DIRECT-WRITE PRECISION RESISTORS FOR CERAMIC PACKAGES

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ABSTRACT

A direct-write approach to fabricate high precision resistors is reported. Special attention is paid to the effect of print thickness on the resistance value of buried resistors after a low temperature co-firing process. The results show that the direct-write approach provides a superior line definition and thickness control over a traditional screen printing process. Microstructural analysis indicates that there is an interdiffused layer developed between the resistor material and the low temperature co-fired ceramic substrate. These observations are consistent with electrical measurements which show that resistance increases as the effective cross-sectional area is reduced. The resistance data show that the standard deviations for resistors printed on a 6" x 6" area are 5% and 15% for the direct-write and the screen-printed patterns, respectively.

INTRODUCTION

The ability to fabricate high precision buried resistors into low temperature co-fired ceramics packages (LTCC) offers strategic advantages in component miniaturization, increased reliability, and greater functionality in advanced electronic systems. However, the traditional approach of screen printing for fabricating these thick film resistors has been limited by the thickness variations and firing control which ultimately limits the precision of these components. In addition, traditional screen printing is poorly suited for rapid prototyping and small-lot manufacturing. To address these needs, a direct-write approach is being developed for fabricating high precision resistors. This approach uses a commercial Micropen system to deposit thick film resistor slurries in precise patterns. With this computer-controlled technique, components can be immediately constructed layer-by-layer without introducing any screens or stencils. Parts can be fired after each layer is deposited or co-fired during a single firing schedule. The Micropen system is also inherently capable of laying down multiple materials in a single layer which facilitates embedding of various passive components into LTCC. This trend towards higher level integration, analogous to integrated circuits, places increasing demand on fabrication processes and manufacturers.

Like most direct-write techniques, the Micropen provides rapid prototyping and agile manufacturing capacities for fabrication of thick film hybrids. In today's climate of cost reduction and rapid turnaround, these important features are receiving a great deal of attention. Sometimes, the real advantages of these newly developed technologies have been overlooked. For example, consider the advantage of high precision parts made by these computer-controlled close-loop systems. Figure 1 compares the edge definition of printed resistors made by screen printing to those fabricated using the Micropen. This figure clearly demonstrates the superior edge definition of the Micropen direct-write technique. These advantages have yet to be fully implemented to exploit the potential of these new technologies. The main purpose of this article is to put the advantage of precision control into proper perspective. This is accomplished through the investigation of print thickness and line definition of this direct-write technology, as

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it relates to the tolerance of resistors. In addition, we will demonstrate an improved temperature-coefficient-of-resistance tracking for a high-aspect-ratio, fine line, thick film resistor network by taking advantage of this high precision direct-write technology. Finally, specific issues relating to the precision control of the buried resistors in the LTCC will be discussed.

Figure 1. A direct comparison of printing quality (a) standard screen printing - 20 mils x 50 mils (thick film configuration) and (b) Micropen direct-write high aspect ratio pattern - 4 mil line and 4 mil spacing (thin film configuration).

EXPERIMENT

Micropen

Direct deposition of precise patterns was accomplished using a commercial Micropen system (Ohmcraft, Inc.). This device has been described elsewhere [1]. The system uses a computer-driven x-y stage for printing; and the print pattern is defined by a computer-aided design (CAD) instruction file. The CAD file can be easily modified and permits on-line changes. Multiple materials can be laid out on different design layers in a CAD file and printed onto a single layer. This benefit eliminates the tooling cost and time for making screens and stencils that are traditionally used in a screen-printing process.

The Micropen uses a wide range of nozzles 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 mils. The slurry is delivered to the print head by a pump block, which uses a displacement control from two internal chambers to provide smooth, continuous slurry delivery. Slurries are easily loaded into a syringe that screws into the pump block assembly. A key to uniform and reproducible processing is eliminating air bubbles from the slurry, which can be accomplished by centrifuging the loaded syringe and bleeding the pump block.

The Micropen also uses force feedback control on the pen tip to stabilize the printing conditions. The feedback is achieved by balancing the upward force on the pen (due to the extruding slurring) and the downward force applied by an electromagnet, as illustrated in Figure 2. The result is both excellent control of print thickness and the ability to follow changes in the topography (i.e., height) of the work-piece. Several prototype components have been fabricated by taking advantage of these features [2].

In this paper, 896 resistors with four different geometries were used to compare the thickness variation and electrical performance for direct-write and screen-printing processes. Four different resistor geometries, 40 X 40, 40 X 20, 20 X 20, and 20 X 40 mils, were used for evaluation purposes. A nozzle of 10 mils outer diameter and 7 mils inner diameter was used to write the test pattern onto a 6" x 6" low temperature co-firable green tape (Dupont A951).

Screen Printing

The same test pattern was screen printed onto the low temperature co-firable green tape (Dupont A951), using a 325 mesh screen with 0.5 mil emulsion. To minimize the thickness variation adjacent to the conductor pattern, the resistor layer was laid down prior to printing of the conductor layer. Samples fabricated by Micropen and screen printing were fired side by side in a box furnace, according to the firing profile suggested by Dupont.

The thickness variation of the dried resistor pattern was determined by a non-contact laser profilometer. The resistance of these fired resistors was measured by a four-point measurement from a digital multimeter. Scanning electron microscopy (SEM) was used to measure the fired thickness and identify possible reactions at the resistor-dielectric interface.

Figure 2. 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.

RESULTS & DISCUSSION

In the engineering community, the final resistance value of a fired thick film resistor is typically correlated to its dry thickness. This empirical practice improves process control so the tolerance of the resistors can be assured. Figure 3 shows the thickness control of the Micropen system for a Dupont buried resistor ink. Cross Section, the parameter plotted on the horizontal axis in figure 3, controls the cross-sectional area of the printed traces. For a given size of pen tip, this parameter determines the thickness of the print if the writing force holds constant. Results show that Micropen is able to precisely control the printed thickness within 3 μm .

Figure 3. The print thickness as a function of cross-sectional setting for Micropen.

Figure 4 illustrates the resistance value of buried resistors as a function of the printing thickness. Results show that the resistance (as measured after firing) is inversely proportional to the thickness of the dry film. In general, thickness measurements on post-fired resistors, also indicate this same inverse proportionality. Because these buried resistors are difficult to trim

after the co-firing process, precision control of the print thickness is critical to assuring tolerances are met.

Figure 4. The resistance of buried resistors as a function of dry thickness.

Preliminary data from Energy Dispersive Spectroscopy (EDS) exhibits inter-diffusion of elements from green tape to the resistor, and vice versa. For example, calcium (from the green tape) was found to diffuse into the resistor, while barium, strontium, and zinc (typically observed in the resistor) were found to diffuse into the green tape. Figure 5 (a) displays a Backscattered Electron (BE) image obtained on a cross-sectional cut through a resistor. This (BE) images shows a "halo" effect on the outside boundaries of the resistor resulting from diffusion of the resistor into the tape. Additional evidence of chemical re-distribution is seen in Figure 5 (b). This figure is an X-ray map of Zn and it clearly indicates that zinc (a constituent of the resistor) has re-distributed along the resistor/Dupont-tape interface and some zinc has even diffused into the green tape. The existence of this inter-diffused layer could significantly reduce the effective cross-sectional area for the charge carriers to pass through the resistor pattern. Since the resistance is inversely proportional to the actual cross-sectional area of the resistor trace, these resistance values can then be fitted into a simple relationship

$$R (\text{resistance}) = \frac{a}{(t - 2t_o)} \quad (1)$$

, where a is a proportional constant which relates to the geometry and resistivity of the ink, t is the total thickness, and t_o is the thickness of the inter-diffused layer. Because these resistors are embedded in the low temperature co-fired tape, there are two reaction layers (one on each side) which directly contact the green tape. As a result, a factor of two was introduced into equation (1). Based on this above relationship, an estimated $5.4 \mu\text{m}$ thickness of dry resistor layer has inter-diffused with the glass constituents from the green tape. Considering a shrinkage factor after a co-firing process (typical 13%), the estimation is in a good agreement with the SEM results.

In a traditional screen-printing process, bowing of the screen can cause the printed thickness to be thinner at the center than at the edges and to be thicker adjacent to the conductor pattern. The same effect would also affect the printing thickness across the squeegee. In fact, we have observed that the average thickness of the resistors at the edges is generally thicker than those at the center. In a direct comparison with a Micropen-deposited pattern, the thickness variations for a screen-printed pattern is two times greater than the direct-write technology, where the variations for screen printing and Micropen are 9.9 % and 4.4 %, respectively. It is obvious that the direct-write technology provides a better control on the print thickness. These

thickness variations are immediately reflected by the electrical measurements where the resistance variations for screen printing and Micropen are 15% and 5%, respectively.

Figure 5. The SEM microphotographs of (a) backscattered electron image and (b) X-ray mapping of the zinc element close to the resistor and green tape interface.

The value of a film resistor is determined by the material used and a geometric factor. In a two-dimensional system it is a common practice to regard the film thickness as relatively invariant. Therefore, the resistance of a thick film resistor is determined by the material resistivity in terms of ohms per unit area, and the geometric factor based on the number of unit areas (squares) in series. Higher resistance values can be achieved by either using a material with high sheet resistivity or increasing the number of squares, or both. In the case of thin film resistor fabrication, a homogenous material is used and the photolithographically defined thin film resistors enjoy superior tolerance and temperature stability over the traditional thick film resistors. Unfortunately, there is a limit to geometrical manipulation of thin film resistance values. The number of squares may be increased by decreasing the line width, but this can be done only up to a point. Beyond this point, proportionately more substrate area is required. In thick film technology, the sheet resistivity is adjusted over a range of several decades by changing the ratio of conductive phase and glass phase in the ink. However, the increased resistivity of the material through dilution eventually reaches a level where other characteristics are severely degraded; e.g., stability and temperature coefficient of resistance. This could pose a potential problem especially when multiple materials are used to fabricate a wide range resistor network. With the ability to produce high aspect ratio, fine line traces, the direct-write Micropen system can make similar use of the geometrical advantages from thin film technology by depositing wide-ranging multi-value networks in a single ink composition. This ability is particularly useful with respect to ratio tolerance for components such as a voltage divider as a function of temperature. Figure 6 (a) illustrates the resistance values of a traditional thick film configuration voltage divider consisting of a higher resistivity ink (Dupont 1749) and a lower resistivity ink (Dupont 1731). It is clear that both inks behave differently. The resistance value decreases as temperature increases for the high resistivity ink, while it increases for the low resistivity ink. Consequently, the resistance ratio for this voltage divider varies about 4 percent from -100 to 100°C , with respect to the value designed at room temperature.

In contrast, if we replace the high value resistor from a thick film configuration with a high aspect ratio "thin film configuration" employing the same low resistivity resistor ink, the temperature tracking between two resistors is substantially improved (see Figure 7). As a result, the resistance ratio decreases to 1.6 percent for the same temperature range. Because resistors in

this divider are composed of the same ink (Dupont 1731), this network has excellent tracking characteristics, thereby further justifying their adjustment to close relative value.

Figure 6. (a) The resistance values of R_l and R_h as a function of temperature for low sheet resistivity (Dupont 1731) and high sheet resistivity (Dupont 1749) inks, and (b) the percentage of changes in resistance ratio as a function of temperature.

Figure 7. (a) The resistance values of R_{thin} and R_{thick} for resistors with a thick film configuration and a thin film configuration as a function of temperature, and (b) the percentage of changes in resistance ratio as a function of temperature (Dupont 1731).

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