EFFECTS OF ASSEMBLY PROCESS VARIABLES ON VOIDING AT A THERMAL INTERFACE

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ABSTRACT

Too often, the effects of assembly process parameters are not sufficiently accounted for in the optimization of thermal interface performance. This becomes increasingly critical as demands on this performance continue to grow and alternative processes are developed. Notably, stencil printing is proving a competitive alternative to the traditional dispensing of thermal interface materials (TIMs), with potentially significant gains in units processed per hour (UPH) for some applications. The two techniques may, however, pose quite different challenges in terms of material flow, the resulting filler particle distribution and the risk of air bubble entrapment. Another part of the adhesive attachment process certain to affect void formation and growth, as well as possibly filler particle distribution, is the final cure. In addition, voids may severely reduce assembly robustness and reliability. The present work offers a discussion and a first case study to identify and illustrate voiding mechanisms for a particular TIM between a heat spreader and the back of a flip chip. Pronounced differences were observed between stencil printing and dispensing in terms of initial void formation, apparently related to the specific properties of the material. Measurements of the effects of heat ramp rate and peak temperature showed the subsequent evolution and final void size distribution to be determined by the initial part of the cure profile up to the material gelling temperature.

KEY WORDS: thermal interface material, stencil printing, dispensing, voiding, deposit shape

INTRODUCTION

Most high performance ASIC packages are driving out heat in excess of 40 – 100 watts [1]. This high heat flux needs to be dissipated in an extremely efficient manner so as to maintain package and board temperatures within reasonable limits. Most high-end packages (such as flip chip ball grid arrays) dissipate a substantial part of the heat from the back of the die to a heat sink or a heat spreader via a TIM. In such designs, the efficiency of the transfer through the TIM often becomes extremely important.

The total thermal resistance of the structure is determined by the bulk thermal conductivity of the TIM and the thermal resistances at the interfaces between this and the silicon die and heat spreader. As bulk conductivities continue to improve and TIM thicknesses are reduced, interface resistances are starting to dominate overall performances, notably because of the presence of microvoids and/or a ‘starvation’ of conductive filler particles there. Also, voids at the interface not only have a detrimental effect on the interfacial resistance, but they may enhance the risk of pop-corning in subsequent mass reflows, and they have been seen to strongly affect adhesion and thus overall package reliability.

Thermal modeling of various advanced packages, along with experimental measurements of thermal resistances, is quite widely covered in the literature [2, 3]. So are the effects of parameters such as bondline thickness on the performance of various TIMs in mechanical and reliability tests. However, little or no literature seems to address alternative deposition techniques or effects of assembly process parameters. These issues are the focus of a major manufacturing process research effort funded by the Area Array Consortium [4]. Below, we present a preliminary study of issues associated with voiding during the automated attachment of a heat spreader or lid to the back of a flip chip BGA.

Major concerns in any high volume manufacturing process include process throughput and materials consumption or waste. As outlined next, stencil printing here offers some clear advantages over dispensing for component manufacturing. However void entrapment, and perhaps even filler particle distribution, during deposition and lid placement may depend quite strongly on the deposition technique and the resulting deposit shape. As we shall see, which technique performs better in this respect must also depend on the properties of the TIM.

Of course, we are more concerned with the final void distributions *after* adhesive cure. While this is certain to be affected by the initial distribution of placement voids, details of the cure process are seen to have a major effect as well.

Stencil Printing Vs. Dispensing

Thermal interface adhesives, gels, and grease formulations are commonly applied by a dispensing process. Dispensing offers the convenience of editing a computer program to adjust deposit patterns with no need for custom templates or tooling, as is required during stencil printing. However, dispensing is a serial operation, whereby each individual die receives material one at a time, which in a medium to high volume manufacturing environment, can easily become the bottleneck process.

Stencil printing offers a competitive alternative to dispensing, as the process is capable of printing material on several die simultaneously. Stencil printing is particularly attractive for reducing process cost in high volume operations that may have limited production floor space where a single printer can surpass the output of multiple dispenser machines, as shown in the following example.

Dispensing

Number of Parts	1	2	3	4	5	6	7	8	9	10
Transport Time	5	5	5	5	5	5	5	5	5	5
Fiducial Time	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5
Process Time	3	6	9	12	15	18	21	24	27	30
Time Per Cycle	10.5	14.5	18.5	22.5	26.5	30.5	34.5	38.5	42.5	46.5
UPH	343	497	584	640	679	708	730	748	762	774

Printing

Number of Parts	1	2	3	4	5	6	7	8	9	10
Transport Time	5	5	5	5	5	5	5	5	5	5
Fiducial Time	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Process Time	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Time Per Cycle	20	20	20	20	20	20	20	20	20	20
UPH	180	360	540	720	900	1080	1260	1440	1620	1800

Table 1. Dispensing and Printing Process Time Comparison**

** Both are model scenarios and do not represent actual test

Table 1 lists the predicted amount of process time for either dispensing or stencil printing a single part in a carrier and up to a full carrier of ten at a time. The transport time for each technique is assumed to be the same at 5 seconds. The model assumes that both techniques will take 2.5 seconds to locate fiducials for a single unit. Note that fiducial capture time increases by 1 second for each additional unit added to the carrier in the dispense process as local fiducials will be required. For stencil printing, there is no additional fiducial capture time penalty when more units are introduced to the carrier since only a global fiducial alignment strategy is used. In the process time category, dispensing takes an additional time penalty when additional units are added since the dispenser needle travels one unit to the next in a serial sequence. For stencil printing the process time is constant because, all units, regardless of the number will be processed in the same amount of time it takes for the print head to travel across the stencil. Analyzing the results, as more units are added to the carrier, the more advantageous the stencil printing process for outsourcing a higher UPH compared to dispensing.

The same model is shown graphically in Figure 1. The dispenser process can produce more parts per hour when set up with only 1 or 2 parts per carrier. Both processes are evenly matched at about 3 units per carrier, and then anything more shows significant gains for the stencil printing process. At 9 units per carrier the printer is capable of processing twice the number of units per hour as the dispensing process.

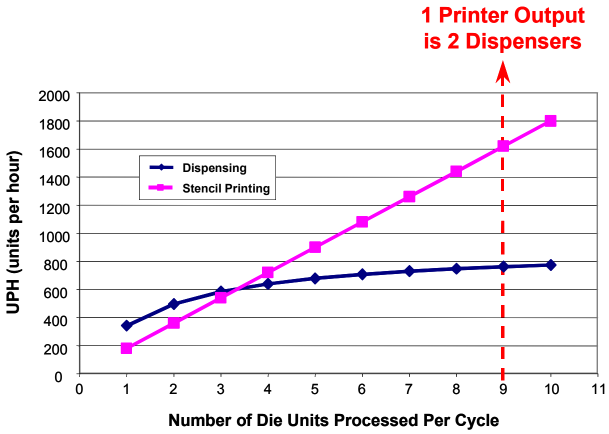

Fig.1 Dispensing and Printing Process Comparison

During stencil printing, a squeegee blade is the traditional means used to transfer the TIM across a stencil, as indicated in Figure 2. If the print material is sensitive to change from continuous open exposure, an enclosed printhead system can be substituted to provide environmental protection in a sealed vessel. Such a system is shown in Figure 3, where pressure is applied directly onto the material to provide excellent aperture filling performance.

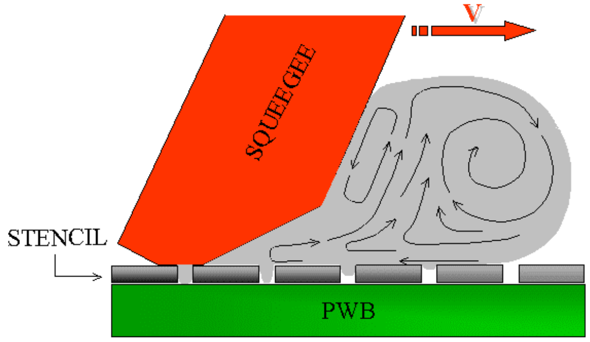

Fig.2 Squeegee Based Stencil Printing Process

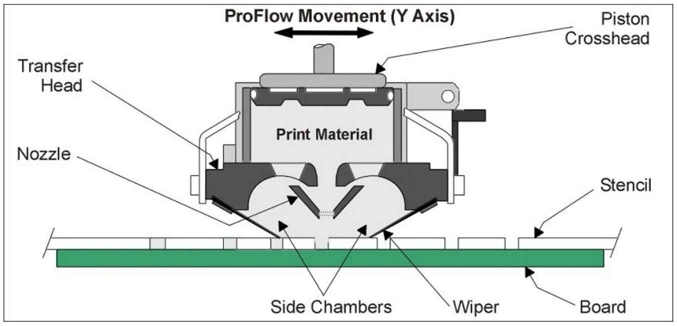

Fig.3 Enclosed Printhead Printing [Courtesy DEK Printing Machines]

Aperture openings in the metal stencil define the areas where material is deposited onto die that are automatically aligned to it below. Following the print stroke, the printed die are separated from the stencil and exit the machine. The process sequence repeats as new parts are introduced.

There are several stencil printing parameters that the operator can fine tune to achieve accurate and repeatable results. Some of those parameters are briefly mentioned here: (1) Print speed is a critical parameter that dictates the speed at which the squeegee runs across the stencil. It determines the shearing rate of the print material and the time an aperture is exposed to the print material. Depending upon the material properties a print speed may be high or low. (2) Separation speed determines the speed at which the die separates from the stencil after the print stroke. This speed is important because it can alter the shape of the deposit and determine the amount of material that may remain in the aperture or at the bottom of the stencil and not get transferred to the die. (3) The choice of the squeegee material (i.e. metal or polyurethane) could also be significant because it can affect the scooping behavior of the deposit material and hence, the resulting shape. (4) Also depending upon the usage, stencil-undercleaning methods may need to be evaluated. Different methods available are dry wipe, vacuum wipe, or solvent wipe. A combination of these wiping methods can also be used with options for fine adjustments. The most important of all variables is the design of a proper stencil, which contributes the largest part to defining the final size and shape of the deposit. Typical apertures are designed to produce deposits that have flat surfaces, however, there are also stencil design strategies in place that produce consistent "Hershey kiss" like high aspect ratio profiles, resembling deposits generated by dispensing.

Entrapment of Air

When a flat lid surface is forced down on an irregularly shaped deposit surface, it is almost certain that voids will be formed. During compression, some of these voids may escape but many will remain trapped. In addition, the flow of the material during compression is certain to affect the wetting. Wetting here refers to the adhesion of the TIM to die and heat spreader surfaces. Even at low compression speeds, the flow speed of the spreading interface material increases rapidly and it ends up being tremendously high (typically ~ 1m/s). Accordingly, the wetting to the lid and die surface is certain to be quite low, at least near the edges. This is likely to cause submicroscopic voiding or porosity on anything but atomically flat surfaces. Such effects, as well as potential effects of the highly turbulent flow on the filler particle distributions immediately next to the surfaces, may well remain too small to observe directly but still affect thermal performance considerably. If so, we might expect an initial distribution across (almost) the entire die surface, such as readily achieved by stencil printing (doing the same by dispensing will usually not be trivial), to offer the best achievable wetting and performance because of the much lower flow speeds involved in covering most of the surfaces. The effects are, however, not easily separated from others related to the flatness of the deposit top surface.

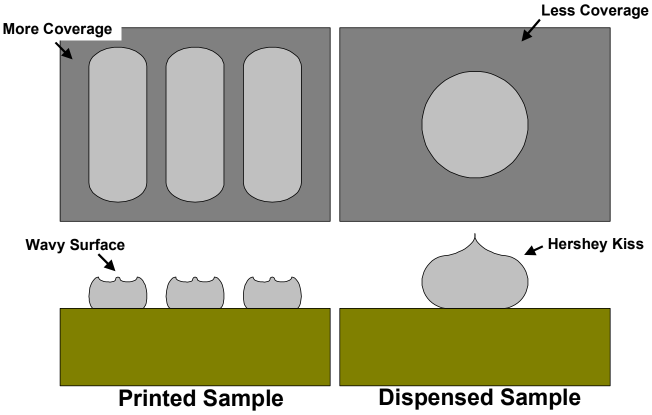

Fig.4 Deposit Shapes from Printing and Dispensing

Figure 4 shows sketches of deposit shapes achieved in our stencil printing and dispensing experiments. Printing required a minimum of 3 stencil apertures, rather than a single one, to minimize 'scooping out' of the deposit. This presents an obvious potential for entrapment of voids during compression (lid placement) as the flow fronts from the adjacent deposits meet, in which case the stencil aperture shapes may have to be redesigned. That did, however, not prove to be necessary in our experiment.

As sketched, dispensing has a tendency to initially leave "Hershey kiss" shaped deposits. Depending on the material properties these may rapidly 'relax', but it remains exceedingly difficult if not impossible to avoid 'peaks and valleys' if dispensing over a large area. This almost certainly leads to the entrapment of bubbles at the lid surface in placement. On the other hand a single, taller dot may avoid that but then larger fractions of the die and lid surfaces are not covered until the compression (lid placement) stage and then mostly at very high speeds.

Stencil printing does, as said, offer the potential for less bubble entrapment at the die surface along with a more uniform coverage. The top surface of the deposit may, however, still be wavy or textured with hills and valleys when observed under magnification. Figure 5 shows a laser profilometer scan of surfaces achieved for a particular TIM with our three-aperture stencil design. The scan clearly shows the wavy top surface of the printed deposits in this case.

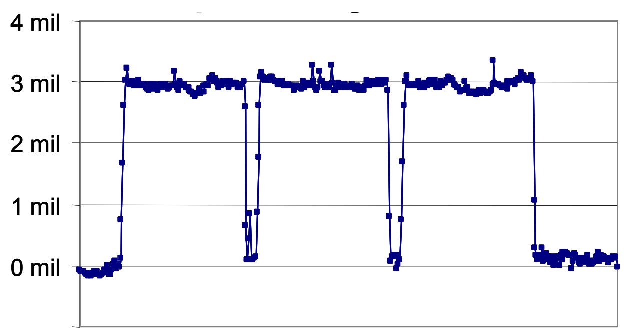

Fig.5 Printed Deposit Height Profile (3 Aperture Design)

Deposition & Placement

Experiments were conducted using a commercially available TIM. This was a primerless silicone adhesive with aluminum oxide filler particles primarily used in heat sink attachment. The filler particles had a bimodal distribution with large spherical and smaller irregularly shaped ones. Dispensing was performed with a manual dispenser and a 18-gage needle (50 mil O.D. & 28 mil I.D.), all material deposited in a single large dot near the middle of the chip. In the case of stencil printing flip chips were carefully aligned to the three apertures in our stencil and the TIM printed manually with repeated strokes to ensure a complete fill. For the present experimental purposes complete coverage on the die was not intended. However, as expected independent experimentation with a similar flip chip assembly has demonstrated complete coverage with a negligible amount of overflow or waste of material, but no attempts were made to optimize stencil aperture design for the present chips.

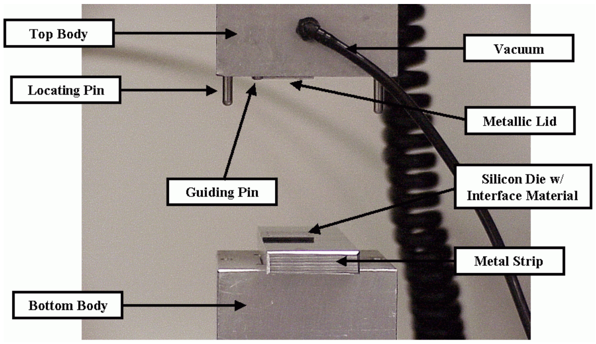

Fig.6 Placement Fixture

Following TIM deposition the chips were then mounted in a special fixture and a special placement apparatus used to place corresponding, extremely flat, 20 mil thick copper heat spreaders at a realistic speed to achieve bondline thickness of a mil (refer Figure 6). The material was then cured according to vendor recommendations. Cross sectioning however, revealed 2-3 mil bond lines. This could be due to the spring back after compression and before cure or during cure resulting in an increased gap size.

Scanning acoustic microscopy (C-SAM) was used to inspect the TIM for voids after cure. None of the dispensed assemblies showed any detectable voiding at this stage (Figure 7). In viewing this image we re-emphasize that the issue is voiding and that no attempt had been made to optimize materials coverage. A number of the printed assemblies did, however, show numerous voids (typically more than 30), as shown in Figure 8.

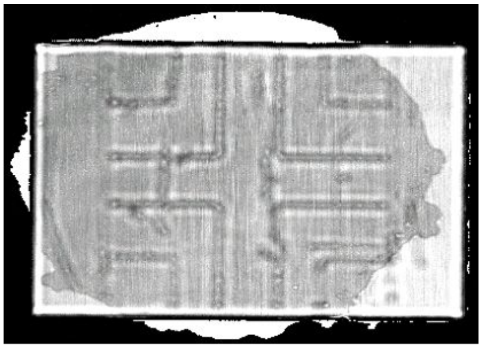

Fig. 7 C-SAM Image of Dispensed Sample

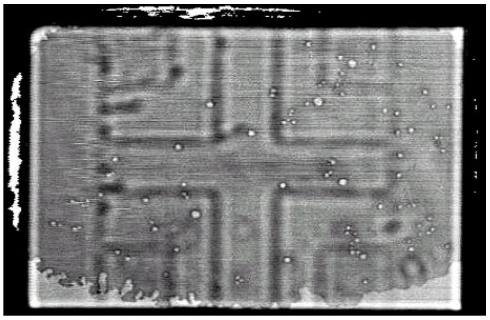

Fig. 8 C-SAM Image of Printed Sample (Print #5)

Closer inspection of the stencil printing behavior on several days of experimentation showed a clear variation with time during printing. Figure 9 compares deposits achieved as 'first prints' of a series (the three on the left) with those achieved after 4 preceding ones (the three on the right). The first print is seen to result in nice and flat deposits with crisp edges and no indication of a surface morphology. The fifth print in the series, on the other hand, led to wavy top surfaces and clearly irregular edges. The scan in Figure 5 was of the latter deposits. This behavior may well reflect some kind of material degradation with time and/or working on the stencil, but that was considered irrelevant for the present purposes. Important was that the first prints usually did not lead to any detectable voids, i.e. as expected there was indeed a clear correlation between deposit surface morphology and initial voiding.

Fig.9 Comparison of Clean Print (Print #1) Resulting in No Voids (Left) and Wavy Top Surface (Print #5) Resulting in Numerous Voids (Right)

Cure

Effects of the cure parameters were investigated for the same TIM using only dispensed samples, thus ensuring no detectable void entrapment at room temperature. We caution, however, that this does not by any means guarantee that submicroscopic voids and porosity had not been entrapped. In fact, we would expect voids to have nucleated before cure.

The TIM was first deposited on a glass slide by dispensing and a second glass slide then placed on top, compressing the material to a gap of 1 mil. Maintaining this gap with a continued load and spacers at the ends the 'assembly' was placed on a tabletop heater and cured. The resulting void evolution was observed in real time under a microscope at 50X magnification with a detection limit of 1 mil diameter voids.

The curing parameters evaluated were the rate of heating and the peak temperature. The two ramp conditions tested were (1) rapid heating 40°C/min from 25°C to 150°C, and (2) slow heating 8°C/min from 25°C to 150°C. In both cases heating was followed by a 20 min cure at 150°C. A separate experiment compared voiding in a 90 min cure at 100^{o}C and a 20 min cure at 150^{o}C, both after heating at 40^{o}C/min.

With slow heating, 1-4 mil diameter voids would appear around 55°C, and these would then grow to 10-15 mil by the time the temperature reached 70°C. Around 70°C, the material would begin to gel and the sizes and number of voids would remain unchanged after that. In total, slow heating would lead to a small number of large voids.

With rapid heating, 1-2 mil diameter voids would again appear around 55°C, but in this case they were not seen to grow after that. The observation of a much larger number of (small) voids in this case might suggest that at least part of the void growth seen for slower heating occurred by coalescence and ripening. Coalescence refers to aggregation of small voids whereas ripening refers to growth of large voids at the expense of smaller ones.

Additionally, outgassing in cure was quantified by simple weight loss measurements using a microbalance and Thermo Gravimetric Analyzer (TGA). A Differential Scanning Calorimeter (DSC) was used to determine the onset of gelling and cure. TGA measurements on uncovered samples revealed more than twice as high a mass loss during the slow heating up to the gelling temperature as compared to fast heating. This suggests that part of the growth is likely to be associated with outgassing of volatiles into the voids, i.e. that rapid heating may lead to a somewhat smaller total void volume.

Not surprisingly, no difference was observed for the two different peak cure temperatures, i.e. only the heating up to about 70°C is important.

Conclusions

Thermally conductive adhesives may be deposited by two very different techniques, stencil printing and dispensing. From an automated manufacturing perspective either offers obvious advantages for different applications. Notably, stencil printing may offer a much higher throughput in component manufacturing. The techniques do, however, also have very different effects on void formation and thus presumably on overall thermal performance. Stencil printing is seen to require a relatively low viscosity, high surface tension material to ensure a smooth deposit surface.

The curing process also had an influence on void evolution, faster heating up to the gel point leading to a larger number of smaller voids. It remains to be ascertained whether this is always an advantage. Coalescence or ripening of a fixed void (porosity) volume into fewer, larger voids might actually reduce the overall thermal resistance. On the other hand, indications are that faster heating allows for less void growth through outgassing of volatiles as well.

Acknowledgements

The authors would like to thank Shafi Saiyed for helping out with the heating ramp rate and the peak temperature study.

References

1. Kohli, P., Sobezak, M., Bowin, J., Mathews, M., "Advanced Thermal Interface Materials for Enhanced Flip Chip BGA", 2001 Electronics Component Technology Conference, Orlando, FL, May 2001.
2. Ramakrishna, K., Lee, T., "An Evaluation of Thermal Enhancements to Flip-Chip-Plastic-Ball-Grid-Array (FCBGA) Packages", 2003 ASME International Mechanical Engineering Congress, Washington, D. C., November 2003.
3. Pinjala, D., Khan, N., Ling, X., Teo, P., Wong, E., Iyer, M., Lee, C., Rasiah, I., "Thermal Design of Heat Spreader and Analysis of Thermal Interface Materials (TIM) for Multi-Chip Package, 2002 Electronics Components and Technology Conference, San Diego, CA, May 2002.
4. Area Array Consortium 2004, www.uic.com