Journal of Electrochemistry

Volume 28
Issue 7 *Special Issue on Electronic Electroplating (Ⅱ)*

2022-07-28

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Bai-Zhao Tan

Jian-Lun Liang

Zi-Liang Lai

Ji-Ye Luo
1. School of Chemical Engineering and Light Industry, Guangdong University of Technology, Guangzhou, Guangdong 510006, P.R. China;, luojiye@gdut.edu.cn

Recommended Citation

Bai-Zhao Tan, Jian-Lun Liang, Zi-Liang Lai, Ji-Ye Luo. Electrochemical Deposition of Copper Pillar Bumps with High Uniformity[J]. *Journal of Electrochemistry*, 2022 , 28(7): 2213004.
DOI: 10.13208/j.electrochem.2213004
Available at: https://jelectrochem.xmu.edu.cn/journal/vol28/iss7/7

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J. Electrochem. 2022, 28(7), 2213004 (1 of 10)

[Article] DOI: 10.13208/j.electrochem.2213004 Http://electrochem.xmu.edu.cn

Electrochemical Deposition of Copper Pillar Bumps with High Uniformity

Bai-Zhao Tan[1#], Jian-Lun Liang[1,2#], Zi-Liang Lai[1], Ji-Ye Luo[1*]
(*1. School of Chemical Engineering and Light Industry, Guangdong University of Technology, Guangzhou, Guangdong 510006, P.R. China; 2. Jihua Laboratory, Foshan, Guangdong 528200, P.R. China*)

Abstract: Electrochemical deposition of copper pillar bumps (CPBs) is one of the key technologies for the advanced packaging. In this study, the effects of the additive concentration, the electrolyte convection, the current density, and the electroplating system on the uniformity of the CPBs have been systematically investigated. The results showed that the profiles of the CPBs were mainly determined by the additive concentration, the bath convection and the current density, while the heights of the CPBs were mainly affected by the electroplating system. For the CPBs profiles, it was found that the low leveler concentration and high current density would generally result in domed shape, while the uneven agitation would lead to inclined surface. For the heights of CPBs, the macroscopic uniformity could be dramatically improved by a sophisticatedly designed electroplating system. These results can provide basic guidance for the optimization of the CPBs electroplating.

Key words: copper pillar bump; electrochemical deposition; uniformity; additive; leveler

1 Introduction

The continuous miniaturization, versatility, and high performance of electronic devices promote the development of 2D integrated packaging technology towards 2.5D or 3D integrated packaging[1]. Traditional flip-chip packaging using controllable collapse chip connection (C4) technology remains a series of challenges for the high-density chip packaging with ultra-fine pitch[2, 3]. Copper owes the leading advantages for flip chip bumps to replace the Sn-Pb or lead-free solders, due to its superior electrical and thermal conductivity, excellent electromigration resistance, proper coefficient of thermal expansion (CTE) property, and high melting point (will not collapse in the reflow process). In 2006, Intel first introduced the copper pillar bumps (CPBs) in its 65 nm node CPUs. Since then, CPBs have been widely used in advanced packaging[4-6].

The fabrication of the CPBs, as illustrated in Figure 1, mainly includes several steps: (1) the polyimide (PI) coating and developing, in which a layer of PI is prepared between the CPBs and the substrate to reduce the stress; (2) the under bump metallurgy (UBM) fabrication, in which a layer of Ti (or TiW) is sputtered as a barrier layer (to prevent the mutual diffusion between the aluminum pad and the Cu seed layer, and provide a better adhesive layer for the Cu seed layer), and a layer of Cu is deposited on the surface as the seed layer; (3) the photoresist (PR) coating and developing to prepare the designed pattern; (4) copper pillar bumps electrochemical deposition; (5) follow-up processes, such as the solder electroplating (a Sn-Ag cap is electrodeposited on the Cu pillar top), PR removing and UBM etching. After the final reflow, a vertical copper

Cite as: Tan B Z, Liang J L, Lai Z L, Luo J Y. Electrochemical deposition of copper pillar bumps with high uniformity. *J. Electrochem.*, 2022, 28(7): 2213004.

Received: 2022-03-01, Revised: 2022-04-18. #The authors contributed equally to this work. *Corresponding author, Tel: (86-20) 39322231, E-mail: luojiye@gdut.edu.cn pillar bump with a hemispherical solder cap is prepared. In the fabrication process, the most challenging step is the electrochemical deposition of the CPBs[7]. To facilitate the following solder electroplating and the final flip chip packaging, the CPBs are required to be very uniform. First, the top surface of each CPB needs to be flat (microscopic uniformity) for good Sn-Ag solder contact. In addition, the whole CPBs heights also need to be consistent (macroscopic uniformity) for well die attach in the flip chip packaging. The flatness and the height uniformity of CPBs will generally improve the reliability of the package interconnect.

Currently, the copper electrochemical deposition for the electronics is mainly based on the acid copper sulfate electroplating[8-10]. The electrolyte is composed of copper sulfate, sulfuric acid, chloride, and a trace amount of organic additives. According to additive's functionality, these components are generally categorized as accelerator, suppressor and leveler. To fabricate the CPBs with high uniformity, both the organic additives and the electroplating conditions play an important role in the electrochemical deposition process[3, 11-16]. In industry, with the optimized additives and electroplating conditions, the uniformity of electroplated CPBs could be achieved as low as about 5% at a current density of 10 ~ 20 A·dm^{-2} [7, 11, 12, 22].

In this study, the effects of the additive's concentration, the electrolyte convection, the current density, and the electroplating system on the uniformity of the CPBs have been systematically investigated.

2 Experimental

2.1 Reagents and Materials

The virgin make-up solution (VMS) was composed of 200 g·L^{-1} $CuSO_4 \cdot 5H_2O$, 100 g·L^{-1} H_2SO_4, and 50 mg·L^{-1} Cl^-. The organic additives used in the electroplating include an accelerator B, a suppressor C, and a leveler L, which all were prepared in the laboratory.

As shown in Figure 2a and Figure 2b, both the small wafer coupons (50 mm × 50 mm) and whole 12-inch wafers (provided by Guangdong Fozhixin Microelectronics Technology Research Co., Ltd) were used as

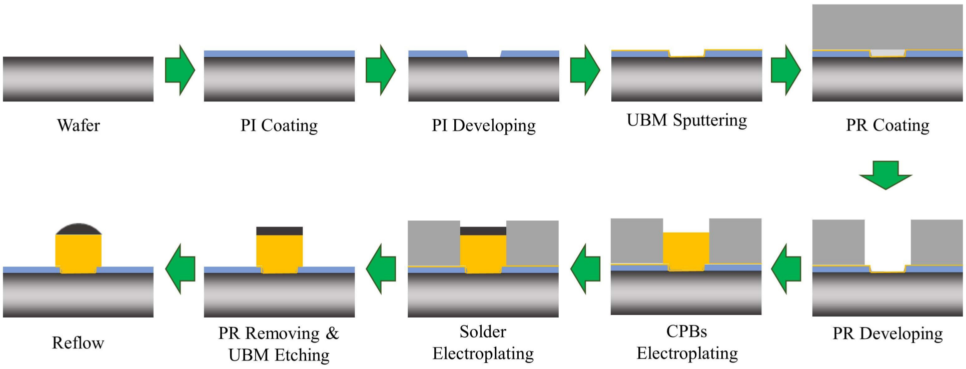


Figure 1 The schematic diagram of copper pillar bumps fabrication process. (color on line)

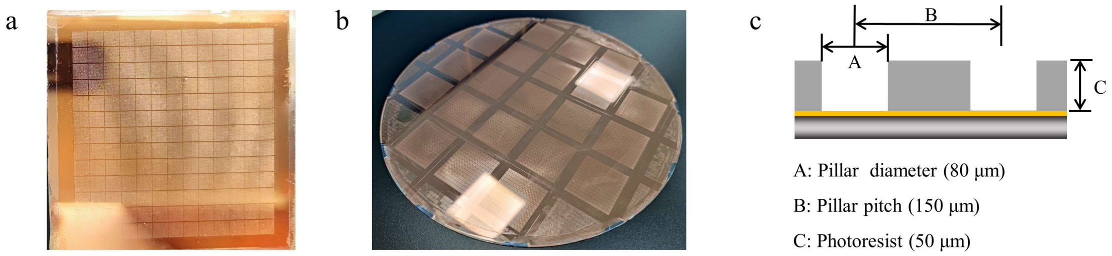


Figure 2 The wafer samples used in this study. (a) 50 mm × 50 mm small wafer coupon; (b) 12-inch wafer; (c) schematic illustration of the pattern. (color on line)

the testing samples for the CPBs electroplating, on which 100 nm Ti and 300 nm Cu were pre-deposited as the UBM layer. The diameter and depth of the features on the wafers were 80 μm and 50 μm, respectively (as shown in Figure 2c).

2.2 Electroplating Methods

In this study, a 4-L and a 40-L high-precision silicon wafer electroplating systems (Yamamoto-MS, Japan) were used for the small wafer coupons and 12-inch wafers electroplating, respectively. As shown in Figure 3a and Figure 3b, the two Yamamoto-MS electroplating systems were basically the same except for the different volumes. Figure 7c is the schematic diagram of the electroplating system. The testing samples were vertically placed in the tank and the electrolyte convection was provided by an overflow-mechanism and a paddle agitator. The distance between the cathode and paddle, and the paddle speed could be adjustable. To investigate whether the different designed electroplating systems would affect the uniformity of the CPBs, an ACM Ultra ECP ap equipment (ACM, China) has also been used for the electroplating, in which the wafers were horizontally placed in the tank. In all systems, the anodes were soluble phosphorus-containing copper slices (the phosphorus content ranged 0.04% ~ 0.065%).

Before the electroplating, the wafer samples have been pre-cleaned by air plasma to remove the residues in the features and increase the wettability of the testing samples[17]. Then the wafer coupons were immersed in 10 g·L^{-1} sulfuric acid solution and treated with vacuum to exclude the residual air in the features and make sure the completely wetted features[14]. The electroplating temperature was controlled at 25 ℃, and the distance between the cathode and the anode was 50 mm for the Yamamoto-MS systems. The area ratio of the cathode to the anode was 1:1. The current density used in this study was 10 A·dm^{-2} unless otherwise noted.

2.3 Characterizations of the Copper Pillar Bumps

The profiles and the heights of the electroplated CPBs were collected by an Olympus OLS4100 confocal laser scanning microscope (CLSM). To quantitatively characterize the uniformity of the CPBs, the special parameters, such as the total indicated runout (TIR) and within-die coplanarity (WID) are proposed to describe the profile flatness and the height coplanarity of the CPBs, respectively. As shown in Figure 4a, the TIR value is determined by the height difference between the pillar center and edge. The closer the TIR value is to zero, the flatter the top profile is, which will facilitate the Sn-Ag solder contact in the following packaging process. In addition, a positive TIR value means a domed shape of the CPB; while a negative value indicates a concave profile. The WID, as shown in Figure 4b, is determined by the heights of different CPBs in a die. Similarly, the smaller value of WID suggests superior uniformity of the CPBs, which will be beneficial for the flip chip contact.

3 Results and Discussion

3.1 Effect of Additive Concentration on Electrochemical Deposition of CPBs

The effects of the additive concentration on the

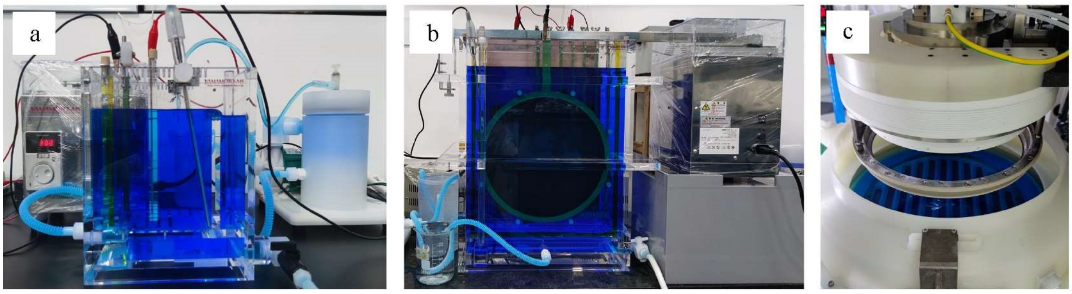


Figure 3 High-precision silicon wafer electroplating systems. (a) 4-L volume and (b) 40-L volume, and (c) ACM Ultra ECP ap equipment. (color on line)

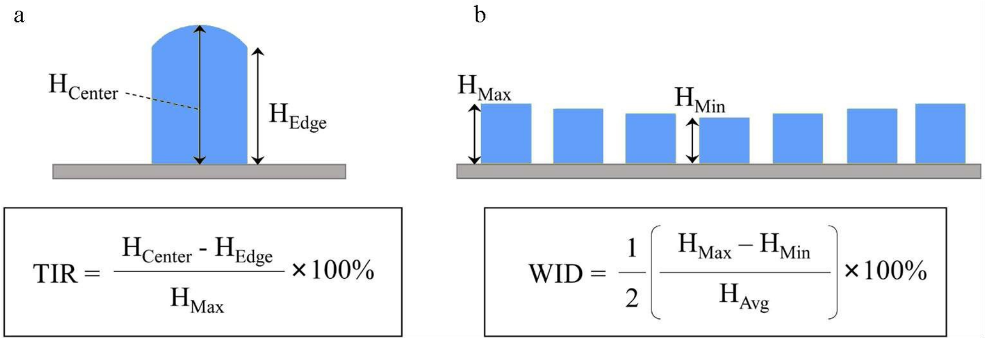


Figure 4 The uniformity characterization method of the copper pillar bumps. (color on line)

uniformity of the electroplated CPBs were investigated by the orthogonal analysis. A L_9 (3^3) orthogonal table was chosen in the experiment. The TIR_{avg} and WID values of the CPBs are calculated and taken as the indexes, in which the TIR_{avg} is the average TIR values of the CPBs on the coupon. Small wafer coupons were used in the electroplating experiments, in which the current density was fixed at 10 $A \cdot dm^{-2}$ and the electroplating time was settled at 18 min. The CPBs morphologies and orthogonal test results are summarized in Figure 5 and Table 1, respectively.

The orthogonal test results showed that the order of the three additives on the TIR values is: L > B > C (The *R* values are 25.9%, 2.3%, and 2.1%, respectively). The TIR values of the electroplated CPBs are mainly determined by the leveler L; while the accelerator and suppressor have less impacts on the CPBs morphology. Specifically, at a low concentration of leveler (1 $mL \cdot L^{-1}$, as shown in Figs. 5a, 5f, and 5h), the obtained CPBs show a domed profile (the positive $TIR_{avg} \approx 20.3\%$). When the concentration of leveler was increased to 3 $ml \cdot L^{-1}$, the top surface of the copper pillar gradually changed to flat and the TIR_{avg} dramatically decreased to about -0.3% (as shown in Figs. 5b, 5d, and 5i). As the leveler concentration was further increased to 5 $mL \cdot L^{-1}$, the top surface of the electroplated CPBs changed to concave and the TIR_{avg} value decreased to about -5.6% (as shown in Figures. 5c, 5e, and 5g). In summary, the morphologies of the electroplated CPBs changed from the convex, through flat, and finally to concave with the increase of leveler concentration. A possible explanation is that the inhibition effect of the leveler is not enough at low concentration. Considering the diffusion boundary layer distribution in the feature, the Cu ions diffused to the center of the feature bottom should be faster than that diffused to the edge or corner[18], thus, leading to a domed shape (as shown in Figure 6a). As the

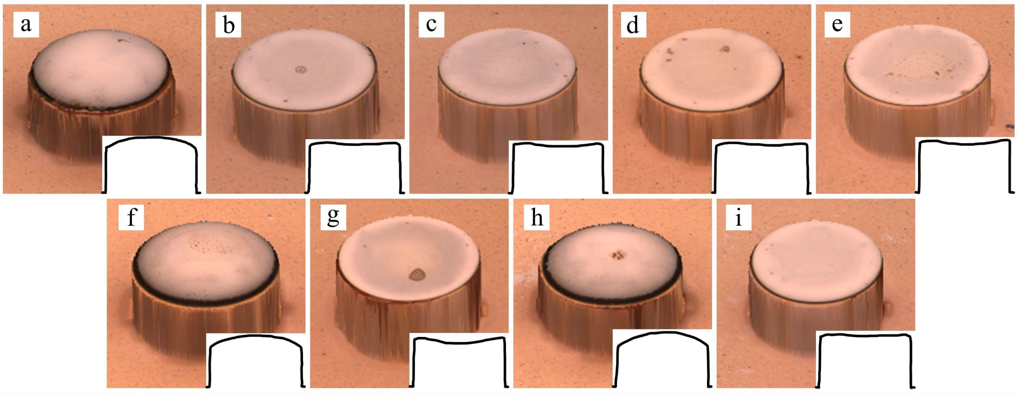


Figure 5 The CLSM images of the CPBs electroplated with different additive concentrations. (a) ~ (i) corresponding to the test numbers 1 ~ 9 in Table 1. (color on line)

Table 1 Orthogonal test results and range analysis

Test	B ($\mathrm{mL \cdot L^{-1}}$)	C ($\mathrm{mL \cdot L^{-1}}$)	L ($\mathrm{mL \cdot L^{-1}}$)	TIR_{avg}	WID
1	1	5	1	17.2%	15.8%
2	1	10	3	-0.8%	14.6%
3	1	20	5	-5.3%	16.7%
4	2	5	3	0.3%	18.2%
5	2	10	5	-4.2%	19.4%
6	2	20	1	21.9%	14.5%
7	4	5	5	-7.3%	19.8%
8	4	10	1	21.6%	13.7%
9	4	20	3	-0.5%	18.1%
			TIR_{avg}		
*k*1	3.7%	3.4%	20.3%		
*k*2	6.0%	5.5%	-0.3%		
*k*3	4.6%	5.4%	-5.6%		
R	2.3%	2.1%	25.9%		
			WID		
*k*1	15.7%	17.9%	14.7%		
*k*2	17.4%	15.9%	17.0%		
*k*3	17.2%	16.4%	18.6%		
R	1.6%	2.0%	4.0%		

leveler concentration increases, the diffused leveler concentration at the center of the feature bottom is slightly higher than that at the feature corner. This will inhibit the reduction of the copper ions at the bottom center and offset the benefits of higher concentration of Cu ions, finally reaching a nearly equal electrodeposition rate at the whole bottom surface to afford a flat deposited copper layer (as shown in Figure 6b). With a further increase of the leveler concentration, the additive at the bottom center should be much higher than that at the bottom corner, leading to a slower copper reduction rate at the bottom center than that at the bottom corner. Accordingly, a concave CPBs profile is produced (as shown in Figure 6c).

For the macroscopic uniformity, the WID values of the copper pillars electroplated with different concentrations of the accelerator, suppressor, and leveler on-

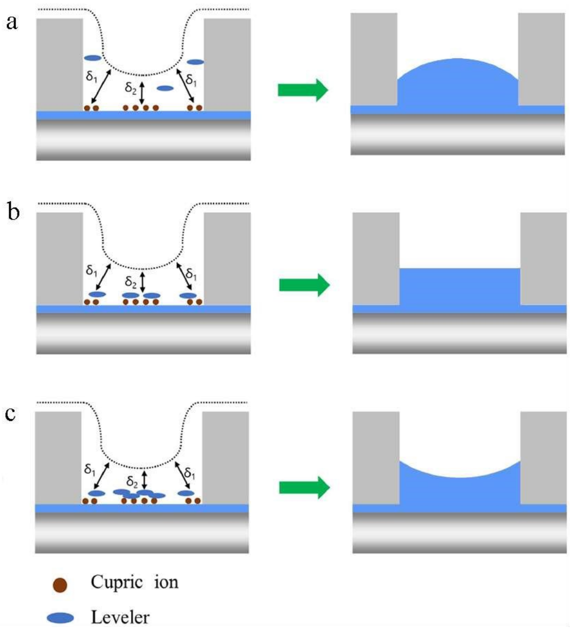


Figure 6 Schematic illustrations for the effect of the leveler concentration on CPBs profile. The dotted line represents the diffusion boundary layer distribution. (color on line)

ly slightly changed (as shown in Table 1, the *R* values for the accelerator, suppressor, and leveler are 1.6%, 2.0%, and 4.0%, respectively), which imply that the CPBs heights are not as susceptible to the additive's concentration as the top morphologies. According to Faraday's law, with the same electroplating time, the height of the electroplated CPBs is determined by the current density. The slightly changed WID values also indicate that the concentration of the additives has limiting effects on the current density distribution in the wafer sample.

3.2 Effect of Electrolyte Convection on Ele-Electrochemical Deposition of CPBs

The convection of the electrolyte is one of the most important factors affecting the electroplating of CPBs. To explore the influence of the electrolyte convection direction on the uniformity of the CPBs, three kinds of agitation methods were employed. The first one was a unidirectional convection from the sample bottom to top by air bubbles; the second agitation was a unidirectional convection from the left side of the sample to the right side by magnetic stirring; the third one was a reversible convection from side to side provided by a designed vertical rod, as illustrated in Figure 7.

The electroplating condition was the same as that described for the orthogonal experiments. 2 $mL\cdot L^{-1}$ of accelerator B, 10 $mL\cdot L^{-1}$ of suppressor C, and 3 $mL\cdot L^{-1}$ of leveler L were added into the electrolyte. The electroplating results are summarized in Table 2. For the first case with a unidirectional convection from bottom to top, the copper pillar obviously inclined in the *Y*-axis direction with a lower height at the top part. For the second sample, the copper pillar inclined in the *X*-axis direction with a lower height at the right part. However, in the third method with bi-directional agitation, no incline was found on the top of the electroplated CPBs. The effect of the electrolyte convection on the CPB's profile may arise from the adsorption of the additives. According to the convection-dependent adsorption behavior of additives[19-21], unidirectional agitation results in a non-uniform convection state of the electrolyte on the pillar surface, where the convection is stronger at the area opposite to the direction of fluid motion and weaker at the area parallel to the direction of fluid motion. This generally leads to a slower copper deposition rate at the top part (as shown in the case of Figure 7a) or the right part (as shown in the case of Figure 7b) of the copper pillar forming inclined profiles. Therefore, the convection uniformity of electroplating bath should be carefully controlled to improve the flatness of copper pillars.

On the contrary, the agitation method has less effect on the WID values of the CPBs. The influence of electrolyte convection on microscopic uniformity is greater than that on macroscopic uniformity, which is similar to the effects of organic additives.

3.3 Effect of Current Density on Electrochemical Deposition of CPBs

The current density is another important factor affecting the electroplating results. Generally, higher current density affords higher production efficiency, which is favorable in the actual industry manufacturing.

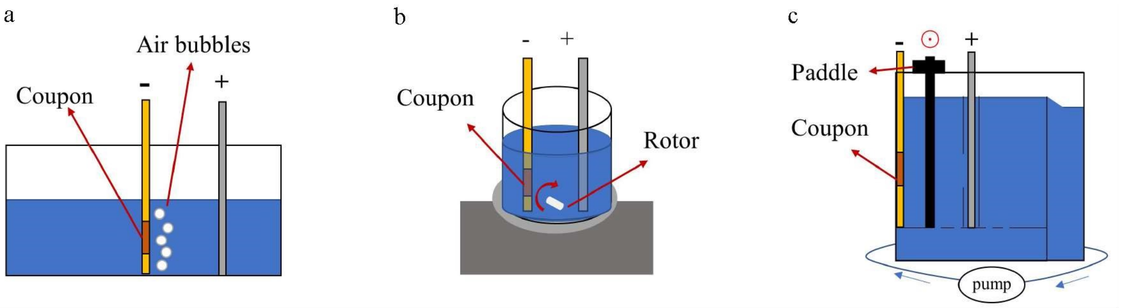
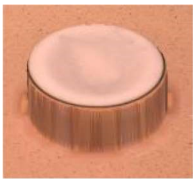
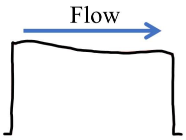
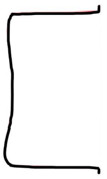
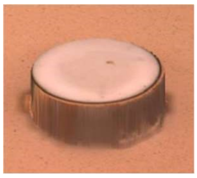
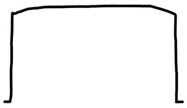
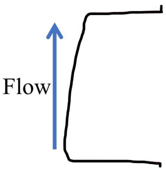
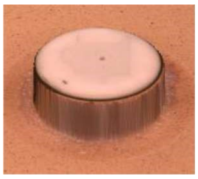
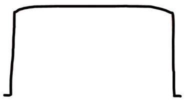
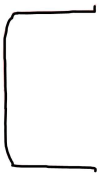


Figure 7 Electrolyte agitation methods. (a) air bubbles from bottom to top; (b) unidirectional magnetic stirring; (c) reversible convection provide by a paddle. (color on line)

Table 2 Effect of the electrolyte convection on the CPB's profiles

Flow condition	Appearance	X- axis profile	Y- axis profile	TIR$_{avg}$	WID
X- axis unidirectional flow				-10.2%	14.1%
Y- axis unidirectional flow				10.3%	12.1%
Reversible flow				2.6%	12.9%

In this section, the current densities of 10 $A\cdot dm^{-2}$, 13 $A\cdot dm^{-2}$ and 18 $A\cdot dm^{-2}$ were used for the electroplating of CPBs.

As shown in Figure 8, the TIR values for the current densities of 10 $A\cdot dm^{-2}$, 13 $A\cdot dm^{-2}$, and 18 $A\cdot dm^{-2}$ were -7.1%, 6.2%, and 12.2%, respectively. Obviously, the TIR values of the electroplated CPBs increased with the increase of current densities. Correspondingly, the top shape of the electroplated copper pillar changed from concave to convex. The possible reason is that with the increase of current density, more Cu ions would be consumed at the bottom center of the feature due to the closer diffusion boundary layer (as shown in Figure 6), which finally leads to a domed shape. While for the macroscopic uniformity, the height co-planarity of the CPBs is hardly affected by the current density. The WID results indicate that the change of the current density value also has minor influence on the current density distribution in the wafer sample.

3.4 Effect of Electroplating System on Ele-Electrochemical Deposition of CPBs

In addition to the small wafer coupons, whole 12-inch (300 mm) wafers have also been used to test the uniformity of the electroplated CPBs. Due to the design of the cathode clamp, the electroplating current travels from the wafer edge to the center, resulting in a higher current density at the edge than that at the center of the wafer. The uneven distribution of the current density on the 12-inch wafer generally leads to a significant difference in the heights of electroplated CPBs (higher at the edge and lower at the center).

In this study, two different electroplating systems, namely, a vertical plating equipment and a horizontal plating equipment were used to test the 12-inch wafer electroplating (as shown in Figure 3b and Figure 3c), and the results are summarized in Table 3.

For the vertical electroplating, the average height of the CPBs deposited in the area I is significantly higher than that in the areas II and III. In addition, the height of the copper pillar in the area II is also slightly higher than that in the area III. As mentioned above, this is because the current density in the wafer decreases from the edge to the center. While for the microscopic uniformity, the uneven distribution of current density has minor influence on the TIR value (all TIR values are smaller than 10%). However, due to the higher current density at the wafer edge, the CPBs at the wafer edge show a more domed shape

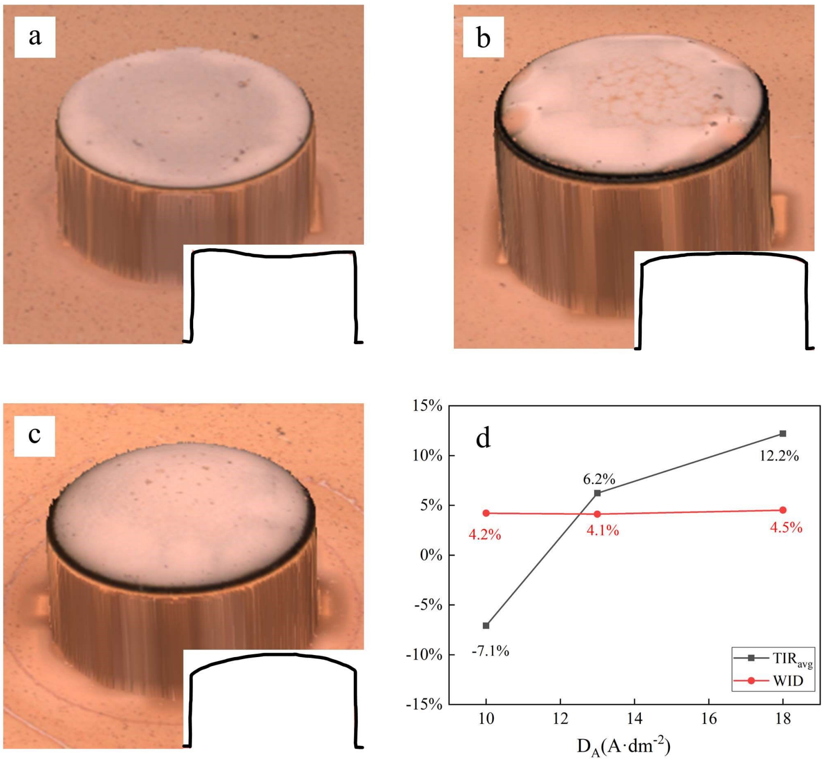
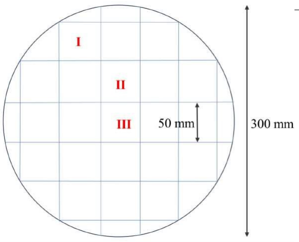


Figure 8 The uniformity of CPBs electroplated with different current densities. (a) 10 A·dm^{-2}; (b) 13 A·dm^{-2}; (c) 18 A·dm^{-2}; (d) a summary. (color on line)

Table 3 Effect of electroplating system on the uniformity of the CPBs

12-inch wafer schematic	Electroplating equipment	Area	Average height of CPBs (μm)	TIR$_{avg}$	WID
	Vertical Plating Equipment	I	36.4	6.2%	19.3%
		II	26.6	2.6%	5.7%
		III	24.3	3.9%	4.2%
	Horizontal Plating Equipment	I	38.5	3.8%	6.0%
		II	38.1	3.6%	2.7%
		III	37.7	3.5%	2.3%

(TIR ≈ 6.2% in the area I, which is larger than that in the area II or III). The result is in accordance with the discussions in the above section about the effect of the current density.

For the horizontal electroplating, benefiting from more sophisticated design (stronger mass transfer, unique designed paddle and chamber, the second anode accessory)[22], the system provides a much superior macro-uniformity for the electroplated CPBs. As shown in Table 3, the copper pillar heights in the areas I, II, and III are all around 38 μm. Due to the well-distributed current density on the whole wafer, the TIR values obtained from the copper pillars in different areas also are close (all about 3.5%).

The electroplating results indicate that the system design has a strong effect on the macroscopic uniformity. A more sophisticated design can greatly improve the macroscopic uniformity of electroplated

CPBs.

4 Conclusions

In this study, the effects of the additive's concentration, the bath convection, the current density, and the electroplating equipment on the uniformity of CPBs were investigated. It was found that the concentration of additive, electrolyte convection and current density mainly affected the shape profile of the CPBs (namely, the microscopic uniformity), but less affected the height of pillars. Instead, the system used in the electroplating had a strong influence on the height of copper pillars (i.e., the macroscopic uniformity). Specifically, for the additives, the leveler showed the dominant influence on the morphology of CPBs. With the increase of the leveler concentration, the profiles of the CPBs gradually changed from concave to convex. For the bath convection, it was found that unidirectional agitation generally led to inclined surface, thus, dramatically deteriorated the microscopic uniformity of CPBs. The current density also showed a significant impact on the profile of CPBs. Generally, higher current density results in a more domed shape. While for the electroplating system, the current density distribution on the wafers could be dramatically improved with sophisticated design, which is conducive to enhancing the macroscopic uniformity of CPBs.

Acknowledgements:

The authors thank the National Natural Science Foundation of China (Grant No. 22178071) and Guangzhou Basic and Applied Basic Research Foundation (Grant No. 202102021029) for financially supporting this research.

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高均匀性的铜柱凸块电镀

谭柏照[1#], 梁剑伦[1,2#], 赖子亮[1], 罗继业[1*]

(1. 广东工业大学轻工化工学院, 广东 广州 510006; 2. 季华实验室, 广东 佛山 528200)

摘要: 随着电子产品的小型化、多功能化和高性能化的发展,促使着 2D 集成封装向 2.5D 或 3D 集成封装发展。铜柱凸块电镀是晶圆级三维封装的关键基础技术之一。本文研究了铜柱凸块的电镀均匀性与添加剂浓度、镀液对流、电流密度和电镀设备之间的影响规律。研究结果表明, 添加剂浓度、镀液对流以及电流密度对单个铜柱凸块的平整度影响较大,而对铜柱凸块高度的均一性影响较小。相反,电镀设备对铜柱凸块的高度均一性的影响较大, 而对铜柱凸块的平整度影响较小。在三种有机添加剂中, 整平剂对铜柱凸块的平整度影响最大, 随着镀液中整平剂浓度的增加,铜柱凸块顶部形状由凸起、变为平整、再转变为凹陷。电镀液的单向对流会导致所沉积铜柱凸块形貌发生倾斜。 高的电流密度会导致凸顶的铜柱凸块形貌。精密设计的电镀设备可以提高晶圆上电流密度分布的均匀性, 继而大幅提高电镀铜柱凸块的共面性。本文的研究结果可为铜柱凸块的电镀优化提供指导。

关键词: 铜柱凸块; 电化学沉积; 均匀性; 添加剂; 整平剂