Effect of Plasma Treatment of Au/Ni/Cu bond pads on Process Windows of Au Wire Bonding

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Abstract—The wire bondability of Au/Ni/Cu bond pads with different Au plating schemes, including electrolytic and immersion plates, are evaluated after plasma treatment. The plasma cleaning conditions, such as cleaning power and time, are optimized based on the process window and wire pull strength measurements for different bond pad temperatures. Differences in the efficiency of plasma treatment in improving the wire bondability for different Au plates are identified. The plasma cleaned bond pads are exposed to air to evaluate the re-contamination process and the corresponding degradation of wire pull strength. The changes in bond pad surface characteristics, such as surface free energy and polar functionality, with exposure time are correlated to the wire pull strength, which in turn provides practical information about the shelf life of wire bonding after plasma cleaning.

Index Terms—Au wire bond; Au/Ni/Cu bond pad; process window; plasma treatment; surface energy.

I. INTRODUCTION

Wire bonding is still the far most popular first-level interconnection technology used in electronic and photonic packaging. The conventional wire bond pads consist of a 1-1.25μm thick electrolytic Au plate over a 4-5μm thick electrolytic Ni layer on a FR-4 woven glass reinforced epoxy laminate printed circuit board [1]. In recent years, techniques based on immersion Au plating over electroless Ni plating have been developed to replace the conventional expensive, electrolytic Au plating [2]. In our previous paper [3], process windows were successfully established and the corresponding wire bond strengths were evaluated for several different Au/Ni bond pads that were produced using different plating methods. Important properties of the bond pads, including Au layer thickness, surface morphology, surface roughness and elemental composition were characterized to correlate these parameters with the wire bonding quality. It was highlighted that the surface morphology of bond pads produced by different Au plating methods was different. The immersion plating method produced a fine, thin Au layer. The surface roughness of bond pads created by electrolytic plating decreased as the Au layer thickness increased. The thinner was the Au layer in the electrolytic plate, the higher were the hardness, the surface roughness and the risk of Ni migration onto the Au surface, both of which adversely affected the wire bondability and process window. A much wider process window was constructed for the immersion Au plate than the electrolytic plate with an equivalent Au thickness, confirming the immersion plating process is a low cost alternative for wire bonding. Its bond strengths with respect to bond power were also comparable to those for the bond pads with a thick electrolytic Au layer.

The wire bondability and wire bond quality in low temperature thermosonic bonding rely heavily on the surface characteristics of bond pads as well as the degree of contamination. The organic contaminants of a few nm in thickness are present on the bond pad surface, which originate from additives in the plating bath, outgases of die attach and soldermask curing, or exposure to air [4-6]. The contaminant layer not only prevents intimate contacts and interdiffusion from taking place between the wire and bond pad surface [7-10], but also reduces the temperature rise arising from ultrasonic scrubbing [8], thereby requiring a higher activation energy to be supplied by external heating for making a successful bond [11]. Apart from the organic contaminant, metal oxides present on the Au surface influence the wire bonding by acting as a lubricant that reduces the friction between the bond materials, preventing weld formation [8,12]. Plasma cleaning with optimized process conditions amongst various dry and wet cleaning methods, has been found most efficient to remove the organic contaminants, restoring the original wire bondability of bond pads [2,13-15]. The oxygen plasma can react with the hydrocarbon in the organic contaminant to form volatile compounds like H2O, CO2 and CO, which are then removed by the vacuum system [16-18]. Argon plasma can knock off the metal oxides by the sputtering action [7,12,17,18]. A clean domain can be generated when the wire and the plasma treated bond pad come into contact [8]. This allows intermolecular diffusion to take place across the...
interface with reduced activation energy. As a result, the required bond power, bond temperature and bond time can be reduced accordingly. This is beneficial to wire bond strength since the reduction in wire deformation can make a stronger wire heel.

As the continuation of our previous work [1] on bondability of thermosonic Au wire bond, this paper studies specifically the benefits of plasma cleaning in improving the process window for wire bondability. Particular focus is placed on the effects of exposure time after plasma cleaning on the changes in surface energy and the corresponding bondability. This study will identify the maximum time that the cleaned bond pads can be allowed in air before wire bonding must be carried out without losing the benefits of plasma cleaning.

II. EXPERIMENTS

A. Wire Bond Pad Metallizations

The PCB substrate and wire bond pads used in this paper were selected amongst the six different Au/Ni/Cu metallizations with different Au layer thicknesses studied in our previous work [3]. They were Samples 2, 4 and 5: the first two bond pads consisted of electrolytic Au plates with different Au layer thicknesses and the last bond pad consisted of a very thin immersion Au layer, as summarized in Table 1. These metallizations were prepared on a 0.8mm thick FR-4 type glass fabric/epoxy laminate with a Tg of about 120°C (supplied by Universal Printed Circuit Co. Ltd, Hong Kong). For Samples 2 and 4, a solder mask was applied after Au plating, while for Sample 5 the solder mask was applied before Au plating. The gold thickness was measured using an x-ray film thickness gauge. The surface morphologies obtained from the scanning electron microscopy and an optical profiler are presented in Fig. 1. Both Sample 2 and 5 with a very thin Au layer exhibited a nodular profile with grain boundaries, reflecting the morphologies of the underlying Ni layer. The surface feature of the underlying Ni layer was almost completely concealed when the thicker Au layer was used in Sample 4.

B. Plasma Treatment

The bond pads were subjected to a plasma treatment to remove any contamination on the surface using a plasma cleaning system (Branchy Plasma Cleaner (P100E)). The plasma process conditions, including the cleaning power and time, were optimized to achieve best bond pad surface characteristics. The gas pressure was 120 mTorr and the gas flow rate was 5 sccm. Because the Ar gas alone was not adequate to thoroughly clean the bond pad surface, a mixture of Ar and O2 gas was used initially for either 1 min or 5 min, followed by Ar gas treatment for another 1 min. Two cleaning powers were used: namely 100W and 400W. The parameters used in the four different plasma treatment sample groups are summarized in Table 2. Unless otherwise specified, the Group A was applied.

C. Wire Bonding and Wire Pull Test

The thermosonic wire bonding process and the wire pull tests used were essentially the same as those applied in the previous study [3]. Au wire wedge bonding was performed on a wedge bonder (ASM model AB559A) equipped with a 61.2kHz transducer (Uthle model) and a wedge tool (SPT model, FP308-TI-1820-L-CGM). The gold wire (supplied by Tanaka) was 25.4µm in diameter, has an elongation of 0.5-3% and tensile strength of 12-17gf. No dies were mounted on the PCBs and both the 1st and 2nd bonds were made directly on the PCBs, with the distance between the bonds about 1.5mm and the average loop height 0.328mm. The bond pads were preheated to a temperature ranging between 60°C and 120°C before wire bonding. The bond pad temperature was measured using a non-contact infrared thermometer. The nominal bonding time was 20ms, and the bond force applied was 20gf. The bond power was increased from 50mW to 600mW at 10-15mW intervals as far as successful bonds could be made. The wire bonding process windows for three bond pad metallization schemes were established using various combinations of bond power (Samples 2, 4 and 5) and bond pad temperature (Sample 2). Twenty wires were bonded for each set of conditions. An overriding criterion used to determine successful bonds in this study was no 2nd bond peel off. The average pull strength lower than the industry minimum of 5gf was also used to identify the effect of plasma treatment.

The wire pull tests were carried out to measure the wire bond quality using a wire pull tester (Royal Instrument System 550). A modified pull test was carried out by placing the testing hook closer to the 2nd bond, approximately 1/4 of bond distance from 2nd bond as schematically shown in Fig. 2. A load was applied to pull the hook upwards until the wire rupture or the 2nd bond was lifted off the bond pad, and the corresponding force was recorded as the wire pull strength.

In addition to wire pull strength, the extents of wire deformation was also measured, which may provide information about energy consumed during the wire bonding process [19,20]. Large wire deformation corresponds to a high bonding power with the most energy consumed to deform the wire, whereas a low wire deformation with a strong bond corresponds to an adequate processing condition. The deformed wire widths of the 2nd bond were measured using a profilometer to an accuracy of 0.5µm. The wire deformation ratio is defined as the ratio of the wire width, W, to the original wire diameter, D (Fig. 3):

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\text{Deformation ratio} = \frac{W}{D} \quad (1)
\]

D. Characterization of Bond Pad Surfaces

The surface elemental compositions of the bond pads were evaluated using an X-ray photoelectron spectroscopy (XPS, Surface analysis PHI5600). The XPS scan size was about 600µm in diameter and the nominal analyzing depth was 8nm. The degree of bond pad contamination was quantified by measuring the contact angles [1]. The shape of probe liquid droplets formed on the bond pad surface depends strongly on
the thermodynamic nature of the top layer. When the surface is hydrophilic, the droplet will spread out forming a low contact angle; and when the surface is hydrophobic, the water tends to stand up on the surface with a high contact angle, $\theta$ [7, 10, 13]. Since most organic contaminants are hydrophobic, the contact angle method is a relatively simple and efficient method for the measurement of hydrophilicity or cleanliness of the surface. The contact angles were measured using two probing liquids, de-ionized (DI) water (a polar liquid) and diiodomethane (a non-polar liquid), on a goniometer (KRÜSS G10). The polar and dispersion surface energies are 26.0 and 46.8 mN/m respectively for de-ionised water, and 44.1 and 6.7 mN/m respectively for diiodomethane [21]. Micro-syringes were used to dispense droplets of 2 to 4 µl on the substrate surface. With the aid of an illuminator and a camera, the images of droplets were captured, which were then analyzed using an image analyzer to determine the contact angles. The contact angles were read within 20 s of droplet formation to avoid evaporation of liquid. At least five measurements were made for each set of condition, and the average values were used to calculate the surface energies.

The theoretical considerations of wetting are based on the Young-Dupre equation that defines the work of adhesion, $W_a$, between the liquid and solid as a function of $\theta$ [22]:

$$W_a = \gamma_1 + \gamma_2 - \gamma_{12} = (1 + \cos \theta) \gamma_{12}$$  \hspace{1cm} (2)

where $\gamma_1$, $\gamma_2$ and $\gamma_{12}$ are the surface free energies of liquid, solid and the interface, respectively. The work of adhesion is defined as the work required separating the interface between the phases 1 and 2 from their equilibrium state. The total surface energy consists of two components, namely the polar and dispersion (or non-polar) components, $\gamma_2^p$ and $\gamma_2^d$, respectively. The polar interactions include dipole-dipole, dipole-induced dipole and hydrogen bonding interactions. These surface energy components can be determined based on the geometric mean approximation combined with equation (2) [23]:

$$\gamma_{12} = \gamma_1 + \gamma_2 - 2 \left[ \left( \gamma_1^d \gamma_2^d \right)^{\frac{1}{2}} + \left( \gamma_1^p \gamma_2^p \right)^{\frac{1}{2}} \right]$$  \hspace{1cm} (3)

If two liquids of known two components of surface energies, $\gamma_1^p$ and $\gamma_1^d$, were used in the contact angle measurements, the corresponding solid surface energies can be determined.

III. RESULTS AND DISCUSSION

A. Optimization of Plasma Treatment Condition

To identify an optimized plasma treatment condition that can produce highest wire bondability, Sample 2 bond pads were subjected to four different combinations of plasma cleaning power and duration, before wire bonding. The bond pad temperature was varied between 60 and 110°C to study its effect on process window and wire pull strength with respect to bond power after plasma cleaning. The pull strengths of the wires produced at different temperatures are plotted as a function of bond power in Fig. 4. The pull strengths of the wires for a given plasma cleaning condition were essentially similar, independent of bond pad temperature, although they were only marginally higher when bonding was made at the higher temperature end (110°C) in some cases (Group D). This observation is in spite the fact that a high bond pad temperature allowed successful bonds to be made using a low bond power. As expected, the higher the bond power, the lower the pull strength, consistent with our previous results [3]. With increasing the bond power above the threshold level required to make successful bonds, the extra energy arising from the high bond power is consumed to deform the wire, weakening the neck and eventually causing the pull strength to decrease. The wire deformation ratio, shown in Fig. 5, increased generally with increasing bond power for all temperatures studied. This trend holds for all sample groups with different plasma conditions, which also exhibited similar wire pull strengths. This observation indicates that the plasma cleaning condition, such as cleaning power and exposure time, had an insignificant influence on wire bond quality once bonds could be successfully made. The XPS result also suggests that the four different plasma treatment schemes were effective in removing almost all Ni content on the top Au layer surface. The Ni impurity in the form of nickel oxide on the bond pad is harmful to wire bond strength [24].

The above results on wire bondability are summarized using a process window where the combinations of wire bond power and bond pad temperature that can produce successful wire bonds are identified, as shown in Fig. 6. On the left hand side of the lines, these parameters were inappropriate to produce successful bonds, i.e. ‘unbondable’, and on the right hand side, ‘bondable’. A major finding from the process window is that wire bonds could be made at temperatures as low as 60°C that was high enough to provide a sufficient energy to bond without sacrificing the wire pull strengths (9-10gf). Only Sample group D required at least 70°C for successful wire bonding. The inverse relationship between the temperature and bond power indicates that if a low temperature were to be used for wire bonding, it is necessary to apply a higher bond power to make up for the reduced thermal energy. This means that a high bond pad temperature is generally preferred because it can yield a wider process window. The samples cleaned at a low power (at 100W for Groups A and B) resulted in wider process windows than those cleaned at a high power (at 400W for Group C and D) for all temperatures studied. The long treatment time (Groups B and D) appears to be detrimental to bond pad cleanness [25] because the oxygen plasma can react chemically with the epoxy-based solder mask, posing a danger of recontamination of the metallized bond pad. The AFM images taken of the soldermask surfaces immediately after the plasma treatment, as shown in Fig. 7, partly support the above statement. The root mean square surface roughness values for the samples with longer plasma treatment ($R_{rms}$ = 118 and 157nm, respectively, for Groups B and D) were much higher than those with shorter treatment ($R_{rms}$ = 36 and 97nm, respectively, for Groups A and C), as a result of nonuniform, localised depletion of low molecular weight polymer.

Base on the above observations, it can be said that a low plasma cleaning power with a short exposure time is preferred. Overall, Group A was identified as the best plasma cleaning condition in this study that yielded the widest process window
with high pull strengths at all temperatures. Thus, Group A condition was chosen in the following section for further study.

B. Effects of Plasma Treatment on Process Window and Wire Pull Strength

The effect of plasma cleaning on wire bondability of three different bond pads was studied, and the major results are presented in Fig. 8. The pull strength data obtained at bond powers above 230mW are not shown here. As expected, the wire pull strength decreased consistently with increasing the bond power [3]. The electrolytic Au bond pads (Samples 2 and 4) could be bonded successfully using a lower bond power after plasma cleaning (Fig. 8(a)). The lowest bond powers for successful bonds before plasma treatment were 128mW and 101mW, respectively for Sample 2 and 4, which were reduced to 75mW and 65mW after plasma cleaning. These improvements arose from the reduction in ultrasonic energy required to push aside the contamination to allow direct contact between the wire and the bond pad surface [4,12]. The corresponding wire pull strengths were improved after plasma cleaning, the improvement being more pronounced for Sample 4 than Sample 2 especially at low bond powers, confirming the benefits of a thick Au layer. However, the pull strengths after plasma cleaning were all greater than about 6gf, above the industrial lower threshold of 5gf, when moderately high bond powers up to 230mW were used. The effect of plasma treatment on wire pull strength was associated with reduced deformation ratio, as shown in Fig. 9 (a).

For Sample 5 with immersion Au plating, the improvement was less significant. The pull strength increased marginally, and the lowest threshold bond power for a successful bond could not be further reduced (Fig. 8(b)). There were also negligible changes in wire deformation ratio (Fig. 9(b)). A possible reason for these observations is that the immersion Au plate (Sample 5) was not heavily contaminated because the solder mask was applied before the electroless Ni and immersion Au plating. Meanwhile, solder mask was applied after electroplating for the electrolytic Au (Sample 2 and 4). This means that the surface contamination due to outgassing of organic compounds during soldermask curing was eliminated in Sample 5. The XPS analysis on bond pad surfaces, however, was not able to distinguish whether the detected carbon originated from solder mask curing or from ambient environment. Furthermore, the etching process of the electrolytic Au plate exposed the underlying Cu and Ni layers to the ambient environment, whereas the etching process was not required and the underlying metal layers were always fully covered by Au in the immersion Au plating process. Therefore, the improvement by plasma treatment was less significant.

The process windows are compared between the as-received and plasma cleaned samples, as shown in Fig. 10. On the right hand side of the windows at high bond power ends are the regions corresponding to average pull strengths below 5gf. For both the Au layers produced by electrolytic and immersion methods, plasma cleaning improved the process window. The improvement was most significant for the thick Au layer (Sample 4) with more than three-times the previous window size. An enhanced interfacial contact between the wire and bond pad was mainly responsible, allowing easy formation of micro-weld [12] because the motion for sweeping away the contaminants was not necessary. With the clean bond pads, the ultrasonic energy is less likely to be wasted to deform the wire. Unlike the electrolytic Au plate (Samples 2 and 4), the inability of the immersion Au plate (Sample 5) to make wire bonds at bond powers lower than about 100mW even after plasma cleaning may be caused by the high hardness of the bond pad. According to the hardness measurement in our previous studies [1,3], the hardness of the immersion Au bond pad was higher than the electrolytic Au plated bond pad because of the contribution by the underlying hard Ni layer. A high hardness was correlated to a low pull strength for similar bond pad metallizations [1].

C. Effect of Exposure to Air after Plasma Treatment

The effect of exposure time to air after plasma cleaning on wire bondability was evaluated for Samples 4 and 5 bond pads. The cleanliness of the bond pads after exposure to the ambient environment was quantified based on the contact angle measurement, the XPS elemental composition analysis and the wire pull test. The contact angles of DI water on bond pad surfaces at different exposure time after plasma cleaning are illustrated in Fig. 11, and the corresponding surface free energies are plotted in Fig. 12 using Equation (3). The initial contact angles of DI water immediately after plasma cleaning of both samples were below the readable limits (about 8-10°), indicating hydrophilic nature of the surfaces. Storage in air for 1 h increased the contact angles to a range of 20-30° through hydrophobic recovery of the surface. The contact angles increased sharply in the first 8 h because of rapid re-contamination, and those after 8 h of exposure were about 60° and 50° respectively, for Samples 4 and 5. The contact angle became almost saturated after about 24 h of exposure for Sample 4, whereas the contamination still continued after 24 h for Sample 5. Because most organic contaminants are hydrophobic in nature, the contact angles by the non-polar probing liquid, diiodomethane, remained relatively unchanged.

The total surface energies for all samples decreased with exposure time, the decrease in the first few hours of exposure being most significant as a result of organic contamination. After 8 h of exposure, the surface energies saturated and remained almost unchanged until 24 h. The total surface energies obtained after 24 h of exposure were still slightly higher than those obtained in the as-received condition. This indicates that a slightly longer exposure time would be necessary to match that of the as-received status. The sensitivity of surface energy drop with exposure time was similar for all metallization schemes, indicating similar thermodynamic characteristics for all surfaces. It is interesting to note that the polar surface energy component decreased whereas the dispersion component increased before saturation after more than 8 h of exposure. The polar component was
almost negligible after exposure for over 24 h, indicating the bond pad surface was heavily contaminated.

The XPS analysis was conducted to correlate the above thermodynamic characteristics with elemental compositions of the surface. General survey spectra for typical bond pad surfaces obtained before plasma treatment (i.e. as-received) and after exposure to air following the plasma treatment are shown in Fig. 13. Although the survey spectra for all surfaces were basically similar, there was a large reduction in carbon content from 47% to 32% after plasma cleaning, and a gradual increase from 32% to 37% upon recontamination after 24 h of exposure. The changes in carbon content were accompanied by significant changes in surface functionality. To determine the nature of the contamination, the C1s peaks were curve fitted using the corresponding binding energies. Fig. 14 shows the shape changes in C1s peak with different exposures durations; and Table 3 summarizes the area percentages of the individual functional groups. There were three major surface functionalities, namely the C-H group (at binding energy of 285.0eV), the C-O group (at binding energies between 286.4 to 286.5eV), and the carboxylic (O=C=O) (between 289.1 to 289.3eV) functionalities. It is interesting to note that the content of C-O functionalities increased, whereas the contents of C-H and O=C=O functionalities decreased with exposure time, which agreed with the changes in surface energy component (Fig. 12). The increase in polar functionalities, such as carboxyl group O=C=O, after plasma treatment was correlated to the improvement in wire bond strength [1], which is also confirmed in the following wire pull test results.

There was a functional similarity between the surface energy/polar functionality and wire pull strength with respect to exposure time. The drop in pull strength was most significant in the first few hours for both samples, as shown in Fig. 15. After 8 h of exposure, the pull strength became almost saturated for Sample 4, whereas it continuously decreased even after 24 h of exposure for Sample 5. The wire pull strength became almost equivalent to that for the as-received condition after about 24 h of exposure. From the industry’s practical viewpoint, it is recommended that wire bonding be made within the maximum allowable exposure time of about 8h after plasma cleaning under an optimized condition. However, no significant effect on wire bond strength was reported [25] when plasma cleaned plastic ball grid array packages were wire bonded after delay up to about 100 h.

IV. CONCLUDING REMARKS

The process windows for successful wire bonds and wire bond strengths were evaluated for several Au/Ni/Cu bond pads that were produced using different plating methods. The following results can be highlighted from this study:

1. A major finding of this study is that Au wire bonds could be made at temperatures as low as 60°C without sacrificing the wire pull strengths when optimized process conditions and plasma cleaning are applied. Process windows were established to identify the combinations of important parameters, such as wire bond power, bond pad temperature and Au layer thickness, which could produce successful wire bonds.

2. Based on the process window and wire pull strength, Group A (with a low plasma cleaning power of 100mW and short total exposure time of 2 min) was identified as the best plasma cleaning condition for all temperatures studied.

3. Plasma cleaning enhanced the wire bondability as well as the wire bond quality. The improvements in process window and wire pull strength after plasma treatment were more pronounced for the electrolytic Au bond pad than for the immersion Au plate.

4. The plasma cleaned bond pads tended to be recontaminated once exposed to air. To avoid serious deterioration of wire bondability, it is recommended that the bond pads be wire bonded within 8h of exposure to air.

5. The recontamination of plasma cleaned bond pad surface was quantified based on the XPS analysis and contact angle measurements. There was a functional similarity between the bond pad surface characteristics, such as surface energy and polar functionality, and the wire pull strength with respect to exposure time after plasma cleaning.

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