THE ULTIMATE FLIP CHIP – INTEGRATED FLUX/UNDERFILL

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Abstract

Flip Chip's design-win success rate has exceeded all marketing expectations. Cellular phones, pagers, disk drives, computers, engine controllers and new, contactless smart cards are now employing Flip Chip as the best avenue to *smaller-faster-cheaper*. Flip Chip is also gaining popularity for multi-chip packages and micro-BGAs, replacing wire bonding as lead count increases and performance demands rise.

Most Flip Chips require underfill, said by many to be a "bottleneck" - the down-side of this otherwise simple technology. The common capillary flow underfills have achieved very fast flow with only a 5-minute cure, but dispensers, ovens and extra time are still penalties. Newer, pre-dispensed flux-underfills appear to ease but not eliminate these issues. So what is the solution that will fully enable Flip Chip technology?

Activity is underway to produce a solid flux-underfill system that can be applied directly to the Flip Chip or wafer. Solid flux and underfill materials have been developed that can be coated or printed in a liquid state and then solidified. The hardened flux-underfill is designed to melt, promote soldering and then harden into a protective inert polymer during the solder reflow step. The use of solid polymers, instead of liquid resins, allows reworkable thermoplastics to be used. While many issues remain, progress continues. Results are compared to the most advanced capillary flow and pre-dispense type underfills. The ultimate Flip Chip is a ready-to-bond "package" complete with flux and reworkable underfill. Simplicity wins!

Introduction

The ***Packaging Revolution*** of the 1990's continues to produce very significant and increasingly rapid changes to our electronics industry. The changeover from feed-through device assembly to surface mount components took about 80 years, but the transition from perimeter leads to area array appears to 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 by the Flip Chip.

The 1st generation Direct Chip Attach (DCA) was restricted to ceramic substrate for many reasons, especially thermomechanical compatibility. Ceramic-based Flip Chip (FC) still holds 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. The computer, automotive and other industries continue to rely on Flip Chips assembled to low expansion ceramic substrate.

Today, diverse industries are moving this appealing Flip Chip 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.

This "simple" conversion from low-expansion ceramic to high-CTE (Coefficient of Thermal Expansion) organic printed circuit boards (PCB) is a very significant change because of the high stress produced during thermal excursions occurring during product use. The chip-to-PCB thermal mismatch reduces reliability to an unacceptable level. Fortunately, placing underfill between the chip and substrate increases reliability by an order of magnitude and more. 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 X-Y plane expansion 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.

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.

While underfill may be the simple solution to a complex thermomechanical problem, the process steps required add cost, reduce yield and the equipment can occupy as much floor space as the chip assembly line. Underfill productivity improvements, like fast flow and snap cure, have not satisfied 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 Achilles heel that will restrict 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 examine all the potential classes of underfill.

POST-DISPENSED UNDERFILL

The post-dispensed class is the original and simplest type of underfill. The more common name is "capillary flow" because material is "pulled" along by surface energy or capillary action. The capillary flow underfills are applied to the Flip Chip assembly with wetting of substrate and chip occurring simultaneously and so we can not divide the application point categories into substrate and chip surface.

Flip Chips are assembled to the substrate, tested and then underfilled last, hence the term post-dispense, although “flow type” and “capillary flow” are the popular terms. However, 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 driving force that produces 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. Addition of wetting agents generally produces the desired low surface tension. The energy of wetting is the “engine” that pulls the underfill through the gap while viscosity acts to retard the flow. Filler particles used in underfill adds complexity to the flow phenomenon, however, but rheologists have been able to describe underfill behavior mathematically.

Although earlier capillary flow underfills experienced “snail paced” flow rates due to higher viscosity resins and poor 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 add a time penalty and increase the cost. But if the capillary flow underfills are "maxed" out, perhaps underfill will remain the necessary evil that limits the technology. But the bottleneck can be removed! Table 1 summarizes general performances of underfills vs. time. Note that improvements are leveling off.

TABLE 1

Year	Flow Rate @ 80C	Cure Time
Pre-1995	<1cm/min	3-6 hrs. @ 150^{o}C
1995	2 cm/min	30 min. @ 150^{o}C
1996	2.5 cm/min	15 min. @ 150^{o}C
1997	3.0 cm/min.	5 to 6 min. @ 165^{o}C
1998	3 to 3.5 cm/min.	4 to 5 min. @ 165^{o}C

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 2 shows the likely classes of underfill.

TABLE 2

Application Point	**PHASE**	**Pre-Dispense**	**Post-Dispense**
On Substrate	**Liquid**	available	not applicable
	Solid	available	not applicable
On Chip or Wafer-Applied	▨	▨	▨
	Liquid	not applicable?	?
	Solid	R&D stage	not applicable
On Substrate & Chip	▨	▨	▨
	Liquid	available	available
	Solid	not applicable	not applicable

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, *pre-dispense* although some refer to these as "no flow" underfills because there is no capillary flow. The pre-applied 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 typically 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 pre-applied underfills was to slow down the polymerization rate. Standard underfills are designed to cure at about 150^{o}C. When the temperature is boosted to 215^{o}C to 225^{o}C used for solder reflow, polymerization is greatly accelerated. Chemical reactions typically double in rate for every 10 ^{o}C increase in temperature. The acceleration at 220^{o}C can cause a standard underfill to harden well 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 pre-applied underfills require a total reformulation.

Several companies have explored pre-applied 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 examine 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 patterns are very critical. Too much underfill will cause the chip to “float” and form incomplete solder joints or none at all. But too little 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. But even if the correct volume and pattern of underfill is dispensed, the remaining steps of 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 is a tendency to trap air as the bumped chip is placed into the underfill unlike capillary underfills where the flow front displaces air. Figure 1 compares post-dispensed capillary flow to pre-dispensed no flow type of underfill.

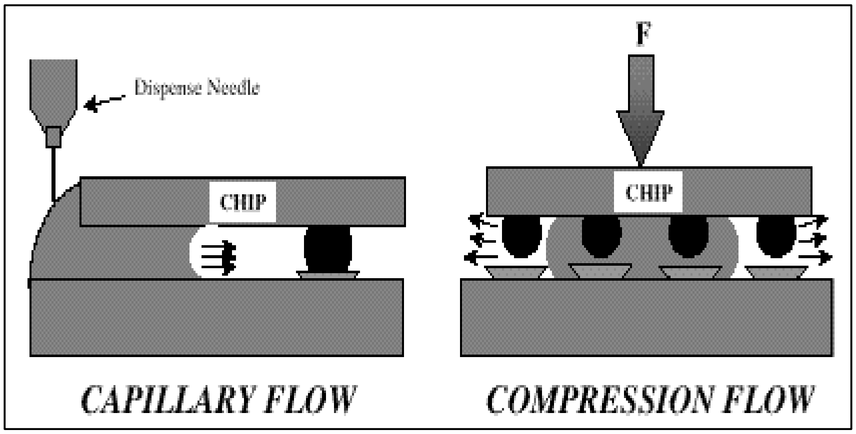


FIGURE 1 – Georgia Tech – ref.1

Air entrapment remains one of the main problem areas with the pre-dispensed liquid underfills. While the capillary flow system displaces air as the liquid flows under the chip, this is not the case when the chip is placed onto pre-dispensed liquid. One of the more successful techniques, called compression flow[1], is shown in Figure 2. The downward movement causes the “no flow” underfill to flow outward to the edges of the chip. The compressed underfill, with a generally symmetrical outward flow pattern, helps displace air and may be the preferred process. Techniques have been worked out, principally by Georgia Tech. Table 3 lists some of the considerations for pre-dispense underfills.

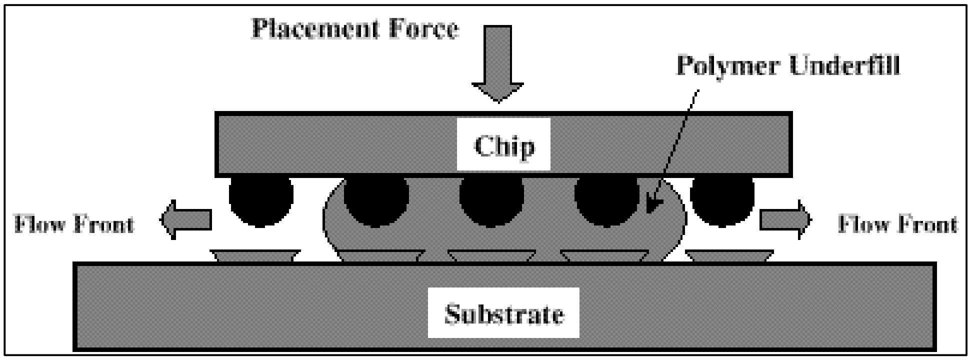


Figure 2 – Georgia Tech – ref.1

Table 3 - considerations for dispense-first underfills

♦ 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 that the short exposure to approximately 220^oC is all that is required. However, the complete curing of a thermosetting underfill precludes rework. The opportunity for pre-testing is lost because soldering and underfill curing occur concurrently.

Another strategy is to greatly reduce the polymerization rate so that reflow-soldering conditions will only gel the underfill. Now the chip can be reworked. However, the assembly must be post-baked after testing to fully cure the underfill. The retarded polymerization chemistry 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. Since capillary flow systems can underfill in seconds and cure in minutes, the productivity gain for the reworkable product appears to evaporate. We need to keep in mind that all capillary flow underfills can permit rework provided that testing is done after reflow soldering, but before underfilling. It is worth mentioning that pre-dispensed underfill has had some commercial success in the realm of conductive adhesive assembly, notably by Fujitsu of Japan.

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 lend itself to wafer-level applications, however. Now let’s move to solid underfill.

Pre-Dispensed Solid Underfills

Conventional thinking might suggest that underfills must be liquids, or at least pastes, since they must flow. But solid “underfills” have been used commercially for many years. A close look at Anisotropic Conductive Adhesives (ACA) shows that the system contains essentially a solid underfill. We can view ACA film for Flip Chip assembly as solid underfill containing a small percentage of isolated conductive particles. Figure 3 shows a diagram of such an 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 differential movement that would destroy the Flip Chip joints. The ACA film and the underfill really do have much in common. Now let’s get back to underfills.

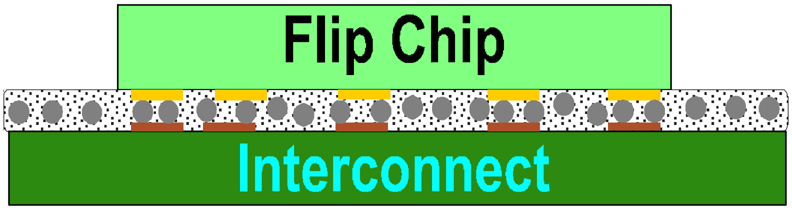


Figure 3 - ACA

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-to-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. Underfill could be applied by either the board manufacturer or by the Flip Chip assembler.

One company recently introduced a solid film referred to as “resin sheet” underfill[6]. Here’s how it works. The resin sheet is first laminated to the circuit board using a custom machine. The Flip Chip assembly step, similar to the process for ACA films, requires force to be applied so that the chip bumps will displace the resin and make contact with the circuit pads. Once again, a special Flip Chip bonder must now be used. While the resin film underfill certainly demonstrates that solid underfill is possible, the benefits provided 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 could be applied to a Flip Chip as film or as a paste that is hardened. There is already some precedent for this type of process in the die attach adhesive field. Thermoplastic die attach adhesives, such as Staystik®, are sold as both films and pastes. The liquid form may be applied to the back of a wafer and then hardened by solvent evaporation. Spin coating, stenciling and screen-printing have been used successfully. The wafer is diced after the adhesive is hardened. Adhesive-coated wafer can be sawn without difficulty provided that the blade and substrate are kept below the softening point of the polymer. While a die attach adhesive is not an underfill, properties are somewhat similar and the wafer-level coating method seems applicable. We should keep in mind that underfills are basically laminating adhesives as are die attach materials.

Wafer-Level Solid Underfills

The most reasonable location for solid underfill is on the bottom, or bump side, of the chip. A Flip Chip that is provided with the necessary underfill now takes on characteristics of a Chip Scale Package (CSP). The solid **"flipped underfill"** should also have flux characteristics. The "no flow" underfills and resin sheet products have demonstrated that this can be done. There is one more important property to be considered for 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 would transform the Flip Chip into a true package. Most packaging specialists require that a package must be removable and preferably reworkable to qualify as a genuine electronic package. Chip Scale Packages (CSP) have had the advantage of reworkability along with other features, but at a cost penalty. The addition of a solid reworkable flux/underfill to the FC moves it to the CSP domain. There are very significant ramifications for this type of package. We may note that wafer-level flux-underfill moves the material application from the assembler to the semiconductor realm.

There are at least three approaches for constructing a *ready-to-assemble* Flip Chip Package. A single material approach can be used where flux and underfill properties are achieved in a single system. This is the approach taken by those involved in pre-dispensed liquid underfills, but out of necessity. 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 two-layer system is also feasible because of the solid materials. Underfill and flux can be kept separate making the chemistry easier, but application more complex. The two-layer system is referred to 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.

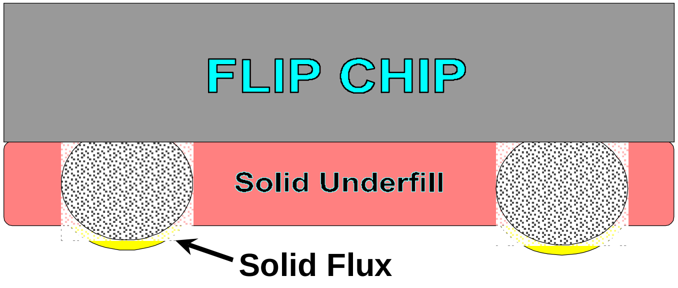
Solid underfill can also be applied to the wafer before it is bumped. Lasing or other imaging means could be used to open chip pad areas prior to bumping. Flux would be applied after bumping.

Two-Layer Flux & Underfill Applied to Bumped Wafer (Type 2)

The two-layer concept involves applying a reworkable underfill to the bottom of the bumped chip at wafer-level and flux to the proximity of the bumps. The underfill can be a thermoplastic that introduces the reworkability property. The material could be applied as a liquid or paste from solvent 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 the preferred approach. A variety of thermoplastics are available that can be considered. Thermoplastic films and pastes are now used for reworkable die attach applications[7]. Some of these die attach products are applied as pastes to the back of wafers followed by drying as mentioned earlier. These systems can be modified with the appropriate silica fillers to become underfills coated onto the active side of the die. We have selected several thermoplastic resin/solvent systems from our Staystik die attach adhesives line for modification into underfills.

The next step is to apply the flux to bumps although this can also be done prior to underfill application. Again, a number of methods are available, including simply dipping the wafer into a thin layer of flux so that only the bumps are coated. Today, flux is applied to the bumps of individual Flip Chips by just such a dipping method using a rotating fluxing drum available from many assembly machine vendors. Drying would harden the flux, once applied. Figure 4 shows the final result for the two-layer process. The flux system that we have chosen is a solid version of our commercial epoxy-based flux called Chip Flux 2020.

Figure 4 – Type 2 Flux-Underfill System



Type 2 Flux-Underfill System

Single-Layer Flux & Underfill Applied to 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°C. Our own 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.

Coat-First Flux-Underfill System

We have previously demonstrated that thermoplastic die attach adhesive pastes can be precisely applied to wafers, but to the back. Spin-coating is the most common method, but stenciling and screen printing are also used. Once the solvent-based polymer is applied and leveled, the material is converted to a solid film by oven drying. These processes have been used commercially with some of the Staystik® die attach pastes.

Thermoplastic die attach films are often pre-cut into complex shapes called preforms for use in attachment of modules and other small circuits that must be electrically or thermally connected to housings and other circuits. Laser machining has been used for some time for efficiently and cleanly cutting both filled and unfilled films.

A wafer-level underfill could be applied to the active side of a wafer by the same techniques. The dried thermoplastic underfill film would then be patterned by laser machining, to open the chip pad areas that would already have Under-Bump Metalization (UBM). Any number of conventional or novel techniques would then form solder bumps. Solder paste stenciling, followed by reflowing would be a likely candidate method. The thermoplastic underfill could reach a softening point provided that no deleterious deformation occurs. Metal Fluid Jetting (MFJ) and even solder wave coating, could be practical.

STATUS

The type 2 system was constructed by dip coating flux onto bumps and drying, followed by stencil printing thermoplastic paste onto the wafer. The dried 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 running 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 product 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 5 shows the 12.5 mm x 12.5 mm quartz chip applied to a copper disk after a type 2 system was constructed.

Figure 5 – Type 2

Work also continues on the type 1 system that is based on an epoxy flux system, but with monomers that can give linear polymers. The material has an initial melting point of 100^{o}C while in its flux phase. Exposure to reflow soldering conditions causes the melting point to increase to around 150^{o}C. Adjustments are being made to increase the melting point to about 180^{o}C.

We have previously demonstrated that thermoplastic die attach adhesive pastes can be precisely applied to wafers, but to the back. 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 Metalization (UBM). Solder bumping methods will include printing paste, but also Metal Fluid Jetting (MFJ) and 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 the 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 is likely 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 moved from board-level application to semiconductor processing. The bumping provider may ultimately become the underfill supplier offering “flipped underfill” with Flip Chips.

Acknowledgements

Professor Daniel Baldwin, of Georgia Tech, provided helpful discussions related to pre-dispensed underfills. Rick Godin, of MPM/Speedline, offered insight into Metal Fluid Jetting.

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