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Direct-Write Fabrication of Integrated, Multilayer Ceramic Components

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Abstract. The need for advanced electronic ceramic components with smaller size, greater functionality and enhanced reliability requires the ability to integrate electronic ceramics in complex 3-D architectures. However, traditional tape casting and screen printing approaches are poorly suited to the requirements of rapid prototyping and small-lot manufacturing. To address this need, a direct-write approach for fabricating highly integrated, multilayer components using a Micropen to deposit slurries in precise patterns is being developed at Sandia. This approach provides the ability to fabricate multifunctional, multimaterial integrated ceramic components (MMICCs) in an agile and rapid way. Commercial ceramic thick-film pastes can be used directly in the system, as can polymer thick-film pastes (PTF). The quality of printed components depends on both the rheology and drying behavior of the pastes. Pastes with highly volatile solvents are inappropriate for the Micropen. This system has been used to make integrated passive devices such as RC filters, inductors, and voltage transformers.

Keywords: direct fabrication, micropen, polymer, thick-film, ceramic thick-film, multilayer, rheology, MMICCs, passive components

Introduction

High reliability passive components (i.e., capacitors, resistors, and inductors) and packaging substrates are commonly made using multilayer ceramic constructions. However, the desire to achieve further miniaturization, greater functionality and enhanced reliability in advanced electronic and microelectromechanical systems is driving the development of more highly integrated components based on combining different functional ceramics together into complex 3-D architectures. There are numerous examples achieved by electronic ceramic manufacturers in which various materials have been combined to produce monolithic, multilayer ceramics with sophisticated functionality such as filters [1,2] and solid-state dc–dc converters [3]. Similarly, significant work is being done to permit the embedding of passive components into low-temperature cofireable ceramic (LTCC) packages [4]. This trend towards higher level integration, which is the passive component analog of an integrated circuit (IC), places increasing demands on fabrication processes and manufacturers.

The usual technique for making these multilayer, multi-material, integrated ceramics is based on cofiring of laminates made from layers of green tapes onto which features such as conductor traces have been screen printed. This manufacturing method, driven by the needs for low cost and high production volumes, has been refined over decades of development. While this approach works well for simple parts such as multilayer capacitors that contain only a single active ceramic, fabricating multifunctional components in complex geometries is a significantly more challenging problem. Furthermore, commercial development of sophisticated integrated ceramics has emphasized a highly empirical approach, making the technology inaccessible for low-volume, specialty components.

To overcome this limitation, a direct fabrication approach is being developed at Sandia that simplifies the processing and provides greater flexibility than would otherwise be possible with tape casting and screen printing approaches. The goal is to provide a rapid prototyping and agile manufacturing approach to fabricating multifunctional, multimaterial integrated ceramic components (MMICCs). This work is based on the use of a commercial micropen system [5,6,7] for depositing electronic-grade slurries in precise patterns. In this article, the direct fabrication approach is introduced along with a discussion of some of the critical technical issues. In addition, a number of devices that have been fabricated using the micropen are illustrated.

Micropen Fabrication

The Micropen system (Ohmcraft, Inc.), a computer automated device for precision printing of ceramic slurries [5], is illustrated in Fig. 1. The system uses a computer driven *x-y* stage for printing, where the print pattern is defined by a CAD instruction file. The CAD file can easily be modified, which permits on-line design changes. This feature is in contrast to screen printing where a new screen is required for a pattern change. The cross-sectional area of the printed feature is determined by the nozzle dimensions. The Micropen can use a wide range of nozzle sizes to optimize different print geometries. The finest nozzle for high-definition patterns has an inner diameter of 1 mil and an outer diameter of 2 mil. More typical nozzles range from outside diameters of 4 mil to 10 mil. The slurry is delivered to the print head by a pump block, which uses two internal chambers to provide a smooth, continuous delivery of slurry. Slurries are easily loaded into a syringe which screws into the pump block assembly. A key to achieving uniform and reproducible processing is the elimination of air bubbles in the slurry, accomplished by centrifuging the syringe and bleeding the pump block. Any thick-film paste that is appropriate for screen printing can be used in the system. The typical solids loading for these slurries is 25–30 vol%.

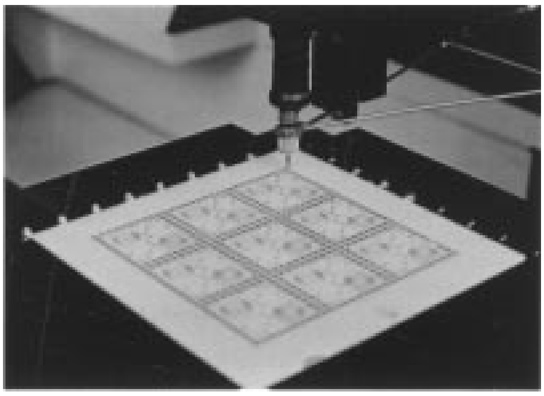

Fig. 1. Photograph of the Micropen print head during a printing operation. Adapted from [5].

The Micropen uses force feedback control on the pen tip to stabilize the printing conditions. Feedback is achieved by balancing the upward force on the pen due to the extruding slurry and the downward force applied by an electromagnet. This control leads to both excellent control of the print thickness and the ability to print over variations in the topography (i.e., height) of the workpiece. The system is also inherently capable of depositing multiple materials in a single layer, which cannot be done with conventional tape casting techniques. Since the workpiece needs to support the force of the pen, however, any underlying slurry layer must be dried before printing on top of it. In contrast to other rapid prototyping techniques, this limitation restricts the system from the continuous processing of structures. However, it is ideally suited for the step and repeat procedures which are more appropriate for multilayer, multimaterial electronic components.

The system relies on good bead definition to build accurate parts. The electrical properties of electronic components deposited with the Micropen often depend on the accuracy of the line width which is in turn influenced by the degree of bead spreading after the line has been printed. Minimum feature sizes and the minimum spacing between components are also influenced by bead spreading. Electronic components that are too close together may be subject to shorting or electromigration. The rheology of the slurries used in this system was investigated to gain an understanding of its influence on bead shape. This information will provide valuable feedback for component design and will drive materials processing as new slurries are developed for the system.

Paste Rheology and Printing Characterization

Several commercial thick-film pastes have been investigated and used to characterize the printing

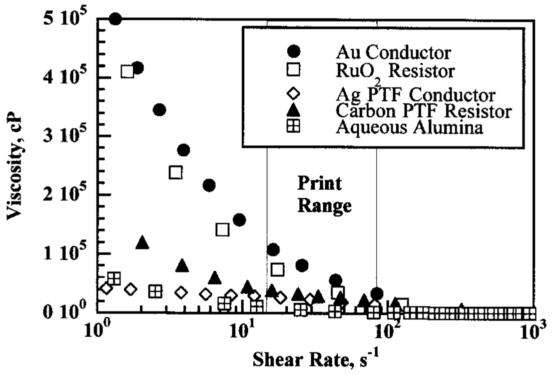

Fig. 2. Viscosity as a function of shear rate for commercial screen printing inks and aqueous alumina slurry.

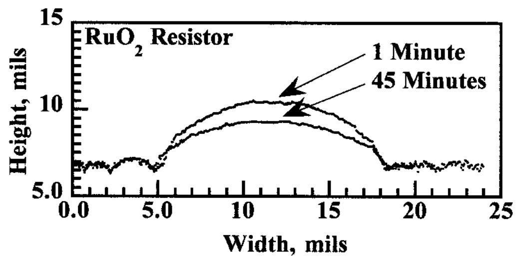

Fig. 3. Profile of a resistor paste bead printed with the Micropen at times of 1 min and 45 min after printing.

process. The materials used in the work were a gold conductor paste (DuPont 5715) and a RuO_2-based resistor (DuPont 1731), both post-fire pastes. Additionally, two commercial polymer thick film (PTF) pastes were investigated. These were a silver conductor (Minico M-4100) and a carbon resistor (Asahi TU-1k). Both of the PTF pastes consist of solids (either silver or carbon) loaded in an epoxy carrier and are designed to be printed on FR-4 epoxy board. An aqueous alumina slurry was also investigated to determine the feasibility of developing aqueous slurries of electronic ceramics for the Micropen. These materials are included in this paper to illustrate the range of materials that may be deposited with the Micropen.

The rheology of the pastes was characterized using a controlled stress rheometer*. Viscosity as a function of shear rate for each of the pastes is shown in Fig. 2. Included on the plot is the calculated range of shear rates experienced during printing [8]. This data demonstrates that all the pastes are shear thinning. While there is a wide range of viscosities at low shear rates, the viscosities tend to converge at shear rates which are typical of the printing process. Consequently, the optimal print parameters do not vary greatly for different thick-film formulations. However, differences in the slurry viscosity at low shear rates, which corresponds to settling conditions, is critical for optimizing materials for either high definition patterns or for smooth filled regions. It has been observed that viscous slurries typically lead to sharply defined traces, whereas the more fluid pastes flow together during settling to give a relatively smooth surface for filled areas. Note the similarity in the rheology of the silver PTF paste and the aqueous alumina. Based on this observation, it might be expected that these two pastes would behave the same when printed. However, it was observed that the alumina paste dried too quickly to be printed, whereas the silver PTF could be printed readily. This observation emphasizes the role that the solvent plays in making a suitable paste.

The slumping behavior of each paste was investigated by depositing a single bead onto a substrate and characterizing the shape of the bead via laser profilometry.† Pastes were deposited using a 10 mil tip and bead profiles were obtained at times ranging from 1 min to 1 h after printing. The post-fire inks were deposited onto alumina substrates, while the PTF inks were deposited onto FR-4 epoxy board. From these profiles, the bead width and area as a function of time after printing were obtained. Profiles similar to the profile shown for the RuO_2 resistor paste in Fig. 3 were obtained for all of the pastes printed in the Micropen. Figure 4 plots width and cross-sectional area as a function of time after printing. Minimal spreading was observed after the first minute beyond printing. However, a significant change in the cross-sectional area of each bead was noted over the course of the hour. This change in area is attributed to drying shrinkage. Although not presented here, it has been observed that when much larger beads ($\approx$ 35 mil) are printed, rheological differences become quite significant. Additionally, enhanced solvent extraction, either through the use of a more volatile solvent or by printing onto a porous substrate, results in significantly better bead definition [9].

*Bohlin CS-10, Bohlin Instruments, Cranbury, NJ 08572

†CyberScan Cobra, CyberOptics, Minneapolis, MN 55416

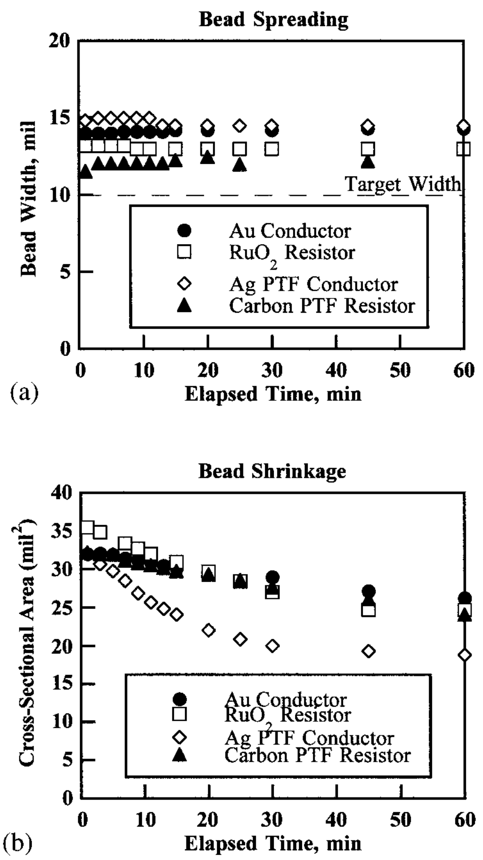

Fig. 4. (a) Spreading and (b) Shrinkage as a function of time after printing of thick film inks printed with the Micropen.

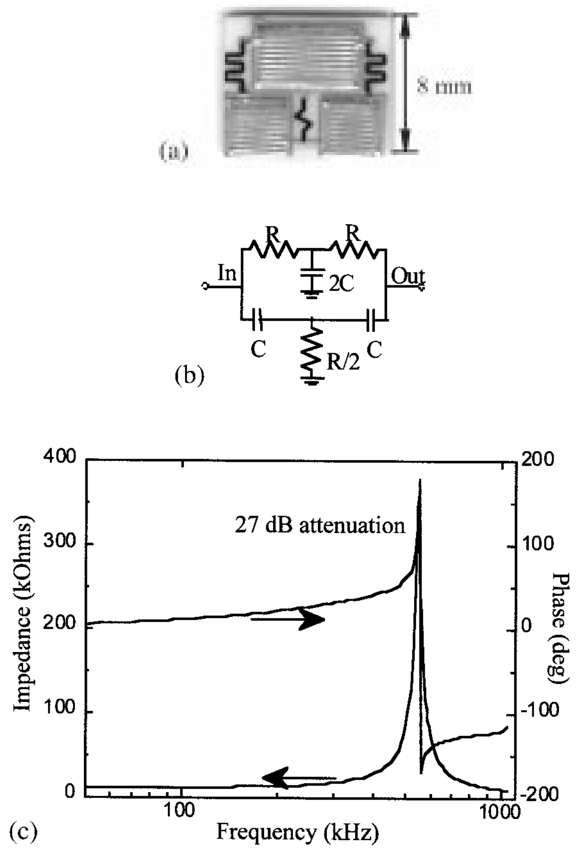

Fig. 5. (a) Photograph of 4-layer band reject filter fabricated with the micropen, (b) Schematic diagram of band reject filter, (c) Impedance response for a typical micropen band reject filter.

Prototype Components

The Micropen system has been used to prototype various electronic components. The materials used for producing these components were a crossover dielectric (Ferro 10-38N), a Ag conductor (Ferro 1039), and a RuO_2-based resistor (Ferro 87-102). Figure 5a shows a R-C band reject filter fabricated with the micropen, based on the schematic circuit layout in Fig. 5b. The capacitors are parallel plate capacitors with a single dielectric layer. The impedance response is shown in Fig. 5c, which indicates a 27 dB suppression at the reject frequency, which is given by $f_C = (\pi RC)/2$. The sharpness of the attenuation is given by achieving good matched values for the capacitors and resistors.

The capability of the Micropen to accommodate various topographies has also been utilized to build a multi-turn voltage transformer structure, as shown in Fig. 6a. The transformer is built by interleaving dielectric layers and Ag conductor traces. It has been fabricated with an outer winding of six turns and an inner winding of three turns so that the device can be used for 2:1 and 1:2 voltage conversion. This construction relies on the ability of the micropen to print at a range of heights and would be extremely difficult to fabricate using standard tape/screen printing methods. This design works well, but the conversion efficiency (Fig. 6b) of this prototype is relatively poor since a low permeability dielectric was used for the prototyping rather than a high permeability ferrite. In addition, we have successfully fabricated a flat eight turn solenoid (L $\sim$ 1 μH @ 1 MHz), and a multitap voltage divider, which are shown in Figs. 7a and 7b, respectively. These devices have all been printed on alumina substrates. However, the process has also been used to fabricate components on LTCC tapes and on Mylar and Teflon

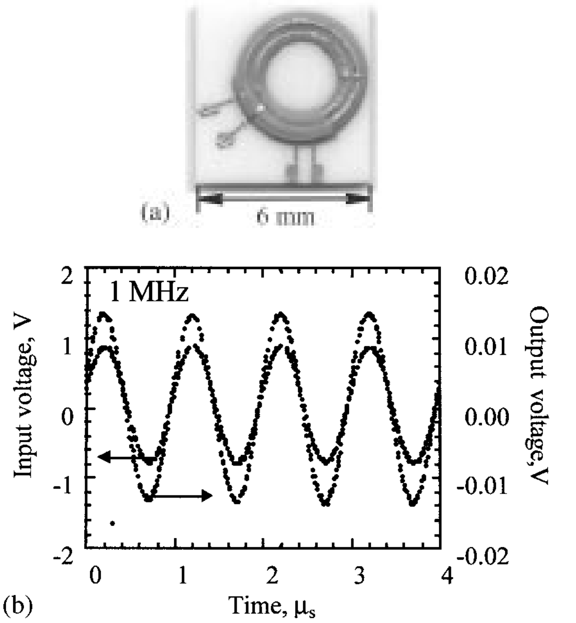

Fig. 6. (a) Picture of multiturn voltage transformer fabricated with independent Ag spiral windings (6 outer turns, 3 inner turns) and crossover dielectric, (b) Plot of input vs. output voltage for the transformer.

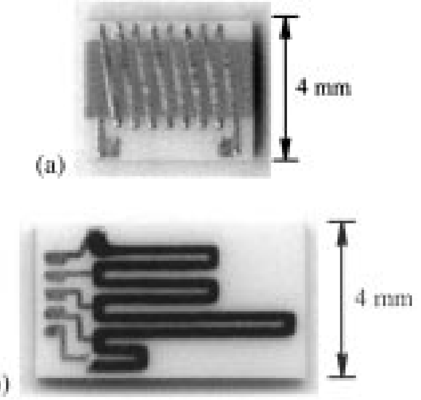

Fig. 7. (a) Flat solenoid fabricated by connecting lower half windings and upper half windings around thick-film dielectric (L $\sim$ 1 μH @ 1 MHz) (b) Multitap voltage divider for 10:1, 7:1, 4:1, and 2:1 voltage division. A 10 kΩ/sq resistor with Ag electrodes is used.

substrates that allow free standing components to be built.

There are also two issues that are critical to the fabrication of multilayer, multimaterial ceramic components, which can only be quickly mentioned in this article. The first is sintering compatibility, since differential shrinkage tends to cause defects in multilayered cofired structures. To assess the cofire-ability of various thick films, the sintering behavior of individual thick-film layers prepared with the Micropen using two different experimental techniques are being characterized. These results will be published in a future publication [10]. The other issue is reactions between dissimilar materials. While some reaction between layers is useful to promote adhesion, extensive reaction needs to be avoided. Reaction rates between materials, which we are being evaluated using hot-stage X-ray diffraction techniques, will determine whether various material systems can be integrated.

Conclusions

A direct-write approach for fabricating highly integrated, multilayer components using a micropen to deposit slurries in precise patterns has been described. With this technique, components are constructed layer by layer, simplifying fabrication. The Micropen can accommodate the wide range of slurry rheologies corresponding to most commercial thick-film pastes. However, aqueous slurries, despite having a rheology similar to the more fluid commercial pastes, dry too rapidly to be printed. It has been observed that the quality of print features depends on both slurry rheology and rate of solvent extraction. The direct-write approach provides the ability to fabricate multifunctional, multimaterial integrated ceramic components (MMICCs) in an agile way with rapid turnaround, and has been used to fabricate devices such integrated RC filters, multilayer voltage transformers, and other passive components.

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