Performance of Co-Fired Buried Resistors in A6S Tape

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ABSTRACT

This paper reports work on next generation of co-fired buried resistors for Ferro’s A6S tape system and CN33-398 (100%Ag) conductor. A study of LTCC co-fired buried resistors in the resistivity range of 35 \( \Omega \square \) to 100 K\( \Omega \square \) has been performed. Resistivity and temperature coefficient of resistance (TCR) versus resistor size and post-firings were investigated and are reported.

Key Words: LTCC, buried resistors, post-firing, anomalous conductivity loss, TCR

INTRODUCTION

Low temperature co-fired ceramic (LTCC) is employed for the fabrication of high reliability, compact, low-cost electronic modules. Integrating resistors and capacitors into the LTCC structure reduces the number of interconnects, assembly time, and the overall package cost.

Resistors with dimensions starting at 40 mils x 40 mils are commonly used. The need for the increased integration density requires further size reduction of resistors integrated into LTCC structure. Co-fired buried resistors should have acceptable resistor performance over a wide range of sizes and be stable with post-firings.

Cost reduction is important to the integration of passive components. Therefore the use of resistor terminations made of silver-based conductor inks with very low palladium content or with no palladium is preferable. However, moderate diffusion of silver from the conductor into resistor creates additional problems. In general, silver diffusion affects resistivity, TCR values after initial firing, and their shifts after post-firings.

This paper presents results of recent work in the development of the next generation of co-fired buried resistors in A6S tape with 100% silver conductor. Resistors in the resistivity range of \( \sim (35 \Omega \square \sim 100 \text{ K}\Omega \square) \) were investigated.

EXPERIMENTAL PROCEDURE

Resistive ink compositions were formulated using proprietary glass frits and ruthenium-based conductive phase powders. Appropriate amounts of selected powders were mixed with organic vehicle and three roll milled.

LTCC structure was fabricated using a stack of 4 layers 10 mil thickness each of Ferro A6S tape, which was laminated in an isostatic laminator at 70°C and 3000 psi.

Termination conductor ink CN33-398 was screen printed and dried at 80°C for 10 minutes. Then, resistive inks were screen printed to a dried thickness 21 ± 2 \( \mu \text{m} \). Resistor patterns with resistor size from 15x15 mils to 80x80 mils were used for resistor fabrication.

![Fig. 1 Test Pattern](image-url)
Blank tape of 10-mil thickness was placed on top of the pattern and laminated using isostatic laminator to create a buried resistor structure. The patterns were fired at a peak temperature of 850°C using a standard Ferro profile for LTCC materials and re-fired in belt furnace using regular 10 min at 850°C profile.

After the first firing and each refiring, the parts were tested in a Wilkins Engineering TCR Test System from -55°C to +125°C with reference point +25°C. Resistance readings were taken at each 10°C and saved for further calculations.

RESULTS AND DISCUSSION

Migration of Silver from Termination to Resistor

The resistor performance is affected by resistor-conductor interactions resulting from diffusion of silver from termination to resistor.

Silver diffusion zone length was evaluated using X-ray microanalysis method. Maximum silver diffusion intensity was found for 100%-silver termination materials. Silver diffusion is restrained if palladium is present in the conductor ink composition.

The silver diffusion zone may extend up to ~15 mils distance from each side of resistor-conductor boundary after initial firing. Each additional post-firing may enlarge the diffusion zone.

Based on this observation, resistor size 30x30 mils to 40x40 mils can be considered as critical. Special attention must be paid to resistors smaller than (40x40) mils.

Low-Ohmic Range: Resistor Performance Dependence on Resistor Size

Performance of new low-ohmic co-fired buried resistors in A6S tape in quite narrow resistor size range was described in the paper [1]. Proceeding with this investigation, figs. 3 & 4 present resistivity and TCR data for resistors with square side size from 15 mils to 80 mils.

Refire stability is shown on Figs. 5-7. Despite the noticeable diffusion of silver for smaller resistors, resistor compositions were adjusted to minimize resistivity and TCR values changes after three refirings over a wide range of resistor sizes.

For all low-ohmic resistors (from 30 Ω/□ to 1,000 Ω/□), resistivity change did not exceed ± 5%, and TCR values stayed within ± 100 ppm/°C range after three refirings.
Higher Resistivity Range: Anomalous Conductivity Loss Problem

Further LTCC resistor development has been driven by the need for higher coverage, more precise performance, and lower process sensitivity.

At the lower resistance ranges (less than \(10^3\) ohms per square) sheet resistance of thick film resistors gradually depends on content of components. In this case resistivity is easy to control by variation of the constituent's ratio in composition. Reproducibility of these resistors is sufficiently high and sensitivity to firing conditions is low.

Higher resistivities can be obtained by decreasing the conducting phase content. There is a serious problem in this range because the dependence of resistivity versus the content of components in resistive compositions is practically non-controllable. Reproducibility of resistor parameters slumps, and the electrical characteristics are highly sensitivity to firing conditions. Ruthenium-based resistors exhibit critical concentrations and a critical conduction behavior according to the following equation [2]:

\[ R = \frac{R_o}{(x-x_c)^t} \]

The exponent (t) in the dependence of resistance (R) on ruthenium oxide concentration (x) is higher for ruthenium dioxide (t \(\sim\)3) than for pyrochlore resistors (t \(\sim\) 2). For higher resistivities, the ruthenium dioxide loading (x) is much closer to the critical concentration (\(x_c\)) than for pyrochlore oxides.

However, employing ruthenium dioxide as a conductive phase for co-fired resistors was substantiated in the paper [3]. The choice was made because of the good stability of ruthenium dioxide. It is not prone to decomposition by reduction, or by leaching of ceramic constituents into the surrounding vitreous phase, as is frequently seen with some of the more complex pyrochlore phases which have been used in resistor systems.

Ruthenium dioxide is usually used in resistor series up to 1,000 Ohm members. For higher resistivity members, the percolation limit is approached if very dilute levels of ruthenium dioxide are utilized. Functionally, this is seen as a very steep and uncontrollable dependence of resistivity on conducting loading [3].

Similar case of a striking increase in resistivity and a method for fixing the problem was described in another paper [4]. The reason
of anomalous loss of conductivity in low-RuO$_2$ content thick film resistors is the critically low concentration of Ru ions/clusters in the glass. The effect on sheet resistance on the volume percentage of conductive phase is particularly critical at the higher resistance ranges ($10^4$ to $10^7$ ohms per square). Very small changes in the percentage of functional phase of the resistor (dilution curve slope) have very large effects on sheet resistance. Advances in this area have made these changes less critical and therefore reduced the process sensitivity of the resistor composition [5].

The smaller rate of change in slope of the dilution curve for high–resistance inks manifests itself as insensitivity to firing temperature [6].

Another approach to solving the anomalous conductivity loss problem was presented by the author [7,8]. A new kind of high ohmic resistors with low sensitivity to firing/refiring conditions and effectively controlled dilution curve slope was described.

**Higher-Ohmic Co-fired LTCC Resistors**

Development of co-fired LTCC resistors in higher resistivity range requires taking into consideration some additional problems along with resistor-tape interactions, shrinkage mismatch, and multiple refirings requirement.

Fig.8 shows resistivity dependence on resistor size of non-adjusted inks. Initial sheet resistivity may vary from ~3 KΩ/□ to ~9 KΩ/□ while resistor size is increasing from 15x15 to 80x80 mils.

**Fig.9** represents relative resistivity change of the same ink versus number of firings. The resistivity decrease achieved after first refiring was ~50%, and ~70% after third one.

The ability to withstand several refirings at 850°C is among the basic requirements to LTCC resistors. Also, aspect ratio and TCR curve shape in the temperature range from -55°C to 125°C must be taken into consideration during resistive compositions development.

Fig.10 shows resistivity test data of 100 KΩ/□ ink for square resistors from 15x15 to 80x80 mils size. Resistivity values stayed within 100 KΩ/□ ± 20%.

**Fig.10** Resistivity vs. Resistor Size

Relative resistivity change values of the same ink did not exceed ± 10% for resistors made of 100 KΩ/□ ink, as shown in Fig.11.
To meet the requirement of stable and precise TCR, the ratio between hot and cold TCRs must be controlled.

Experimental resistors were tested in the temperature range from -55°C to +125°C so continuous TCR curves could be obtained. Usually, cold TCR values are more negative than hot TCR values resulting in substantial slope of the TCR curve.

TCR curve slope after initial firing and following refirings may be precisely adjusted, as shown in Fig. 14.

The 3-D view chart in Fig. 15 represents dependence of resistivity on number of firings and resistor size of 100 KΩ/□ ink for square resistors printed in configurations from 15x15 to 80x80 mils.
A correlation between hot and cold TCRs is a matter of importance for precise resistors. Normally cold TCR appears more negative than hot TCR and mostly at lower loading conductive phase fractions. Glass chemistry also contributes significantly to this phenomenon.

The higher resistivity and the wider resistor size range, the bigger is the difference between hot and cold TCR. As it can be seen from Fig.16 and Fig.17, TCR curve slopes may be effectively controlled in the investigated resistor configuration range.

**SUMMARY**

New experimental buried resistors printed on 100%-silver conductor terminations and co-fired in A6S tape were investigated in the range of resistor sizes from 15 x15 to 80 x 80 mils. Developed formulations allowed obtaining resistivities from 35 Ω/□ to 100 KΩ/□. Observed resistivity change after three refirings did not exceed ± 20%. The slopes of TCR curves were controlled and minimized. TCR absolute values complied with the ± 200 ppm/°C requirement after three refirings.

**REFERENCES**

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