J-STD-030
December 2000

Guideline for Selection and Application of Underfill Material for Flip Chip and other Micropackages

Draft 7

Underfill Adhesives for
Flip Chip Applications Task Group (5-24f)

ASSOCIATION CONNECTING ELECTRONICS INDUSTRIES

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1 Scope

This guideline covers polymer based underfill materials intended for use in electronic packaging assembly applications to relieve stress on joints that interconnect flip chips (FC), chip scale packages (CSP) and ball grid arrays (BGA) to an interconnecting substrate.

1.1 Purpose

The purpose of this document is to establish evaluation criterion for material, that when used in combination with the assembly and joining processes, will substantially increase the thermal fatigue life of I/O connections (e.g., solder bumps, gold bumps, conductive adhesive, combinations) particularly when there is coefficient of thermal expansion (CTE) mismatch, substantially different expansion values between the flip chip or other package and the assembly substrate.

1.2 Intent

The intent of the document is to help in identifying underfill materials whose properties are compatible with component assembly joints to reduce thermomechanical stress so that performance of the assembly is enhanced. The additional role of underfill is protecting the device from environmental factors and increasing strength. Materials used in underfill applications should not adversely affect device reliability (ionic impurities, alpha emitters) nor degrade electrical performance. Evaluation methods are provided in the document that are intended to be used for assessing underfill material performance in specific applications. Methods are also included that will assist in estimating processing time.

2 Applicable documents

2.1 IPC

IPC-T-50 Terms and Definitions for Interconnecting and Packaging Electronic Circuits
IPC-SM-782 Surface Mount Design and Land Pattern Standard
IPC-SM 785 Guidelines for Accelerated Reliability Testing of Surface Mount Solder Attachments
IPC-SM-840 Qualification and Performance of Permanent Solder Mask
IPC-TM-650 Test Methods Manual
TM 2.4.28 Adhesion, Solder Mask (Non-Melting Metals)
TM 2.6.1 Fungus Resistance Printed Wiring Materials
TM 2.6.3.3 Surface Insulation Resistance, Fluxes
TM 2.6.14.1 Electrochemical Migration Resistance Test

2.2 Joint Industry Standard

J-STD-004 Requirements for Soldering Fluxes
J-STD-012 Implementation Of Flip Chip and Chip Scale Technology
J-STD-020 Moisture/Reflow Sensitivity Classification for Non-Hermetic Solid State Surface Mount Devices
J-STD-026 Semiconductor Design Standard for Flip Chip Applications
J-STD-028 Performance Standard for Construction of Flip Chip and Chip Scale Bumps

2.3 American Society for Testing and Materials (ASTM)

ASTM-D-150 Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation
ASTM D257 Standard Test Methods for DC Resistance or Conductance of Insulating Materials

ASTM D792 Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement
ASTM D1002 Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)
ASTM D1210 Standard Test Method for Fineness of Dispersion of Pigment-Vehicle Systems by Hegman-Type Gage
ASTM D2556 Standard Test Method for Apparent Viscosity of Adhesives Having Shear-Rate-Dependent Flow Properties

3 Terms and Definitions

All terms and definitions used throughout this handbook are in compliance with IPC-T-50. Definitions denoted with an asterisk (*) below are reprints from IPC-T-50. Other specific terms and definitions, essential for the discussion of the subject, are provided below.

TO BE BUILT

4 Background – why is underfill needed, type of underfill

5 Design Considerations – need more info about what to consider if underfill is used

5.1 Footprint Design

While designing IC's with pad locations for wire bonding is generally well understood, this is unfortunately not true for flip chip technology. Flip chip offers new freedoms such as placing bumps internal to the die edge, over circuitry or in array format depending on the bump technology. Along with these new freedoms come different constraints with the bump process capability and the ability to route the next level of assembly. To produce a successful bump footprint design, it takes much more than just following design rules. It takes a design team with packaging expertise to ensure that the final product is a success.

The drive for flip chip technology often stems from a need to miniaturize, to obtain electrical performance improvements or to accommodate interconnect density demands. All of these needs highlight the critical nature of a comprehensive design - a footprint design that is completed in concert with the design of the next level of assembly.

There are many dangers for those unwilling to address the design requirements up front. For miniaturization, a poor IC footprint design may result in assembly process or substrate yield losses as trace width and pitch is reduced, resulting in increased system costs. For electrical performance, the next level of assembly design may have routing parasitics which eliminate the benefits achieved in the die design. A poor chip footprint design with high interconnect density, may require extra routing layers driving system costs much higher. Hence, interactive design is crucial to obtaining a viable flip chip product.

A final reason for interactive design is that substrate capabilities and bump capabilities are ever evolving in terms of mechanical, electrical, thermal and fanout capabilities as well as in terms of cost. This document can not foresee these changes so it is imperative that the IC footprint design be completed interactively with those up to date on the latest capabilities and costs.

5.2 Pad Redistribution

A bumping alternative for those chips which weren't designed specifically for flip chip is to redistribute the pads into pad configuration which meets the bumping design rules and which can be flip chip assembled more readily. See Section 3.4.3 for more information on the redistribution process.

5.3 Gap Size

Gap is the space between the assembled device and substrate with the bump, or joining structure serving as the stand-off. Gap size is important in determining the appropriate filler size in underfill. Bump pitch can also be a determining factor for filler size. Gaps should be measured and not just estimated since a number of factors can

influence the true value. For example, the presence of flux residue can reduce the gap to a fraction of the calculated value. Excessive eutectic solder bump collapse due to overly large bonding pads and can reduce the gap to a level where underfill will not flow. The reflow profile can also change the gap size.

6 Raw Materials Characteristics – need more info on resin/liquid properties

Underfill is typically a mixture of low-expansion filler in a liquid prepolymer that can be cured to a solid composite with the desired CTE value.

6.1 Filler Properties

Typically, fused silica (SiO_2) is used as a filler. However, alternatives such as alumina (Al_2O_3), boron nitride (BN), and other materials may be used. The type of fused silica, particle size, particle distribution, particle geometry, particle surface area, density, alpha emissions, surface treatments as well as other attributes are important in the filler selection process. The rate of filler settling is dependent upon, the density of the filler, the particle size of the filler, the specific resin(s), and the viscosity of the filled encapsulant. See 8.7.2 on phase separation for further information on filler settling.

6.1.1 Filler Size

Successful underfilling requires that the filler particles are smaller than the gap size. The maximum particle size is critical to ensure underfill of small gaps typical of flip chip assemblies. Maximum filler diameter should be 1/2-to-1/3 the gap size. Filler particles may also become trapped between bumps. Flux often surrounds bumps and can significantly reduce the channel size. Very small filler particles (< 5 μm) may reduce flow rate.

The supplier should report the maximum particle size of the filler to determine compatibility with users minimum gap size. Particle size of the filler can be determined by using progressively smaller mesh screens or by means of a particle size analyzer.

6.1.2 Filler Material Type

There are a number of different types of fillers that can be used in underfill encapsulants. Silica is most prevalent, however in high power dissipation applications a more thermally conductive filler may be used. Alumina is an example of a more thermally conductive filler. The underfill supplier should report the filler type to users.

6.1.3 Percent by Weight

Typically, the filler comprises a large portion (60% - 75% by weight) of the formulation. Underfill suppliers prepare formulations in terms of weight percent versus volume percent. The weight percentage may be significantly different than the volume percentage.

6.1.4 Density

Typically, density of the underfill is reported by suppliers. It is usually in the 1.5 g/cc to 2.0 g/cc range. The underfill density is influenced greatly by the filler density. Typically, ASTM-D-792 or similar method is used to determine density. In low-viscosity underfill systems, filler settling is a concern. See 8.7.2.1 for more information. Underfills with higher density fillers may be more predisposed to filler settling or stratification, particularly during high-temperature cures.

Thermal gravimetric analysis (TGA) residue of a "wet" specimen may be used to determine relative filler content. The TGA may also be used to determine if filler settling may have occurred by curing a highly vertical but thin specimen and analyzing the top and bottom of the specimen for relative filler content.

6.2 Viscosity

Tight monitoring of the material viscosity is crucial for achieving a stable process and a good quality underfill layer. Viscosity measurement method should be agreed between used and vendor. A suggested test method is ASTM D2556.

Viscosity of underfill can also be monitored using the thixotropic index. Viscosity is measured by a rotating spindle rheometer at two different rotational speeds. The thixotropic index is then calculated using the formula:

$$Thixotropic \quad index = \frac{V_1}{V_2}$$

Although thixotropic index may not be a critical parameter, it is important in characterizing the underfill material. In order for capillary action to take place, one needs both a reasonable amount of clearance between the mounting substrate and the dye, and a underfill material that is viscous has sufficient viscosity in order to allow the principles of capillary action to come into effect. Therefore, the methodology of comparing the rotational characteristics at two different speeds are mainly to insure that there is consistency within the materials.

6.3 Gel Time

The gel time refers to the point where the liquid begins to exhibit pseudoelastic properties. This gel time will vary, depending on the curing system used and any preheating of the encapsulant prior to or during dispensing.

After the underfill process is complete, users may elect to gel the underfill so that many devices can be collected and final cured in a batch mode. The gel process may reduce issues associated with filler settling and moisture absorption, that can occur if underfill is maintained under the chip uncured for extended periods of time. Precautions need to be taken to ensure the gel point is not attained while the underfill encapsulant is still in the syringe or during the underfill process, due to exposure to the heated stage.

Underfill suppliers should provide gel time requirements for their respective encapsulant. A test performed on a hot plate known as the stroke gel test can be used to determine gel times in a cursory manner. Typically, the gel time for underfills is in the range of 5 min - 20 min at 121°C.

6.4 Flux Compatibility

Consideration should be given to underfill compatibly with the fluxing agent that is used during the soldering process. This especially applies to "no-clean", fluxes that may leave a residue on the substrate or on the underside of the die/package. For fluxes where cleaning is required, flux residues are normally cleaned prior to the underfill process; however, some trace amounts of residue may remain.

Therefore, compatibility or underfill materials with flux residues should be verified. This may be done by comparing the adhesion strength of ICs adhered to fluxed versus non fluxed surfaces. Similar tests at various temperatures and humidity conditions may be useful.

6.5 Alpha Particle Emissions

Certain levels of alpha emissions (from uranium and thorium isotopes) are known to cause soft errors in memory devices (i.e., DRAMs , SRAMs). The permissible levels are very application specific. In general, the proximity of the alpha emission source to the bump diameter and chip structure needs to be considered to estimate the soft error rate. In order for alpha particles to cause soft errors, the following conditions must be met:
(1) alpha particles must be located near the active circuitry area
(2) alpha particles must have a direct line of sight to the active circuitry area
(3) devices need to be sensitive to alpha radiation.

The most prevalent sources of alpha radiation in a typical flip chip assembly are; high lead solder (0.05 α/cm^2-h – 10.0 α/cm^2-h), alumina (0.1 α/cm^2-h), chip underfill (0.002 α/cm^2-h - 0.02 α/cm^2-h) and plastic mold compound (0.04 α/cm^2-h). In terms of underfill materials, the filler material is the primary source of α-emissions. In comparison to the high lead solder, the underfill encapsulant is less of a concern for α-emission. Underfill suppliers typically use filler material that has very low α-emissions (in the ppb range). Presently, particle barriers; (i.e., passivation layers) and optimized circuit designs are used to minimize exposure of sensitive circuitry to α particles. Synthetic silica fillers are available with nearly zero emissions, but at higher cost.

7 Materials Packaging, Handling and Storage

7.1 Packaging

Underfill is most commonly packaged in sealed plastic syringe bodies designed for automatic dispensing machines. The syringes are available in a wide variety of sizes based on metric volume in cubic centimeters (cc). Most suppliers should place a human, or machine readable label directly on the syringe body that indicates product, lot, expiration data and other information. The human readable label for very small syringes, such as 3 cc, may be placed on the external bag. Most production lines use 10 cc or larger syringes that can accommodate the label. Labeling shall be capable of surviving designated storage conditions.

7.1.1 Containers

Containers are typically plastic syringes that are compatible with automatic dispensing liquid dispensing machines.

NOTE: Many sizes are available and the user should select a size that will fit his specific equipment.

The syringes should be fitted tightly with end caps and seals to prevent leakage during shipment and warm up. Several plunger styles are available. The plunger should permit smooth continuous flow of the material. Syringes and closures should meet standards for the dispensing equipment intended. Optionally, the syringes can be sealed in plastic bags to prevent moisture condensation upon removal from freezer storage.

7.1.2 Voids/Bubbles in Packed Material

Containers should be relatively free of air bubbles that can interfere with dispensing and cause voids under components. Ideally, they are totally void free.

7.2 Storage Conditions

Underfill is commonly a reactive one-part epoxy material that is freezer stored for extended life, from -20°C to -50°C. Cold storage generally prevents filler settling by greatly increasing viscosity or actually solidifying the underfill. The supplier should list optimal storage conditions and expected life within which the material remains useable in terms of viscosity, flow, and other performance criteria.

7.3 Preconditioning

Underfill that is freezer-stored must be brought to ambient conditions prior to dispensing. Condensation of water from the atmosphere will occur with cold samples and should be wiped off the container prior to use. Some products may be packaged with a sealed plastic bag surrounding the container. This outer covering should be removed only after the product is at ambient temperature in order to prevent moisture contamination.

7.4 Usage Life (Shelf Life)

Underfill remains useful only when it can be dispensed, flowed, and cured properly. Most underfill products change over time, even under freezer conditions. Freezer-stored materials slowly polymerize at ambient conditions that produce an increase in viscosity and thus reduce dispensing rate and underfill rate. The following tests are intended to measure changes caused by filler settling and polymerization as well as reduction of polymer catalytic activity.

7.4.1 Viscosity Change

Filler settling and polymerization will result in a viscosity increase. Underfill should be measured after storage using method in 6.2. An increase of 20% may be acceptable for most applications. Values of 50% or more increase are considered unacceptable since dispenser control may become difficult and underfill flow rates may also decrease.

7.4.2 Flow Rate Change

A test should be developed by the user to be run with dispensing equipment. The dispense flow rate measurement method in 8.4.1 can be used to assess the change. The flow rate of the underfill is monitored as a function of time. Thus the time per amount dispensed is typically recorded over an 8 hour period.

Typical usage life limits indicated by reduction of dispensing flow rate is shown in Table 7-1. Specific shelf life and flow rate reduction limits for each material could be obtained from material vendors.

Table 7-1:Typical Usage Life Limits

Class 1	Class 2	Class 3
50% reduced dispensing rate	40% reduced dispensing rate	30% reduce dispensing rate

7.4.3 Settling Test

A simple gage of filler settling is used to measure the first and last dispensed portions from a needle syringe that has been stored vertically. The first sample will contain more filler and have a higher viscosity if settling occurred. The last portion of underfill dispensed would consequently have less filler and have lower viscosity. Use the method in 6.2 for viscosity measurements.

8 Application Process

The material should only be used at the supplier recommended temperature typically at ambient. A syringe cooling device is sometimes necessary to keep the syringe at ambient when inside an automatic dispenser that is heating the flip chip package. A plastic syringe, the most common container, may be used manually by removing the dispense end cap and installing a needle of the appropriate size recommended by the material supplier. A plunger may also be necessary if not included as is the case when the package is intended for automatic dispensers. Alternately, the pressure supply end may be fitted with a cap attached to a pneumatic dispenser. Production assembly typically utilizes an automatic dispenser designed to accept standard syringes.

The flip chip or other micropackage assembly is positioned under the dispensing head. The substrate may be heated to increase the flow rate of underfill. Both the dispensing needle and the substrate platform may be heated. Dispensing equipment is now available specifically for underfill. Material suppliers should specify the recommended temperature range for optimum flow; between T_1 (temperature where viscosity is significantly lower) and T_2 (gel point). The common flow out temperature range is 60°C to 100°C with 80°C nominal.

8.1 Dispensing Procedures

Underfill must be dispensed close to the edge of the assembled flip chip or other package. Underfill can be dispensed from 1, 2, or 3 sides, but at least one side must be left open so that displaced air will not be trapped under the device. The underfilling process can be divided into two steps, fill and fillet. See Figure 8-2.

The fill stage involves dispensing underfill at one or more edges of the die or package and allowing the material to flow to opposite sides by capillary action. It is important that a reservoir of liquid be maintained at the edge at of the device so that air bubbles are not introduced. Once underfill has flowed completely and is present at all sides of the device, the fillet step is carried out.

The fillet step involves dispensing additional underfill along the device edges not used in the fill step. A fillet on all sides of the die is thought to increase reliability and to reduce the possibility of delamination or die cracking. In some cases an adequate fillet maybe formed during the fill process, therefore a filleting step may not be required. Cosmetics are also improved that can be important in packages such as flip chip-BGA. Figure 8-2 shows underfill dispensing.

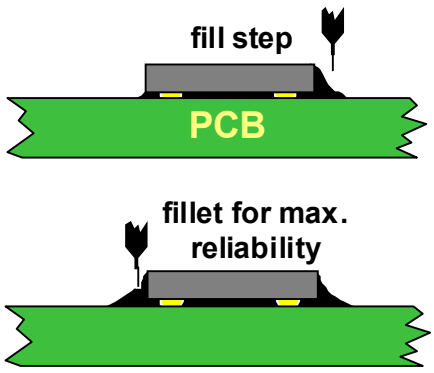

Figure 8-2: Underfill Dispensing

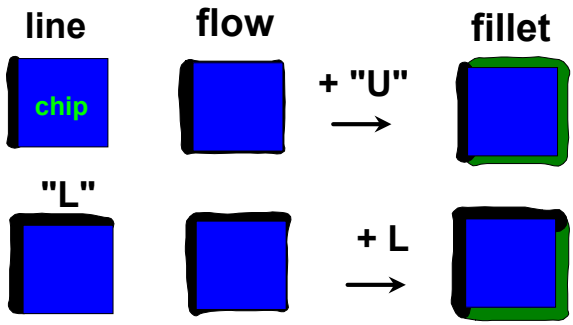

Figure 8-1: Examples of Dispensing Pattern
(The fillet is shown in a different color for clarity only.)

8.2 Dispensing Patterns

Several dispensing patterns are used for applying underfill to die and packages. The simplest pattern involves applying underfill to a single side and maintaining a reservoir as material wicks between the package and substrate. When flow is complete, underfill is applied to the remaining three sides using a "U" pattern to form a fillet. The pattern, called line/U, is shown in Figure 8-1 and is recommended for larger and more complex products since it has the lowest chance of air entrapment.

Another common flow pattern recommended for fast processing of smaller or simpler devices involves dispensing an "L" of material (two sides), waiting for flow out and the dispensing an inverted "L" to complete the fillet as shown in Figure 8-1. Other patterns can be used but the line/L, double L, and their variations are most common today.

8.3 Process Parameters

Accuracy of the amount of underfill fluid dispensed, and the tolerances of the underfill gap influence the variation in fillet shape, height, and width.

Changes in fluid viscosity over the working life of underfill fluids can change the flow rate of the fluid for time, pressure, and auger pump dispensers. Periodic recalibration, either manually or in an automated fashion, can prevent changes in amount of fluid dispensed. Servo-controlled piston or linear pumps that are insensitive to viscosity changes can also be used to control dispensing accuracy.

Multiple pass dispensing patterns can help reduce or control the fillet width.

The timing of the fillet pass can be critical in some cases to prevent cavitation on the side or first-dispensed sides.

8.4 Flow Rate

The dispense flow rate measurement and underfill flow rate measurement can be assessed utilizing tests that have been developed by suppliers, users and industry sponsored efforts. Flow properties as the underfill is dispensed from the syringe/needle at the chip to substrate gap area and as the underfill flows under the chip are both important from the users perspective.

8.4.1 Dispense Flow Rate Measurement

In order to characterize the flow behavior and determine shelf life/pot life stability of the underfill, a simple test involving a standard syringe size, needle type and geometry, set of specific pressure and temperature conditions, the flow rate at the dispense station can be evaluated. Dispensing can be conducted in an aluminum dish placed on a scale so that the amount (weight) of the underfill can be determined as a function of time. This information may be recorded as weight per time or time per weight. This flow rate (weight per time) may correlate with the underfill rate; however underfill rate rely on capillary action, and are influenced by chip size and stand off height. The

specific details of the testing conditions need to be coordinated with the encapsulant supplier.

8.4.2 Underfill Flow Rate

The underfill flow rate or underfill time is one of the key attributes of an underfill encapsulant. Suppliers typically use smooth or frosted glass slides with a predetermined gap established by shim stock to evaluate underfill times. In some cases, a fixture is used to maintain a stable gap and provide a more efficient (more than one slide assembly can be prepared at a time) means of running the test.

The fixture is placed on the hot plate and monitored for the selected underfill temperature (typically 60°C - 100°C). When the selected temperature is reached, underfill material is dispensed at the gap area. The flow front is timed to determine the time required to reach 1 cm. Information regarding underfill time and voiding predisposition can be obtained.

Other methods, such as glass slides set up with a variable gap that runs from ~0.13 mm to zero (creates a wedge shape) can be used to expeditiously determine the compatibility of an underfill with various gap sizes. Another approach, that may be utilized more by IC manufactures, is the use of a quartz bumped die that is consistent with the IC size to be used in the application. Different combinations of substrates with slides such as FR.-4, silicon etc. can be evaluated. The predisposition to voiding can also be assessed before and after cure. The glass slide/Quartz die tests are not designed to reflect underfill times in specific applications, since solder masks, chip size, chip passivation coating, bump count, bump spacing, bump location and surface cleanliness will all have a dramatic effect on underfill times. This test may be used to compare alternative encapsulant suppliers, alternative underfill temperatures, and shelf life/pot life of underfill encapsulants.

8.5 Flow Out and Bleed

Flow out is the distance that the composite underfill flows away from the die/package. Bleed refers to underfill phase separation away from the die/package (see 8.7.2). The polymer resin system may flow outward (advancing contact angle) from the die/package leaving filler behind. Bleed distance will exceed flow out distance when phase separation occurs and some underfills will show this phenomenon because of the relatively smooth and spherical filler.

The amount of flow out and bleed is the measured distance that the resin advances. In some applications, it is important to control the flow out/bleed to maximize the packaging density. There is not necessarily any reduction in reliability of the flip chip or other underfilled component, however material that flows away from the die can cause problems by covering tooling holes, fiducials, connectors, assembly pads and test points.

Since there are a variety of underfills that have different viscosity and wettings capabilities, flow out/bleed can be optimized through underfill materials selection. The dispensing rate, amount, pattern and substrate preheat temperature also can be adjusted to help contain underfill in the assembly zone.

8.6 Spread/Slump

The test method for spread/slump is:

a) using either a screen or stencil, deposit at least 3 dots of adhesive 0.65 cm diameter and 0.25 mm thick on to a clean frosted glass microscope slide (The printed pattern shall be of uniform thickness.);
b) prepare two test specimens;
c) specimen no. 1 shall be stored for 50 min to 70 min at 25 °C ± 5 °C and 50 RH ± 25 RH;
d) specimen no. 2 shall be cured as per supplier's instructions;
e) measure the percentage increase in adhesive dot diameter compared with the initial pattern.

When tested in accordance with the specified test method, the test pattern shall not increase by more than 10% (or other agreed value) of the printed dot diameter.

8.7 Application Problems

8.7.1 Air Entrapment

Figure 8-3 shows the air entrapment phenomenon caused when material is dispensed from more than one side of a complex device. Flow tends to proceed most rapidly along the bumps.

Although trapped air can be identified by imaging methods or the use of a transparent glass die, a simpler method is to clamp the bumped die or package to a glass slide and observe the flow pattern. Alternatively, the bumps can be bonded to glass with adhesive as described in 8.8.2.

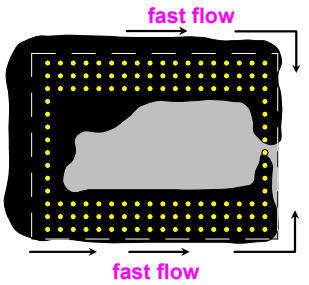

Figure 8-3: Air Entrapment

8.7.2 Phase Separation

Underfill is typically a composite of solid dielectric filler suspended in a continuous liquid organic phase. Since filler density is nearly always greater than that of the organic medium, phase separation can occur by the following mechanisms:

8.7.2.1 Gravitational Phase Separation

Gravitational phase separation may occur when filler settle out in low-viscosity underfills especially if they are left at room temperature for long periods (See Figure 8-5). The settling problem is further exacerbated by heating that can substantially reduce viscosity. The result will be a greater concentration of filler near the substrate surface and resin enrichment at the device interface. Long periods between dispense and cure or very slow ramp up to cure temperature can result in excessive settling although a small amount will not significantly affect reliability. One solution is to gel the underfill soon after flow out.

8.7.2.2 Dynamic Phase Separation

Dynamic phase separation may occur when the organic phase moves rapidly under a device and past bumps by capillary (surface tension) action (See Figure 8-6). The denser filler will tend to move slower than the liquid phase so that filler is concentrated at the dispense end of the device. Some separation is normal for fast flow underfills. Cross-sectioning will detect both types of phase separation shown in figure 3.4. The very high filler loading necessary to achieve a low CTE, however, make it difficult for significant filler separation to occur. While phase separation is a concern, it may not have a significant affect on reliability of the assembly.

8.7.2.3 Filtering Phase Separation

A phenomenon, called “filtering”, can cause drastic and unacceptable phase separation. This happens when filler particles become trapped between the substrate and package or between bumps (See Figure 8-4). Filtering phase separation is easily seen in a cross-section. In extreme cases, the no filler particle or only the smallest ones, are seen beyond the blockage point that is usually a bump. The problem is seen in assemblies with low bump height (< 50 µm) and fine pitch (< 250 µm). Although engineering calculations may conclude that both gap height and pitch are sufficient to allow the unhindered passage of filler particles in a particular underfill, presence of contamination or flux residue can significantly reduce both. It may be necessary to cross-section in both X and Y directions to visualize the problem. See trouble shooting described in Section 14.

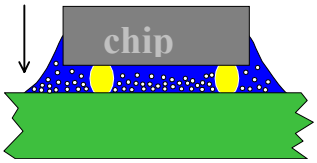

Figure 8-5: Gravitational Phase Separation

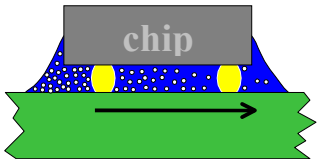

Figure 8-6: Dynamic Phase Separation

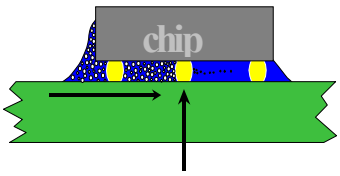

Figure 8-4: Filtering Phase Separation

8.8 Evaluation Methodology

A number of destructive and nondestructive techniques are utilized to access the fill quality of underfill encapsulant of a flip chip assembly. The quality of the fill is typically measured in terms of completeness of fill, location, size and frequency of voids, cracks in the assembly, and homogeneity of the underfill encapsulant (e.g., channeling and resin/filler phase separation). In a destructive mode, cross sectioning the assembly can yield information with regard to encapsulant homogeneity and major voiding. In some cases, in particular with flexible circuits after cure, the IC can be peeled away and the fill removed to examine the IC and substrate for void location, size, and frequency. An effective nondestructive method of imaging bumps, bump connections, and underfills, is known as acoustic micro-imaging. Other nondestructive industry standard methods such as X-ray may be used. In addition, a newer method using IR is under investigation.

8.8.1 Acoustic Micro-Imaging

The specific technique utilized is referred to as C-mode scanning acoustic microscopy (C-SAM). It is a reflection-mode acoustic microscope. The instrument's ultrasonic scan head, alternately beams ultrasound into the sample and receives the returned or reflected echoes. The ultrasound is reflected from various interfaces in the interior of the assembly. Due to the small size of the bumps, high acoustic frequencies of 100 MHz - 180 MHz are used to achieve high resolution. Voids or discontinuities as small as 13 µm may be detected, contingent upon the frequency of operation and the sample design. Typically, the assembly is imaged from the top side (nonactive or backside of IC). The reflected echoes can be manipulated so that a specific interface (e.g., IC-to-underfill) can be assessed. The interfaces of the underfill-to-IC and underfill-to-substrate, as well as the bulk material can be evaluated for cracks, voids, and the distribution of filler particles.

8.8.2 Assembly to Glass for Flow Visualization

Although a package-to-glass assembly is not a perfect model, it can be a powerful aid to understanding flow and problems with air entrapment or phase separation. Any bumped die or package can be bonded to the glass using the appropriate adhesive applied to the bumps. Commercial conductive adhesives are available for bonding flip chips to substrate. The newer epoxy-based fluxes can also be used. Flux can be applied from a fluxing drum or by pressing the bumps against a thin layer of flux on a flat plate. A similar process using adhesive, commonly called "polymer dip chip," can be used for this assembly. Adhesive is applied with a fluxing drum or coated onto a planar surface with a doctor blade or coating bar. The flux or adhesive height should be less than the bump height. The bumped package is dipped into the flux or adhesive and removed with the material clinging to the bumps. The package can now be placed onto the glass and hardened. The advantage of adhesive is that it can be hardened at relatively low temperatures compared to the flux. This final assembly can be used to study underflow. Ideally, a camera is placed under the glass. However, since capillary flow (surface wetting) is a strong force, the flow can be viewed through the glass (under a microscope) with the assembly upside down. This method allows assessment of air entrapment caused by nonsymmetrical flow patterns, but will not always demonstrate phase separation dependent on solder joint widening or reduced gap.

8.9 Pot Life (In Dispenser)

The dispense flow rate measurement method in 8.4.1 can be used to assess change. Underfill encapsulant is typically checked for dispensing rate after 8 hours at ambient conditions. A reduction of 50% in the dispensing flow rate is generally considered the limit of pot life. The method in 8.4.2 (on underfill flow rate) should be used to assess

changes in underfill rate. Although viscosity can also be used to estimate pot life, dispense and flow rate tests are much more meaningful.

Cure rate can also be tested using method in 6.3 (on gel time) although cure rate is rarely reduced for material kept at ambient conditions in closed containers.

9 Cure Process – info on undercured

9.1 Applied Life (After Dispensing)

Underfill should be cured soon after dispensing and flow out. The curing step should occur within 8 hours after dispensing, unless the assembly is maintained in a controlled (low humidity) environment. However, in situations where there is considerable time between dispensing and flow, the applied life test should be made. The underfilled sample is cured after standing in the uncured state for the maximum time anticipated between dispense and cure. A cross section should be examined for filler settling (see 8.8). Significant settling, where there is a pronounced phase separation between resin and filler, is indicative of potential reliability problems.

The gel time property of the materials (see 6.3) should be considered when addressing applied life of the dispensed materials. After the application process is complete, users may elect to gel the underfill to avoid long exposure to the atmosphere and substrate that may inhibit curing. Certain epoxy chemistries may exhibit shorter gel times upon exposure to atmospheric moisture indicating higher reactivity. Products will cure quickly, however, cross linking will not occur resulting in lower T_g values, poor solvent resistance and thermal instability.

9.2 Process Parameters

The curing process will have a significant effect on final cured properties, especially the glass transition temperature (Tg) and the CTE. The process parameters that influence the cured properties include the rate of heating (ramp up) and cooling, maximum temperature and time at temperature.

9.2.1 Cure Schedule

Typically, cured properties listed on underfill data sheets are reported as total time at a given temperature. Heat-up rates to this maximum temperature, and cooling rates are not always specified in the cure schedules provided by the manufacturers.

For most materials, higher temperatures for longer periods produce higher Tg, lower CTE and greater adhesion (optimal cure). In some cases, alternative cures schedules will be provided (e.g.; lower temperatures, shorter duration, etc.). Two-step cures may also be used to reduce shrinkage and minimize stress for strain-sensitive applications. It is important to keep in mind that as cure schedules are altered, final properties will vary.

9.2.2 Heating Rate

This heating rate may influence the quality and reliability of the assembly. Acceptable heating rate is influenced by the mechanical and physical properties of the substrate, topography of the die, and the underfill material.

In general, slower heating rates may result in filler settling, but less warpage/stress on the assembly. A fast heating rate (high ramp) for some underfill materials can cause one or more of the reactive monomers to volatilize. Each formulation must be tested for this phenomena. Therefore, users need to be cognizant of the curing schedule utilized and work closely with the underfill supplier to ensure the desired cured properties are attained.

9.3 Void Formation/Outgassing

Outgassing in rigid underfill systems is a concern if there are solvents and/or diluents present in the encapsulant. Moisture present on/in the IC passivation layer or substrate solder mask may also be a concern with regard to outgassing during the curing process.

The visual detection of voids in the encapsulant after underfill, but prior to curing may be minimal, however after the curing process is complete, voids that may have been undetectable in the pre-cure condition may have increased in size and are now evident. Therefore, curing the specimen is important to assess voiding formation. While suppliers

strive to provide underfill systems that will not form voids, the specific application may be designed or processed in such a manner that exacerbates void formation. Therefore, underfills must be tested in the end use application to ensure that there is minimal or no void formation.

Using the technique described in 8.8.2, an assessment of the void formation can be made. Typically, the underfilled glass assembly is examined before and after cure under a microscope for voiding formation. Quartz bumped die may also be used to assess void formation that reflects a more realistic test environment. To assess actual IC devices, the acoustic micro imaging technique may be used as described in 8.8.1.

9.4 Cure Verification

Curing of the underfill should be verified by comparing the fillet with a known cured sample. Pin probing is commonly used to qualitatively test the hardness of cured underfill at full T_g of the underfill. Some materials change their appearances and/or optical characteristics once cured. These effects can be used as cure indications. Some underfill products have color reaction cure indicators.

The most accurate determination of reaction rates, cure kinetics and degree of cure is by thermal analysis such as DSC and TMA. However, cured underfill is typically hard and will not dent with pin probing. Solvents, such as IPA, should not remove more than a trace of colorant.

TMA frequently requires a second scan in order to get consistent readings. The first scan tends to postcure the sample resulting in misleading readings for the second scan. DSCX should be used to qualify degree of cure and determine T_g. TMA can be used to determine CTE and the ultimate T_g of the fully cured material. Typical one-step "optimal cure" schedules for underfills range from 0.15 h - 1.5 h @ 140°C - 165°C.

10 Cured Underfill Characteristics

10.1 Appearance

10.1.1 Fillet formation

Fillets distribute stress and can increase reliability. Fillet height, volume, and spread vary due to inconsistency in substrate, die, solder mask, and flux residue. The lowest fillet usually occurs at the corners of a die. Typically, fillet forms to a height of, at least, 50% at the center of perimeter or 20% of die height at all corners. The fillet should not cover the back side of the die as it can make inspection difficult and interfere with heat sink attach.

10.1.2 Color (Dye/Pigment)

Most underfills are colored for visualization. Nonconductive dye is preferred over the older carbon black that may reduce flow rate and possibly influence high frequency signal quality. Both pigment and soluble dyes are used.

10.2 Adhesion

Direct determination of the bond strength and/or the adhesion strength of the underfill layer to the silicon passivation is a very difficult task. The difficulty is associated with the brittleness of the silicon material, that breaks in unpredictable ways, strongly affecting the spread of the experimental value. For comparative estimations for the shear/adhesion strength of different materials, a suggested test method is ASTM D1002.

Underfill encapsulants exhibit some similarities in terms of fit, form, and function with conventional die attach materials that have been used for decades. With this in mind, the adhesive strength of the underfill may be evaluated as die attach materials have been tested over the years by means of shear and tensile testing. Peel testing may also be used on flexible substrates. Lap shears may also be used to attain relative strength values.

When bond strength of cured underfill is compared using variations in flux, die passivation, PCB solder mask, chip size, encapsulant formulations etc, an estimation on adhesion and compatibility could be established. However, further analysis is needed to detect physical changes in the underfill due to chemical incompatibility, e.g. flux interaction. A significant reduction in bond strength over flux indicates incompatibility. The bond failure at the

flux-to-substrate interface is seen in wax and camphor-based fluxes and is unacceptable. If the adhesion failure is between the flux and underfill, the surface should be checked to see if uncured material is present that would indicate cure inhibition.

NOTE: As the expected field failure is fatigue fracture (adhesive or cohesive) of the underfill layer, the obtain shear strength values might not be a good predictor for the material behavior. A qualification test that predicts the underfill life under field conditions, usually temperature cycling, is still the only way of estimating the underfill material performance.

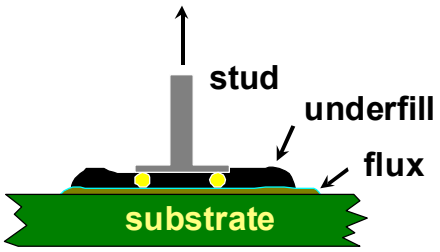

Figure 10-1: Underfill Adhesion Test

10.2.1 Die Shear

A modification of an existing military test method may be used to evaluate underfill encapsulants as follows. Use a standard Kovar™ tab with gold flash approximately 6.35 mm x 6.35 mm and use a 0.05 mm - 0.13 mm standoff of either solder balls or copper wire spacers to form a controlled gap. Place adhesive (keeping filleting within 25% - 50% of Kovar tab height) on the substrate to be tested with standoff and place Kovar™ on underfill encapsulant and cure. Measure adhesive strength with a suitable shear tester.

10.2.2 Tensile Strength (Stud Pull)

Tensile testing utilizing a stud pull tester (e.g., Sebastion from Quad Group) or an Instron tensile tester may be used. Tests are presently being evaluated at suppliers and users of underfill encapsulants. One approach is to attach a die (without bumps) to a substrate using copper wire spacers (0.05 mm - 0.13 mm in diameter) to establish the gap. First, the adhesive is stenciled onto the substrate (e.g., FR-4), then the spacers are placed in the adhesive, followed by placement of the silicon die and heat cured. After cure, a stud is adhesively attached to the die using a lower temperature heat cure. (If the die to the stud ratio is large, an alumina spacer plate is used between the stud and die.) A stud pull tester is used to assess tensile strength. See Figure 10-1. Variations in die passivation, PCB solder mask, chip size, encapsulant formulations/suppliers etc. can be evaluated. Results to date are considered preliminary; therefore typical values are not available at this time.

10.2.3 Lap Shear/Peel Strength

Lap shear testing using 1 x 4 aluminum or FR4 bars with and without solder mask may be used to assess the lap shear strength of underfill encapsulants. An overlap of 1 x 0.5 is used for the bond area. ASTM D1002 describes the general approach. A spacer wire is used to maintain the desired gap. Preliminary values for aluminum-to-aluminum with a 0.13 mm gap are in the 10.3 MPa - 13.8 MPa range. Peel strength may be assessed when using flexible substrates.

10.3 Shrinkage and Induced Stress

A die or package under stress will typically show a slight bending that can be measured by an interferometer or other sensitive methods. A perfect die/package under zero stress will have an infinite radius of curvature. As stress is increased, the radius will be reduced to a measurable value. While more work needs to be done in this area, a radius of curvature R_c above 2 meters is in a very low stress situation. Values under 1 m indicate that stress may be a concern. Values below 500 mm are indicative of excessive stress. R_c is only an indicator and acceptable values will vary depending on package size, thickness, modulus, substrate and joints. R_c will be of the greatest value if a correlation is made between the value and the number of temperature cycles to failure.

10.4 Young's Modulus

Young's modulus (modulus of elasticity) or stiffness, is the ratio of stress to strain. The higher the modulus value, the higher the rigidity of the material. A high modulus or rigid material is considered desirable at this time. Currently, further investigations are ongoing to evaluate low modulus underfill encapsulants. At this point, not all suppliers report a Young's modulus value. Typical reported values for underfills are in the 10 GPa - 4 GPa (flexural).

10.5 Coefficient of Thermal Expansion (CTE)

Presently, it is generally believed that the CTE of the underfill should approximately match that of the interconnect system (i.e., solder bump, adhesive joint, etc.). The intent is for the underfill to expand and contract in unison with the interconnect material (an a_1 range of 25 ppm/°C - 30 ppm/°C is typical for tin/lead solders). However, there is continuing debate on the optimal CTE for underfill encapsulants. Some believe that the CTE should be closer to that of substrate, i.e., FR4 x-y plane, (an a_1 range of 15 ppm/°C - 20 ppm/°C). Typical CTEs for underfills using optimal cure schedules are in the 18 ppm/°C to about 30 ppm/°C when properly cured. Conductive adhesives generally have higher CTE values than solder (50 ppm/°C - 60 ppm/°C) and may tolerate underfills with similar CTE values.

The CTE above the glass transition temperature, designated as a_2, generally is much higher (300 - 400%) than a_1. This is the reason why most underfills are formulated to have a T_g value well above the use temperature.

10.6 Glass Transition Temperature (Tg)

The desired T_g has been typically determined by the maximum end use and/or qualification upper most temperature exposure. Common T_gs for underfill encapsulants using the optimal cure schedule is in the 150°C - 170°C range.

Recently introduced underfills, said to have intrinsic stress relieving properties, may have considerably lower Tg values (100 - 120°C) while still able to survive temperature cycling above Tg. As noted in 10.5, Tg is much less significant if expansion above and below the glass transition region is similar ($a_1 \sim a_2$). The SIR materials are said to undergo a minor phase transition so that $a_1 \sim a_2$.

10.7 Flammability

When coated over solder-mask covered FR-4 material, the combination of adhesive and solder-mask-coated PCB shall meet UL 94V-0 or UL 94V-1 requirements. Testing all be in accordance with UL 94.

10.8 Chemical Stability

As epoxy based material is the material of choice for the underfill layer, a high degree of chemical stability is expected. The chemical stability and activity of the underfill should be similar or superior to the silicon encapsulant materials used in electronic industry. In some cases, when some reworkability is required, a material that can be dissolved by specific solvents can be employed.

10.8.1 Resistance to Solvents

Prepare cured test specimens as indicated in 8.6 and immerse them in solvents listed in Table 10-1 for 15 minutes. Hang samples, to dry, for 10 minutes in normal ambient conditions. There shall be no evidence of degradation in surface characteristics, such as chalking, tackiness, blistering, swelling, or color change when examined visually. The user should test the cured adhesive for resistance to other solvents or chemicals likely to be encountered in this specific manufacturing process, during rework or in the final environment.

Table 10-1: Conditions for Chemical Resistance Testing

Chemical	Thermal conditions
Isopropyl alcohol	Ambient
Glycol-based cleaner	Ambient
Deionized water	Ambient
10% alkaline detergent (pH 13)	60 °C ± 5 °C

10.9 Moisture Absorption

Moisture absorption of underfill encapsulants can be an issue, since absorbed moisture in microvoids/craze sites in critical locations may exacerbate corrosion of aluminum circuitry at the IC. In addition, the Tg, modulus, adhesion, and other properties may be reduced thereby reducing high temperature exposure tolerance. Underfill suppliers typically use a 24 h immersion in boiling water, measuring weight gain as a result. At this point, not all suppliers report moisture absorption values, but typical values fall in the 0.3 % - 1.0 % range.

10.10 Hydrolytic Stability

The 0.317 mm line and 0.159 mm spaced comb test pattern is to be used in this test. Coated substrates shall be conditioned at 97 °C ± 2 °C and 90% RH for 28 days. The specimens should not show air bubbles before conditioning when examined under strong back lighting. A saturated solution of potassium sulfate in a desiccator (or similar container) placed in an oven at 97 °C ± 2 °C is normally used to achieve these conditions.

When prepared and conditioned as described above, there shall be no evidence of chalking, cracking or general degradation when examined visually. Touching the surface with an absorbent cotton swab should not result in the adhesion of cotton fibers. There should be no evidence of copper corrosion under the coating.

10.11 Non-Nutrient

When tested in accordance with IPC-TM-650, 2.6.1, the cured adhesive shall not contribute to, support, or be degraded by biological growth.

10.12 Surface Insulation Resistance

The 0.317 mm line and 0.159 mm spaced comb test pattern is to be used for surface insulation resistance. Apply the adhesive under test in stripes, over the comb pattern, using either a stencil or glue dispenser. Test according to IPC-TM-650, Test Method 2.6.3.3. The conditions for acceptance are application specific.

10.13 Electrochemical Migration Resistance

The 0.317 mm line and 0.159 mm spaced comb test pattern is to be used for electromigration resistance test. The patterns should not be subjected to hot air solder leveling (HASL) to ensure that there is no interference from residual HASL flux. Apply the adhesive under test in stripes, over the comb pattern, using either a stencil or glue dispenser.

Termination details are the same as for the insulation resistance, except that 1 megaohm current limiting resistors are required outside the test chamber for leads 1, 3, and 5 of each test pattern.

Test conditions are 85 °C and 85% RH. Samples are allowed to stabilize under these conditions for at least 70 hours. An initial surface insulation resistance measurement is then made using a test voltage of 100 V dc ± 10 V dc.

A bias voltage of 10 V dc ± 1 V dc is then applied for 500 hours. At the end of this time, the power supply is disconnected and the surface insulation resistance remeasured under the environmental test conditions and with the test voltage (100 V dc ± 10 V dc), of the same polarity as the bias voltage.
The acceptance criteria should be specified.

10.14 Volume Resistivity

Typically, ASTM D257 is used @25 °C @ 500 volts in order to measure volume resistivity. Essentially, it is the

materials ability to resist the passage of electric current through its volume. Typical values range from 10^{14} Ω-cm to 10^{15} Ω-cm in the cured state; higher values yield better insulating properties. It is affected by: temperature, humidity, degree of cure, contamination, and voids or cracks.

10.15 Dielectric Constant

Typically, ASTM D150 is used @25 °C in the kHz or MHz range in order to measure the dielectric constant. Essentially, it is the ratio of the capacitance of the insulating material to that of air (air=1). Typical values range from 3 - 4 in the cured state for underfills; lower values yield better insulating properties. It is affected by: temperature, humidity, degree of cure, contamination, and voids or cracks.

11 Workmanship

11.1 Substrate Preparation

The flip chip area on the substrate needs to be as flat as possible by design. Coatings or surface preparation materials should be evaluated so that they do not interfere with the underfill material. Vias under the die should be filled flush to the surface to prevent voiding. The dispensing side(s) should be given enough clearance for needle movement. Flexible circuits should be rigidly supported under the assembly area.

11.2 Cleaning Before Underfill

Particulate, adhesive squeeze out (adhesive type flexible circuits), and removable flux residues should be removed or minimized prior to the underfill process. The effects of contaminant on the underfill may fall into the following categories:

1) Particulate, flux and adhesive squeeze out may reduce the effective gap size under the die.
2) They can also cause non-uniform filler distribution or filler filtering.
3) Flux residues may reduce the bonding strength of underfill to the surfaces unless they are compatible.
4) Flux residue may also reduce the Tg of the cured underfill when mixed into the underfill.

11.3 Cleaning After Cure

Post underfill cleaning is not a process requirement, but it is often required by the product. Most thermoset underfill materials will not be affected by cleaning processes. If thermoplastics (not very common) are used in the underfill, the cleaning agent (i.e., solvent) and processes (i.e., temperature and pressure) must be evaluated.

12 Reliability

12.1 Ionic Content

Ions, especially chloride (Cl^-) and sodium (Na^+), can cause corrosion on die pads and even printed circuit conductors. Aluminum die pads are especially sensitive. Die passivation and the metallurgy underneath the bumps will determine how sensitive the package will be. Some bumps provide a good seal while others, like the gold stud, leave aluminum exposed. The industry has sought to limit the amount of reactive ions in underfill and general encapsulants to less than 10 ppm for each ion. Typical extraction at 121 °C for 20 hours is used on cured and ground samples of underfill.

12.2 Chemical Resistance

The underfill material might offer some degree of protection for the die and the solder interconnection when used under harsh environmental conditions. The expected protection has only limited value, i.e., a relatively large amount of contaminants are already left on the die surface by the non-clean flux process. Also, moisture can penetrate through the material, activating any ionic contamination existing on the die. The best protection against corrosive environments is using (1) silicon oxide, silicon nitride, etc. for good sealing of the die and (2) under ball metallurgy that has a strong adherence to the sealing material.. When deposition of metals that have poor adhesion to the die passivation (e.g., nickel) is employed, a qualification test is required in order to establish if the proposed solution is compatible with the environmental conditions expected in the field.

12.3 Mechanical Integrity

Under consideration

12.4 Temperature and Humidity

As mentioned before, the materials used for die underfill do not hermetically seal the package, moisture penetration and moisture absorption being expected. Beside activating the ionic contamination existing on the die and possibility of electromigration when voids or delaminations are present, moisture penetration can create problems similar to popcorning in surface mounted devices. This might be a serious problem for components that are not activated continuously and are exposed to high humidity environments while cold (pagers or portable phones for example). As the moisture accumulates in microcracks along the die surface, powering the die after long time exposure to a high humidity environment might produce sudden delamination of the die. Also, water absorption increases the specific volume and reduces the remanent after curing stress. This creates the danger of pulling the solder balls due to the creation of an axial stress. The problem can be eliminated by proper electrical design, good thermal management and proper material selection.

It is highly recommended that the selected material not only has low water content, but both the change in specific volume and modification of the adhesion strength with the water content are low.

12.5 Post Soldering Processes

As a general rule, the underfill is applied after the soldering/reflow process, as the last step in the manufacturing process. It is important that the material selected as well as the process of underfilling will not damage the already formed interconnections. This is particularly important, considering that reworking after the underfill layer is introduced is almost impossible. Strong variations of the underfill layer during the curing process are undesirable because they can introduce strong remanent stresses that might have a negative effect on field reliability. Also, the underfill layer contains fillers that are intended to control the CTE of the material. These fillers might be abrasive and their geometry and concentration, if wrong selected, might produce damage of the passivation layer of the silicon die. The probability of damaging the passivation layer is increased if the assembly has to pass temperature cycling during the qualification tests or under the field conditions.

As no cleaning is usually performed after the solder reflow, it is expected that the surfaces that the underfill should adhere will show a certain degree of contamination. Most of the contaminants are associated with the flux residue from the non-clean fluxes. The compatibility between the flux and the underfill material is crucial in order to achieve a good adhesion of the underfill layer.

In some cases, a solder reflow process might take place after the underfill layer was applied and cured. Under such circumstances, a possible problem might be the lifting of the die and destruction of the interconnect due to an uncontrolled expansion or melting (if thermoplastic materials are used) of the underfill layer. If such manufacturing conditions might occur, a material that can withstand high-temperature and has a high glass transition point should be selected.

12.6 Temperature Cycling

The primary function of the underfill layer is to maintain the mechanical integrity of the assembly flip-chip/board, over the period of time specified as useful life of the product and under the specified environmental conditions. In the absence of underfill, the mismatch in expansion due to chance in temperature conditions of the assembly chip-substrate, the compliance of the solder balls is expected to allow for small displacements between the chip and substrate and avoid the creation of strong shear stresses that might destroy the assembly. If the mismatch in the CTE between the board and the chip is small, for example silicon chip on ceramic substrate, the elongation of the solder balls during the thermal cycle is small and the expected fatigue life of the assembly is relatively long. Good matching of the CTE between the chip and substrate, as for example using aramid fiber-base composites (e.g., Kevlar™), eliminates entirely the potential fatigue failure of the flip-chip interconnect. By contrast, the existence of a large mismatch in the CTE between silicon and normal FR-4 technology board will result in a very short fatigue life and it makes mandatory the use of underfill material for any useful application.

The existence of an underfill material, also called encapsulant, reduces the displacement of the substrate against the

die and it reduces the deformation of the solder balls during the thermal cycle. By eliminating the initial compliant interface, the free movement of the die against substrate is eliminated, and, at the same time significant stresses are developed inside the underfill layer and at the interface between this layer and the chip interface. A very rigid underfill will completely eliminate the problem of the solder fatigue. At the same time, if the movement of the die is eliminated, very large shear stresses are developed on the chip interface, in some cases exceeding the adhesion strength of the underfill material to the die surface and producing failure by delamination. In order to avoid this type of failure, a proper selection of the underfill material, as a function of the adhesion strength should be performed. A high adhesion strength allows for a selection of a more rigid material that in return will extend more the fatigue life of the solder interconnect.

As in the case of two different materials with different CTEs that are joined rigidly together, when the temperature changes, the assembly bows in order to accommodate the mismatch in expansion between the two different material layers. This type of deformation might produce axial stress in the solder balls that can produce the fracture of the ball, especially when the assembly is exposed at low temperature. The axial stresses developed in the solder interconnect are function of the remanent stresses created during the underfill curing stage and the underfill material CTE. A correct selection of the material properties will maintain the axial stress in the ball around zero or continuous compression.

Numerical simulations performed at the University of Minnesota show that, using direct chip attachment on FR-4 technology boards, the life of the solder joint in fatigue is increased six times if an underfill material with a Young's Modulus of 14 GPa and a CTE of 31 ppm/°C is employed. A material with such properties is expected to produce a shear stress in excess of 30 MPa on the interface between the underfill material and the chip. Such a value might be excessive if the technology requires polyimide on top of the chip passivation. For values of the Young's Modulus above 10 GPa, the axial stress in the solder balls is practically a function of the material's CTE only. Since it is desirable to keep the axial stress at a minimum value, a CTE of 28 ppm/°C or greater will keep the tensile stress on the solder ball at practically zero.

12.7 Moisture Resistance

An underfilled package should be tested and classified as reported in J-STD-020. In addition, the underfill moisture affinity could be reported in terms of the weight percent gain as a function of 85 °C/85% RH exposure. Typical exposure time is 168 h at 85 °C/85% RH .

13 Other Considerations – add future development trend

13.1 Self Fluxing

Self fluxing underfill may emerge as an attractive material that combines the reflow flux and underfill into one operation. However, visual inspection and rework become impossible once such underfill is incorporated in to the process.

13.2 Reworkability

When the cost of rework can be justified, reworkable underfill becomes a material of choice. At that time, materials suppliers should provide rework equipment information and rework processes. While reworkable underfills are not generally available, materials are being suggested that may eventually allow practical rework.

13.3 Curing Indication – Conflict, 10.1 implies existence already

Since there is a lack of an in-line inspection method to verify the curing, it would be desirable if the underfill material can change its optical properties (e.g., color change) once cured.

13.4 Thermal Management

Thermally conductive underfill may be required for heat dissipation purposes. Today's common filler is spherical silica that does not provide significant thermal conductivity. More thermally conductive filler minerals, such as nitrides, can be made in an approximate spherical shape in the size required for underfill. Thermally conductive underfills may become available if there is sufficient demand and the higher cost is acceptable. However, since the solder joint is an efficient thermal conduit and array bump patterns can be designed for thermal piping, thermal

underfills may not be generally required. Heat sinks applied to the back (top) of the die/package also represent another heat management option.

14 Trouble-Shooting

14.1 Inadequate Flow

14.1.1 Viscosity

Measure the viscosity to make sure it is in the specified range. Verify that the material is intended to flow at the desired rate. Some materials have rates of less than 1 cm/min/80°C. If the viscosity is higher than stated in the specifications, the material may be cold or age-caused partial polymerization.

14.1.2 Wetting

Good flow requires good wetting that, in turn, requires that the surface tension of the underfill be lower than that of the surface energies of the die/package or substrate to be wetted. Certain contaminants, e.g., silicones, may lower the surface energies of the surfaces, causing non-wetting or dewetting.

14.1.3 Mechanical Blockage

The most common reason for inadequate flow is mechanical blockage by too small a gap, dense bump pattern, excessive flux residue, too thick a solder mask or some other means of restricting movement of the filler. Since the epoxy system can flow along extremely small channels, it is the mineral filler that gets blocked. Phase separation in specific areas, such as after a bump, suggest mechanical blockage (see Figure 8-4).

14.2 Phase Separation

First, make sure that phase separation of the solid filler from the underfill liquid is not due to blockage (see 8.7.2.3). Very low viscosity systems (<5 Pa·s) may show phase separation if the path is rather long, e.g., large die. This is a natural consequence of material science and a different underfill may be required. Underfill with a higher resin viscosity or smaller filler size will typically show lower phase separation. Also note that a modest amount of filler/resin separation does not necessarily mean reduced performance.

14.3 Voids

14.3.1 Voids Before Cure

If voids are detected in the "wet" underfill, it is highly likely that air is being trapped by the wrong flow pattern or that air bubbles are in the material as packaged or from the dispensing set up. Dispense and examine underfill on a glass slide for bubbles. Examine flow out by the method described in 8.8.2.

14.3.2 Voids After Cure

Voids after cure can be due to trapped air. Check the uncured sample by method 8.8.2 and look closely for microscopic voids. Heating during curing will cause large expansion. If no voids are visible in uncured samples, a possible sources are volatilized water from the substrate or die/package. Predry the assembly before underfilling. If the void problem continues, volatilization of underfill material is likely. A slower temperature ramp or a gel stage may be required. A nonreactive (e.g., solvent) may be present in the material that is producing the void.

14.4 Inadequate Cure

Most underfill will not cure to 100% since reactants do become trapped in the cross-linked matrix as the polymerization advances and assemblers are reluct6ant to cure above the T_g where there is sufficient molecular cure. The adequately cured underfill should (1) be very hard, (2) not dented by probing, and (3) resist color rub-off by solvent. If the material is definitely not cured, the most likely cause is insufficient temperature at a long enough duration. Material suppliers specify cured conditions without allowing for ramp-up. Make sure that the actual die/package reaches temperature by using a small thermocouple. A less likely possibility is catalyst inhibition by contamination, e.g., flux residue.

14.5 Poor Adhesion

Most organic substrate, solder masks and underfills are made with a high epoxy content and these systems are usually compatible. Factors that reduce adhesion include:
(1) the presence of contaminants, especially incompatible flux residue
(2) moisture in the substrate
(3) specific underfill is not suited for the assembly die/package interface.
Marginal adhesion can be improved by boosting the cure temperature. Improved adhesion, can be obtained by a prebake at 150 ^{o}C/30 min

14.6 Thermal Cycle Failure

Causes of premature thermal cycle failure are:

- poor adhesion;
- moisture in assembly;
- voids;
- modulus of underfill is too high or low;
- cure temperature is too low;
- excessive shrinkage of underfill (low R_c).

Minutes of Meeting
Underfill Adhesives for Flip Chip Applications Task Group, 5-24f
IPCWorks, Miami, FL

Date and Time: September 15, 2000, 1:30 – 3:00 PM
Meeting Chaired by: Brian Toleno, EMPF/ACI, Chair of Task Group
Minutes Completed by: Brian Toleno, EMPF/ACI, Chair of Task Group

Summarized Results

1 Welcome and Introduction by Karen Tellefsen, vice-chair of the Solder Materials Subcommittee, 5-24.

2 The Anti-Trust statement and Principles of Standardization were briefly presented.

3 History of the project was presented by Jane Koh, IPC staff liaison. This task group was formed in fall 1997 to take over from a small Joint Standard Committee the project of publishing J-STD-030 "Qualification and Performance of Underfill Materials For Flip Chip and Other Micropackages". 6 drafts were developed since then, by 2 different groups of people. Draft 2 that was presented to the floor is 80% complete, supported by a group of people who believes that the technology is not mature enough for standardization. Draft 3 to 6 were supported by a different group of people who tried to change the document into a specification. Due to the lack of unified goal, the project did not have a firm membership base. Previous chairman, Mr. Ken Lewey, Multicore, had to resign from the leadership role due to employment change. The leadership positions of the group are now vacant.

4 The attendees were encouraged to take up these leadership positions. Brian Toleno, EMPF/ACI and Fonda Wu, Raytheon Systems Company had volunteered to co-chair the task group.

5 Opinions were sought from the attendees about what type of documentation they need. Users, suppliers and test labs representatives present were asked how they are dealing with the current non-existence of industry consensus standards or guidelines.
Consensus from the floor is:

- For standards, test methods are required. Currently there are too many materials in the market to have standardized generic test methods.
- Technology may be too new to force into standardized testing and specification.
- Guidelines, check list for users may/would be more useful

6 Upon that consensus, J-STD-030 will be redesignated as IPC-HDBK-030 with the title changed to "Guideline for Selection and Application of Underfill Material for Flip Chip and other Micropackages"
Action item: Jani Elik to work on combining purpose and intent for a new draft of this guideline document.

7 Volunteers were invited to review the existing J-STD-030 Draft 2. All task group members were encouraged to bring ideas about issues to be addressed by the document for next meeting.
Action items: the following task group members to seek assistance from internal co-workers to review the technical contents of J-STD-030 Draft 2.
John Rohlfing, Delphi/Delco
Simin Baghert, Celestica
Greg Parks/Brian Toleno, EMPF/ACI
Dave Schneider, Kester Solder
Karen Tellefsen, Alpha Fry Technologies

8 Next meeting: 16 January 2001 in conjunction with APEX in San Diego, CA.