

DC-Hydrogen Plasma Cleaning A Novel Process for IC-Packaging

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Abstract

An advanced plasma cleaning process which differs from conventional plasma cleaning has been used for cleaning of organic and metallic chip carriers prior to gold-ball wire bonding. The plasma process is based on an argon-hydrogen discharge generated between the heated filament (cathode) and the chamber walls (anode). The discharge is characterized by high currents from 10A to 100A and low voltages of 20-30V, which allows a soft and very efficient cleaning by chemical reactions only and avoiding sputtering of material.

The plasma chemistry has been investigated *in-situ* by plasma process monitoring of copper substrates. Volatile hydrogen compounds are formed during cleaning, which then are pumped away. The plasma treated surfaces have been analyzed *in-situ* by Auger electron spectroscopy. The effect of plasma cleaning on substrate potential (grounded, floating and biased potential) has been investigated in view of cross contamination, substrate heating and plasma penetration into magazines. The role of hydrogen and oxygen as cleaning gases is discussed with respect to the cleaning efficiency and the long-term-cleaning effect. The effect on wire bondability has been examined by shear- and pull force measurements.

The investigations clearly show that this simple and environmentally friendly process is an effective method to reduce organic and some inorganic contamination. No particular plasma process optimization or cleaning control is required if hydrogen is utilized as a process gas. The effect of plasma treatment results in drastic improvement of the wire bondability and reliability

1. Introduction

In an IC-assembly, a clean surface is a vital prerequisite for any type of attach process, such as wirebonding and molding. This is true in particular for more complex package types with several hundreds of I/O's, such as multichip modules (MCM) or ball grid arrays (BGA). Such packages generally consist of polymer resin like FR4 or BT, and reinforced fiber, and must therefore be processed at reduced temperatures where processing can become critical.

There are nowadays different approaches to reduce contamination on organic and metallic surfaces. Conventional methods such as wet chemical cleaning or solvent degreasing have the drawback that traces of the process chemicals are left on the treated surface. Also dry cleaning technologies based on cleaning with reactive gases like O₂ [1,2,3], HCl, CCl₄[4] or SF₆ may have some disadvantages. Its use might be environmentally problematic, traces of the working gas may be left on the treated surface or the cleaning process may be effective only for very specific contaminants.

In this work we have investigated a novel plasma cleaning process based on a low energy argon-hydrogen DC hot-filament discharge plasma [5]. Physical and chemical properties are discussed and the impact of plasma cleaning on wire bondability is presented.

2. Experimental Setup and Process Description

Experimental Setup

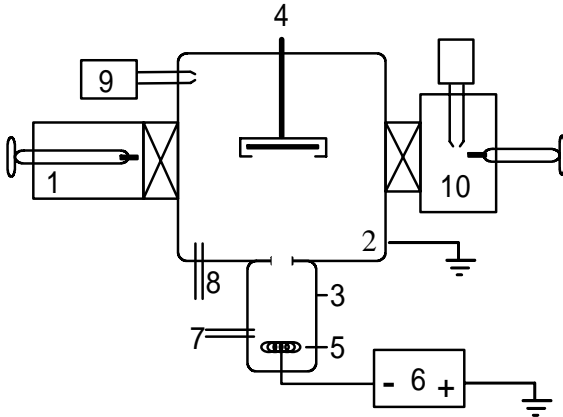


Fig.1 Schematic drawing of the plasma cleaning module. For a detailed description see text.

Figure 1 displays schematically the plasma cleaning module used for the experiments. Substrates are introduced in the load lock (1) and transferred to the plasma chamber (2) to which a plasma source (3) [6] is attached. The substrate holder (4) is mounted electrically insulated, but can be grounded or negatively biased with respect to the grounded chamber by a power supply. The plasma source consist of the heated filament (5) mounted in a separate cavity. An orifice connects the cavity to the cleaning chamber. The dense Ar/H₂ plasma discharge between the heated filament (cathode) and the chamber walls (anode) is established by applying a negative voltage (6) to the filament. For voltages as low as 25-30V DC, discharge currents up to 100A can be achieved. The working gas, usually argon, is fed directly into the plasma source (7). Hydrogen and/or other reactive gases such as oxygen were fed either together with the working gas or directly into the cleaning chamber at (8). Typical flows for both gases were 20-50 standard cubic centimeters per minute (scm).

The plasma process has been analyzed by a Plasma Process Monitor (9) [7], attached to the cleaning chamber. The effect of the plasma treatment on the metallic surface has been investigated by Auger Electron Spectroscopy (AES). The spectrometer (10) is located in a separate chamber, also attached to the cleaning chamber. This allowed the plasma treated samples

to be transferred under vacuum for surface analysis.

3. Results and Discussion

3.1 Characterization of the plasma process

The voltage distribution in the plasma is characterized through a plasma potential which is very close (+/-1V) to the anode potential. The floating potential, that is, the potential acquired by an isolated substrate when immersed into the plasma, is typically around -10V. Plasma monitoring reveals H₃⁺, ArH⁺, H⁺, H₂⁺ (in this order) to be the most abundant ion species in the discharge. The kinetic energy of these ions is close to ground -1V to 0.5V and is well confined within +/-1eV. Figure 2 shows as example the energy distribution spectrum as measured for H₃⁺ for different discharge currents.

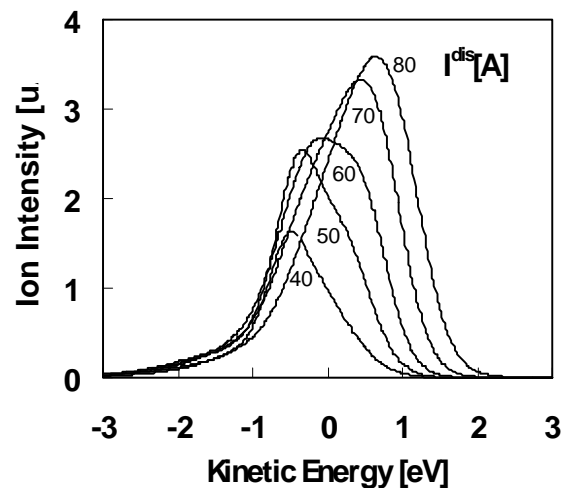


Fig. 2 Plasma monitoring spectra of the energy distribution of H₃⁺ ions for different discharge currents. The energy scale is given with respect to the anode potential.

Cleaning consisted of exposing metallic and organic chip carriers to the plasma for 5-10min at a pressure of the order of 5*10⁻³mbar. The substrates were exposed either directly to the plasma or within slotted magazines (see below). Depending on the substrate is at a floating (1), grounded (2) or biased (3) potential, cleaning proceeds very differently. For (1) and (2) cleaning occurs by surface contamination forming hydrogen volatile compounds like CH₄, PH₃, H₂O

with highly reactive hydrogen radicals and low energetic hydrogen ions. For grounded substrates, plasma chemical reactions are further enhanced by the large amount of so-called fast electrons (20-30eV) in the discharge. Because of the absence of any sputtering processes (see below), both cleaning types are named *plasma chemical cleaning*.

Plasma physical cleaning, occurs when bias voltages larger than the sputter threshold (about 20V) are applied to the substrate. Cleaning is then caused by high energetic ions which remove by physical impact all type of surface atoms, in particular non volatile species such as metal atoms.

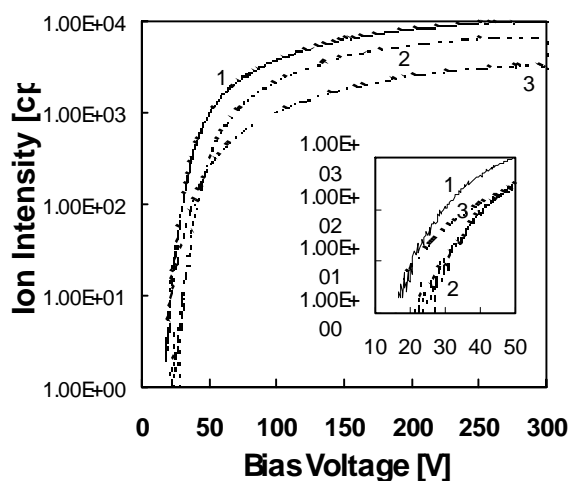


Fig. 3 Plasma monitoring spectra of the substrate ion density in the plasma as a function of the substrate bias potential for Cu(1), Ni(2) and Al(3) substrates.

This is shown in figure 3, where the measured ion intensities vs the substrate bias potential for Cu, Ni and Al substrates are reported (Ar:H₂ flow 20:0). From a bias potential of -50V to -20V, the observed ion intensity decreases by more than two decades. Since the plasma potential is close to ground the applied bias potential corresponds to the kinetic energy of the sputtering ions. The estimated sputter threshold for Cu, Ni and Al is 18eV, 21eV and 15eV, and compares well with the literature values of 17, 21eV and 13eV [8]. The observed range for the floating and grounded potential is therefore well below the sputter

threshold for most materials, that is, no sputtering occurs for these conditions.

Compared to plasma chemical cleaning, plasma physical cleaning has therefore the serious drawback that a portion of the sputtered, non volatile species is redeposited all over the process chamber. This increases the risk for cross-contamination especially when different types of substrate materials are processed in the same cleaning module. Moreover, plasma physical cleaning is not self-terminating on metallic surfaces as it is the case for plasma chemical cleaning. Very precise process optimization or even tool for end-point detection may thus be indispensable for certain applications.

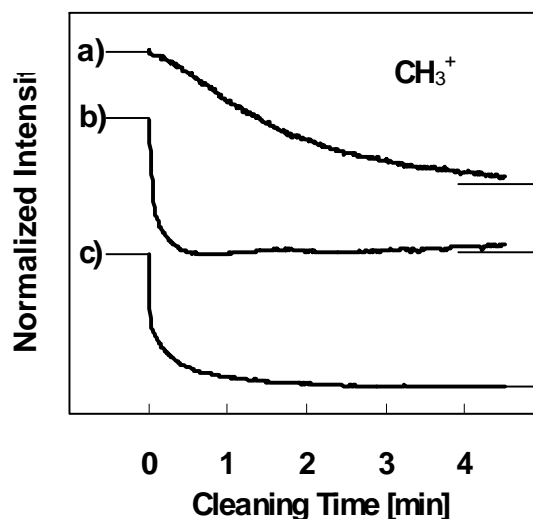


Fig. 4 Plasma monitoring spectra of CH₃⁺ ion intensity for cleaning of Cu substrates as a function of the cleaning time. Curves a), b) and c) indicates cleaning at floating, grounded and biased substrate potential, respectively. The intensity is normalized to a linear scale for better comparison. The corresponding limits are indicated by the horizontal lines.

The above findings are summarized in Fig. 4, where we have plotted the corresponding plasma monitoring spectra for CH₃⁺, one of the by-products formed during cleaning of a copper leadframe. The normalized ion current intensities for the substrate at floating (a), grounded (b) and biased (c) potential are shown. The decay of the curves indicate the typical cleaning time for carbon contamination. As expected, it is shortest

for physical cleaning and for cleaning at grounded potential. Cleaning time increases by up to 5 min for floating substrates. No Cu was detected for modes (a) and (b), in agreement with the results plotted in Fig.3.

The corresponding temperatures measured on the metallic substrate holder are reported in Fig. 5. The temperature is lowest for cleaning under floating conditions (a). It increases for cleaning under biased (150V) (b) and grounded (c) conditions, where further heating is caused by ion bombardment and by electrons (resistive heating), respectively. For typical cleaning times of 10min and discharge currents of 40A the temperature of the above specified system (Fig.1) does not exceed 100°C on floating substrates. On organic substrates even lower temperatures are reached.

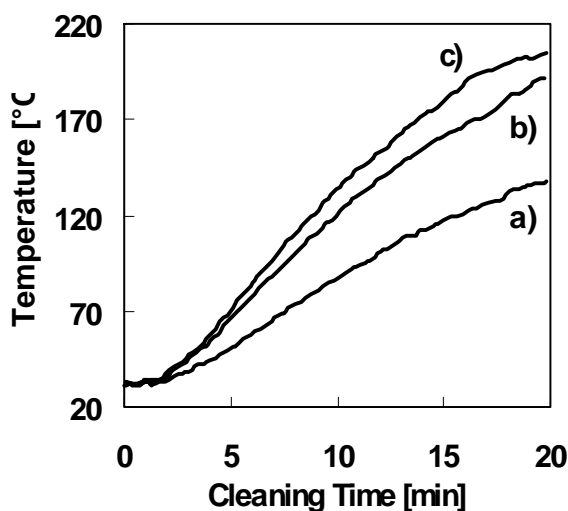


Fig.5 Temperature dependence measured on the metallic substrate holder as a function of the cleaning time for cleaning with the substrate at floating (a), biased (150V) (b) and grounded (c) potential.

The effect of cleaning is reported in figure 6. Curve a) displays the typical Auger spectrum as obtained on an untreated Cu lead frame. O and C are usually the most dominant contamination. Cl, S, P and N occur only as traces in this case but can be more pronounced on samples stored under bad conditions. Curves b), c) and d) have been recorded after a plasma treatment of 10 min with the substrate at floating, grounded and biased (150V) potential, respectively. For all cleaning

modes a considerable reduction of C and O can be observed. The signals of the other contamination are usually below the noise level, and the peak to peak amplitude of O and C decreases by an order of magnitude. P and S occur in small concentration in this particular leadframe material, and can not, therefore, be regarded as real contamination. As mentioned above, cross contamination may be a serious drawback of plasma physical cleaning. Indeed, by comparing spectrum b) and c) with d) one notes that three new peaks appear at energies around 590, 640 and 690eV after sputter cleaning. We attribute these features to the LMM Auger lines of Fe atoms. These are liable to be sputtered away from the chamber walls or the substrate holder and redeposited onto the Cu substrates. More details about this experiment can be found in [9].

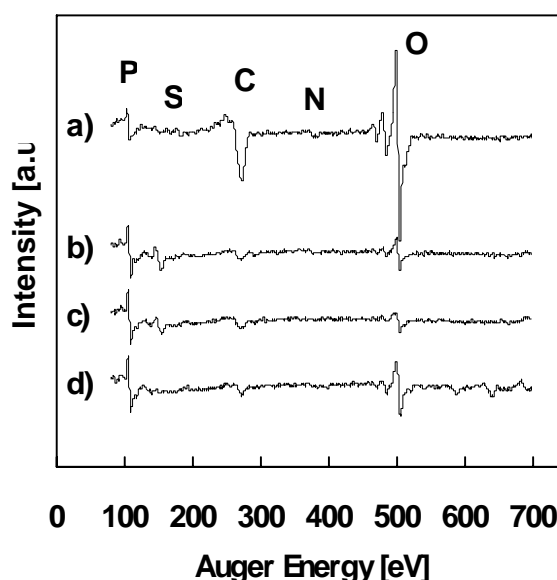


Fig. 6 Auger spectra obtained on an untreated copper leadframe (a) and on copper lead frames plasma cleaned at floating (b), grounded (c) and biased (150V) (d) substrate potential.

Beside the risk of cross contamination and substrate heating, plasma physical cleaning has other, more technical drawbacks concerning cleaning in magazines. Figure 7 displays the effect of substrate potential on plasma penetration through a metal grid. About a quarter of the area of the metal plate is perforated by 3mm thick holes. The metal grid is at floating potential in a)

and at biased potential in b). It is easy to recognize, that the glow discharge flows through the grid in case a), whereas it is repelled by the negative bias potential in case b). Repulsion occurs also for grounded potential (not shown here). The luminosity of a glow indicates the generation and therefore the presence of a high density of reactive species in the plasma. The density decreases rapidly outside the glow region, where hence also the effect of cleaning is reduced. Figure 7 further shows the very advantage of this plasma to penetrate into very thin spacing in the order of mm. This enables very efficient cleaning even in (perforated!) magazines, as will be shown in the next Section.

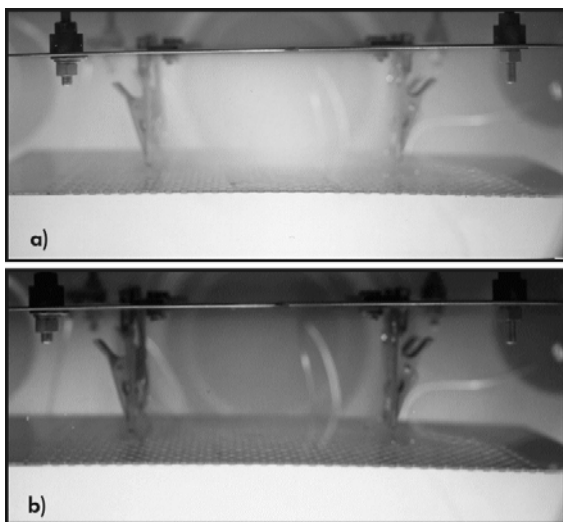


Fig. 7 Photograph showing the penetration of the plasma beam (high luminosity) through a perforated (3mm holes) metal plate, with the plate at floating (a) and biased potential (b).

3.2 Selection of the Plasma Process

Experimental setup:

Gold ball wire bonding has been performed on an ESEC 3006 F/X wire bonder, equipped with the High Frequency (128kHz) Option for wire bonding on organic substrates. For shear and pull force measurements of ball and wedge bond, respectively a DAGE BT 2400 tester has been used. Further details concerning the individual experiments are indicated in the text.

Based on the above findings, only plasma chemical cleaning with the substrate at floating potential has been applied for the wire bonding experiments.

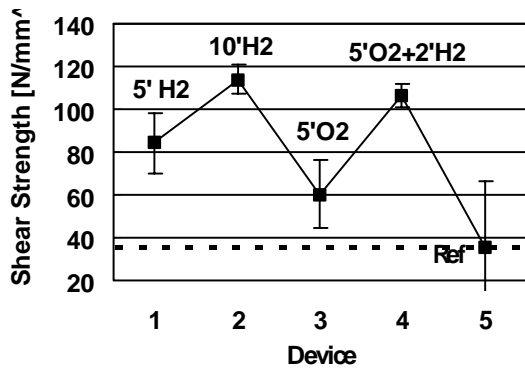
First, only for plasma chemical cleaning a soft, i.e., a damage free plasma treatment can be expected. Apart from substrate damage, we know from literature [10] that high energetic particles can also lead to electron-hole pair formation in the device insulators (oxides and nitrides), causing possible changes of the electrical characteristics of the device. Second, only for cleaning at floating potential, sufficient plasma penetration into magazines can be expected.

Role of the process gas

Before presenting the wire bonding results, let us first discuss the role of the process gas. There is indeed some controversy over the choice of the process gas where plasma cleaning is concerned, i.e., hydrogen vs oxygen. In figure 8a) and b) we compare the effect of these two gases on wire bondability of a silver plated copper leadframe (PLCC44). Ball bonding occurred on Al1%Si pad metallization at a bond temperature of 220°C. The chips were strongly contaminated and therefore of poor wire bondability as becomes clear from the low shear strength value of only 40N/mm² for untreated substrates (Fig 8a). Three different plasma treatments have been carried out:

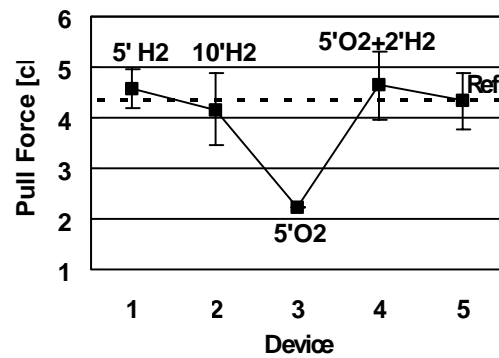
- a: hydrogen plasma for 5 and for 10min
- b: oxygen plasma for 5min
- c: oxygen plasma for 5min followed by hydrogen plasma for 2min.

The partial pressure of hydrogen was $3 \cdot 10^{-3}$ mbar, that of oxygen of $1 \cdot 10^{-1}$ mbar. Figure 8a) shows that both process gases significantly improve the contact quality of the ball bond. The corresponding values for the grading are given in the table.



G d	5' H ₂	10' H ₂	5' O ₂	5'O ₂ /2'H ₂	Ref
1	90%	30%	100%	13%	37%
2	10%	70%		87%	
3					63%

Fig. 8a Shear strength measured on Al1%Si without (Ref) and with different plasma treatments in hydrogen plasma (5&10min), oxygen plasma (5min), oxygen plasma (5min) followed by hydrogen plasma (2min). The table gives the corresponding shear grading.



G d	5' H ₂	10' H ₂	5' O ₂	5'O ₂ /2'H ₂	Ref
2	38%	30%		63%	30%
4	62%	70%		27%	70%
5			100%		

Fig. 8b Pull force measured on Ag plated leads (PLCC44) without (Ref) and with different treatments in hydrogen plasma (5&10min), oxygen plasma (5min), oxygen plasma (5min) followed by hydrogen plasma (2min). The table gives the corresponding pull grading.

The improvement achieved with hydrogen is clearly superior to that achieved with oxygen. Note that no gold shear failures occurred for oxygen treated samples. Note also the enormous increase of the shear strength on samples which were first exposed for 5min to an oxygen and then for 2min to a hydrogen plasma (c). Furthermore, in contrast to hydrogen, oxygen plasma was found to deteriorate the wirebondability on prolonged cleaning. This is due to a thickening of the respective oxide layers on the Al (chip) and the Ag (finger) metallization on prolonged plasma exposure. In figure 8b) one notes a drastic decrease of the wedge bond quality after the treatment in the oxygen plasma, and a renewed increase after only a short treatment in the hydrogen plasma. Whereas in Fig. 8b) no change of the pull values occur on cleaning in hydrogen (a) or in oxygen followed by hydrogen (c), the substrate becomes practically non-bondable after cleaning in oxygen plasma (b). As expected, 100% wedge lift failure occurs. (see Table).

There is another concern about utilizing hydrogen for cleaning of copper substrates, namely the risk of hydrogen embrittlement. This effects modifies the grain boundary of copper. Cracks in the copper layer may then occur when stress is applied, as e.g., during the bond process. This effect could cause serious problems on organic chip carriers, where rather thin Cu-layer are used for the pad metallization. In Fig. 9 we compare the cross section obtained on an untreated copper lead frame (a) and a copper lead frame exposed for 1 hour to a hydrogen plasma (b). On this scale a change of the grain structure would be visible in the case of hydrogen embrittlement. In Fig 9b) no modification, i.e., no plasma damage of the bulk structure can be observed. This is not that surprising, since hydrogen embrittlement of copper is known to occur only under very special conditions, that is, at normal pressure and for very high bulk temperatures typically above 1000°C. These requirements are clearly not given in our case.

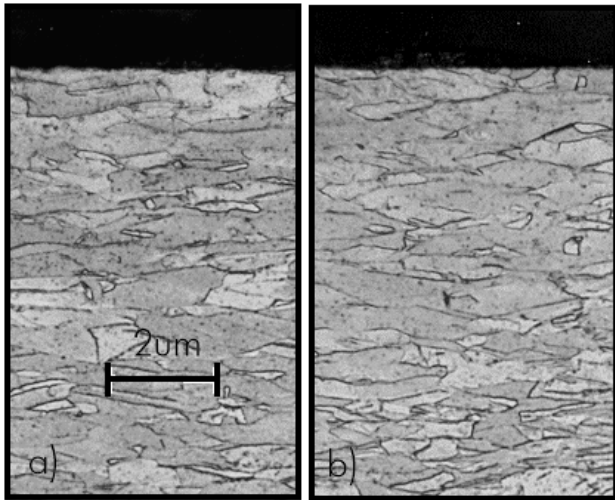


Fig. 9 Cross section through the surface region of an untreated (a) and a plasma treated (b) copper leadframe. Sample stem from the same strip. 60 min plasma cleaning at floating substrate potential. No plasma damage is observed.

On BGA substrates, wedge bonding is usually achieved on gold plated fingers where bond pad oxidation is not an issue. However, gold plating on BGA is usually too thin to prevent pin-hole formation down to the underlying metal layer, normally nickel. In an oxygen plasma, oxide growth through the gold plating may still occur, and reduce the wire bondability similar to what is observed on silver plated leadframes. Furthermore, when organic substrates are exposed to an oxygen plasma, a white powder is sometimes formed on its surfaces. This powder is known to have a very negative impact on mold adhesion.

The risk of oxidation of pad metallization and epoxy resin can be reduced, of course, by accurately optimizing the process parameters of the oxygen plasma, such as the power, the process time and the gas pressure. Plasma process optimization is complex and time consuming, however, and inhomogeneities due to spatial variation of the plasma discharge are difficult to avoid. Hydrogen plasma cleaning, on the other hand, is not found to deteriorate either mold adhesion or wire bondability, even after prolonged cleaning. In addition, almost no process optimization is required for hydrogen plasma

cleaning, except for the process time. It must be increased for strongly contaminated substrates as may have been noted above in figure 8a). From this and because of further advantages concerning the long term stability of plasma treated surfaces (below), hydrogen has been favored over oxygen in the following experiments.

3.3 Wire bonding results

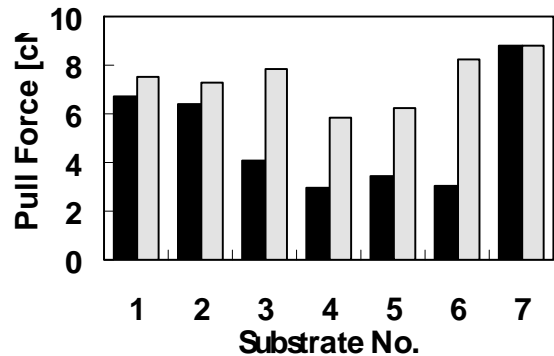


Fig. 10 Pull force measured on different types of MCM substrates without (black) and with (gray) a plasma treatment of 5min at floating substrate potential

Figure 10 displays an example of the effect of plasma cleaning on the wedge bond quality for different types of MCM substrates. Bonding occurred at temperatures between 100 and 160°C depending on the substrate material. 3 mm long and 25µm thick wires were bonded, and pulling was done a ball:wedge distance of 3:1, i.e, close to the wedge. On untreated substrates mostly wedge lift- or breakage at wedge failures occurred, indicating the very poor surface quality of these samples. The situation changed drastically after a short plasma treatment of 10min. No wedge lift was observed and for the most part breakage at neck failures occurred, instead. An exception is substrate #7, where high pull forces were obtained also without cleaning. However, it must be pointed out, that a much thicker gold plating has been for this substrate type. With a thickness of 1µm it is about 10 times as thick as that used for the others. These findings reveal an important aspect of plasma cleaning: Besides of improving the wire bondability, plasma cleaning clearly enlarges the variety of substrate

types and of material combinations that can be used for gold ball wirebonding.

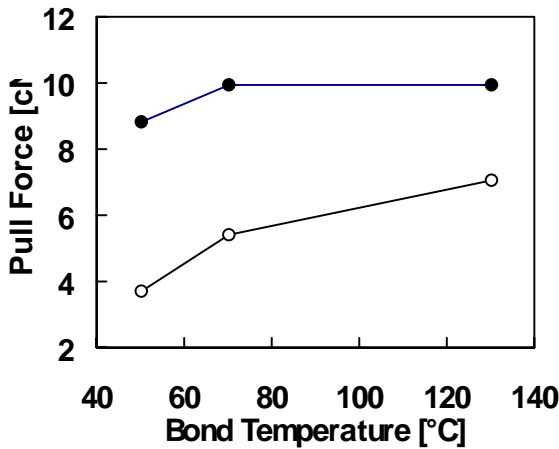


Fig. 11 Pull force as a function of the bond temperature obtained on an untreated (open dots) and plasma treated (closed dots) FR4 substrate. (For more details see text.)

This is also shown in Fig. 11, where the pull values with (closed dots) and without (open dots) plasma cleaning of an FR4 substrate are presented. Again, a drastic improvement of the wedge bond quality is observed. This is rather surprising, if one considers that the substrate was laid out for Al-wedge wedge and not for gold-ball wire bonding. On such substrates gold plating is extremely thin, since it is not supposed to act as bonding surface, but is thought to prevent the underlying nickel layer from oxidizing.

The findings reported Figs. 10 and 11 are classic examples to show on the one hand the negative influence that contaminants can have on wire bondability and on the other hand the efficiency of an hydrogen plasma to remove such contaminants. However, these results have been obtained on test vehicles, which were of very poor wire bondability. Substrates of such a quality are not typical for production. Nevertheless, an important increase of the wire bondability and in particular of the reproducibility can also be obtained on production material. The BGA substrates used for the following experiments were of known reduced bondability. Figure 12 shows the average, the standard deviation and the

minimal value of the pull force as measured over 40 wires. The data are plotted versus the device position for an untreated (open dots) and plasma treated (closed dots) BGA (BT resin) substrate. 3 mm long and 25um thick wires were bonded at a temperature of 120°C on gold plated fingers. Pulling was performed at a ball:wedge distance of 1:2. Plasma cleaning was carried out with the strips filled into a magazine, which was horizontally slotted for better plasma penetration (see Section 3.1).

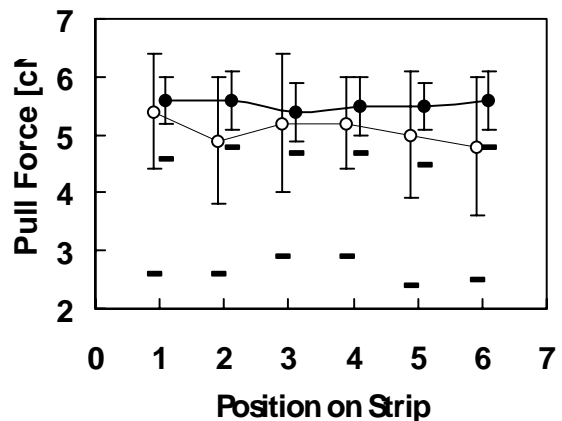


Fig. 12 Average, standard deviation and minimum of the pull values as a function of the position on the strip as obtained on an untreated (open dots) and a plasma treated (closed dots) BGA substrate. Sample size is 40. Wire bonding was performed at 120°C. For more details see text.

As expected for the better surface quality, the improvement of the average values of the pull force turns out to be smaller compared to that shown in Figs. 10 and 11. Note, that even on the untreated substrates, in most part (>60%) wires failure occurred at the neck where high pull values results. The positive effect of the plasma treatment becomes clear, however, when the corresponding minimal values for the pull force are examined. They increase from typically 2.5cN on the untreated strip up to typically 4.5-5cN on the plasma treated strip. Note also the lower standard deviation and the reduced scattering of the pull values from device to device.

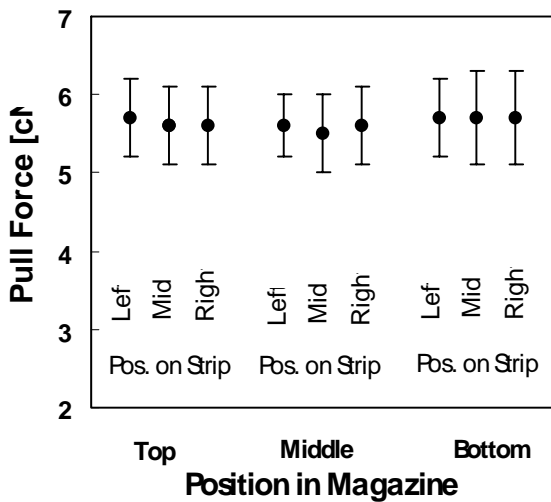


Fig 13 Pull values versus the position on the strip and versus the position of the strip within the magazine as obtained on plasma cleaned BGA substrates. Plasma cleaning of 10 min was performed with the magazine at floating potential.

The good uniformity of cleaning is also confirmed by the data shown in Fig.13, where the corresponding pull data obtained after plasma cleaning with the strips in the magazine are shown. The pull values as a function of the strip position are reported for the top, the central and the bottom lead frame position in the magazine.

Apart from the cleaning efficiency itself, another important factor is the sensitivity of plasma treated surface on recontamination. That is, the period of time within which the cleaning effect persists after plasma treatment. The reactivity of a surface depends on the quantity and types of dangling bonds present at the surface. Activated surfaces occur, for example, after plasma cleaning in an oxygen plasma. Such substrates must necessarily be processed as soon as possible after the cleaning procedure in order to avoid a renewed degradation of the wirebondability. In contrast to oxygen, hydrogen passivates the topmost surface atoms thus protecting the surface from chemical reactions with ambient air. This results in an excellent long-time behavior of the cleaning effect which lasts for several days. This is shown in Figure 14, where we have plotted the pull values as a function of the storage time after

plasma cleaning. The same type of BGA substrate as for the previous investigation has been used for the experiment. As expected, no decrease of the wirebondability (wedge contact quality) occurs even after a longer storage of 1 week.

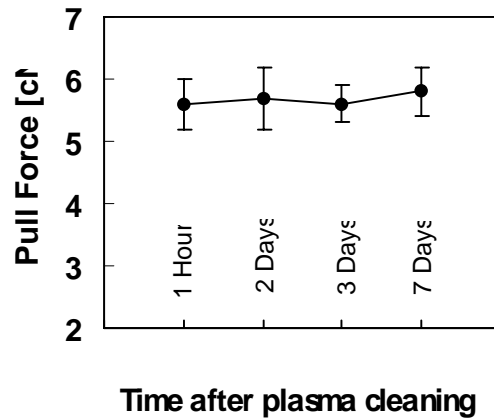


Fig. 14 Pull force obtained on BGA substrates versus the storage time after plasma cleaning. Storage occurred in ambient air. No degradation of the wire bondability is observed within a period of one week. Sample size is 40

In this work, the main attention has been devoted to the wedge bond contact quality. Only little has been reported on the effect of plasma cleaning on ball bond improvement. Indeed, in contrast to the wedge contact, the ball shear values usually do not increase that much on plasma cleaning, unless the pad metallization is of poor surface quality. (see for example Fig. 8). The ball bond contact is apparently less sensitive on surface contamination than the wedge bond contact. However, this does not mean that plasma cleaning does not have a positive impact on ball bondability. The positive effect becomes clear when the “bond force vs. ultrasonic power” process window for the ball bond is examined. We found plasma cleaning to significantly enlarge the process window. This might become of very importance for fine pitch wire bonding, where reduced bond force and ultrasonic power settings must be used to achieve small bonded balls. These results will be presented in a future work.

4. Conclusion

A low energy hot-filament plasma has been used to efficiently clean IC-packaging substrates prior to wire bonding. Bond contact analysis demonstrate a drastic increase of the wire bondability and the reliability after plasma cleaning. The plasma process is not critical with respect to substrate damage, substrate heating, cleaning time, type of contamination, and the long term behavior of the cleaning effect. The good plasma penetration through small spacing allows for effective cleaning within slotted magazines.

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Biography

Nico Onda joined ESEC in 1996 as a Process Engineer. He is involved in the development of high frequency wire bonding, as well as in studies on plasma cleaning and related processes.

Nico Onda received his diploma in Physics in 1989 from the Swiss Federal Institute of Technology in Zürich (ETHZ), Switzerland, where he also completed his Ph.D., in 1994, in the field of molecular beam epitaxy and electric quantum transport in 2-dimensional systems. He then worked for a year at the "Neu Technikum Buchs" (NTB), where he investigated the effect of plasma cleaning on metal and semiconductor surfaces, in collaboration with Balzers Ltd and ESEC SA.