Maximizing Protection of Flip Chip Interconnects

NCP and NCF Property and Process Optimization Deliver High-Reliability Results

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As data demands and digitalization accelerate, new advanced packaging technologies including 2.5D and 3D integration are becoming the norm rather than the exception for many applications – particularly within the high-performance computing sector. To achieve the functional increases required for higher processing capabilities, efficiently integrating more I/O per die has given rise to the use of copper (Cu) pillars as a replacement for traditional solder bump flip-chip interconnects. This approach has been used for some time but Cu pillar and through-silicon via TSV designs, like other packaging techniques, are being challenged by complex assembly processes and resulting obstacles, including good alignment and reliable joint interconnections when bump pitch is less than 100 µm.

Using a thermocompression bonding (TCB) process (**Figure 1**) as opposed to a traditional C4 assembly process can help mitigate these concerns and the use of pre-applied underfills – whether paste or film – has shown excellent interconnect protective benefits. However, both non-conductive paste (NCP) and non-conductive film (NCF) underfills must be formulated for process compatibility, the assurance of good solder joint formation and void-free gap filling for maximum effectiveness. This paper will discuss recent analyses to understand optimization of NCP and NCF formulations, application considerations, and processing to ensure robust joint protection for next-generation Cu pillar chip designs.

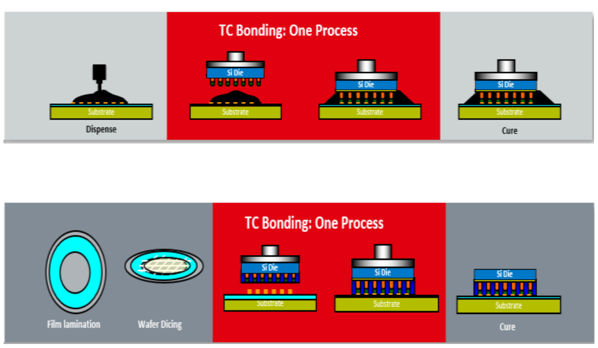

Figure 1: NCP (top) and NCF (bottom) TCB Processes

NCP and NCF Simplify Processing, Provide Faster, More Thorough Protection

One of the main benefits of using NCP or NCF and TCB, which is a simpler process than capillary flow underfill, is that during TCB, solder interconnection and bump protection are achieved in a single step. Both types of materials can be used on a variety of designs depending on process preference but, in general, NCF – which is applied to the bumped wafer before dicing -- is preferred when using die that are less than 100 µm thick and when designs integrate vertical die stacking, as in the case of high bandwidth memory (HBM) packages. NCF and NCP allow for small keep-out-zones (KoZs), which make both solutions advantageous for system-in-package (SiP) and multi-chip module (MCM) designs. (**Table 1**)

	NCP	NCF
Application/format	Pre-applied/liquid	Pre-applied/film
Die attach equipment	TC bonder	TC bonder
Si node (<10nm)	Excellent	Excellent
Die thickness	>60um	<50um
Cu pillar diameter (<25um)	Excellent	Excellent
Bump pitch (<80um)	Excellent	Excellent
Narrow gap (<30um)	Excellent	Excellent
Substrate thickness (<400um)	Excellent	Excellent
Keep out zone (KoZ)	<0.5mm	<0.5mm
Design rule flexibility enabler	2.5D & Cu pillar	2.5D & 3D stack

Table 1: Application Space for NCP and NCF

Key to a successful TCB process is the optimized formulation of the NCP and/or NCF material, with the below properties as primary considerations:

- Filler loading percentage for CTE control
- Filler particle size and resin compatibility for achieving rheology target
- NCF material transparency for fiducial recognition (die singulation and bonding)
- Glass transition temperate (Tg) > 125° C
- High modulus
- Low CTE1 and CTE2

Together, these properties will dictate rheological behavior, curing kinetics, CTE control, void-filling capability and solder joint interconnection integrity. TCB is a challenging process and its success is dependent on many factors and optimization based on the device and material being employed. Variables include die size, bump count and pitch, bump layout, substrate thickness, pad finish, solder mask and design. The most common issues observed with unsuccessful TCB processes are voiding and poor solder joint interconnection.

Using these understandings, NCP and NCF materials were formulated (**Table 2**) with optimized material properties and a study was conducted to compare the materials and their performance within the TCB process to analyze the impact of dispense volume and patterns (in the case of NCP), as well as bond force, contact temperature and ramp rate.

	Unit	NCP A	NCF B
Viscosity, (at 5 rpm)	mPas	12,500	-
Lowest Melt Viscosity	Pas	-	1,727 @138
Filler loading	wt%	52.50	40
Coefficient of Thermal Expansion, CTE 1	ppm/ºC	29	40
Coefficient of Thermal Expansion, CTE 2	ppm/ºC	94	137
Glass transition Temperature, Tg	ºC	187	166
Storage Modulus @25° C	GPa	7.40	6.70
Storage Modulus @250° C	GPa	0.60	0.13

Table 2: NCP and NCF Material Properties

<u>NCP</u>

NCP dispense patterns and volume, along with viscosity and cure kinetics, can impact the formation of voids during the TCB process. If there is insufficient material due to dispense pattern irregularity, then voiding may result. To understand the influence of dispense designs, the authors studied a variety of NCP patterns and then evaluated voiding performance. Ultimately, it was determined that an asterisk with dots or a rosette pattern would produce the best outcome. (**Figure 2**)

Once the dispense pattern was confirmed, the effect of search height and speed were evaluated. A range of search heights (0.15 mm, 0.20 mm, 0.30 mm and 0.50 mm) and speeds (from 0.10 mm/sec to 0.25 mm/sec) were investigated and it was determined that a slower bond speed helps minimize voids by enabling more thorough flow and area filling by the NCP. (**Figure 3**)

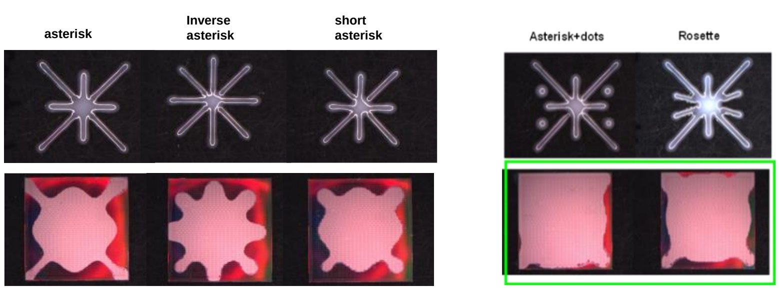

Figure 2: NCP Dispense Patterns

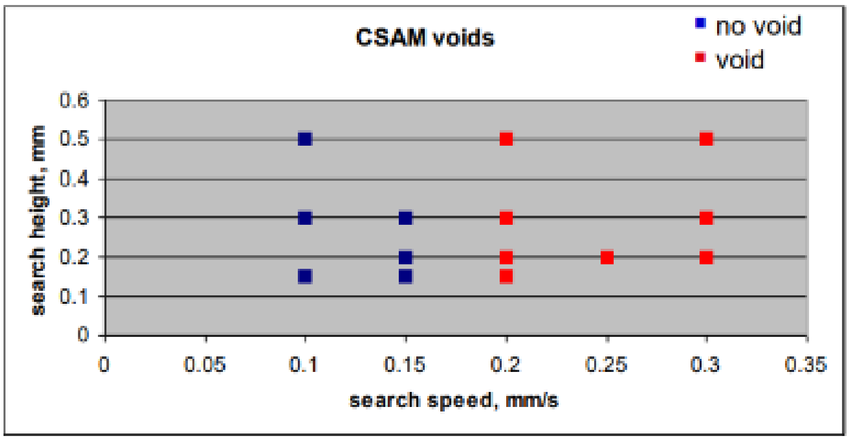

Figure 3: Search height and search speed impact on voiding performance.

NCF

Because NCF is applied onto a bumped wafer using a vacuum lamination process, the quality of the lamination and the achievement of a void-free result is dependent both on material properties and well-controlled process parameters. In this study, a 50° C lamination temperature, 10 second vacuum time, and 60 second pressure time at 0.5 Mpa pressure resulted in good gap filling and no voiding between bumps.

The NCF TCB process analysis examined contact temperatures (from 130 °C to 210°C), bond forces (25 N, 50 N and 75 N) and ramp rates (from 60° C/sec to 100°C/sec). Based on these experiment variables, joint shape and voiding trends were observed. Results showed that a combination of low contact temperature and low bond force did not produce good joints. Overall, a slower ramp rate of less than 80° C/sec produced the best results, with contact temperature not having a significant effect on void performance. In general, a slower heating ramp rate allows the material more time to flow and push out any voids. It was observed that a faster heating ramp rate is good for solder interconnection, while a slower ramp rate produces void-free results. Bond force and contact temperatures impact solder joint formation and should be balanced with ramp rate voiding optimization. (**Figure 4**)

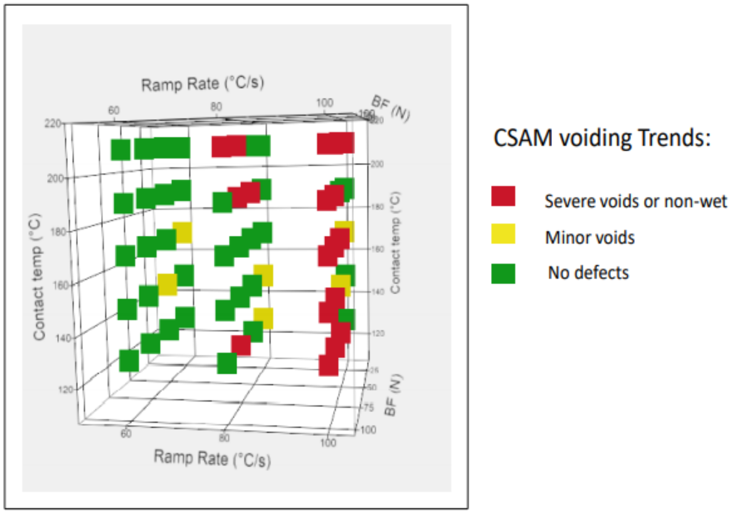

Figure 4: Contact temperature, ramp rate and bond force influence on NCF voiding performance.

Conclusion

This study analyzed both NCP and NCF within the TCB process to better understand key material properties and process parameters to produce high-reliability outcomes. It is understood that the material attributes central to a robust TCB process are rheology and cure kinetics, with poor solder interconnection and voiding being the most common issues encountered in TCB processing. When using NCP for bump protection, this study revealed that an optimized dispense pattern with controlled NCP volume will allow good NCP flow and coverage with void-free performance. Critical TCB parameters when using NCP are search height and search speed. In addition, the boding parameters of the NCF material were also evaluated, with specific study of bond force, contact temperature and ramp rate and their impact on solder joint interconnection and voiding performance. Results suggest that a bond force greater than 25 N, a contact temperature of around 170^{o} C, and a faster ramp rate produce good solder wetting. For optimal conditions, a ramp rate of 80^{o} C/sec, a higher bond force and a contact temperature of 170^{o} C or less are recommended for good solder wetting and joint quality with no voids.

This article is a summary of study results originally presented in an in-depth paper at ECTC 2021.