Direct Write Electronics – Thick Films on LTCC

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Abstract

For low volume, high value microelectronic applications reducing cost and time to initial production parts in Low Temperature Cofired Ceramics (LTCC) play a big part in customer satisfaction. Using Direct Write Electronics (DWE) for conductor printing and other structures has the potential to reduce time to production through elimination of intermediate tooling and to reduce waste by applying expensive materials only where they are needed. Additional benefits may be realized by using DWE: wire bonds may be replaced by dispensed conductors; individual layers and parts may be uniquely labeled at the time of printing to improve traceability of product throughout the line and reducing manufacturing errors. This paper investigates using engineered fluid dispensing to print interior and exterior conductors on a demonstration Multi-Chip Module (MCM). Industry standard materials and processes are used to form individual layers of unfired LTCC tape, as well as the forming and filling of interlayer connecting vias with conductive thick film paste. Conductor patterns on each layer are created by dispensing modified Au conductor paste with a commercial three-axis machine with a fine-tipped dispensing pump. Standard processes for collation, lamination, and sintering were followed by aerosol jet printing of Ag ink with a commercial print head mounted on a custom, 6-axis positioning gantry to form wire bond replacements, part identification and individualized markings. Resultant parts are tested for electrical functionality and cross sections are compared to in-progress build photos and line measurements to study the effect of the new printing method vs. structures produced with standard conductor printing processes.

Key words

Aerosol Jet, Direct Write Electronics, Engineered Fluid Dispensing, LTCC

I. Introduction – Why do this?

For the foreseeable future Low Temperature Cofired Ceramic (LTCC) will be the baseline process for Multi-Chip Module (MCM) substrates construction at the NNSA's Kansas City Plant (KCP). Our challenge is to find ways to reduce product development time and cost. We believe that the rapidly-growing field of Additive Manufacturing (AM) holds the key to furthering both of these goals. For low volume, high value microelectronic applications reducing cost and time to initial production parts in LTCC is important for customer satisfaction. This is especially true during the product development cycle. Using Direct Write Electronics (DWE) for conductor printing and other structures has the potential to reduce time to production through elimination of intermediate tooling and to reduce waste by applying expensive materials only where they are needed. A software-based method of transferring designs to substrates, rather than physical masks, allows one to sequentially print each layer in an LTCC panel stack – avoiding the normal practice of making many copies of each layer after a painstaking setup process for each layer's conductor screen – and move directly to assembly and completion for a rapid test of the design. Additional benefits may be realized by using DWE: wire bonds may be replaced by dispensed conductors; individual layers and parts may be uniquely labeled at the time of printing to improve traceability of product throughout the line and reducing manufacturing errors.

This paper is a report on an investigation in the use of engineered fluid dispensing to print interior and exterior conductors on a demonstration MCM and assess the success of our investigation to date. To complete this study the "product" graphics and identification markings will be printed and the substrates will be assembled with discrete and IC components electrically connected using aerosol jet Ag ink as wire bond replacements. While some of the full suite of planned tests have been completed and indicate promising results, full electrical testing, comparisons to in-process build photos, cross sections, CT scans and x-rays are planned. Since the ultimate goal of this project is to replace screen printed LTCC conductors and other MCM structures, we'll further compare results to those from

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current build methods as well.

II. Proposed vs. Current Process

It is assumed the reader is familiar with basic LTCC and LTCC MCM process and assembly steps; references for those who would like to learn more are provided. At this stage in our investigation we intend to replace only the method for printing internal and external conductors on LTCC and wire bonding to IC components. All other processes: unfired tape preparation, via forming and filling, cavity formation, collation, lamination and cofiring are performed using standard processes.

Instead of employing a screen printer with its attendant need for sets of patterned screens to create our conductor lines the same conductor paste qualified for current, screen printed, production will be used but dispensed using a custom CAD/CAM platform equipped with a commercially sourced print engine (hereafter “primary print engine”). Using the primary print engine with its 3-axis computer controlled positioning system patterns are simply downloaded as needed, making it easy to switch layer patterns rapidly. Any required paste modifications and final dispensing parameters would be determined with trials initially using stand-in materials until qualified pastes could be obtained. Requirements for conductor pastes to be used were: compatible with currently qualified tape, suitable for internal and external conductors, and wire bondable.

With respect to making electrical contact between the MCM substrate and attached surface mount components (SMC), and the IC, the normal process would be to solder the SMCs in place, affix the IC and then make wire bonds between the MCM pads and the IC. For this study all electrical connections between the IC and the MCM substrate will be made using the aerosol jet Ag ink as a wire bond replacement. Though it is out of scope for the current study, one sample part should be conventionally wire bonded to make another important comparison. SMCs will be attached and connected using conductive epoxy.

III. Process and Trials as Performed

Project:

Once the team had decided on a demonstration sample to build (Fig. 1) and general plans for construction we began working with the paste manufacturer for the chosen material with modifications thought most likely to succeed with our equipment – mostly lower viscosity.

It was felt that with the initial dispensing nozzle and parameter choices that a less-viscous version of the standard paste could increase chances for success. But normal long lead times for conductor pastes, along with our proposed modifications, were pushing the date for actual printing experiments out too far to publish results this year, possibly beyond the official FY14 end date for this project. Instead

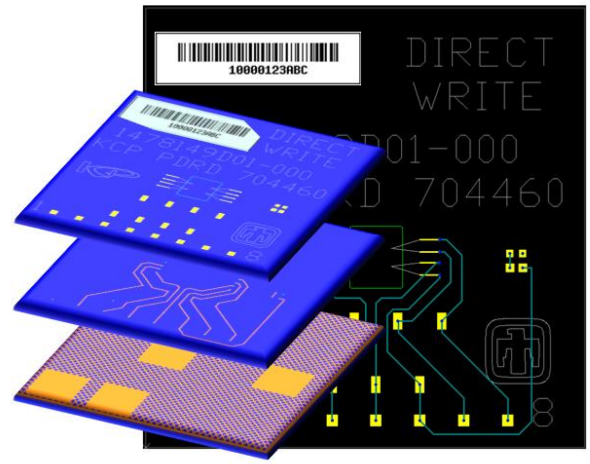

Fig. 1: Original planned demonstration part

an order for a small quantity of one paste was placed and work was begun with alternate dispense methods and materials to get a feel for performance.

Commercial Ag Paste Experiments:

All LTCC tape used in this investigation was 3” square and 10mil thick (unfired) which, aside from the *xy* dimensions, is the same as that used in our current products. For a quick check on the concept we began with SNL’s Robocasting unit. Robocasting, an Engineered Fluid Dispensing (EFD) process developed at SNL, is in the same process category as that used on the primary print engine later employed, but without the precision and need for tightly controlled distances between the dispensing tip and the substrate. Work was began with a supply of Ag paste that was known to not be compatible with co-firing - lower firing point, lower viscosity Ag paste normally used in hybrid circuits on fired PZT, quartz and glass. It was available as a material for quick experiments and, aside from the viscosity it was thought the rheological properties would approximate those of compatible materials. We could see from the first attempts (Fig. 2) that this combination would not produce the sort of precision we were looking for. There was a definite lack of control of the starts and stops, and the printed serpentine traces, while uniformly formed, were too wide for our application. Firing these initial trials showed just how poorly matched the materials were: the tape is normally fired at a max temperature of 850°C but the conductor paste normally only sees 590°C peak. Unsurprisingly the resultant panels were not planar.

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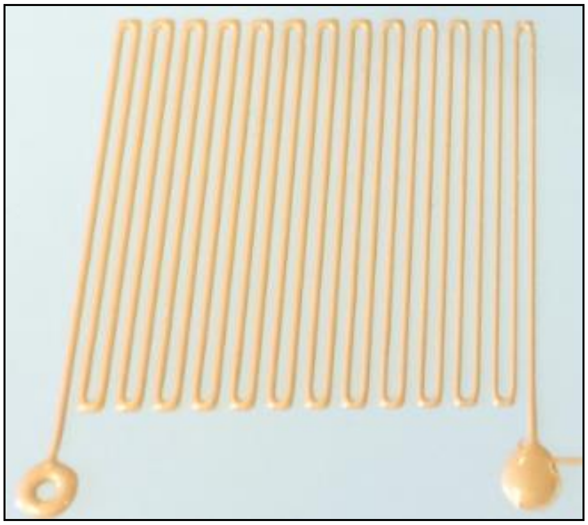

Fig. 2: Robocast Ag ink on unfired LTCC

Though we knew it was not suitable for the final parts the Ag paste gave us a relatively inexpensive way to see how the primary print engine would perform. With the greater precision of the primary print engine unit we were able to see the possibilities inherent in this method: Lines were much more crisp and uniform, starts and stops were clean and of the desired size. This test also showed us some anomalies. Line thickness was found to be slightly thinner when printing in one direction than when printing a parallel line in the other. This was attributed to interactions between the substrate and the tip, possibly not co-planar. The other was a distinct oscillation in the line path with abrupt orthogonal change in printing direction. (Fig. 3)

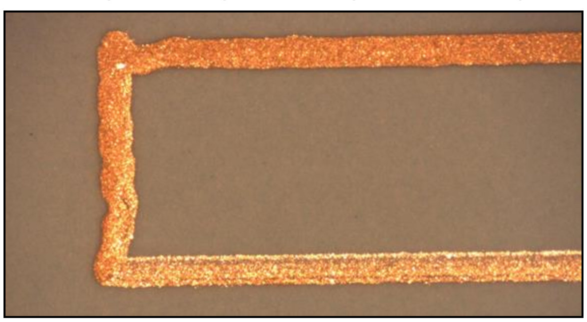

Fig. 3: Velocity change oscillations

This is attributed to oscillations in the print head/gantry when required to rapidly decelerate in one direction and accelerate at 90° to the prior trace. Feed forward controls would remove this effect, but for this project a small radius curve replaces sensitive sharp corners.

Commercial Au Paste Experiments:

While working with the paste vendor on the ultimate choice of conductor paste work was began using quantities of one of our chosen materials. This paste was more viscous than design due to its age and history, but it was closer to what we would use in the final demonstration units.

Experiments with this batch of paste were performed using only the primary print engine and standard tape printing only serpentine patterns. In the initial prints line quality was not good with deposition variation and occasional skips that were attributed to the condition of the paste and a dispensing recipe not optimized for the new material. Later prints of the serpentine pattern were successfully made using more optimized dispensing parameters. Line widths were in the 150–200 micron range with dried thickness in the 35 micron range. Several test panels were printed, laminated with patterns mutually perpendicular with an added blank sheet on top. As is true for all LTCC fired substrates in this study these panels were laminated and fired using SNL's standard process parameters (Table I).

The post fired x-ray image (Fig. 4) show slight distortion of the as-printed patterns. Cross sections through a portion of the sample show fired internal conductors consistent with

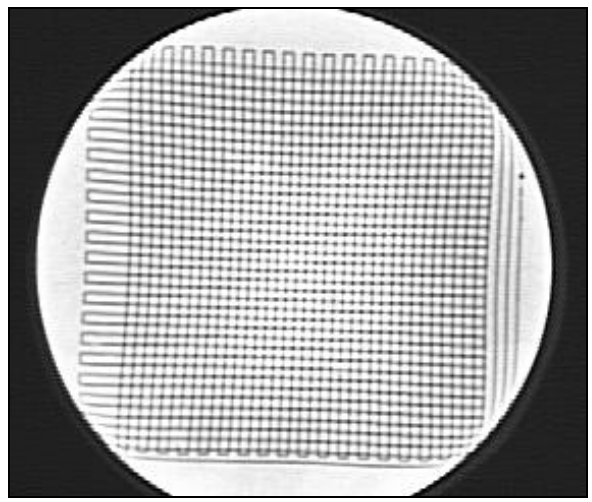

Fig. 4: X-ray image of 3-layer LTCC; two layers with DWE serpentines laminated at 90° to each other

the as printed measurements: Line width in the cross section perpendicular to the cross section plane (Fig. 5) is approximately 165 microns at this spot with an elliptical cross section and max thickness of 28 microns. The cross section through the perpendicular line has a thickness varying from 18 – 25 microns. Other than a layer-to-layer line thickness variation which could be the case in an early test it is more likely this line was not sectioned at its maximum thickness.

In comparison, typical published results indicate yield conductor thickness in the 5 – 8um range.

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Fig. 5: Cross sections from above sample. Line thickness consistent with printed thickness.

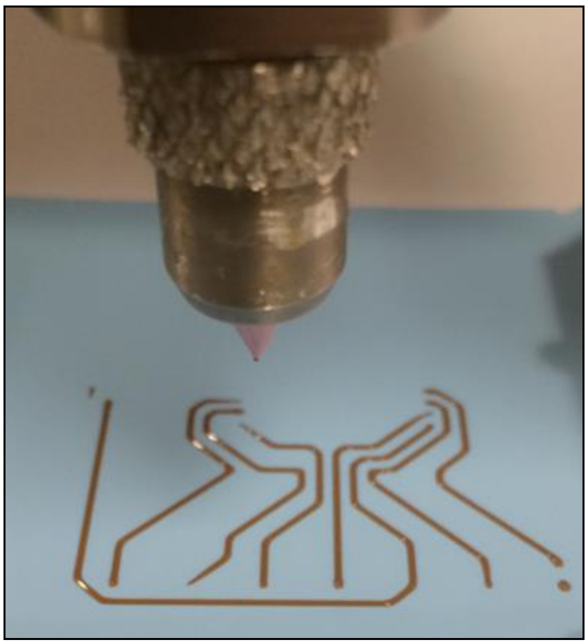

Fig. 6: First print of layer 3. Au conductive paste on unfired LTCC.

Another batch of newer conductor paste was obtained and first attempts were made to print patterns from the demonstration sample. By this time the investigation showed that good quality, as provided conductor paste from the vendor was capable of yielding the line width and thickness performance we required. At this point in the project the design of the via pattern and alignment features was not final so a via fill stencil was not yet available. There were no vias in this first print where the project stands at this writing. (Fig. 6).

For these final test panels Direct Write (DW) printing processes were employed for the metallization of the electrically conductive pathways on the unfired LTCC substrates. To accomplish this the primary print engine was used to deposit unmodified and commercially available thick film gold inks onto unfired LTCC substrates. Build planes were laser mapped and mechanically translated to ensure parallelism with the machine axis and orthogonality with the end effector, a 125 micron diameter ceramic capillary. Print orifice geometry, volumetric deposition rate, translational print speed, and the working distance of the print nozzle to the substrate all governed minimum feature resolution and were carefully determined to realize a minimum practical printing condition.

Metallized single and laminated layers were subsequently co-fired using a bulk thermal process (Table 1).

Compatibility of the DW printing method with that of the Au ink and substrate selection was verified post thermal processing and was found to be within the expected shrinkage range of the LTCC system. X-ray images of laminated systems were obtained to verify print geometry. The test circuits fabricated for this effort resulted in 100 – 125 micron wide, 9 micron thick printed conductors over areas of up to 50mm^2. For the laminated systems and in the

Table I: Firing Profile

	Temperature (°C)		Time	Ramp Rate
Step	Start	End	(min)	(°C/min)
1	20	50	10	3
2	50		1	
3	50	450	133	3
4	450		120	
5	450	850	200	2
6	850		45	
7	850	350	48	10.5
8	350		1	
9	350	200	8	18
10	200		1	
11	200	50	15	10
12	50		1	

absence of punched and filled vias, a laser machining process was used to selectively define blind holes in a co-fired layup to serve as DC resistance measurement test points. Continuity was successfully verified and resistances of various-length traces were measured to assess linearity (Table II) (Fig. 7).

Table II: Line resistance linearity

		Resistance (ohm)		
Trace	Len (cm)	Bulk Value	Measured	Error
1	3.3	1.3	3.2	146%
2	6.5	2.6	7.7	196%

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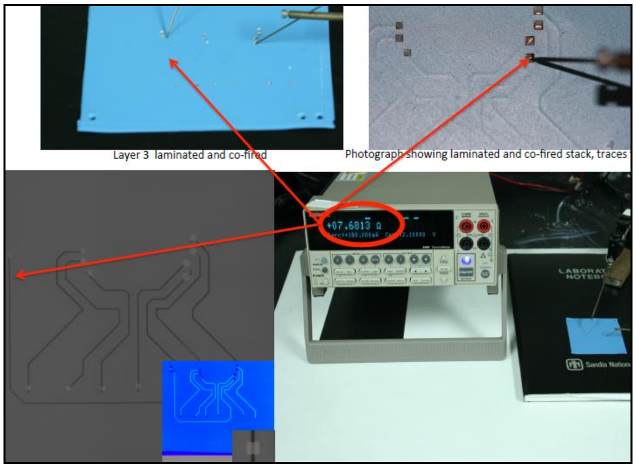

Fig. 7: Laser milled vias, resistance measurement

IV. Conclusion

Initial results and observations show this investigation is succeeding at demonstrating the ability to use DWE to pattern internal and external conductors on unfired state LTCC: patterns generated so far are sharp and within the acceptable range for thickness and width for the application. At this point in the investigation we are confident that the demonstration MCM will be completed this fiscal year and many of the planned tests showing suitability of the process for patterning LTCC inner and outer conductors will be completed.

Some of the challenges envisioned for the task were no challenge at all; others – not enumerated in the body of the paper – are problems to be attacked in the following years of this investigation. One such issue was that of creating graphics, text, and bar/QR codes on the printed surface. The current primary print engine does not have a text/font library and certainly no bar/QR code tool path generator. These are surface issues on top of the general need for improved Electronic Design Automation (EDA) software to address this simple issue as well as to ease the transition into 3-dimensional DWE and circuit optimization. For now these patterns are laboriously created manually.

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