



Plasma for Underfill Process in Flip Chip Packaging

Jack Zhao and James D. Getty
Nordson MARCH
2470-A Bates Avenue
Concord, California 94520-1294
USA

Abstract

Driven by the fast growing demand for smaller, faster, 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 successful flip chip packaging, the underfill process plays an important role because it can significantly increase the reliability and quality of the package. It can also increase the thermal fatigue life of the solder bump interconnects, protect the interconnect from the environment, and provide robustness against mechanical shock.

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

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

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

Introduction

Flip chip packaging has become a very popular advanced packaging method because of its speed, I/O density, and heat dissipation performance properties. To ensure the highest reliability and yield in flip chip assembly, the underfill process plays a critical role. Underfill can reduce the relative displacement between the die and substrate, thus minimizing the stress in the solder interconnection that arises from thermal cycling and mechanical loading of the structure. Furthermore, underfill can provide protection to the device from environmental attacks and improves mechanical reliability of flip chip packages.

The underfill process can encounter numerous challenges, such as slow wicking speed, lower and unbalanced fillet height, and possible delamination. Lower and unbalanced underfill height will decrease a flip chip device's tolerance to thermal and mechanical shock and delamination, forcing the solder balls to withstand the majority of deformation of the package assembly during cycling loading, which leads to premature shear failure. Slow wicking speed will decrease the throughput of production and thus increase the cost of products. All of the 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 the 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 and fillet uniformity, and underfill adhesion of flip chip devices; and altering surfaces for better

adhesion in lamination, mold, and encapsulation processes [2, 3]. This paper will briefly introduce plasma technology, previous work, and show experimental data.

Plasma Technology

Often described as the fourth state of matter, plasma is a partially ionized gas with an electrically neutral mixture of physically and chemically active gas phase species, including ions, electrons, free radicals, photons, and neutral particles. The reactive radical species are capable of chemical work by chemical reaction, whereas the ionized atomic 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]. A typical example of surface cleaning by physical bombardment is the Argon plasma process. Oxygen plasma can do both physical and chemical work on surfaces because of the existence of both ions and free radicals.

Plasma applications can utilize one of two modes, direct or downstream. 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 is aggressive, fast, and effective. However, it might damage some devices which are sensitive to ultraviolet (UV) light, an emission from photons, and/or charge damage, a byproduct of 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 sensitive to UV exposure and/or ion bombardment. The downstream process is slower relative to a direct plasma process. Theoretically, the IFP process is

considered 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 experiment's 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 influences 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 the die surface is lower than that on the substrate surface.

A further experimental result indicated that the surface contact angle at the center of the die and on the substrate beneath the flip chip is dependent upon the plasma source gas. In general, an 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 die and substrate surface contact angles decrease 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 a 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 indicated that the total oxy-functional group increases about 19 percent. The increase in oxy-functional groups on the surface can interact and chemically bond the underfill materials during the underfill process [1]. The greater the concentration of oxy-functional groups, the lower the potential for delamination. Removing contaminants on the interfaces and chemically activating the surface might minimize the possibility of interface delamination.

Plasma for the Underfill Process

Good performance in the 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 which 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 the 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 may cause fillet cracking and package failure. The low surface energies of the substrate and die influence both fillet height and uniformity. Our previous work indicated that the fillet height on the 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

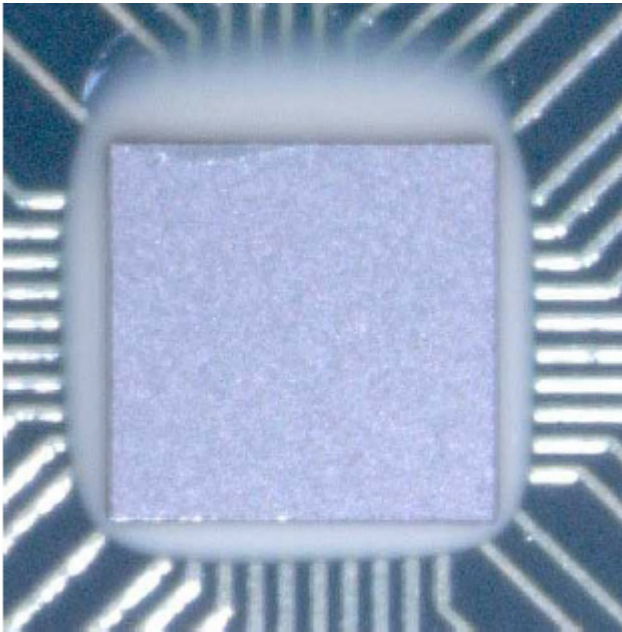
In order to illustrate how plasma improves underfill dispensing performance, three samples (A,B,C) with different surface finishes and/or die sizes have been used for evaluation. The results are shown in Table 1. It is clear from the data that plasma treatment increases the wicking speed, manifested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

Sample Information					
		Sample 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 μ m	200 μ m	12.5 μ m	
Joint		100 μ m	100 μ m	350 μ m	
Plasma Parameters					
O2	100 sccm	400 W	200 m Torr	3 min	
Result					
		Time to Flow-Out (sec)			
		Average	St. dev	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		

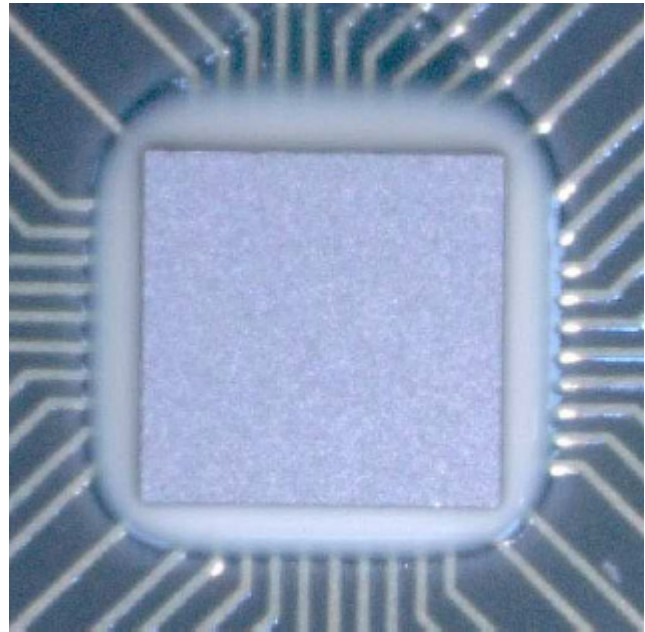
*Table 1: *All Samples were treated in an AP-1000, batch plasma machine from Nordson MARCH*

There is no visual difference between plasma treated and untreated substrates in X-ray images. However, the difference of underfill performance is noticeable upon completion of the underfill dispensing process. The comparison of optical images between plasma treated and untreated flip chips after the underfill curing process is shown in Figure 1. Without plasma treatment, the underfill imbalance and bleed-out on the dispensing side is much larger than that on the opposite side. This difference is significantly reduced in the flip chip that received plasma treatment. It is clear that

plasma treatment improves the underfill uniformity along the edge of the flip chip.



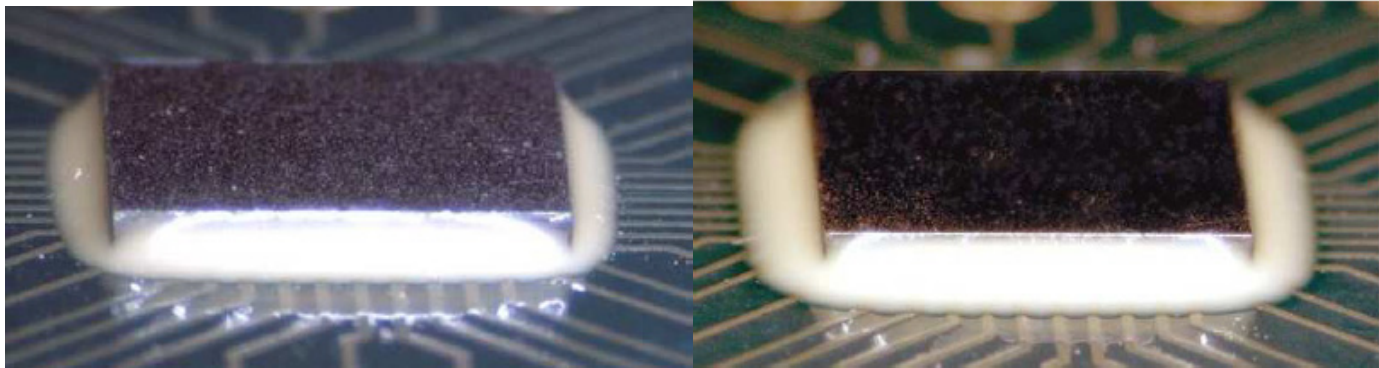
(a) No Plasma



(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 material occupies more area for the plasma treated flip chips than for untreated ones at the corners. This 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 the chip during the underfill dispensing process.

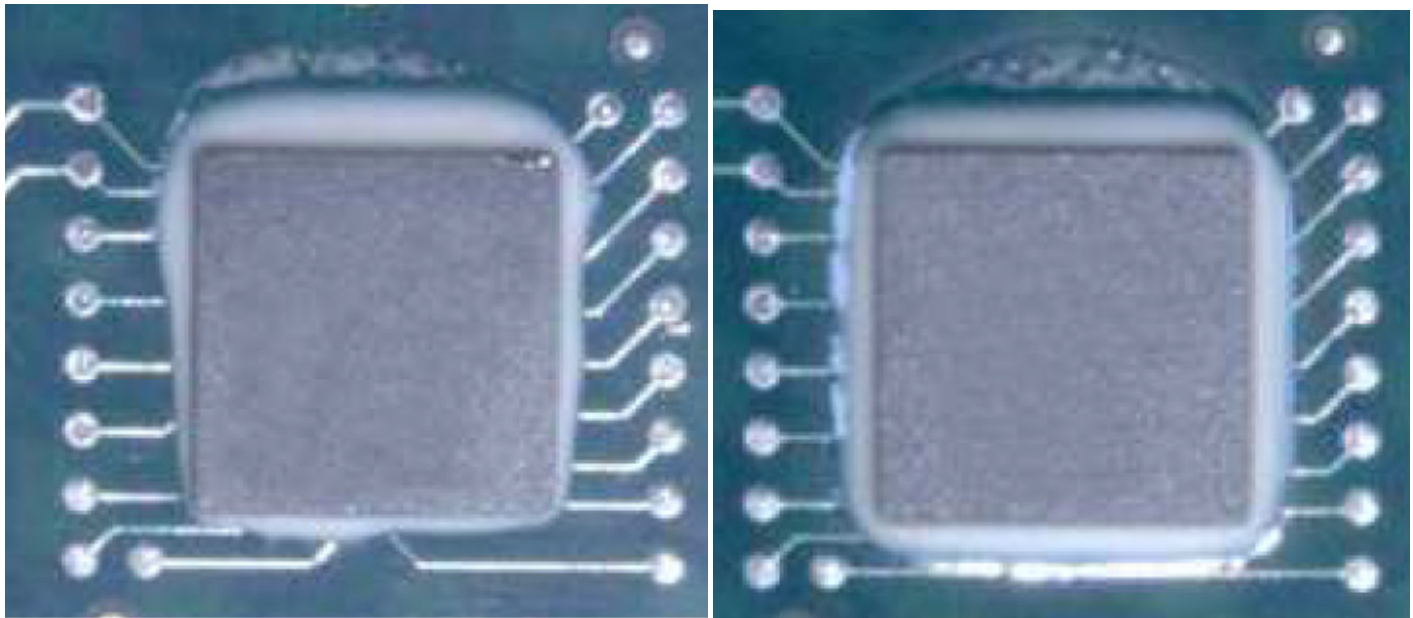


(a) No Plasma

(b) Plasma Treated

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

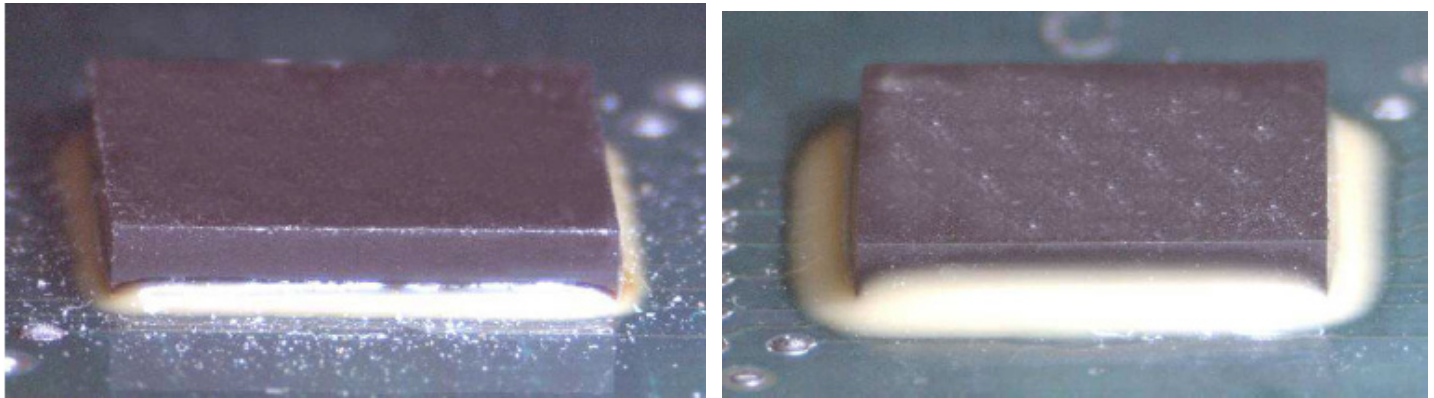
Figures 3 and 4 show the optical images of CSP packages after underfill curing. The trend is the same as what we see in Figures 1 and 2. In summary, the plasma treatment prior to underfill improves the underfill performance by increasing wicking speed, balancing fillet height, and improving fillet uniformity.



(a) No Plasma

(b) Plasma Treated

Figure 3. Top view images of CSP after the 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 to delaminate 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 affect 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 confocal scanning acoustic microscopy (C-SAM) is used to evaluate if the devices pass the temperature cycling test. Table 2 shows the result of C-SAM analysis after the temperature cycling test. All samples used for this evaluation were flip chips with gold finishes. The temperature cycling range is -40 to 125 °C. This result indicates that the O₂ plasma-

treated samples did not show any device failure after 4000 temperature cycles while untreated samples showed 11.3% and 7.5% failures, respectively.

Table 2. Result of Temperature Cycling Test

Substrate	Finish		No. of Cycles			
			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
PCB	AU	Plasma	0/50	0/50	0/50	0/50
		No Plasma	0/40	0/40	1/40	2/40

In order to determine the plasma performance for adhesion improvement, the adhesion force was measured with Lap Shear and T-peel tests. (see Figure 5). The materials used for testing were FR-4 coated with solder mask 125 micron thick polyimide film and a Henkel underfill material. The sample's width was 10 mm and the adhesion area was 10 mm x 25 mm. Two plasma modes were used for this evaluation. Direct plasma was run in an AP-1000 plasma treatment system, using 120 sccm of argon or oxygen gas, 400 W RF power and 200 mT pressure for 120s. IFP plasma was run in the XTRAK-IFP system, using 45 sccm of oxygen gas, 200 W RF power and 200mT pressure for 120s.

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.

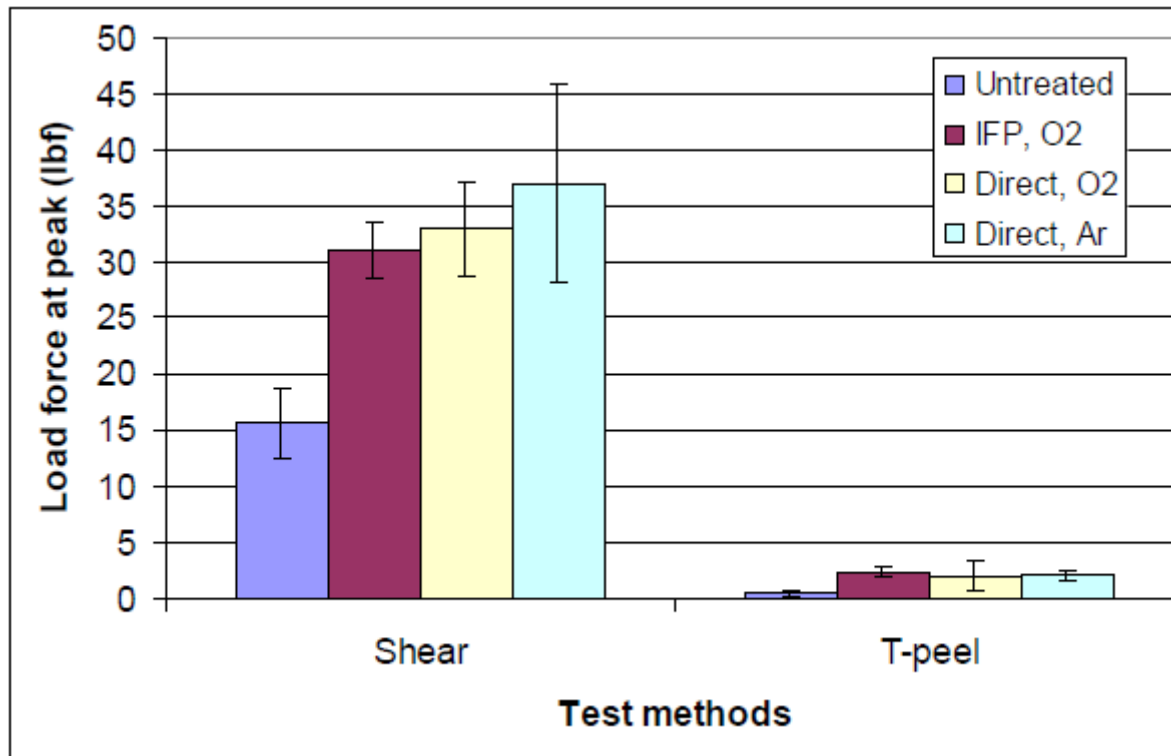


Figure 5. Shear and peel force comparison between the plasma treated and untreated samples.

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 device failure, as found in temperature cycling tests, thus it promotes the device's reliability.

REFERENCES:

[1] Jack Zhao, James Getty, and Daniel Chir, "Plasma Processing for Enhanced Underfill," Chip Scale Review, July 2004.

[2] James Getty, "How Plasma-Enhanced Surface Modification Improves the Production of Microelectronics and Optoelectronics," Chip Scale Review Jan/Feb 2002.

[3] Jack Zhao, James Getty, and Lou Fierro, "Plasma and its Application in Printed Circuit Board Manufacturing," TPCA Forum Oct. 3-Nov. 1, 2003.

[4] James Getty and Jack Zhao, "Plasma Treatment for Underfill Process in Flip Chip Packaging", Pan Pacific Microelectronics Symposium, 2005 proceedings, Kauai, Hawaii, Jan 25-27, 2005.

Author Biographies

Dr. Jack Zhao

Dr. Zhao is applications scientist and director of applications in Asia for Nordson MARCH. He is responsible for process development, technical support and R&D. He holds a doctorate in chemical engineering and has worked in the semiconductor industry for over 15 years and the plasma application field for nearly 20 years. Email: Jack.Zhao@nordsonmarch.com

Dr. James D. Getty

Dr. Getty joined Nordson MARCH in 2000 and has served as president since 2012. Prior to becoming president, he led Nordson MARCH's applications engineering and business development activities, including the marketing activities supporting the business' semiconductor, printed circuit board, and life sciences market segments. Dr. Getty has a B.S., Chemistry

from the University of California at Irvine and a Ph.D. in Physical Chemistry from the University of California at Davis.