Using Argon Plasma to Remove Fluorine, Organic and Metal Oxide Contamination for Improved Wire Bonding Performance

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ABSTRACT

Commercially-available plasma cleaning systems using Argon gas can be used for effectively cleaning Fluorine, organic, and metal oxide contamination from the surface of a variety of microelectronic wire bonding pads in order to measurably improve the performance and reliability of wire bonding.

Microelectronic devices and the substrates to which they are attached come in many forms, including the following: Organic ball grid array (BGA) strips, metal lead frames, semiconductor die ("computer chips"), and microelectronic packages (such as flip-chip devices) held in metal boats or trays for processing. Thus, it is important to also provide suitable substrate handling capabilities in conjunction with the aforementioned Argon plasma cleaning processes.

An Argon-based plasma cleaning process has significant and measurable benefits [1] when used before wire bonding, because it removes all kinds of contamination via ion bombardment (also known as "sputtering") without causing a chemical reaction or oxidation on the surface of the substrate. This is a key characteristic of Argon plasma cleaning, because chemical reactions, additional oxidation, or degradation of the metallization layers at this stage of packaging are extremely undesirable.

Using Argon plasma, contaminants are literally knocked off of the surface of the substrate at the molecular level, and exhausted out of the process chamber before re-deposition can occur. Moreover, Argon plasma is effective for many types of contamination such as Fluorine, organic contamination and metal oxides, because it is largely non-selective and removes all these contaminants at a similar rate.

In addition to contamination removal which benefits wire bonding, Argon plasma is also used to physically roughen a substrate, and to activate chemical bonds on the surface in order to improve bondability and adhesion after wire bonding (resulting in overall better device reliability).

The Argon plasma cleaning process is highly flexible and can be tailored to improve wire bonding for many kinds of materials, and wire bonding processes. By changing basic process parameters such as process gas flow rate, process pressure, RF power setting, and/or chamber configuration, commercially-available plasma systems can deliver a suitable Argon-based plasma cleaning process for almost any type of substrate and wire bonding process.

Argon plasma cleaning performance can be quantifiably and scientifically measured, and is both traceable and reproducible for Q.A. purposes.

For example:

1. Immediately after plasma cleaning, wettability testing can be done using a water drop tester in order to confirm the effectiveness of the plasma cleaning step. Wettability can correlate to improved bondability, and is a desirable result to confirm right after Argon-based plasma cleaning.
2. Wires can be bonded to both plasma cleaned and non-plasma cleaned bond pads and pull tests can be conducted to confirm improvements with Argon plasma cleaning. These tests can be done by using commercially-available bond pull testing equipment.
3. Finished packages that have been plasma cleaned and not plasma cleaned can also be tested for reliability. There are many semiconductor packaging industry-defined standards and testing procedures (i.e. JEDEC standards) that stress the finished packages in regard to mechanical stress, temperature cycling, and power cycling in order to confirm reliability improvements by using Argon plasma cleaning.

Although it will not be discussed in detail within this paper, in addition to actual contamination removal, Argon plasma can also be used to improve wire bonding performance by physically roughening the bond pads, and by activating the surface of the bond pads in order to improve adhesion. This contributes to better overall device reliability.

PERFORMANCE CRITERIA FOR ARGON-BASED PLASMA CLEANING

For the purposes of evaluating the effectiveness of

Argon-based plasma cleaning of contamination from wire bonding pads, the following criteria and corresponding values were used.

Criteria	Requirement
Average **Etch Rate** (Sputtering Rate) of Gold (Au)	≥ 250 angstroms/min.
Contact Angle, Post-Plasma Treatment, using Contact Angle Meter (CAM) & De-ionized Water Dropper	≤ 30 degrees
Wire Bond Pull Strength, measured using a commercially-available Pull Tester	≥ 5 grams
CpK, Calculated from Wire Bond Pull Strength Data	≥ 1.33

Figure 1. Criteria for evaluating an Argon plasma cleaning process used to improve wire bonding performance.

THROUGHPUT CONSIDERATIONS FOR A PLASMA CLEANING PROCESS

Typical Argon-based plasma cleaning processes can remove most contamination from the surface of the substrate in about 30 seconds, which in most cases is sufficient to improve wire bonding performance.

It is important to note that contamination may be Fluorine (or another type of halogen,) organic contamination, or metal oxides (such as Nickel oxide.) The actual contamination may also be a combination of these types of contaminants. This is a common situation in actual manufacturing facilities.

Given a Gold etching rate of ≥ 250 angstroms/minute, and using an advanced automated strip handling system integrated to a specialized plasma processing module, a throughput of up to 640 strip units per hour (UPH) per plasma system can be achieved. However, if the contamination layer is particularly thick or difficult to remove, then the estimated throughput values should be adjusted accordingly.

EXPERIMENTAL SET-UP AND METHOD

A commercially-available plasma cleaning system with a 13.56 MHz radio frequency (RF) generator was used. The system had two (2) mass flow controllers (MFC). Semiconductor-grade Argon gas was used as the process gas. The lower electrode upon which the samples were placed was temperature-controlled during and between process runs using a closed-loop chiller unit.

Because each process run was relatively short (set-point was 30 seconds RF-On time per substrate), it was not necessary to cool the electrode for the sake of maintaining a low substrate temperature. In fact, a simple "finger-touch" test confirmed that little substrate heating occurred during each process run. Instead, it was deemed desirable to hold the electrode at a constant temperature during and between all runs (from start to finish) in order to eliminate electrode temperature as a source of process variation.

The strip samples (Qty. 100 total) were Copper-based metal lead frames, coated with Palladium, Nickel, and thin Gold. Each chip mounting site on the substrates had 32 bond pads (distributed 8 per side.) Similarly, each chip had 32 bond pads (also 8 per side.) A number of chips were mounted to each lead frame using oven-cured die attach epoxy, but not every chip mounting site was covered with a chip because it was necessary to do water droplet tests on some of the lead frames.

All 100 strip samples were treated in order to create simultaneous metal oxide (Nickel oxide), Fluorine, and organic contamination over the surface of the substrate. Confirmation of contamination was verified using an XPS technique (XPS is X-ray Photoelectron Spectroscopy, also known as ESCA.)

Note that Nickel oxide forms above the thin Gold layer, because the pure, un-oxidized Nickel metal tends to migrate through the thin gold layer during processing, and when it reaches the surface of the substrate, it oxidizes upon exposure to the ambient environment.

Due to the presence of three distinct types of contamination on these samples (Fluorine, organic contamination, and Nickel oxide), it was necessary to choose a plasma cleaning process that would remove all three kinds of contamination without causing damage to the bond pads or increasing the amount of oxidation. Therefore, an optimized Argon-only (i.e. non-Oxygen, non-Hydrogen) plasma cleaning recipe was chosen as the most suitable process for this contamination cleaning application.

The contaminated samples were split into 4 groups, 2 of which received wire bonding:

- Group 1 (Qty. 25): Non-wire bonded and non-plasma cleaned control for water droplet testing.
- Group 2 (Qty. 25): Non-wire bonded and Argon plasma cleaned for water droplet testing.
- Group 3 (Qty. 25): Wire bonded and non-plasma cleaned control for pull testing.
- Group 4 (Qty. 25): Wire bonded and Argon plasma cleaned for pull testing.

A commercially-available Contact Angle Meter (CAM) was used to conduct water droplet tests on each substrate in groups 1 and 2, and the resulting data was collected and tabulated. 10 sites per substrate were measured, and measurement sites were chosen all over the surface of each substrate in order to confirm process uniformity.

Wire bonding of groups 3 and 4 was done using 25 nm Gold wire. For the bonded chips, all 32 sets of bond pads (32 on the chip and the corresponding 32 on the substrate) were bonded. Pull testing was then done to 5 chips per substrate by pulling on the substrate bond pads, again with measurement sites chosen all over the surface of each substrate in order to confirm process uniformity. The resulting data was collected and tabulated.

EXPERIMENTAL RESULTS I - WATER DROPLET TESTS

Water droplet test results for one of the 25 control substrates (designated substrate "X") are shown below.

Criteria	Result
Contact Angle, Average, **Pre-Plasma Cleaning** (10 points on 1 substrate)	91.0 degrees

Figure 2. Pre-Plasma Cleaning Water Droplet Test Results for Substrate "X."

Water droplet test results for all 25 control substrates (i.e. the average of the 25 individual averages) are shown below.

Criteria	Result
Average of 25 Contact Angle Averages, **Pre-Plasma Cleaning**	91.6 degrees

Figure 3. Average of 25 Contact Angle Averages, Pre-Plasma Cleaning.

These results show that the water droplets had a nearly vertical contact angle, and indicate that the substrate surface energy was low prior to plasma cleaning.

Water droplet test results for one of the 25 Argon plasma cleaned substrates (designated substrate "Y") are shown below.

Criteria	Result
Contact Angle, Average, **Post-Plasma Cleaning** (10 points on 1 substrate)	**< 10 degrees** (drops completely "wet out")

Figure 4. Post-Plasma Cleaning Water Droplet Test Results for Substrate "Y."

Water droplet test results for all 25 Argon plasma cleaned substrates (i.e. the average of the 25 individual averages) are shown below.

Criteria	Result
Average of 25 Contact Angle Averages, **Post-Plasma Cleaning**	**< 10 degrees** (drops completely "wet out")

Figure 5. Average of 25 Contact Angle Averages, Post-Plasma Cleaning.

These results confirm that the water droplets had a nearly horizontal profile after Argon plasma cleaning. These results indicate that the substrate surface energy was increased by Argon plasma cleaning.

EXPERIMENTAL RESULTS II – PULL TESTS

Pull test results for one chip site on one of the 25 control substrates (designated chip site "A") are shown below.

Criteria	Result
Average Wire Pull Strength, **Pre-Plasma Cleaning** (32 wires)	3.9 grams
Standard Deviation	1.4 grams
CpK	-0.27 (LCL = 5 grams)

Figure 6. Pre-Plasma Cleaning Pull Test Results for Chip Site "A.".

Pull test results for all 25 control substrates (the average of all the chip site averages) are shown below.

Criteria	Result
Average of All Chip Site Averages, **Pre-Plasma Cleaning**	3.2 grams
Standard Deviation	0.8 grams
CpK	-0.74 (LCL = 5 grams)

Figure 7. Average of Pull Test Averages, Pre-Plasma Cleaning.

These results show that the absolute pull strength is low. In fact, it is on average well below the target of 5 grams, which results in a negative CpK value (by this definition, the wire bonding process is "out of control," and process improvements would need to be implemented before production could continue.)

Moreover, there is a large amount of deviation in the pull strengths between chip sites. This implies two things: (1) There is contamination on the bond pads interfering with the wire bond process by contributing to a sub-optimal intermetallic boundary in the wire bond, and (2) Not all the bond pads are equally/uniformly contaminated. This data indicate variation in pull strength correlates to variation in the amount/uniformity of contamination.

Pull test results for one chip site on one of the 25 plasma cleaned substrates (designated chip site "B") are shown below.

Criteria	Result
Average Wire Pull Strength, **Post-Plasma Cleaning** (32 wires)	**10.6 grams**
Standard Deviation	0.8 grams
CpK	2.37 (LCL = 5 grams)

Figure 8. Post-Plasma Cleaning Pull Test Results for Chip Site "B."

Pull test results for all 25 plasma cleaned substrates (the average of all the chip site averages) are shown below.

Criteria	Result
Average of All Chip Site Averages, **Post-Plasma Cleaning**	**10.4 grams**
Standard Deviation	0.4 grams
CpK	4.48 (LCL = 5 grams)

Figure 9. Average of Pull Test Averages, Post-Plasma Cleaning. .

These results show that the absolute pull strength is improved, and also pull strength deviation is reduced due to Argon-based plasma cleaning. On average, the results are well above the target of 5 grams. CpK values are greater than the target CpK value of 1.33. This implies that the wire bonding process is both meeting absolute pull strength requirements and is "in control."

The reduction in pull strength deviation can be attributed to the fact that once the bond pad is cleaned of all the contamination, over-cleaning does not further benefit the wire bonding process. In fact, we can surmise over-cleaning might have at least two negative results: Thin layers (such as the thin Gold layer) may be etched completely away, and valuable production time may be wasted.

This is why it is important to use only an optimized Argon-based plasma cleaning recipe, one developed especially for a customer's particular wire bonding process and semiconductor packaging requirements.

EXPERIMENTAL RESULTS III – XPS RESULTS

Finally, X-Ray Photoelectron Spectroscopy (XPS) was used to confirm that the Argon-based plasma cleaning was removing contaminants from the surface of the substrate. XPS measurements were done on the bond pads before and after Argon plasma cleaning to show any improvement.

As a result, Fluorine was removed to the point of non-detection after Argon plasma treatment. Carbon (an indicator of organic contamination) and Oxygen (an indicator of oxide contamination) levels were both reduced.

A summary of XPS results is shown in the table below.

Criteria	Result
Fluorine %, **Pre-Cleaning**	4.9%
Fluorine %, **Post-Cleaning**	**Not detected**
Carbon %, **Pre-Cleaning**	48.7%
Carbon %, **Post-Cleaning**	**35.2%**
Oxygen %, **Pre-Cleaning**	16.3%
Oxygen %, **Post-Cleaning**	**11.7%**

Figure 10. Summary of X-Ray Photoelectron Spectroscopy (XPS) Results Before and After Argon Plasma Cleaning.

SUMMARY OF WATER DROPLET AND PULL TEST RESULTS

The table below shows a summary of water droplet and pull test results.

Criteria	Result
Contact Angle, Average, **Pre-Plasma Cleaning** (10 points on 1 substrate "X")	91.0 degrees
Contact Angle, Average, **Post-Plasma Cleaning** (10 points on 1 substrate "Y")	**< 10 degrees** (drops completely "wet out")
Average of 25 Contact Angle Averages, **Pre-Plasma Cleaning**	91.6 degrees
Average of 25 Contact Angle Averages, **Post-Plasma Cleaning**	**< 10 degrees** (drops completely "wet out")
Average Wire Pull Strength, **Pre-Plasma Cleaning** (32 wires on substrate "A")	3.9 grams
Average Wire Pull Strength, **Post-Plasma Cleaning** (32 wires on substrate "B")	**10.6 grams**
Average of All Chip Site Averages, **Pre-Plasma Cleaning**	3.2 grams
Average of All Chip Site Averages, **Post-Plasma Cleaning**	**10.4 grams**

Figure 11. Summary of Water Droplet and Pull Test Results.

CONCLUSION

Using an advanced plasma cleaning system and an optimized Argon-based plasma cleaning recipe, it is possible to achieve successful contamination removal results contributing to improved wire bonding. The data show that this is the case even when several types of contamination are simultaneously present.

This is important because in a semiconductor packaging facility, it is almost impossible to limit contamination to a single source. Multiple contamination sources are almost always present. Having an effective countermeasure by using Argon-based plasma cleaning is important in order to increase production yields, reduce scrap, and produce highly-reliable semiconductor devices.

By using a commercially-available RF plasma cleaning system and an optimized Argon-based plasma recipe, it is possible to achieve successful cleaning results, even when a several types of contaminants are simultaneously present.

ARGON PLASMA CLEANING TO ROUGHEN SUBSTRATE SURFACE, IMPROVE ADHESION AND INCREASE WETTABILITY

When doing microelectronic packaging, the material deposited after plasma cleaning should make complete contact with the underlying surface. Also, the material placed down should have maximized adhesion to the underlying layer.

Argon plasma treatments are an attractive solution to remove contamination without causing damage to the substrate or device package. As long as the plasma cycle time is short enough, the substrate does not experience excessive heating or become damaged during plasma processing.

In reality, most substrates and/or devices are robust and can easily handle the small temperature increases associated with short Argon plasma cleaning processes ("short" plasma cleaning processes typically have an RF-On time of between 30 and 300 seconds.) Short plasma cleaning processes are also highly effective.

Furthermore, Argon plasma treatments are well known for their ability to increase the adhesion ability of a surface by a process called "surface activation"[2]. Making a hydrophobic (non-wettable) surface into a hydrophilic (highly-wettable) surface using Argon plasma is also documented[3, 4].

An increase in the hydrophilic characteristic of a surface correlates directly to an increase in both pull and shear strengths[5]. Having materials bond as strongly as possible to the underlying layers is highly desirable in order to maximize the reliability and quality of the finished product.

The effectiveness of the plasma treatment can be measured using a commercially-available Contact Angle Meter (CAM) and water dropper. Prior to Argon plasma treatment, contact angle measurements >90 degrees are common. After a suitable Argon plasma treatment, the contact angle of many surfaces decrease 10 degrees or less (That is, the drop completely "wets out" and becomes horizontal to the surface of the substrate). A surface with a contact angle of 10 degrees or less is referred to as "highly-wettable."

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