Laser Ablation of Thin Films on LTCC

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Abstract

Direct Digital Manufacturing techniques such as laser ablation are proposed for the fabrication of lower cost, miniaturized, and lightweight integrated assemblies with high performance requirements. This paper investigates the laser ablation of a Ti/Cu/Pt/Au thin film metal stack on fired low temperature cofired ceramic (LTCC) surfaces using a 355 nm Nd:YAG diode pumped laser ablation system. It further investigates laser ablation applications using unfired, or 'green', LTCC materials: (1) through one layer of a laminated stack of unfired LTCC tape to a buried thick film conductor ground plane, and (2) in unfired Au thick films. The UV laser power profile and part fixturing were optimized to address defects such as LTCC microcracking, thin film adhesion failures, and redeposition of Cu and Pt. An alternate design approach to minimize ablation time was tested for efficiency in manufacture. Multichip Modules (MCM) were tested for solderability, solder leach resistance, and wire bondability. Scanning electron microscopy (SEM) as well as cross sections and microanalytical techniques were used in this study.

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Key words
Ablation, Laser, LTCC, Thin Film

I. Introduction

We demonstrate the implementation of laser ablation of thin films on LTCC to form the pattern of critical circuit features, some examples of which are shown in Figure 1. These include traces, solderable pads, wire bondable pads, and unique structures consisting of metallized valleys to be shown later in this paper. Work was conducted in four phases: Efforts began with an elementary feasibility study, then progressed to improved settings to support next-assembly processes—mainly wire bonding and soldering. Subsequently, edge contour definition and surface damage effects were addressed that could constitute reliability problems. Many important aspects don't readily appear in an optical top view so Scanning Electron Microscopy (SEM), cross-sectioning, and accompanying microanalyses were performed to supplement visual inspection. We will discuss how settings were changed to reduce cracking, debris, and undesirable contours. We will highlight work

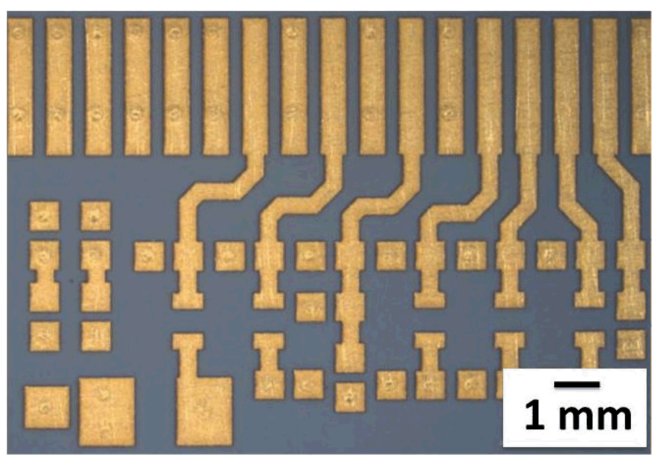


Figure 1. Laser ablation of critical circuit features in thin films on fired LTCC.

that is still needed to assure success of this technique. We will also evaluate laser ablation of unfired tape and thick film conductors in a natural extension to more-refined features interior to the circuits. Finally, a technique has also been prototyped that minimizes the degree of laser cutting necessary.

II. Background

Low Temperature Cofired Ceramic (LTCC) is a well-known substrate technology for multilayer circuits. Its three dimensional capabilities have been exploited for shaped circuits, sensors, actuators, and non-electronic applications as well. LTCC remains a technology of choice for high frequency circuits for its excellent material properties, nearly unlimited stacking capability, form and fit versatility, and environmental performance. The background work, as well as that presented in this report, were performed on one of several, popular commercial LTCC tapes—the DuPont™ 951 system (DuPont™ is a trademark of the E.I. duPont de Nemours and Co, Wilmington, DE). We have used a conventional firing profile that included a burnout dwell at 450ºC and a final firing dwell at 850ºC.

Most such circuits would use cofired conductors on outer surfaces. The choice of a thin film outer conductor instead of a co-fired thick film conductor has been justified previously [1, 2]. The present technique involves uniform coating with a thin film stack. Ion milling, in combination with photolithography, is used to define the conductor traces, solder and wirebond pads, as well as other features for a multichip module (MCM). A well-known problem is matching tape shrinkage upon cofiring (with a specified tolerance) to the fixed dimensions of the photolithographic mask. Otherwise, the photoresist is an effective barrier for the ion milling operation. Although ion-milling provides excellent feature definition, it requires photolithographic operations that include the exposure of LTCC circuits to various processing fluids. Throughput has been improved by automating the various process steps. However, there are high capital costs associated with the ion milling equipment.

Although ion milled MCMs have been very successful, as prototypes mature into actual product, there is increased emphasis to reduce the costs, increase manufacturing throughput and reduce flow time. An evaluation was undertaken to determine if laser ablation as a means to define the thin film patterns could address these concerns. An ancillary benefit is that laser ablation eliminates the need for waste disposal of hazardous chemicals.

A high-level comparison of characteristics of ion milling and laser ablation is shown in Table 1.

Table 1. Comparison of selected laser ablation factors to ion mil factors.

Ion Mill

- High equipment cost
- Batch process, parallel
- Requires photolithography
  - Glass masks
  - Photoresist
  - Mask aligner
  - Develop
  - Strip
-

Laser Ablation

- More affordable equipment (3:1)
- Batch process, serial
- Requires ‘cleaning’
- Larger heat-affected-zone
- Artifacts
  - Deep cut at line edges
  - Other edge effects
  - Secondary cracking in open areas
- Manual loading, unloading
- Agile programming

Literature studies have documented the attributes of laser ablation as a tool for building microelectronic circuits [3, 4]. The ability to tailor the energy input to specific areas of the circuit provides the flexibility needed to control material response with respect to absorption and related effects such as substrate melting, resolidification artifacts, and metal redepostion. Redeposition has been described as inevitable to some degree; but, it needs to be minimized to prevent foreign object debris (FOD) that interferes with wire bonding, soldering, and electrical integrity. Other process details are beam width and raster profile that are used to define edge ‘cuts’ or hatching cuts. As with any subtractive process, the ability to remove only what is necessary for the design to function with the intended circuit geometries generally improves manufacturing efficiency.

Our work was performed on commercial laser systems in collaboration with DuPont™ Electronic Technologies and LPKF Laser & Electronics AG (Garbsen, Germany, abbreviated LPKF). Early work was done at DuPont on an LPKF ProtoLaser U. The bulk of the work was done at LPKF on an LPKF ProtoLaser U3 in order to take advantage of the power mapping feature [5]. Both systems are 355 nm diode-pumped Nd:YAG UV laser systems. The parameters that were altered included laser power, pulse frequency, travel speed, and configuration definition for the hatch/contour modes. A hatch cut consists of a parallel raster in a single direction. A cross-hatch cut consists of two hatch cuts in orthogonal orientations. A contour cut traces the edges of the pattern. A high-level summary of the laser parameters is provided in Table 2.

Table 2. Laser Parameter Summary

Experimental Phase	1	2	3	4
Laser Model	U	U	U3	U3
Power (W)	2.5 - 3.0	2.5 - 3.0	6.7	1.1 / 0.5
Frequency (kHz)	150	150	150	75
beam spot size (µm)	20	20	15	14
beam pulse (µm)	15	15	12	7
Travel Speed (mm/sec)	75	100	100 - 250	600
Air Pressure	NO	NO	NO	YES
Contour Reps	2	1	1	0 - 2
Hatch Reps	2	1	1	1-6*

* Cross-hatch used

The thin film stack was comprised of 0.20 µm Ti as the adhesion layer to the LTCC substrate. The remainder of the thin film layer included 4.0 µm Cu followed by a 2.0 µm platinum (Pt) barrier layer and lastly, a 0.38 µm gold (Au) that formed the exposed surface.

The test patterns were analyzed using the scanning electron microscope (SEM). It was advantageous to document features by either the secondary electron (SE) mode, which shows primarily topological features, and the back scattered electron (BSE) mode, which can detect chemical species variations. The SEM techniques were used for both surface investigations as well as the microanalysis of cross sections created by metallographic preparation techniques. To augment the BSE image results, energy dispersive x-ray (EDX) analysis was used to also map, qualitatively, the distribution of elemental species that are a part of the test pattern.

Phase 1 Results

Features from an initial test pattern for the thin film metal stack are shown in Figure 2 including (a) square 150 µm and 200 µm wirebond pads, (b) square 0.86 mm and 0.97 mm solder pads, and (c) S-band RF transmission lines. Early efforts involved the LPKF U laser at DuPont and employed initial settings that were optimized previously for thick film Au metallization. These patterns showed promise but highlighted the need for process improvements. As well as being a practical necessity, wirebonding is a useful diagnostic technique but wirebond pads were not resolved and no wirebonding was performed on phase 1 parts. In addition, the laser ablation in open areas caused excessive loss of substrate material.

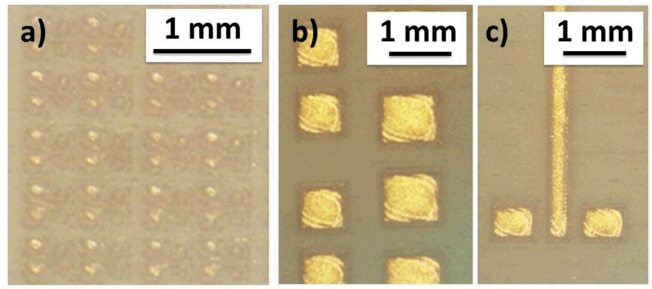


Figure 2. Phase I study a) Wirebond pads, b) Solder pads, and c) Transmission line segment.

Phase 2 Results

A second phase of the study employed the same laser as used in phase 1, but with optimized settings to address poor definition of fine features, excessive ablation of open areas, and redeposited material that led to poor wirebonding. These concerns were addressed primarily by varying the travel speed of the laser beam. A comprehensive test pattern was used and is partially shown in Figure 3.

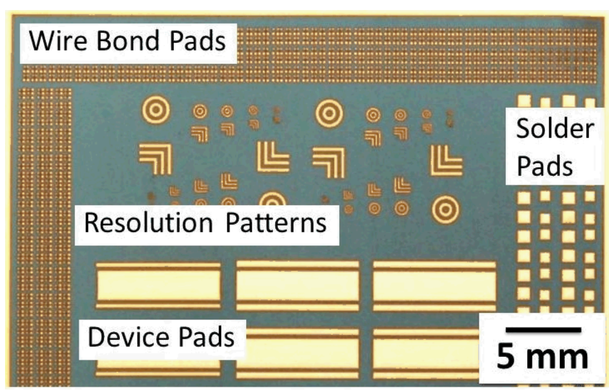


Figure 3. Test pattern consisting of representative wirebond, solder bond, and die attach pads as well as various resolution patterns.

The wirebond pads were still not bondable as evidenced by low pull strengths and numerous locations where bond 1 (gold ball) failed to adhere to the pad ("no-stick" failure mode). Several bonds that adhered initially later lifted under relatively benign handling conditions. The poor wirebonding result (Table 3) was later attributed to redeposited material.

A comparison of the laser-ablated and non-laser-ablated LTCC surfaces is shown in Figure 4. The hatch cut was performed in a single orientation (top-to-bottom) as is evident in Figure 4a. The grooves created by the laser ablation path are approximately 10-15 µm wide (yellow arrow).

Table 3. Ball Bond Testing of 1 mil wire

Phase	1	2	3	4
Average Pull Strength	N/A*	5.01g	11.35g **	12.25g
Standard Deviation	N/A*	2.13g	0.70g **	0.77g
Mean minus 3 Standard Deviation	N/A*	> Zero	9.25g **	9.94g

*6 x 6 and 8 x 8 mil pads not defined, not tested
**bonding on 38 mil square pads

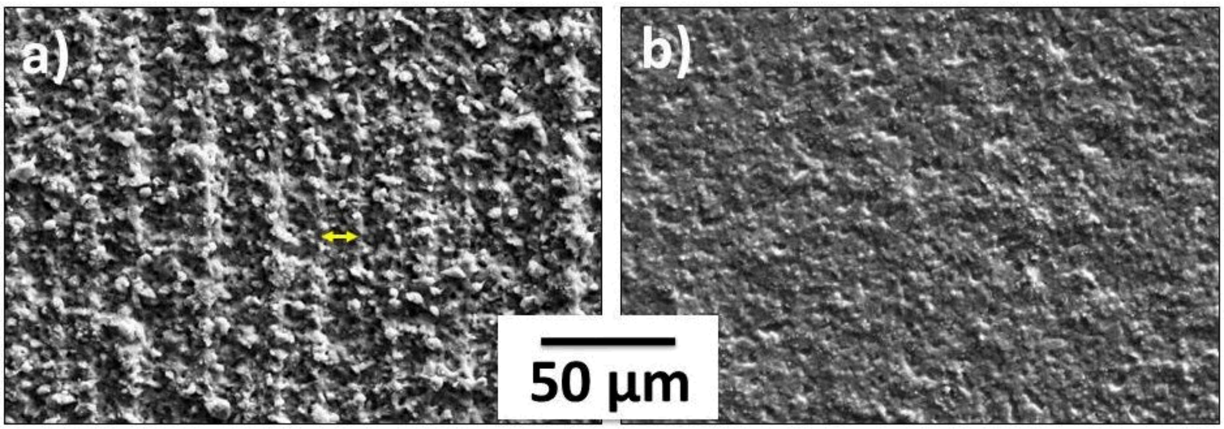


Figure 4. Comparison of a) laser-ablated surface and b) non-ablated surface.

A comparison is made between the SEM/BSE images in Figure 5 that further highlights differences between the two surfaces. After taking into account the added topography, the SEM/BSE image in (a) indicates a redistribution (coarsening) of the SiO_2 and Al_2O_3 phases. The added structure included an increased degree of porosity on the laser ablated surface. The laser ablation caused rapid melting and resolidfication of the LTCC surface as signified by the rounded particles. Finally, surface cracks are present, some of which are indicated by the magenta arrows.

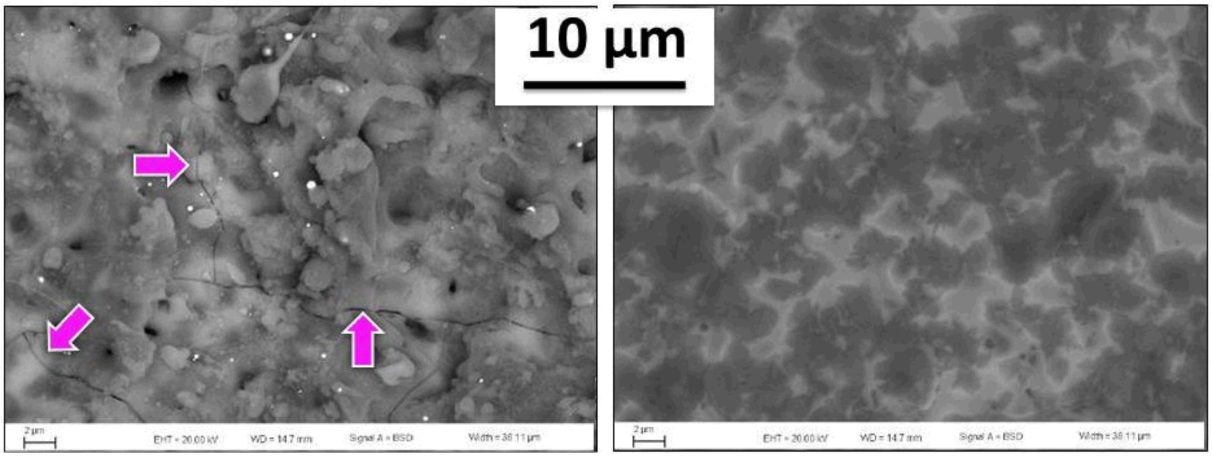


Figure 5. (a) Cracking (magenta arrows) observed in early work that examined the laser-ablation of LTCC. (b) The non-ablated surface used for comparison purposes.

The extent of surface modification caused by laser ablation warrants an effort to confirm that the LTCC substrate will not fail, catastrophically when exposed to next-assembly process shock-and-vibration conditions experienced in use.

An examination was made of the definition of the metallization edges; those results are illustrated in Figure 6.

The schematic diagram in the high magnification image show, qualitatively, the surface profile trace at the edge of the thin film feature. The groove depth created by the laser was estimated to be approximately 30 µm. The thickness of the thin film stack is 6.6 µm.

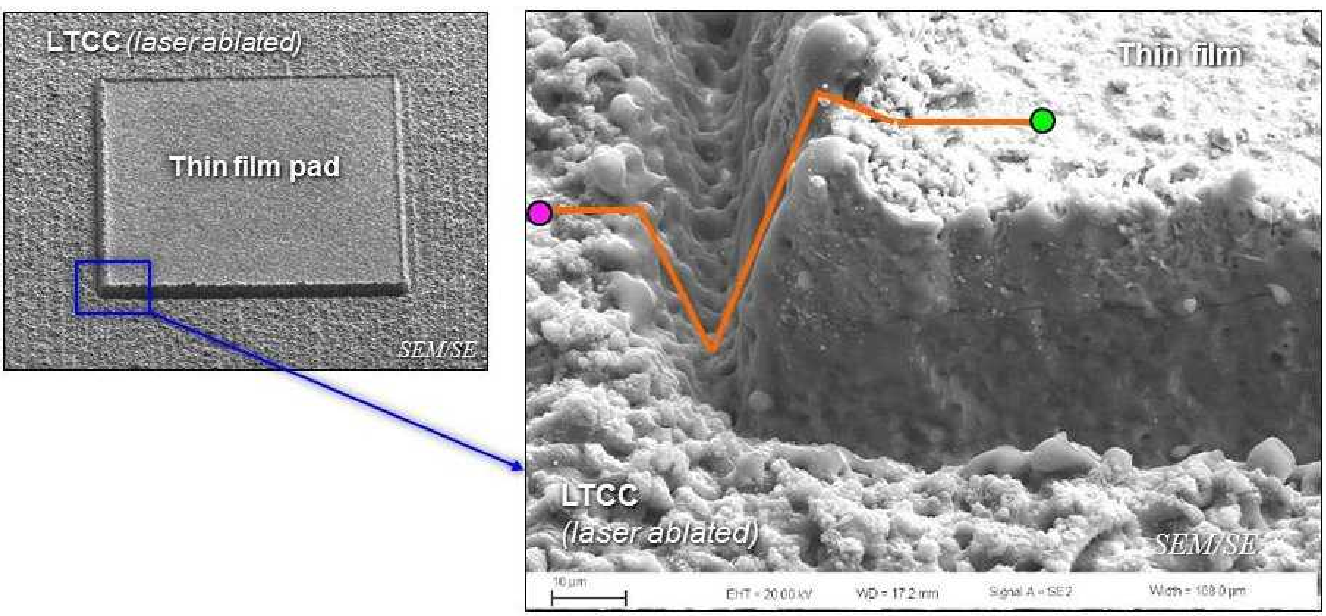


Figure 6. Edge definition is shown by these SEM/SE images of a thin film pad corner. The schematic diagram illustrates the general profile of the pad edge.

The SEM/energy dispersive x-ray (EDX) analysis was used to determine the chemistry structure of the thin film stack exposed by the laser ablation process. In particular, the buildup of material at pad edges can be a problem on closely spaced wirebond pads as it interferes with the wire bonding process. Energy-dispersive X-ray analysis maps were produced, which are shown in Figure 7, that indicate that Cu is the primary constituent at the pad edge. Furthermore, Cu (purple map) is the primary element that is redeposited on top of the Au layer (strawberry) of the pad.

The presence of Cu on top of the thin film pad oxidized, resulting in a degradation to the wire bond pull strength. The soldering behavior is more forgiving and it was possible to solder to these films using the traditional 63Sn-37Pb (wt.%) solder.

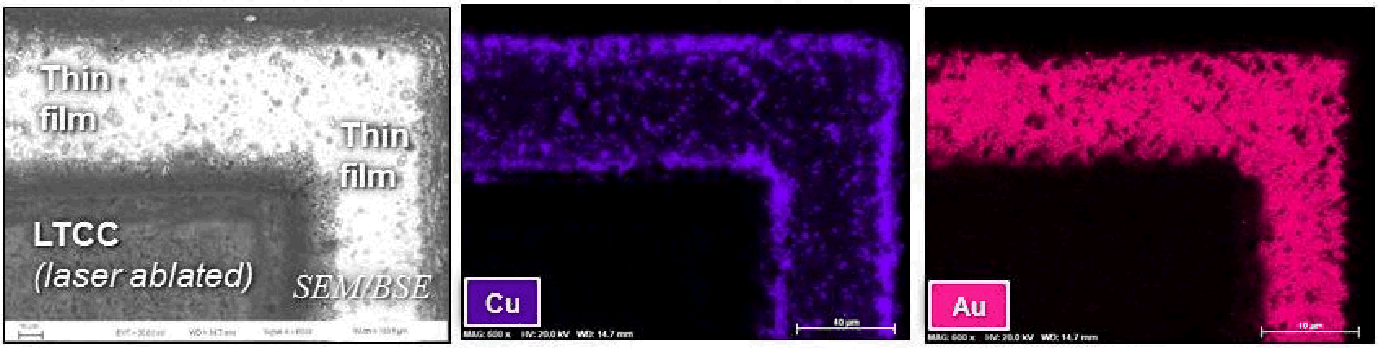


Figure 7. EDX maps in a corner of a thin film resolution feature illustrate copper redistribution and gold coverage.

Phase 3 Results

Phase 3 efforts were performed on-site at LPKF, using the LPKF U3 laser system. The LPKF process parameters were defined as 6.67 watts laser power, 15um beam spot size, 12um beam pulse width, and 250 mm/s travel speed. The raster format consisted of one hatch pattern and one contour pattern. No cross-hatch pattern was used in part of the study.

Both the LPKF ProtoLaser U and U3 models utilize a 355nm tripled Nd:YAG source with 6W power. However, the original ProtoLaser U source did not allow for power mapping and a 20µm beam was reduced to approximately 15µm on the U3. Delivered power on the U could be modified/reduced only by adjusting the laser travel speed and pulse frequency. The U3 model has power mapping capability that allows laser power adjustment from 0.5 to 6 W, or less depending on the requested frequency. The U3 settings can then be modified for the laser travel speed and pulse frequency to provide greater control on the energy delivered and multiple repetitions can be assigned within the software to control the rate of ablation.

The SEM/BSE images in Fig. 8 show the pad edge definition by cross section profile. While the general ablation step removes approximately 13 µm of LTCC, the edge definition results in a loss of 19 µm *or* 30 µm of material. The asymmetry to the edge valley depth is reproducible throughout all of the patterns on the LTCC. Upon reviewing the laser path data, it was determined that the software had calculated the hatch paths at a proximity which causes overlap with the contour laser path in select areas depending on the resolution grid for path calculation. It is apparent these areas cause the asymmetric valleys and deeper cuts where laser path overlap exists. Software improvements are being implemented due to the effect discovered. The operator can modify the calculation before processing to prevent areas of overlap and variations in depth of cut or disable the contour path altogether. In some RF applications, a more pronounced contour may be desired for wave propagation and variations in the contour path laser settings are controllable apart from laser settings used for the hatch areas.

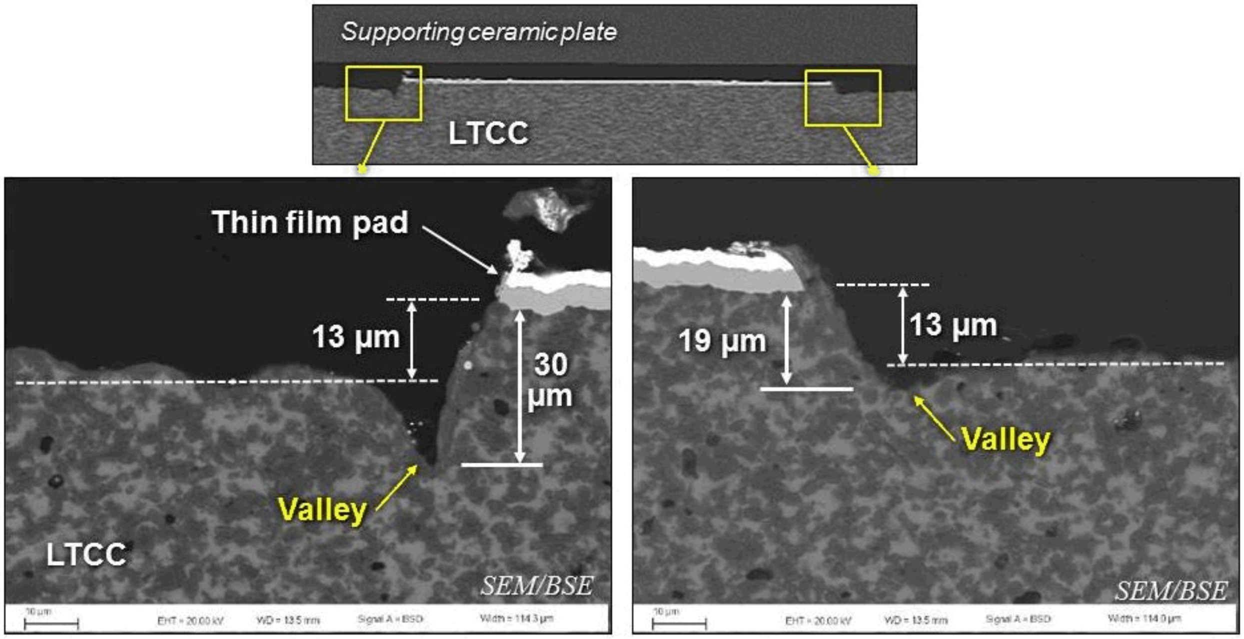


Figure 8. Cross sections illustrating deep cuts at pad edges. The asymmetry to the depth of the valley adjoining the pad was reproducible over the pattern..

The degree of surface alteration is illustrated by the SEM image pair in Fig. 9. The SEM imaging modes were: (a) SEM/SE and (b) SEM/BSE. The red arrows identify the depth of surface that experienced melting and resolidification. The topological information was provided by the SEM/SE image in Fig. 9a. That layer does not show the individual alumina grains and silica glassy matrix that characterizes the bulk material. There was minor cracking in the layer that resulted from the rapid solidification. The SEM/BSE image in Fig. 9b shows that there is an absence of the individual phase morphology that characterized the bulk material. The gray tone shows that the two phases were intermixed as a result of the melting event. Given the fact that this altered phase distribution is present everywhere that LTCC has been exposed by the ablation process, it must be verified that the new morphology does not alter either the electrical properties (e.g., dielectric constant) or mechanical performance (e.g., fracture strength) of the LTCC material.

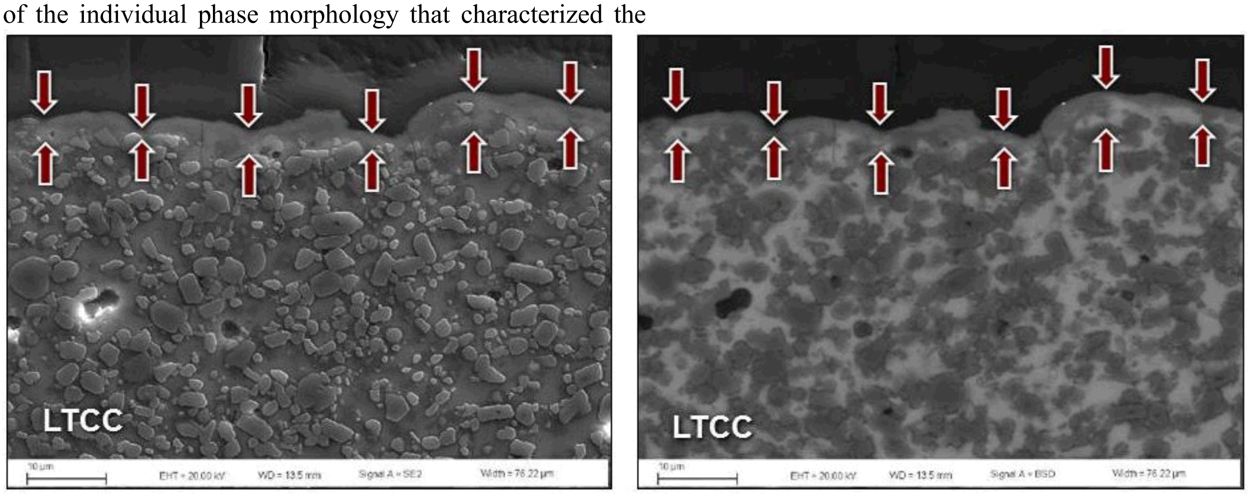


Figure 9. These SEM images show the melting and resolidification layer (between red arrows) that resulted from the laser ablation process, using the two SEM imaging modes: (a) SE and (b) BSE.

The analysis of these test vehicles also documented an infrequent occurrence of thin film delamination from the LTCC near to the laser ablated surface. Although rare, it is prudent to understand the root-cause vis-à-vis the need to optimize the laser ablation parameters.

The wire bond results are shown in Table 3 (phase 3). Phase 3 results were slightly below historic values due to raised edges on the 150µm and 200 µm pads that interfered with bonding, depending on bond orientation.. Failure modes on phase 3 were divided as such: 'golf club' bonds, bond lifts and neck and mid-span breaks on 150µm and 200 µm pads. However, failure modes consisted of neck and mid-span breaks only on the larger, 0.97mm, pads. This reflects the effect of edge definition problems for the smaller pads through phase 3.

Phase 4 Results

The effective laser power was reduced considerably in subsequent evaluations. The ability to perform power mapping and operate at lower power was appealing in terms of reducing surface damage on, and lost material from, the LTCC surface as well as to minimize redeposition of the metals. A laser ablation DOE was completed at the LPKF site. A new baseline process was defined for structuring the thin film metal stack which included laser power at 1.1 watts laser power, 75KHz beam frequency, 14um beam spot size, 7um beam pulse width, 600 mm/s travel speed, four cross hatch cuts, and no contour pass.

These first experiments involved a DOE that was used to determine the optimum settings. Microcracking, which was one of the control metrics that was minimized in this exercise, is shown in Fig. 10. The SEM image in Fig. 11 shows that the parameter optimization was capable of reducing edge build-up on the pads, as well.

The 0-2 contour cuts and 1-6 hatch cuts, which were included in the phase 4 study, were made to the thin film pattern in order to confirm the optimized parameter space. The optimum configuration was determined to be 4 cross-hatch cuts and no contour cuts. The overall results are listed below:

1) Cracking was reduced, significantly.

2) Surface contamination by redeposition was curtailed, which was documented, not only by the EDX analysis, but also by excellent wire bonding results. An EDX spectrum from the pad surface verifies that copper contamination was not a factor in the wirebonding results (Figure 12).

3) Wirebonding strengths were high as shown in Table 3. Failure modes on phase 4 pads consisted exclusively of neck and mid-span breaks that are observed as the norm on typical ion-milled pads.

4) Solderability, which was excellent on patterns defined in phase 3, was retained at this level in phase 4 as demonstrated by Fig. 12.

5) A cleaning step is still necessary to assure the removal of FOD created by redepostion, but had not yet been defined in the process development.

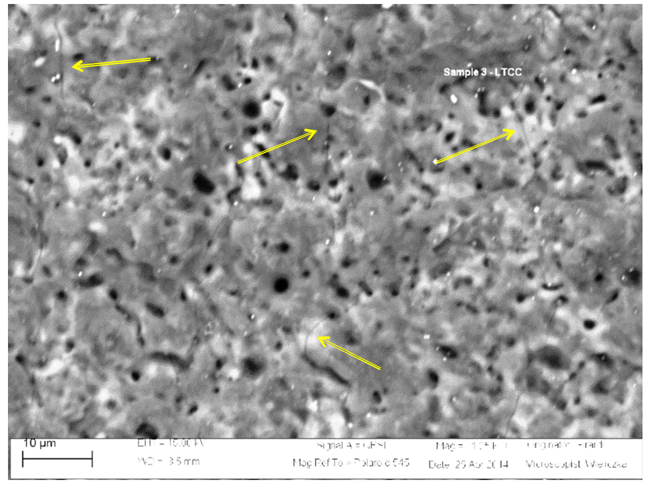


Figure 10. Surface cracking is shown for a test piece from the phase 4.

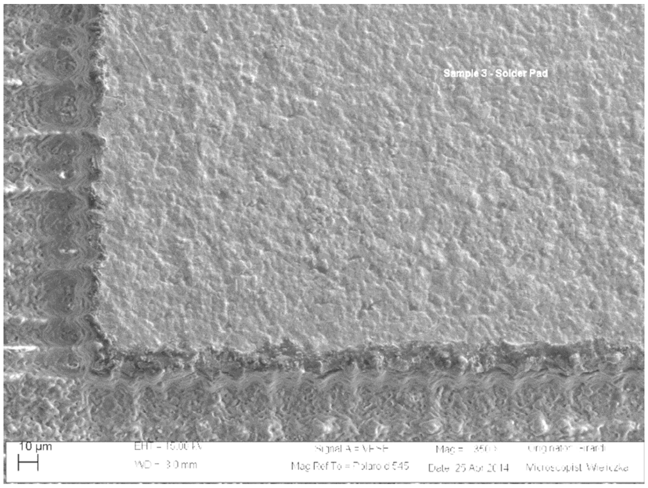


Figure 11. Optimum setting without edge build-up.

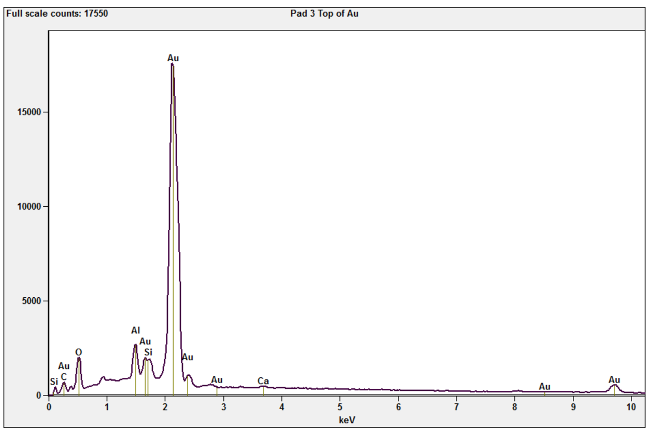


Figure 12. EDX spectrum from phase 4 thin film pad surface illustrating the lack of copper contamination.

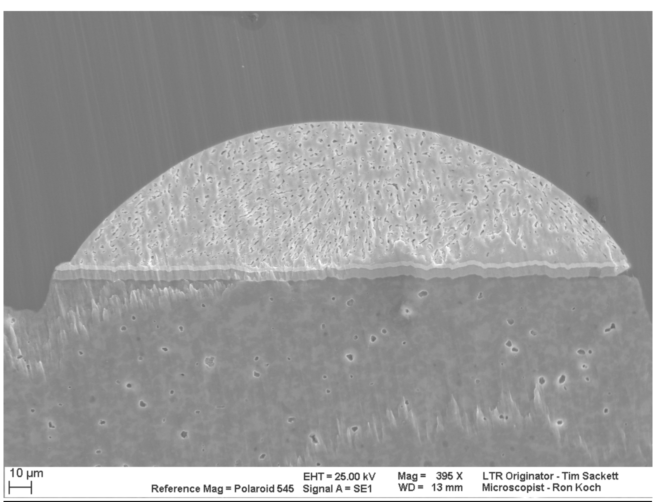


Figure 13. Soldering remains feasible in phase 4 results.

Definition of thick film on unfired tape

A natural extension of laser ablation is the definition of fine features in thick film that can be incorporated in inner layers as well as on the surface of LTCC. Toward that end, features such as that shown in Figure 14 were defined for subsequent lamination and cofiring, shown in Figure 15.

A new baseline process was defined for structuring the unfired thick film gold which included 0.36 watts laser power, 75KHz beam frequency, 14µm beam spot size, 7µm beam pulse width, 800 mm/s travel speed, two cross hatch cuts, and no contour pass.

The serpentine pattern in Figure 14 shows open areas that need to be characterized for suitability. The features are 50 µm lines and 50 µm spaces. The spaces in Figure 15 contain fired porosity whose cause needs to be determined. It may be the case that the lamination pressure is not high enough to mend gaps caused by ablation steps.

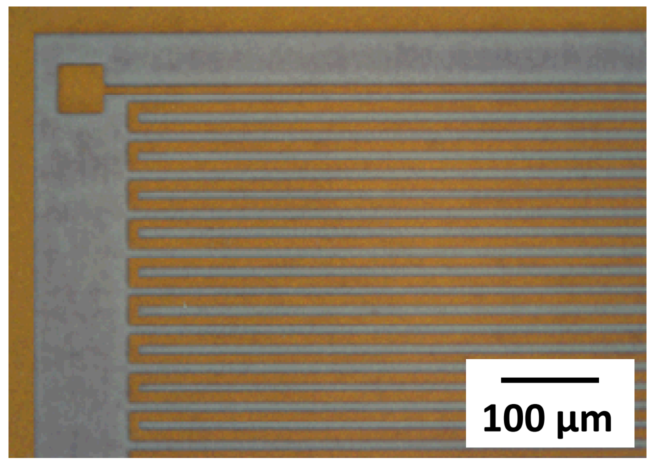
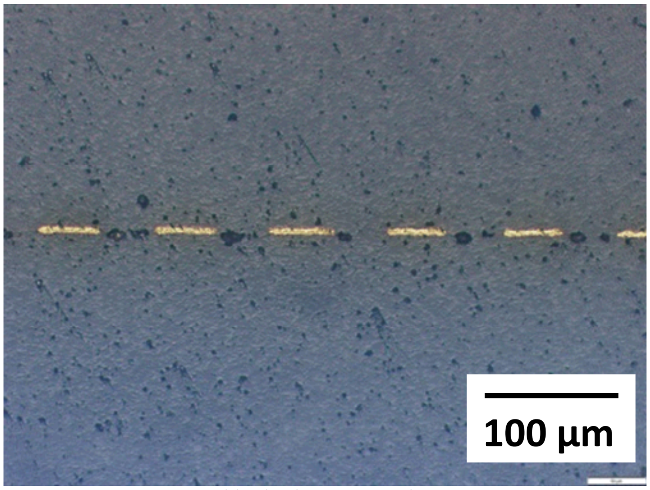


Figure 14. Thick film on unfired LTCC tape defined with 50 µm lines and 50 µm spaces.



Double check micron marker

Figure 15. Cross sectional optical view showing laminated and fired result of unfired definition of thick film lines.

Unfired Definition of shielding valleys

Previous work has described our use of metallized valleys as part of a shielding strategy in conjunction with seal frame walls. This approach is also described in literature [6]. Presently, these are fabricated with high speed milling. The new baseline process defined for structuring the unfired material (0.36 watts laser power, 75KHz beam frequency, 14µm beam spot size, 7µm beam pulse width, 800 mm/s travel speed) was applied to fabricate such a faraday valley as shown in Figure 16. Penetration to the buried ground layer was achieved using 12 cross hatch cuts, and no contour pass. This technique will be optimized in upcoming work.

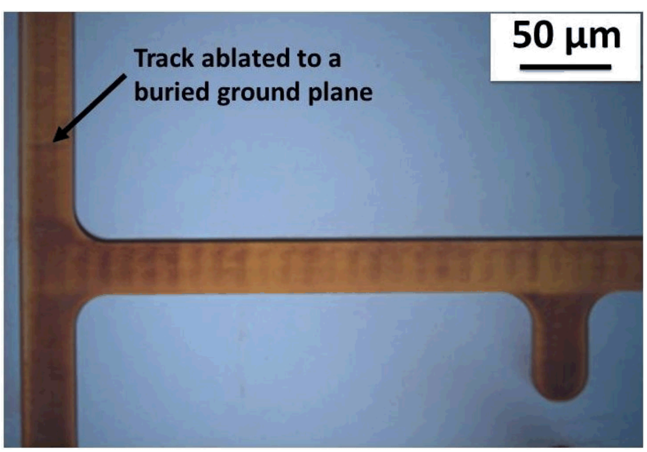


Figure 16. Definition of a defined plunge valley in unfired LTCC.

Minimal Ablation

A further design was implemented since the laser is a subtractive technique to reduce the amount of cutting required. This was done by providing minimal cuts needed to provide isolation. A dielectric mask can further provide pad definition and other considerations will occur with respect to spacing to transmission lines and vertical connection requirements for other sensitive features. The reduced amount of cutting, however, reduces the processing time by a factor of 1/3. A comparison of this approach to the baseline approach is shown in Figure 17.

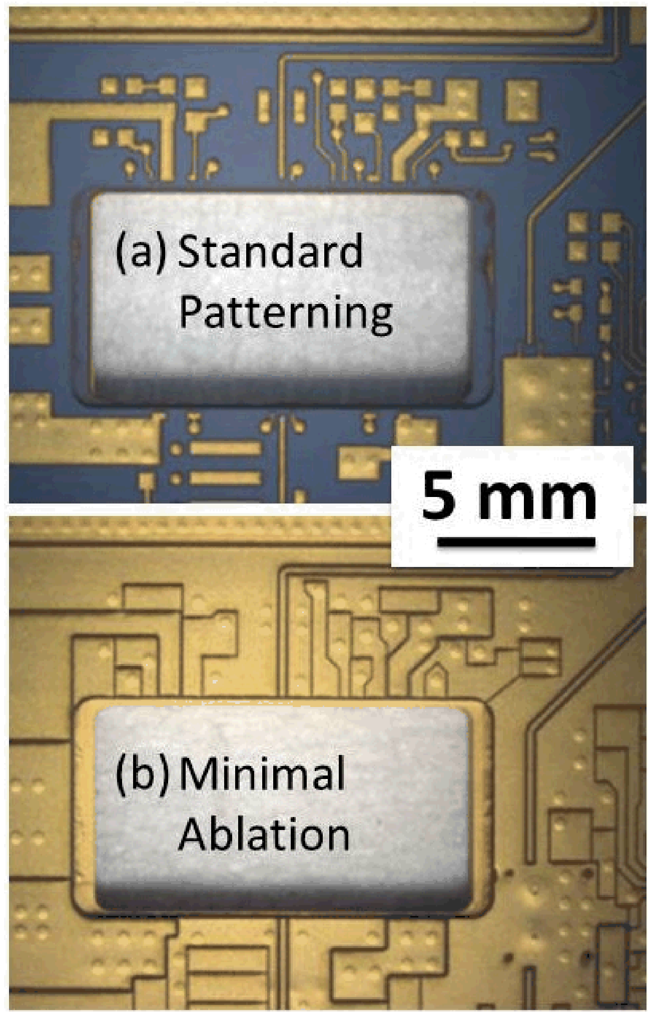


Figure 17. A minimal ablation approach was used to reduce processing times.

III. Conclusion

Successful laser ablation of the thin film metallized LTCC and green LTCC/thick films was demonstrated. The advantage of laser ablation over Ion Milling / Photolithography in the fabrication of samples was clearly shown. The four phased study highlighted the importance of enhanced power mapping to achieve the desired laser ablation result in the diverse applications demonstrated. Confirmation testing of the new process developed will include HALT, peel test, aged adhesion, and cross section on fully assembled MCMs. Based on the excellent electrical yield achieved on the functional units, it has been shown that laser ablation can be used to deliver fast turnaround prototype units for design validation. Further work utilizing laser-ablation to reduce the substrate form factor is underway.

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