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Surface Roughness Effect on Copper-Alumina Adhesion

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Abstract

The surface roughness of the substrate itself could play an important role for the bonding at the interface. In this paper, a correlation of the surface roughness of a rigid alumina substrate and its 2D model of estimated surface area has been studied using Atomic Force Microscopy (AFM). With rougher surface, the adhesive strength between a deposited copper film and the alumina substrate is higher due to the larger contact area at the interface. For 99.99% pure copper- 96% pure alumina, this effect can account for an adhesive strength increment of more than 50%.

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1. Introduction

The problem of delamination or debonding is a very serious failure path for all microelectronic packaging systems [1, 2]. This underlies the critical importance of metallization adhesion to the substrate, especially under harsh operating environments.

Proper adhesion between metal lines and the substrate can be affected by the modified surfaces which have been treated chemically or physically. Past studies have reported the effect of surface morphology to the adhesion efficiency between materials. Kim et. al. [3] has reported that adhesion for copper/chromium on polyimide substrate can be improved by roughening the substrate surface using inductively coupled oxygen plasma. Surface roughening is ascribed to the increase in the measured peel strength due to the surface area enlargement. Egitto and Matienzo [4] have also shown that smoother surface results in smaller surface area and leads to poorer adhesion. This work introduces a simple model to relate surface area with surface roughness of the Al_2O_3 substrate. In addition, the impact of surface roughness to the adhesion measurement has also been evaluated.

For packaged devices, the reliability of the system does not only depend on the die attach, wire bonding and the lid sealing. The substrate used for the package also plays a significant role for the system to survive under the robust environment such as elevated temperature and high pressure. Advanced ceramics such as alumina (Al_2O_3), aluminum nitride (AlN), and silicon carbide (SiC) are very attractive for electronic packaging applications because these types of materials are able to work at high power, high frequency and high temperature atmosphere. In particular, Al_2O_3 with unique properties such as excellent chemical inertness; good thermal and mechanical stability, as well as high hardness, is a

well-developed and commercialized ceramic substrate for hybrid ICs and MCM [5-9]. In this work, the consequence of the alumina substrate's surface morphology for the copper metallization application has been evaluated. The adhesion strength for Cu- Al_2O_3 increases with surface roughness up to a roughness of 500nm. With 10% increment of total contact area, the adhesion strength for this bonding has been enhanced by more than 50%, with an average adhesive strength of 18MPa.

2. Experimental Setup

Copper (Cu) thin film was deposited on the commercial alumina (Al_2O_3) substrate (0.6 mm x 3 mm x 3 mm) by DC magnetron sputtering. The commercial Al_2O_3 substrates with purity of 99.6% and different surface roughness were used for the adhesion strength comparisons.

Al_2O_3 substrates were first dice-sawed into 3 mm x 3 mm pieces using DISCO DFD 6361 fully automated dice saw equipment at a speed of 4 mm/s. The cut substrates were then grouped according to different surface roughness whereby the first group of the substrate with lowest surface roughness has been polished using the standard chemical and mechanical polishing method while the other two groups of substrates were non-polished after fabrication. The substrates were then ultrasonic cleaned using acetone, followed by 2-propanol for ten minutes each. After that, some of the substrates were heat treated at 500°C for 1 hour prior to deposition in order to check the effect of moisture to the bonding between the deposited film and the Al_2O_3 . Cu thin film (Cu target with purity of 99.99%) was then sputtered onto the substrate under the process pressure of 10mTorr with 250 W of process power and 0V substrate bias voltage without annealing. Before the deposition process, the chamber was pumped down to 12 μ Torr.

The surface roughness and the surface area estimation of the ceramic substrate was analysed using atomic force microscopy (AFM DI 3100). Root mean square (R_{MS}) roughness was calculated using a $20\mu\text{m}^2$ scan area. Trapezium rule of calculation in 2D model for estimated total surface area will be introduced.

The fabricated devices were then evaluated with pull strength measurements reflecting interfacial adhesion strength. The adhesive strength measurement is taken based on the average measured results from 20 test specimens. A loading speed of $10\mu\text{m/s}$ was applied and carried out at room temperature condition. The value of bonding strength was calculated by dividing the load used to separate the deposited film from the substrate to the area in contact. A diagram of the test sample for adhesion measurements is presented in Fig. 1. Scanning electron microscopy (SEM) is used with dual beam focused ion beam (FIB) to observe for changes in surface morphology of the sputtered films coated under different conditions.

Fig. 1. Schematic illustration of adhesion testing

3. Results and Discussions

Table 1
Al₂O₃ substrates with different surface roughness

Sample	Rms (nm)	AFM image
S1	10 - 200
S2	200 - 350

S3 350 - 500

The surface roughness of the Al₂O₃ substrates have been analysed using AFM and the results were listed in Table 1. It has been grouped into three surface roughness named as S1; S2 and S3. Comparison of the bonding strength using the Delaminator Test Manager (DTSTM) was shown in Fig. 2 with three different surface roughness and different surface pre-treatments.

It was clearly shows that deposition of metal film right after substrate heat treatment at 500°C for 1 hour has higher adhesion strength. This has been done to remove excess moisture trapped inside the Al₂O₃ substrate. The substrates are very porous in nature. Level of porosity is still considered high even it has been polished. Solvent cleaning under ultrasonication was done for every substrate before proceeding to the next cleaning steps. Flowing of solvent into the porous Al₂O₃ was uncontrollable and cannot be avoided. In order to reduce the humidity level of Al₂O₃, heat treatment prior to bonding is necessary to provide better bonding at the interface. This was done to avoid the moisture attacked at the interface by hydrating the metal coated during the deposition process.

Fig. 2. Adhesion strength measurement for Cu/Al₂O₃ with different surface roughness and surface pre-treatments

Fig. 3. Correlation of Surface roughness to the surface contact area and bonding strength between Cu and Al₂O₃

Besides of moisture effect, we can also see that the adhesion strength increases with surface roughness for both surface pre-treatments. This can be correlated with the total surface contact area of Cu and Al₂O₃. With the simple 2D model of trapezium rule calculation (see Eq. 1), we were able to estimate the total contact area using AFM analysis.

$$A_{total} = 0.5 \times s \times \left[\sum_{n=1}^{34} (a_n + a_{n+1}) \right] \quad (1)$$

where A_{total} = Total surface area correlated with surface roughness

s = Spacing between two measured lines

a = Measured surface distance

One may want to use rough surface to prevent adhesion; but there were also some cases using rougher surface to decrease the contact angle for better bonding. In the case of Cu-Al₂O₃ bonding, substrate with higher surface roughness is able to improve the bonding strength at the interface. With rougher surface, it has about 10% of increment in the total surface contact area as indicated in Fig. 3. From the measurement as shown in Fig. 2, the average adhesive strength for the heated samples increases

from 11.5MPa (S1 samples) to 18.0MPa (S3 samples). It achieves more than 50% of enhancement based on these 10% of surface area enlargement.

Throughout the sputtering deposition process, atoms were landed onto the Al₂O₃ surface randomly and energetically. Under the high deposition pressure, more atoms were able to travel from the target to the substrate and tried to seal or fill up all the porous surfaces. Fig. 4 shows the formation of columnar Cu thin film on the Al₂O₃ substrates with two different surface roughness. Encapsulation of the sputtered atoms on to the Al₂O₃ substrate especially at the peak and valley areas or irregularity plane was shown in Fig. 4(b) as indicated in the circled area

Fig. 4. Cross-sectional views of deposited Cu film on Al_2O_3 surface (a.) S1 sample (b.) S2 sample

Surface scanning on the Al_2O_3 using backscattered electron imaging (BEI-SEM JOEL 6360) have also been done after the adhesion testing. From the images shown in Fig.5, we can clearly see that the Cu residuals still adhere tightly on the surface especially at the pore and void areas mainly using mechanical interlocking bonding mechanism [10] and it could have contributed toward the improvement in bonding. Energy dispersive X-ray (EDX) analysis has been analysed at the area indicated in Fig. 5 to verify the elements present on the surface after the pulling test.

Fig. 5. BEI images and EDX analysis on Al_2O_3 failure sites (a.) S1 sample (b.) S2 sample after tensile test

However, the surface porosity for these two substrates with different surface roughness was actually similar statistically. Consequently, the mechanical interlocking mechanism based on porosity is unable to explain their difference in adhesive strength. For that reason, in this study, we are trying to find out the effect of surface roughness to the bonding strength for Cu- Al_2O_3 by analyzing the total surface area in contact at the interface. From the mapping analysis presented in Fig. 6, we were able to observe large fraction of Cu were adhered strongly on the porous regions and clearly shown in the SEM images in Fig. 5, but there were some tiny Cu residuals distributed on the entire Al_2O_3 surface. The mapping analyses were done corresponding to the BEI images in Fig. 5. With higher surface roughness, there were more spaces and vacancies for the sputtered atoms to make contact on the bonded surfaces. Therefore, the number of bonds per unit area was increases with the surface roughness of the Al_2O_3 substrate, contributing to a higher adhesive strength. This is because more energy is needed to break the bonds between the bonded materials during the tensile test.

Fig. 6. SEM-Mapping analysis on Al_2O_3 failure sites (a.) S1 sample (b.) S2 sample after tensile test

Fig. 7. SEM images on Cu failure sites (a.) S1 sample (b.)

S2 sample after tensile test

Fig. 7 shows the ductile failure site on Cu surfaces after the adhesion testing by pulling it apart from the Al_2O_3 substrate with different surface roughness. The broken areas on the Cu surfaces were basically due to the locking bonding effect at the interface. These two images enable us to notice that the Cu film deposited was following the surface morphology of the substrate itself. This was an evidence to prove the contact area theory we have proposed in this study whereby the substrate with higher surface roughness was able to contribute more contact area and results in higher adhesive strength at the interface between the bonded materials.

4. Conclusion

For all types of bonding, appropriate surface pre-treatment is needed prior to deposition. For Cu- Al_2O_3 bonding, heat treated substrates at 500°C for 1 hour is necessary to eliminate excess moisture trapped inside the porous Al_2O_3 . This was done to prevent hydrating effect at the interface area. With the experimental and calculation works presented, we can predict that there is an increment of 10% for the total surface contact area with the roughness change of 500nm and this effect is able to achieve more than 50% of improvement for the adhesive strength. With wider and larger surface area in contact, the number of bond per unit area between the bonded materials will be largely increased. This results in higher adhesive strength at the interface because more energy is required to initiate the bond breakage between deposited Cu atoms and the Al_2O_3 substrate.

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Appendix

Imagine that the line with different roughness has been stretched in a straight line with the surface distance given in the section analysis using AFM. We were able to calculate the area for each section using the trapezium rule and estimate the total surface area by summing up all the sections as shown below.

Estimated surface area:

$$= \text{Area 1} + \text{Area 2} + \dots + \text{Area 34}$$

$$= 0.5 \times s \times [(a_1 + a_2) + (a_2 + a_3) + \dots + (a_{34} + a_{35})]$$

$$= 0.5 \times s \times [\sum_{n=1}^{34} (a_n + a_{n+1})]$$

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