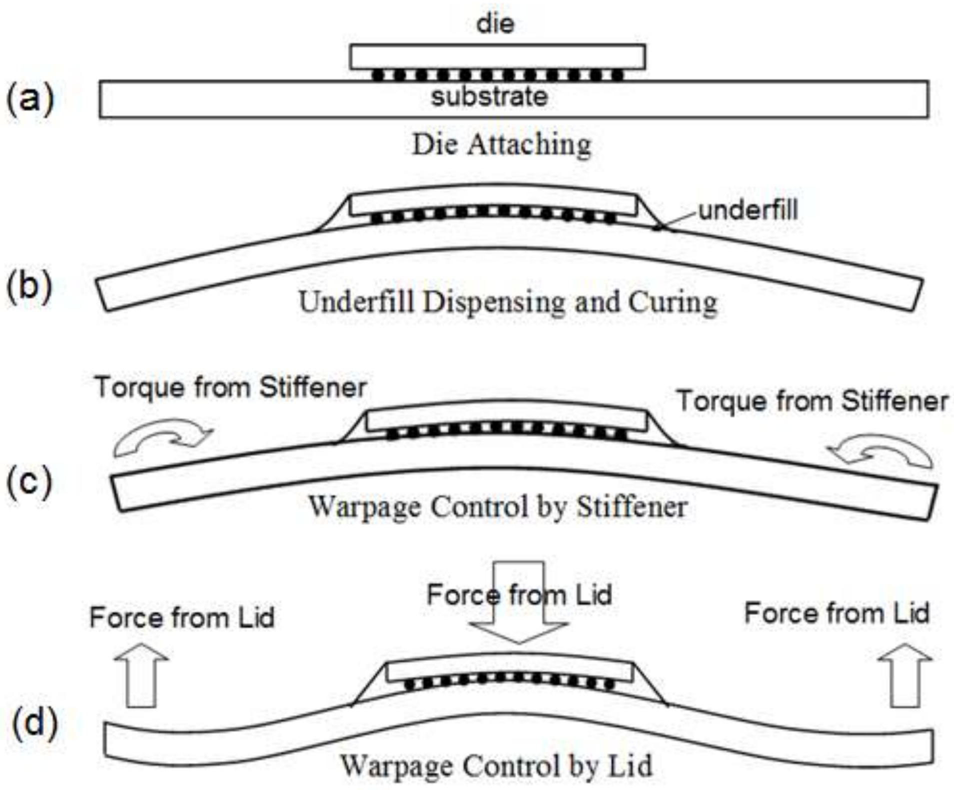
Finite Element Analysis (FEA)

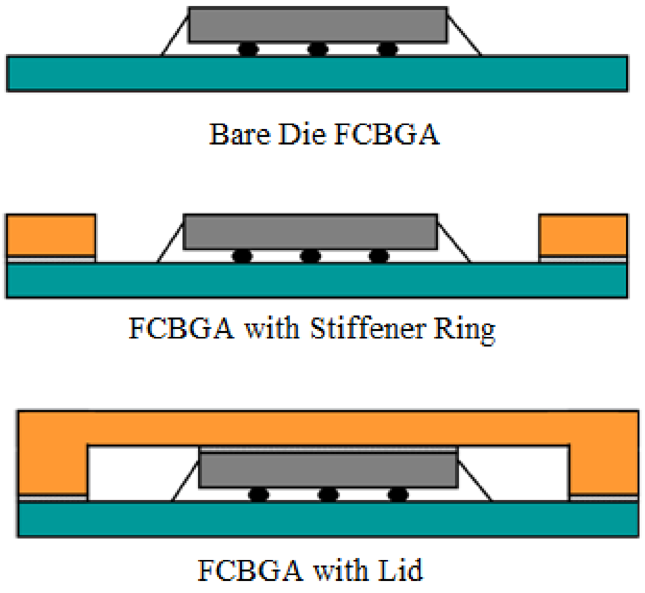
- Analytical solutions are usually not applicable to complex problems.
- Based on dividing the problem into discrete elements for which analytical solutions exit.
- Analytical equations are then formed into a matrix and solved simultaneously.
- Method may require multiple iterations to converge and may have to divide "time" steps to reach a solution.
- Used for structural, thermal, EMI, fluid dynamics, diffusion, stock analysis, etc.



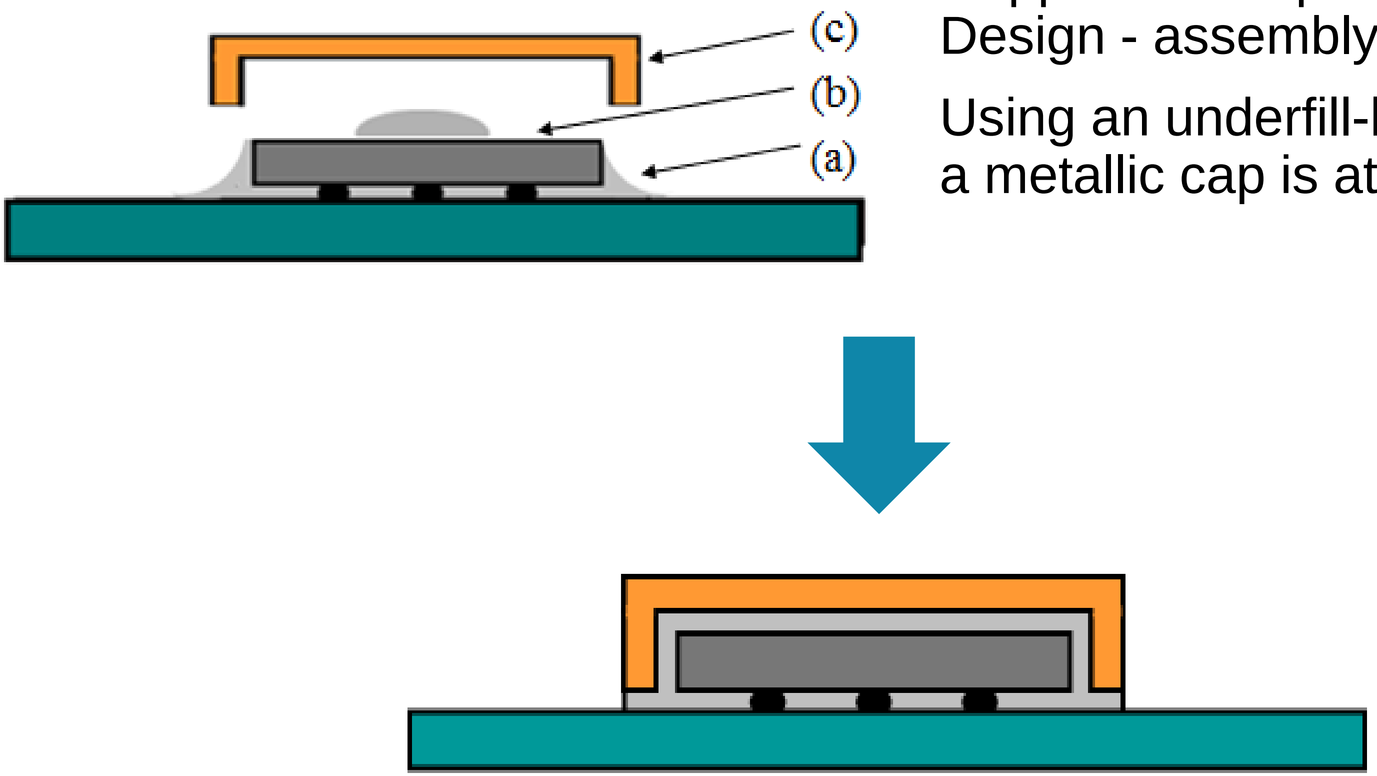
Bracket meshed into 11,295 elements.

Application – Warpage Analysis





Application – Warpage Control

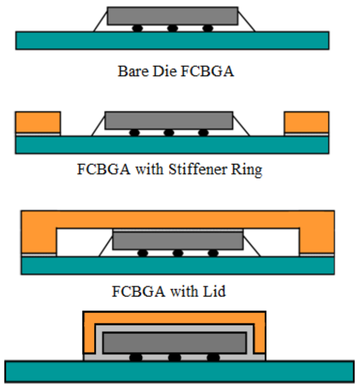


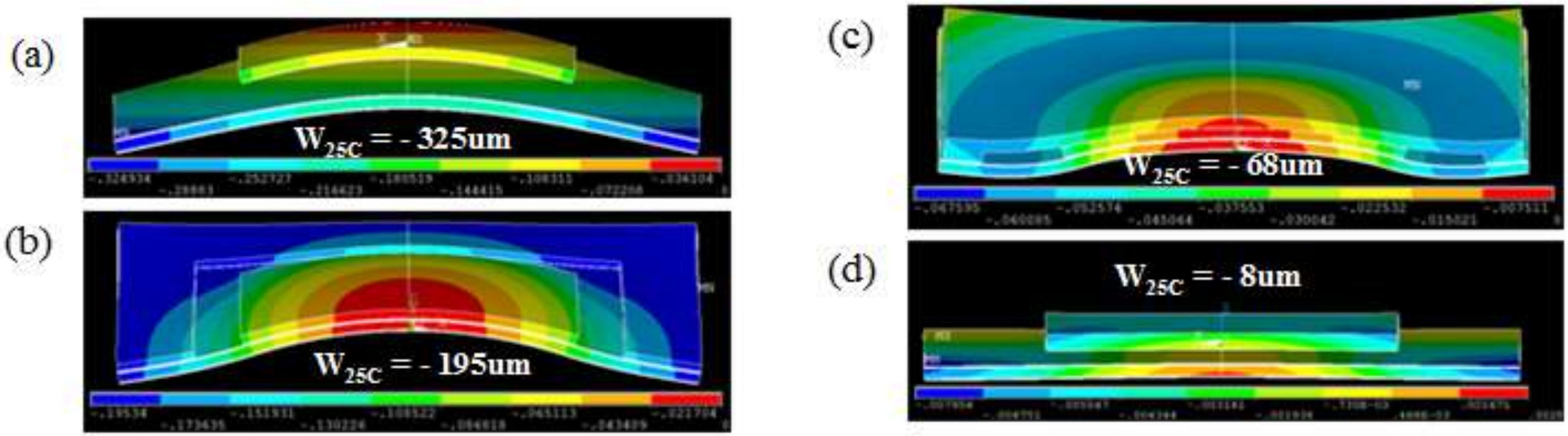
Capped-Die Flip Chip Package Design - assembly process

Using an underfill-like encapsulant, a metallic cap is attached to the die.

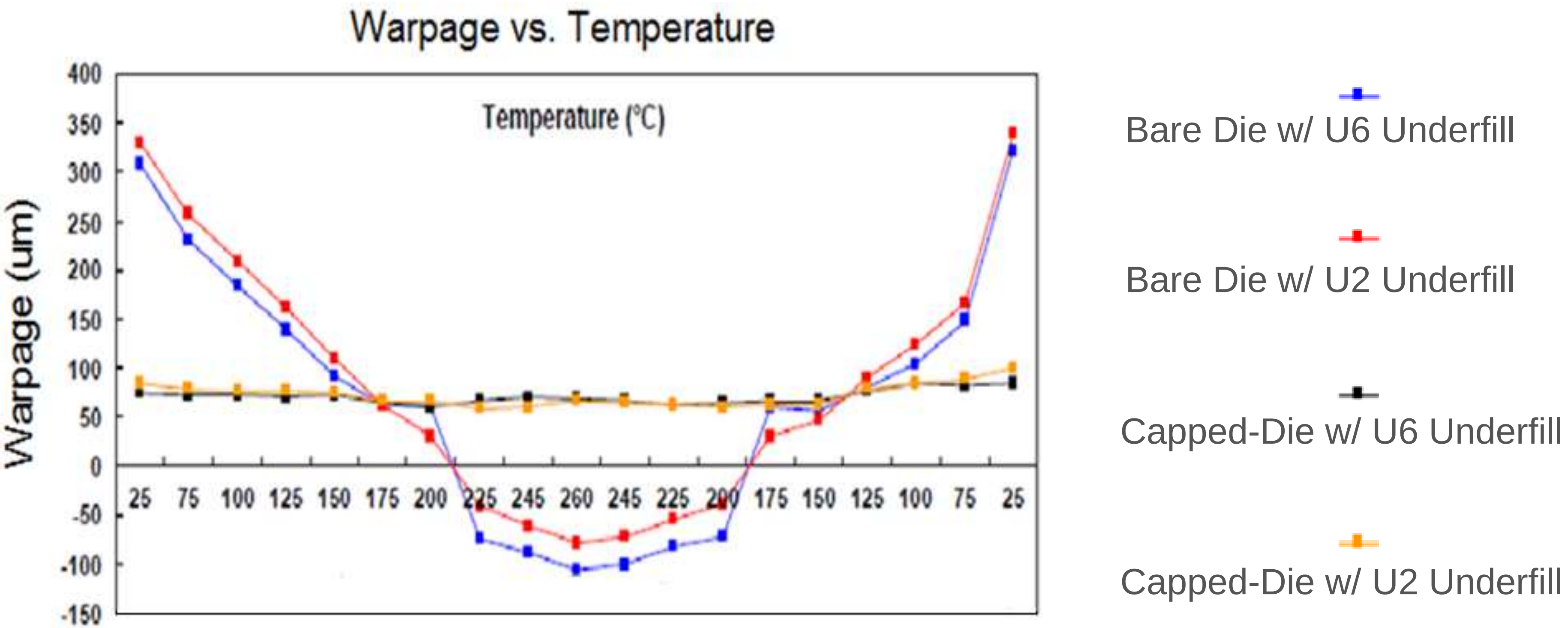
Comparison for Warpage Control Methods by FEA

a) Bare die on substrate
b) Package with stiffener
c) Package with lid
d) Capped-die package





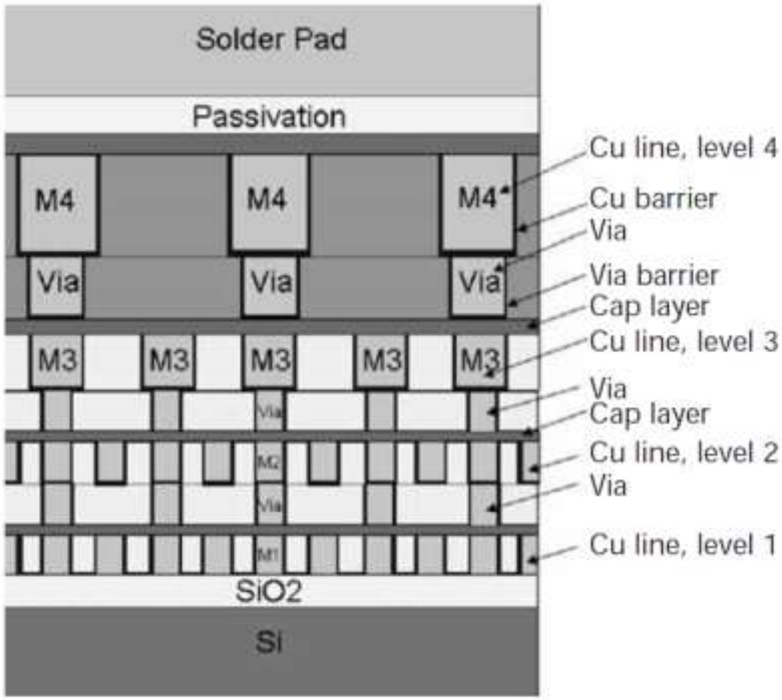
Experimental Verification - Warpage

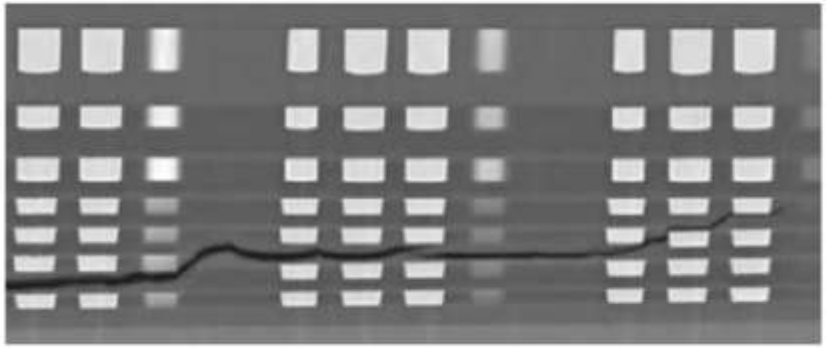


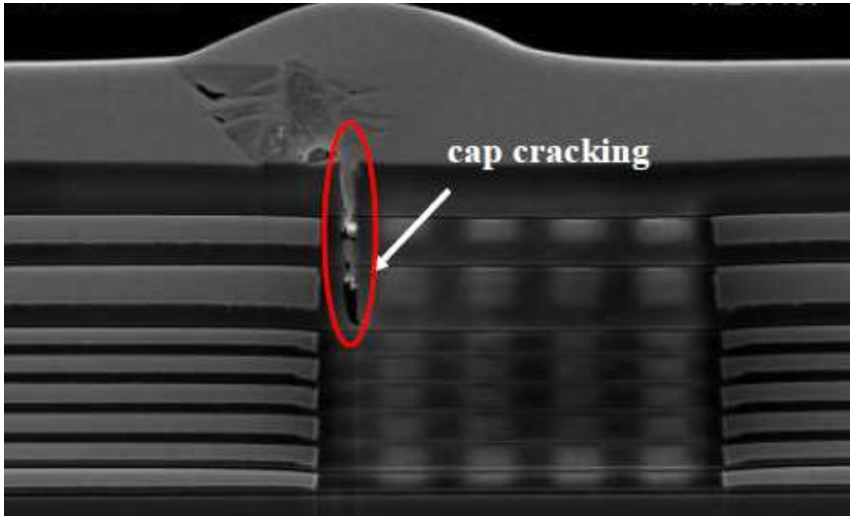
Shadow Moiré Data

Shen Y, Zhang L. Zhu WH, Zhou J, Fan XJ. Finite-element analysis and experimental test for a capped-die flip-chip package design, *IEEE Transactions on Components, Packaging and Manufacturing Technology*. 6(9), 1308 – 1316. 2016.

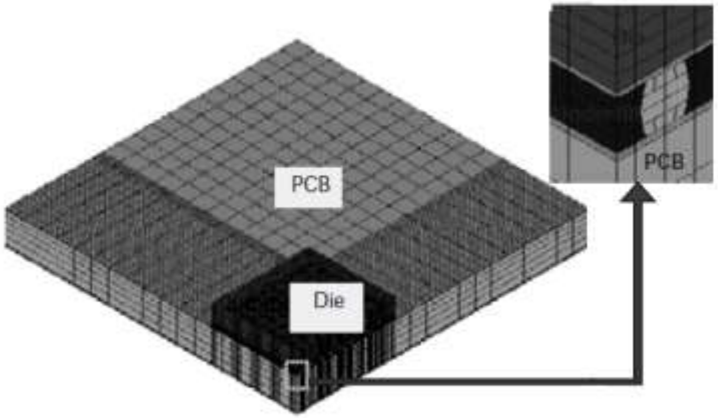
Chip-Package Interaction (CPI)



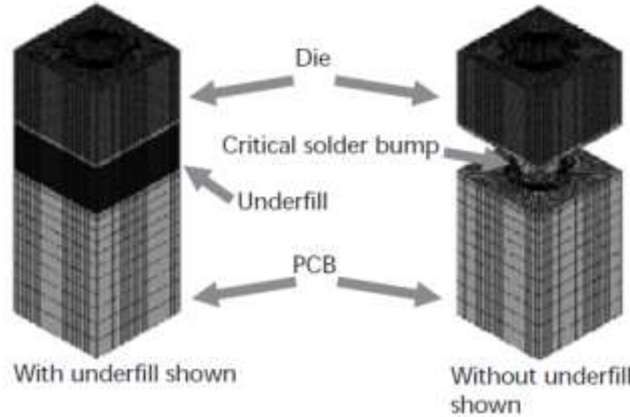




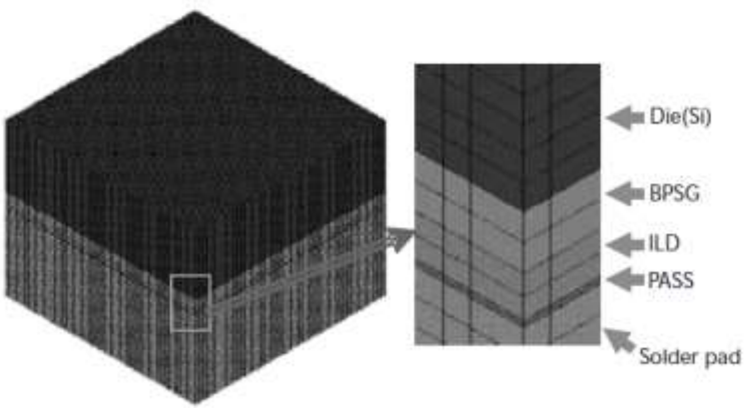
Multilevel Sub-modeling Technique



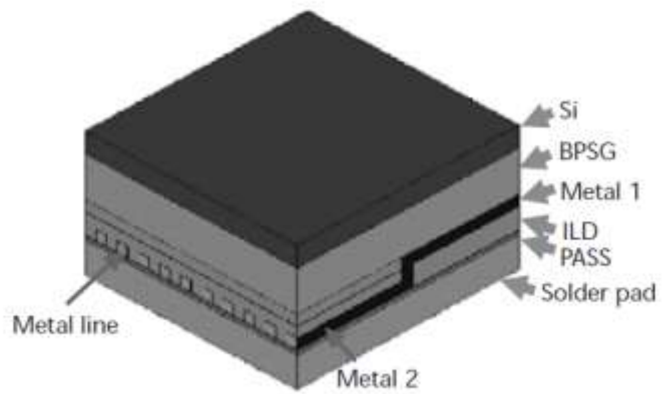
(a) package level



(b) critical solder level



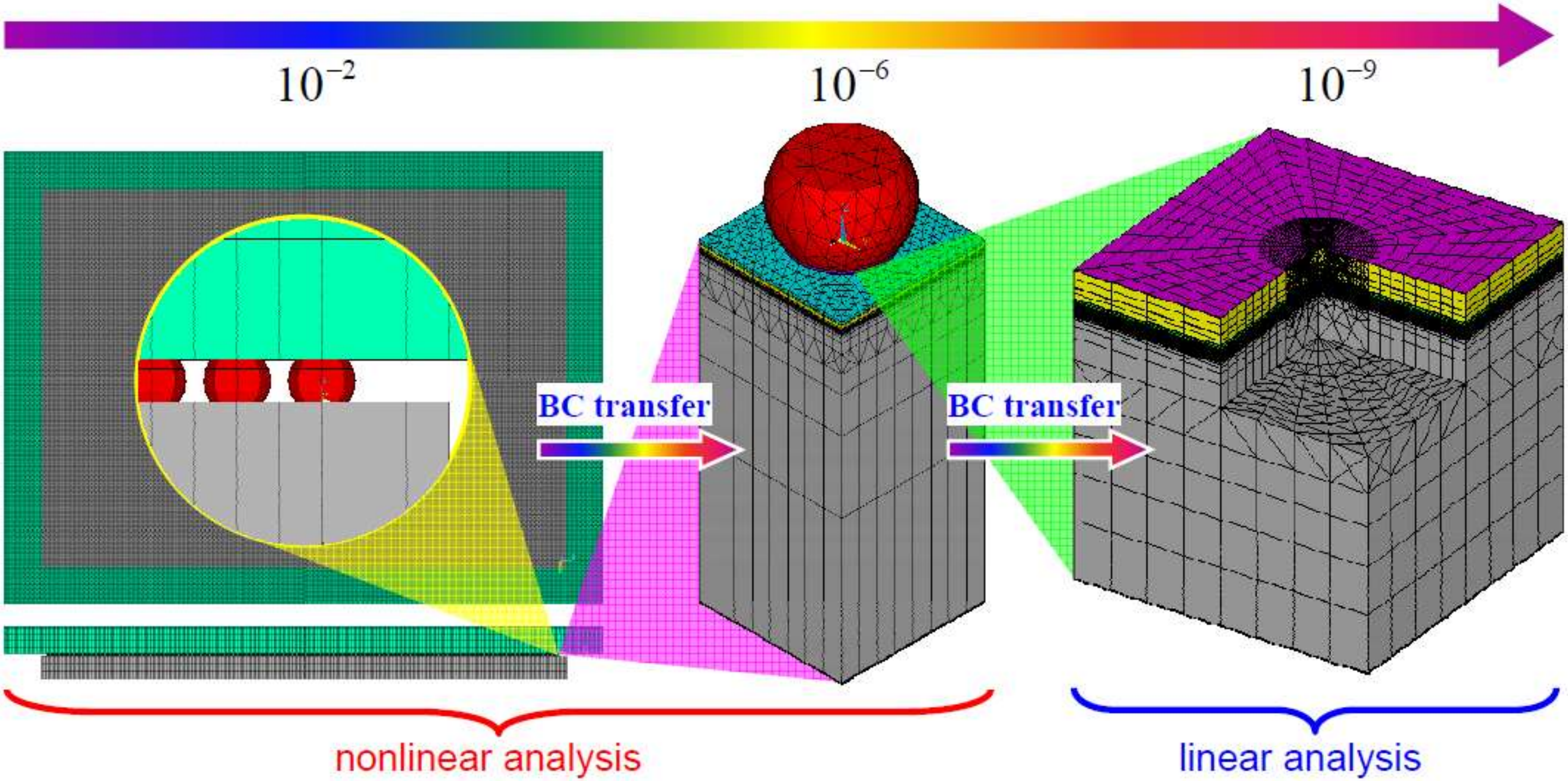
(c) die-solder interface level



(d) interconnect level

Xuefeng Zhang, Se Hyuk Im, Rui Huang, and Paul S. Ho, Chip-Package Interaction and Reliability Impact on Cu/Low-k Interconnects, Chapter 2, UT Austin 2008/

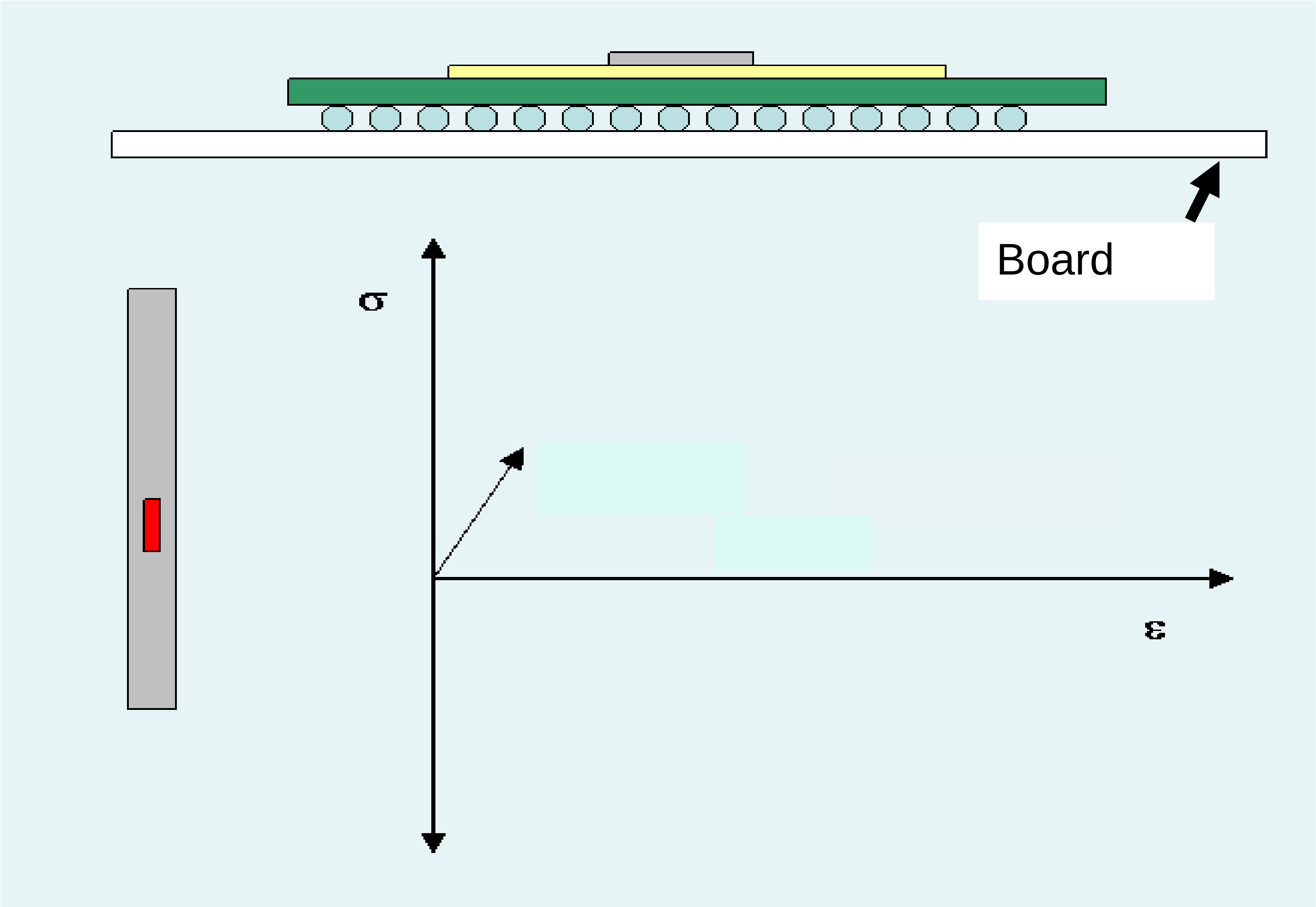
Multilevel Sub-modeling Technique



- Multilevel models are chained to obtain the driving force for delamination.
- Thousands of lines in ANSYS APDL codes have been written for the model.
- Typical model has one million DOF and takes a few hours to solve.

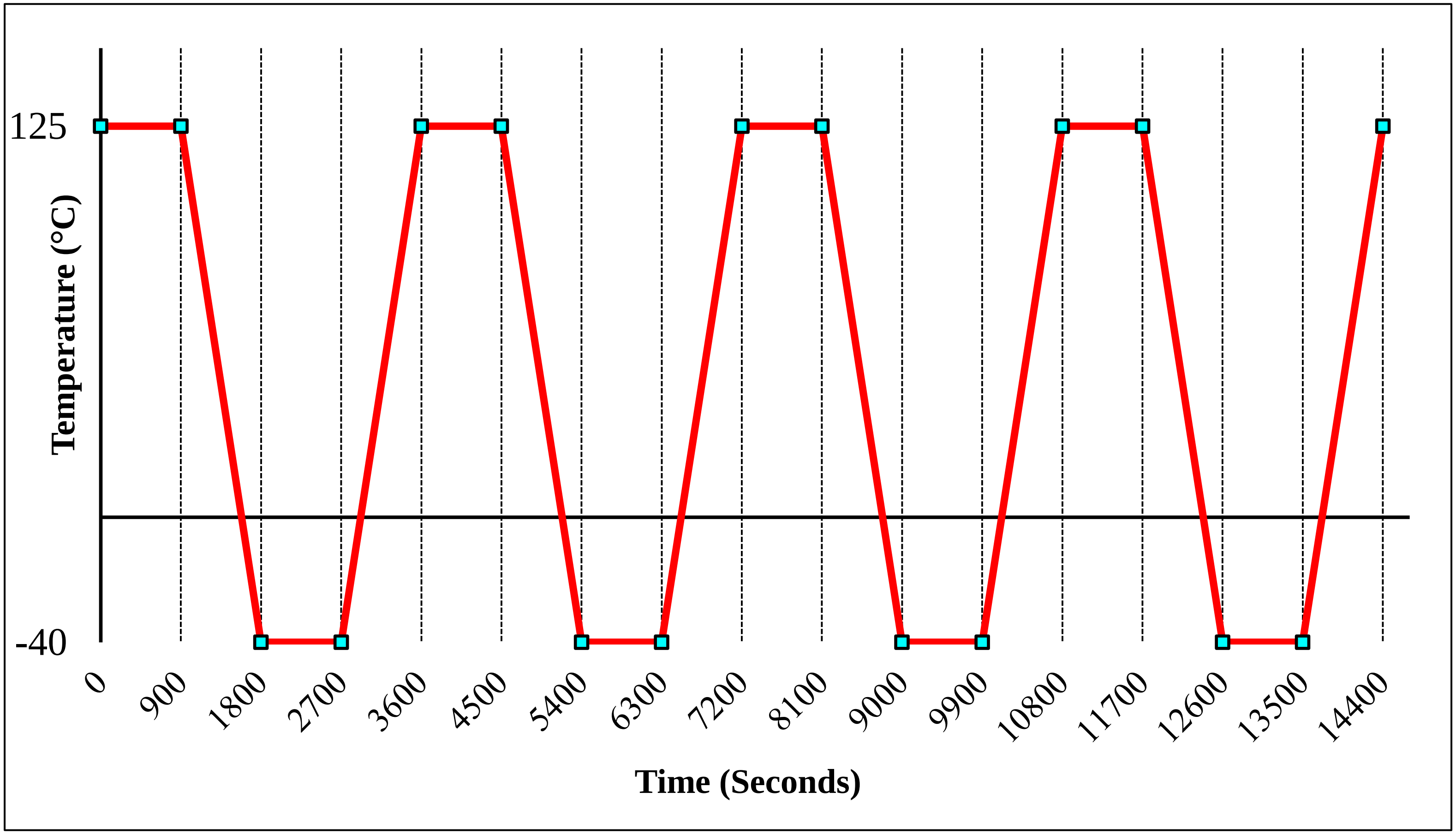
XH Liu, TM Shaw, G Bonilla - Advanced Metallization Conference, 2010 - sematech.org

Temperature Cycling

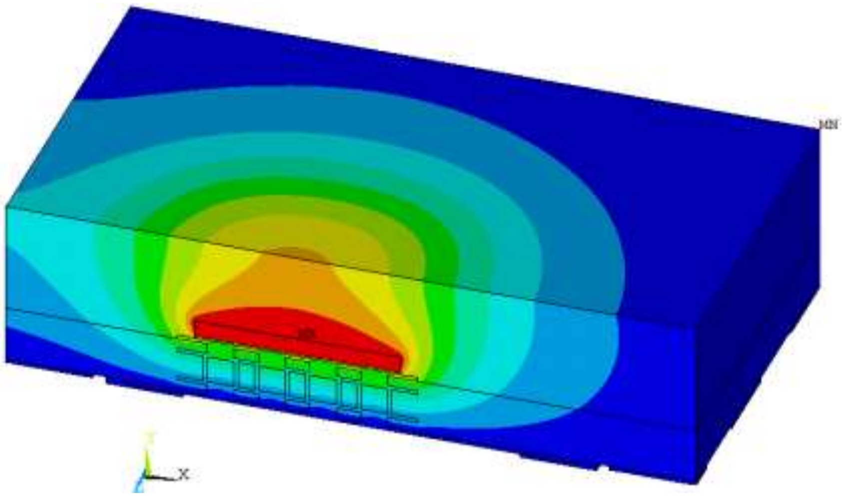


Temperature Cycling

- **Temperature cycling – uniform temperature condition assumed**

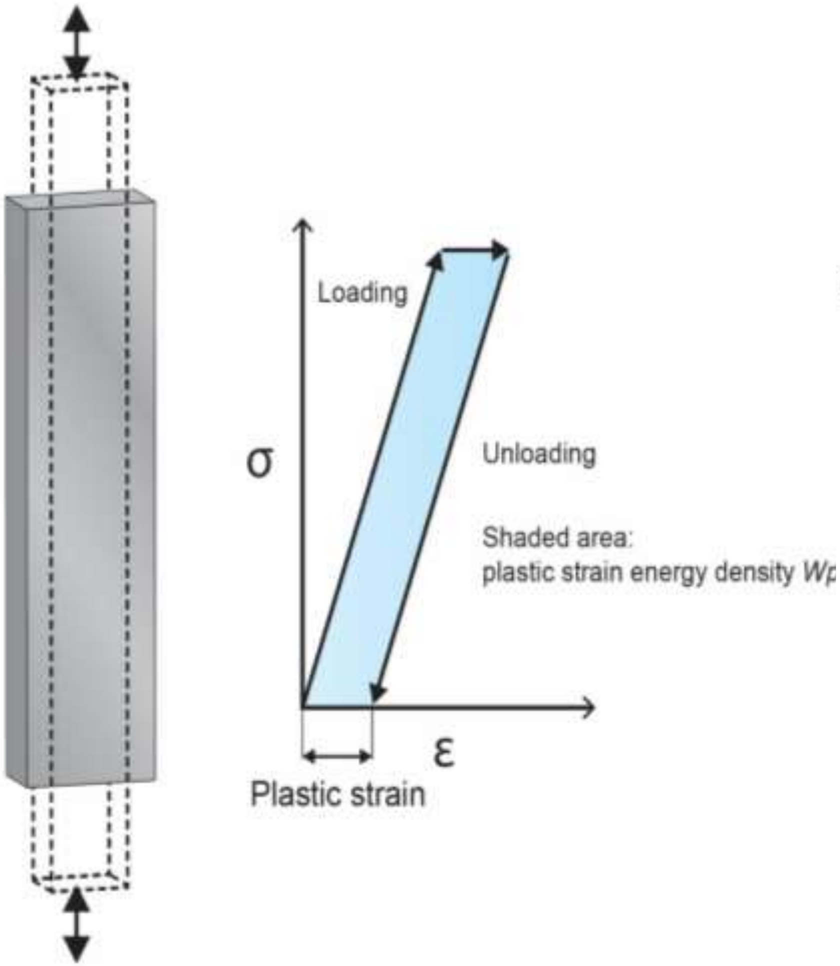


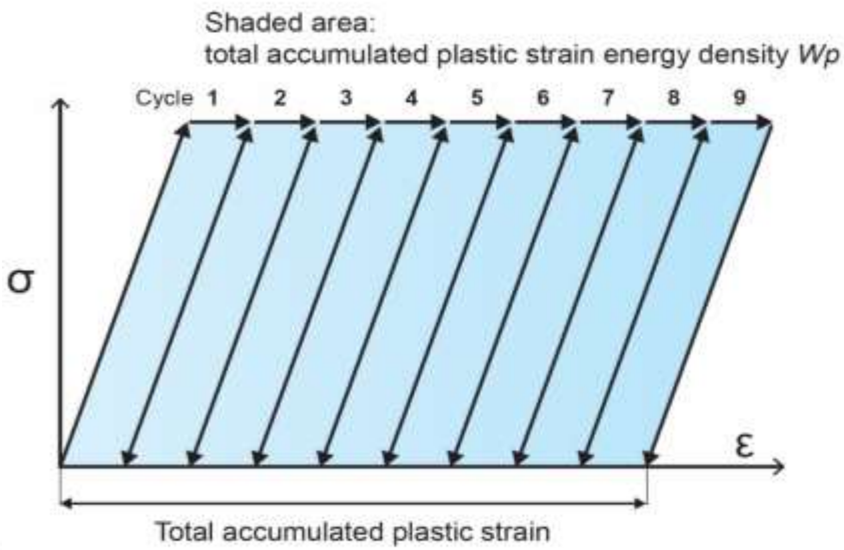
Power Cycling



- Temperature gradient exists.
- Much less severe than temperature cycling.

Fatigue Life Estimate





$$W_p = \int_0^{\varepsilon_p} \sigma d\varepsilon_p$$

$$N_f = A\left(\Delta W_p\right)^{-n}$$

Coffin-Manson Equation

Solder Creep Equations (ANAND Model)

- Anand's model (rate-dependent visco-plastic model)

$$\frac{ds}{dt} = \left\{ h_0 (|B|)^{\alpha} \frac{B}{|B|} \right\} \frac{d\varepsilon_p}{dt}$$

$$\frac{d\varepsilon_p}{dt} = A \left[\sinh\left(\frac{\xi \sigma}{s} \right) \right]^{-\frac{1}{m}} \exp\left(-\frac{Q}{RT} \right)$$

$$B = 1 - \frac{s}{s^*}$$

$$s^* = \hat{s} \left[\frac{d\varepsilon_p/dt}{A} \exp\left(-\frac{Q}{RT} \right) \right]^n$$

Variable/Parameter	Meaning	Units
s_0	initial value of deformation resistance	Stress
Q/R	Q = activation energy R = universal gas constant	Energy/volume Energy/(volume temp)
A	pre-exponential factor	1/time
ξ	multiplier of stress	Dimensionless
m	strain rate sensitivity of stress	Dimensionless
h_0	hardening / softening constant	Stress
$\hat{s}$	coefficient for deformation resistance saturation value	Stress
n	strain rate sensitivity of saturation (deformation resistance) value	Dimensionless
α	strain rate sensitivity of hardening or softening	Dimensionless

Anand Constants for Various Solder Alloys

Parameter	SAC105	SAC305	SAC387	SAC405	SnPb	SnPbAg	SnAg
s_0	2.3479	18.07	3.2992	20	12	12.41	39.09
Q/R	8076	9096	9883	10561	9200	9400	8900
A	3.773	3484	15.773	325	4.2E6	4E6	2.23E4
ξ	0.9951	4	1.0673	10	1.5	1.5	6
m	0.4454	0.2	0.3686	0.32	0.3	0.303	0.182
h_0	4507.5	144000	1076.9	8E5	1.4E3	1379	3321.15
$\hat{s}$	3.5833	26.4	3.1505	42.1	14	13.79	73.81
n	0.012	0.01	0.0352	0.02	0.071	0.07	0.018
α	2.1669	1.9	1.6832	2.57	1.31	1.3	1.82

SAC105 D. Bhate et al., *Constitutive Behavior of Sn3.8Ag0.7Cu and Sn1.0Ag0.5Cu Alloys at Creep and Low Strain Rate Regimes*, IEEE Transactions on Components and Packaging Technologies, Vol. 31, No. 3, September 2008, p. 622.

SAC305 Motalab et al., *Determination of Anand Constants for SAC Solders using Stress-Strain or Creep Data*, ITherm 2012, pp. 909-921.

SAC387 D. Bhate et al., *Constitutive Behavior of Sn3.8Ag0.7Cu and Sn1.0Ag0.5Cu Alloys at Creep and Low Strain Rate Regimes*, IEEE Transactions on Components and Packaging Technologies, Vol. 31, No. 3, September 2008, p. 622.

SAC405 W. Qiang et al., *Experimental determination and modification of Anand model constants for Pb-free material 95.5Sn4.0Ag0.5Cu*, in EUROSIME Conf. IEEE, 2007.

SnPb R. Darveaux, "*Effect of simulation methodology on solder joint crack growth correlation*," in Electronic Components & Technology Conf. IEEE, 2000 .

SnPbAg R. Darveaux, "*Effect of simulation methodology on solder joint crack growth correlation*," in Electronic Components & Technology Conf. IEEE, 2000.

SnAg Wang, Z. Cheng, K. Becker, and J. Wilde, *Applying Anand model to represent the viscoplastic deformation behavior of solder alloys*, ASME Journal of Electronic Packaging, Vol. 123, 2001.

Solder Creep Equations

Solder alloys	C_1 (1/sec)	C_2 (1/Pa)	C_3	C_4 (°K)
95.5Sn-3.9Ag-0.6Cu	441000	5×10^{-9}	4.2	5412
63Sn-37Pb	926(508 - T)/T	1/(37.78x106 - 74414T)	3.3	6360

$$\frac{\partial \varepsilon}{\partial t} = C_1 \left[\sinh\left(C_2 \sigma\right)\right]^{C_3} \exp\left(\frac{-C_4}{T}\right)$$

C_1, C_2, C_3, C_4 are the input constants for ANSYS finite element program. The stress unit is Pa.

Lau, Dauksher, and Vianco, "Acceleration Models, Constitutive Equations, and Reliability of Lead-Free Solders And Joints", *IEEE Electronic Components and Technology Conference*, June 2003, pp. 229-234.

Solder Creep Equations (NEW)

Solder alloys	C_1 (1/sec)	C_2 (1/Pa)	C_3	C_4 (°K)	
95.5Sn-3.9Ag-0.6Cu	441000	5×10^{-9}	4.2	5412	Sandia
Sn(3.5-3.9)Ag(.5-.8)Cu	500000	10×10^{-9}	5.0	5807	Agilent
Fraunhofer's LF	277984	24.47×10^{-9}	6.41	6504	IZM

$$\frac{\partial \varepsilon}{\partial t} = C_1 [\sinh(C_2 \sigma)]^{C_3} \exp\left(\frac{-C_4}{T}\right)$$

C_1 , C_2, C_3, C_4 are the input constants for ANSYS finite element program. The stress unit is Pa.

Lau, J., and W. Dauksher, "Creep Constitutive Equations of Sn(3.5-3.9)wt%Ag(0.5-0.8)wt%Cu Lead-Free Solder Alloys", in *Micromaterials and Nanomaterials*, edited by B. Michel, IZM, Berlin, Germany, 2004, pp. 54-62.

Solder Creep Equations

SnPb Creep Equation

SnAgCu Creep Equation

Elastic

Grain Boundary Sliding (GBS)

Matrix Creep (MC)

SnPb:

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + B_1 D\left(\frac{\sigma}{E}\right)^3 + B_2 D\left(\frac{\sigma}{E}\right)^7$$

where

$\dot{\varepsilon}$ = Total Strain Rate (1/sec)

σ = Stress (MPa)

E = Modulus of Elasticity (MPa) = $(56000 - 88T)$

T = Temperature (K)

$B_1 = 1.70\times10^{12}$ 1/sec

$B_2 = 8.90\times10^{24}$ 1/sec

$$D = \exp\left(\frac{-5413}{T}\right)$$

SnAgCu:

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + A_1 D_1\left(\frac{\sigma}{\sigma_n}\right)^3 + A_2 D_2\left(\frac{\sigma}{\sigma_n}\right)^{12}$$

where

$\dot{\varepsilon}$ = Total Strain Rate (1/sec)

σ = Stress (MPa)

E = Modulus of Elasticity (MPa) = $(59533 - 66.667T)$

T = Temperature (K)

$A_1 = 4.0\times10^{-7}$ 1/sec

$A_2 = 1.0\times10^{-12}$ 1/sec

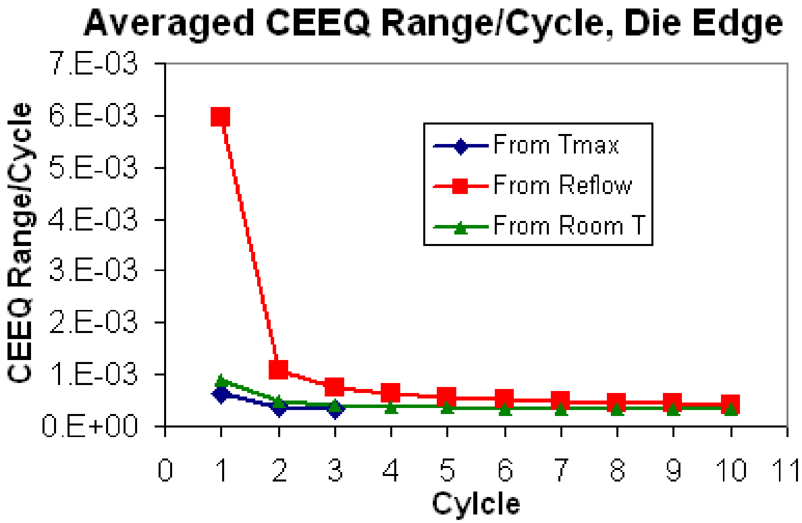
$D_1 = \exp(-3223/T)$

$D_2 = \exp(-7348/T)$

$\sigma_n = 1$ MPa

Best Practice (1) - Stress-Free Setting

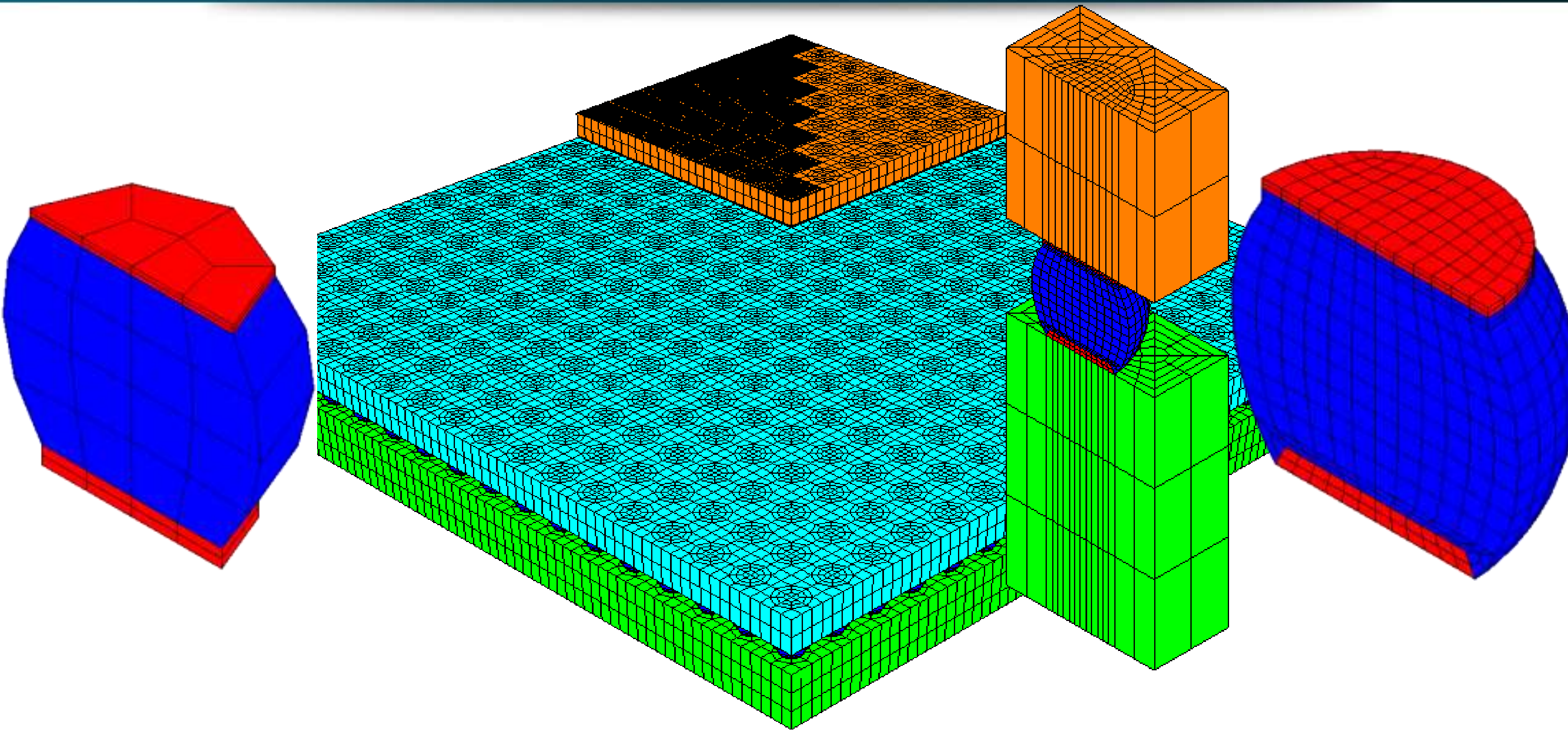
- Three most commonly used initial stress-free temperatures
  - The solidus temperature of solder material (e.g., for SnAgCu, this temperature is 217°C)
  - The room temperature as initial stress-free (e.g. 25°C)
  - The high dwell temperature of thermal cycle or operating conditions (denoted as T_{max}, e.g. =125°C for thermal cycling from -25°C to 125°C)



- **T_{max} as stress-free condition is recommended.**

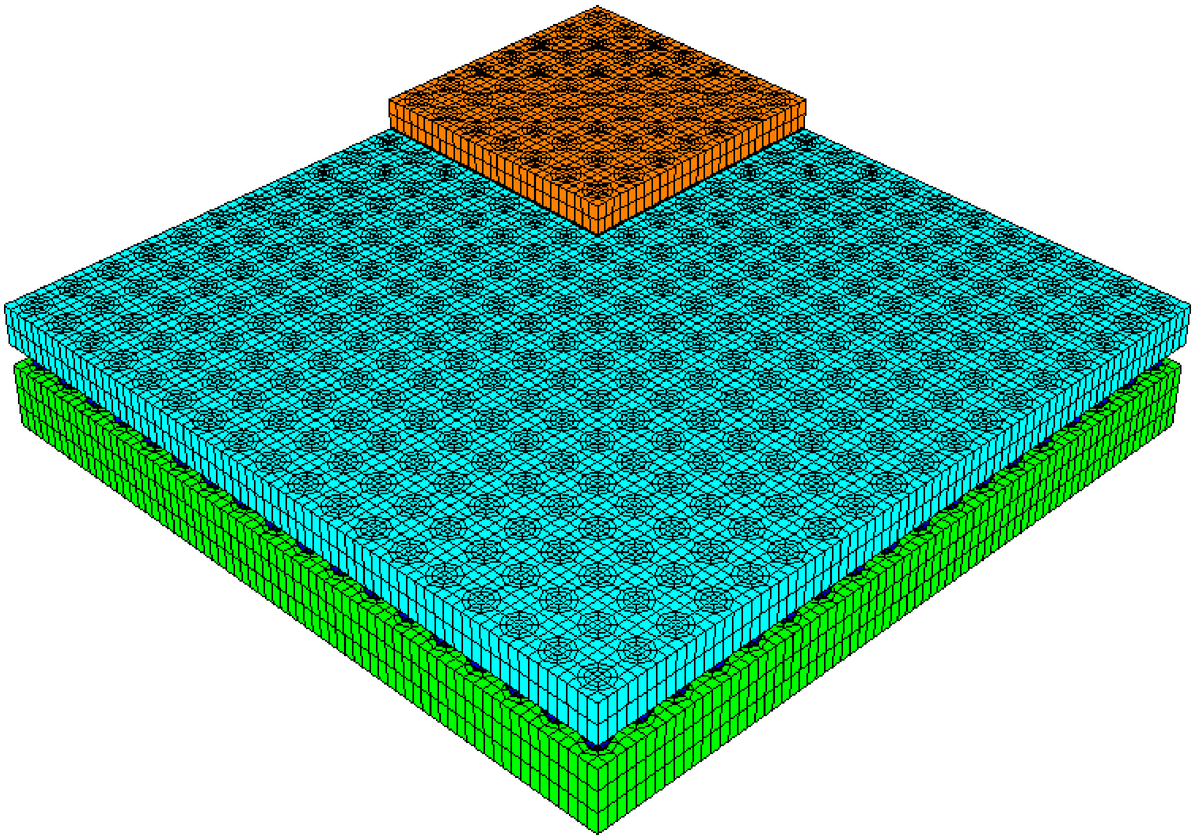
Fan XJ, Pei M, Bhatti PK. Effect of finite element modeling techniques on solder joint fatigue life prediction of flip-chip BGA packages. Proc. of Electronic Components and Technology Conference (ECTC), 972-980. 2006.

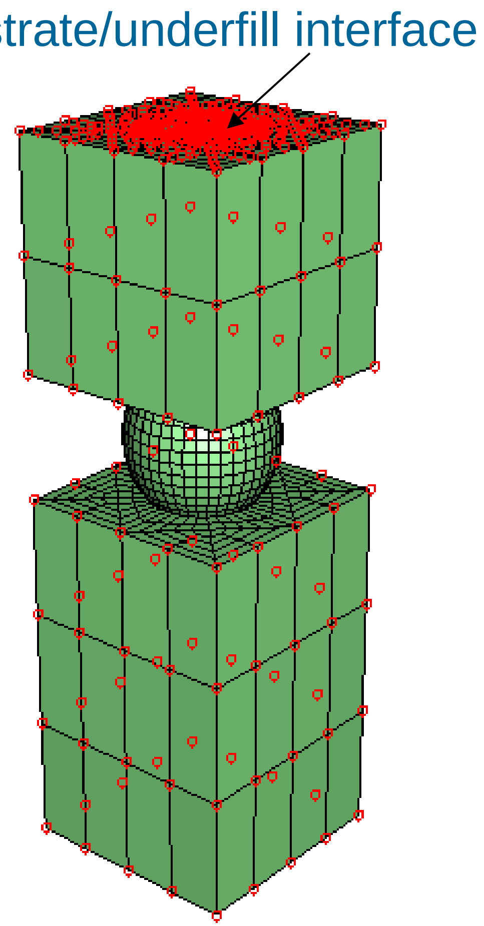
Best Practice (2) – One Global Model (Full Model)



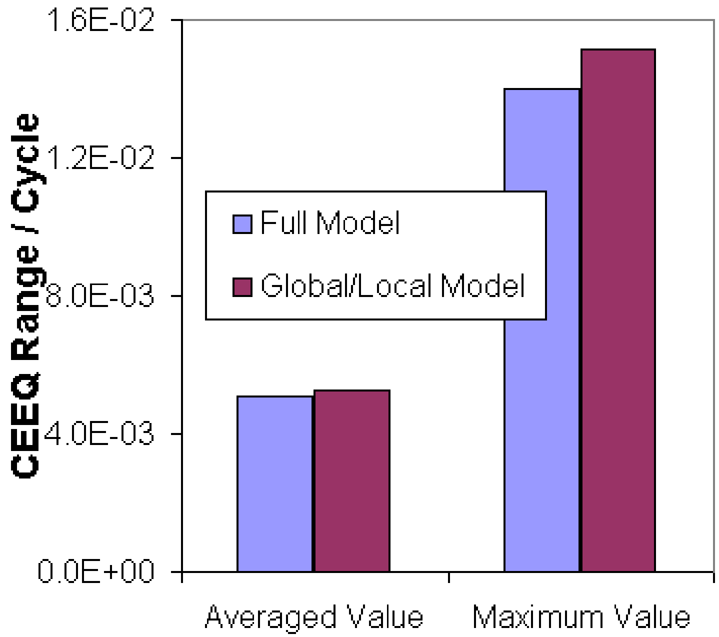
- Coarse element at most of the places
- Refined element at critical solder joints
- No tie element is used
- Refined solder balls consider both SMD and MD pads

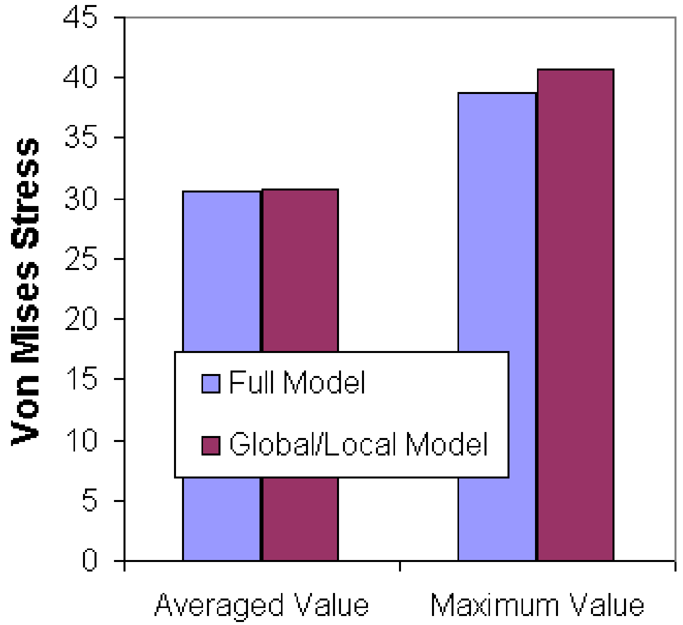
Best Practice (2) – Sub-modeling (Global/Local)





Comparison - Global/Local Model and Full Model



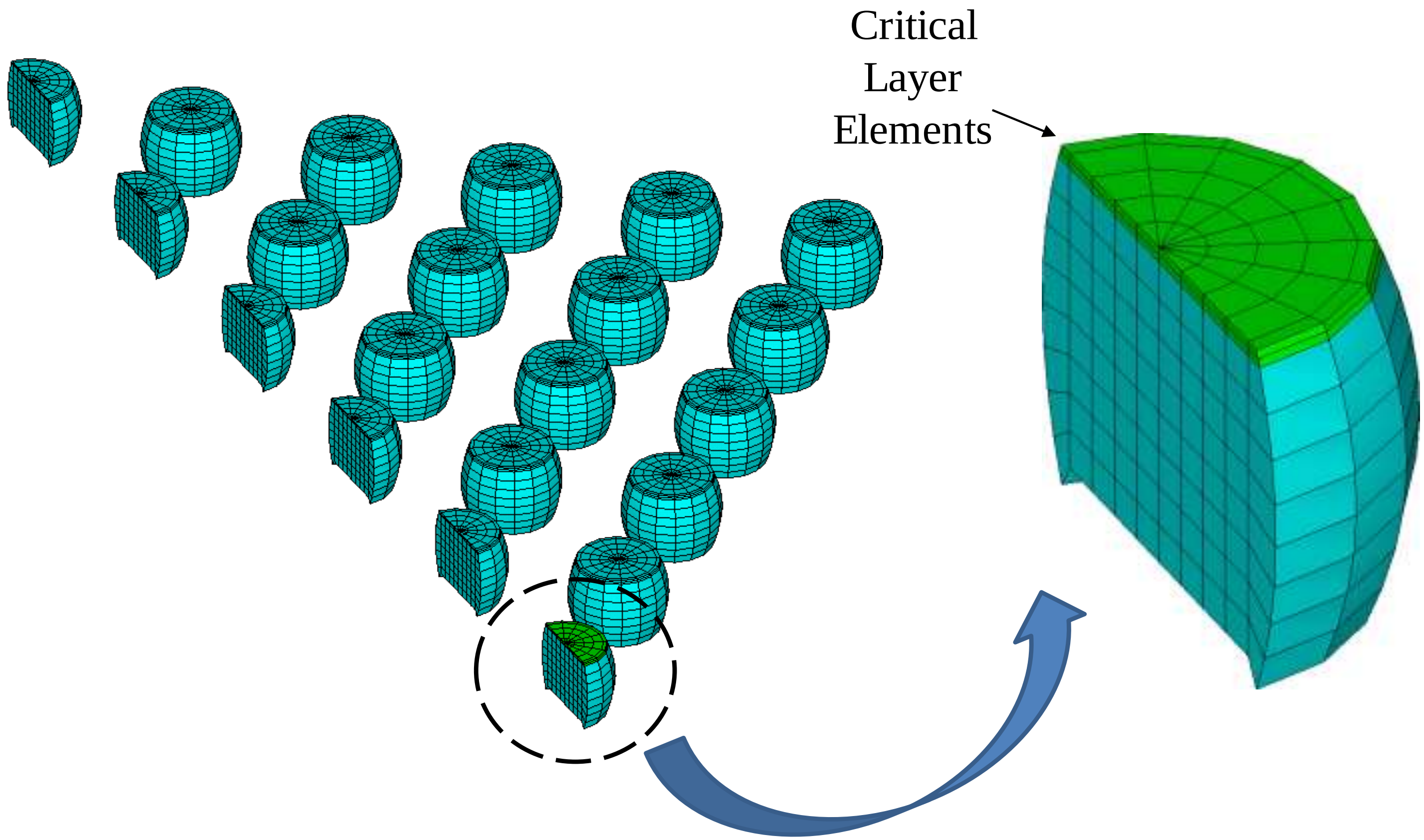


- – The global/local modeling approach provides satisfactory results for the volumetrically averaged and maximum values
- – For some location, the difference in maximum value can be as high as 20% (not shown here)

- **"Full Model" is recommended.**

Best Practice (3) - Volume Averaging

$$\Delta W_{ave} = \frac{\sum \Delta W_i V_i}{V_i}$$



ΔW_{ave} = average inelastic strain energy density accumulated per cycle for fixed thickness layer elements

ΔW_i = strain energy density accumulated per cycle for each element i

V_i = volume of each element i

- **Volume averaging over a fixed thickness of thin layer is recommended.**

Best Practice (4) - Worst Case Solder Joint Location

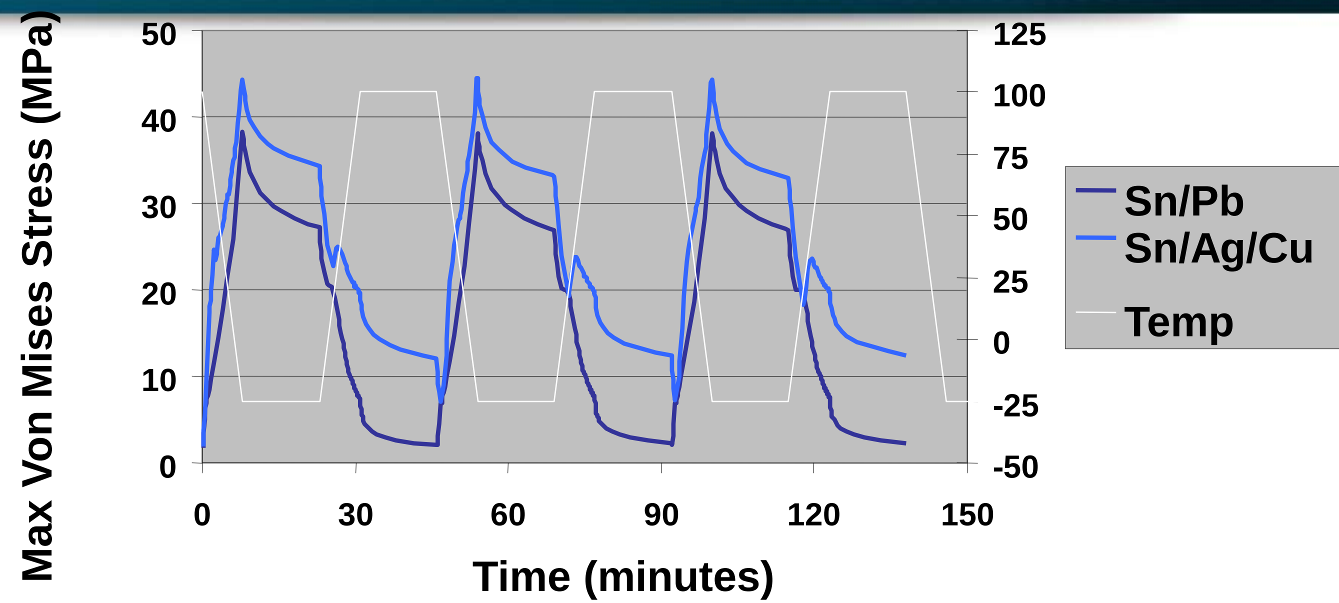
- For FC-BGA package
  - It's commonly accepted that the worst case solder joint is located in the outermost along diagonal direction under the die shadow.
- Metrics
  - Von Mises stress, creep strain, creep strain energy density, peel stress
  - Maximum value, averaged value
- Results
  - Averaged per-cycle creep strain and stress shows the worst-case solder joint at the middle of die edge
  - The maximum value of these two parameters show the worst joint at the die corner
  - Peel stress finds the maximum tensile stress at the joint one row inside from the die shadow corner

- Experimental data
  - The solder joint one row inside from the corner of die shadow usually has the highest crack growth rate
  - All solder joints along the die edge have comparable crack growth rates
- **Correlation with experimental data is recommended.**

Bhatti PK, Pei M, Fan XJ. Reliability analysis of SnPb and SnAgCu solder joints in FC-BGA packages with thermal enabling preload. Proc. of Electronic Components and Technology Conference (ECTC), 601-606. 2006.

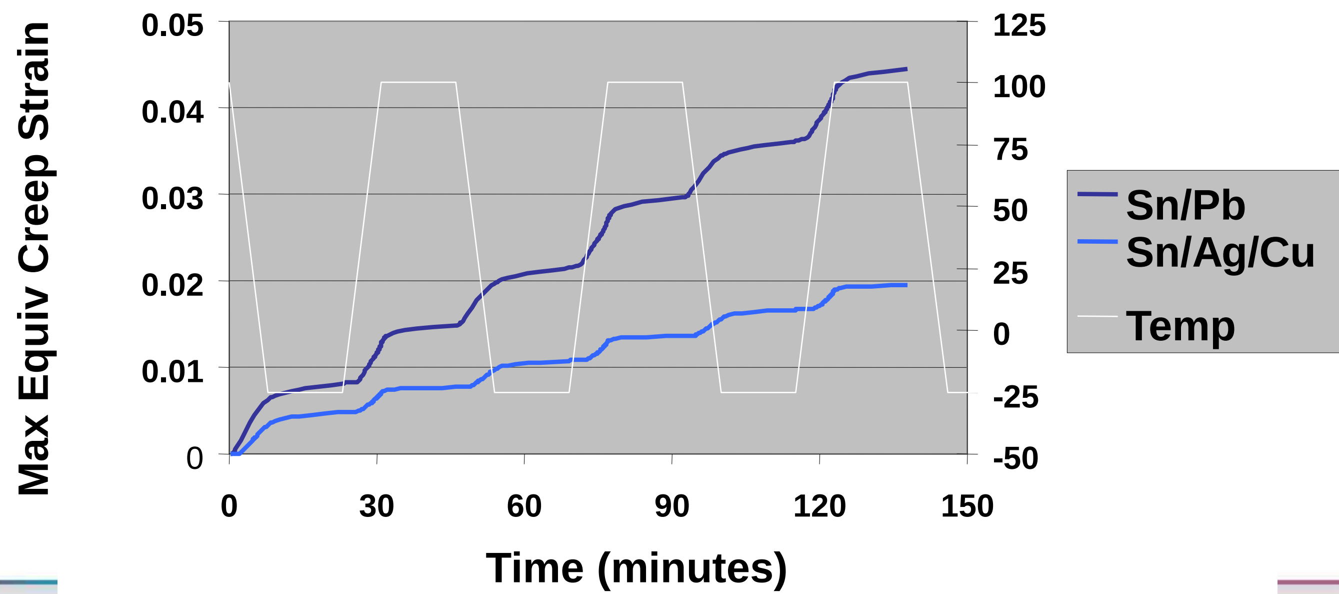
General Results: SnPb vs. SnAgCu

Maximum Von Mises Stress (MPa)

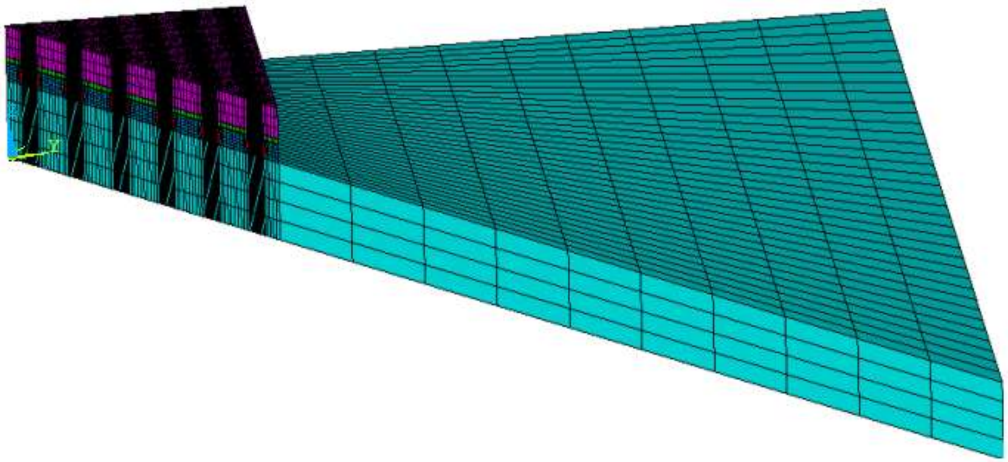


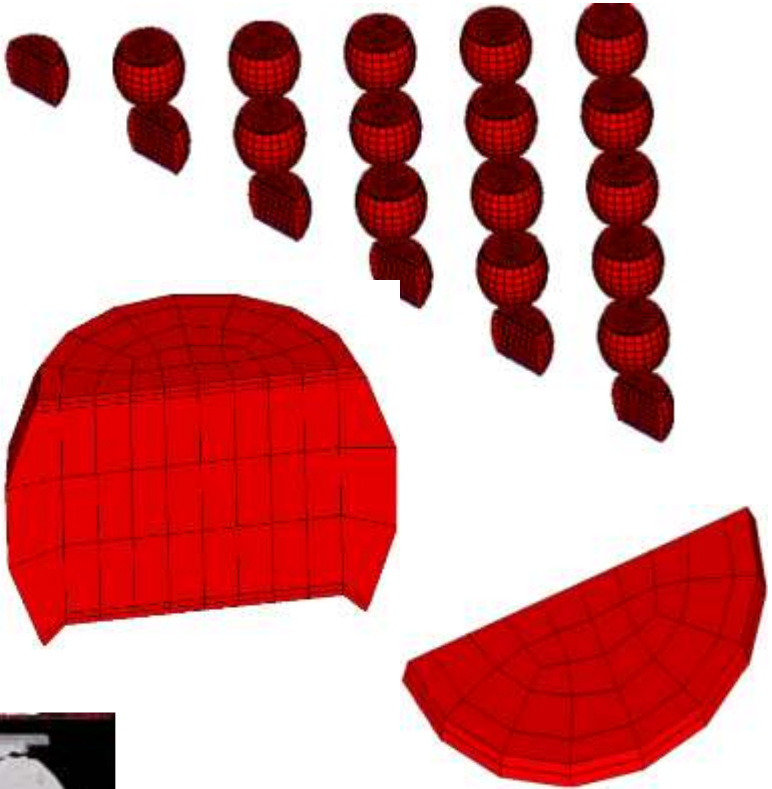
Temperature range -25 to +100°C

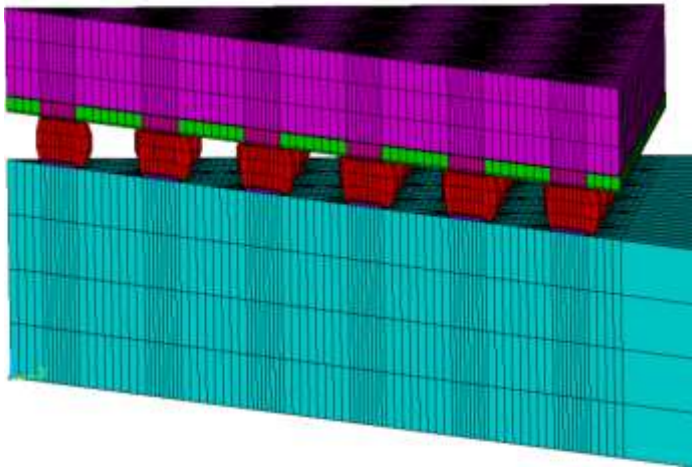
Maximum Equiv Creep Strain



Wafer Level Package (Fan-in WLP) – Worst Location

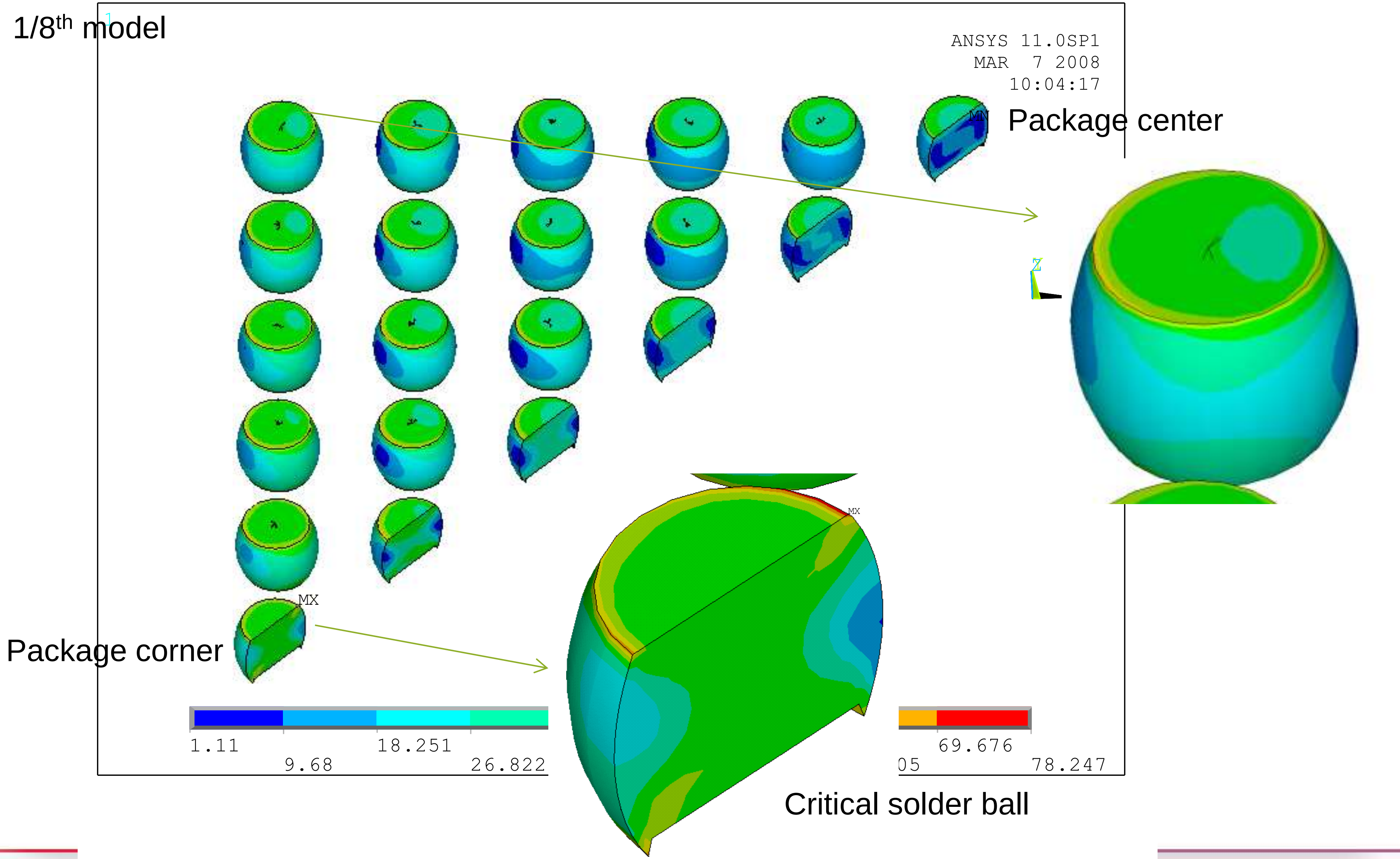






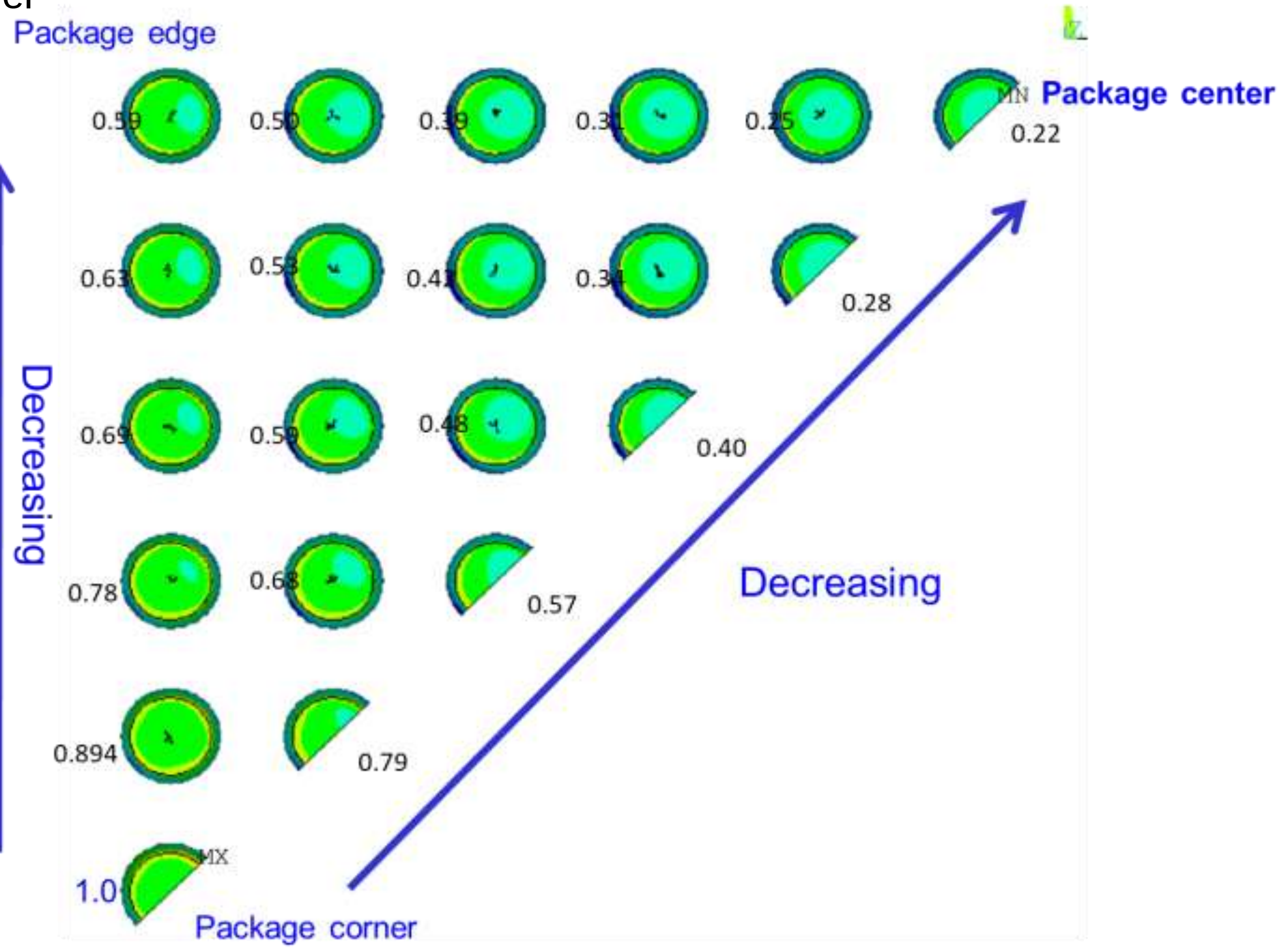
$$\Delta W_{ave} = \frac{\sum \Delta w.v}{\sum v}$$

WLP - von Mises Stress Map in Solder Balls



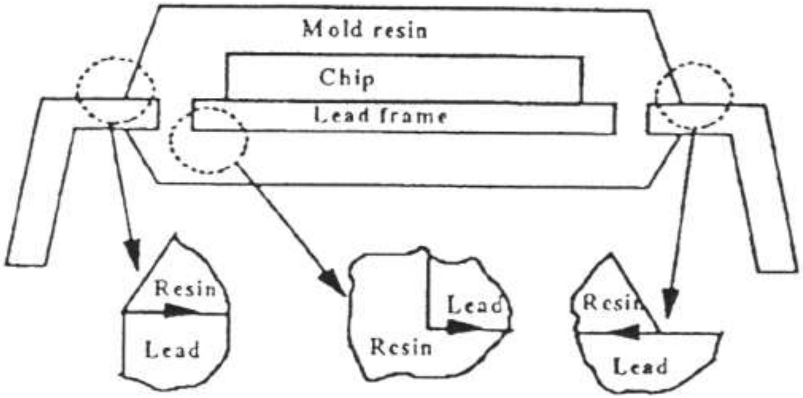
WLP - Plastic Work Density Map

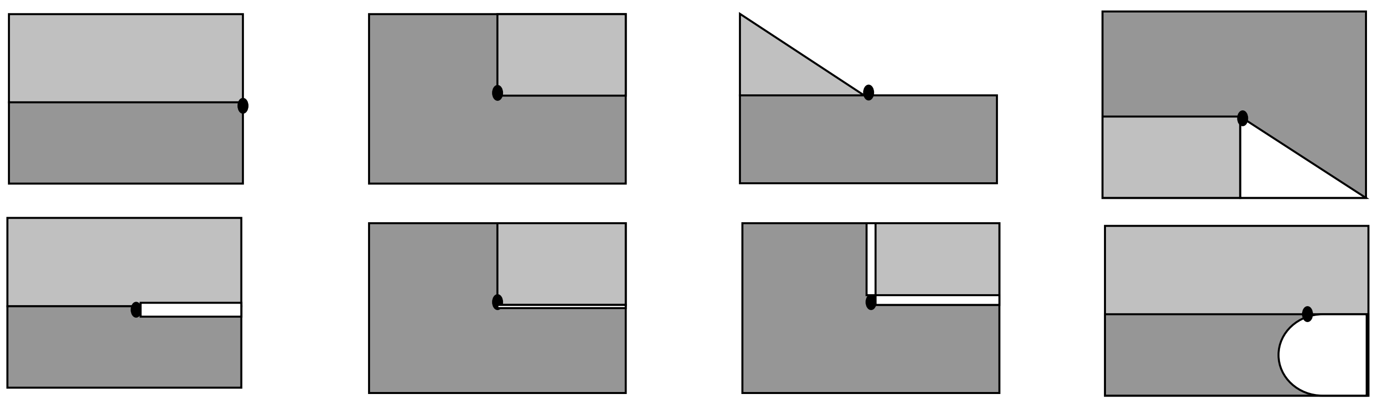
1/8th model



Fan XJ, Varia B, Han Q. Design and optimization of thermo-mechanical reliability in wafer level packaging, *Microelectronics Reliability*, 50, 536–546, 2010.

Stress Singularities in Material Joints





Fan XJ, Wang HB, Lim TB. Investigation of the underfill delamination and cracking for flip chip modules under temperature cyclic loading. *IEEE Transactions on Components, Manufacturing and Packaging Technologies*, 24(1), 84-91. 2001.

Summary

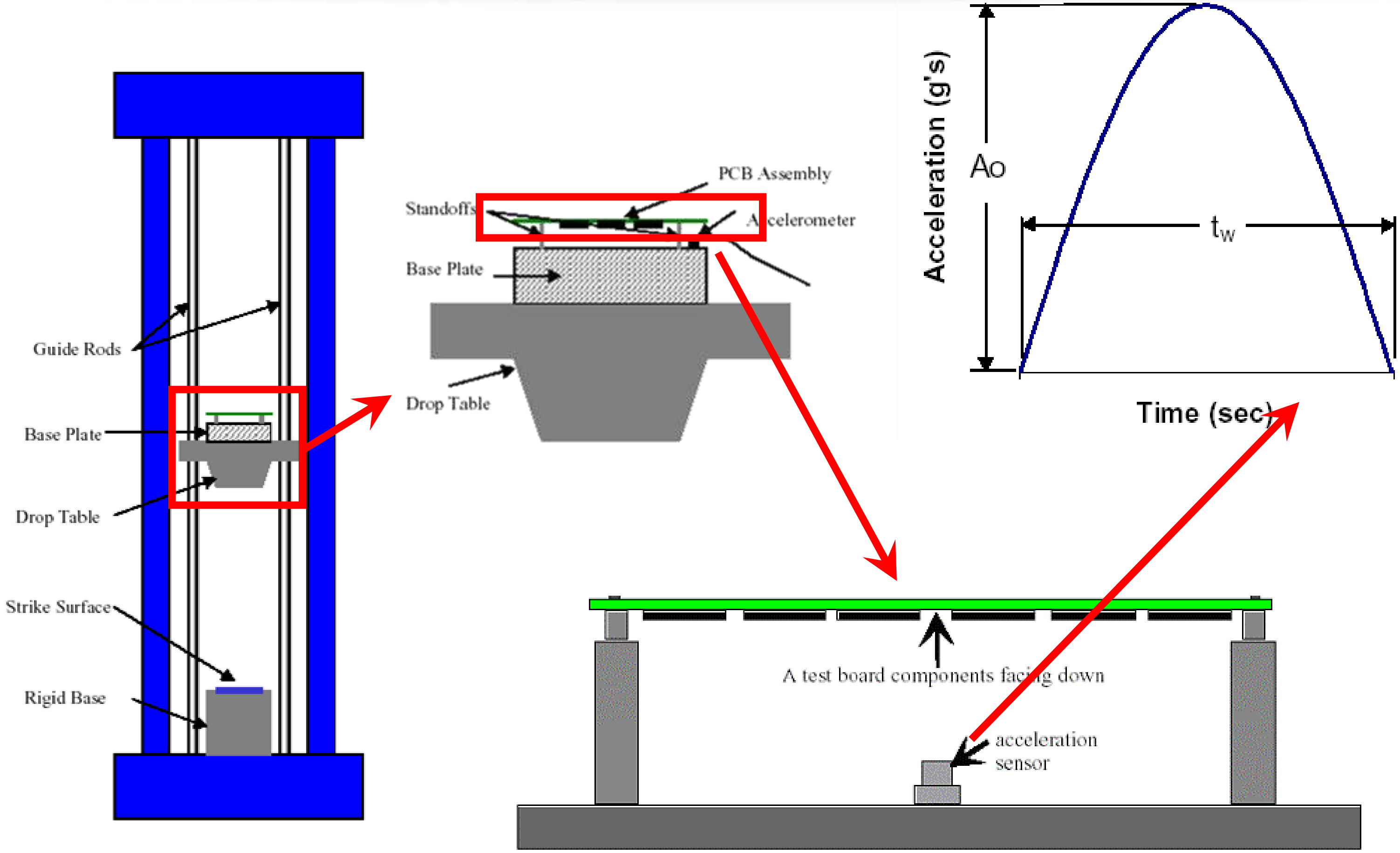
- Thermal mismatch vs. temperature gradient
- Analytical solution
  - Layered structure (stress, warpage, effective CTE)
  - Cylindrical structure (TSV)
- Die-level thermal stress – thermal stress in TSV
- Package-level thermal stress problem – warpage
- Chip-package interaction (CPI) – submodeling technique
- Board level thermal stress problem
  - Solder ball thermal cycling (Flip chip BGA, WLP)
  - Creep equations
  - Best method for practice
    - Initial stress free condition; full model vs. global/local model; worst solder ball location, volume averaging
- Stress singularity of joint materials

- Introduction
- Temperature Loading
- Mechanical Loading
- Moisture Loading
- Electrical Current Loading - Multi-Physics Modeling
- Summary

Outline

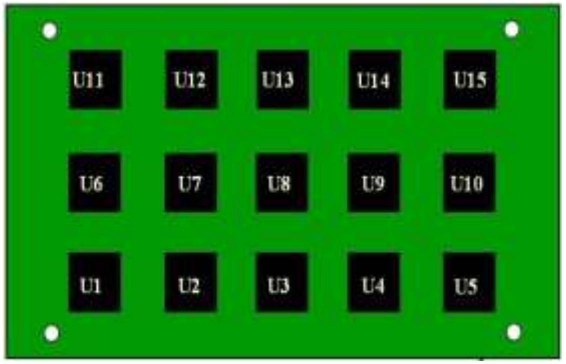
- **JEDEC drop test standard (old and new)**
- **Simulation method**
  - Input G
  - Large mass
  - Input D
  - Direct acceleration
  - Global/local method
- **4-point bending test**

JEDEC Drop Test Set-Up



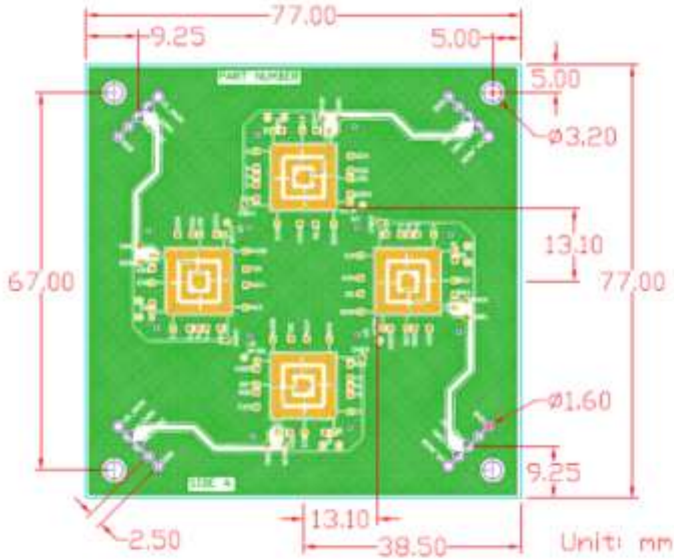
- Peak acceleration: 1500g
- Impulse time: 0.5ms with half-sine shape

JEDEC Test Standard JESD22-B111 (Old)

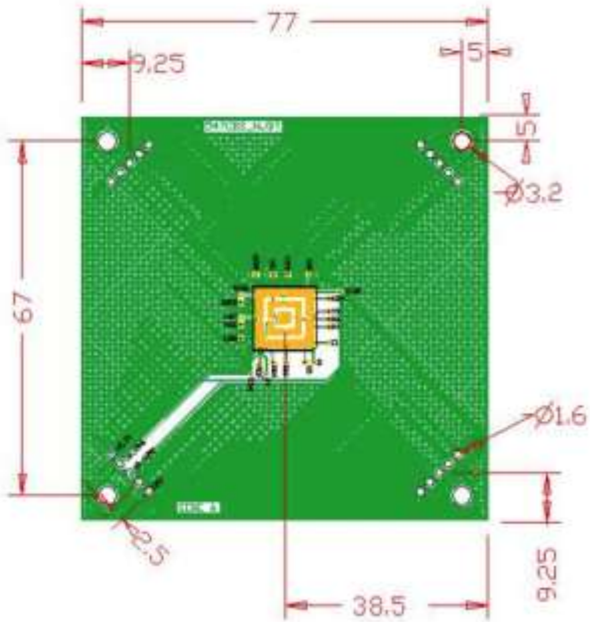


Group	Number Components	Component Location
A	4	U1, U5, U11, & U15
B	4	U2, U4, U12, & U14
C	2	U6 & U10
D	2	U7 & U9
E	2	U3 & U13
F	1	U8

JEDEC Test Standard JESD22-B111A (New, 11/2016)

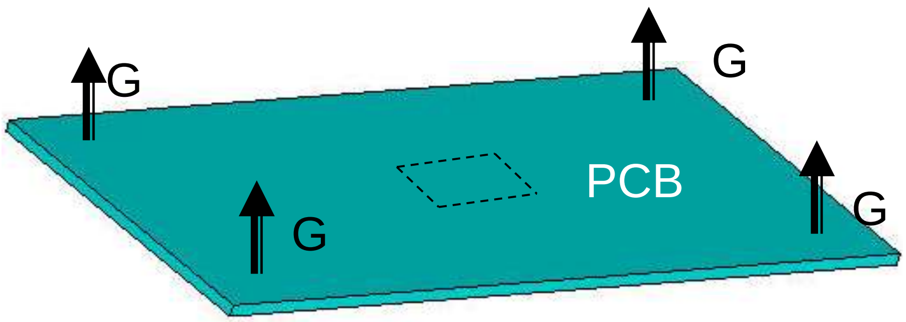


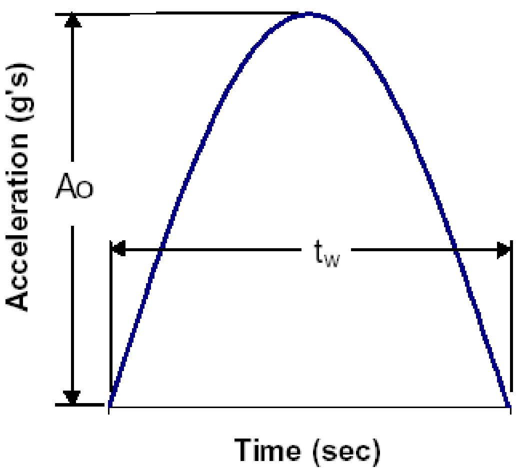
(a)



(b)

FEA Modeling: Input-G Method





$$\{M\}[\ddot{u}_1] = \{C\}[\dot{u}_1] + \{K\}[u_1] = 0$$

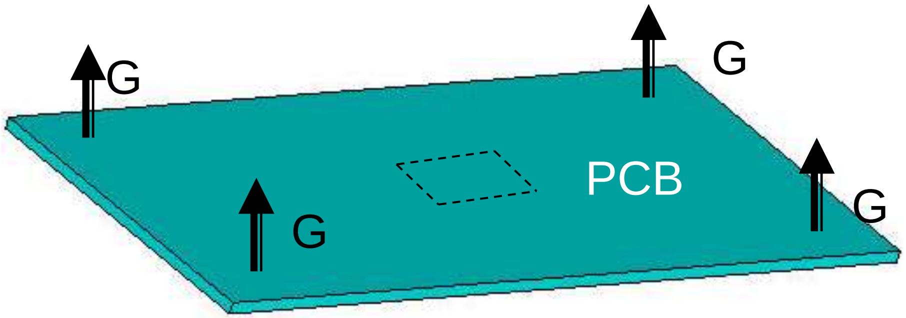
with initial conditions

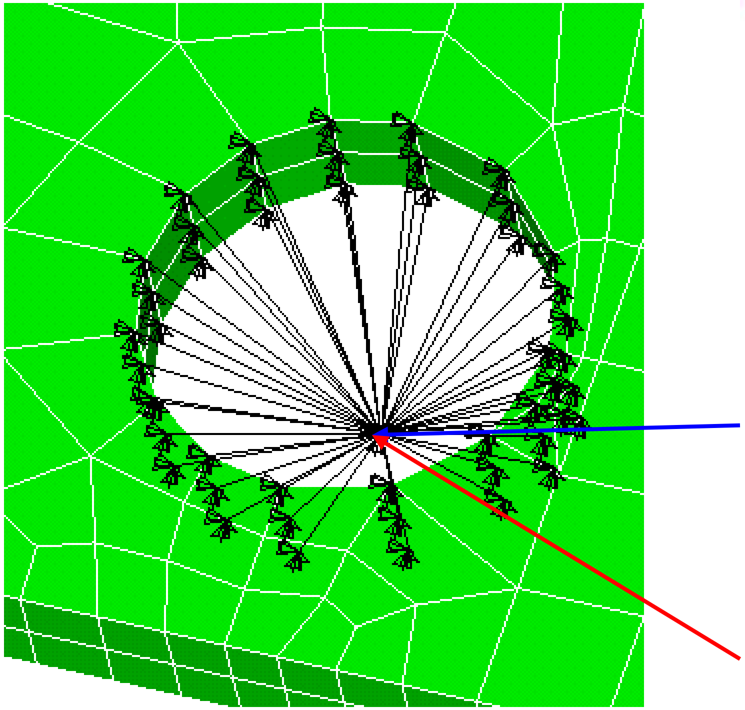
$$[u_1]|_{t=0} = 0, \qquad [\dot{u}_1]|_{t=0} = \sqrt{2gH}$$

and boundary condition

$$a = \begin{Bmatrix} 1500g \sin\frac{\pi t}{t_w} & \text{for } t \le t_w, \quad t_w = 0.5 \\ 0 & \text{for } t \ge t_w \end{Bmatrix}$$

FEA Modeling: Input-G Method



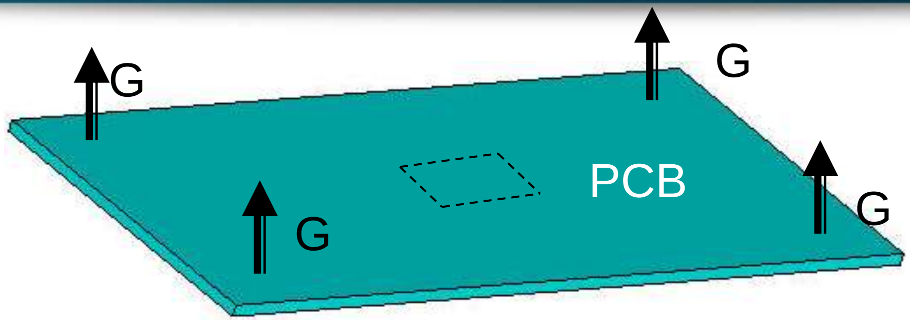


Large Mass Method

Large mass 10^8 times mass of structure coupled (1mm away from PCB bottom)

Acceleration = 1500 × g × sin (pi × t/0.5)
Force = 10^8× Acceleration

FEA Modeling: Input-D Method



$$\{M\}[\ddot{u}_1] = \{C\}[\dot{u}_1] + \{K\}[u_1] = 0$$

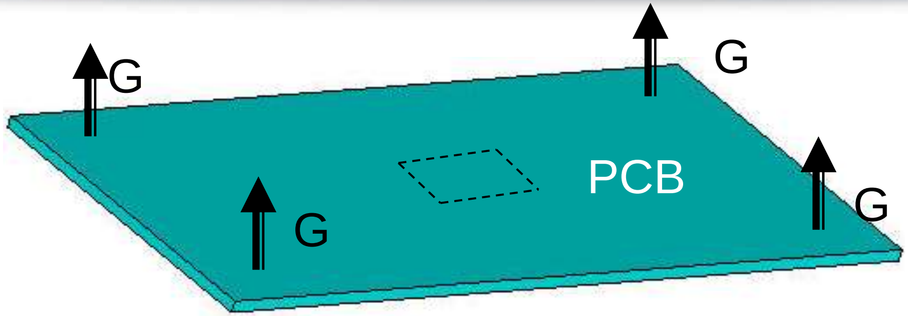
with initial conditions

$$[u_1]|_{t=0} = 0, \qquad [\dot{u}_1]|_{t=0} = \sqrt{2gH}$$

and boundary condition

$$[u_1]|_{\text{at hole}} = \begin{cases} -\left(\frac{t_w}{\pi}\right)^2 (1500g)\sin\frac{\pi t}{t_w} + \left(\frac{t_w}{\pi}(1500g) + \sqrt{2gH}\right)t, & t \le t_w \\ \left(2\frac{t_w}{\pi}(1500g) + \sqrt{2gH}\right)t - \left(\frac{t_w}{\pi}\right)^2 (1500g), & t \ge t_w \end{cases}$$

FEA Modeling: Direct Acceleration Method



$$\{M\}[\ddot{u}_2] + \{C\}[\dot{u}_2] + \{K\}[u_2] =$$

$$\begin{Bmatrix} -\{M\}1500g\sin\frac{\pi t}{t_w} & t \le t_w, t_w = 0.5 \\ 0 & t \ge t_w \end{Bmatrix}$$

with initial conditions

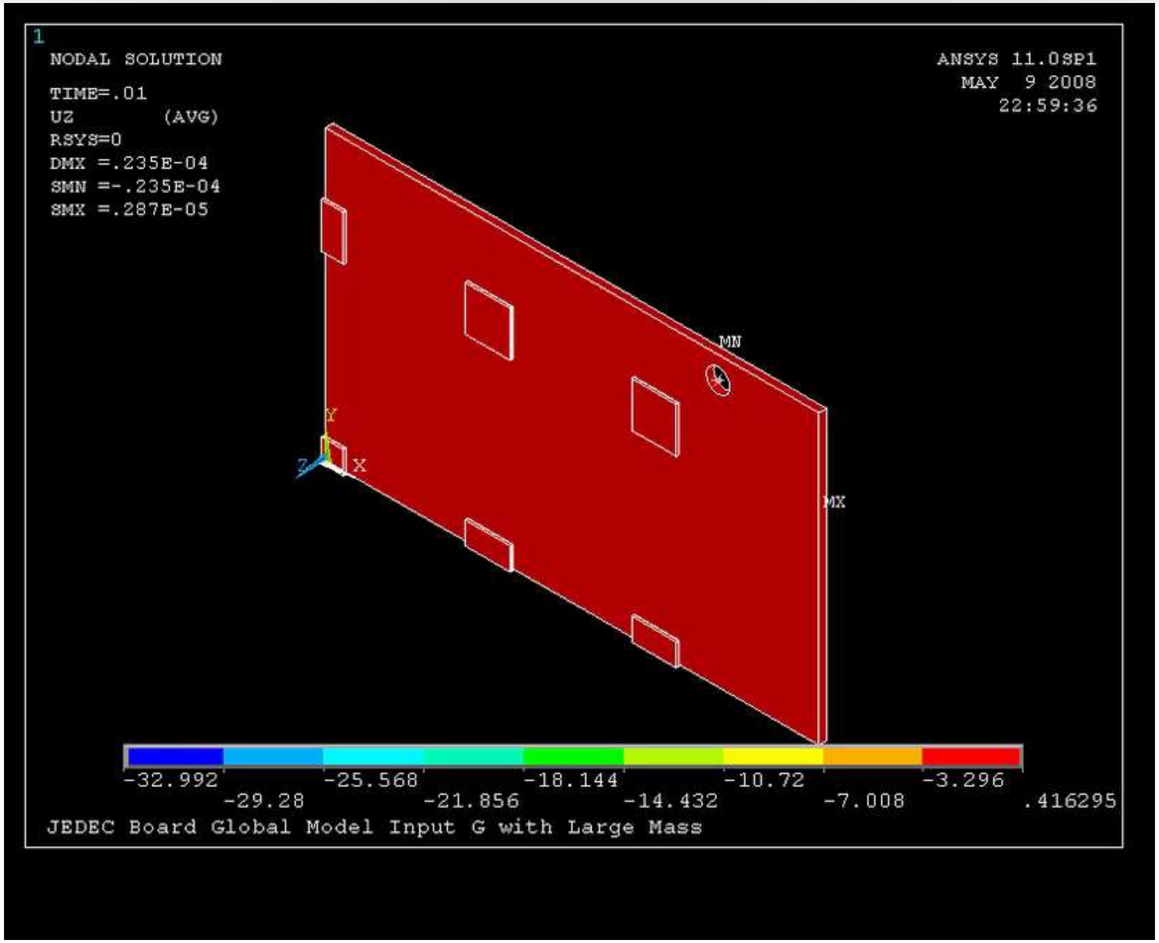
$$[u_1]|_{t=0} = 0, \qquad [\dot{u}_1]|_{t=0} = \sqrt{2gH}$$

and boundary conditions

$$[u_2]|_{\text{at hole}} = 0$$

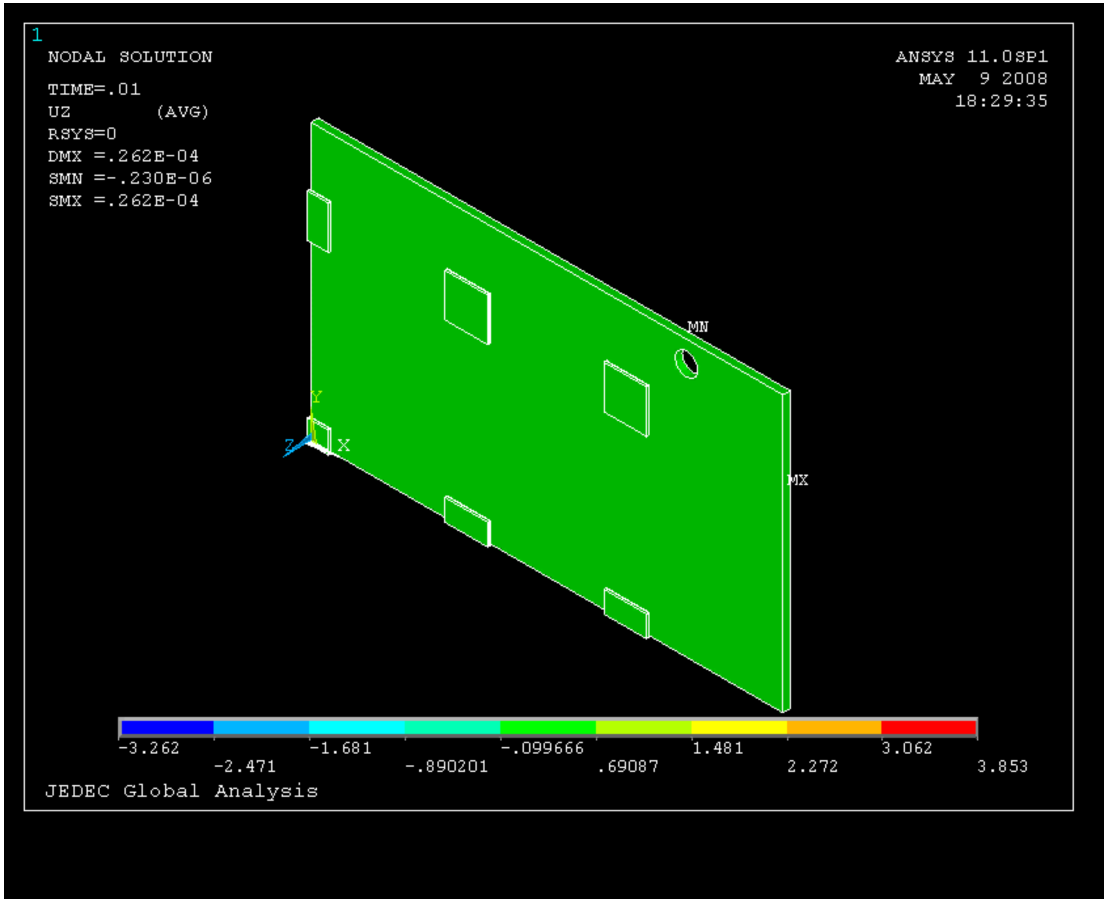
Fan XJ, Ranouta AS, Dhiman HS. Effects of package level structure and material properties on solder joint reliability under impact loading. *IEEE Transactions on Components, Packaging and Manufacturing Technology*. 3(1), 52-60. 2013.

Input-G Method – Board Vibration



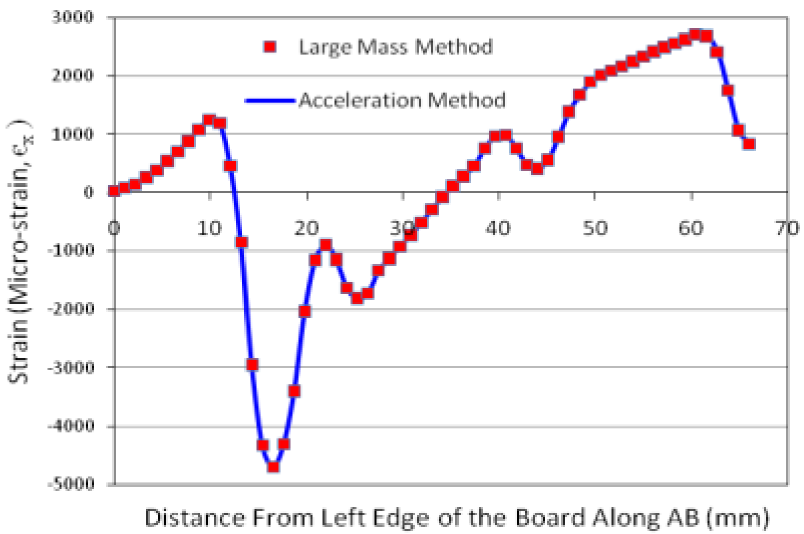
- Since acceleration impulse is given on the screw locations, the displacements are not fixed and the board is moving in one direction.

Direct Acceleration Method – Board Vibration

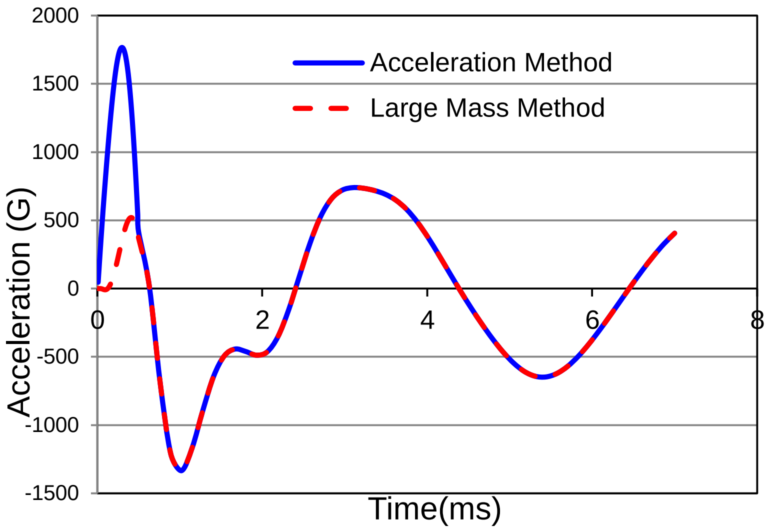


- Since the displacement is fixed at the screw locations, the board is vibrating as expected.

Input-G vs. Direct Acceleration Method



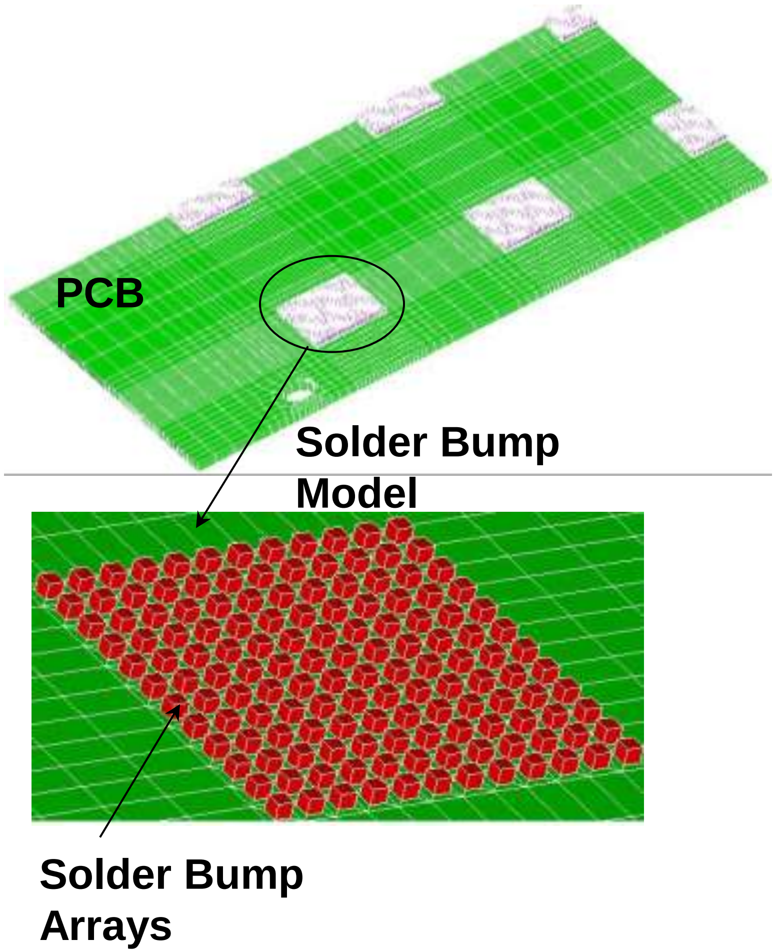
Distribution of Board Strain in x direction along line AB at t = 1.5 ms

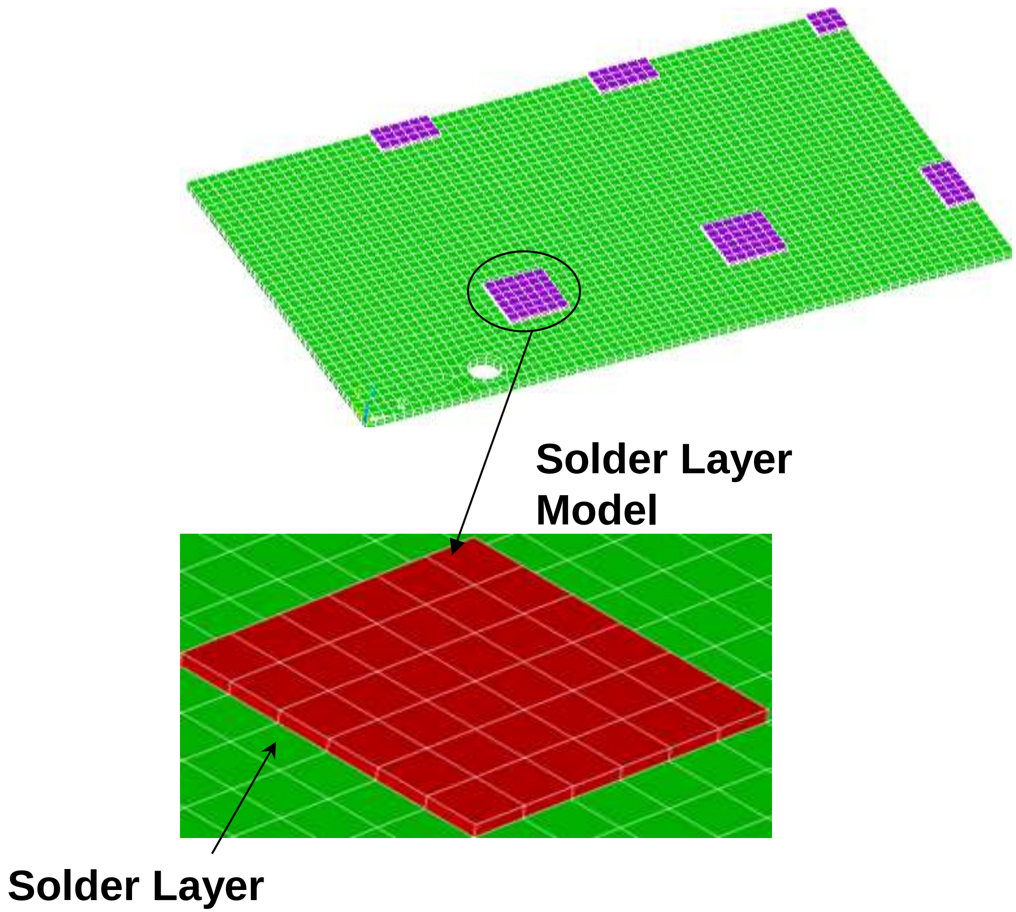


Comparison of acceleration time history

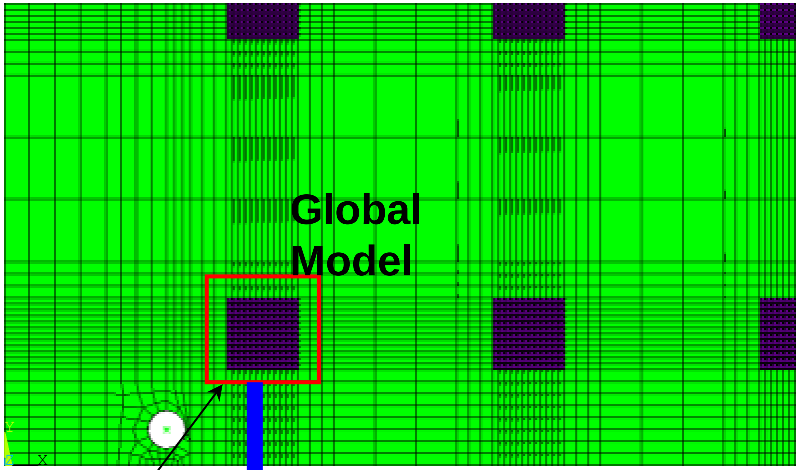
- **Direct Acceleration method is recommended, but all methods provide identical results.**

FEA Global Model



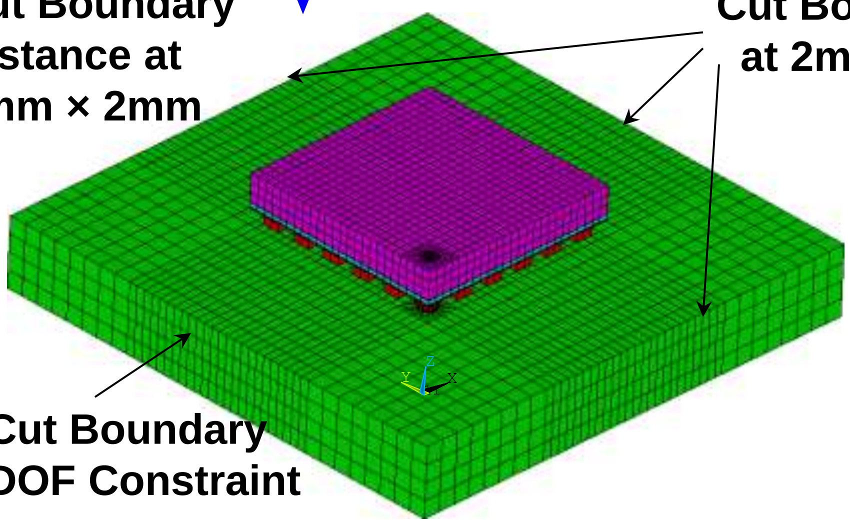


FEA Local Model



Cut Boundary Distance at 2mm × 2mm

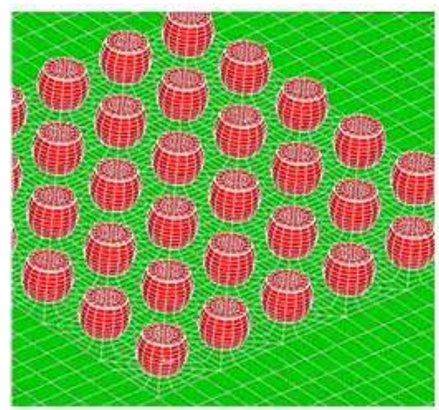
Cut Boundary DOF Constraints at 2mm × 2mm



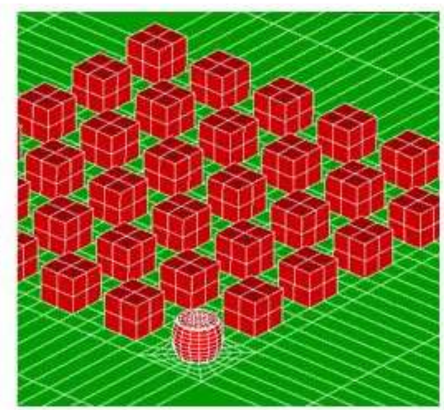
Cut Boundary DOF Constraint

Local Model

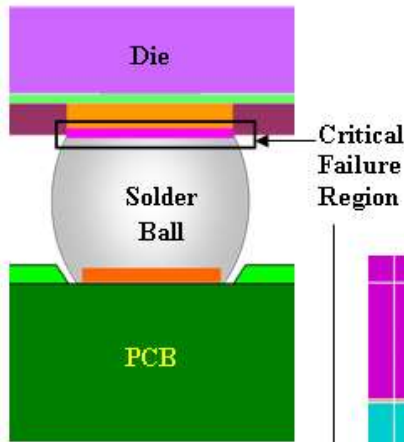
Local Model 1



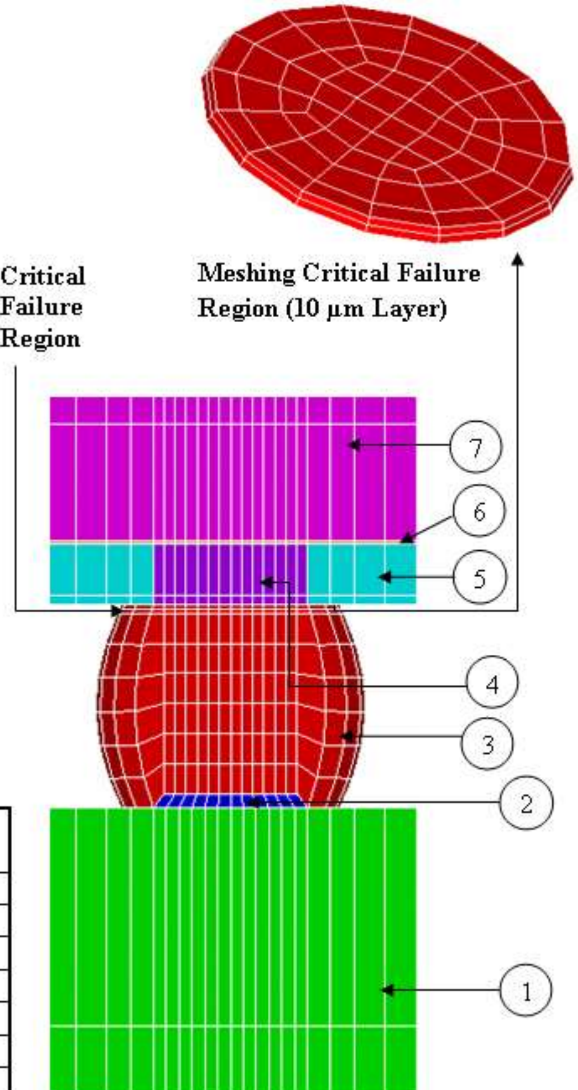
Local Model 2



FEA Local Model – Solder Joint



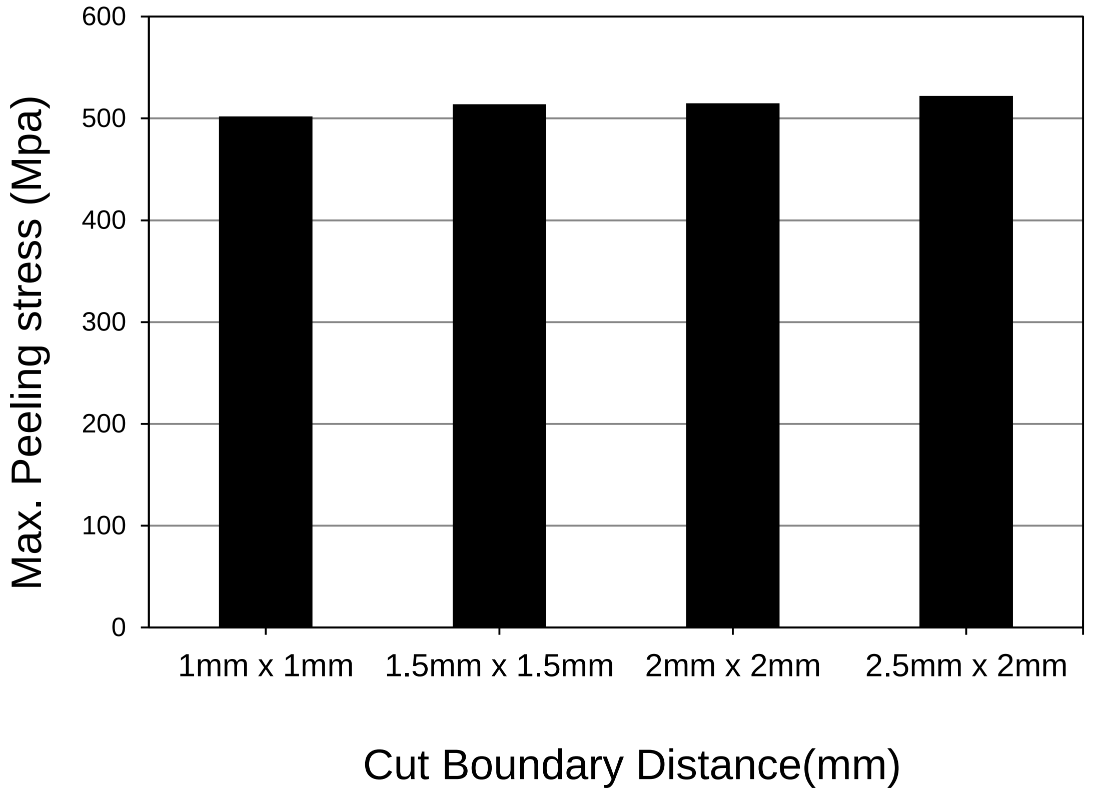
Schematic View of Cu Post WLP



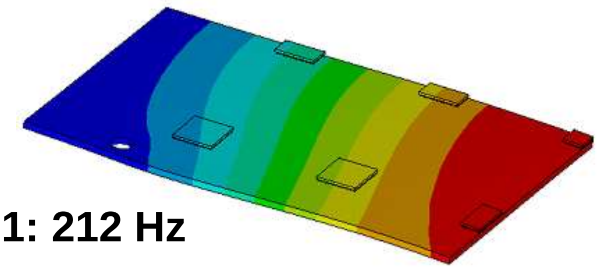
Part No.	Part Name
1	PCB
2	PCB Pad
3	Solder Ball
4	Copper Post
5	Epoxy
6	Passivation
7	Silicon Die

FE Model of Detailed Solder Ball

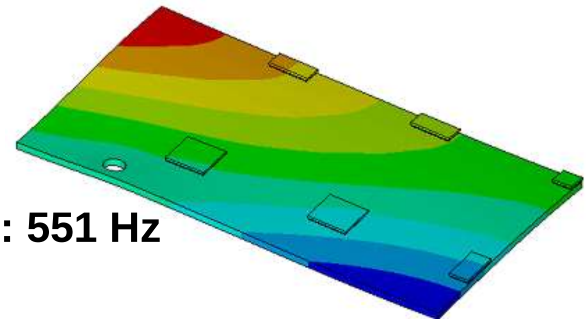
Effect of Cut Boundaries in Sub-modeling



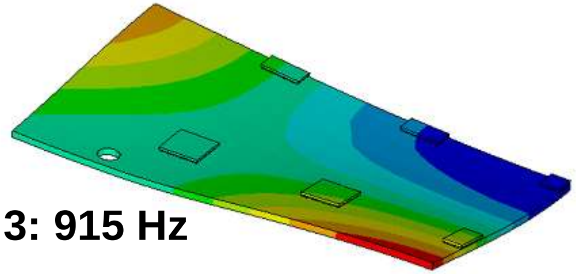
Global Model Results – Frequency and Mode Shape



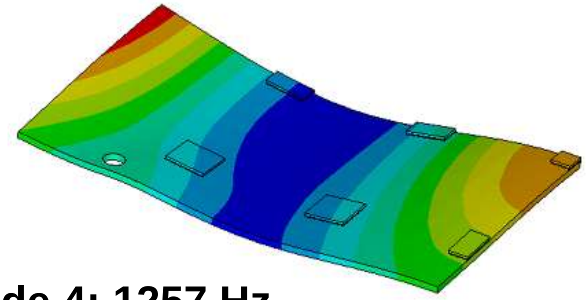
Mode 1: 212 Hz



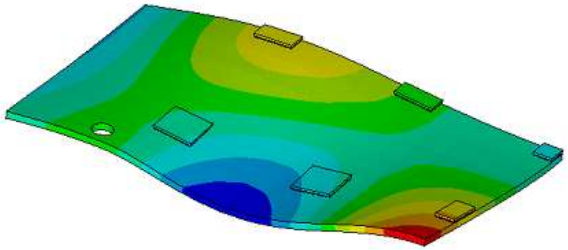
Mode 2: 551 Hz



Mode 3: 915 Hz

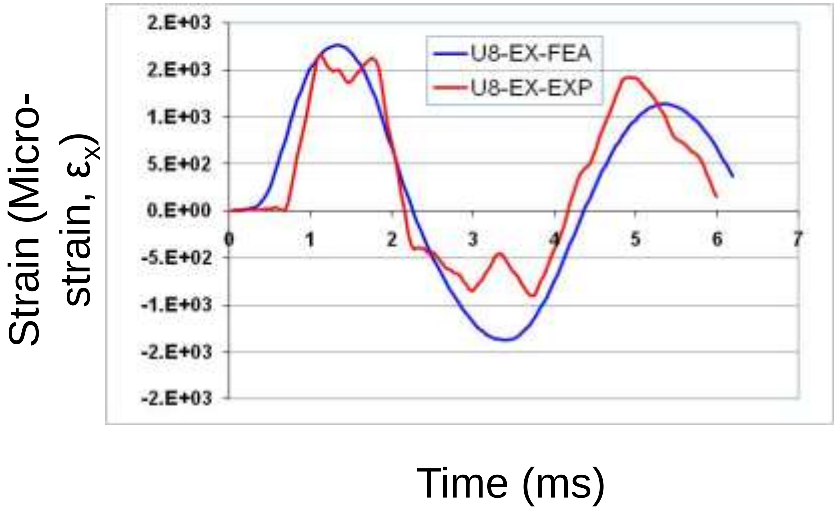


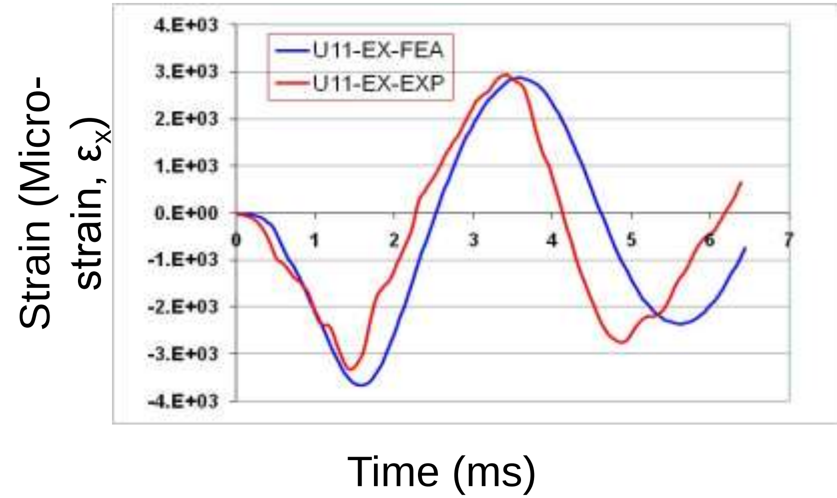
Mode 4: 1257 Hz

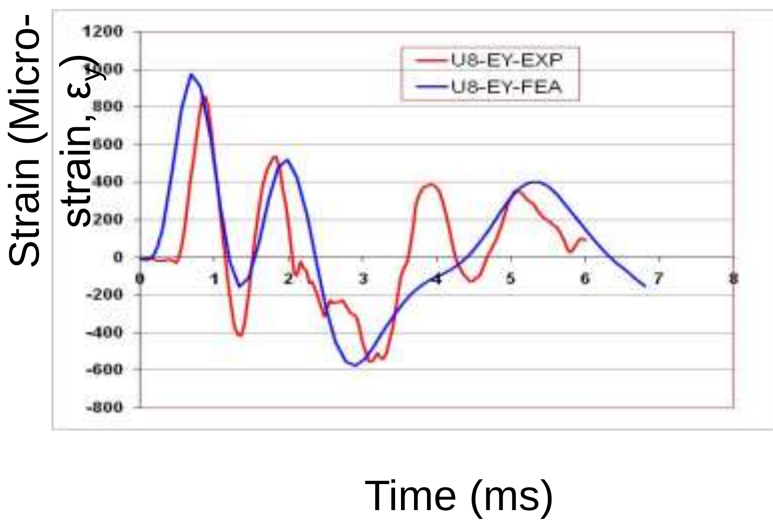


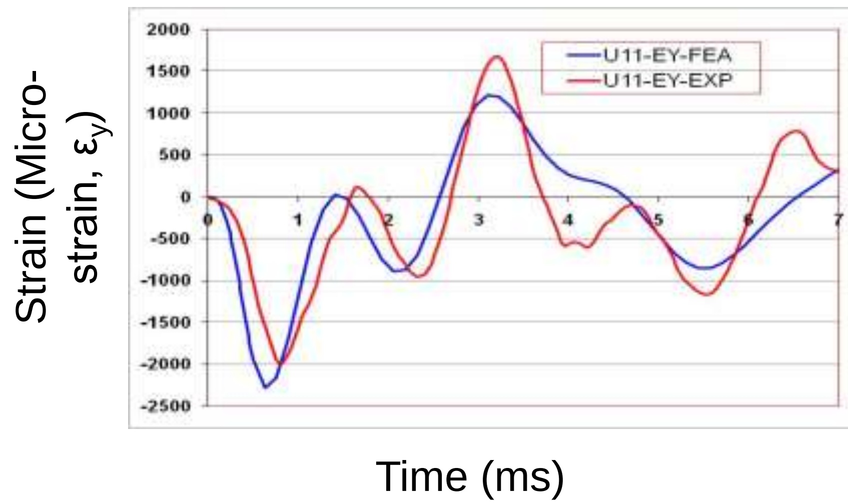
Mode 5: 2193 Hz

Experimental Validation

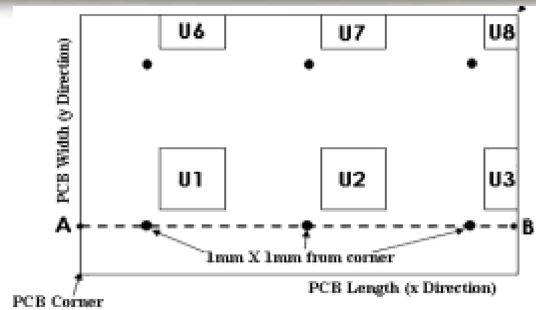


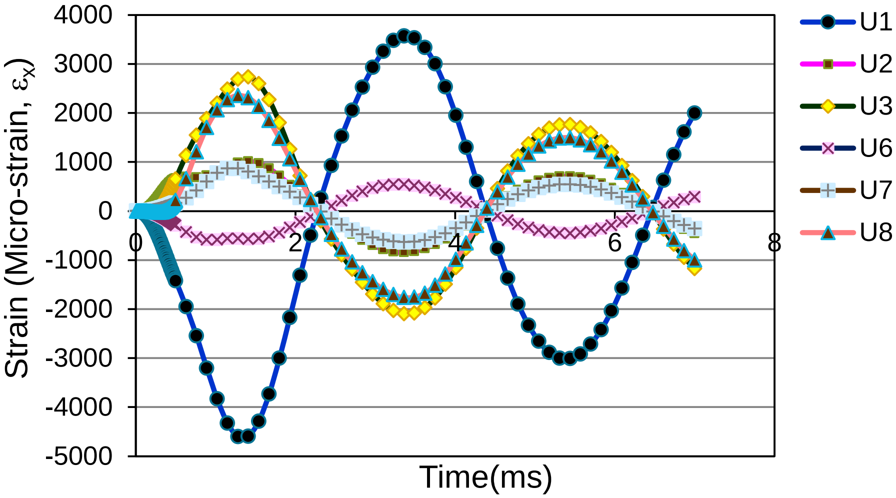




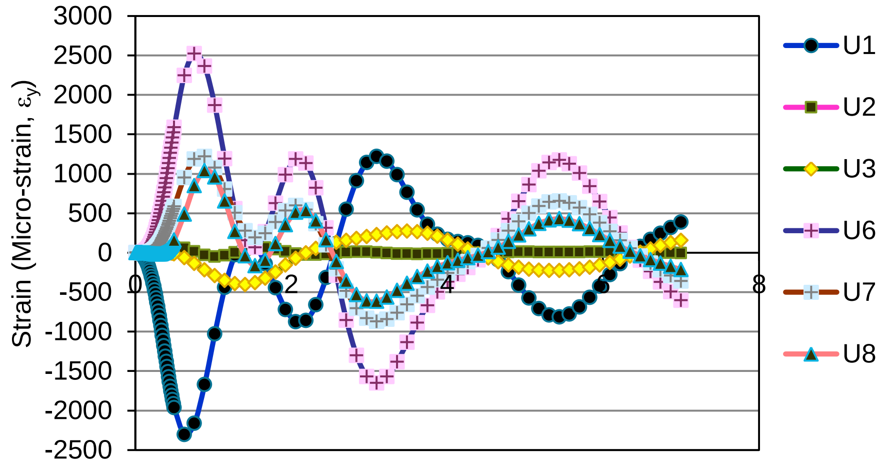


Board Strain Analysis: Package Corner Strain(ε_x)



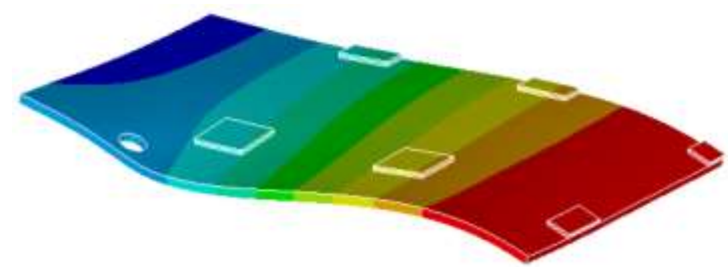


Strain History in x Direction

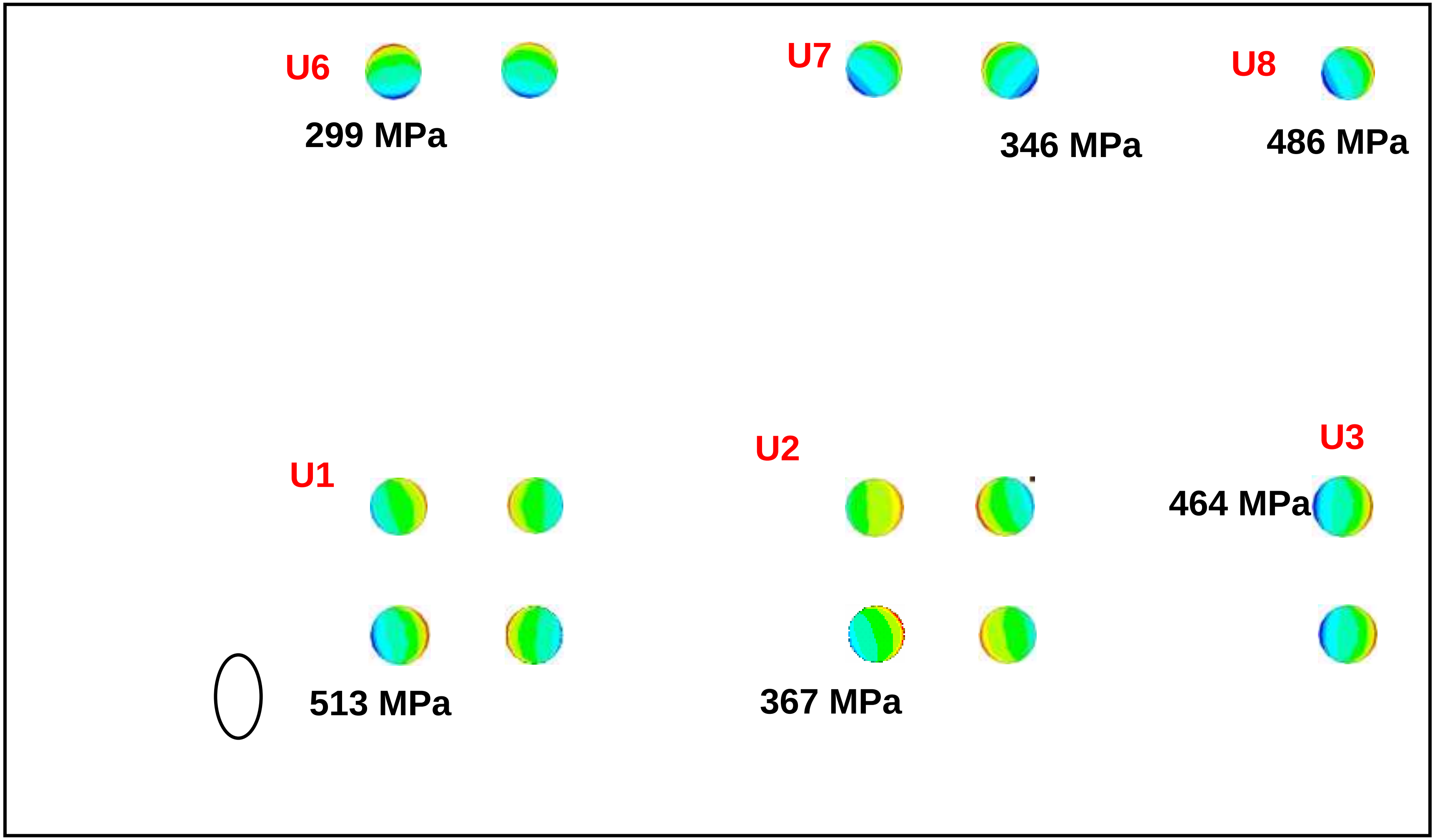


Strain History in y Direction

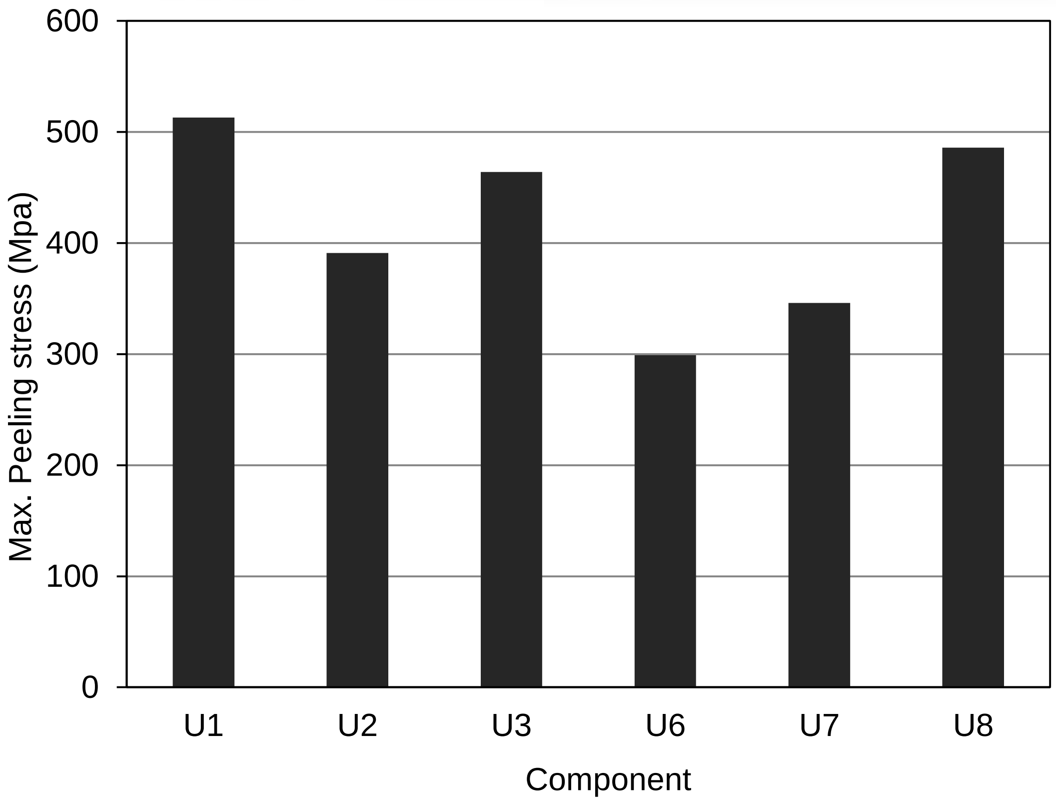
- **U1>U3>U8>U2>U7>U6.**
- **U8 bends in opposite direction to U1.**



Ball Stress Contour Plot on ¼th JEDEC Board

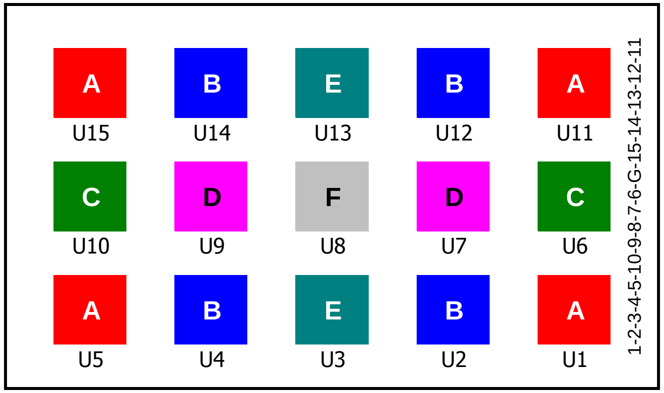


Maximum Peel Stress



Overall, the stress developed in components can be ranked as:

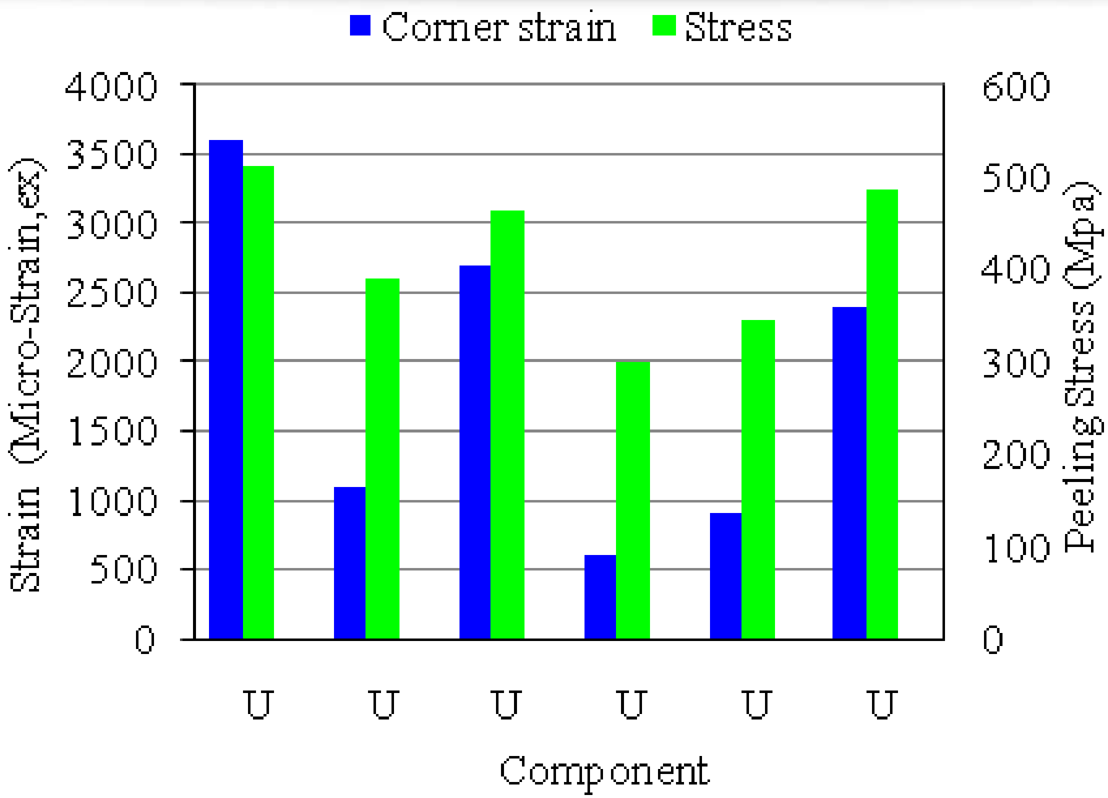
U1>U8>U3>U2>U7>U6



Failure rank:

- **Group A (U1, U5, U11 and U15)> Group F (U8) > Group E (U3, U13).**

Correlation of Solder Joint Stress and Board Strain



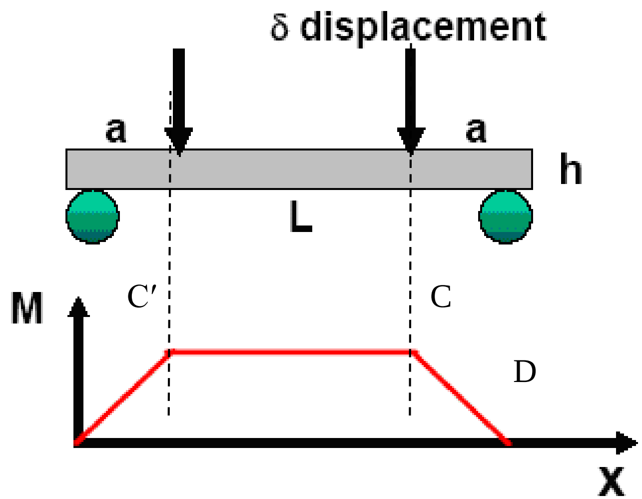
Board Strain Ranking: U1>U3>U8>U2>U7>U6

Solder Joint Stress Ranking:U1>U8>U3>U2>U7>U6

- **Exact correlation does not exist for strain and stress values.**

Fan XJ, Ranouta AS. Finite element modeling of system design and testing conditions for component solder ball reliability under impact. *IEEE Transactions on Components, Packaging and Manufacturing Technology*. 2(11), 1802-1810, 2012.

4-Point Bending Test



Segment CC’

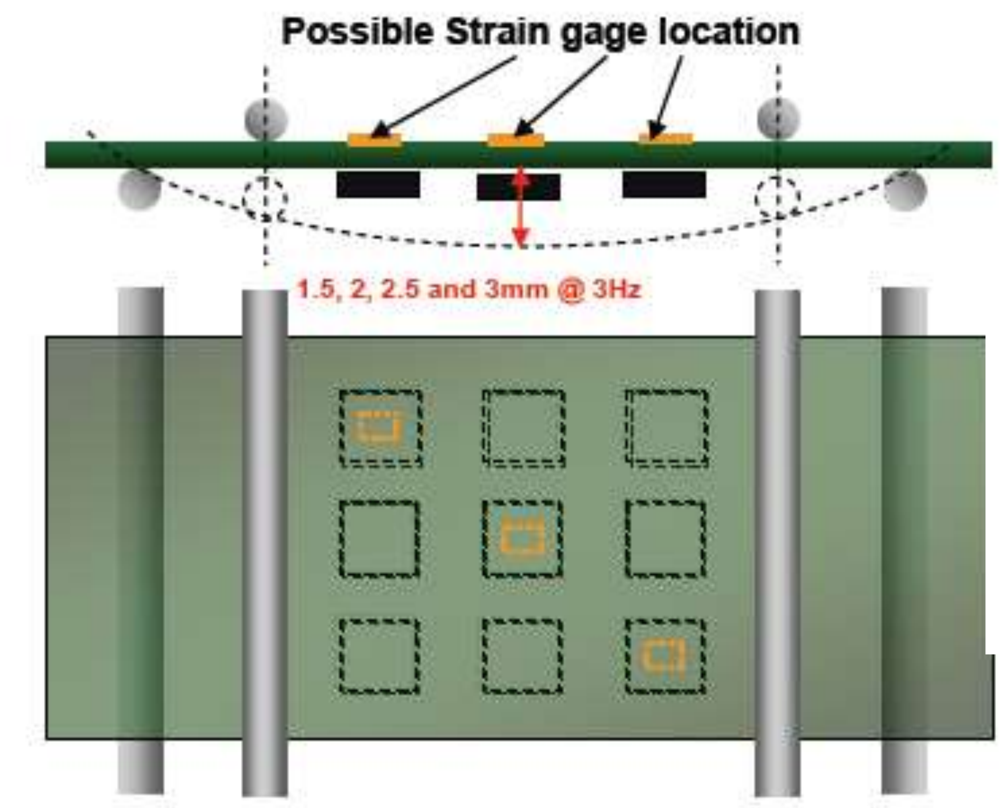
$$\varepsilon_x = \frac{3h\delta}{a(3L-4a)}$$

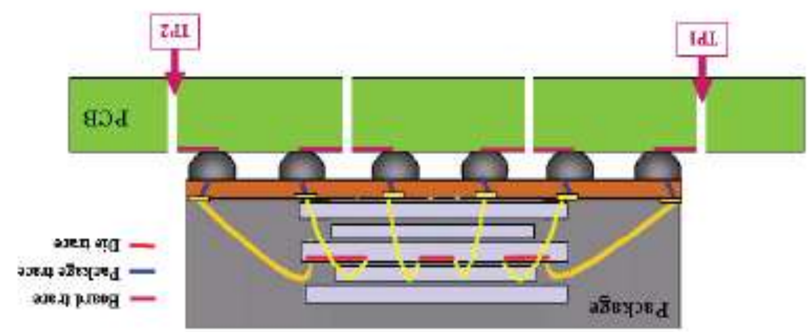
Segment CD

$$\varepsilon_x = \frac{12h\delta}{L^3}x$$

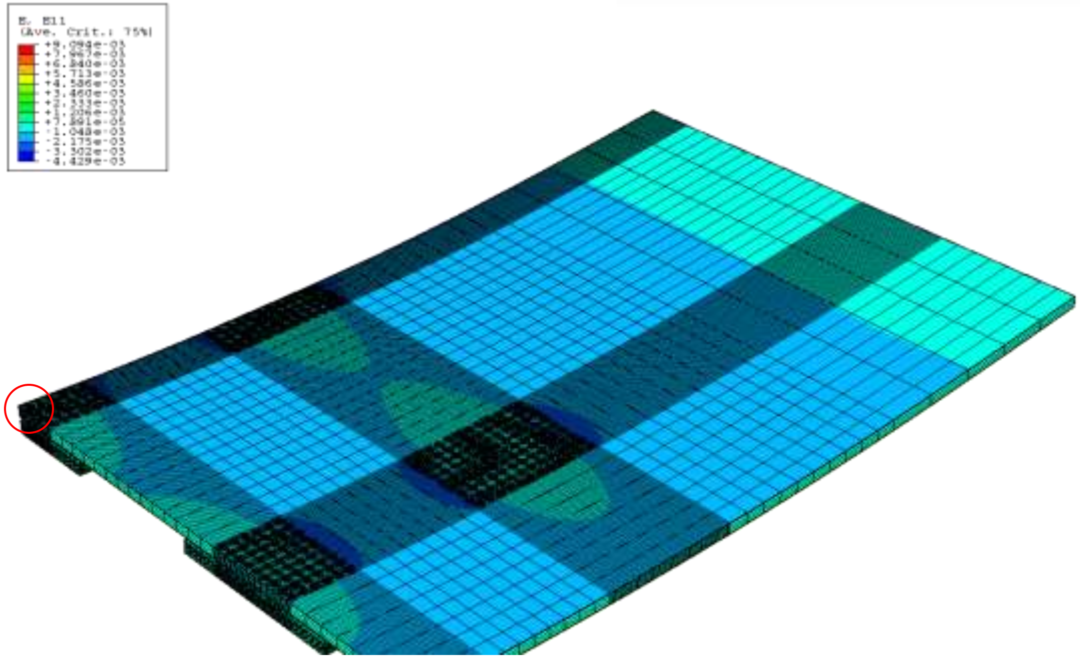
4-Point Bending Test

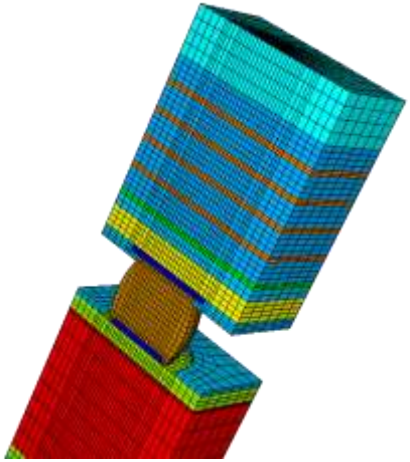
- 4PT bending test to take advantage of uniform strain BC for each component.
- JEDEC board + 9 components with electric monitoring for each one of them.
- Cyclic testing of freq 3Hz @ 1.5mm, 2mm and 2.5mm deflections to DC failure.





Cyclic Bending: Modeling Methodology

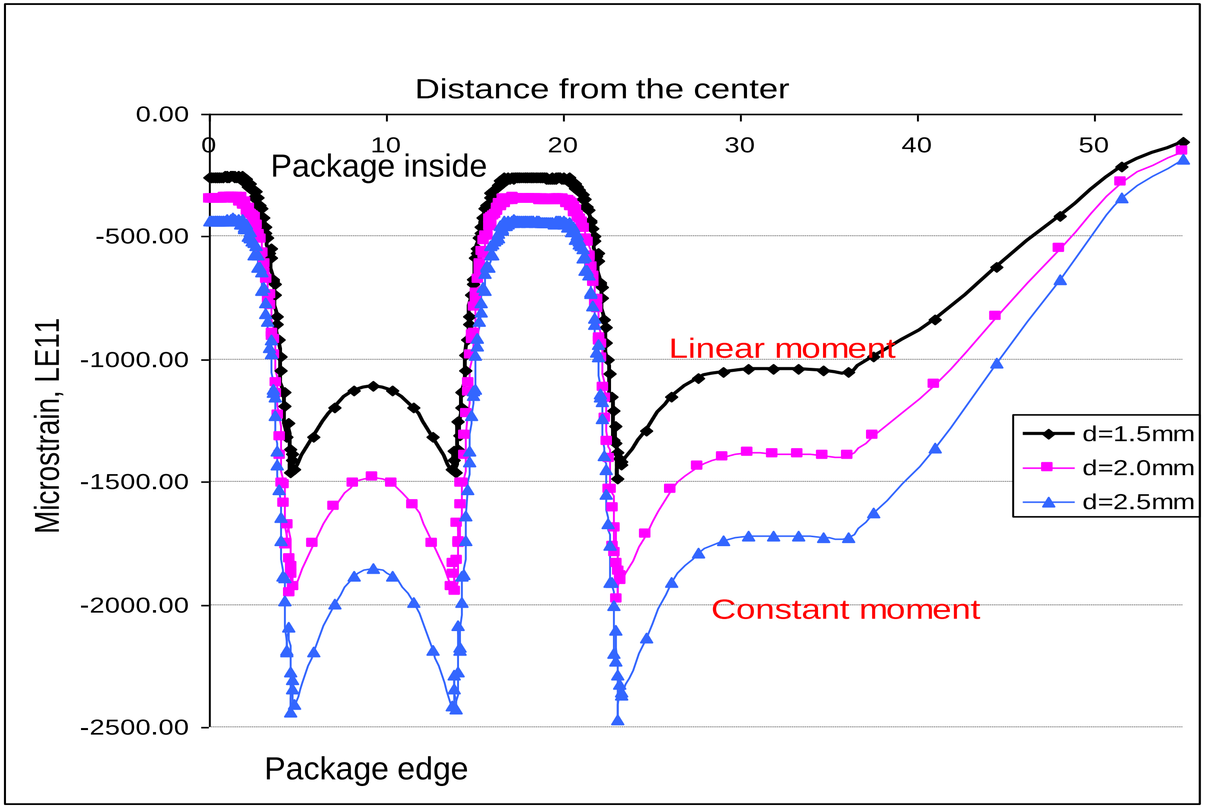




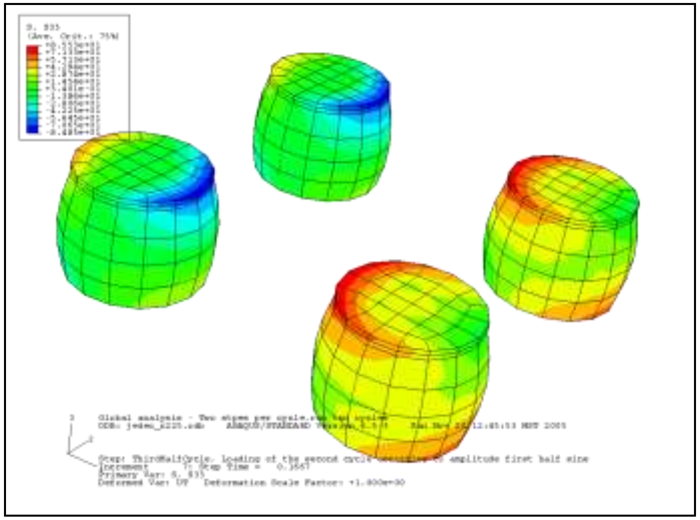
- Global/local modeling methodology
  - Elastic global model.
  - Local models use EPP SAC405 solder material properties.

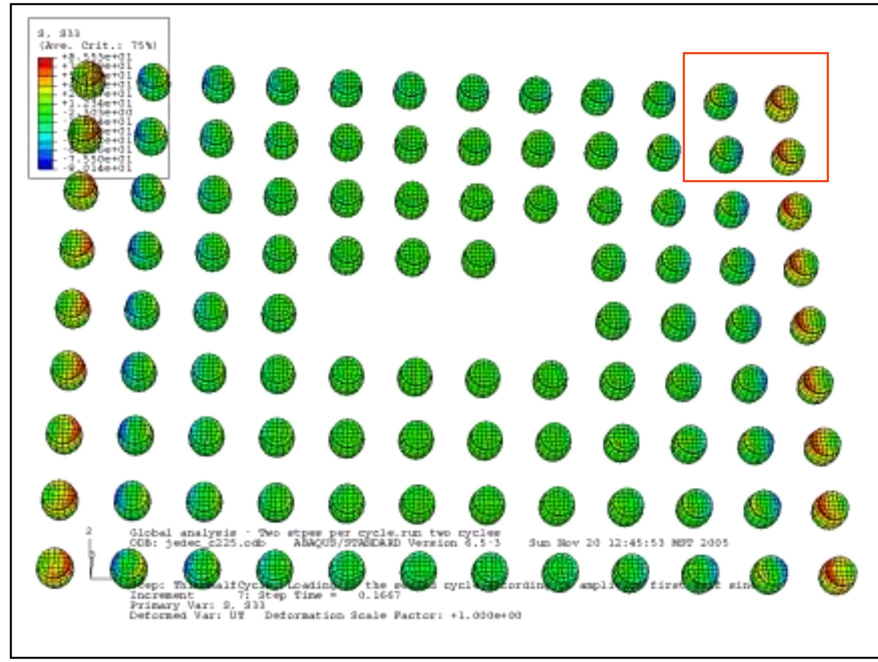
M Xie, Solder Reliability Models in 4 Point Bend, Intel, 2006.

Strain Distribution



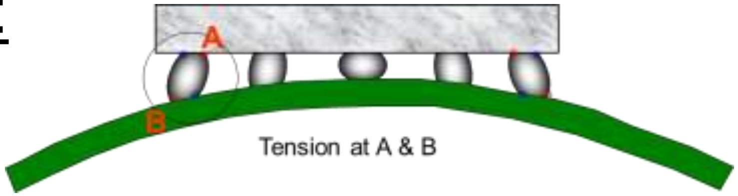
Board Side or Package Side?





- Consistency with failure propagation in terms of peeling stress
  - Package side: inside-out
  - Board side: outside-in
- Failure happens more likely at the package side: higher failure parameter value.

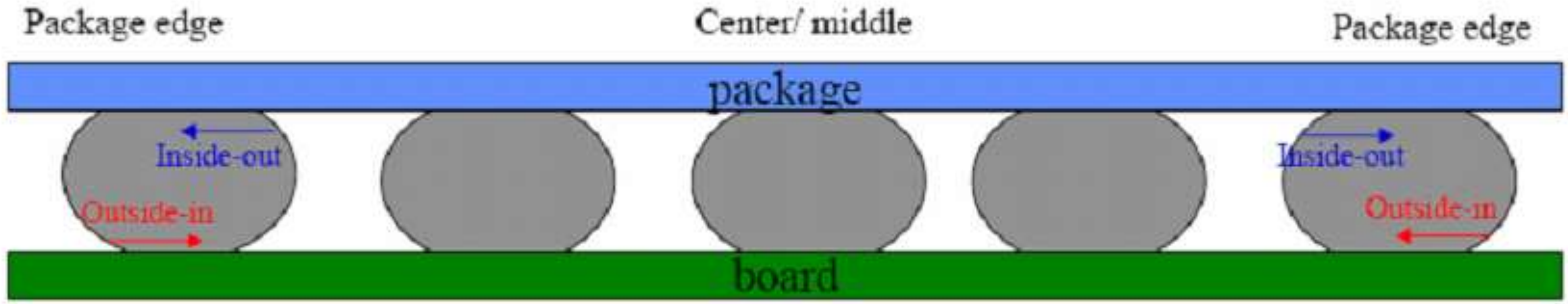
Failure Pattern



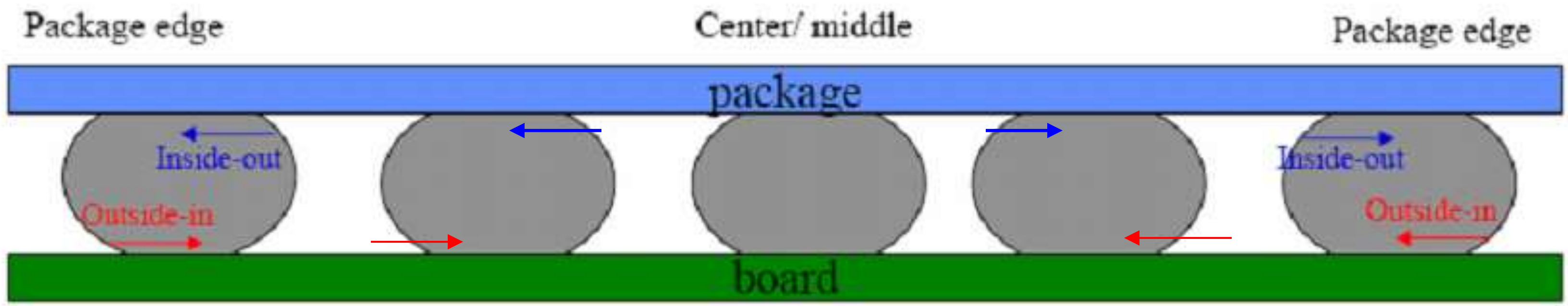
Solder joint crack propagation direction:

- Package side: inside-out
- Board side: outside-in

Sequential Failure (1.5mm deflection)



Simultaneous Failure (2.5mm deflection)



Zhou T and Fan XJ. Effect of system design and test conditions on wafer level package drop test reliability. SMTA International. October 2013.

Summary

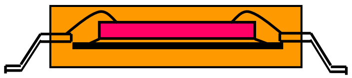
- **JEDEC drop test standard**
  - JESD22-B111, old one, with 15 components
  - JESD22-B111A, new one, with 4 components or 1 component
- **Finite element modeling**
  - Input G method, large mass method, input displacement method, direct acceleration method
  - Global/local modeling
  - Peel stress used as indicator for failure
- **Four-point bending test and modeling**
  - Global/local modeling
  - Global with linear elastic but nonlinear geometry analysis
  - Local model with elastic-plastic modeling

- Introduction
- Temperature Loading
- Mechanical Loading
- Moisture Loading
- Electrical Current Loading - Multi-Physics Modeling
- Summary

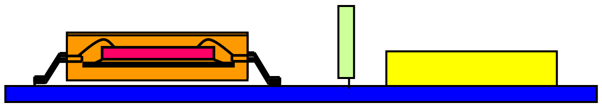
Outline

- **Introduction**
- **Moisture related reliability testing**
- **Moisture diffusion modeling**
- **Vapor pressure theory**
- **Hygroscopic swelling**

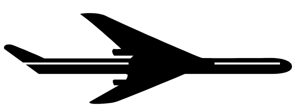
Moisture Absorption of Electronic Packages



Individual component



Surface mount to board



storage

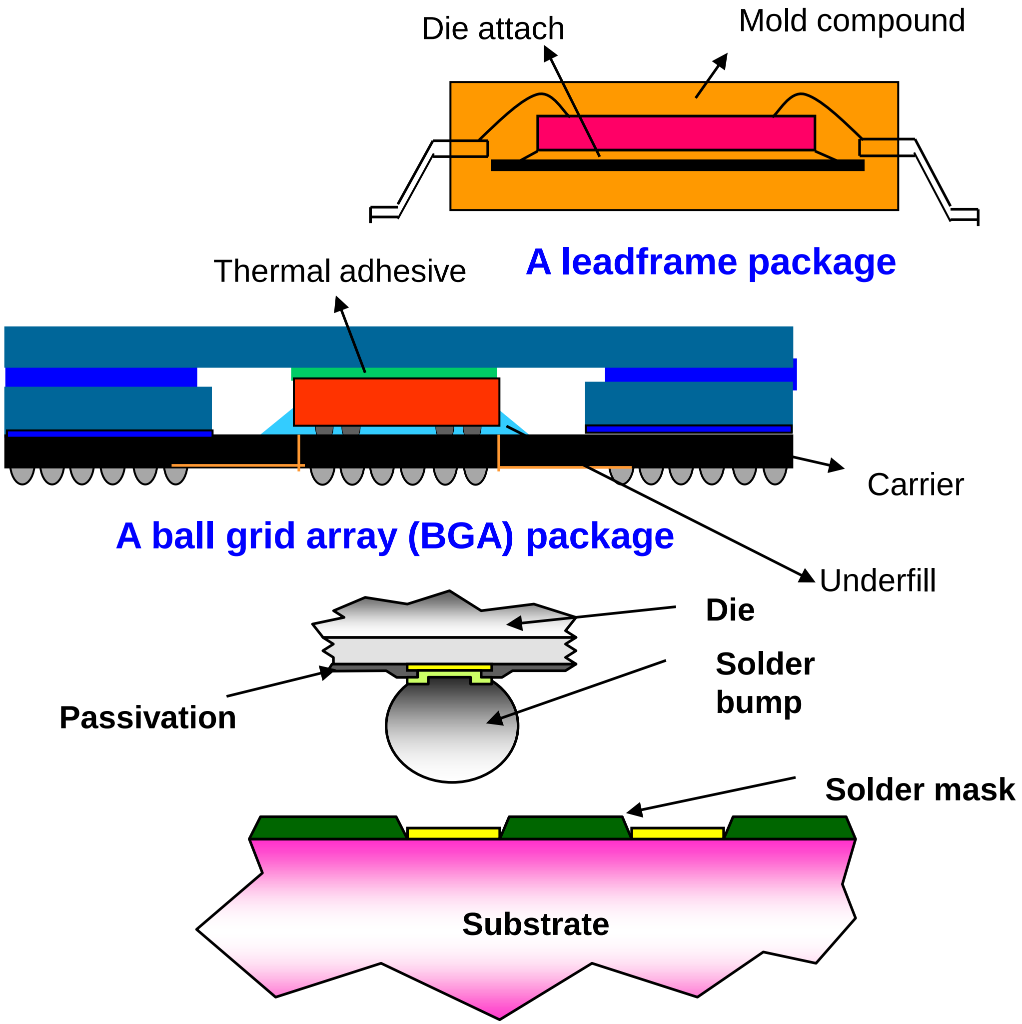
shipment

- Electronic packages absorb moisture in uncontrolled humid conditions prior to the surface mount on board.

Fan XJ, Suhir, E. (eds.). *Moisture Sensitivity of Plastic Packages of IC Devices*. Springer, New York, 2010.

Polymer Materials in Electronic Packaging

- Bulk-form
  - encapsulation (e.g. mold compound)
  - substrate …
- Adhesives
  - die-attach, underfill
  - thermal adhesives …
- Thick- or thin- film
  - solder mask
  - passivation

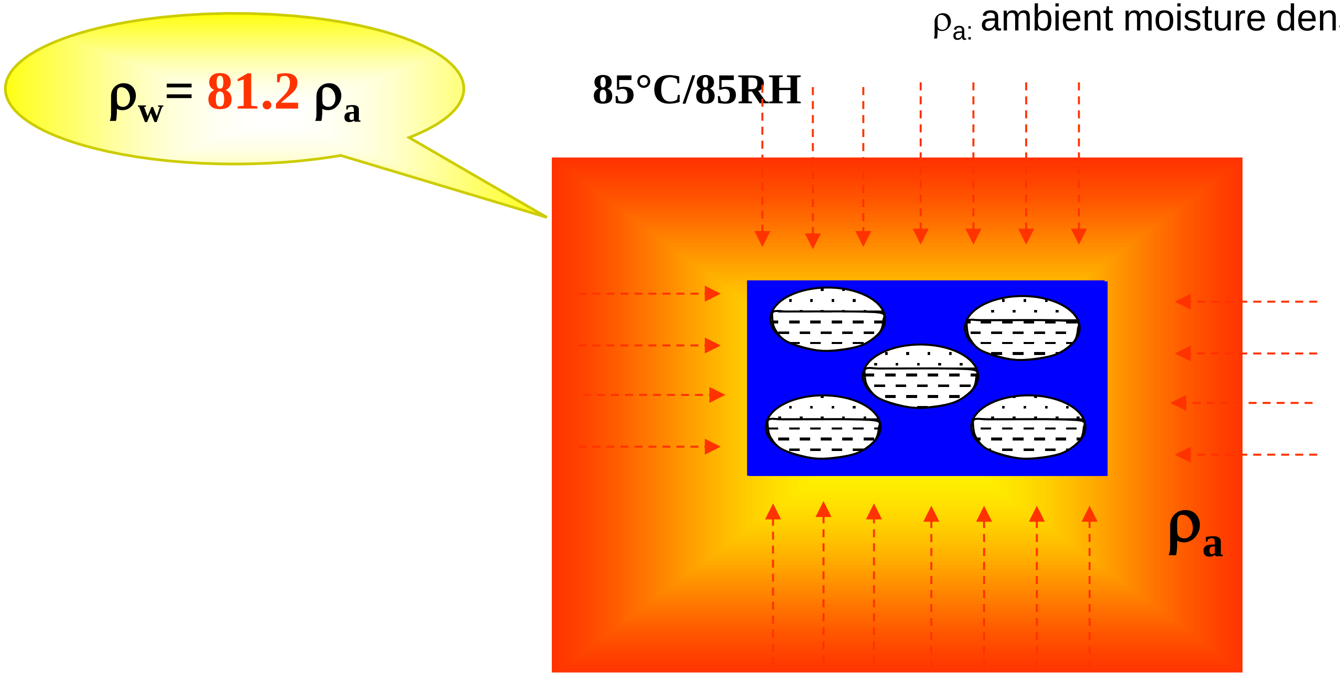


- **Polymeric materials are susceptible to moisture absorption.**

Moisture Absorption in Polymeric Materials

$\rho_{w:}$ moisture density in polymeric material

$\rho_{a:}$ ambient moisture density under 85°C/85%RH



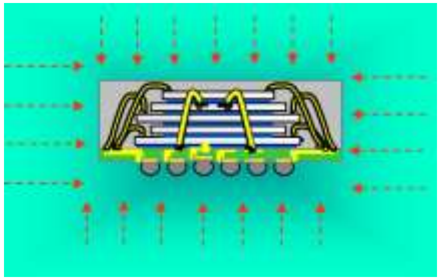
Moisture condensation in a typical underfill

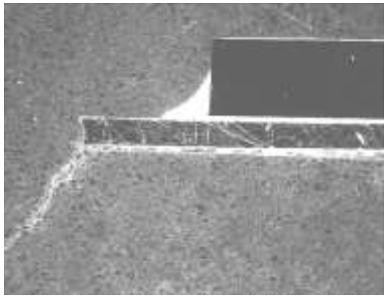
- **Under 85°C/85%RH condition, ρ_w= Csat = 2.47e-2 g/cm^3 = 81.2 ρ_a (Csat: saturated moisture concentration)**
  - Moisture is condensed into liquid state.
  - Moisture exists in micro-pores or free volumes (in bulk or at interface).
  - Moisture vaporizes at reflow, possibly still at mixed liquid/vapor phases.

Fan XJ, Lee SWR, Han Q. Experimental investigations and model study of moisture behaviors in polymeric materials. *Microelectronics Reliability* 49, 861–871. 2009.

Moisture Related Testing

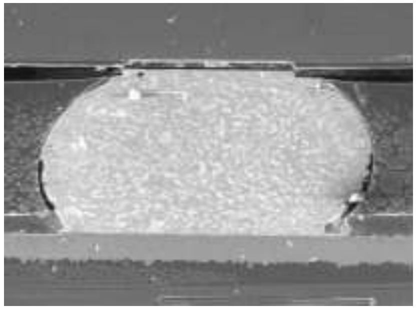
- Moisture sensitivity test



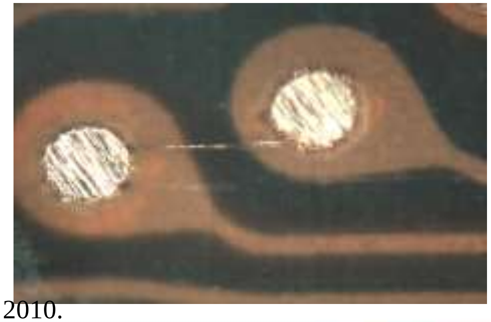


Stage 1: Moisture absorption **Stage 2: Soldering reflow**

- Highly accelerated stress test (HAST)



- Biased HAST



Fan XJ, Suhir, E. (eds.). *Moisture Sensitivity of Plastic Packages of IC Devices*. Springer, New York, 2010.

Basic Concepts of Moisture Diffusion

- What is the Relative Humidity (RH)?
  - Defined as vapor pressure ratio associated with temperature T

$$RH = \frac{Actual\ \ vapor\ pressure of\ the\ air}{Saturated\ \ vapor\ pressure of\ the\ air} \times 100\%$$

- Moisture concentration, C (x, t; T, RH)
  - Mass of moisture per unit volume of substance.
- Diffusion Coefficient / Diffusivity, D(T)
  - Measures the rate of mass diffusion
  - Defined as the amount of mass flux per unit concentration gradient (m^2/s)
  - A function of material and temperature
- Saturated Moisture Concentration, C_{sat}(RH, T)
  - The maximum mass of moisture per unit volume of the substance kg/m^3.
- Solubility, S(T) – Henry's law
  - The ability of the substance to absorb moisture
  - Defined as the maximum mass of moisture per unit volume of the substance per unit pressure ($kg/(m^3Pa)$).
  - A function of material and temperature

$$S = \frac{C_{sat}}{P}$$

where P = **ambient** pressure in given RH

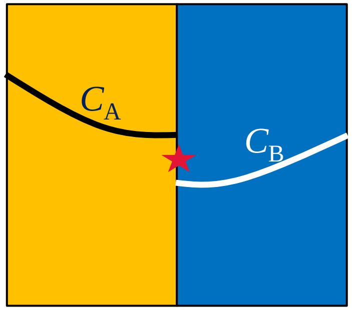
Moisture Diffusion Modeling

- **Fickian diffusion theory**

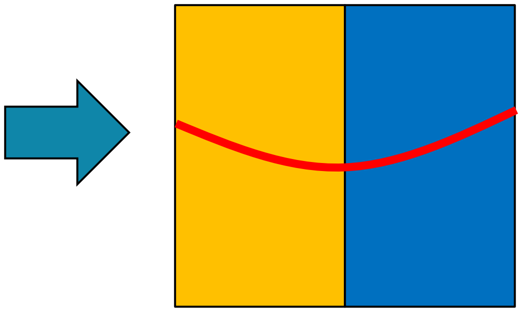
$$\frac{\partial C}{\partial t} = -\nabla \cdot \left(-D_0 \nabla C\right)$$

$\boldsymbol{C}$**:** Concentration, kg/m^3; $\boldsymbol{D_0}$**:** diffusivity, m^2/s

- **Discontinuity at interface**



Concentration discontinuity



After normalization

An Overview of Moisture Diffusion Modeling

	Normalized field variable	C_{sat}: temperature-dependent	RH: time-dependent	Non-Henry's law	ANSYS	ABAQUS
Galloway et al. (1997)	C/S	✓	✓	✗	✗	✓
Wong et al. (1998)	C/C_{sat}	✗	✗	✗	✓	✗
Jang et al. (1993)	C/M	✗	✓	✗	✗	✗
Wong et al. (2016)	C/C_{sat}	✓	✓	✗	✗	✗
Markus et al. (2016)	C	✓	✓	✗	✗	✗
Chen et al. (2017)	a_w	✓	✓	✓	✓	✓
Ma et al. (2019)	C/K	✓	✓	✗	✓	✓

Ma L, Joshi R, Newman K, X.J. Fan, Improved Finite Element Modeling of Moisture Diffusion Considering Discontinuity at Material Interfaces in Electronic Packages, ECTC 2019

Water Activity Theory

- Water activity a_w is a continuous field variable derived from chemical potential.
- Moisture flux in terms of water activity gradient.

$$\mathbf{J}_{\mathrm{m}} = -K_i D_{0,i} \nabla a_w$$

- Moisture concentration is given as

$$C = K\, a_w$$

K: generalized solubility, kg/m^3

- Moisture diffusion equation

$$\frac{\partial (K_i a_w)}{\partial t} = \nabla \cdot \left(K_i D_{0,i} \nabla a_w\right)$$

- Water activity is continuous and no normalization is required for multi-material system.

Chen LB, Zhou J, Chu HW, Zhang GQ, Fan XJ. Modeling Nonlinear Moisture Diffusion in Inhomogeneous Media. *Microelectronics Reliability. 75 (2017) 162–170.* 2017.

Current Moisture Diffusion Theory in ANSYS

- $\bar{C} = \frac{C}{C_{\text{sat}}}$ is used as field variable.

$$\frac{\partial (C_{sat}\bar{C})}{\partial t} = \nabla \cdot \left(D\nabla (C_{sat}\bar{C})\right) + G$$

$$C_{sat}\frac{\partial \bar{C}}{\partial t} + \bar{C}\frac{\partial C_{sat}}{\partial T}\frac{\partial T}{\partial t} = \nabla \cdot \left([D]C_{sat}\nabla \bar{C} + \bar{C}\frac{\partial C_{sat}}{\partial T}\nabla T\right) + G$$

where

- D : diffusivity matrix
- C (x,y,z,t) : concentration
- G: diffusing substance generation rate per unit volume
- ∇: gradient operator= $\left\{\frac{\partial}{\partial_x}\frac{\partial}{\partial_y}\frac{\partial}{\partial_z}\right\}$, $\nabla \cdot$: divergence operator

- **In the above formulation, C_{sat} is considered as temperature-dependent only.**
- **However, C_{sat} is both time- and temperature- dependent in general.**

Henry's Law in Moisture Diffusion

- $C_{\mathrm{sat}} = p_{\mathrm{amb}} S$

$$E_p = 4.01 \times 10^4 \left(\frac{J}{mol}\right) = 0.415\ (ev)$$

$$p_0 = 3.82 \times 10^{10} (Pa).$$

p_{amb}: ambient partial vapor pressure $p_{\mathrm{amb}} = RH\ p_g(T) = RH\ p_0 e^{\left(-\frac{E_p}{RT}\right)}$ (p_g is saturated vapor pressure)

S : solubility $S(T) = S_0\, e^{\left(\frac{E_s}{RT}\right)}$

$$C_{sat} = RH\ p_0 S_0\ e^{\left(\frac{E_s - E_p}{RT}\right)} = RH\ K_0 e^{\left(\frac{-E_k}{RT}\right)} = RH(t)K(T)$$

$$K = K(T) = K_0 \exp\left(-\frac{E_k}{RT}\right)$$

$$K_0 = p_0 S_0, \qquad E_k = E_p - E_s$$

- In general, C_{sat} (RH (t), T(t)) is both time- and temperature-dependent.
- Therefore, ANSYS cannot solve the problem with varying RH as function of time.

New Normalization Theory - $\bar{C}_K$ Approach

- $\bar{C}_K = \frac{C}{K}$ is used as field variable.
- $K(T)$: generalized solubility (kg/m^3)

$$\frac{\partial(K\bar{C}_k)}{\partial t} = \nabla \cdot \left(D\nabla(K\bar{C}_k)\right)$$

$$\Rightarrow k\frac{\partial\bar{C}_k}{\partial t} + \bar{C}_k\frac{\partial K}{\partial T}\frac{\partial T}{\partial t} = \nabla \cdot \left([D]K\nabla\bar{C}_k + \bar{C}_k\frac{\partial K}{\partial T}\nabla T\right)$$

- The governing equation is exactly identical to the diffusion equation in ANSYS.
- $\bar{C}_K$ turns out to be the water activity a_w (Chen et al.), which has been proved to be continuous at interface.

Analogy using ANSYS

- Field variable and material property input

Field Variable	Material Property
$\bar{C}$	C_{sat}
$\bar{C}_k$	K

$$K = \frac{C_{sat}}{RH}$$

- Boundary condition

	$\bar{C}$	$\bar{C}_k$
Absorption	1	RH
Desorption	0	0

$$\frac{C_{sat}}{K} = RH(t)$$

- Initial condition

	$\bar{C}$	$\bar{C}_k$
Absorption	0	0
Desorption	1 (if fully saturated initially)	1 (if fully saturated initially)

- In using ANSYS,
  - $\bar{C}$ is replaced by $\bar{C}_K$.
  - Temperature-dependent material property C_{sat} is replaced by general solubility K.
  - Boundary condition is now changed to $\bar{C}_K$= RH.

Element Options in ANSYS

- **Two different types of element option**
  - **Diffusion element**
    - Plane 238 (2D, Quadratic)
    - Solid 239 (3D, Quadratic)
      - Degree of Freedom (DOF) label; CONC
  - **Coupled element**
    - Plane 223(2D , Quadratic)
    - Solid 226(3D , Quadratic)
      - Thermal-diffusion (100010)
        - DOF label: TEMP,CONC
      - Thermal-structural-diffusion (100011)
        - DOF label: TEMP, UX, UY, UZ , CONC
      - Structural-diffusion (100001)
        - DOF label: UX,UY,UZ, CONC

- Since the general diffusion equation in ANSYS involves with temperature derivative with respect to time when *K* is temperature-dependent, the coupled element (thermal diffusion, or thermal-structural-diffusion) must be used.

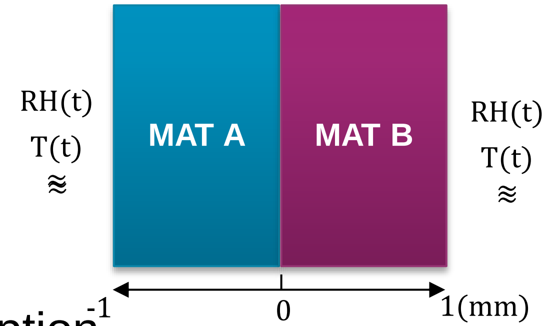
Case Study – Varying RH and Temperature

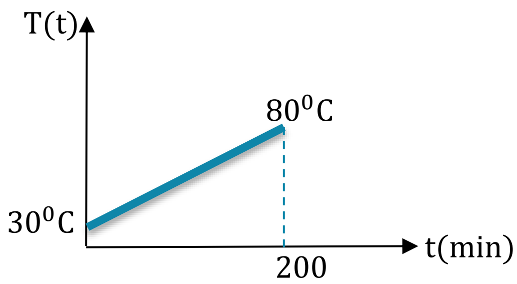
- A 1-D bi-material absorption problem with varying RH and Temperature
  - Initial condition: dry at 30^0C
  - Ambient temperature profile is given below to simulate a absorption process

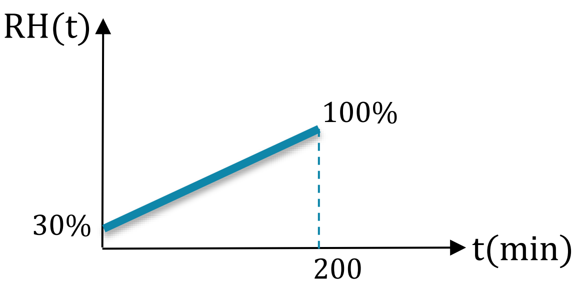
$$T(t)\ [^0C] = 30 + \frac{50t}{200} \qquad 0 < t \le 200\ (\text{min})$$

  - Relative humidity profile is given below to simulate a absorption process

$$RH(t) = 0.3 + \frac{0.7t}{200} \qquad 0 < t \le 200\ (\text{min})$$







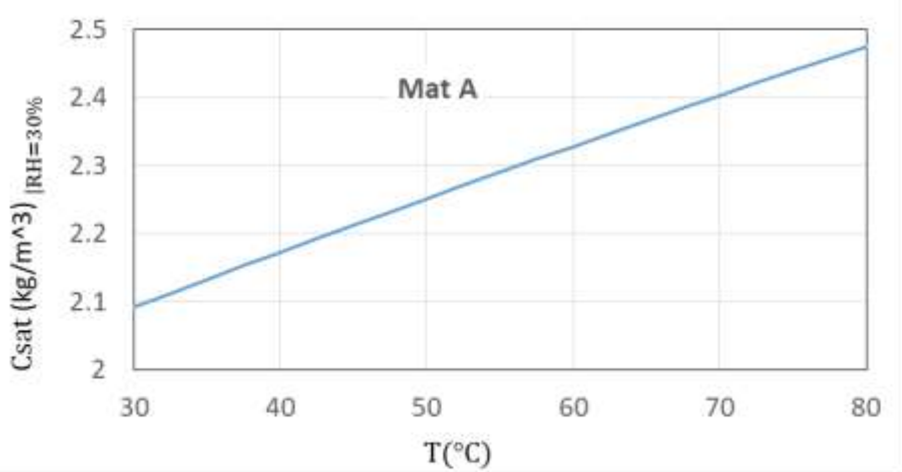
- Material properties

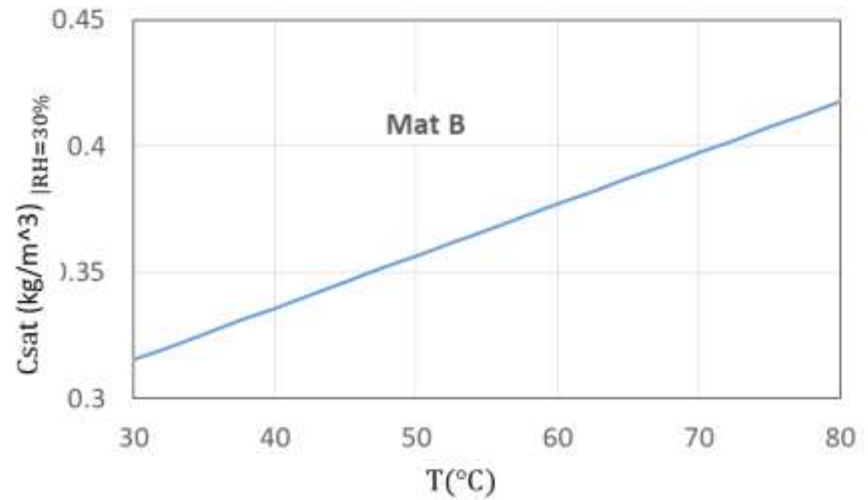
Properties	Mat A	Mat B
$D_0(m^2/s)$	5.0×10^{-3}	4.0×10^{-3}
$E_D(ev)$	0.518	0.518
$S_0(Kg/m/Pa)$	6.0×10^{-10}	2.0×10^{-10}
$E_s(ev)$	0.383	0.362

- For this problem, C_{sat} is both time and temperature-dependent.

C_{sat} as a Function of Temperature

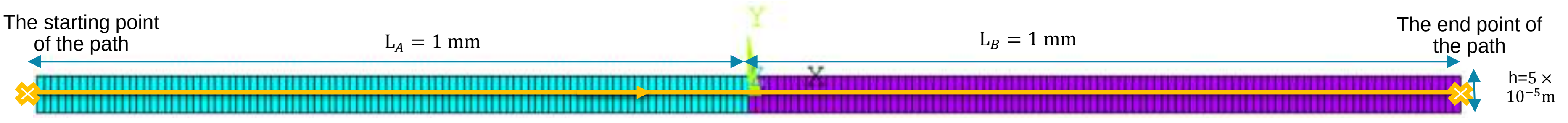
- For the given material properties (C_{sat} at $30\%RH$)

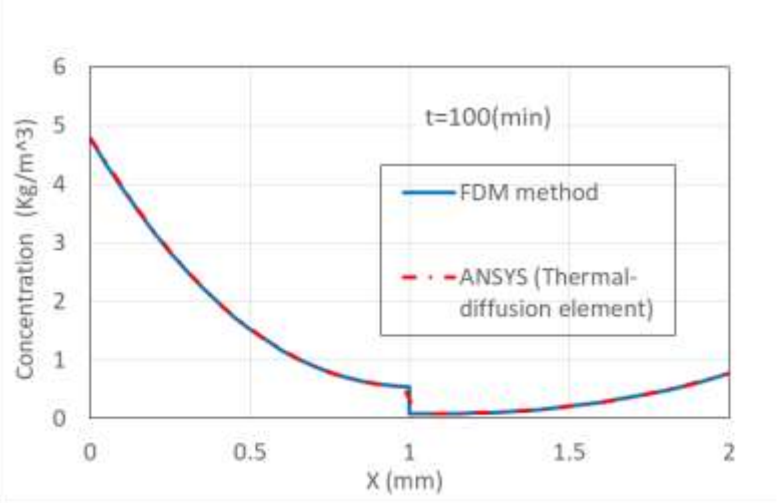


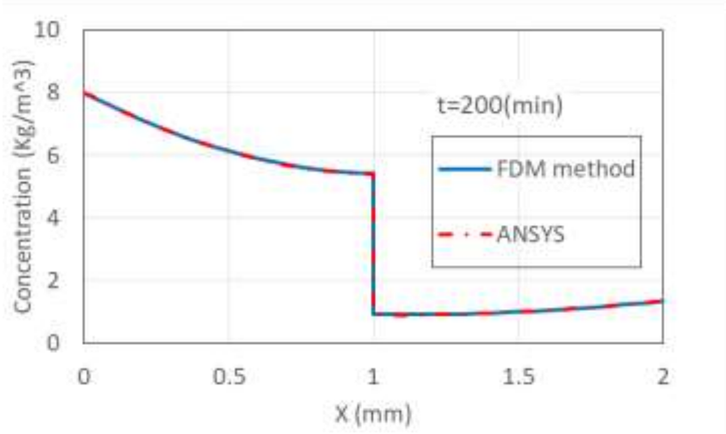


Finite Element Model and Results

- 1-D problem is constructed by a 2-D element strip model.
- Finite difference method (FDM) is used for verification.

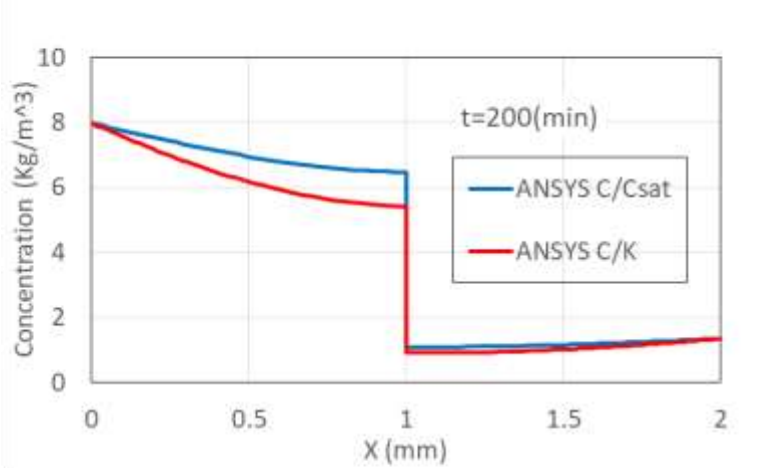






- **Coupled thermal-diffusion element presents correct results.**

$\bar{C}$ vs. $\bar{C}_k$ Approach



- $\bar{C}$ (coupled element with thermal-diffusion)

$$C_{sat}\frac{\partial\bar{C}}{\partial t}+\bar{C}\frac{\partial C_{sat}}{\partial T}\frac{\partial T}{\partial t}+\bar{C}\frac{\partial C_{sat}}{\partial t}=\nabla.\left([D]C_{sat}\nabla\bar{C}+\bar{C}\frac{\partial C_{sat}}{\partial T}\nabla T\right)$$

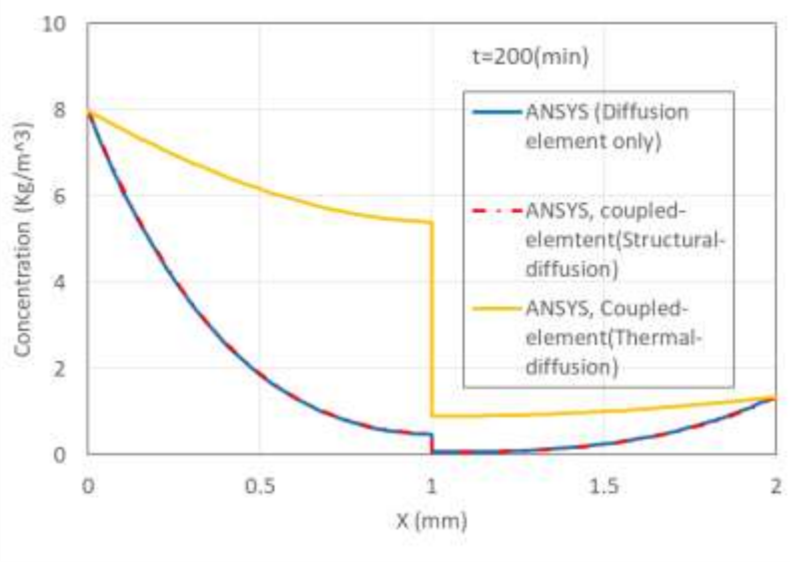
Not included in ANSYS

- $\bar{C}_k$ (coupled element with thermal-diffusion)

$$K\frac{\partial\bar{C}_k}{\partial t}+\bar{C}_k\frac{\partial K}{\partial T}\frac{\partial T}{\partial t}=\nabla\cdot\left([D]K\nabla\bar{C}_k+\bar{C}_k\frac{\partial K}{\partial T}\nabla T\right)$$

- Since C_{sat} is temperature-dependent and time-dependent, the results obtained by $\bar{C}$ are incorrect.

Comparison Among Different Elements in ANSYS



- Diffusion element only

$$K\frac{\partial \bar{C}_k}{\partial t} = \nabla \cdot ([D]K\nabla \bar{C}_k)$$

- Coupled element with structural-diffusion

$$K\frac{\partial \bar{C}_k}{\partial t} = \nabla \cdot ([D]K\nabla \bar{C}_k)$$

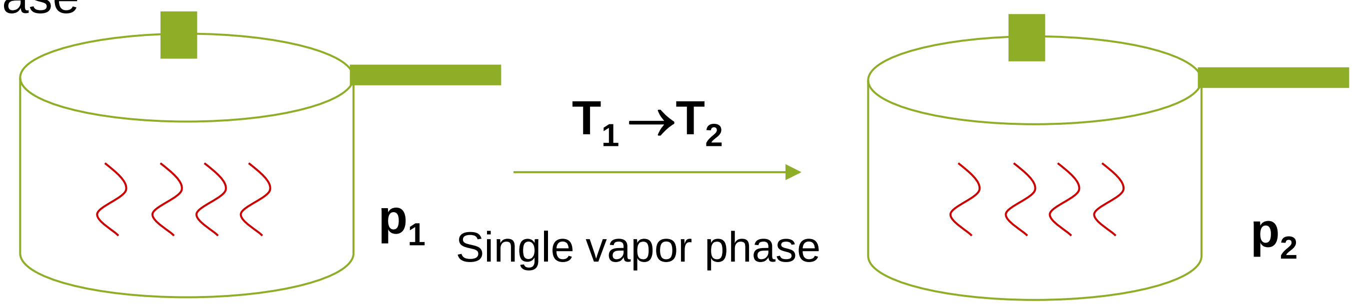
- Coupled element with thermal-diffusion

$$K\frac{\partial \bar{C}_k}{\partial t} + \bar{C}_k\frac{\partial K}{\partial T}\frac{\partial T}{\partial t} = \nabla \cdot \left([D]K\nabla \bar{C}_k + \bar{C}_k\frac{\partial K}{\partial T}\nabla T\right)$$

- The Diffusion element only and the coupled element with structural-diffusion option present the same incorrect results.

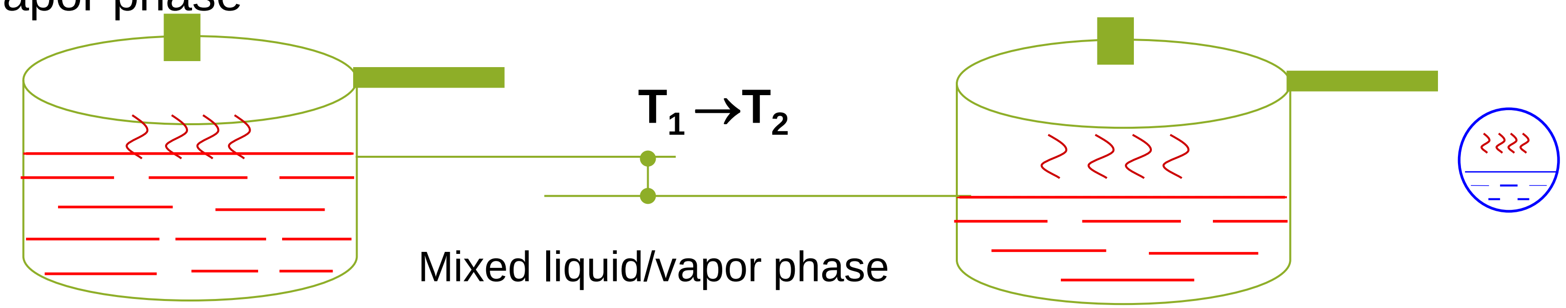
Vapor Pressure Model - Example: Pressure Cooker

- Vapor phase



  - Moisture in single vapor phase;
  - $\rho < \rho_g(T)$, **ρ: moisture density over the total volume of cooker**; $\rho_g(T)$: saturated moisture vapor density.
  - **Ideal gas law can be used: $p_2 = p_1 T_2 / T_1$**

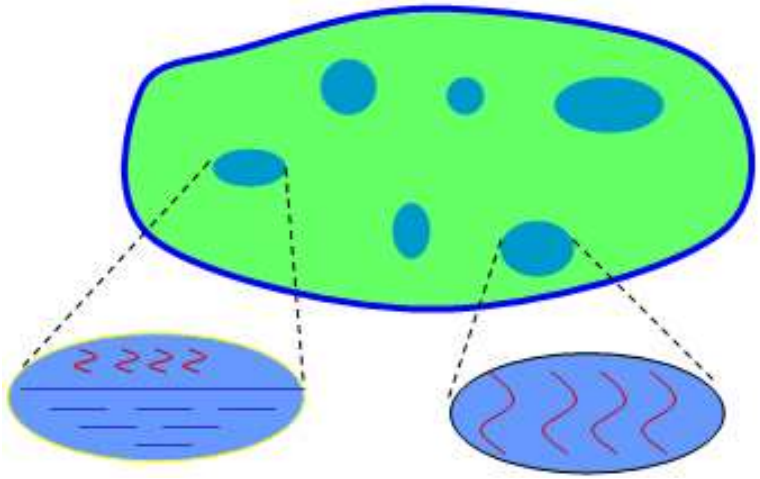
- Liquid/vapor phase



  - Moisture in two-phases – water/vapor mixed;
  - $\rho > \rho_g(T)$ - liquid-vapor phase , **ρ: moisture density over the total volume of cooker**; $\rho_g(T)$: saturated moisture vapor density
  - Saturated vapor pressure remains regardless of water level

Vapor Pressure Model

- Moisture in free-volumes 'free' to vaporize
- Two distinct states
  - Single vapor phase
  - Mixed liquid/vapor phase
- Saturated moisture density $\rho_g(T)$

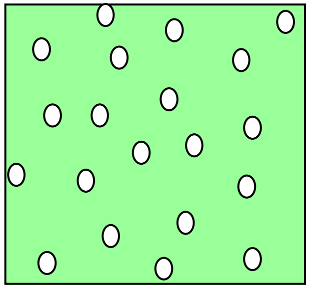


Mixed liquid/vapor phase **Single vapor phase**

Vapor Pressure Model

$$\rho = \frac{\mathrm{d}m}{\mathrm{d}V_f} = \frac{\mathrm{d}m}{\mathrm{d}V}\frac{\mathrm{d}V}{\mathrm{d}V_f} = C / f$$

dV_f : void volume in a REV (representative elementary volume)
dV : total volume of a REV
dm : total moisture mass
f : void volume fraction dV_f/dV
ρ : apaprent moisture density



REV

$$p(T) = \frac{RT}{MM_{H_2O} f} \cdot C \qquad \text{when } C(T)/f < \rho_g(T)$$

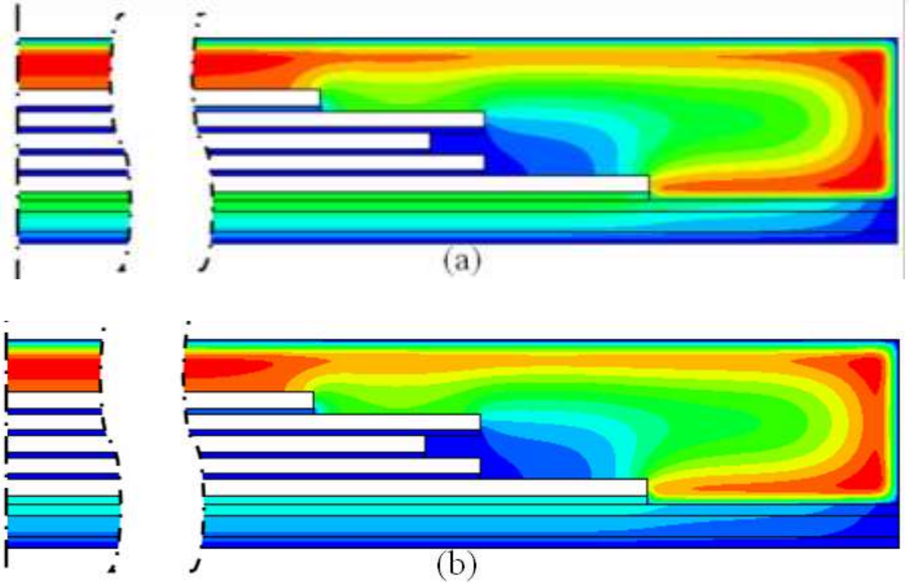
$$p(T) = p_g(T), \qquad \text{when } C(T)/f \geq \rho_g(T)$$

Fan XJ, Zhou J, Zhang GQ, Ernst LJ. A micromechanics based vapor pressure model in electronic packages. *ASME Journal of Electronic Packaging* 127 (3), 262-267. 2005.
Xie B, Fan XJ, Shi XQ, Ding H. Direct concentration approach of moisture diffusion and whole field vapor pressure modeling for reflow process: part I – theory and numerical implementation. ASME Journal of Electronic Packaging 131(3), 031010. 2009.

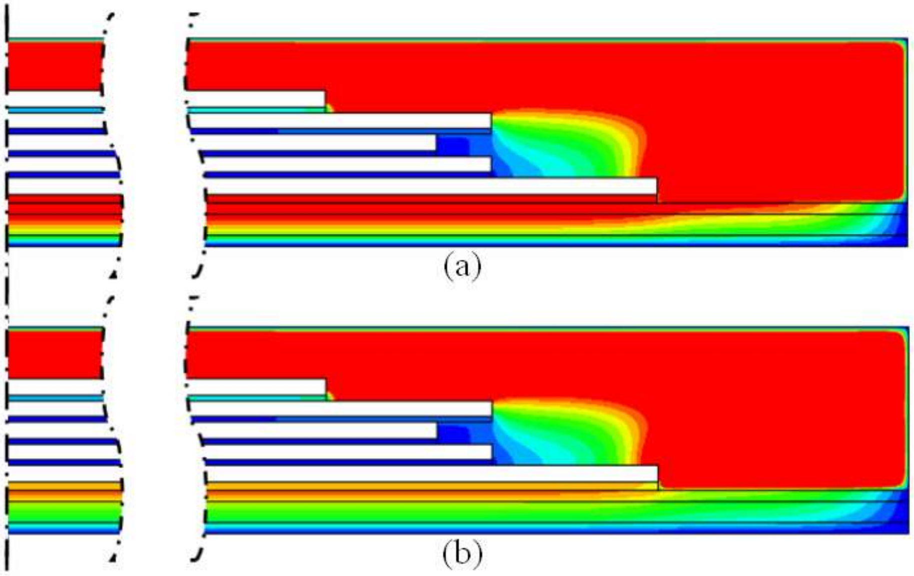
Steam Table - p_g

T(°C)	20	30	40	50	60	70	80
ρ_g(g/cm^2×10^{-3})	0.017	0.03	0.05	0.08	0.13	0.2	0.29
p_g(MPa)	0.002	0.004	0.007	0.01	0.02	0.03	0.05
T(°C)	90	100	110	120	130	140	150
ρ_g(g/cm^2×10^{-3})	0.42	0.6	0.83	1.12	1.5	1.97	2.55
p_g(MPa)	0.07	0.1	0.14	0.2	0.27	0.36	0.48
T(°C)	160	170	180	190	200	210	220
ρ_g(g/cm^2×10^{-3})	3.26	4.12	5.16	6.4	7.86	9.59	11.62
p_g(MPa)	0.62	0.79	1	1.26	1.55	1.91	2.32
T(°C)	230	240	250	260	270	280	290
ρ_g(g/cm^2×10^{-3})	14	16.76	19.99	23.73	28.1	33.19	39.16
p_g(MPa)	2.8	3.35	3.98	4.69	5.51	6.42	7.45

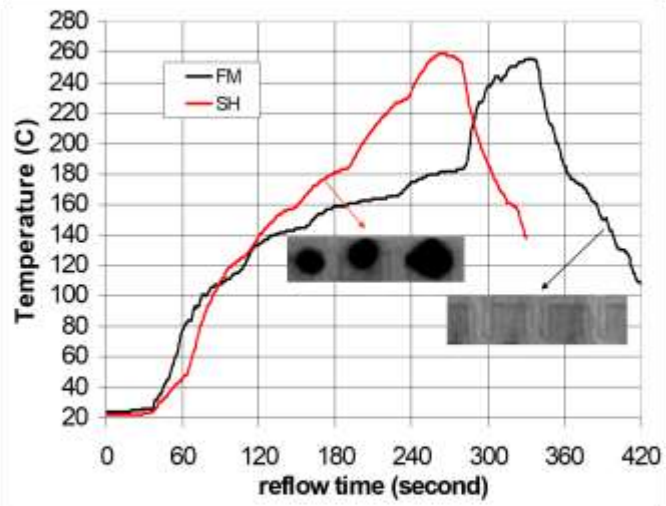
Vapor Pressure: Effect of Reflow Profiles



Moisture diffusion modeling: a) SH, b) FM

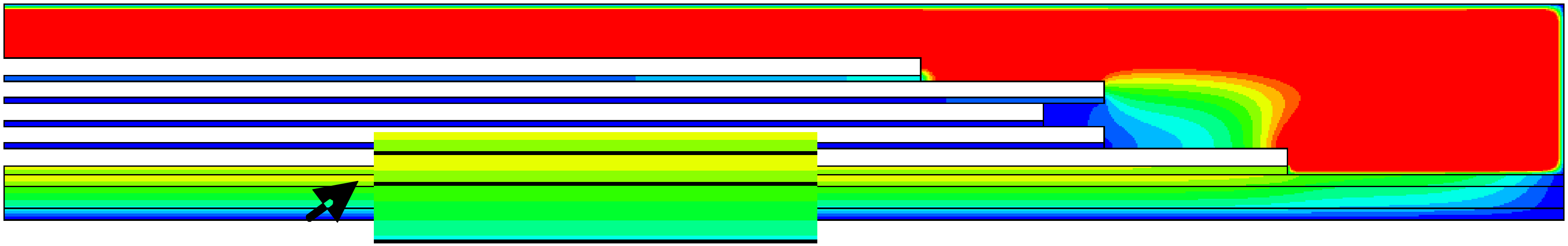


Vapor pressue modeling: a) SH, b) FM

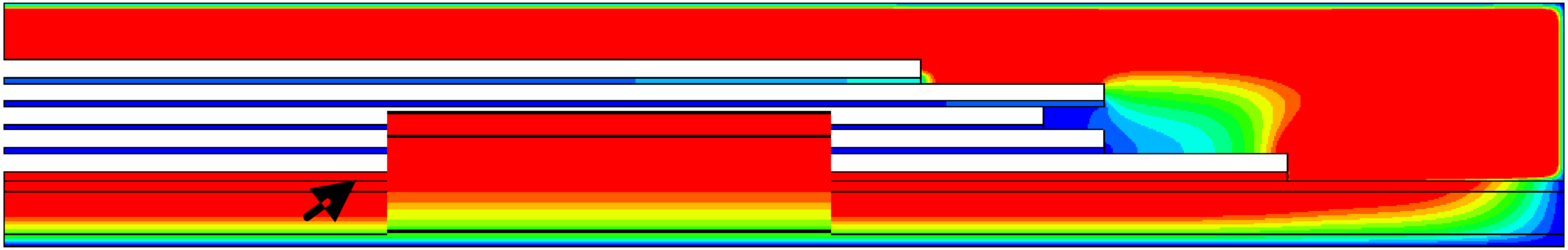


Vapor Pressure Modeling

CSP with thinner substrate



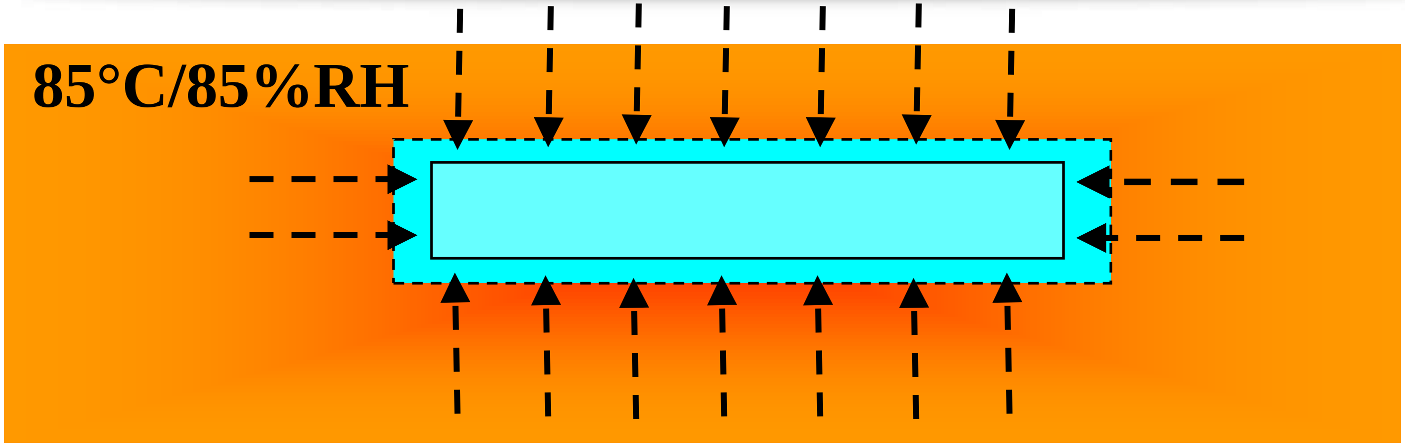
CSP with thicker substrate



– About 50% reduction on vapor pressure at 250˚C in the bottom DA film between two thicknesses of substrate

Xie B, Fan XJ, Shi XQ, Ding H. Direct concentration approach of moisture diffusion and whole field vapor pressure modeling for reflow process: part II – application to 3-D ultra-thin stacked-die chip scale packages. *ASME Journal of Electronic Packaging* 131(3), 031011. 2009.

Hygroscopic Swelling



Expansion strain due to hygroscopic swelling

~0.29%

$\varepsilon^{hygro} = \beta * C$

Expansion strain due to temperature change of 100°C

~0.25%

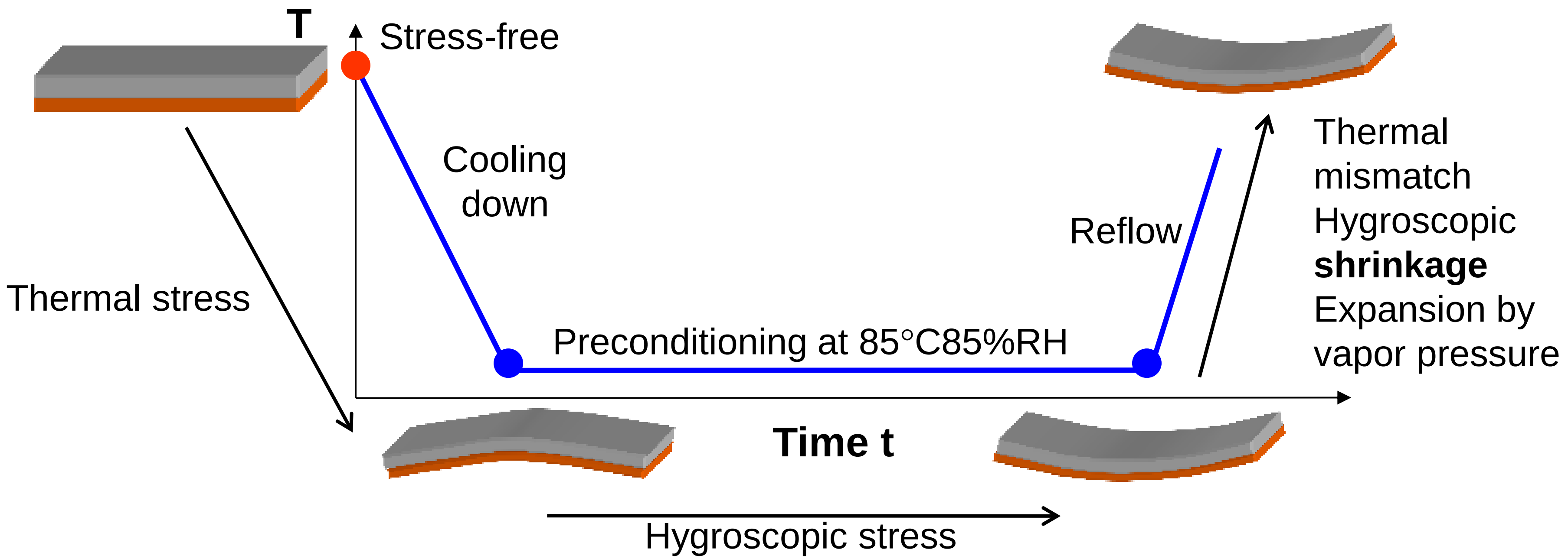
$\varepsilon^{thermal} = \alpha * \Delta T$

β– the coefficient of hygroscopic swelling

C – moisture concentration

Hygroscopic mismatch is comparable to thermal mismatch in causing mechanical stresses

Temperature-Moisture-Deformation Problems



- How to perform integrated modeling to accurately capture stress developments in each stage?

Material Properties to be Needed

$$\varepsilon_{ij} = \frac{1+\nu}{E}\sigma_{ij} - \frac{\nu}{E}\sigma_{kk}\delta_{ij} + (\alpha\Delta T + \beta C + \frac{1-2\nu}{E}p)\delta_{ij}$$

α: coefficient of thermal expansion (CTE)

β: coefficient of hygroscopic swelling (CHS)

C: moisture concentration

T: temperature, p: vapor pressure

Implementation in ANSYS

$$\varepsilon^{\mathrm{volu}} = \alpha\Delta T + \beta C + \frac{1-2\nu}{E} p$$

$$\Rightarrow \quad \varepsilon^{\mathrm{volu}} = \alpha\Delta T + \beta\left(C + \frac{(1-2\nu)p}{\beta E}\right)$$

BF,,TEMP,n_temp

BF,,FLUE, b1+b2

Body Forces in ANSYS: Temp and Flue

- Total volume strain

$$\varepsilon = \alpha\,(T-T_{ref}) + \beta C$$

BF,,TEMP,n_temp **BF,,FLUE,n_C**

ANSYS built-in swelling function $\varepsilon^{sw} = \beta(\Delta C)^n$

ε^{sw} :swelling strain
β :swelling coefficient
C :a fluence

```
TB,SWELL,1
! C72=10 FOR ACTIVATION OF USERSW
! EPS=C67*(FLUENCE)^C68 WHERE C67=SWELLING COEFFICIENT
TBDATA,72,10
TBDATA,67,β,1
```

Implementation in ANSYS

```
TB,SWELL,MAT
TBDATA,72,10
TBDATA,67,β,1
```

ldread,temp,,,,,moisture,rth

```
*do,i,1,total_node
*get,C,node,i,ntemp
```

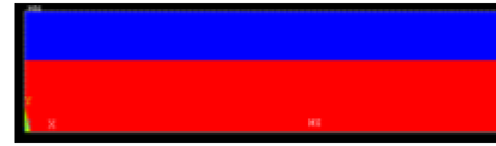
BF,i,FLUE,C

```
*enddo

BF,,Temp,T_reflow

solve
```

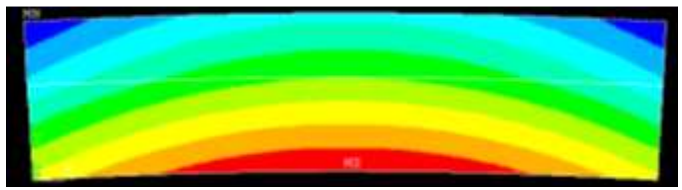
- Moisture diffusion (including desorption) modeling needs to be solved first and separately.
  - ANSYS 17.2 or later provides **coupled element**
    - Plane 223(2D , Quadratic)
    - Solid 226(3D , Quadratic)
      - **Thermal-structural-diffusion (100011)**
        - **DOF label: TEMP, UX, UY, UZ , CONC**

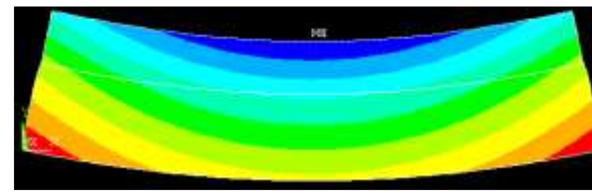
Example: Bi-Material Configuration

Moisture concentration contours



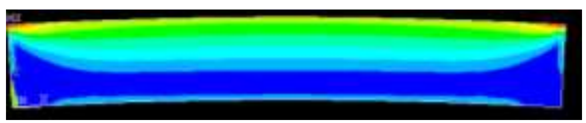
Deformed shape contours



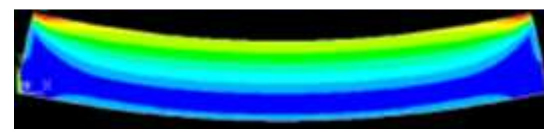


von Mises stress Contours in MC

Max stress =4.96MPa



Max stress =20.99MPa

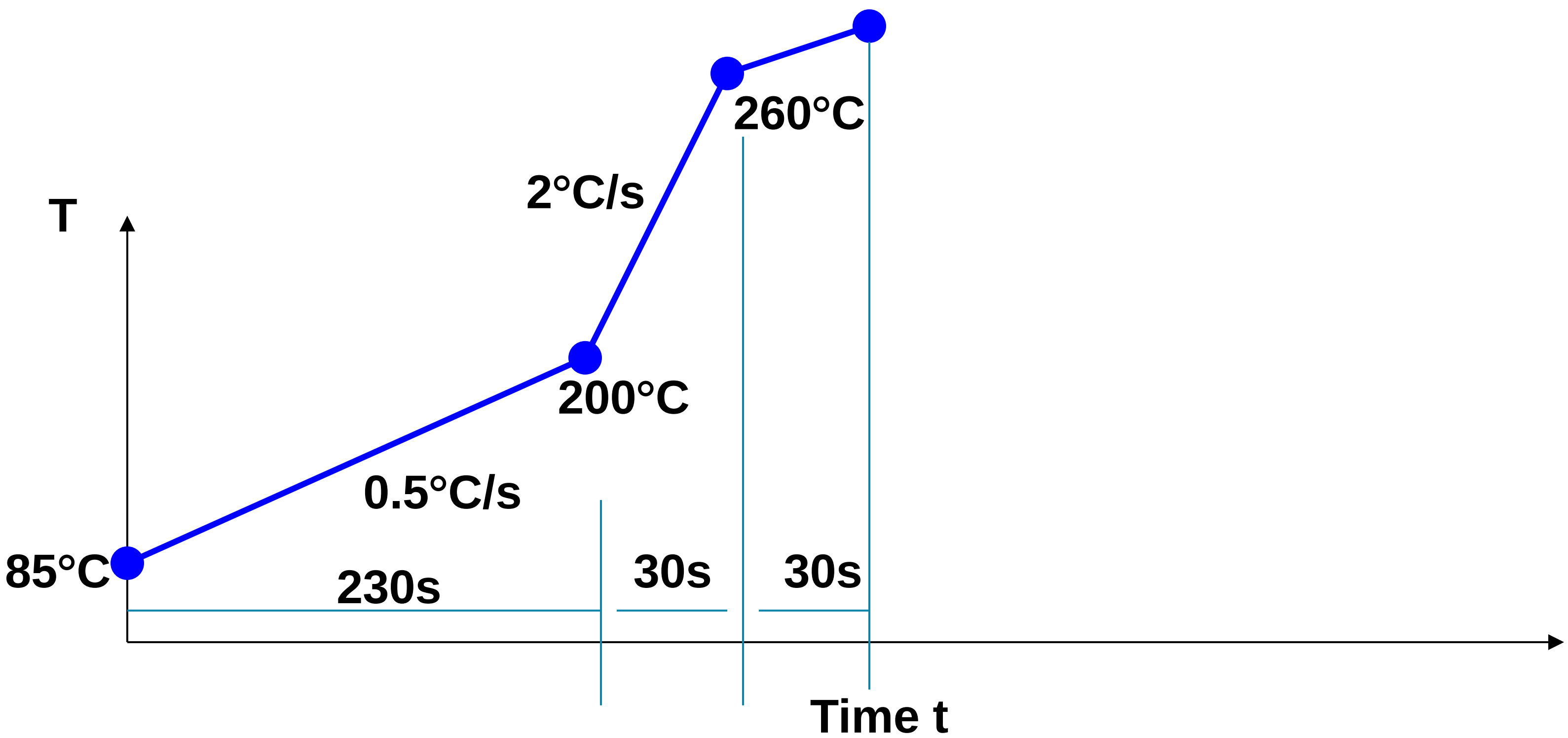


Time = 1hour @85°C/85%RH

Time = 18hour @85°C/85%RH

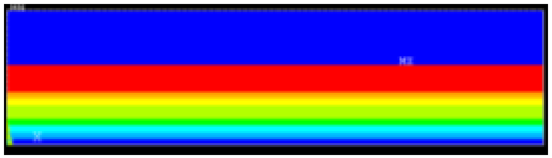
Fan XJ, Zhao JH. Moisture diffusion and integrated stress analysis in encapsulated microelectronics devices. Proc. 12th. Int. Conf. on Thermal, Mechanical and Multiphysics Simulation and Experiments in Micro-Electronics and Micro-Systems (EuroSimE 2011). pp8. Linz, Austria. April 18-20, 2011.

Example: Reflow Profile Setting

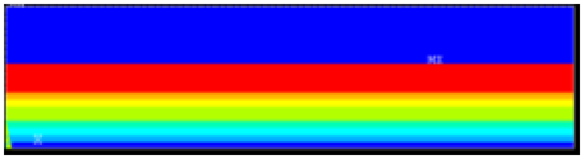


Moisture Concentration and Vapor Pressure Contours

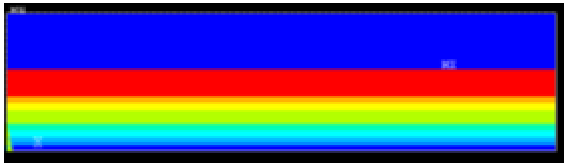
Max C = 3.54μg/mm^3
T=200°C



Max C = 2.11μg/mm^3
T=260°C

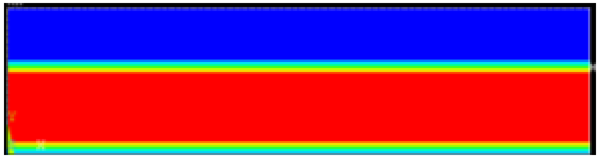


Max C = 1.05μg/mm^3
T=265°C

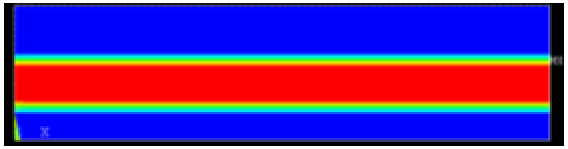


Moisture concentration contours

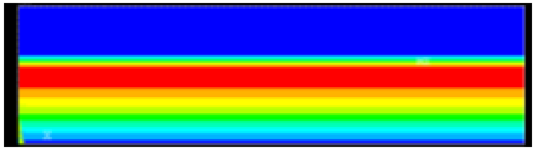
Max p = 1.55MPa
T=200°C



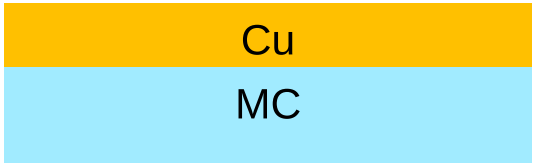
Max p = 5.84MPa
T=260°C



Max p = 0.5e-3MPa
T=265°C



Vapor pressure contours



Results of Integrated Stress Modeling

200°C

	Von Mises Stress in Epoxy (MPa)	Von Mises Stress in Cu (Mpa)
T	2.4	8.7
T + H	4.9	17.3
T + H + V	6.3	22.9

260°C

	Von Mises Stress in Epoxy (MPa)	Von Mises Stress in Cu (Mpa)
T	6.0	21.9
T + H	7.2	27.5
T + H + V	11.2	38.9

260°C after 30sec hold

	Von Mises Stress in Epoxy (MPa)	Von Mises Stress in Cu (Mpa)
T	6.0	21.9
T + H	6.3	24.7
T + H + V	6.3	24.7

Summary

- **For a general moisture diffusion problem with temperature-dependent C_{sat} and varying ambient RH and temperature with time**
  - $\bar{C}_k$ must be used and the coupled element with thermal-diffusion or thermal-structural-diffusion option must be applied at the same time.
- **ANSYS built-in $\bar{C}$ approach cannot solve the problem with varying RH correctly.**
  - ANSYS diffusion element only
    - C_{sat} must be temperature-independent. Temperature gradient is not considered.
  - ANSYS coupled element with structural-diffusion option.
    - C_{sat} must be temperature-independent. Temperature gradient is not considered.
  - ANSYS coupled element with thermal-diffusion option (or thermal-structural-diffusion) option
    - If $\bar{C}$ is used, RH must be constant.
    - If $\bar{C}_k$ is used, no restriction for any diffusion problems.
- **Vapor pressure model**
- **Thermal-hygro-mechanical modeling**

- Introduction
- Temperature Loading
- Mechanical Loading
- Moisture and Humidity
- Electrical Current - Multi-Physics Modeling
- Summary

Outline

- **Electrical-Thermal-Mechanical Modeling**
- **Electromigration**

Electrical-Thermal Modeling

- Governing equations

Current flow: (electrostatics)

$$\nabla^2 V = 0 \Longrightarrow \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0$$

$$\Downarrow$$

Heat conduction: (steady-state)

$$k_T \nabla^2 T + \frac{1}{\rho}\left|\nabla V\right|^2 = 0$$

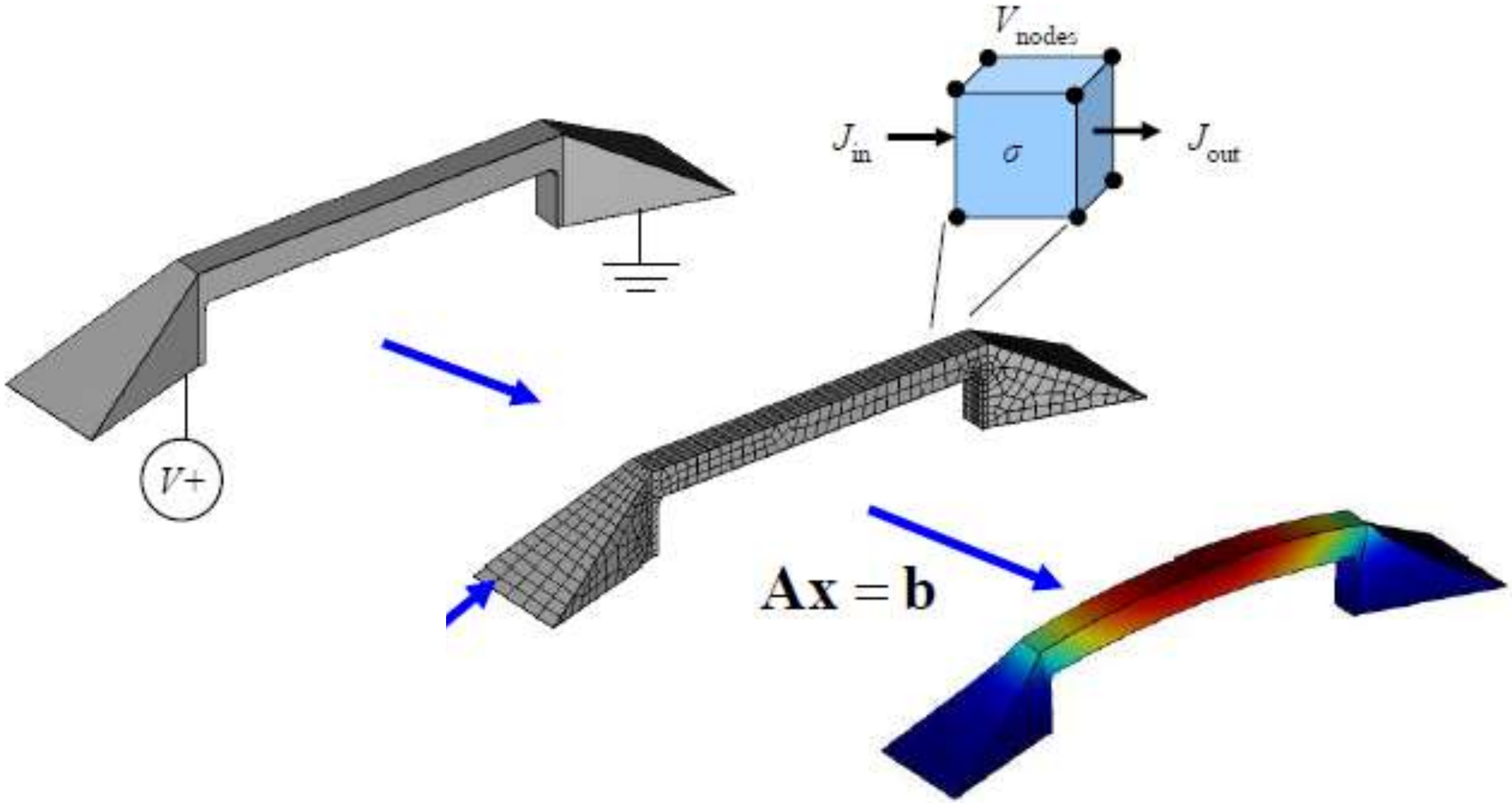
Joule heating $\left|\vec{j} \cdot \nabla V\right| = \frac{1}{\rho}\left|\nabla V\right|^2$

$$\vec{j} = -\frac{1}{\rho}\nabla V$$

- Current flow generates joule heating at any location.
- Joule heat is applied as heat source in heat diffusion in solids.
- Joule heat term: $q_0 = \frac{1}{\rho}\left|\nabla V\right|^2$
- We solve this multi-physics problem one step at a time
  - Both problems are diffusion-type
  - Two problems are sequentially coupled if electric conductivity does not vary with temperature

Example: A Microresistor Beam in MEMS

- Current flow modeling

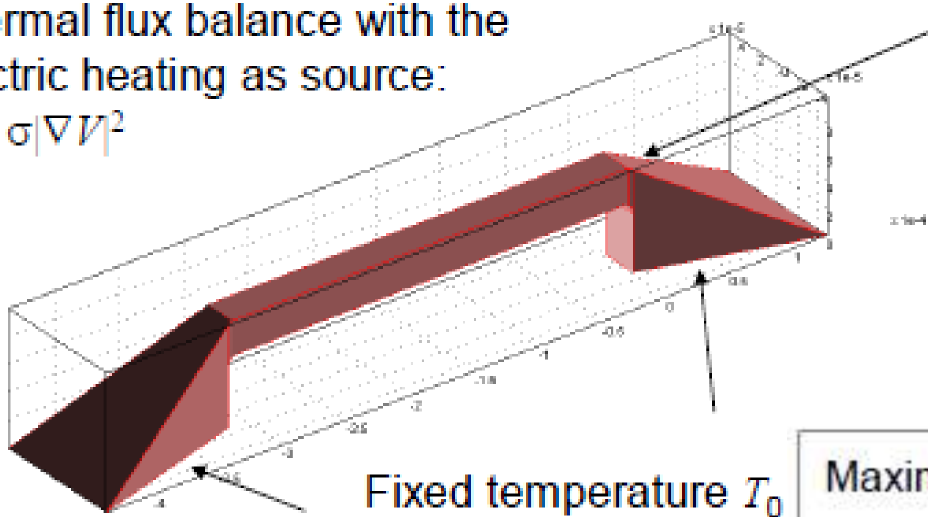


COMSOL Multi-Physics Modeling Tutorial.

Thermal Modeling

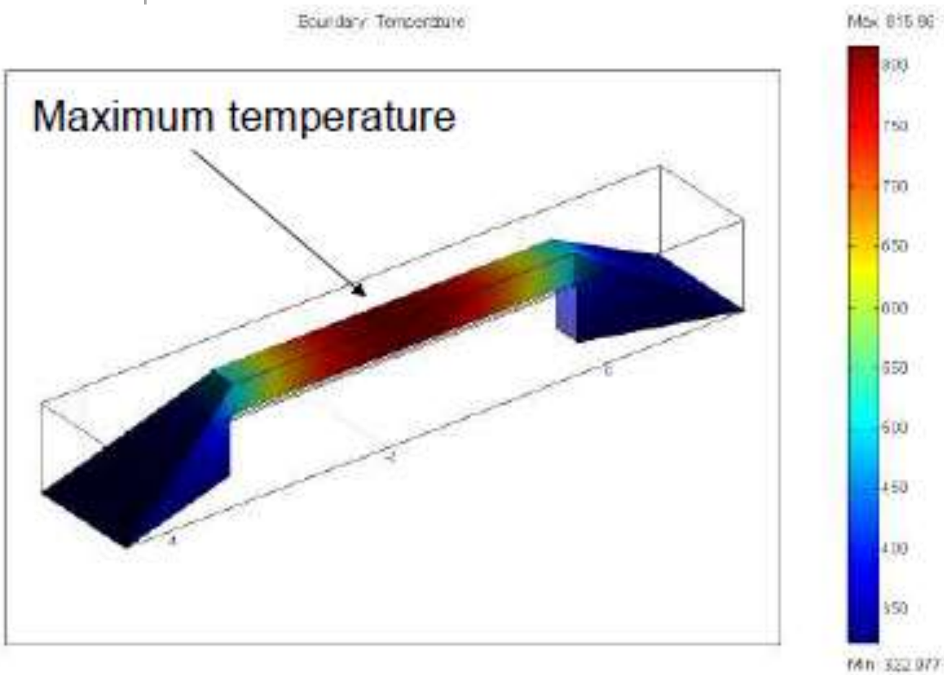
Inside the material:
Thermal flux balance with the electric heating as source:
$Q = \sigma|\nabla V|^2$

Convection conditions flux out:
$h^*(T-T_{amb})$



Fixed temperature T_0

Maximum temperature



Thermal-Mechanical Modeling

- Governing equations

$$\nabla \cdot k[\nabla T] = c_p \rho \frac{\partial T}{\partial t}$$

$$G\nabla^2 u_i + (\lambda + G)e_{,i} - [\frac{E}{1-2\nu}\alpha T]_{,j} + X_i = 0$$

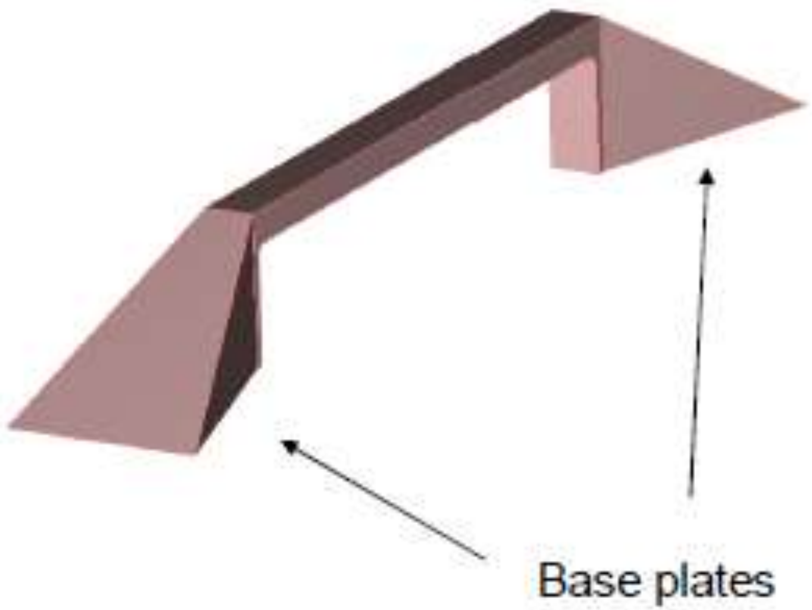
u_i : the component of displacement vector
e : the total volumetric strain $e=u_{i,i}$
X_i : the component of body force vector.

- Temperature load is applied in the form of ‘body force’ in mechanical analysis

Electrical-Thermal-Mechanical Modeling

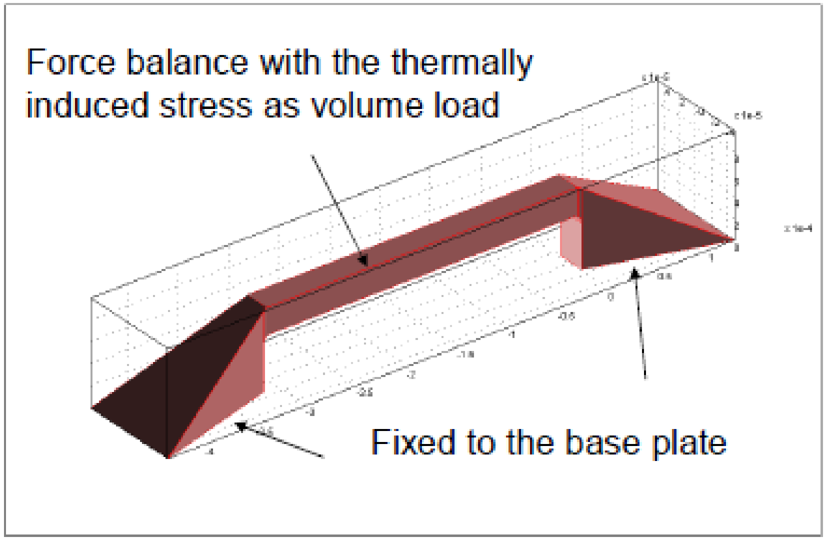
- MEMS: microresistor beam modeling

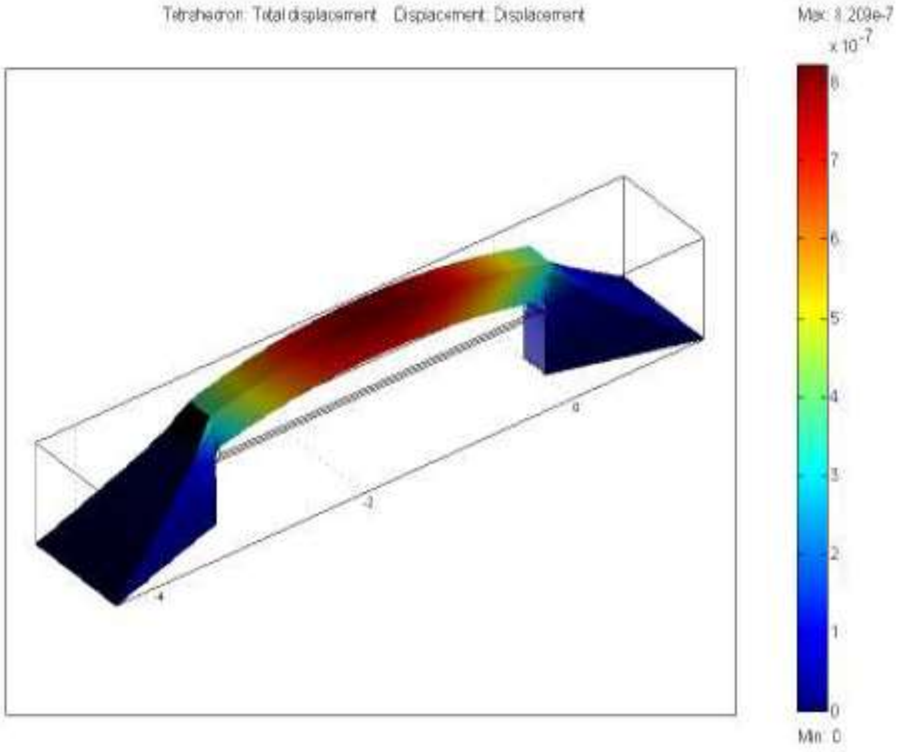
- MEMS actuator application
- Electrical current
  - DC balance for conductive media
  - Fixed potentials generate potential difference ΔV=2V
- Heat transfer
  - Thermal flux balance with the resistive heating as source
- Structural analysis
  - Force balance with the thermally induced stress as volume load



Mechanical Modeling

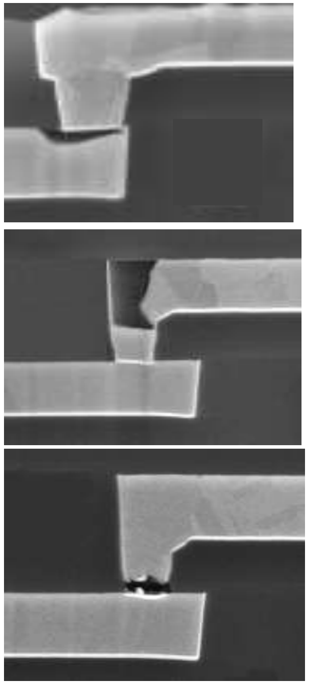
- Results, Deformation

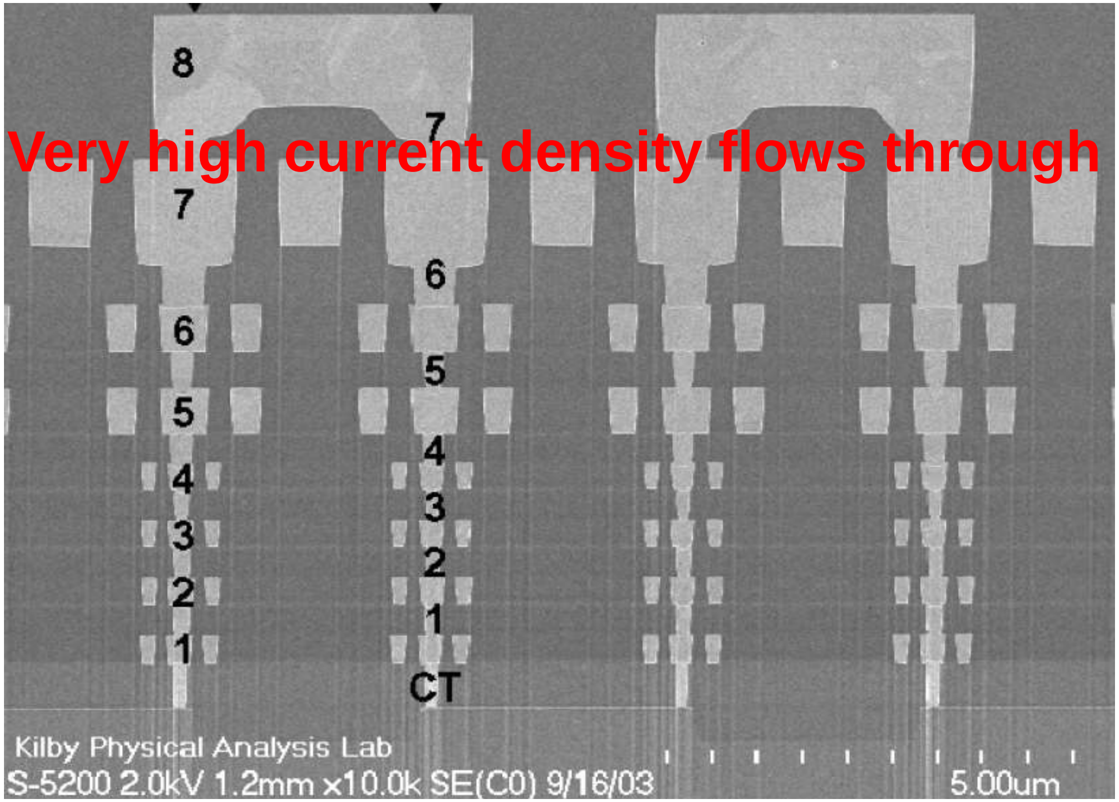




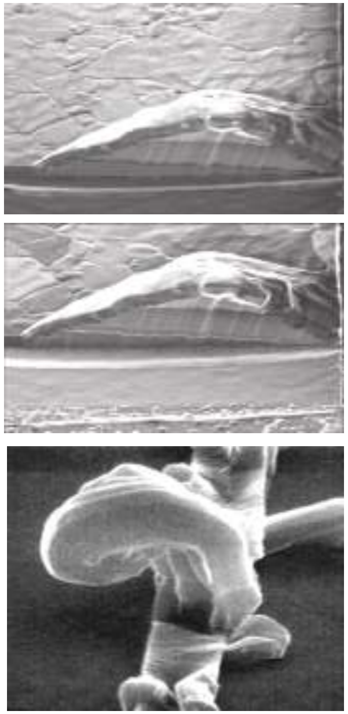
What is Electromigration (EM)?

Void





Hillock

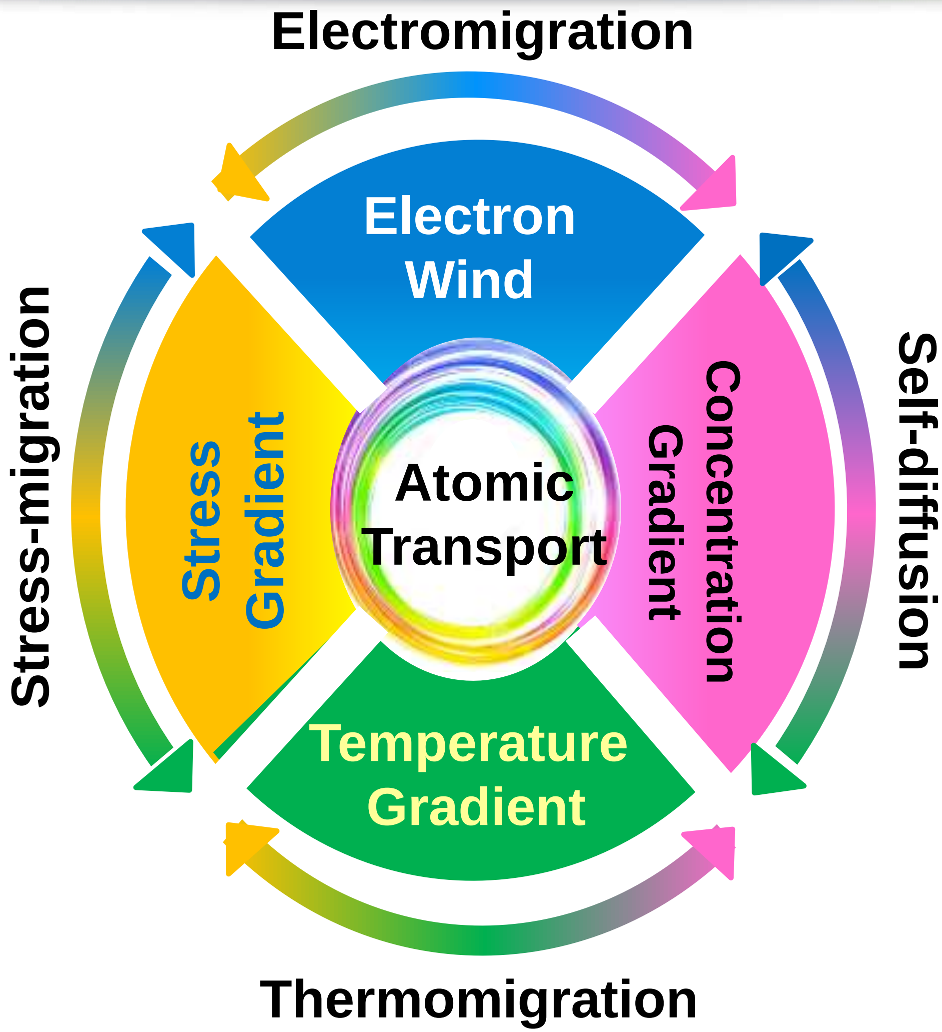


- **Electromigration is a process of mass transport in the current-carrying metal under the driving forces generated by electric field.**
- **Electromigration is the most persistent reliability problem in interconnect technology in semiconductor device.**

K.N. Tu: EPTC 2008 short course

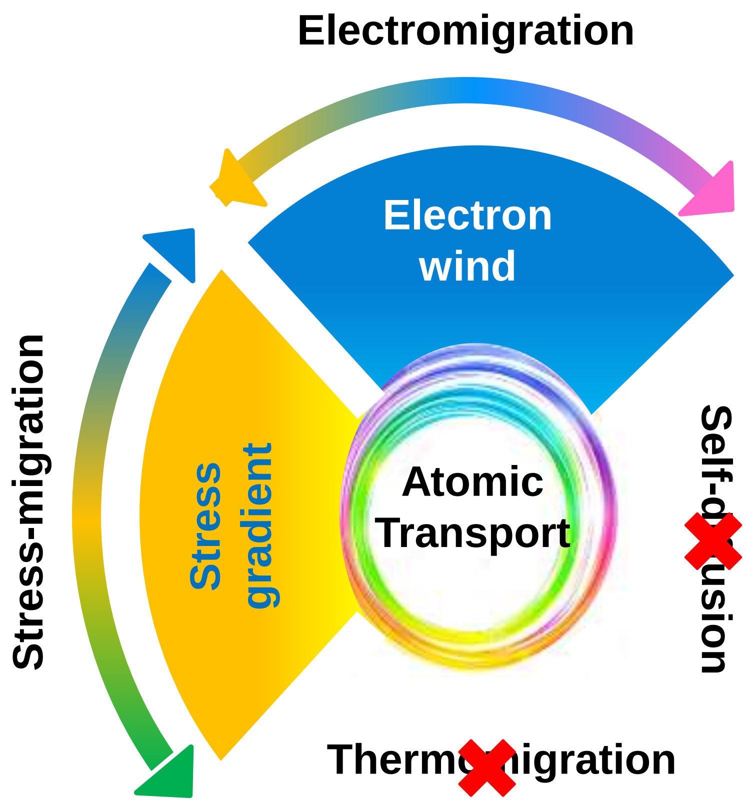
Similar to River Flow…

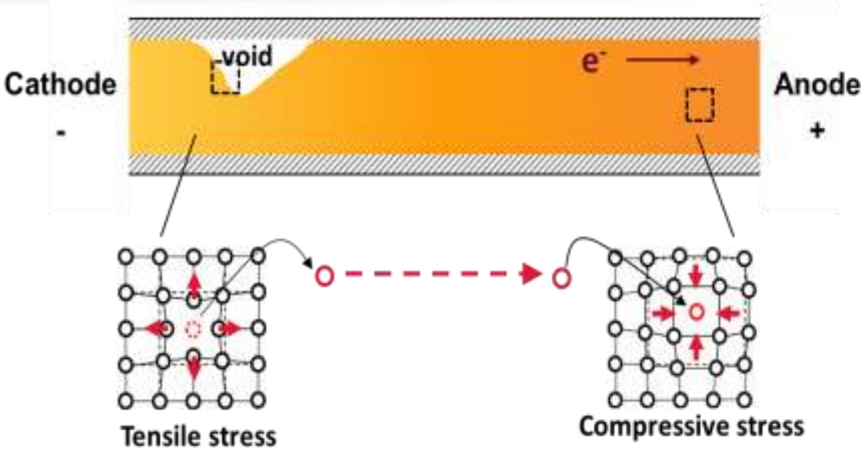
Driving Forces



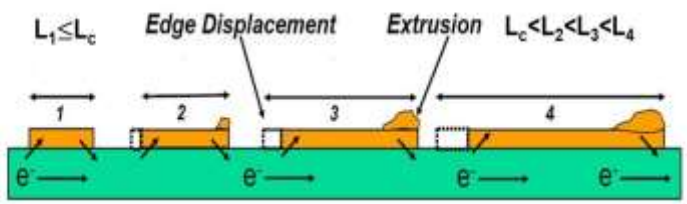
- **The atomic transport is caused by a combination of interacting driving forces that can generate voids at different locations.**

Blech's Theory (1976)





$$Z^{*}e\rho j + \Omega\frac{\partial\sigma}{\partial x} = 0 \quad \Rightarrow \quad jL = \frac{(\sigma_{max} - \sigma_{min})\Omega}{Z^{*}e\rho}$$



- EM flux is entirely balanced by the stress-induced counter flux.
- Blech Product, *jL*, provides a threshold condition of *maximum stress*, below which, electromigration failure will not occur - mechanical failure.

I. Blech and C. Herring, APL, 29, 131, 1976.

Electromigration – a Coupled, Multi-Physics Problem

Total flux in terms of C_v (vacancy concentration)

$$J_v = \frac{D_v C_v}{k_B T}\left(Z^* e \rho \boldsymbol{j} - \frac{k_B T}{C_v}\nabla C_v - f\Omega\nabla\sigma + \frac{Q^*}{T}\nabla T\right)$$

C_v vacancy concentration (m^{-3}),
D_v diffusivity
k_B Boltzmann's constant (J/K),
Z^* effective charge number(>0) ,
f volume relaxation ratio

Ω volume of per atom (m^3)
$\boldsymbol{j}$ current density (A/m^2)
e elementary charge (C)
Q^* heat of transport (kJ/mol)

- **EM is a multiphysics coupled field problem involved with electron wind, chemical potential, stress gradient and temperature gradient.**

An Overview in Literature

	Flux by self-diffusion	Flux by stress	Source/sink term	Constraint condition	Stress equilibrium	EM strain in stress/strain
Shatzkes and Lloyd (1986)	✓	✗	✗	N/A	N/A	N/A
Kirchheim (1992)	✗	✓	✓	✗	✗	✗
Korhonen et al. (1993)	✗	✓	✓	✗	✗	✗
Clement and Thompson (1995)	✗	✓	✓	✗	✗	✗
Sarychev et al. (2000)	✓	✓	✓	N/A	✗	✓
Suo et al. (2003, 2011, 2014)	✗	✓	✓	✗	✗	✗
Sukharev et al. (2004, 2007)	✓	✓	✓	N/A	✓	✗
Maniatty et al. (2016)	✗	✓	✓	✗	✓	✓

- **Inconsistent and incomplete solutions appear in literature.**

New Theory – General Coupling Model

	Flux by self-diffusion	Flux by stress	Source/sink term	Constraint condition	Stress equilibrium	EM strain in stress/strain
Cui et al. (2019)	✓	✓	✓	✓	✓	✓

Journal of Applied Physics

General coupling model for electromigration and one-dimensional numerical solutions

Cite as: J. Appl. Phys. **125**, 105101 (2019); https://doi.org/10.1063/1.5065376
Submitted: 09 October 2018 . Accepted: 19 February 2019 . Published Online: 08 March 2019

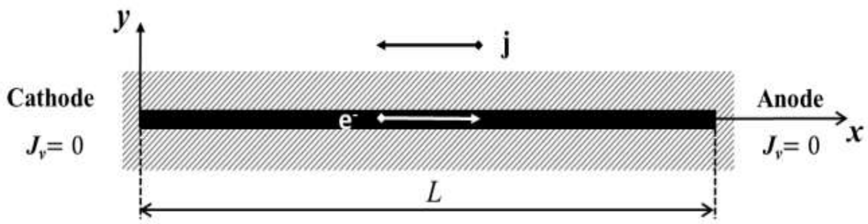
Zhen Cui, Xuejun Fan, and Guoqi Zhang

Puzzle One

- **Volume Strain in Confinement**

Literature

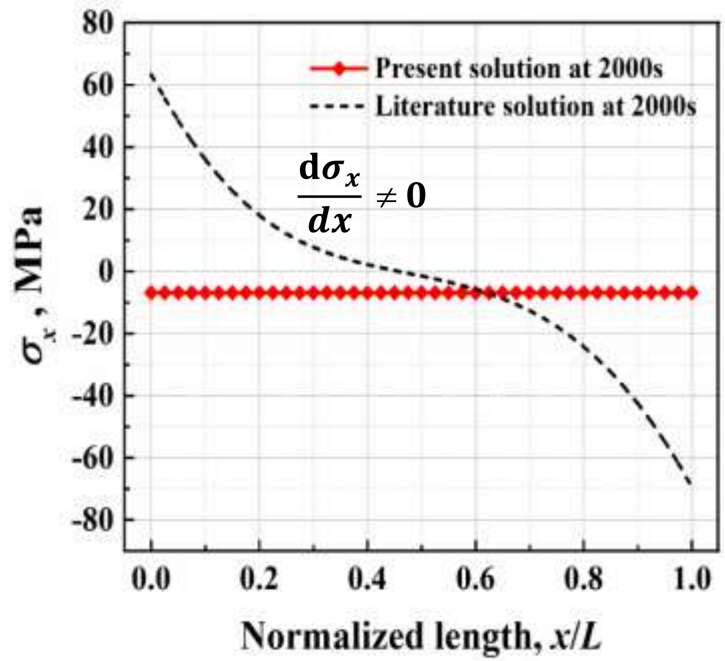
$\theta = 0$ (volume strain equals to zero) anywhere.



Confined conductor configuration

Present solution

$$u(L) = u(0) = 0 \rightarrow \int_0^L \varepsilon_x dx = 0 \rightarrow \int_0^L \theta dx = 0$$



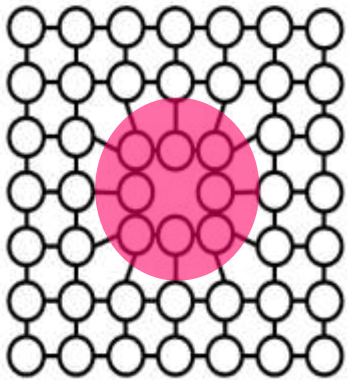
- **Equilibrium ($\frac{d\sigma_x}{dx} = 0$) is violated in the existing literature theory and solutions.**

Puzzle Two

- **Hydrostatic Stress σ vs. Vacancy Concentration C_v**

Literature

$$\sigma = \frac{k_B T}{\Omega} \ln\left(\frac{C_v}{C_{v0}}\right)$$

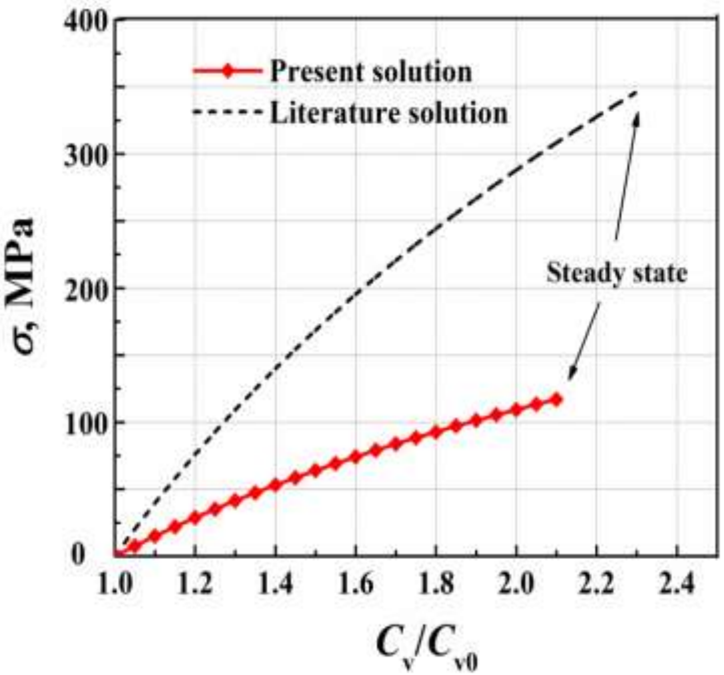


Confined configuration

C. Herring, J. Appl. Phys. 21, 437 (1950)

Present solution

$$\sigma = \frac{2EA}{9(1-v)}\left[\frac{1+v}{2(1-2v)L}\int_0^L \ln\left(\frac{C_v}{C_{v0}}\right)dx + \ln\left(\frac{C_v}{C_{v0}}\right)\right]$$



- **With the exact σ-C_v equation, the stress level is significantly lower.**

Puzzle Three

- **Effect of Self-Diffusion**

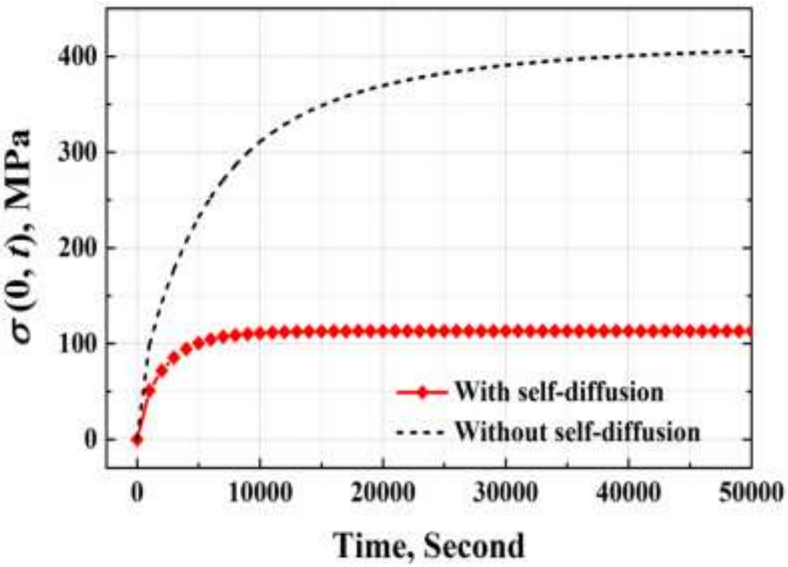
Literature

$$j_v = -\frac{D_v C_v}{k_B T}\left(f\Omega\frac{\partial\sigma}{\partial x} + Z^* e\rho j\right)$$

$$J_v = \frac{D_v C_v}{k_B T}\left(Z^* e\rho \boldsymbol{j} - \frac{k_B T}{C_v}\nabla C_v - f\Omega\nabla\sigma + \frac{Q^*}{T}\nabla T\right)$$

Present solution

$$j_v = -\frac{D_v C_v}{k_B T}\left(\frac{k_B T}{C_v}\frac{\partial C_v}{\partial x} + f\Omega\frac{\partial\sigma}{\partial x} + Z^* e\rho j\right)$$



- **When concentration gradient is considered, the stress becomes further lower.**

Puzzle Four

- **Stress-Strain Relation (Constitutive Equation)**

Literature

Electromigration-induced volume strain

$$\varepsilon_{kk}{}^{EM} = -\frac{\sigma}{B}$$

$$\boldsymbol{\sigma} = 2G\boldsymbol{\varepsilon} + \lambda \mathrm{tr}(\boldsymbol{\varepsilon})\mathbf{I} - B\mathrm{tr}(\boldsymbol{\varepsilon}^T)\mathbf{I}$$

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^M + \boldsymbol{\varepsilon}^T + \boldsymbol{\varepsilon}^{EM} = 0$$

Present solution

$$\varepsilon_{kk}{}^{EM} = g(C_v)$$

$$g(C_v) = -A \ln\left(\frac{C_v}{C_{v0}}\right) \qquad A = \frac{k_B T}{B\Omega}$$

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^M + \boldsymbol{\varepsilon}^T + \boldsymbol{\varepsilon}^{EM}$$

$$\boldsymbol{\varepsilon}^T = \alpha \Delta T \mathbf{I}, \qquad \boldsymbol{\varepsilon}^{EM} = \frac{g(C_v)}{3}\mathbf{I}, \qquad g(C_v) = -A \ln\left(\frac{C_v}{C_{v0}}\right)$$

$$\boldsymbol{\sigma} = 2G\boldsymbol{\varepsilon} + \lambda \mathrm{tr}(\boldsymbol{\varepsilon})\mathbf{I} - B\mathrm{tr}(\boldsymbol{\varepsilon}^T)\mathbf{I} - B\mathrm{tr}(\boldsymbol{\varepsilon}^{EM})\mathbf{I}$$

- **A 3-D, general and self-consistent stress-strain constitutive equation is obtained.**

Puzzle Five

- **Atomic Transport Equation**

Literature

$$\begin{cases} \frac{\partial C_v}{\partial t} + \nabla \cdot \boldsymbol{J}_v = \mathrm{G} & \text{(sink/source term)} \\ \mathrm{G} = \frac{\partial C}{\partial t} \end{cases}$$

$$\frac{\partial C}{C} = d\varepsilon_{kk}^{EM}$$

with approximation

$$\frac{\partial C_v}{\partial t} \ll \frac{\partial C}{\partial t}$$

$$\frac{\partial \varepsilon_{kk}^{EM}}{\partial t} = \Omega \nabla \cdot \boldsymbol{J}_v$$

Present solution

$$\begin{cases} \frac{\partial \theta}{\partial t} = \Omega \, \nabla \cdot \boldsymbol{J}_v \\ \theta = \varepsilon_{kk}^{M} + \varepsilon_{kk}^{T} + \varepsilon_{kk}^{EM} \end{cases}$$

without any approximation

$$\frac{\partial \varepsilon_{kk}^{M}}{\partial t} + \frac{\partial \varepsilon_{kk}^{T}}{\partial t} + \frac{\partial \varepsilon_{kk}^{EM}}{\partial t} = \Omega \nabla \cdot \boldsymbol{J}_v$$

- **Mass conservation equation is used to describe the atomic transport. Thus, the sink/source term is considered naturally.**

New Theory – General Coupling Model

Mass conservation equation:

$$\frac{\partial \theta}{\partial t} = \Omega\, \nabla \cdot \boldsymbol{J}_v$$

$$\boldsymbol{J}_v = -D_v \nabla C_v + D_v C_v \frac{Z^* e \rho \boldsymbol{j}}{k_B T} - D_v C_v \frac{\Omega}{k_B T} \nabla \sigma + D_v C_v \frac{Q^*}{k_B T} \nabla T$$

Constitutive equation:

$$\theta = \mathrm{tr}(\boldsymbol{\varepsilon}), \qquad \boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^M + \boldsymbol{\varepsilon}^T + \boldsymbol{\varepsilon}^{EM}$$

$$\boldsymbol{\varepsilon}^T = \alpha \Delta T \mathbf{I}, \qquad \boldsymbol{\varepsilon}^{EM} = \frac{g(C_v)}{3} \mathbf{I}, \qquad g(C_v) = -A \ln\left(\frac{C_v}{C_{v0}}\right)$$

$$\boldsymbol{\sigma} = 2G\boldsymbol{\varepsilon} + \lambda \mathrm{tr}(\boldsymbol{\varepsilon})\mathbf{I} - B\mathrm{tr}(\boldsymbol{\varepsilon}^T)\mathbf{I} - B\mathrm{tr}(\boldsymbol{\varepsilon}^{EM})\mathbf{I}$$

$$\sigma = \mathrm{tr}\left(\frac{\boldsymbol{\sigma}}{3}\right)$$

Field equations:

$$\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{F} = 0 \qquad \boldsymbol{\varepsilon} = \frac{1}{2}(\nabla \boldsymbol{u} + \boldsymbol{u} \nabla)$$

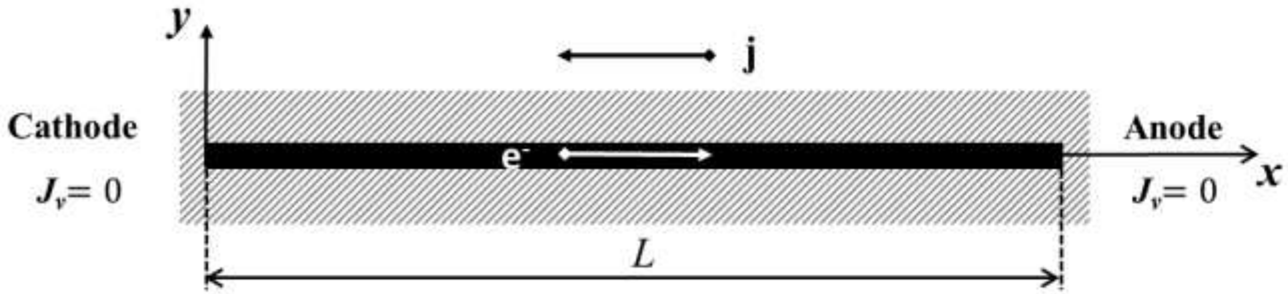
$$\nabla \cdot \boldsymbol{j} = 0, \qquad \boldsymbol{j} = \frac{\boldsymbol{E}}{\rho} = -\frac{\nabla \mathrm{V}}{\rho}$$

$$k \nabla^2 T + \boldsymbol{j} \cdot \boldsymbol{E} = 0$$

Cui Z, et al., JAP, 125, 2019

Totally fixed configuration – 1-D problem

- **Assumptions**
  - 1-D problem: $\varepsilon_y = \varepsilon_z = \varepsilon_{xy} = \varepsilon_{yz} = \varepsilon_{xz} = 0$
  - Current density j is constant and in negative x-axis direction.
  - Temperature is constant – no temperature gradient.
  - Perfectly blocking condition for C_v: $J_v(0,t) = J_v(L,t) = 0$.
  - Mechanically totally fixed: $u(L,t) = u(0,t) = 0$



1-D Governing Equations

$$\frac{\partial\theta}{\partial t} + D_v\Omega[\frac{\partial\left(\frac{\partial C_v}{\partial x} + \frac{f\Omega C_v}{k_B T}\frac{\partial\sigma}{\partial x} + \frac{Z^* e\rho j C_v}{k_B T}\right)}{\partial x}] = 0$$

$$\theta = -A\ln(\frac{C_v}{C_{v0}}) + \frac{3(1-2v)\sigma}{E}$$

$$\sigma = \frac{2EA}{9(1-v)}\ln(\frac{C_v}{C_{v0}}) + \frac{1+v}{3(1-v)}\sigma_x$$

$$\sigma_x = \frac{(1-v)E}{(1+v)(1-2v)}\varepsilon_x + \frac{EA}{3(1-2v)}\ln(\frac{C_v}{C_{v0}})$$

$$\frac{d\sigma_x}{dx} = 0$$

$$\int_0^L \varepsilon_x dx = 0 \qquad u(L,t) = u(0,t) = 0 \rightarrow \int_0^L \varepsilon_x dx = 0 \rightarrow \int_0^L \theta dx = 0$$

$$\frac{\partial C_v}{\partial t} - \frac{1}{L}\int_0^L \frac{\partial C_v}{\partial t}dx = \frac{3(1-v)D_v C_v\Omega}{(1+v)A}\left[\left(1 + \frac{2EA\Omega}{9(1-v)k_B T}\right)\frac{\partial^2 C_v}{\partial x^2} + \frac{Z^* e\rho j}{k_B T}\frac{\partial C_v}{\partial x}\right]$$

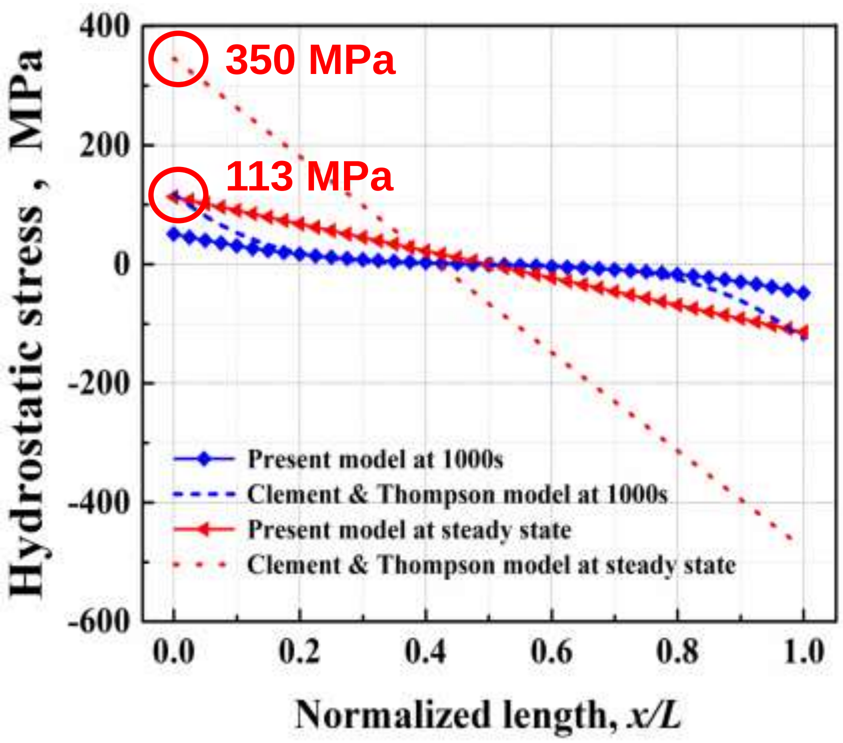
$$\sigma = \frac{2EA}{9(1-v)}[\frac{1+v}{2(1-2v)L}\int_0^L \ln(\frac{C_v}{C_{v0}})\,dx + \ln(\frac{C_v}{C_{v0}})]$$

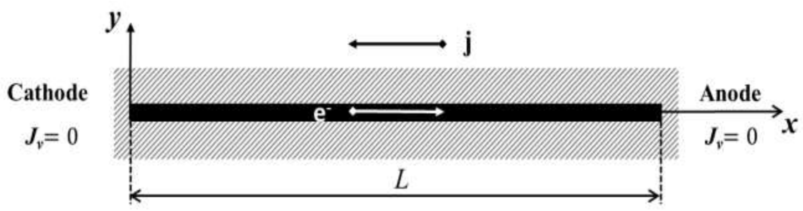
Parameters and Physical Properties

Length of interconnect (*L*)	50 μm	Temperature (T)	500K
Young's modulus (*E*)	70×10^{9} Pa	Poisson ratio (ν)	0.3
Atomic diffusivity (D_a)	3×10^{-16} m^2/s	Vacancy diffusivity (D_v)	3×10^{-9} m^2/s
Atomic volume (Ω)	1.66×10^{-29} m^3	Initial vacancy concentration (C_{v0})	6.02×10^{21} m^{-3}
$D_v C_v = D_a C_a, \quad C_a = 1/\Omega$		Electrical resistivity (ρ)	4.88×10^{-8} Ohm·m
Current density (j)	10^{10} A/m^2	Elementary charge (e)	1.60×10^{-19} C
Effective charge number (Z*)	3.5	Boltzmann constant (k_B)	1.38×10^{-23} J/K
Coefficient of electromigration strain (A)	0.0071		

Cui Z, et al., JAP, 125, 2019

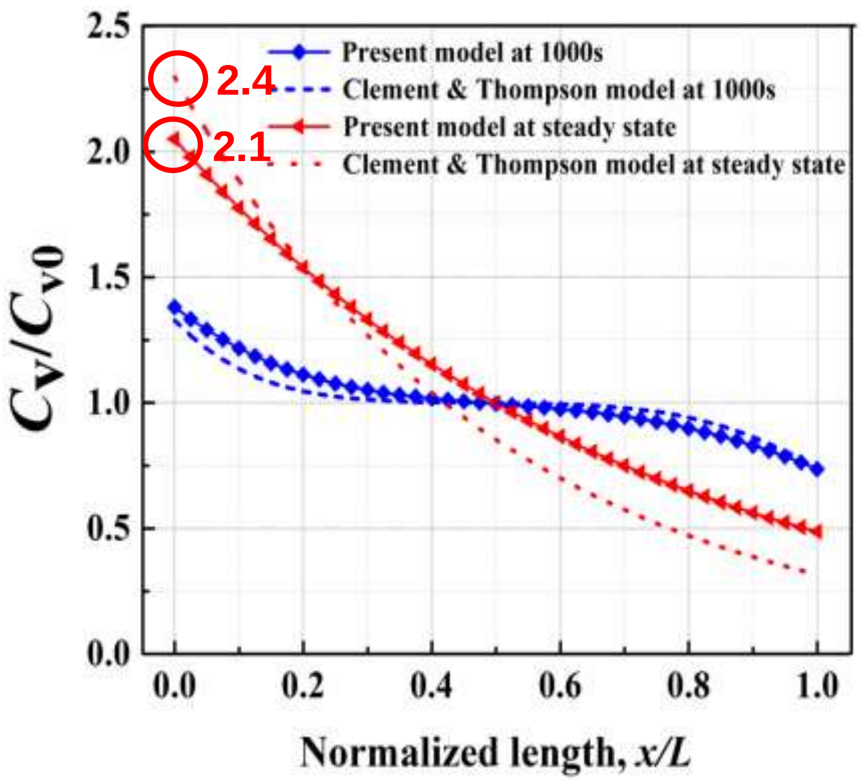
Numerical Results (σ)

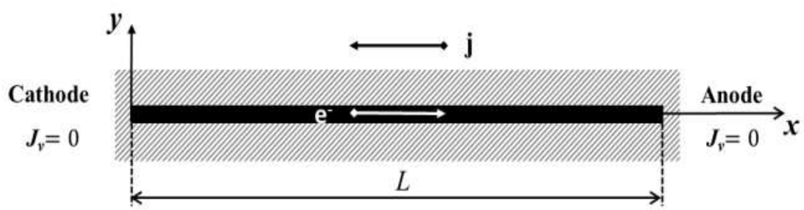




- The present results show significant differences with the previous results, particularly in the magnitude of hydrostatic stress. **(113 MPa vs. 350 MPa: 30% of the stress value obtained).**

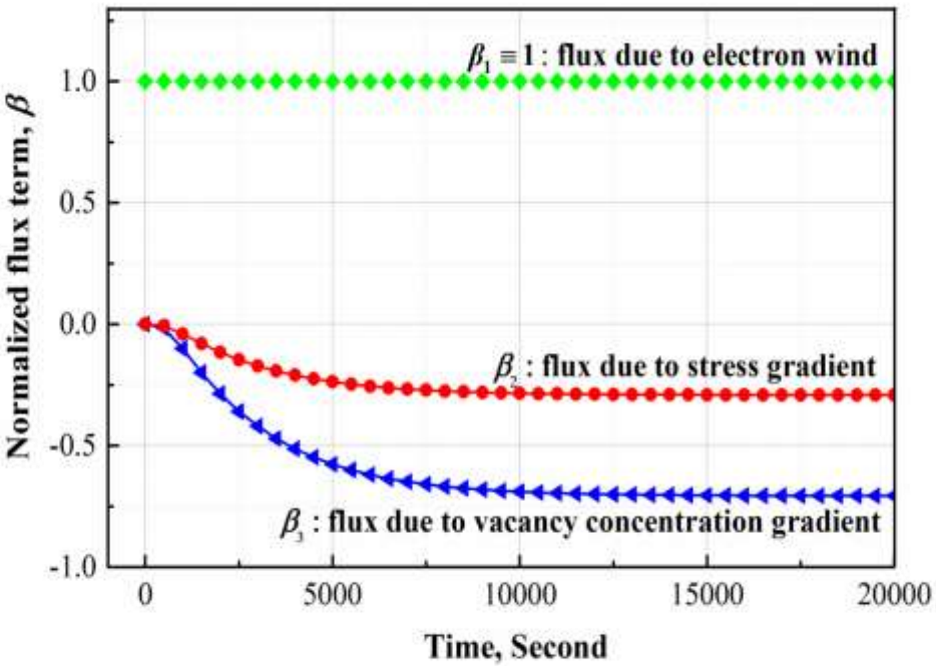
Numerical Results (C_v)





- **Vacancy concentration is comparable with the previous results, even though stress is significantly lower.**

Effect of Self-Diffusion



- Normalized flux term,

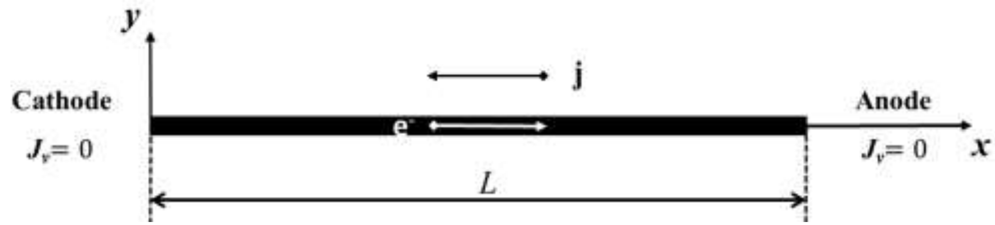
$$\beta_1 = \frac{F_E(x,t)}{Z^* e\rho j}, \quad \beta_2 = \frac{F_s(x,t)}{Z^* e\rho j}, \quad \beta_3 = \frac{F_c(x,t)}{Z^* e\rho j}$$

where

$$F_E = Z^* e\rho j, \; F_s = -\Omega \frac{\partial \sigma}{\partial x}, \; F_c = -\frac{k_B T}{C_v}\frac{\partial C_v}{\partial x}$$

- **Self-diffusion plays more important role than stress in electromigration.**

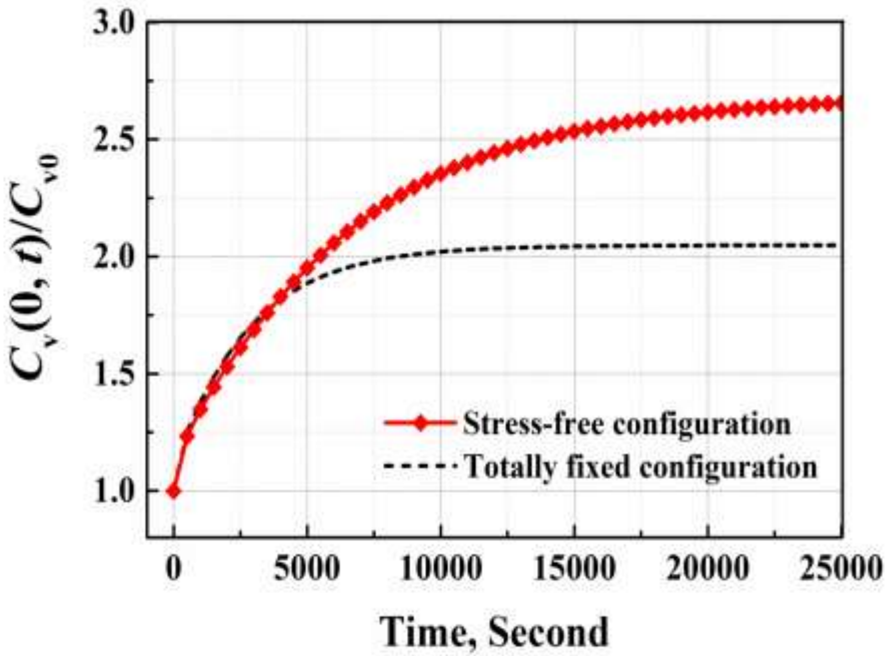
Numerical Results: Stress-Free Condition



- Governing equations,

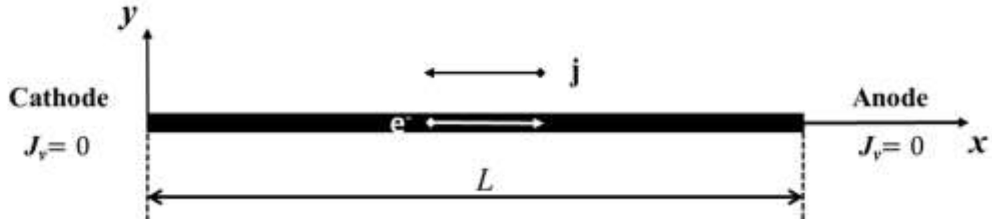
$$\frac{\partial C_v}{\partial t} = \frac{D_v C_v \Omega}{A}\left[\frac{\partial^2 C_v}{\partial x^2} + \frac{Z^* e \rho j}{k_B T}\frac{\partial C_v}{\partial x}\right]$$

$$\sigma = 0$$



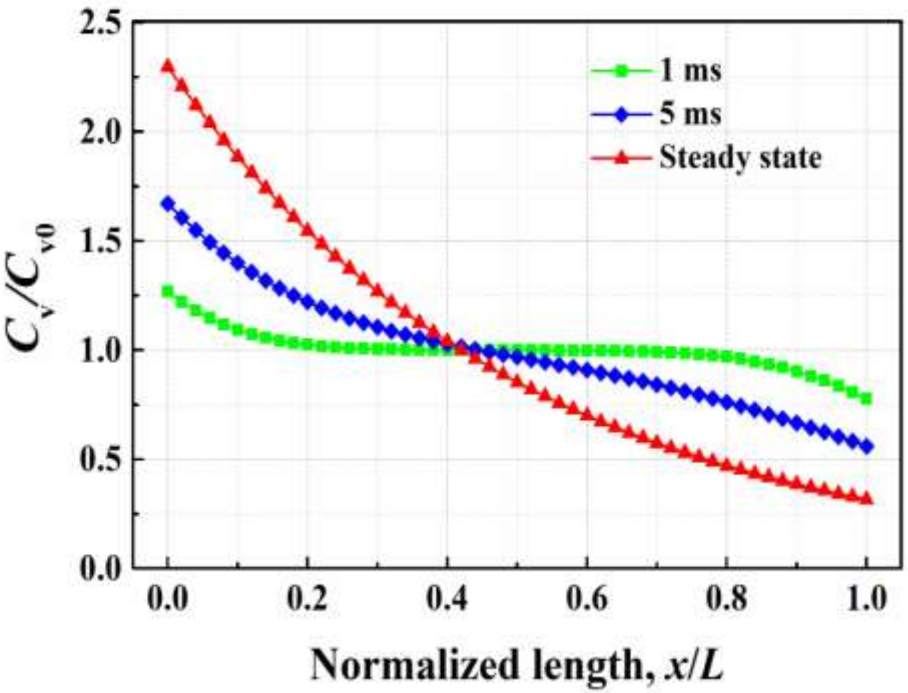
- **Electromigration happens on the same time-scale.**
- **Electromigration is resisted by the counter force due to concentration gradient.**

Stress-Free Condition (Lloyd's Results)



- Governing equations

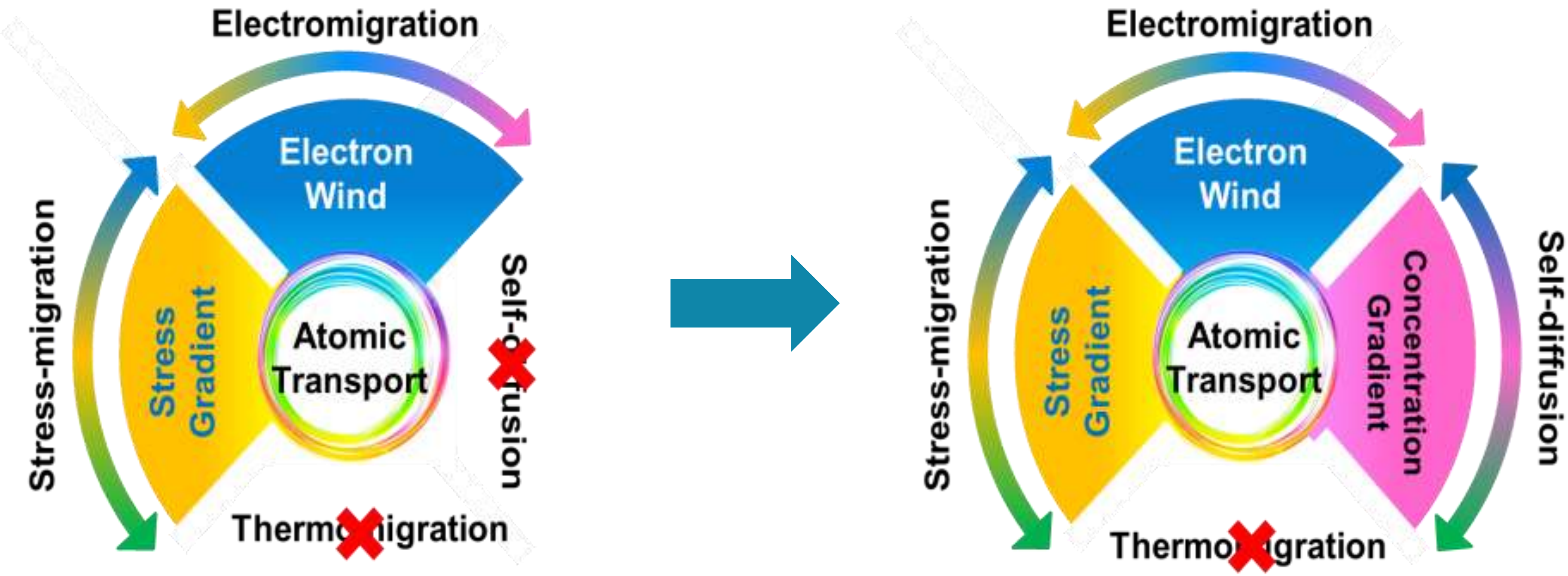
$$\frac{\partial C_v}{\partial t} = D_v\left[\frac{\partial^2 C_v}{\partial x^2} + \frac{Z^* e\rho j}{k_B T}\frac{\partial C_v}{\partial x}\right]$$



- **Electromigration happens in miliseconds.**
- **10^7 orders difference compared to the confined configuration.**

M. Shatzkes and J. Lloyd, JAP, 59, 3890, 1986.

Revisit – Blech's Theory



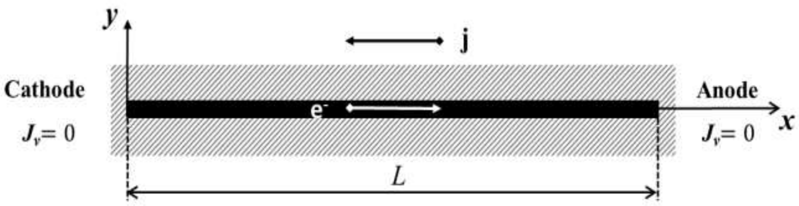
Blech's theory (1976)

Cui, Fan, Zhang (2019)

- **The effect of thermomigration is not taken into the consideration for the purpose of comparison.**

Blech Theory's Extension

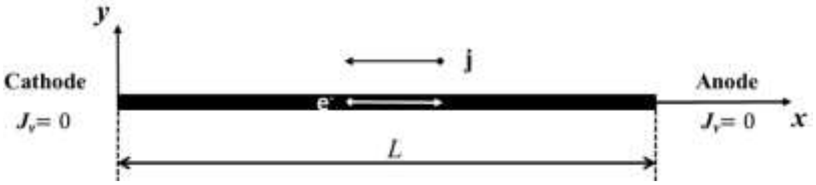
- **Confined Configuration**



$$\left(1+\frac{2EAf\Omega}{9(1-v)k_BT}\right)\frac{\partial^2 C_v}{\partial x^2}+\frac{Z^*e\rho j}{k_BT}\frac{\partial C_v}{\partial x}=0$$

$$jL_B=\frac{2EAf\Omega+9(1-v)k_BT}{9(1-v)Z^*e\rho}\ln\left(\frac{C_{v,max}}{C_{v,min}}\right)$$

- **Stress-free Configuration**

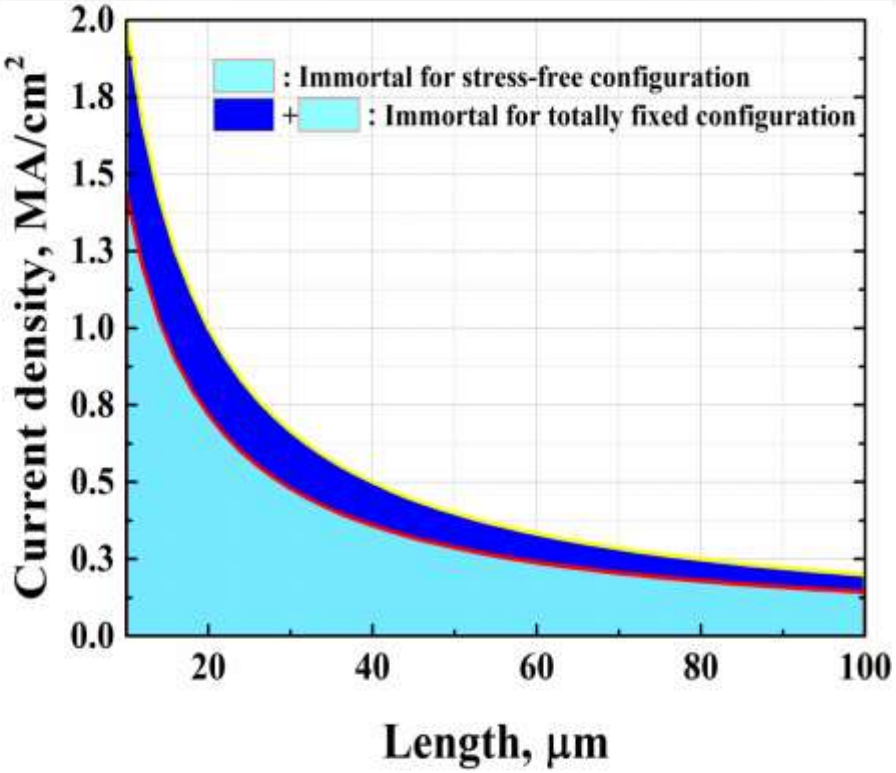


$$\frac{\partial^2 C_v}{\partial x^2}+\frac{Z^*e\rho j}{k_BT}\frac{\partial C_v}{\partial x}=0$$

$$jL_B=\frac{k_BT}{Z^*e\rho}\ln\left(\frac{C_{v,max}}{C_{v,min}}\right)$$

- The product of jL, is obtained for both confined and stress-free conditions.
- The vacancy concentration is used as threshold condition for failure criterion.

Threshold Product Curve



- **The confined metal line can sustain the higher current density than that of stress-free condition.**
- **The experimental results are consistent with the present theoretical predictions.**
  - In Blech's experiment, the measured threshold product for the uncovered metal line is lower than that for the confined metal line.

I. A. Blech, JAP. 47, 1203,1976.

Summary

- Electrical-thermal-mechanical modeling – sequential approach
- Electromigration
  - A 3-D general coupling model for electromigration is developed.

  - 1D solution for the confined configuration is obtained.
  - Mechanical stress-based failure criterion may not be valid anymore.

  - Blech's theory is revisited and reanalyzed.
  - Vacancy concentration, instead of hydrostatic stress, used for failure criterion – a departure from the original view.
  - The new predictions are consistent with experimental observations.

- Introduction
- Temperature Loading
- Mechanical Loading
- Moisture Loading
- Electrical Current Loading - Multi-Physics Modeling
- Summary

Module 1 – Temperature Loading

- **Thermal mismatch vs. temperature gradient**
- **Analytical solution**
  - Layered structure (stress, warpage, effective CTE)
  - Cylindrical structure (TSV)
- **Die-level thermal stress – thermal stress in TSV**
- **Package-level thermal stress problem – warpage**
- **Chip-package interaction (CPI) – submodeling technique**
- **Board level thermal stress problem**
  - Solder ball thermal cycling (Flip chip BGA, WLP)
  - Creep equations
  - Best method for practice
    - Initial stress free condition; full model vs. global/local model; worst solder ball location, volume averaging
- **Stress singularity of joint materials**

Module 2 – Mechanical Loading

- **JEDEC drop test standard**
  - JESD22-B111, old one, with 15 components
  - JESD22-B111A, new one, with 4 components or 1 component
- **Finite element modeling**
  - Input G method, large mass method, input displacement method, direct acceleration method
  - Global/local modeling
  - Peel stress used as indicator for failure
- **Four-point bending test and modeling**
  - Global/local modeling
  - Global with linear elastic but nonlinear geometry analysis
  - Local model with elastic-plastic modeling

Module 3 – Moisture Diffusion and Vapor Pressure

- **For a general moisture diffusion problem with temperature-dependent C_{sat} and varying ambient RH and temperature with time**
  - $\overline{C}_k$ must be used and the coupled element with thermal-diffusion or thermal-structural-diffusion option must be applied at the same time.
- **ANSYS built-in $\overline{C}$ approach cannot solve the problem with varying RH correctly.**
  - ANSYS diffusion element only
    - C_{sat} must be temperature-independent. Temperature gradient is not considered.
  - ANSYS coupled element with structural-diffusion option.
    - C_{sat} must be temperature-independent. Temperature gradient is not considered.
  - ANSYS coupled element with thermal-diffusion option (or thermal-structural-diffusion) option
    - If $\overline{C}$ is used, RH must be constant.
    - If $\overline{C}_k$ is used, no restriction for any diffusion problems.
- **Vapor pressure model.**
- **Thermal-hygro-mechanical modeling.**

Module 4 – Electrical Current Loading

- **Electrical-thermal-mechanical modeling – sequential approach**
- **Electromigration**
  - A 3-D general coupling model for electromigration is developed.
  - 1D solution for the confined configuration is obtained.
  - Mechanical stress-based failure criterion may not be valid anymore.
  - Blech's theory is revisited and reanalyzed.
  - Vacancy concentration, instead of hydrostatic stress, used for failure criterion – a departure from the original view.
  - The new predictions are consistent with experimental observations.

Thank you for your attention.

Questions?