A Novel Approach in HDI Microvia Manufacturing: Understanding Laser Direct Drilling

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Introduction:

Microvia formation by laser is one of the key technologies for high-density printed circuit board production. Commercially available laser drill systems include two kinds of laser technology: CO_2 laser and UV laser. The CO_2 laser is much cheaper and faster than the UV laser but has the disadvantage of low energy adsorption for Cu surface. To overcome this, the industry has mainly been using the conformal mask technique, a complicated imaging and chemical etching process to make an opening in the copper surface to expose the epoxy prior to CO_2 laser drilling (Figure 1).

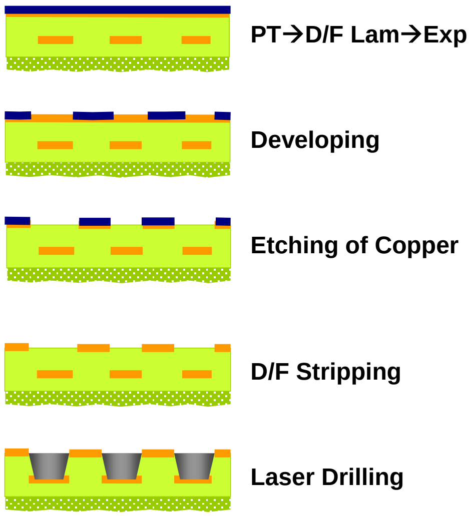


Figure 1. Conformal Mask Process

Yield reduction and the high cost related to the imaging, etching and stripping processes, which range from €3.00/m^2 up to €3.50/m^2, are major concerns for PCB manufacturers. Looking for an alternative, some manufacturers have started to use laser direct drilling (LDD) techniques either with Laser Drillable copper foils, or by applying a black oxide coating on the copper surface prior to laser drilling.

However LDD foils are expensive and the black oxide process is not well suited for thin material handling, has in excess of 2 hours total cycle time, high running costs and difficult waste treatment.

The industry is looking for alternative solutions to the problem of low CO_2 laser energy adsorption of copper surface. Traditional wisdom tells us that darker color and a rougher surface will help energy adsorption, however, in case of PCB laser drilling, which factor has more significant influence?

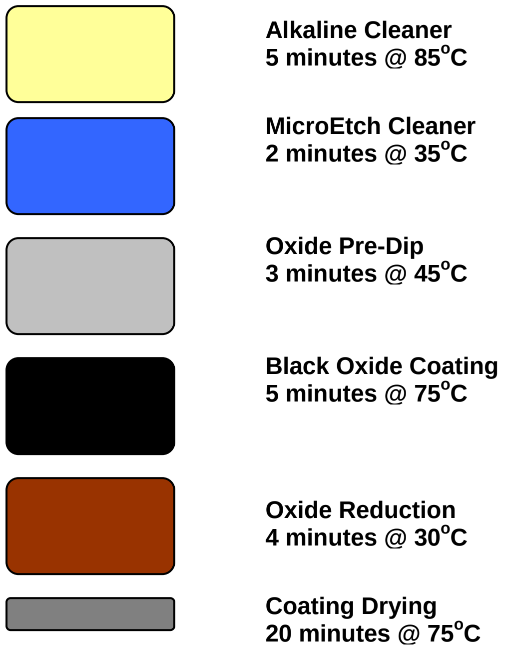


Figure 2. Black Oxide Process Flow

In the current study, a design of experiment was carried out around the factors of color and roughness using Black Oxide and Alternative Oxides processes. Advanced surface analysis devices, i.e. Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM), and Focused Ion Beam (FIB) were employed in order to qualify and quantify the various surfaces conditions. Laser drilling results were recorded and analyzed carefully.

It was found that an evenly etched surface created using an intergranular etching system or Alternative Oxide process, which offers the advantage of easy process control, lower cost and horizontal processing, can be successfully used in micro via drilling by CO_2

laser for HDI board manufacturing. This can replace the conformal mask technique, expensive LDD copper foils, and unreliable black oxide pretreatment before laser drilling (figure 3).

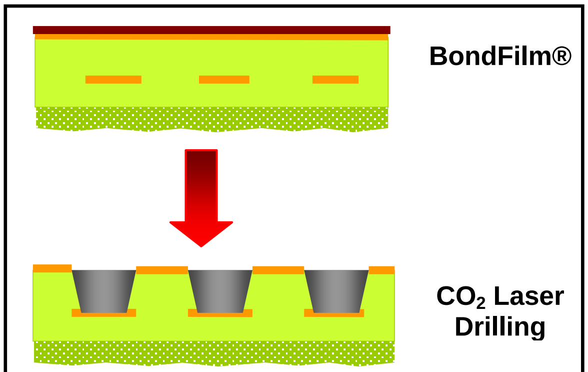


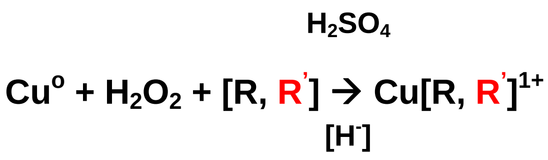
Figure 3. Laser Direct Drilling

Design of Experiment:

There are several significant factor involved with Laser Direct Drilling to ensure excellent laser absorption and consistent via creation. The key parameters are copper thickness prior to laser drilling. Typically this thickness is set 5–7 µm. As discussed earlier CO_2 lasers are not designed to drill through 18 µm thick copper foils as such the foil thickness must be ½ etched to ensure complete laser ablation.

Also significant is the roughness of the surface as measured by AFM and evaluated by SEM. This directly relates to the amount of energy that can be absorbed and it is also inversely related to the amount of energy reflected and lost.

The composition, color, and thickness of the laser drillable coating are also critical to LDD performance. In this case Reduced and Non-reduced Black Oxide Cuprous (Cu_2O), Cupric oxide (CuO) and Cu were investigated. The Oxide alternative chemistry, which is an organically, modified sulfuric acid and hydrogen peroxide microetch, creates a unique type of roughness or Intergranular etched surface (IGE) as well as forming a uniform brown organometallic coating. This organometallic is brown in color and is composed of primarily Cuprous Oxide (Cu^{1+}). The coating thickness is typically 65 – 70 Angstroms.



$$Cu^{o} + H_2O_2 + [R, R'] \xrightarrow[{[H^-]}]{H_2SO_4} Cu[R, R']^{1+}$$

Figure 4. Alternative Oxide Rx Mechanism

In addition to the above the IGE surface was subsequent treated with two post-treatments the first being a thin layer, 0.10 µm of immersion tin to create a gray tin oxide (SnO) coating. The other is a hydroxide based "Enhancer" to remove the excess organometallic coating to study the effect of the coating thickness.

Factor	Low	Mid	High
Etch Depth	0.8 µm	----	1.6 µm
Post Treatment	None	Enhancer*	Immersion Tin

*Enhancer is to remove organometallic

Factor	Low	High
Weight Gain	0.35 mg/cm^2	0.45 mg/cm^2
Reduction	With	Without

A full factorial design of experiment (DOE) was done with replications.

Response(s) & Surface Characteristics:

The primary response of the DOE was the average size of a hole opened in the copper surface after a single CO_2 laser pulse. This pulse width was varied from 6 µs to 24 µs with 2 µs increasing pulse widths. The laser's aperture varied between to opening sizes "5 & 18". The Microvia opening as well as critical via parameters (figure 5) were measured using stereomicroscopy.

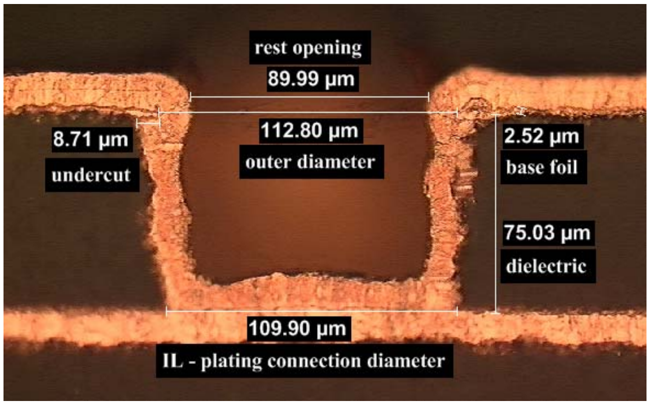


Figure 5. Microvia x-section detail of critical parameters after Laser Direct Drilling

Prior to laser drilling the surfaces were analyzed quantitatively by Atomic Force Microscopy (AFM). The average surface roughness (Ra), as well as absolute difference from the 10 highest peaks to the 10 lowest valleys (Rz) and the "Relative Surface Area Increase" (RSAI) were measured and tabulated.

Process	R_a (nm)	R_{ms}	R_z (µm)	RSAI (%)
IGE 0.8 µm	249	310	1.94	97%
IGE 1.6 µm	354	438	2.61	127%
BO 0.40 mg/cm	160	200	3.21	149%
BO 0.65 mg/cm	200	250	3.48	189%

In terms of surface roughness the above result offer two possible predilections for the out come of the LDD exercise. It would appear that Black Oxide at 0.65 mg/cm^2 in terms of % RSAI and Rz values should yield the largest holes. Black Oxide creates crystals a very thick copper oxide deposit with very large crystals, which provide superior surface area increases.

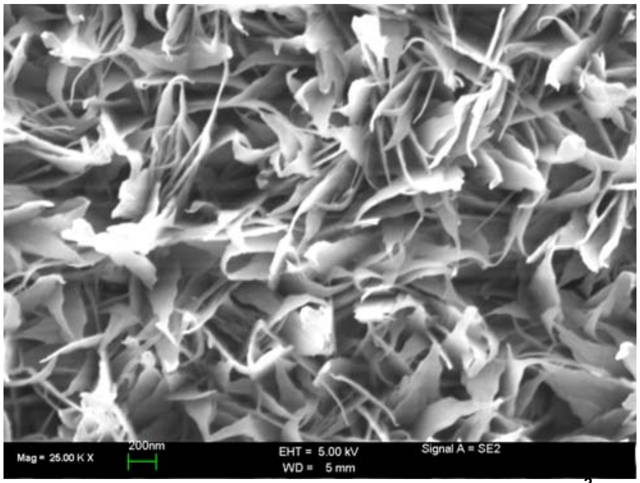


Figure 6. SEM of Black Oxide Surface (0.65 mg/cm^2) at 25,000x Magnification.

However, the surface is not very dense as can be concluded by the low Ra & Rms values. Here we find the IGE surface to have an advantage. The IGE surface although not as rough in terms of Rz and % RSAI but the surface is denser which can also mean better consistency. Not only is the surface denser but there is also a significant amount of organometallic on the surface (Figure 6), in contrast to after Enhancer (Figure 7), which in theory should help to absorb more laser energy.

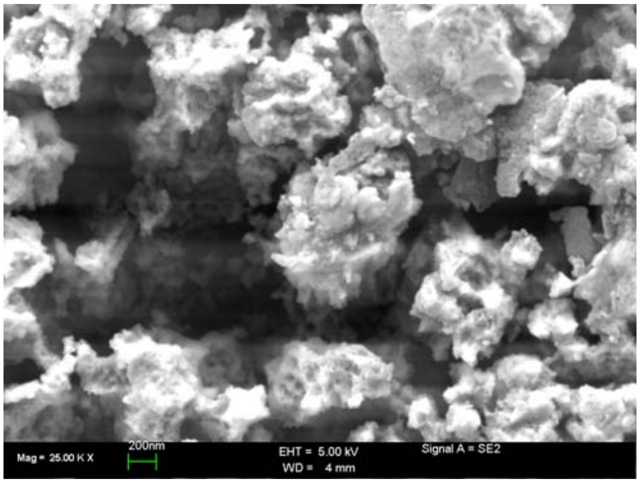


Figure 7. SEM of Intergranular Etched Surface (1.60 µm Etch Depth) at 25,000x Magnification

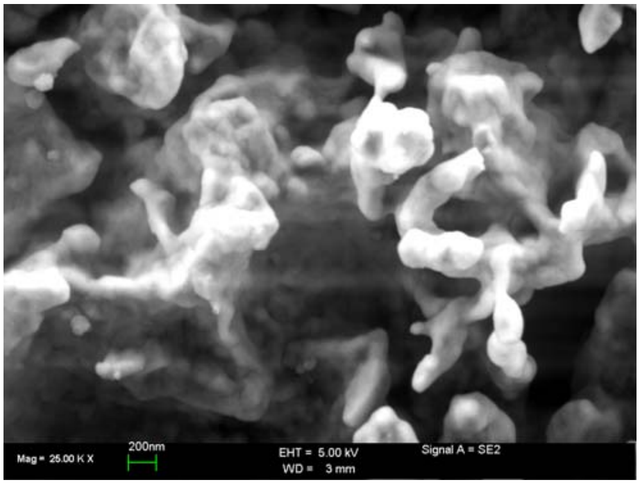


Figure 8. SEM of Intergranular Etched Surface + Enhancer (1.60 µm Depth) at 25,000x Magnification

Results & Discussion:

Combined it appears that the Black Oxide surface is ideal for laser absorption yielding the largest via opening (Figure 5) with a relatively small standard deviation. In direct comparison to the variations of IGE surfaces.

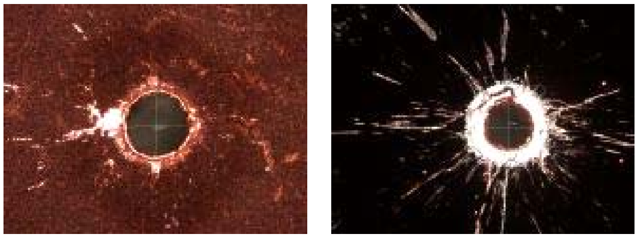


Figure 9. Via Opening in a IGE (Rights) and Black Oxide (Left) Surface after Single Pulse from CO_2 Laser

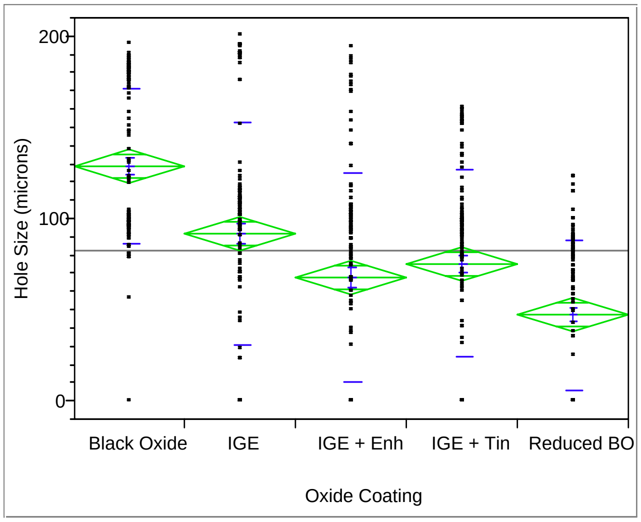


Figure 10. Combine ANOVA for Hole Opening by Surface Treatment

Level	Number	Mean	Std Dev
Black Oxide	120	128.783	42.0176
IGE	120	92.358	60.8486
IGE + Enh	120	68.200	57.1250
IGE + Tin	120	75.717	51.1603
Reduced BO	120	47.467	41.3121

Most interesting is the result for Reduced Black Oxide, which yielded consistently the smallest hole sizes. This is probably due to the fact that reduction removes up to 25% of the oxide layer and changes the structure of the crystals resulting in a “flattened” surface structure.

The combined results give a skewed understanding of what is actually the best surface for LDD. In practice to maintain consistent performance of a Black Oxide bath depositing 0.65 mg/cm^2 would be nigh impossible as the process would have to be run very hot with very high hydroxide content. Over a relatively short period of time the carbonate formed naturally during the reaction would prevent this.

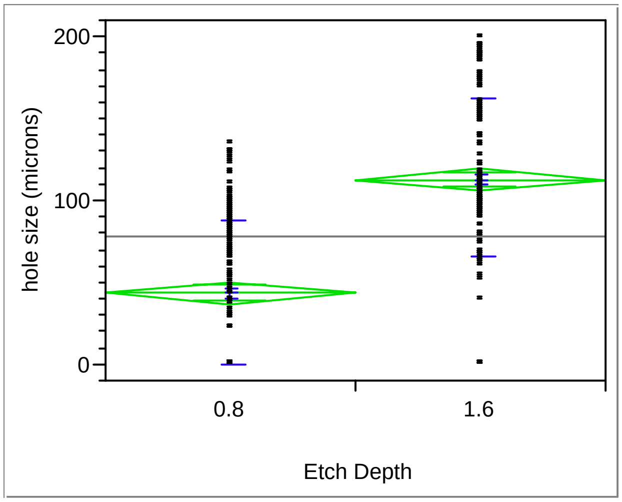


Figure 11. Combine ANOVA for Hole Opening by Surface Treatment

Level	Number	Mean	Std Dev
0.8	180	44.150	43.2860
1.6	180	113.367	47.8889

Also hidden in the IGE results are the effects of etch depth on the absorption potential. Clearly higher etch depths (Figure 11) yield larger hole sizes. Note that prior to drilling all surfaces maintained the same copper thickness. This is explained in that the samples at 0.80 µm have lower RSAI and thinner organometallic deposits versus the 1.6 µm-etched samples.

Thus removing all potential skew effects from the analysis a different picture emerges (Figure 12).

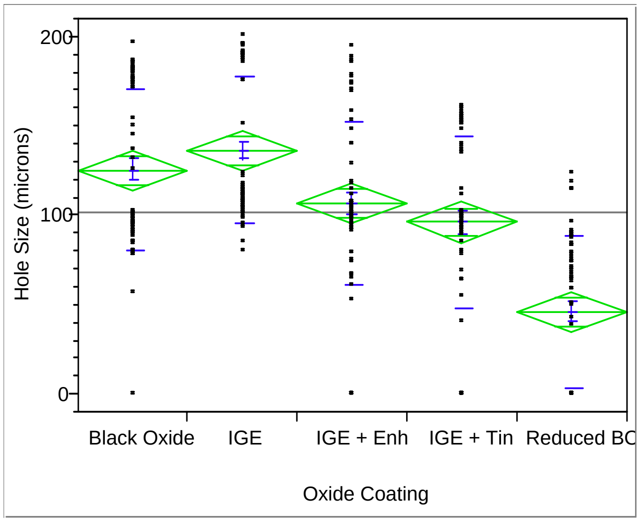


Figure 12. Combined ANOVA for Hole Opening by Surface Treatment

(Table for Figure 12)

Level	Number	Mean	Std Dev
Black Oxide	60	125.600	45.0244
IGE	60	136.317	40.6446
IGE + Enh	60	107.267	45.8494
IGE + Tin	60	96.517	48.3884
Reduced BO	60	46.417	42.6651

The IGE surface without a post treatment yields larger and more consistent holes when compared to "standard" black oxide. The effect of the organometallic thickness can be observed when comparing IGE vs. IGE + Enhancer. IGE + Enhancer yielded 20% smaller holes. This would indicate that the thickness of the coating on the surface enhances direct laser drill ability.

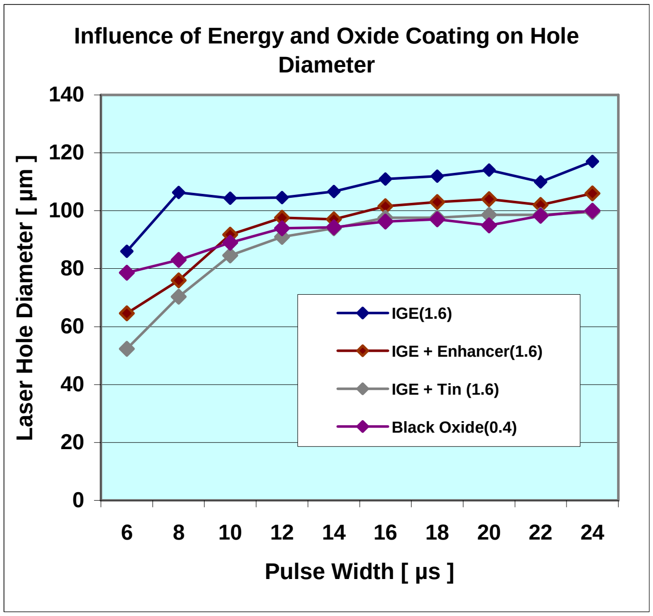


Figure 13. Via Diameter (µm) by Pulse width (µs) using various Oxide Treatments using Aperture Opening 5

The use of tin (IGE+Tin) provided no improvement in performance. In fact the presence of tin reduced the ability of the surface to absorb energy. It is assumed that the lighter color of the surface reflected some of the energy.

The superior performance of the IGE can be explained by the fact that the surface roughness is created directly in the copper surface, which enhances its ability to absorb energy and reduce the amount of light reflection and scatter (Figure 14). While for Black Oxide (Figure 15) the roughness comes from the oxide crystal growth. Although substantial in roughness the copper surface underneath is relatively smooth which possibly accounts for the energy loss. Also the stability or consistency of microvia formation is significantly better when using an IGE.

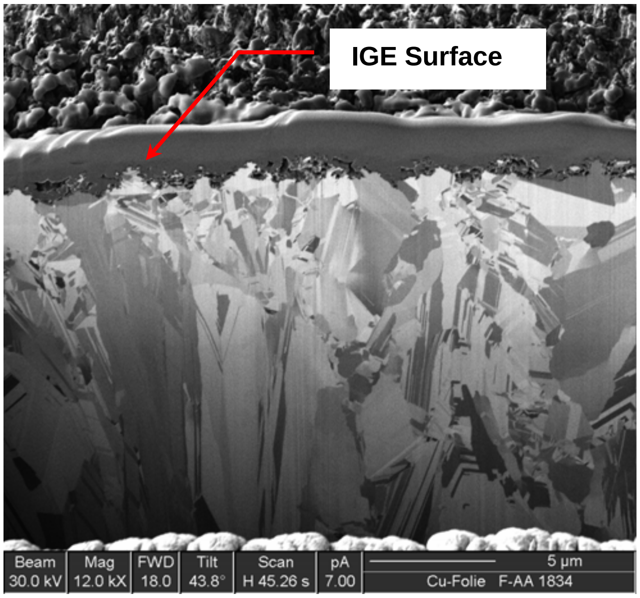


Figure 14. Focus Ion Beam Analysis of an Intergranular Etched Surface

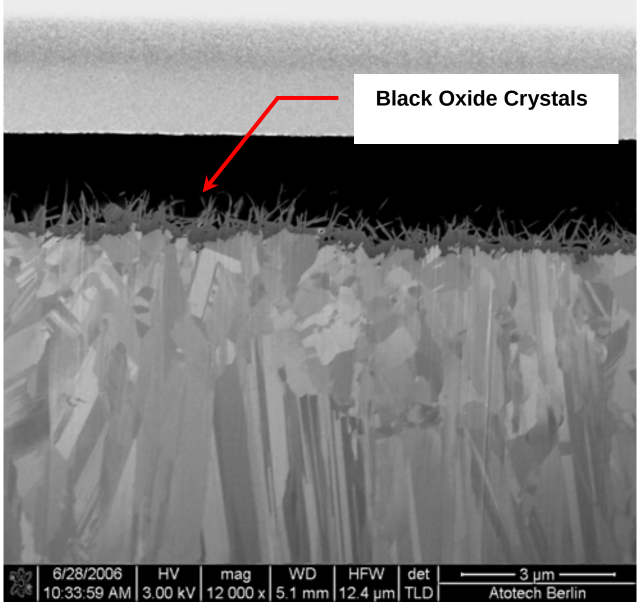


Figure 15. Focus Ion Beam Analysis of an Intergranular Etched Surface

The use of the IGE allows for significantly less energy to be used thus creating a better hole with less undercut and better via shape for subsequent plating.

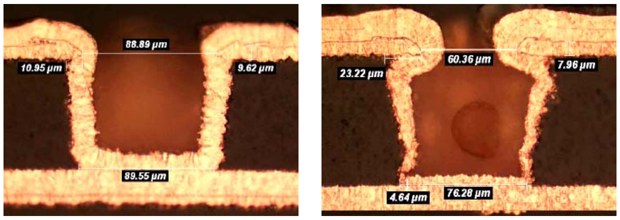


Figure 16. Vias formed with an IGE (Left) and Black Oxide (Right) Surface after Complete CO_2 Drilling and Plating

When the undercut is too great there can be significant problems with plating. Due the hole shape plating folds are likely, also as it is difficult to exchange solution in this hole shape even with advanced flooding systems you can also see in extreme cases rough plating on the capture pad and wedge voids (Figure 16).

When via filling is required this will be incomplete and during soldering the entrapped air will expand rapidly “blowing off” the soldermask and any components above this via hole. (Figure 17)

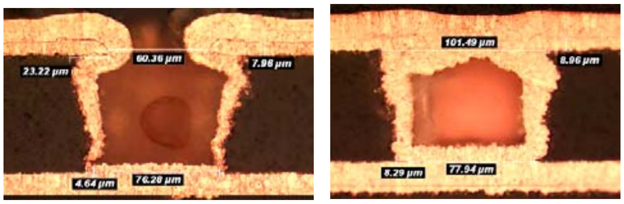


Figure 17. Vias formed with Black Oxide Surface after Complete CO_2 Drilling and Via Filling

This via hole shape will also result in significant problems with Electroless Nickel and Immersion Gold (ENIG) plating and indeed all surface finishes will have difficulty to exchange solution in this hole shape whether plating or coating processes.

Summary & Conclusion:

There are many significant factors in creating microvias using laser direct drilling. We found that surface color; chemical composition, surface roughness and depth of the coating on the surface can affect the ability of the copper surface to absorb CO_2 laser energy. Contrary to belief an IGE prepared surface yields consistently larger vias with excellent shape characteristics. In direct comparison Black Oxide, due to the unstable nature of the surface, could not consistently form vias, yielding some 10 –15% smaller vias than the IGE but more significantly the hole shape was also not as good, which has ramifications for subsequent processes.

The affect or significance of surface roughness has been better quantified for LDD applications.

LDD performance does not depend directly on surface roughness (macro) but more the density of the surface roughness (micro). The color was found to be not as significant as earlier believed with the brown surface of the IGE absorbing energy just as effectively as the velvet Black Oxide surface.

The use of an IGE like BondFilm® LDD which is specially designed to create the optimal intergranular etched surface and to deposit a dense organometallic layer, can greatly improve performance while lowering cost.

BondFilm® LDD is designed for horizontal processing to ensure process stability and consistent performance thus making BondFilm® LDD ideally suited for Laser direct drilling.