Chapter 14 Fundamentals of Package Encapsulation, molding and sealing

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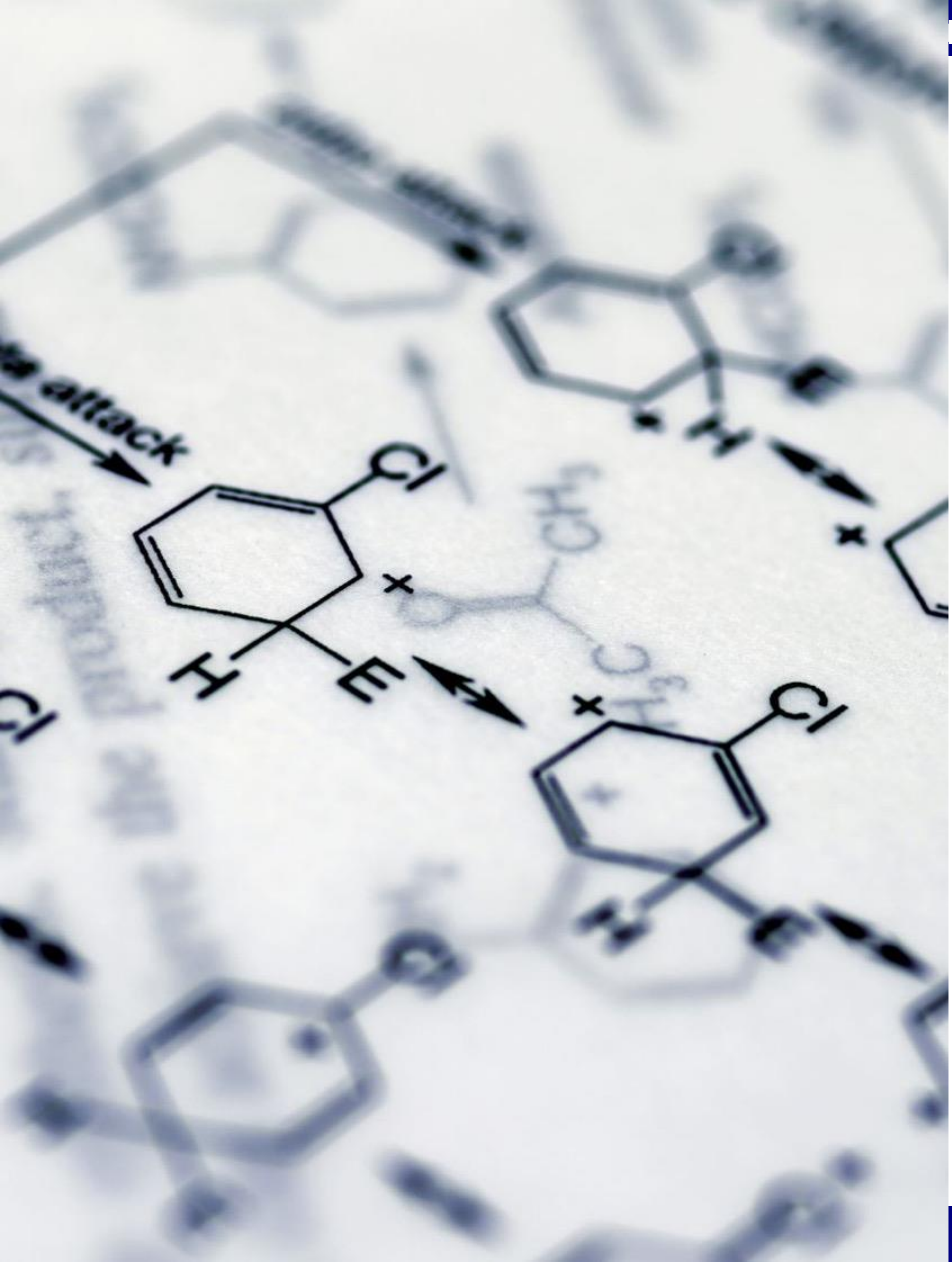


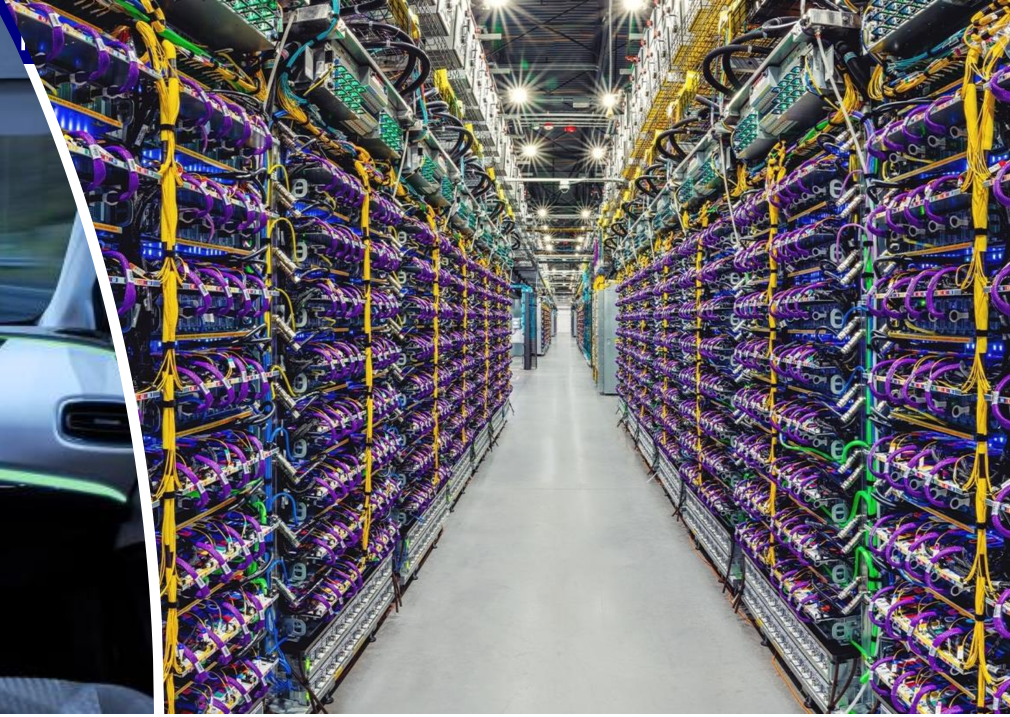
Outline

- 14.0 Materials in Electronic Packaging
- 14.1 What Is Sealing and Encapsulation and Why?
- 14.2 Anatomy of an Encapsulated and a Sealed Package
- 14.3 Properties of Encapsulants
- 14.4 Encapsulation Materials
- 14.5 Encapsulation Processes
- 14.6 Hermetic Sealing
- 14.7 Summary and Future Trends

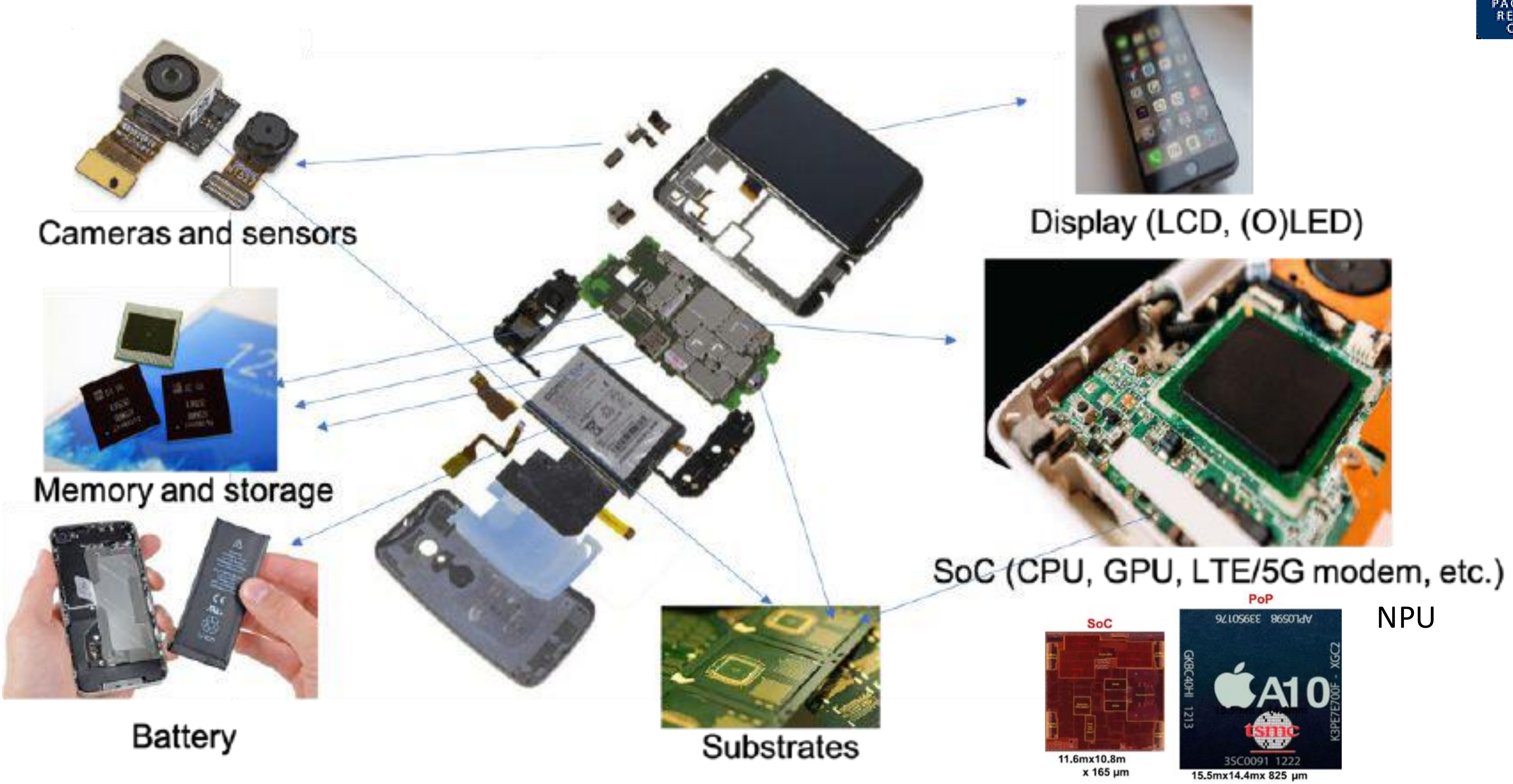
Electronics in various areas and demands

- Consumer electronics
  - Cell phones
  - Display
  - Computers
- Aerospace
- Automotive
- Data center

- Mobility; small, thin, multifunctional, flexible, etc.
- High speed computing
- High bandwidth communication (RF)
- High resolution visualization
- Safe operation and complex control/functions
- Reliability



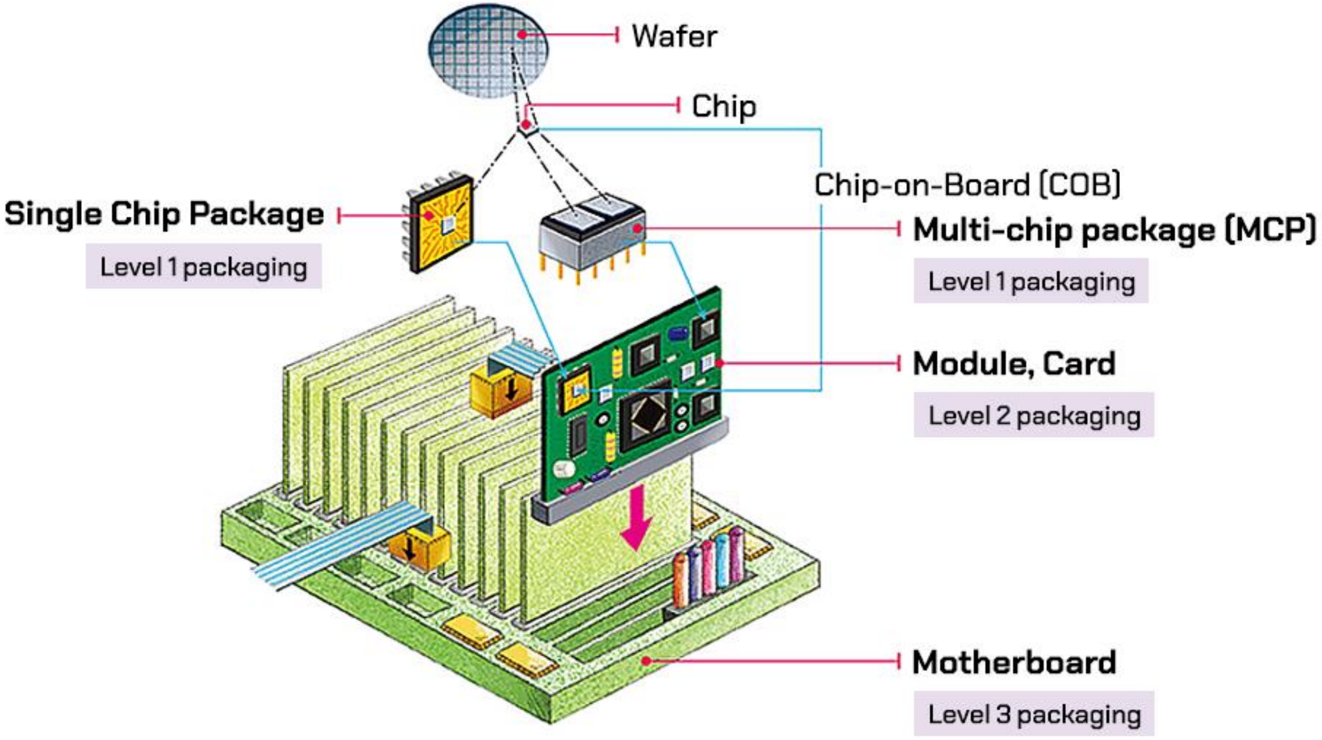
Electronics anatomy and packaging



Fundamentals of Encapsulation and Sealing

Electronic Packaging

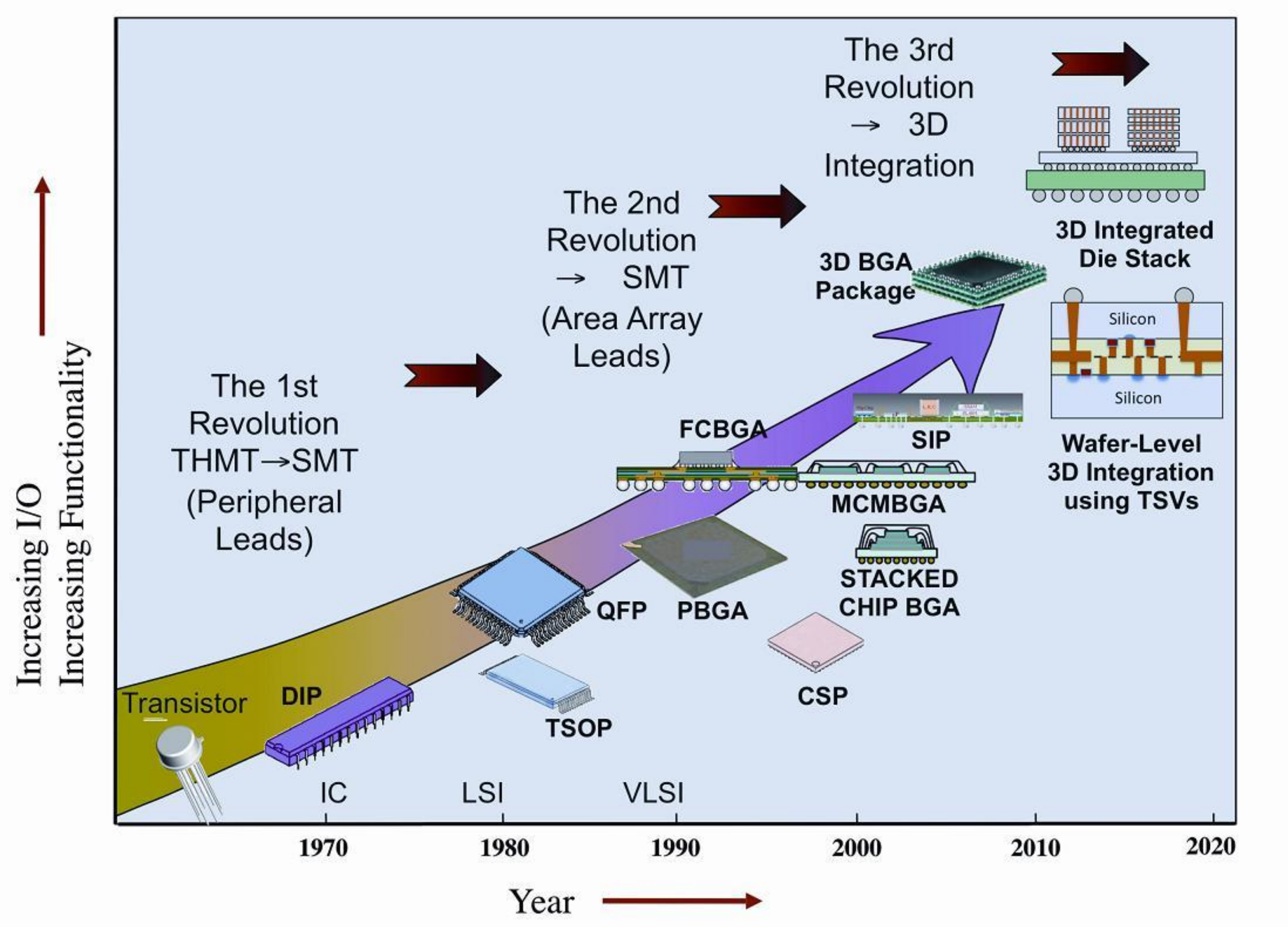
- Electronic packaging is a system integration. Defined as bridge that interconnects integrated circuits and other components into system-level board to form electronic products.
- Functions
  - *Power Distribution*
  - *Signal Distribution*
  - *Heat Dissipation*
  - ***Protection (physical/chemical)***
    - ***Reliability***



Source: *Principle of Electronic Packaging*, p. 5

Microelectronics Packaging Evolution

Interconnection
Technology



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Microelectronics Packaging

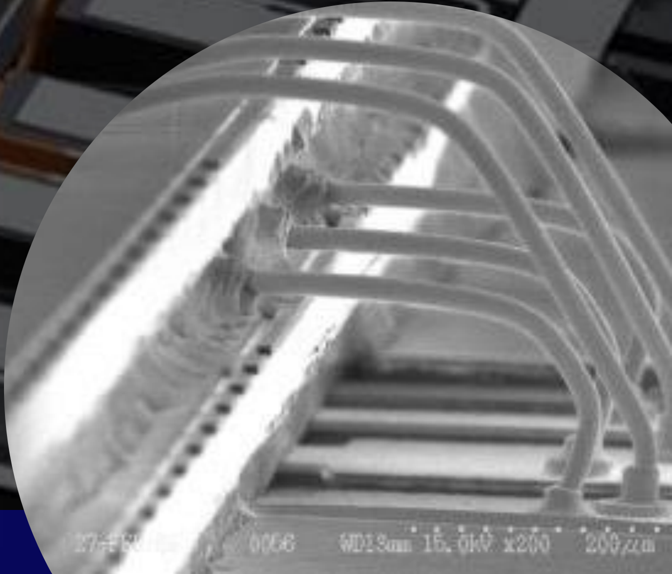
Power Distribution	Heat Dissipation
Signal Distribution	**Protection**

Packaging

Powering

Cooling

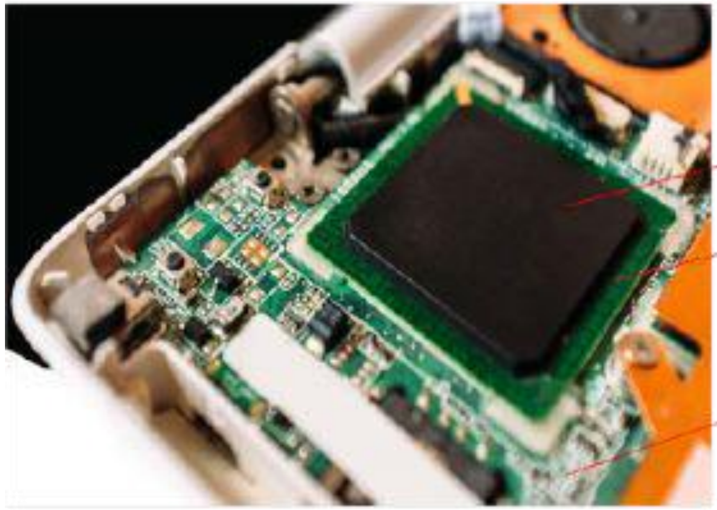
Protecting IC

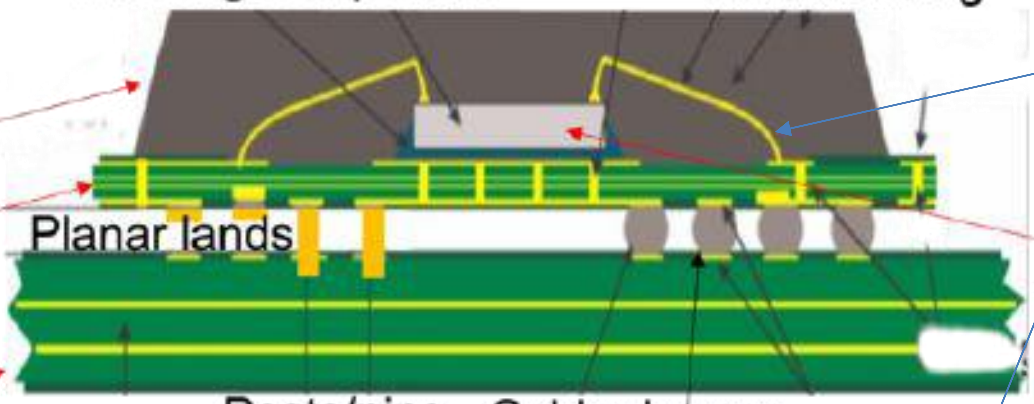


Interconnecting

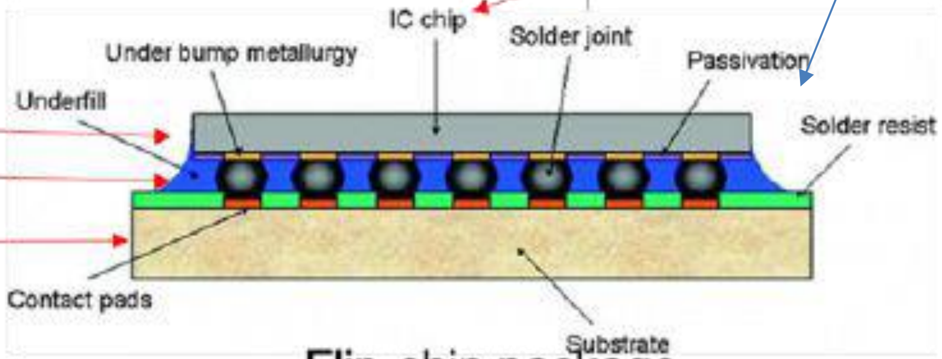
IC packaging and components

- Interconnection/signal/power distribution
- Protection
- Heat dissipation

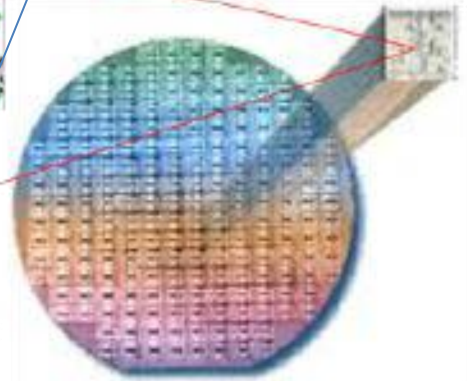

PBGA in a cell phone



BGA package



Flip-chip package


Diced IC die

Silicon wafer

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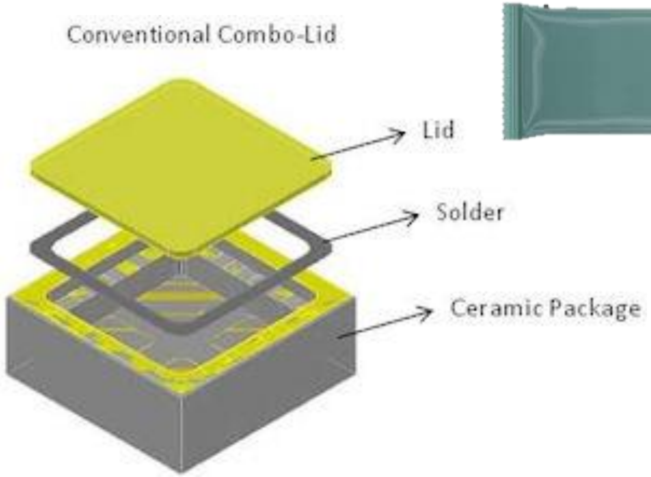
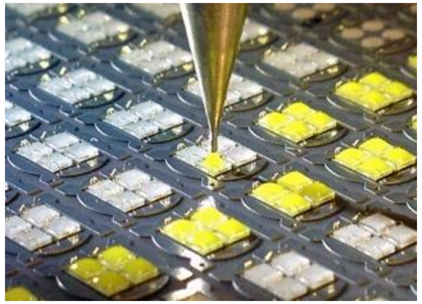
14. 1 What is Sealing and Encapsulation and Why

- Sealing/hermetic packaging
  - Gas tight or impervious to gas flow
  - Metal, ceramics and glass
  - High reliability; medical, optical, automotive, aerospace applications



- Encapsulation/near hermetic packaging
  - Commercial products/applications
  - Low temperature and low cost
  - Polymers

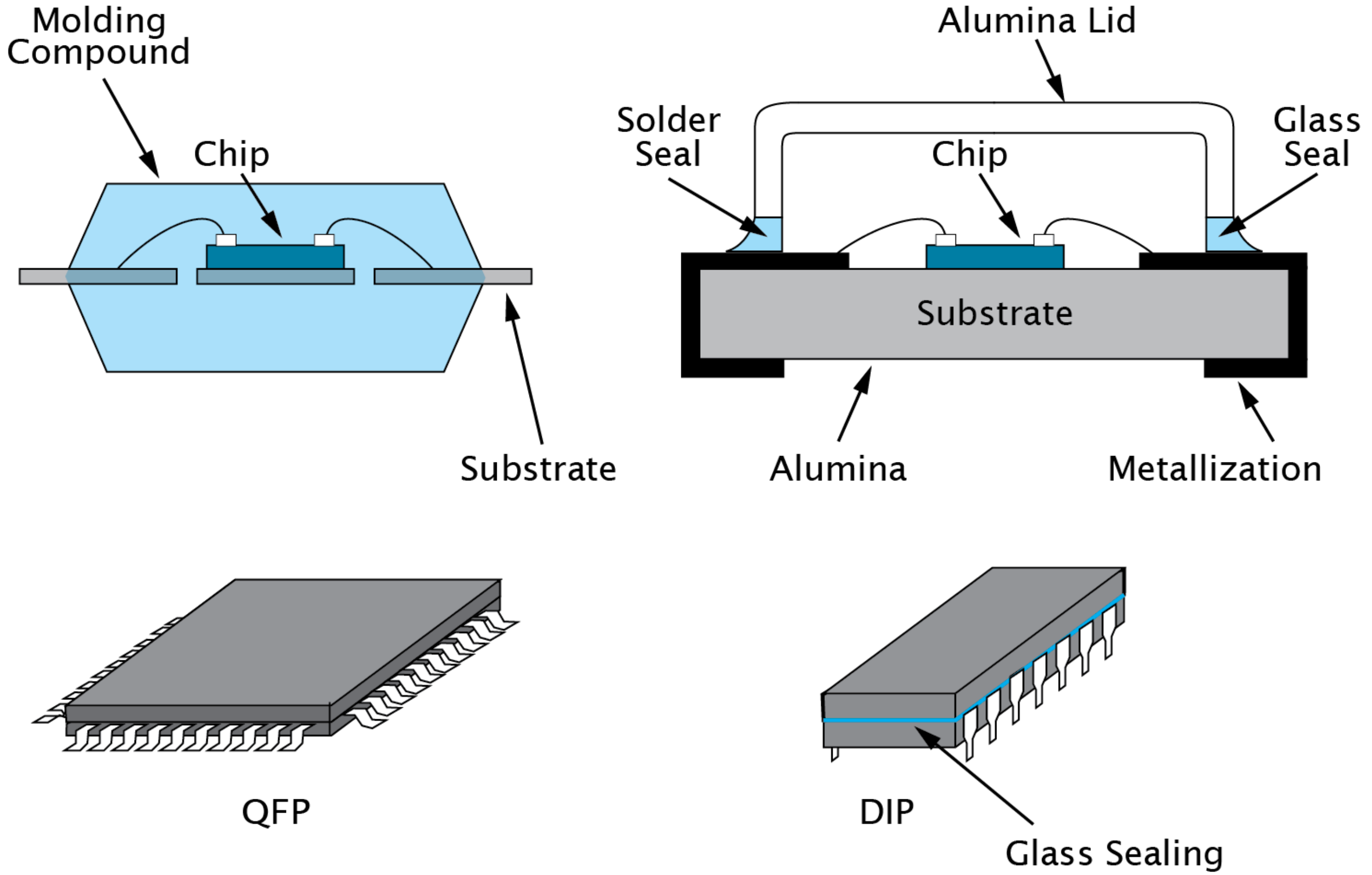
- Great progress made in polymer-based sealing/encapsulation for some of the most demanding applications (chemical, optical)
  - Not only protection but also providing functionality by using functional materials such as electrical (ESD and conductivity); lid bonding, fuel tank sealants, etc.



SOURCE; Google

Fundamentals of Encapsulation and sealing

14.2 Anatomy of an Encapsulated and a Sealed Package



(a) Encapulated Package

(b) Hermetically-seal Package

Fig 14.01 - Example of an encapsulated

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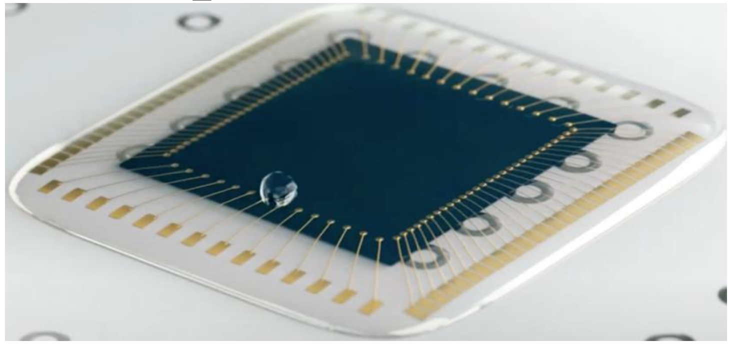
Fundamentals of Encapsulation and Sealing

Fundamentals of Encapsulation and Sealing

- Chemical Protection
  - Moisture; Primary contributor to failure/reliability, delamination, popcorn cracking, require bake-out prior to board assembly, moisture to cured/uncured resin resulting in lowered Tg, modulus, and adhesion, hygrostress by swelling
  - From Salts; mobile ions, corrosion in fine-pitch,
  - From Biological Organisms; insects, or so
  - Atmospheric contaminants; Corrosive acids-NOx and SO_2, acid rain
- Mechanical protection
- Functionality



Fundamentals of Encapsulation and sealing

Protecting ICs Chemically

Environmental pollutants, corrosive ingredients such as salts, biological secretions, mobile ions (Na+, Cl-, etc.)

Moisture (absorption/desorption)

- Delamination, popcorn cracking
- Reduce Tg and E of plastic encapsulants (both the uncured and cured/hydrolysis)
- Deteriorate adhesion of solder balls to epoxy
- Swelling-hygrostress, diffusion controlled, exponential

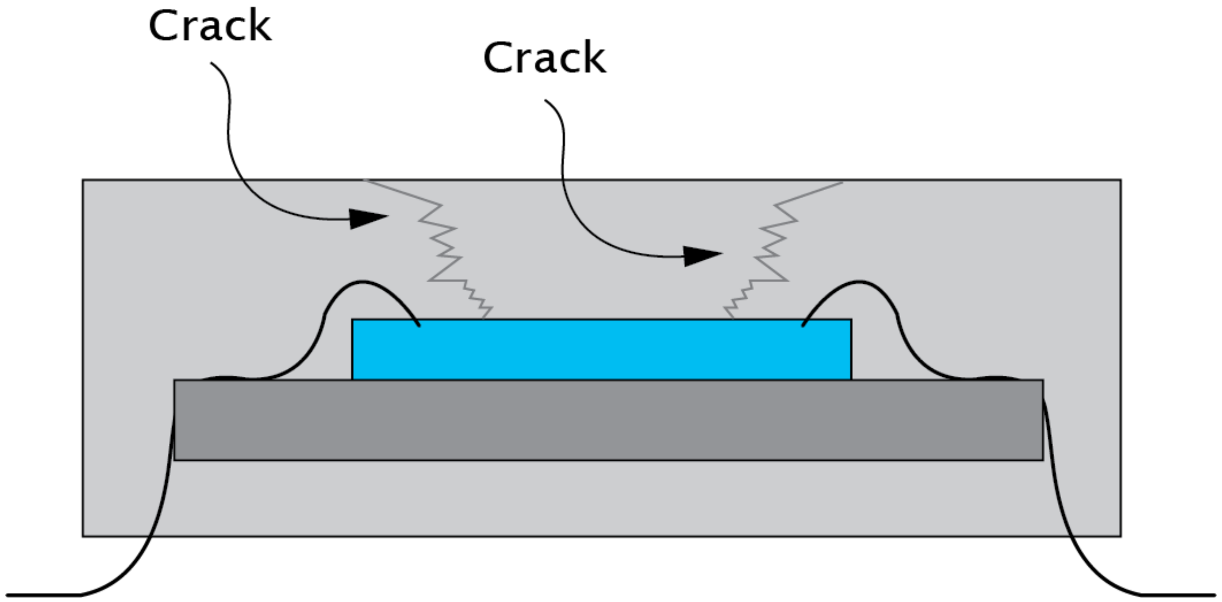
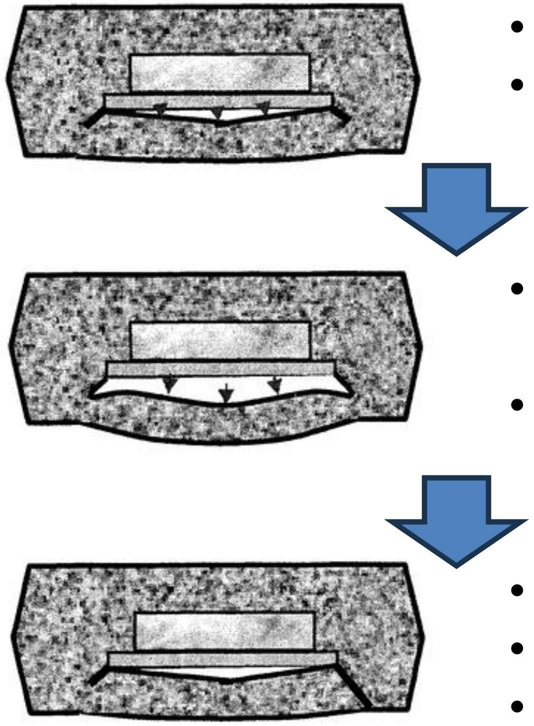


Fig 14.02 - Popcorn effect

$$\frac{W_t}{W_e} = \frac{4}{L}\sqrt{\left(\frac{Dt}{\pi}\right)} \qquad \text{Eq14.1}$$

$$W_e = KH_\alpha \qquad \text{Eq14.2}$$

Popcorn cracking in memory die-EMC

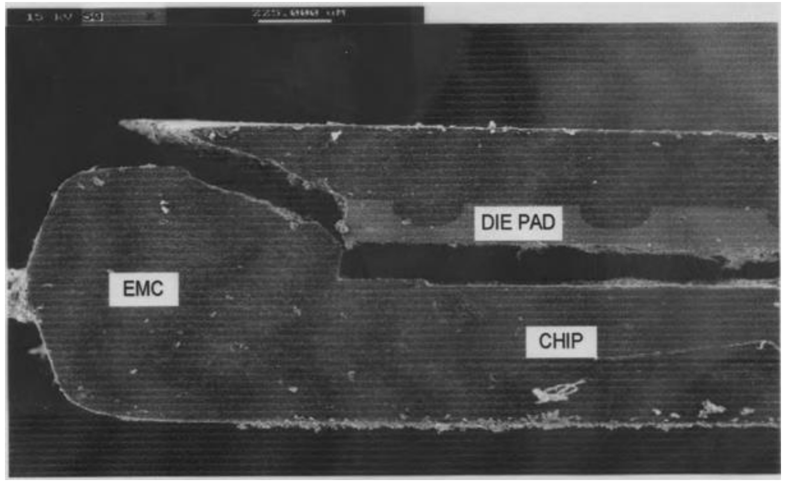


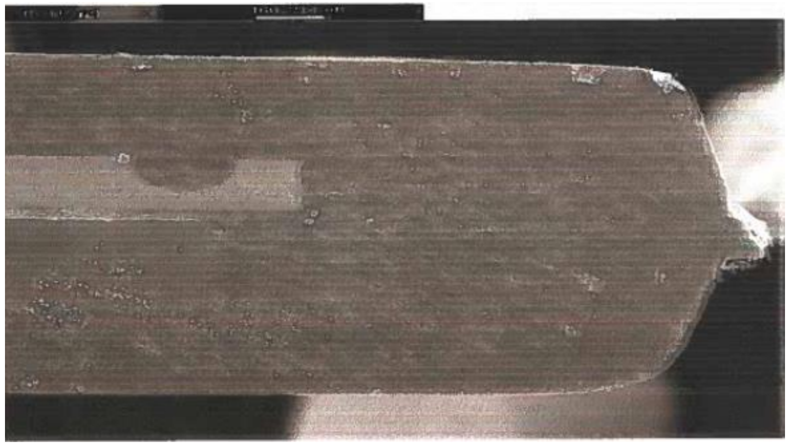
- Delamination
- Crack growth into EMC

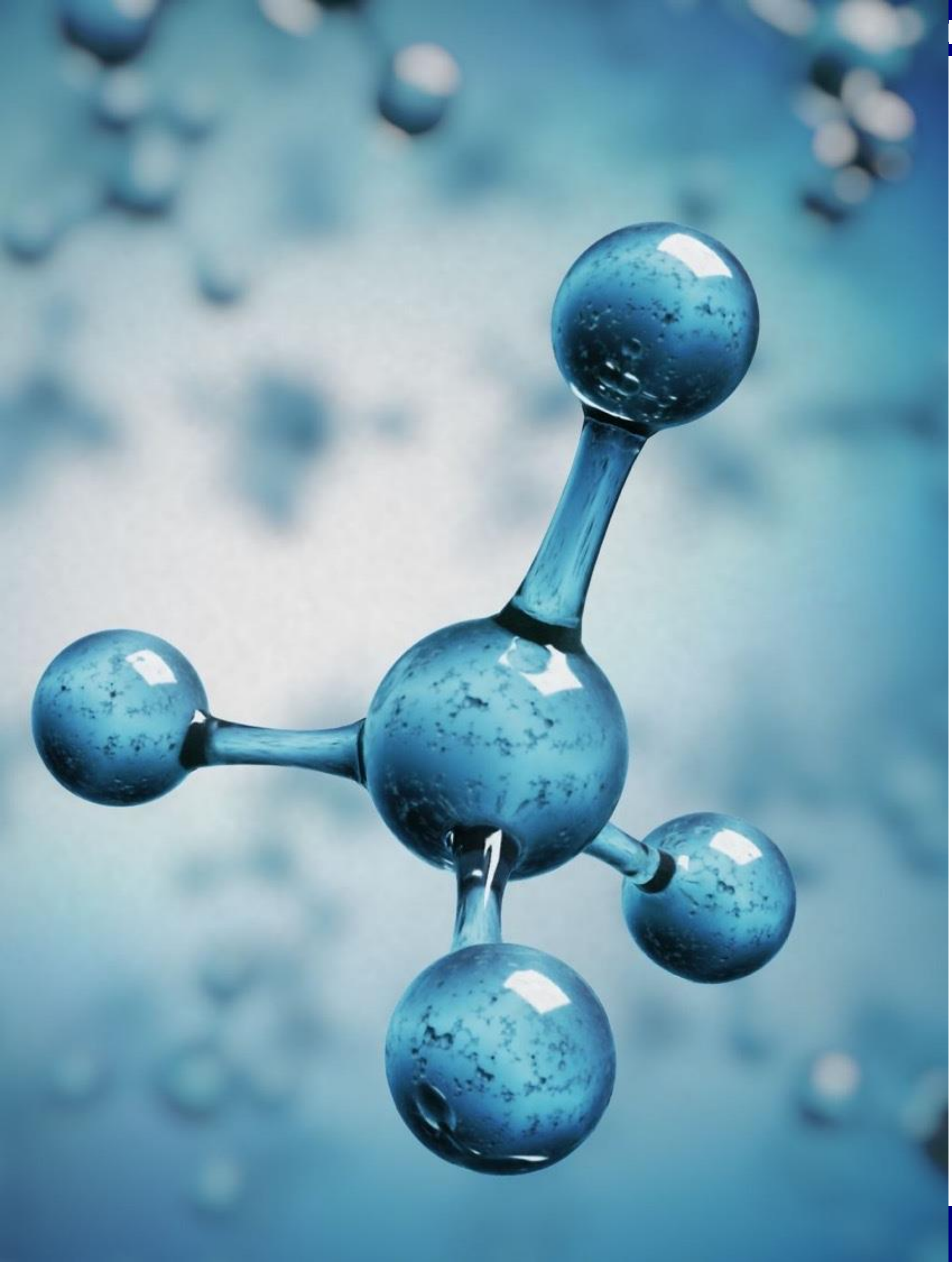
- Plastic deformation inhibiting crack growth
- Vapor pressure increases at elevated temperature

- Critical vapor pressure reaches
- Plastic collapse occurs
- Pressure release to deflate dome

Under standard reliability test (HAST, thermal cycling, thermal shock, etc. with temperature, pressure, bias, or so

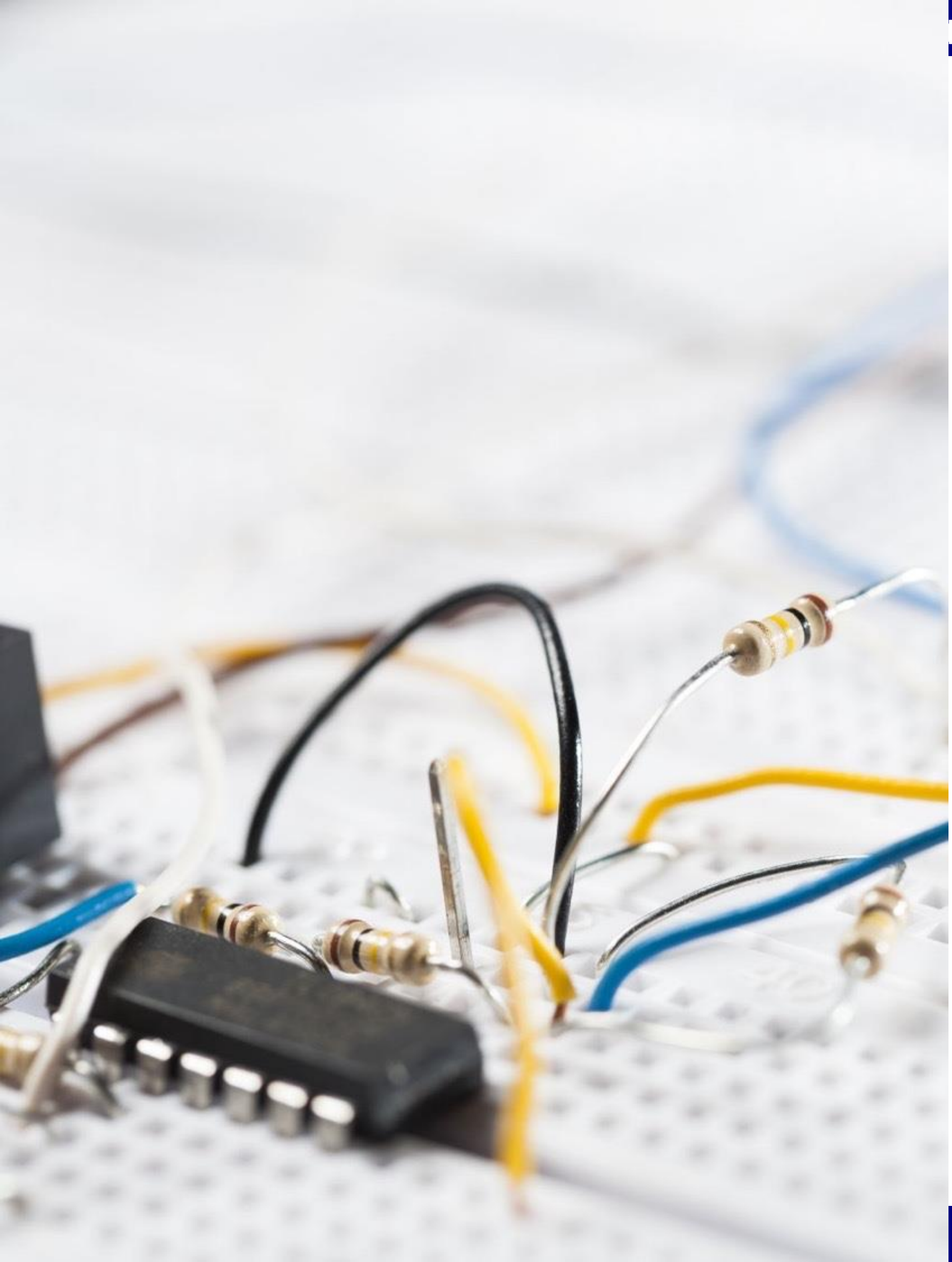






Protecting ICs Chemically (cont’d) Salts, biological organisms and atmospheric contaminants

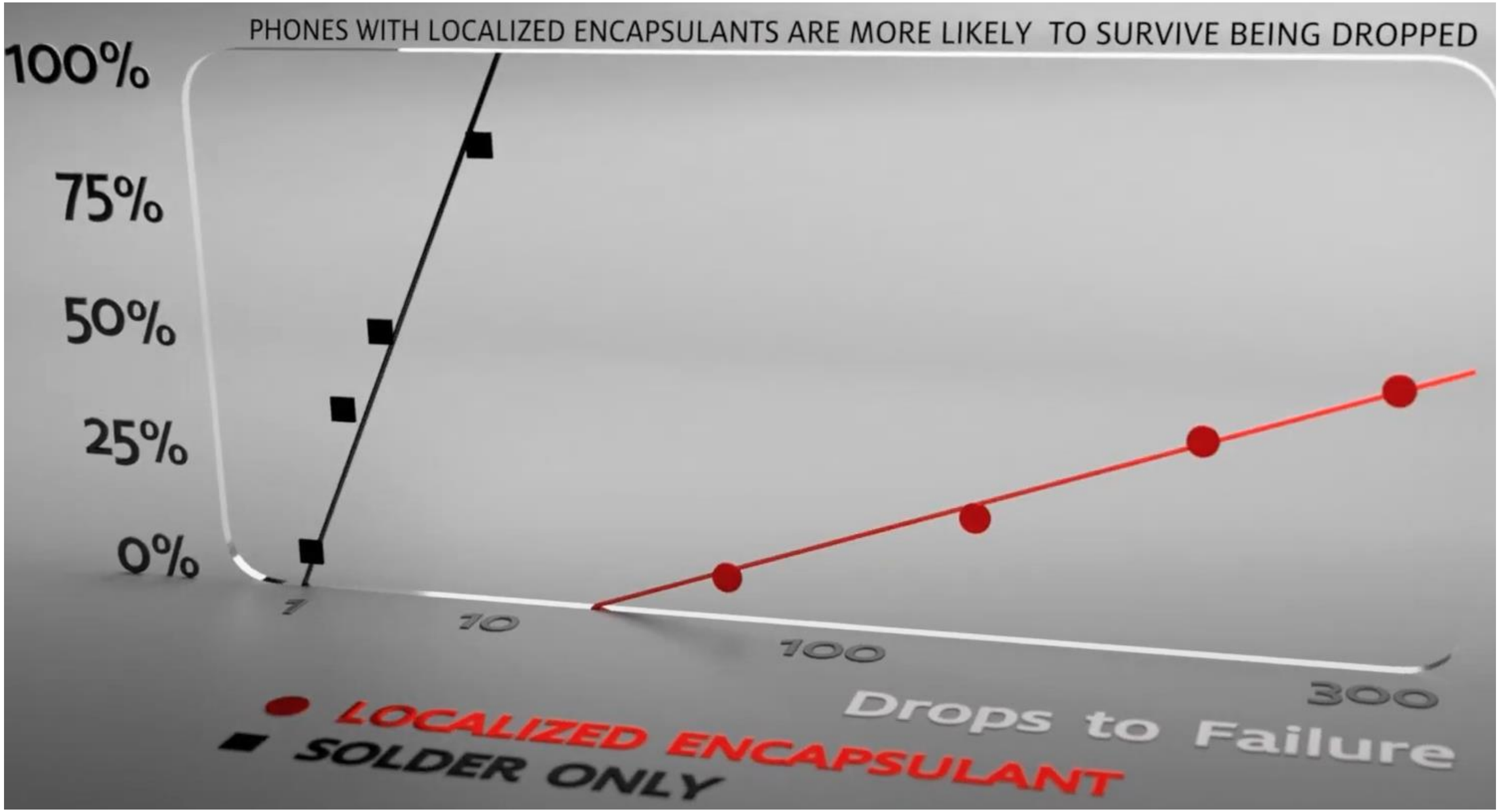
- Ionic contaminants; K+. Cl-, Na, cause electrolytic corrosion, electrochemical migration, very influential onto submicron sized pitch of electrical transmission lines
- Insects, fire-ants cause damage to some telephone switches
- Corrosive gases; NOx and SO2 from fossil fuel burning to form corrosive acids, brings about acid rains



Protecting ICs Mechanically/thermally

- From mechanical impact
- Protecting interconnections (wires and bumps) via encapsulating ICs
- Minimizing strain and distributing stress in the solder joints by underfills

For what Encapsulants are employed



Hermetic vs Non-hermetic

- Criteria of hermeticity; to prevent Helium's diffusion below 10 cm^3/s
- Organic vs inorganic
- Early days Hermetic packages; sealed at IC level by SiN or sealed in metal cases (military and aerospace industries)
- Hermicity by non-hermetic way; plastic packages (non-hermetic) evolved for acceptable reliability and now account for 90-95% of device packages

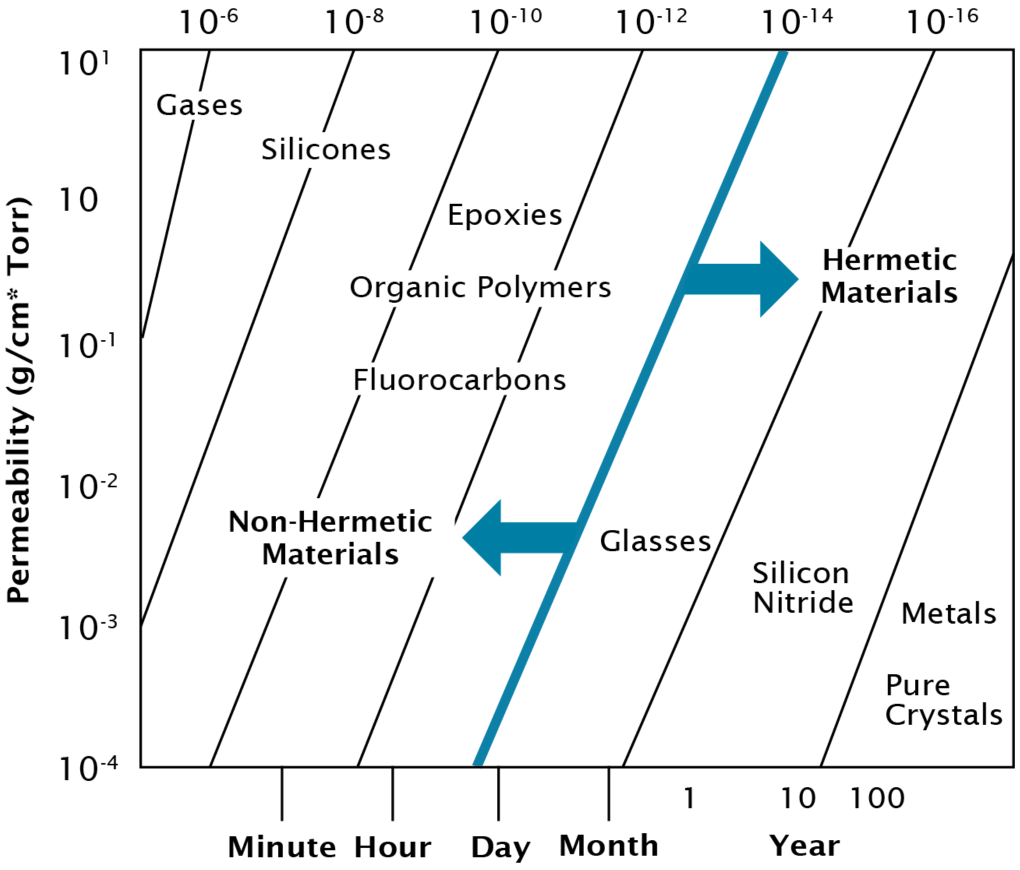


Fig 14.03 - Permeability of water

Moisture effects on Plastic Packages

Acting as a debonding agent between organic materials and substrates

- To form weak hydrated oxide surface
- To break chemical bonds
- To induce depolymerization or degradation; plasticizing, E and Tg reduction

Greater issues in organic materials due to the high water permeability

Trend to Polymer Encapsulants

Early stage of using polymers in electronic package struggled from moisture, interface, stress, etc.

Great progress in polymer chemistry and understanding in filler technologies enabled to achieve enhanced reliability of plastic packaged electronics

Most of modern packages are employing polymers;

- **High purity chemicals, sophisticatedly developed backbone molecules, additives and advanced filler technologies**
  - *Purity →Ionic impurity*
  - *Hydrophobicity →backbone, reduced polarity and free volume*
  - *Filler interfaces and loading techniques*

Accelerated testing-evaluation

To assess non-hermetic packaging

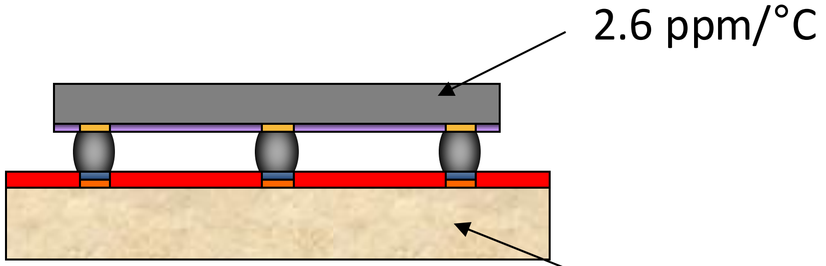
Temperature cycling to induce thermal stress

Correlation between the accelerated tests and real life time is not clearly established yet

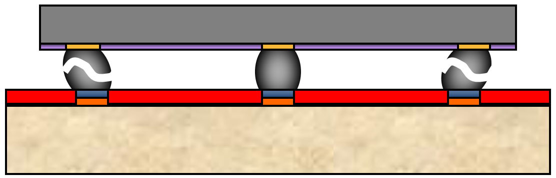
Examples

- Thermal shock: test method: –65°C to 150°C; cycle time: 10 s; dwell time: 5 minutes at each extreme 1000 cycles.
- Salt-spraying time: 24, 48, 96, 240 hours; salt concentration: 0.5–3 percent (NaCl) pH 6.0–7.5, 95°F; deposition rate: 10,000–50,000 mg/m for 24 hours at 35°C.
- Autoclave: 121°C, 100 percent relative humidity (RH), 30 psi (2 atm), with or without bias (pressure pot). Thermal shock

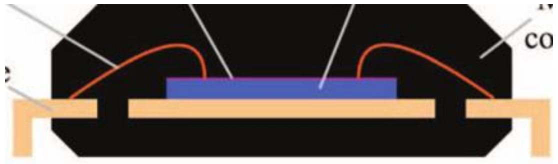
Thermal Stress in Packages

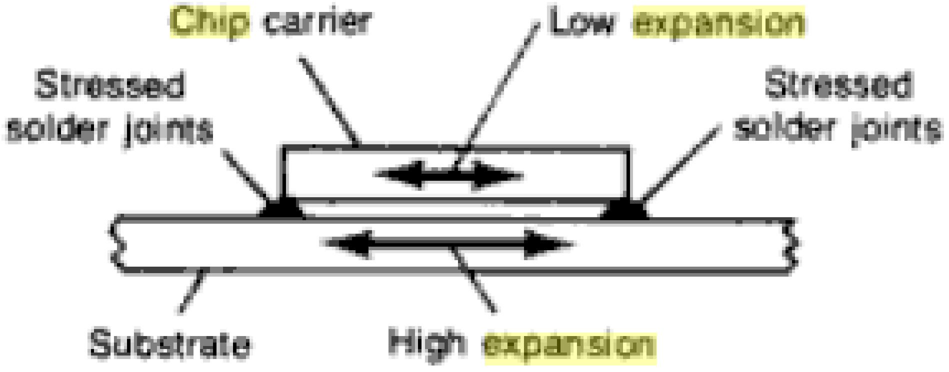


After reflow



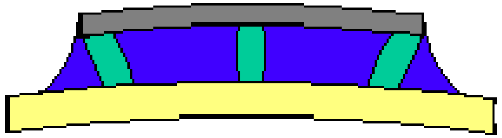
Solder fatigue after thermal cycling





$$\Delta\tau = \frac{D_{NP}\,\Delta(\alpha\Delta T)}{2h}$$

where D_{NP} = largest diagonal distance between solder joints, and h = height

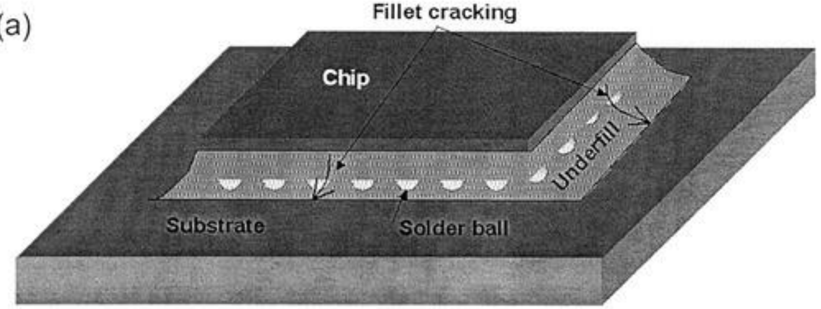


$$s = E \times e = E \times a \times dT$$

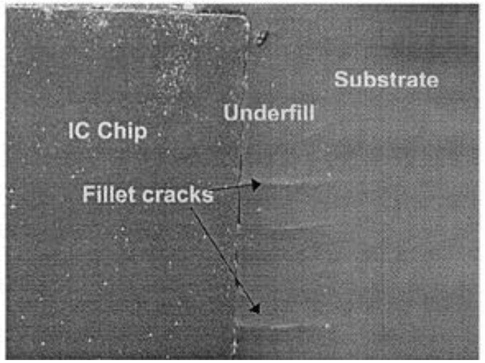
Stress/Modulus/Strain/CTE/Temp

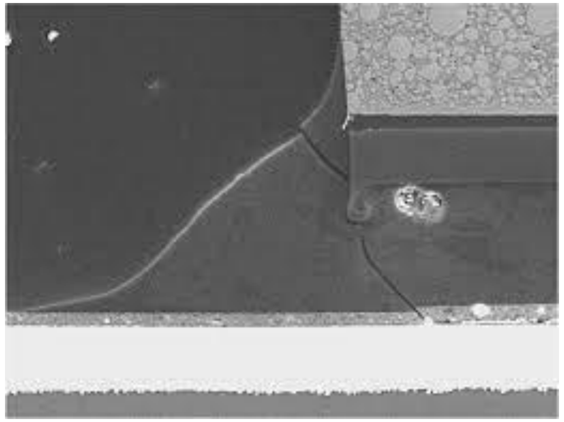
Stressed induced cracking/delamination

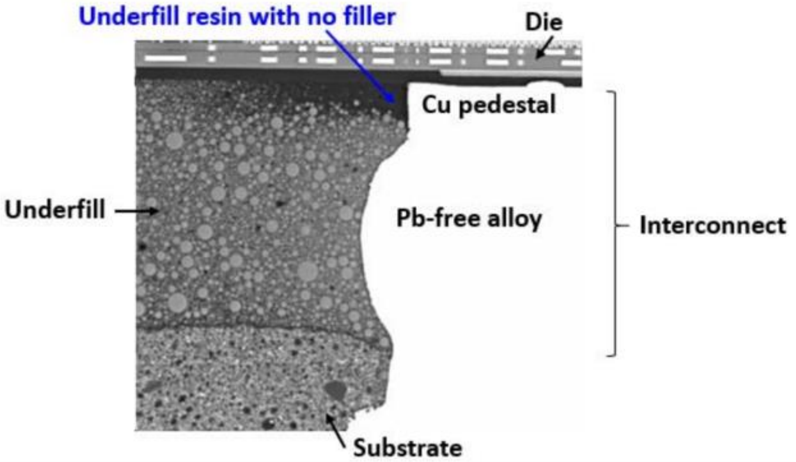
(a)



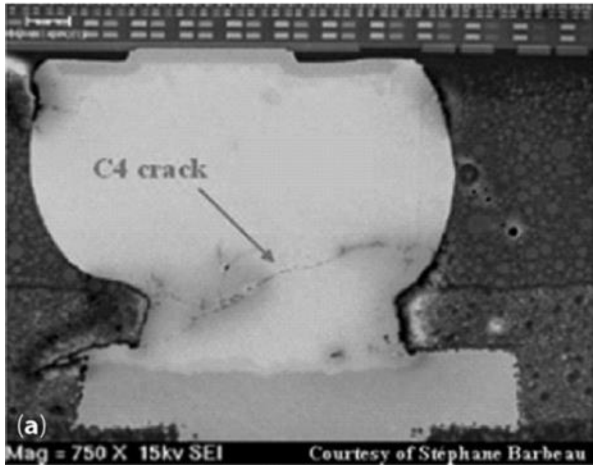
(b)

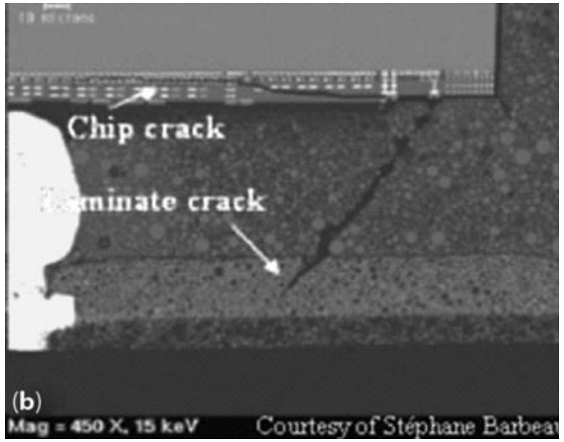






Non uniformly processed UF

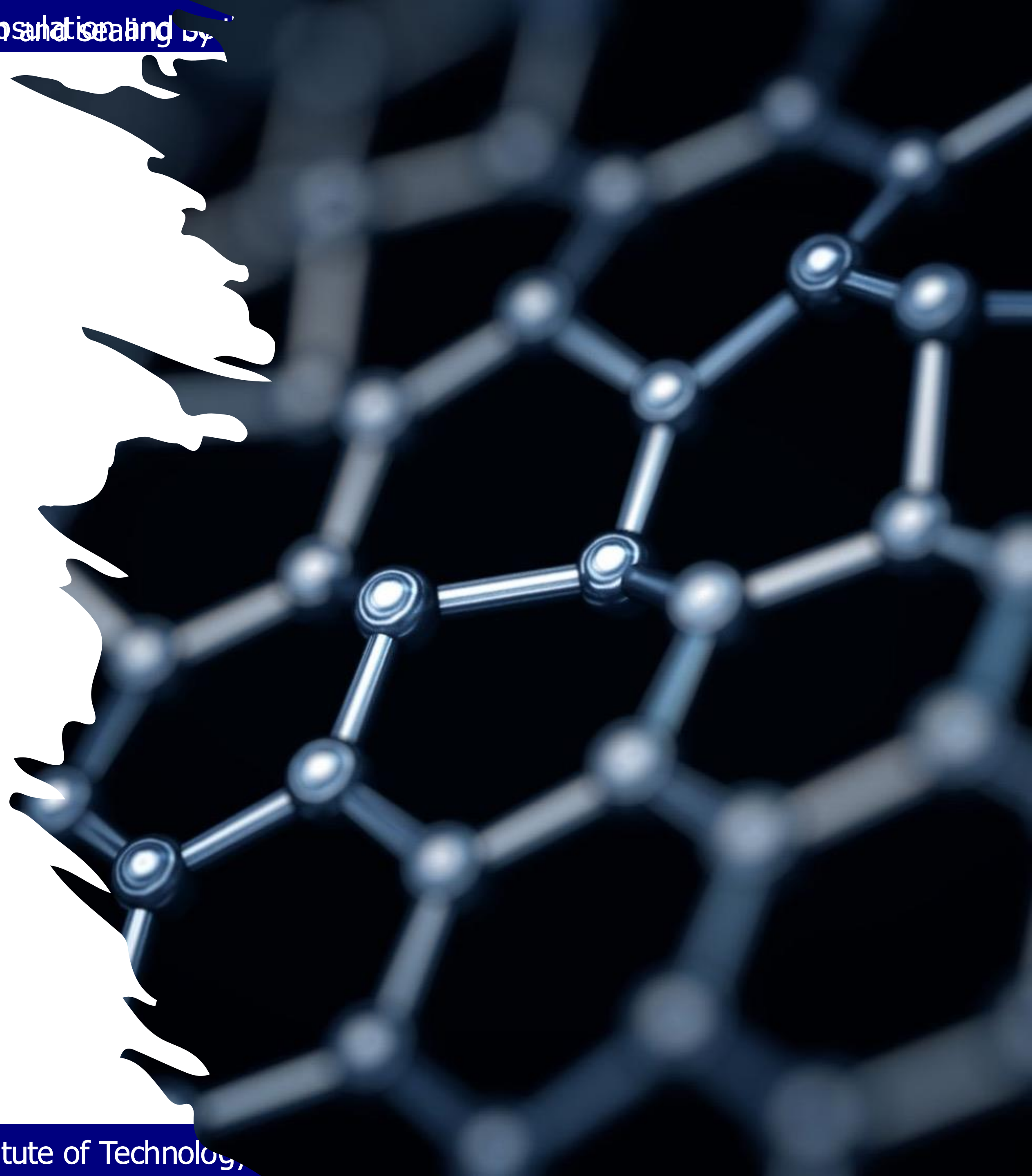




Source; DOI: 10.1002/9781118831373.ch7
https://doi.org/10.1002/app.11988
10.1109/ECTC.2017.84

14.3 Properties of Encapsulants

- Thermo-mechanical properties
  - CTE
  - Tg
  - Young’s modulus, storage and loss modulus
  - Elongation
- Chemical properties
- Physical properties
  - Flow property-Rheology
  - Adhesion



Material requirement for underfill

Properties	Desirable Values	Comments
Flow	>0.5 mm/s	Fast flow with no air bubbles entrapment
Adhesion	>50 MPa shear force	Key to device protection
CTE	18–30 ppm/°C	Matches CTE of solder (26 ppm/°C)
Elongation	>1 percent	Resists CTE mismatch stress
Modulus	5–8 GPa	Provides mechanical coupling
T_g	>130°C	Maintains dimensional stability
Stress after cure	<10 MPa	Minimizes internal stress caused by shrinkage of polymer
Water pickup	<1 percent	Reduces moisture-induced failures
Ionic impurities (Na^+, K^+, Cl^-, Br^-)	<10 ppm	Prevents corrosion and metal electromigration
Thermal stability, 1 percent weight loss	>260°C	Prevents underfill decomposition during solder reflow
Curing time at 160°C	<0.5 hr	Maintains good product output
Volatility during cure	<1 percent weight loss	Maintains correct stoichiometry
Pot life at RT, 20 percent increase in viscosity	>8 hr	Provides long usable underfill life

Table 1. Comparison of properties of typical materials used for MUF and CUF processes.

Property	Units	MUF	CUF
Filler Wt Content	%	85	65
Nom. Filler Size	um	6.1	0.6
Max Filler Size	um	25	3
Viscosity	Pa-S	9.5	50
Tg	C	153	117
CTE Alpha 1	ppm/c	12	31
CTE Alpha 2	ppm/c	45.25	90
Flex Modulus (< Tg)	Gpa	18.875	11
Flex Modulus (> Tg)	Gpa	0.4	0.15

https://shorturl.at/biqr7

- Table 14.1 Flip-Chip Underfill Material Requirements

Stress-strain curves for underfills

- Elastic failure
- Viscoelastic failure
- Toughness
  - Energy to absorb impact
  - Stress intensity factor/Stress release energy

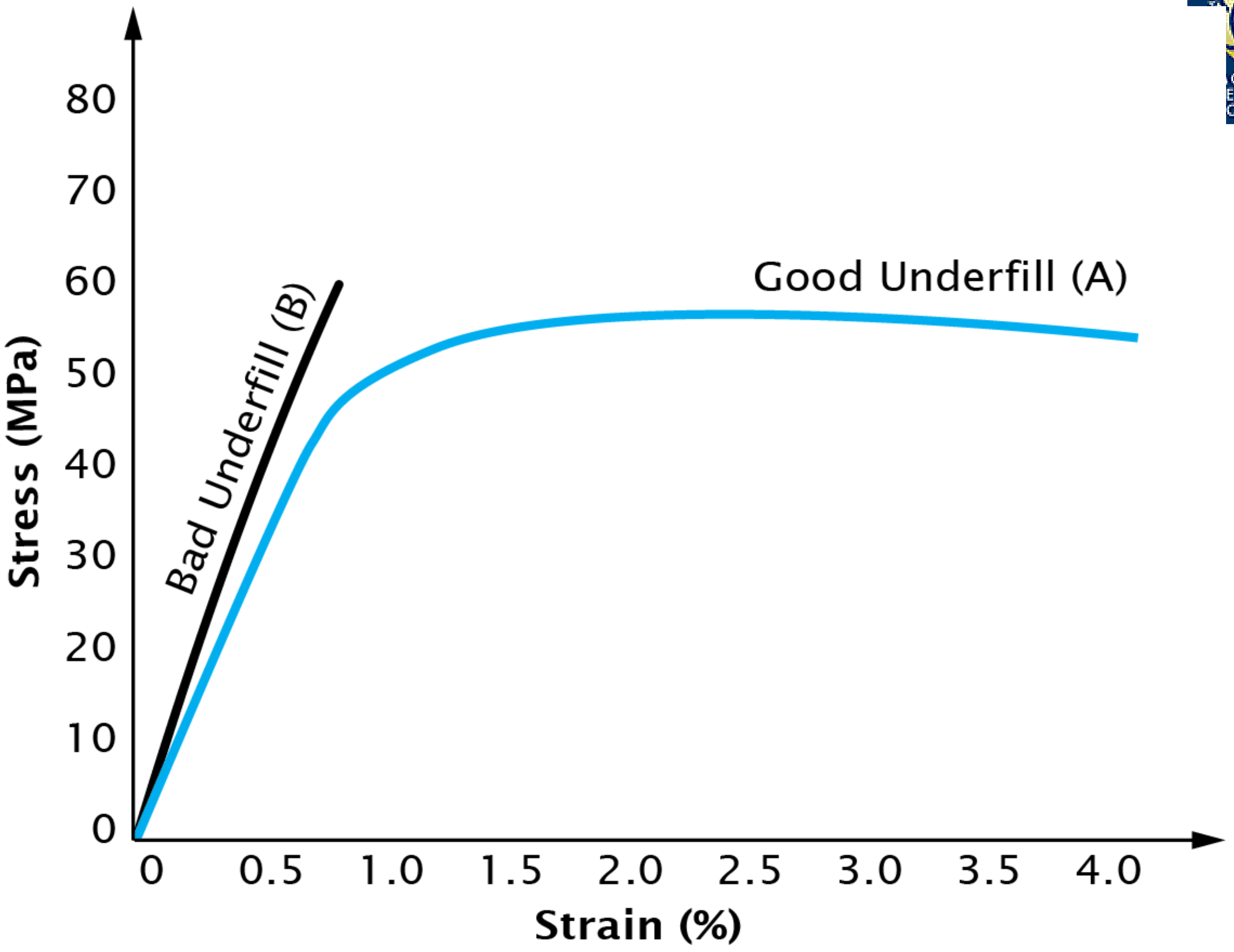


Fig 14.04 - Stress Strain Curves

Table 14.2 Physical Properties of Some Materials of Interest

Material	CTE (ppm/°C)	Modulus (GPa)	Density (g/cc)
Silicon	2.6	107	2.33
Silicon dioxide	0.5	119	2.60
Alumina	6.6	345	3.90
Solder (63Sn/37Pb)	25	50	8.40
Aluminum	23	79	2.90
Molding compound	15	14.2	2.30
FR-4	16	20	1.85

Fundamentals of Encapsulation and sealing

Residual stress

- Major sources of residual stress
  - Initial residual stress during encapsulation (molding/sealing) due to polymerization of polymers
  - Polymerization (curing for thermoset polymers such as epoxy) causes Volume shrinkage →1~2% (linear dimensions) and 3-6% by volume→~20MPa internal stress
  - Once cured, thermal stress brings about reliability issue in packages due to Mismatch in coefficient of thermal expansion (CTE) between encapsulants and mating/adherent substances such as Si dies and substrates

$$\sigma = k \int_{25}^{T_g} E(a_e - a_s)\, dT$$

EQ. 14.3

E is the elastic modulus of the epoxy.

k is a constant.

($\alpha_e - \alpha_s$) is the difference in CTEs between the epoxy and the substrate.

dT is the change in temperature between T of the epoxy and room temperature.

Fundamentals of Encapsulation and sealing

Thermomechanical properties

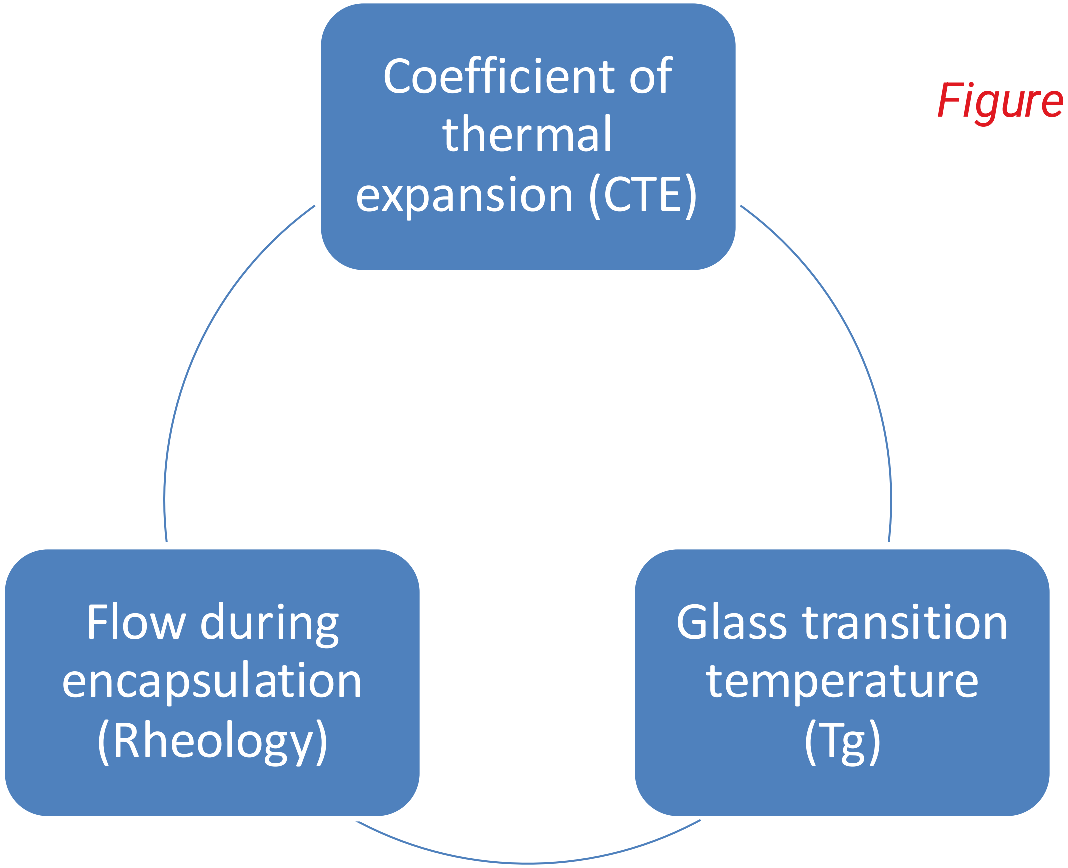


Figure 14.5 Glass transition temperature of polymers.

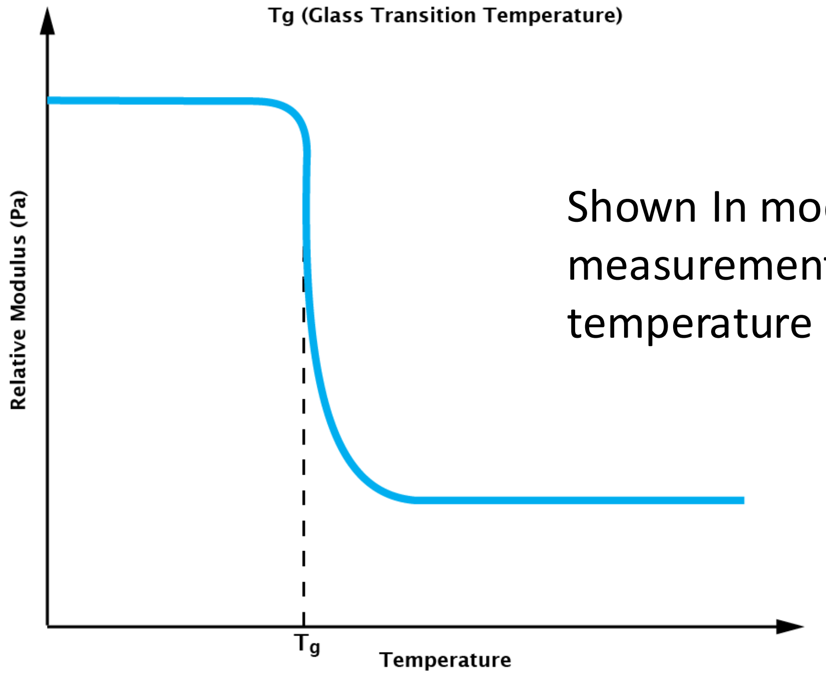
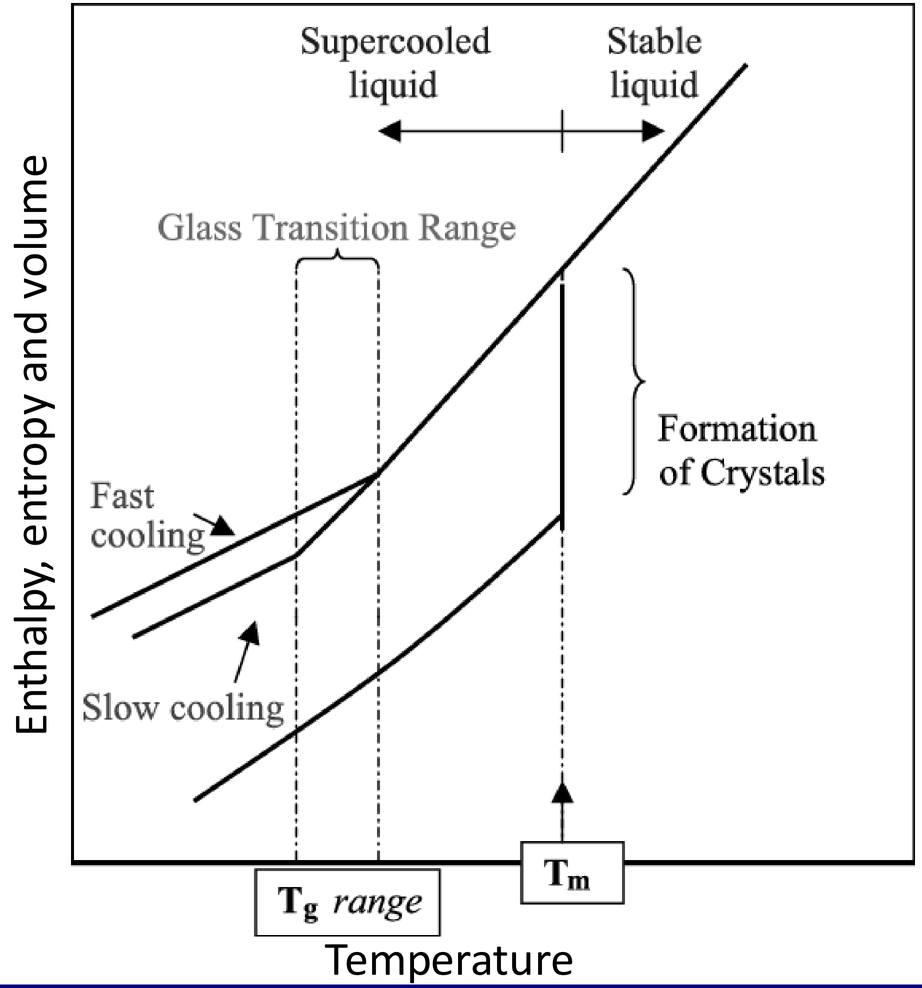


Fig 14.05 - Glass transition temperature

Shown In modulus measurements with temperature

Low viscosity, high surface tension, small wetting angle

Phase transition



- Crystalline materials
  - Metals/ceramics/crystalline polymers)
  - Tm/Tf, latent heat, 1st order
- Glassy materials
  - Organic, amorphous alloy
  - Continuous transition/2nd order
- Mixed
  - Crystalline and amorphous
  - Some polymers

Characterization of Thermomechanical Properties

Uncured resin

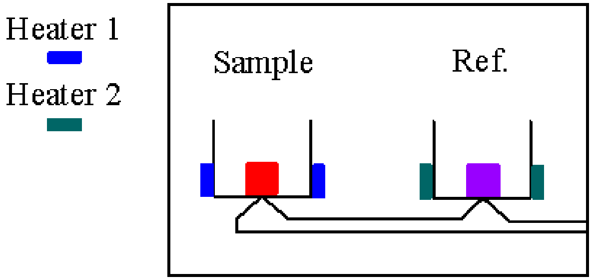
- Cure time and temperature
  - DSC (differential scanning calorimeter)
- Flowability (rheometer/viscometry)

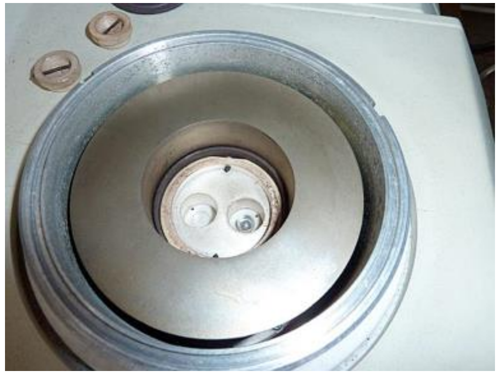
Cured polymer

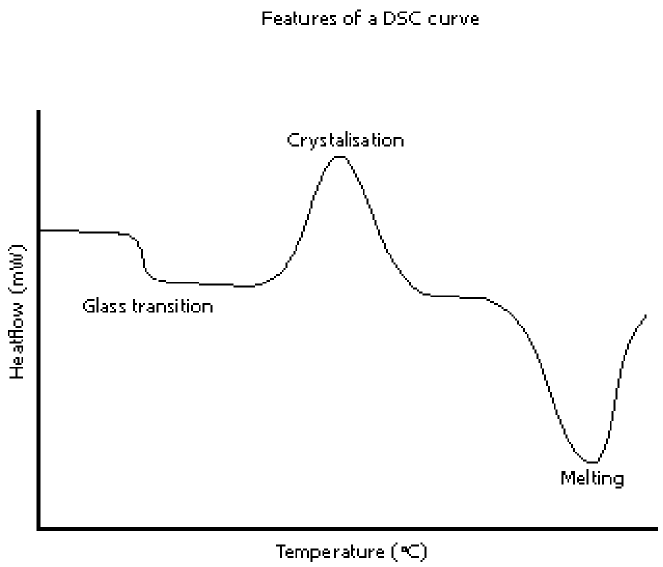
- Coefficient of thermal expansion (CTE)
  - TMA (thermomechanical analyzer)
- Glass transition temperature (Tg)
  - DSC, TMA, DMA (dynamic mechanical analyzer)
  - 2^{nd} order transition (without involving latent heat)
  - Heat capacity change
- Elastic modulus
  - DMA (storage/loss moduli)
  - Tensile/bending test
- Strain at break (tensile/bending test)

DSC (Differential Scanning Calorimeter)

- Difference in the amount of heat required to increase the temperature of a sample and reference is measured as a function of temperature
- To determine exothermic and endothermic behavior

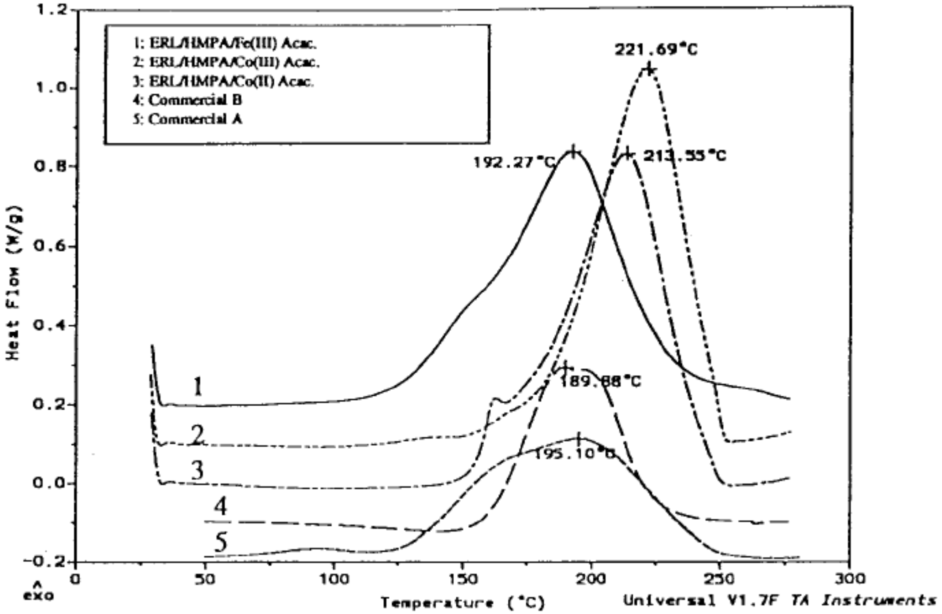


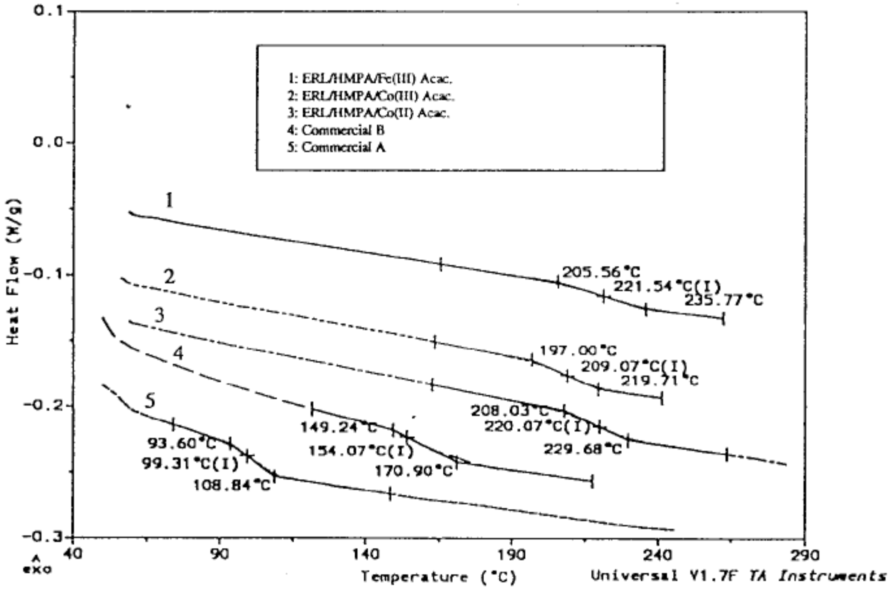




DSC profiles

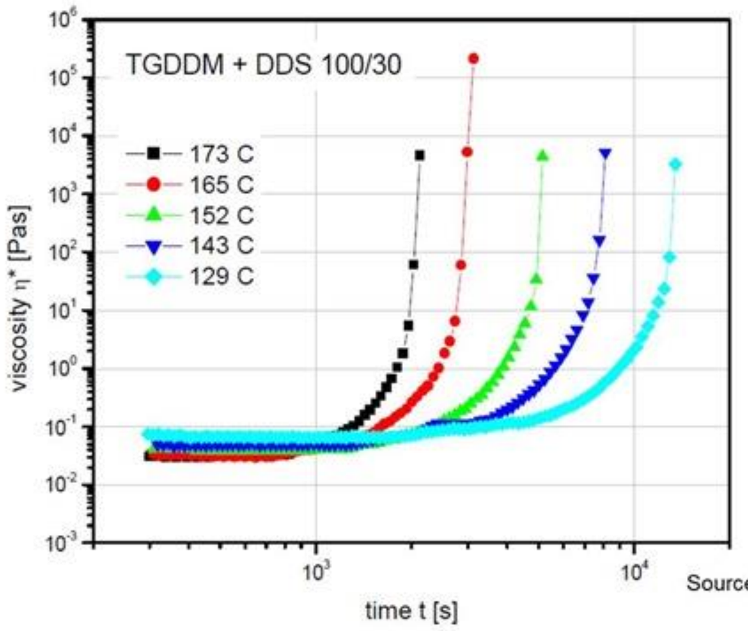
- To characterize curing, melting, crystallization, specific heat
- Isothermal/dynamic scan-->cure kinetics
- Glass transition temperature



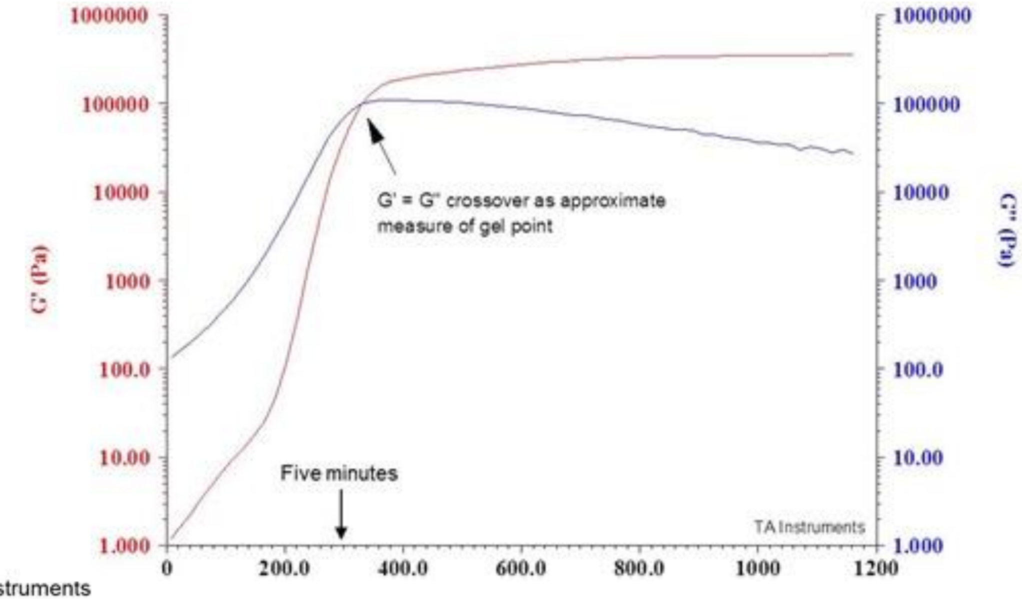


Rheometer/viscometer/spiral flow

- Time @minimum viscosity
- Gel time



Source: TA Instruments

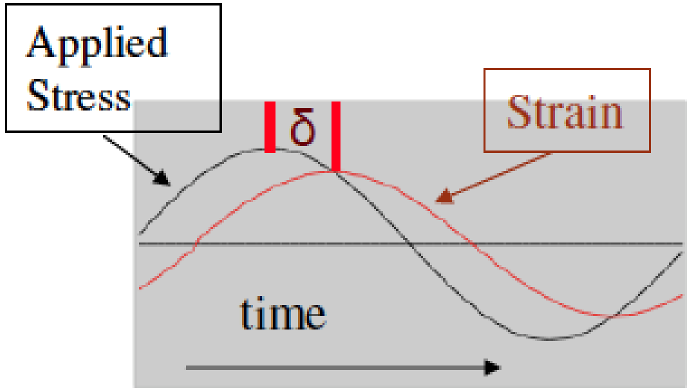


Source; H. H. Winter et. al., Journal of Rheology, v. 31, p. 683-697, 1987

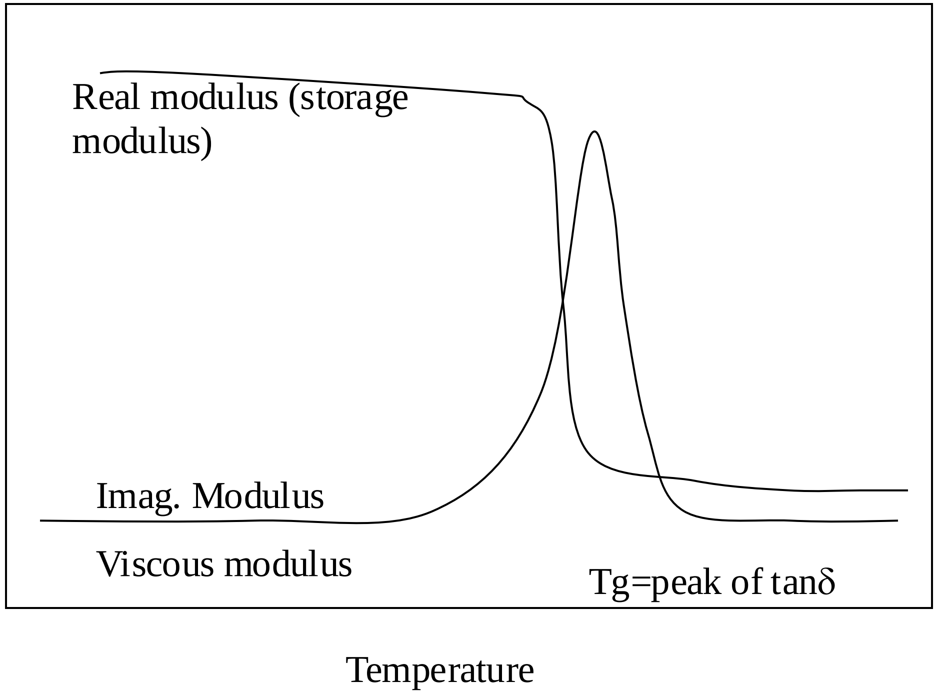
Fundamentals of Encapsulation and sealing

DMA
(Dynamic Mechanical Analyzer)

- For viscoelastic behavior of polymers
- Sinusoidal stress applied and strain in the material measured, to determine the complex modulus (storage/loss modulus)
- $E = E' + iE''$



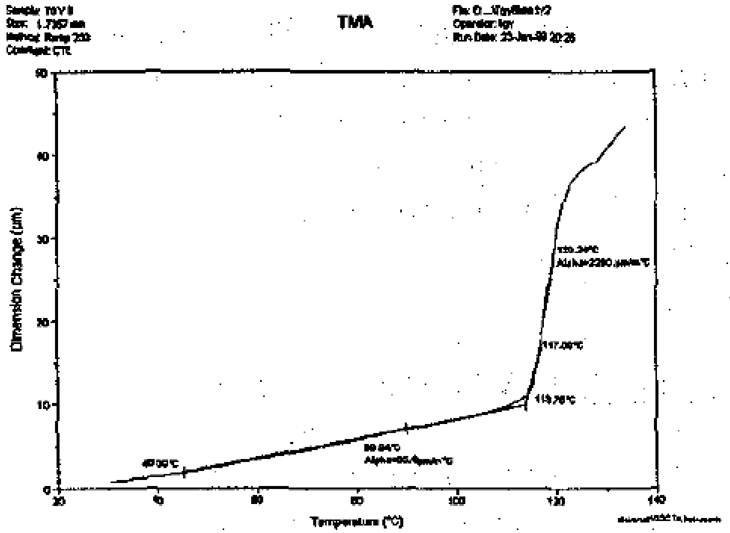
$\tan\delta = E''/E'$



Fundamentals of Encapsulation and sealing

TMA/Dilatometry (Thermomechanical Analyzer)

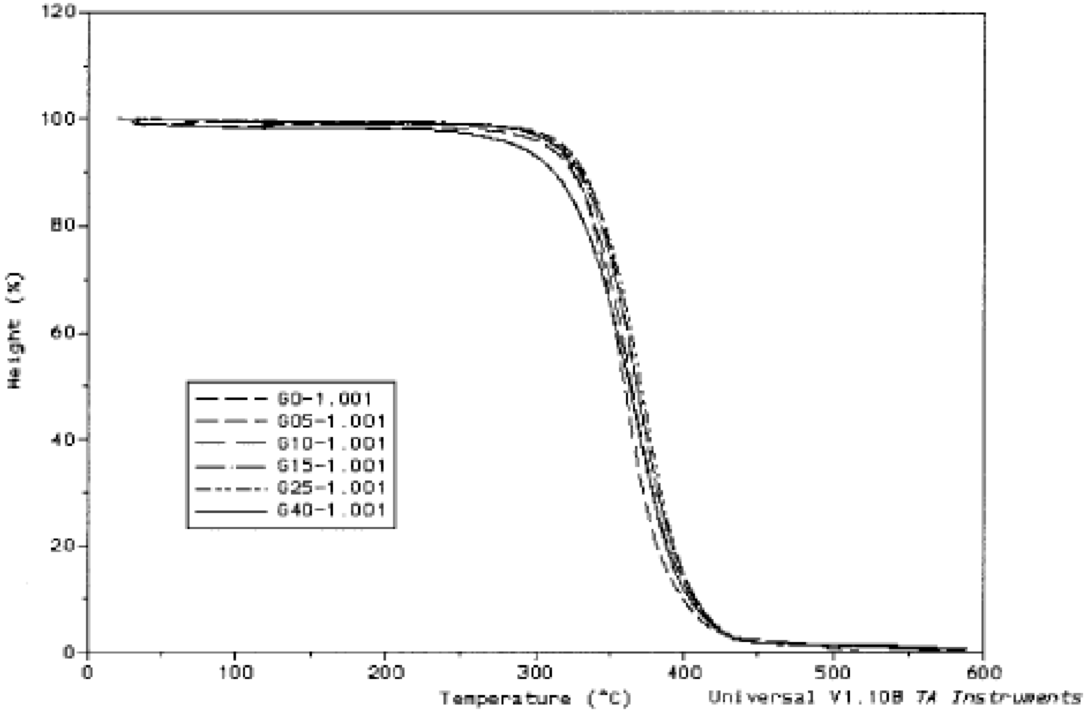
- Measure dimension change with temperature
- Coefficient of Thermal expansion (CTE)



Fundamentals of Encapsulation and sealing

TGA (Thermogravimetry)

- Weight change with temperature
- Residue



Physical Properties

Adhesion

- Failures; damage→microcraking→debonding growth→interfacial delamination
- Bonding mechanisms
  - Primary/Covalent
  - Secondary/Van der Waals and Hydrogen bonding
- Adhesion promotion
  - Chemical/physical methods; interfacial bonding/crack suppressors (toughening)

Interfaces

- Hard/soft passivations (SiO_2, SiN, SiON or PI ,BCB)
- Solder bumps, wires
- Solder mask
- Conductor leads,
- Substrates (BT, FR-4, ceramics)

14.4. Encapsulation Materials

- Epoxy molding compounds (EMC)-leadframe packages, over-molding, MUF
- Underfill material; flip-chip types
- Gloptop; SMT top, LED top (optical function)
- Anisotropically conductive film/paste (ACF/P)
- Non conductive film/paste (NCP)

Example of underfill composition

Table 14.3 Example of a Flip-Chip Underfill Composition

Ingredient	Weight %	Functionality
Bisphenol A diepoxy	5.8	Resin
Cycloaliphatic epoxy ERL4221	12.5	Diluent, cross-linker
HMPA anhydride	13.8	Cross-linker, hardener
2-ethyl-4-methyl imidazole	0.3	Curing accelerator
Pigment (C-black)	0.1	Color coding
Spherical silica filler	67.5	CTE reducer

Material properties required for encapsulants

Low water uptake

Low stress

High strength

High adhesion

High toughness

High flowability

- Base resin
- Filler engineering (loading level, surface treatment, functional property)
- Additives

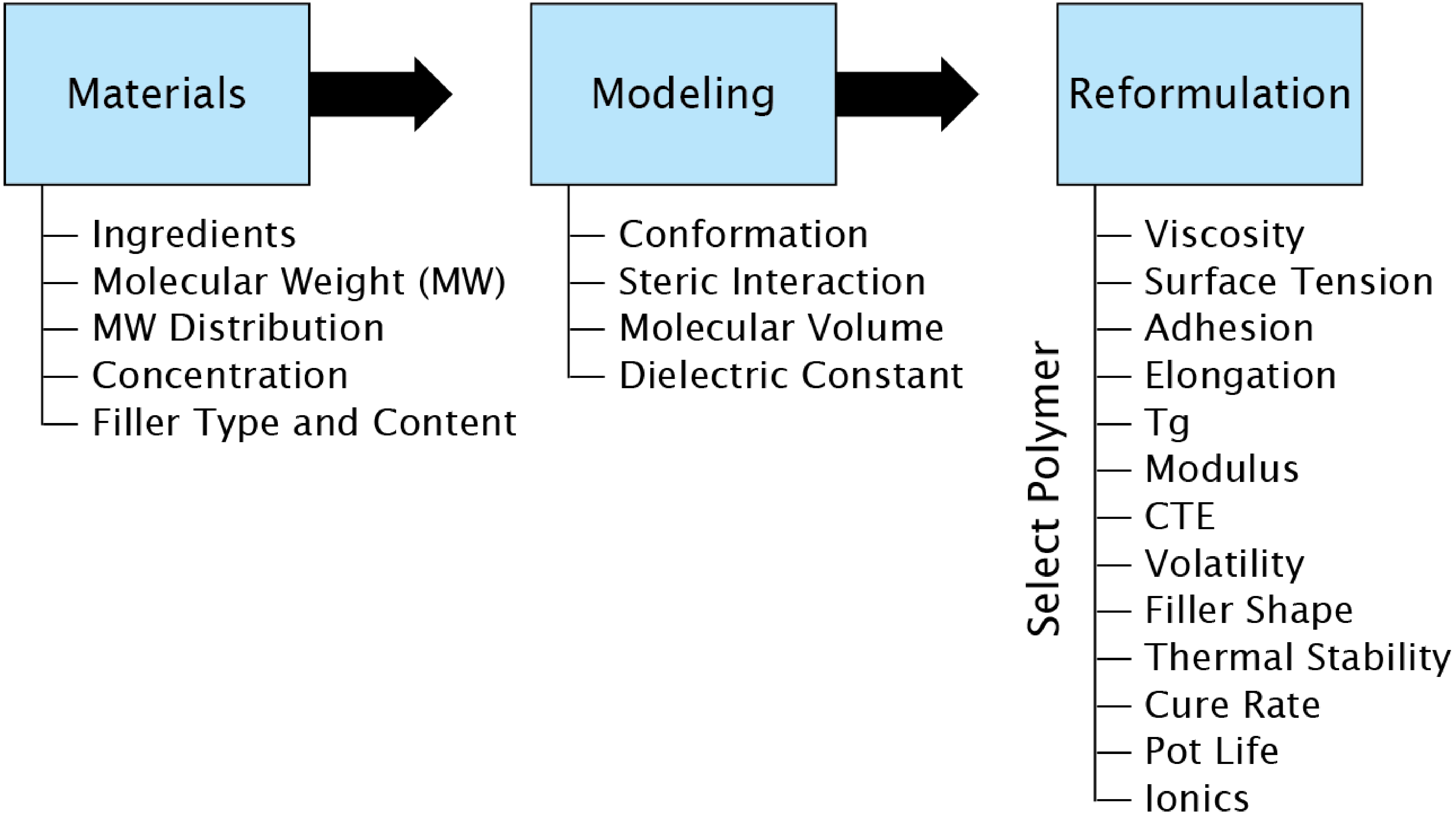
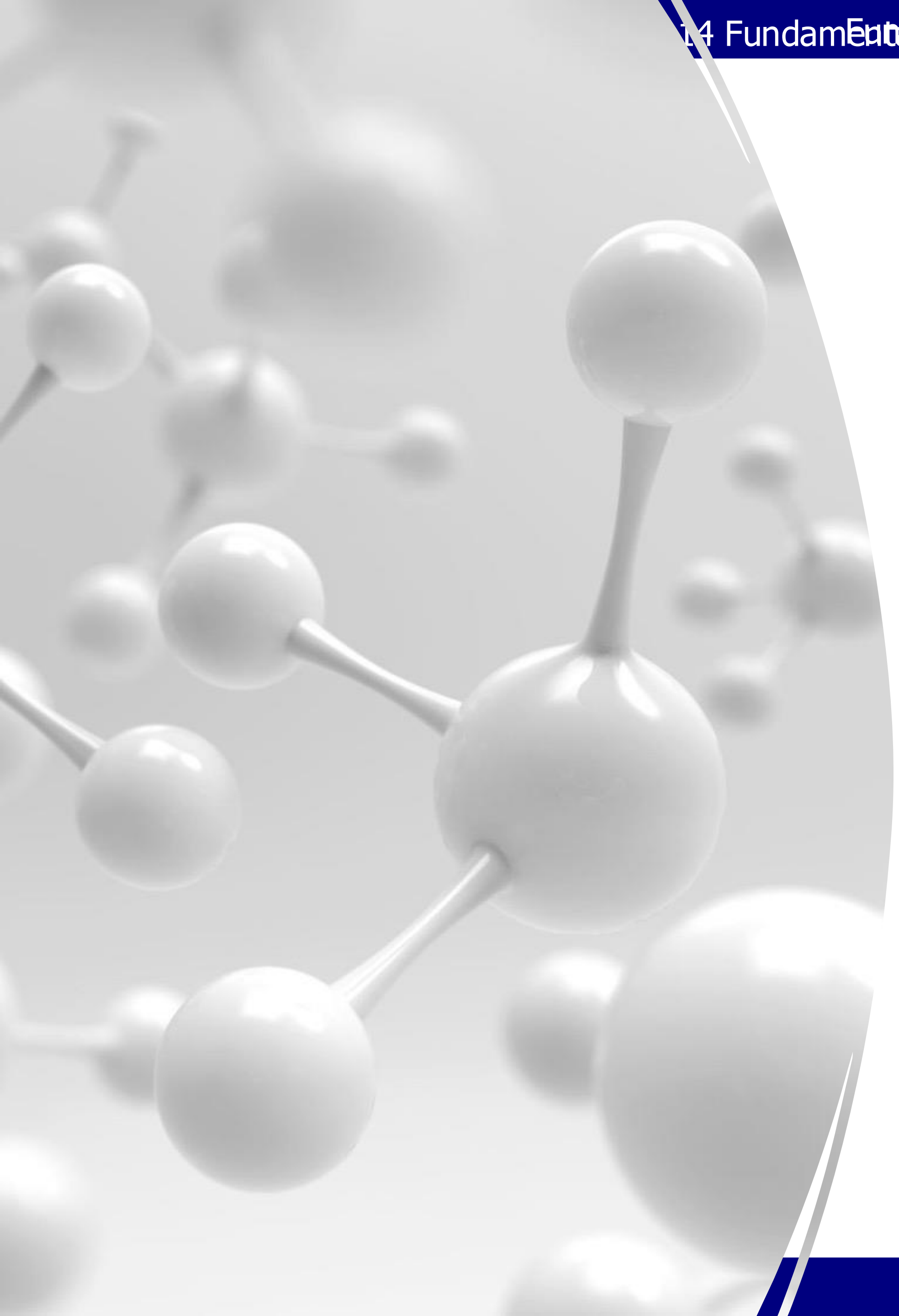


Fig 14.06 - Encapsulation formulation optimization

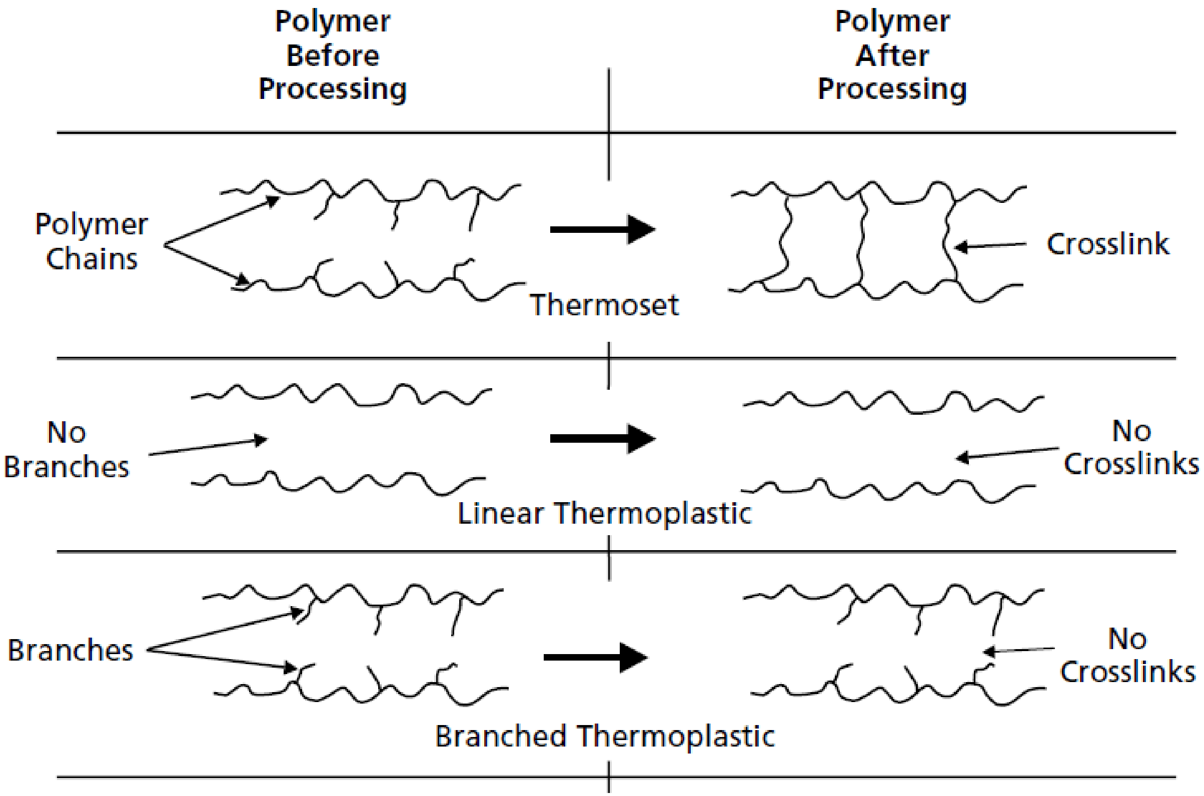
Fundamentals of Encapsulation and sealing

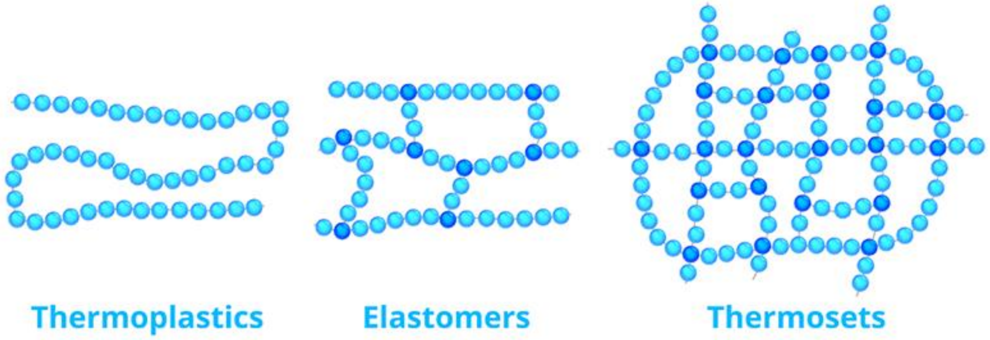


Epoxy and related materials

- Epoxy
- Cyanate ester
- Urethane
- Silicone

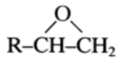
Polymer types



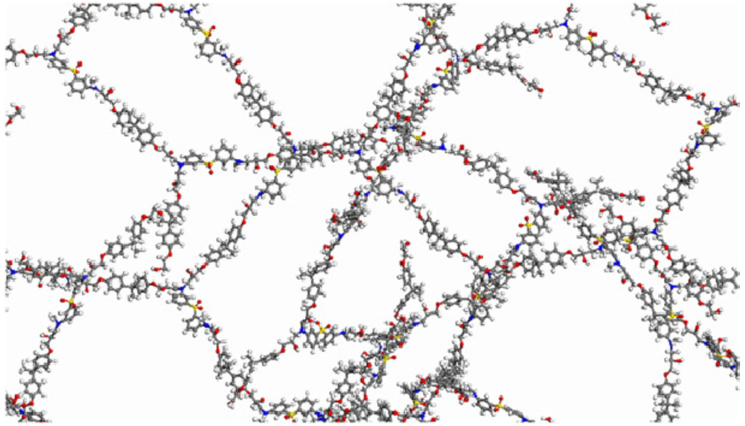


Source; Bufa, Rodolfo Morales Ibarra's thesis

Epoxy

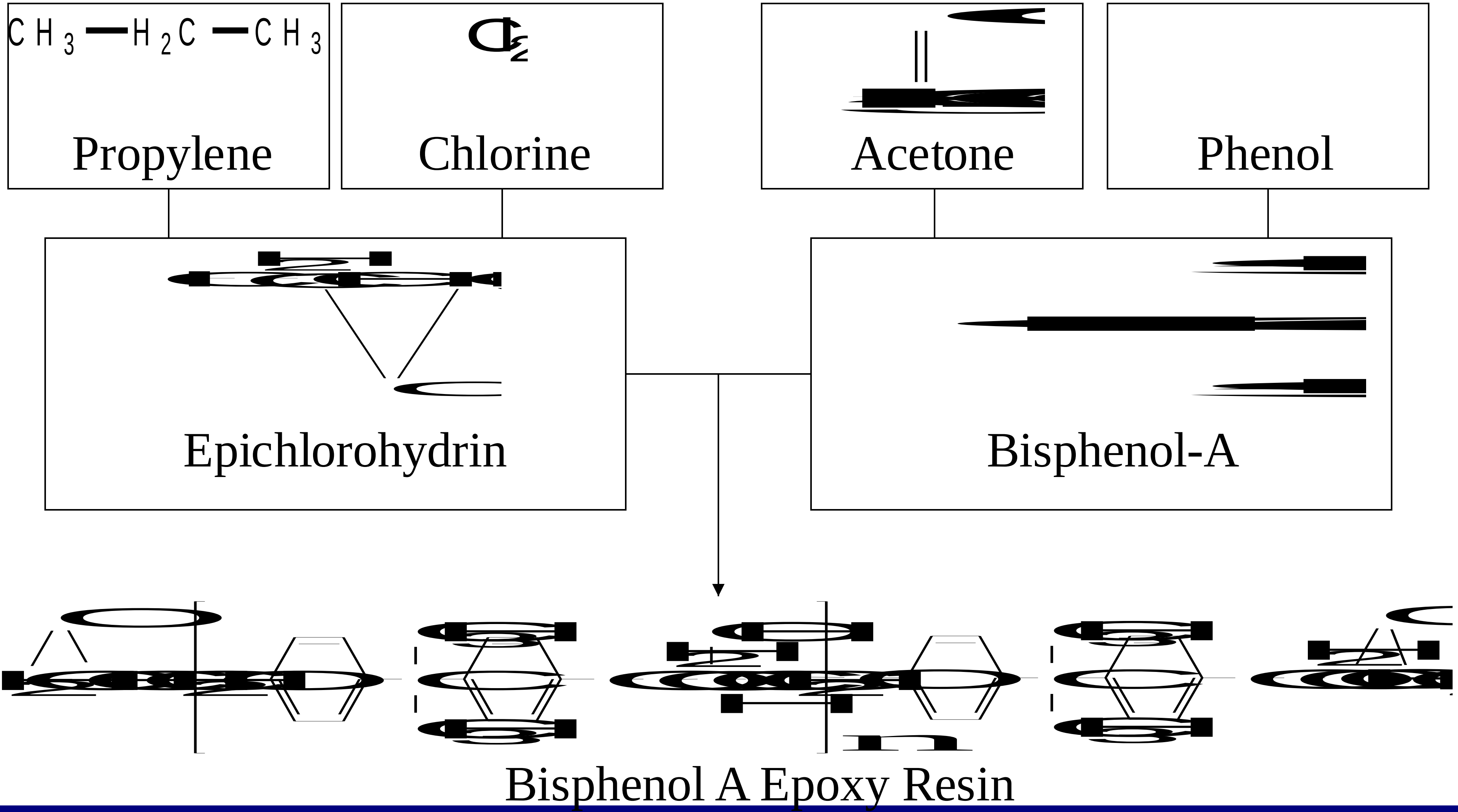


- Containing epoxide ring group
- Various curing agents to open the ring and crosslink→curing
  - Nitrogen containing; Aliphatic/cycloaliphatic/aromatic amines
  - Oxygen containing; Anhydride, carboxylic, phenol
  - Sulfur containing; p-sulfide/mercaptans
  - Catalysts
- # of functional groups
- Oligomers/Branched molecules
- B-stage→ 3D network



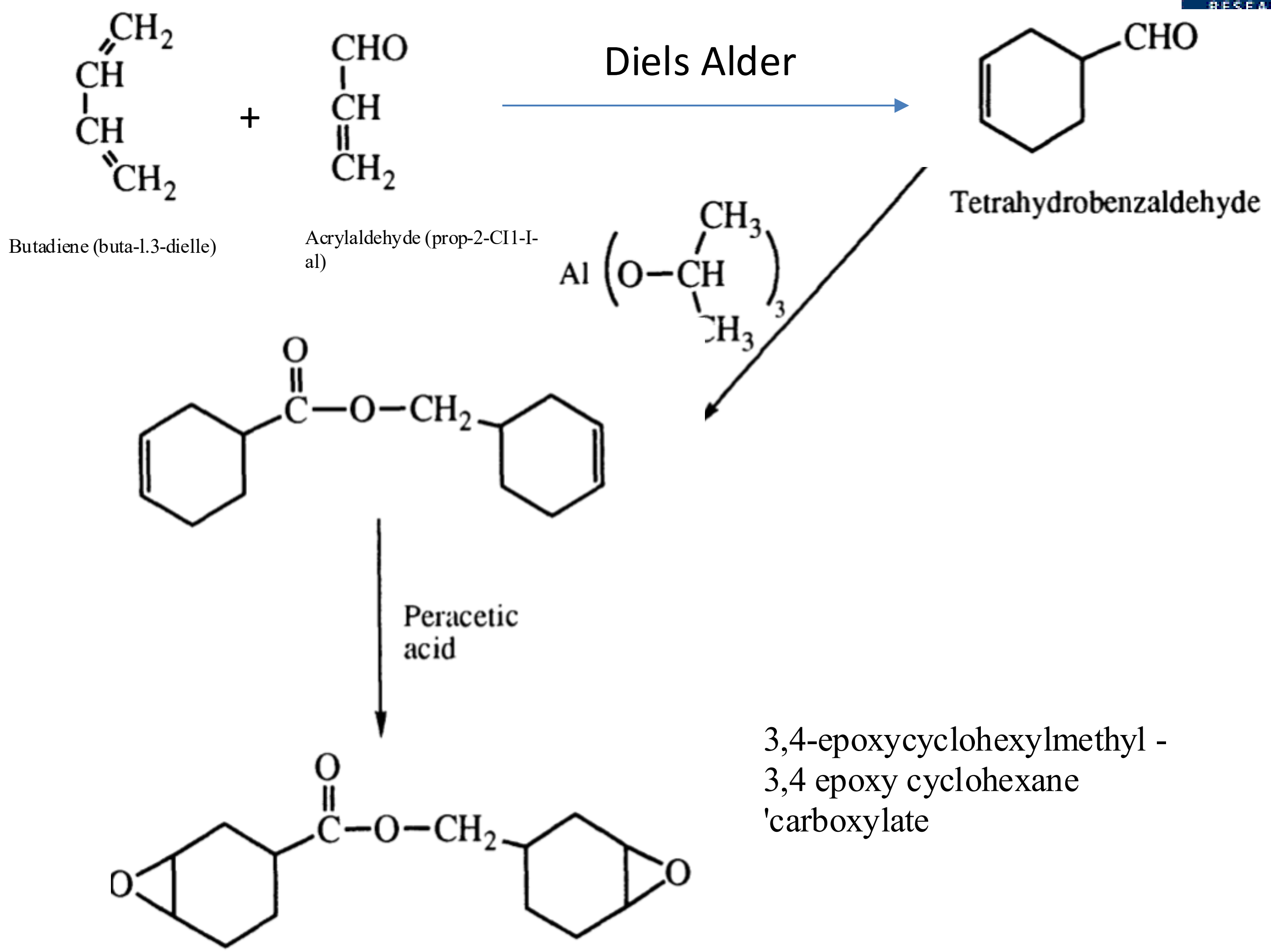
DOI:10.1088/0965-0393/22/2/025013

Manufacturing Process for BIS A-Based Epoxy Resins



Cycloaliphatic epoxy

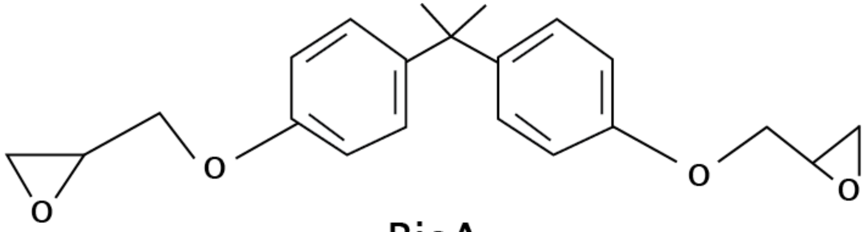
- Free of hydrolysable chloride and inorganic salts (ash)
- No contain aromatic compounds and hence are more stable to UV exposure than BPA



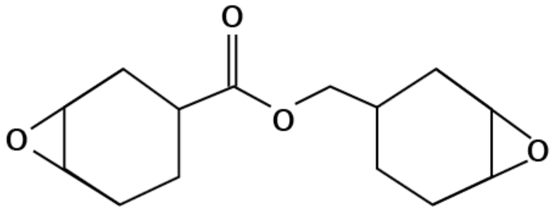
Union Carbide, 1989 ERL-422I Ciba-Geigy CY-179

Fundamentals of Encapsulation and sealing

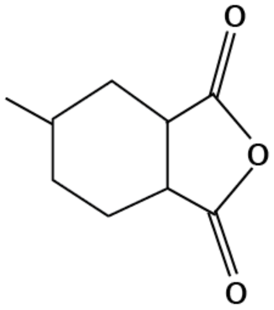
Anhydride-Cycloaliphatic epoxy



BisA



ERL 4221



HMPA

Fig 14.07 - Structures of common ingredients

Low viscosity
Low ion impurity

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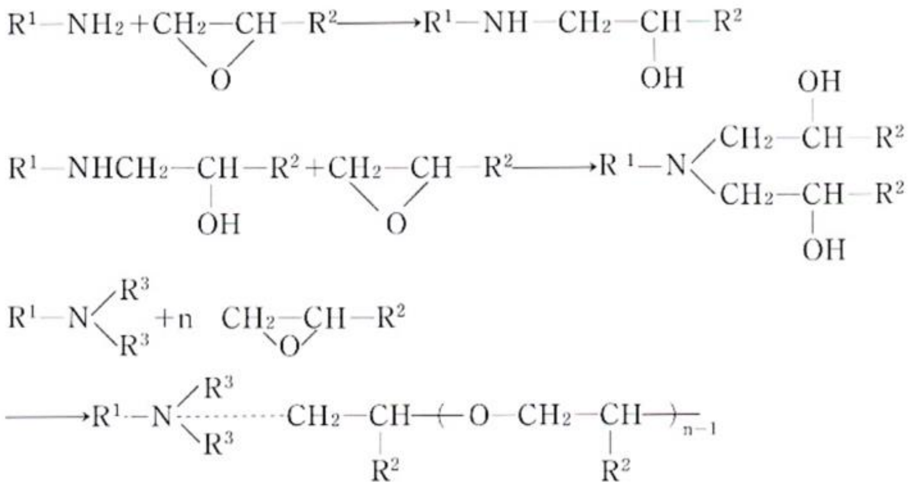
Amine epoxy

- Low temperature cure



Fundamentals of Encapsulation and sealing

Phenolic epoxy

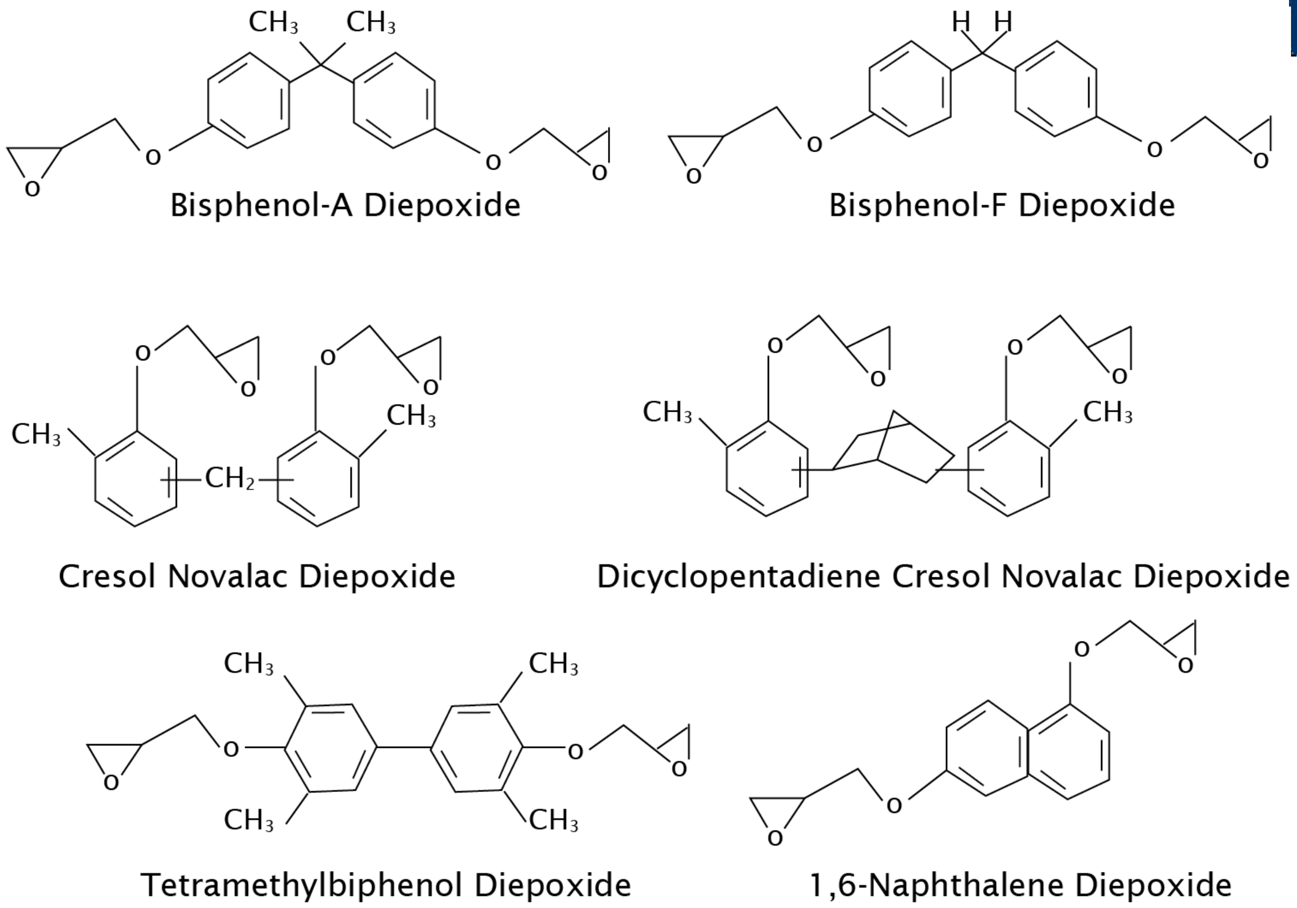


Fig 14.08 - Structures of common aromatic epoxy

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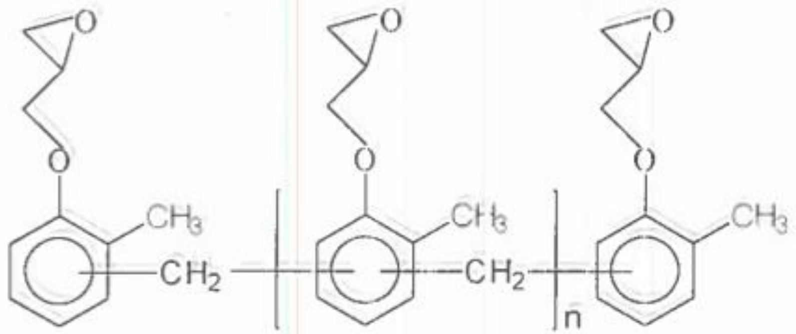
Fundamentals of Encapsulation and sealing

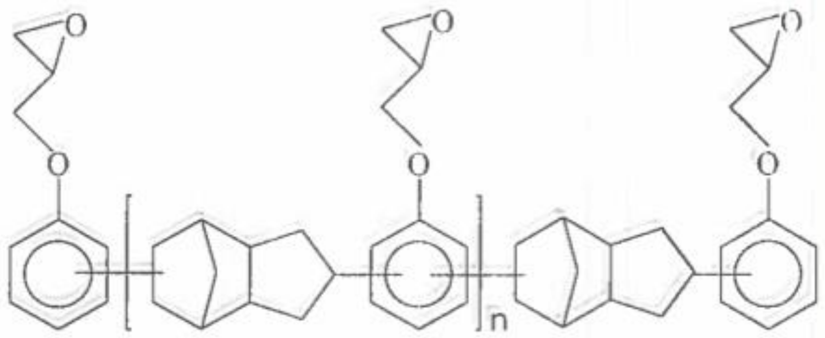
EMC

- Typical recipes
- Epoxy
- Curing agents
- Additives
- Filler
- High filler loading

Epoxies for high performance EMC

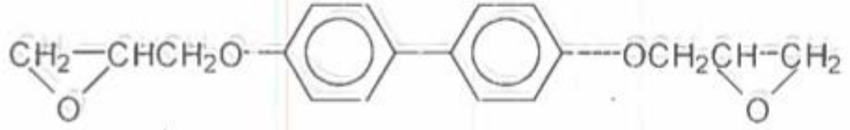


TYPICAL



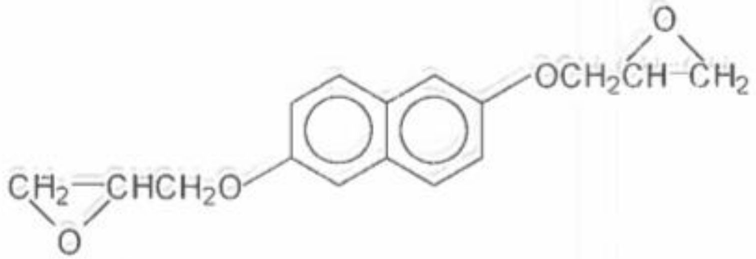
Dicyclopentadiene

LOW WATER UPTAKE, FLOW



Bifunctional Epoxy

HIGH TOUGHNESS, FLOW

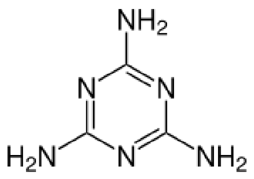


Naphthalene계 Epoxy

LOW WATER UPTAKE

EMC Composition

No	Component	Remarks	Compounding ratio
1	Epoxy	- Binder	4 – 15
2	Hardener	- Curing agent	4 - 10
3	Br-Epoxy	- Organic flame retardant	2 >
4	Sb_2O_3	- Inorganic flame retardant	3 >
5	Filler	- Improving strength, thermal conductivity - Lowing thermal expansion coefficient, moisture absorption	70 – 90
6	Coupling agent	- Improving adhesion between filler and organic materials	1 >
7	Accelerator	- Accelerating reaction of epoxy with hardener	1 >
8	Flexibilizer	- Lowering thermal stress	5 >
9	Wax	- Releasing agent for worability - Improving degree of mixing	2 >
10	Colorant	- Coloring	1 >



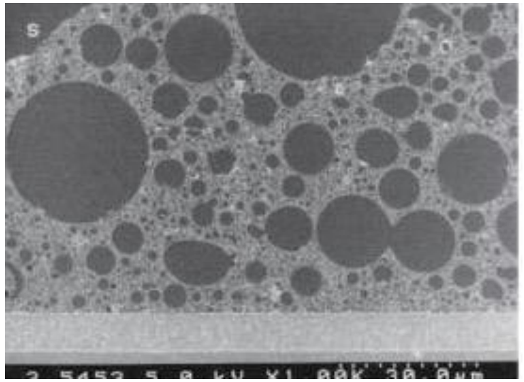
Melamine (FR)

Functional groups in silanes

X-TBN (butadiene acrylonitrile)
Reactive silicone
Sea-island

Filler

- Critical element to govern the properties of compounds due to significant loading levels
- Fused silica (pure, low CTE, low k)
- Different sizes/shapes; multimodal sized with maximum packing factor
- Surface modification with various reactive groups

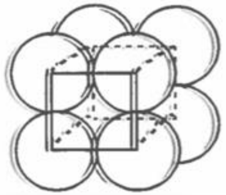


Mooney's Equation

$$\ln\left(\frac{\eta_C}{\eta_0}\right) = \frac{K_E \phi_f}{1 - \phi_f / \phi_m}$$

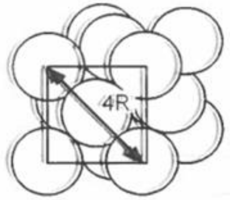
$$\phi_m = \frac{\textit{True volume of the filler}}{\textit{Apparent volume occupied by the filler}}$$

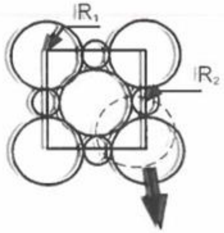
1) Simple cubic



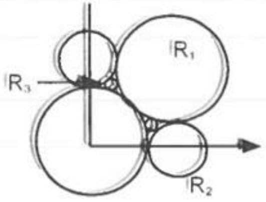
$$\phi_m = \frac{1}{(2R)^3}\left(\frac{4}{3}\pi R^3 \times \frac{1}{4} \times 4\right) = 0.52$$

2) Face centered cubic





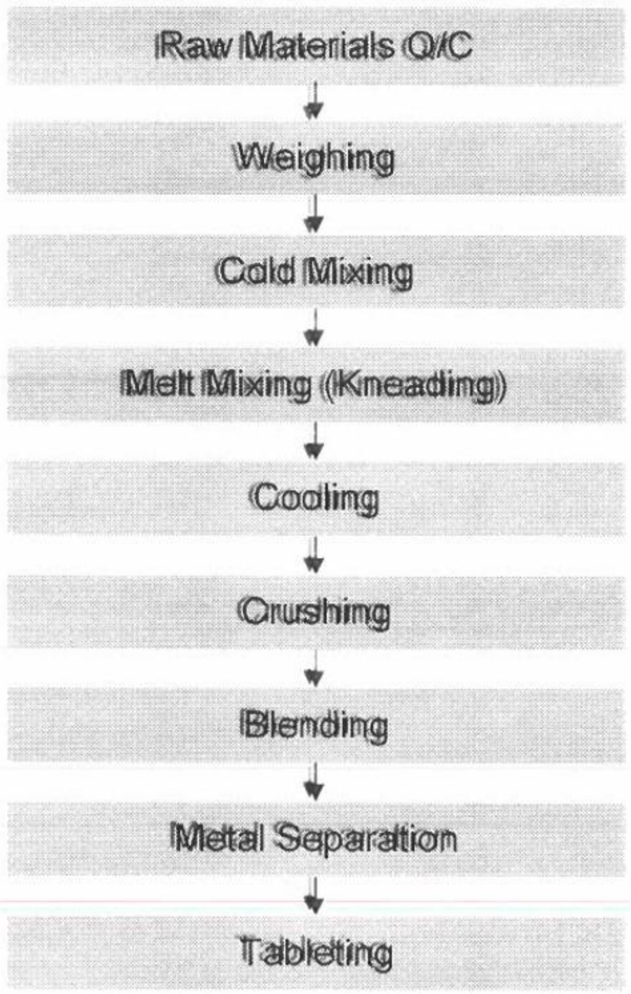
$$\phi_m = \frac{1}{2\sqrt{2}R^3}\left(\frac{4}{3}\pi R^3 \times 4\right) = 0.74$$



$R_1 : R_2 : R_3 = 1 : 0.414 : 0.114$

$\phi_m = 0.793$

Making EMC


Raw Materials Q/C
Weighing
Cold Mixing
Melt Mixing (Kneading)
Cooling
Crushing
Blending
Metal Separation
Tableting

No-Flow Underfill Technology

Georgia Tech PACKAGING RESEARCH CENTER

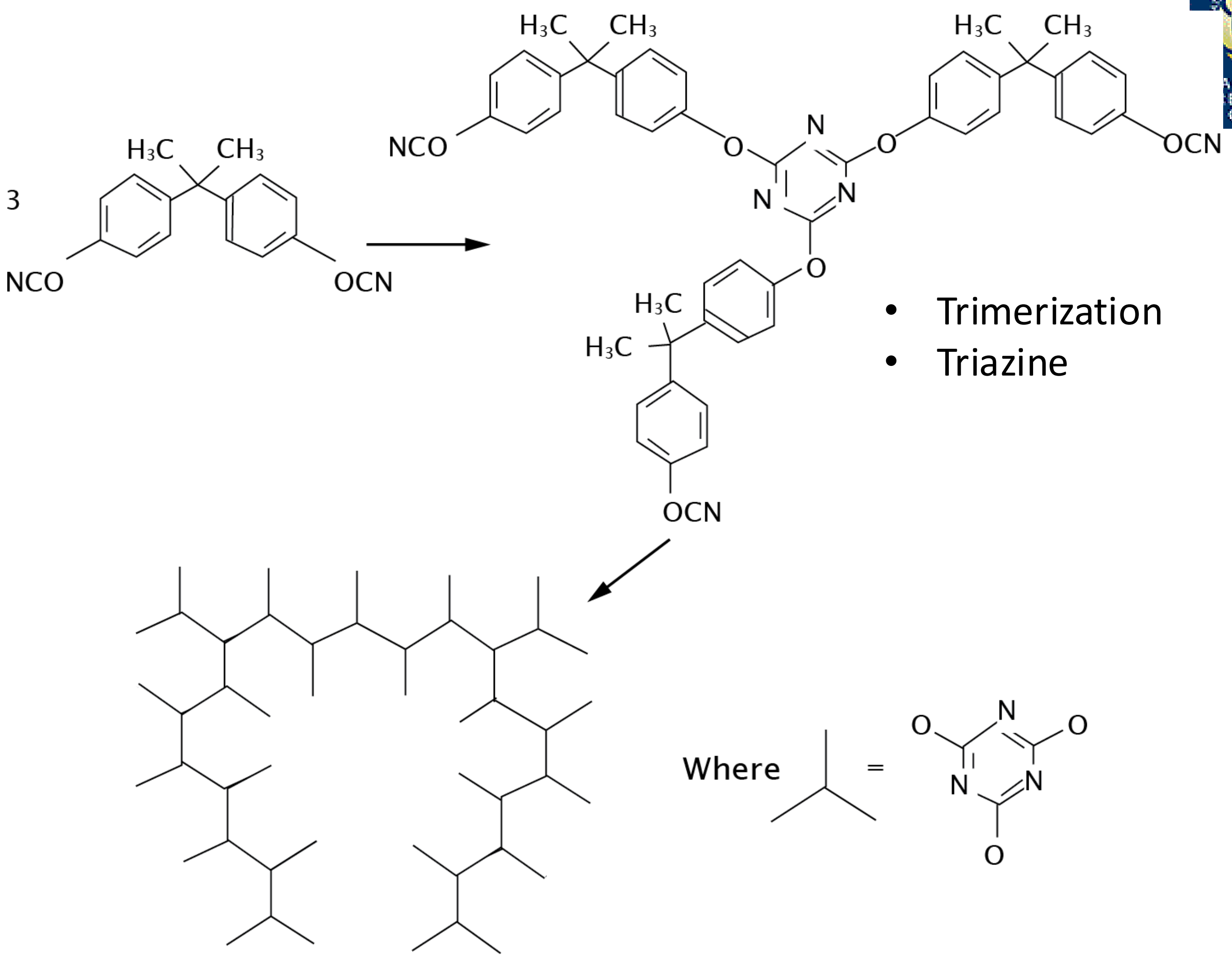
Generic Composition of (No)-Flow Underfill Material

- **Base resin; flowability**
- **Curing agent (hardener); flowability**
- **Latent catalyst; control curing profile for bump materials**
- **(Fluxing agent); enabling in-situ soldering**
- **Modifiers; toughness**
- **Silica filler; CTE control**

Fundamentals of Encapsulation and sealing

Cyanate ester

- High Tg
- Lower water uptake
- Low dielectric permittivity
- Epoxy-cyanate ester (cost reduction and less polar)
- High temperature applications



- Trimerization
- Triazine

Fig 14.09 - Structures of cyanate ester polymerization products

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Fundamentals of Encapsulation and Sealing

Urethane

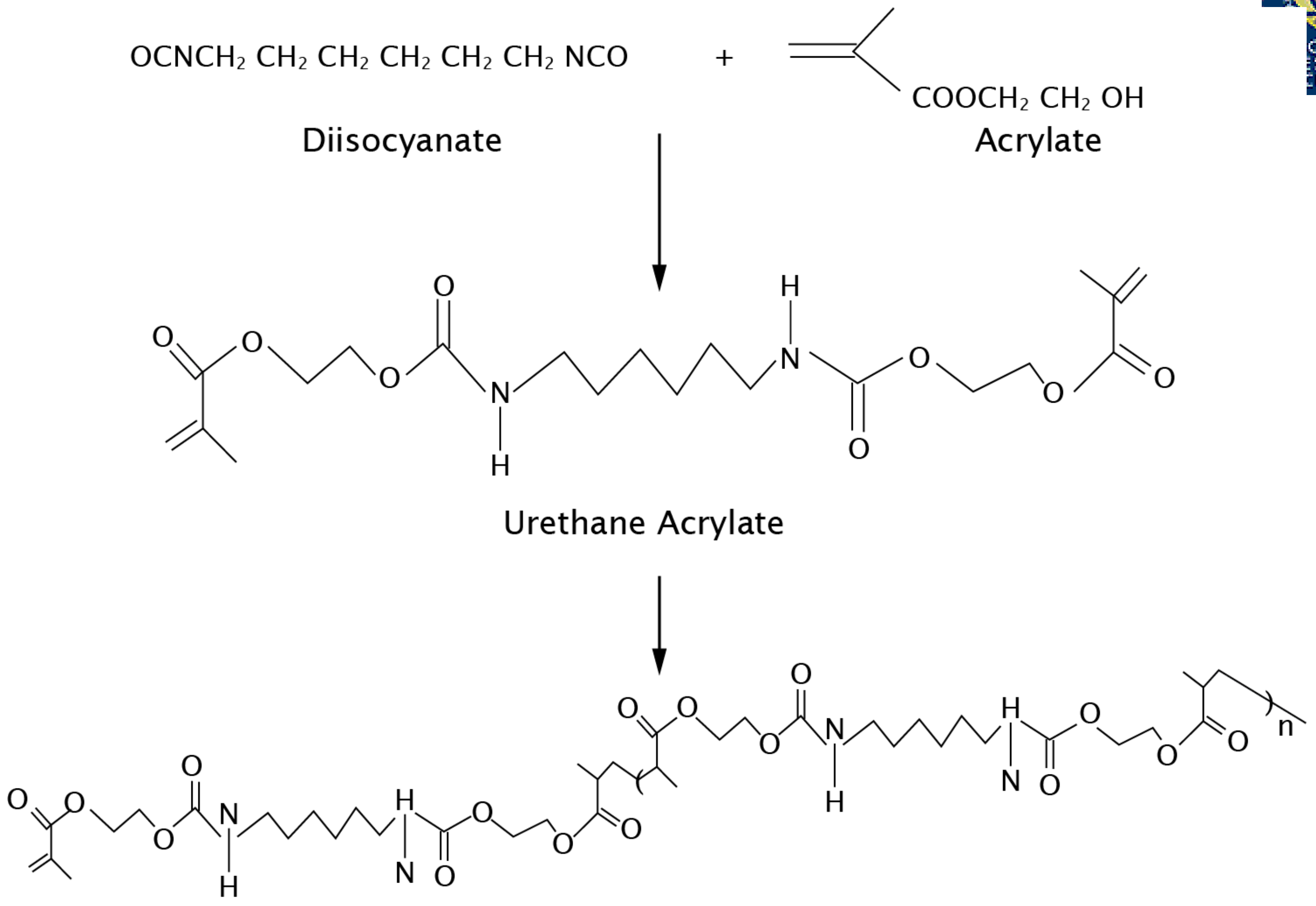


Fig 14.10 - Structures of urethane

Fundamentals of Encapsulation and sealing

Silicone

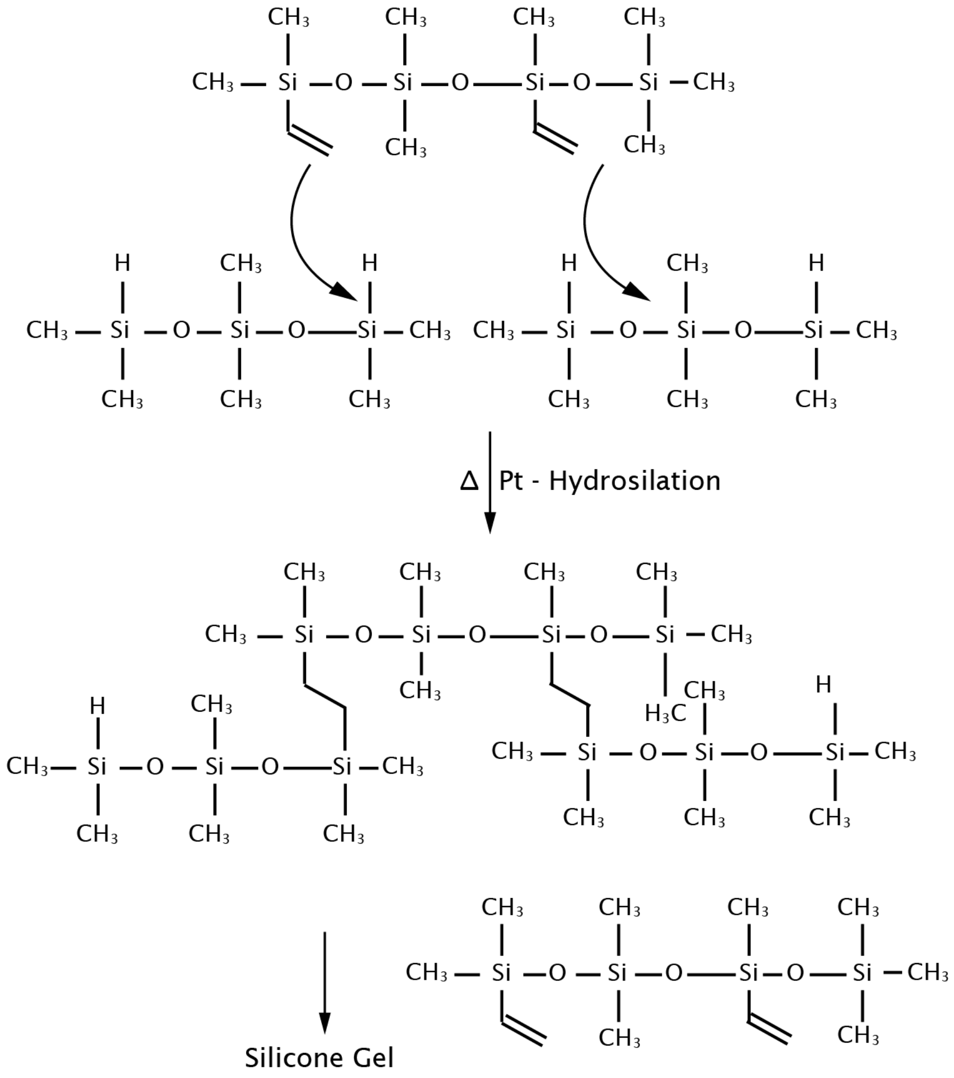


Fig 14.11 - Silicon cross-linking reaction

Fundamentals of Encapsulation and Sealing

Silicone

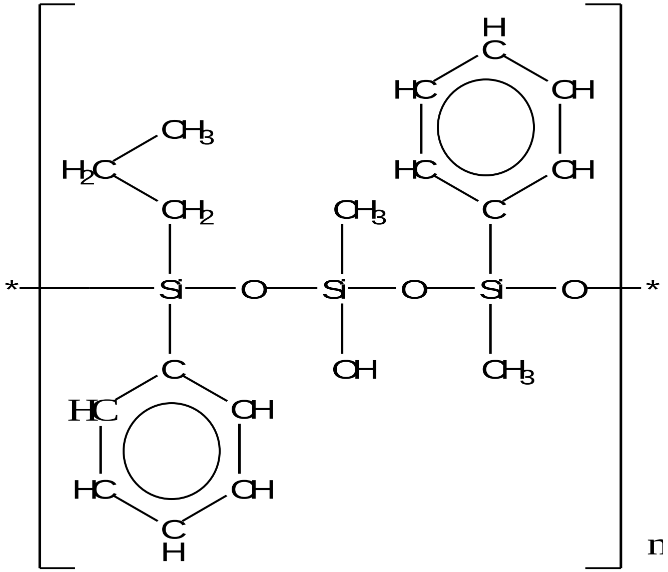
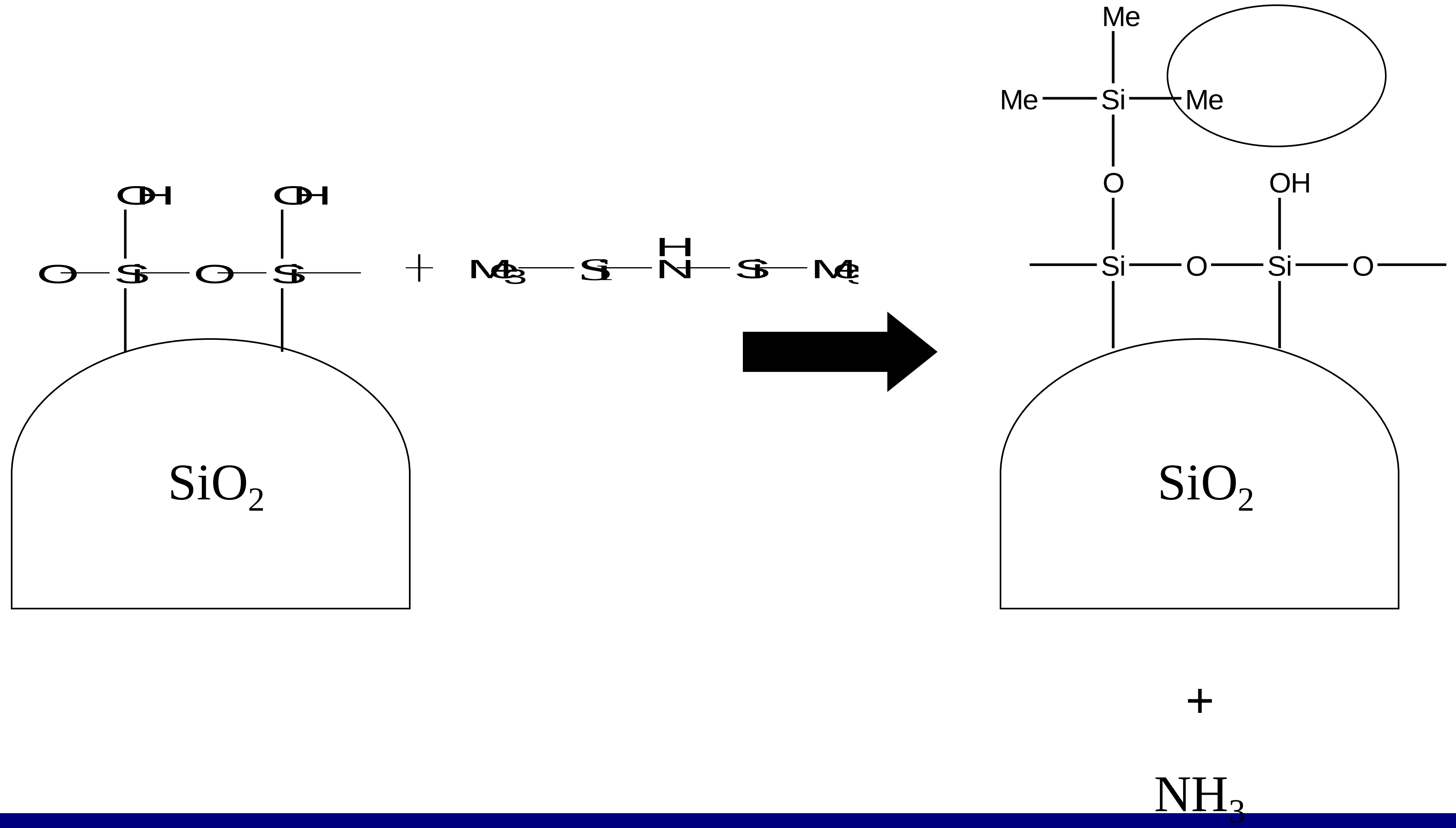


Figure: Silicone structure has a Si-O-Si backbone that provides thermal stability of the material. Hydrocarbons that attach to silicon atoms provide water-repelling properties.

General Properties of Silicone

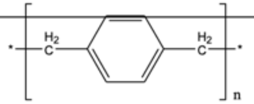
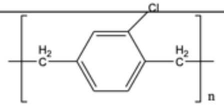
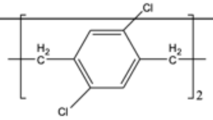
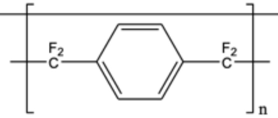
- Superior thermal properties (-100° C → 200-300° C)
- Non-wettable by liquid water
- Resistance to UV and other radiations
- Excellent electrical properties
- Low surface tension
- With additive and thicken agent → Good lubricant
- Long chain PDMS → Biological non-active

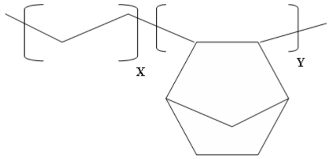
Deactivation of CAB-O-SIL

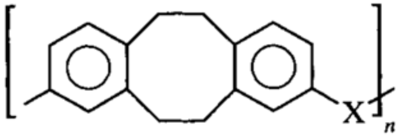


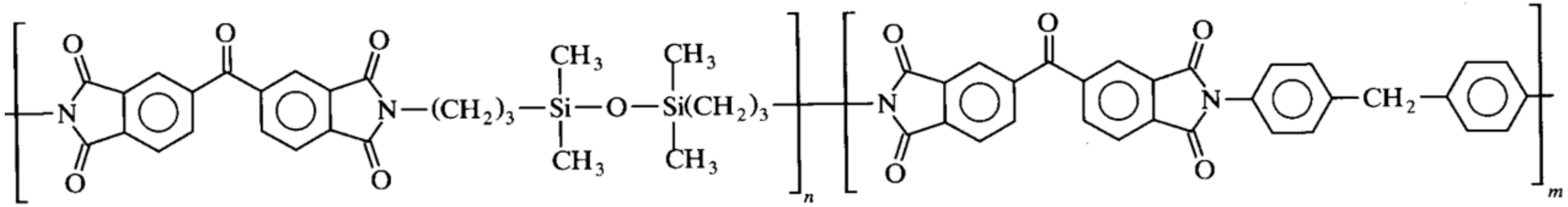
Other polymers

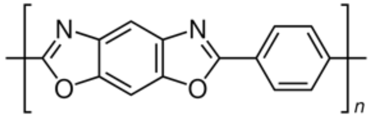
- Parylenes (Poly-Para-Xylylenes)
- Benzocyclobutene (BCB)
- Silicone-polyimide
- Cyclo-olefin copolymers
- PBO (polybenzoxazole)

Type of Parylenes	Deposition Rate (μm/hr)	Dissipation Factor	Properties Dielectric Constant	Water Absorption (%)
N Type:		1	0.0002	0.02
C Type:		3 – 5	0.02	0.06
D Type:		10 - 15	0.01	0.07
F Type:		?	<0.0002	<0.02









14.5 Encapsulation processes

- Cakes Molding
  - Transfer molding
  - Compression molding
- Liquid
  - Cavity filling
  - Glob top
  - Underfilling

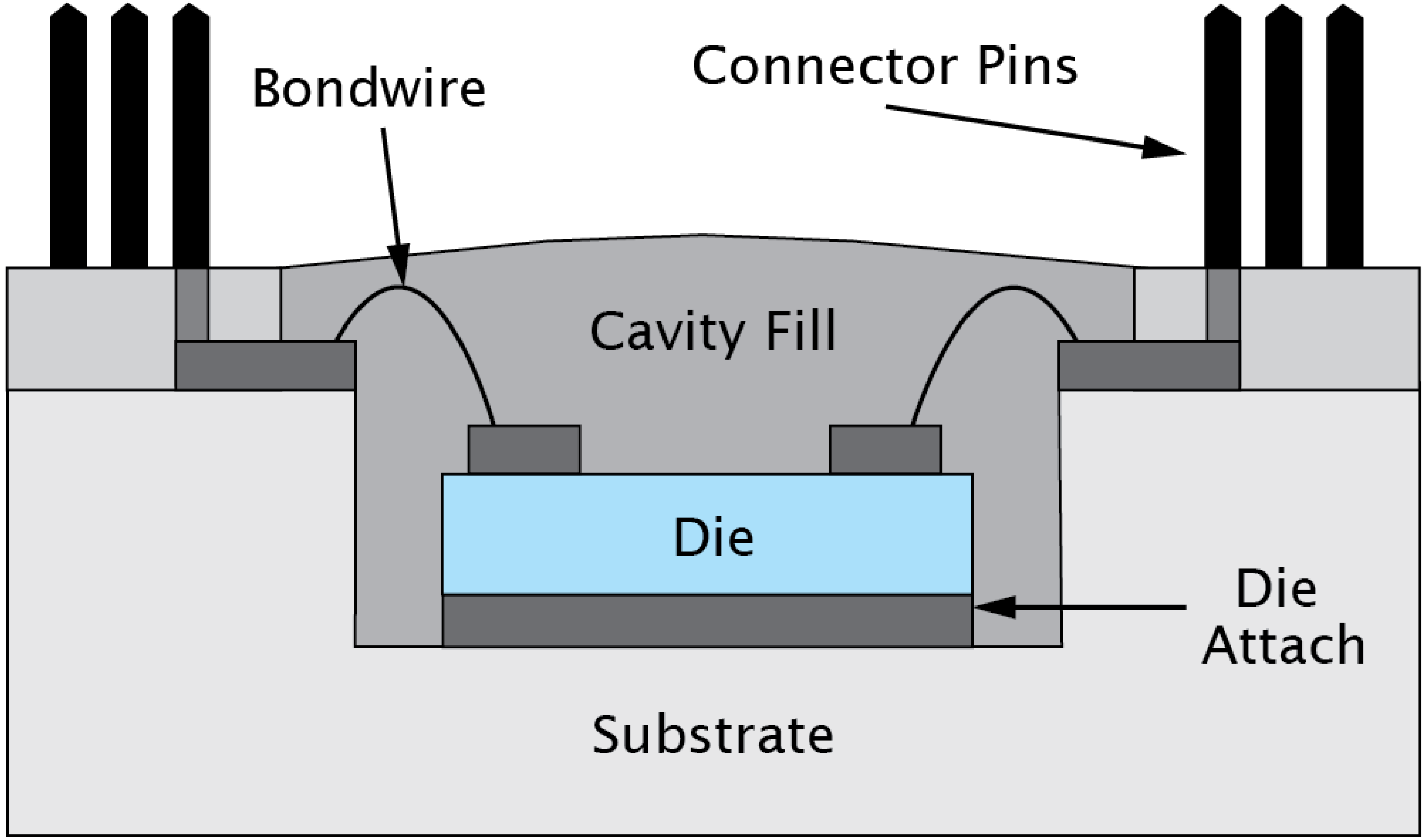
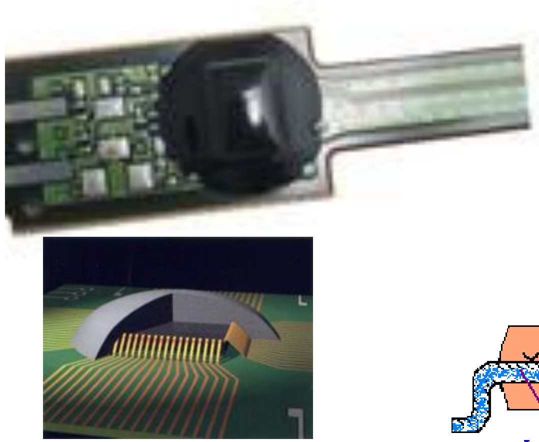


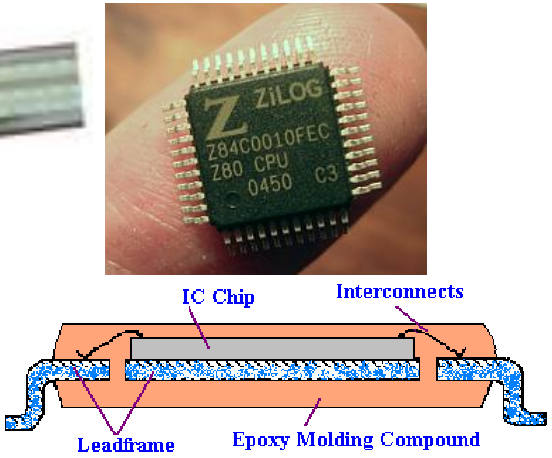
Fig 14.12 - Cavity filling of PGA

Package Encapsulants

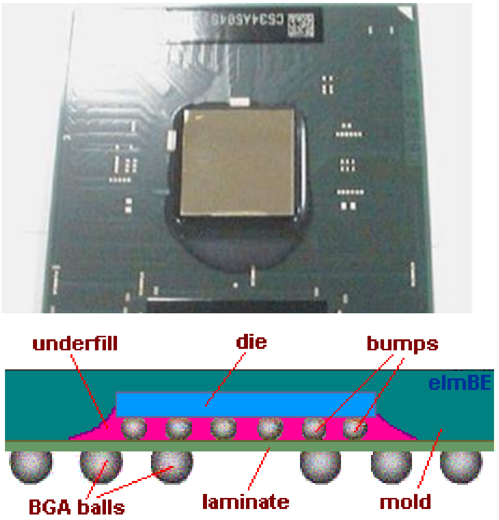
- *Physical/chemical protection of functional chips*
  - *Glob tops*
  - *Epoxy molding compounds,*
  - *Underfills for flip-chip type packages*



Glob top



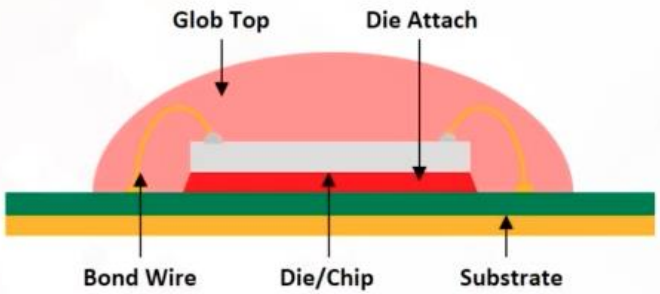
EMC



Underfills

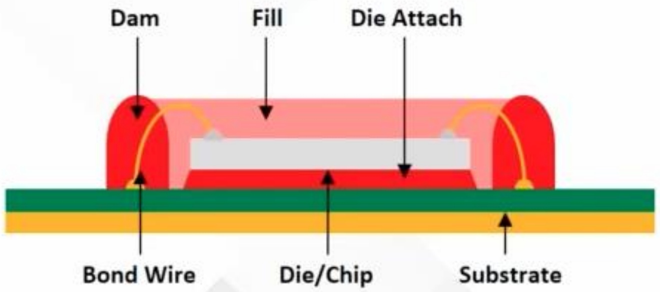
Glob top vs Dam/Fill

Glob Top



- For **small** die sizes below 2x2mm
- Typically higher thickness
- Low viscosity and fine-tuned thixotropy
- **One step** process
- Difficult to control the shape

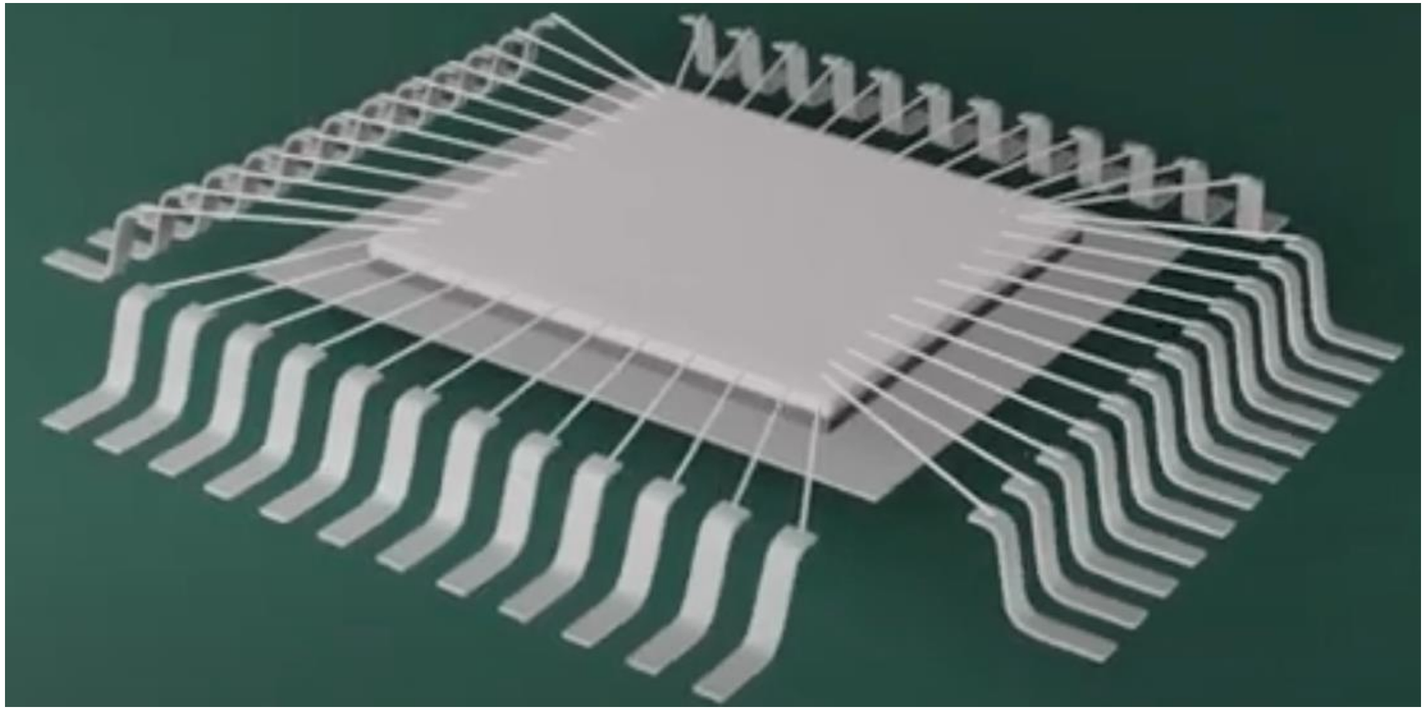
Dam & Fill

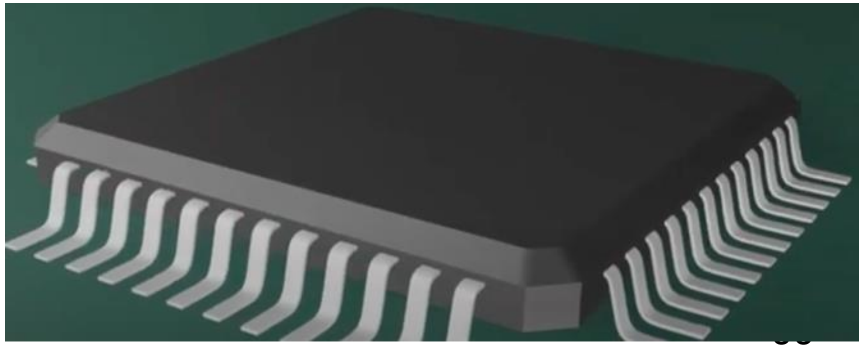


- For **large** die sizes up to 10x10mm
- Square shaped to evenly distribute stress after cure
- Requires High viscosity DAM + Self levelling FILL
- **Two step** process
- Tight space and shape control

From Capling

Molding leadframe based package





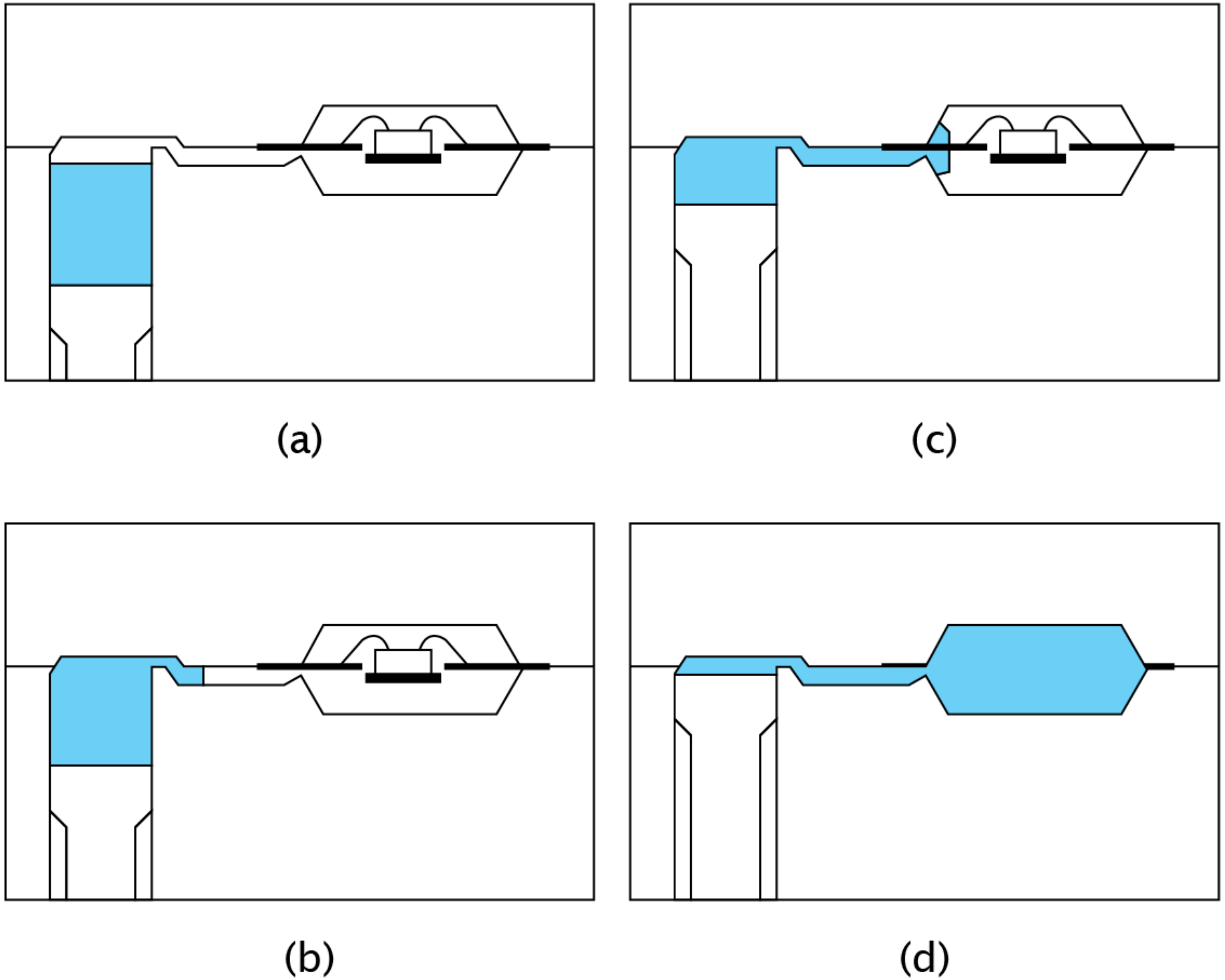
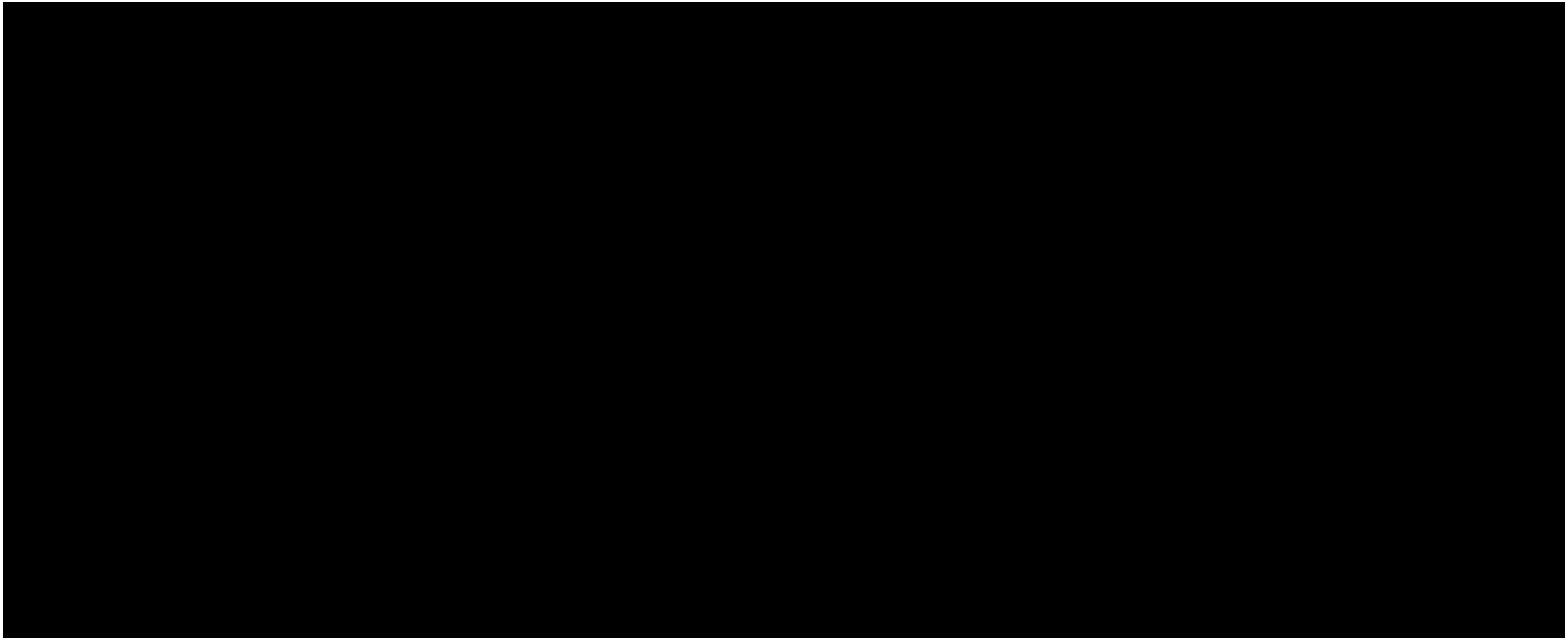


Fig 14.13 - A typical transfer model

- Spiral flow; cm @molding temperature
- Minimum viscosity by capillary rheometer

Transfer molding



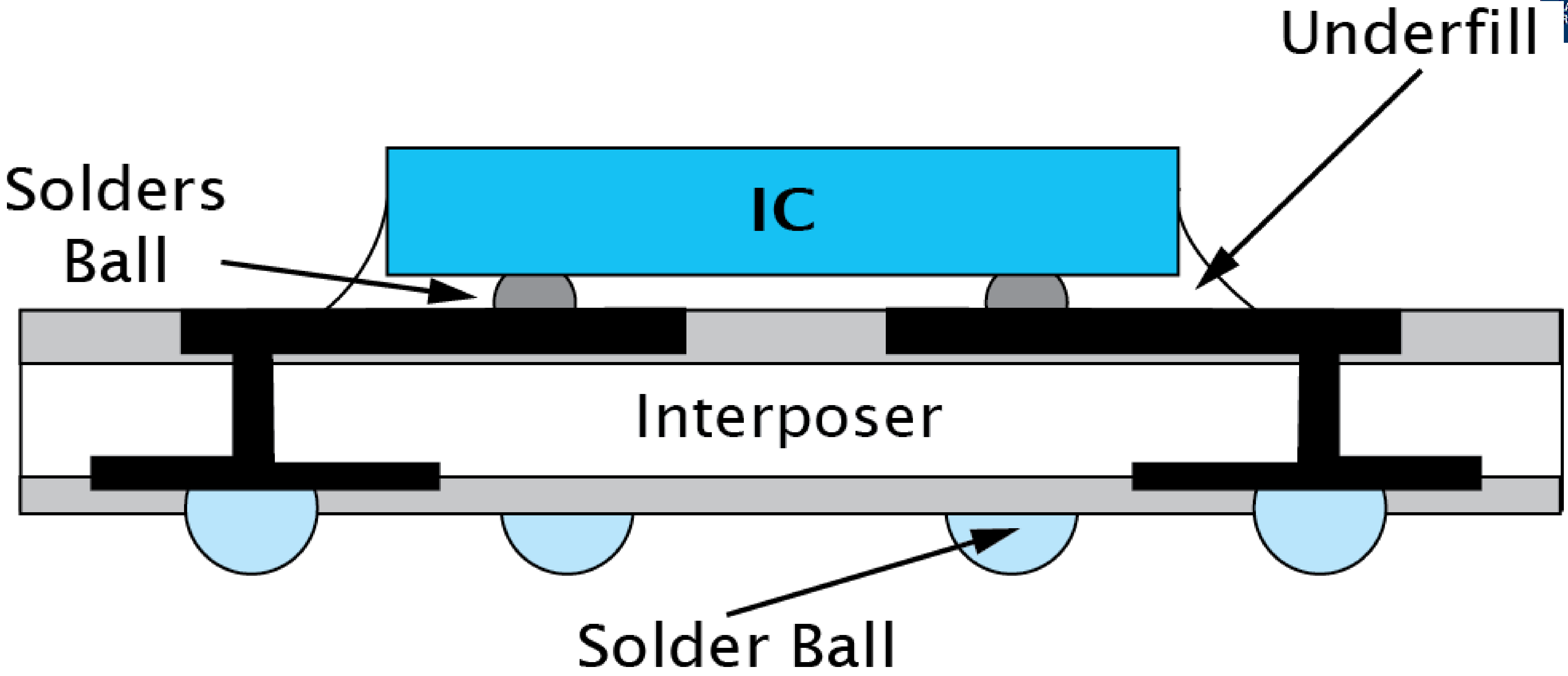


Fig 14.15 - A typical flip-chip BGA

- Underfilling techniques
  - Capillary filling
  - Pre-applied/No-flow
  - Wafer level coating/lamination
  - Molded UF

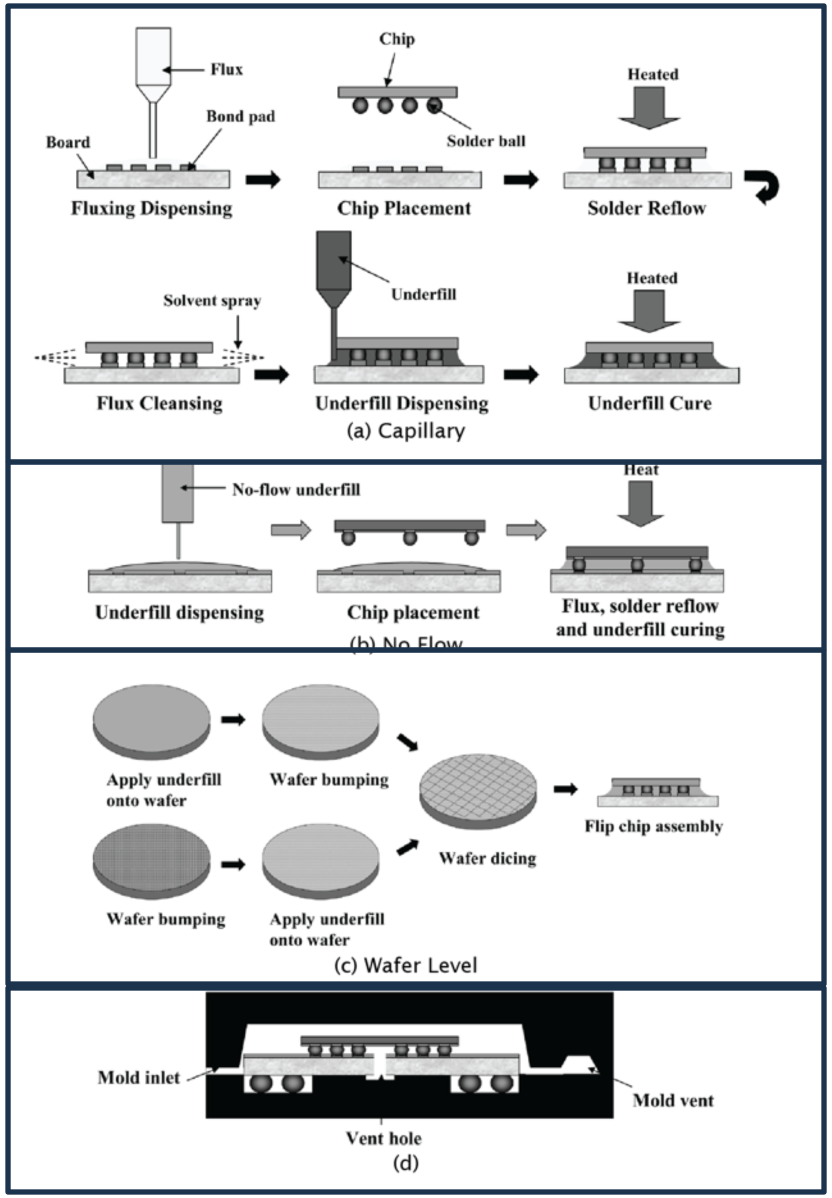
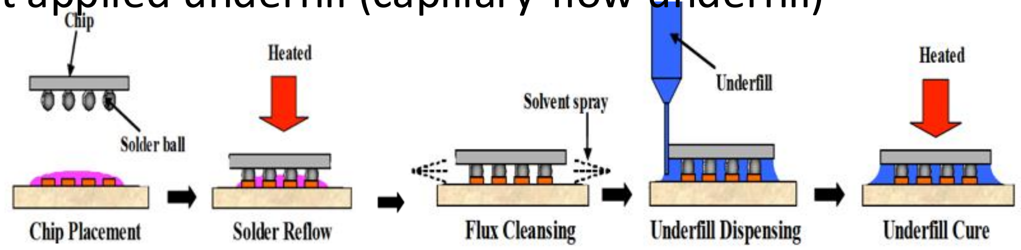


Fig 14.17 - Four underfilling processes

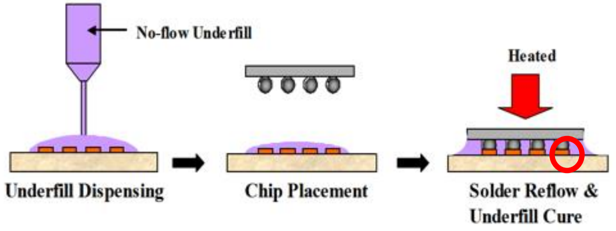
Stress Redistribution of interconnecting joints (chip/wafer/panel level)

- Underfills
  - Capillary flow underfill
  - No-flow underfill
    - Process compatible chemistry
    - Flux, cure temperature
    - TCB compatible
  - Reworkable underfill
    - Chemically or thermally decomposed
    - Expensive boards
  - Wafer level underfill
    - Burn-in and test WF level
  - Molded underfill
  - EMC for FOWLP;

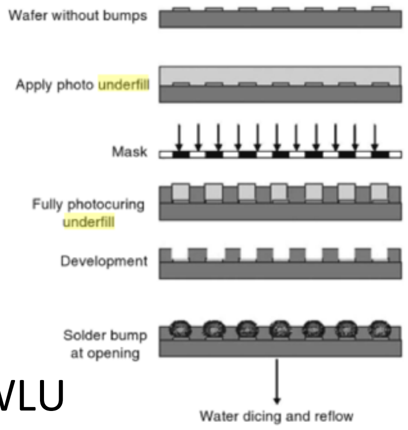
Post applied underfill (capillary-flow underfill)



Pre applied underfill (no flow underfill, NCP, Epoxy flux, etc)

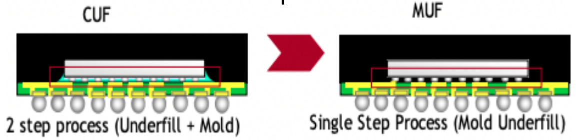


- Flux
- Curing temperature
- Filler trapping

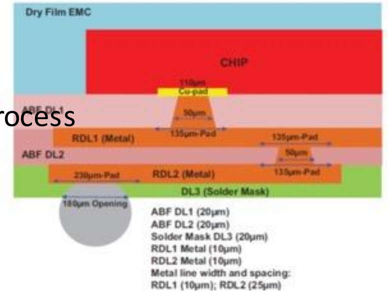


WLU

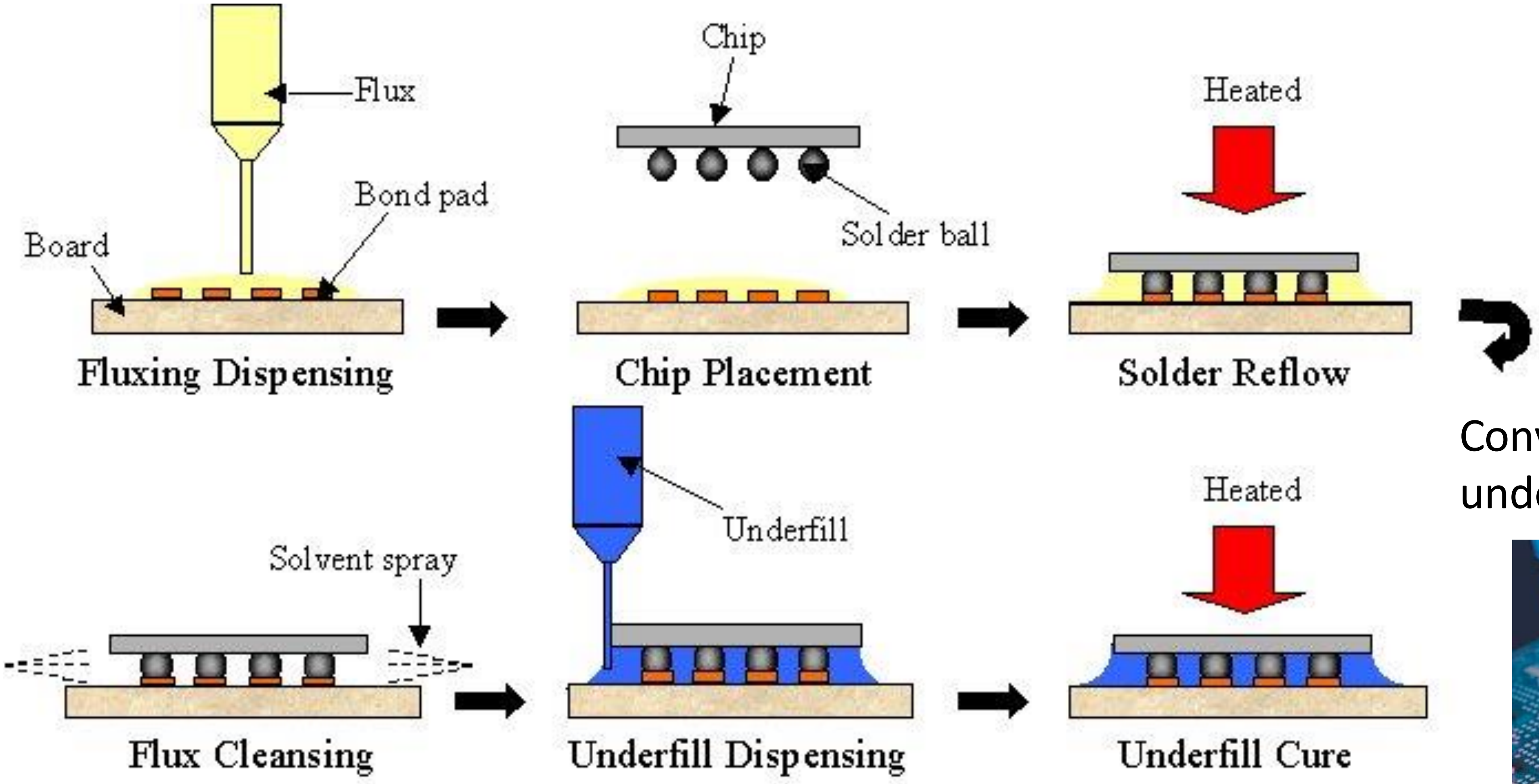
STATS ChipPAC 2010



FO-EMC in Unimicron process
-Low CTE
-Low E
-Warpage



Capillary Flow Underfilling



Conventional underfill

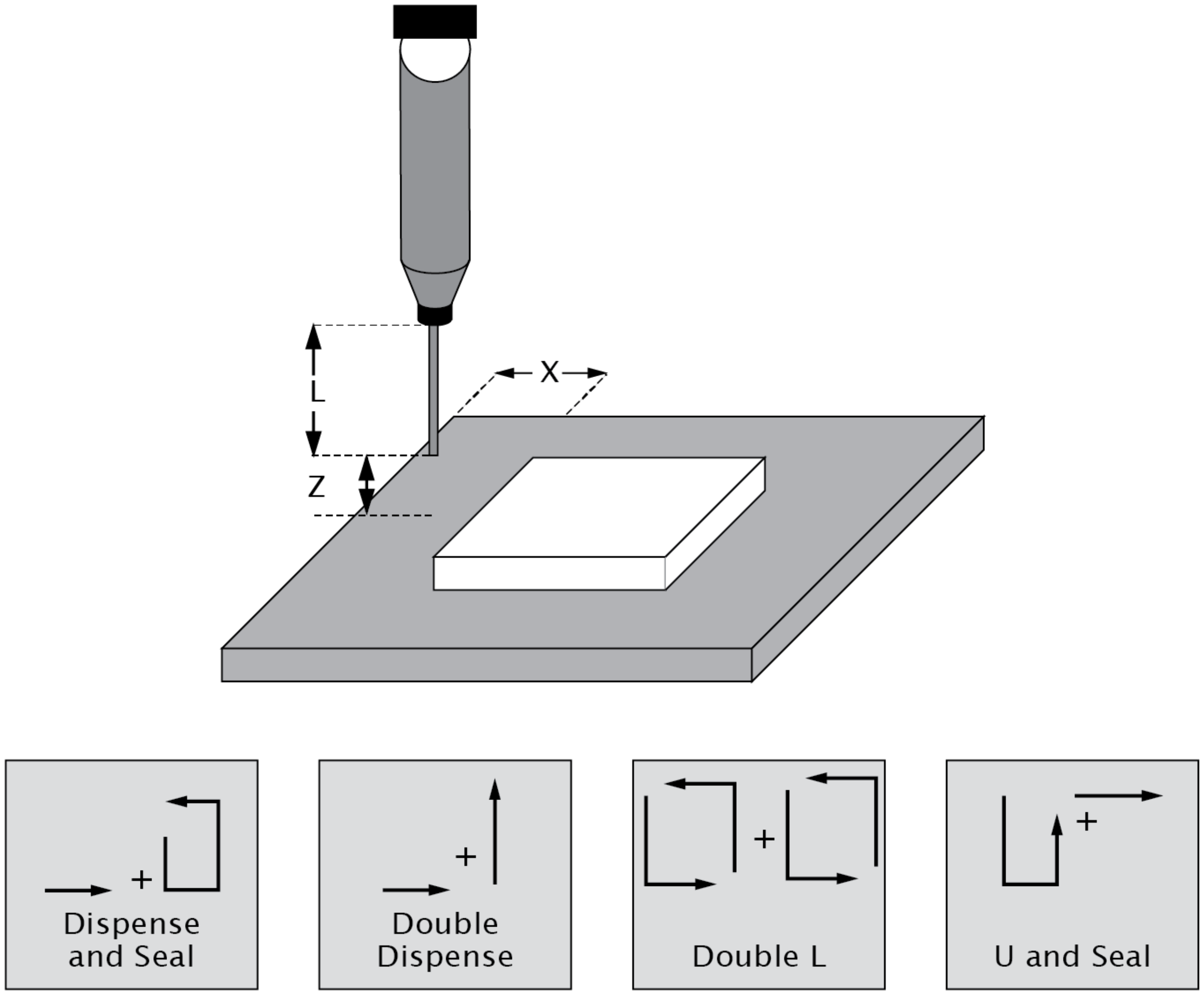
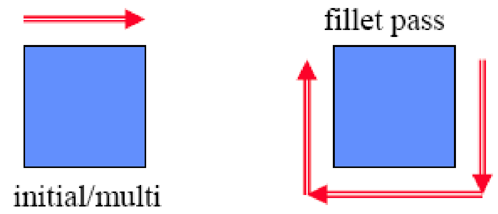


Fig 14.16 - Underfill dispensing

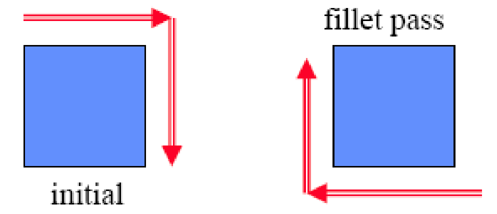
Underfill Dispense Patterns

- Underfill Flow Depends
  - Chip Size/Shape(W_{chip}, L_{chip})
  - Bump/Interconnect Pattern
  - Gap Size (h)
  - Underfill Viscosity
  - Underfill Surface Tension
  - Underfill Wetting Angle
- General Guidelines
  - Chip < 0.25 in: Single Side
  - Chip Between 0.25 & 0.5 in: L-Shaped (single pass)
  - Chip > 0.5 in: Single Multi-Pass
  - Selection governed by cycle time/throughput requirements

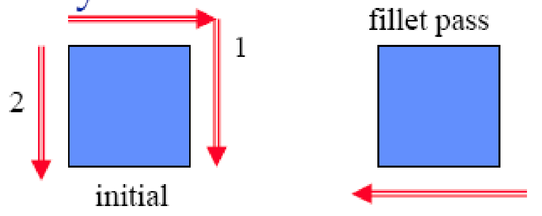
- Single Side and Multiple



- L-Shaped

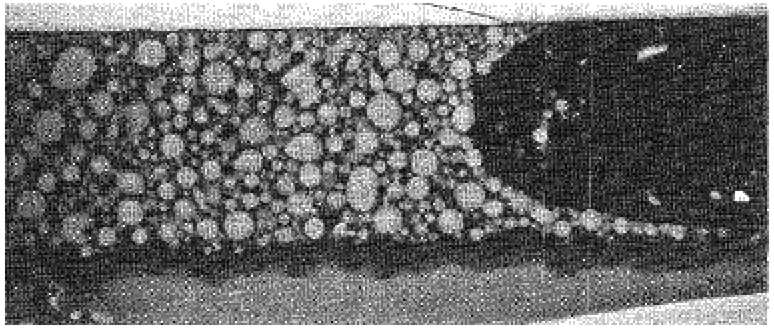


- Hybrid

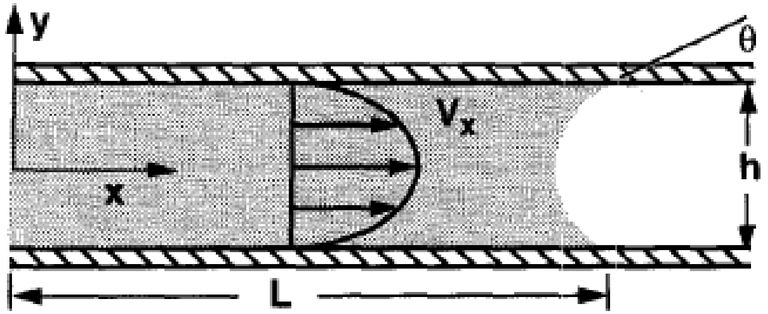


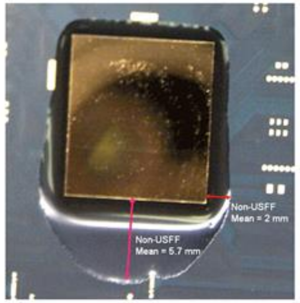
Fundamentals of Encapsulation and sealing

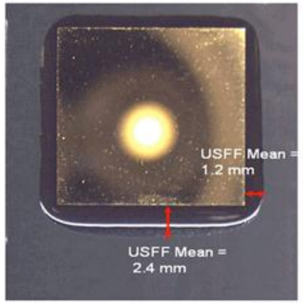
Capillary underfilling



$$t = \frac{3\eta L^2}{h\gamma\cos\theta}$$ Eq 14.4







t is flow time, η is viscosity, L is distance of flow, h is die-substrate gap, γ is surface tension and θ is wetting angle.

- *No solder bumps*
- *No surface roughness*
- *No flux*
- *No other obstructions*

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Underfill Dispense Volume Calculation

Dispense Volume

$$V_{underfill} = V_{Standoff\ Gap} - V_{Bumps} + V_{Fillet}$$

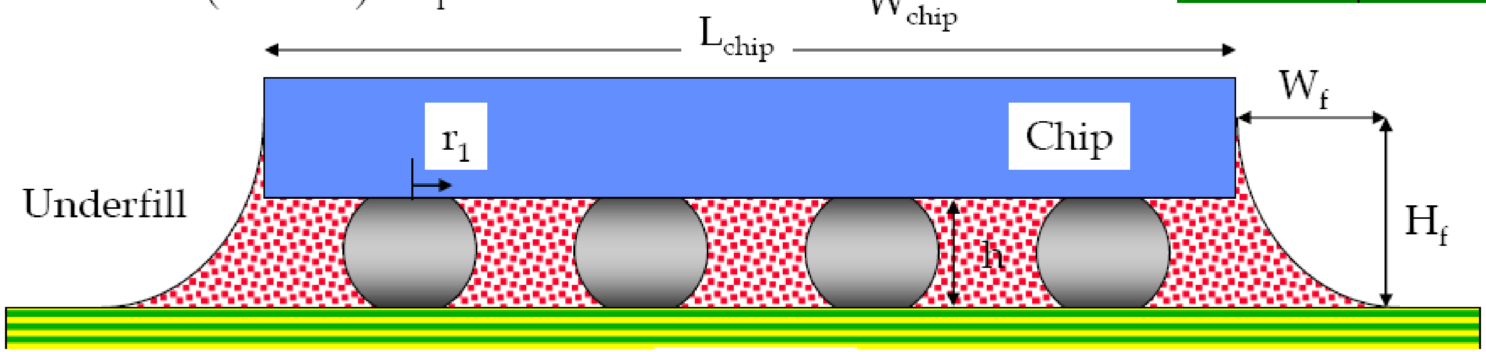
$$V_{Standoff\ Gap} = L_{chip} W_{chip} h$$

$$V_{Bumps} = N_{bumps}\left[\frac{4}{3}\pi R^3 - \frac{\pi}{3} v^2 (3R - v)\right]$$

$$V_{Fillet} = \left[2\left(L_{chip} + W_{chip}\right)\left(H_f W_f\right) + \left(W_f^2 H_f\right)/3\right] SF$$

$$where \quad v(2R - v) = r_1^2$$

Contact Angle (°)	Shape Factor
1	0.1109
5	0.3202
10	0.4739
15	0.5849
20	0.6742
25	0.7505
30	0.8187
35	0.8817
40	0.9416



Source: GT & Asymtek

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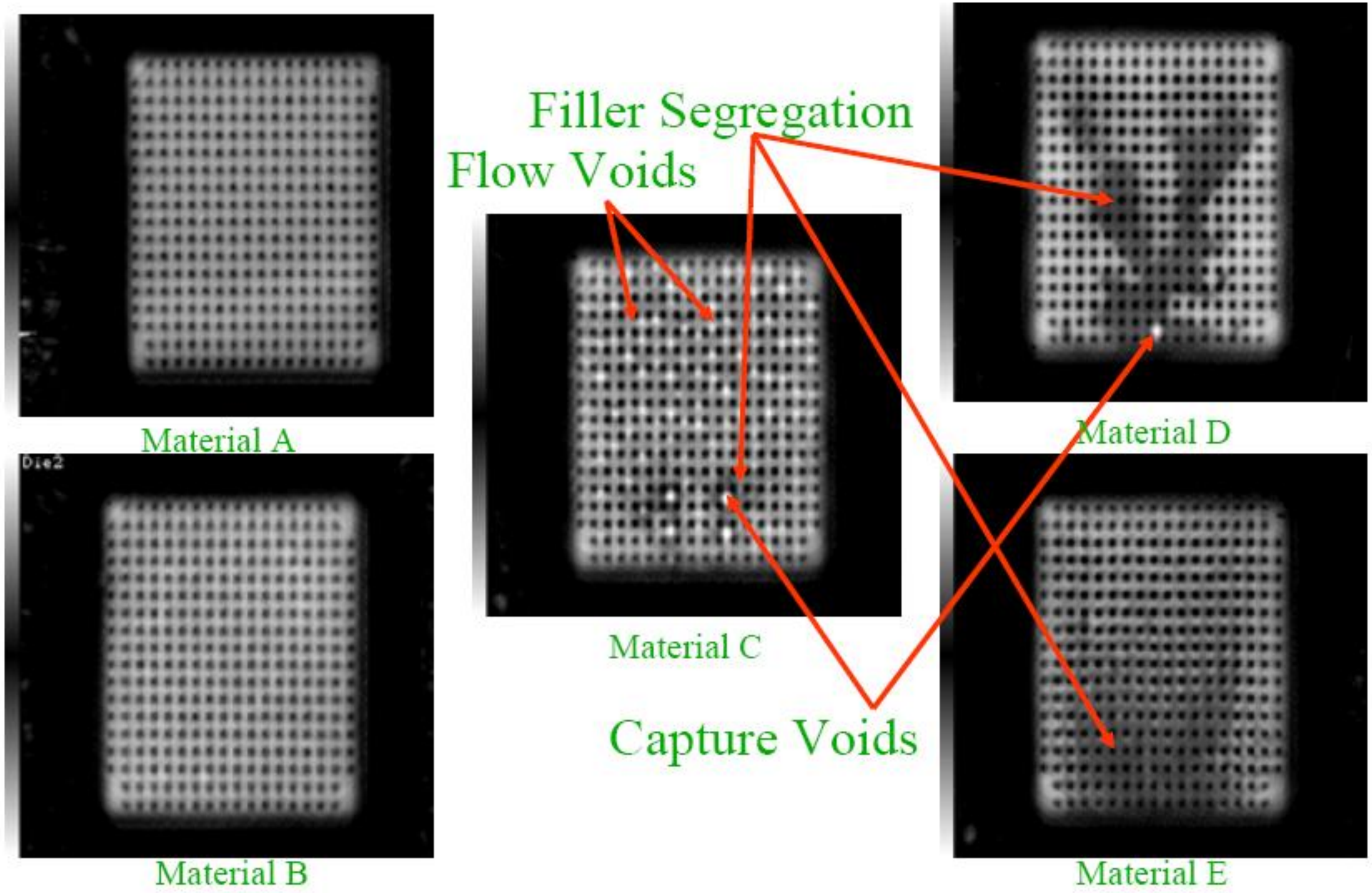
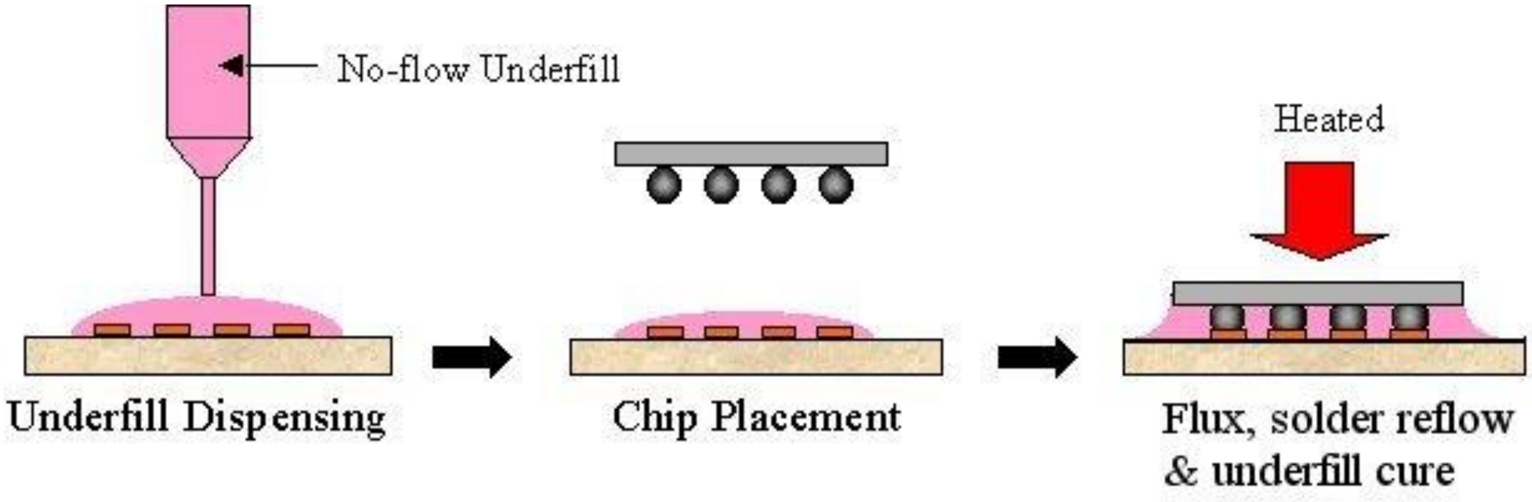
Flow Induced Underfill Defects



C-SAM (scanning acoustic microscopy)

Fundamentals of Encapsulation and sealing

No-Flow Underfill/Epoxy flux



Key material property; self-fluxing

Patented by GT in 2000

No-Flow Underfill Technology

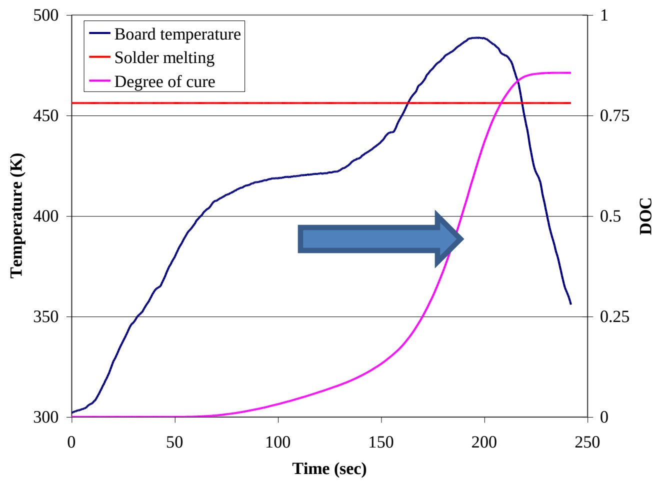
Advantages:

- Elimination of flux dispensing and cleaning steps
- Elimination of underfill capillary flow
- Combination of solder bump reflow and underfill cure
- Higher assembling efficiency and lower cost

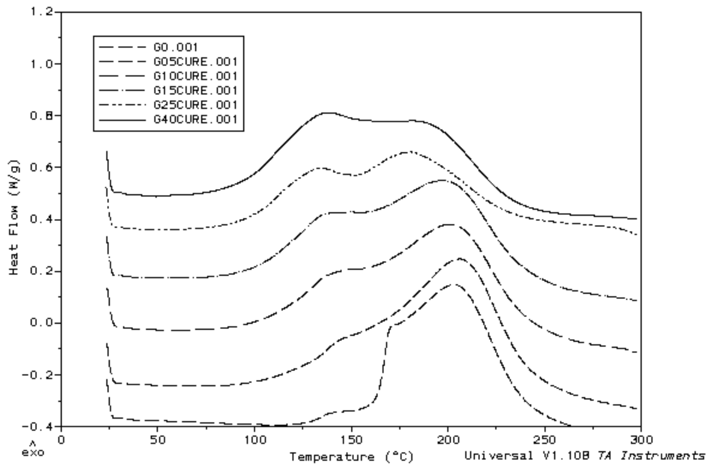
Fundamentals of Encapsulation and Sealing

Key Characteristics of No-Flow Underfill

- Latent curing ability
  - Maintain low viscosity before solder joint formation
  - Completion of reaction after reflow
- Fluxing capability
  - Eliminate the solder oxide and facilitate solder wetting
  - Influence of flux on the material properties of underfill



Reflow profile and modeled curing degree with time



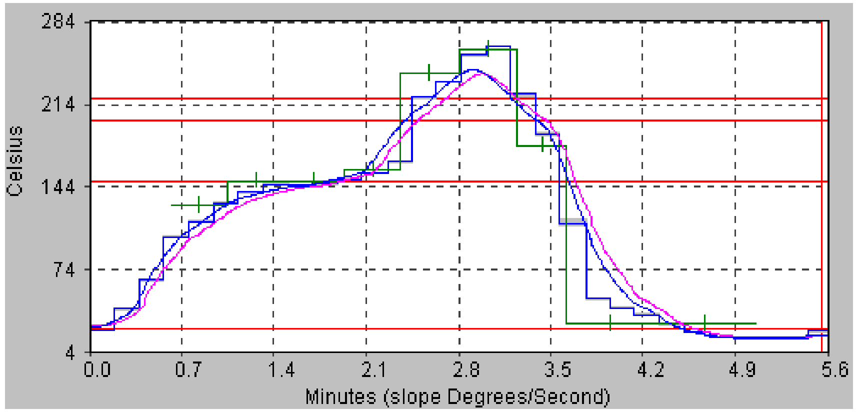
Influence of flux concentration on curing behavior

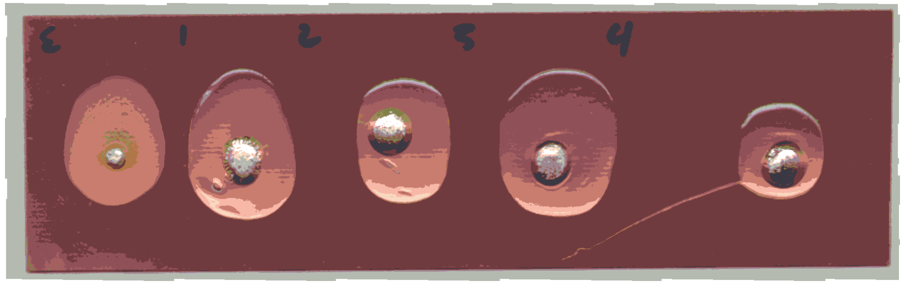
Fundamentals of Encapsulation and sealing

No-Flow Underfill for Lead-Free

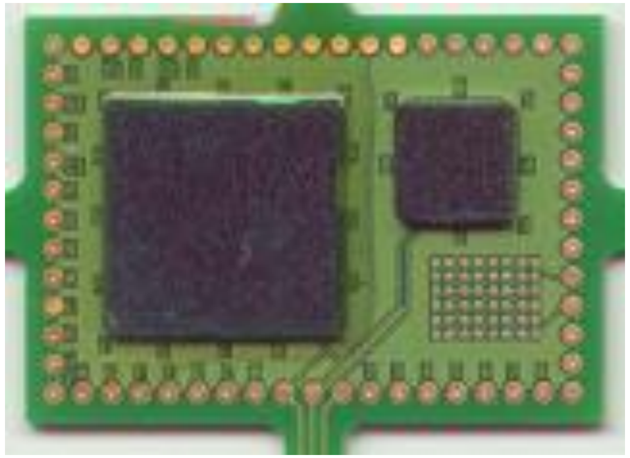
Challenges

- Higher reflow temperature requires higher curing latency
- Lead-free solder needs better fluxing capability





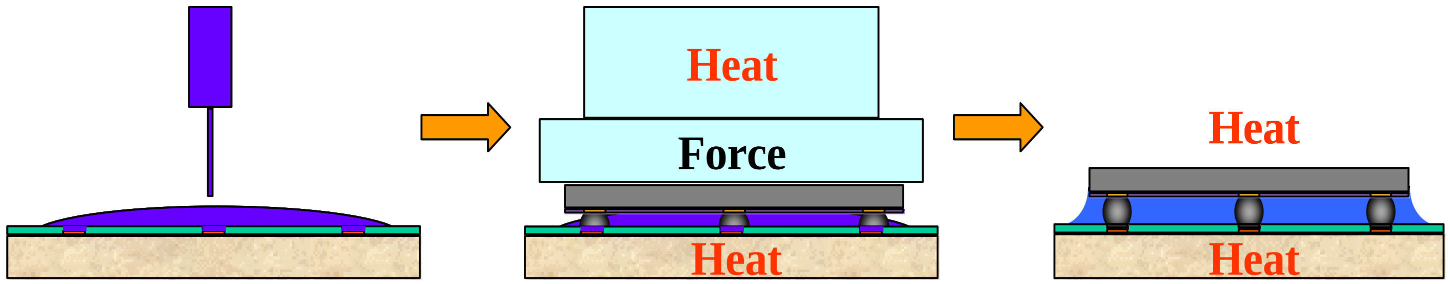
NF E NF A NF B NF C NF D



Daisy chained, periphery array,
pitch size: 200 μm
100 % yield

Reliability of No-Flow Packages

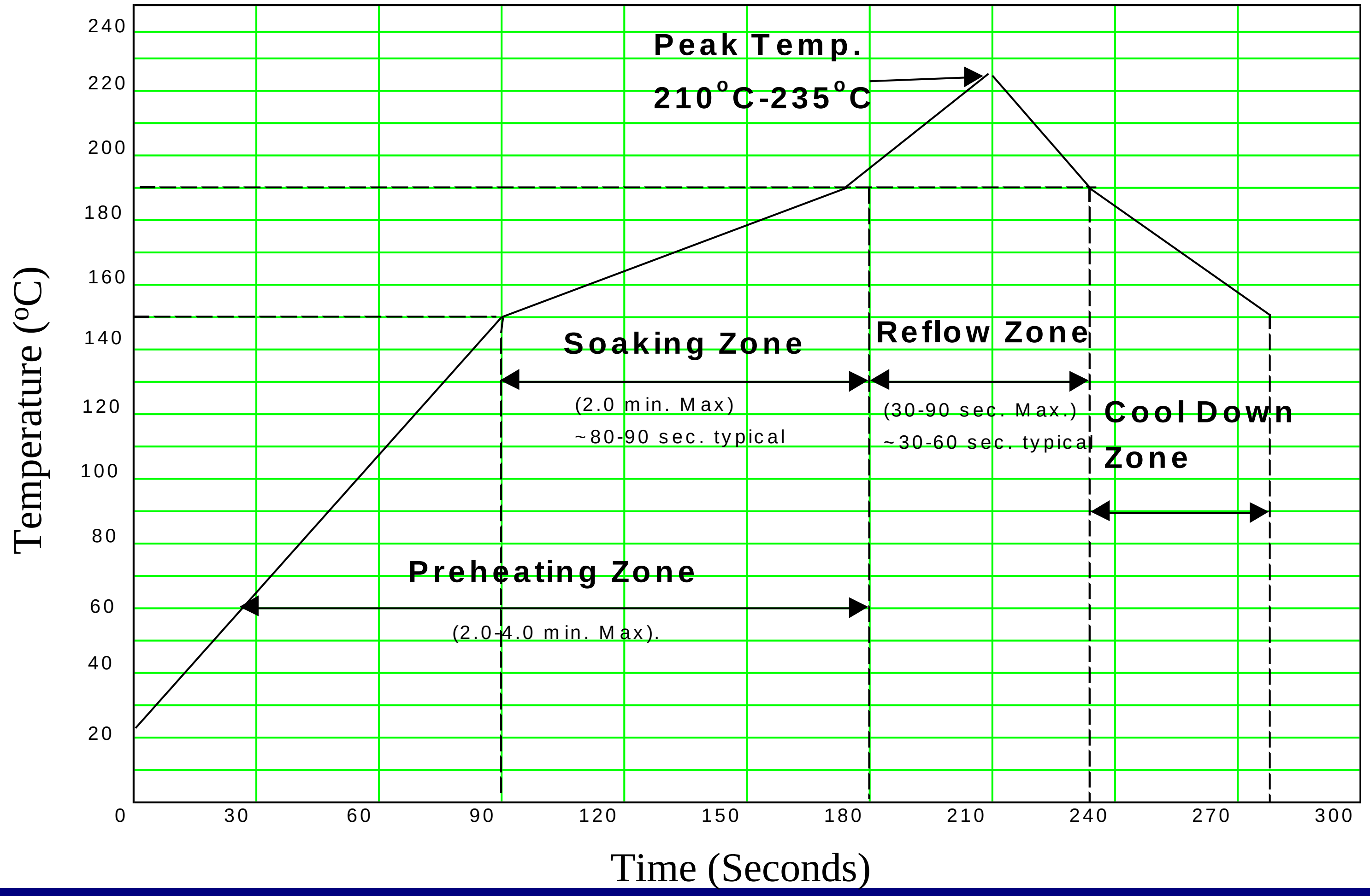
- <u>**Failure mode difference for no-flow underfill**</u>
  - **Localized CTE mismatch between the chip, the underfill, the board, and the solder material is serious**
  - **Low fracture toughness and high CTE mismatch result in underfill cracking**
- <u>**Reliability enhancement for no-flow underfill**</u>
  - **Improve the fracture toughness of no-flow underfill (Moon, Wong, 51st ECTC)**
  - **Low Tg, low modulus underfill (Liu, et al,. 51st ECTC)**
  - **Incorporate nano-silica filler into no-flow underfill (Zhang, Wong, 52st ECTC)**



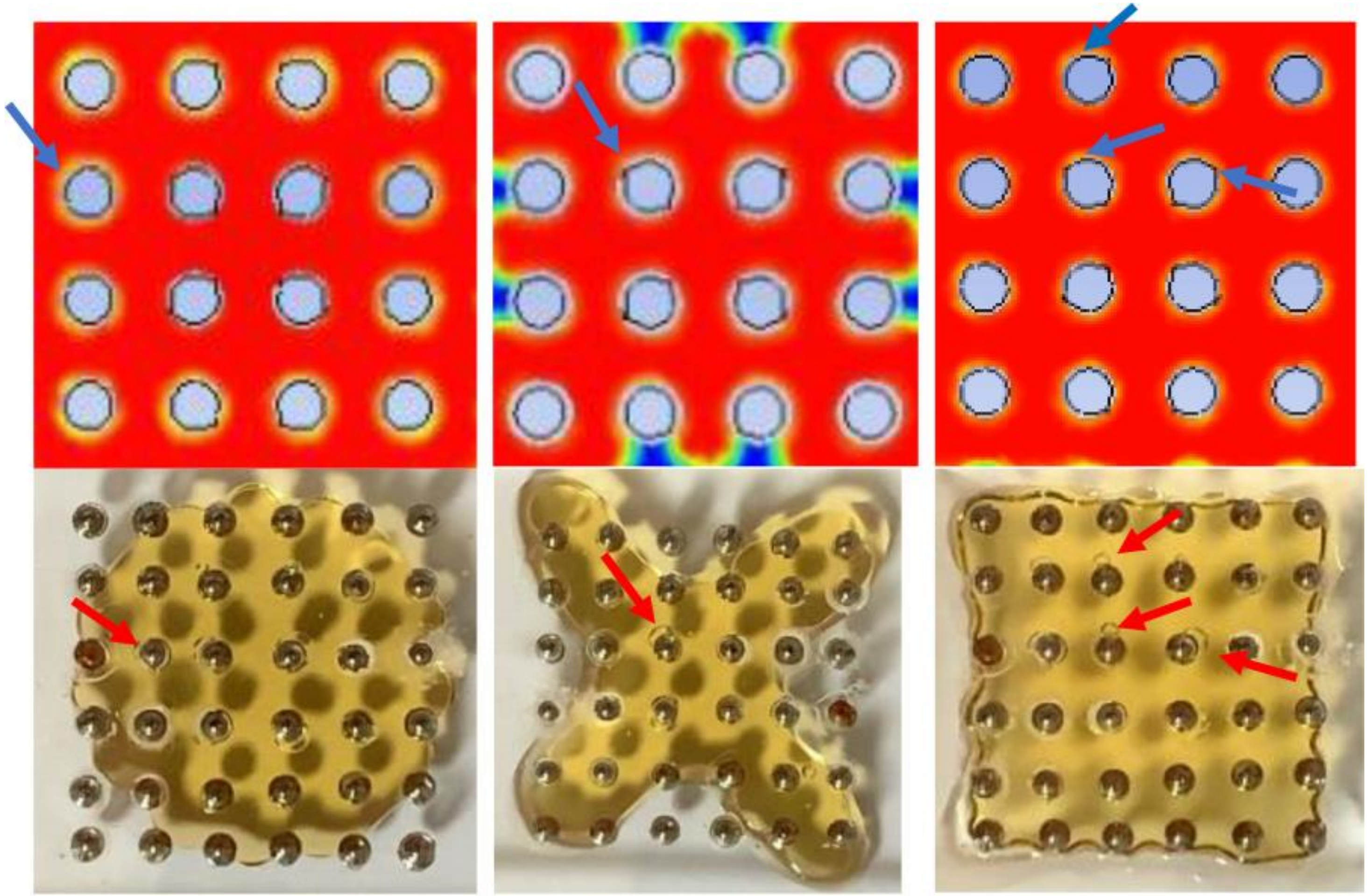
Underfill dispensing **Chip placement and reflow** **Underfill postcure**

No-Flow Underfill Technology (Cont’d)

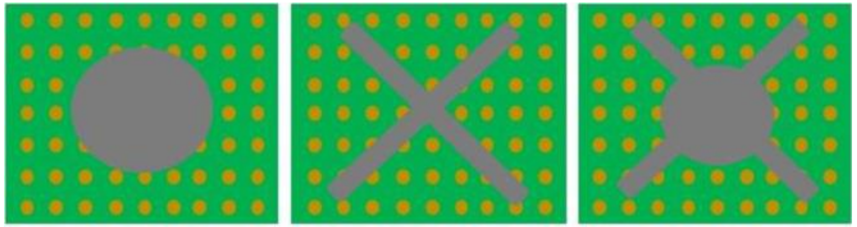
Typical Reflow Profile of Eutectic Sn/Pb Solder



Dispensing patterns for no-flow underfills



(a) (b) (c)



(a) (b) (c)

Dot Cross Combined

https://doi.org/10.1115/1.4049175

Fundamentals of Encapsulation and Sealing

No-Flow Underfill Technology (Cont'd)

Georgia Tech PACKAGING RESEARCH CENTER

Challenges

- **Dispensing**
  - Proper viscosity and surface tension
  - No process voiding
- **Pre-heating zone**
  - Significant decrease of viscosity
  - Easy compressing down of flip-chip
- **Soaking zone**
  - Sufficient fluxing capability
  - Maintenance of low viscosity
- **Reflow zone**
  - Maintenance of low viscosity before solder melting
  - Quick hardening after solder melting
- **Cooling zone**
  - Low shrinkage and low residual stress
  - Excellent thermal, physical, and mechanical properties

Fundamentals of Encapsulation and sealing

No-Flow Underfill Technology (Cont'd)

Generic Composition of No-Flow Underfill Material

- **Base resin**
- **Curing agent (hardener)**
- **Latent catalyst**
- **Fluxing agent**
- **Modifiers**
- **Silica filler**

Fundamentals of Encapsulation and Sealing

No-Flow Underfill Technology (Cont'd)

Possible Base Epoxy Resin System

- **Epoxy Resins**
  - Cycloaliphatic epoxy resins
  - Bisphenol A type epoxy resins
  - Bisphenol F type epoxy resins
  - Naphthalene type epoxy resins
  - Novolac type epoxy resins
  - A mixture of the above epoxy resins

- **Cyanate ester resins**

No-Flow Underfill Technology (Cont'd)

Possible Curing Agents

- Active Hydrogen Compounds
  - Polyamines
  - Carboxylic acids and anhydrides
  - Polymercaptans
  - Polyphenols (such as novolac resins)
- Ionic Initiators
  - Tertiary amines
  - Imidaole and its derivatives
  - Onium salts
  - Phosphorus-containing compounds
  - Metal chelates
- Cross-Linkers
  - Melamine-formaldehyde resins
  - Phenol-formaldehyde resins
  - Urea-formaldehyde resins

No-Flow Underfill Technology (Cont'd)

Possible Latent Catalysts

- Imidazoles and their derivatives
- Quaternary phosphonium compounds
- Metal acetylacetonates
- Tertiary amines
- Thermally and/or photo-sensitive onium salts

Fundamentals of Encapsulation and sealing

No-Flow Underfill Technology (Cont'd)

Possible Fluxing Agents

- **Organic carboxylic acids**
- **Polyols**
- **Resinous (polymeric) fluxes**

No-Flow Underfill Technology (Cont’d)

Possible Modifiers

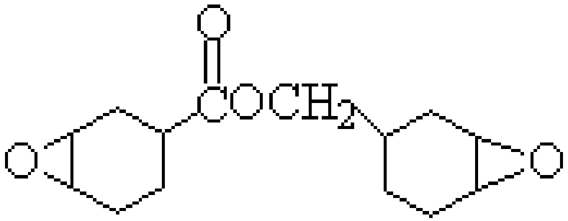
- **Toughening agents**
  - **Reactive type**
    - **CTBN modified epoxy resins**
    - **Reactive CTBN resins**
    - **Rubber modified epoxy resins**
    - **Alicyclic acids**
    - **Reactive polyesters**
    - **Polyamide resins**
    - **Urethane elastomers**
    - **Silicone-epoxy copolymer**
  - **Non-reactive type**
    - **Silicone powder**
    - **Rubber powder**
    - **Thermoplastic powder**
- **Viscosity modifier (such as reactive diluent)**

Fundamentals of Encapsulation and sealing

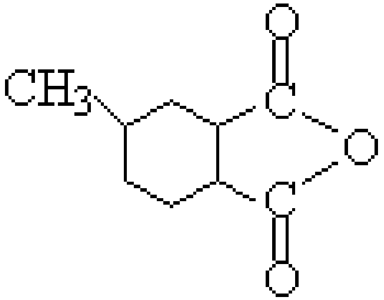
No-Flow Underfill Technology (Cont'd)

GT No-Flow Formulation

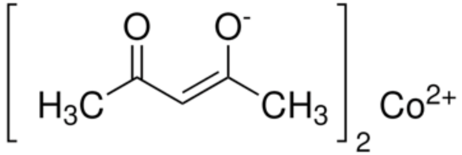
ERL 4221



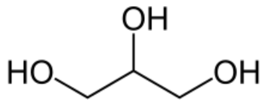
HHMPA



Co(II) Acetylacetonate



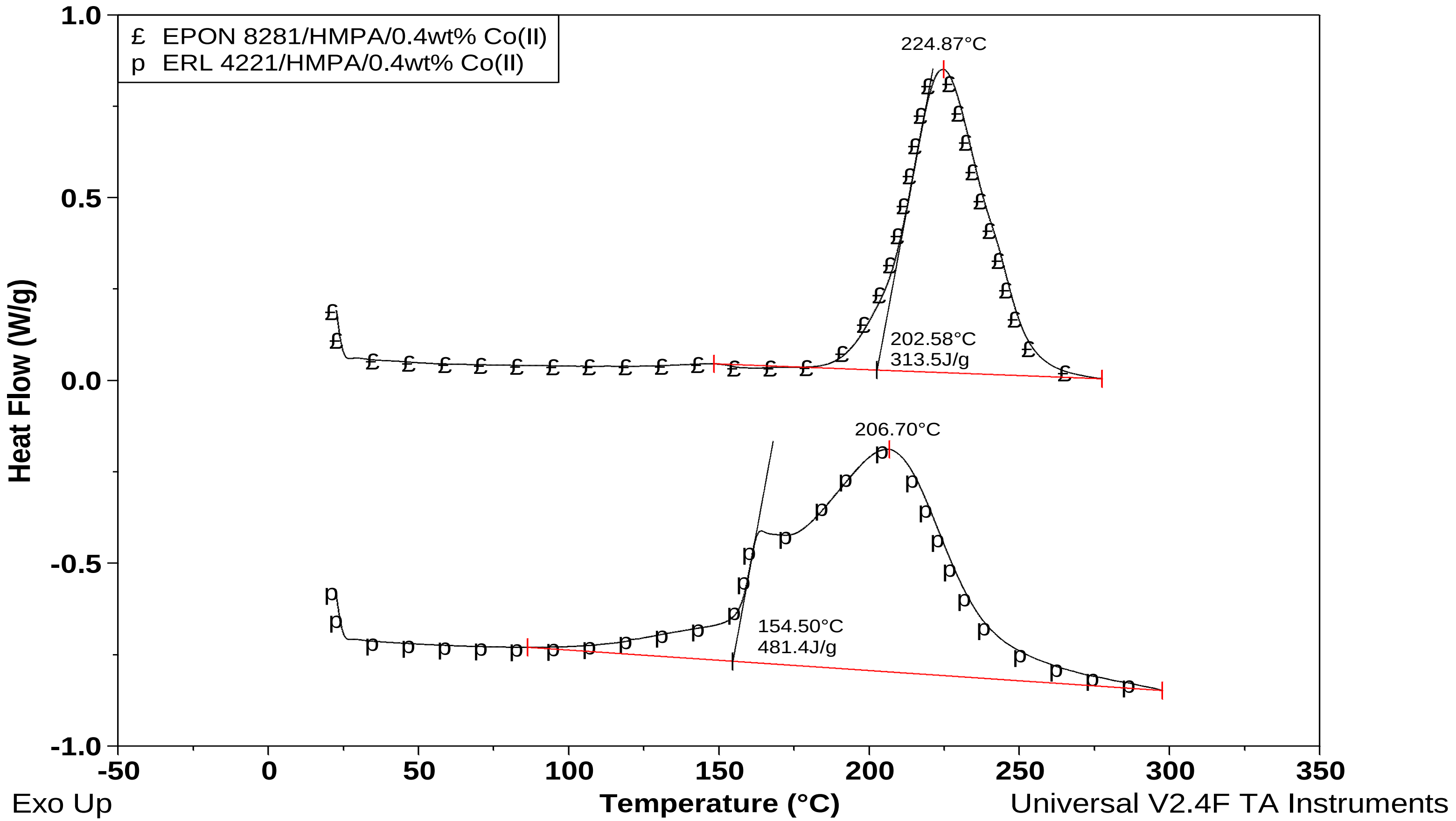
Glycerol



Fundamentals of Encapsulation and sealing

No-Flow Underfill Technology (Cont'd)

Curing of Co(II) Acac. in Epoxy/Anhydride systems

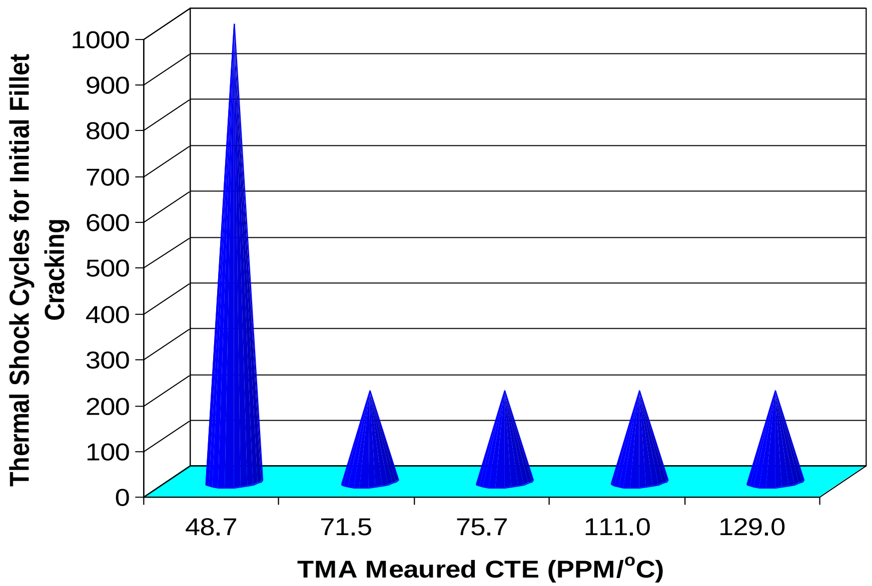


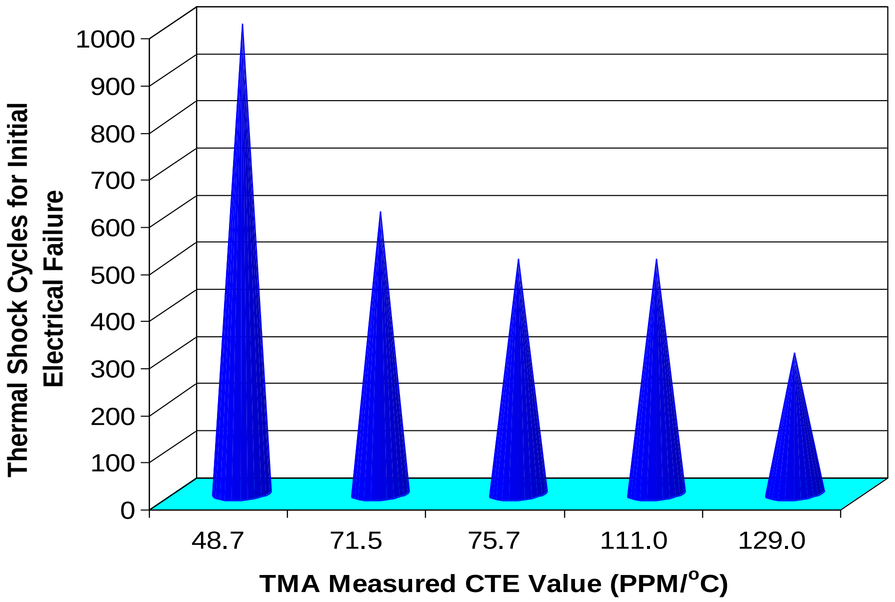
DSC Scan Rate at 5°C/min

Fundamentals of Encapsulation and sealing

No-Flow Underfill Technology (Cont'd)

CTE Effects on Fillet Cracking and Package Reliability





Fundamentals of Encapsulation and Sealing

Reworkable Underfill Technology

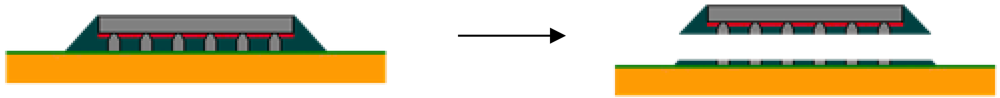
Flip-Chip Rework

Importance

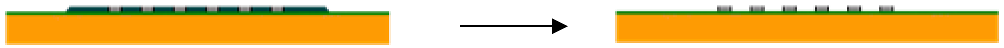
- KGD
- Cost
- Reusing boards

Process

Localized chip removal



Underfill removal and site preparation



Solder replenish
New chip replacement
Underfill dispensing

Reworkable Underfill Technology (Cont'd)

Reworkable Underfill Process

= Capillary - Flow Underfill + Rework

Rework Process

- Localized chip removal
- Underfill removal and site preparation
- Solder replenish
- New chip replacement
- Underfill dispensing

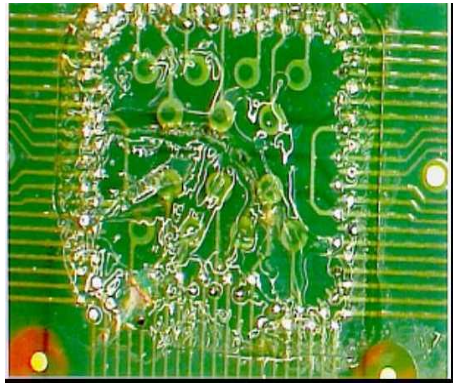
Fundamentals of Encapsulation and sealing

Reworkable Underfill Technology (Cont'd)

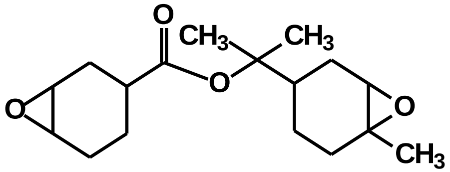
Epoxy Based Reworkable Underfills (Cornell)

Thermally Degradable Epoxies

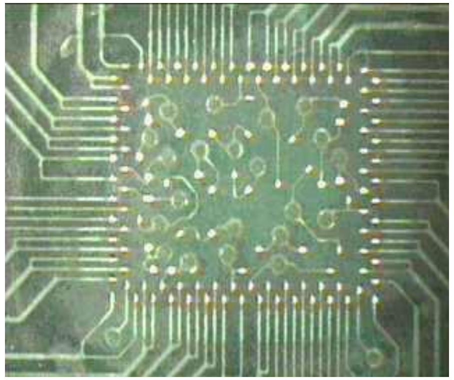
- ☺ Degrade at 200-300°C
- ☺ Allow die to be removed with tweezers on hot-plate
- ☺ Brushing to remove underfill residue



After die removal



Alpha-terpepoxide



After underfill residue removal

Fundamentals of Encapsulation and sealing

Reworkable Underfill Technology (Cont'd)

Non-Epoxy Based Reworkable Underfills

Thermoplastic (National Starch & Chemical)

- ☺ Easy to rework (die removal & residue removal)
- ☹ Low reliability

Fundamentals of Encapsulation and sealing

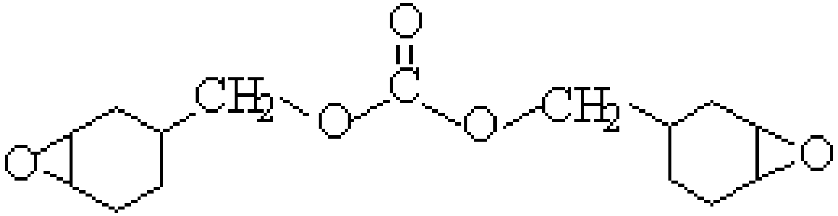
Reworkable Underfill Technology (Cont'd)

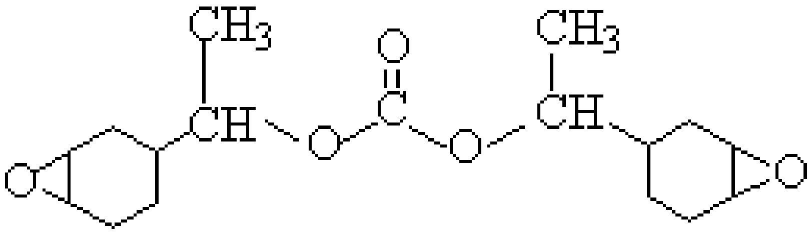
Georgia Tech's Approach I

<u>Thermally degradable epoxies</u>

☺ Degrade ~ 220^{o}C

☺ Have good overall properties



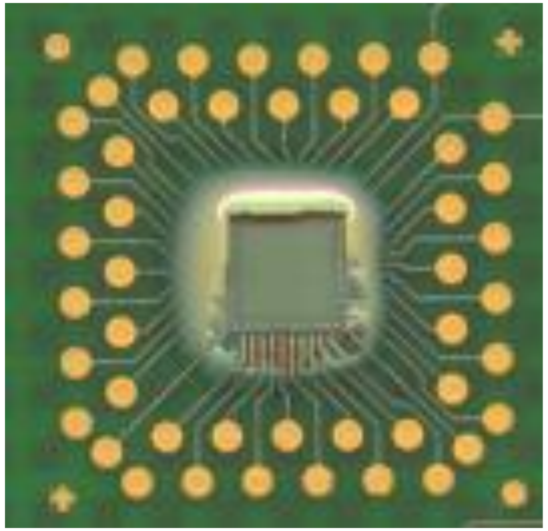


Fundamentals of Encapsulation and sealing

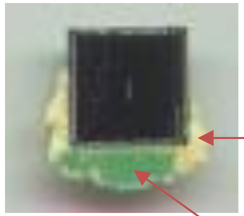
Reworkable Underfill Technology (Cont'd)

Rework Test

Board and Die after Rework



Board



Underfill

Solder mask

Die

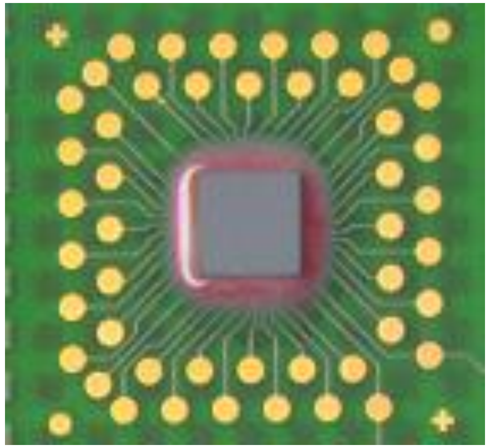
Non-Reworkable Underfill

Fundamentals of Encapsulation and sealing

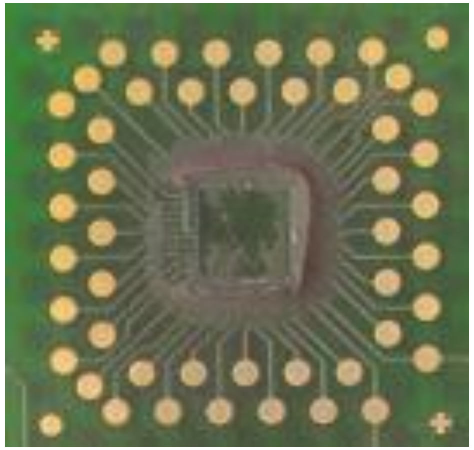
Reworkable Underfill Technology (Cont'd)

Rework Test

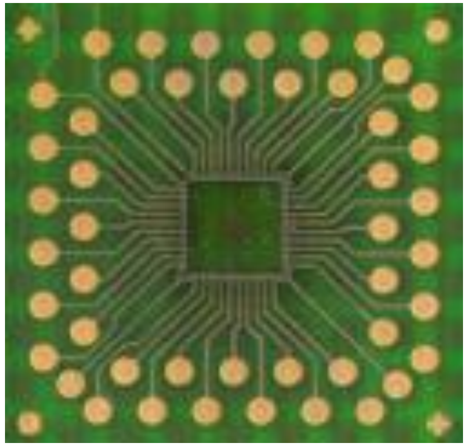
Board Site



Before rework



After die removal



After underfill residue removal

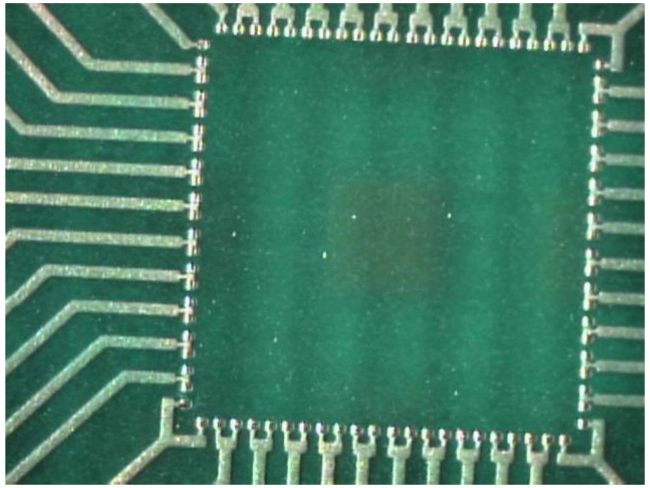
Reworkable Underfill

Fundamentals of Encapsulation and Sealing

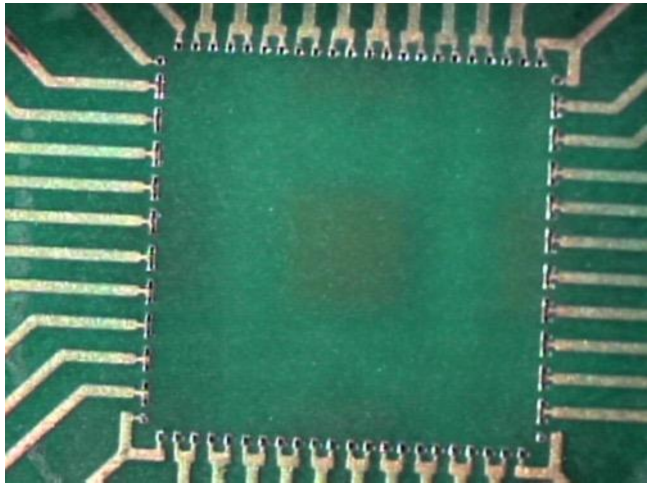
Reworkable Underfill Technology (Cont’d)

Rework Test

Bond Pads



Before rework

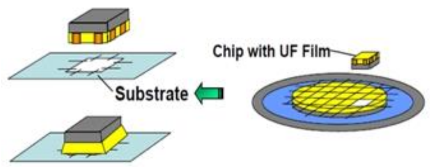


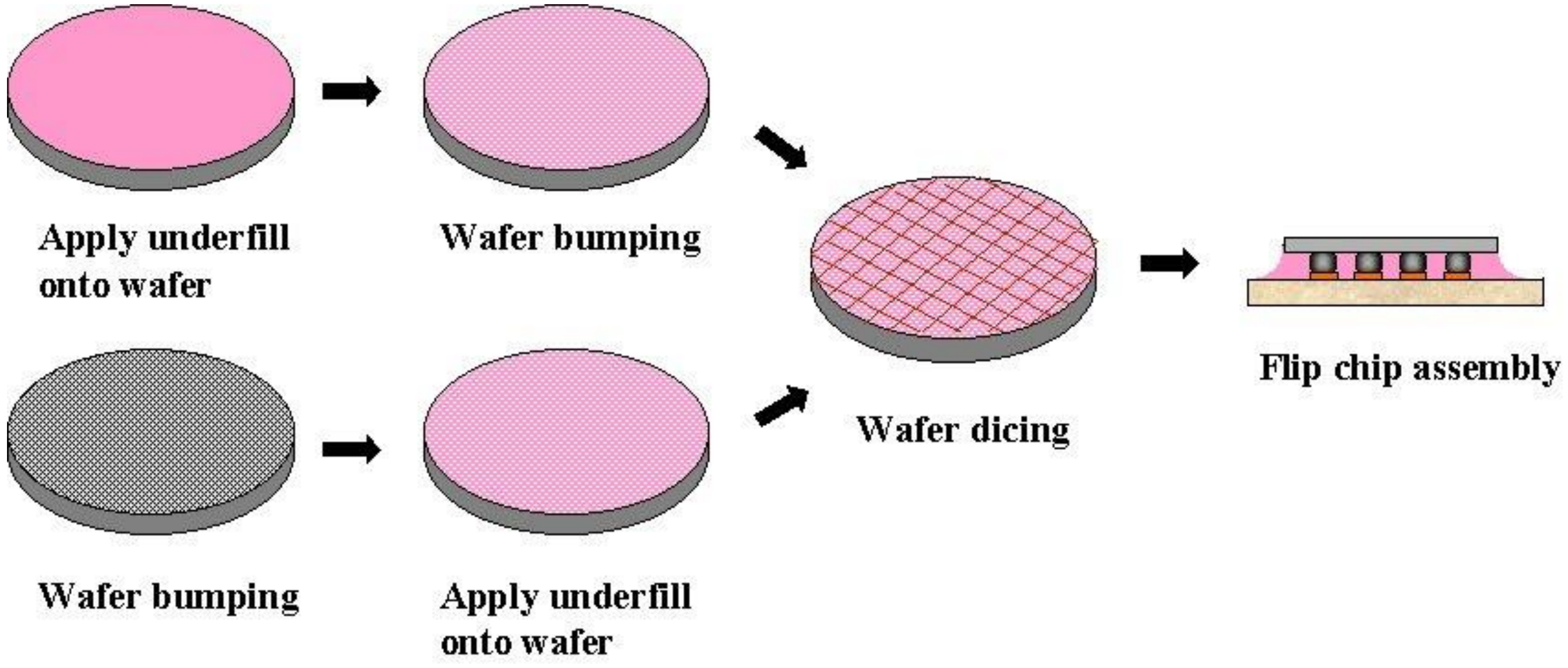
After rework

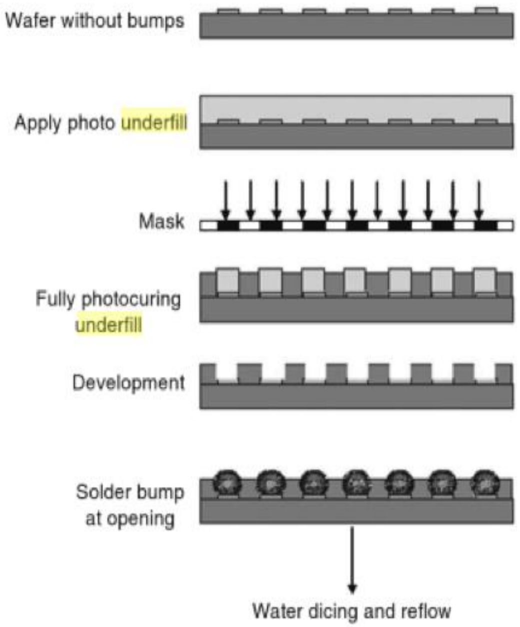
Reworkable Underfill

Fundamentals of Encapsulation and Sealing

Wafer Level Underfill







Key material property; B-staged No Flow Underfill
<u>(Patented by GT in 2002)</u>

Pre-applied UF and bumping

Wafer Level Underfill Technology

Underfill is applied onto the wafer before it is diced.

Advantages:

- Simplification process
- Burn-in and test at wafer level
- Reduction of cost, higher yields
- True SMT transparency of flip-chip

Molded Underfill Technology

Conventional underfilling process

Molding process

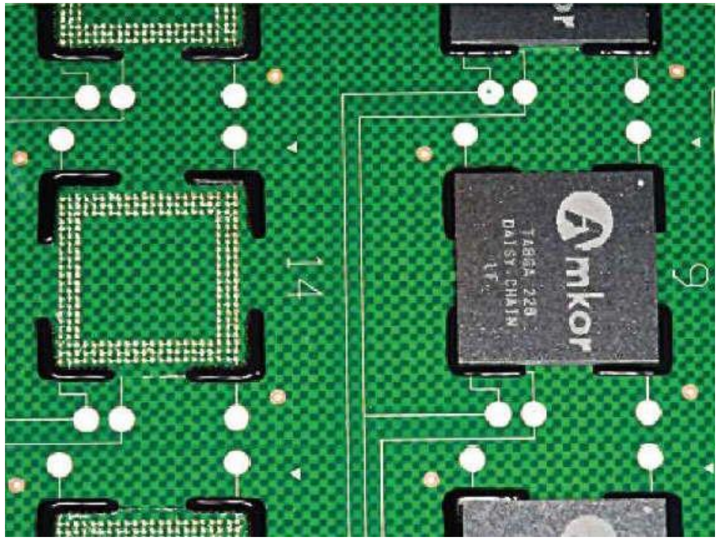
Molded Underfill Technology (Cont'd)

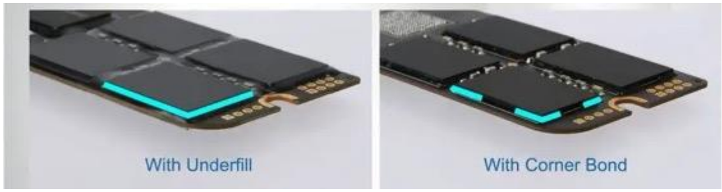
Advantages:

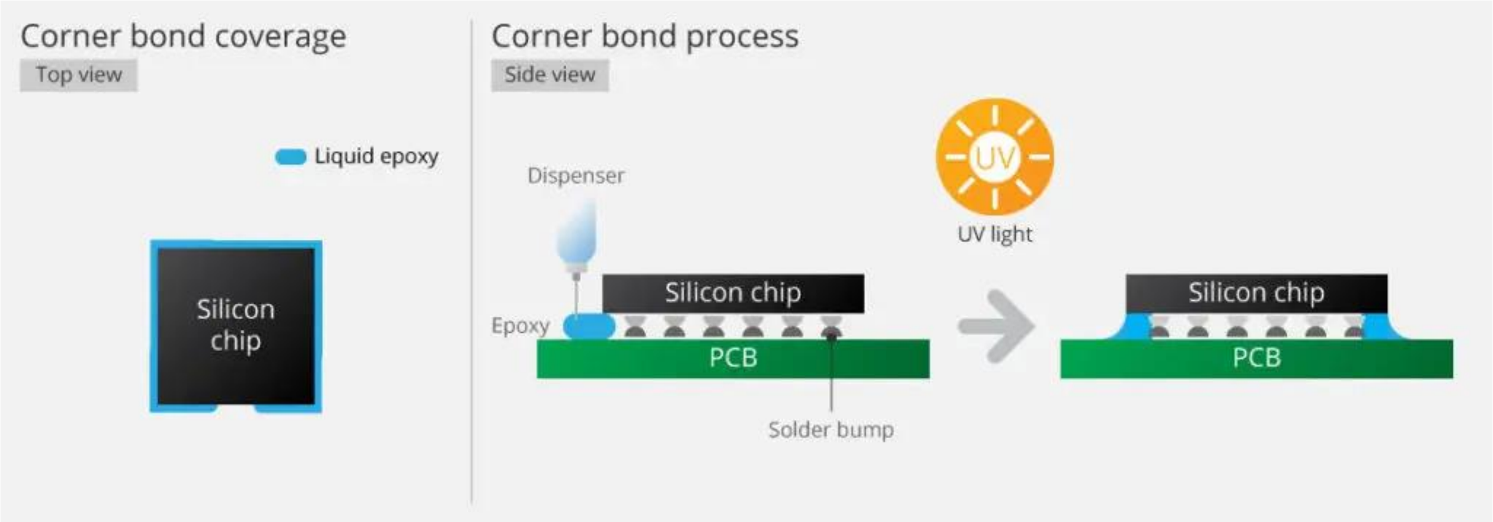
- Replacing underfilling with transfer molding – high throughput
- Based on Epoxy Molding Compound – long pot-life, high reliability
- Extendable to wafer form – low cost

Applications:

Flip-chip in packages (BGA, CSP)
Evolving into FOWLP

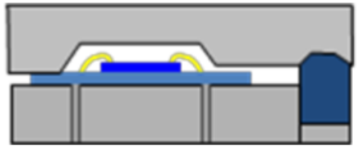
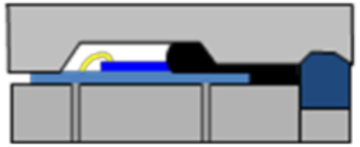
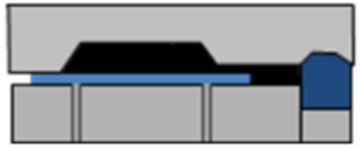


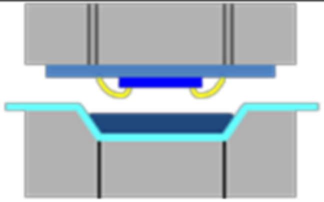
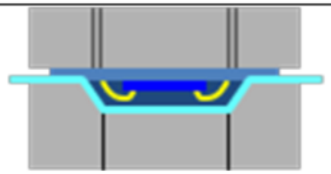

With Underfill
With Corner Bond


Corner bond coverage
Top view
Liquid epoxy
Silicon chip
Corner bond process
Side view
Dispenser
UV
UV light
Silicon chip
Epoxy
PCB
Solder bump
Silicon chip
PCB

Fundamentals of Encapsulation and sealing

Transfer/Compression molding

Step 1: Pellet loading and clamp	
Step 2: mold transfer (plunger up)	
Step 3: filling up	

Step 1: Mold compound measurement	
Step 2: Clamping substrate and putting EMC in tray recipient	
Step 3: Chase clamping and cavity air evacuation (vacuum)	
Step 4: Shutting chase and pressure	

Not much flowing as in transfer molding

108

Board level Encapsulant

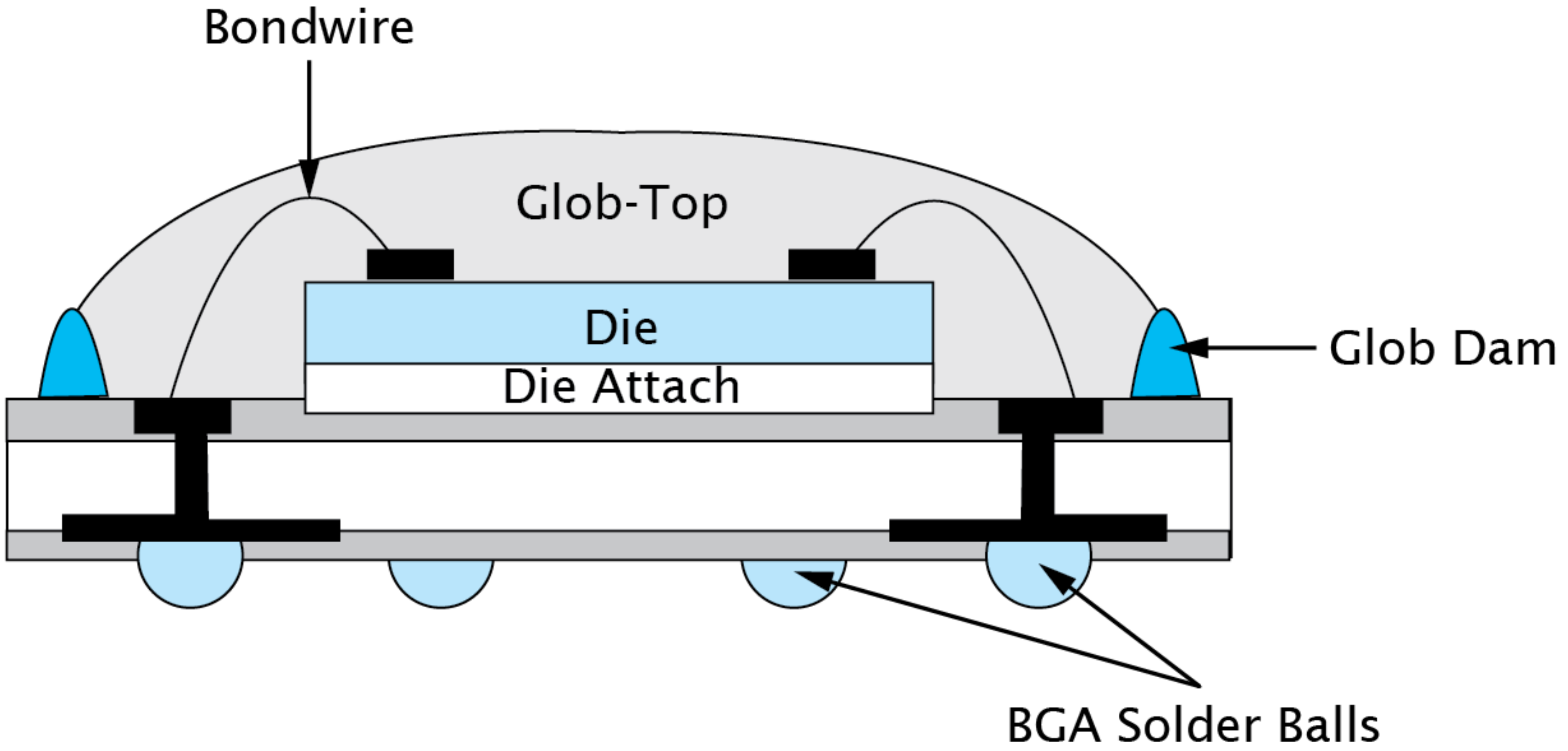
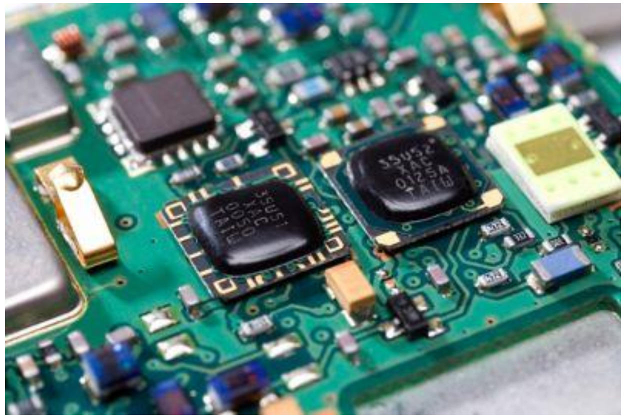
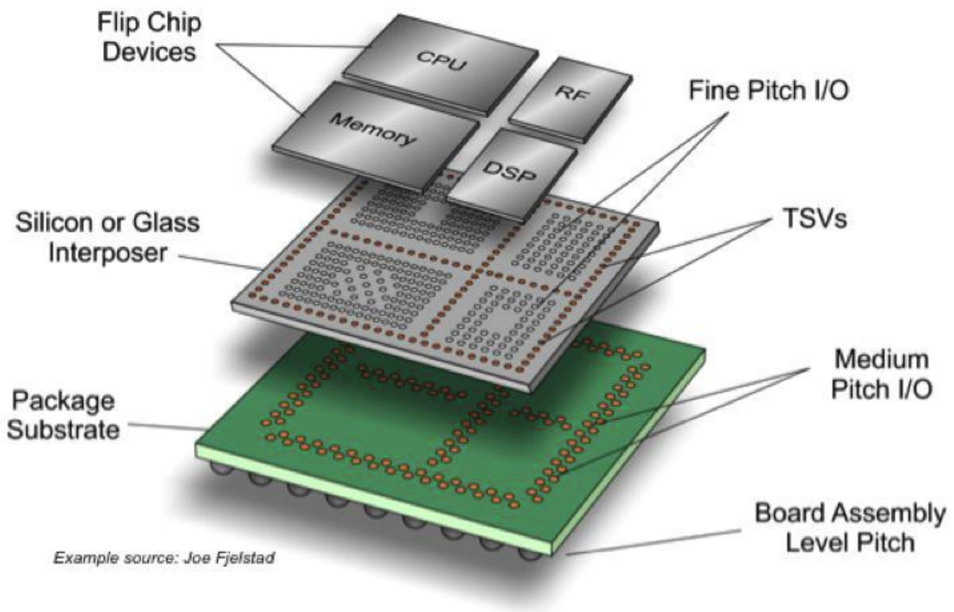
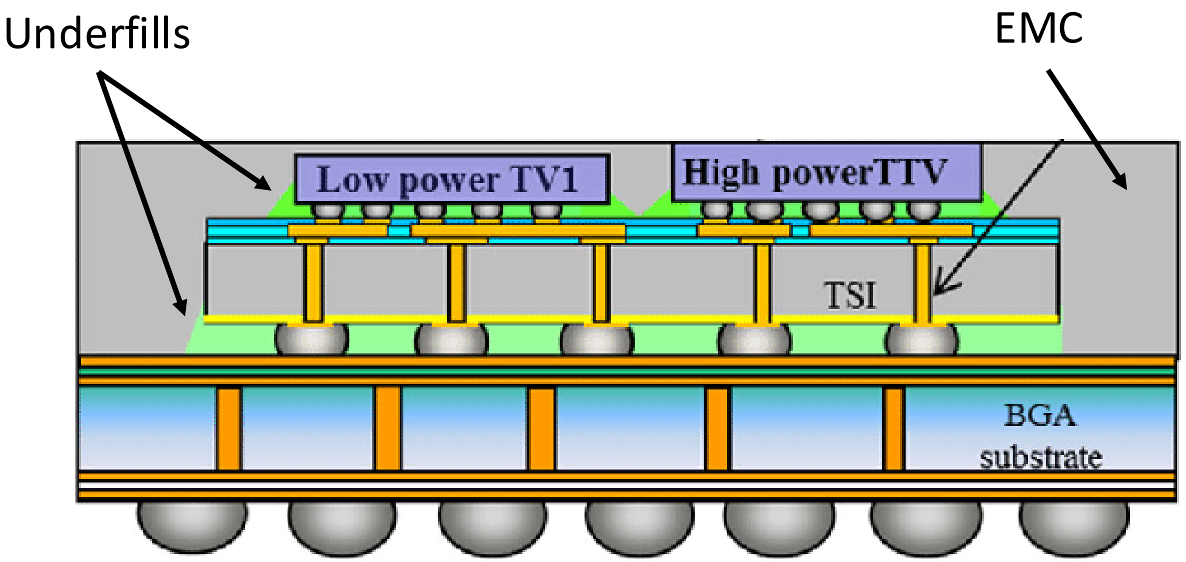


Fig 14.14 - Glob topping a BGA device



Encapsulant Materials used in the state of the art 2.5D/3D Advanced Packaging Solutions

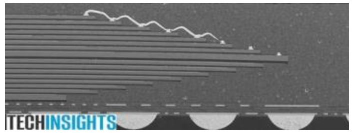




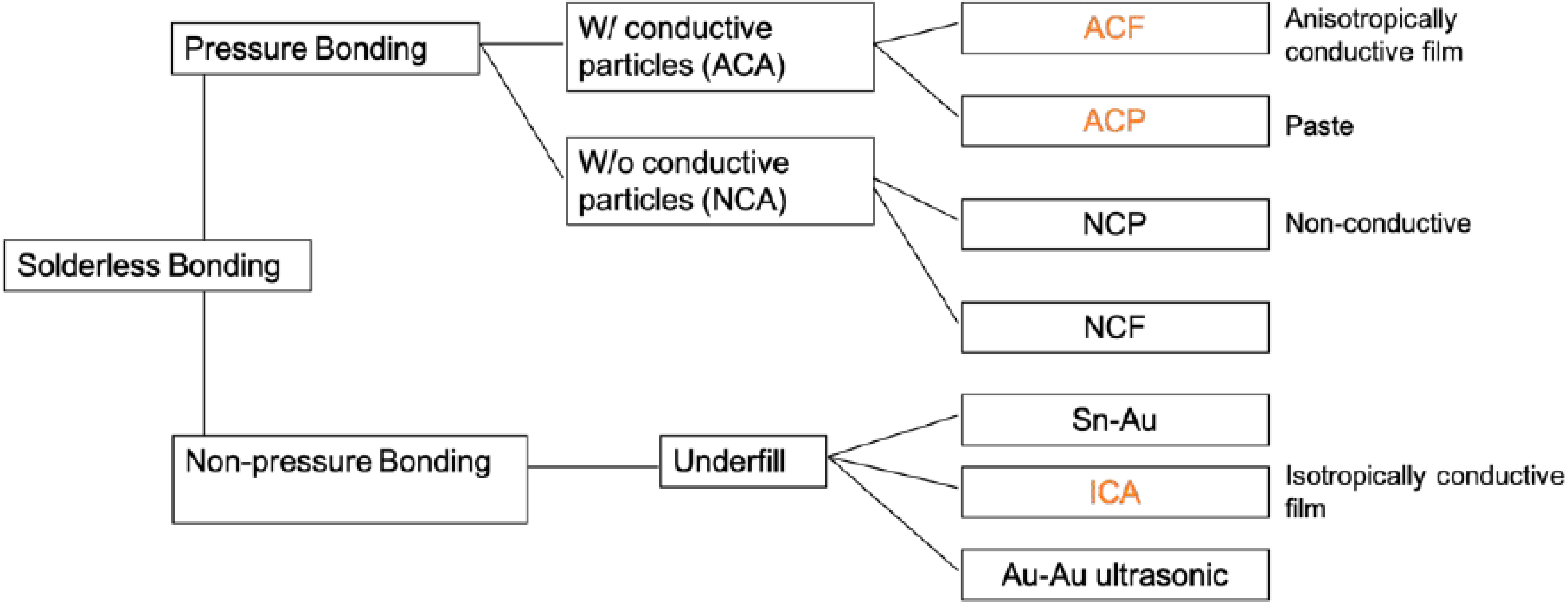
General elements of a 2.5D package (Illustration courtesy of Joseph Fjelstad)

Encapsulation/sealing materials with specific functionality

- Underfill capability with electrical interconnections
- EMC/gloptop for EMI solution
- Encapsulation with electrostatic discharge (ESD) acting like a varistor
- EMC for High thermal conductivity
- Lid bonding materials, fuel tank sealants for ESD
- Die attach film (DAF); 3D die stacking

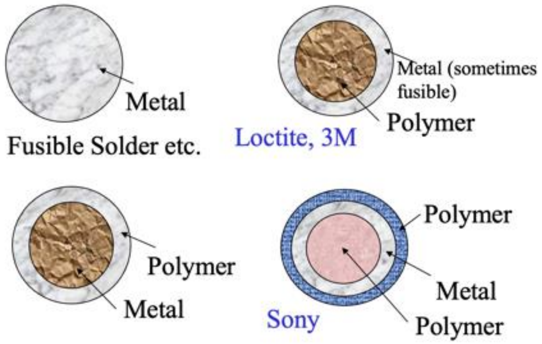


Encapsulation with electrical interconnection



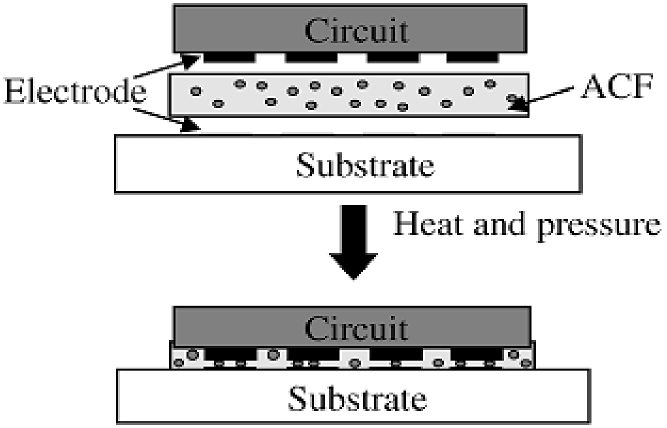
Fundamentals of Encapsulation and sealing

ACF/P and NCF/P → Electrical and Mechanical bonding → UF function



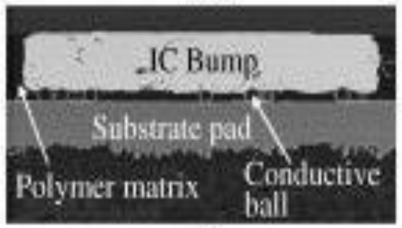
- High Tg, aromatic polymers (polydivinulbenzene, melamin, etc.)

Below percolation of fillers



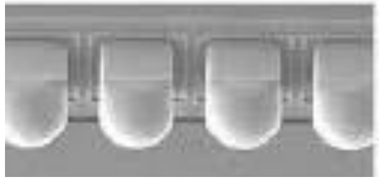
gure 10. Thermo-compression bonding using an ACF.

ACF

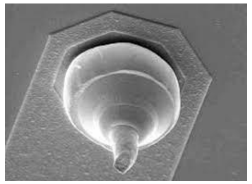


Cu

SnAg-cap

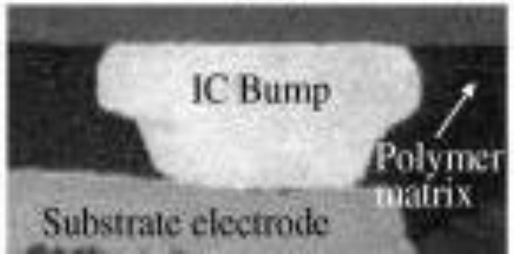


μ-bump



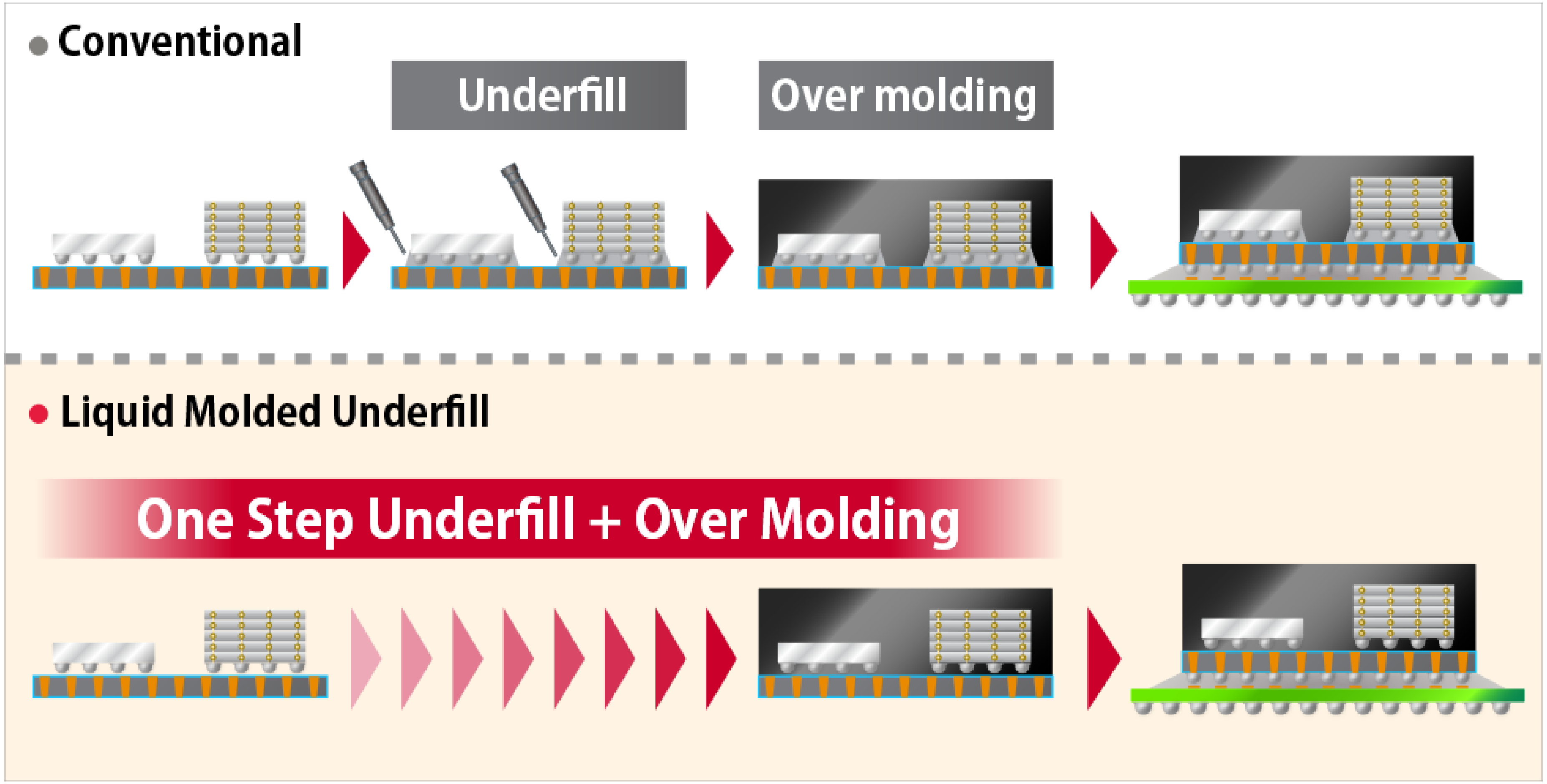
Stud bump

NCP



- For fine pitch COG/COF (glass/flex)
- Thermocompression bonding (TCB); pressure and temperature/ultrasound

Liquid UF for 2.5D/SiP

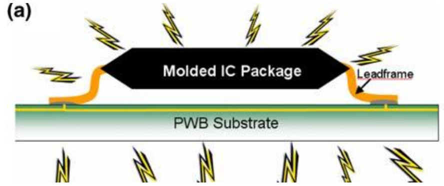


Source; Panasonic

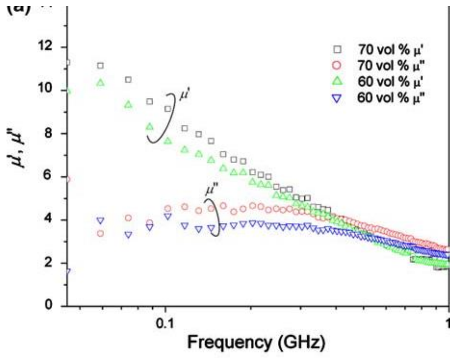
Fundamentals of Encapsulation and sealing

Gloptop for EMI suppressor

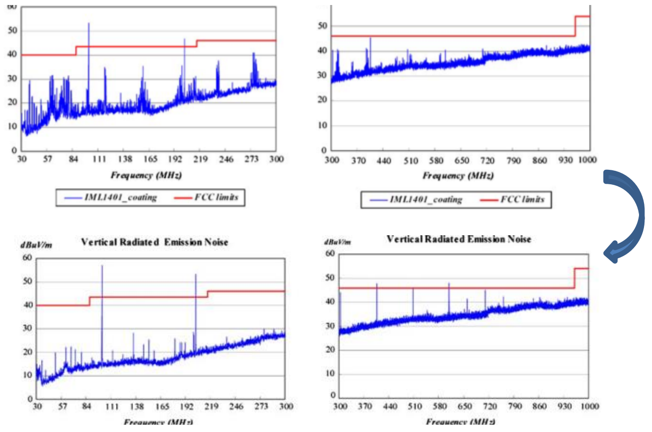
- Objectives: Enhancing electromagnetic compatibility (EMC) of IC packaging
- Approach: Incorporation of soft magnetic fillers (ferrite) into polymers
- Summary: The absorber composite efficiently suppresses MW noise)H-field) in far- and near-field modes.



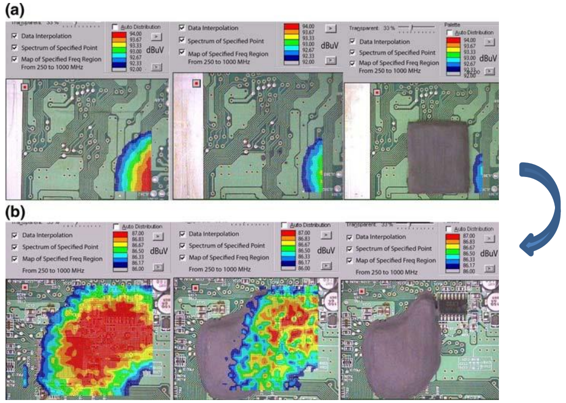
IC Package protection by coating



Magnetic permeability @RF by polymer composite

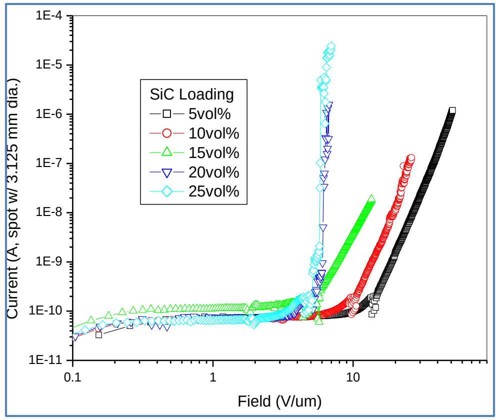


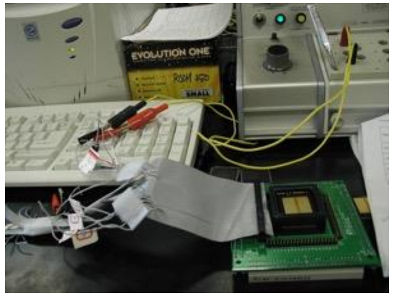
EMI Reduction in near field

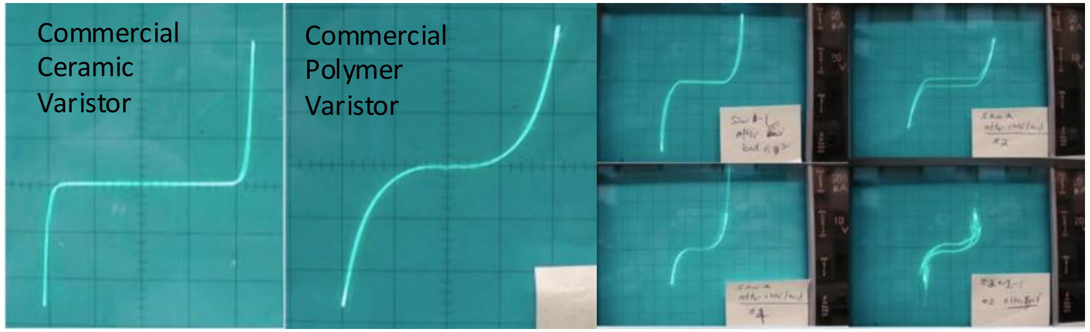


K. Moon, CP Wong, Ferrite Polymer Composite for Improving the Electromagnetic Compatibility of Semiconductor Packaging, J. Electron. Mater. 36 (12), 1711 (2007).

Gloptop as varistor for IC Protection from ESD (Wafer coating), SiC, BC and metal in polymer





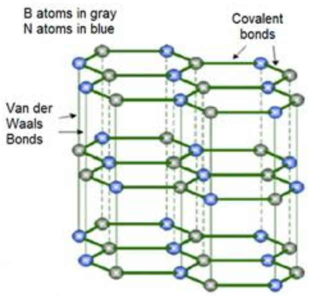


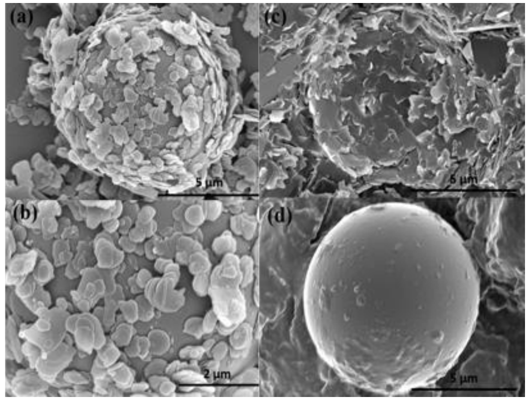
Fundamentals of Encapsulation and sealing

Fillers for High thermal conductivity

- Filler interface chemistry to design molecular couplers to alleviate phonon scattering at interfaces
- High K, low Dk materials

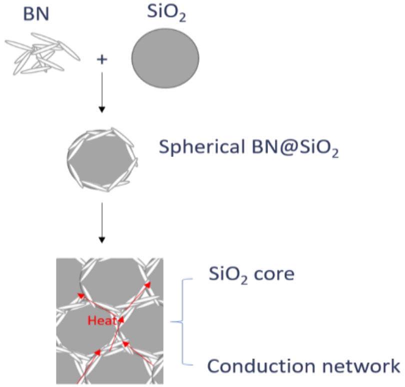
	K(W/mK)	ρ(g/cm³)	CTE (ppm/K)	Dk, 1 MHz, 20C	Cost($/kg)	Comment
Fused SiO_2	1.3	2.2	**0.5**	4.3	**1**	Main filler in EMC
Al_2O_3	30	3.9	8	9.6	5	Conventional for high thermal
AlN	140~180	3.26	4.5	9	40	Irregular shape
h-BN	400 (in plane)	1.9	38(out of plane) -2.72(in plane)	4.4	40-50	2-D shape, hard to mix
SiC	120	3.1	4	10	36	Low Eg
diamond	2000	3.5	0.8	5.7	>1200	Military/aerospace applications
Si_3N_4	10-43	2.4~3.3	1.4-3.7	9.5-10.5		
Epoxy	0.2	1.2	60	4~5	5	





hBN coated SiO_2 (BN@SiO_2)

- Chemical bonding of hBN and SiO_2 via respective functionalization of each
- Enhanced flowability via reduced surface area
- SiO_2 core as co-filler for cost and CTE control
- Phonon conduction path via in-plane hBN

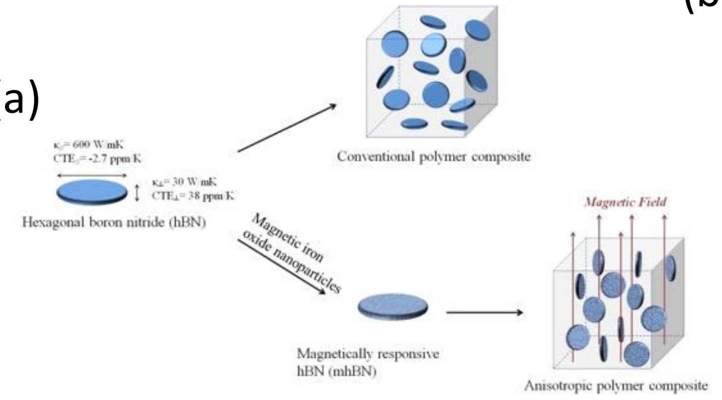


J.Li, K. Moon, CP Wong, et al, *ECTC,* 2020

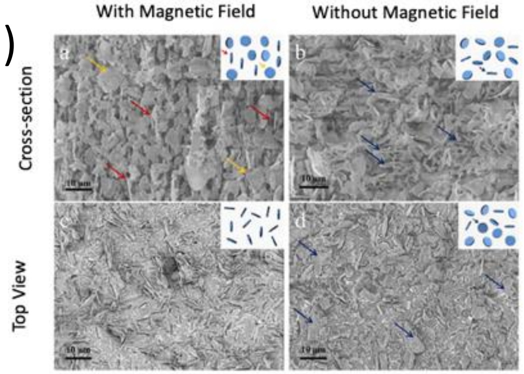
High thermal K Epoxy-cont’d

Magnetic Alignment of h-BN in Polymer Matrix/Underfill

(a)

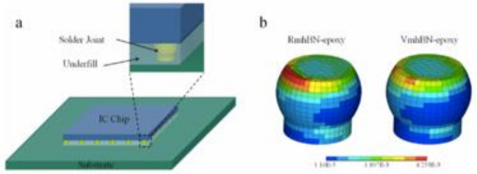


(b)



(c)

Soler joint reliability of anisotropic UF (FEA)



Thermal conductivity

(d)

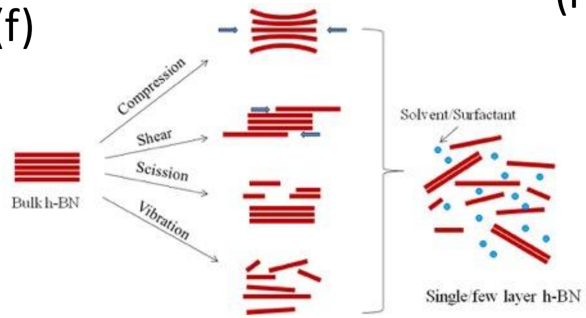
Table 1. Thermal Conductivity Enhancement ($\kappa_{composite}/\kappa_{resin}$) of Various BN−Polymer Composites

materials	filler size (μm)	loading (wt %)	thermal conductivity enhancement
hBN−epoxy[6]	12	20	~3
	60−100	20	~5.6
hBN−polyimide[10]	1 and 0.07	20	~1.5
hBN−photosensitive polyimide[11]	0.07	20	~1.5
hBN−polyimide[15]	0.7	~40	~6.8
hBN−epoxy (this work)	5	20	5.7 (VmhBN−epoxy) 2.8 (RmhBN−epoxy)

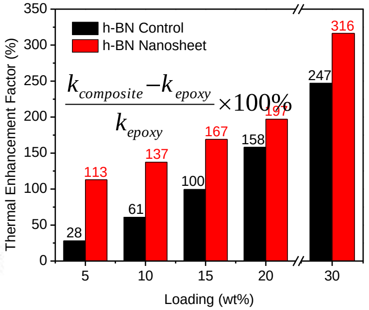
Z Lin, Y Liu, S Raghavan, K Moon, SK Sitaraman, C Wong ACS applied materials & interfaces 5 (15), 7633-7640, 2013.

h-BN exfoliated nanosheets in epoxy

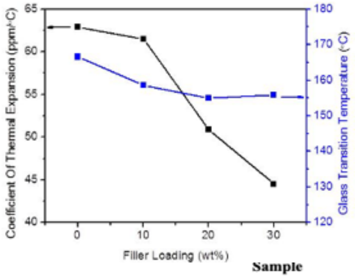
(f)



(h)

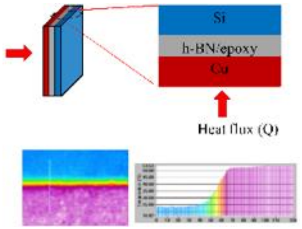


(i)



Thermal resistance between Cu and Si

(j)



(h)

Sample	Thickness (μm)	Power (Wcm⁻²)	Temperature drop (°C)	Thermal Resistance (cm²K/W)
Neat Epoxy	~ 75	15.4	65.8	4.27
5 wt% h-BN nanosheets	~ 75	15.7	29.4	1.87
10 wt% h-BN nanosheets	~ 75	15.7	26.9	1.63
20 wt% h-BNnanosheets	~ 75	15.7	21.3	1.26
30 wt% h-BN nanosheets	~ 75	19.7	19.8	0.96

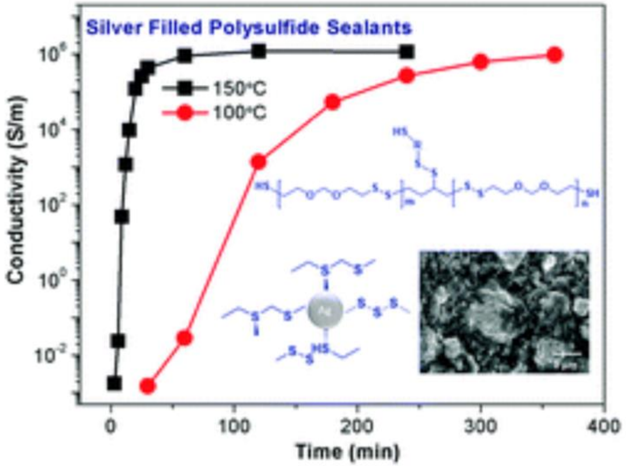
2×

4×

Z. Lin, K Moon, CP Wong, Composites Science and Technology 90, 123-128, 2014.

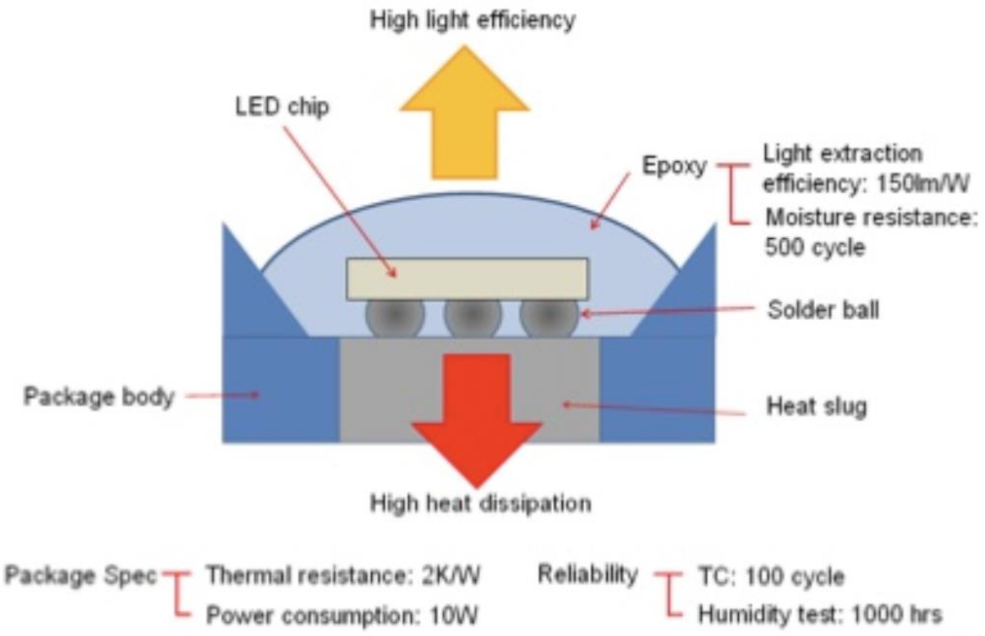
Polysulfide sealants

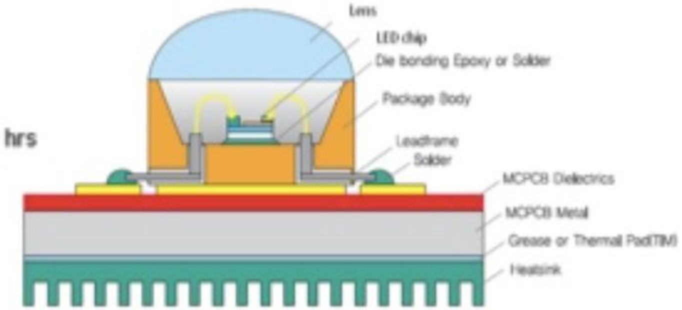
- PS containing ~37% sulfur content demonstrates exceptional resistance to gasoline, fuels, and aviation gas, superior to epoxy, polyurethane, and polyacrylates
- To dissipate static charges
- Unique filler–resin interactions caused low electrical conductivity



https://doi.org/10.1039/C8SM02004C
Processing and characterization of silver-filled conductive polysulfide sealants for aerospace applications

HB-LED encapsulant for light extraction





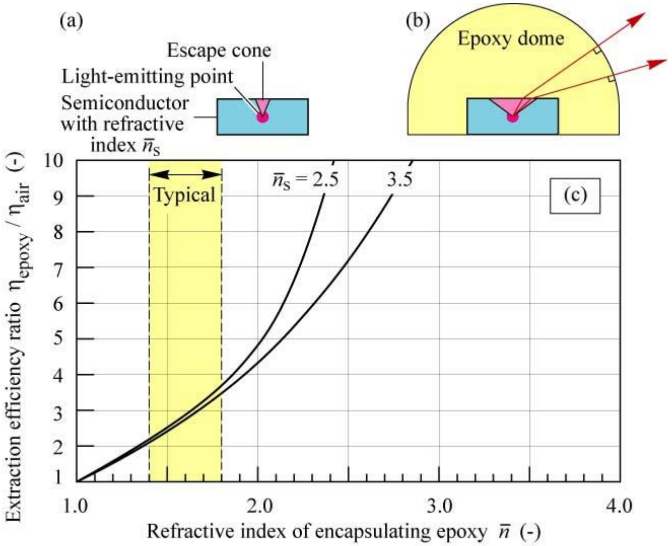
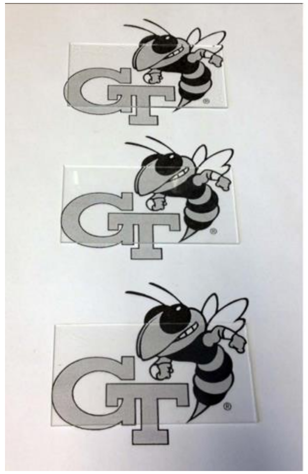


Fig. 5.6. (a) LED without and (b) with dome-shaped epoxy encapsulant. A larger escape angle is obtained for the LED with an epoxy dome. (c) Calculated ratio of light extraction efficiency emitted through the top surface of a planar LED with and without an epoxy dome. The refractive indices of typical epoxies range between 1.4 and 1.8 (adopted from Nuese *et al.*, 1969).

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org



Silicone coated sample

1% TiO_2 nanocomposites coated sample

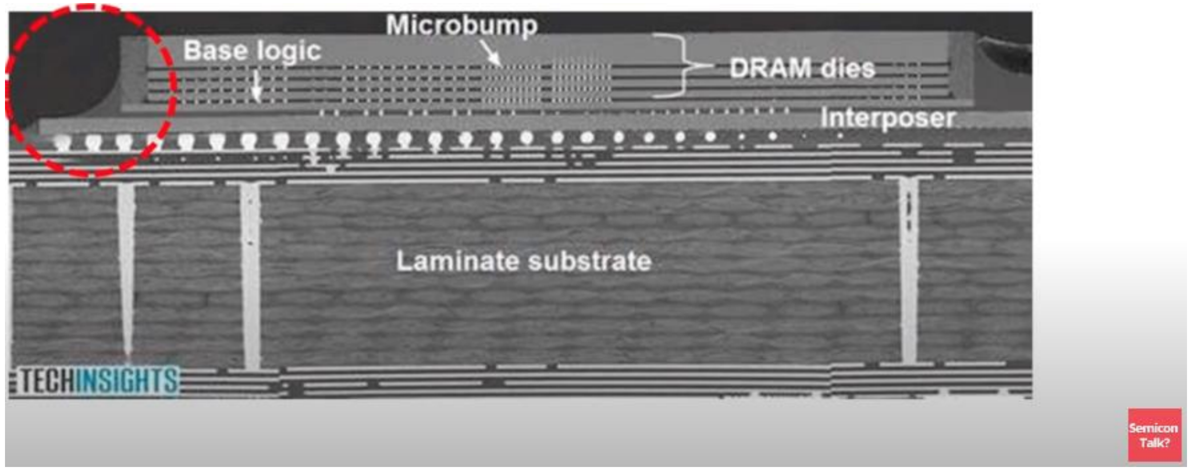
5% TiO_2 nanocomposites coated sample

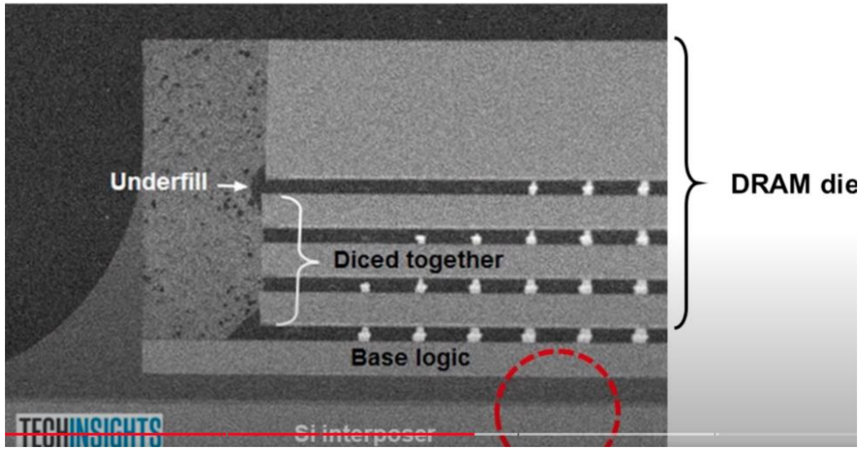
https://shorturl.at/jpDO9

High Refractive Index and Transparent Nanocomposites as Encapsulant for High Brightness LED Packaging

Fundamentals of Encapsulation and sealing

Encapsulation in HBM-SiP

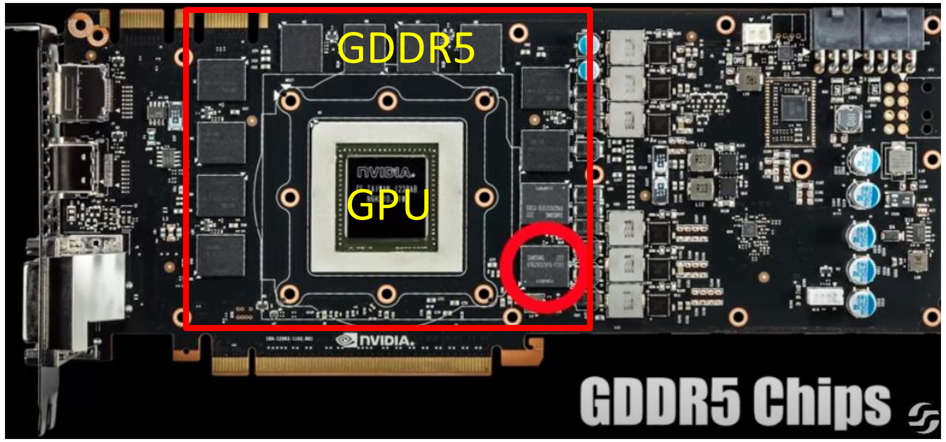




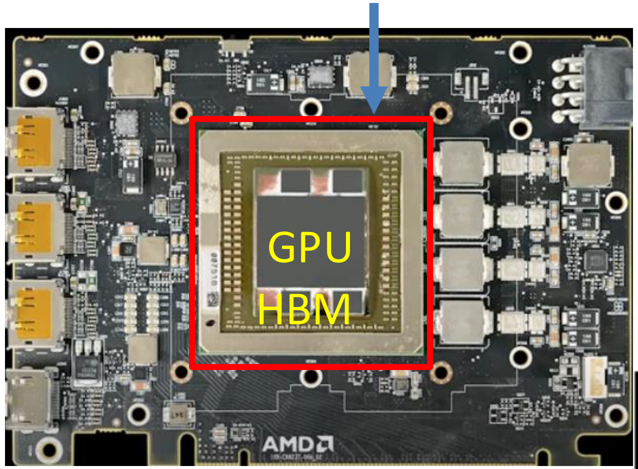
- In die stacking;
  - Materials; DAF, NCP and UF
  - Assembly; thermocompression bonding (TCB)

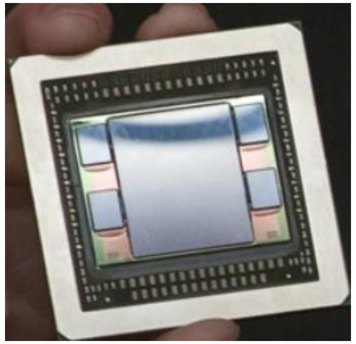
GDDR vs HBM-SiP

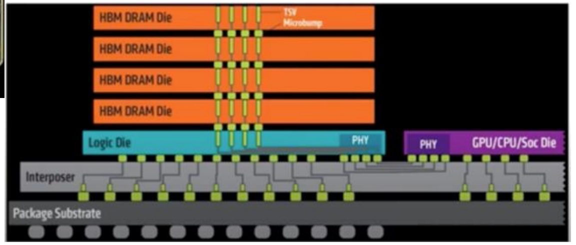
- Graphic DDR (video memory); separate packages between GPU and DDRs
- High Band Width; unified package into SiP



SiP



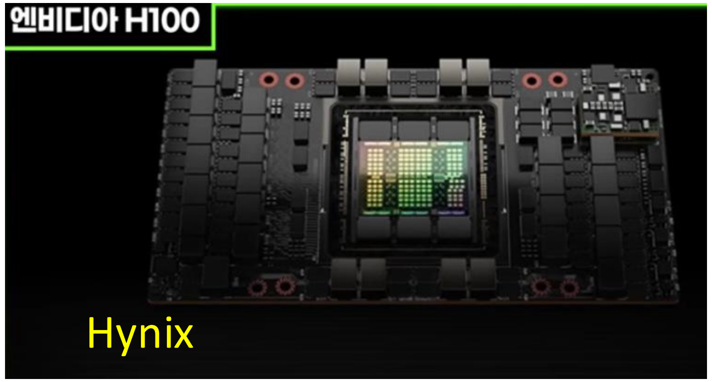


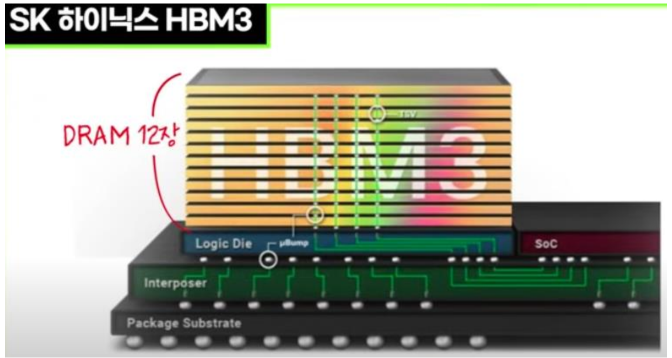


GDDR6 vs HBM

	GDDR6	HBM3
대역폭	64GB/s	819.2GB/s
핀 수	32개	1024개
용량	2GB	24GB
속도(핀 당)	16GB/s	6.4GB/s

Samsung HBM3 found in servers ; Aurora, ElCapitan

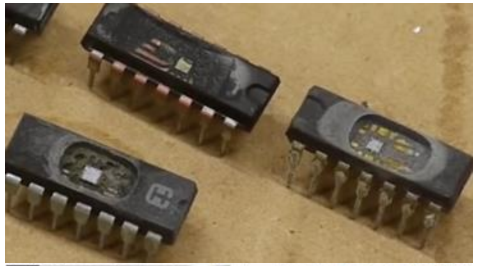


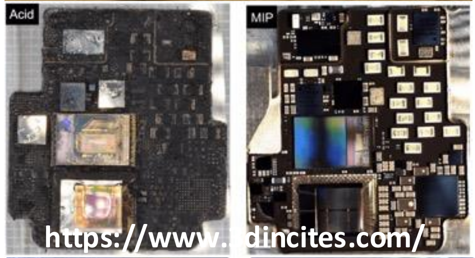


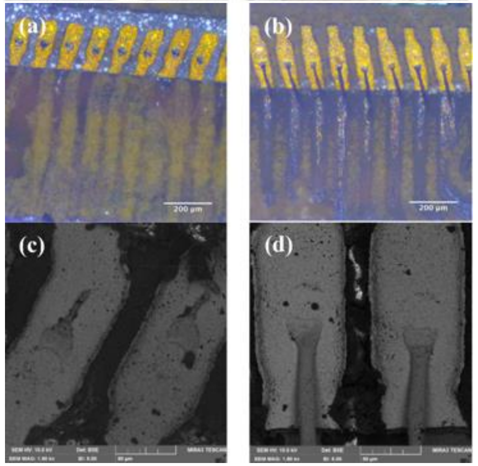
Speed; Intentionally reduced for mitigating thermal and power issues

Decapsulation/Rework

- Decapsulation
  - Failure analyses (to remove encapsulants-top mold, overmold, fillets)
  - Chemical; acids (concentrated/fuming nitric, sulfuric acids, etc), to selectively etching (Al, Cu, Ag, etc.)
  - Physical; laser ablation, CF4-RIE, Plasma (microwave induced), etc.
- Rework
  - Reworkable underfills
    - Process development/optimization
    - Expensive substrates







Kim, Moon, et al., IEEE Trans. CPMT, **9**(8), Aug. 2019.

Summary

- Early days for microelectronics packaging dominated by Hermetic sealing at device level by inorganic thin-films such as silicon oxide and nitride and at package level by metal packages
- Early polymers were incapable of dealing with moisture, thermomechanical properties (CTE, modulus), adhesion, impurity level etc.
- Evolution of Resin chemistry, filler loading technologies and interface engineering enabled near hermetic plastic packaging to meet the requirements for device and system level applications.
- Consequently, polymer encapsulation or molded packaging has established itself as the primary high-volume and low-cost approach and is expected to continue to grow across all but highly reliable space, deep sea, and high-temperature automotive applications.
- Demands on high performance and versatility from polymer encapsulants/sealants and one of key components to enable advanced packaging
  - High temperature sustaining (>250C)
  - High thermal dissipation
  - Tunable electric/dielectric/magnetic properties