The Co-evolution of Carbon-based Direct Metalization Alongside HDI Technology

因应 HDI 技术发展而改良的碳系列直接电镀

by Graham Lee, David Chun, Albert Tseng, Charles Bae, Smith Han, Jordan Kologe, and Bill Bowerman
MacDermid Alpha Electronics Solutions

Abstract

摘要

Electronics manufacturers have chosen carbon-based direct metalization systems over electroless copper processes due to lower cost of ownership and easier-to-maintain equipment. Today, hundreds of high-volume, carbon-based direct metalization lines are in production around the world. The well-documented savings due to lower water usage, less waste generation, a smaller equipment footprint, and lower power consumption are why these systems became popular. In addition to this, these systems do not require precious metals such as palladium to activate printed circuit structures for electroplating, offering significant operations savings.

由于碳系列直接电镀系统拥有成本低和易于维护的优点，电子制造商选择了用其代替化学沉铜工艺。如今，全球各地有数百条高产量石墨系直接电镀生产线。这些系统之所以受欢迎，是因为减少了用水量，减少了废水产生，减少了设备占地面积并降低了能源消耗。 除此之外，这些系统不需要钯等贵金属来活化，从而可显着节约运营成本。

In the latest generation of smartphone technology, high-density interconnect (HDI) technology has pushed the line width and spacing to require the use of ultra-thin copper foils as a starting point. This thin-foil technology requires exacting precision in controlling the copper etch budget during the formation of copper interconnects. Direct metalization processes, like the latest generation of Blackhole, have begun production on 3-micron copper foils for modified semi-additive processing, improving the process overall.

在最新一代的智能手机技术中，高密度互连（HDI）技术朝向更精细的线宽和线距发展，从而需要采用超薄铜箔作为整个生产制程的起点。这种超薄铜箔技术要求在铜互连形成过程中精密控制蚀刻精度。直接电镀工艺（例如最新一代黑孔化技术）已开始在 3 微米的铜箔上进行先进的半加成法生产。

In this article, we walk through a history of how the technology has evolved to this point, including the new breakthroughs in equipment technology that allow this process to create the extremely fine lines and spaces being implemented in flagship mobile designs today.

本文将回顾石墨系直接电镀技术发展历史，包括设备技术的新突破，以及如何应用于当今旗舰手机中设计极精细的线宽和线距。

The History of Carbon Direct Metalization

碳系列直接电镀的历史

Carbon direct metalization processes have been widely used in the circuit board industry for more than 35 years. Widely utilized processes in the industry include Blackhole, Eclipse, and Shadow. The original Blackhole direct metalization technology was patented in 1984 and quickly became a

commercial success as a horizontal process for seeding FR-4 through-hole panels for copper electroplating.
碳系列直接电镀工艺广泛应用于电路板行业已有 35 年之久。工业中广泛使用的工艺包括黑孔、日蚀和黑影。最初的黑孔直接电镀技术于 1984 年获得了专利，并作为电镀 FR-4 通孔面板工艺在商业上取得了成功。
Since Blackhole is a coating process rather than a redox process like electroless copper, the technology is less sensitive to the surface energy of the different dielectric materials, contributing to its adoption for difficult-to-plate materials. Because of this, these types of processes became widely used on polyimide film in flexible circuits and on high-performance and exotic materials like PTFE. Carbon- and graphite-based direct metalization technology is approved for space and military avionics applications under the requirements IPC 6012D, 3.2.6.1.
由于黑孔是涂覆工艺，而不是像化学沉铜那样的氧化还原工艺，因此该技术对不同介电材料的表面活性不敏感，可处理金属化难度高的材料。 因此，这种工艺已广泛用于挠性电路中的聚酰亚胺薄膜、高性能或特殊材料，如聚四氟乙烯（PTFE）。 碳和石墨的直接电镀技术被认可用于航天和军事航空电子应用且符合 IPC -6012D 规范的 3.2.6.1 节的要求，。

Board Evolution
电路板的发展
Leading direct metalization processes have continued to evolve throughout the years with the demands of PCB designs. As the drive for miniaturization resulted in the change from leaded to surface-mounted components, PCB designs evolved to accommodate smaller parts with higher pin counts. This then led to PCBs with higher layer counts, thicker panels, and smaller diameter through-holes. To meet the challenges of high-aspect-ratio holes, line specifications encompassed improvements for solution transfer in small holes. Upgrades, such as the use of ultrasonics to quickly wet holes and remove air bubbles, were implemented, along with in-line air knives and dryers specially modified to dry the small holes on the thicker panels.
随着印制电路板设计的需要，直接电镀工艺在过去几年中不断发展。由于微型化的驱动，由引线元器件发展到表面贴装元器件，PCB 设计演变为要适应具有更多引脚数的微型元器件，这导致 PCB 的层数增加、电路板更厚、通孔直径更小。为了应对高纵横比的挑战，生产线技术规范要涉及对微孔进行溶液传递交换的改进，如使用超声波快速润湿孔和去除气泡，以及改善风刀和烘干机的能力以有效烘干厚电路板上的小孔。
After this, PCB designers reached the next stage: via starvation, the point where the pin count and grid density exceeded the available real estate to drill through-holes and route nets. As the industry moved from BGAs with 1.27–1.00 mm grid to CSPs with 0.80–0.64 mm grid, the microvia became the enabler for designers to meet the challenge of HDI technology.
此后，PCB 设计人员进入了下一个阶段：盲孔饥渴症，引脚数和球栅密度超过了钻孔和布线可用的板面。 随着球栅阵列封装（BGA）的 1.27mm 至 1.00 mm 栅格，转向芯片级封装（CSP）的 0.80mm 至 0.64 mm 栅格的，微盲孔已成为设计人员应对 HDI 技术挑战的利器。
In 1997, the feature phone began using a 1+N_1 design in mass production. This is a one buildup layer with microvias over a multilayer core. As mobile phone production grew, microvias were formed by conformal etch and CO_2 lasers, and later by UV, UV YAG, and combo UV CO_2 lasers. Microvias

allowed designers to rout lines under vias so larger pin grids could be redistributed without increasing layer count. HDI is widely used today in three platforms: miniaturization, advanced packaging, and high performance. The miniaturization seen in mobile phone designs is the current highest volume contributor.

1997 年，功能手机开始使用 1 + N+1 设计进行批量生产；这是在层芯上的叠加层带有微盲孔的设计，随着手机销售量的增长，通过预蚀刻开窗和 CO_2 雷射、UV、UV-YAG 雷射和组合 UV- CO_2 雷射形成微盲孔。微盲孔允许设计人员在盲孔下布线，因此可以在不增加层数的情况下重新分布更多的引脚栅格。HDI 目前广泛应用于三个平台：微型化产品、高阶封装和高性能电子产品。手机设计中的微型化是当前产量最高的应用。

Direct Metalization to the Rescue

直接电镀

Direct metalization systems like Blackhole had to overcome technical hurdles to meet the challenge of metallizing the blind vias and small diameter features of HDI. The small microvia size presented trouble in the removal of the carbon black from the via target pad, which is essential to ensuring clean copper to copper bonds. From a chemical perspective, cleaner and microetch product developments were implemented to improve the lifting of carbon off the copper.

诸如黑孔之类的直接电镀系统必须克服技术障碍，以应对盲孔和 HDI 微小孔型的金属化挑战。当盲孔尺寸缩小之后, 提高了清除盲孔底部碳颗粒的困难度，但是盲孔底部的清洁度有是信赖度的关键因子；所以，开发新的清洁剂和微蚀剂，是改善盲孔底部清洁的方法。

From an equipment perspective, the microetch spray modules of the process were completely reconfigured. The combination of spray–flood–spray bar configurations proved to be the most efficient design. The distance between the nozzle tip and panel surface was reduced, and the pitch of the fan nozzles was narrowed to increase spray impact force on the panel. This design proved beneficial for high aspect holes and blind vias.

另外，依据理论以及实务经验，修改微蚀段的喷管设计为 喷洒-浸泡-喷洒的配置组合，实务上证明是有效的设计。减小了喷嘴与电路板表面之间的距离，缩小了喷嘴之间的间距，增加了对电路板的喷洒冲击力。通过针对细节的掌握，新型的喷管设计可以有效的处理 高纵横比的通孔以及盲孔。

With the next generation of smartphones, makers moved to buildup anylayer designs using stacked vias and no through-holes. This initiated a trend wherein starting copper foil thickness on panels has steadily reduced from 18 µm to 12 µm to 9 µm, as line and spacing has decreased from 60 µm to 40 µm. Each buildup layer in these processes requires a metalization and electrolytic plating cycle with more wet processing capacity.

随着下一代智能手机的发展，制造商开始使用任意层的堆叠盲孔设计而取消的通孔，这引发了一种趋势，即随着线宽和线距从 60µm 减少到 40µm，电路板的制作流程采用的原始铜箔厚度从 18µm 稳定地减少到 12µm 再到 9µm。而任意层线路板的每一个叠加层都需要经过一次金属化和电镀，这样子就大幅度增加了湿制程的产能需求量。

Smartphones were also major users of flex and rigid-flex circuits. Adoption of direct metalization grew significantly in anylayer, FPC, and R/F board production due to the lower cost, less water usage, and less waste generation of the process compared to traditional electroless copper processes (Figure 1).

智能手机也是挠性和刚挠结合电路的主要用户。与传统的化学沉铜工艺相比，直接电镀在任意层、挠性电路板（FPC）和刚挠结合电路板生产中的应用均显着增加，这是因为该工艺与传统的化学铜工艺相比成本更低、用水更少、废水产生更少（图 1）。

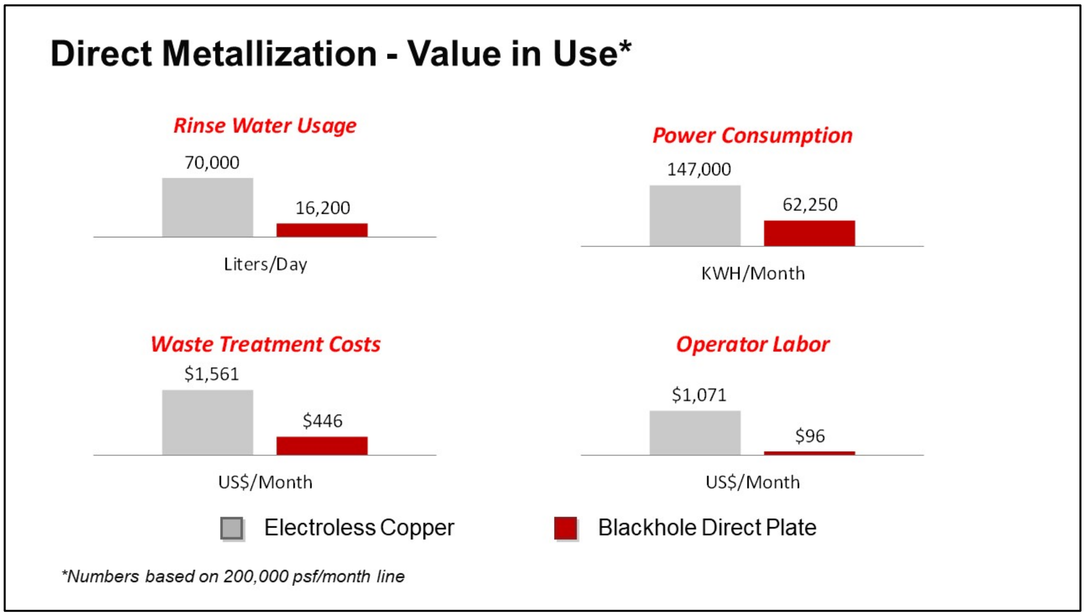

Figure 1: Direct metalization processes offer substantial environmental and financial benefits to fabricators

图 1：直接电镀工艺为制造商带来了巨大的环保和经济利益

Direct Metalization-Value in Use：采用直接电镀节省的成本

Rinse Water Usage：水洗水耗用量

Power Consumption：耗电量

Waste Treatment Costs 废水处理成本

Operator Labor：人工成本

Electroless Copper：化学铜成本

Blackhole Direct Plate：Blackhole 直接电镀成本

Number based on 200000psf/month line：以 20 万平方尺产能的生产线数据为基础

Copper Budget: The New Metric for mSAP Process Performance

铜咬蚀量规格 ：改良型半加成法（mSAP）

Fast forward to today, and the newest generation of smartphones and advanced packaging are utilizing a fabrication technique called the modified semi-additive process (mSAP). mSAP utilizes ultra-thin foils of 3 µm to reach line and spacing of 30/30 µm. The ultra-thin foils require a very exacting copper etch budget in the fabrication process. Specifically, etching of the target pads must be precisely controlled for both traditional electroless copper and direct metalization processes (Figure 2).

现在，最新一代的智能手机和先进的封装逐渐采用替代型的半加成法（mSAP）。mSAP 采用 3µm 的超薄箔来实现 30/30 微米的线宽线距设计。而采用超薄铜箔的生产流程中，需要非常精准的管控各个制程

中的微蚀槽的咬蚀量。特别是对于传统的化学沉铜和直接电镀工艺，必须非常精准地控制表面铜箔的咬蚀量（图 2）。

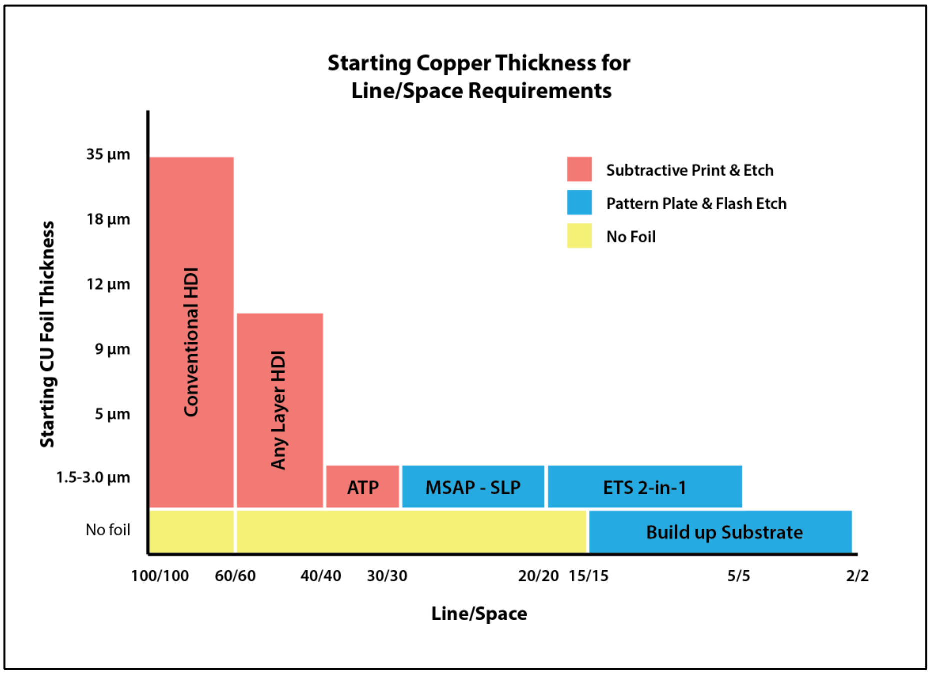

Figure 2: Shrinking line/space requirements for PCBs have created a need for stringent control of etch depth.
图 2：PCB 日益缩小的线宽/线距要求需要严格控制蚀刻深度

Starting Copper Thickness for Line/Space Requirements 满足线宽/线距要求的起始铜厚度
Starting Cu foil Thickness 起始铜箔厚度
Conventional HDI 传统 HDI
Any Layer HDI 任意层 HDI
MSAP-SLP MSAP -类载板
ETS 2-in-1 嵌入式线路载板 2-in-1
Build up Substrate 叠加载板
Subtractive Print & Etch 减成法印制与蚀刻
Pattern Plate & Flash Etch 图形电镀与闪蚀
No foil 树脂

The equipment team and product specialist group at MacDermid Alpha have now taken the development of the carbon black process to the latest stage of its evolution. The newest line configurations for Blackhole Advanced Direct Metalization are capable of mSAP on panels starting with foils as thin as 3 µm, and the entire process has now been optimized for thin foil HDI metalization. MacDermid Alpha 公司的设备团队和产品专家小组现已成功的将碳直接电镀制程应用在最新的领域；最新的、经过优化的碳直接电镀生产线被应用在采用 3 µm 铜箔的 mSAP 生产流程中的金属化制程。

Advancements in Equipment Configurations

设备配置方面的进步

To optimize the direct metalization to work with mSAP processing, several equipment designs were tested and evaluated in pilot-scale lines before ramping up to full production. The result of this is that the process can offer uniformity of the carbon black coating under a wide range of conditions.

为了优化直接电镀工艺以配合 mSAP 工艺，在投入全面生产之前，逐步在实验线上测试几种不同的设备设计。测试结果显示，经由良好的设备设计，可以在一个操作范围宽条件下提供均匀一致的导电碳涂层。

Several equipment modifications were selected for the Blackhole Advanced Direct Metalization system, in particular. A new roller configuration in the carbon application module uses a patented roller with saturation control to ensure the uniformity of the carbon black seed layer. The result of this change is that the carbon dispersion is deposited as a thinner coating and with most of the excess carbon removed from the surface before leaving the module. This is to prevent excessively thick deposits in blind vias or under the knee of the through-hole.

举例来说，在碳系列的直接电镀制程中，采用一中有专利保护的滚轮配置，可以让碳涂层更趋均匀一致。并且降低生产板板面上的碳沉积量、减少碳悬浮液的带出量，同时防止盲孔或通孔孔角处出现过厚碳层。

The etch module was also extensively redesigned. Fabricators are quite concerned about the potential of leaving a target pad that has only been partially cleaned, which leaves carbon residue after processing. In this case, the panel would pass electrical testing but have a reduced cross-sectional area, resulting in the via not being as robust under assembly reflow conditions. With microvia diameters being reduced from a traditional 100–150 microns diameter down to 80–60 microns, the importance of the upgraded etching step is critical to product reliability.

后微蚀槽的设备规格也进行了重新设计。盲孔底部是否有 100%完全清洁干净是厂商最在意的品质问题。如果在盲孔底部的局部有碳残留，在电性测试时是能够通过测试的，但是因为导通的横截面面积减小了、结合力也缩小，导致在组装过程中因未受热应力冲击而出现断裂失效的问题。 随着盲孔直径从传统的 100 微米至 150 微米减小到 80 微米至 60 微米，升级微蚀槽的设备规格对于产品可靠性至关重要。

Studies conducted on how to eliminate the chances of leaving carbon residues in the target pad through modification of the etch module yielded process improvements that are now actively deployed in production. The first major improvement involves the use of a dual sump etching module to provide more precise etch depth controls. The first stage removes the bulk of the carbon from the copper surface, and the second stage contains fresh etch chemistry not contaminated with carbon, which may be redeposited onto the surface. A second improvement incorporates technology found in copper reduction lines for maximizing the uniformity of the etch amount across the panel surface.

通过测试研究修改微蚀槽的设备规格提升制程能力来达到完全清除盲孔底部的的碳残留，目前已应用于量产线。第一个主要改进包括使用双蚀槽来提供更精密的咬蚀量控制。第一阶段去除铜表面的大部分碳，第二阶段采用新鲜干净的微蚀液，避免碳颗粒能会再重新返沾到量产板板面。第二阶段同时采用了减铜线的技术，大幅度度地提高线路板板面上的微蚀量的均匀性。

Reducing variation in the etch depth across the panel surfaces helps to tightly control the total etch amount required to clean the target pads. The coefficient of variation in the etch is tightly controlled by chemistry concentration, spray bar design, and spray pressure parameters (Figure 3).

减少电路板板面咬蚀量的变异值，有助于精准地控制盲孔底部的的总蚀刻量，咬蚀量的变异值是由化学浓度、喷管设计和喷洒压力参数严格控制（图 3）。

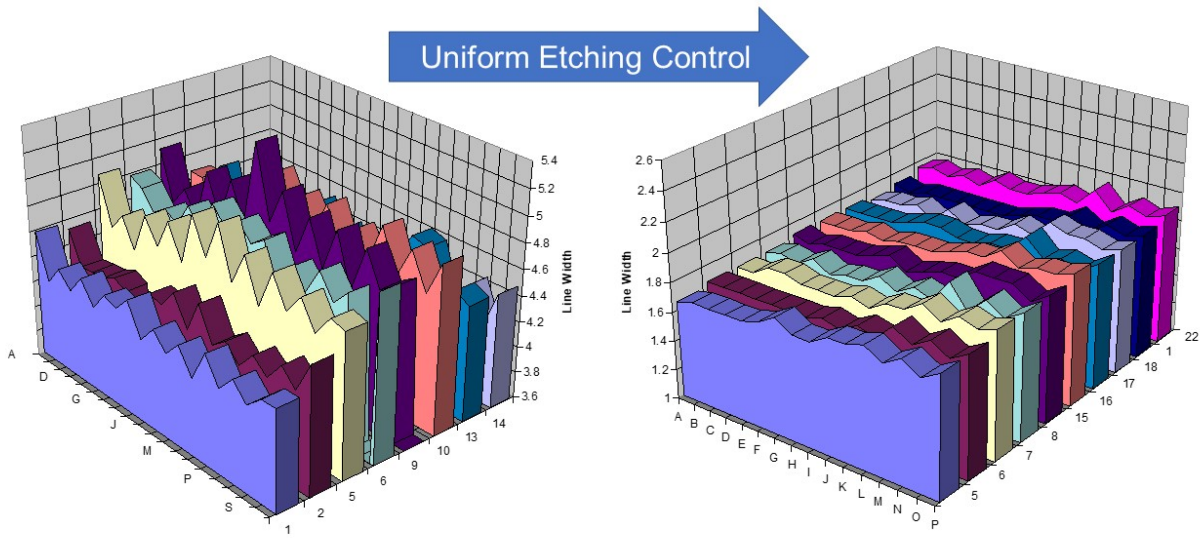

Figure 3: Uniform etching control through equipment and chemical improvements has allowed for the complete removal of carbon residues in target pads.
图 3：通过设备和化学改进的均匀蚀刻控制可以完全去除目标焊盘中的碳残留

Uniform Etcing Control 均匀蚀刻控制　　Line width 线宽

Advancements in Chemistry

化学品改进

In terms of chemistry improvements, traditional cleaner/conditioner and etchant chemistries have been tested and designed with controlled etch capabilities in mind. Cleaners now feature an organic additive that selectively covers copper surfaces but is not attracted to dielectric surfaces. On the copper surfaces, the carbon black is adsorbed on the organic coating provided by this technology over the copper. When the panel enters the etch module, the carbon black is undercut by the etch and lifted off the surface. The organic coating is highly soluble in acid medium and is immediately removed by the microetching step.

在化学品改进方面，对传统的清洁整孔剂和微蚀药水进行了测试和修改，同时考虑控制咬蚀能力。清洁剂中的有机添加剂，选择性地只有沉积在铜表面，不会沉积在树脂材料上。所以，碳颗粒也只会沉积在这一特殊的有机涂层上。当线路板进入微蚀槽时，有机涂层在酸性药水中有很高的溶解性，所以，通过微蚀槽中的酸移除有机涂层、同时侧蚀碳颗粒底下的铜面，可以加速清除同面上的碳颗粒。

In another improvement, two-component microetches are being implemented that remove the dried carbon and reduce the copper roughness. The copper surface is ideal for dry film adhesion, and testing has also shown a smoother target pad is better for microvia reliability. The target pad copper

crystalline structure is ideally prepared as a substrate to form epitaxial growth of the electrolytic copper (Figure 4).
另一个改善项目是，采用双组分的微蚀刻，可以提高去除碳颗粒的能力并且降低铜箔表面的微粗糙度。让铜表面的粗糙度有利于干膜附着。测试结果显示，相对平滑的盲孔底部有助于提高电镀同在盲孔底部信赖性。经过优化的碳系列直接电镀制程之后，盲孔底部的铜箔已经是完全的干净，可以让电镀铜依着铜箔上的铜晶格持续成长而达到最佳的杜铜结合力（图 4）。

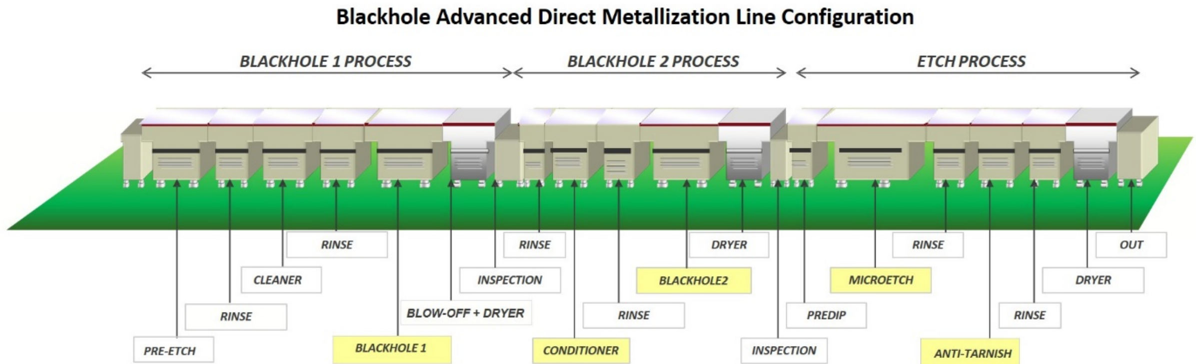

Figure 4: The microetch module has proven to be key to the raising of microvia reliability in direct metalization processes.
图 4：微蚀模块已被证明是提高直接电镀工艺中盲孔可靠性的关键

Blackhole Advanced Direct Metalization Line Configuration 黑孔高阶直接电镀生产线配置
Blackhole 1 Process 黑孔 第 1 段
Blackhole 2 Process 黑孔 第 2 段
ETCH PROCESS 微蚀段
RINSE 水洗
CLEANER 清洁槽
PRE-ETCH 预微蚀
INSPECTION 中检段
BLOW-OFF+DRYER 吹风+烘干机
DRYER 烘干机
PREDIP 降温润洗段
ANTI-TARNISH 抗氧化段

Copper Grain Boundary Improvements
铜晶界的改善

This combination of specific improvements to key process modules and chemistry has resulted in a line capable of running thin foil buildup layers for advanced HDI/mSAP. Microvia reliability is enhanced with a single interface of direct copper to copper bonding, forming a continuous metallurgical structure. The etch chemistry prepares the target pad with an ideal copper topography as the base for copper via fill plating. This promotes the well-defined grain growth of the electrolytic copper on the target pad.

With normal thermo-mechanical cycling, the recrystallization of the copper grain orientation further promotes the desirable continuous metallurgical structure.
关键工艺槽和化学品的特定改进相结合，构成适用于采用超薄铜箔生产的先进 HDI / mSAP 流程。通过铜-铜直接键合的单一界面，形成连续的金属晶格，提高了盲孔的可靠性。微蚀槽的处理让盲孔底部的铜箔形成的理想的微粗糙度，当作填孔电镀铜基底。这促进了盲孔底部上电镀铜的晶格沿着铜箔的晶格持续成长。经过正常的高温热处理之后，铜晶粒出现晶格重组排列而形成的了完整的连续向的金属晶格。

Studies with FIB using lamella cuts show the interface line to be uniform in grain size and structure (Figure 5). After thermal shock or cycling, the line between the target pad and electrolytic copper can be difficult to find. Nano voiding is not present, except for instances where it would be due to factors like oxidization or contamination.
采用 FIB 切割样品形成薄片研的观察分析显示，界面线在晶粒尺寸和结构上是均匀的（图 5），在热冲击或热循环之后，盲孔底部的铜箔和电镀铜之间的界面线很难找到，没有其他制程容易出现的 Nano-void，除非是由于氧化或污染等因素造成的。

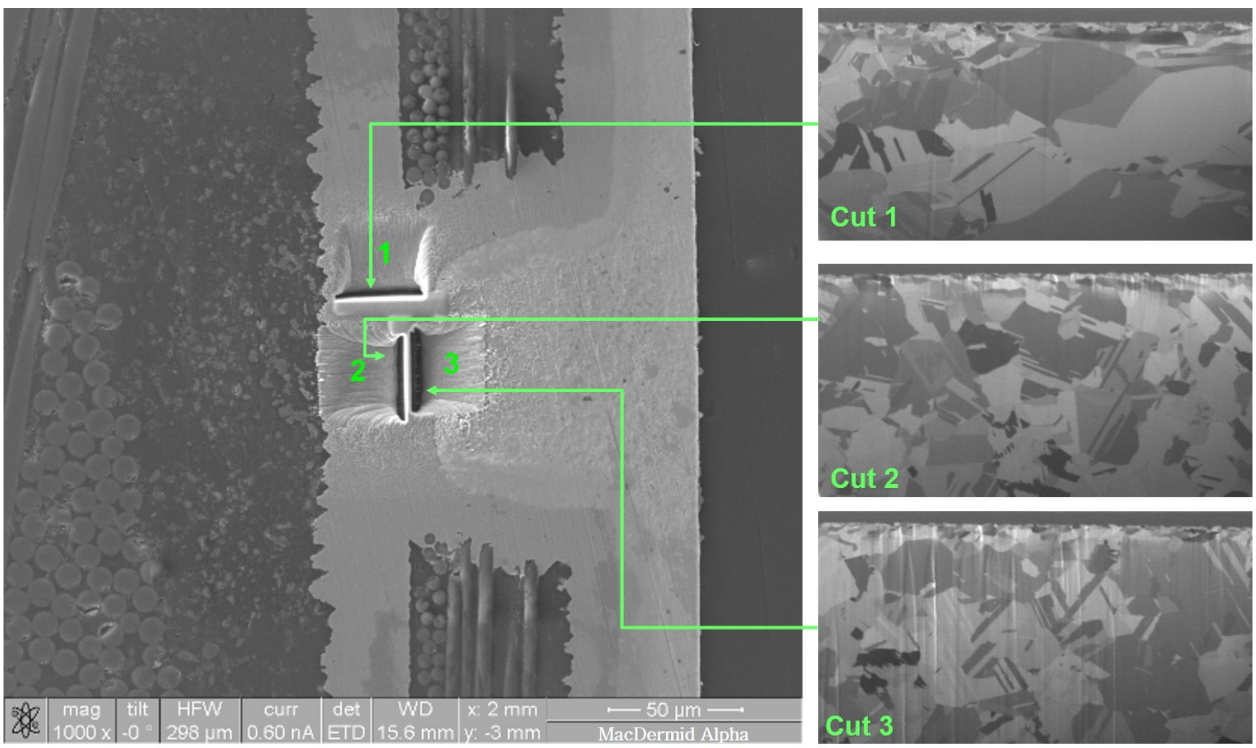

Figure 5: FIB imaging of the interface between the electrolytic copper plating and the target pad. Leading-edge direct metalization technology allows for strong copper-to-copper bonding that performs excellently under thermal stressors.
图 5：电镀铜层和目标焊盘之间界面的聚焦离子束（FIB）成像，领先的直接电镀技术可使强铜-铜键合在热应力下表现优异

Full Steam Ahead
全速前进

Leading-edge direct metalization process lines like the Blackhole Advanced Direct Metalization are now in mass production for mSAP with 3 µm Cu foil layups. These systems utilize controlled etch

equipment configurations in mass production. Qualification testing on 12L anylayer panels processed with this equipment configuration passes IST testing through 300 cycles. In these designs, advanced direct metalization processing was done on anylayers L2-10 and mSAP L3-11. These designs have microvia hole sizes of 80–100 x 45 μm with approximately 2 million interconnects per panel.
直接电镀生产线，如“黑孔”，目前已经用于采用 3 微米超薄铜箔的替代型半加成流程（mSAP）的量产流程上了。这些系统在批量生产中使用精准控制微蚀量的相关设备，用这种设备生产的 12 层任意层电路板已通过了 300 Cycle 的 IST 测试。在上述产品中，黑孔应用在采用 mSAP 流程的 L2/10 和 L3/11，盲孔的尺寸为 80~100 x 45μm，每片线路板含有 200 万个盲孔。
The presence of any carbon residues is checked with AOI, and currently, zero defects have been detected on 5,000 PSM/month of production for this process. The electrolytic plating for these production boards is done on VCP lines with panel plating on the core through anylayers and pattern plating on the mSAP buildup layer. The electron backscatter diffraction (EBSD) image in Figure 6 shows the uniformity of the grain size at the interface between the target pad and electrolytic copper plating.
在制程中使用 AOI 检查是否有碳残留物。检验结果显示在 5,000 PSM/月的产量中，没有检测到任何缺陷。这些电路板的电镀是在垂直连续电镀（VCP）生产线上完成的；内层采用 Tent-Etch 流程的全板电镀，而 mSAP 层必然是采用图形电镀。图 6 中的电子背向散射衍射（EBSD）图像显示了目标焊盘和电镀铜层之间的界面处晶粒尺寸的均匀性。

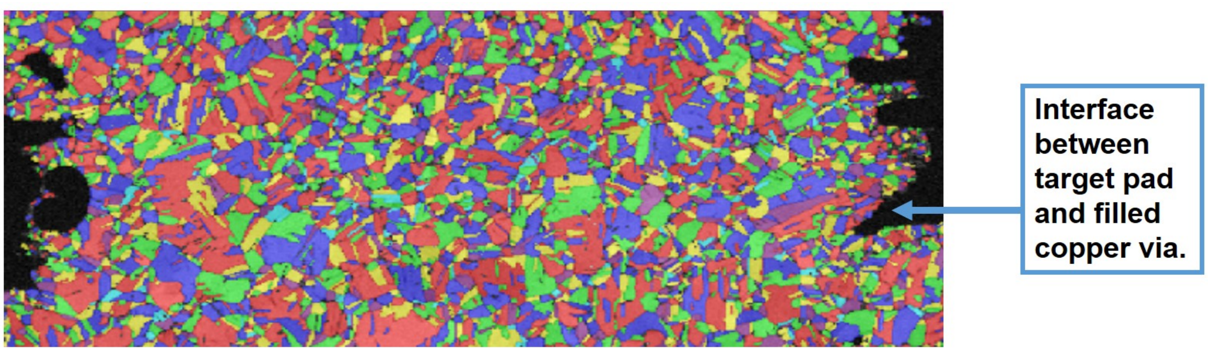

Figure 6: EBSD grain structure of via and target pad cross-section. Panel pre-conditioned at 260°C, followed by 300 cycles at 170°C. The average grain size is 3.12 microns.
图 6：盲孔和目标焊盘横截面的电子背向散射衍射（EBSD）晶粒结构
备注：电路板在 260°C 下进行热处理，然后在 170°C 下循环 300 个周期，平均晶粒尺寸为 3.12 微米。

Interface between target pad and filled copper via
目标焊盘和填孔铜之间的界面

Summary
总结

As miniaturization has driven components to smaller packages with higher pin counts, PCB substrates have evolved to meet the challenge of increased connection density. The microvia has become synonymous with HDI design. As the change in PCB design progressed from through-hole to HDI designs like anylayer and mSAP technologies, direct metalization technologies have made advancements in chemistry and equipment configurations to keep pace with the industry.

随着微型化元器件要求更多引脚数且更小封装，PCB 基板发展需要应对密度增加的挑战。盲孔已成为 HDI 设计的代名词。随着 PCB 设计从通孔发展到 HDI 设计（如任意层和 mSAP 技术）的变化，为了与行业的发展保持同步，直接电镀技术已在化学和设备配置方面取得了一定的进步。

The leading-edge, advanced direct metalization systems currently in production today are providing PCB fabricators of the latest generation mobile interconnection platforms the reliability and performance needed to compete. In new segments, such as those that utilize flexible and rigid-flex circuits or new hybrid materials, carbon direct metalization offers a cost-effective and technology enabling solution for fabricators looking to expand their metalization capacity.

目前，最先进的高阶直接电镀系统正在为最新一代移动装置平台的 PCB 制造商提供竞争所需的可靠性和性能。在新的领域，例如利用挠性和刚挠结合电路，或新混合材料的领域，石墨系直接电镀技术为寻求扩大其电镀能力的制造商提供了一种经济高效的技术解决方案。

Graham Lee: Process Specialist–Metalization
David Chun: Equipment Manager–Asia
Albert Tseng: Product Manager–Asia
Charles Bae: GDAC Leader–Korea
Smith Han: Technical Service Manager
Jordan Kologe: Technical Marketing Specialist
Bill Bowerman: Product Director–Primary Metalization
Graham Lee：电镀工艺专家
David Chun：亚洲设备经理
Albert Tseng：亚洲产品经理
Charles Bae：GDAC 负责人-韩国
Smith Han：技术服务经理
Jordan Kologe：技术市场专员
Bill Bowerman：电镀产品总监