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Moisture Related Reliability in Electronic Packaging

Instructor

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Introduction

- **Name**
- **Organization**
- **Responsibility**
- **Expectations**

Reminder

- **Request**
  - Please keep pagers / phones turned off
  - No email / web surfing
- **Active participation is encouraged**

Acknowledgement

Institute of Microelectronics

T.Y. Tee
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Outline

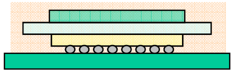
- Introduction
- Moisture absorption, desorption, and diffusion
- Vapor pressure model
- Case study I – underfill selection for FC BGA packages
- Case study II – delamination/cracking in stacked-die chip scale packages
- Accelerated moisture sensitivity test
- Effect of moisture on material properties
- Hygroscopic swelling
- Electrochemical metal migration
- Summary
- References

Introduction

Electronic Packaging Evolution

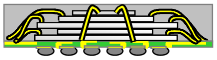

Leadframe based


Substrate based ball grid array (BGA)


Flip chip CSP


Quad Flat Leadless


Flip chip BGA


Stacked chip scale

- **Chip-scale and wafer-level packaging (CSP, WLP)**
- **High-density, high-performance packaging**
- **System in package (SIP)**

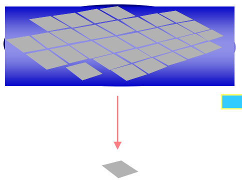
→

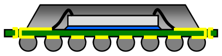
higher performance

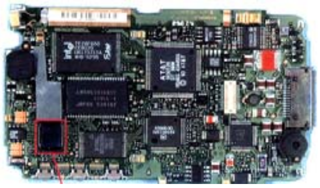
smaller size

cheaper price

Wafer, Package, and Board Levels



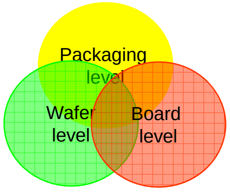




Wafer Fabrication & Backend Process

Electronic Packaging

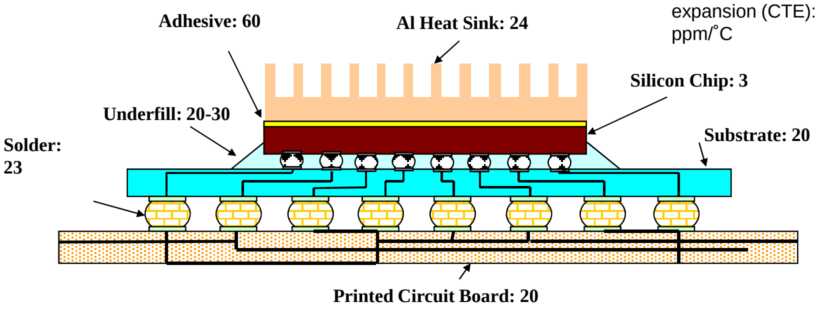
Surface Mounting



- **Design of a package must consider the interactions among wafer, package, and board**

Thermo-Mismatch Induced Stresses

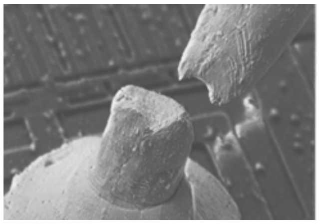
Coefficient of thermal expansion (CTE): ppm/°C



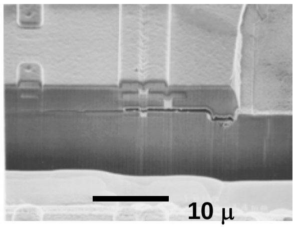
Reference temperature state

Thermal mismatch-induced deformation

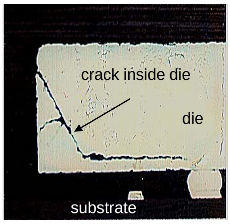
Failures by Thermal-Stresses



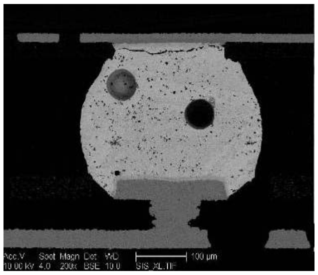
Wire bond damage



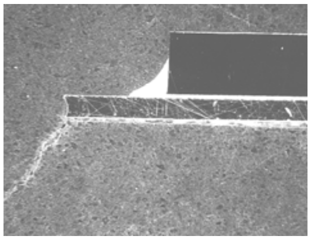
Thin film delamination



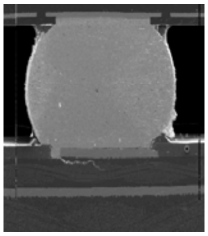
Die crack



Solder ball fatigue crack

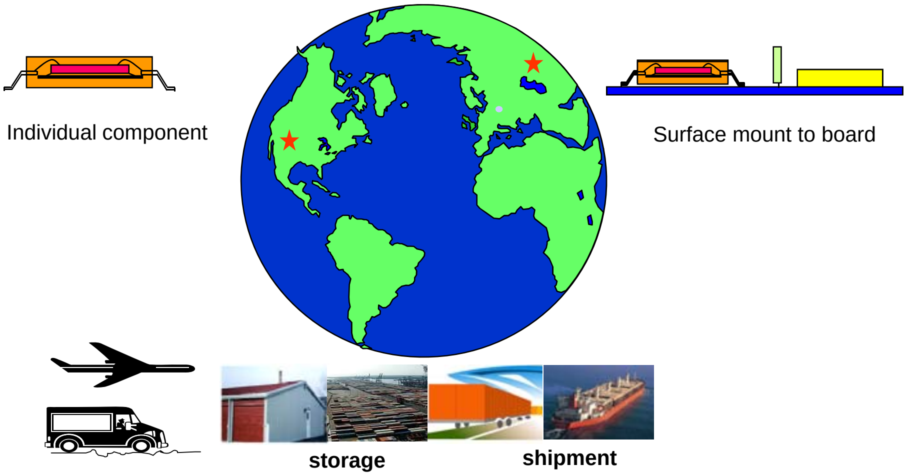


Interface delamination



Substrate cracking

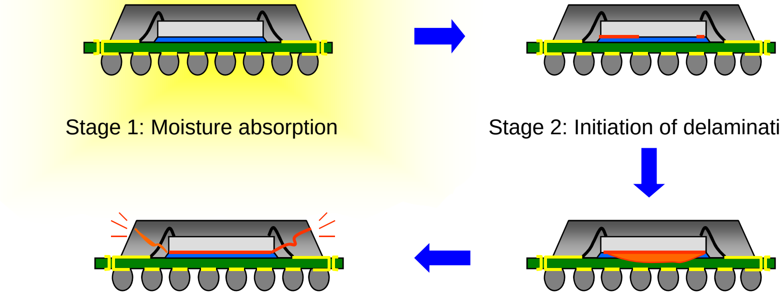
Moisture Absorption of Electronic Packages



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

Popcorn Failures at Soldering Reflow

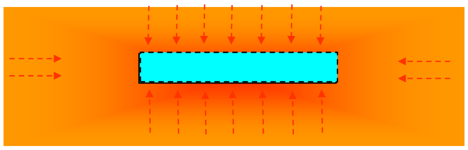
Device exposed to reflow temperature, typically 260°C



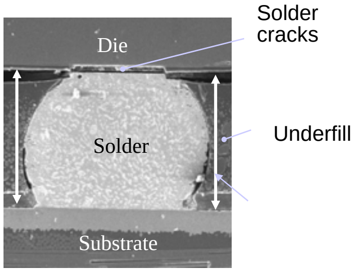
– Vapor pressure and adhesion reduction due to moisture vaporization are key mechanisms

Hygroscopic Swelling under HAST

- Polymer expands upon absorbing moisture – hygroscopic swelling
- Differential expansion results in hygro-mechanical strain and stress (similar to thermal strain and stress)
- Magnitude comparable to & may be larger than thermal stress
- Adhesion degradation



Typical Failure in flip-chip under Pressure cooker test (120°C, 100%RH)

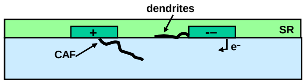


Hygro-swelling induces
- **solder cracking**
- **underfill delamination**
- **BLM, ILD delamination**

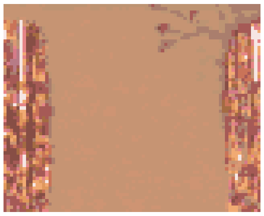
- Hygroscopic swelling and adhesion reduction are main failure mechanisms under HAST.

Electrochemical Migration under BiHAST

- **Conditions**
  - **Moisture absorption/condensation**
  - **Voltage**
  - **Contamination**
- **3 Basic Steps**
  - **Oxidation or dissolution of metal at anode**
  - **Transport of metal ions, across insulator towards cathode**
  - **Reduction and deposition at cathode**



Ref: Katayanagi et al. ESPEC Japan Tech-info Field Report #5, 1996



- Moisture provides electromigration transport path

Moisture Sensitivity Test (Precon)

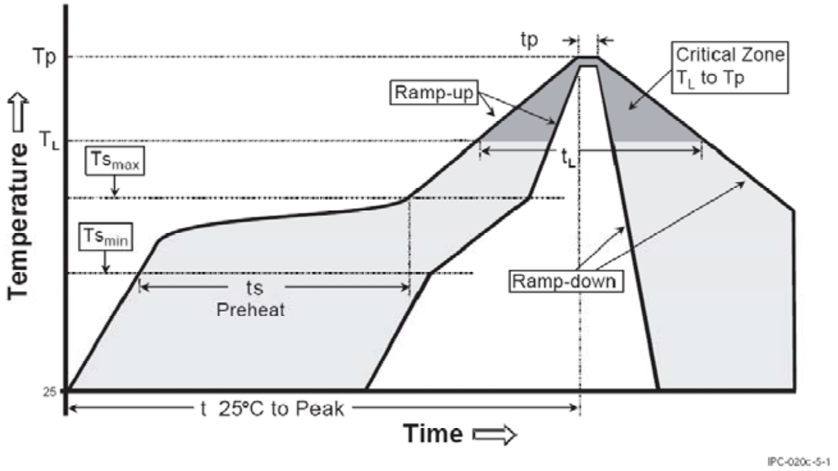
- **IPC/JEDEC J-STD-020C**

Table 5-1 Moisture Sensitivity Levels

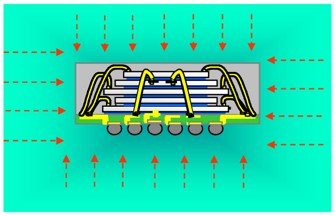
LEVEL	FLOOR LIFE		SOAK REQUIREMENTS Standard		
	TIME	CONDITIONS	TIME (hours)	CONDITIONS	
1	Unlimited	≤30 °C/85% RH	168 +5/-0	85 °C/85% RH	
2	1 year	≤30 °C/60% RH	168 +5/-0	85 °C/60% RH	
2a	4 weeks	≤30 °C/60% RH	696^{2} +5/-0	30 °C/60% RH	
3	168 hours	≤30 °C/60% RH	192^{2} +5/-0	30 °C/60% RH	**MSL 3**
4	72 hours	≤30 °C/60% RH	96^{2} +2/-0	30 °C/60% RH	
5	48 hours	≤30 °C/60% RH	72^{2} +2/-0	30 °C/60% RH	
5a	24 hours	≤30 °C/60% RH	48^{2} +2/-0	30 °C/60% RH	
6	Time on Label (TOL)	≤30 °C/60% RH	TOL	30 °C/60% RH	

Classification Reflow Profiles

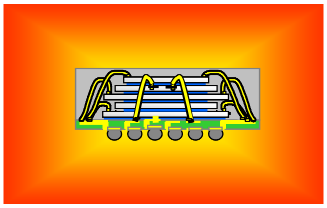
- **IPC/JEDEC J-STD-020C**
  - Soldering reflow traditionally @ 220°C degrees, now moving to 260°C (for no-lead solders).



Moisture Sensitivity Test

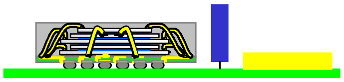


Stage 1: Moisture absorption
(e.g.: 30°C/60%RH for 168 hours)



Stage 2: Soldering reflow
(peak temp: 220°C → 260°C)

storage & shipment



surface mount

- **Moisture**
  - generates high vapor pressure
  - can degrade adhesion strength
  - induces stresses due to hygroscopic swelling

Highly Accelerated Stress Test (HAST)

- **Biased HAST**
- **Unbiased HAST**
  - HAST
  - Autoclave (Steam) – 121°C/100%RH

Environmental Test	Temperature (°C)	Relative Humidity (%RH)	Static /Dynamic Bias (V)
THB	85	85 / 60	0.1 to 7
	55	85 / 60	
	30	85 / 60	
HAST	156	85 / 60 / 50	
	130	85 /60 / 50	
	120	85 /60 / 50	
	110	85 /60	

Summary: Kinetic & Moisture Driven Failures

MECHANISM	DESCRIPTION	DRIVING FORCES	RELIABILITY STRESS
M+ Migration	Metal ion migration between contacts or traces that results in a short circuit	Temperature Humidity Voltage	Biased HAST
Interfacial delamination	Delamination between two materials that were bonded together that result in cracks and open circuits or migration paths (bond breaking with added energy)	Temperature Humidity	HAST / Bi HAST /Precon
Intermetallic IMC formation	Formation of intermetallic compound that is different in volume and with brittle properties that may result in open circuits or shorts	Temperature	Bake
Kirkendall voiding	Occurs with IMCs as charge moves from higher to lower potential area in material	Temperature	Bake Manufacturing
Electromigration voiding	Void left as material is picked up with electron wind (current flow)	Temperature Current Mech. Stress	Electromigration
Thermal material degradation	Thermal resistance and mechanical degradation resulting from polymer degradation and micro-crack	Temperature Mech. Stress	Bake
Dielectric cracking	Cracking in polymers or glasses that results from moisture assisted crack growth propagation	Humidity Temperature	HAST Steam/TH/Precon

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Summary

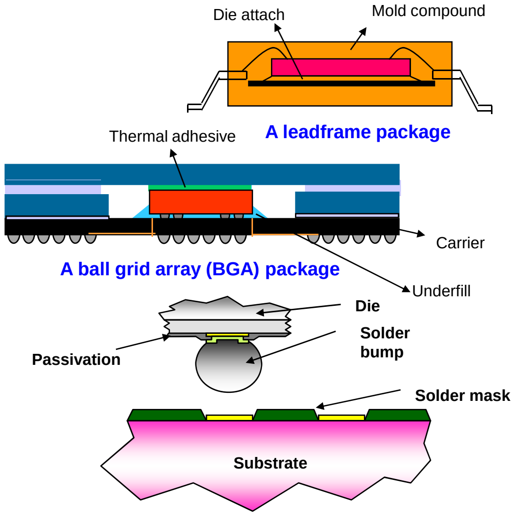
- **3 failure mechanisms due to moisture**
  - ‘Popcorn’ at soldering reflow (vapor pressure, adhesion reduction)
  - Delamination under HAST (hygroscopic swelling, adhesion reduction, moisture aging)
  - Metal migration under BiHAST (e.g. dendritic growth. Moisture, voltage, contamination)
- **3 reliability tests**
  - Moisture sensitivity test (MSL 1, MSL 2, MSL 3 …)
    - MSL 3 - 30°C/60%RH for 192 hours
  - HAST/TH
  - BiHAST/BiTH

Understanding moisture diffusion is a key

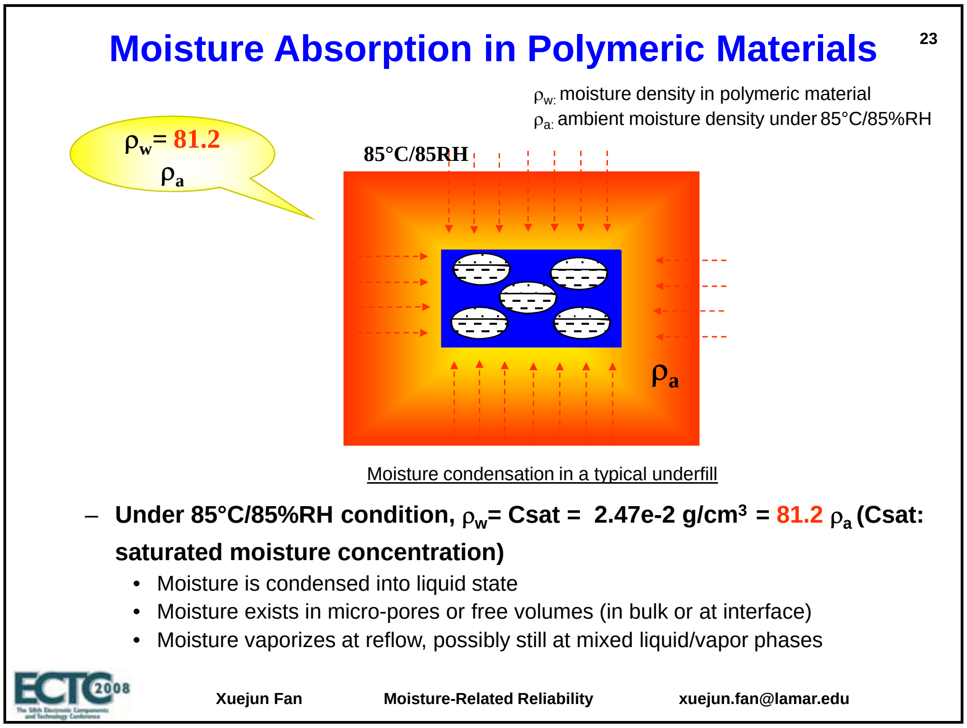
Moisture Absorption, Desorption and Diffusion

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



- **Materials change over a range of temperatures**
- **Susceptible to moisture absorption**

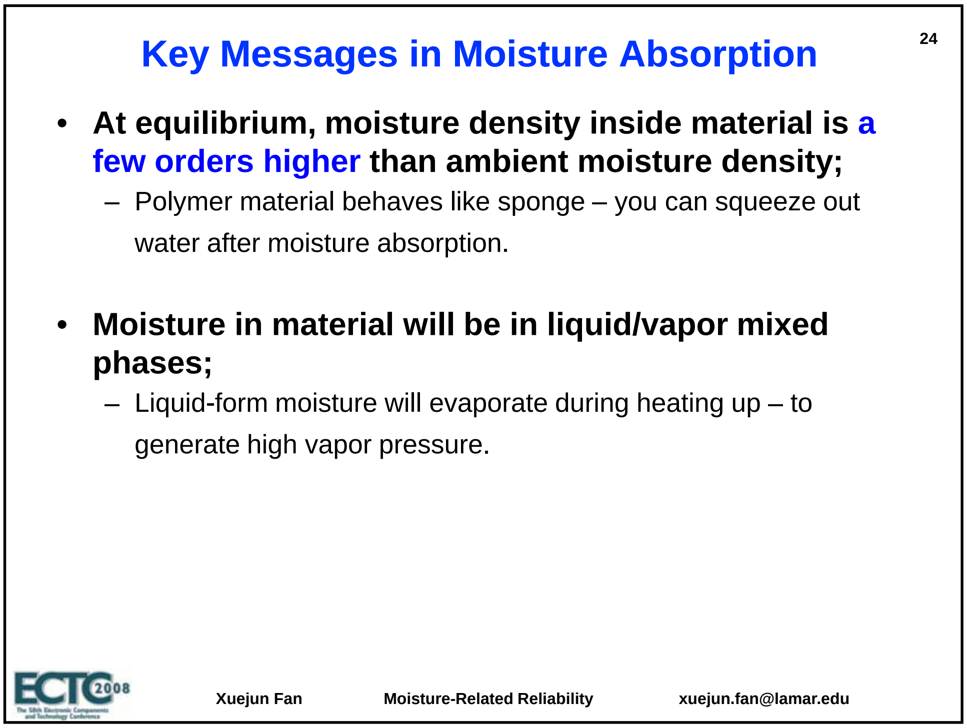


Moisture Absorption in Polymeric Materials

$\rho_{w:}$ 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



Key Messages in Moisture Absorption

- **At equilibrium, moisture density inside material is a few orders higher than ambient moisture density;**
  - Polymer material behaves like sponge – you can squeeze out water after moisture absorption.
- **Moisture in material will be in liquid/vapor mixed phases;**
  - Liquid-form moisture will evaporate during heating up – to generate high vapor pressure.

Fundamentals of Moisture Absorption

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

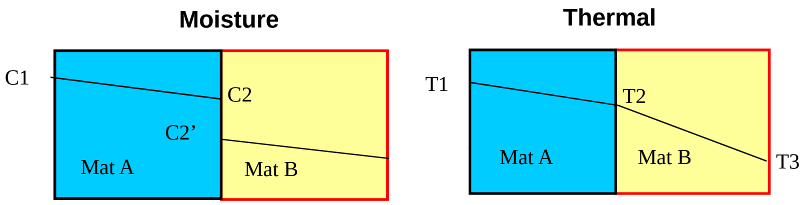
$$RH = \frac{Actual\ vapor\ pressure\ of\ the\ air}{Saturated\ vapor\ pressure\ of\ the\ air} \times 100\%$$

Fundamentals of Moisture Diffusion

- **Fundamental variables and properties**
  - Moisture concentration, $C(\underline{\mathbf{x}}, t; T, RH)$
    - Mass of moisture per unit volume of substance.
  - Saturated moisture concentration, $C_{sat}(T, RH)$
    - Maximum mass of moisture absorbed per unit volume of substance at given temperature and humidity.
  - Diffusivity, $D(T, RH)$
    - A measure of the rate of moisture mass diffusion
    - Defined as the amount of mass flux per unit concentration gradient
- **Fick's diffusion equation**

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right)$$

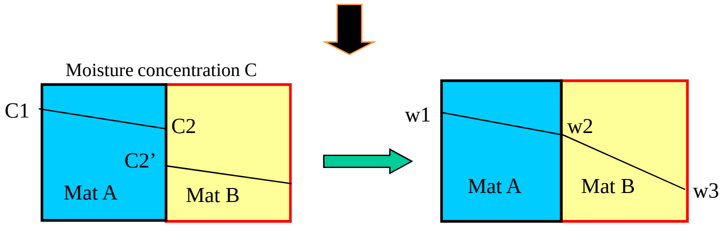
Comparing Moisture Diffusion to Heat Transfer



Discontinuity for moisture concentration

Continuity for temperature

Normalize moisture concentration (φ =C/S or w = C/C_{sat})



Moisture Diffusion Modeling

- **Thermal-moisture analogy**

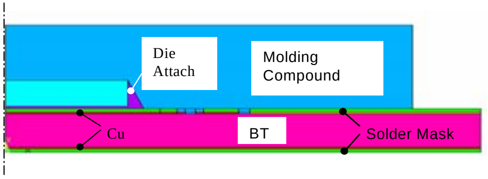
Properties	Thermal	Moisture
Field variable	Temperature, T	φ = C/S
Density	ρ	1
Conductivity	k	D S
Specific capacity	c	S

Moisture concentration: C= φ S

Moisture diffusivity: D = DS/(1xS) = D

Moisture Diffusion Modeling

- **Input**
  - **Preconditioning conditions – e.g. 60°C/60RH**
  - **Diffusivities for each material (die-attach, mold compound, BT, and solder mask)**
  - **Saturated moisture concentration for each material (die-attach, mold compound, BT, and solder mask)**
  - **From material characterization or supplier's data**

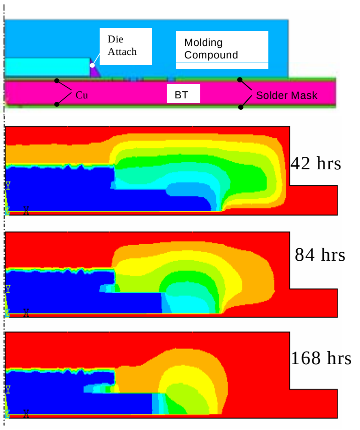


- Output
  - Moisture concentration at each location
  - Package total weight gain: $\sum C^* V_{element}$
- Compare
  - Package weight gain data

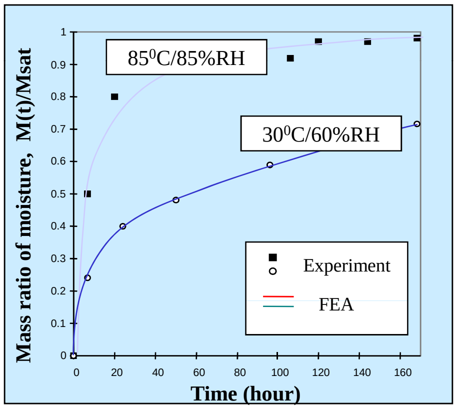
Moisture Diffusion Modeling: Validation

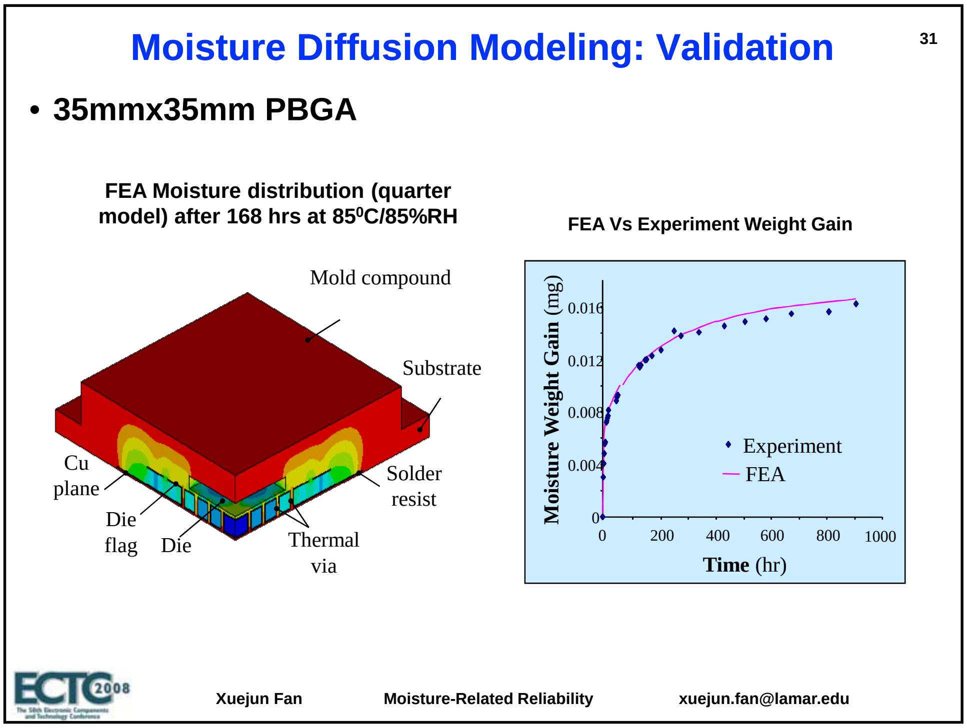
- **3-D PBGA**

FEA Moisture distribution



FEA vs Experiment Weight Gain





Moisture Diffusion Modeling: Validation

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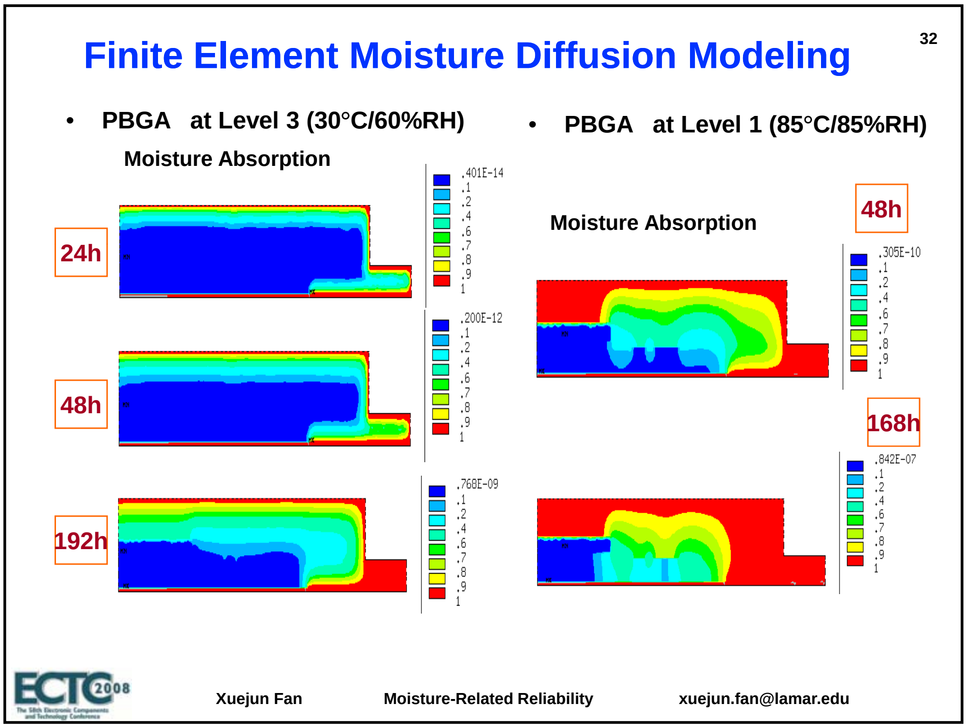
- **35mmx35mm PBGA**

FEA Moisture distribution (quarter model) after 168 hrs at 85^{0}C/85%RH

FEA Vs Experiment Weight Gain

Xuejun Fan **Moisture-Related Reliability** **xuejun.fan@lamar.edu**



Finite Element Moisture Diffusion Modeling

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- **PBGA at Level 3 (30°C/60%RH)**

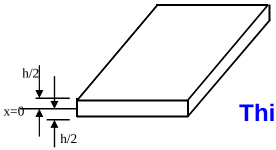
Moisture Absorption

- **PBGA at Level 1 (85°C/85%RH)**

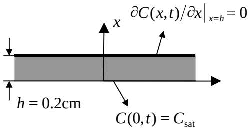
Moisture Absorption

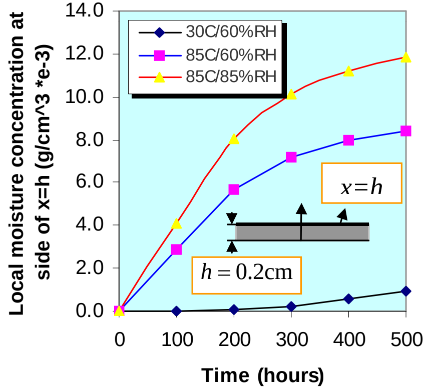
Xuejun Fan **Moisture-Related Reliability** **xuejun.fan@lamar.edu**

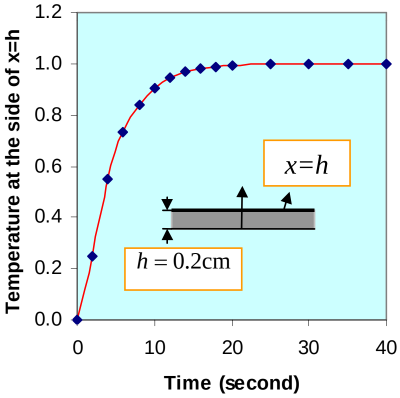
Moisture Diffusion vs. Heat Conduction



Thickness: 2mm

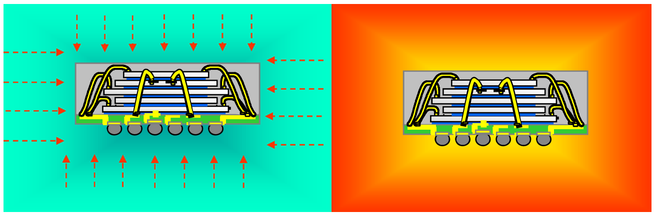






- **In most cases, the thermal modeling can be decoupled with moisture diffusion modeling**

Moisture Desorption



Moisture absorption
(e.g. 30°C/60%RH:168 hours)
(Factory environment after opening dry-bag)

Moisture desorption
(reflow process)

- **Moisture desorption takes place at reflow**
  - Elevated temperature, varying as function of time
  - Short time period (3 – 5 minutes)
  - Diffusivities a few orders higher

Moisture Desorption Modeling

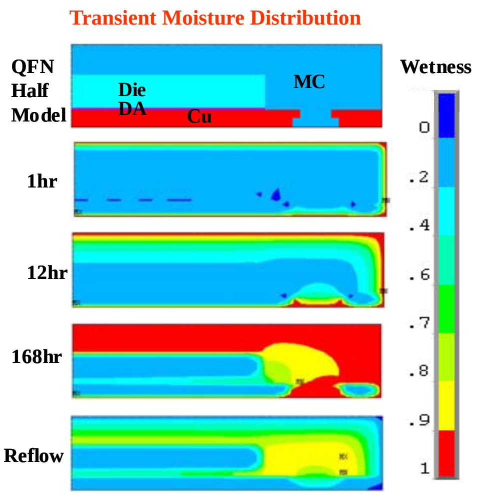
$$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z^2}=\frac{1}{D}\frac{\partial\varphi}{\partial t}+\frac{\varphi}{D\cdot S}\frac{\partial S}{\partial t}$$

$$\frac{\varphi}{D\cdot S}\frac{\partial S}{\partial t}\neq 0$$

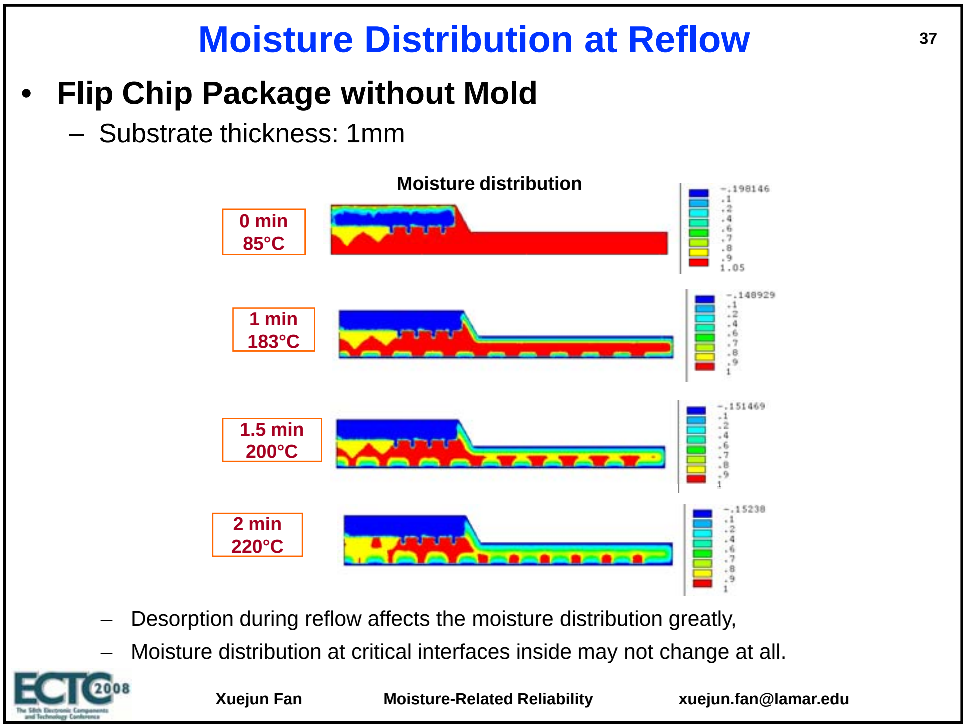
- **φ =C/S, S=S(T) = S[T(t)] = S(t)**
- **Normalization approach doesn't work!**
- **Direct moisture concentration approach (DCA) can be introduced (B. Xie et. al. ECTC 2007)**
- **An exception**
  - **Normalization approach with C/Csat is still applicable when Csat is assumed independent of temperature over entire reflow period**

Moisture Desorption at Reflow

- **Desorption effect is considered (QFN Package)**



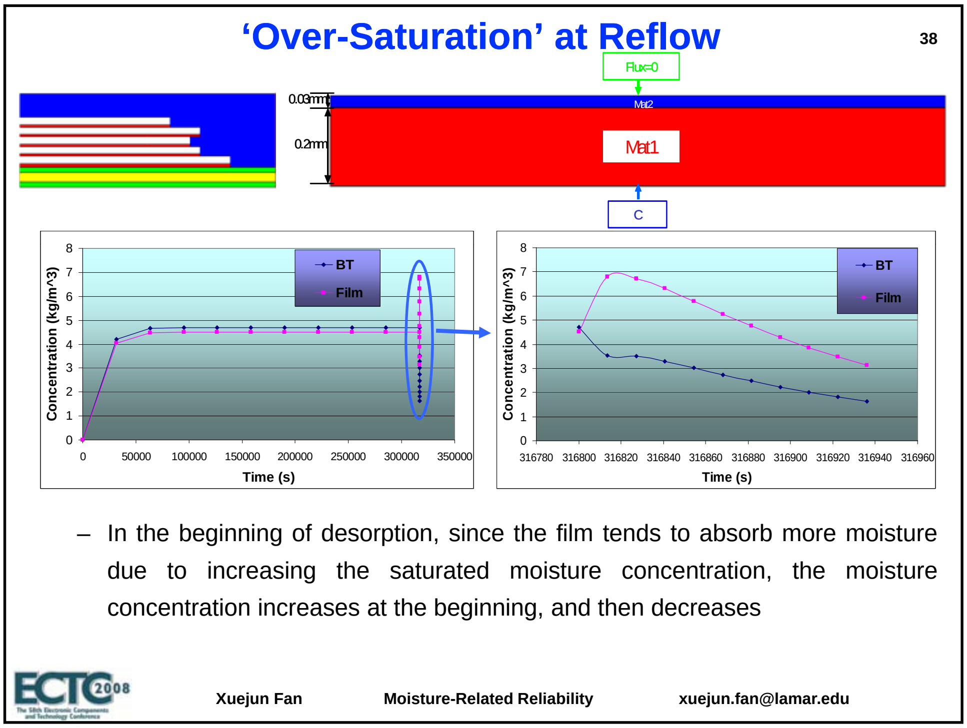
- **After 168 hours at 85°C/85%RH**
  - The package is almost fully saturated with moisture
- **During reflow,**
  - External package surface loses a significant amount of moisture due to high moisture desorption rate
  - Moisture concentration in the interior of the package remains relatively unchanged
  - The local moisture concentration along critical interfaces determines the strength of interfacial adhesion and magnitude of internal vapor pressure induced



Moisture Distribution at Reflow

- **Flip Chip Package without Mold**
  - Substrate thickness: 1mm

  - Desorption during reflow affects the moisture distribution greatly,
  - Moisture distribution at critical interfaces inside may not change at all.



‘Over-Saturation’ at Reflow

- In the beginning of desorption, since the film tends to absorb more moisture due to increasing the saturated moisture concentration, the moisture concentration increases at the beginning, and then decreases

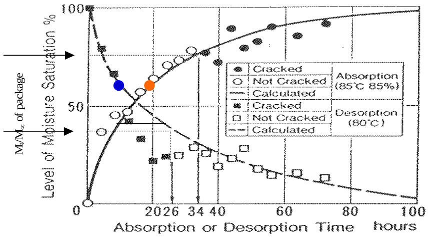
Package Total Weight Gain vs. Local Moisture Concentration

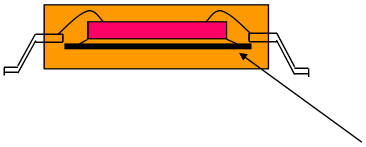
- **QFP package - moisture absorption – 40% saturated weight gain**

- **QFP package - moisture absorption until saturated weight. Then desorp until 40% saturated weight gain**

- **The first case passed pre-con test, will the second case pass?**

Moisture Absorption versus Popcorn Cracking

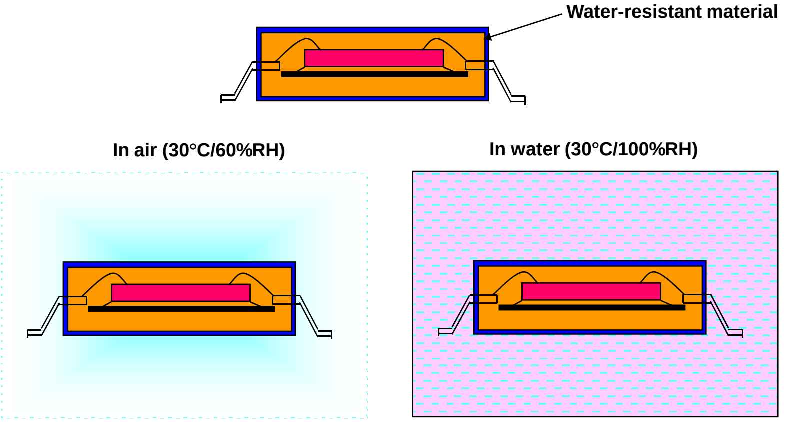




Local moisture concentration *C for the first case is less than the second case*

- Package cracking is *independent* of the total mass of moisture in the package (Kinato et al, IRPS, 1988);
  – But *dependent* on the local moisture concentration in the package

Moisture Absorption vs. Water Absorption



Moisture gain in package

No moisture gain in package

- Some materials are water-resistant, but absorb moisture in air.

Material Related Properties

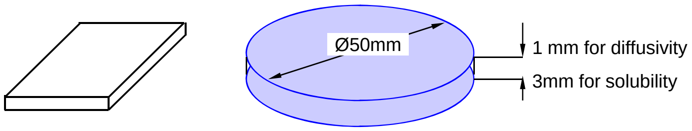
- Diffusion Coefficient / Diffusivity, D(T)
  - Measures the rate of mass diffusion
  - Defined as the amount of mass flux per unit concentration gradient (m^2/s)
  - A function of material and temperature
- Saturated Moisture Concentration, $C_{sat}(RH, T)$
  - The maximum mass of moisture per unit volume of the substance kg/m^3.
- Solubility, S(T)
  - 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

Characterization Method

- **Procedures** - documented in the following standards
  - Semi G66-96 Test method for the measurement of moisture absorption characteristics for semiconductor plastic molding compound
  - ASTM D570-95 Standard test method for moisture absorption of plastics
  - BS 2782: Part 4-1983, ISO 62 -1980
  - Method 430A Determination of water absorption at 23^{0}C
  - Method 430B Determination of water absorption at 23^{0}C with allowance for water-soluble matter
  - Method 430C Determination of boiling water absorption
  - Method 430D Determination of boiling water absorption with allowance for water-soluble matter

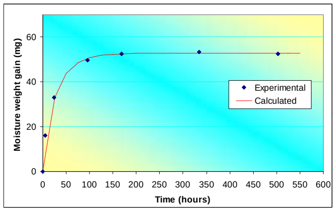


Solubility and Diffusivity - Experimental Characterization

- **Source of Error**
  - Specimen Preparation
    - Minimize voids
    - Sufficient aspect ratio to
      - promote 1-D diffusion and minimize edge effect
  - Measurement
    - Inaccurate measurement
      - Total weight of specimen*1%*1% > scale resolution
    - Improper measurement frequency
      - Too frequent : excessive disturbance to TH chamber
      - Too sparse : missing data

Experimental Data Analysis

- **Sample requirement: t << length or width**
- **1D diffusion valid, and**



$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}$$

  - C: moisture concentration (mg/cm^3)
  - D: diffusivity (cm^2/sec)
- **Diff. eq. can be solved with initial and boundary conditions**

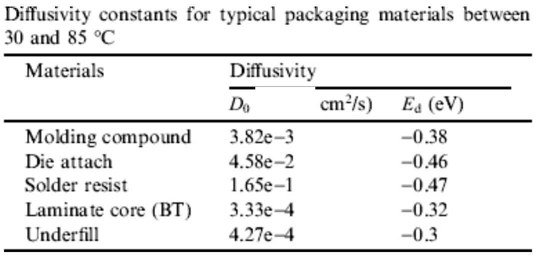
$$\frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-\frac{(2n+1)^2 \pi^2 D}{h^2} t \right]$$

M_t: weight gain at time t
M_∞: saturated weight gain
h: thickness

Temperature Dependency of Diffusivity

- **Diffusivity D(T) vs. temperature T – Arrhenius relation**

$$D = D_0 \exp\left(\frac{E_d}{kT}\right)$$



Diffusivity constants for typical packaging materials between 30 and 85 °C

Materials	Diffusivity	
	D_0 cm^2/s)	E_d (eV)
Molding compound	3.82e−3	−0.38
Die attach	4.58e−2	−0.46
Solder resist	1.65e−1	−0.47
Laminate core (BT)	3.33e−4	−0.32
Underfill	4.27e−4	−0.3

- D increases with temperature exponentially
- Near or above T_g, the Arrhenius relation is described with a new set of constants reflecting the change in the molecular structure of the material across the transient temperature.

Temperature Dependency of Solubility

- **Solubility vs. temperature – Arrhenius Relation**

$$S = \frac{C_{\mathrm{sat}}}{P} = S_0 \exp\left(\frac{E_s}{kT}\right)$$

C_{sat} (60%RH) and activation energy of typical packaging materials

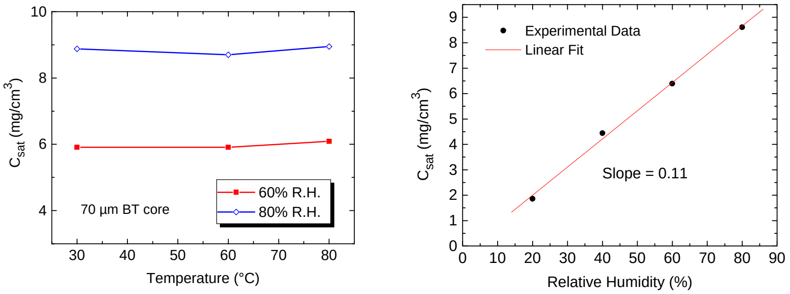
Materials	C_{sat} (mg/cm^3)		E_s (eV)
	30 °C	85 °C	Curve fit
Molding compound	1.76	1.81	0.44
Die attach A	7.53	7.41	0.45
Die attach B	7.07	9.56	0.37
Solder resist	15.9	16.8	0.44
Laminate core (BT)	4.83	4.5	0.46

- When temperature increases solubility decreases (activation energy positive)

Temperature and Humidity Dependency of C_{sat}

- **Csat = p*S**
- **p = RH * p_{sat} (T) = RH * p_0 exp (- E_p/ kT)**
- **Csat = RH * p_0 exp (- E_p/ kT)* S_0 exp(E_s/kT) = RH*C_0 exp [(E_s-E_p)/kT]**

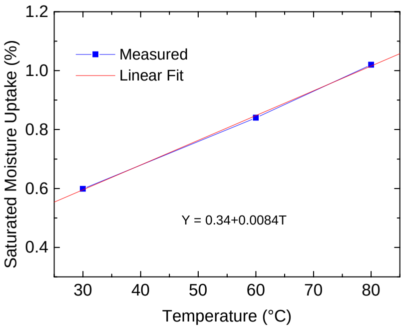
In-Situ Moisture Measurement for BT-Core



- Saturated moisture concentration under fixed humidity independent of temperature below Tg (e.g. BT-core)
- Saturated moisture concentration linear with humidity

Saturated Moisture Concentration vs. Temperature

- **A low-Tg die-attach film**
- **60%RH**



  – Within the temperature range, it seems that the saturated moisture content increases linearly with increasing temperature

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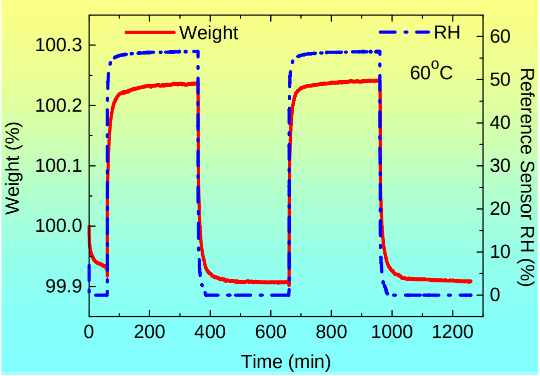
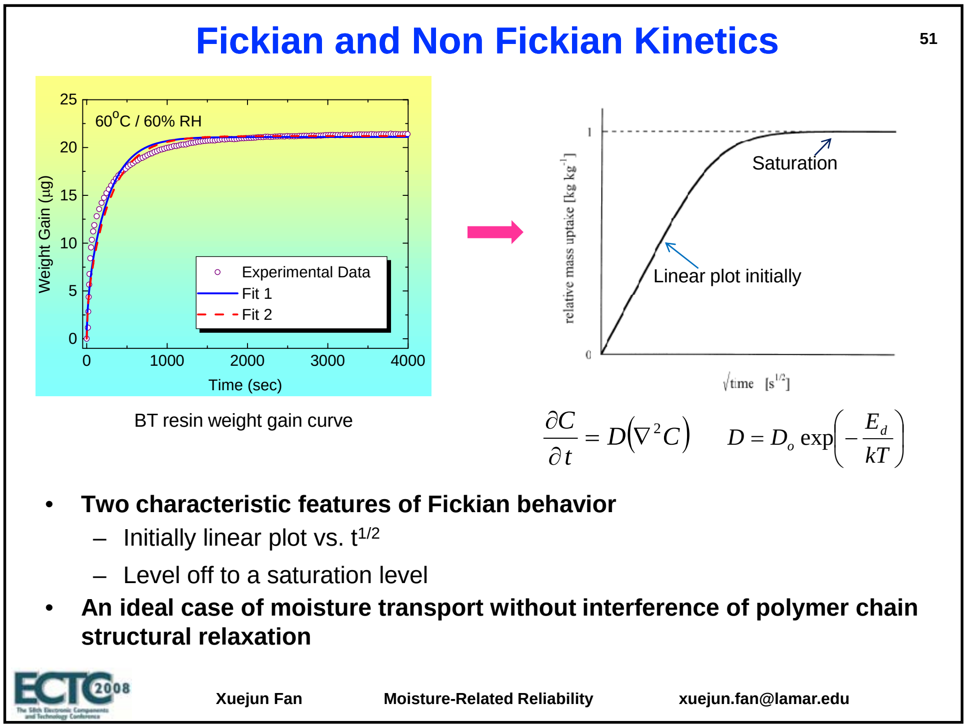
Moisture Absorption and Desorption

Moisture absorption-desorption experiment for BT-core



- **The subsequent absorption-desorption cycles were repeatable**
  - The sample reaches approximately the same saturated moisture level during sorption and it loses the same weight upon drying
- **This indicates that there is no chemical reaction between the water molecules and the material**

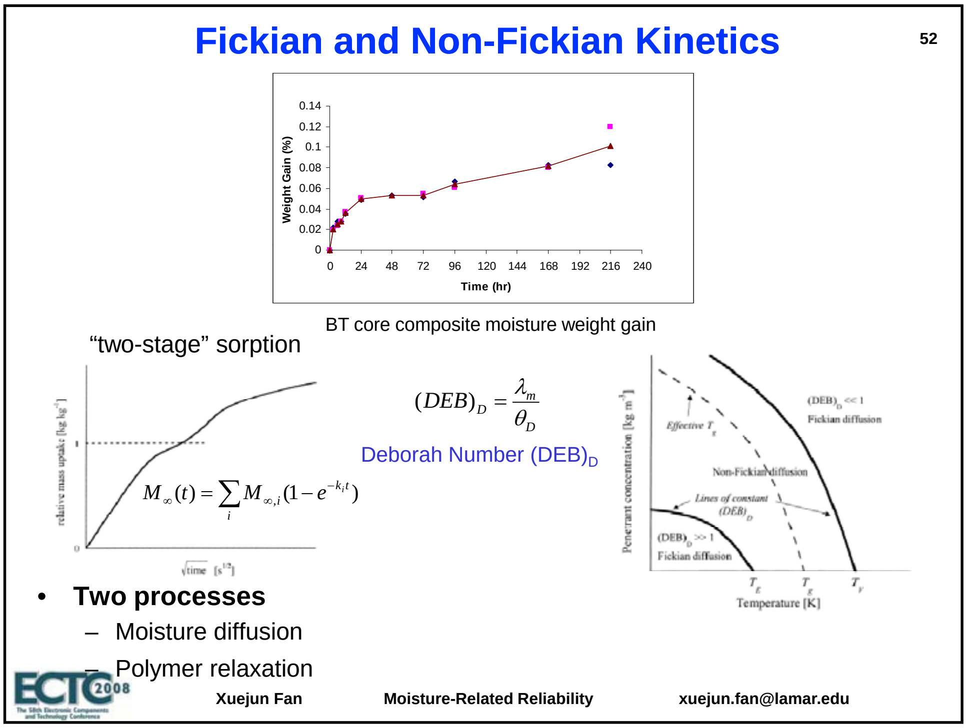


Fickian and Non Fickian Kinetics

BT resin weight gain curve

$$\frac{\partial C}{\partial t} = D\left(\nabla^2 C\right) \qquad D = D_o \exp\left(-\frac{E_d}{kT}\right)$$

- **Two characteristic features of Fickian behavior**
  - Initially linear plot vs. $t^{1/2}$
  - Level off to a saturation level
- **An ideal case of moisture transport without interference of polymer chain structural relaxation**



Fickian and Non-Fickian Kinetics

BT core composite moisture weight gain

“two-stage” sorption

$$M_\infty(t) = \sum_i M_{\infty,i}(1 - e^{-k_i t})$$

$$(DEB)_D = \frac{\lambda_m}{\theta_D}$$

Deborah Number $(DEB)_D$

- **Two processes**
  - Moisture diffusion
  - Polymer relaxation

Non-Fickian Moisture Absorption and Desorption

- **Two types of mold compound** **(2mm thickness)**

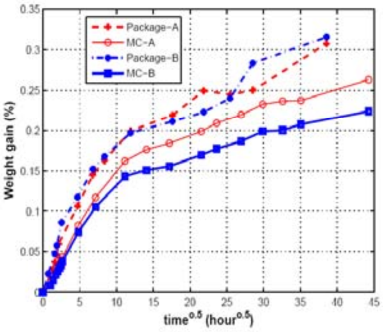
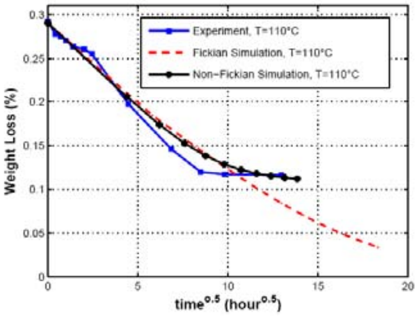


Fig.1 Experiments on moisture uptake of samples with exposed time at 85°C/85%RH.

Moisture absorption

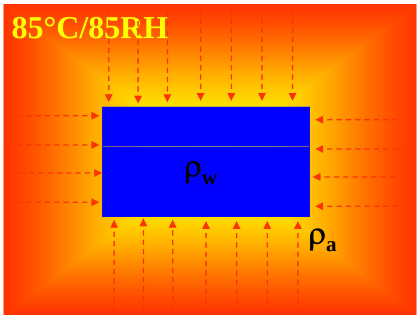


Moisture desorption

- **After 12 weeks, saturation condition has not been reached**
- **After 24 hours desorption at 110°C, a residual moisture content of about 40% saturation level was observed**

Ack: H. Shirangi, J. Auersperg, EuroSimE 2008, 455-462

States of Moisture in Polymers



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

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

ρ_w **= (20 -200)**ρ_a

- **Where to stay?**
  - Free volume or micro/nano pores
- **Moisture state**
  - Bound water (hydrogen bond)
  - Unbound water (liquid or gas)

Summary

- Moisture in polymer materials will be in liquid/vapor mixed phases
- Moisture concentration is discontinuous along bi-material interface –special treatment such as normalization must be applied
- Local moisture concentration, not total moisture weight gain, determines package moisture performance
- Moisture absorption is different from water absorption
- Moisture absorption is a reversible process for Fickian type of moisture diffusion
- Diffusivity, solubility and saturated moisture concentration are moisture related properties

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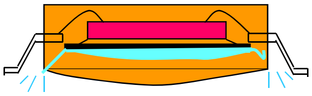
Vapor Pressure Model

Introduction - Popcorn Failure



- Moisture is vaporized at high temperature
- Vapor pressure plays a critical role in popcorn failure
- Vapor pressure exists anywhere in package where moisture resides

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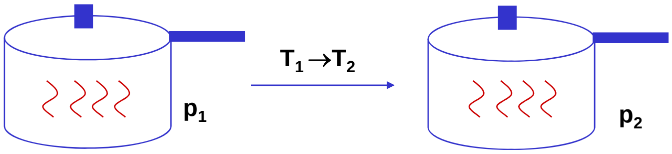
Example: Pressure Cooker

- **Vapor phase**

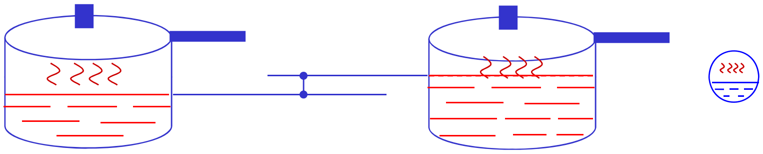


Single vapor phase

  - 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:** $p_2 = p_1 T_2 / T_1$

Example: Pressure Cooker

- **Liquid/vapor phase**



Given temperature T (e.g., 170°C)

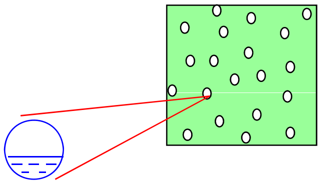
  - Moisture in two-phases – water/vapor mixed;
  - $\rho > \rho_g(T)$ - liquid-vapor phase , **ρ: moisture density over the total volume of cooker**; $\rho_g(T)$: saturated moisture vapor density
  - $\rho = m_m/\text{volume}$ – apparent moisture density
  - Saturated vapor pressure remains regardless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

---

Multi-Scale Analysis

- **Representative Elementary Volume (REV) concept**
  - **Microscopic level**
- **Moisture condensed into mixed liquid/vapor phases**
- **From macroscopic to microscopic**
  - f: interstitial space fraction (or free-volume fraction)
  - C: moisture concentration (from moisture diffusion at macroscopic level)
  - ρ: moisture density in pores

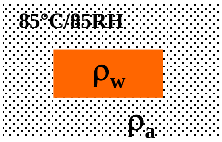
$$\rho = \frac{\mathrm{d}m}{\mathrm{d}V_f} = \frac{\mathrm{d}m}{\mathrm{d}V}\frac{\mathrm{d}V}{\mathrm{d}V_f} = C/f$$

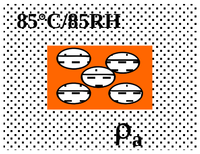


A representative elementary volume

  - $\rho < \rho_g$ (T): single vapor phase
  - $\rho \geq \rho_g$ (T): mixed liquid/vapor phase

Example: Moisture Density in Free Volumes





- **Apparent moisture density over voids- ρ**

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

ρ_w= Csat = 81.2 ρ_a

ρ =Csat/f = 1624 ρ_a

f=5%

Steam Table

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

Saturated Vapor Pressure

$$P_{sat}(kPa) = \exp(a_0 + a_1 x + a_2 x^2 + a_3 x^3)$$

$$where\ x = \frac{1}{273 + T(^oC)}$$

$$a_0 = 16.033225\ ,\ a_1 = -3.5151386\ \times 10^3, a_2 = -2.9085058\ \times 10^5,\ a_3 = 5.0972361\ \times 10^6$$

- **The saturated vapor pressure, Psat(T), is the pressure at which liquid water and water vapor can coexist at temperature T.**
- **The amount of water vapor (Psat(T)) the void can hold increases with temperature.**

Moisture State in Voids

- **Single vapor phase when**

$$\rho \le \rho_g(T_0)$$

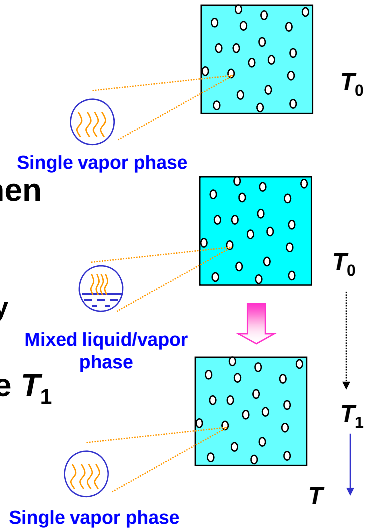
- **Mixed liquid/vapor phase when**

$$\rho > \rho_g(T_0)$$

  - ρ_g **- the saturated vapor density**

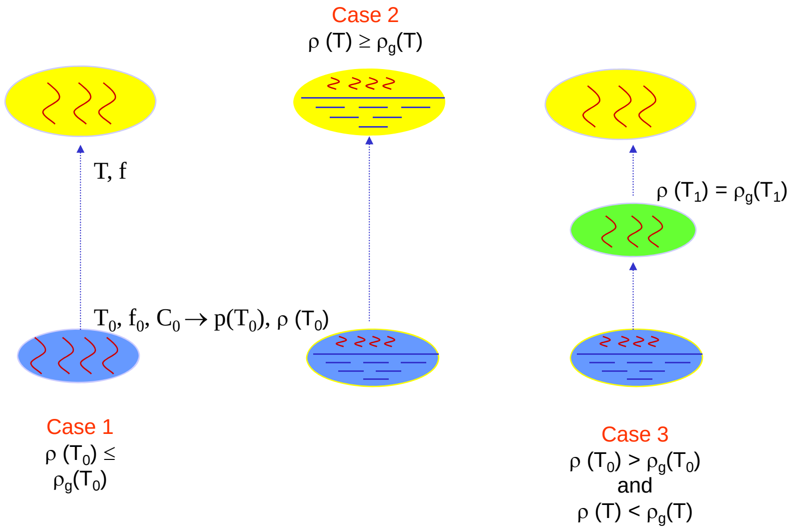
- **Phase transition temperature T_1**

$$\rho(T_1) = \rho_g(T_1)$$



T_0: moisture pre-conditioning temperature

Vapor Pressure Model



Case 2

$\rho\ (T) \geq \rho_g(T)$

T, f

$\rho\ (T_1) = \rho_g(T_1)$

$T_0, f_0, C_0 \rightarrow p(T_0), \rho\ (T_0)$

Case 1

$\rho\ (T_0) \leq \rho_g(T_0)$

Case 3

$\rho\ (T_0) > \rho_g(T_0)$

and

$\rho\ (T) < \rho_g(T)$

Vapor Pressure Model

Case 1: $C_0 / f_0 \leq \rho_g(T_0)$

Case 2: $\frac{C_0}{f}\frac{1-f}{1-f_0}e^{-3\alpha(T-T_0)} \geq \rho_g(T)$

Case 3: $C_0 / f_0 > \rho_g(T_0)$

and $\frac{C_0}{f}\frac{1-f}{1-f_0}e^{-3\alpha(T-T_0)} < \rho_g(T)$

$$\boxed{p(T) = \frac{C\,p_g(T_0)}{\rho_g(T_0)f}\frac{T}{T_0}\frac{1-f}{1-f_0}e^{-3\alpha(T-T_0)}}$$

$$\boxed{p(T) = p_g(T)}$$

$$\boxed{p(T) = p_g(T_1)\frac{T}{T_1}\frac{f(T_1)}{f}\frac{1-f}{1-f(T_1)}e^{-3\alpha(T-T_1)}}$$

where

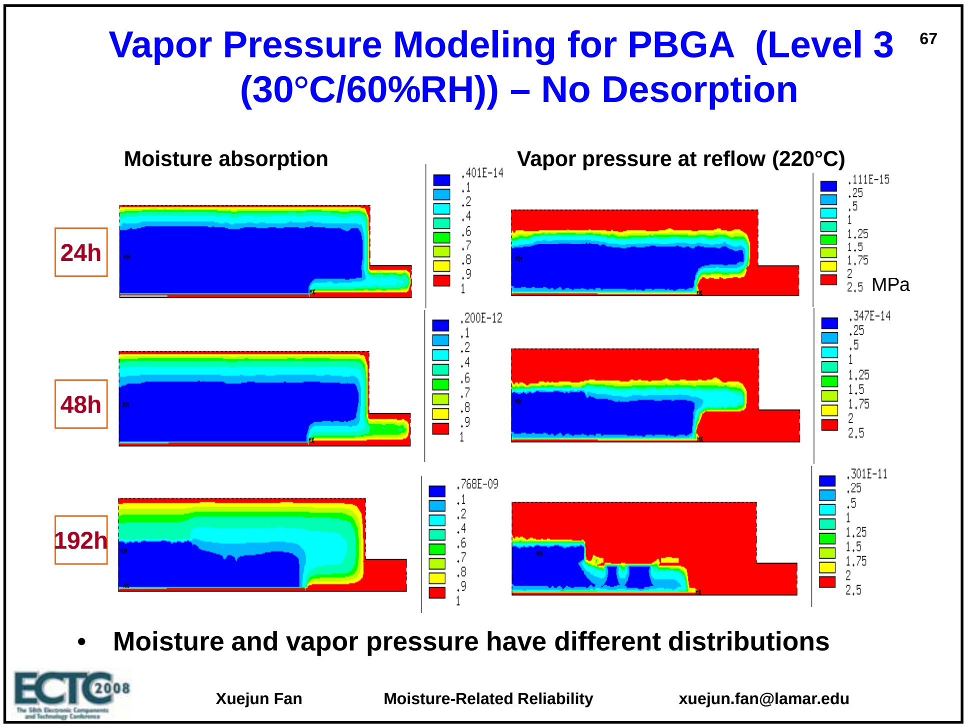
$$\frac{C}{f(T_1)}\frac{1-f(T_1)}{1-f_0}e^{-3\alpha(T-T_1)} = \rho_g(T_1)$$

↑ Vapor phase only

↑ Liquid/vapor phase

↑ Transition from liquid to vapor

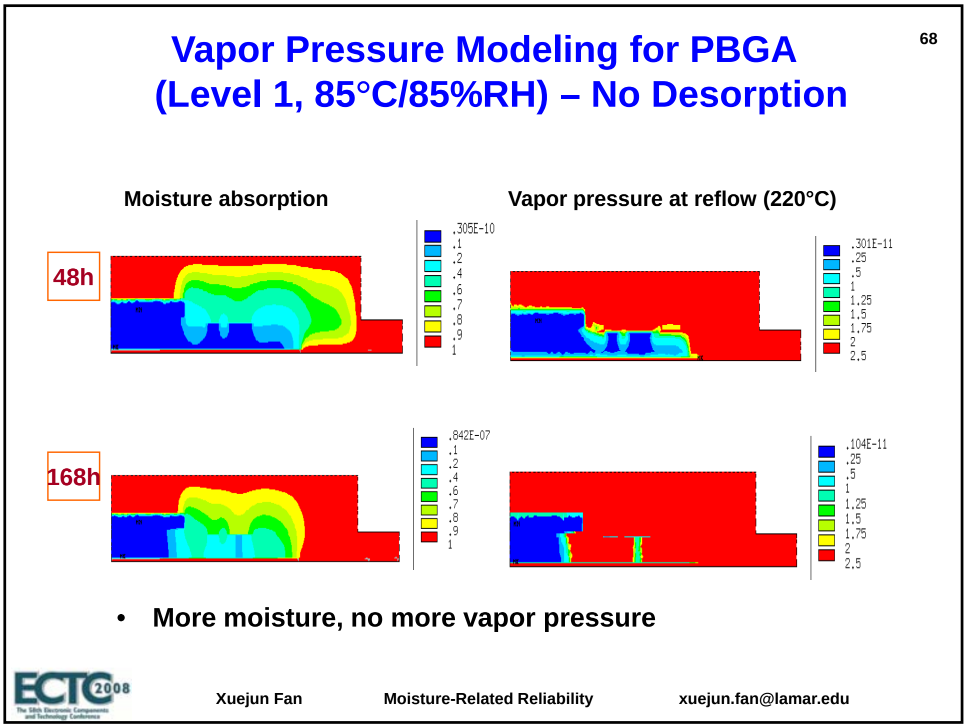
- The vapor pressure is related to the local moisture concentration *C*
- Local moisture concentration *C,* changes with moisture desorption in reflow



Vapor Pressure Modeling for PBGA (Level 3 (30°C/60%RH)) – No Desorption

Moisture absorption | **Vapor pressure at reflow (220°C)**

- **Moisture and vapor pressure have different distributions**

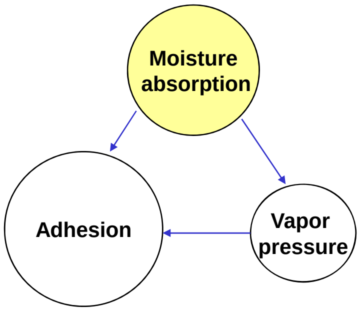


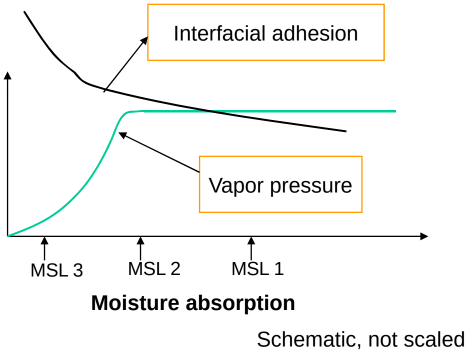
Vapor Pressure Modeling for PBGA (Level 1, 85°C/85%RH) – No Desorption

Moisture absorption | **Vapor pressure at reflow (220°C)**

- **More moisture, no more vapor pressure**

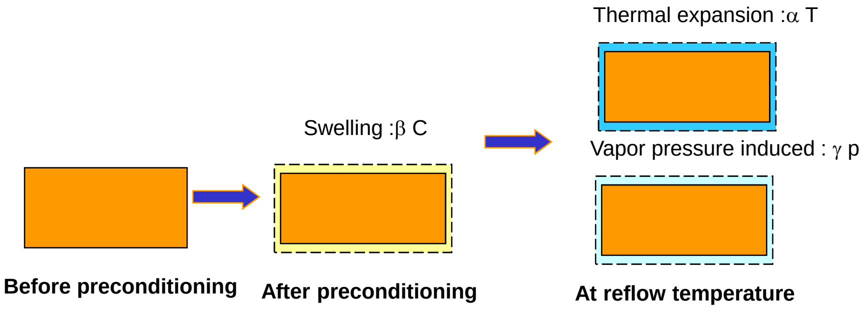
Failure Mechanism – Interfacial Delamination





- **Moisture affects the package reliability at reflow from two aspects: generating vapor pressure and degrading the interfacial adhesion, respectively.**

Vapor Pressure Induced Expansion



Volume expansion:
Thermal expansion-induced $3\alpha\,\Delta T \approx 21$ e-3
Vapor pressure-induced $dV/V = 3(1-2\nu)\,p/E \approx 9.3$ e-3

ΔT : 220-150 = 70°C, E: 300 MPa , p: 2.32MPa , ν : 0.3, α: 100ppm

- Vapor pressure introduces additional mismatch.
- Vapor pressure-induced expansion is directly related to the vapor pressure distribution, rather than moisture distribution.

Vapor Pressure Induced Expansion

	Mold Compound		Die Attach	
	Total Strain	Equivalent mean CTE (ppm/°C)	Total Strain	Equivalent mean CTE (ppm/°C)
Thermo-mechanical	1.53e-3	34	7.65e-3	170
Hygro-mechanical	1.57e-3	34.9	3.22e-3	71.6
Vapor Pressure	8.14e-4	18.1	2.16e-2	479.6
Integrated (total)	3.91e-3	87	3.25e-2	721.2

- **When vapor-pressure induced expansion is included**
  - Stress-free at T0 and cooling down (or heating up) to T1
  - The total 'thermal strain' = α (T1-T0) + (1 - 2ν) p/ E
  - Equivalent coefficient of thermal expansion
    - α + (1 - 2ν) p/ E /(T1-T0)

TY Tee et al, ECTC 2002

Summary

- **The saturated vapor pressure, Psat(T), is the pressure at which liquid water and water vapor can coexist at temperature T**
- **Vapor pressure will remain saturated as long as the moisture is in liquid phase during reflow**
- **Moisture affects the package reliability at reflow from two aspects: generating vapor pressure and degrading the interfacial adhesion, respectively.**

Case Study I: Underfill Selection for Flip Chip BGA on Moisture Sensitivity Performance

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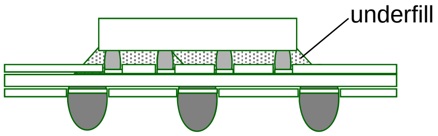
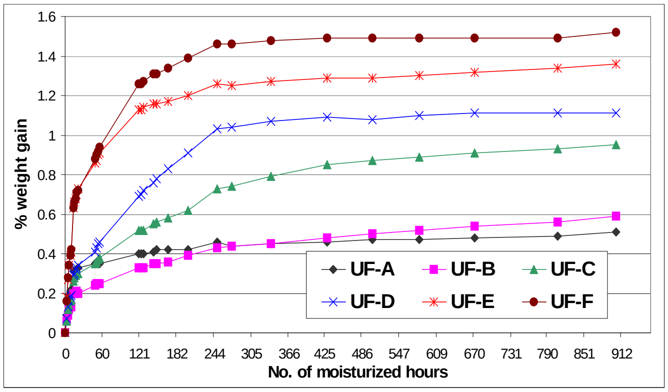
Underfill Selection in Flip Chip Packages

- **To perform the moisture sensitivity test to evaluate underfill performance**
- **Test vehicle**
  - Flip chip PBGA, 10x10mm die, 27x27cm BT substrate (0.4 mm core thickness), double layer
  - Underfill materials: 6 kinds of underfills
- **Material properties**
  - Modulus (E)
  - Viscosity
  - CTE
  - Tg
  - Moisture related properties (diffusivity, solubility …)
  - Adhesion (fracture toughness)



Underfill Material Properties - Moisture Absorption (85°C/85%RH)



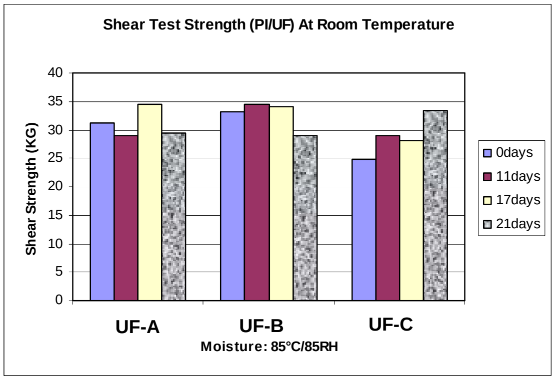
- UF-A < UF-B < UF-C < UF-D < UF-E < UF-F

Underfill Material Properties - Mechanical and Thermal Properties

	CTE1	CTE2	Tg	E1, E2	
UF	ppm/°C	ppm/°C	°C	GPa	
UF-A	31	90	133	8	1.7
UF-B	18	40	128	12	4
UF-C	25	93	117	9.6	1.4
UF-D	27	78	144	7	4.5
UF-E	68	197	155	2.2	1.05
UF-F	61	199	102	2.7	0.05

– It seems the underfill A is an ideal candidate material.

Adhesion at Room Temperature with Moisture



- **No significant difference in underfill adhesion strength at room temperature with moisture**
- **Adhesion at room temperature is not sensitive to moisture**

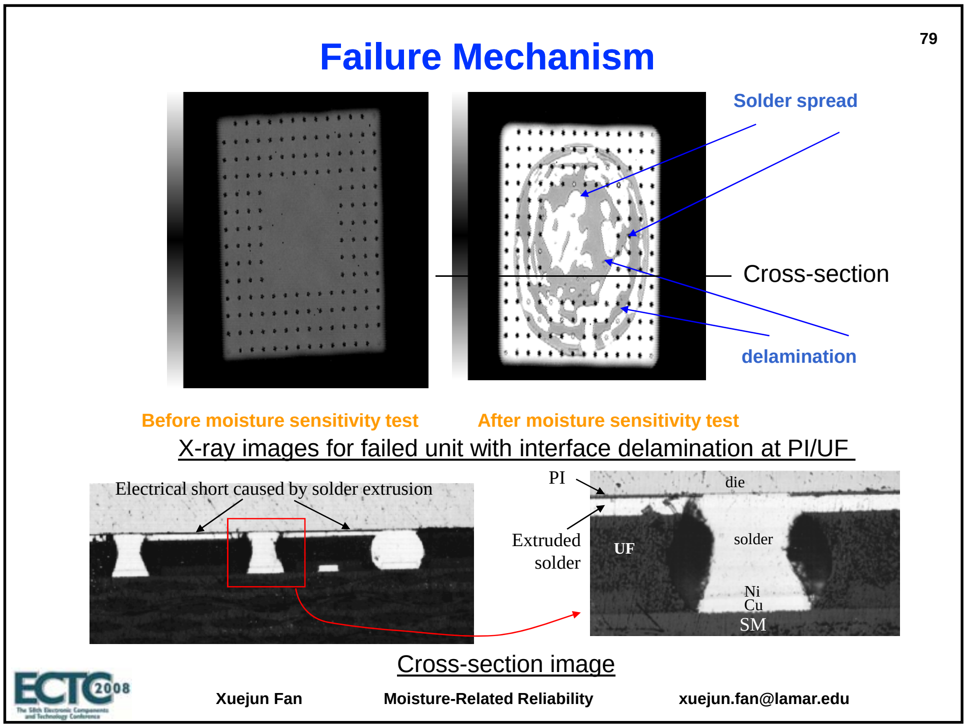
Summary of Moisture Sensitivity Test Results for Flip Chip Packages

- **For controlled samples tested in Level 3 (30°C/60 %RH) (UF-A)**

Leg ID	Configuration	# unit with this failure mode
A1	ball layout 1, molded	3/24
A2	ball layout 1, not molded	5/24
A3	ball layout 2, molded	4/24
A4	ball layout 2, not molded	6/24

- **For UF-C and UF-E**

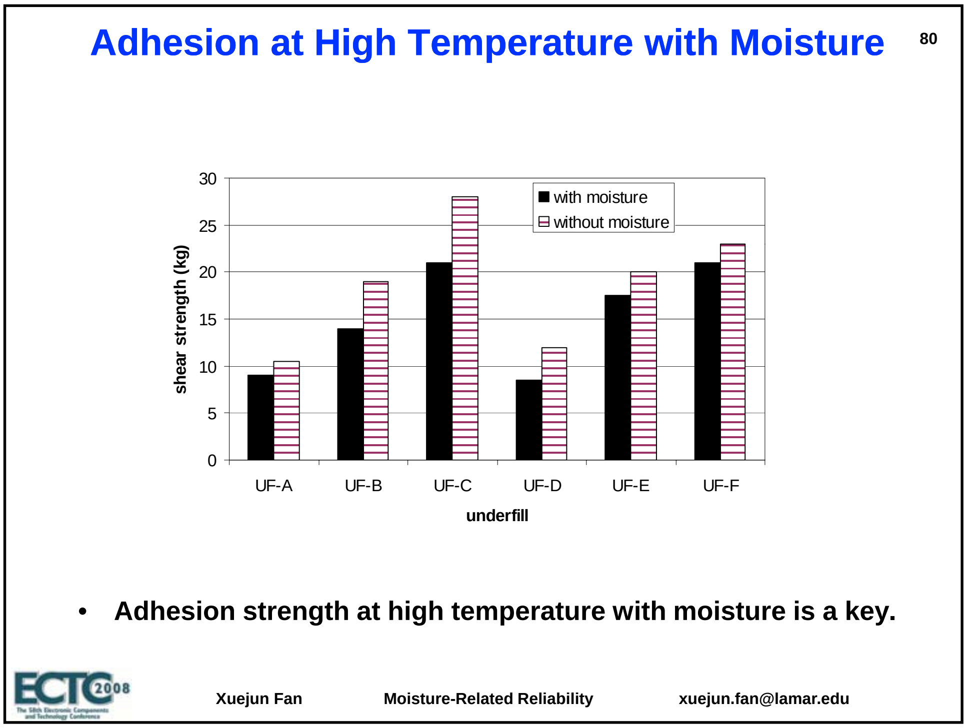
Underfill	Total number of failure units	
	MSL 3	MSL 2
UF-C	0/24	0/18
UF-E	0/18	Not Available



Failure Mechanism

X-ray images for failed unit with interface delamination at PI/UF

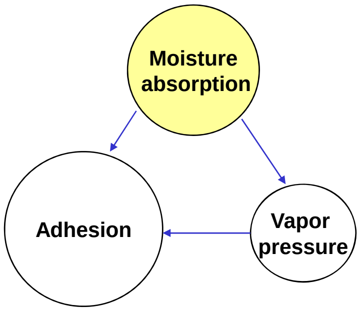
Cross-section image

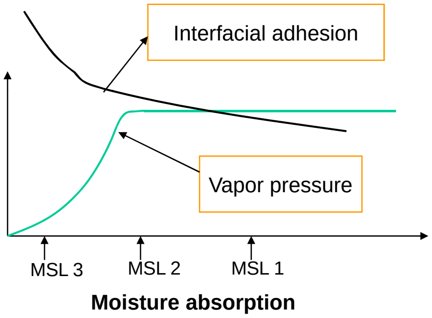


Adhesion at High Temperature with Moisture

- **Adhesion strength at high temperature with moisture is a key.**

Failure Mechanism – Interfacial Delamination

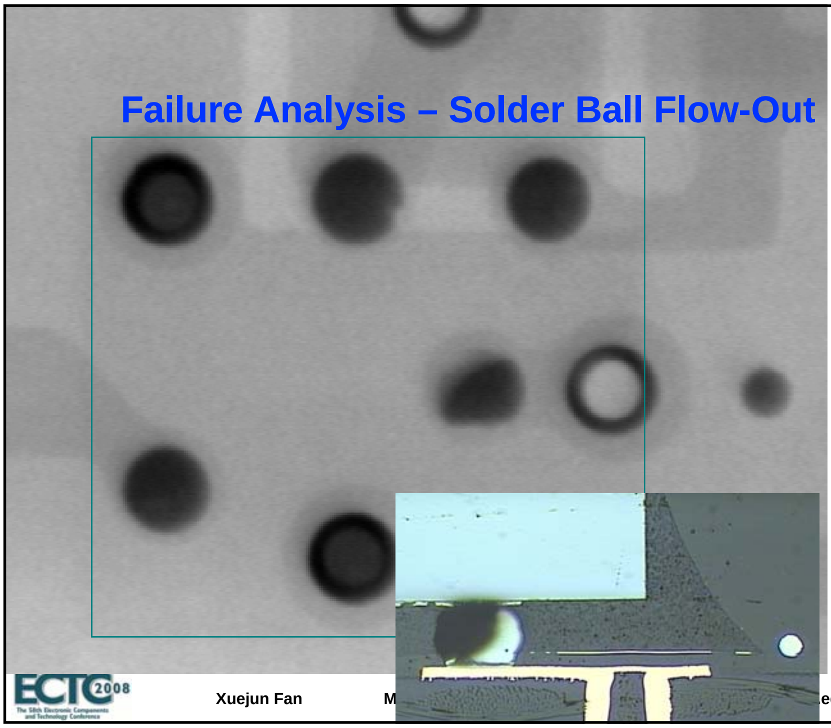




Schematic, not scaled

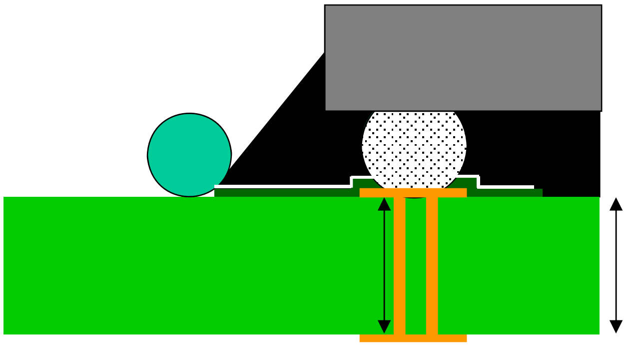
- **Moisture affects the package reliability at reflow from two aspects: generating vapor pressure and degrading the interfacial adhesion, respectively.**

Failure Analysis – Solder Ball Flow-Out



Failure Mechanism

- Initiation of delamination around thermal via between UF and solder resist
- Vapor pressure propagates the delamination
- If the delam reaches edge of underfill (exit point) the pressure of moisture will make the melt solder to flow out



Key Messages

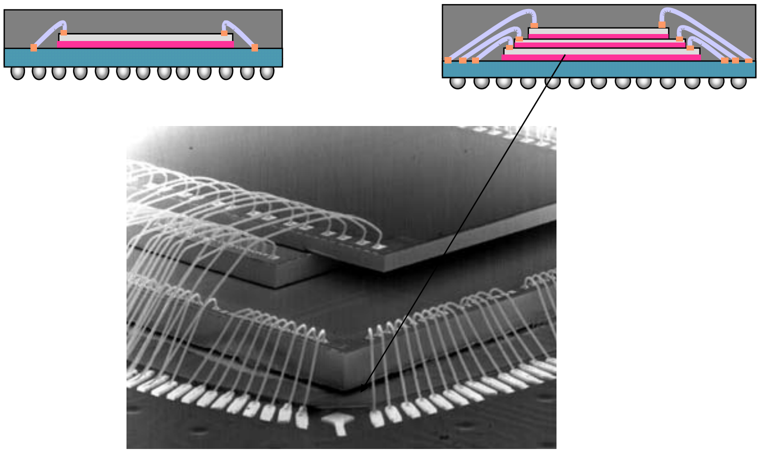
- **For underfill material, since material's modulus is relatively high, cohesive delamination is not a concern**
- **Underfill material properties of diffusivity and solubility are not critical properties for package performance at reflow;**
- **The adhesion at high temperature with moisture is a key.**

Summary

- Delamination at UF/PI or UF/SR is common failure mode for FC BGA. No cohesive failure observed since UF has relatively high modulus
- Diffusivity and saturated moisture absorption are not critical parameters in selecting underfill for moisture performance
- Adhesion at room temperature with moisture may not reflect the material behavior at reflow temperature
- Adhesion at high temperature with moisture is key

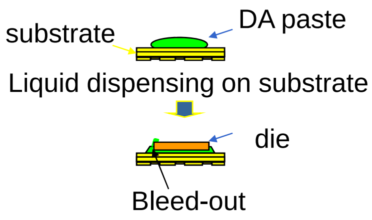
Case Study II : Delamination/Cracking in Stacked-Die Chip Scale Packages

From Single-Die Chip Scale Package (CSP) to Stack-Die Chip Scale Package

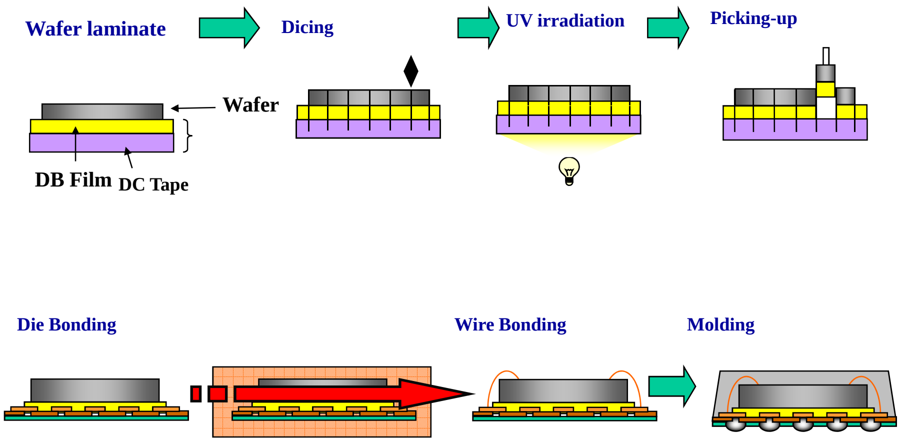


General Assembly Process

- **Assembly issues with traditional die-attach paste by liquid dispensing**
  - Bleed-out to contaminate bond-pad with thinner die down to 3mil or below
  - Die cracking and handling

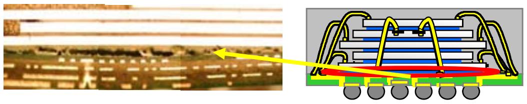


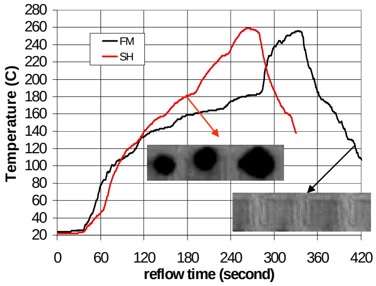
Process Flow Using Wafer-Level Film



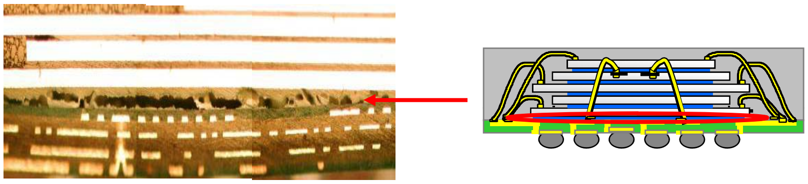
Die-Attach Film Delamination/Cracking

- **Experimental observations**
  - Failures at the bottom die-attach film after precon
  - Cohesive voiding/cracking dominant
  - Very sensitive to soldering reflow profile

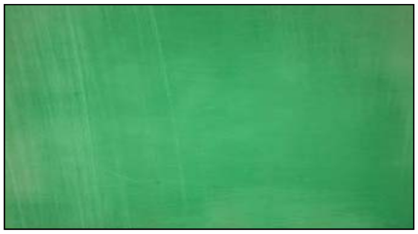




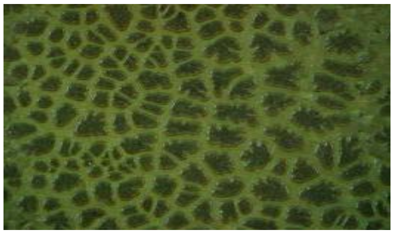
Failure Mechanism



Before reflow

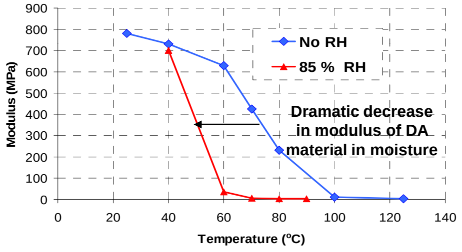


After reflow

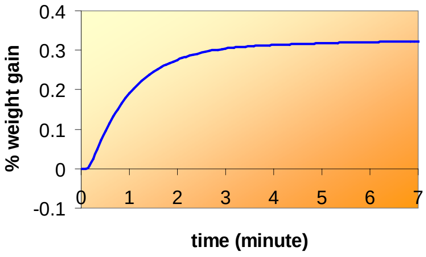


Fundamentals: Material Characterization

Effect of moisture on DA material properties

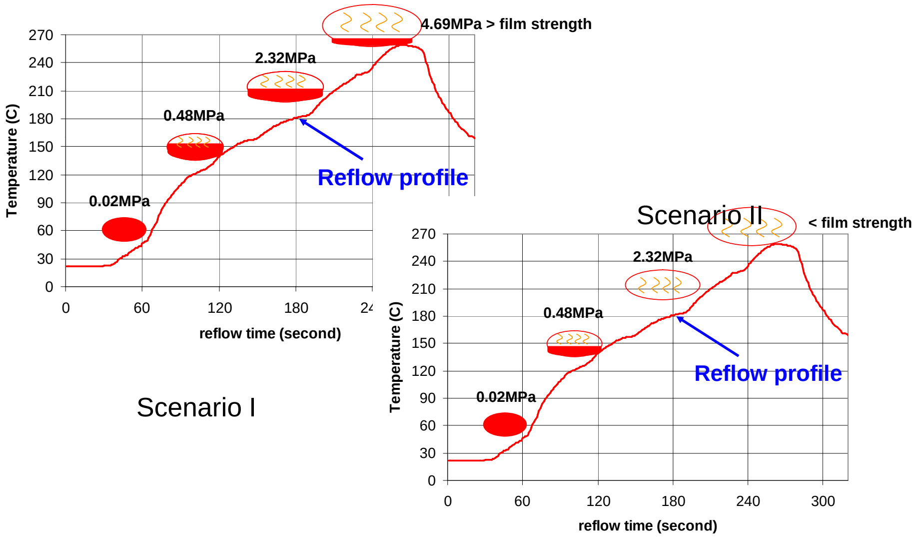


Die attach material moisture uptake



- DA film Tg is low, and drops with moisture exposure
- DA modulus is less than 3MPa at reflow temperature, even lower than the saturated vapor pressure (4.7MPa@260°C)
- Moisture uptake in DA is very fast
  - Faster than observed in previous literature

Hypothesis: Two Scenarios on Vapor Pressure Buildup During Reflow



– Vapor pressure is dominant driving force for cohesive failure

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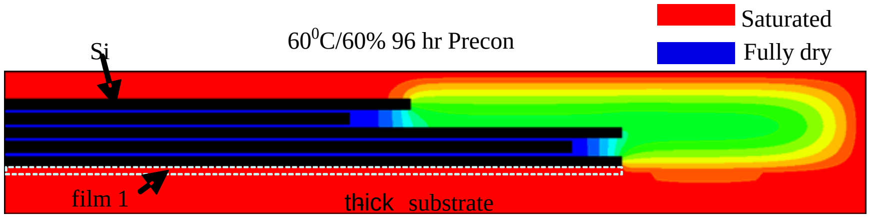
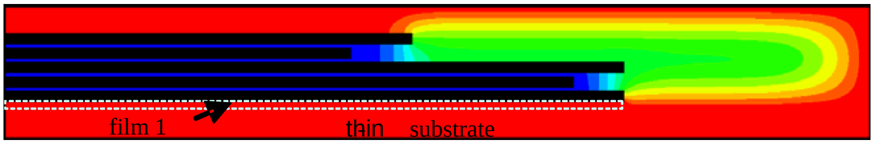
Moisture Diffusion Modeling

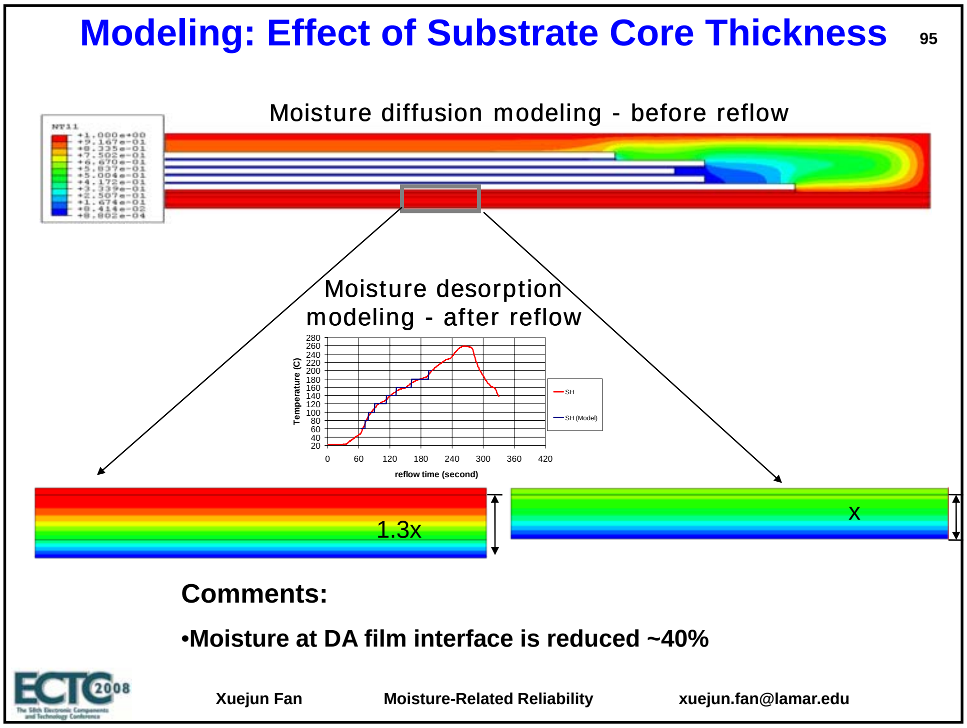


No appreciable difference in moisture saturation after precon with difference substrate thickness



Comments:

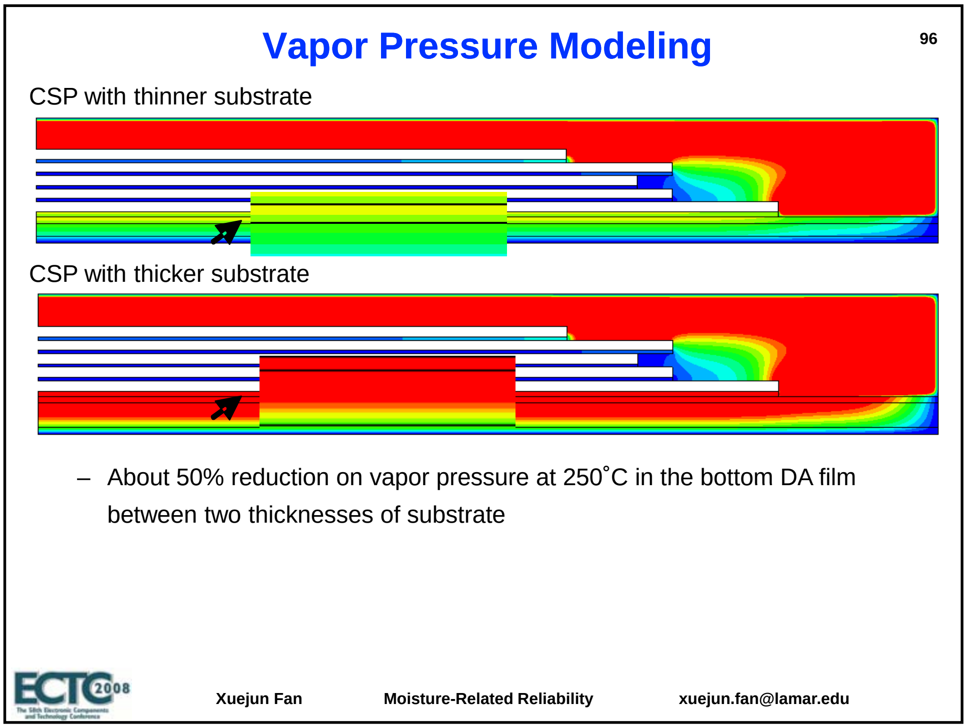
•**Substrate thickness has no effect on final moisture saturation of package materials after moisture preconditioning.**



Modeling: Effect of Substrate Core Thickness

Comments:

- **Moisture at DA film interface is reduced ~40%**



Vapor Pressure Modeling

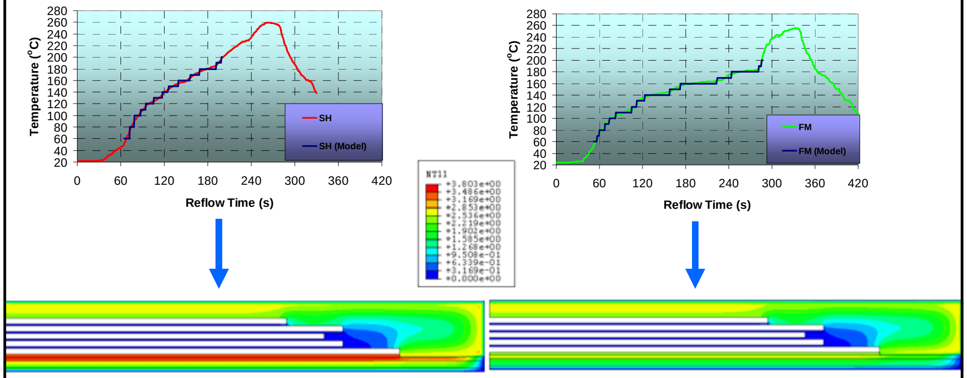
CSP with thinner substrate

CSP with thicker substrate

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

Modeling: Effect of Reflow Profile

Interface moisture content comparison between two reflow profiles from 60ºC~200ºC



Comments:

•moisture at DA film interface is reduced ~40%

Validation: Experimental Results

Thickness (μm)	Leg1	Leg 2	Leg 3	Leg 4	Leg 5
Solder Mask	1x	1.02x	1.04x	1.04x	1.37x
Inner Cu density	0%	50%	50%	50%	50%
BT-Core	1y	1.09y	1.43y	1.47y	1.44y
Total	1z	1.20z	1.47z	1.47z	1.53z
Delam Rate	0%	7%	32%	47%	100%

Comments:

- BT-core thickness is largest modulator

Desorption Model

$$C(x,t)/C_{\text{sat}} = \sum_{n=0}^{\infty} \frac{[2(-1)^n]e^{-\lambda_n^2 D\,t/h^2}}{\lambda_n}\cos(\lambda_n(h-x)/h)$$

$$\lambda_n = (\frac{2n+1}{2})\pi$$

C	moisture concentration in film
C_{sat}	saturated moisture concentration

$$C/C_{sat} \sim \exp\left(-\frac{D\,t}{h^2}\right)$$

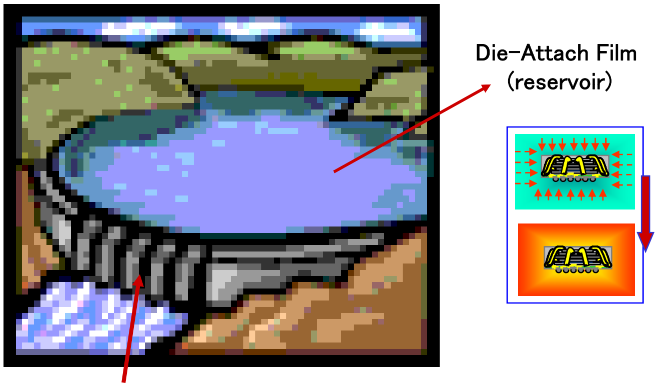
D: substrate diffusivity
t: time
h: thickness

D ↑ t ↑ h↓ ⇨ C/C_{sat} ↓

The local moisture concentration depends on the thickness and the diffusivity of substrate, and reflow time.

How Would Moisture Escape?

D ↑ t ↑ h ↓ ⇨ C/C_{sat} ↓



D: diffusivity
t: time
h: thickness

Substrate (moisture escape path)

Reflow time, substrate diffusivity, and substrate thickness are three key parameters to determine the moisture loss.

Summary

- **Cohesive voiding/cracking of die-attach film was observed**
- **Very sensitive to reflow profiles**
  - Desorption plays a significant role
- **Very sensitive to substrate thickness**
- **Reflow time, substrate diffusivity, and substrate thickness are three key parameters to determine the moisture loss**

Accelerated Moisture Sensitivity Test

Accelerated Equivalent

- **IPC/JEDEC J-STD-020C**

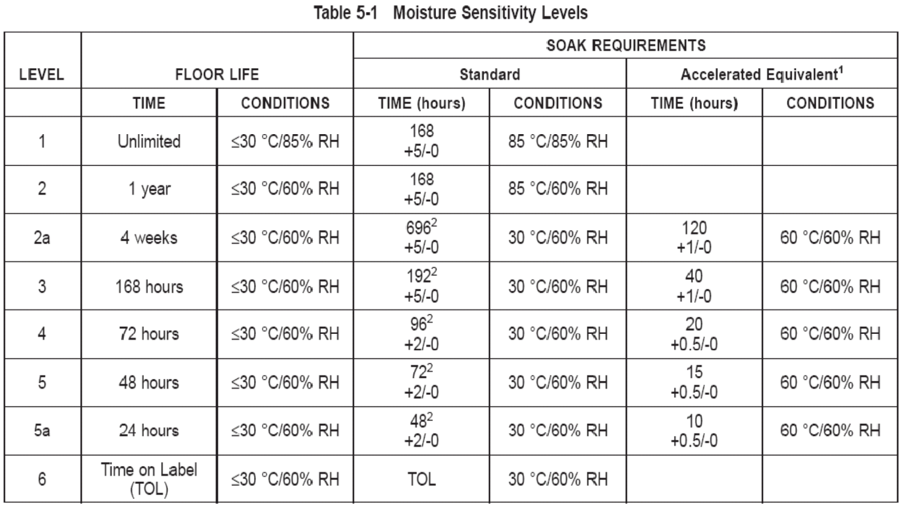
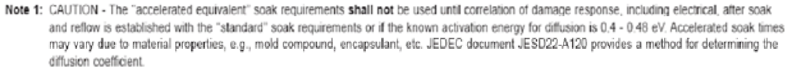


Table 5-1 Moisture Sensitivity Levels

LEVEL	FLOOR LIFE		SOAK REQUIREMENTS			
			Standard		Accelerated Equivalent[1]	
	TIME	CONDITIONS	TIME (hours)	CONDITIONS	TIME (hours)	CONDITIONS
1	Unlimited	≤30 °C/85% RH	168 +5/-0	85 °C/85% RH		
2	1 year	≤30 °C/60% RH	168 +5/-0	85 °C/60% RH		
2a	4 weeks	≤30 °C/60% RH	696[2] +5/-0	30 °C/60% RH	120 +1/-0	60 °C/60% RH
3	168 hours	≤30 °C/60% RH	192[2] +5/-0	30 °C/60% RH	40 +1/-0	60 °C/60% RH
4	72 hours	≤30 °C/60% RH	96[2] +2/-0	30 °C/60% RH	20 +0.5/-0	60 °C/60% RH
5	48 hours	≤30 °C/60% RH	72[2] +2/-0	30 °C/60% RH	15 +0.5/-0	60 °C/60% RH
5a	24 hours	≤30 °C/60% RH	48[2] +2/-0	30 °C/60% RH	10 +0.5/-0	60 °C/60% RH
6	Time on Label (TOL)	≤30 °C/60% RH	TOL	30 °C/60% RH		

Accelerated Equivalent

- CAUTION - The ‘‘accelerated equivalent’’ soak requirements **shall not** be used until correlation of damage response, including electrical, after soak and reflow is established with the ‘‘standard’’ soak requirements or if the known activation energy for diffusion is 0.4 - 0.48 eV. Accelerated soak times may vary due to material properties, e.g., mold compound, encapsulant, etc. JEDEC document JESD22-A120 provides a method for determining the diffusion coefficient



Note 1: CAUTION - The "accelerated equivalent" soak requirements **shall not** be used until correlation of damage response, including electrical, after soak and reflow is established with the "standard" soak requirements or if the known activation energy for diffusion is 0.4 - 0.48 eV. Accelerated soak times may vary due to material properties, e.g., mold compound, encapsulant, etc. JEDEC document JESD22-A120 provides a method for determining the diffusion coefficient.

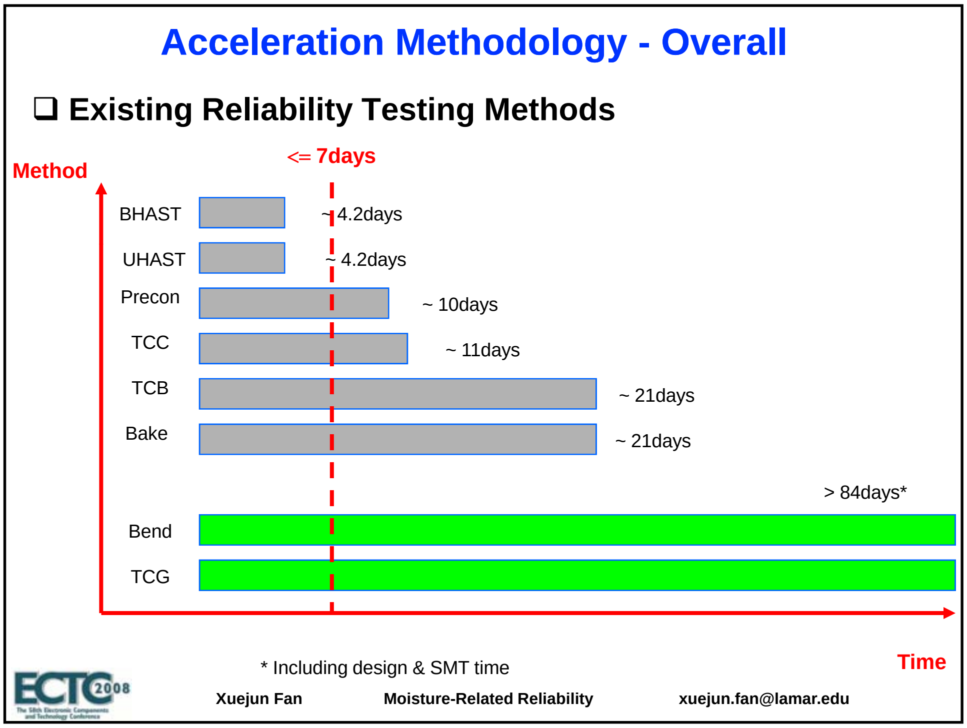
Acceleration Methodology

- **Equivalent Concentration Methodology**
  - – Local Moisture Concentration as primary failure driver
    - **R.L. Shook, B.T. Vaccaro, D.L. Gerlach, "**Method for Equivalent Acceleration of JEDEC/IPC Moisture Sensitivity Levels**", 36th IRPS, 1998**
  - – Technique
    - – Use 1-D moisture diffusion analytical analysis
  - – Established a consistent accelerated M.S. test which is independent of package form (for leaded package only) and materials (assuming that MC has similar diffusivity)

Acceleration Methodology

- – Failure occurs in interface involving only one diffusive material; e.g. Cu pad - mold compound – leaded package
- – Acceleration factor is independent of package form and thickness
- – FEA moisture diffusion modeling is not even necessary
- – Acceleration factor (AF) can be simply computed from the diffusivity of mold compound as

$$AF = \frac{D_{acc}}{D_{std}}$$

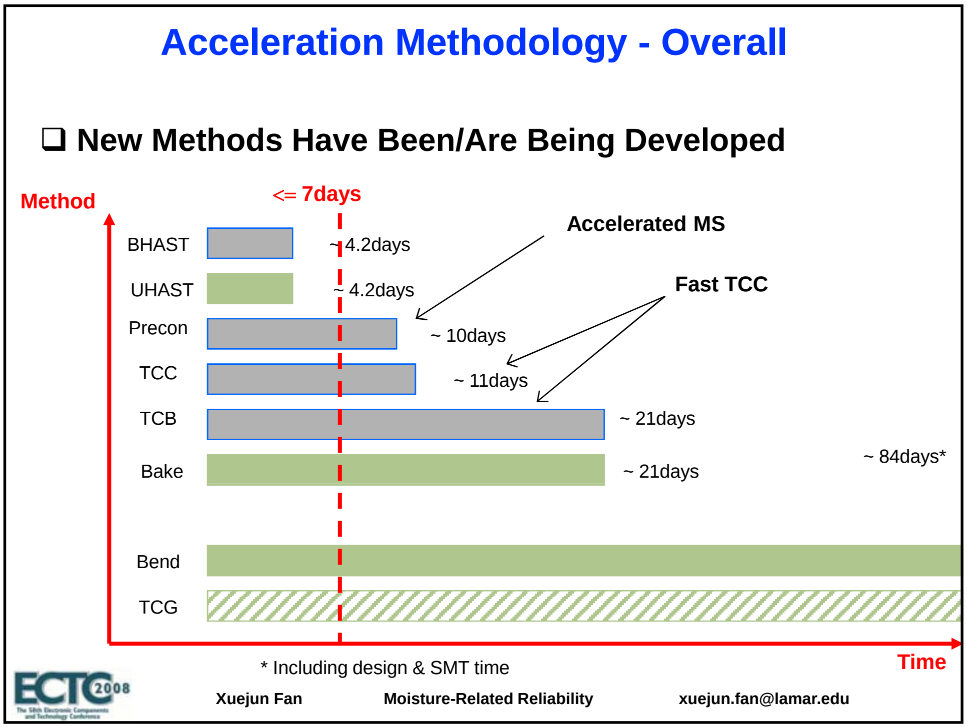


Acceleration Methodology - Overall

❑ Existing Reliability Testing Methods

* Including design & SMT time

Xuejun Fan **Moisture-Related Reliability** **xuejun.fan@lamar.edu**



Acceleration Methodology - Overall

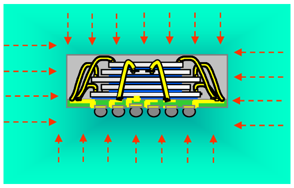
❑ New Methods Have Been/Are Being Developed

* Including design & SMT time

Xuejun Fan **Moisture-Related Reliability** **xuejun.fan@lamar.edu**

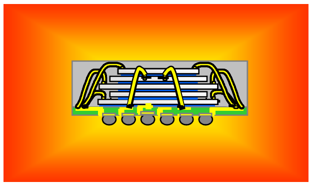
Acceleration Methodology

❑ **Testing Method**

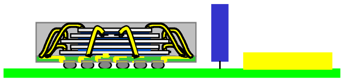


Stage 1: Moisture absorption (e.g.: 60C/60%RH for 88 hours)

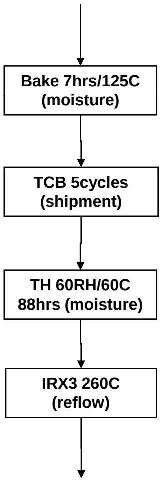
Storage & Shipment



Stage 2: Soldering reflow (peak temp: 220C → 260C)



surface mount



Bake 7hrs/125C (moisture)

TCB 5cycles (shipment)

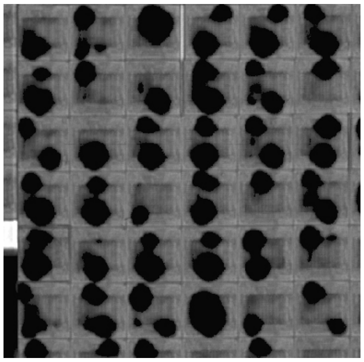
TH 60RH/60C 88hrs (moisture)

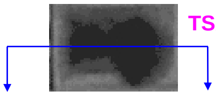
IRX3 260C (reflow)

Acceleration Methodology

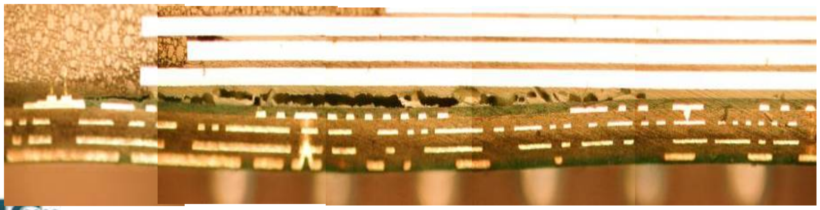
❑ **Accelerated test should ensure**

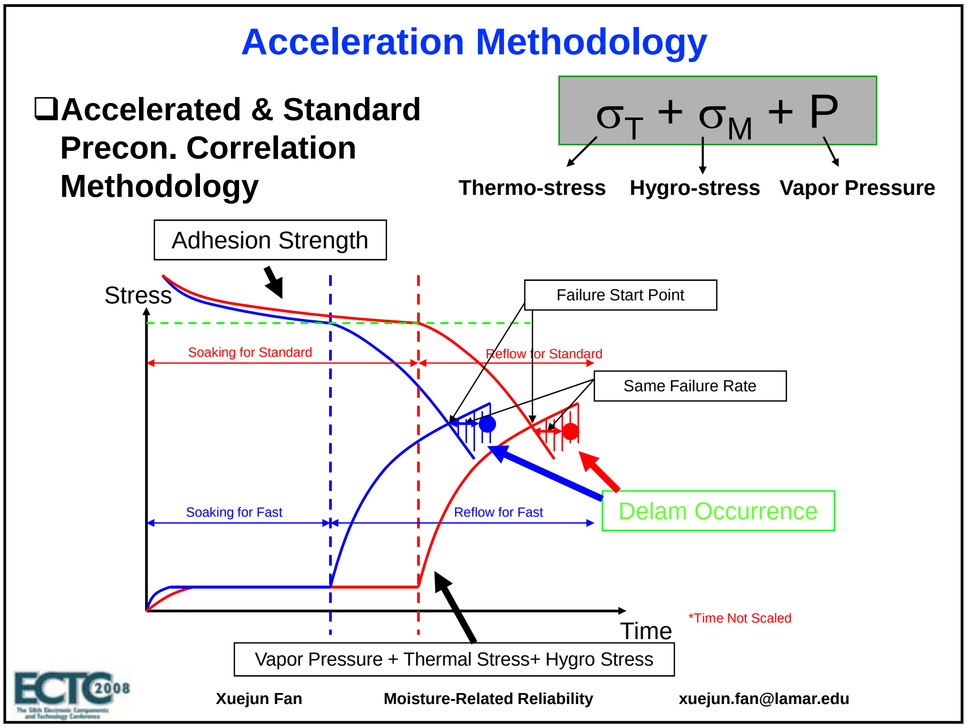
- **same failure mode/mechanism;**
- **similar failure rate.**





TSAM image

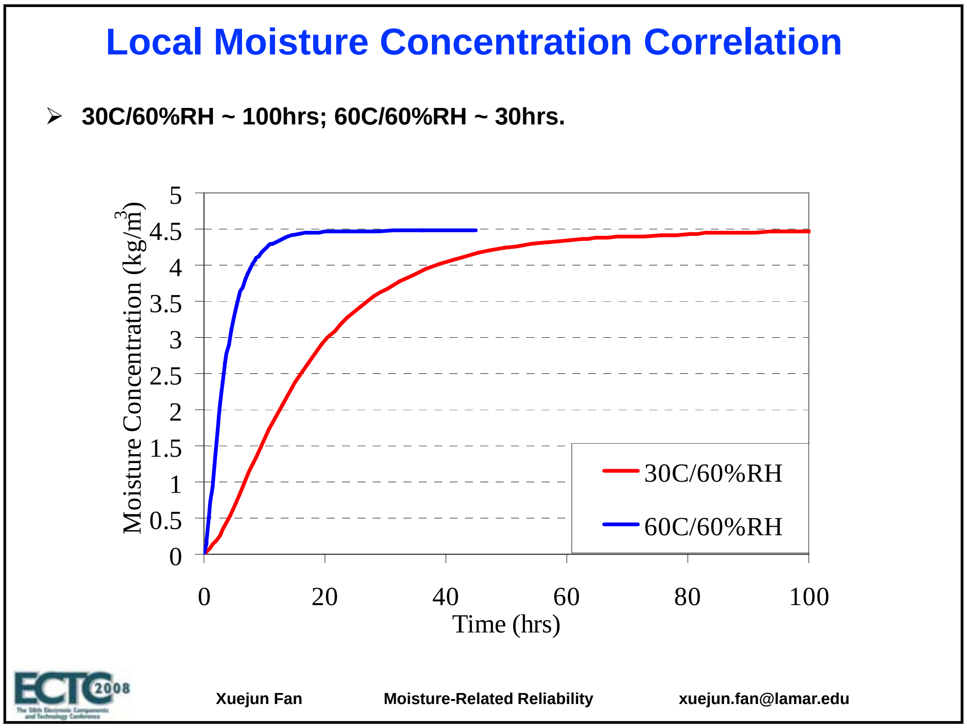




Acceleration Methodology

- Accelerated & Standard Precon. Correlation Methodology

$$\sigma_T + \sigma_M + P$$

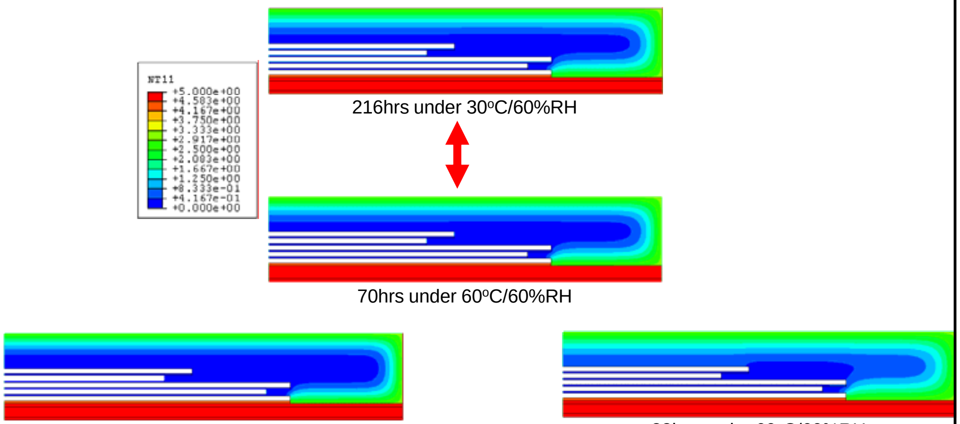


Local Moisture Concentration Correlation

- 30C/60%RH ~ 100hrs; 60C/60%RH ~ 30hrs.

Global Moisture Concentration Correlation

- 216 hrs 30C/60%RH matches with 70hrs 60C/60%RH



216hrs under 30°C/60%RH

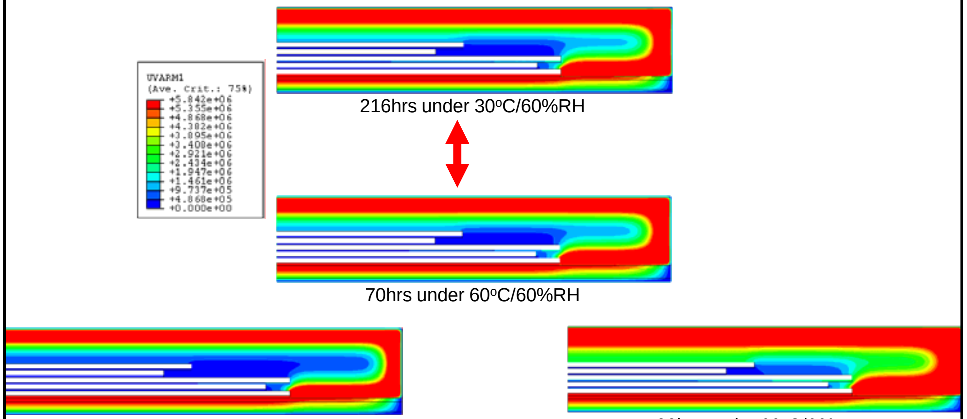
70hrs under 60°C/60%RH

45hrs under 60°C/60%RH

88hrs under 60°C/60%RH

Vapor Pressure Correlation

- 216hrs 30C/60%RH matches with 70hrs 60C/60%RH



216hrs under 30°C/60%RH

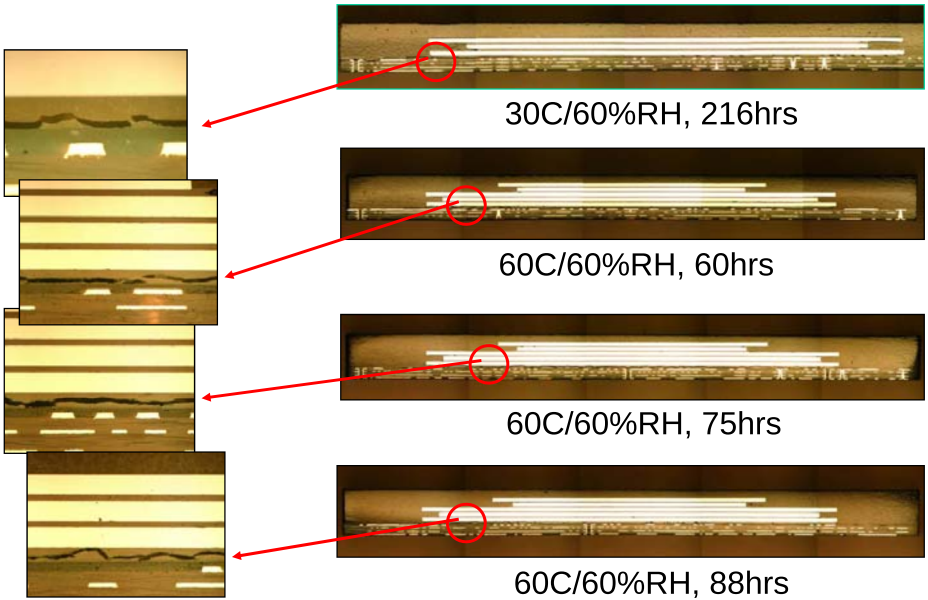
70hrs under 60°C/60%RH

45hrs under 60°C/60%RH

88hrs under 60°C/60%RH

Validation

- ☐ **Failure Mode/Mechanism**



30C/60%RH, 216hrs

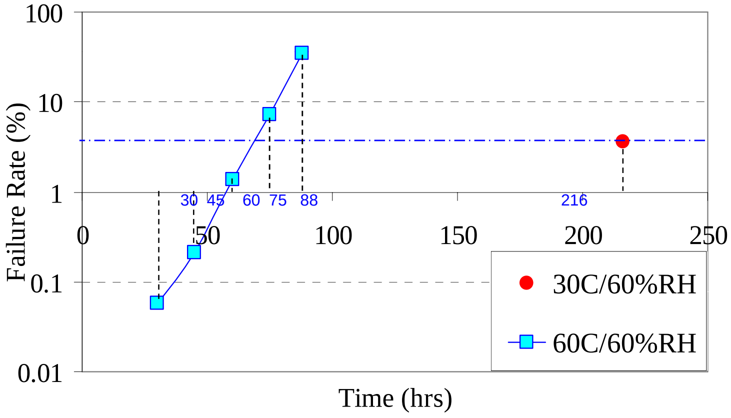
60C/60%RH, 60hrs

60C/60%RH, 75hrs

60C/60%RH, 88hrs

Validation

- ☐ **Failure Rate**
  - ➢ **FR at 216hrs 30C/60%RH is similar with that at 68.5hrs 60C/60%RH**



Summary

- **Equivalent concentration methodology**
  - Identifies local moisture concentration as the primary failure driver
    - J-STD-020C
    - Simple to use
    - Caution necessary when applied to leaded packages of different materials
    - Caution necessary when applied to organic substrate based packages
- **New methodology**
  - Local moisture concentration equivalency
  - Global moisture distribution equivalency

Effect of Moisture on Material Properties

General Observations

- Moisture has little effect on Young’s modulus
- Moisture has little effect on visco-elastic properties
- Moisture has little effect on CTE
- Moisture generally reduces the Tg in the range of 10°C–20°C
- Moisture has significant impact on interface adhesion strength

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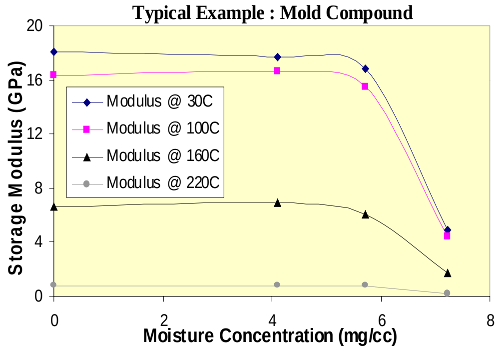
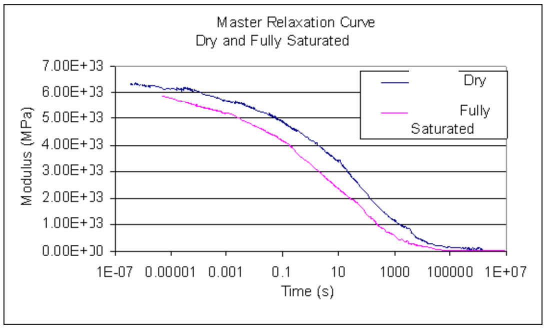
Example: Effect of Moisture on Modulus

- Effect of moisture on storage modulus

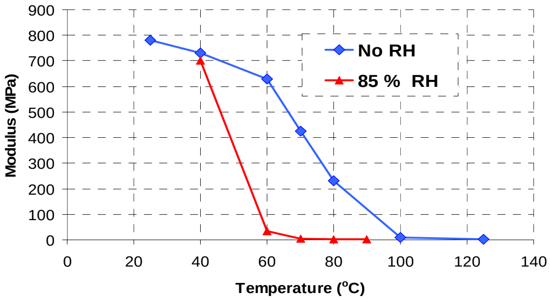


Example: Effect of Moisture on Viscoelastic Properties

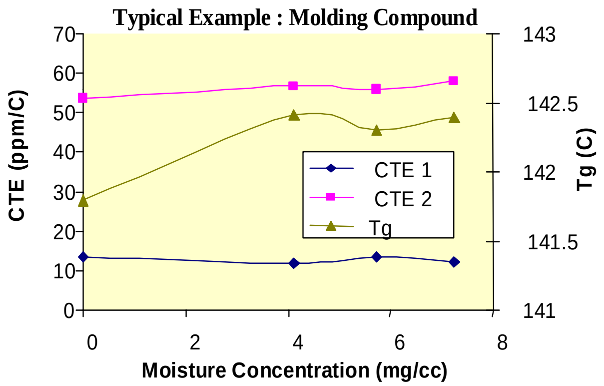


- A slight drop in modulus with moisture was observed

Example: Effect of Moisture on Tg

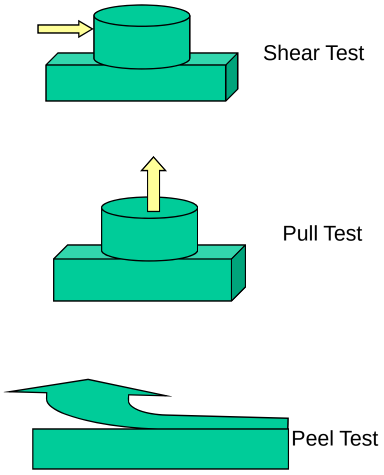


Example: Effect of Moisture on CTE and Tg

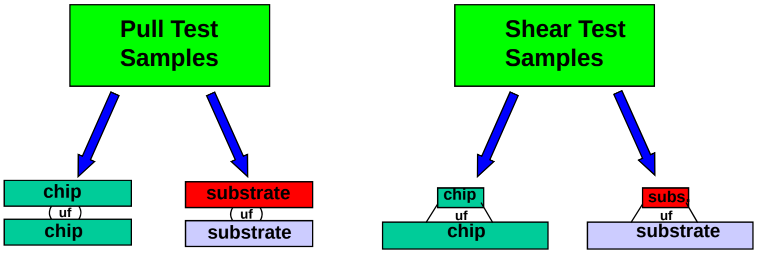


Adhesion Test Techniques

- **Interfacial fracture toughness measurement**
  - 4-point bend test
  - Double cantilever beam test
  - Compact tension test
- **Adhesion measurement**
  - Shear test
  - Pull test
  - Peel test
  - Torque test
- **Sample configurations**
  - Pre-cracked
  - Not pre-cracked
  - Sandwiched
  - Button shape



Adhesion Test Sample Configuration: Pull and Shear



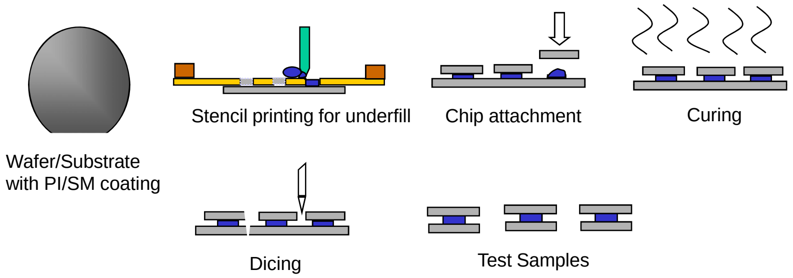
Pull Test Samples

Shear Test Samples

- **Test samples**
  - Same materials on both sides
    - To eliminate the thermal stress effect
    - To keep the interface same on both sides

Test Sample Preparation

- **Process for the test sample preparation**



- **The adhesion samples were done on the whole wafer**
  - Consistent underfill wetting area
  - Consistent underfill wetting location
  - Consistent underfill height
  - Failure mode can be controlled

Adhesion Test DOE

- **For underfill/polyimide interface (UF/PI)**
  - Shear test at room temperature (25°C)

UF/PI, Shear Test, Room Temperature, Chip to Chip Sample				
Underfill	Dry	85°C/85RH	85°C/85RH	85°C/85RH
		11 days	17 days	21 days
UF-1	V	V	V	V
UF-2	V	V	V	V
UF-3	V	V	V	V

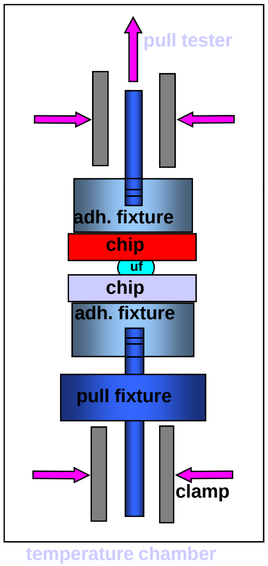
- Sample size: 16

  - Shear test at reflow temperature (220 °C)

Underfill	Dry	30°C/60RH	85°C/60RH	85°C/85RH
		21 days	21 days	21 days
UF-1	V	V	V	V
UF-2	V	V	V	V
UF-3	V	V	V	V

- Sample size: 16

Pull Test Set-Up

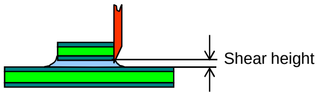


- **New pull fixture for pull test**
  - Can operate under high temperature.
- **Adhesion between sample and fixture**
  - Require high Tg (>200°C) with low curing temperature (<160°C) and short curing time.
- **Since the underfill wetting area << interface area at sample/fixture**
  - failure always occurs at UF/PI interface.

Shear Test Set-Up

- **Micro-mechanical test system: DAGE Series 4000 with hot plate (temperature range 25°C - 300°C)**
  - Fixed (hot plate &) test table
  - Full automatic test process
  - Adjustable test parameters
- **Adjustable parameters**
  - Shear speed
  - Shear height
  - Load range

Tester: DAGE Series 4000

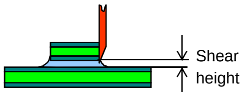


Shear test sample

- **The failure mode and adhesion results are very sensitive to the parameters setting such as shear height and shear speed.**

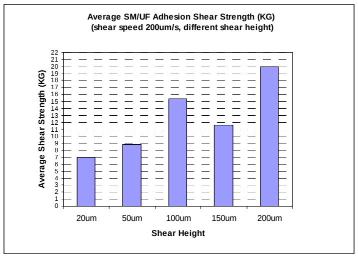
Effect of Shear Height

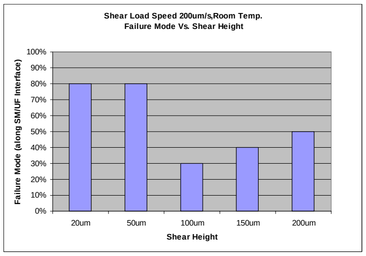
- **For underfill/solder mask interface (UF/SM)**
  - Shear test at room temperature under different set-up conditions



- Sample size: 16

Load Speed 200um/s Str.Unit:KG					
Shear Height	20um	50um	100um	150um	200um
Average	7.014125	8.796125	15.329	11.60275	20.013
Stdev.	1.227535	1.851912	8.304412	4.213173	6.81709

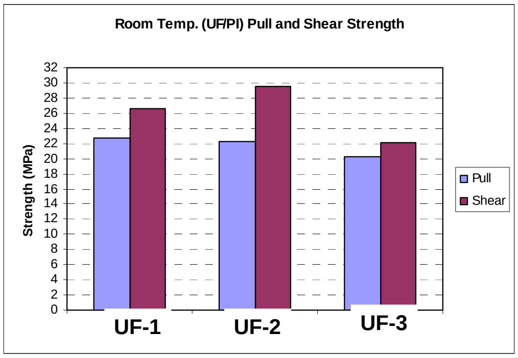


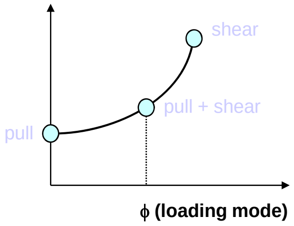


- The adhesion strength and failure mode strongly depend on the shear height

Adhesion Results: Pull vs. Shear

- **Adhesion test results**
  - Comparison between pull and shear at room temperature for UF/PI

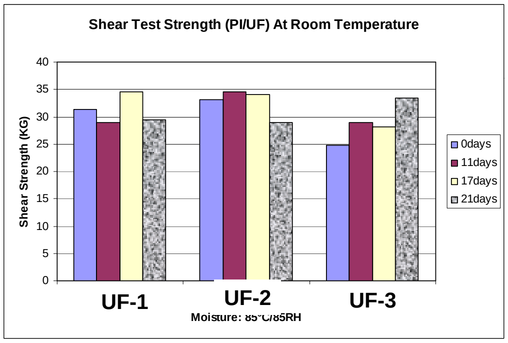




- **Pull strength is lower than shear strength, but not significant**

Adhesion Test Results at Room Temperature

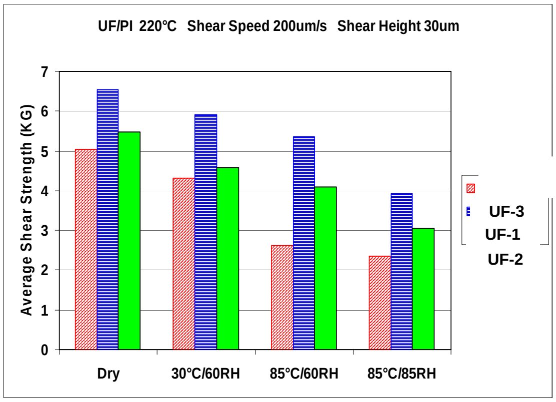
- **Summary for shear test at room temperature for UF/PI**



- No significant difference for the adhesion strength among three underfills at room temperature
- For these three underfills, the adhesion strength at room temperature is not sensitive to moisture

Adhesion Test Results at Reflow Temperature

- **Summary of adhesion tests at reflow temperature 220°C**
  - **UF/PI interface**



Sample size: 16

Failure mode: 100%

Stdev.: < 15%

Moisture absorption time: 21 days

– Interfacial adhesion at UF/PI decreases with moisture absorption

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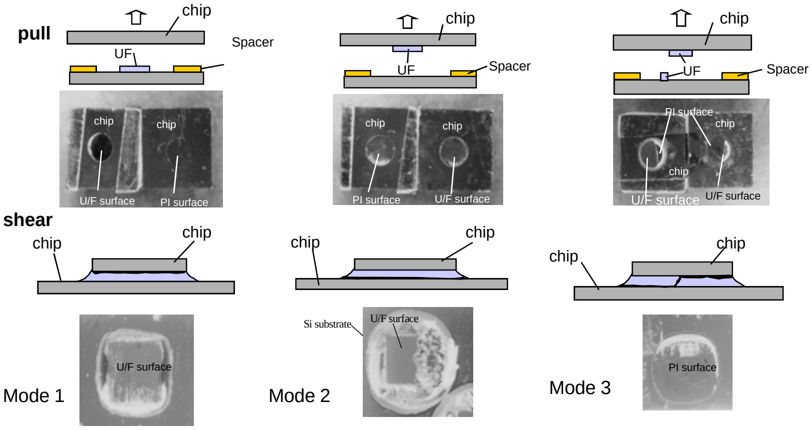
Adhesion Test Results: Failure Mode

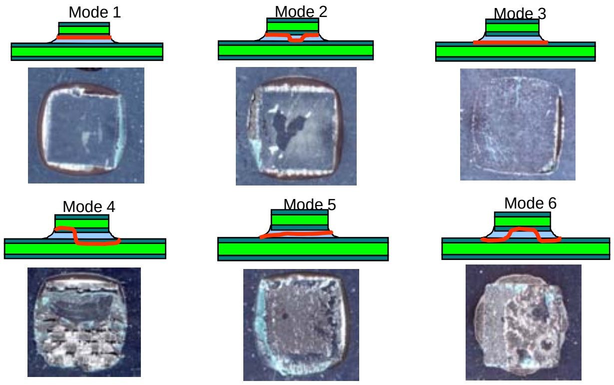
- UF/PI interface: Failure mode



– Almost 100% failures occur at UF/PI interface under both pull and shear tests

Adhesion Test Results

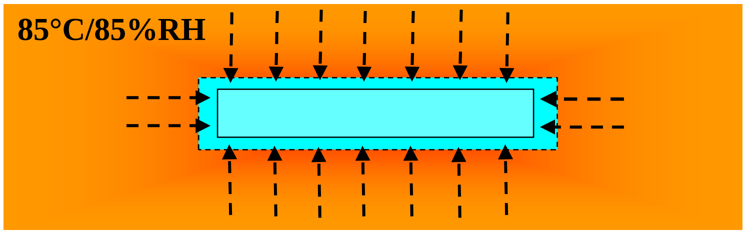
- **UF/SM interface: failure mode**



  - Failure modes are more complicated than that of UF/PI adhesion test.

Hygroscopic Swelling

Hygroscopic Swelling



Expansion strain due to hygroscopic swelling

~0.29%

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

β– the coefficient of hygroscopic swelling
C – moisture concentration

Expansion strain due to temperature change of 100°C

~0.25%

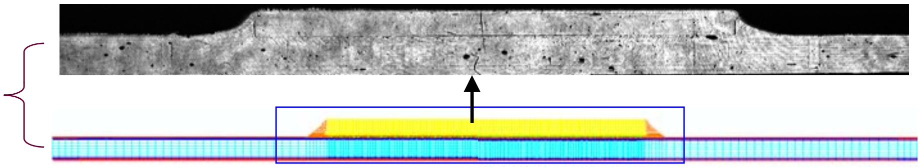
$\varepsilon^{thermal}=\alpha*\Delta T$

Hygroscopic mismatch is comparable to thermal mismatch in causing mechanical stresses

---

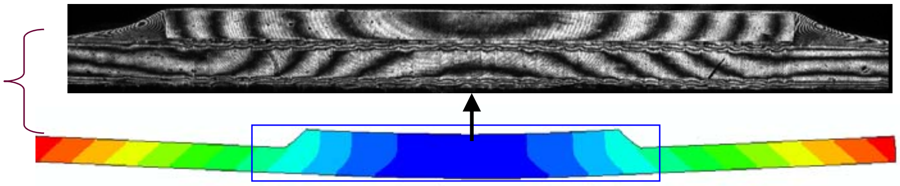
Validation: Moiré Interferometry Measurement

Before HAST



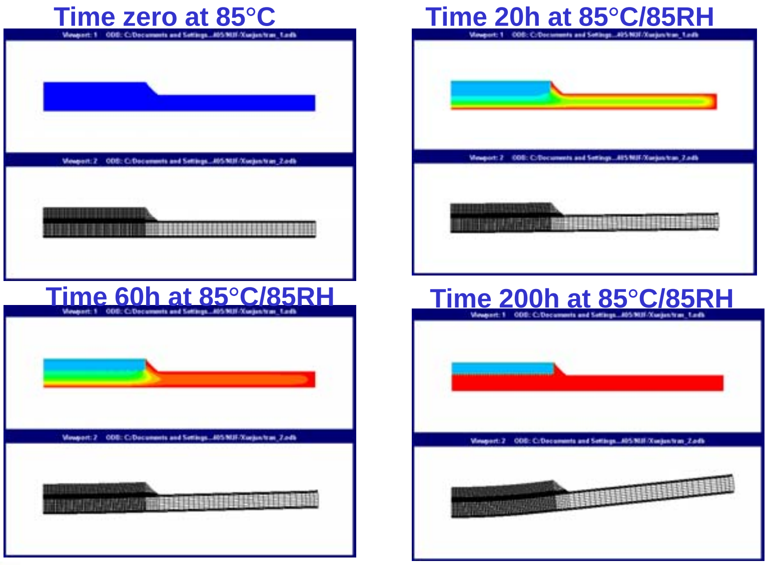
Time zero before HAST at 85°C

After HAST



Time 168h after HAST at 85°C/85RH

Hygroscopic Swelling-Induced Deformation



Time zero at 85°C

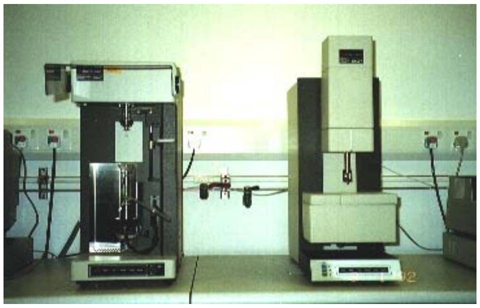
Time 20h at 85°C/85RH

Time 60h at 85°C/85RH

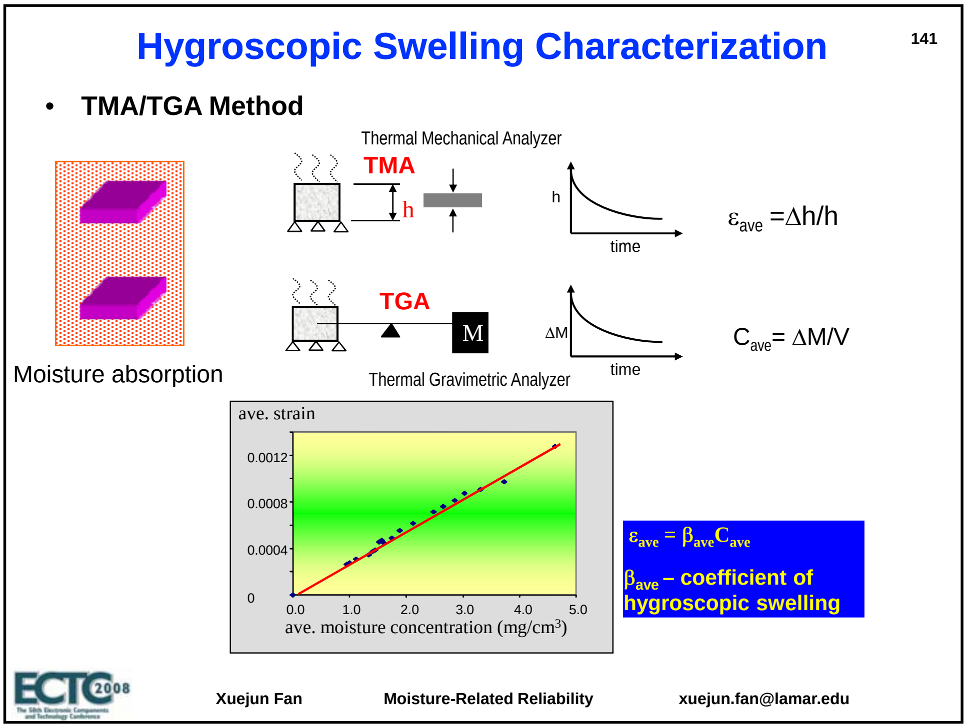
Time 200h at 85°C/85RH

Hygroscopic Swelling Characteristics

- **Characterization Technique – TMA/TGA Method**
  - Machine
    - Two standard thermal analysis instruments (TGA & TMA)
  - Specimen
    - Identical shape and size so as to ensure identical moisture absorption and desorption rate



TGA **TMA**



Hygroscopic Swelling Characterization

- **TMA/TGA Method**

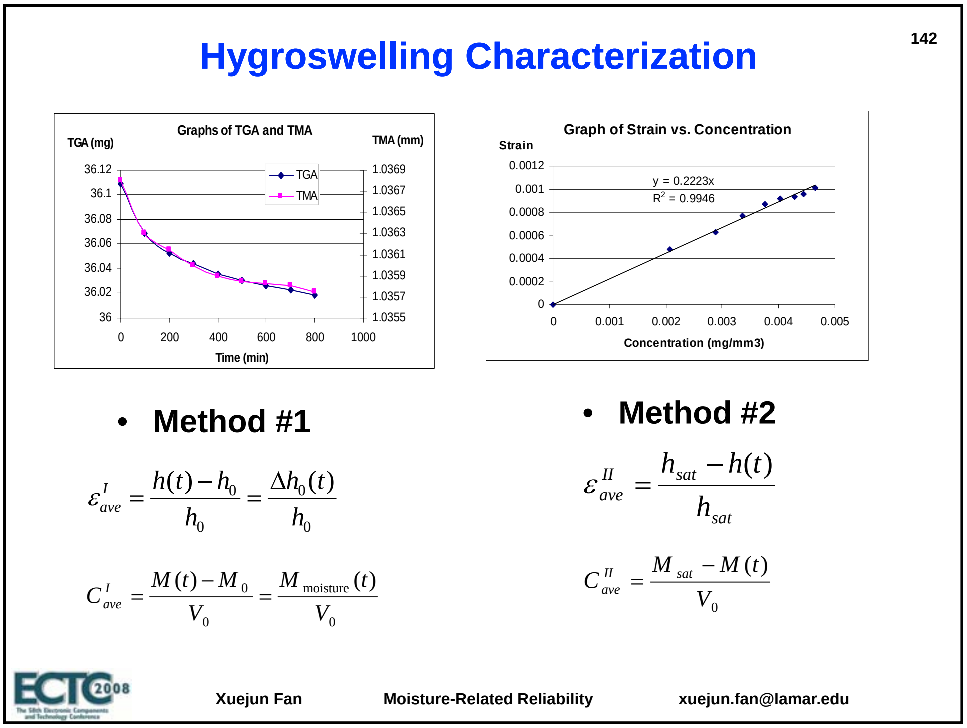
$\varepsilon_{ave} = \Delta h/h$

$C_{ave} = \Delta M/V$

Moisture absorption

$\varepsilon_{ave} = \beta_{ave} C_{ave}$

β_{ave} – coefficient of hygroscopic swelling



Hygroswelling Characterization

- **Method #1**

$$\varepsilon^{I}_{ave} = \frac{h(t)-h_0}{h_0} = \frac{\Delta h_0(t)}{h_0}$$

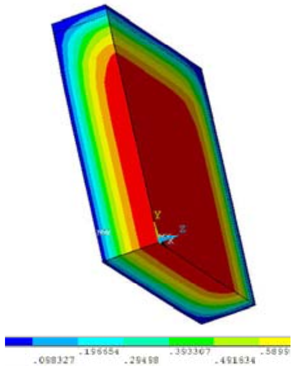
$$C^{I}_{ave} = \frac{M(t)-M_0}{V_0} = \frac{M_{\text{moisture}}(t)}{V_0}$$

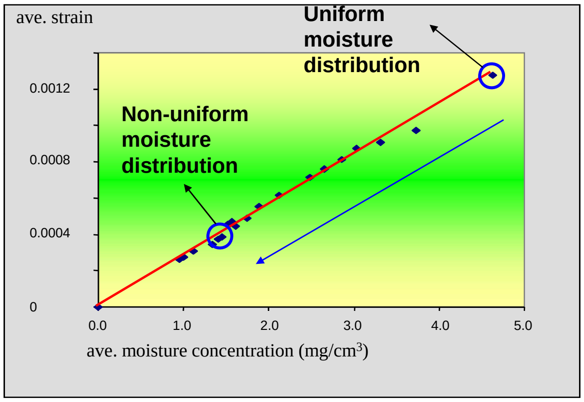
- **Method #2**

$$\varepsilon^{II}_{ave} = \frac{h_{sat}-h(t)}{h_{sat}}$$

$$C^{II}_{ave} = \frac{M_{sat}-M(t)}{V_0}$$

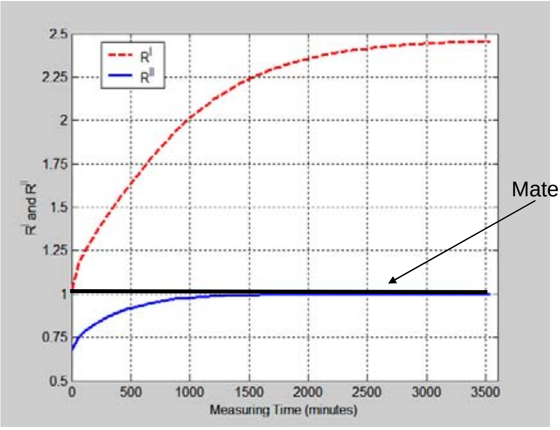
Issues





- **What's impact of non-uniform moisture distribution across the test specimen during measurement?**
- **$\beta_{ave} = \varepsilon_{ave}/C_{ave}$ – Can the averaged β_{ave} represent the true material property of hygroscopic swelling?**

Theoretical Predictions

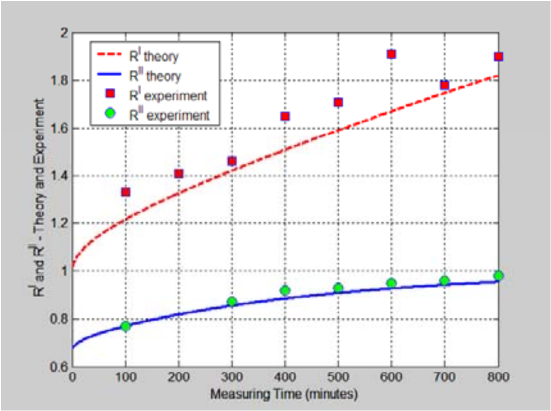


Material constant

- **The error can be as big as 250% due to moisture non-uniformity.**
-

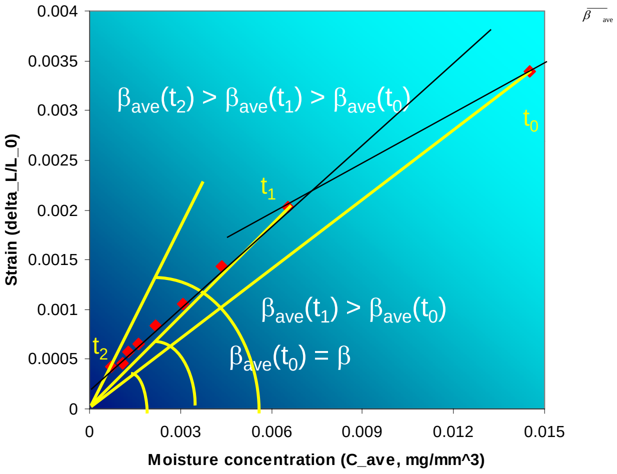
$$\beta_{ave}^{II} \le \beta \le \beta_{ave}^{I}$$

Experimental Verification



- **Good Correlation between theoretical prediction and experimental results is obtained.**

Regression Analysis



- **Linear regression further introduces the randomness in determining the coefficient of hygroscopic swelling.**

Guideline in Hygroswelling Characterization

- **Specimen fully saturated before measurement**
- **Dry the specimen completely**
- **Measure moisture loss and dimension change under TGA and TMA for only two points – fully saturated and fully dry conditions**
- $\beta = (L_{sat} - L_{dry})^{*}V/L_{dry}{}^{*}(M_{sat} - M_{dry})$

Hygroscopic Swelling and Free Volume

- **How hygroscopic swelling is induced?**

Hygroscopic swelling induced volume change

$$\frac{\Delta V}{V} = 0.3\%$$

Free volume fraction

$$f_0 = \frac{V_{free\ volume}}{V} = 3\%$$

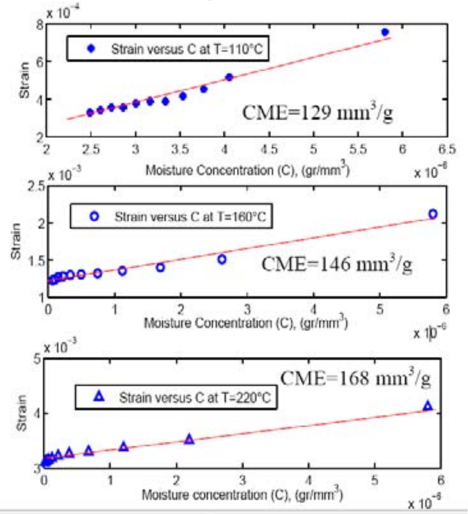
- **The hygroscopic swelling is only a small fraction of the total free volume**
- **Swelling is caused by water molecules bound to the polymer matrix and not by free water molecules**
- **Free volume fraction estimate without considering swelling effect is acceptable**

$$\varepsilon_{\text{swelling}} = \beta C \quad \Rightarrow \quad \varepsilon_{\text{swelling}} = \beta C^{\text{bound water}}$$

What Are Gaps Now?

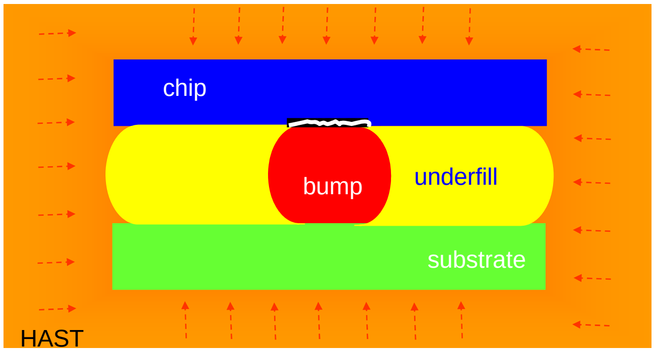
- **The dependency of the coefficient of hygroscopic swelling on temperature unknown**
- **The dependency of the coefficient of hygroscopic swelling on RH unknown**
- **$\beta = \beta$ (T, RH) ??? Will follow Arrehnius relation?**

Hygroscopic Swelling Measurement at Different Temperatures



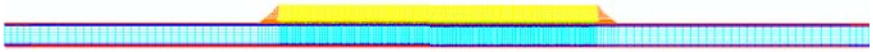
Ack: H. Shirangi, J. Auersperg, EuroSimE 2008, 455-462

BLM/ILD Failure Mechanism Hypothesis during HAST

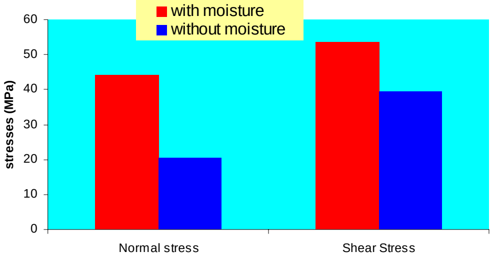


- **Due to hygro-swelling, tensile stress/strain is generated in BLM/ILD layer to cause delamination/cracking.**

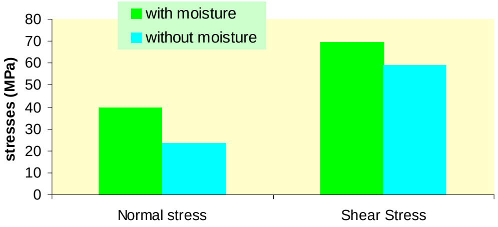
BLM Stresses after HAST



ILD stresses (MPa) at 85C after HAST



ILD stresses (MPa) at 25C after HAST



Equivalent Coefficient of Thermal Expansion (CTE) – Linear Analysis

- **The hygroswelling introduces additional mismatch**
  - Hydroswelling strain can be treated as additional thermal strain in addition to thermal strain
- **Linear thermal stress analysis**
  - Stress-free at T_0 and cooling down (or heating up) to T_1
  - The total 'expansion strain' = $\alpha (T_1 - T_0) + \beta^* C$
  - Equivalent coefficient of thermal expansion
    - $\alpha + \beta^* C / (T_1 - T_0)$
- **When vapor-pressure induced expansion is included**
  - Stress-free at T_0 and cooling down (or heating up) to T_1
  - The total 'thermal strain' = $\alpha (T_1 - T_0) + \beta^* C + (1 - 2\nu)\, p / E$
  - Equivalent coefficient of thermal expansion
    - $\alpha + \beta^* C / (T_1 - T_0) + (1 - 2\nu)\, p / E / (T_1 - T_0)$

  - The above analysis assumes
    - Linear analysis
    - Vapor pressure and moisture is uniformly distributed (the worst case)

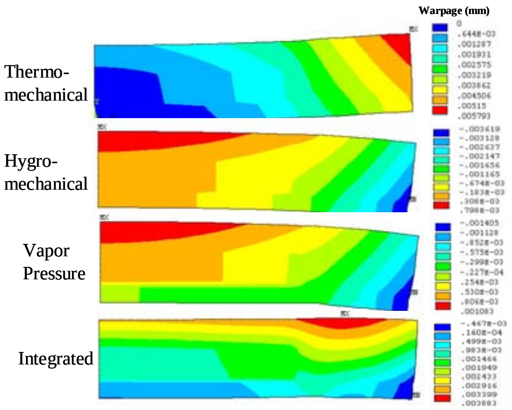
Moisture and Hygroswelling Properties

Materials	**D (mm^2/s)**	**CME (mm^3/mg)**	**Csat (mg/mm^3)**	**Total hygro strain (CME x Csat)**
Underfill A	**9.02e-6**	**0.18**	**0.0152**	**0.0027**
Underfill B	**1.55e-6**	**0.22**	**0.0329**	**0.0072**
Underfill C	**1.14e-5**	**0.31**	**0.0112**	**0.0035**
Mold Compound	**2.79e-6**	**0.4**	**0.0043**	**0.0017**
Solder Mask	**4.83e-5**	**0.2**	**0.0143**	**0.0029**
BT Substrate	**2.13e-6**	**0.4**	**0.0075**	**0.0030**

	Mold Compound		Die Attach	
	Total Strain	Equivalent mean CTE (ppm/°C)	Total Strain	Equivalent mean CTE (ppm/°C)
Thermo-mechanical	**1.53e-3**	**34**	**7.65e-3**	**170**
Hygro-mechanical	**1.57e-3**	**34.9**	**3.22e-3**	**71.6**

Integrated Package Stress and Warpage (QFN Package)

Package Warpage during Reflow



- **Thermo-mechanical model has upward warpage, opposite in direction as compared to hygro-mechanical, and vapor pressure induced.**

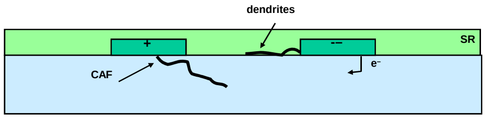
Summary

- **Polymer expands upon absorbing moisture – hygroscopic swelling**
- **Hygroscopic strain is comparable to & may be larger than thermal strain**
- **$\varepsilon = \beta C$: β - hygroswelling coefficient – can be measured by TGA/TMA**
- **Hygroscopic swelling and adhesion reduction are main failure mechanisms under HAST**

Electrochemical Metal Migration

Electrochemical Migration under BiHAST

- **Conditions**
  - **Moisture absorption/condensation**
  - **Voltage**
  - **Contamination**
- **Two different failure mechanisms**
  - **On surface: dendritic growth**
    - Electrolytic dissolution of metal at anode followed by the reduction and deposition of metal ion at cathode
  - **Below surface: conductive anodic filament (CAF)/ conductive filament formation (CFF)**
    - Growth initiates at anode and proceeds along separated fiber/epoxy interface



<u>Ref</u>: Katayanagi et al. ESPEC Japan Tech-info Field Report #5, 1996

- Moisture provides electromigration transport path

Fundamentals of Electrochemical Migration

- **Dendritic growth**

@ V ≥ 1.23V – electrolytic decomposition of water:

$H_2O \rightarrow H^+ + OH^-$

- ***At the Anode: oxidation and metal loss***
  - **production of hydronium ion:**

    $H_2O \rightarrow ½O_2\uparrow + 2H^+ + 2e^-$
  - **electrolytic dissolution of metal:**

    $M \rightarrow M^{n+} + ne^-$

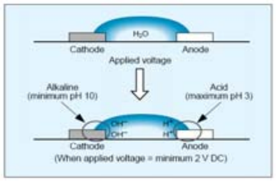
    $Cu \rightarrow Cu^{n+} + ne^-$ (n = 1,2)
- ***At the Cathode: reduction and protective effects***
  - **production of hydroxyl ion:**

    $2H_2O + 2e^- \rightarrow H_2\uparrow + 2OH^-$
  - **reduction of metal:**

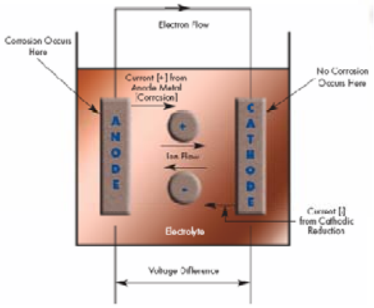
    $M^{n+} + ne^- \rightarrow M$

    $Cu^{n+} + ne^- \rightarrow Cu$ (n = 1, 2)

The production of H^+ at the anode and OH^- ions at the cathode creates a pH gradient between these electrodes



Changes in pH in the vicinity of the electrodes

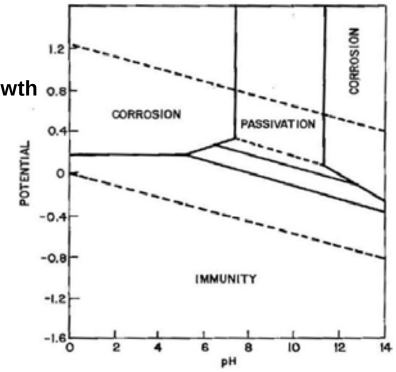


The Electrochemical Cell

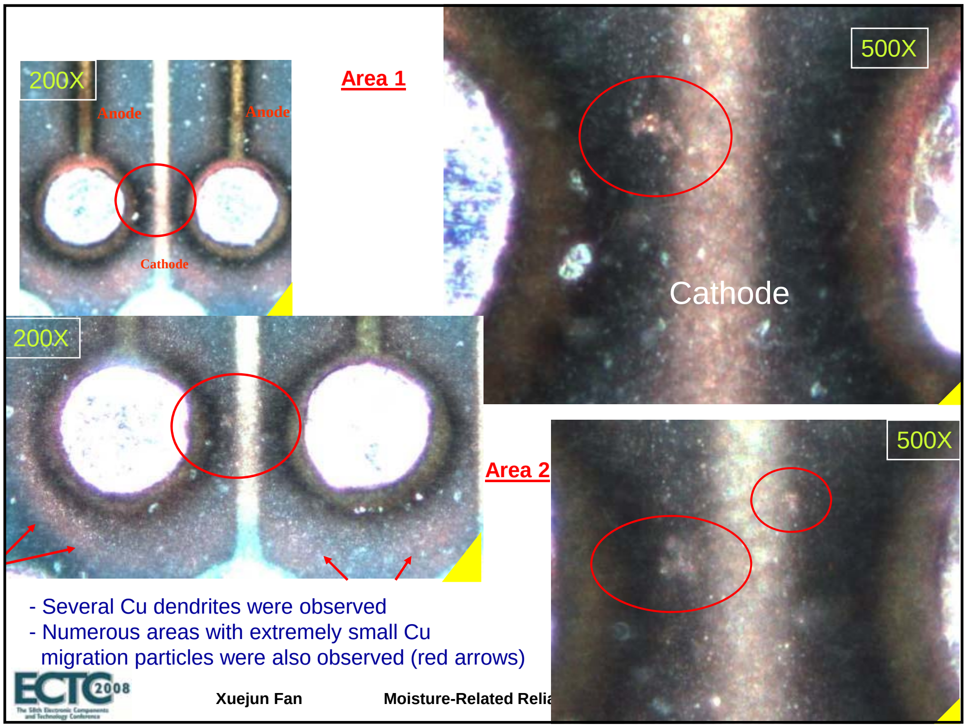
Fundamentals of Electrochemical Migration

- **From the Pourbaix diagram for copper**
  - pH 7 to 11: copper is passivated; no corrosion will occur
  - < pH 7: copper corrosion occurs at potentials greater than 0.2V
  - > pH 5: solubility of copper ions declines rapidly, becoming nearly insoluble at ~ pH 8.6
- **At the anode, H^+ caused a drop in local pH → soluble Cu^{n+}**
- **At the cathode, the copper ions become insoluble and precipitate out**

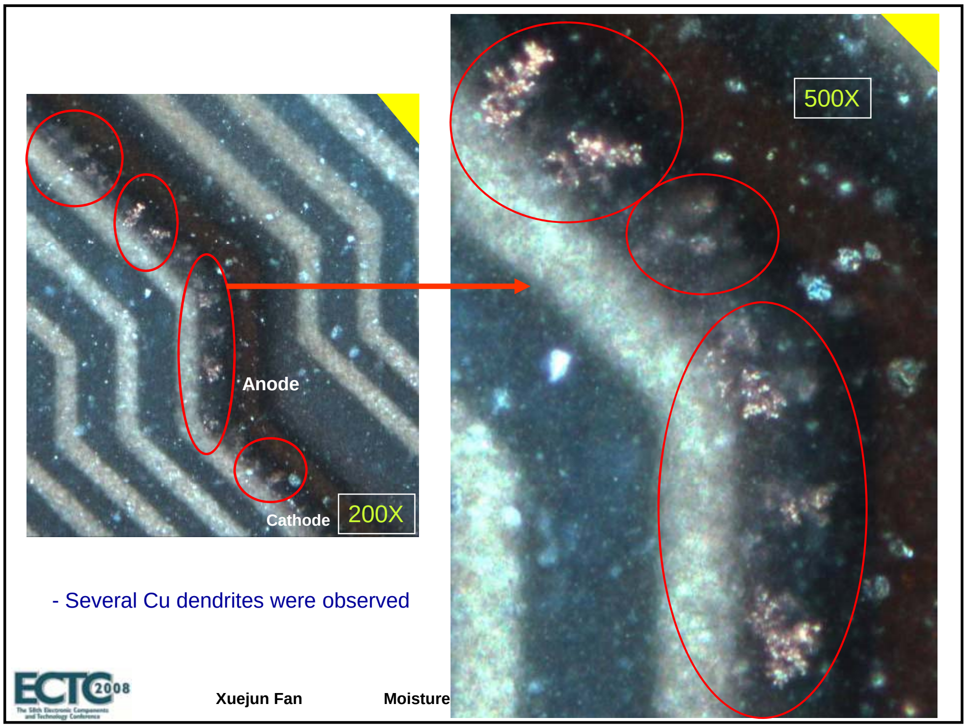
- **Electrical failure occurs when contact is made**
- **If bias voltage is removed prior to contact, growth will terminate due to the cessation of the electrochemical reaction**



Simplified Pourbaix Diagram for Copper

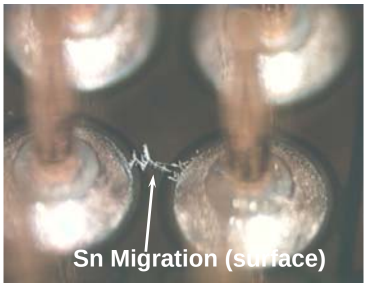


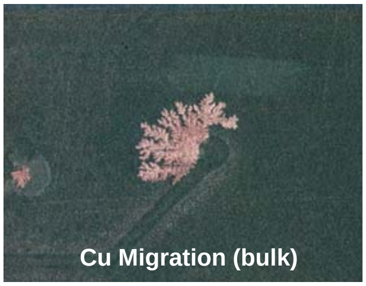
- Several Cu dendrites were observed
- Numerous areas with extremely small Cu migration particles were also observed (red arrows)



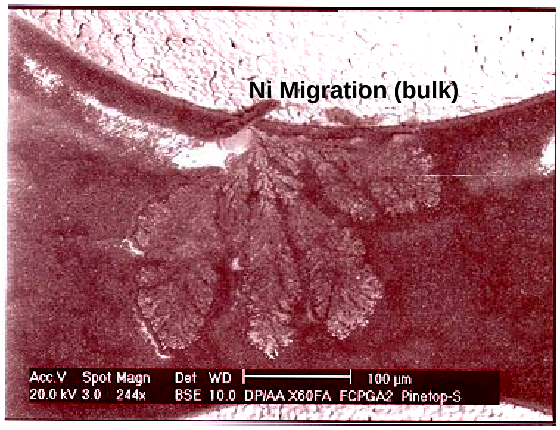
- Several Cu dendrites were observed

Examples: Metal Migration Types



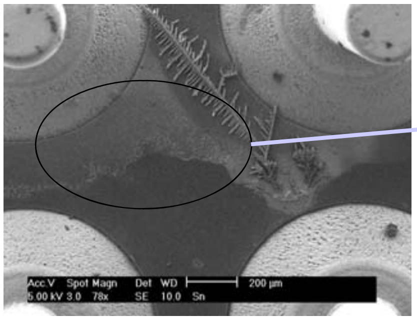


Surface and bulk metal migration

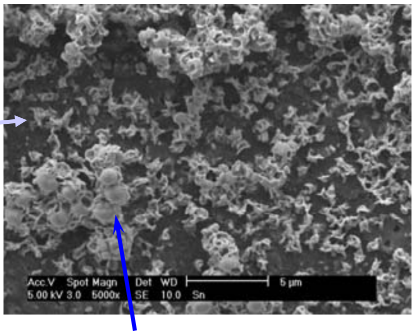


HAST Metal Migration - Continued

Surface Migration: in plane



*Sn/Sn oxide stains on the periphery of pins with the solder bridging material.



Crystal particles ready as nuclei for further growth due to water condensation

Dendritic Growth

Anode Reactions

1. Metal oxidation creating metal ions that migrate towards the cathode. When the metal ions reach the cathode, dendritic growth can occur.
2. Halide ion breakdown of the passive film creating freshly exposed metal surface.
3. The oxidation can eventually lead to an open circuit failure.

Cathode Reactions

1. Chemically formed metal oxides or hydroxides followed by dissolution of these species. This will lead to erosion of the cathode causing an open circuit failure.
2. Reduction of dissolved metal ions leading to nucleation and growth of metal dendrites. This would lead to the formation of anode-cathode short failure.

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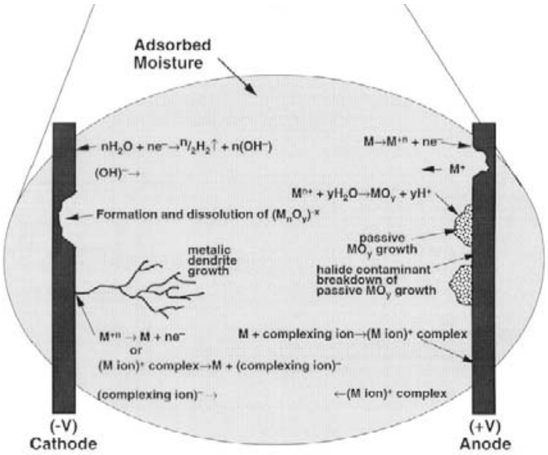
Summary: Metal Migration Mechanism



B

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Metal migration process:

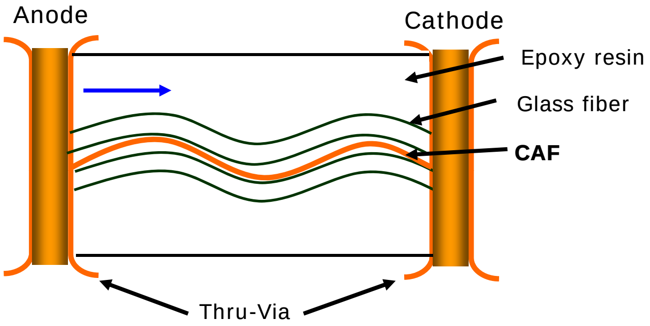
- Electro-dissolution (anode)
- Ion transport
- Electro-deposition (cathode)

Dendrites growth:

- Initiation
- Propagation

Dendrites shape:
- flow of species involved in the electrolytic process
- path of current flow (electric field)
- Critical over-potential or critical current density

Conductive Anodic Filament (CAF) Failure



Anode: $Cu_{(s)} \rightarrow Cu^{n+}_{(aq)} + ne^-$

$H_2O \rightarrow ½O_{2(g)} + 2H^+_{(aq)} + 2e^-$

- Electrochemical corrosion process that grows from anode to cathode along delaminated fiber/epoxy interfaces
- Dropping pH value at anode results in soluble Cu corrosion product. This corrosion product proceeds through any weak interface/voids/opening from anode to cathode due to the pH gradient

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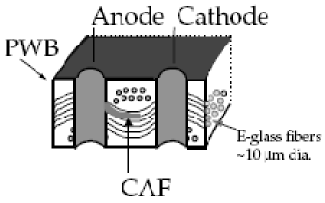
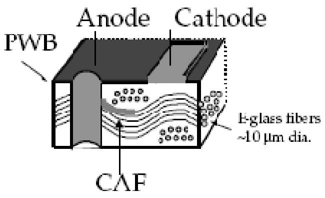
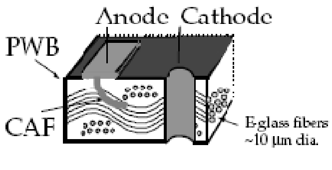
Conductive Anodic Filament (CAF) Failure



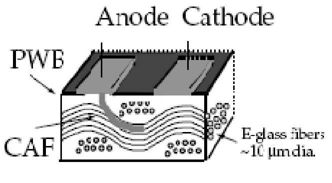
a: hole-to-hole



b: hole-to-trace



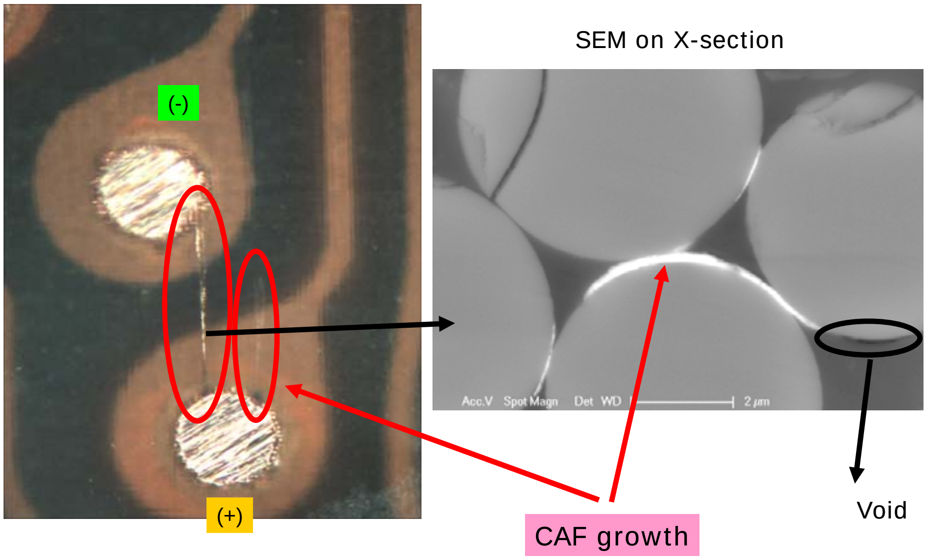
c: trace-to-hole



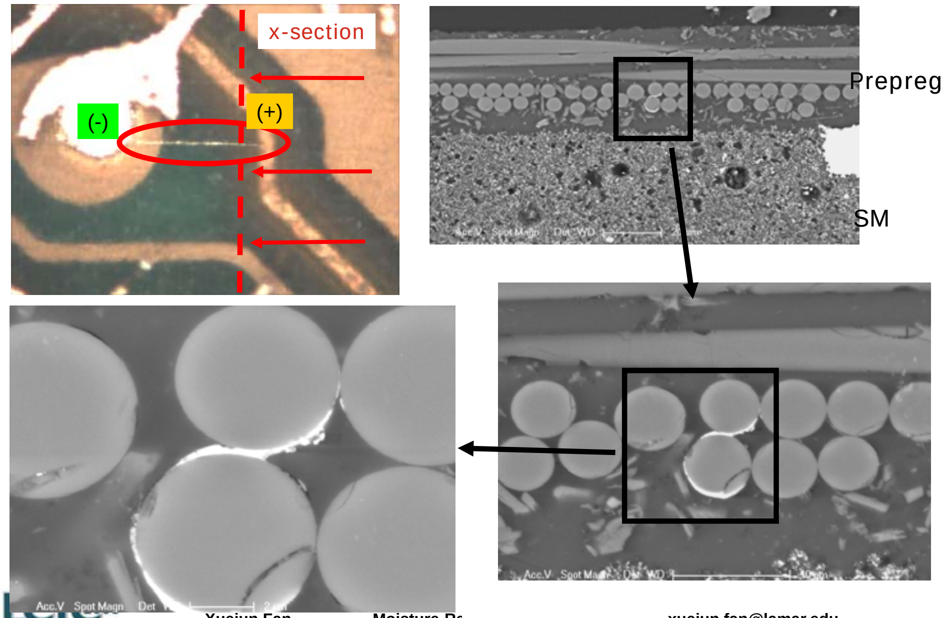
d: trace-to-trace

Example: Via to Via

SEM on X-section

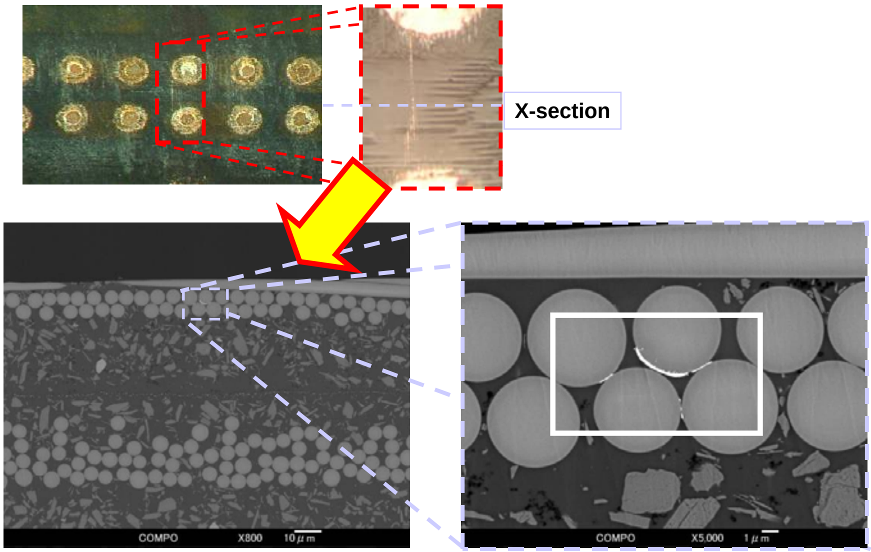


Example: Via to Trace



Intel package FA

Example: CAF Failure



Dendritic Growth vs. CAF Growth

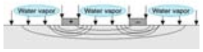
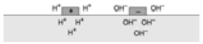
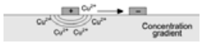
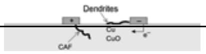
- A dendrite can be observed on the surface of PCB & substrate. However, CAF can occur in sub-surface associated with glass fibers/epoxy resin interface.

- A CAF grows from an anode to a cathode. However, a dendrite grows from a cathode to an anode with needle like/tree like shape.

- A CAF is made from soluble copper salt at anode and built at anode by turning to insoluble salt due to pH effect. Dendrite occurs as a result of solution at anode and plating at cathode.

Contributory Factors

ENVIRONMENT ⟷ **MATERIALS** ⟷ **PROCESS**

Reaction	Mechanism (schematic)	Acceleration Factors
Water adsorption and diffusion		• Moisture content • Temperature • Material quality
Changes in pH due to the electrolysis of water (acidization)		• Voltage • Moisture content • Temperature
Copper elution and copper ion diffusion (diffusion)		• Voltage • Moisture content • Material quality • pH, impurity ions • Dissolved oxygen content
Electron transfer and ion migration (reduction)		• Voltage • Material quality • pH, impurity ions

Ref: Katayanagi et al. ESPEC Japan Tech-info Field Report #5, 1996

Contributory Factors:

- **Environment – Temperature, Humidity, Voltage, Contaminants**
- **Materials – Package Materials Selection and Suppliers**
  substrate dielectrics, solder resist, flux and flux residue, Cu-plating chemistry, Cu metallization (line width/spacing and geometry) underfill chemistry (water adsorption isotherm, ionic content/contamination, CTE), *etc.*
- **Process – Package Assembly**
  baking, fluxing, soldering, cleaning, *etc.*

Contributory Factors

Foreign materials/defects/contaminants sources

- **materials-based sources – substrate manufacturing process**
- **assembly processes – residual ionic contaminants**
- **environmental sources – airborne dusts, *etc.***

Foreign materials and defects contribution to ECM failure – extrinsic factors

- **conductive bridges**
- **trace defects – extraneous material, mouse bites, breaks**
- **moisture condensation sites**

Summary

- Moisture provides metal migration /electron transport path. In a dry environment, metal migration is not a concern at all
- If bias voltage is removed prior to contact, growth will terminate due to the cessation of the electrochemical reaction
- Contamination changes local pH environmental conditions and thus accelerate the metal migration. For example, Na+ residue from SR developing solution and flux

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Summary

Summary

- Moisture Related Reliability Tests
- Moisture absorption, desorption, and diffusion
- Vapor pressure model
- Case study I – underfill selection for FC BGA packages
- Case study II – delamination/cracking in stacked-die chip scale packages
- Accelerated moisture sensitivity test
- Effect of moisture on material properties
- Hygroscopic swelling
- Electrochemical metal migration

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End of the Course

Questions?