Patterning of Electroless Copper Deposition on Low Temperature Co-fired Ceramic

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Abstract

The metallization of low temperature co-fired ceramic (LTCC) is typically done with commercially available silver or gold pastes using conventional screen printing processes. However, for some applications such as substrate integrated waveguides and high performance planar components where the metallization of vertical side walls is required, screen printing is difficult to apply. In such cases, electroless plating of copper can be employed to metallize the fired LTCC, which would also be a promising alternative to the high cost metals such as Ag and Au. In this study, electroless copper plating was combined with KrF excimer laser machining to deposit selective copper patterns on fired LTCC. Using this approach, a functional circuit was fabricated and electrically tested. The mask projection technique of the excimer laser can be used to create complex patterns on LTCC and initial work has been carried out to realize planar passive component layouts, including a capacitor and an inductor. The minimum feature size of the deposited copper that could be achieved in these designs was below 50 µm.

Introduction

Metallization is a major requirement for substrate materials in the electronics industry for inter-level connections, integrating and assembling other components to the substrate and fabricating passive devices. For high frequency devices, low temperature co-fired ceramic (LTCC) is often used as a substrate material. For LTCC metallization, screen printing onto the unfired material is the most widely used method, but typically requires the use of high cost metal pastes containing silver and gold to avoid oxidation issues during the subsequent firing. Furthermore, tape shrinkage during firing and screen printing capabilities limit the dimensions of features and restrict the passive components that can be fabricated on green state LTCC. For example, x and y shrinkage affects the metal line widths and separations, which are key factors for the performance of passive components such as capacitors. Also, any non-uniformity of shrinkage will affect the shape of the metal lines. As the commercial world requires convenient and low cost process technologies for mass production, alternative metallization methods should be considered. In recent years, several metallization techniques such as ink jet printing, electroless plating and electrolytic plating have been employed for fired (LTCC) [1, 2, 3].

In addition to the metallization of planar LTCC structures, there is increasing interest in developing three-dimensional structures in LTCC, such as substrate-integrated waveguides (SIW). A dielectric-filled waveguide formed in a substrate is particularly interesting due to its lower loss and fabrication simplicity that can dramatically reduce the cost of millimeter-wave systems [4, 5]. However, such structures require the metallization of vertical side walls, for which screen printing techniques are difficult to apply. Resistors, capacitors and inductors can also be embedded, instead of using additional surface-mount technology (SMT) components, potentially leading to very small transceiver modules. For embedded components, such as capacitors, smaller, more complex structures are desirable to improve device performance.

This research therefore focusses on selective electroless copper deposition on fired LTCC, as an alternative to the use of thick film pastes deposited prior to the firing process. In this work, an excimer laser using a mask projection technique was combined with electroless copper plating to achieve the required patterns on fired LTCC. These patterns included complete circuit layouts and planar passive components. Figure 1 shows the overall process route where fired LTCC samples were first covered with dry film photoresist and the laser machining process was used to remove the photoresist only from the areas to be metallized. This technique not only roughens the LTCC surface to improve metal adhesion, but also enables 3D structures such as trenches and wells to be developed. A key advantage of the mask projection technique of the excimer laser (Figure 2) is the ability to prepare complex high resolution patterns directly, without the need to translate the laser across the surface. After laser machining, the presence of the remaining photoresist allows the Pd catalyst activation to take place only on the machined surface for the subsequent selective electroless copper deposition.

This paper presents the initial results of this research investigating circuit fabrication and capacitor / inductor patterning on fired LTCC. Analysis of the machined features and copper deposition was carried out and feature sizes determined. The capability of the process and future work to increase the performance of the components is further discussed.

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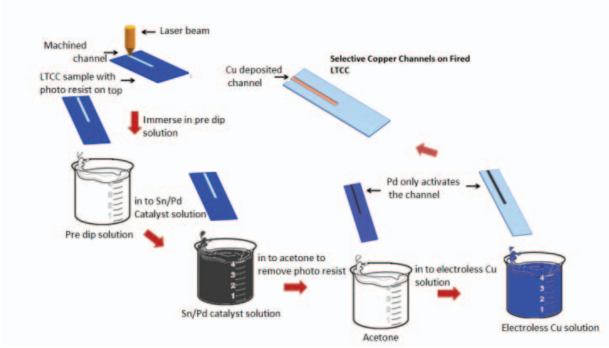

Figure 1 Schematic diagram of the selective electroless copper deposition process.

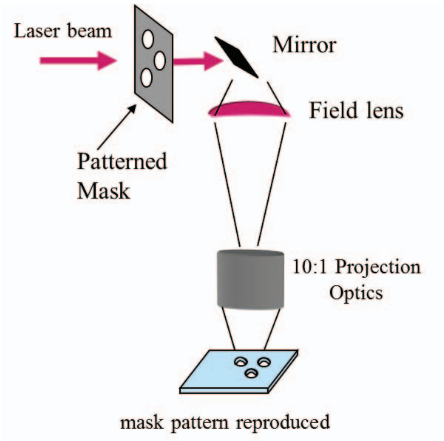

Figure 2 Schematic diagram of the mask projection technique of the excimer laser

Experimental

A. LTCC sample preparation

Double layer fired LTCC (DuPont 9K7) was used in the experiments and was laminated and fired according to the manufacturer's instructions. Samples were soaked in a 10 vol % Decon 90 solution for 24 hours at room temperature to clean the surface. These were then rinsed with distilled water and dried. A dry film photoresist (~40 µm thick) was then applied on both sides of the LTCC samples using an Albyco photopro 33 laminator operating at 110 ^{0}C. The samples were then exposed to UV light to harden the resist and the protective plastic layer on the resist was removed before machining.

B. Excimer laser machining process

A Lambda Physik Lasertechnik LPX200 KrF pulsed excimer laser system operating at 248 nm wavelength with maximum output energy of 250 mJ/pulse and pulse duration of 20 ns was used to machine the patterns. As shown in figure 2, the process uses a mask projection technique to shape the beam which is then followed by 10:1 reduction optics that reduce it to the final feature size at the sample surface. The maximum power per unit area of the excimer laser beam is achieved at the focal point of the optical lens. At this point the laser beam is at its smallest diameter and capable of giving maximum irradiance on the processed material [6]. The focal spot of the laser beam was determined by machining a series of spots onto a glass slide covered with permanent marker ink and for each one changing the work piece vertical position. By observing the quality and the size of the machined features, the optimum position was determined. Different masks were then used to create different patterns for electroless plating as described in the following sections.

i. Circuit Fabrication

When producing the circuit pattern, an ~2.3 mm x 2.3 mm square mask (figure 3) was used to give an ~230 µm x 230 µm spot at the surface. This was used to machine the conductor lines by moving the sample stage horizontally using a CNC program to form the required circuit pattern which was machined using a repetition rate and feed rate of 20 Hz and 5 mm/min respectively and with five passes of the laser in order to increase the depth. After preparation of the tracks, an ~10 mm x 10 mm square mask was used to directly machine square connection pads for component interconnection.

Figure 3 The mask used to machine the circuit pattern tracks

ii. Capacitor/Inductor Patterning

To create the inductor and capacitor designs, a mask of the required pattern was prepared by chemically etching a brass sheet. The optical images of the masks are shown in figure 4 and show clearly the reproduction of the original CAD image. The capacitor was designed with dimensions of 10 mm x 10 mm and the radius of the inductor design was ~4.4 mm. These masks were then used to machine matching structures in the LTCC surface. In this case, the samples were exposed to 100 shots of the laser beam without moving the stage and using a repetition rate of 10 Hz.

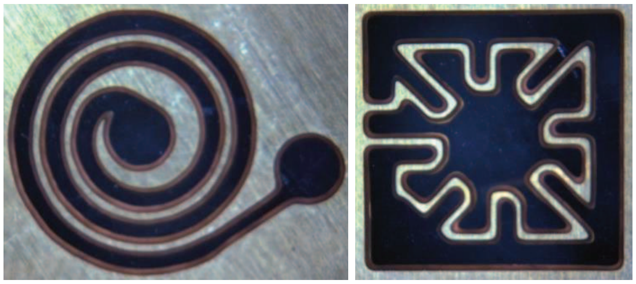

Figure 4 Masks produced in brass sheet. Masks are approximately 10 mm in width

C. Electroless Cu deposition

After machining the required patterns, the LTCC samples were rinsed thoroughly with de-ionized water to remove any debris left from the machining process. These samples were then immersed in a pre-dip solution for 2-3 minutes. Then the surface activation was carried out by immersing the samples in a Sn/Pd catalyst (Circuposit^{TM} Catalyst 3344/4444) solution for 3-4 minutes. In this step, due to the presence of the photoresist, only the machined parts were exposed to the catalyst for the surface activation. The LTCC samples were then rinsed with de-ionized water to remove excess catalyst. After the rinsing process, the remaining photoresist was removed by immersing in acetone. After rinsing with de-ionized water and drying, the samples were then immersed in the electroless copper bath (Circuposit^{TM} 3350-1) for one hour at 40 ^{0}C. After the deposition process, the samples were rinsed with de-ionized water and dried with a specimen dryer.

Results and discussion

A. Laser machining of photoresist and LTCC

Figure 5 (a) shows an optical micrograph of the LTCC surface with photoresist layer after excimer laser irradiation. The photoresist was cleanly machined away which is to be expected for this high energy laser source interacting with a polymer. The machining of the LTCC was significantly slower and the surface morphology of the irradiated surface showed a relatively rougher surface compared to the original plain LTCC surface (figure 5 (b)). From a previous study [5], it was found that the KrF excimer laser has the capability to remove the material from the LTCC surface to create a trench. At the same time it introduces a roughness to the machined surface that can be beneficial for metal to substrate adhesion.

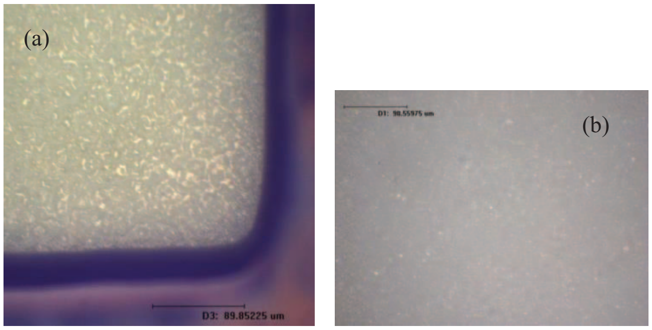

Figure 5 Optical micrographs of LTCC surfaces (a) after excimer laser irradiation (b) plain LTCC

B. Circuit pattern preparation

Figures 6(a) and 6(b) show the optical micrographs of a conductor pad and a conductor line respectively after electroless copper deposition. These images indicate the uniformity of the copper deposits with well-defined edges and the highly selective nature of the deposition only on the machined surface. The widths of the conductor lines showed agreement with the expected beam spot size and confirmed that the machining was done at the beam focus position. The thickness of the copper was estimated to be 3 µm according to the plating rate provided in the supplier's data sheet (0.5 µm in 10 minutes). In this particular application, the number of shots per area of the laser was kept to a minimum where it was sufficient enough to remove the photoresist and roughen the surface for better adhesion.

Figure 7(a) shows a complete circuit pattern prepared in this way, again highlighting the selectivity of the surface activation and copper deposition. To assemble a functional device, lead free solder paste was applied using a syringe to the copper connection pads and components were manually placed. The sample was then passed through a conventional reflow oven to form a complete circuit (figure 7(b)). The circuit was electrically tested with an input voltage of 4.5 V and the flashing LED indicated the presence of continuous and conductive copper deposits and effective solder joints.

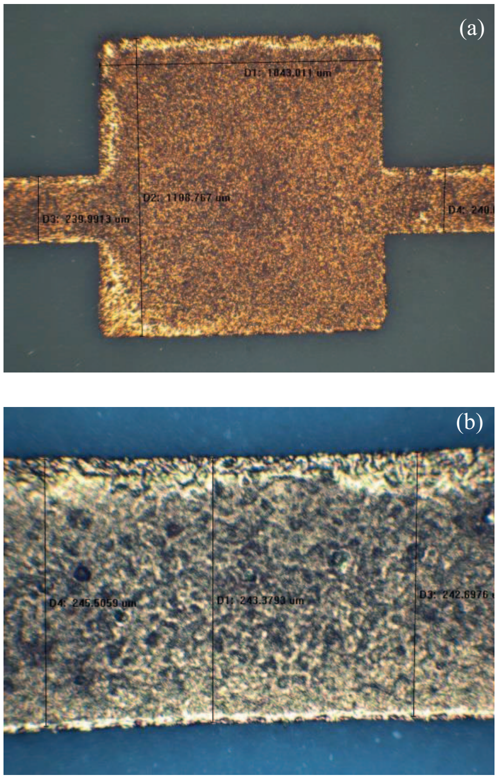

Figure 6 Optical micrographs of the copper deposits on fired LTCC (a) conductor pad (b) conductor line

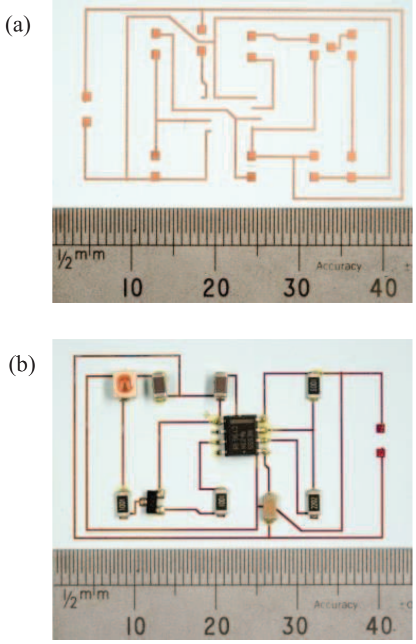

Figure 7 (a) Deposited copper on circuit pattern (b) Complete circuit after component assembly

C. Inductor/capacitor patterning

Of particular interest in this study was the use of the mask projection technique to create complex patterns suitable for novel designs of passive components. With conventional planar processing (i.e. on a single layer) capacitors have been realised using 2D interdigitated structures that rely on the fringing electric fields between the plate fingers, as illustrated in figure 8(a). However, using laser machining and electroless deposition to create plated recesses, it should be possible to prepare capacitors that are effectively 2.5D structures, offering high edge capacitances, as illustrated schematically in figure 8(b). With further process modification, the plated recesses could also be filled to reduce the ohmic losses associated with both capacitors and inductors, as illustrated in figure 8(c). Moreover, when trying to increase the capacitance of the conventional interdigitated capacitors, either length of the fingers or the number of fingers can be increased within a fixed surface area. With the former, excess series inductance within the individual fingers is introduced, leading to spurious resonances. With the latter, distributed transmission line effects are introduced, leading to phase distortion. The solution under investigation is to introduce a pseudo-fractal approach to the design of the interdigitated fingers [7], whereby a radial fractal has the series inductance of the fingers increasing with distance. In this work, the preparation of such structures on LTCC using excimer laser machining and electroless copper metallization was investigated. Here, given the limited minimum feature size and maximum available area, only a small order of fractalization could be introduced. Structures with lower minimum feature size and/or larger surface area are to be investigated in the future.

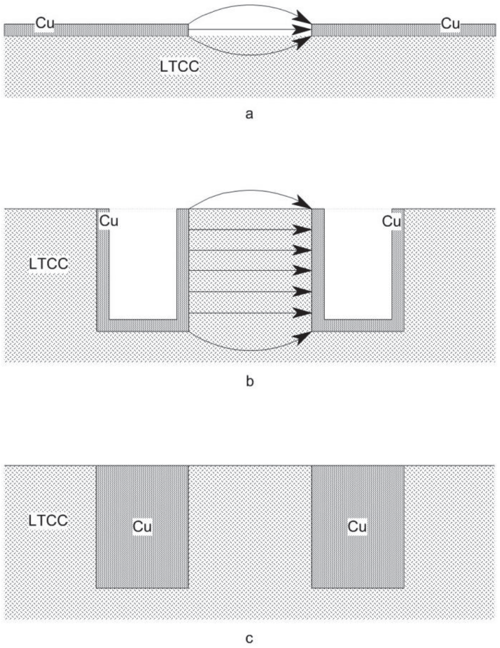

Figure 8 (a) Electric field between plates with standard printing technique; (b) Electric field between plates with plated recesses; (c) Conductor filled recesses

The projection optics technique of the excimer laser system was used to machine the planar components on fired LTCC using designed masks. The great advantage of using projection optics is that it enables complex patterns to be created without the need to raster a beam spot across the surface, with associated limitations due to the spot dimensions: this enables features below 10 µm in size to be prepared. Furthermore, as the size of the final machined features is reduced by ten times from that of the mask, complex patterns can be prepared from masks that are relatively easily fabricated using standard lithographic or other micromachining techniques (Figure 4).

Using the method described in figure 1, several patterns of inductors and capacitors were prepared on LTCC. Figures 9(a) and 9(b) show the initial structures machined into the photoresist on the LTCC surface. These features had identical shapes to the projection masks confirming the reproducibility of the mask projection technique.

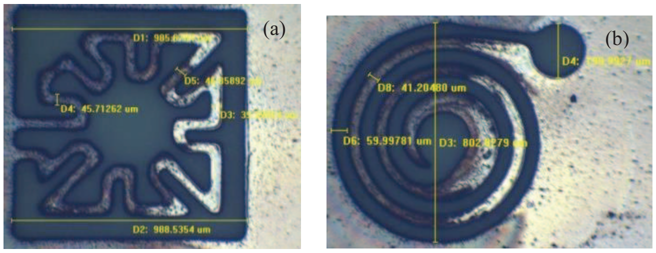

Figure 9 Optical micrographs of machined features in photoresist on LTCC (a) capacitor (b) inductor.

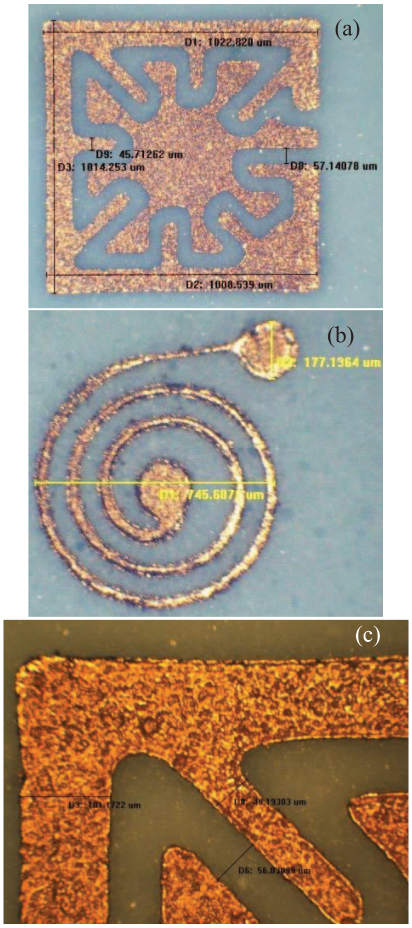

Figure 10 Optical micrographs of electroless deposits on machined features (a) capacitor (b) inductor (c) magnified image of the capacitor

As seen earlier for the circuit patterns, it was found that the electroless copper deposition was highly selective such that the structures were accurately reproduced (Figures 10(a), (b), (c)). The overall size of the deposited capacitor was approximately 1 mm x 1 mm and showed the expected 10:1 size reduction from the original mask. The gap between the deposits was below 60 µm and the minimum dimension of the deposits was below 50 µm.

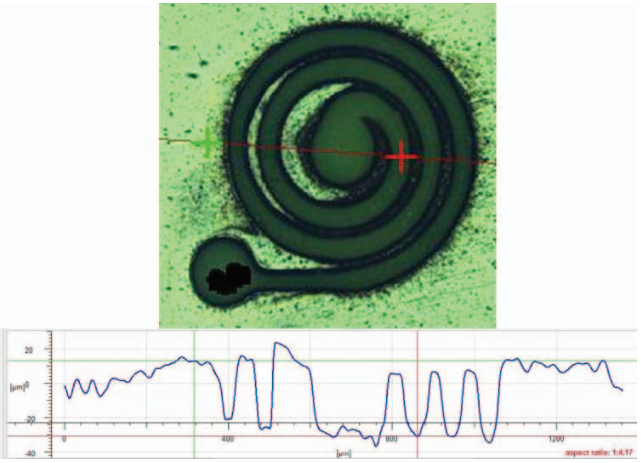

Figure 11 2-D surface profile across the machined inductor. In this case the LTCC is covered with photoresist

Figure 11 shows the 2-D profile taken across an inductor structure machined into the photoresist on LTCC (machined with 100 laser shots). Although all the photoresist was removed in the exposed areas (creating the deep wells observed), only a small amount of LTCC was removed with these laser parameters such that only a shallow trench was created. As described previously, to increase the performance of these planar components, a deeper trench should be created and filled or coated with the copper. The results presented are the initial findings of this study and show the feasibility of fabricating complex and small features on fired LTCC. Structures with lower minimum feature size, higher order of fractalization and/or larger surface area are to be investigated. In addition, electroless copper metallized vias will be explored to create devices with, for example, a radial fractal capacitor on one side of the LTCC interconnected to an Archimedes spiral inductor on the other side.

Conclusions

The mask projection technique of the KrF excimer laser system was successfully employed to machine patterns on LTCC covered with dry film photoresist. These patterns were then selectively plated with electroless copper using Sn/Pd catalyst solution to activate the LTCC surface. The fabrication of a complete functional circuit was demonstrated. The initial results indicate the feasibility of realizing planar passive components on LTCC, and the optimization of the process and characterization of the performance of these components shall be addressed in the future.

Acknowledgments

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