EFFECT OF THE MICROSTRUCTURE OF Ni/Au METALLIZATION ON BONDABILITY OF FR-4 SUBSTRATE

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ABSTRACT

The present work is an investigation concerning the effect of microstructure of nickel/gold metallization on the bondability of gold thermosonic wirebonding, as well as aluminum ultrasonic wirebonding on FR-4 substrate. Microstructures with different bondability were studied using transmission electron microscopy (TEM) and an X-ray energy dispersive spectrometer (EDS). It was found that for Au/Au thermosonic wirebonding, the thickness of the gold layer played a critical role in bondability and the thickness was further dependent on the content of phosphorous in nickel layer.

Key words: Wirebonding FR-4 substrate Ni/Au metallization Microstructure TEM

INTRODUCTION

Wirebonding is the microelectronic interconnection technique most commonly used in the semiconductor packaging industry. Many materials can be used as the bonding substrate depending on the application. For low-cost Chip-on-Board (COB) technology, the substrate usually used is FR-4 material (glass fiber reinforced epoxy) due to its low cost, and electroless nickel/gold is recommended for the metallization because it can adapt complex circuit challenges. However, for thermosonic wirebonding, two problems may arise with this type of substrate. In general, the typical bonding temperatures for thermosonic wirebonding range from 150°C to 200°C [1], so one of the problems is the bonding temperature which has to be limited to 125°C, i.e. the glass transition temperature (T_g) of FR-4 material. Otherwise, the softened substrate will lead to degradation of bond quality. The second problem is the limited thickness of the gold layer due to the immersion mechanism of gold. Therefore, bondability of the FR-4 substrate needs to be properly understood.

Up to now, some work has been done to evaluate the bondability of FR-4 substrate for aluminum ultrasonic wirebonding at room temperature [2]. However, the bondability of thermosonic bonding with FR-4 substrate has not yet been systematically studied. The present work is part of an investigation into bondability, which places emphasis on the effect of microstructure of nickel/gold metallization on bonding quality.

EXPERIMENTAL

Wirebonding was carried out on bare FR-4 test boards with electroless nickel/gold metallization. The pad size on the substrate is 1.5 x 1.0 mm and the bonding distance is 1.5 mm. Gold wire and aluminum wire of 25 μm in diameter were used for ball/wedge thermosonic wirebonding and wedge/wedge ultrasonic bonding respectively, as shown in Figures 1a and 1b. The temperature for thermosonic bonding was 105°C. Bonding quality was examined by measuring bond strength, both through the bond pull test and the ball bond shear test. The microstructure of the nickel/gold metallization was studied using SEM JEOL JSM-840A and TEM JEOL 2000 FX with EDS.

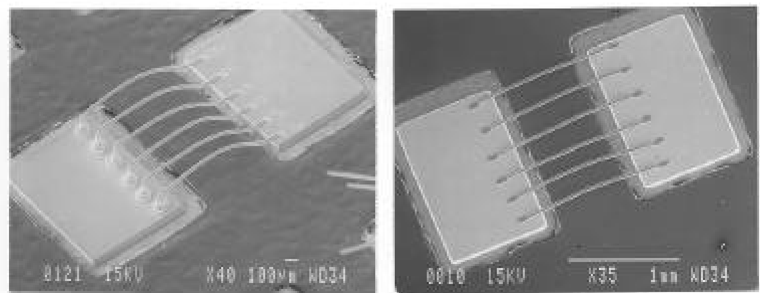


Figure 1. Au thermosonic ball/wedge wirebonding (a) and Al ultrasonic wedge/wedge wirebonding (b).

RESULTS AND DISCUSSION

Bond quality

In this experiment, it was found that the mean pulling strengths of the Al/Au wedge bonds on all test boards were similar, between 8.0-9.0 gf. However, the strengths of the Au/Au bonds showed considerable differences. Based on the strength of the Au/Au bond, the test boards were divided into two groups (Table 1). Group 1 consisted of the boards with high bond strength and Group 2 had the low strength. It was further found that in Group 1 most failures appeared at the transition of the ball bonds (first bonds), i.e. immediately above the ball (Figure 2). This means that the weak point in the wire loop, rather than the bondability issue, induced the failure. On the other hand, in the case of Group 2, failures mostly took place at wedge bonds (i.e. second bonds) in the form that the bond lifted off the bonded pads (Figure 3), which exhibits the poor adherence of the bonding surface. The shear testing of Au/Au ball bonds also showed a similar result: the shear strength of the bonds on Group 2 boards was worse than that on Group 1 substrate (Table 1). Therefore, the bondability of the Group 1 substrate is good for both types of wirebonding, whereas Group 2 boards are only good for Al/Au wirebonding.

Table 1. Bond strength of test boards of Group 1 and Group 2.

Wire		Au wire				Al wire	
Bond		Group 1		Group 2		Group 1	Group 2
Strength test		Pull	Shear	Pull	Shear	Pull	Pull
Failure position	1st bond	99%	100%	34%	100%	98%	100%
	Middle	0	0	0	0	0	0
	2nd bond	1	0	66%	0	2%	0
Strength (gf)	Maximum	8.0	132.4	7.1	122.5	13.7	12.0
	Minimum	4.3	100.3	2.5	57.5	5.5	6.8
	Mean	6.2	118.3	4.5	94.2	8.4	8.9

The result indicates that the bondability of Au/Au wirebonding can be easily influenced by the features of the bonding substrate. To understand the mechanism, an investigation was carried out into the microstructure of the nickel/gold layer in the two groups of substrates.

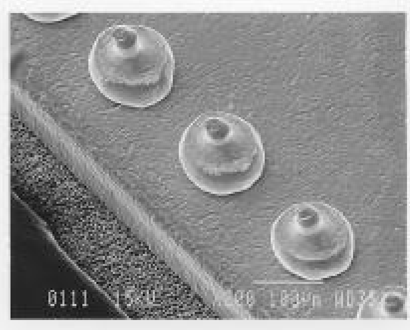


Figure 2. Loops broke at the first (ball) bond of Au wirebonding on the substrate of Group 1 in the pull test (pull strength: 7.8 gf).

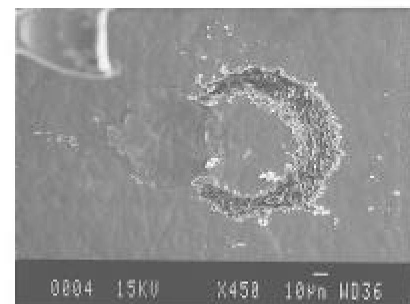


Figure 3. The second bond of Au wirebonding lifted off substrate of Group 2 in the pull test (pull strength: 2.7 gf).

<u>The effect of the microstructure of the Ni/Au layer on bondability</u>

<u>Microstructure of Ni/Au metallization.</u> Figure 4 is a TEM photograph that shows the general microstructure of nickel/gold electroless metallization. The nickel layer had an amorphous structure as revealed by selected electron diffraction analysis. The gold layer consists of small grains the size of tens of nm. The high volume boundaries could offer fast diffusion paths for the atoms of the matrix (for example nickel) onto the gold surface, especially at elevated temperatures. It has been noticed that no voids were found in this case, but high levels of hydrogen gaseous entrapment were observed in the electroplating gold layer [3].

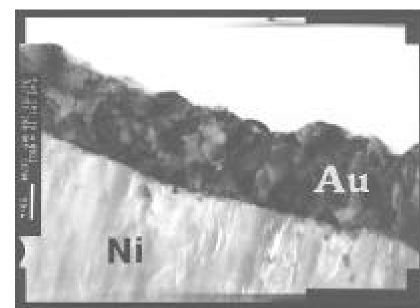


Figure 4. The microstructure of Ni/Au metallization.

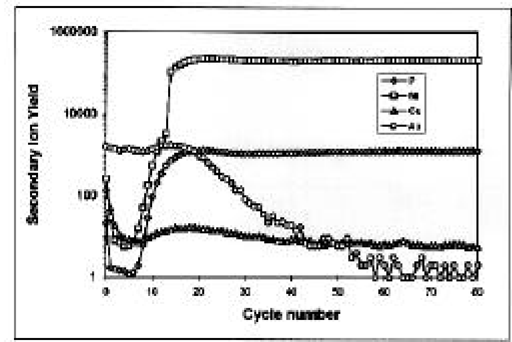
In addition, chemical analysis was carried out. Figure 5a is the spectrum of SIMS depth analysis from the top surface of the nickel/gold layer. Quantitative composition from this analysis is difficult due to the wide variation of secondary ion yield as a function of the atomic number. However, from the spectrum, it can be found that some impurities (copper, nickel etc.) have segregated on the gold top surface, and the nickel layer is composed of nickel and phosphorus. EDS

analysis also confirmed the result which indicated the existence of nickel and phosphorus, as well as a little copper in the nickel layer (Figure 5b). The source of the copper is not clear, it could come from the copper matrix below the nickel/gold metallization by diffusion or from the nickel or gold plating bath, or from some other source such as the copper support ring for the TEM specimen etc.

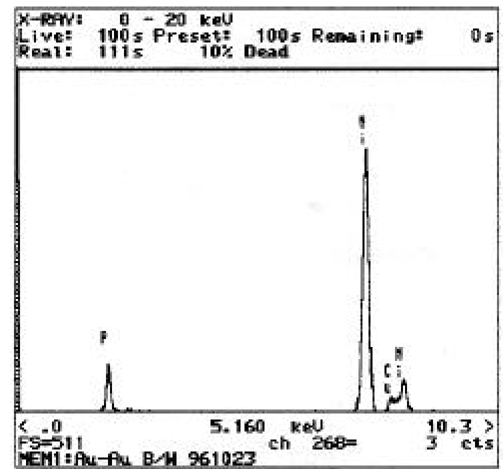
Metallization of Group 1 and Group 2. Figures 6a and 6b show the microstructure of the nickel/gold metallization of Group 1 and Group 2 boards respectively. It can be seen that gold thickness on the Group 1 boards was uniform, about 100 nm. However, the layer on Group 2 was rather thin and uneven in terms of thickness. Some parts only were only 20 nm thick. The top surface hardness was thus different, inversely proportional to the gold thickness, as shown in Table 2. For the Group 2 substrate, the surface with the thin gold layer was hardly deformed during bonding, resulting in the poor bondability. Therefore, a gold layer of 100 nm thickness is needed for good bondability of thermosonic wirebonding.

Table 2. Knoop hardness (HK) of the top surface of substrate.

Test board		Group 1	Group 2		Ni
Au thickness		150 nm	100 nm	< 50 nm	0 nm
Hardness (HK)	1	253	547	889	998
	2	212	547	889	1097
	3	240	569	807	989
	Mean	235	554	862	1007



(a)



(b)

Figure 5. SIMS (a) and EDS (b) analysis show the composition of Ni/Au metallization.

A further investigation into the microstructure of the substrate was performed by measuring the phosphorous in the nickel plating layer. It has been pointed out that the phosphorous content in the nickel layer can dramatically affect the properties of the layer [4], thus playing an important role in gold layer properties. In this work, EDS analysis was carried out on the nickel layer near to the nickel/gold interface; the result is shown in Table 3. The substrate of Group 1 had a uniform and thicker gold layer, the phosphorous which was detected in its nickel matrix was always more than 10 wt.%. However, the phosphorous level varied with the gold layer thickness in Group 2. In other words, a thick gold layer was always accompanied by a high phosphorus level . Therefore, it is reasonable to infer that high phosphorous level in the nickel layer is a necessary factor for obtaining a thick gold layer.

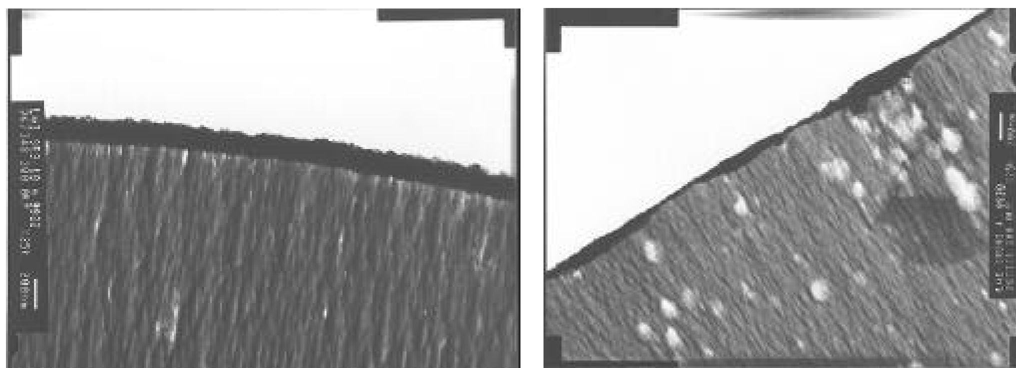


Figure 6. The cross-section of Ni/Au metallization of the substrate of Group 1 (a) and Group (2).

Table 3. The effect of nickel layer phosphorous content on gold thickness.

Board	Group 1			Group 2								
Au layer	150 nm			100 nm			80 nm			20 nm		
Analysis	1	2	Mean	1	2	Mean	1	2	Mean	1	2	Mean
P (wt.%)	10.3	10.4	10.3	9.7	9.5	9.6	8.0	8.8	8.4	6.0	7.0	6.5

The mean phosphorous level in the top surface of the nickel matrix prior to gold plating was also measured. The value was 11.8 wt.% for Group 1 and 6.8 wt.% for Group 2. The phosphorous content in the nickel surface of Group 1 boards was obviously higher than for Group 2, consistent with the results as shown in Table 3.

The result is interesting because it reveals a relationship between the thickness of the gold layer and the phosphorous level in the nickel layer, i.e. the thickness of the gold layer increases with the phosphorous content in the nickel matrix. However, controlling the phosphorous level is not easy because many factors can influence the phosphorous content. The pH value in the nickel bath is one of these factors, see Table 4 [5]. It shows that an acid-based nickel bath is favorable to the qualified layer. However, a wide range of phosphorous levels can be formed in the nickel layer even with a single nickel bath, as indicated by the uneven distribution of phosphorous in the nickel matrix of Group 2 boards. A further investigation showed that even in the nickel layer on Group 1 substrate, the phosphorous level also varied, decreasing in the center part of the pad (Figure 7), although the gold thickness in the pad side was rather homogeneous. Therefore, other factors such as matrix surface status, temperature and its distribution, plating operation and so on, have to be closely regulated during nickel plating.

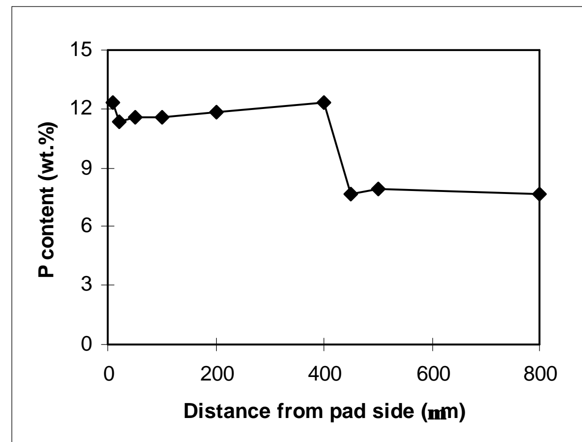


Figure 7. Phosphorous content distribution with the distance from the pad side.

Table 4. The variation of phosphorus level with pH [5].

pH	4-5	8-9	9-10
P level (wt.%)	10-12	5-8	2-5

CONCLUSIONS

This work studied the microstructure of electroless nickel/gold metallization of FR-4 boards. The microstructure is an important issue for controlling bondability of gold wire thermosonic bonding. For Au/Au wirebonding, bondability is dependent on the thickness of the gold layer – a thick gold layer will have a favorable effect on bondability. The thickness is further governed by nickel structure below the gold layer, especially the phosphorus content, which results from the electroless nickel/gold plating process. Therefore, plating requires precise bath control.

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