The Co-Evolution of Carbon-Based Direct Metallization alongside High Density Interconnect Technology

By Graham Lee, David Chun, Albert Tseng, Charles Bae, Smith Han, Jordan Kologe and Bill Bowerman

Electronics manufacturers have chosen carbon-based direct metallization systems over electroless copper processes due to lower cost of ownership and easier-to-maintain equipment. Today, hundreds of high volume carbon-based direct metallization 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. In the latest generation of smartphone technology, high density interconnect 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 metallization processes like the latest generation Blackhole have begun production on 3-micron copper foils for modified Semi-Additive Processing, improving the process overall. 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.

The History of Carbon Direct Metallization

Carbon direct metallization processes have been widely used in the circuit board industry for more than 35 years. Widely utilized processes in the industry include ones such as Blackhole, Eclipse, and Shadow. The original Blackhole direct metallization 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. 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 metallization technology is approved for Space and Military Avionics applications under the requirements IPC 6012D, 3.2.6.1.

Board Evolution

Leading direct metallization 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 thru-holes. To meet the challenges of high-aspect ratio holes, line specifications encompassed improvements for solution transfer in small holes. Upgrades like the use of ultrasonics to quickly wet holes and remove air bubbles were implemented, along with in-line air knifes and dryers specially modified to dry the small holes on the thicker panels.

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 though-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 micro via became the enabler for designers to meet the challenge of High-Density Interconnect (HDI) technology. In 1997, the feature phone began using a 1+N+1 design in mass production. This is a one buildup layer with micro vias over a multilayer core. As mobile phone production grew, micro vias were formed by conformal etch and CO_2 lasers and later by UV, UV YAG and combo UV CO_2 lasers. Micro vias 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 currently highest volume contributor.

Direct Metallization to the Rescue

Direct metallization 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 micro via size presented trouble in 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 micro etch product developments were implemented to improve the lifting of carbon off the copper. From an equipment perspective, the micro etch 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.

With the next generation of the smartphones, makers moved to a build-up Any-Layer 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 to 40 µm. Each buildup layer in these processes requires a metallization and electrolytic plating cycle with more wet processing capacity.

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

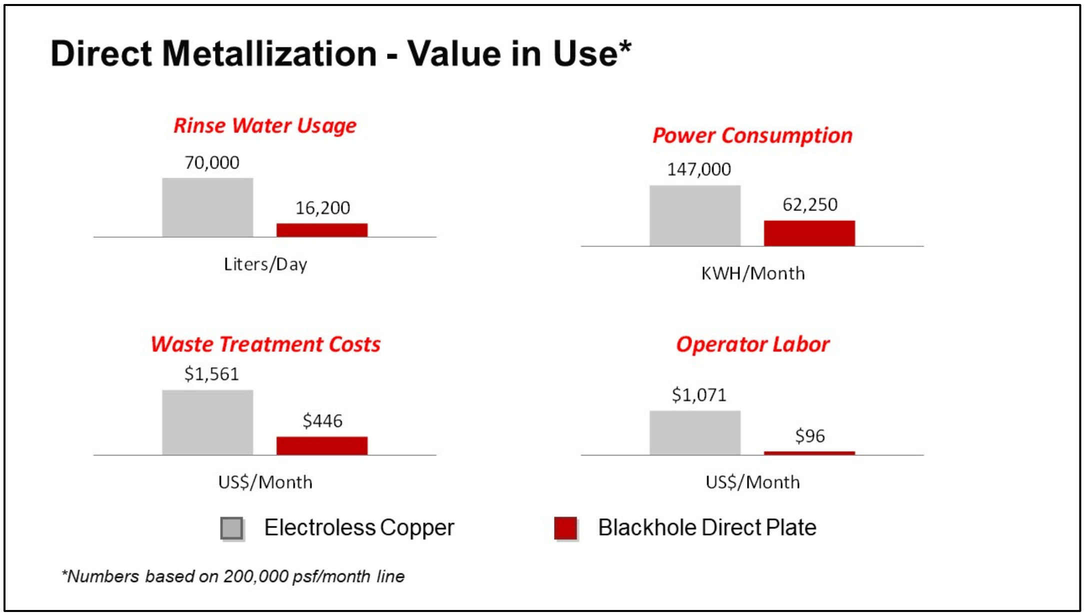

Figure 1: Direct metallization processes offer substantial environmental and financial benefits to fabricators

Copper Budget: The New Metric for mSAP Process Performance

Fast forward to today, the newest generation of smartphones and advanced packaging are utilizing a fabrication technique called mSAP or modified Semi Additive Process. 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 metallization processes.

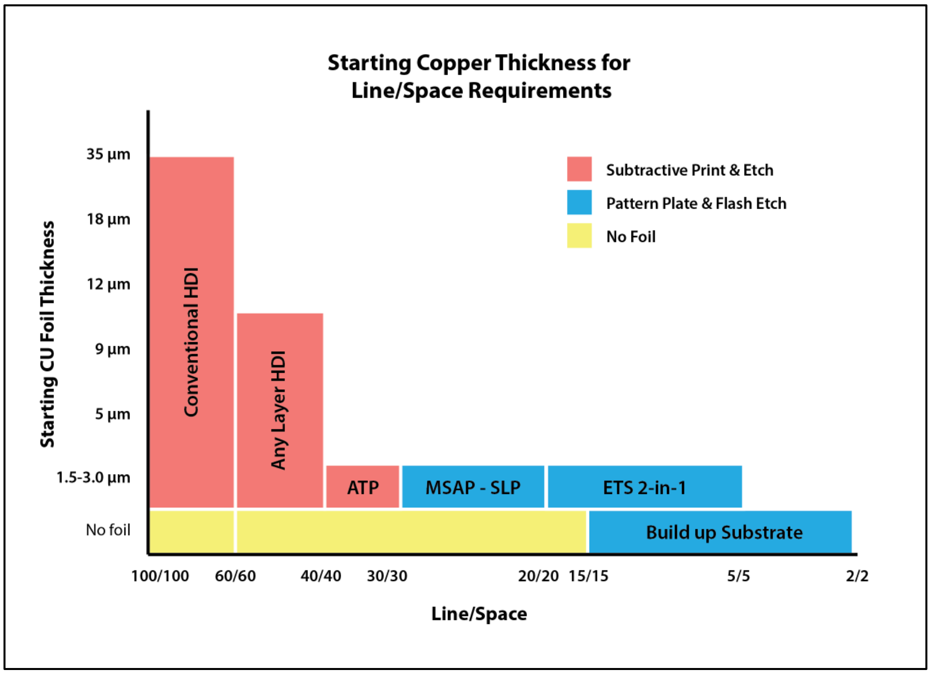

Figure 2: Shrinking line/space requirements for PCBs have created a need for stringent control of etch depth

The equipment team and product specialist group at MacDermid Alpha have now taken development of the carbon black process to the latest stage of its evolution. The newest line configurations for Blackhole Advanced Direct Metallization 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 metallization.

Advancements in Equipment Configurations

To optimize the direct metallization 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.

Several equipment modifications were selected for the Blackhole Advanced Direct Metallization 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.

The etch module was also extensively redesigned. Fabricators are quite concerned about the potential of leaving target pad that has only been partially cleaned, leaving 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 micro via 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.

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. 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.

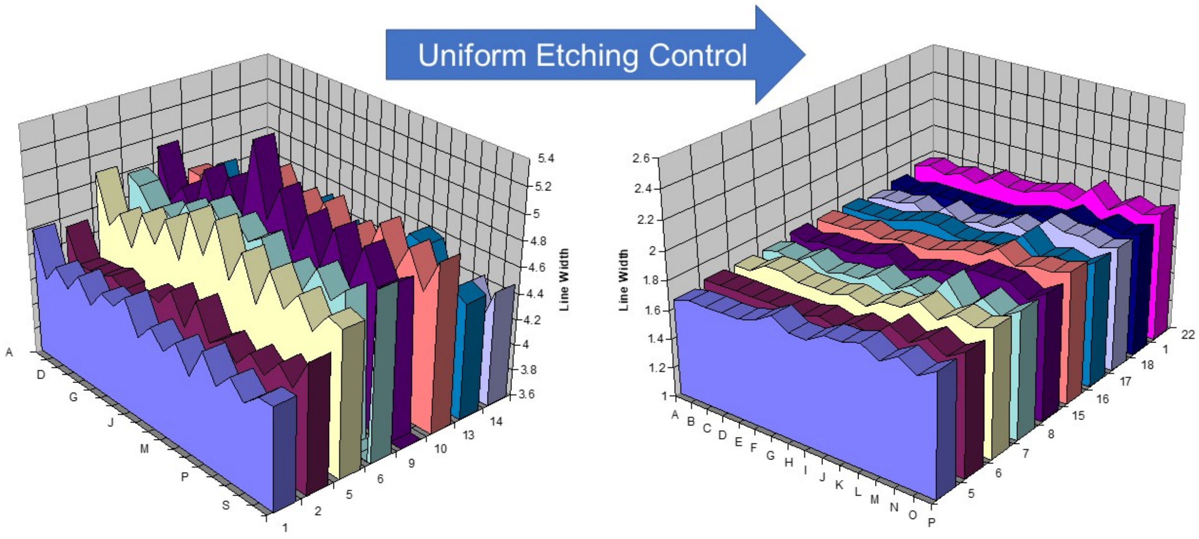

Figure 3: Uniform etching control through equipment and chemical improvements has allowed for complete removal of carbon residues in target pads.

Advancements in Chemistry

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 micro etching step. In another improvement, two-component micro etches 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 micro via reliability. The target pad copper crystalline structure is ideally prepared as a substrate to form epitaxial growth of the electrolytic copper.

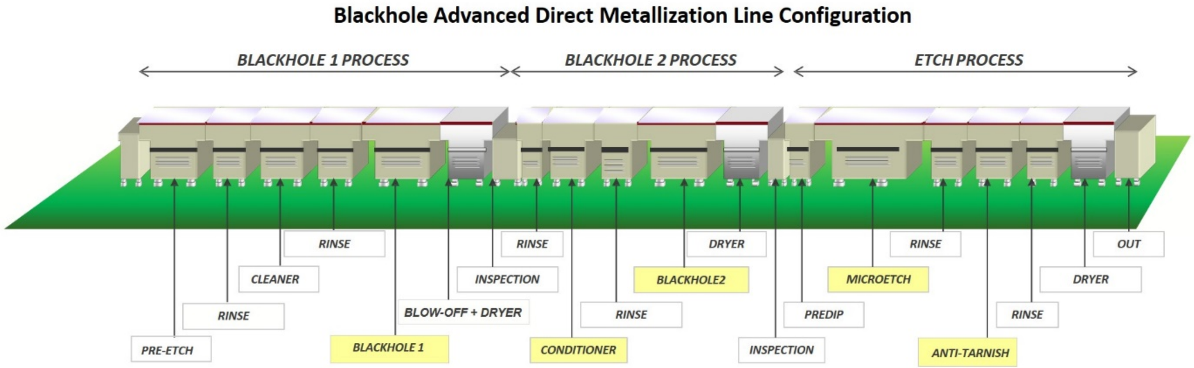

Figure 4: The micro etch module has proven to be key to the raising of micro via reliability in direct metallization processes.

Copper Grain Boundary Improvements

This combination of specific improvements to key process modules and chemistry have resulted in a line capable of running thin foil build-up layers for advanced HDI / mSAP. Micro via 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.

Studies with FIB using lamella cuts show the interface line to be uniform in grain size and structure. 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.

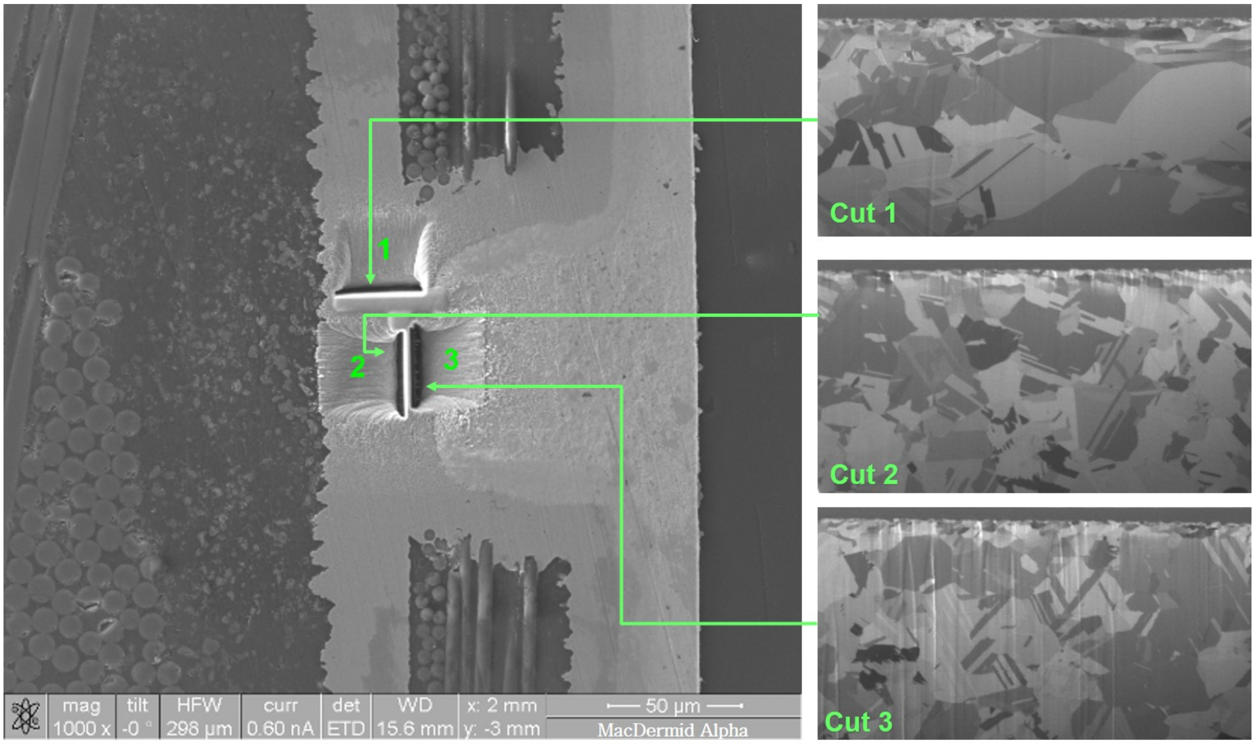

Figure 5: FIB imaging of the interface between the electrolytic copper plating and the target pad. Leading edge direct metallization technology allows for strong copper-to-copper bonding that performs excellent under thermal stressors.

Full Steam Ahead

Leading edge direct metallization process lines like the Blackhole Advanced Direct Metallization are now in mass production for mSAP with 3 µm Cu foil layups. Thes systems utilize controlled etch equipment configurations in mass production. Qualification testing on 12L Any-Layer panels processed with this equipment configuration passes IST testing through 300 cycles. In these designs, advanced direct metallization processing was done on Any-Layers L2-10 and mSAP L3-11. These designs have micro via hole sizes of 80-100 x 45 µm with approximately 2 million interconnects per panel. 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 Any-Layers and pattern plating on the mSAP buildup layer. The Electron Backscatter Diffraction (EBSD) image below shows the uniformity of the grain size at the interface between the target pad and electrolytic copper plating.

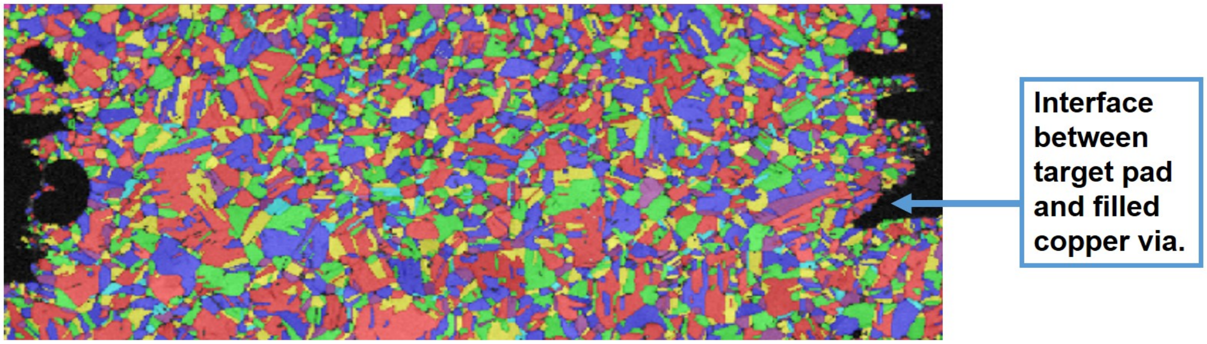

Figure 6: EBSD grain structure of via and target pad cross-section. Panel pre-conditioned at 260°C followed by 300 cycles at 170°C. Average grain size is 3.12 micron.

Summary

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 micro via has become synonymous with HDI design. As the change in PCB design progressed from through hole to HDI designs like Any-Layer and mSAP technologies, direct metallization technologies have made advancements in chemistry and equipment configurations to keep up pace with the industry. The leading edge advanced direct metallization 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 metallization offers a cost-effective and technology enabling solution for fabricators looking to expand their metallization capacity.