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Physical Surface Treatments for Improving Direct Copper Bonding

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Abstract

Cu direct bonding is one of the key technologies for 3D chip stacking. How to achieve robust Cu to Cu bonding at low temperatures under low vacuum is a crucial issue for mass fabrication. In this study, the parameters of pre-treatments, including annealing and and plasma exposure time, are controlled and investigated. Nanoindentation and AFM are applied to clarify the relationship between the superficial hardness, roughness and Cu-to-Cu joint strength. An optimal pre-bonding treatment condition will be proposed and explained from the aspect of surface morphology as well as the types of defects in the subsurface region.

1. Introduction

In order to allow conductance between stacked ICs, jointing by metallic connections is necessary[1,2]. Cu to Cu bonding is ideal to form required interconnections. Breakthroughs in direct Cu bonding have been accomplished in recent years. However, strict processing requirements, e.g. high vacuum, long bonding time and excess coating (intermediate layer), limit its industrial application [3,4]. Numerous reports have been devoted to enhance Cu to Cu bonding via surface plasma activation. It was suggested that surface activation and thus hydrophilicity can be achieved by plasma exposure [5,6]. Direct bonding is a process through the van der Waals force between two atomically clean surfaces to actualize jointing. For example, in 2015 Chua et al.[7] accomplished room temperature Cu to Cu bonding with the assistance of Ar/H_2 plasma treatment under 10^{-4} torr. The results also show that the water contact angle was 3° right after sputtering and plasma exposure, and increased drastically in several hours. Therefore, it is important to execute bonding immediately after plasma activation.

Another developing surface modification pretreatment for direct Cu bonding is a combined process with diamond cutting, formic acid vapor and vacuum ultraviolet irradiation [8]. The bonding can be achieved even at 175°C. It was reported that nano-sized grains underneath the diamond cut surface accelerate metallurgical interdiffusion between Cu-Cu interface.

To avoid time consuming high vacuum process and sophisticated diamond cutting, this research aims to develop a low-temperature low-vacuum Cu to Cu bonding to meet the requirement for practical application. Low vacuum air plasma was adopted for surface hardening rather than surface activation. Cu blocks with different annealing conditions were used as test materials. The relationships between hardness, roughness and joint strength were discussed

2. Results and discussion

Pretreatments including annealing and atmospheric air plasma were performed. Unlike usual plasma treatment, in this experiment the plasma bombarded Cu surface was stored in air for several hours followed by cleaning procedure by citric acid solution. Fig. 1 shows average surface roughness of the Cu samples subjected to different pretreatments. It can be found that both annealing at 500°C and air plasma bombardment resulted in a more rugged surface. For the as-received Cu, the roughness was 2.01nm for non-plasma treatment, 2.36nm for 1 min exposure and 3.03nm for 3 min exposure. As for 500°C-annealed samples, the average roughness was much greater, which increased from 2.97nm (non-plasma treatment) to 4.07nm (1 min exposure), 7.94nm (3 min exposure) and then 7.72nm (5 min exposure).

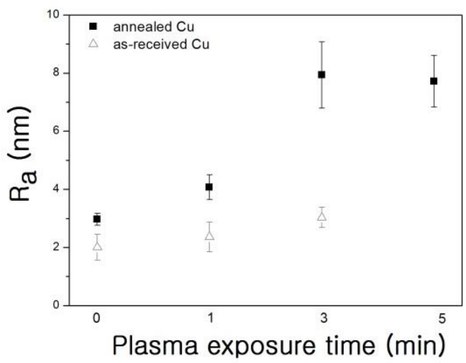
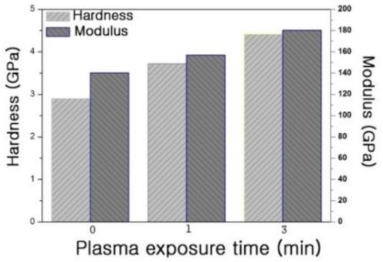
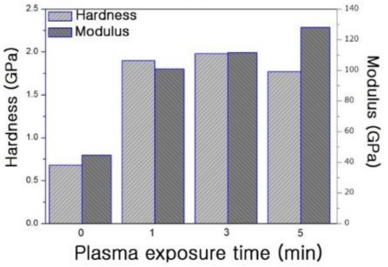


Fig. 1 Average roughness of annealed and as-received Cu after air plasma pretreatment

Nanoindentation was conducted on the Cu surface. Figs. 2(a) and (b) illustrate the average hardness and elastic modulus of the sub-surface region where the penetration was about 10 nm. It can be distinguished that plasma bombardment hardened the surface of the samples no matter they were as-received or annealed. The hardness of as-received samples ranged from 3GPa to 4.5GPa. Annealing at 500°C certainly softened the samples. The average hardness was reduced to 0.7GPa to 2 GPa. It can be found as to annealed samples hardness remained constant or even slight decreased after 3 minute plasma exposure, but the modulus kept on rising.



(a)



(b)

Fig. 2 Average hardness and modulus of the subsurface region of Cu after air plasma pretreatment: (a) as received and (b) 500°C annealed.

The treated samples were bonded using a thermal compression bonder at 250°C in N_2. The bonding time was 20 min for as received samples and 30 min for annealed ones. Remarkably, Fig. 3 illustrates the shear strength of the joints bonded by as received Cu were much greater than those bonded by annealed samples. A highest joint strength of about 55 MPa can be obtained for as received Cu after plasma pretreatment for 3 min.

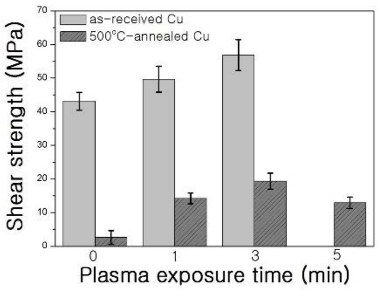
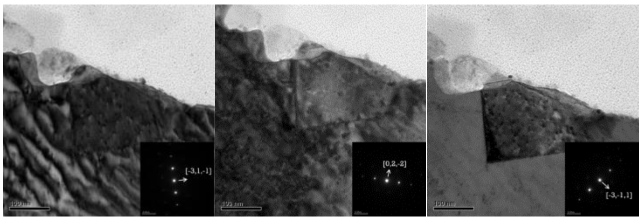


Fig. 3 The shear strength of joints directly bonded with Cu samples subjected to air plasma pretreatment for different periods of time

Considering the factors affecting the bonding strength, the results depict that annealing and thus a soft Cu substrate resulted in a poor degree of bonding. A greater hardness of the received samples is beneficial for bonding. A subsequent plasma bombardment even enhance the bonding more. Fig.4 shows the TEM images of annealed Cu subjected to 1 min plasma bombardment. No distinguishable line or planar defects (dislocations or stacking faults) can be found [9]. The residual stress estimated from GIXRD data (Fig. 5) indicates that plasma bombardment introduced a compressive stress field. Accordingly, it can be suggested that lattice distortion thus formed brought about a harder/stiffer Cu substrate and thus greater driving force for interdiffusion of Cu from both sides. Low defect density and rough surface by annealing show opposite contribution.



(a) (b) (c)

Fig.4 Two-beam TEM analysis of annealed Cu after 1 min plasma pretreatment with different beam axes: (a) [-3,1-3], (b) [0,2,-2], (c)[-3,-1,1]

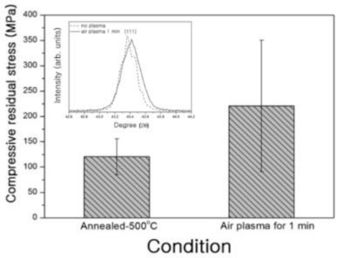


Fig. 5 The residual stress of the annealed Cu after air plasma pretreatment for 1 min

3. Conclusion

The effect pre-treatments of annealing and air plasma exposure was investigated systematically. To eliminate influence of surface activation, storage in air for hours and subsequent acid cleaning were performed. Experimental results suggest that an effective interdiffusion promoted by compressive stress field through air plasma bombardment can achieve firm Cu-to-Cu bonding with the joint strength up to 55 MPa. Full annealing deteriorated joint strength due to softened substrate and rugged bonding surface. An optimal pretreatment conditions can be determined from the considerations of surface roughness and subsurface hardness.

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