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Thin Film on LTCC for Connectivity and Conductivity

Wolf, J. A.[1*], and Peterson, K.A.[2]

[1] NNSA's Kansas City Plant, Kansas City, MO USA
*Phone: 816-997-2127 Email: awolf@kcp.com
[2]Sandia National Laboratories, Albuquerque, NM, USA,

Abstract

The topic of this paper is the development, and characterization of multilayer thin films on Low Temperature Co-fired Ceramic (LTCC) for the purpose of attaining robust connectivity and improved conductivity, aimed at the RF single digit GHz frequency range. The aspect of connectivity primarily covers both standard SnPb eutectic solder as well as Au wire/wedge connections to the same thin film materials. This multi-purpose film ages well, as do solder joints—even after rework. In circuit development, this allows the re-appropriation of solder pads for wire bond purposes and vice versa, greatly enhancing the flexibility of the substrates. The useful lifetime of such substrates has been extended significantly by this work. The photolithographically-defined circuits further enable smaller features and tolerances and better geometrical uniformity. Vias received special attention due mainly to topography encountered at via boundaries and at the top of vias. Preparation and pattern generation for the thin film traces and pads will be discussed with attention to each material and thickness. Ion milling and post-processing for solder masking as well as unique soldering properties of the film edges are also presented. Results for adhesion and performance with respect to the various functions will be presented, as well as a detailed study of the thin film integrity and robustness.

Key Words: LTCC, thin film, PVD

1. Introduction

This paper describes the enhancement of our Low Temperature Co-fired Ceramic (LTCC) Multi Chip Module (MCM) functionality by deposition of thin film materials on the surface. The goal – in anticipation of robustness, reliability, manufacturability and performance benefits that thin film technology could deliver – was to achieve a structure that would exhibit good adhesion and good RF conductivity while lending itself to both solder and wire bond connectivity and die attachment. An added benefit would be the finer structure size and tolerances for surface devices. For this purpose, the Ti/Cu/Pt/Au thin film multilayer system on LTCC has been successfully developed (Figure 1), which exceeds the desired criteria and current advanced development MCM requirements. As a multipurpose film, it even offers enhancements and versatility for future requirements. It further improves manufacturability at an acceptable cost, due to simplification of other processing. It has been selected as the baseline technology for future advanced LTCC MCM prototypes.

Thin film material added to and substituted for thick films provides real advantages to LTCC modules. It provides conductivity suitable for the RF single digit GHz frequency range while permitting a range of connections including Au wedge, ball, and ribbon bonds, Al wire bonds, PbSn-

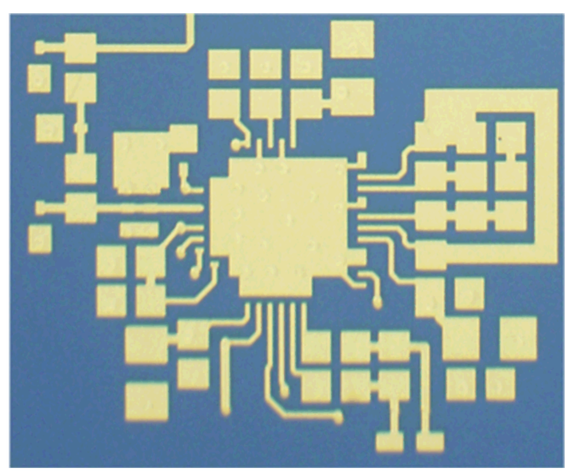

Figure 1: Thin film pattern definition on LTCC.

soldered device, connector, and cable connections, polymer die attach, and Au-Sn brazed connections. It is anticipated that higher temperature eutectic joints, such as Au-Si, can also be realized with additional work. The ability to deposit thin films on LTCC permits a wide assortment of traditional thin film capabilities to be initiated for critical new functions for the LTCC community in general and more specifically also the LTCC single digit GHz range transceiver community.

2. Background

Thick film-based Low Temperature Co-fired Ceramic (LTCC) technology is well-known in the literature [1]. Literature further documents its appeal to ceramic sensor and system applications (macro-, meso-, and micro-) [2,3]. Initially, thin film circuits were fabricated on alumina substrates and provided benefits for many RF hybrid microcircuits [4,5]. Much of the emphasis on thin films on LTCC then centered on circuits built atop LTCC using Cu- or Al-based conductors and polymer-based dielectrics that were otherwise applied to silicon and other substrates [6]. These are commonly referred to as 'multilayer' to incorporate the repeated use of several thin film/dielectric layers. In this paper the term 'multilayer' is used for a thin film material consisting of multiple different individual layers of pure metals stacked on top of each other that function as a single metallization layer.

Others have reported the use of thin films on LTCC – some for property evaluations such as under bump metallization [7], high-temperature brazing [8,9], some for devices [10], and some as laboratory demonstrations [11]. Some employ techniques that are additive, subtractive or both [12]. The driver in one such application was improved design options and microwave performance by providing smaller feature sizes with good control [10]. Fine lines have also driven other implementations of thin film materials series [13]. The adhesion layer served a double-purpose as a patternable resistor. These authors report that their DP951 and 943 LTCC material is fully compatible with wet and dry etching. Some authors mention chemical incompatibilities with LTCC that need special attention [11,12], such as reconciling acid baths' negative effect on adhesion strength. Thin film is compared to a new fine line structuring technique [14] which, although not a thin film, also involves holohedral application of a conductor followed by patterning.

This present publication reports on the successful thin film multilayer development that is able to combine the LTCC and thin film capabilities and advantages and enables future access to the full scope of thin film components. Thus LTCC could benefit from what previously has been considered a competition with discrete thin film passive components [15]. The current driving forces for this research and development, in rough order of priority, are reliability and robustness, manufacturability, performance, cost, and miniaturization. This prioritization may change as time passes and, for instance, the benefit from thin film passives is incorporated.

3. Procedure

The LTCC Substrate

The LTCC substrate is a conventional eight-layer board fabricated using commercial tapes, pastes, and industry standard processing techniques. Vias are filled with a specified via-fill material and thick film internal traces are screen-printed on unfired LTCC tapes. Extensive trade-offs exist in the decisions on how to use cavities, in view of flatness and dimensional requirements. Thick film techniques for the surface metallization have previously been the norm. But the solderable thick film compositions are subject to leaching in soldering processes during fabrication and to intermetallic phase formation in subsequent processing, testing and dormant storage. Brazing with AuSn solders, surface mount with PbSn or lead-free solders, and wirebonding with Au require different pastes, potentially resulting in a large number of subsequent re-firings. For triple printed-dried-fired solderable metallization and associated dielectrics, resistors, and brazed seal frames, the special processing could require as many as 14 post-firing steps at 850°C. The advantages of having a cofired substrate, including cost-effectiveness, are being lost at that point.

The Metal Multilayer

For the use of thin films on the surface of LTCC all vias in the top and bottom tape layers are filled with a specified via fill material. Then co-fired barrier pads with a diameter that is slightly larger than the via diameter are printed on every via. These pads serve a double purpose as a cover pad and a barrier pad. The cover function smoothens the rough topography of the via surface and provides a gradual transition that permits the thin film to create a continuous coating from the LTCC surface onto and over the top of the thick film structures as shown in Figure 2. This is specifically necessary at the circumference of vias, where post-up and similar co-fire effects can create 'moats' and other rough topography with height variations on the order of 5μm – 10μm or more. The barrier function was important in thick film hardware. Any desired thick film traces or structures, either co-fired and/or post-fired, would also be printed.

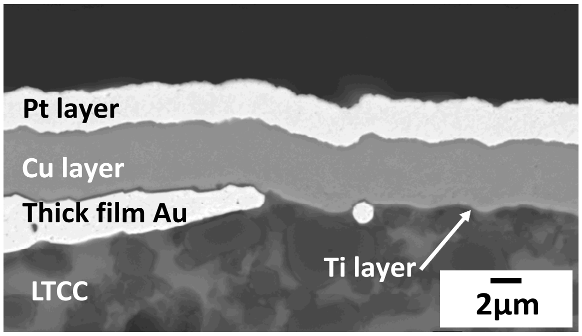

Figure 2: The thick film cover pad presents no topography problems for the thin film transitioning from bare LTCC.

However, the thin film multilayer is designed to fulfill all requirements of connectivity, and no thick film prints other than the barrier pads are necessary for standard performance and functionality. For purposes of brevity this publication will be intentionally limited to a discussion in the absence of other thick film features on the surface. After the final firing, the LTCC substrate is mounted in a vacuum chamber for the deposition of the thin film multilayer via electron beam evaporation (four pocket source) Physical Vapor Deposition (PVD).

The various requirements for MCMs have led to the development of a particular type of metallic multilayer that consists of four different layers: Ti, Cu, Pt, and Au. The first layer is a Ti adhesion layer for robust and reliable attachment to the LTCC ceramic and metallic features (Figure 2&3). The adhesion layer is covered with an approximately 4µm thick Cu layer which provides good RF conductivity and amounts to a few 'skin depths' at single digit GHz frequencies. This combines the conductivity advantages of Cu with the advantages of the cofired substrate. Based on its thickness this layer can assist in mitigating more extreme rough topographical features with sharp, almost vertical, height changes that would present step coverage problems. More gradual height changes and morphology are maintained throughout the multilayer system (see e.g. Figure 2 over the unintentional thick film Au residual dot underlying the thin film in the middle right of the picture). The third layer is Pt which provides a solderable base for electrical and mechanical connectivity. In addition the Pt acts as a barrier to prevent Cu from diffusing to the surface. Both the Pt and the Cu layers also help to keep solder from penetrating to any underlying thick film gold which would result in a profuse reaction and failure. The fourth thin film layer is Au, which covers the platinum and assures solderability and wire bondability (with Au wire and ribbon, ball and wedge bonding).

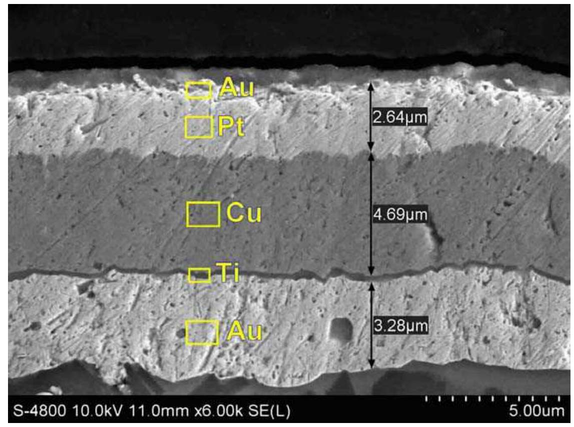

Figure 3: Cross section of the metal multilayer showing most individual thicknesses. The thick Au layer at the bottom is a thick film deposit.

Each of the metals is deposited during the same vacuum cycle in a four pocket e-gun evaporator. Initial deposition occurs at 225°C.

Pattern definition

The pattern definition has been carried out by shadow masking, lift-off techniques, and by ion milling. The use of physical masks is feasible but involves many logistical issues which are considered in the final technique selection. For instance, continuous seal rings are not possible in a single step. Lift-off processing requires exceptional attention to surface cleanliness which can be altered by the very wet processing which defines the pattern. Also, vias can trap substances due to their inherent porosity, possibly requiring a change to an alternate, more dense via-fill material. The current preference for circuit definition is ion milling. As such, deposition of the metal stack occurs over the entire substrate. The photopatterning is conducted with dry film photoresist which is laminated to the panel and exposed and developed. The ion milling occurs in the open areas while the thickness of the remaining photoresist protects the traces and pads that are in the design. The substrate is cooled during the milling using a cooling stage which employs helium as a heat transfer material. Milling occurs with alternate steps at incident beam angles of 45° and 18° from the normal for complete milling with good feature and edge definition and without residual material remnants.

4. Results and Discussion

Adhesion

Adhesion has been investigated using Sebastian-like pull-testing and component shear-testing. Some initial testing of aged parts has also been performed. Shear testing is important because discrete devices are used – especially for tuning purposes in development. It is important to consider the failure mode along with the load to determine whether the values provide a boundary on the understanding of the strength or an actual strength. The pull-testing resulted in a wide variety of failure modes, including LTCC tape failure, failure of the Ti/LTCC adhesion interface, and epoxy or solder failure of the stud attachment. All pull strengths and failures indicate a good performance, based on stud diameter and attachment mode. The majority of shear testing resulted in failures only within the surface mounted components. Again, all shear failures indicate a good performance, based on the variety of device sizes. The aging conditions included up to 25 days at 170°C. Even after this treatment the initial results indicate that there is still good adhesion, despite the fact that the thin film material has been compromised to a certain extent. The collective adhesion study at this time points to the Ti/LTCC interface as the least strong link in the entire structure. However, the thin film multilayer with the Ti adhesion layer still satisfies rigorous acceptance criteria for robustness and performance. More work is necessary to determine the full effect that aging has on the thin film multilayer structure.

An edge-peeling effect of the thin film can be initiated as an artifact of sawing through the thin film in the absence of metal-free 'streets' which are industry-standard. This does not occur with proper practice and, therefore, does not affect performance.

Soldering

The solderability to the thin film has been excellent, both in laboratory tests and in prototype assemblies. Soldering and wirebonding exhibit interdependence on gold thickness selections, so an engineering balance is reached. This solder performance is excellent whether the solder is applied as a paste, preform, or in a continuous film. The soldering is hampered only by alteration of surface conditions which can occur by copper diffusing to the surface or tin diffusing to the via fill material after long times at elevated temperature. Even in the event of such extreme diffusion the adhesion of the thin film and solder system to the underlying LTCC was not compromised, as was witnessed in cross sections after 25 days at 170°C.

The solder initially wets to the gold surface, which it typically dissolves in the liquid state, (Figure 4) and secondarily is wetted and adhered to the surface of the Pt. Nickel is a common wettable barrier material in the literature, however, the desired

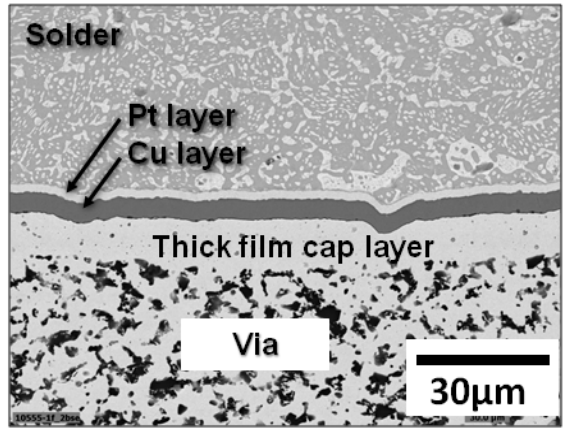

Figure 4: The gold thin film is taken into solution on soldering to the multilayer. The Ti layer is not resolved at this resolution.

dual functionality of both solder and wire bond connectivity would require a large amount of gold in order to maintain the necessary surface purity for the wire bond. This would, at the same time, increase the gold-tin brittleness in a highly detrimental fashion.

The thin gold layer that is dissolved into the solder yields a concentration that is below 1% in a surface mount joint and ten times lower where a backplate is attached, which helps to avoid effects of gold-embrittlement.

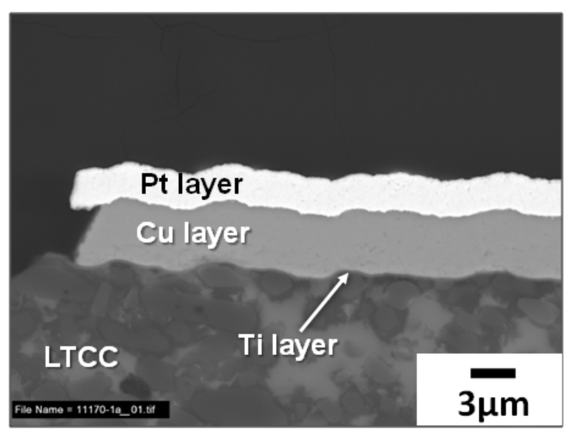

Figure 5: Illustration of edge definition resulting from ion milling. The Au layer is not resolved at this magnification.

The shape and composition of the exposed line edges has been determined to provide an 'effective solder stop' in that solder does not round the corner between the Pt on top and the Cu beneath (Figure 5). This is more effective than a polymer solder stop which is leading to a re-evaluation of the design placement of such a solder stop coating.

Die attach and epoxy bleed out

Whereas the extremely good wettability has been beneficial for soldering, it has been detrimental when it comes to the phenomenon known as 'epoxy bleed out'. This phenomenon occurs where resin from a curing or aging epoxy creeps out beyond the perimeter of the die attach boundary. The different surface of the thin film multilayer as compared with a thick film surface, be it either increased smoothness, denser material or increased surface activity, facilitates the creep of the epoxy material to greater distances. If this behavior reaches the wirebond pads, wirebonding is adversely affected. A plasma clean or UV ozone cleaning is typically employed to address this contamination, but not all devices will tolerate plasma cleaning.

Wire bonding

Many times, surface mount techniques are employed on MCMs using polymers for attachment of discrete devices. For reliability reasons, we prefer soldered attachments for these components. However, both the solder and the polymer attachment precedes the wirebonding, so the cleanliness of the surface is of utmost importance. This cleanliness is established through careful aqueous cleaning followed by plasma cleaning, where permitted.

Various wire bond parameters, including wire, ribbon, ball and wedge bonding have been evaluated both with respect to their consistency for effective manufacturing processes and their initial and ultimate strength for maintaining reliable connections. In addition factors such as bond pad size, loop height, bonding angle and capillary size have been taken into account. Both the pull strengths and failure modes have yielded excellent results for a range of combinations, and the thin film material has been determined to be preferred for wire bond connectivity.

RF performance

The RF performance has not been extensively quantified. Rather, test circuits were built in both thick film and thin film versions to perform a direct comparison. The performance, to first order, is equal to – and possibly greater than – that for the thick film versions. The line edges are more precise, with tolerances of ± several microns compared to thick film values of ± 12μm (0.0005"). The thickness is uniform across the entire width of the line, as evidenced in many of the figures which all show typical cross section results. Notice that in all cases the roughness of the underlying surface is maintained and translated directly through to the surface of the thin film multilayer. Specifically Figure 5 demonstrates the typical sharpness of the edges of the thin film multilayer, where the edge is shown to have a sloped indentation of approximately half the layer thickness respectively (~1μm for the Pt and ~2μm for the Cu).

Minimum feature size

One of the benefits of thin films and the associated patterning are the possibility of making finer lines and spaces which enhances miniaturization and performance. The skin depth determines Cu thickness (and Ti thickness, to a point) whereas solder joint integrity limits the Au thickness and depends on the Pt thickness. The wirebondability depends on the Au thickness as well. One of the drawbacks to ion milling is that the minimum photoresist thickness is thicker than that for chemical etching or lift-off techniques in order to continue to protect the thicker metallization through prolonged milling. Naturally, this thicker photoresist combined with the thicker metallization limits the minimum line/space size. The current photoresist thickness is 43μm, which permits the resolution of 100μm lines and spaces in the initial designs. Further work is being performed to determine a reliable and consistent minimum spacing.

Rework

Rework is an issue that is frequently tolerated in complex, high-value MCMs. The extensive testing of the MCMs itself may induce a variety of failures. Epoxy rework occurs at 160°C, while solder rework occurs at regulated temperatures above 183°C. The compatibility of these thin films with rework has been evaluated specifically and emphasized by high temperature aging studies. These studies are still on-going for quantitative evaluation, but preliminary results are available. Functional parts have been subjected to up to nine standard solder reflow/rework cycles, and no change in performance, reliability or robustness has been detected. In addition, targeted single pad hand solder rework has been performed many times and on many different pads. The ability to rework a pad has not been lost even after more than twenty hand solder rework cycles on the same pad, and the RF functionality of those pads is still comparable. The combination of pads and components are still reliable and to first order observation still satisfy the reliability requirements.

Prototyping

While the robustness for rework adds to the superiority of the thin film material, the fact that the same thin film material can be used for either solder or wire bond connectivity after fabrication makes it ideal for prototypes. The ability to repurpose various nodes (engineering change pads) as well as to learn a great deal from a single piece of hardware, due to its extraordinary life in the hands of testing experts who made modifications for tuning and function and have ‘haywired’ fixes on the fly, is invaluable during the development stage of a new circuit. The direct transition of the part into a robust, reliable and manufacturable part with high performance using the same thin film materials at the end of the development phase is seamless and cost effective.

In the course of this development fully functional parts at single digit GHz range have been fabricated with a wide variety of parameters. The final versions of the parts consist of LTCC substrates utilizing the Ti/Cu/Pt/Au thin film multilayer for surface connectivity, ion milling for pattern generation and solder stop for material protection. Subsequent assembly methods include soldering (including back plate), die attach, wire bond, seal frame and lid. The parts have performed very well, not only in their as-fabricated stage but also after various environmental aging studies and tests, including electronic functionality. The thin films are proving to be a viable and strong enabler for critical new functions for the LTCC community in general and more specifically also the LTCC single digit GHz range transceiver community.

5. Summary

Thin film metallization on LTCC has been developed and characterized, leading to reliable interconnections and near optimum performance in RF test transceivers. Adhesion is achieved with a thin titanium layer, while a thick copper metallization is responsible for multiple benefits including conductivity. A thick platinum layer is incorporated for solder connectivity, wire bond surface integrity, manufacturability and reliability. The top surface consists of a gold layer that delivers wire bond manufacturability and inertness, and it preserves wettability for soldering. Ion milling is effective at producing good line/space combinations with good conductor edges. The overall system of this thin film multilayer on LTCC yields high reliability and robustness. The performance is enhanced, and the simplification of other related processes makes the manufacturability cost-effective. Miniaturization is achieved due to finer line/space resolution. Future efforts are envisioned to further improve these and related aspects of thin films on LTCC.

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7. References

[1] Y. Imanaka, Multilayered low temperature cofired ceramics (LTCC) technology," Springer, New York, (2005).

[2] M.R. Gongora-Rubio, P. Espinoza-Vallejos, L. Sola-Laguna, J.J. Santiago-Aviles, "Overview of low temperature co-fired ceramics tape technology for meso-system technology," Sensors and Actuators A 89 (2001) 222-241.

[3] L.J. Golonka, "New application of LTCC technology," Proc. 28th Int. Spring Seminar on Electronics Technology, (2005) 148-152.

[4] R. Berry, P. Hall, and M. Harris, Thin Film Technology, Van Nostrand, New York, (1968).

[5] L. Maissel and R. Glang, Handbook of Thin Film Technology, McGraw-Hill, New York, (1970).

[6] G. Messner, I. Turlik, J. Balde, P. Garrou, Thin Film Multichip Modules, International Society for Hybrid Microelectronics (ISHM), (1992).

[7] N.Duan , J.Scheer, J.Bielen, M.van Kleef, "The influence of Sn–Cu–Ni(Au) and Sn–Au intermetallic compounds on the solder joint reliability of flip chips on low temperature co-fired ceramic substrates,"

[8] N. Okamoto, K. Miura, K. Kondo, T. Asano, and H. Banno, "Brazing technology for low temperatura cofired ceramics and its application to MCM," Proceedings of the IEEE/CPMT International Electronics Manufacturing Technology (IEMT) Symposium, pp. 40-43, 1995.

[9] C. Walker, F. Uribe, S.L. Monroe, J.J. Stephens, R.S. Goeke, V.C. Hodges, "High-temperature joining of low temperature co-fired ceramics", 3rd International Brazing And Soldering Conference (IBSC) (April 23-26, 2006)
San Antonio, pp. 54-59.

[10] J. Müller, D. Schwanke, T. Haas, E. Feurer, B. Schweizer, A. Klaassen, "Improved design options and microwave performance by combining thin film with LTCC," Workshop Proceedings WS8, 33rd European Microwave Conference, October 6, 2003, Munich.

[11] B. Anderson, S. Horio, K.Kobayashi, N. Tamada, "Thin film fine pattern technology for LTCC multilayer substrates," Proceedings: Electronic Components and Technology Conference, 2007, pp. 59-64.

[12] S. Hildebrandt, K.-J. Wolter, "Thin film structuring on LTCC", 2008. ISSE '08. 31st International Spring Seminar on Electronic Technology (2008) 526 – 530.

[13] Muller, J.; Perrone, R.; Thust, H.; Drue, K.-H.; Kutscher, C.; Stephan, R.; Trabert, J.; Hein, M.; Schwanke, D.; Pohlner, J.; Reppe, G.; Kulke, R.; Uhlig, P.; Jacob, A.F.; Baras, T.; Molke, A., " Technology Benchmarking of High Resolution Structures on LTCC for Microwave Circuits," Electronics Systemintegration Technology Conference, (2006) 111 – 117.

[14] D. Stopel, K.-H. Drue, S. Humbla, M. Mach, T. Mache, A. Rebs, G. Reppe, G. VogtI, M. Hein, and J. Muller, "Fine-Line Structuring of Microwave Components on LTCC Substrates," 3rd Electronic System-Integration Technology Conference (ESTC), Berlin, 2010 , pp. 1 – 6.

[15] C. Reynolds, "Passives for RF Design," RF Design, August 2005, pp 28-33.