High-Throw DC Acid Copper Formulation for Vertical Continuous Electroplating Processes
适用于垂直连续电镀工艺的高分散能力直流酸性镀铜溶液配方

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Abstract
摘要

The electronics industry has grown immensely over the last few decades owing to the rapid growth of consumer electronics in the modern world. New formulations are essential to fit the needs of manufacturing printed circuit boards and semiconductors. Copper electrolytes for high throwing power applications with high thermal reliability and high throughput are becoming extremely important for manufacturing high aspect ratio circuit boards.

现代消费类电子产品发展速度极快，电子行业在过去的几十年里突飞猛进。新的电镀铜配方是制造印制电路板和半导体的必然需求。具有高分散能力，出色的热可靠性以及能进一步提高产量的酸铜电镀液，在高纵横比线路板生产过程中变得极为重要。

Here we discuss innovative DC copper metallization formulations for hoist lines and vertical continuous plating (VCP) applications with high thermal reliability and throughput for high aspect ratio PCB manufacturing. The formula has a wide range of operation for current density. Most importantly, plating at high current density using this DC high throw acid copper process offers high throughput, excellent thermal reliability, and improved properties for present-day PCB manufacturing. The operating CD range is 10–30 ASF where micro distribution of ≥ 85% for AR 8:1 is achievable. This formulation offers bright ductile deposits where plating parameters are optimized for improved micro-distribution and the properties of the plated copper deposit such as tensile strength and elongation. The thermal reliability and properties of the deposits were examined at different bath ages. Measured properties are: Elongation ≥ 18% and tensile strength ≥ 40,000 psi. All the additives can be easily controlled by cyclic voltammetry stripping (CVS) analysis.

本文我们会讨论可以同时用于传统垂直生产线和垂直连续电镀线（VCP）应用的创新性直流电镀铜金属化配方，用于制造高纵横比 PCB，能保证极高的热可靠性并能进一步提高产量。该产品配方有着非常宽泛的电流密度操作窗口。最重要的是，对于如今的 PCB 制造，使用此高分散能力直流电硫酸铜溶液进行生产可以应用较高电流密度，实现较高的产量并保证出色的热可靠性，进一步提升产品的性能。对于此配方产品来说，在电流密度 10–30ASF 范围内，纵深比 AR 为 8:1 的通孔深镀能力可以达到≥85%。同时，这一配方产品可以得到具有光泽性，并有很好的延展性的沉积铜。通过对其电镀参数进行优化，可以让镀铜沉积物的微观分布得到改善，从而进一步提升抗拉强度和延伸率等性能。通过检测不同使用寿命下电镀液获得的镀铜层物理性能，我们能得到优越的镀层物理性能指标：延伸率≥18%，抗拉强度≥40000 磅/平方英寸。所有的添加剂组分都可以通过循环伏安法测量仪器（CVS）分析并进行控制。

Introduction
简介

Copper has a high electrical conductivity and is relatively inexpensive compared to other high conductive metals such as silver. Therefore, the use of copper in the mass production of PCBs and semiconductors grew exponentially in the last few decades[1]. With today’s complex circuit board designs an even deposition with specific physical properties is necessary to meet the standards. Especially with high aspect ratios, through-hole plating to obtain desired plating distribution is much more challenging. During the quality control inspection, a board can be rejected if there is insufficient copper on the center walls of the through-holes. Moreover, plated copper should meet the minimum requirements of physical properties such as tensile strength and elongation (T&E) to withstand the high temperature applications[2].

铜具有较强的导电性，而且与其他像银这样的高导电性能的金属相比，成本要低一些。因此，在过去的几十年中，PCB 和半导体的大规模生产对铜材料的使用量呈指数增长[1]。随着线路板设计，生产的日益复

杂，对镀铜层沉积的均匀性和物理性能有了更高的要求。尤其对于较高纵横比通孔的电镀，在整个通孔获得均匀的镀层分布是一个很大的挑战。在 PCB 厂的质量检验中，如果通孔的中心孔壁镀铜厚度达不到标准，那么这块电路板会被客户拒收。另外，电镀铜层应该满足 PCB 行业或者客户对于产品物理特性的最低要求，例如抗拉强度和延伸率（T&E），这样才能满足高温环境下的应用[2]。

Sulfuric acid copper baths are heavily used in the PCB industry due to their low maintenance cost as compared to other acids like MSA (methane sulfonic acid). Typical sulfuric acid copper baths contain copper sulfate, sulfuric acid, chloride ions, and organic additives. These additives play a crucial role in controlling the deposit distribution as well as the properties. To meet specific objectives of a plating process these additives should be monitored and controlled properly. The additives work in combination and when controlled within a given range improve thickness distribution, mass transfer, eliminate nodule formation and can fill blind vias. Namely these additives are levelers, brighteners, and suppressors. The leveler is a mild suppressor that adsorbs onto specific locations such as corners and peaks of base materials[2].

PCB 行业中大量使用了硫酸铜镀液，这是因为和其他酸性溶液比起来（比如 MSA（甲磺酸）），它的维护成本要低一些。一般的硫酸铜镀液含有硫酸铜、硫酸、氯离子和有机添加剂。这些添加剂在控制沉积物分布和性能上发挥了重要作用。为了满足电镀过程的特定目标，添加剂的浓度需要得到合理的监控。在特定控制范围内，各添加剂协同作用，可以改善厚度分布、物质迁移，消除电镀颗粒结节，并填充盲孔。也就是说，这些添加剂能起到整平、增亮和抑制的作用。整平剂是一种较弱的抑制剂，可以吸附到特定位置上，比如基材的微观谷处或峰处[2]。

In the presence of a micro profile the diffusion layer tends to be thin at the peaks and thick at the valleys. In this case, if plated without a leveler the micro profile will be exaggerated. On the other hand, if a leveler is present the plating on the peaks will be suppressed and the micro profile will be diminished. Brightener is also called an anti-suppressor and as the name implies it reduces the suppression. Most importantly, it also acts as a grain refiner to deposit copper with a fine grain structure in random orientation[4]. Therefore, brightener has the most influence on final structure and physical properties of the deposit such as tensile strength and elongation.

在微观轮廓面前，扩散层会在基材峰处趋于变薄、在谷处趋于变厚。这种情况下，如果在电镀时不使用整平添加剂，微观轮廓会被进一步扩大。另一方面，如果使用了整平添加剂，那么峰处的电镀就会被抑制，微观轮廓就会减弱。光亮剂也叫做抗抑制剂，它能减少抑制作用。最重要的是，它同时也是一种晶粒细化剂，可以帮助沉积得到不具有方向性[4]且具有完美晶体结构的铜层。因此，光亮剂对沉积物的最终结构和物理性能（例如抗拉强度和延伸率）有着最为重要的影响。

The suppressor works in the presence of chloride ion to adsorb onto the cathode and increase the effective thickness of the diffusion layer[3]. Consequently, the plating current increases and the deposit becomes more uniform and a densely packed copper deposit can be obtained without burning. This modified diffusion layer improves the distribution of the deposit especially in high throw applications. Owing to the growth of high aspect ratio circuit board manufacture, the demand for high throw acid copper electrolytes has increased dramatically over the past few decades. Especially DC copper plating for high aspect ratio electroplating is extremely desirable due to simplicity of the process and inexpensive equipment requirements[1, 2].

抑制剂在氯离子的作用下吸附在阴极上，增加了扩散层的有效厚度[3]。因此，随着电镀电流升高，沉积层变得更加均匀，并且可以在不烧焦的情况下得到更紧密的沉积铜层。这一改良过的扩散层可以帮助改善镀层的分布，尤其是在高分散能力应用过程中。随着具有高纵横比通孔的线路板制造的不断发展，在过去的几十年中，市场对具有高深镀能力的酸性电镀铜产品的需求急剧攀升。尤其是对高纵横比通孔直流电镀通产品的需求极大，因为这种工艺相对简单，且所需设备成本不高[1, 2]。

In this work, we present an innovative DC high throw acid copper electroplating system with high thermal reliability and even copper metallization in high aspect ratio PCBs. This system also allows the plating to be done at high current density without surface imperfections. The allowable CD ranges from 10–30 ASF and the micro distribution(MD) measured is ≥ 85% for the AR 8:1.

在本文中，我们会展示一种革新性直流高深镀能力酸性电镀铜系统，可以在具有高纵横比的 PCB 上得到较高的深镀能力同时具有优异的热可靠性。这一系统可以在高电流密度下进行电镀，并且没有表面外观问题（颗粒，烧焦等）。电流密度 CD 范围是 10–30ASF，纵横比 AR 8:1 的情况下测量到的微观分布（MD）是≥85%。

Numerous tests were performed to obtain high MD at various current densities with enhanced mechanical properties of the plated metal such as tensile strength and elongation. Thermal reliability and structure of plated copper was also studied.

为了获得较高的深镀能力、增强电镀金属的机械性能（例如抗拉强度和延伸率），我们在不同电流密度下进行了多次测试。同时还研究了电镀铜的热可靠性和结构。

Conditions and Bath Components

条件和电镀液成分

Table 1 shows the operating conditions and optimum additive levels. Typically, the high throw bath has high acid to achieve higher conductivity inside the holes.

表 1 显示了操作条件和最佳的添加剂含量。一般情况下，镀液的酸性越强高分散能力越高，引文镀液在孔内的导电性更强。

Table 1: Bath components.

表 1：镀液成分

Parameter	Range	Optimum
Anode Current Density	1.0 – 3.5 ASD (10-32 ASF)	2.2 ASD (20 ASF)
Temperature	20 – 27°C (68 - 80°F)	23°C (73°F)
Material A Wetter	3 – 8 mL/L	5 mL/L
Material A Brightener	0.7 – 1.3 mL/L	1 mL/L
Material A Leveler	7 – 13 mL/L	10 mL/L
Copper Sulfate ($CuSO_4 \cdot 5\ H_2O$)	60 – 80 g/L	70 g/L
Free Sulfuric Acid 66°Be Electronic Grade	190 – 210 g/L	200 g/L
Chloride Ion (Cl^-)	50 – 70 ppm	60 ppm

参数	范围	最佳数值
阳极电流密度	1.0–3.5ASD (10-32ASF)	2.2 ASD (20 ASF)
温度	20℃–27 ℃(68-80 °F)	23℃ (73°F)
材料 A 润湿剂	3 – 8 mL/L	5 mL/L
材料 A 光亮剂	0.7 – 1.3 mL/L	1 mL/L
材料 A 整平剂	7 – 13 mL/L	10 mL/L

参数	范围	最佳数值
硫酸铜($CuSO_4\cdot 5H_2O$)	60 – 80 g/L	70g/L
游离 Be 电子级 66° 硫酸溶液	190 – 210 g/L	200 g/L
氯离子（Cl^-）	50 – 70 ppm	60 ppm

Test Vehicles

测试板

Various test panels with different thicknesses and hole diameters were used covering a range of aspect ratios. The test vehicles used in the process evaluation were 1.6 mm, 2.4 mm and 3.2 mm thick boards and the through-hole diameters were 0.2 mm, 0.25 mm and 0.35 mm. The through-hole aspect ratio (AR) varied from 4.6:1 to 16:1. All geometries for each test board thickness were plated at the same time in the same tank and throw power was later calculated by using cross section analysis.

选用了不同厚度，不同通孔孔径的测试板，覆盖了一定范围的纵横比。工艺能力评估测试中使用的板厚度为 1.6 mm、2.4 mm 和 3.2 mm，通孔直径分别是 0.2 mm、0.25 mm 和 0.35 mm。通孔纵横比（AR）范围是 4.6:1 至 16:1。不同厚度测试板都在同一时间电镀于同一个镀槽中，完成后进行金相切片测量计算出相应的深镀能力

The process flow included the following operations:

- Acid cleaner—wets the hole and remove any organic contaminants
- DI water rinse
- Micro-etch—further roughening the surface and ensures excellent copper to copper adhesion
- DI water rinse
- Acid dip—acidifies copper surface prior to plating
- Electroplating of copper in acid copper bath

工艺流程包括以下操作：

- 酸性清洁剂——将孔润湿并移除所有有机污染物
- 去离子水冲洗
- 微蚀刻——进一步粗化表面，确保铜层之间的完美粘合
- 去离子水冲洗
- 酸浸——在电镀之前酸化铜表面
- 在酸性铜镀液中电镀铜

Cross-Section Analysis

金相切片分析

Cross-section analysis was started with the sample preparation process by punching or routing sections from a desired area on the board or test panel. Pre-grinding of the coupon was done to get a flat surface closer to the through-holes. Plastic index pins were used to align the coupon vertically to the grinding surface. A fast-cure acrylic resin was used to mount the coupons. A ratio of 1-to-1, hardener-to-resin, was used to provide optimum penetration and a quick cure rate (10–15 minutes). After the sections hardened they were subjected to grinding, polishing, and microscopic inspection to obtain micro distribution. Figure 1 shows a cross-section of a through-hole indicating the points of thickness measurements.

金相切片分析是从样品准备过程开始的，是从线路板或测试面板的测量区域内切割下一部分。为了得到更贴近通孔的平整表面，要预先对切片进行研磨。使用塑料定位针将切片和研磨表面垂直对齐。然后使

用快速固化的丙烯酸树脂来装填切片。硬化剂和树脂的比率是 1:1，它可以实现最佳渗透效果，达到较快的固化速率（10–15 分钟）。在切片固化之后，会继续研磨、抛光并用金相显微镜测量检测，从而得出深镀能力数据。图 1 是一个通孔的横截面，显示出了测量厚度的点。

Microdistribution

微观分布

The micro distribution is defined as the ratio of the average copper deposit thickness in the center of the through-hole to the average copper deposit thickness at the surface. It is calculated according to the following equation:

微观分布的定义是通孔中央沉积铜的平均厚度和表面沉积铜平均厚度的比。根据以下公式计算得出：

$$Microdistribution = \frac{(C + D)/2}{(A + B + E + F)/4} \times 100\% \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad \boldsymbol{Eq\ 1}$$

$$微观分布 = \frac{(C + D)/2}{(A + B + E + F)/4} \times 100\% \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad \boldsymbol{公式\ 1}$$

Figure 1: Cross-section of plated panel.

图 1：电镀面板的横截面

Results

结果

Microdistribution

微观分布

Micro distribution (MD) is the ratio between the average plated thicknesses in the middle of the hole to the average plated thickness on the surface as shown in Figure 1. Care should be taken when using MD % due to the difference in the board thickness, as the same diameter hole will be more difficult to plate in the thicker board as shown in Figures 2, 3, and 4. At the same current density, the same diameter hole has lower MD in a thicker board. For instance, a 0.2 mm hole in a 1.6 mm board at 10 ASF gave 90% MD measurement, while a 0.2 mm hole in a 2.4 mm board at 10 ASF gave only 75% MD measurement. Furthermore, a 0.2 mm hole in a 3.2 mm board gave 61% MD. Therefore, aspect ratio should be used to define the difficulty of the plating.

微观分布（MD）是孔中央平均镀层厚度和表面平均镀层厚度的比值，如图 1 所示。要谨慎使用 MD%，因为板厚是有差异的，而且直径相同的孔在图 2、3、4 所示的更厚铜板上电镀时难度会更大。在同一电流密度下，相同直径的孔在较厚线路板上的 MD 较低。举个例子，1.6 mm 厚板上直径为 0.2 mm 的孔在 10ASF 下测量到的 MD 是 90%，而 2.4 mm 厚板上直径为 0.2 mm 的孔在 10ASF 下测量到的 MD 是 75%。此外，3.2 mm 厚板上直径为 0.2 mm 的孔测量到的 MD 是 61%。因此，纵横比应该用来界定电镀的难度。

Another crucial factor which determines the MD % is the mass transfer, which is directly proportional to the diffusion. While several factors influence diffusion, one significant factor is the current density at which the plating is done. At high cathodic current density, the abundance of electrons at the cathode accelerates the reduction reaction of copper ions to copper metal at the cathode. Due to this the copper ions in the diffusion layer will exhaust rapidly. If the copper ions in the diffusion layer continue to drop without replenishment from the bulk electrolyte, the deposit could show severe surface burning and cause poor distribution. On the other hand, at relatively low current density the plating rate will be low with the depletion of copper ions in the diffusion layer due to the reduction reaction. Since the plating rate is low there will be enough time for the copper ions in the bulk electrolyte to replenish the diffusion layer. Owing to this equilibrium there will be an even distribution and no burning will occur.

另一个决定 MD%的关键因素是传质性能，它与扩散程度成正比。虽然有很多因素都会影响到扩散程度，但在电镀完成时电流密度就成了一个很重要的因素。阴极电流密度较高时，阴极周围的大量的电子会加速铜离子还原为铜金属。因此，扩散层里的铜离子将快速耗尽。如果扩散层的铜离子不断减少而且没有从扩散层外电镀液中得到补充，那么沉积物会出现严重的表面烧焦并引起分布不均。另一方面，在电流密度相对较低的情况下，电镀速率较慢，扩散层中铜离子消耗也较慢。因为电镀速率较慢，所以电镀液中的铜离子有足够的时间可以补充到扩散层中。正是这种平衡保证了分布的均匀性并且不会出现烧焦。

This phenomenon is clearly shown in Figures 2, 3, and 4. As an example in Figure 2, at 10 ASF a 0.35 mm hole showed 99% MD whereas when the CD increased to 20 ASF the MD dropped to 95% for the same hole in the same board thickness and further, at 30 ASF the MD dropped to 87%.

图 2、3、4 清晰地显示了这种现象。以图 2 举例，10ASF 下孔径为 0.35 mm 的孔显示出的 MD 是 99%，而当 CD 上升至 20ASF 时，同样厚度板子上同一个孔的 MD 降到了 95%，而当 CD 继续上升到 30ASF 时 MD 降到了 87%。

Figure 2: Micro distribution for 1.6 mm panel aspect ratio: 8:1, 6.4:1, and 4.6:1.
图 2：厚度 1.6 mm，纵横比为 8:1、6.4:1 和 4.6:1 的面板的微观分布

Figure 3: Micro distribution for 2.4 mm panel aspect ratio: 12:1, 9.6:1, and 6.9:1.
图 3：厚度 2.4 mm，纵横比为 12:1、9.6:1 和 6.9:1 的面板的微观分布

Figure 4: Micro distribution for 3.2 mm panel aspect ratio: 16:1, 12.8:1, and 9.1:1.
图 4：厚度 3.2 mm，纵横比为 16:1、12.8:1 和 9.1:1 的面板的微观分布

Surface, Structure, and Morphology

表面、结构和形态

All the plating conditions produced smooth, ductile, uniform, and mirror-bright surfaces. Excellent leveling was seen inside the hole as shown in Figure 5. Further, Figure 5 shows no thin copper at the knee in the cross-sectional images for the 1.6 mm thick board plated at current densities 10, 20, and 30 ASF respectively. Uniform fine-grained copper layers throughout the hole is observed. After the microscopic evaluation, the sections were further evaluated using scanning electron microscopy (SEM). Figure 6 shows the results from the SEM analysis where three different areas were analyzed; inside the hole, corner, and the surface. Despite the current density difference at the corner and inside the hole or at the surface, the morphology shows the same fine equiaxial grains. No preferred orientation like columnar grains were observed.

所有的电镀条件都能产生平整、易延展、均匀、光亮如镜面般的表面。如图 5 所示，孔内非常平整。图 5 还进一步显示了 1.6 mm 厚的线路板在电流密度是 10、20 和 30ASF 下进行电镀时横截面图像中孔角铜层厚度均匀，没有厚度减薄现象。在孔中观察到了均匀的，晶格结构良好的铜层。在金相显微镜检测之后，会使用扫描电子显微镜（SEM）对横截面进行进一步评估。图 6 显示了三个不同区域的 SEM 分析结果；这三个区域是孔内、孔角和表面。尽管这三个位置的电流密度各不相同，但它们的形态都呈同样的晶格结构。没有观察到柱状结晶这样的不良晶格。

Figure 5: Cross-sections of through-holes plated at a) 10 ASF; b) 20 ASF; c) 30 ASF; 1.6 mm test panel.
图 5：在 a) 10 ASF、b) 20 ASF、c) 30 ASF 下电镀的通孔的横截面；测试面板厚度为 1.6 mm
Figure 6: Scanning electron microscopy (SEM) of IST 22-layer through-holes plated at 10 ASF with 2.4 mm test panel.
图 6：板厚为 2.4 mm、在 10ASF 下电镀的 22 层通孔在 IST 扫描电子显微镜（SEM）下的分析图

Physical and Thermal Properties

物理性能和热性能

Final deposit plated under the influence of additives suppressor, grain refiner, and leveler will show characteristic physical properties. These properties also depend on the plating rate or current density, temperature at which the plating is done, and the morphology. For instance, a densely packed equiaxial deposit will have better physical properties than a columnar deposit. Most important to PCB manufacturing are tensile strength and elongation %, where these properties show the tolerance of the deposit for thermal stress.

在抑制剂、晶粒细化剂和整平剂这些添加剂的影响下，电镀得到的最终沉积物会显示出特有的物理性能。这些性能同样也取决于电镀速率或电流密度、电镀时的温度和形态。比如说，致密的等轴结晶比柱状结晶的物理性能要强。抗拉强度和延伸率%对PCB制造来说是最重要的，因为这些性能表示了镀铜层对热应力的耐受程度。

$$Mean\ average\ cross\ sectional\ area\ (in2) = \frac{Weight\ of\ the\ sample\ (lbs)}{Length\ of\ tensile\ sample\ (in) x\ density\ of\ copper\ (g/in3)} \ldots \boldsymbol{Eq\ 2}$$

$$\text{平均横截面积}(in2) = \frac{\text{样品重量}\,(lbs)}{\text{样品拉伸长度}\,(in) \times \text{铜密度}\,(g/in3)} \ldots \textbf{公式2}$$

$$Tensile\ Strength\ = \frac{Maximum\ load\ (lbs)}{Mean\ cross\ sectional\ area\ (in2)} \ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots \boldsymbol{Eq\ 3}$$

$$\text{抗拉强度} = \frac{\text{最大负载}(lbs)}{\text{横截面积}(in2)} \ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots \textbf{公式3}$$

$$Elongation = \frac{(Length\ at\ break - Original\ gage\ length)}{Original\ gage\ length}\ x\ 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \boldsymbol{Eq\ 4}$$

$$\text{延伸率} = \frac{(\text{断裂时长度}- \text{原始测量长度})}{\text{原始测量长度}} \times 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \textbf{公式4}$$

Physical properties were measured according to the IPC TM-650, 2.4.18.1 test method. Sample strips were extracted and baked in an oven at 125°C for four to six hours. An industry mechanical test instrument was used to test the strips. The measurements were used to calculate tensile strength and elongation % using equations 2, 3, and 4. Table 2 shows the results at two different bath ages, fresh bath and bath aged around 50 Ah/L. According to the results properties did no change much with the bath age.

物理性能是根据IPC TM-650，2.4.18.1测试方法进行测量的。取出试样条后将其在125 °C的烤箱中烘烤4~6小时。测试试样条时使用了工业机械测试仪器。测量方法使用了公式2、3、4来计算抗拉强度和延伸率%。表2显示了在两种不同使用寿命镀液中的性能结果——新鲜镀液和老化到50 Ah/L左右的镀液。实验结果显示，其性能受镀液老化程度的影响不大。

Table 2: Physical properties.

表 2:物理性能

Property	Fresh Bath	Aged Bath
Tensile Strength (psi)	43,120	44,470

Property	Fresh Bath	Aged Bath
Elongation %	22.18	26.35

性能	新鲜镀液	使用过的镀液
抗拉强度(psi)	43,120	44,470
延伸率%	22.18	26.35

Further, to evaluate thermal characteristics of the deposit, the 6X solder shock resistance test was performed on plated through-holes in accordance with IPC TM-650 2.6.8. Solder shock (SS) conditions were 10 seconds float at 288°C for six times on the same side of the test coupon. Results are shown in Figure 7. After 6X SS testing, no corner cracks, barrel cracks, or hole wall pull-away was observed.

为了进一步评估镀铜层的热性能，根据 IPC TM-650 2.6.8 对电镀通孔进行了 6 次漂锡热测试。漂锡条件是将测试样品的同一侧放在 288℃的锡炉中进行 6 次持续 10 秒的漂浮，接受热冲击。结果如图 7 所示。在 6× SS 测试之后，没有观测到孔角断裂、孔壁断裂或孔壁分离缺陷。

Figure 7: 6× thermal shock test.

图 7：6×热冲击测试

Interconnect stress testing (IST) was also carried out to further characterize the deposit. IST testing is an accelerated test method used to evaluate the integrity of interconnects and plated through-holes. This method utilizes electrical currents passed through a circuit in the board at sufficient resistance to increase temperature. Coupons were run through assembly simulation called preconditioning prior to cycling. Coupons were tested prior to preconditioning for continuity. Figure 8 shows the assembly of through-holes in an IST coupon and the electrical continuity.

为了进一步确定电镀沉积铜层特性，还对其进行了内互连应力测试（IST）。IST 测试是一种加速测试方法，用来评估线路互连和电镀通孔之间的完整性和可靠性。这种方法是利用电流通过线路板中具有足够电阻的线路，并提升电镀铜线路的温度来实现的。测试板在循环评估前要进行模拟装配，这一步骤叫预处理。在预处理之前要对样品的连续性进行测试。图 8 显示了一个 IST 样品中通孔的组装以及导电连续性。

Figure 8: Assembly of through-holes in an IST coupon. Power is shown in gold and the sense is in blue.

图 8：IST 样品中通孔的组装，金色是电源，蓝色是传感线

A coupon was sacrificed to determine the current needed for preconditioning. All coupons were preconditioned six times to 260°C prior to cycling at 150°C to 500 cycles or to failure. After preconditioning, baseline resistance readings were established and the temperature cycling was started. Each thermal cycle consists of passing sufficient current through the internal power circuit to elevate the temperature to 150°C, then subsequent cooling down to ambient temperature. During the temperature cycling, resistance is monitored on the power circuit and the sense circuit. If the resistance is >10% over the established baseline on either circuit, it is considered a failure and the test is halted. Material type and complexity of the build have an influence on the cycles to failure. Table 3 shows the results from the IST test and all five coupons tested passed the 500 cycles test. This test also confirms and agreed with the 6X solder shock test. Figure 9 shows a cross-section of a through-hole with 22 layers extracted from the IST test panel after plating.

我们使用了一个样品来确定预处理时所需的电流。所有的样品都要预处理 6 次，让温度升到 260℃，然后才能在 150℃的温度下进行 500 次热循环或者直到失效。在预处理后，可以确定基准电阻读数，然后开始

温度循环。每个热循环都是将足够的电流通入内部电源电路中将温度升高至 150 ℃，然后再将其温度冷却至室温。在温度循环过程中，会对电源电路和传感测量电路的电阻进行监控。如果这一过程中，任何线路的电阻值比确立的基准值多出 10%以上，就会被认定为失效，从而中断测试。材料种类和线路板结构复杂程度对达到失效的循环次数有一定的影响。表 3 显示了 IST 测试的结果，以及所有 5 个通过了 500 次测试循环的样品。这一测试和 6×焊接冲击测试的结果一致。图 9 是 IST 测试面板在电镀后其 22 层通孔的横截面。

TABLE 3: Interconnect Stress Testing (IST) data.

表 3:互连应力测试(IST) 数据

Material A bh, p2-s2, 6xpre cond_dat.csv					
Coupon #	#2	#4	#6	#9	#11
Cycles	500	500	500	500	500
%P	0.430	0.267	0.405	0.264	0.462
%S	1.243	1.240	3.038	2.878	1.392
Material A - p2s2, 6xpre_dat.csv					
Coupon #	#2	#3	#6	#9	#11
Cycles	500	500	500	500	500
%P	0.000	-0.380	0.072	-0.462	-0.393
%S	-0.070	-0.280	-0.069	-0.355	-0.591

材料 A bh, p2-s2, 6xpre cond_dat.csv					
样品#	#2	#4	#6	#9	#11
循环次数	500	500	500	500	500
%P	0.430	0.267	0.405	0.264	0.462
%S	1.243	1.240	3.038	2.878	1.392
材料 A - p2s2, 6xpre_dat.csv					
样品#	#2	#3	#6	#9	#11
循环次数	500	500	500	500	500
%P	0.000	-0.380	0.072	-0.462	-0.393
%S	-0.070	-0.280	-0.069	-0.355	-0.591

Figure 9: Cross-sections of IST 22-layer through-holes plated at 10 ASF with 2.4 mm test panel.

图 9：板厚为 2.4 mm、在 10ASF 下电镀的 22 层通孔的 IST 横截面

Conclusions

结论

An excellent formula was developed for DC copper metallization for hoist lines and VCP applications. The operating CD range is 10–30 ASF where, micro distribution of ≥85% for AR 8:1 is achievable. Deposits were bright and ductile and also met IPC standards for the properties such as tensile strength and elongation. The thermal characteristics of plated copper also met the IPC standards and showed no failure during the solder shock tests. Coupons also passed the 500 cycles in IST testing. All the organic additives can be easily monitored by industry CVS analysis.

一个非常出色的电镀酸铜配方已经被开发完成，它是一个可以用于传统垂直电镀生产线以及垂直连续电镀生产的直流酸铜电镀工艺。电流密度操作范围是 10–30ASF，可以为 AR 为 8:1 的通孔获得≥85%的深镀能力。电镀铜层的表面光亮度更高、延展性更优异，能满足 IPC 的性能标准（如抗拉强度和延伸率）。电镀铜的热性能同样满足 IPC 标准，镀层通过漂锡冲击测试没有发生断裂，镀层样品均在 IST 测试中通过了 500 次循环评估。所有的有机添加剂组分都可以通过 CVS 进行分析管控

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