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Electrochemical Deposition of Copper Pillar Bumps with High **Uniformity**

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

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ao Tan^{1#}, Jian-Lun Liang¹ th *Coetrochem.* 2022, 28(7), 2213004 (1 of 10)

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Bai-Zhao Tan¹⁰, Jian-Lun Liang¹²⁰, Zi-Lia $\begin{array}{lll}\n&\text{\#} & \mathcal{R} & \mathcal{L} \\\n&\text{\#} & L & \text{\#} \\
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&\text{\textbf{Bai-Zhao Tan}^{1#}, Jian-Lun Liang} & \text{24-Liang Lai} & \text{35-Liaug Lai} \\\n&\text{\#mical Engineering and Light Industry, Guangdong University of Technology, } \\\n&\text{\#10006, P.R.$ (a) $\frac{1}{2}$ $\frac{1}{2}$

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, Ji-Ye Luo^{1*}

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uangdong 528200, P.R. China)

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Copper Pillar Bumps with High Uniformity

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 Electrochemical Deposition of
 Copper Pillar Bumps with High Uniformity

Bai-Zhao Tan^{is}, Jian-Lun Liang^{12s}, Zi-Liang Lai¹, Ji-Ye Luo¹ **Electrochemical Deposition of**
 Copper Pillar Bumps with High Uniformity
 $Bai-Zhao Taniⁿ$, Jian-Lun Liang^{1,28}, Zi-Liang Lai¹, Ji-Ye Luo¹

(*I. School of Chemical Engineering and Light Industry, Guanglong Universi* **Electrochemical Deposition of**
 Copper Pillar Bumps with High Uniformity

Bai-Zhao Tan¹⁸, Jian-Lun Liang¹²⁹, Zi-Liang Lai¹, Ji-Ye Luo¹

(*I. School of Chemical Engineering and Light Industry, Guangdong Universi* Bai-Zhao Tan¹⁹, Jian-Lun Liang¹³⁹, Zi-Liang Lai¹, Ji-Ye Luo¹

(*I. School of Chemical Engineering and Light Industry, Guangdong University of Technology,

<i>buanglion, Guangdong 510006, P.R. China; 2. Jihua Laborat* (*I. School of Chemical Engineering and Light Industry, Guangdong University of Technology,

Guangchou, Guangdong 510006, P.R. China; 2. Jihua Laboratory, Foshan, Guangdong 528200, P.R. China)
 Abstract: Electrochemical* Guangzhou, Guangdong 510006, P.R. China: 2. Jihua Laboratory, Foshan, Guangdong 528200, P.R. China)
 Abstract: Electrochemical deposition of copper pillar bunnes (CPBs) is one of the key technologies for the advanced pa **Abstract:** Hetrotehemical deposition of copper pillar bumps (CPHs) is one of the key technologies for the advanced packaging.
In this study, the effects of the additive concentration, the electrolyte convection, the curr **A bstract:** Electrochemical deposition of copper pillar bumps (CPBs) is one of the key technologies for the advanced prockaging

In this study, the effects of the additive concentration, the electrolyte convection, the c **Abstract:** Electrochemical deposition of cooper pillar bumps (CPBs) is one of the key technologies for the avenaecd packaging.
In this study, the cifest of the udditre connectation, the electrolythe convertion, the curre In this study, the effects of the additive concentration, the electrolyte convection, the current density, and the electrophaing system
on the uniformity of the CPBs have been systematically investigated. The results show ²⁴, Zi-Liang Lai¹, Ji-Ye Luo^{1*}
 titry, Guangdong University of Technology,
 ratory, Foshan, Guangdong 528200, P.R. China)
 a) is one of the key technologies for the advanced packaging.
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thoratory, Foshan, Guangdong 528200, P.R. China)

The polyimization of the key technologies for the advanced packaging.

The results showed that the profiles of the CPBs were *thoratory, Foshan, Guangdong 528200, P.R. China)*

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2DBs) is one of the key technologies for the advanced packaging.

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1 Introduction

al flip-chip packaging using controllable collapse

the stress; (2) the under bump metal

chip connection (C4) technology remains a series of

chiallenges for the high-density chip packaging with

ultra-fine pitch^{[2, 2}]

packaging[4-6].

towards 2.5D or 3D integrated packagingⁱⁱ. Tradition-
and bip-chip packaging using controllable collapse the stress (2) the under brunp metallurgy (UBM) fab-
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¹The fabrication of the CPHs, as illustrated the riging-
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1, mainly includes several steps: (1) the polyimi

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The continuous miniaturization, versatility, and

The fabrication of the CPBs, as illustrated in Figure

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The continuous miniaturization, versatility, and

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1, mainly included several steps: (1) the poly PBs) is one of the key technologies for the advanced packaging.

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Convection, the current density, and the electroplating system

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The results showed that the profiles of the CPBs were mainly a

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current density, while the heights of the CPBs were mainly af-
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The fabrication of the CPBs, as illustrated in Figure

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The fabrication of the CPBs, as illustrated in Figure 1, mainly includes several steps: (1) the polyimide (PI)

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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 pre-
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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 pre-
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pillar bump with a hemispherical solder cap is pre-

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protant role in the electrochemical deposition of the electroc ¹¹(*Lectrochem.*) 2022, 28(7), 2213004 (2 of 10)

pillar bump with a hemispherical solder cap is pre-

additives and the electroplating conditions play an im-

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port $\frac{4}{5}$ (*L Electrochem.*) 2022, 28(7), 2213004 (2 of 10)

pillar bump with a hemispherical solder cap is pre-

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pillar bump with a hemispherical solder cap is pre-

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pillar bump with a hemispherical solder cap is pre-

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ing step is the electrochemical deposition rockets, ± 0.22 , ± 0.23 , ± 0.22 , ± 0.23 , ± 0.22 , ± 0.23 , ± 0.21 , ± 0.22 , ± 0.21 , H(EF)(*J. Electrochem.*) 2022, 28(7), 2213004 (2 of 10)

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CPBs⁷⁷. To facilitate the following solder electrophal⁴ electrophality conditions, the uniformity of elect CPBsⁿ. To facilitate the following solder electroplat-
clectroplating conditions, the uniformity of electro-
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requir ing and the final flip chip packaging, the CPBs are plated CPBs could be achieved as low as sboot 5% at excellered to be very uniform. First, the top surface of a current density of 10 - 20 A -dm² fi-th- 12 , and 12

 $\# \# \# (J. Electron) \geq 222, 28(7), 2213004 (2 of 10)$
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additives and the electroplating conditions play an im-
portant role in the electrochemical deposition pro-
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additives and the electroplating conditions play an im-

portant role in the electrochemical deposition pro-

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electroplating conditio 2.2 **Experimental**

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ditives and the electroplating conditions play an im-
rtant role in the electrochemical deposition pro-
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additives and the electroplating conditions play an im-

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electroplating condi $1004(2 \text{ of } 10)$

and the electroplating conditions play an im-

in the electrochemical deposition pro-

industry, with the optimized additives and

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cal solder cap is pre-
additives and the electroplating conditions play an im-
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al deposition

2 Experimental

 $mg \cdot L^{-1}$ Cl. The organic additives used in the electron cess^{[3,11-14}]. In industry, with the optimized additives and
electroplating conditions, the uniformity of electro-
plated CPBs could be achieved as low as about 5% at
a current density of $10 \sim 20$ A·dm²^[7,11,12,22] electroplating conditions, the uniformity of electro-
plated CPBs could be achieved as low as about 5% at
a current density of $10 \sim 20 \text{ A} \cdot \text{dm}^2 \sqrt{1.11 \cdot 1.2 \cdot 221}$.
In this study, the effects of the additive's conc plated CPBs could be achieved as low as about 5% at
a current density of $10 \sim 20 \text{ A} \cdot \text{dm}^2$ $\frac{10,11,12,221}{10,11,12,22}$.
In this study, the effects of the additive's concentration, the electroplating system on the

 \pm (*E* \neq (*L Electrophem*,) 2022, 28(7), 2213004 (3 of 10)
the testing samples for the CPBs electroplating, on
and make sure the completely wetted features^{[40}. The
which 100 nm Ti and 300 nm Cu were pre-deposited el **in Figure 3** and Figure 3022, 28(7), 2213004 (3 of 10)

the testing samples for the CPBs electroplating, on and make sure the completely wetted features^{[40}]. The

which 100 nm Ti and 300 nm Cu were pre-deposited electr th $(2\frac{m}{2} + 1)$ and $(2\frac{m}{2} + 1)$ and $m = 0$ and **EVALUATION THE UNIT (EXECT ACCONSEDNATION** (16TD)

the testing samples for the CPIBs electroplating, on and make sure the completely wetted features¹⁹¹. The

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which 100 nm Ti and 300 nm Cu were pre-deposited

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as the UBM lay the testing samples for the CPBs electroplating, on and make sure the completely wetted features¹¹⁴. The which 100 nm Ti and 300 nm Cu were pre-deposited electroplating temperature was controlled at 2.5 °C, as the UBM la which 100 nm Ti and 300 nm Cu were pre-deposited electroplating temperature was controlled at 25 °C,

as the UBM layer. The diameter and depth of the fea-

tures on the walkers were 80 µm and 90 µm, respec-

was 50 mm for as the UBM layer. The diameter and depth of the fea-
nuclear and the distance between the catubode and the anote
tively (as shown in Figure 2e). was 50 mm for the Yamando-MS systems. The area
tively (as shown in Figure 2e) tures on the wafers were 80 µm and 50 µm, respec-
was 50 mm for the Yamamoto-MS systems. The area
nivoly (as shown in Figure 2c).
2.2 Electroplating Methods
density used in this study was 10 A -dm³ unless oth-
In this tively (as shown in Figure 2c). Traits of the cantood to the anode was 1:1. The current

2.2 Electrophating Methods

con wafer electroplating systems (Yamamoto-MS, electric and this study was 10 A·dm³ unless oth-

con wa 2.2 Electroplating Methods

In this study vas 10 A \cdot dm² unless oth-

In this study, a 4.1 and a 40-t-1 high-precision sili-

converts redictor and a 40-t-1 high-precision sili-

2.3 Characterizations of the Copper P In this study, a 4-1, and a 40-1, high-precision silicary the electromal compare incerted class content algo and lagaret corpors and plaqaret class (Yamamoto-MS, 2.23 Characterizations of the Copper Pillar lapan) were use con wafer electroplating systems (Yamannoto-MS, **2.3 Characterizations of the Copper Pillar**

Japan) were used for the small wafer coupons and

Japan) is empty and Figure 3a and Figure 3b, the two Yamannoto-MS

The profil samples were vertically placed in the tank and the (TIR) and within-die coplanarity (V
electrolyte convection was provided by an over-
to describe the profile flamess and
flow-mechanism and a paddle agitator. The distance

 $\# \ell \# (J. Electron) \ge 222, 28(7), 2213004 \text{ (3 of 10)}$
the testing samples for the CPBs electroplating, on and make sure the completely wetted features^[14]. The
which 100 nm Ti and 300 nm Cu were pre-deposited electroplating temp $\frac{dE}{dt}$ (*L Electrochem.*) 2022, 28(7), 2213004 (3 of 10)
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the testing samples for the CPBs electroplating, on

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which 100 nm Ti and 300 nm Cu were pre-deposited

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the testing samples for the CPBs electroplating, on
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as the UBM 28(7), 2213004 (3 of 10)
and make sure the completely wetted features^[14]. The
electroplating temperature was controlled at 25 °C,
and the distance between the cathode and the anode
was 50 mm for the Yamamoto-MS systems 28(7), 2213004 (3 of 10)
and make sure the completely wetted features^[14]. The
electroplating temperature was controlled at 25 °C,
and the distance between the cathode and the anode
was 50 mm for the Yamamoto-MS systems 28(7), 2213004 (3 of 10)
and make sure the completely wetted features^[14]. The
electroplating temperature was controlled at 25 °C,
and the distance between the cathode and the anode
was 50 mm for the Yamamoto-MS systems 28(7), 2213004 (3 of 10)
and make sure the completely wetted features^[14]. The
electroplating temperature was controlled at 25 °C,
and the distance between the cathode and the anode
was 50 mm for the Yamamoto-MS systems 28(7), 2213004 (3 of 10)

and make sure the completely wetted features^[14]. The

electroplating temperature was controlled at 25 °C,

and the distance between the cathode and the anode

was 50 mm for the Yamamoto-MS sys 28(7), 2213004 (3 of 10)

and make sure the completely wetted features^[14]. The

electroplating temperature was controlled at 25 °C,

and the distance between the cathode and the anode

was 50 mm for the Yamamoto-MS sys 28(7), 2213004 (3 of 10)

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electroplating temperature was controlled at 25 °C,

and the distance between the cathode and the anode

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and make sure the completely wetted features^[14]. The

electroplating temperature was controlled at 25 °C,

and the distance between the cathode and the anode

was 50 mm for the Yamamoto-MS sys (7), 2213004 (3 of 10)

I make sure the completely wetted features^[14]. The

ctroplating temperature was controlled at 25 °C,

1 the distance between the cathode and the anode

s 50 mm for the Yamamoto-MS systems. The a 28(7), 2213004 (3 of 10)

and make sure the completely wetted features^[14]. The

electroplating temperature was controlled at 25 °C,

and the distance between the cathode and the anode

was 50 mm for the Yamamoto-MS sys $\frac{28(7)}{213004}$ (3 of 10)
and make sure the completely wetted features^[14]. The
electroplating temperature was controlled at 25 °C,
and the distance between the cathode and the anode
was 50 mm for the Yamamoto-MS sys 电化学(*J. Electrochem.*) 2022, 28(7), 2213004 (3 of 10)

The electroplating, on and make sure the completely wetted features^[14]. The

Cu were pre-deposited electroplating temperature was controlled at 25 °C,

and depth

Bumps

Japan) were used for the small wafer coupons and

26 Haroh wafers cleared phosphorus-controlling respectively. As shown in Forpolities and the chights of the clear

in Figure 3 and Figure 3b, the two Yamannoto-MS CPBs wer 12-inch wafers electroplating, respectively. As shown The profiles and the heights of the electroplated

in Figure 3 and Figure 13b, the two Yamanoto-MS — CPBs were colleted by an Olympus OLS4100 con-

electroplating syste Figure 3a and Figure 3b, the two Yamamoto-MS CPBs were collected by an Olympus OLS4100 con-
etroplating systems were basically the same except focal laser scamping microscope (CLSM). To quanti-
the different volumes. Figu electroplating systems were basically the same except

for all laser seaming microscope (CLSM). To quani-

for the different volumes. Figure 7e is the schematic attively characterize the uniformity of the CPBs, the

diagr for the different volumes. Figure 7c is the schematic

diavely characterize the uniformity of the CPBs, the

diagram of the electroplating system. The testing

special parameters, such as the total indicated transact

dec diagram of the electroplating system. The testing

samples were verically placed in the tank and the colf. (TR) and within-die copharanty (WID) are proposed

electrolyte convection) was provided by an over-

to describe t cally placed in the tank and the (TIR) and within-dic coplanarity (WID) are proposed
ion was provided by an over-
to describe the profile flatness and the height copla-
antivy of the CPBs, respectively. As shown in Figure electrolyte convection was provided by an over-
to describe the profile flatness and the height copla-
mechanism and a paddle agitator. The distance mairly of the CPBs, respectively, As shown in Figure
between the calibde 28(7), 2213004 (3 of 10)

and make sure the completely wetted features^[14]. The

electroplating temperature was controlled at 25 °C,

and the distance between the cathode and the anode

was 50 mm for the Yamamoto-MS sys 28(7), 2213004 (3 of 10)

and make sure the completely wetted features^[14]. The

electroplating temperature was controlled at 25 °C,

and the distance between the cathode and the anode

was 50 mm for the Yamamoto-MS sys 28(7), 2213004 (3 of 10)

and make sure the completely wetted features^[14]. The

electroplating temperature was controlled at 25 °C,

and the distance between the cathode and the anode

was 50 mm for the Yamamoto-MS sys $2\pi(1)$, 2213004 (3 of 16)
and make sure the completely wetted features^[14]. The
electroplating temperature was controlled at 25 °C,
and the distance between the cathode and the anode
was 50 mm for the Yamamoto-MS sy and make sure the completely wetted features^[14]. The
electroplating temperature was controlled at 25 °C,
and the distance between the cathode and the anode
was 50 mm for the Yamamoto-MS systems. The area
ratio of the c electroplating temperature was controlled at 25 °C,
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 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 $10 \text{ A} \cdot \text{dm}^2$ unless otherwis 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 $10 \text{ A} \cdot \text{dm}^2$ unless oth-
erwise noted.
2.3 Characterizations of the Copper Pil ratio of the cathode to the anode was 1:1. The current
density used in this study was $10 \text{ A} \cdot \text{dm}^2$ unless otherwise noted.
 2.3 Characterizations of the Copper Pillar
 Bumps

The profiles and the heights of the density used in this study was $10 \text{ A} \cdot \text{dm}^2$ 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 OLS410 erwise noted.
 2.3 Characterizations of the Copper Pillar
 Bumps

The profiles and the heights of the electroplated

CPBs were collected by an Olympus OLS4100 con-

focal laser scanning microscope (CLSM). To quanti-

t **2.3 Characterizations of the Copper Pillar**
Bumps
**The profiles and the heights of the electroplated CPBs were collected by an Olympus OLS4100 con-
focal laser scanning microscope (CLSM). To quanti-
tatively characteri Bumps**
The profiles and the heights of the electroplated
CPBs were collected by an Olympus OLS4100 con-
focal laser scanning microscope (CLSM). To quanti-
tatively characterize the uniformity of the CPBs, the
special para The profiles and the heights of the electroplated
CPBs were collected by an Olympus OLS4100 con-
focal laser scanning microscope (CLSM). To quanti-
tatively characterize the uniformity of the CPBs, the
special parameters, CPBs were collected by an Olympus OLS4100 con-
CPBs were collected by an Olympus OLS4100 con-
focal laser scanning microscope (CLSM). To quanti-
tatively characterize the uniformity of the CPBs, the
special parameters, suc From the controllary and the flip chip controllary and Extra the flip control or the flip contristatively characterize the uniformity of the CPBs, the special parameters, such as the total indicated runout (TIR) and within tatively 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 o special parameters, such as the total indicated runout
(TIR) and within-die coplanarity (WID) are proposed
to describe the profile flatness and the height copla-
narity of the CPBs, respectively. As shown in Figure
4a, the orthomology and within-die coplanarity (WID) are proposed
secribe the profile flatness and the height copla-
y of the CPBs, respectively. As shown in Figure
he TIR value is determined by the height differ-
between the pill describe the profile flatness and the height coplarity of the CPBs, respectively. As shown in Figure, the TIR value is determined by the height difference between the pillar center and edge. The closer TIR value is to zer

Figure 11

Figure 11 $\frac{H_{\text{Euler}}}{H_{\text{Max}}} \times 100\%$

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

Figure 4 The uniformity characterization method of the copper pillar bumps. **Example 19 Fig. 2013**
 Example 4 The uniformity characterization method of the eoper pillar humps. (color on line)
 Example 4 The uniformity characterization method of the coper pillar humps. (color on line)

uniform Figure 4 The uniformity chromate and the copper pillar bands of the the order in policies and Halusty contents are the solutional test results are the solutional or the coperation of the electroplated CPBs were investigat TIR = $\frac{H_{\text{Couter}} - H_{\text{bdisp}}}{H_{\text{bMax}}} \times 100\%$
 Example 1.1
 Example TIR = $\frac{4.65 \text{ m}}{\text{H}_{\text{M}_{\text{R}_{\text{R}}}}}$ × 100%

H_{Max} The $\frac{4.65 \text{ m}}{\text{H}_{\text{M}_{\text{R}_{\text{R}}}}}$ × 100%

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

formity of the electroplat **Example 19**
 Example 19 Eigure 4 The uniformity characterization method of the copper pillar bumps, (color on line)

uniformity of the electroplated CPBs were investigat—

the obtained CPBs show a domed profile (the positive

dely the orthogon **uniformity** of the electroplated CPBs were investigat-

uniformity of the electroplated CPBs were investigat-

the obtained CPBs show a domed profile (the positive

d by the orthogonal analysis. A L₂ (3⁵) orthogonal uniformity of the electroplated CPBs were investigat——the obtained CPBs show a domed profile (the positive
ed by the orthogonal analysis. A L₄ (3) orthogonal TR_{*ng*} \approx 20.3%). When the concentration of leveler
table uniformity of the electroplated CPBs were investigat—

the obtained CPBs show a domed profile (the positive

do by the orthogonal analysis. A L₃ (3³) orthogonal TR_{wa} and

tube was chosen in the experiment. The TIR_w ed by the orthogonal analysis. A L₂ (3²) orthogonal TIR_{en} = 20.3%). When the concentration of leveler

fable was chosen in the experiment. The TIR_{ence} induction was increased to 3 ml -L¹, the top surface of the table was chosen in the experiment. The TIR_{nes} and

was increased to 3 ml·L¹, the

WID values of the CPBs are calculated and taken as

per pillar gradually changed t

the indexes, in which the TIR_{nes} is the average in the experiment. The TIR_{nog} and

was increased to 3 ml -L', the top surface of the cop-

nec CPBs are calculated and taken as

per pillar gradually changed to flat and the TIR_{nog} dra

which the TIR_{nog} is the avera $\begin{bmatrix} \n\text{min} \\ \n\text{min} \\ \n\end{bmatrix}$ $\times 100\%$

a domed profile (the positive

the concentration of leveler

⁻¹, the top surface of the cop-

ged to flat and the TIR_{svg} dra

bout -0.3% (as shown in Figs.

e leveler conce $\frac{H_{\text{Min}}}{2}$

WID = $\frac{1}{2}$ $\left(\frac{H_{\text{Max}} - H_{\text{Min}}}{H_{\text{Avg}}}\right) \times 100\%$

r bumps. (color on line)

the obtained CPBs show a domed profile (the positive

TIR_{avg} $\approx 20.3\%$). When the concentration of leveler

was inc Min

WID = $\frac{1}{2}$ $\left(\frac{H_{\text{Max}} - H_{\text{Min}}}{H_{\text{Avg}}}\right) \times 100\%$

r bumps. (color on line)

the obtained CPBs show a domed profile (the positive

TIR_{wg} $\approx 20.3\%$). When the concentration of leveler

was increased to $3 \$ **EVALUATE:**
 SET ALTERT THE THE THANGE THE ANCHE THE ANCE THE ANGLE THANGE THANGE THANGE THANGE THANGE THANGE 20.3%). When the concentration of leveler was increased to 3 ml·L¹, the top surface of the copper pillar gra For the CALCE 11

WID = $\frac{1}{2}$ $\left(\frac{H_{\text{Max}} - H_{\text{Min}}}{H_{\text{Avg}}}\right) \times 100\%$
 r bumps. (color on line)

the obtained CPBs show a domed profile (the positive

TIR_{aw} $\approx 20.3\%$). When the concentration of leveler

was x 100%

x 100%

med profile (the positive

concentration of leveler

e top surface of the cop-

to flat and the TIR_{avg} dra

-0.3% (as shown in Figs.

weler concentration was

⁻¹, the top surface of the

to concave and **EVALUATE:**

WID = $\frac{1}{2}$ $\left[\frac{H_{\text{Max}} - H_{\text{Min}}}{H_{\text{Avg}}}\right] \times 100\%$

The bumps. (color on line)

the obtained CPBs show a domed profile (the positive

TIR_{awg} $\approx 20.3\%$). When the concentration of leveler

was incre **VALUATE ASSOCUTE ASSOCUTE ASSOCUTE ASSOCUTE ASSOCUTE CONSTANT (SCALUTE ASSOCUTE)** The obtained CPBs show a domed profile (the positive $TIR_{\text{avg}} \approx 20.3\%$). When the concentration of leveler was increased to 3 ml·L⁻¹, WID = $\frac{1}{2} \left(\frac{H_{\text{Max}} - H_{\text{Min}}}{H_{\text{Avg}}} \right) \times 100\%$

The bumps. (color on line)

the obtained CPBs show a domed profile (the positive

TIR_{aws} $\approx 20.3\%$). When the concentration of leveler

was increased to 3 ml·L WID = $\frac{1}{2} \left[\frac{H_{\text{Max}} - H_{\text{Min}}}{H_{\text{Avg}}} \right] \times 100\%$

r bumps. (color on line)

the obtained CPBs show a domed profile (the positive

TIR_{awg} $\approx 20.3\%$). When the concentration of leveler

was increased to 3 ml·L⁺¹ WID = $\frac{1}{2}$ $\frac{1$ 2 $\left\lfloor \frac{\text{H}_{\text{Avg}}}{\text{H}_{\text{avg}}} \right\rfloor$

r bumps. (color on line)

the obtained CPBs show a domed profile (the positive

TIR_{sN} \approx 20.3%). When the concentration of leveler

was increased to 3 ml·L⁻¹, the top surface o r bumps. (color on line)

the obtained CPBs show a domed profile (the positive

TIR_{sng} $\approx 20.3\%$). When the concentration of leveler

was increased to 3 ml·L⁻¹, the top surface of the cop-

per pillar gradually chan roumps. (coor on me)

the obtained CPBs show a domed profile (the positive

TIR<sub><sup>ang</sub> $\approx 20.3\%$). When the concentration of leveler

was increased to 3 ml·L⁻¹, the top surface of the cop-

per pillar gradually changed</sub></sup> the obtained CPBs show a domed profile (the positive TIR_{sng} $\approx 20.3\%$). When the concentration of leveler was increased to 3 ml·L⁻¹, the top surface of the copper pillar gradually changed to flat and the TIR_{sng} dr the obtained CPBs show a domed profile (the positive

TIR_{wg} $\approx 20.3\%$). When the concentration of leveler

was increased to 3 ml·L⁻¹, the top surface of the cop-

per pillar gradually changed to flat and the TIR_{wg} TIR_{avg} \approx 20.3%). When the concentration of leveler
was increased to 3 ml·L⁻¹, the top surface of the cop-
per pillar gradually changed to flat and the TIR_{avg} dra
matically decreased to about -0.3% (as shown in Fi was increased to 3 ml·L⁻¹, the top surface of the cop-
per pillar gradually changed to flat and the TIR_{sng} dra
matically decreased to about -0.3% (as shown in Figs.
5b, 5d, and 5i). As the leveler concentration was
fu

			电化学(J. Electrochem.) 2022, 28(7), 2213004 (5 of 10)		
			Table 1 Orthogonal test results and range analysis		
Test	$B(mL \cdot L^{-1})$	$C(mL \cdot L^{-1})$	$L(mL \cdot L^{-1})$	TIR_{avg}	$\mathop{\rm WID}$
	$\mathbf{1}$	\mathfrak{H}	$\mathbf{1}$	17.2%	15.8%
2	$\mathbf{1}$	10	3	$-0.8%$	14.6%
3		20	5	-5.3%	16.7%
4	2	5	3	0.3%	18.2%
5	2	10	5 $\mathbf{1}$	-4.2% 21.9%	19.4% 14.5%
6	2 4	20 5	5	$-7.3%$	19.8%
8	4		1		
$\boldsymbol{9}$	$\overline{4}$	10 20	\mathfrak{Z}	21.6% -0.5%	13.7% 18.1%
			$\ensuremath{\mathsf{TIR}_{\mathrm{avg}}}$		
k ₁	3.7%	3.4%	20.3%		
$k2\,$	6.0%	5.5%	$-0.3%$		
$k\sqrt{3}$	4.6%	5.4%	$-5.6%$		
\boldsymbol{R}	2.3%	2.1%	25.9%		
			WID		
k ₁	15.7%	17.9%	14.7%		
$k2\,$	17.4%	15.9%	17.0%		
$k\sqrt{3}$	17.2%	16.4%	18.6%		
$\cal R$	1.6%	2.0%	4.0%		

6c).

 $\frac{16}{2}$ **Example.** (*L. Electrochem.*) 2022, 28(7), 2213004 (6 of 10)

19 slightly changed (as shown in Table 1, the *R* values clind in the *Y*-axis direction

for the accelerator, suppressor, and leveler are 1.6%, th

indicate that the concentration of the additives has

innting effects on the current density distribution in

tives^{[89,21}], unidirectional agitation
 3.2 Effect of Electrolyte Convection on Ele-

some convection of th the wafer sample.

Som convection state of the electrolyte on the pillar
 S2. Effect of Electrophet Convection on Ele
 State of Electrophetical Deposition of CPBs S2. Effect of Electrophetical Deposition of CPBs 3.2 Effect of Electrolyte Convection on Electrochemical Deposition of CPBs

The convection is stronge

The convection of child motion

The convection of the electrolyte is one of the the sea parallel to the direction of
 Electrochemical Deposition of CPBs opposite to the direction of fluid motion and weaker
convection of the electrolyte is one of the at the same parallel to the direction of fluid motion.
mportant factors affecting the e The convection of the electrolyte is one of the at the area parallel to the direction of fluid motion.

mors important factors affecting the electrolyting of This gronzellal leads to a slower copposition

cCPBs. To explor most important factors affecting the electroplating of This generally leads to a slower copper deposition

crowection direction and the top part a the top part and the top part (as shown in the case of Figure 7a)

convect CPBs. To explore the influence of the electrolyte rate at the top part (as shown in the case of Figure 7a)

convection direction on the uniformity of the CPBs, or the right part (as shown in the case of Figure 7a)

convec

described for the orthogonal experiments. $2 mL \cdot L^{-1}$ 3.3 Effect of Current Density on Electro $mL \cdot L^{-1}$ of leveler L were added into the electrolyte.

 \exists up \exists \exists # $\{\forall \exists x \in \mathbb{R} \mid \exists x \in \mathbb{R} \}$ # \exists 4.0%, and 4.0%, respectively), which imply that \exists the accelerator, suppressor, and leveler are 1.6%, the top part. For the second sample, the copper pillar 2.0%, and 4.0%, re 2.0%, and 4.0%, respectively), which imply that the $\frac{4!}{2!}$ (*L Electrochem.*) 2022, 28(7), 2213004 (6 of 10)

1y slightly changed (as shown in Table 1, the *R* values clined in the *Y*-axis direction with a lower height at

for the accelerator, suppressor, and level $\frac{4k}{2}(L\text{ }Electrochem})$ 2022, 28(7), 2213004 (6 of 10)

ly slightly changed (as shown in Table 1, the R values

clind in the Y-axis direction with a lower height at

for the accelerator, suppressor, and levelcar en 1.6%,

the **EVALUATION**
 EVALUATION EXALUAT EXALUAT TEM EXALUAT SO 2.2.2.2.2.2.3.004 (6.6.1.0)
 EVALUAT EXALUAT TEM EXALUAT SO EXALUAT SOMET AND THE SAME SOMET AND THE SAME SOMET ALT AND SOME THAT AND SOME THE SAME CPBS hei Height of the electroplated CPBs is determined by the acordication and the electroples of the electroplated the electroplated CPBs height of the accelerator, suppressor, and leveler are 1.6%, the top part. For the second **EVALUAT CONSTER 1998**
 EVALUAT CONSTER 1999
 EVALUAT CONSTER 1999
 EVALUAT CONSTER 1999
 EVALUAT CONSTER 1999
 EVALUAT CONS, and 4.0%, respectively), which imply that the inclined in the *Y*-axis direction with **EVACUAL Electrochem.**) 2022, 28(7), 2213004 (6 of 10)

19 Slightly changed (as shown in Table 1, the R values clined in the Y-axis direction with a lower height at

for the accelerator, suppressor, and leveler are 1.6%, **EVALUATION 19**
 EVALUATION 19
 EVALUATION 19
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 EVALUATION 19
 EVALUATION 19
 EVALUATION 19 THE COND CONTO THE CONDUCT TO THE CONDUCT ON THE CONDUCT ON A 400%, respectively, which imply that the **EVALUATION 19.12.2 Effective Convection**.) 2022, 28(7), 2213004 (6 of 10)

19. Slightly changed (as shown in Table 1, the R values climated in the Y-axis direction with a lower height at

2.0%, and 4.0%, respectively), w **ELECT (***Electrochemical*) 2022, 28(7), 2213004 (6 of 10)
 Electrochemical Deposition of CP (*Electrochemical***) 2022, 28(7), 2213004 (6 of 10)

and evolucing the vertex of CP (***Electrochemical***) and leveler are 1.6%, th** the electrolyte in the electrolyte in the electrolyte convection and the convertion of the electrolyte in the convertion of the convertion of the convertion of the electrolyte, where the convertion of the electrolyte in t most important factors affecting the electroplating of ly slightly changed (as shown in Table 1, the *R* values

clined in the Y-axis direction with a lower height at

for the accelerator, suppressor, and leveler are 1.6%,

the top part. For the second sample, the copper pill ly slightly changed (as shown in Table 1, the R values

cined in the Y-axis direction with a lower height at

for the accelerator, suppression, and level are 1.6%,

convention divergents are not as susceptible to the addi for the accelerator, suppressor, and leveler are 1.6%, the top part. For the second sample, the copper pillar
2.0%, and 4.9%, respectively), which imply that the inclined in the X-axis direction with a lower height rat. C 2.0%, and 4.0%, respectively), which imply that the inclined in the X-axis direction with a lower height at CPIs, heights are not as susceptible to the additive's the right part. However, in the third nethod with concentr CPBs heights are not as susceptible to the additive's

concentration as the top memphologies. According to bi-directional agitation, no inclinic was found on the

concentration is the top memphologies. According to the de concentration as the top morphologies. According to bi-directional agitation, no incline was found on the convection of the decrement of the signify Faraday's law, with the same electroplating time, the top of the electroplate CPBs. The effect of the electroplate CPBs is determined by the troley convection on the CPB's contract that the concentration of the additives height of the electroplated CPBs is determined by the trolyte convection on the CPB's profile may arise
current density. The slightly changed WID values also from the adsorption of the additives
indicate that the concentr current density. The slightly changed WID values also from the adsoption of the additives. According to the indicate tast the concentration of the additives has convection-dependent adsoption behavior of additional rod, a ning effects on the current density distribution in
 EVACACACACACACACACACACACACACACAC some form convercion stats of the electroplye on the pillar
 EXECTECT of Electroplye Convection on Ele-
 Exercetion of CPBs
 Exe EXECUTE: EXECUTE: $(28(7), 2213004 (6 of 10))$
clined 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 $(28(7), 2213004)$ (6 of 10)
clined 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 $(28(7), 2213004)$ (6 of 10)
clined 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, $(28(7), 2213004)$ (6 of 10)

clined 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. Howe $\frac{1}{28(7)}$, 2213004 (6 of 10)

clined 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. $(28(7), 2213004 (6 \text{ of } 10))$
clined 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, $(28(7), 2213004)$ (6 of 10)
clined 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 $(28(7), 2213004)$ (6 of 10)
clined 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 $(28(7), 2213004)$ (6 of 10)
clined 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 28(7), 2213004 (6 of 10)
clined 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 $2(7)$, 2213004 (6 of 10)
clined 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 28(7), 2213004 (6 of 10)

clined 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 $(28(7), 2213004 (6 \text{ of } 10))$

clined 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, $2.28(7)$, 2213004 (6 of 10)

clined 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. Howev , 28(7), 2213004 (6 of 10)

clined 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, **Example 12** is the top part of 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, clined 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 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 o 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 elec-
trolyte 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 elec-
trolyte convection on the CPB 's profile may arise
from the ads bi-directional agitation, no incline was found on the
top of the electroplated CPBs. The effect of the elec-
trolyte convection on the CPB 's profile may arise
from the adsorption of the additives. According to the
convec of the electroplated CPBs. The effect of the elec-
lyte convection on the CPB's profile may arise
m the adsorption of the additives. According to the
avection-dependent adsorption behavior of addi-
es^[19-21], unidirectio trolyte convection on the CPB's profile may arise
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convection-dependent adsorption behavior of addi-
tives^{[19-21}], unidirectional agitation results in a non-uni-
form from the adsorption of the additives. According to the
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tives^[19-21], unidirectional agitation results in a non-uni-
form convection state of the electrolyte on the pilla convection-dependent adsorption behavior of addi-
tives^[1921], unidirectional agitation results in a non-uni-
form convection state of the electrolyte on the pillar
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a tives^[1921], unidirectional agitation results in a non-uni-
form convection state of the electrolyte on the pillar
surface, where the convection is stronger at the area
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the top part (as shown in the posite to the direction of fluid motion and weaker
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et at the top part (as shown in the case of Figure 7a)
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of th This generally leads to a slower copper deposition
rate at the top part (as shown in the case of Figure 7a)
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of the copper pillar forming inclined profiles. There-
fore 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. There-
fore, the convection uniformity of electroplating bath
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Table 1, the R values clined in the Y-axis direction with a lower height at

and leveler are 1.6%, the top part. For the second sample, the copper pillar

which impl

		电化学(J. Electrochem.) 2022, 28(7), 2213004 (7 of 10)			
		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		Flow		$-10.2%$	14.1%
Y - axis unidirectional flow			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 electroplat- ing of CPBs. 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. Obvious- ly, the TIR values of the electroplated CPBs in- creased with the increase of current densities. Corre- spondingly, 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 cen- ter of the feature due to the closer diffusion boundary layer (as shown in Figure 6), which finally leads to a	As shown in Figure 8, the TIR values for the current		center).	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 electro- plated CPBs (higher at the edge and lower at the 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	

Reversible flow

In this section, the current densities of 10 A·dm², 13 design of the cathode clamp, the electroplating current

A·dm² and 18 A·dm² were used for the electroplat-

and the wafer edge to the enter, re Reversible flow

In this section, the current densities of 10 A-dm², 13

A-dm² adesgon of the carbode clamp, the electroplating current

A-dm² and 18 A-dm² were used for the electroplat-

Travels from the wafer ed Exercisive lines
 Exercisive lines
 Exercisive and B A chari² were used for the electroplat-

That in an infinite of CPBs.

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A·dm² ware used for the clectroplate travels from the wafer edge to the center, resulting in

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A-dm² and 18 A-dm² were used for the electroplat-
travels from the wafer edge to the center, resulting i In this section, the current densities of 10 A -dm², 13 design of the cathode clamp, the clectroplating current
A -dm² and 18 A -dm² are used for the electroplat-
travels from the wafer edge to the enert, resulting A -dm⁻ and 18 A -dm⁻ were used for the electroplat-

ravels from the wafer edge to the center, resulting in

a higher current density at the edge than that at the

As shown in Figure 8, the TIR values for the current ing of CPBs.

a higher current density at the colge than that at the

As shown in Figure 8, the TIR values for the current of the wafer. The uneven distribution of the

densities of 10 A -dm², 13 A -dm² current densit As shown in Figure 8, the TIR values for the current center of the wafer. The undensities of 10 A \cdot dm², 31 A \cdot dm², and 18 A \cdot dm² current density on the 12-in were -7.1%, 6.2%, and 12.2%, respectively. Obvio densities of 10 A^{-t}dm², 13 A^{-dm2}, and 18 A^{-dm2} current density on the 12-inch wafer generally leads
were -7.1%, 6.2%, and 12.2%, respectively. Obvious-
to a significant difference in the heights of electroplates
-7.1%, 6.2%, and 12.2%, respectively. Obvious-

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EIR values of the electroplated CPBs in-

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pillar changed from concave to convex. The pos spondingly, the top shape of the electroplated copper
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design of the cathode clamp, the electroplating current
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In this study, two different electroplating systems,
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In this study, two different electroplating systems,

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In this study, two different electroplating systems,

namely, a vertical plating equipment and a horizontal

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electroplating (as shown in Figure 3b and Figure In this study, two different electroplating systems,
namely, a vertical plating equipment and a horizontal
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CPBs.

4 Conclusions

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In this study, the effects of the additive

In this study, the effects of th **EVALUATE 1999**

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CPBs.

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packaging (ICEPT-HDP), USA: IEEE, 2011.

In this study, the effects of the additive's

[3] H density, and the electroplating equipment on the $\text{ECEP}(L \text{Electrochem.}) 2022, 28(7), 2213004 (9 of 10) \newline \text{CPBs.} \newline \text{COPCLUSIONS} \newline \text{and} \newline \text{In this study, the effects of the additive's
concentration, the bath convection, the current
concentration, the both convection, the current
density, and the electroplating equipment on the
uniformity of CPBs were investigated. It was found to find a high density packaging (CEPT-HDP), USA: IEEE, 2011. \newline \text{the concentration of additive, electrolyte} \newline \text{and high density packaging (CEPT-HDP), USA: IEEE, 2012. \newline \text{the concentration of additive, electrolyte} \newline \text{$ **EXECTE 1998**
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density, and In this study, the effects of the additive's

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IS Wang X J. Zlusng CV. Copper pi uniformity), but less affected the height of pillars. (CSTIC), USA: IEEE, 2017.

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strong influence on the h Instead, the system used in the electroplating had a

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the macroscopic uniformity). Specifically, for the p strong influence on the height of copper pillars (i.e., study on advanced electric-package
the macroscopic uniformity). Specifically, for the Technology, 2017, 38(2: 99-101.
dadditives, the leveler showed the dominant inf The authors thank the National Natural Science Eveler concentration, the profiles of the CPBs

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bath convec gradually changed from concave to convex. For the

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gatation generally led to inclined surface, thus, $\frac{1}{2}$ Melvin C, Roelis D. Newt-generation or
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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