

Development of Ball Grid Array Packages with Improved Thermal Performance

Y.Y. Ma, Desmond Y.R. Chong, C.K. Wang, and Anthony Y.S. Sun

Package Design and Analysis Center
United Test and Assembly Center Ltd
5 Serangoon North Ave 5
Singapore 554916

Email: yy_ma@sg.utacgroup.com

Abstract

To provide electronics packages with sufficient cooling during applications to secure improved reliability and performance of the packages has been one of the challenging tasks for their manufacturers and end users. Since the introduction of the standard Ball Grid Array (BGA) package, continued efforts by package developers have successively resulted in a family of thermally enhanced BGA packages. The eXtra Performance BGA (XP-BGA) package is one of its latest members developed as a cost competitive package for thermal margin. To demonstrate the effectiveness of the XP concept introduced by UTAC, this paper assessed the thermal performance for the two typical BGA families, i.e. FBGA 15x15mm and PBGA 35x35mm, by applying different thermal enhancement methods. Simulation shows that thermal resistance can be reduced by 17% and 25% for XP-FBGA 15x15mm and XP-PBGA 35x35mm respectively at still air comparing with their standard BGA versions. Package thermal performance was observed to improve even more at moving air. Three-dimensional finite volume simulations were further utilized to analyze the impact of several XP related variables on the package thermal performance. XP-FBGA 15x15mm and XP-PBGA 40x40mm Multi-Chip Package (MCP) were selected as test vehicles to study their thermal performance sensitivity to the change of design, materials, process and application environment. The development of XP-BGA achieving thermal performance comparable to that of an EBGA is realized with much lower cost and higher throughput. Package structures, CFD models, and simulation data are presented and discussed.

1. Introduction

The continuing demand of system miniaturization has been driving the microelectronics industry to the development of consumer electronics that is smaller and faster, with more functionality but at a lower price. The many flavors of BGA packages have made them popular options for graphics, PLDs, DSPs, ASIC, gate arrays and memory packages in that, compared with traditional Surface Mount Technology (SMT) components, they have higher I/O density, lower assembly cost, self-alignment capability during reflow, lower package profile, higher electrical and thermal performance.

In response to the increasing demand for higher speed and power of semiconductor devices together with die shrinkage and functional integration, various thermally enhanced BGAs were invented to increase package power dissipation capability, such as Heat Slug PBGA (HS-PBGA)[1], Enhanced BGA (EBGA)[2], Bottom Heat Slug BGA (BHS-BGA)[3], Tape BGA (TBGA)[4], Super BGA (SBGA)[5], Viper BGA (VBGA)[6], Metal BGA[7], Cu-Core BGA[8], Ultra BGA[9], etc. While being able to meet different level of heat dissipation requirements, they have their own inborn limitations, e.g. HS-PBGA is a cost effective option for large size packages, it is not practical for packages with small form factor, e.g. FBGA, since there is no sufficient space for the heat slug. EBGA can dramatically reduce the package thermal resistance, however, it is very expensive, and a portion of the valuable substrate real estate has to be sacrificed for die-down cavity, leading to a significant reduction of availability of I/Os. BHS-BGA has the same problems as EBGA although its exposed pad enables injecting heat directly from the chip to the ground plane of the PCB.

The XP-BGA package was developed in order to provide comparable thermal performance to that of the thermally enhanced BGAs while minimizing, if not fully getting rid of, those adverse limiting factors.

2. Construction of XP-BGA

Fig. 1 illustrates the design of an XP-BGA. The mold cap typically extends to the edge of the laminate.

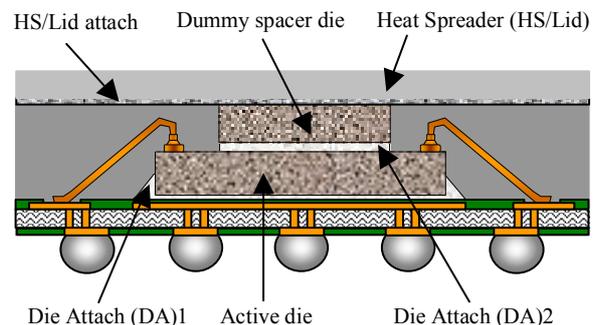


Fig. 1 Schematic of XP-BGA

A quick examination of the XP concept used for BGA packages reveals two pronounced features with respect to the standard BGA packages, i.e. a Dummy Spacer (DS) die on top of the active die and a flat Heat Spreader (HS) or lid on top of the package. The former offers a direct thermal path from the active die surface to the heat spreader and the

latter provides a good thermal coupling to the peripheral solder balls by reducing spreading thermal resistance.

Compared with cavity-up thermally enhanced BGAs like HS-BGA, the XP-BGA package does not require an imbedded heat slug, which can occupy space within package and may obstruct mold flow. Its external flat heat spreader is able to accommodate changes in die size, leaving more room for bonding wires, multiple dice and passives if any, and maximizing the heat spreading effect at the same time. Attached after post mold cure, it eliminates the need for special optimization of existing design and process for standard BGAs. On the other hand, unlike cavity-down thermally enhanced BGAs or cavity-up BGAs with bottom heat slug, XP-BGA is able to maximize the utilization of the substrate for routing and interconnects. In addition, the use of flat heat spreader and mirror Si wafer for spacer effectively simplifies the material preparations. Therefore, XP-BGA offers a promising low cost solution for high performance applications.

3. Assessment of effectiveness of XP concept

In order to obtain a clearer picture of the XP concept in terms of its thermal performance improvement for BGA packages, it is quite natural to position it against a backdrop of BGA packages using various conventional thermal enhancement techniques.

3.1 Description of BGA packages

Two typical BGA packages, i.e. FBGA 15x15mm and PBGA 35x35mm, were selected for evaluation.

FBGA 15x15mm has a full array of ball population matrix of 18x18, among which there are 10x10 array of center thermal balls. The substrate is 4 metal layer BT with total thickness of 0.288mm. There are 10x10 thermal vias in substrate connecting all the thermal balls to the GND planes. Ball pitch is 0.8mm. A Si die of 6.5x6.5mm in size, dissipating power of 2W, is over-molded with mold thickness of 0.6mm.

For PBGA 35x35mm, the solder balls with 1.27mm pitch are patterned as a depopulated array where 18x18 array of center balls are removed from a full array of 26x26 solder balls. There are 6x6 array of thermal balls located at the center of a 4 metal layer BT substrate with thickness of 0.56mm. The die size is 10x10mm with power level of 3W, Mold cap thickness is 1.17mm.

The BGA packages were mounted on a 4L (2s2p) JEDEC standard test board with [10]/without [11] direct thermal attachment mechanisms.

3.2 Description of thermal enhancement techniques

Approaches such as Drop-in Heat Slug (HS), XP, Bottom Heat Slug (BHS), combination of XP and BHS, and Enhanced cavity-down (E) were adopted to enhance the thermal performance of the above-mentioned two BGAs. Due to space constraints, HS is not applicable to FBGA 15x15mm. There are no substrate thermal vias or thermal balls for packages using E or BHS for thermal enhancement as in either case the die is directly attached to the heat spreader instead of substrate.

3.3 CFD modeling

FLOTHERM[®] [12], a leading Computational Fluid Dynamics (CFD) code specially developed for the electronics industry, was employed to conduct thermal analysis. Compared with its Finite Element Method (FEM) counterpart like ANSYS[®], it has the advantage of solving for heat transfer and air flow simultaneously within electronic systems. Therefore it not only calculates the temperature distribution in the package and its surrounding air, but evaluates the velocity and pressure fields of air flow as well, eliminating the input of convection heat transfer coefficient required by FEM codes, which can be quite subjective and suspicious.

Full 3-D FLOTHERM[®] models were used in this analysis. However, a CFD tool is not able to model detailed package structures. For all the cases studied package parts were represented as a series of embedded conductive solid cuboidal blocks with either isotropic or orthotropic thermal conductivities. Table 1 lists the material properties used for this study.

Table 1 Thermal properties for BGA families

S/n	Material	K (W/mK)	
		FBGA 15x15	PBGA 35x35
1	Mold compound	0.68	0.99
2	Die attach	0.3	0.4
3	Substrate dielectric	0.337	
4	Substrate trace	390	
5	PCB dielectric	0.3	
6	PCB trace	390	
7	Solder	50.9	
8	Lid attach	2.5	
9	Lid/HS	390	
10	Die	Temp dependent*	
11	Bond wire	296	

$$*K(\text{Si}) = 117.5 - 0.42 \times (T - 100)$$

Only those vias under the die were included in the models for PBGA 35x35mm while all the vias, whether thermal or electrical, under or not under the die, were considered for FBGA 15x15mm. Traces in substrate and PCB were smeared with dielectric over the whole layer with volumetrically averaged thermal conductivity. Similar approaches were taken to estimate the equivalent thermal conductivity of vias and bonding wires. Radiation was applied to all the exposed surfaces, whose emissivity was assumed to be 0.8.

Localized grid was used to capture temperature profile and flow pattern in the areas of interest or where rapid changes are expected. Grid-dependent solution studies were performed by adjusting grid size. It is assumed that a converged result has been achieved if the junction temperature is decreased by less than 1% with a finer gridding.

Laminar and turbulent flow are assumed for natural and forced convection [13,14] respectively with ambient temperature of 50 °C.

3.4 Results and discussions

Fig. 2 shows the simulation results for FBGA 15x15mm family. A 17% reduction in the free convection θ_{JA} is observed when XP concept is applied to a standard FBGA. As the dummy spacer die and the heat spreader in XP-FBGA help the heat flow from the active die to the top surface of the package, comparing with normal FBGA, a reduction of up to 30% in the thermal resistance is found at an air speed of 3m/s. In terms of thermal performance, the FBGA 15x15mm family can be ranked (worst first) as follows,

1. 224B EBGA
2. 324B FBGA
3. 324B XP-FBGA
4. 224B BHS-FBGA
5. 224B XP-BHS-FBGA

It may be surprising that the thermal performance of the EBGA is found to be the worst of the family. It is due to the fact that its unique cavity-down configuration makes it impossible to add any thermal balls under the die. Therefore, EBGA is not a popular thermal enhancement method for BGAs with small package size.

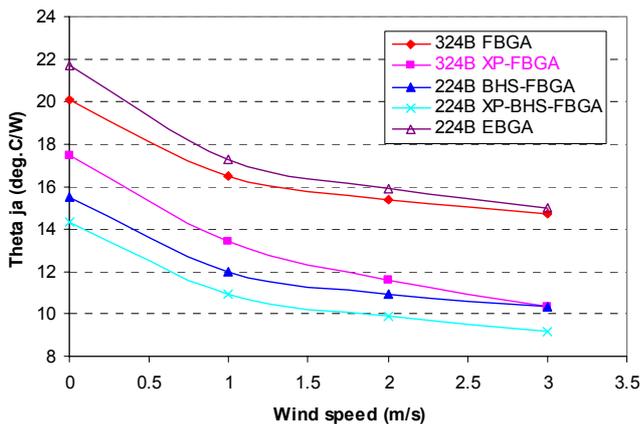


Fig. 2 Thermal performance comparison (FBGA 15x15mm)

As shown in Fig. 3, if XP concept is adopted, thermal performance of a standard PBGA 35x35mm can be improved by 25% and 38% at still air and moving air with 3m/s velocity respectively. An inspection of thermal resistance of PBGA 35x35mm family gives the following order (highest first),

1. 388B PBGA
2. 388B HS-PBGA
3. 388B XP-PBGA
4. 352B EBGA
5. 352B BHS-PBGA
6. 352B XP-BHS-PBGA

It is quite remarkable to notice that the thermal performance of an XP-PBGA 35x35mm is comparable to that of an EBGA 35x35mm.

As can be seen that for both FBGA and PBGA families, BHS is the most effective way to reduce θ_{JA} , especially for FBGA where heat can be drawn directly from the die to the PCB with less spreading. The effect of additional XP on the

θ_{JA} reduction of a BHS-BGA is also quite noteworthy, and vice versa.

Attractive may it be, BHS-BGA is difficult to be SMT compatible, and like cavity-down BGAs, is much more expensive. The beauty of using XP for thermal enhancement is low cost and universal of application.

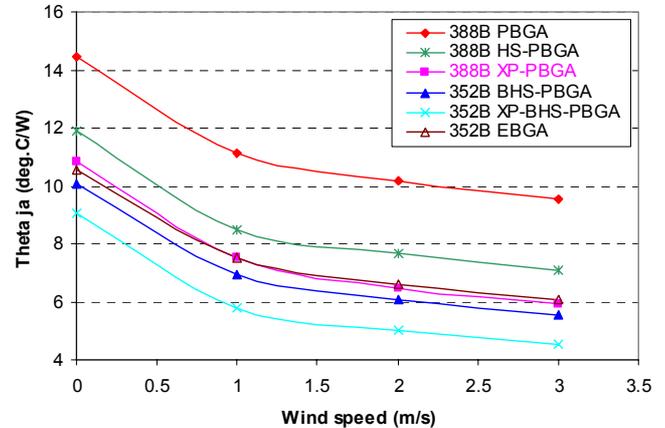


Fig. 3 Thermal performance comparison (PBGA 35x35mm)

4. Sensitivity studies of XP-BGA packages

Once the idea of XP has been proved as a successful thermal enhancement tool, its application to different BGA packages is expected and optimization of its design, materials and process is preferred.

4.1 Description of XP-BGA packages

To cover a wider range of BGA size and represent more BGA configurations, XP-FBGA 15x15mm and XP-PBGA 40x40mm Multi-Chip Package (MCP), with heat spreader thickness of 0.2mm and 0.5mm respectively, were selected for this study.

The structure of the former is exactly the same as that of the one described in section 3.1 except that the die size is enlarged to 8x8mm.

Fig. 4 provides the schematic of the XP-PBGA 40x40mm MCP comprising a center die of 7.8x7.8mm in size and four identical dice, two at each side, of 5.07x5.07mm in size stacked with a spacer of 4.0x3.75mm in size. Die power is 4.5W and 0.5W for center and side die respectively. The 4 layer BT substrate has two 70um inner copper planes and a full ball matrix of 31x31 with ball pitch of 1.27mm. There are 6 peripheral rows of solder balls and 7x7 array of center thermal balls. Mold cap thickness is 0.7mm.



Fig. 4 Package structure (XP-PBGA 40x40mm MCP)

Table 2 summarizes the material properties used in the simulation. For MCP package, maximum chip temperature rise is used as an index for performance comparison due to lack of JEDEC standard for thermal characterization of

MCP [15]. The ambient temperature in this case is 70 °C. A cross-sectional plot of temperature field of the MCP at still air is shown in Fig. 5.

Table 2 Component thermal properties

S/n	Material	K (W/mK)	
		XP-FBGA 15x15	XP-PBGA 40x40 MCP
1	Mold compound	0.8	0.88
2	Die attach	0.3	1.2(center)/0.3(else)
3	Substrate dielectric		0.337
4	Substrate trace		390
5	PCB dielectric		0.3
6	PCB trace		390
7	Solder		50.9
8	Lid attach		2.5
9	Lid/HS		390
10	Die	Temp dependent*	
11	Bond wire		296

*K (Si) = 117.5 - 0.42 x (T - 100)

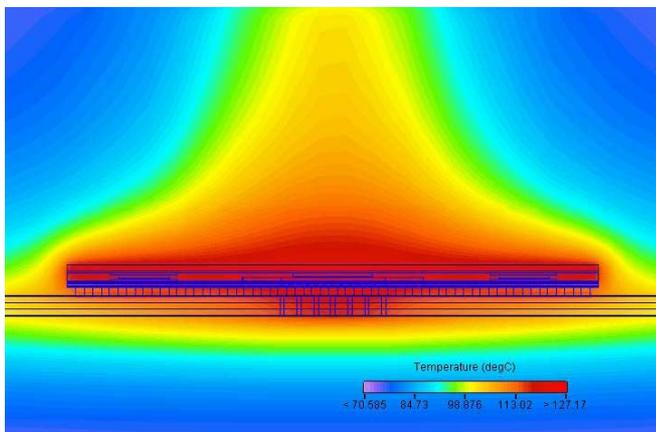


Fig. 5 Cross-sectional view of temperature distribution (XP-PBGA 40x40mm MCP, still air)

4.2 Results and discussions (XP-FBGA 15x15mm)

4.2.1 Effect of dummy spacer die size

It is noted in Fig. 6 that θ_{JA} decreases by 3% for package with a dummy spacer die of 6x6mm in size compared with that without a dummy spacer die.

The dummy spacer die does not play a significant role in reducing θ_{JA} . However, a 96% increase of θ_{JC} is found for the package without a dummy spacer die. This is because the dummy spacer die promotes heat conduction from the chip to the heat spreader, which is important in applications with an external heat sink.

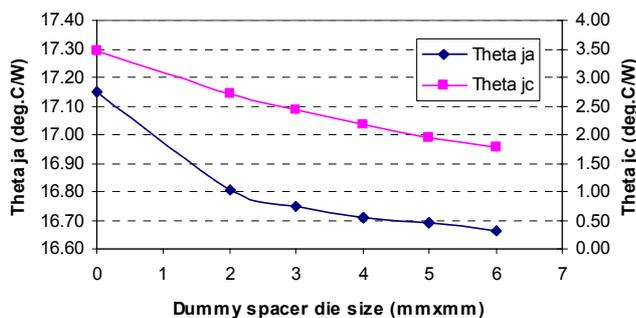


Fig. 6 Effect of dummy spacer size

4.2.2 Effect of lid attach coverage

It can be seen from Fig. 7 that θ_{JA} and θ_{JC} increases by 2% and 3% respectively when lid attach coverage is 60% compared with a fully covered package. The impact of partial coverage of lid attach adhesive is insignificant.

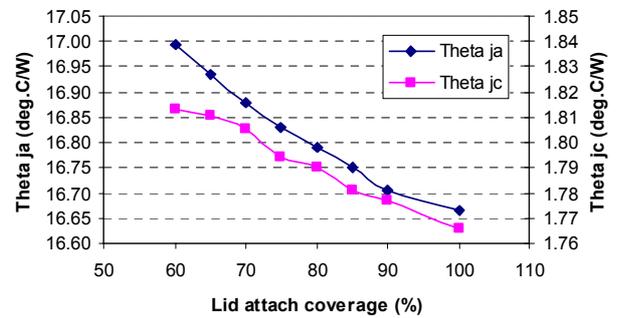


Fig. 7 Effect of lid attach coverage

4.2.3 Effect of lid attach thermal conductivity

Fig.8 clearly demonstrates that lid attach thermal conductivity has little impact on the package thermal performance at still or moving air test conditions. A weak influence of its bond line thickness can thus be expected.

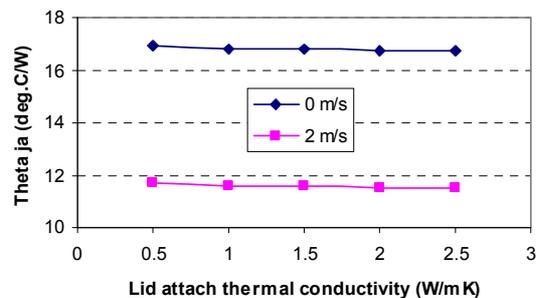


Fig. 8 Effect of lid attach thermal conductivity

4.2.4 Effect of HS thickness and thermal conductivity

Fig.9 indicates an almost linearly increase of package thermal performance with heat spreader thickness. However, its effect is very limited as only 3% of thermal resistance reduction is observed for a heat spreader thickness of 1mm. Besides, little impact of heat spreader thermal conductivity is found once it exceeds 200W/mK.

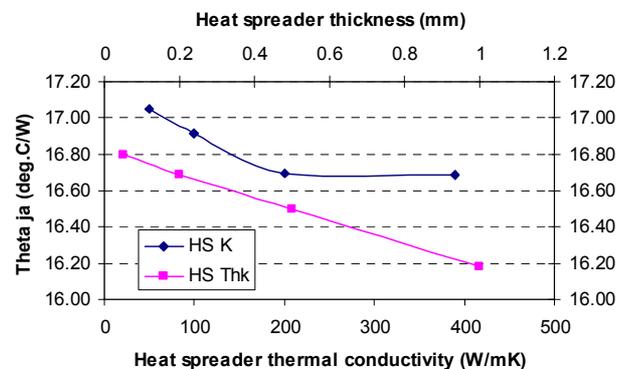


Fig. 9 Effect of HS thickness and thermal conductivity

4.2.5 Effect of distance between active die and HS

Since the presence of a dummy spacer die does not help reduce θ_{JA} very much, it is interesting to study how θ_{JA}

changes with the distance between active die and HS when there is no dummy spacer die in the XP-FBGA.

Thermal resistance of the baseline package, i.e. the one with a dummy spacer die, is shown in Fig. 10 with a 0 distance. Comparing with this baseline FBGA, only 5% and 8% increase of thermal resistance at still air and moving air speed of 2m/s respectively are observed when the distance increases to 2.75mm.

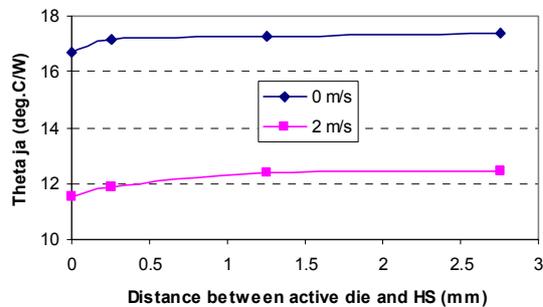


Fig. 10 Effect of distance between active die and HS

4.3 Results and discussions (XP-PBGA 40x40mm MCP)

4.3.1 Effect of dummy spacer die, mold flash and lid attach coverage

Table 3 summarizes the impact of some process and application related variables. Thermal performance of the MCP without a dummy spacer die reduces by about 8% maximum at wind speed of 1m/s. The difference between a perfectly packaged MCP and a worst packaged one is found to be within 2.5% in terms of maximum chip temperature rise. Although the effect of mold flash and incomplete lid attach coverage is more obvious for MCP with a dummy spacer die, it is still very limited.

Table 3 Effect of process and application related variables

Dummy spacer die	Mold flash (thk = 30 um) (%)	Lid attach coverage (%)	Wind speed (m/s)	Max. chip temp. rise (deg.C)
Yes	0	100	0	56.37
			1	38.98
	100	80	0	57.34
			1	39.92
No	NA	100	0	59.58
			1	42.15
	NA	80	0	59.87
			1	42.36

4.3.2 Effect of lid attach thermal conductivity

It can be inferred from Fig. 11 that package thermal performance is not sensitive to the change of lid attach thermal conductivity and its bond line thickness.

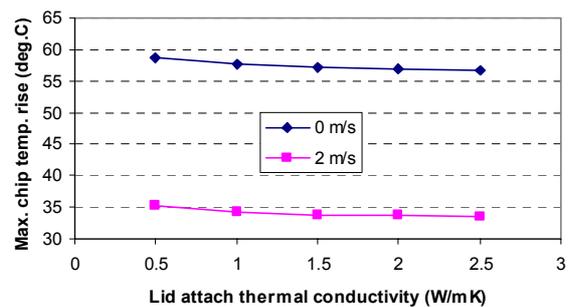


Fig. 11 Effect of lid attach thermal conductivity

4.3.3 Effect of HS thickness and thermal conductivity

Fig. 12 suggests a similar trend for the impact of heat spreader thickness and thermal conductivity. Package thermal performance improves dramatically with the increase of either heat spreader thickness or its thermal conductivity initially, but its further increase only marginally reduces the maximum chip temperature. The turning point seems to be at 0.5mm for heat spreader thickness and 200W/mK for heat spreader thermal conductivity.

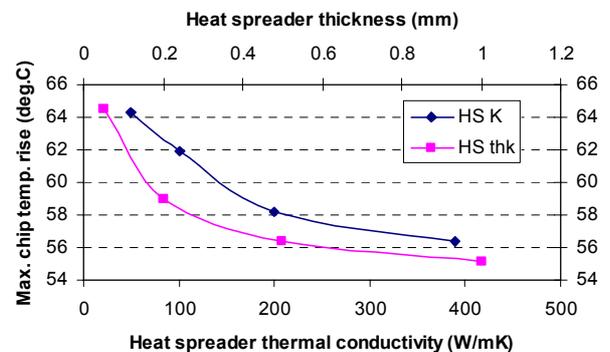


Fig. 12 Effect of HS thickness and thermal conductivity

4.3.4 Effect of distance between active die and HS

Thermal performance of the MCP without a dummy spacer die, as shown in Fig. 13 where 0 distance indicates that of the package with a dummy spacer die, is much more sensitive to the change of distance between active die and heat spreader when the distance is small or there is forced air flow. A comparison of Fig. 10 and Fig. 13 supports the observation that this distance has a much more thermal impact on XP-PBGA 40x40mm MCP than on XP-FBGA 15x15mm, especially at a wind speed of 2m/s. It is best explained by the fact that XP offers a more effective solution of reducing spreading resistance of a package with larger body size.

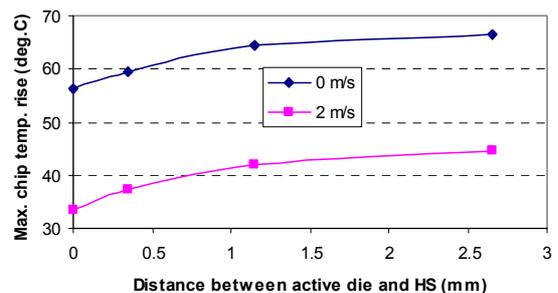


Fig. 13 Effect of distance between active die and HS

5. Conclusions

In this paper, a newly developed thermal enhancement concept for BGA packages was investigated against other conventional techniques through Predictive Engineering approaches. With the aid of CFD simulations, the XP technology has been found to be comparable to that of Enhanced cavity-down and superior to that of drop-in Heat Slug in terms of its effectiveness of improving package thermal performance. This capability, together with other inherent desirable features such as considerable reduction of assembly cost and realization of a much more flexible and general package design, makes it an ideal solution not only for high power low profile FBGAs and CSPs where space constraints exclude applications of common thermal enhancement methodologies, but for high performance MCPs and SiPs where an excellent thermal coupling among the dice and solder balls is needed.

The optimization of XP method was then carried out with sensitivity studies for a wide range of its variables using XP-FBGA 15x15mm and XP-PBGA 40x40mm MCP as test vehicles. For packages without an external heat sink and within practical variable range, design variables such as heat spreader and mold cap thickness, material variables such as thermal conductivity of lid attach and heat spreader, and process variables like lid attach coverage and its bond line thickness have only limited impact on package thermal performance at still air. For applications involving moving air, the distance between active die and heat spreader has a significant influence on thermal performance of XP-PBGA 40x40mm MCP, therefore, a dummy spacer die should be kept in such cases. It, however, is not necessary for XP-FBGA 15x15mm even under forced convection. For packages with an external heat sink, variables need to be controlled are dummy spacer die size, mold flash thickness, thermal conductivity and bond line thickness of lid attach.

6. Future work

Experimental correlation of simulation results for XP-BGA packages are under way.

Acknowledgments

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