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Discussion on Pulse Electroplating of Ultra-High Aspect Ratio Printed Circuit Boards and Its Process Parameters

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ABSTRACT

This paper presents a study on pulse electroplating and its parameter control methods for ultra-high aspect ratio applications. To address the plating challenges of ultra-thick micro-hole structures with an aspect ratio ⩾ 30:1, an optimized process based on pulse electroplating is proposed. By establishing an electric field distribution model and ion transport kinetic equations, the effects of pulse parameters (frequency, duty cycle, peak current density) on coating uniformity, deep plating capability, and hole wall quality are systematically investigated. Experimental results indicate that when the pulse frequency is set to 1000 Hz, the duty cycle to 30%, and the peak current density to 4-6 A/dm², the deep plating capability (TP value) for micro-holes with an aspect ratio of 30:1 reaches 80.4%, with a coating porosity of <0.5%. The findings provide a theoretical basis and process guidance for electroplating structures with ultra-high aspect ratios.

KEYWORDS

Ultra-high aspect ratio; Pulse electroplating; Pulse parameters

1 Introduction

1.1 Research background

With the rapid development of fields such as 5G communication and new energy, devices like high-density packaging substrates and lithium electrode tabs have placed higher demands on micro-hole electroplating. Traditional direct current (DC) electroplating tends to exhibit issues such as the "dog bone" effect at aspect ratios greater than 12:1 (where the copper layer in the middle of the hole is too thin while the ends are excessively thick) and stress concentration in the plating layer, leading to a decline in device reliability. For example, in micro-hole structures with an aspect ratio of 30:1, the deep plating capability (TP value) of traditional processes is typically below 60%, with porosity exceeding 1%.

1.2 Advantages of pulse electroplating

Pulse electroplating can significantly improve plating quality by periodically interrupting the current:

Reducing concentration polarization: Periodic current interruption accelerates the renewal rate of the diffusion layer, alleviating the imbalance of ion concentration gradients within the holes.

Suppressing hydrogen gas evolution: This reduces the mechanical impact of bubble retention on the plating layer.

Improving metal ion mass transfer: By adjusting the forward and reverse currents in the pulse, the mass transfer kinetics within the holes can be optimized.

2 Theoretical foundation2.1 Mathematical model of pulse electroplating

A three-dimensional transient electrochemical model is established to describe the relationship between metal ion concentration distribution and current density during the electroplating process:

$$\frac{\partial c}{\partial t} = Dabla^2 C - \upsilon \cdot ablaC + \frac{M}{nF}\left(\frac{i(t)}{\delta}\right)$$

Where:

C: Metal ion concentration

D: Diffusion coefficient

v: Solution flow velocity

i(t): Pulse current density

δ: Diffusion layer thickness

2.2 Mechanism of key parameter influence

Table 1

Parameter	Influence Dimension	Mechanism of Action
Frequency (f)	Mass Transfer Kinetics	f↑ → Diffusion layer renewal rate ↑, accelerating ion replenishment, but excessively high frequency may lead to insufficient mass transfer;
Duty Cycle (D)	Metal Deposition Amount	D↑ → Effective electroplating time ↑, but excessively high D increases the risk of bubble entrapment;
Peak Current Density (I)	Polarization Degree and Grain Refinement	I↑ → Overpotential ↑, promoting grain refinement, but excessively high values may increase the brittleness of the coating.

3 Experimental methods

3.1 Process flow

A standard process flow for high-density packaged substrates is adopted, with key steps including:

Inner layer processing: Material Cutting → Lamination (L2/L3-L92/L93) → Inner Layer Circuit → Acid Etching → AOI Inspection;

Outer layer processing: Pressing → Copper Reduction → Drilling (Hole Diameter 0.25mm, Aspect Ratio 30:1) → Copper Plating → Pulse Electroplating → Resin Plugging → Copper Plating → Outer Layer Circuit → Electroless Nickel Gold → Forming Inspection.

3.2 Test samples

Substrate: BT resin substrate, thickness 7.5mm, hole diameter 0.25mm;

Plating solution system: Sulfuric Acid (200g/L) + Copper Sulfate (75g/L) + Cl^- (60ppm) + Additive A (1.8ml/L) + Carrier (33ml/L).

3.3 Process parameter matrix

Table 2

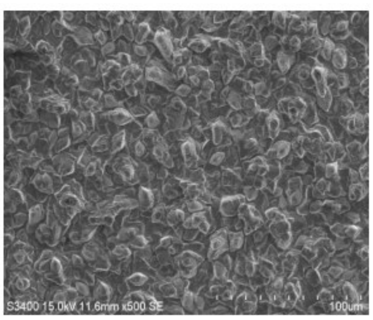
Group	Frequency (Hz)	Duty Cycle (%)	Peak Current (A/dm²)
A	500	20	3
B	1000	30	4.5
C	2000	40	6

3.4 Characterization methods

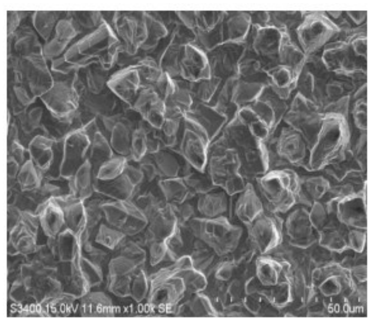
Hole filling integrity: Observed through SEM to analyze the distribution of the coating on the hole walls (Figures a-c);

Coating quality: SEM + EDS surface scanning (500X/1000X) to analyze element distribution and porosity;

Performance Testing: TP value (deep plating capability), porosity, coating ductility (three-point bending test).



SEM+EDS 面扫描（500X）



SEM+EDS 面扫描（1000X）

Figure 1

4 Results and discussion

4.1 Parameter optimization trends

4.1.1 Frequency effect

500Hz: Severe over-plating at the hole entrance (Figure a), TP value is only 62%;

1000Hz: Best hole filling uniformity (Figure b), TP value reaches 80.4%;

>1500Hz: Insufficient mass transfer leads to interruption in hole filling (Figure c).

4.1.2 Duty cycle influence

D < 25%: Insufficient deposition rate, hole center is not fully filled (Figure a);
D = 30%: Deep plating capability reaches its peak (Figure b);
D > 40%: Increased bubble entrapment within the holes, porosity rises to 0.8% (Figure c).

4.1.3 Critical current density

The experiment found that the critical current density $I_c \approx 4.5\ A/dm^2$
$I < I_c$: Hole filling speed is limited;
$I > I_c$: Coating brittleness significantly increases (Figure 1 shows better coating ductility than Figure 2).

4.2 Special challenges and solutions for ultra-thick structures

4.2.1 Imbalance of ion concentration gradient

When the aspect ratio is >20:1, the Cu^{2+} concentration at the bottom of the hole is insufficient. By introducing a pulsed reverse current compensation ($-0.5A/dm^2 \times 10ms$), with a forward-to-reverse current ratio set at 1:-3, the thickness of the coating at the bottom is significantly improved.

4.2.2 Joule heating accumulation effect

Using an intermittent pulsed mode (working for 5s / pausing for 2s):
Reduces Joule heating accumulation, preventing coating burn;
Improves ion concentration distribution, reducing bubble entrapment.

5 Process optimization plan

5.1 Segmented pulse strategy

A three-stage pulsed plating process is designed:
Pre-plating stage: $1.5\ A/dm^2$ (Duty Cycle 50%), activating the hole walls;
Main plating stage: $2.5\ A/dm^2$ (Duty Cycle 30%), for rapid filling;
Finishing stage: $1.0\ A/dm^2$ (Duty Cycle 70%), for surface leveling.

5.2 Development of additive synergy

A composite additive system is developed:
Carrier agent (Polyethylene Glycol): Improves uniform plating capability;
Leveling agent (Alkynol Derivatives): Inhibits dendrite growth;
Accelerator (Thiourea Compounds): Enhances deep plating capability.

6 Conclusion and outlook

Future research can further explore the effects of multi-physical field coupling (such as ultrasonic-assisted pulsed plating) on ultra-high aspect ratio micro-hole plating, combined with machine learning to optimize process parameters. Additionally, the development of new environmentally friendly plating solutions and low-stress coating technologies will promote the wider application of this process in fields such as aerospace and semiconductor packaging.

About the Author

Xiangshu Ji, Male, born in 1982 in Dongfang, Hainan. Graduated from China University of Geosciences with a bachelor's degree. Senior Engineer with years of experience in PCB product development, technical research, and materials research. Has published over 10 academic papers on PCBs. Currently serves as the Deputy General Manager of Zhejiang Wanzheng Electronic Technology Co., Ltd., primarily engaged in research on military aviation circuit board materials, PCB product development, and technical support.

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