What is encapsulation and What is Sealing, Encapsulation Requirements, Encapsulation Materials, Encapsulation Processes, Hermetic Sealing
Introduction

- Sealing and Encapsulation are two major protecting functions of IC packaging
- Used to protect IC from environment and mechanical defects
- This chapter is all about the understanding of encapsulation and sealing processes used in IC packaging
What is Encapsulation and What is Sealing?

- Encapsulation protect device packages by isolating the active devices from environmental pollutants (chemical protection), and at the same time offering mechanical protection.
- Encapsulation is also known as organic (ex. plastic) overcoat as shown in Figure (b). It’s inexpensive, but protection is not permanent, typically controlled by permeation properties of the polymeric resin used.
- Inorganic is called sealing as shown in Figure (a), is a permanent by being hermetic, but the process cost is expensive.
What is Encapsulation? and What is Sealing?

• Performance of encapsulation is dependent to **dimensional stability**, resistance to **thermal excursion**, **permeation from environment pollutants** and **thermal dissipation** from heat generated by the package devices.
Why is Encapsulation Necessary?

Encapsulation provides both mechanical protection of the IC ⇒ reasonable life expectancy can be achieved across various field conditions.

1 : Chemical Protection

1. Protecting from environmental pollutants by encapsulation, constitutes a robust packaging practice.
2. Corrosive ingredient, such as salts and other biological secretions ⇒ among the harmful components present in the field.
   Example
   i. Sodium (Na) can diffuse rapidly to the device junction, pick up the electron and ruin the device.
   ii. Chloride (Cl) ions under bias will accelerate the corrosion of the aluminum metallization
3. Moisture and other atmospheric pollutants, are the key factors that seriously degrade the electronic product’s service life.
Chemical Protection

Protection from Biological Organisms.
- Insects can be attracted by the electric field generated by a functioning electronic device.
- Corrosive secretion and droppings left within the switching boxes could cause damage.
- Frequency dependence studies have revealed that insects are more responsive to electric fields generated at higher frequency.

Protection from Atmospheric Contaminants.
- Corrosive gases present in air as by-products from fossil fuel burning (e.g. nitrogen oxide (NO$_x$) and sulfur dioxide (SO$_2$)) is harmful to electronic devices.
- These gases form corrosive acids when reacting with moisture in the air.
- Acid rain can reach a pH as low as 5 in the presence of these oxides, and will become extremely corrosive to all exposed devices, significantly reducing their effective service.
Chemical Protection

Protection from Salts
- Ionic contaminants such as sodium, potassium and chloride affects the reliability
- Presence of salts, corrosion of the IC metallization is accelerated.
- Sources of salts can be biogenic (e.g. sweat) or abiogen (e.g. from sea water or dicing operation)
- Most IC conductors are submicron in line widths and micrometer or less in pitch, very small amounts of localized corrosion are all that is necessary to produce an open circuit or change the electrical characteristics of the device sufficiently (noise or error in signal)
- Critical factors in determining the accelerated corrosion
  1. Coating thickness of the encapsulant
  2. pH solution of exposed device
  3. Applied device voltage
Chemical Protection

Protection from Moisture

- Moisture is a major contributor to packaging failures in electronic products, degrading their performance and reliability.
- Rapid water desorption from polymeric packaging during board level assembly is a major cause of delamination (pop corning effect in SMT) between device surface and plastic molded cases.
- The vapor pressure build-up within the packages sometimes lead to cracks the plastic cases.
- There are needs to use of dry packing method by IC manufacturers and moisture bake-out by system manufacturers just prior to board assembly.
- Moisture attacks both the uncured and cured epoxy material, degrading the intrinsic mechanical properties that are designed to protect the electronic packages.
Moisture can be relatively easily absorbed into plastic molded components. However, when these components go through the solder reflow process, the absorbed moisture vaporizes, and it generates an enormous pressure as to crack the components.
2. Mechanical Protection

- Mechanical protection is a second important protective function that an encapsulate can offer to electronic package.
- Interconnect only provides very minimum structural integrity due to wire bond can be as fine as 25 µm and bumps as small as 50 µm in diameters
- Mechanical protection is achieved in two ways.
  i. Prevention of mechanical damage by the use of encapsulation over IC
  ii. Minimization of strain in the solder joined by underfill between IC and package substrate
- With encapsulation, these fine structures are more robust.
Fundamentals of Encapsulation and Sealing

Hermetic versus Non-Hermetic Sealing

- Products normally were designed to be cost-effectively whereas decision are made based on consideration of cost of manufacture, production volume expected use environment or market and expected volume going into various markets.
- Hermetic versus non-hermetic can be seen as compromise between cost and performance (performance include reliability as well as other consideration)
- **Hermetic** – defined as one that prevents the diffusion of helium below a leak rate of $10^{-8}$ cm$^3$/s.

- Non-hermetic – has a leaking rate higher than hermetic.
Permeability of Water Through Organic (Non-hermetic) and Inorganic (Hermetic) Materials

Hermetic is inorganic, non-hermetic are not.
Hermetic starts with glasses and continues on to metals.
Polymer and gases as illustrated on the left side are non-hermetic.
Hermetic versus Non-Hermetic Sealing

- In early day- hermetic sealed metal cases were used to protect sensitive chips from environmental stresses.
- Moisture related problems prompted the military and aerospace industries to require hermetic packages in order to achieve their long-term reliability.
- Hermetic packages utilize a sealed environment that is impervious to gases and moisture to protect the devices.
- Final sealing in hermetic is accomplished with caps or lids using glass or metal seals.
- Hermetic packaging proved to be a robust method of achieving long field life.
- However due to lower cost, the non-hermetic plastic molded packaging is more popular especially for electronics destined for commercial and industrial market.
- Non-hermetic does not imply non-reliability, plastic packages are not hermetic, yet demonstrate acceptable reliability and now account for approximately 90-95% of all device packages.
- Furthermore, hermetic packages have higher dielectric constant, which results in a slower signal speed.
Fundamentals of Encapsulation and Sealing

Moisture Absorption of Encapsulants

- Moisture can also have deleterious effects on the long-term adhesion between organic materials and the substrate being protected.
- Moisture acts as a debonding agent through a combination of the following mechanisms:
  i. The moisture reacted metal surface can form a weak, hydrated oxide surface
  ii. Moisture-assisted chemical bond breakdown
  iii. Moisture-related chemical degradation or depolymerization
- Organic materials are not hermetic and allow moisture to penetrate and absorbed
- Permeation rates and moisture absorption characteristics varies across organic materials.
- In plastic packaging’s infancy, corrosion was found to be the primary cause of failure, due to poor adhesion and high levels of mobile ions contaminants in the materials. Moisture and mobile ions were identified as major contributor to corrosion, among other failure mechanisms.
Moisture Absorption of Encapsulants

- Improvement in plastic packaging materials and processes against corrosion lead to reliability that approaches the hermetic packages in preventing the ingress (right to enter) and engress (right to leave) of moisture at the package perimeter during its operating life, thus achieving excellent long-term reliability.

- The word hermetic is defined as completely sealed by fusion (taupan), solder and so on, so as to keep air, moisture or gas from getting in or out or other word air tight. In hermetic practise such seal are non-existent.

- In practice, hermetic sealing still allow a small gas molecules that typically enter the package over the time through diffusion and permeation. However, long life can still be obtained in the field because of slow nature of this activity.
Organic Came a Long Way

- Traditional plastic molded package and polymer encapsulated circuit have problems due to initial high purity polymer material’s availability for encapsulation.
- The inability of early polymers to sufficiently retard the deleterious effects of moisture, led to poor performance, both in accelerated testing and in the field.
- Inadequate adhesion, contaminants within the material itself, incompatible thermal expansion, and resultant stress related problems and a relatively immature knowledge in filler technology prevent acceptance of plastic packaging.
- With significant efforts in the areas of resins, fillers, material formulation and process development work, polymer packaging finally began to make its presence in 1970s.
- Continuing significant progress was also made in the improving the quality of the glass passivation layer over the active areas of the device, as a first line of defense against moisture related problem; these technological acted as the fundamental base that was needed for polymer packaging to be accepted, ultimately to its widespread use.
Organic Came a Long Way

- At early stage of plastic packaging, many failure modes were identified and material concerns were addressed which resulted in different polymers and polymer formulation that closely matched the application requirements.
- This lead to recent acceptance of plastic packages as approaching the reliability of hermetic packages in many applications and environment.
- Today, plastic molded package are the most dominant method use in commercial and industrial grade electronics, was estimated 90% of all integrated circuits are marketed in this form.
Fundamentals of Encapsulation and Sealing

Adhesion is Very Critical
- Good interfacial adhesion between polymers and packages is important.
- Corrosion protection and adhesion properties are closely linked, and long term reliability requires long term adhesion.

Accelerated Testing Helps to Select the Right Material
- Temperature cycling does not test the corrosion-resistant properties of the package and polymer system, but it test the assembly to endure the stresses imparted by the various materials that make up the device (interconnect and polymer encapsulation)
- New criteria of accelerated test for plastic components to that meet the military application (MIL-STD-883)
  1. Thermal shock: test method -65°C to 150°C; cycle time 10s; dwell time 5 min at each extreme 1000 cycles
  2. Salt spraying time : 24, 48, 96, 240 hours: salt concentration 0.5 -3% (NaCl) pH = 6.0 -7.5, 95°F; deposition rate 10,000-50,000 mg/m² for 24 hours at 35°C
  3. Autoclave : 121°C, 100% relative humidity (RH), 30psi (2 atm), with or without bias (pressure root)
Encapsulation Requirements

1. Encapsulants must have the required **mechanical, thermal and chemical** properties.

2. **Flow and adhesion** are the two primary physical properties that any encapsulants should be optimized to perform.

3. **Tg of the material must be outside of reliability testing window** (-65 to 150°C) for robust encapsulated package.

4. **Good material properties** (elongation break, elastic modulus and low moisture absorption) **is achievable with a mixture of epoxy and filler**. Single epoxy does not present these properties.
Encapsulation Requirements

**Mechanical**
- Good encapsulant should be its good stress-strain behavior.
- Graph shows of two encapsulant materials.
- Material A fails at low strain and has low toughness, and it not acceptable material.
- Material B, on the other hand is ideal.

Stress Strain Curves of Good (Material B) and Bad (Material A) Encapsulation Materials
Encapsulation Requirements

Thermomechanical considerations
• Ideal case, CTE of molding compound should be close to Si (2.6 ppm/°C) as possible and CTE of underfill should be as close to the solder bump (25 ppm/°C).
• These properties ensure low stress between chip and underfill as well as between solder and underfill.

Residual Stress
• Most resin systems used in encapsulation develop various degrees of residual stress after cure
• Two major residual stress
  1. Shrinkage of resin-about 3-6% by volume after curing, this produce residual stress ~20MPa after cure.
  2. Thermomechanical loading due to mismatch of CTEs of constituent material between cure temperature and storage (room) temperature.
  3. It can estimated

\[
\sigma = \int_{25}^{T_g} E (\alpha_e - \alpha_s) dT
\]

\[\sigma = \text{epoxy film stress; } E \text{ – elastic modulus of the epoxy; } k = \text{constant; } (\alpha_e - \alpha_s)\]
difference in CTEs between epoxy and substrate
Encapsulation Requirements

**Thermal properties**
Requirements for CTE vary significantly with the type of encapsulants in need. Resin’s CTE is about 50-80 ppm/°C and required additional filler to lower the CTEs. The lower the CTE the better, but CTE is normally controlled by how much silica filler (CTE ~ 0.5 ppm/°C) can be formulated into the resin without compromising flow and adhesion during molding.
**Encapsulation Requirements**

**Flow During Encapsulation**
- The initial form of molding is in solid preform.
- The flow characteristics of the molten compound is very critical in high yield manufacturing process.
- Good wetting to the surface and void-free filling are considered good flow characteristics.
- The time required for an underfill to flow between the die-substrate gap.  
  Underfill time \( \approx \frac{3\eta L^2}{h\gamma \cos \theta} \)

- Underfill flow time point of view – lowest viscosity, highest surface tension and smallest wetting angle.
- Other liquid encapsulants – underfill, cavity fill, glop-top, conformal coating.

\( \eta = \text{viscosity} \quad L = \text{Distance of flow} \quad h = \text{Die –substrate gap} \)
\( \gamma = \text{surface tension} \quad \theta = \text{Wetting angle} \)
Definition of Glass Transition Temperature

**Glass Transition Temperature (Tg)**
Is defined as the temperature at which the transition from solid to liquid phase take place.

Above this temperature, the modulus is low and nearly constant as shown in figure.

Polymers are rigid and brittle below their glass transition temperature and can undergo plastic deformation above it. Tg is usually applicable to amorphous phases and is commonly applicable to glasses and plastics.
Encapsulation Requirements

Physical Properties (Adhesion)

- Is defined as **the measure of the strength between two interfaces**.
- A robust encapsulation provides strong adhesion to the device encapsulate interfaces → so package can withstand under thermal stress.
- Chemical (covalent) and mechanical (van der waals) bonding can be incorporated to achieve a desirable result.
- Example: Use of adhesion promoters in the encapsulant formulations to improve chemical.
- Stages of adhesion failure in electronic packages: Damage initiation, microcrack formation, debonding growth and finally interfacial delamination.
Encapsulation Requirements

Physical Properties (Interfaces)

- Is defined as any physical or chemical layer, often in atomic scale between two materials.
- Interfacial adhesion exists.
  1. Between device hard passivation (silicon dioxide, silicone nitride, silicon oxynitride)
  2. Soft buffer coat (polymide or bezoclyclobutene on top of hard passivation)
  3. Encapsulants.
- Adhesion between encapsulant and bond wire or solder bumps is a secondary concern.
- Interface between solder mask, exposed conductor leads and substrate (FR-4, BT, ceramics) and encapsulating materials all require good adhesion to prevent failure
Encapsulant Materials

The most common encapsulants fall into four generic categories.

1. Epoxy (Anhydride epoxy, Amine epoxy, Phenolic Epoxy)
2. Cyanate ester
3. Silicones
4. Urethane
Encapsulation Processes

Molding
Transfer molding is the major encapsulating processes in the IC packaging. The molding process is similar with chapter 3. Simple mass production and low cost method for most device encapsulate. However, it not suitable for flip chip and cavity fill type PGA (pin-grid array).

Molding is applied by transfer pressure to flow on top or around the die and its first level interconnection. Mold pellet is placed into the transfer pot and it soften at an elevated temperature for a preset time before it is pushed by a plunger. The units are either cured in line or sent for a separate cure oven to achieve the desired mechanical and moisture resistance properties of the mold material.
Liquid Encapsulation

- An effective way to ensure reliability of fine-pitch, low-gap devices, is to first dispense an encapsulant in a liquid form, and then cure to form a solid encapsulated package.
- In liquid encapsulation, **material utilization** can be maximized, as compared to inefficient use of molding compounds in the transfer molding.
- Liquid encapsulants can be **designed** into different viscosity grades to fit into **different flow** requirements.
- Three most used liquid encapsulation processes are:
  1. Cavity Filling
  2. Glop-Topping
  3. Underfilling
Cavity Filling

- Mainly used in **ceramic chip carriers**
- Cavity has interconnect leads and pads prefabricated to accommodate the die.
- After die attach and wire bonding, the cavity is filled with a liquid encapsulant for environmental pollutants, and mechanical protection.
- Simple process, but liquid filling nature requires the device to be placed in a cavity of predefined size and shape.
- Hermetic sealed can be achieved with use of metal lid if higher reliability is desirable.
Glob Topping

- Glob-topping uses a damming material to form an enclosure so that a liquid encapsulant can be dispensed on top of wirebonded device.
- The glob dam may optional if
  1. The profile of the glob is not critical,
  2. The device to be protected is so small → bond wire exposure is unlikely.
- Std glob-topping process consists of die attach, wirebonding, dam dispensing and cure, glob-top dispensing and cure.
- Convenient alternative for liquid encapsulants (other than cavity filling) → no special requirement for the substrate.
Glob-Top/Dam & Fill
Glob top encapsulation is applied on top of the die after the first level interconnection is formed. Thermoset polymer is dispensed with a needle nozzle at a location or in a form of line(s) to cover the entire die and the first level interconnection. The units are then sent for cure to achieve the desired mechanical and moisture resistance properties of the encapsulation material.
**Underfilling**

- Underfill is the most critical operation in flip chip assembly.
- The temperature set at 70-100°C to aid underfill flow, and a syringe of underfill is dispensed from the barrel through a needle to the edge of the die.
- Underfill parameters – dispense pattern, head speed, needle size and length (L), needle to substrate (Z), and die to edge (X).
Mechanism of UF Encapsulation

With underfill the stress is redistributed
Substrate and chip are interlocked by underfill
Joint is protected by underfill
Conventional Process Flow

1. Align bumped pads on chip with substrate pads
2. Reflow the assembly to create solder joints
3. Dispense underfill and flow under chip
4. Cure underfill
Flip Chip with Conventional Underfill

Process Disadvantages

1. Slow - 4-5 minutes (for 6 mm die w/ 3mil gap)
2. Performed at device level - can be bottleneck
3. Lengthy cure (1-4 hours) - separate process
4. Sensitive to air entrapment (voids)

Material Disadvantages

1. Thermoset materials - not reworkable
2. Material properties - often at odds w/ process requirements
   a. High filler loading - slows flow under die
   b. Low filler loading - susceptible to popcorning
3. Cure sensitive properties - short floor life (need to cure immediately after dispensing)
4. Solvent use can cause voiding or bubbling
Flip Chip with No-Flow Underfill Process

**Process**

1. Dispense no-flow underfill over entire chip area

2. Chip placing (aligned before dispensing)

3. Reflow solder joints and Cure underfill
HERMETIC SEALING

• Sealing is a process that contains the electronic packages within an inert environment (Hermetic packages)
• The process consists of following step:
  1. Fused Metal Sealing
  2. Soldering
  3. Brazing
  4. Welding
  5. Glass Sealing
Sealing of Various Ceramic Package Types:

(a) Side Braze Ceramic Packages

(b) Side Braze Ceramic Packages

(c) Chip Carrier (SLAM)

Side-brazed package - a type of ceramic dual-in-line package wherein the leads are brazed to the sides of the package
Parallel Seam or Welding

AC Welding Transformer

Copper Electrode

High Resistance Lid

Substrate

Work Table
Electrode Welding

Welding Transformer (D.C. Capacitor Discharge)

Copper Electrode

High Resistance Lid

Substrate

Work Table
EXAMPLE OF CERAMIC PACKAGES

- Side Braze Packages
- Leadless Chip Carrier Packages
- Ceramic SOIC
- Ceramic PGA Packages
Fig. 2.5. Ceramic packages a) dual-inline package CerDIP, b) flat pack package, c) ball grid array (Courtesy: Amkor).