Plasma for Underfill Process in Flipchip Packaging

Application Note

Published by
March Plasma Systems
www.marchplasma.com

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Abstract

Driven by the fast growing demand for smaller, fast, and higher I/O electronic devices, flip chip technology has attracted significant attention in the electronic packaging industry. Flip chip is a proven packaging technology due to its high performance, reduced form factor and greater I/O density.

In the successful flip chip packaging, the underfill process plays an important role because it can significantly increase the reliability and quality of the package, as it can increase the thermal fatigue life of the solder bump interconnects, protects the interconnect from the environment and provides robustness against mechanical shock.

Plasma treatment prior to the underfill process brings many benefits to the underfill dispensing process, such as increases wicking speed, improves fillet height and its uniformity, and promotes the interface adhesion. As a result, plasma treatment prevents delamination and void formation that can result in a shortened lifetime for microelectronic devices.

Many factors in plasma process affect the plasma performance for underfill process. Selection of appropriate plasma chemistry and configuration is critical to the successful implementation of plasma prior to the underfill step. The flexibility of the radio frequency, low pressure plasma allows the user to successfully utilize plasma for numerous material set. In this paper, plasma chemistry and plasma performance with die, substrate and underfill material will be reviewed and new experiment data will be showed.

Key words: Plasma, underfill, passivation, delamination, flip chip package.

Introduction

Flip chip packaging becomes a very popular advanced packaging because of its high speed, high I/O density, and good heat dissipation performance. To ensure the highest reliability and yield in flip chip assembly, the underfill process plays a very important role. Underfill can reduce the relative displacement between the die and substrate, thus the stresses in the solder interconnection that arise from the thermal cycling and mechanical loading are reduced. Furthermore, underfill can provide the protection to the device from environment attack and improves mechanical reliability of flip chip packages.

Many challenges can be met in the underfill process, such as low wicking speed, lower and unbalanced fillet height and possible delamination. Lower and unbalanced underfill height will decrease flip chip device’s tolerance to thermal and mechanical shock and delamination may force the solder balls to withstand the majority of deformation of the package assembly during cycling loading, leading premature shear failure. And low wicking speed will decrease the throughput of production and, thus increase the cost of products. All of these underfill challenges are related to the properties of the substrate, underfill fluid, and flip chip device, such as die size, gap, bump density, differing die passivation materials, and surface property of substrate. While the packaging materials, geometries and underfill fluids are specified, underfill performance is only dependent on the surface properties of the substrate and die.

Plasma surface modification, which is widely used in the surface cleaning, activation and modification fields for enhancing surface adhesion, improving surface bondability, and tailoring surface energy, becomes a key factor for a successful underfill process in flip chip packaging [1]. The plasma process has been proven for applications such as improving the pull strength of wire bonds; increasing fillet height, fillet uniformity, and underfill adhesion of flip chip devices; and altering surfaces for better adhesion in lamination, mold and encapsulation processes [2, 3]. In this paper, plasma technology will be briefly introduced, previous work will be reviewed and new experimental data will be shown.

Plasma Technology

Plasma often described as is the fourth state of matter out of solid, liquid, and gas. Plasma is partially ionized gas with an electrically neutral mixture of physically and chemically active gas phase species, including ions, electrons, free radicals, photos and neutral particles. The reactive radical species are capable of chemical work by chemical reaction, whereas the ionized atom and molecular species are capable of physical work through sputtering. As a result, plasma can perform numerous surface modification processes including surface activation, contamination removal, crosslinking, and etch by chemical reaction, and physical bombardment [2]. Typical example of surface cleaning by physical bombardment is Argon plasma process. Oxygen plasma can do both physical and chemical work on surface because of the existence of both ions and free radicals.

Two plasma modes, downstream and direct plasma modes, can be chosen in actual plasma application. In direct plasma mode, the substrate is directly exposed in the glow discharge zone. As both ions and free radicals are involved in the process, direct plasma process is an aggressive, faster and effective plasma process. However, it might damage some devices which are sensitive to the UV and ion bombardment.

With downstream plasma, including ion free plasma (IFP), the substrate is placed outside the plasma glow discharge zone, normally downstream of the gas flow. Downstream plasma is a mild plasma process since most of the ions and UV light are filtered before the activated species reach the substrate surface. This process is acceptable for devices which are very sensitive to the UV exposure and ion bombardment. The downstream process is slower relative to a direct plasma process. Theoretically, IFP process is considered as the pure chemical process since only uncharged particles, mainly free radicals, participate in the surface modification.

Review of Previous Work

Plasma for Surface Modification Beneath The Die

Previous work has proven that plasma active species can penetrate into the small gap between the die and substrate and activate the surface beneath the die. This surface activation is the key issue for the application of plasma for underfill process [4]. The experimental results indicated that the surface wettability under the flip chip die depends on the geometry of the flip chip, the flip chip package materials and plasma chemistry. The chip size affects the surface cleaning effectiveness in flip chip packaging. With the decrease of the die size, the surface contact angle on the center of both the die and substrate decreases, meaning that the plasma cleaning effectiveness increases with decreasing die size. The surface material also affects the surface contact angle after plasma treatment. Under the same plasma condition, the surface contact angle on die surface is lower than that on the substrate surface. The further experiment result indicated that the surface contact angle at the center of the die and on the substrate beneath the flip chip is impacted by the plasma source gas. In general, the oxygen-based plasma has a greater impact on the contact angle than either nitrogen or argon. The contact angle trend is: O_2 plasma > N_2 plasma > Ar plasma. Lower contact angle or higher surface energy can be obtained via oxygen plasma treatment. Furthermore, the surface contact angle die and substrate decreases with an increase in the ratio of oxygen in O_2/Ar and O_2/N_2 gas mixtures under the same plasma conditions.

Plasma treatment also modifies the surface composition beneath the die with polyimide passivation layer. When comparing oxygen content in the polyimide with untreated and treated samples, the oxygen composition on the die surface increases approximately 36 percent after oxygen IFP plasma treatment. The surface functional group analysis indicates that the total oxy-functional group increases about 19 percent. The increase in oxy-functional groups is responsible for the improved adhesion of the underfill fluid to the polyimide passivation since oxy-functional groups on the surface can interact and chemically bond the underfill materials during underfill process [1]. The greater the concentration of oxy-functional groups, the less likely it is for delamination to take place. Removing contaminants on the interfaces and chemically activating the surface might minimize the possibility of interface delamination.

Plasma For Underfill Process

The good underfill performance in underfill dispensing process includes high wicking speed, high fillet and uniform fillet height. It is desirable that the underfill fluid dispenses quickly but also produces a sufficient fillet height with good uniformity. A general criterion of fillet height is greater than 20 percent of the height of the die and a fillet imbalance is lower than 30 percent of the die.

Wicking speed of underfill is inversely proportional to the flow-out time, which is proportional to the cosine of contact angle ($T= 3\mu L^2/h\gamma cos\theta$, T is flow-out time in seconds; μ is fluid viscosity; L is flow distance; h is gap or bump height; γ is surface tension of liquid vapor interface, and θ is the contact and wetting angle). For certain flip chip packages, the lower the contact angle, the faster the wicking speed, and therefore, the higher the production line throughput.

An example from our previous work showed that the contact angle on the center of the die (20 mm x 20 mm size, bumped side) was 40-degrees before plasma treatment and 20-degrees after plasma treatment [1]. The reduction in contact angle translated into a reduction in flow-out time from 60 to 22 seconds, a 270-percent improvement. That means the throughput significantly improves when plasma is used in underfill dispensing process of flip chip packaging.

Typically, a more uniform fillet height results in a more reliably packaged device, as non-uniform fillet heights often result in uneven stresses on the chip, which could cause fillet cracking and package failure. The low surface energy of both the substrate and die impacts both fillet height and uniformity. Our previous work showed that the fillet height on opposite side increased from 12.4% to 27.70% and imbalance of fillet height decreased from 44.2 % to 12.60 % after oxygen IFP plasma treatment [1], which meets the criteria of fillet height and uniformity in flip chip packaging industries.

New Experimental Data and Discussion

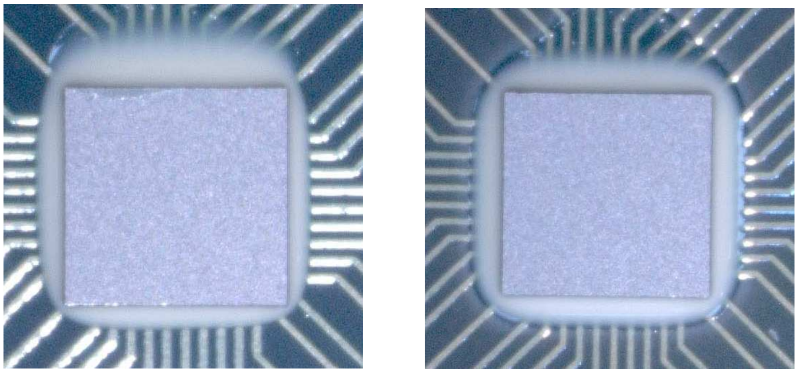
Plasma For Underfill Dispensing Performance

In order to present how plasma improves the underfill dispensing performance, three samples (A, B, C) with different surface finishes and/or die size have been used for evaluation and the results are shown in Table 1. It is clear that from the data that plasma treatment increases the wicking speed, manifested in the reduction in flow out from 11 % to 37% during underfill dispensing process. The result is consistent with previous results but the magnitude of improvement was lower due to the differences in materials. Specifically, the plasma treatment increases the surface energy which allows for an increased wicking speed. The improvement of wicking speed depends on the surface finish and die size. Flip chip with gold finish shows better wicking speed improvement after plasma treatment. Furthermore, flip chip with larger die size shows more significant improvement.

Sample information				
		Smaple A	Sample B	Sample C
Die size		5 X 5 mm	5 X 5 mm	7 X 7 mm
Surface finishes		Cu/Ni/Au	Cu/OSP	Cu/Ni/Au
Pitch between joints		200 um	200 um	12.5 um
Joint		100 um	100 um	350 um
Plasma parameters				
O2	100 sccm	400 W	200 mTorr	3 min.
Result				
		Time to Flow Out (sec)		
		Average	Stdev	Improvement
Sample A	Untreated	9.07	1.61	17%
	Treated	7.56	1.58	
Sample B	Untreated	9.64	1.34	11%
	Treated	8.6	1.77	
Sample C	Untreated	24.23	4.15	37%
	Treated	15.26	1.75	

Table 1: *All samples were treated in AP-1000, batch plasma machine from March Plasma Systems

There is no visual difference between plasma treated and untreated substrates in X-ray images. However, the difference of underfill performance can be revealed when underfill dispensing process has been finished. The comparison of optical images between plasma treated and untreated flip chip after underfill curing process is shown in Figure 1. Without plasma treatment, the underfill imbalance and bleedout on the dispensing side is much larger than that on the opposite side. This difference is significantly reduced after plasma treatment. It is clear that plasma treatment improves the underfill uniformity along the edge of the flip chip.



(a) No Plasma

(b) Plasma treated

Figure 1. Top view images of flip chip after underfill curing process:

Figure 2 shows the underfill performance from the side view. The fillet height difference between plasma treated and untreated samples can be found at the corners of the device. The underfill fills more for the plasma treated flip chips than for untreated ones at the corners. This result also indicates that plasma increases the surface energy, resulting in improving the fillet height around the periphery of the flip chip and promoting underfill fluid to cover the corners of it during underfill dispensing process.

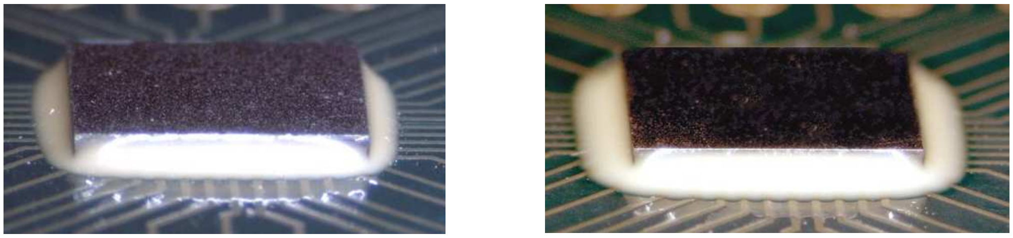

(a) No Plasma (b) Plasma treated

Figure 2. Side view images of flip chip after underfill curing process

Figures 3 and 4 show the optical images of CSP packages after underfill curing. The trend is same as what we see in Figures 1 and 2. In summary the plasma treatment prior to underfill improves the underfill performance by increasing wicking speed, increasing filet height and filet uniformity.

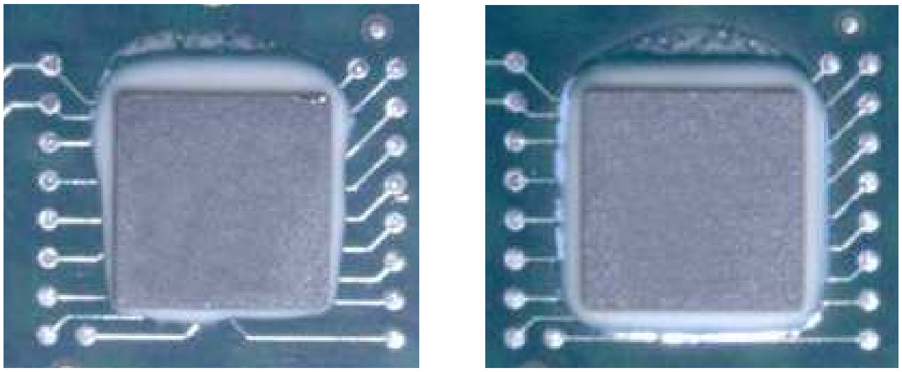

(a) No Plasma (b) Plasma treated

Figure 3. Top view images of CSP after underfill curing process:

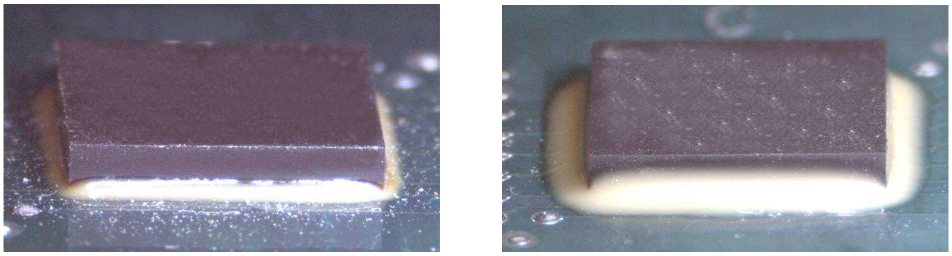

(a) No Plasma (b) Plasma treated

Figure 4. Side view images of CSP after underfill curing process

Plasma For Adhesion

Poor adhesion between the die passivation layer and underfill, between the metal finishes and the underfill, and between the underfill and substrate often cause the interface delamination problems in flip chip packages. Delamination of a flip chip package is most often seen at the interface between the underfill material and the die passivation layer, typically around the edges of the die. There are numerous factors that impact underfill adhesion, including surface contamination and the chemical nature of the passivation layer. Fortunately, plasma can remove contamination and chemically modify the surface to enhance adhesion.

Generally, the temperature cycling test is used for interface delamination evaluation and SCAM is used to evaluate if the devices pass the temperature cycling test. Table 2 shows the result of CSAM analysis after temperature cycling test. All samples used for this evaluation were flip chips with gold finishes. The temperature cycling range is -40 to 125 °C. The result indicates that the O_2 plasma treated samples did not show any device failure after 4000 temperature cycling testing while untreated samples showed 11.3% and 7.5% failures respectively.

Table 2. Result of Temperature Cycling Test

Substrate	Finish		No. of Cycling			
			1000	2000	3000	4000
PCB	Au	Plasma	0/58	0/58	0/58	0/58
		No Plasma	0/62	0/62	1/62	6/62
BGA	Au	Plasma	0/50	0/50	0/50	0/50
		No Plasma	0/40	0/40	1/40	2/40

Same temperature cycling test results indicated O_2 plasma treated samples with OSP finishes did not show significant reliability improvement. The possible reason is that plasma process is not sufficient enough to remove organic residuals and activate the surface. Further studies are in progress to understand this observation.

In order to determine the plasma performance for adhesion improvement, Lap shear and T-peel tests were run and the adhesion force was measured (see Figure 5). The materials used for testing were FR-4 coated with solder mask, and 125 micron thick polyimide film. A Henkel underfill material was used. The sample's width was 10 mm and the adhesion area was 10 mm × 25 mm. Two plasma modes were used for this evaluation. Direct plasma was run in an AP-1000 plasma treatment system. The following plasma conditions were used: argon or oxygen plasma, 400 W, 120 sccm, 200 mTorr and 120 seconds; and IFP plasma was run in the XTRAK-IFP system with plasma condition: oxygen plasma, 200 W, 45 sccm, 200 mTorr and 120 seconds.

Figure 5 illustrates that the strength of the interface adhesion improves after plasma treatment. The shear and peeling force increase about 216 percent and 435 percent respectively after plasma treatment. The failure mode also changed from polyimide-underfill adhesion failure to polyimide film cohesion failure (film breaks) in shear test. These results indicate that a plasma-treated surface can improve the adhesion and decrease or eliminate the delamination in flip chip packages.

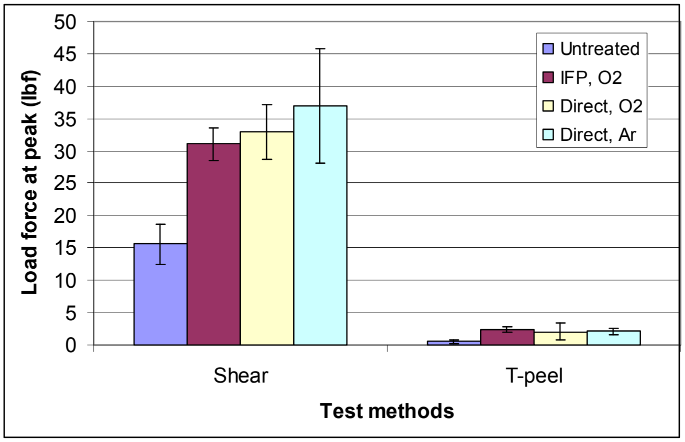


Figure 5. Shear and peel force comparison between the plasma treated and untreated samples.

Conclusion

Plasma treatment can be successfully applied to capillary underfill processes. Plasma treatment significantly improves underfill dispensing performance and the adhesion at the interface and therefore decreases or eliminates the interface delamination. Visual inspection indicates that plasma improves the fillet height and uniformity. Oxygen plasma treatment decreases or eliminates the device failure in temperature cycling test, thus promotes the device's reliability.

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