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Characteristics of thick film resistors embedded in low temperature co-fired ceramic (LTCC) substrates

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Abstract

Commercial thick film resistors were embedded in low temperature co-fired ceramic (LTCC) substrates, and co-fired with substrates at temperatures between 800 and 900 °C. Adding glass frit and amorphous SiO_2 to calcium borosilicate glass ceramic substrates has not only lowered the shrinkage of the substrates, but also improved adhesion and maintained structure integrity of the resistor films. During sintering, the conductive phase particles in the resistor became agglomerated and sedimented, and glass diffused into the LTCC substrate layer. Increasing the dwelling time, the overall resistivity of the co-fired films decreased due to sedimentation of agglomerated conductive particles. The liquid eutectic phases penetrated into the substrates added with either SiO_2 or glass frit that the volume fraction of conductive particles was increased. The resistivity of the embedded resistors was determined by the volume fraction of conductive particles, which was influenced by the conductive particles sedimentation, microstructure of resistor films, and inter-diffusion between the resistors and substrates.

Keyword: Embedded resistors; LTCC materials; Glass ceramics

1. Introduction

In recent years, low temperature co-fired ceramic (LTCC) substrates integrated with passive devices have been used extensively for high-density packaging module,[1–3] and high performance wireless components.[4] Resistors and capacitors are the basic components embedded into LTCC multilayer substrates whereby a three-dimensional (3D) circuit is constructed. High glass content in both the LTCC substrates and resistors have usually induced mutual interaction at the interfaces among the basic components after subsequent heat treatment. The interaction depending on the chemical compositions and sintering schedule needs to be regulated before the device is successfully implemented into a 3D assemblage. Calcium-anorthite ($CaAl_2Si_2O_8$) from interface reaction was found in the thick film resistors embedded in cordierite-glass substrate, and this has unfavorably affected the electrical properties of the films.[5–7] With the Al_2O_3 content reduced in the substrate, not only the reaction forming calcium-anorthite was successfully suppressed, but also the overall resistivity remained unaffected even if the glass phase separation had occurred in the embedded film.[8]

In this study, resistors from commercially available paste were embedded in commercial glass ceramic substrates of low Al_2O_3 content. The electrical properties of such resistors subjected to different sintering conditions were determined. Inter-diffusion of glass phase between the substrate and resistors, and sedimentation of conductive particles was characterized for the overall resistivity of the LTCC resistors. The conducting mechanism in the resistors based on the overall resistivity and microstructure is discussed.

2. Experimental procedure

LTCC substrates were prepared using commercial powder of calcium borosilicate glass-ceramic (L1, Ferro, San Narcos, CA, USA) and the same powder added with 5 wt% amorphous silica (SiO_2). The powders mixed with organic binder (B-73305, Ferro, San Narcos, CA, USA) at 50:50 ratio were ball-milled using high-purity alumina balls before tape-cast to desired thickness. Silver–palladium conducting paste (Shoei D-4430, Tokyo, Japan) was printed on the green tape and dried at 130 °C for 30 min. Ruthenia (RuO_2)-based resistor paste (Shoei R-2310,

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Japan) with the sheet resistivity of 10^3 Ω/□ was then printed on the Ag–Pd-coated green tape and dried similarly. The printed resistors were of 10 mm long × 2.0 mm wide × 0.02 mm thick in dimension before firing. The printed green tapes were laminated at 60 °C under 20 MPa pressure for 3 min in an isostatic pressing chamber (VF-1000, PTC, CA, USA). The laminated samples were heated to 450 °C with a 10 °C/h heating rate for binder burnout before co-firing was conducted at 850 °C for 15 min to 4 h by a heating rate of 2 °C/min.

Sintered sample resistance was measured by the two-point probe technique. The samples were cut perpendicular to substrate surface along the longitude of the resistor layer. Cross-section samples were then polished using diamond films to 1 μm surface roughness before etching with diluted 3 vol% HF + HCl solution. Analysis of microstructure was performed with scanning electron microscopy (SEM, Hitachi S-2700, Tokyo, Japan). Interdiffusion between the resistors and LTCC substrate was examined using energy dispersive X-ray spectroscopy (EDS, 432C, Noran, USA) equipped with SEM. Crystalline phases of the co-fired resistors were determined by X-ray diffractometry (XRD) using XGEM-4000 (Scintag, CA, USA). Interaction between the resistors and LTCC substrate was studied by observing the XRD profile of the mixed powder pressed to pellets and subjected to similar co-firing schedule.

3. Results and discussion

Diffusion of silver inner electrode occurred during sintering of calcium borosilicate (L1) substrate made the dielectric surface become light yellow. It appears that adding SiO_2 or glass frits to substrate L1 has effectively reduced silver diffusion into the L1 substrate that its surface maintained white in color.[9]

The linear shrinkage incurred to the substrates was reduced by 5% from 20 to 15% with 5 wt% SiO_2 addition (Fig. 1). Adding glass frits, although had the similar effect was less pronounced at 18% linear shrinkage. All powder compositions for substrate started shrinking at ∼670 °C, as shown by dialtometry analysis. When sintered at 800 °C, the initial composition L1 and that added with 5 wt% glass frits have both been vitrified when the linear shrinkage was leveled off at 20 and 18%, respectively. The powder compact of L1 + 5 wt% SiO_2 shrank by approximately 15% at 820 °C when its final density leveled off (Fig. 1).

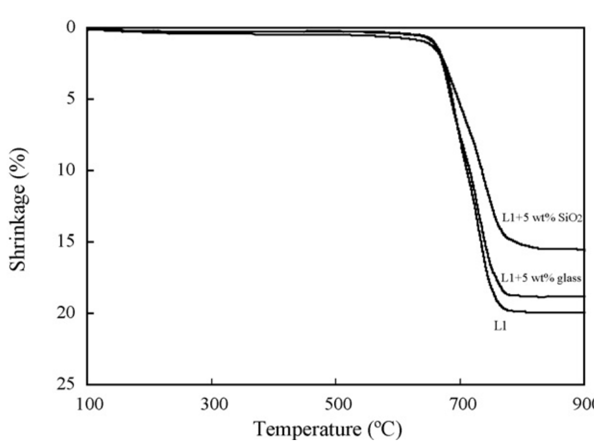

Fig. 1. Dialtometry measurement of L1, L1 + 5 wt% amorphous silica, and L1 + 5 wt% glass frit.

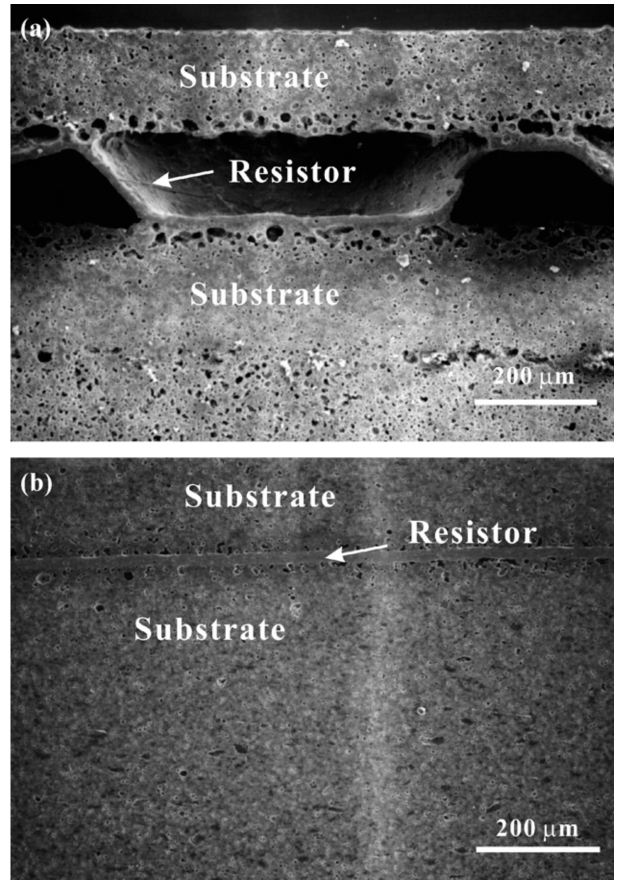

Fig. 2. Microstructures of resistors embedded in: (a) L1 and (b) L1 + 5 wt% amorphous SiO_2 substrates.

The soft-point of resistor glass was at temperature about 550 °C, which was more than 100 °C lower than the initial sintering temperature of the L1 substrate, 670 °C. The difference shrinkage behaviors between substrate and resistor films had deformation or delamination localizing at interface between them (Fig. 2(a)). When 5 wt% amorphous SiO_2 was added to the L1 substrate, the embedded resistor remained its structure integrity (Fig. 2(b)). In the previous investigation,[10] organics decomposition and expansion of the paste were counted for the delamination of the embedded electrode. In this study, soften temperature and shrinkage rate differences between resistor and substrates were two major factors influenced the structure integrity of the embedded resistors.

After heat-treated at 800 °C for 60 min, wollastonite ($CaSiO_3$) and CaB_2O_4 have emerged in all sintered compacts, as indicated in Fig. 3. Fig. 4(a–c) shows the microstructure of Shoei 1 kΩ/□ resistors embedded in the substrates of: (a) L1, (b) L1 + 5 wt% SiO_2, and (c) L1 + 5 wt% glass frit. The conductive particles in the resistor film agglomerated to the much larger sizes of ∼200 nm are evidenced by white particles revealed by SEM/SEI indicated in Fig. 3. The agglomerated conductive particles in fact contained conductive RuO_2 particles separated