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## Mask and Mask-less Injection Molded Solder (IMS) Technology for Fine Pitch Substrate Bumping

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# Mask and mask-less injection molded solder (IMS) technology for fine pitch substrate bumping

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## Abstract

We report the results on a new pre-solder bumping technology of injection molded solder (IMS) for fine pitch organic substrates. Pure molten solder is injected through a reusable film mask (mask IMS) or directly injected without a mask (mask-less IMS) on the pads of an organic substrate to overcome the limitation of current pre-solder bumping technologies such as solder paste stencil printing and micro-ball mounting.

In the case of mask IMS, targeted solder height over the solder resist (SR) is designed into the mask which has desirable thickness and holes size. Three different solder bump heights such as 30, 50, and 70 microns over SR were demonstrated for commercial organic substrates which have a pitch of 150  $\mu\text{m}$  for 5,000 area array pads. To show the extendibility of the mask IMS bumping method to very fine pitch applications, 100  $\mu\text{m}$  pitch bumping of 10,000 pads and 80  $\mu\text{m}$  pitch bumping of 15,000 pads were demonstrated.

In mask-less IMS, the pure molten solder is directly filled into the opening volume of the SR. After the injection of molten solder, solidification of the solder under low oxygen leads to solder protrusions above the SR surface because 100 % pure solder is filled into the whole SR opening volume. For a 150  $\mu\text{m}$  pitch commercial substrate, we demonstrated minimum bump heights of 15  $\mu\text{m}$  over the 20  $\mu\text{m}$  thick SR. Since there is no need to align mask and substrate, the mask-less IMS method lowers process costs and makes the process more reliable. By manipulating the opening in the SR, it is possible to enable variations in the height of the solder bumps.

Flux or formic acid is not needed during solder injection of both described processes, but a low oxygen environment must be maintained.

In this paper, we will discuss laboratory scale processes and bump inspection data, along with the discussion of manufacturing strategies for IMS solder bumping technology for fine pitch organic substrates.

## 1. Introduction

In first level organic packaging, flip chip interconnects are formed by the connection between solder or copper bumps on

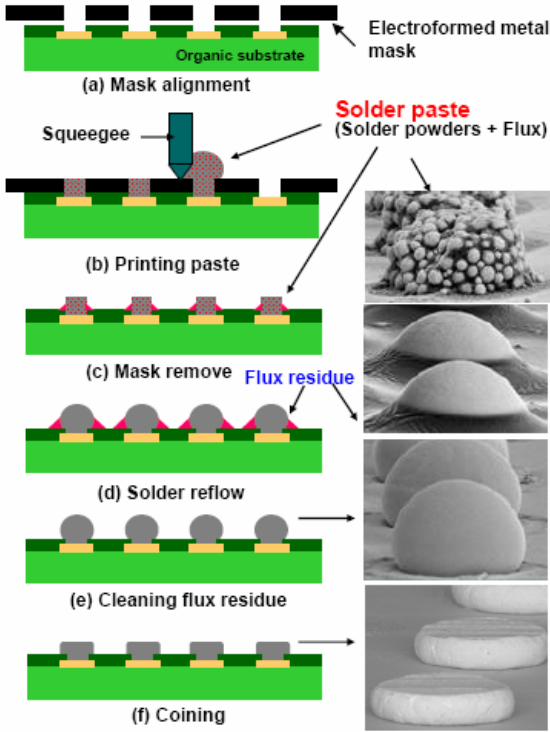
the chip side and pre-solder bumps on the organic substrate side. The pre-solder bumps on the substrates help to overcome flip chip assembly yield losses caused by substrate warpage and die bump height variations.

The pre-soldering process is not an expensive process in the overall organic substrate manufacturing process, but it is a very important process because the role of the pre-solder bumps is getting more important as flip chip technology requires continuously higher performance.

Recently, many researchers have reported that copper column flip chip joints can handle higher current density and have stronger resistance against electromigration induced failure [1-3]. The thick copper die bump helps to move the current crowding region from the solder region to the copper region in a flip chip joint [4].

When copper column bumps are used as die bumps, the pre-solder bumps on the substrate need a higher volume and better co-planarity than conventional pre-solder bumps which are for solder die bumps. Since copper is stiffer than solder materials, copper columns in flip chip interconnects lead to increased chip-package-interaction stresses transmitted to the back-end-of-line of low-k or ultra low-k layers. Therefore, a desirable copper/solder ratio per joint is needed to reduce stresses. Increasing the substrate pre-solder bump volume decreases the copper/solder ratio per joint and helps reduce the stress. Also, when copper die bumps are used without solder caps, the flat copper bump requires a round pre-solder bump top on the substrate to avoid void formation at the copper/solder interface after assembly processing. Therefore, round pre-solder bumps require good co-planarity without the need of a bump coining process.

The current manufacturing technology for forming solder bumps on organic substrates is the solder paste stencil printing method [5]. Figure 1 shows the process flow of the solder paste stencil printing method for organic substrates. The stencil printing method is suitable for forming low cost pre-solder bumps on pads of organic substrates which have island type I/Os because no additional lithography is needed. However, due to significant volume reduction of the solder paste after reflow, the maximum pre-solder bump volume is limited for a given pitch using the stencil printing method which therefore can not readily be extended to less than 150 micron pitch. The flux volume in the solder paste is about 50 %, and flux bridging after stencil printing leads easily to pre-solder bump bridging after solder reflow.

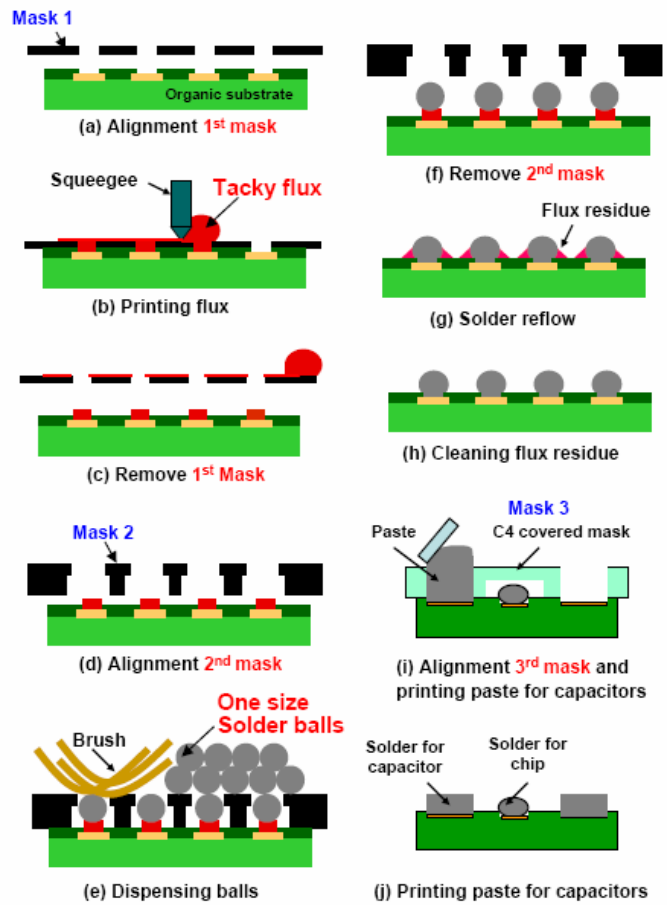


**Figure 1.** Stencil printing method for substrate bumping.

Pre-solder application technologies such as micro-ball mounting eliminate the volume reduction problem by using preformed solder balls and tacky flux applied separately in place of solder paste [6]. Figure 2 shows the process flow of solder bumping on organic substrates by the micro-ball mounting method. Clearly, the micro-ball mounting process is complicated and more expensive than the stencil printing method. Two masks and thus two alignment steps are needed to dispense the tacky flux and the micro-balls respectively for the C4 pads. The cost of pre-form solder balls increases significantly as the ball size decreases. An additional mask and alignment step is needed to screen solder paste for capacitor pads which need more than 20 times the solder volume of C4 pads. Thus an additional stencil printing process is required to form solder bumps on the capacitor pads after the ball mounting process for the C4 pads. Further, the micro-ball mounting method can not be used to bump different size C4 pads on one substrate because only one size preformed ball can be used per mask. If the same solder volume is used for differing pads sizes, solder bump height co-planarity suffers. There are many patents to introduce methods to form co-planar pre-solder bumps for variable solder resist openings on one substrate using the micro ball mounting technique [7,8]. However, those methods are very difficult to realize in a manufacturing process.

We report here results for two types of new solder bumping technologies for fine pitch organic substrates. Pure molten solders are injected onto the pads of organic substrates

through a reusable mask (mask IMS) or are injected directly without a mask (mask-less IMS).



**Figure 2.** Micro-ball mounting method for substrate bumping.

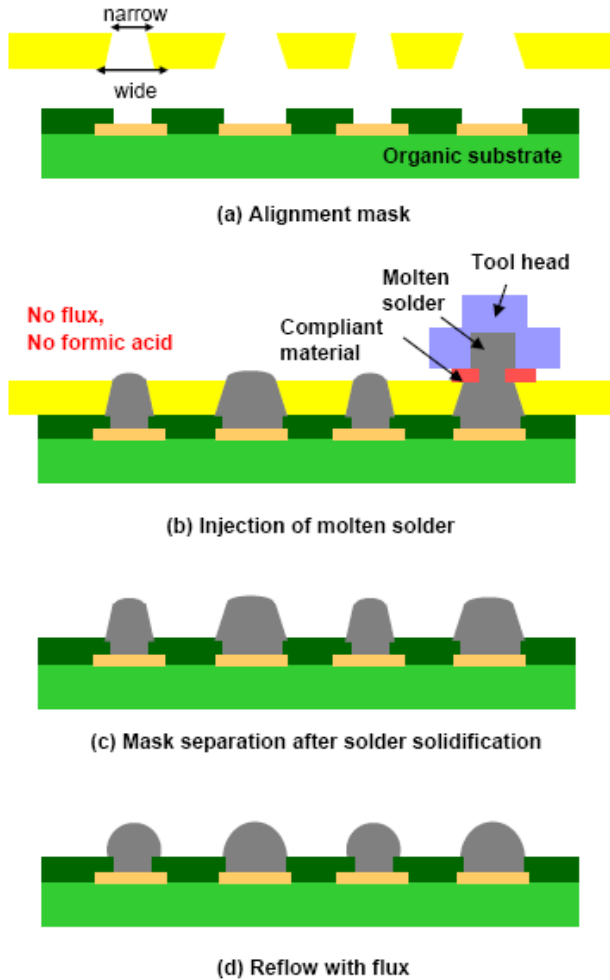
## 2. Experiments

### 2-1. Mask IMS

The experimental procedure for mask-IMS substrate bumping is shown in Figures 3 and 4.

First, a flexible mask is prepared by programmable UV laser drilling of a Kapton® polyimide film based on the design of the position of the solder mask openings of the organic substrate. The holes in the mask have a tapered sidewall which helps to ease separation of the mask after solidification of the injected solder. The holes in the polyimide (PI) mask are aligned to the substrate pads with the wider mask hole openings facing the organic substrate. After aligning mask holes and substrate pads using a process in which pressure and temperature are optimized, the tool head scans the surface of the film mask, and molten solder is injected into the aligned holes. The molten solder fills the holes in the mask and the solder resist pad volume of the substrate. The flexible mask follows any substrate non-flat contours and enables good contact between mask and organic substrate avoiding solder leakage. As shown in Figure 3 (b),

the solder injection tool head is provided with a compliant material which spreads the compressive force between head and film mask, resulting in good contact between tool head, mask, and substrate, such that gaps that could cause leakage are eliminated. The mask is sufficiently flexible to track the topography of the substrate under the influence of the compressive force that is distributed by the compliant material [9]. The compliant material also works well to wipe molten solder after injection from the tool head, so no solder material is left on the surface of the mask.



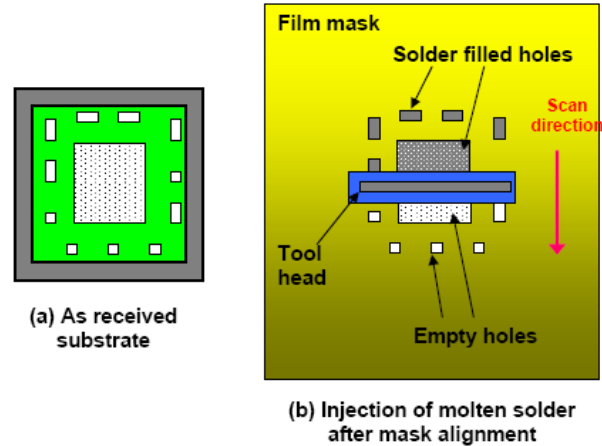
**Figure 3.** A side view of the mask-IMS method for substrate bumping.

For the molten solder injection process, flux or formic acid are not needed, only environmental control to guarantee a low oxygen content to prevent pad oxidation is required. After the solder has solidified and adheres to the pads, the mask is separated from the substrate and is reused in the next run. The solder volume over the solder resist is identical to the mask hole volume. The pre-solder bump volume above the solder resist can be changed easily by changing the mask hole size and / or the mask thickness. Also, the pre-solder bump co-planarity is very good even if the opening diameter and the thickness of the solder resist are not uniform.

As shown in Figure 3, IMS can make various pre-solder bump volumes in a single pass and still maintain good co-

planarity when the substrate has differing solder resist opening diameters.

The mask-IMS process is simple and similar to the stencil printing method, but IMS can achieve higher volume solder bumps for a given pitch and can be applied for finer pitch applications because only molten pure solder is used instead of solder pastes which have 50 volume % of flux.



**Figure 4.** A top view of the mask-IMS method for substrate bumping.

## 2-2. Mask-less IMS

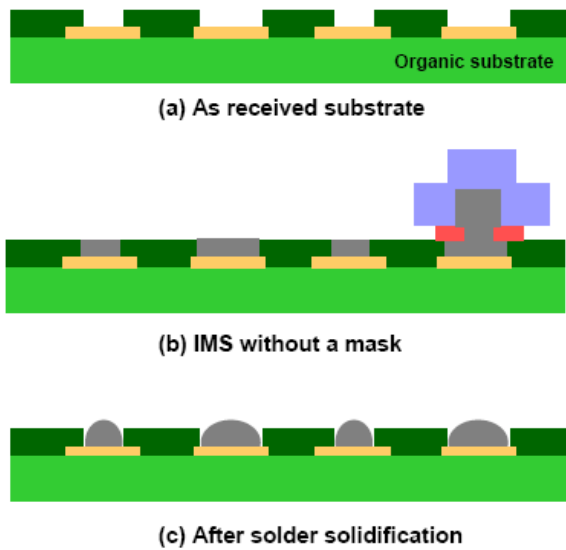
Whenever masks are used for a solder bumping process, the issue of mask cost and alignment between mask and substrate arises.

As described in Figure 3, a compliant material on the bottom of the application head spreads out uniformly the compressive force and prevents leakage between tool head and mask and between mask and substrate. Therefore, when a low-friction compliant material is used, the formation of pre-solder bumps on an organic substrate using molten solder injection is possible without a mask.

The process flow of mask-less IMS bumping for organic substrates is shown in Figure 5. The solder resist layer defines recessed regions with a certain volume above the wettable pads. Molten solder is directly injected into this volume and fills the solder resist opening completely. After solder solidification in a low oxygen environment, the solder forms generally spherical balls which extend above the surface of the solder resist layer.

In the mask-less IMS method, there is no issue with alignment between mask holes and substrate pads. Since mask alignment is a time-consuming process step, elimination of this step lowers the process cost and makes the process more reliable.

Detailed experimental results will be explained in the Results and Discussion section.



**Figure 5.** Schematic diagrams of maskless-IMS method for substrate bumping.

### 3. Results and Discussion

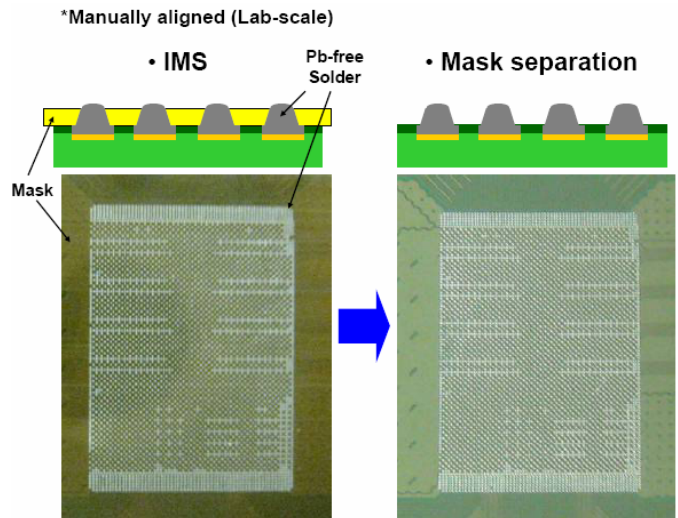
#### 3-1. Mask IMS on 150 $\mu\text{m}$ pitch organic substrates

In lab scale processing, the mask IMS substrate bumping technology has been developed using singulated organic substrates with a minimum pitch of 150  $\mu\text{m}$ . The size of the organic substrate was 42.5 x 42.5 mm and the C4 area was 11.1 x 15.4 mm containing 4,503 C4 pads. The thickness of the laminate substrate was 0.79 mm. The solder resist opening diameter was 80  $\mu\text{m}$  and the solder resist height above the pad was around 20  $\mu\text{m}$ .

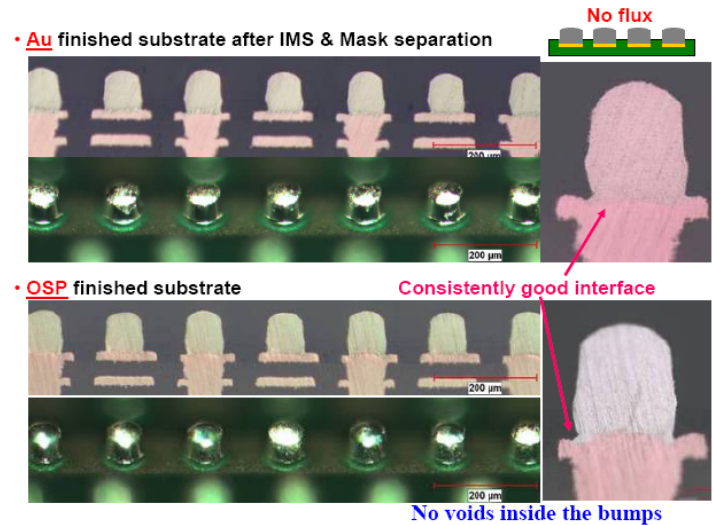
Figure 6 shows a commercial substrate after molten solder injection with an aligned mask and after separation of the mask, respectively. The thickness of the mask was 50  $\mu\text{m}$  and the hole diameter (wider side) in the mask was 76  $\mu\text{m}$ . The solder material used in this study was Sn-3.5 wt% Ag. As shown in Figure 6, after IMS the solder was only filled in the mask holes. No solder material was left on the surface of the mask and no leakage was detected between mask holes on the substrate. After separation of the mask, the solidified solder bumps were only located on the C4 pads. All pad openings were filled with solder and 100 % solder bumping yield was easily achieved in our manual, laboratory scale operation. The compliant material efficiently wiped away the solder from above the mask.

As mentioned in the experimental section, the IMS process does not need flux or formic acid. Figure 7 shows side views and cross-sectional images of mask IMS bumped OSP and Au finished substrates. The cross-sectional images clearly show that the IMS bumps have consistently good interfacial microstructures on both surface finishes. As shown in Figure 7, IMS substrate bumps have a column shape which follows the mask hole shape. The column shaped bumps indicate that the IMS method can be applied to very fine pitch

and very high volume applications. In addition to the column shape, round bump tops can be formed during solidification in low oxygen content atmosphere. This round top helps to reduce the stress on the mask holes during the mask separation process.



**Figure 6.** Mask-IMS bumping on 150  $\mu\text{m}$  pitch commercial organic substrate.



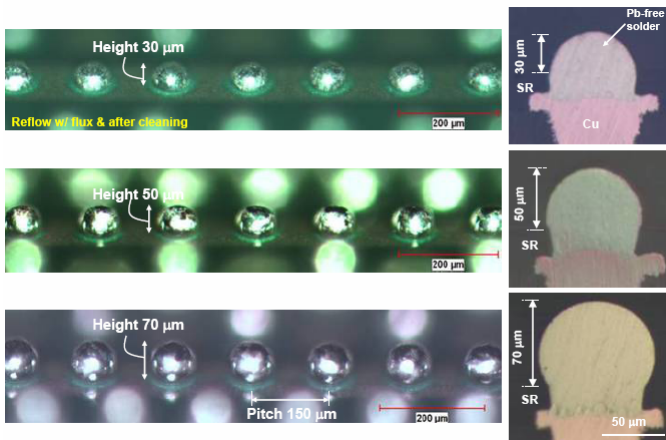
**Figure 7.** Cross sectional images and side view of mask IMS bumped Au and OSP finished 150  $\mu\text{m}$  pitch organic substrates.

One of the key advantages of the mask IMS substrate bumping technology is that the solder bump volume can be controlled for various applications by changing the mask thickness and/or holes sizes. Figure 8 shows one example of increasing the solder bump volume by fixing the mask thickness at 50  $\mu\text{m}$  and varying the holes sizes. In this study,

three different holes sizes, 50, 75, and 100  $\mu\text{m}$  in diameter (wider side), were used.

Figure 8 shows the 30, 50, and 70  $\mu\text{m}$  height bumps over the solder resist surface at a 150  $\mu\text{m}$  pitch. Further extendibility to even taller bumps is feasible.

Making high volume bumps on a substrate is one of the key advantages of IMS in which the entire solder volume required for flip chip interconnects between a chip and a substrate can be supplied solely from the substrate without having bumps on the chip. In the Cu pillar case, decreasing the Cu pillar height reduces the stress on the ultra low-k dielectric layer in the back-end-of-line during assembly, in addition to decreasing the Cu die bumping cost.



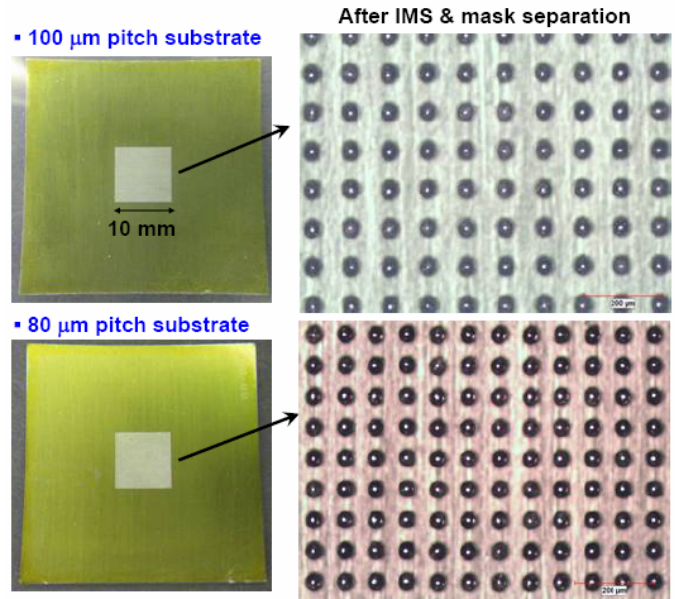
**Figure 8.** Side view and cross sectional images of Mask-IMS bumped organic substrate after solder reflow.

### 3-2. Mask IMS on 100 $\mu\text{m}$ and 80 $\mu\text{m}$ pitch substrates

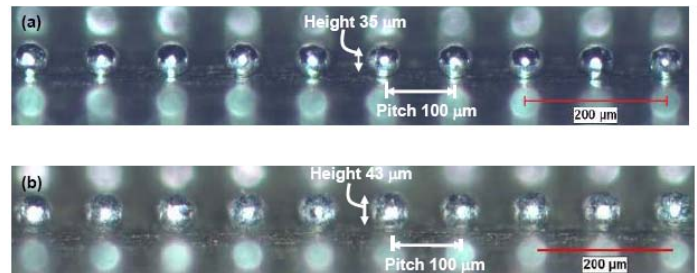
Since there are no commercial organic substrates which have less than 100  $\mu\text{m}$  pitch, polyimide patterned copper plates were processed internally at IBM for both 100 and 80  $\mu\text{m}$  pitch feasibility demonstration. The polyimide patterned copper plates had a 10 x 10 mm C4 area for a 42.5 x 42.5 mm substrate size. The polyimide height above the pads on the copper plate was around 6  $\mu\text{m}$  and the polyimide opening diameter was around 50  $\mu\text{m}$  for 100  $\mu\text{m}$  pitch substrates and 40  $\mu\text{m}$  for 80  $\mu\text{m}$  pitch substrates, respectively. The number of C4 pads was 10,000 for the 100  $\mu\text{m}$  pitch substrates and 15,625 for the 80  $\mu\text{m}$  pitch substrates, respectively. The surface finish was electrolytic Ni/Au.

Figure 9 shows the whole substrate and magnified images of the IMS bumped 100  $\mu\text{m}$  and 80  $\mu\text{m}$  pitch substrates. No missing pads nor solder bridging was found; a 100 % solder bumping yield was achieved easily even with a laboratory scale process.

Figure 10 shows side views and cross sectional images of reflowed bumps on the 100  $\mu\text{m}$  pitch substrate applied using a 37.5  $\mu\text{m}$  thick mask with (a) 50  $\mu\text{m}$  holes and (b) 60  $\mu\text{m}$  holes.



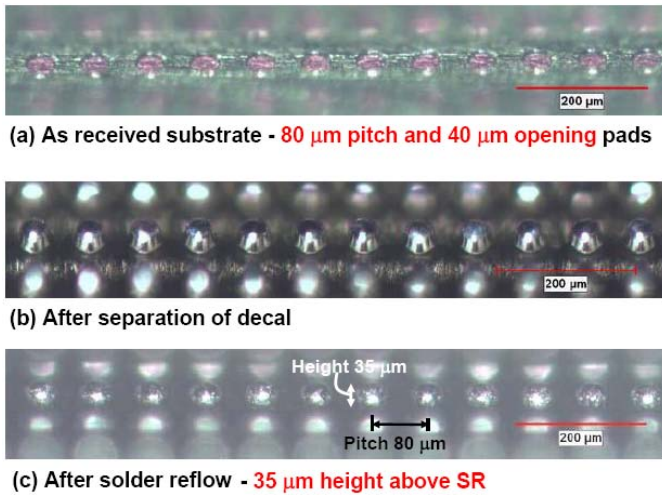
**Figure 9.** Mask-IMS bumping results on 100  $\mu\text{m}$  and 80  $\mu\text{m}$  pitch polyimide patterned copper plates.



**Figure 10.** Mask-IMS bumps on 100  $\mu\text{m}$  pitch substrates.

Figure 11 shows mask IMS bumping results on a 80  $\mu\text{m}$  pitch copper plate. The thickness of the mask was 37.5  $\mu\text{m}$  and the hole diameter was 50  $\mu\text{m}$ . The IMS bumps show column shape and round tops as shown in Figure 11 (b). The reflowed bumps have a very high volume of 35  $\mu\text{m}$  height above the PI which is close to the whole interconnect volume between chip and substrate after flip chip assembly.

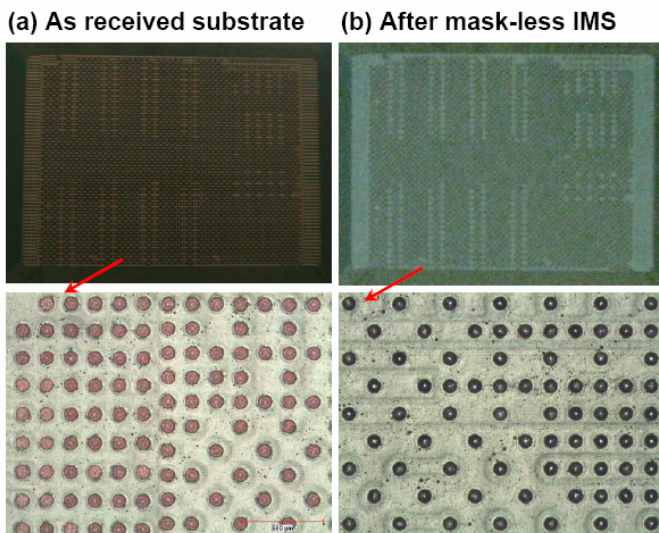
The mask IMS substrate bumping method can be applied to form higher solder bump volumes and finer pitch substrates. It does not need additional solder materials cost or upgrade of molten solder injection tool for applying it to finer pitch substrates. A simple change of the mask design enables high volume solder bumps on a fine pitch substrate.



**Figure 11.** Side view of mask IMS bumps on 80  $\mu\text{m}$  pitch substrates by using 37.5  $\mu\text{m}$  thick mask with 60  $\mu\text{m}$  dia. holes.

### 3-3. Mask-less IMS on 150 $\mu\text{m}$ pitch organic substrates

Figure 12 shows the whole C4 area and magnified images of the as received 150  $\mu\text{m}$  pitch organic substrate and after injection of molten solder without a mask. The as-received OSP finished substrate shows the pads to be below the SR surface. The mask-less IMS bumped substrate shows the solder bumps to be above the SR surface. The mask-less IMS process leads to 100% fill of the SR opening with pure solder since molten solder itself is injected without flux. The solder material used for mask-less IMS was Sn-3.8Ag-0.7Cu.

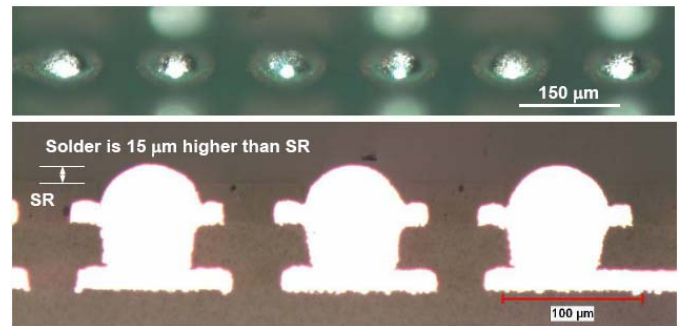


**Figure 12.** Mask-less IMS bumping results on 150  $\mu\text{m}$  pitch organic substrate.

In some instances, a nitrogen environment during the IMS process serves to make the solder “ball-up” during the solidification of the injection molten solder. Thus, the

presence of a nitrogen environment has the potential to eliminate the subsequent reflow process typically used in other cases. This further reduces the number of process steps and thus cost.

Figure 13 shows the cross sectional image of mask-less IMS on a 150  $\mu\text{m}$  pitch standard substrate. It demonstrated minimum height bumps of 15  $\mu\text{m}$  above the SR even though a mask is not used. In mask-less IMS, it is possible to enable variations in the solder bump volume by manipulation the opening in the solder resist (SR). For example, when the SR opening is wider, a larger volume of injected solder material can be accepted and thus form a higher bump height than a standard SR pad opening.



**Figure 13.** Side view and cross-sectional images of mask-less IMS bumping results on 150  $\mu\text{m}$  pitch organic substrate.

### Conclusions

New substrate bumping methods using molten solder injection with a flexible mask or without a mask were investigated. This paper focused on laboratory scale fabrication and showed the various advantages of the IMS (Injection molded solder) substrate bumping technology.

In mask-IMS, solder bump volume and applicable pitch can be controlled easily by changing mask thickness and / or hole diameter. We demonstrated 70  $\mu\text{m}$  height solder bumps above the SR on 150  $\mu\text{m}$  pitch substrates and 35  $\mu\text{m}$  height solder bumps above the SR on 80  $\mu\text{m}$  pitch substrates.

Mask-less IMS, direct injection of molten solder without a mask, is a very simple and reliable process with low cost compared to any other bumping methods. Around 15  $\mu\text{m}$  height solder bumps above the SR were demonstrated on 150  $\mu\text{m}$  pitch standard organic substrates. Modification of the SR opening design could increase the bump height.

Both mask-IMS and mask-less IMS can achieve good coplanarity even though the substrate may have differing solder resist opening sizes.

The IMS substrate bumping method has many advantages and is not just an incremental improvement to allow finer pitches, but is a fundamental change in the overall interconnect strategy.

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