Managing Voids in Underfill Process with 5-micron Gap Under Large Die

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Abstract

Microelectronic packaging is continuously becoming smaller and denser, thus allowing for more functionalities and smaller devices including portable products. Flip-chip among other technologies continues to enable such trends. In fact denser arrays such as copper pillars or micro bumps of various metallurgies seem to be the technology of choice for the near future electronic interconnect. A technique is reviewed for successfully underfilling a $3cm^2$ Indium Phosphide flip-chip die mounted on a silicon substrate with 5 microns gap and large number of I/O (about 0.3 million indium bumps) connected in daisy chains. The method that resulted in a void-free underfill consisted of line dispensing along one side of the die such that the flow of the capillary fluid was normal to the direction of the daisy chains. For dot-dispense, substrate surface treatment and more careful design of dispense sequence helped to reduce voids. This study was compared to a manual dot-dispense technique that was unable to meet production throughput requirement, accuracy, repeatability and void-free. Achievement of void-free automated underfill into a 5-micron gap with complex features underneath a large flip chips will encourage today's microelectronic packaging industry to meet the challenges of smaller and denser components.

Key words: flip chip, underfill, capillary force, dispense, voids, surface treatment

Introduction

The usage of organic flip chip has introduced an important step of underfill into the assembly processes [2, 5, 6]. Underfill encapsulation which uses a thermoset polymer epoxy that fills the gap between the flip chip and the substrate. Underfill helps reduce stress on the bumps caused by a thermal mismatch between the die and the substrate, limits creep movement of solder joint and reduces cracks that are initiated at the bounding interface [6].

Capillary underfill is used to create a pseudo-hydrostatic compression interface for the interconnect components between the flip chip and silicon substrate. It largely enhances the solder fatigue resistance and provides mechanical support to the flip chip interconnect assembly [3]. The technology to underfill flip chips was introduced in 1980's and was broadly accepted as an industry breakthrough. It has been the electronic packaging standard since 1990's. There are reviews and technical papers of capillary underfill in literature and the mechanism underneath is well known. Polymer epoxy is dispensed via jetting along the die edge and the surface tension pulls the fluid into the gap between the flip chip and the substrate. Jetting here means that the fluid droplet or stream has enough momentum to break from dispenser nozzle and to shoot on the substrate. The underfill process follows Young-Mills equation that relates fluid surface curvature to pressure difference across the surface and momentum conservation law during the underfill process [1, 3, 7]. It derives the popular equation of underfill flow out time, T, which is proportional to the fluid viscosity and the square of the chip length, and inversely proportional to the gap height, surface tension and cosine of the contact angle. Then epoxy cures at room temperature or higher. To speed the underfill process, substrate is heated (typically 70^{o}C-90^{o}C) to reduce fluid viscosity. Underfill should fully fill the entire space under the chip without air bubbles or voids. If voids or bubbles are present, they tend to lower the support for the bumps due to reduction of hydrostatic compression around the bumps.

The industry request of smaller and denser components in flip chip (e.g. 50-75um gap and 100-200um pitch) constantly push underfill application engineers and scientists to the frontier of their fields. To redefine technical limits, advanced dispense solution, new fluid and surface treatment appear to target quicker underfill time and fewer voids defects [4].

Nordson Asymtek recently worked on a project for an automated dispense application for an underfill encapsulation of an Indium Phosphide flip chip, bonded on a silicon substrate (figure 1a). The gap between the flip chip and the substrate is 5um and the die is 1.79cm in width and 1.57cm in length. The Indium bump pitch is about 25um.

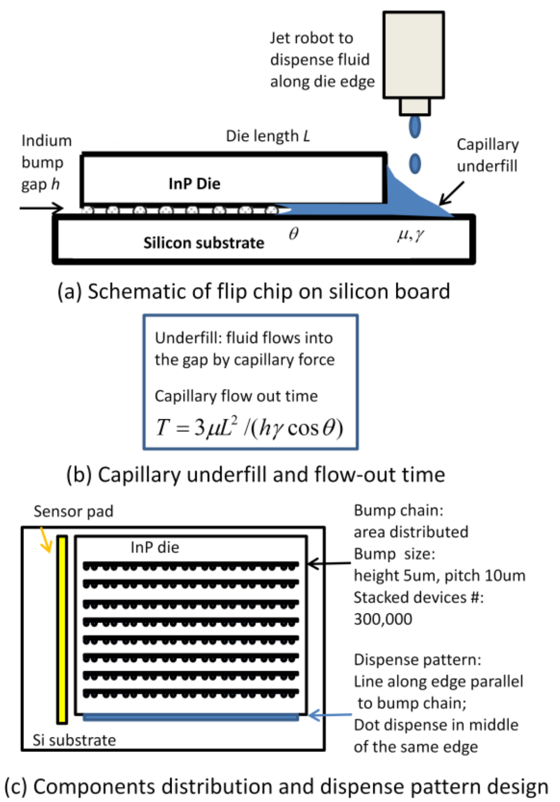


Figure1. (a) Schematic of InP flip chip attached to silicon substrate though Indium bumps, (b) Capillary underfill process, (c) components distribution on device and dispense pattern design.

The challenge of this work comes from the 5um gap and 25um bump pitch, both of which are one order of magnitude smaller than industry standard minimum (e.g. 50um gap, 200um bump pitch). Underfill time would be more than one order of magnitude longer than regular small gap underfill. This is not a major concern for automated dispense system which applies parallel processes of component load, pre-heat, dispense, post-heat and unload. Also, automated dispense system is able to dispense other units during the wait time between multiple passes for one unit. The throughput in this case is determined by underfill flow time divided by the number of units processed in parallel. Today's cutting edge dispense technique, high speed jetting and motion control make the total dispense process only a few seconds per unit.

Void defects around dense and small bump arrays are a major concern for this study. Indium bumps of 5um height and 25um pitch interconnect 300,000 devices within the silicon substrate. These 300k devices with bumps are connected as bump chains and are area distributed as shown in figure 1 (c). Epoxy is mixed and de-gassed in a centrifuge prior to use. Epoxy is then introduced into the dispenser using a prime process to limit air bubbles in the fluid inside the dispenser. Dispense configuration that provides best dispense parameters and the least possibility of voids is then chosen. Dispense pattern is carefully designed based on both the distribution of bumps underneath the die and the dimension restriction by components around the die (figure1 c).

Epoxy with viscosity of 225-425 cPs and pot life of 8 hours is used for this 5um gap underfill (6 hours fluid working time is minimum for daily production). The "fast flow" version for this fluid with viscosity of 100-200 cPs was also tested in manual process for comparison. The fluid cures at 80C for three hours, or 23C for 48 hours. Substrate heating is used for faster underfill times. Underfill flow out condition was visually monitored through a machine camera and high resolution microscope. Underfill void defects were inspected with IR microscope.

For the manual dispense process to underfill the 5um x 3cm^2 gap, a capillary tube is used to transfer fluid in a form of a droplet. The fluid droplet is placed in the middle of the long side of the chip while using a stereo microscope. This process allows for underfilling 3 to 5 parts per day with a limited control of the fluid weight or volume. During dispense, components next to the die should not to be contaminated. Using this manual process with dispense weight accuracy of ±0.3mg, the finished part will likely be either under fed (fluid dose not flow out along the four edges) or over fed (fluid flows out, spreads and wets the sensor area). In this study, we are looking into opportunities to have process automation with precise control of dispense weight and position.

Setup and experiment design

Nordson Asymtek Spectrum 820 and DJ9000 are used for this study to provide process automation, high throughput, accurate dispense volume, precise location and real time mass flow verification to track fluid viscosity.

Jetting of a single line beside the long edge of die (figures 1c) is studied first. This long edge is parallel to area distributed bump chains which allow the underfill fluid to flow across the bump chains while generating fewest voids [4]. It should be noted that this underfill flow time is longer than underfill flow time along the bump chains. Jetting will dispense the line within one second, allowing the full length of underfill front to simultaneously reach and cross the bump chains. This reduces the possibility of fluid to wet along the chains causing more voids. Three 0.5mg lines were dispensed for the total of 1.5 mg with the time interval of 2-3 minutes between the first two line dispenses, and then 5-7 minutes before the third line dispense. The time interval is based on observation of slight over feed at the gap entrance and without significant accumulation (figure 2). The total dispense time is about 16 minutes. Total underfill flow time is about 30 minutes, which is 15 minutes faster than manual dot dispense.

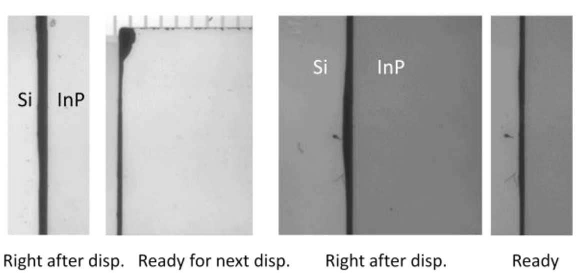


Figure 2. (a) Line and (b) dot dispense on parts.

Dot dispense is also studied due to potential restriction on dispense location (figure 2b). 30-35 dots of 0.05mg each were jetted in the middle of the die edge. Dispense interval between each dot was 10 seconds which was gradually increasing to 1 minute. Utilizing the dot dispense process, the fluid fills the gap slower than line dispense, with total dispense time about 22 minutes. Underfill flow-out time was 30 to 40 minutes.

This experiment design also includes a preliminary study of improving voids when dispense is performed via a dot dispense. If dot dispense is utilized, the underfill front will arrive at the center of bump chains earlier than it arrives the periphery area. Then the fluid front might quickly wet along the bump chain in the direction from center towards side edges. This may introduce non-uniform wetting and trap air bubble around periphery area between bump chains and die edge. Plasma surface treatment was applied prior to dispense in order to enhance spreading of fluid along the die edge. This test was performed on a glass slides 38umx5cmx3.75cm and black underfill fluid.

Results

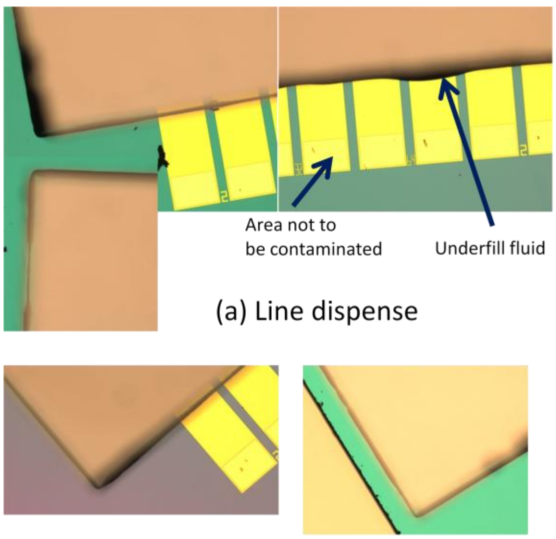
Substrate temperature of 40-50^{o}C was chosen for this study for faster underfill. Fluid was jetted on glass slides to inspect dot and line appearance. Dots land on glass from 1mm dispense gap with no satellite or splash. Dot and line thickness was measured and used as reference for dispense distance from the die edge.

Fluid was then jetted on parts, from 1mm height above the silicon substrate (0.3mm higher than die) and 0.375mm away from the InP chip edge where underfill starts. Fluid properly wets silicon substrate while keeping the InP die clean. The fluid then immediately entered the gap and continuously flew in. Fluid was pulled into the 5um gap by capillary force.

Time interval between the dispense time of the line and the dot was determined based on observation, e.g. to start the next dispense as quick as possible with no significant fluid accumulation, or to start next dispense as slow as possible without starving the underfill process.

Precise weight control to full fill gap without contaminating nearby sensors

System calibrated process jetting (CPJ) allows for precise weight control for dispensed dots and lines which is useful for (1) underfill application with tight keep-out zone and (2) a process that needs to constantly adjust for varying fluid viscosity. For example in this study, underfill fluid needs to fully fill the gap without contaminating components that are 0.8mm away from the die. Also, the fluid pot life is 8 hours so fluid viscosity increases within the first few hours. Once jetting configuration is determined, the system can jet a certain number of shots into a scale embedded in the platform. The system weighs the total amount of the dispensed fluid and calculates weight per shot. The dispense program defines the total weight of a line or dot and system will calculate the required number of shots to meet the requirement.



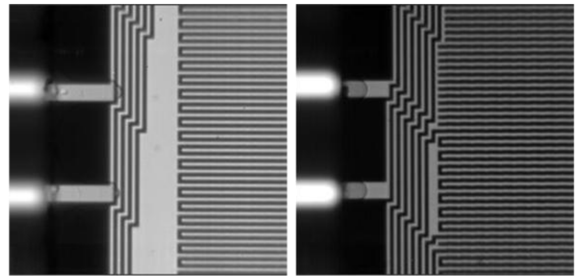
(a) Line dispense

(b) Dot dispense

Figure 3. Cured underfilled parts by (a) line and (b) dot dispense on customer parts: weight control CPJ provides full fill of the gap without contaminating nearby sensors (800um away from die edge).

Study under micro scope clearly showed that, after cure, 1.5-1.7mg line or dot fully filled the gap underneath the die with a small fillet along the edges of die (figure 3). Underfill fluid appeared along all four edges of the die while no contamination on the components was observed, e.g. metal probe pads 800um away from the die edge.

Both 1.5mg and 1.7mg to fully fill the die gap without contaminating adjacent sensors. Critical difference was observed under high precision IR microscope. In line dispense (figure 4), extra 0.2mg of fluid provided more fillets around the InP chip that prevented air penetrating into die gap though mini channel between bound pads, a phenomenon caused by fluid shrinkage during cure or temperature drop when parts were transported from heated underfill platform to preheated oven.



(a) Line dispense 1.5mg (b) Line dispense 1.7mg

Figure 4. Extra 0.2mg of fluid provided fillets that prevented air penetrating into die gap though mini channel between bonding pads, a phenomenon caused by fluid shrinkage during cure or temperature drop when parts were transported from heated underfill platform to preheated oven.

<u>Void-free by line dispense parallel to area distributed bump chains</u>

Underfilled parts were cured and inspected under Infrared microscope. All parts that were dispensed by lines were shown to be free of any voids (figure 5a). According to the orientation of the bump chain, fast dispense of multiple thin lines along the die edge parallel to chain array is the ideal dispense pattern.

Parts that were dispensed by the dot dispense had large voids or air bubbles around the periphery of bump chains, i.e. between the bump chains and die edge. Small voids were also observed within bump chains, especially around those distorted bumps. However, there were cases of voids-free within bump chain by the manual dot dispense using the fast flow version of the underfill fluid. This fast flow fluid was not tested by automated dispense.

Underfilled parts that were dispensed by manual or automated dot dispense always have one or more large voids around the lower corners of die which were close to the edge where underfill initiates (figure 5b, c). This illustrates that this void is caused by the pattern of dispense location. Larger voids were observed when parts were dispensed with aged fluid. Fluid viscosity tends to increase and the flow rate decreases.

The case of the fewest large void by dot dispense was observed when fluid was in early part of its pot life, and shorter intervals were used between 30 dots of 0.05mg each. For example to underfill the part shown in figure 5 (b), fluid was at the middle of its pot life with no drop in flow rate, thus no change in fluid viscosity. Dot dispense interval was short as to not result in significant fluid accumulation at the dispense spot. Total time for fluid to fully fill the gap was similar to that by line dispense. For this case, a few small voids were observed within bump chains which suggests that higher substrate temperature or surface treatment are needed for lower friction around the Indium bumps.

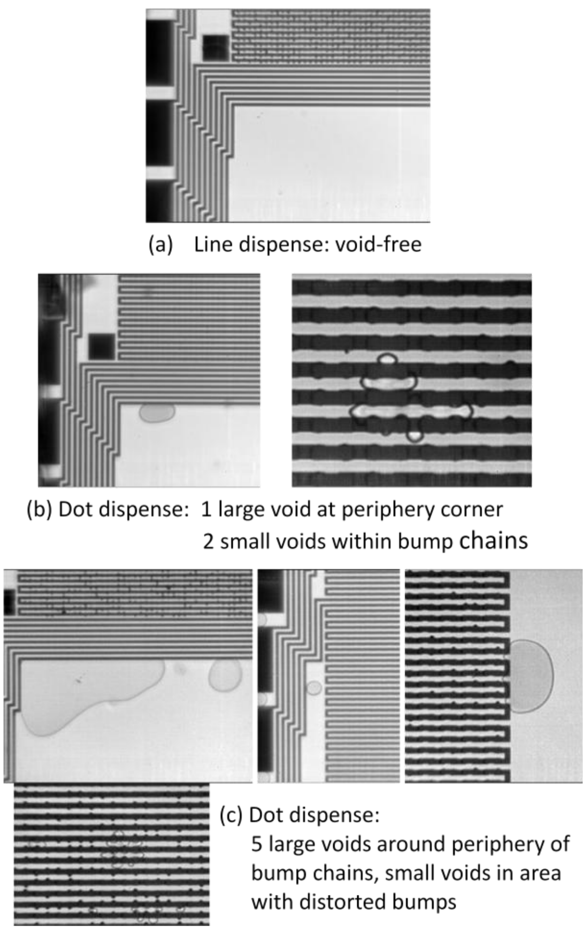


Figure 5. (a) Void-free line dispense and (b, c) trouble shooting on dot dispense induced voids around die periphery area between bump chains the die edges, and within bump chains.

The big voids by dot-dispense, in the original manual process and present automatic process, are not in the bump chain area. These voids are around the periphery of bump chains. In cases of manual dot dispense, when lower-viscosity version of the same fluid was used, there were no voids in the chain area. However, air bubbles still exist around the chain periphery. So in further study to reduce voids by dot dispense, we focused on the large voids generated around periphery. It is believed that these voids are air bubbles trapped by fluid not uniformly wetting around components or die corners. For the present case of dot dispense, after underfill reaches the bump chain, fluid tends to move along the bump chains and toward the side edges. This fluid pattern causes a non symmetrical wetting around the periphery of center area of the distributed bump chain arrays. The size of those air bubbles is measured to be in the range of 50-100um. Quick line dispense will have fluid front arrive the bump chain at the same time and then cross the bump chains slowly and uniformly.

In the following subsections, we optimize the dispense methodology to improve flow uniformity and corresponding reduction in air bubbles.

Control of fluid feeding interval to provide steady boundary condition

All parts that were line dispensed were inspected to be voids free. Time intervals between the three 0.5mg line dispenses were carefully adjusted to make sure that fluid was dispensed shortly after most of the fluid had flown into the gap but before the fluid completely flown under the part. The time intervals for line dispense was 2-3 minutes between the first two 0.5mg dispenses, then 5-7 minutes to dispense the rest 0.5mg. If complete fill was not observed during inspection, extra 0.2mg was added 15 minutes after the third 0.5mg dispense. The total complete underfill time was around 30 minutes. It was determined from IR inspection that this 0.2mg extra material helped to prevent air penetration into the gap caused by fluid shrinkage. To optimize machine time, three sequences of 0.57-0.6mg dispense would be ideal, such that the total dispense time is 8-10 minutes. Multi-pass function allows dispensing other parts during the waiting time.

It is more challenging to provide uniform underfill using dot dispense as it was found to be the case in this study. Large voids (air bubbles) were observed by IR microscope at the part's lower corners showing the geometry effect. To reduce voids, faster dispense of dots is better as long as fluid does not significantly accumulate and spread out. The optimized time interval (finished part example in figure 5b) between dots is shown in table 1 below. The total machine time is 22minutes, 6 minutes longer than the above line dispense.

Table 1. Time interval between 0.05mg dots.

Dot sequence	Waite time (sec)
1st and 2nd	0
2nd and 3rd	10
3rd and 4th, 4th and 5th	20
5th and 6th	30
6th and 7th, 7th and 8th	40
8th and 9th … 22nd and 23rd	45
23rd and 24th … 29th and 30th	60

A preliminary test of surface treatment that improves flow uniformity by dot dispense

Dot dispense may be preferred due to potential dimensional restrictions of the dies. In this further study, we focus on making underfill by the dot dispense to be as capable as line dispense. One approach is, the moment that the fluid is entering the gap, to make the dot spread quicker along the edge than it moves inward. Plasma treatment will help to provide a cleaner and more active surface at the gap entrance than the area deeper into the gap. This is due to limited mean free path for ionized gas particles during the plasma treatment process.

This is a preliminary study, not applied to actual parts. For better control of the experiment and to track instant flow condition underneath the gap, transparent glass slides and black underfill fluid were used. This test fluid had a viscosity, at temperature of 60-90^{o}C, in the same range as that of the clean fluid used by this study at temperature of 20-50^{o}C. The glass chip is 38um x 5mm x 3.75mm to maintain a similar effect on fluid traveling time (t ~ Length^2 / Gap) as that of the actual parts (5um x 1.79mm x 1.57mm). Glass parts were prepared in two conditions, (1) pre-baked at 165C for 1 hour, (2) prebake and then plasma treated for different surface energy, e.g. mild, median, strong treatment. Dot dispense is done by hand and time interval is short but without significant fluid accumulation around the dispense location. Glass part is placed on a hot plate for substrate temperature control.

Pre-baking for improved moisture control of the underfilled surfaces is considered a basic step for surface treatment/maintain prior to underfill. Substrate heating allows the underfill to flow faster. The underfill gap significantly affects fluid spreading at the gap entrance. Fluid flow from dot dispensed underneath smaller gap (e.g. 38um compared to 60um gap) tends to be faster along edge than it is for underneath a larger gap. With substrate temperature set at 90^{o}C, a faster spreading of fluid along edge of the gap was observed on parts that were pre-treated by plasma (figure 6 a-c).

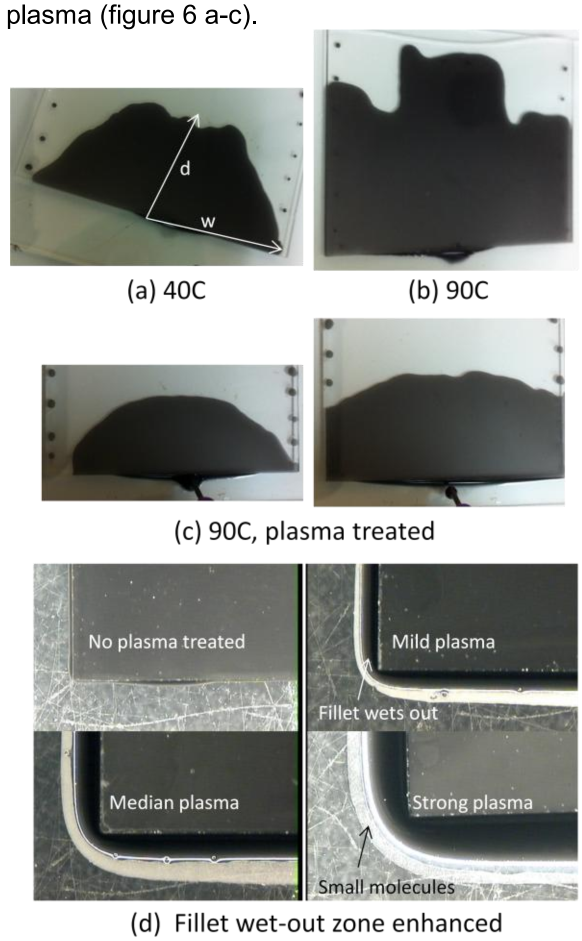


Figure 6. Dot dispense on glass test parts with gap of 38um. Substrate temperature and surface treatments are (a) 40^{o}C, (b) 90^{o}C, (c) 90^{o}C, strong plasma treated along the die periphery area, (d) underfill fillet wet-out zone enhanced by plasma treatments.

This enhanced flow speed toward the side edge of underfill front can be quantified by the ratio of length that the front travels inwards divided by length towards the side edge. This ratio is calculated from the moment when flow reaches side edge, i.e. *d/w* shown in figure 6(a). Table 2 contains the ratio at different experiment conditions, e.g. temperatures of 40°C, 90°C, 90°C and mild, median and strong plasma treatment with center area blocked or not, 90°C and strong plasma treatment for larger gap 60um. For plasma treatment, some of the slides have the gap blocked among the center area such that only 3-4mm width area underneath the gap is exposed to plasma. This is similar to condition for actual parts since the dense bump chain will block most plasma gas. The plasma used for this study has particle mean free path of approximately one millimeter so there is only slight difference in spreading speed along edge as the function of the gap center being blocked or not.

Table 2. Underfill front orientation and fillet wet-out zone width at different experiment conditions.

Experiment conditions	Underfill moving inward / towards side edge, d/w	Fillet wet-out zone (mm) of large, small molecules
90°C, strong plasma, large gap	1.16	
90°C	0.92	0.112, 0.120
40°C	0.8	
90°C mild plasma on edge only	0.7	0.522, 0.732
90°C median plasma	0.65	
90°C, median plasma on edge only	0.6	0.748, 1.192
90°C strong plasmas	0.6	1.245, 1.838

A side effect should be noted. The surface treatment can increase fillet wet-out zone along the edge which may contaminate components by the die edge. This fillet wet-out zone width is shown in figure 6 (d) and included in table 2. The dark zone is the fillet fluid and the light areas are small molecule materials from the fluid. Considering both the enhanced spreading of fluid along edge within the gap and wider fillet wet-out zone, mild plasma treatment may be considered for further study on actual parts. The recipe for this treatment is 100 watts power at 30% of 100 sccm Argon gas flow for duration of 1 minute, with pressure around 360 milli-Torr.

As a summary, the preferred solution to duplicate an “I” line dispense from dot dispense on glass slides is to use higher substrate temperature, slight over dispense at gap entrance, smaller underfill gap and mild plasma treatment. Since the actual part has underfill gap of 5um, i.e. fluid wets slower overall while moves quicker along the entrance edge, the optimal parameter settings to achieve uniform wetting front may change from what was learned from the above test.

Once again, it is observed that a precise control of dispense weight and the time interval between dispenses are critical to reduce voids and air bubble under a die with small gap with complex structures.

Conclusion and discussions

Aided by a state of the art automated dispenser, we were able to achieve void-free underfill in a 5 microns gap flip chip with complex features. The challenge of this work is the 5um bump gap and 25um bump pitch, both of which are one order of magnitude smaller than industry standard minimums (e.g. 50um gap, 200um bump pitch). Small dots of few nanoliters were jetted from above the die and quickly formed a thin line beside the die edge which is parallel to area distributed bump chains. This dispense method allows the capillary underfill fluid front line to reach the first row of bump chain at the same time and then to flow across the bump chains while generating fewest voids. Lines were dispensed multiple times in certain sequence to fill the gap. All parts underfilled by the line-dispense process were investigated to be voids-free after cure. For dot-dispense, substrate surface treatment and more careful design of dispense sequence helped to reduce voids.

In this study, the improvement of dispense method on actual parts include, (1) use of state of the art automated dispense at higher throughput and precise control on weight, time and position, (2) changing from dot dispense to high speed line-dispense along one side of die such that the flow of capillary underfill fluid was normal to the direction of bump chains and resulted voids-free underfill, (3) to use time-dependent dispense interval to ensure the gap entrance constantly supplied with fluids without significant accumulation, (4) to constantly check and correct system mass flow rate which compensates for variation of key parameters including viscosity, increase fluid and substrate temperature to maintain faster underfill with fewer voids. Due to potential dimensional limitation, follow up study will focus on dot dispense optimization to also achieve voids free and faster underfill. Parameters in this experiment will include (1) higher substrate temperatures of 60°C-80°C, (2) the fluid used in this study as well as its fast flow version, (3) various levels of plasma treatment at the gap entrance. Preliminary test on plasma treatment was done on glass test slides. Pre-baking to remove surface moisture is required if parts are not maintained in humidity controlled environment.

Acknowledgement

The author would like to thank Doctors Horatio Quinones and Jiangang Zhao for their guidance, Mr. Mani Ahmadi for his support.

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