Transforming Flip Chip into CSP with Reworkable Wafer-Level Underfill

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ABSTRACT
Many packaging specialists believe that Flip Chip is the **final destination** in our technology roadmap – *the ultimate "package"*. There is general agreement that Direct Chip Attach (DCA) provides the smallest possible footprint, the lowest profile, the highest electrical performance and also the greatest I/O capacity. Nothing can be smaller, thinner and lighter than the bare die. Yet others view the Flip Chip as only a partial solution and not even a true package. Both views are correct.

First and foremost, the electronic package must offer protection to the semiconductor device. The package must also be removable and preferably reworkable. The assembled FC remains unprotected until the underfilling step, however. Underfill adds the requisite protection and also greatly extends reliability for organic substrate systems. Underfill can be thought of as a post-packaging encapsulant material. But, while the underfill adds protection, it usually eliminates die removability and the important rework option. The underfill not only takes away one attribute while giving another, it also adds extra steps that increase manufacturing time, cost and complexity.

Many consider the "underfill problem" to be the *Achilles' heel* of Flip Chip since it will ultimately hold back this otherwise powerful technology. The maligned underfill material is not the core problem however. Today's process is! Closer examining of the *underfill dilemma* led us to conclude that "no flow" underfill was a move forward but an interim step. No flow products, a class of pre-dispensed underfills, still add special processes and equipment to the standard SMT assembly method but can allow an in-line process to operate. While "no flow" underfill may not be the final answer, the predispense approach is the way to go.

One simple concept is to predispense underfill onto the chip (wafer) and then solidify the material. The underfill, with flux properties, becomes an integral part of the Flip Chip. Underfilling becomes a semiconductor process just like bumping. Flip Chip assembly is returned to the realm of SMT to aptly suit the existing equipment and process infrastructure. The integral flux-underfill should be reworkable, a task made easier by the solid underfill strategy. Success with a wafer-level underfill system will make the entire process transparent to the component assembler. The Flip Chip becomes fully enabled and transformed into a true package – a simple and effective CSP. The ramifications are far reaching.

Key words: bumping, CSP, Flip Chip, flux, rework, underfill, wafer-level.

INTRODUCTION
The 1990's ***Packaging Revolution*** continues to produce swift and highly significant changes in our electronics industry. The transition from feed-through device assembly to surface mount components took about 80 years, but the shift from perimeter to area array appears to be happening in just a single decade. Our relentless quest for *smaller-faster-thriftier* electronics primarily driven by miniaturization and portability is now propelling the industry into chip-scale and chip-size packaging. The ultimate destination may be "packageless" components as embodied in the Flip Chip.

The 1st generation Direct Chip Attach (DCA) was restricted to ceramic substrate for valid reasons especially thermomechanical compatibility. Ceramic-based Flip Chip (FC) continues to hold an enviable record of success in main frame computers and automotive controllers. Reliability and performance have been nothing short of incredible. IBM claims to have once passed 60,000 thermal cycles in what may have also been a record of test perseverance. Much of the computer and automotive industries continue to rely on Flip Chips assembled to low expansion ceramic substrate. Figure 1 shows one of the earliest 1st generation FCs used on ceramic modules.

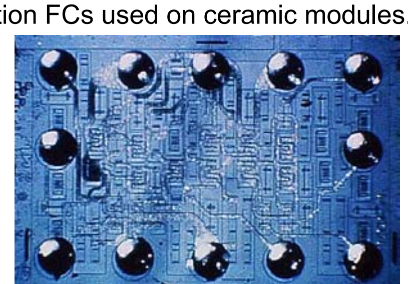

Figure 1: 1st Generation FC – IBM

Today, diverse industries are launching this enticing technology into the world of consumer electronics where portability, power and performance (P^3) demands are outstripping the capacity of standard SMT packaging and even BGAs. Flip Chip certainly holds the title for speed, performance and density. Cost reduction required a shift to organic substrate, however. We will use the term 2nd generation Flip Chip to signify this changeover to organic substrate, the use of underfill and related new bumping methods. Figure 2 shows a Pentium II CPU representing the latest 2nd generation Flip Chip with 2100 bumps.

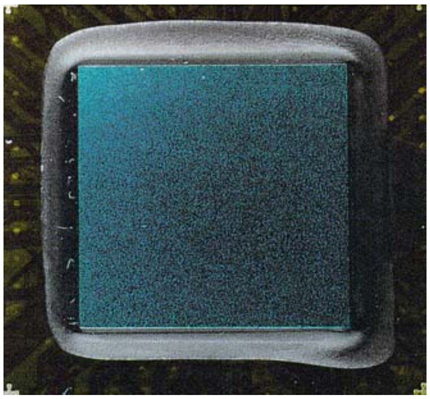

Figure 2 - Pentium II Flip Chip - Prismark

This "simple" conversion from low-expansion ceramic to high-CTE (Coefficient of Thermal Expansion) organic printed circuit boards (PCB) is a very consequential change because of the high stress produced during thermal cycling that can be expected during product use. The chip-to-PCB thermal mismatch drastically diminishes reliability. Fortunately, placing underfill between the chip and substrate multiplies reliability by at least an order of magnitude. Underfill is simply an adhesive that mechanically couples the chip-to-substrate to restrain most of the lateral movement between the two interfaces. The interconnect joints are therefore protected and preserved. It is important to keep in mind that only the expansion in the X-Y plane is coupled. The Z-axis is unrestrained and underfill must be compatible with the joints. Note that underfill does not need to match the CTE of the chip as shown in Figure 3.

Underfill products are now available that deliver on the promise of providing the reliability required for 2nd generation Flip Chip on organic platforms. Millions of Flip Chips are now being assembled on FR4 and BT laminate for a wide range of products like cellular phones, pagers, disk drives, memory modules and much more. Many products have been in the field for five years or more without any reliability issues. Now that quality and performance are assured, the focus has shifted to manufacturing productivity.

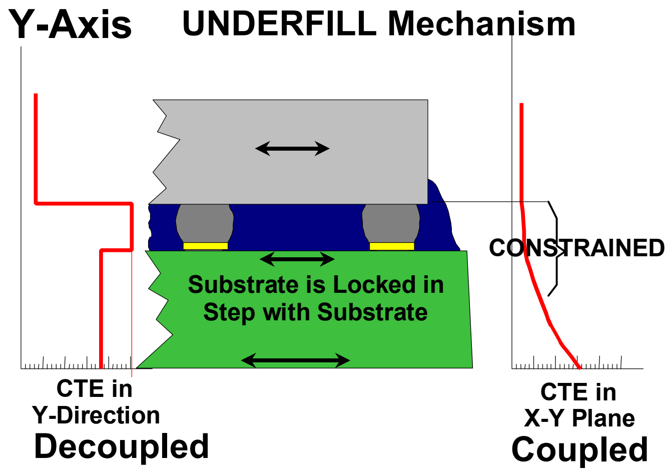

Figure 3

While underfill may be the simple solution to a complex thermomechanical problem, the process adds cost, reduces yield and the extra equipment can occupy as much floor space as the chip assembly line. Underfill productivity improvements, like fast flow and snap cure, no longer satisfy the assemblers, however. Underfilling is still an off-line process requiring major capital investments. Many feel that underfill, while enabling 2nd generation Flip Chip, is still the process bottleneck that will limit growth. Can we circumvent the underfill problem? The answer requires that we take a broader view of underfill and consider radically different processing methods. We first need to investigate all the potential classes of underfill.

POST-DISPENSED UNDERFILLS

The post-dispensed class is the original and most obvious type of underfill. The popular term is "capillary flow" because surface energy or capillary action "pulls" material along. The capillary flow underfills are applied to the Flip Chip assembly with simultaneous wetting of substrate and chip. Therefore we can't divide the application point into substrate and chip surface.

Flip Chips can be assembled to the substrate, tested and then underfilled last, hence the term post-dispense can be used. Some assemblers add underfill before testing since the underfilling and hardening could possibly cause joint or component failure. The underfilled chip is not readily reworkable The dynamics of the filling process require that the underfill be in a liquid state, at least during the flow stage. Surface tension is the "engine" that drives capillary flow and the phenomenon is well understood within the realm of surface chemistry and fluid dynamics. Capillary flow processing utilizes the basic wetting principals of surface chemistry. Intramolecular attraction must exceed intermolecular forces. The underfill resin molecules (continuous phase) must be more strongly attracted to the Flip Chip and substrate surfaces than to one another so that an advancing contact angle is achieved. Advancing contact angle means that the underfill wets the surface and advances forward – the liquid molecules are being attracted to the surface substrate molecules or atoms. This is accomplished by insuring that the surface tension (σ) of the underfill is lower than the surface energy of the solid surfaces to be wet. Wetting agents generally produce the desired low surface tension. The free energy of wetting is the source that pulls the underfill through the gap while viscosity acts to resist flow.

Although early capillary flow underfills exhibited "snail pace" flow rates because of high viscosity resins and deficient filler morphology, today's materials flow rapidly and cure in minutes. But we are approaching the limits of productivity improvement. Resin viscosity can't be made much lower, surface tension cannot be dropped much more, filler particles can't be made much smoother and catalysts can't be made much faster. The very best underfills still add the time penalty and increase the product cost well beyond the material cost. But if the capillary flow underfills are "maxed" out, perhaps underfill will remain the necessary evil that limits the technology. However, the bottleneck can be removed! Figures 4 and 5 summarize general performances of underfills vs. chronological time. Note that improvements have leveled off in the past year and major increases in performance for capillary flow are not likely.

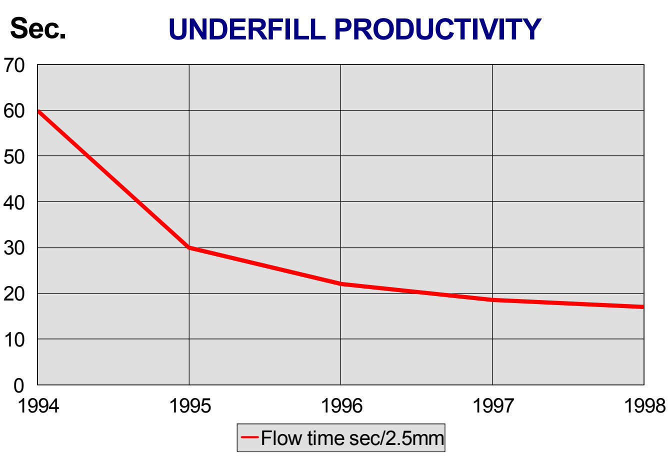

Figure 4: Flow Time vs. Chronological Time

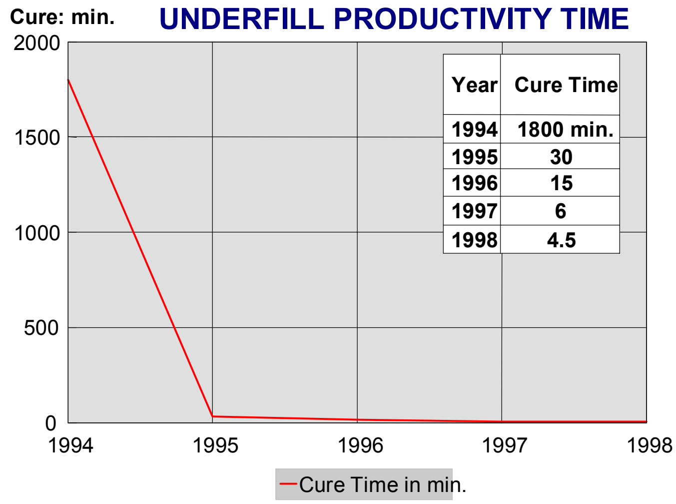

Figure 5: Cure Time

PRE-DISPENSED UNDERFILL

The pre-dispensed class of underfill has several subcategories since material can be applied to the substrate or unassembled chip. More significantly, the underfill can be a SOLID. Now, let's look at the various sub-classes before going into more detail. Table 1 shows the likely classes of underfill.

APPLIED to:	PHASE	Pre-Dispense	Post-Dispense
Substrate	Liquid	available	NA
	Solid	available	NA
Chip or Wafer			
	Liquid	NA?	?
	Solid	R&D	NA
Both Concurrently			
	Liquid	available	available
	Solid	NA	NA

Table 1

Liquid On Substrate Underfill

Scientists and technologists have spent several years working on underfills that can be applied to the substrate before the Flip Chip is assembled, hence the term, *predispense* is appropriate although some refer to these as "no flow" underfills because there is no capillary flow. The predispense type of underfill product must also provide the flux activity required for the solder bumps to form joints with the pads on the substrate. Most of today's underfills are based on anhydride hardeners that afford some level of flux action anyway. Anhydrides hydrolyze to carboxylic acids that are common ingredients for flux. Carboxylic acids can also be used and such systems are available commercially as epoxy-based fluxes, like Chip Flux 2020.

The first challenge for the predispense underfills was to slow down the polymerization rate. Standard underfills are designed to cure at about 150°C. When the temperature is boosted to 215 to 225°C, used for solder reflow, polymerization is greatly accelerated. The acceleration at 220°C can cause a standard underfill to harden before solder has properly melted and formed joints. Even if catalysts are completely removed leaving only resin and hardener, the rate may still be too fast. The predispense underfills require a total reformulation.

Several groups have explored predispense underfills and a few commercial products have become available. Georgia Tech has done substantial work in this area and reported on it extensively [1 – 5]. Let's look at how the pre-applied process is used and investigate the advantages and limitations. The process begins by dispensing the underfill onto the Flip Chip bonding site of the substrate. The work at Georgia Tech has shown that both the amount of material dispensed and the pattern is very critical. Excessive underfill will cause the chip to "float" and form incomplete solder joints or none at all. Insufficient will cause large voids under the die and incomplete filleting. The underfill must be symmetrically dispensed or the chip will tend to skew or move off center. Once the correct volume and pattern of underfill is determined, the process must be carefully controlled for acceptable results.

Ideally, the Flip Chip is placed in a way that assists in displacing air so that voids are minimized. There can be a tendency to trap air as the bumped chip is placed into the underfill unlike capillary underfills where the flow front displaces air. Figure 6 compares post-dispensed capillary flow to predispense no flow type of underfill.

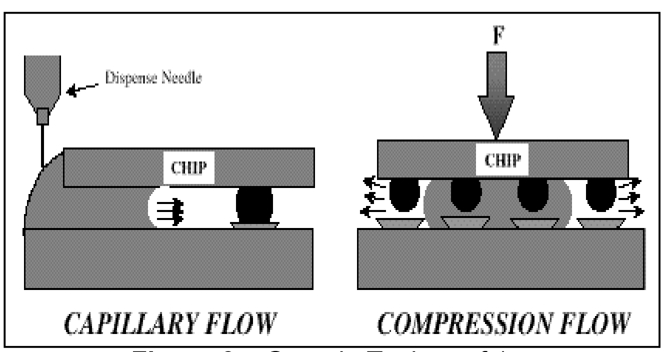

Figure 6 – Georgia Tech – ref.1

Air entrapment remains one of the concerns with the predispense liquid underfills and work continues to optimize the process. The downward movement causes underfill to flow outward to the edges of the chip. Dispensing a viscous underfill in a symmetrical pattern and compressing it by pressing the Flip Chip downward, produces an outward flow pattern that helps displace air. This may be the preferred process and more results are expected from Georgia Tech this year. List 1 gives some of the considerations for predispense underfills.

List 1: Predispense Underfill

- Smaller bump size reduces voiding.
- Larger pitch reduces voiding.
- Substrate temperature is critical for each underfill material to reduce voiding.
- Too low a viscosity allows gravity flow that increases voids.
- Low deposition height increases voids and causes starvation.
- High viscosity allows compression flow to dominate and is preferred.

Once the underfill dispensing process is selected, the curing strategy must be considered. Should the cure chemistry be designed for complete polymerization during solder reflow? The resin/hardener reactivity can be adjusted so solder reflow heating of approximately 220°C is all that is required. However, the complete curing of a thermosetting underfill precludes rework unless the system can be made to polymerize into a thermoplastic.

Another strategy is to reduce the polymerization rate so that reflow soldering only gels the underfill. Now the chip can be reworked. However, the assembly must be post-cured after testing to fully harden the underfill. The delayed polymerization used to prevent full curing during soldering now works against productivity. A 1-hour post-bake is typically needed for the "reworkable" "no flow" underfills according to commercial literature.

The predispense-on-substrate class of underfill can allow Flip Chips to be assembled in-line with a process very much like standard SMT. Problems remain, but work continues. The "no flow" strategy is moving us closer to a painless FC assembly process. But let's continue to explore other modes of underfilling.

Liquid On Chip Underfill

Underfill paste could also be applied to the bottom of the Flip Chip. This might reduce the problem of air entrapment but increases the dispensing complexity. The chip could be dipped into a reservoir of material or temporarily inverted for the application step. Liquid on chip does not really appear to add important benefits so let's move to solid underfill.

PREDISPENSE SOLID UNDERFILLS

Conventional wisdom might suggest that underfills must be liquids, or at least pastes, since they must flow. But solid "underfills" have been used for many years. A closer look at Anisotropic Conductive Adhesives (ACA) shows that the system contains essentially a solid underfill [6]. We can view the ACA film as solid underfill containing a small percentage of isolated conductive particles. Figure 7 shows a diagram of the FC-ACA assembly. Some may argue that the dielectric film is really an adhesive and that is correct. As stated earlier, underfill should be viewed as adhesive film that mechanically joins the Flip Chip to substrate. Underfill laminates the Flip Chip to the substrate and this adhesive mechanical coupling reduces the destructive differential movement. The ACA film and the underfill certainly do have much in common. Now let's get back to underfills.

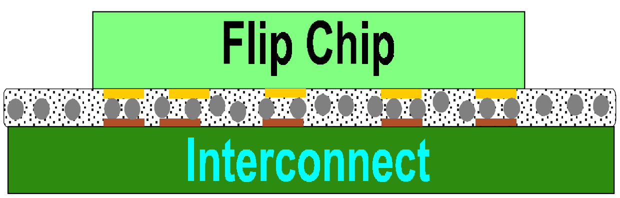

Figure 7 - ACA

What properties are required for a solid underfill? The final material, after Flip Chip assembly and full processing, should have properties similar to the commercial capillary flow products after they are cured. The Coefficient of Thermal Expansion (CTE) should be reasonably low (<35 ppm/^{o}C) and the various thermal properties, especially glass transition temperature (T_g) should be adequately high, more than 125^{o}C, unless thermal expansion above T_g (α_2) does not increase significantly. These properties are not difficult to achieve. The material would also need to bond strongly to chip and substrate in film form. ACA films have long demonstrated the viability of bonding using heat and pressure, so this should not be a serious challenge. Solid die attach adhesives have also proven the efficacy of solids, but more on this later. A solid phase underfill allows much more versatility than liquid systems since the material can be applied to the substrate, chip or both surfaces.

Solid Underfill On Substrate

We can apply a solid underfill to the substrate either as a paste that is hardened or as a film. A paste could be printed or stenciled and then dried or B-staged. The dry format would allow boards to be handled and even shipped to other locations. Either the PCB maker or the Flip Chip assembler could apply underfill.

A solid underfill was recently announced [7]. Here's how it works. A resin sheet is first laminated to the circuit board using a custom machine. The Flip Chip assembly step is similar to the process for ACA films and requires downward force so that the chip bumps displace the resin to make contact with the circuit pads. A special Flip Chip bonder must now be used. While this type of product clearly demonstrates that solid underfill is possible, the benefits appear to be somewhat offset by requiring a laminator and a customer bonder. Do we really want to place underfill on the substrate?

Solid Underfill on Chip Adhesives

Underfill can be applied to a Flip Chip as film or paste that is later hardened. There is a precedent for this type of process within the die attach adhesive field. Thermoplastic die attach adhesives, such as Staystik®, are available as both films and pastes. The liquid form can be applied to the backside of a wafer and then hardened by solvent evaporation. Spin coating, stenciling and screen-printing have all been used successfully. The wafer is diced after the adhesive is hardened. Although die attach adhesive is not an underfill, properties are somewhat similar and the same wafer-level coating methods are applicable.

Wafer-Level Solid Underfills

The most reasonable location for solid underfill is on the bottom, or bump side, of the chip. Flip Chips with integral underfill take on the characteristics of Chip Scale Packages (CSP). The solid **"flipped underfill"** should also have flux characteristics. "No flow" underfills have demonstrated that fluxing agents can be incorporated. There is one more important property to add to the wafer-level solid film underfill. The product should be reworkable and remain so after assembly and any post processing steps. A readily reworkable underfill transforms Flip Chip into a true package since this is really a requisite to qualify as an electronic package. The addition of a solid reworkable flux/underfill to the FC moves it to the CSP domain. There are very significant ramifications for such a package. Also note that wafer-level flux/underfill moves the underfill from the assembler to the semiconductor realm.

There are at least three approaches for constructing a ***ready-to-assemble*** FC "package". A single material strategy can be used but flux and underfill properties must be achieved in one material. However, the goal of achieving reworkability in a single flux-underfill is more difficult, but achievable. We will refer to the single flux-underfill as a Type 1 material.

A 2-layer system is also feasible because of the solid nature of the materials. Underfill and flux can be kept separate making the chemistry easier, but application more complex. The 2-layer system is designated as Type 2. While the term "layers" is used, flux may be localized on bumps and not necessarily formed as a stratum on the underfill.

Solid underfill can also be applied to the wafer before it is bumped. Lasing or other imaging means could be used to open chip pad areas prior to bumping. Flux would be applied after bumping and we refer to this approach, mask, flux and underfill, as Type 3. Let's explore each type in more detail.

2-Layer Flux & Underfill on Bumped Wafer (Type 2)
The 2-layer strategy involves applying a reworkable underfill to the bottom of the bumped chip at wafer-level and then flux to the proximity of the bumps. The underfill can be a thermoplastic that introduces the reworkability property. The material can be applied as a liquid prepolymer or a solvent solution paste by spin coating, stencil printing, spraying or any number of methods used for liquid dispensing. The underfill could also be applied as a film by lamination but this is not a preferred approach. A variety of commercial thermoplastics can be considered. Staystik thermoplastic films and pastes are presently used as reworkable die attach adhesives [8]. Some of these die attach products are used as pastes applied to the back of wafers followed by drying as was mentioned earlier. These systems can be modified with the appropriate silica fillers to become coatable underfills. We have selected several thermoplastic resin/solvent systems from our die attach adhesives materials for conversion to underfills.

The next step is to apply the flux to bumps although this can also be done prior to underfill application. Once again, a number of methods are available including material transfer by dipping the wafer into a controlled thickness reservoir of flux paste or liquid. Flux is already applied to the bumps of individual Flip Chips by just such a dip transfer method with a rotating fluxing drum that is available from many assembly machine vendors. Roller coating is another option. Drying hardens the flux, once applied. Figure 8 shows the construction for the 2-layer process. Note that flux can be applied first and cover more of the bump. The flux system that we have chosen is a solid modification of our commercial epoxy-based flux called Chip Flux 2020.

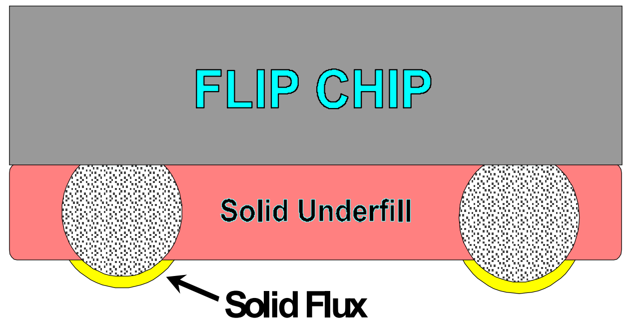

Figure 8 – Type 2 Flux/Underfill

1-Layer Flux & Underfill on Bumped Wafer (Type 1)
A single-layer reworkable flux-underfill solid presents several non-trivial technical challenges but none of the required properties are mutually exclusive. The material must be an underfill and therefore have a lower CTE, a high T_g and good adhesive characteristics but only after solder reflow. Flux properties are only needed during solder attachment and many chemistries are available from the no clean flux area. The fully processed product should become reworkable at about 180 to 190 ^{o}C. One strategy has been to start with a solid epoxy-based flux and design a polymerization chemistry that produces linear rather than the more typical cross-linked polymerization. The linear polymer, that may also have a low level of cross-links, will soften at elevated temperatures to provide reworkability. The objective is to get debonding at an elevated temperature, not necessarily melting of the underfill.

Coat Before Bumping Flux-Underfill (Type-3)
We have demonstrated that our thermoplastic die attach adhesive pastes can be precisely applied to wafers but to the smooth backside. Spin coating is the most common method while stenciling is becoming more popular. Once the solvent-borne polymer is applied and leveled out, the material is converted to a solid film by oven drying. These processes are used commercially with Staystik® die attach pastes.

Film type thermoplastic die attach adhesives can be pre-cut into complex shapes called preforms for attachment of modules and small circuits for electrical and thermal connection to housings or other circuits. Laser machining is used for clean and efficient machining of both filled and unfilled polymer films.

A thermoplastic that is modified to an underfill can be applied to the active side of a wafer by the same techniques. Laser machining can then create pad openings in the dried thermoplastic underfill film. The chip pad areas should already have Under-Bump Metallization (UBM). Any number of conventional or novel solder bumping methods can then be used that do not require mask removal. Solder paste stenciling, followed by reflowing is one of the simpler methods. The thermoplastic underfill can reach a softening point provided during bump processing provided that no harmful deformation occurs. Metal Fluid Jetting (MFJ), using MPM/Speedline equipment, also appears practical and work will continue.

STATUS

The 1st approach, a Type 2 system, shown in Figure 9, was constructed by dip-coating flux onto bumps and drying followed by stencil printing thermoplastic paste onto the wafer. The hardened underfill left about 1/3 of the flux-coated bump exposed to allow for solder bump collapse. Single transparent 12.5 mm X 12.5 mm Flip Chips were also coated for preliminary testing of materials. The transparent quartz chips simplify the detection of voids. Coated chips were tested by placing them onto copper disks and processing through a reflow oven set at a typical soldering profile peaking at 220°C. Good flux action was seen. The underfill, selected from a Staystik® adhesive with a bonding temperature of 200°C, bonded to the copper without applying external force. These preliminary results are encouraging, but considerable work must still be done. Figure 10 shows a similar 12.5 mm x 12.5 mm quartz chip applied to a copper disk using a Type 1 system and processing in a reflow oven.

Figure 9 – Type 1

Figure 10 – Type 2

Work continues on a solid Type 1 system that is based on an epoxy flux system, but with monomers that can yield linear thermoplastic polymers. The tested material has an initial softening point of 100°C while in its flux phase. Exposure to reflow soldering conditions causes the melting point to increase to around 160°C. Adjustments are being made to increase the melting point to about 180°C.

We have previously demonstrated that thermoplastic die attach adhesive pastes can be precisely applied to wafers, but to the backside. We do not expect any issues with coating the active side. Laser machining will be the primary approach for exposing pads that will already have Under Bump Metallization (UBM). Solder bumping methods will include printing paste, but also Metal Fluid Jetting (MFJ) and micro-solder wave coating.

CONCLUSIONS

While state-of-the-art underfills flow rapidly and cure in less than 5 minutes, the time and equipment burden required for underfilling limits Flip Chip technology. Solid flux/underfill systems can be made an integral part of the Flip Chip to smash the underfill "bottleneck". **Reworkability** is a key property that can be more easily incorporated into solids. Reworkable integral flux-underfill Flip Chip is a true Chip Scale Package that will take advantage of the SMD infrastructure. Our initial work has gone a long way in demonstrating the feasibility of solid underfill/flux. Continued work in this area can be expected to produce the desired product that will have major ramifications for the packaging industry. A move to wafer-level converts the Flip Chip to a ready-to-bond CSP and allows in-line high-speed assembly. Underfill is thus moved from board-level application to semiconductor processing. The bumping provider may ultimately become the underfill supplier offering "flipped underfill" Flip Chips.

ACKNOWLEDGEMENTS

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