

# Plasma Clean to Reduce Wire Bond Failures

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## Introduction

Many books and articles have been written by wire bonding experts about wire bonding. Very often, plasma treatment is referred to therein as a means to influence the bonding process or the long-term reliability of the bond. Significantly fewer, however, are the articles written by plasma experts on the applications of plasma in microelectronics packaging, and in particular, on the use of plasma prior to wire bonding. One reason for this, in a world which is acclimatized to statistical process control, may be that plasma deals with the “unknown”, that which is “out of control”. A further reason may be that a plasma process is defined by quite a large number of parameters, and it’s not always clear why one combination of settings works for one application while a second application, to all intents and purposes analogous, works best with a completely different set of parameters. Plasma has something of the aura of “alchemy” or a “black box”. There are, nonetheless, realistic expectations about what plasma can contribute both to the performance of a wire bonding process and to the long-term reliability of the packaged device. There is also a certain logic to be followed in developing a plasma process, even if it is not so hard and fast as some may like.

The benefits of plasma are to be found in two different areas: the wire bonding process itself, or what we might call “the statistics”, and the long-term reliability of the device, or what we shall refer to as “device reliability”. Although the two are to some extent interrelated, it is easiest, for clarity’s sake, to treat them separately.

## Plasma and the “Statistics” of the Wire Bonding Process

### Variety of Bonding Surfaces

Today, most “first” bonds are still made to an aluminum metallization on a semiconductor device and most “second” bonds to gold. This picture, however, is changing very rapidly with the introduction of copper (and other) wires and of new metallizations on both the devices and the leadframes, or substrates, they are bonded to. Here, we already encounter a source of diversity in the plasma process: flash gold of 50nm may be treated very differently than 2 microns of thick gold. A nickel/palladium metallization on an IC will be treated differently than aluminium. Metal leadframes can be treated very differently than BGA substrates.

While tight process control in the semiconductor industry does tend to result in a rather predictable metallization, the processes in the printed circuit board and plating industries inherently show more variability. It is not strange to source BGA substrates from three vendors, all who were supplied the same specification, and find that they result in three different sets of wire bond statistics.

### Contamination on the Surface to be Bonded

In an ideal world we would be bonding onto clean metal surfaces, with the possible exception of a thin oxide layer, on both the semiconductor device and the substrate or leadframe we are connecting it to.

In practice, there are a number of sources of surface contamination which influence the wire bond statistics and the device reliability.

These include:

- Inorganics, particularly fluorine, on the IC pad whose origins lie in the wafer processes which precede singulation.
- Organic contamination arising from outgassing and bleeding of the die attach adhesive. These can be found both on the IC metallization and on the leadframe or substrate.
- “Atmospheric” contamination which is present in the air and which deposits onto the bond pads. This is largely organic, but traces of inorganics from the atmosphere are also often present.
- Products of “diffusion” resulting from grain boundary migration of underlying metal layers: best known are nickel migration through flash gold and palladium migration.
- Excessive oxide on the surface of aluminum and copper.

Wire bond statistics tend to be influenced primarily by the presence of organics and oxides while long term reliability is more generally influenced by inorganic contamination. There is, however, an area of overlap.

While plasma can, in principle, deliver a perfectly clean metal surface for wire bonding, it has been repeatedly demonstrated that a metal surface becomes contaminated with atmospheric organics within just a few hours of plasma treatment. This effect is particularly noticeable in a cleanroom which, although “particle free”, can have high concentrations of organics arising from the plastics, surface finishes, and people present and which can be concentrated through recirculation of cleanroom air.

### **Effects of Surface Contamination on Wire Bond Statistics**

The problem with contaminants is simply that they cover the surface we want to bond to, preventing us from making a good bond. In addition, the presence of contaminants is “non-systemic”; they appear and disappear, are non-uniformly distributed and almost impossible to locate, identify, and quantify. A bonding process can run for hours or days without issues and suddenly go out of control for no apparent reason. The immediate solution is often to turn up ultrasonic power (change of a controlled parameter) with all the accompanying consequences.

The key issues we see are:

- Non-Stick on Pad (NSOP)
- Lifts
- Decrease in average shear strength
- Decrease in bonded area
- Decrease in average wire-pull strength
- Cratering and other damage arising from a too aggressive bond process

Lifts are regarded differently by different operators. For some operators a lift which is within specification is regarded as acceptable. For most applications requiring some degree of reliability a lift is never an acceptable failure mode. The question is whether you will capture a few randomly

distributed “lifts” which have not yet revealed themselves as such. Decreases in bonded area, average shear strength, and pull strength are all indicators that when the bond is made, the area of contact between the bond wire and the pad will be sub-optimal. This is due to the surface contaminant impeding the process of “welding”. In addition, it is known that, at the moment the bond is made, the contact area is never one hundred percent, but it increases with time to give a stronger bond through the process of grain boundary migration. Surface contamination will interfere with this process, leading to a bond which does not reach its maximum potential strength. This is one area where sub-optimal wire bond statistics will influence device reliability. If the bond area is not maximized the bond will fail earlier during reliability testing.

## **Influence of Plasma Treatment on Wire Bond Statistics**

Turning the above around, it’s easy to deduce that the benefits of plasma include the following:

- Reduction or elimination of NSOPs
- Reduction or elimination of lifts
- Increase in average shear strength
- Increase in bonded area
- Increase in average wire-pull strength
- Increase in process window for the bonding process
- Reduction or elimination of cratering and other damage arising from a too aggressive bond process

Since as we mentioned, contaminants cover the bonding surface preventing a good bond, it is quite possible that plasma will serve to eliminate short-term, non-systemic excursions from a process that is otherwise running very stable with a high process capability. However, even a highly capable process which is running below its ultimate potential will deliver sub-optimal device reliability. An optimized wire bond process which maximizes bonded area and minimizes pad damage will always deliver better reliability than a sub-optimized process.

## **Plasma and Device Reliability**

### **Failure Modes during Reliability Testing**

Despite the considerable variety now found in combinations of bond wires and metallizations, the failure modes which are seen during reliability testing tend to be common to all metallurgical systems. Monometallic systems form a “class within a class” in this case rather than an exception.

The difference from one metallurgical system to another is not so much the failure mode as the susceptibility to this failure mode: the time to failure.

With some simplification we can say that the most predominant causes of failure involve the following:

- Poorly formed bonds fail much faster than well-formed bonds,
- Well-formed bonds which are free of contaminants will ultimately fail by Kirkendall voiding (polymetallic systems), but usually well beyond the required lifetime of the package

- Failures of “well-made bonds” which compromise the reliability of the package are usually the consequence of contaminant accelerated voiding (Horsting Effect) and/or corrosion due to contaminants

Framed in this way, the connection with bond pad contamination is readily apparent. Assuming that our bonding process is well optimized and that our metallizations are “in order” in terms of thickness, adhesion, surface topography, density, and so on, the cause of a poorly formed bond, i.e. a bond with a low bond area consisting largely of non-coalesced microbonds, is almost always organic contaminants on the surface of the bond pad. The reasons why such bonds fail very much faster than we might expect are somewhat complex and go beyond the scope of this overview. However, the solution to the problem-- “clean your bond pad” -- is delightfully simple.

Most common polymetallic systems form intermetallics. The most widely studied is undoubtedly the gold-aluminium combination. The formation of an intermetallic is the essential first step of forming the bond and intermetallics will be formed during the production process, burn-in, and use of the components. Given that intermetallic formation is essentially the diffusion of one metal into the other (with the creation of chemical compounds between the two metals), and that eventually one of them will be exhausted by this process, the end result is always failure. When the bond is clean of contaminants, however, the “time to failure” is usually much longer than the design lifetime of the part and so intermetallic formation and the resultant Kirkendall voiding is not a problem in practice. The intermetallics are strong and electrically conductive.

The problems arise when the surfaces which are bonded are not clean, but are contaminated with inorganic materials, in particular halogens. The halogens may be present as a result of wafer processes, environmental contamination, or may be present in the molding compound used in the device package. By a somewhat complicated mechanism known as the Horsting Effect and, like Kirkendall voiding, a consequence of the diffusion of one metal into the other, the halogens become concentrated into zones at the metal interface where they greatly accelerate the process of void formation, but also represent a site at which corrosion will take place. Halogens which are not incorporated in the bond interface, but which are in contact with the metal surface, particularly at the perimeter of micro-welds, are able to form electrochemical cells which lead to rapid corrosion. A poorly formed bond, with low bond area and a large number of micro-welds, will have a greater perimeter length than a well-formed bond and so be more susceptible to this corrosion mechanism.

Of the three failure mechanisms mentioned above, this latter is the most prevalent since the majority of integrated circuits today make use of gold wire bonding onto an aluminium metallization. Despite the complexity of the failure mechanism, the solution is once again delightfully simple: “clean your bond pad”.



**Figure 1. Bench-top plasma cleaning system for surface activation and adhesion improvement (AP600)**

## Developing a Plasma Process

We have reached a point where it's easy to believe that by ensuring a clean surface to which we can wire bond plasma it will always result in improved "wire bond statistics" (even if it's only by eliminating non-systemic excursions) and improved device reliability. In our "ideal world" we would use a plasma which sputters all the organic and inorganic contaminants from our bond pads and delivers the perfectly clean bond pad leading to maximized "wire bond statistics" and maximized "device reliability". This, however, is where the complexity begins.

This solution, which would be a high power argon direct plasma at relatively low pressure, is sometimes used. It can be used on some metal leadframes with power devices. The issues that limit its applicability are the effects of sputtering and overheating. Metal leadframes are not typically susceptible to overheating, and the re-deposition of sputtered material is only an issue when it is significant and results in a change in surface resistivity or device performance, i.e. leakage currents or changes in device characteristics. Sputtering away organic contamination, which we have seen has the largest effect on wire bond statistics, is, however, much slower than removing it in a "chemical plasma" such as oxygen, but oxygen plasma is almost ineffective against inorganic contaminants. Oxygen is also not indicated in most instances where we are dealing with oxidizable metals such as copper or palladium.

Here we have the first "polarity" that we need to consider when designing a plasma process: sputtering plasma or chemical plasma? In most cases we choose a process which combines both effects, i.e. mixtures of oxygen and argon. For oxidizable surfaces this is most commonly a mixture of hydrogen and argon. This choice leads directly to the next polarity. Chemical plasmas work best at higher pressures (250 – 2000mT) whereas sputtering plasmas require low pressures (150 – 250mT) to maximize the mean free path of the energetic ions that perform the sputtering. In fact, since organic contamination is our most common issue, we typically start with a higher pressure oxygen

plasma and tend to make it more aggressive (by lowering pressure, adding argon, and increasing plasma power) if we see that we are dealing with significant amounts of inorganic contamination or if there is an indication that we could reduce cycle time, and therefore increase production throughput, by using a more aggressive plasma process. Turning up the power too much, particularly with organic substrates, can result in overheating and can result in excessive sputtering, for example of flash gold. So depending on the parts we want to wire bond, leadframe or organic substrate, thick or thin gold, sensitive or robust components, very fine pitch or large pitch (at very fine pitch changes in surface resistivity become more important) we manipulate the “levers” of the plasma process. The objective is to define a process window where we maximize the cleaning effect, but avoid the potential “downside” of an over-aggressive plasma. Given the number of variables involved, both in the nature of the parts and the plasma parameters that can be varied, a Design of Experiment (DoE) is often a useful approach. One has to bear in mind that DoEs, like SPC, are designed to work in a world of controlled and predictable “cause and effect,” which contamination normally is not!

## Going Into Production

### From Process Development to Production

While we have described contamination as “almost impossible to locate, identify and quantify” it does tend to obey its own “statistics” in most cases, moving within certain ranges. The consequence of setting up a plasma process on a limited sample of parts is understandably that the “sample average” will not equate to the “process average”. Consequently, when moving from process development to production it is commonly necessary to re-position the plasma process to deal with the “worst case” that might be found in production.

In addition, when introducing a plasma process one will, for the first time, be dealing with a normalized, clean surface, a surface which essentially is known and “always the same”. This almost always requires a re-centering of the wire bond process.

### Quality Management

It is always a nervous moment when discussing introducing a plasma process. There’s always someone who wants to measure the surface before and after plasma to be sure that it’s done what it should do. It can be done. In setting up the process a good number of customers will try to understand why their wire bonding process is “out of control”; what’s on the surface? X-Ray photoelectron spectroscopy (XPS) alone or in combination with Time-of-Flight Single Ion Mass Spectrometry (TOF-SIMS) can provide insights into what is on the surface. This information can also be useful in deciding which plasma process to use. Neither technique, however, is practicable for production QC and both are very expensive to operate. In addition, today’s contaminant may not be tomorrow’s contaminant so any QC routine set up to monitor contamination may end up measuring the wrong thing or miss something which has appeared today, but wasn’t there yesterday. The approach which is followed in setting up a plasma process nonetheless provides a level of security which in most cases is adequate. The plasma process is set up to clean the bond pads in the “worst case”. Without asking exactly what the contaminants are today, the plasma process is set up to deliver a normalized, clean surface. This surface will deliver the wire bonding statistics that were established during process development. Ultimately, all operators end up using wire bonding statistics (which they were following anyway) as the indicator that the plasma process is doing what

it should do. Plasma systems are designed to run a very repeatable process, with accurate control of gas flow, RF power, process pressure, and process time. The experience in practice, with many hundreds of machines running plasma before wire bonding, is that if the input to the process remains unchanged (nature of semiconductor device and leadframe/substrate) and the wire bonding process is stable, then the wire bonding statistics are very stable.

## Compatibility and Concerns

Questions often arise about the effects of the plasma on the semiconductor devices; are there issues with ESD, device parameter changes, charging, etc? Some of these, such as overheating and sputtering with redeposition, are the possible consequences of choosing incorrect process parameter settings and have been dealt with above. As a reference point, it may be noted that virtually every microprocessor and every memory device passes through a direct plasma prior to wire bonding (or in wafer level package processing) without compromising function or reliability. Used correctly, plasma is safe and effective. There are, nonetheless, classes of semiconductor devices which are sensitive to direct plasmas. Devices with open junctions, image sensors, EEPROMs and some types of power devices cannot be exposed to direct plasma without causing performance changes or, in some cases, catastrophic damage. In some cases, a plasma which essentially eliminates the RF field, the presence of charged and energetic particles, and the light which is inherent in the plasma process, can offer a solution. Nordson MARCH's "ion-free plasma" is one such system.

It will always be the responsibility of a (potential) plasma user to ensure that there is no compatibility issue with his devices, but your plasma equipment manufacturer can assist in making this evaluation.



**Figure 2. High Throughput Plasma Treatment System (FlexTRAK)**

## Summary

The introduction of an appropriate plasma process prior to wire bonding will always deliver a cleaner surface to bond to. Potential benefits are improved wire bond statistics, improved device reliability, and the elimination of excursions caused by non-systemic influences (random pollution of the surfaces to be bonded by uncontrolled factors).

John Maguire has been Business Manager, Europe for Nordson March since 2006. With a degree in chemistry from the University of Bath (UK) and a doctorate in polymer chemistry from the University of the South Bank (London, UK), Mr. Maguire combines a strong technical background with thirty years of experience in the European PCB, electronics, microelectronics and semiconductor industries. Working together with specialised distributors in each region and segment, Mr. Maguire's first strategic objective is to ensure that plasma processing emerges from its „Black Box“ and takes its place as a well known and well understood solution to many challenges in the electronics industry and other market segments.