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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. For rapid prototyping and small-lot manufacturing, traditional tape casting and screen printing approaches are poorly suited. To address this need, we are developing a direct-write approach for fabricating highly integrated, multilayer components using a micropen to deposit slurries in precise patterns. With this technique, components can be constructed layer by layer, simplifying fabrication. It can also be used to produce structures combining several materials in a single layer. The parts are either cofired or sequentially fired, after each layer is deposited. Since differential shrinkage can lead to defects in these multilayer structures, we are characterizing the sintering behavior of individual layers. This technique has been used to fabricate devices such integrated RC filters, multilayer voltage transformers, and other passive components. The direct-write approach provides the ability to fabricate multifunctional, multimaterial integrated ceramic components (MMICCs) in an agile and rapid way.

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. Currently 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 embedding of passive components into low-temperature cofireable ceramic (LTCC) packages. This trend towards higher level integration, which is the passive component analog of an integrated circuit (IC), places increasing demand 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 with screen printed features, such as conductor traces. This manufacturing method has been refined over decades of development, driven by the needs for low cost and high production volumes. 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

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challenging problem. Consequently, commercial development of sophisticated integrated ceramics has emphasized a highly empirical approach, making the technology impractical for low-volume, specialty components.

To overcome this limitation, we are developing a direct fabrication approach 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 [4,5,6] for depositing electronic-grade slurries in precise patterns. In this paper, we discuss several specific issues that are critical to the direct fabrication of MMICCs by the micropen approach, such as the relationship between slurry rheology and print topology. Characterization of the sintering behavior of thick films, which is critical for assessing cofireability, has also been carried out using two different approaches. Finally, a number of specific devices that have been fabricated using the micropen are illustrated.

EXPERIMENTAL

Micropen

Direct deposition of precise patterns is being accomplished using a commercial Micropen system (Ohmcraft, Inc.), which is an automated printing device for ceramic slurries [5]. The micropen has a computer driven x-y stage that uses CAD file instructions, which permits easy on-line design changes in contrast to screen printing where a new screen is required for a pattern change. It is also inherently capable of laying down multiple materials in a single layer, which cannot be done with conventional tape casting techniques. The micropen utilizes nozzles with an inner orifice diameter as small as 1 mil and an outer diameter down to 2 mil for high definition patterns. A critical feature of the Micropen is the force feedback control on the pen tip, which is based on balancing the upward force on the pen due to the extruding slurry and the downward force applied by an electromagnet, as illustrated in Fig. 1. This control leads both to a very reproducible print topology and the ability to print over variations in the topography (i.e., height) of the workpiece. However, since the workpiece needs to support the force of the pen, any underlying slurry layer must be dried before printing on top of it.

The other critical feature of the system is the pump block, which uses two internal chambers to provide smooth, continuous delivery of slurry. The slurries are loaded into a syringe which screws into the pump block assembly. To get uniform and reproducible processing it is critical to eliminate air bubbles in the slurry, which is accomplished by centrifuging, and in the pump system, which is done by bleeding the pump block.

Materials

Commercial thick-film slurries were used to characterize the printing process and to fabricate components. The materials used in the work were: a crossover dielectric (Ferro 10-38N), a Ag conductor (Ferro 1039), and a RuO₂-based resistor (Ferro 87-102). Slurry viscosities were characterized using a Brookfield viscometer with a cone and plate attachment.

Operation

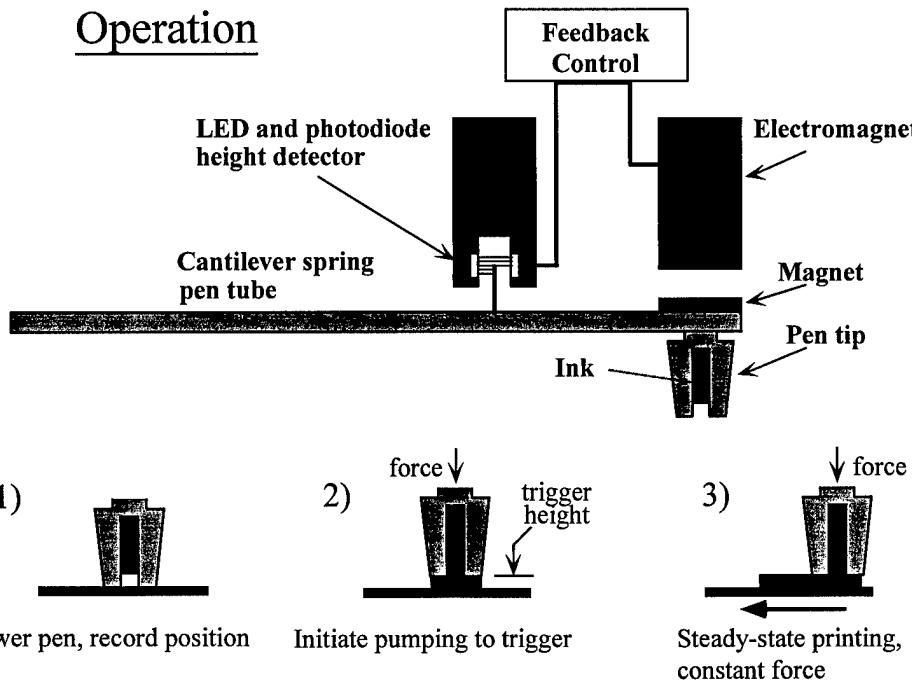


Figure 1. Schematic diagram of the micropen print head showing the photo detector system for height control and the electromagnet force balancing system. The lower drawings illustrate the steps to initiate slurry printing.

Sintering

Two different systems were developed to characterize the sintering behavior of individual thick film systems. While detailed descriptions will be published elsewhere [7], schematic diagrams of the two systems are given in Fig. 2.

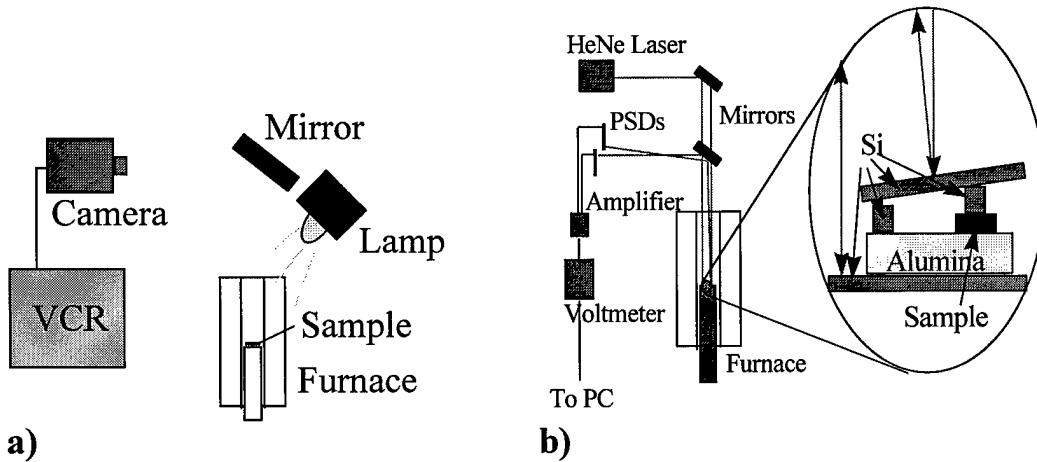


Figure 2. a) Schematic diagram of system for measuring (lateral) sintering behavior of free-standing films. b) Schematic diagram of system for measuring z-axis sintering behavior of laterally constrained films.

Figure 2a shows the arrangement used to determine the sintering behavior of unconstrained, free-standing thick films. Square samples were patterned with the micropen onto teflon or mylar substrates, so that the thick-film sample could be removed from the substrate producing a free-standing thick film piece with an area of 4mm x 4mm and a thickness of 75-100 μm (2-3 print layers). The samples were fired on top of a quartz setter, which did not react with the samples during the measurements. The sintering behavior was characterized by continuously monitoring the x-y dimensions of the sample with the video recorder during heating.

In contrast, Fig. 2b illustrates the arrangement for characterizing the sintering behavior of films constrained in the x-y plane. These measurements also used samples with an area of 4mm x 4mm and a thickness of 75-100 μm that were deposited onto alumina substrates. A dual laser beam system was used to determine the z-axis shrinkage of the film by comparing the deflection of a reference laser beam to the deflection of an incident parallel beam from a mirror positioned on the sample as shown in the inset of Fig. 2b. The laser beam deflections were continually monitored during heating using position-sensitive photodetectors. The optical path length from the sample mirror to the photodetector was ~ 1.5 m, which enabled small changes in the angular deflection of the sample mirror and, thus, very small changes in the sample thickness to be accurately determined. It should be noted that this system was developed after it was determined that a standard extensometer could not be used, since it applied enough pressure to the sample to locally deform it during firing.

RESULTS

Slurry viscosities as a function of shear rate are shown in Fig. 3, which demonstrate that all the thick film pastes are shear thinning. There is a wide range of viscosities for these materials at low shear rates. However, the range of viscosities converge at higher shear rates, which are typical of the printing process. The range of shear rates (dv/dr) typical of the printing process was

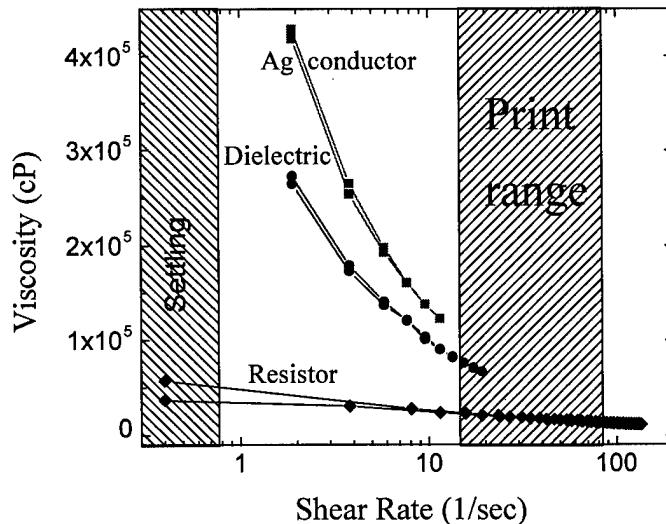


Figure 3. Viscosity vs shear rate behavior for the electronic thick films used.

estimated using the following equation for an incompressible, Newtonian fluid with no flow against the wall of the orifice:

$$dv/dr = (4/\pi) (Q/R^3) , \quad (1)$$

where Q is the volumetric flow rate (typically $\sim 10^{-5}$ cm³/sec) and R is the inner orifice diameter (2-10 mil). The settling rates correspond to the high viscosity range.

An attractive feature of the Micropen is that the print topology is fairly insensitive to the slurry viscosity. This feature is illustrated in Fig. 4, which shows profilometry traces obtained on line prints of the dielectric, conductor, and resistor using identical print conditions. However, the slurry viscosity at the low shear rates is critical for optimizing materials for either high definition patterns or for filled regions. The most viscous slurry (Ag conductor) leads to sharply defined traces, whereas the more fluid resistor paste flows together to give a relatively smooth surface for filled areas, which are typical of thick-film resistors.

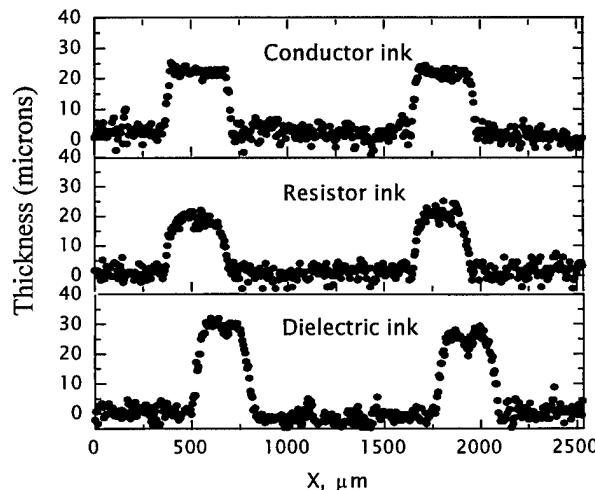


Figure 4. Profilometer traces showing that the print topologies for materials with different viscosities are very similar and good using identical print parameters.

Figure 5 illustrates the sintering behavior, at a constant heating rate of 20°C/hr, for the three thick-film systems. The Ag conductor sinters at a much lower temperature than the other two materials, which is not ideal for cofiring compatibility. The free sintering rate is also higher than the constrained sintering rate, which is commonly observed and is due to internal stresses in the constrained system [8]. The shrinkage curves for the dielectric and resistor systems both show a rather abrupt onset of sintering (at 725°-800°C), which is typical for liquid-phase sintering systems above the liquidus. The temperature compatibility also promotes good cofireability. In addition, the free and constrained shrinkage curves for these two materials are essentially identical, which is also consistent with a liquid-phase mechanism, since a liquid phase tends to limit stress buildup. It should also be noted that the total volume shrinkage is nearly equivalent for each material in both constrained and unconstrained sintering, which is anticipated and verifies good correlation between the two experimental methods.

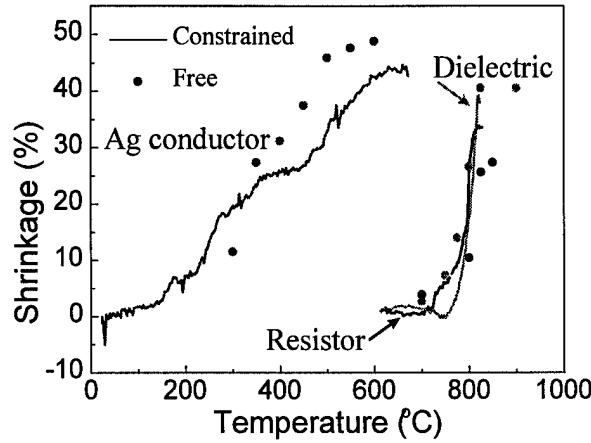


Figure 5. Measurements of the sintering behavior (% shrinkage vs temperature) at constant heating rate (20°C/hr) for three thick-film systems. Measurements were carried out with the two experimental setups to determine the constrained and unconstrained sintering behavior.

Prototype Components

The Micropen system has been used to prototype various electronic components. Figure 6a shows a R-C band reject filter fabricated with the micropen, based on the schematic circuit layout in Fig. 6b. The capacitors are parallel plate capacitors with a single (crossover) dielectric layer. The impedance response is shown in Fig. 6c, 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.

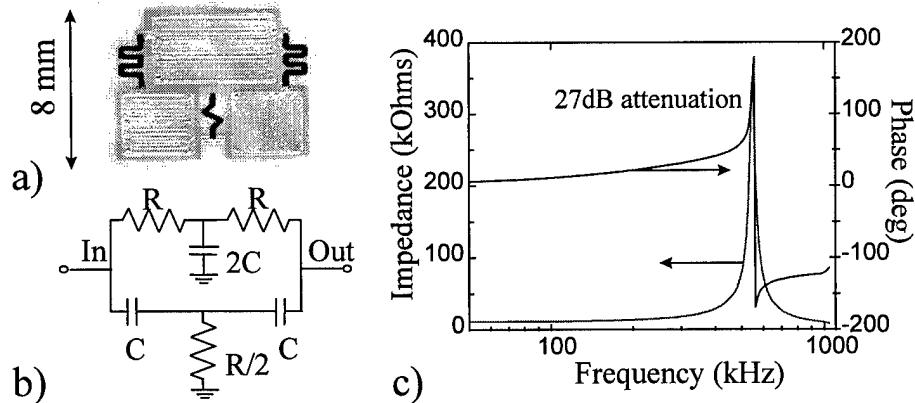


Figure 6. a) Photograph of 4-layer band reject filter fabricated with the micropen, b) schematic diagram of band reject filter, c) impedance response for a typical micropen band reject filter.

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. 7a. The transformer is built 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. 7b) of the initial 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 ($L \sim 1 \mu\text{H}$), and a multitap voltage divider, which are shown in Figs 8a and 8b, respectively. While these devices are all printed on alumina substrates, the process has also been used to fabricate components on tapes and on mylar and teflon substrates that allow free standing components to be built.

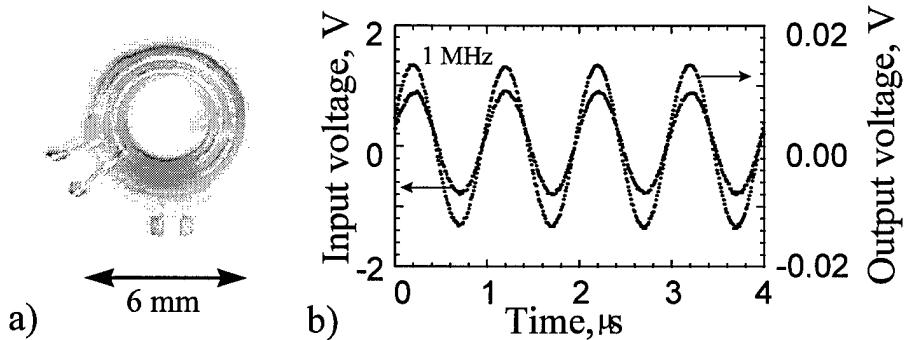


Figure 7. A) Picture of multturn voltage transformer fabricated with independent Ag spiral windings (6 outer turns, 3 inner turns) and crossover dielectric. Plot of input vs output voltage for the transformer.

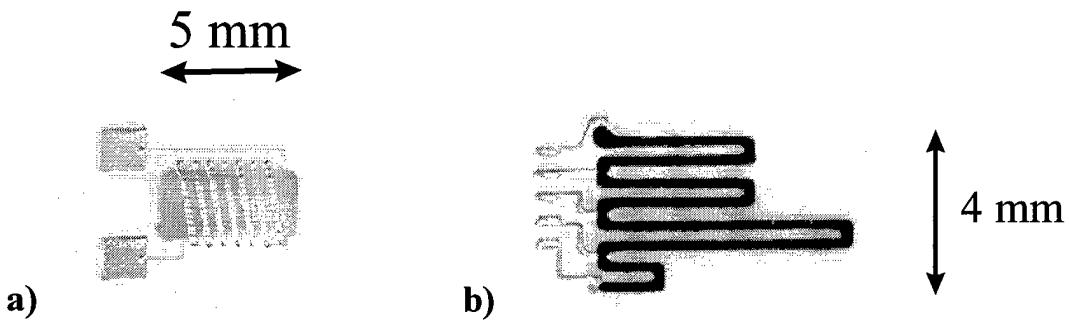


Figure 8. a) Flat solenoid fabricated by connecting lower half windings and upper half windings around thick-film dielectric ($L(@ 1 \text{ MHz}) \sim 1 \mu\text{H}$), b) Multitap voltage divider for 10:1, 7:1, 4:1, and 2:1 voltage division. A $10\text{k}\Omega/\text{sq}$ resistor with Ag electrodes is used.

CONCLUSIONS

We have demonstrated a direct-write approach for fabricating highly integrated, multilayer components using a micropen to deposit slurries in precise patterns. With this technique, components are constructed layer by layer, simplifying fabrication. The quality of print features depends on slurry viscosity; however, the micropen can use a wide range of slurry viscosities

with minimal optimization. Since differential shrinkage can lead to defects in these multilayer structures, we have developed two techniques for characterizing the sintering behavior of individual layers, which should help in assessing cofireability. Finally, the micropen technique has been used to fabricate devices such integrated RC filters, multilayer voltage transformers, and other passive components. The direct-write approach provides the ability to fabricate multifunctional, multimaterial integrated ceramic components (MMICCs) in an agile way with rapid turnaround.

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