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LTCC system with new high-ε_r and high-Q material co-fired with conventional low-ε_r base material for wireless communications

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Abstract

The authors have developed a new LTCC material with characteristics of high dielectric constant (ε_r), high quality factor (Q) and low temperature coefficient of capacitance (TCC). This material can be co-fired with a conventional base LTCC material and buried resistors with low temperature coefficient of resistance (TCR). The base material which consists of Al_2O_3 filler and glass, has low ε_r of 8.7 at 3 GHz. The newly developed LTCC material, which consists of Ba–(Re)–Ti–O filler, Al_2O_3 filler, and glass, has the following characteristics of ε_r of 15.1, Q of 900 at 3 GHz, and TCC of −10 ppm/K. The buried resistors consist of RuO_2 and glass. Two different LTCC materials, a resistor material and a silver electrode paste can be co-fired as multi-layer substrates and are regarded as a new LTCC system.

Constrained sintering could be applied to this LTCC system and the dimensions of substrates could be controlled with quite high accuracy. This LTCC system is expected to contribute to further miniaturization of RF circuits and the reduction of electrical loss.

Keyword: LTCC system

1. Introduction

In recent years, miniaturization of electronic components and devices for wireless and mobile applications has been stepped up. It seems this tendency will continue for the meanwhile and may get even stronger in the future. Low temperature co-fired ceramic (LTCC) technology is one of the most promising approaches for realizing miniaturization of RF circuits for wireless communications. However, as long as only conventional LTCC material with low dielectric constant (ε_r), low quality-factor (Q) and large temperature coefficient of capacitance (TCC) (i.e. material K8) continues to be used, further miniaturization will run into a limit. The authors have thus developed a new LTCC material with high ε_r, high Q and near-zero TCC (i.e. material K15) that can be co-fired with a conventional base LTCC material. Adding a resistor material and silver electrodes that can be co-fired with these LTCC materials, we present a new LTCC system with several advantages as follows. Cross-talk noise between lines and electric signal delay are suppressed by positioning the electric-signal wiring on low-ε_r material layers. Downsizing or lowering the profile of substrates (e.g. decrease number of capacitance layers) can be achieved by forming internal capacitors on high-ε_r material layers. Constrained sintering could also be applied to this LTCC system.

In this paper, we discuss details of the properties of the multi-layered LTCC substrates. Finally we review the future targets for LTCC materials and substrates.

2. Experimental procedure

2.1. Material and specimen preparation

Material K8 was prepared from Al_2O_3 and Ca–Al–B–Si–O glass. The Al_2O_3 powder has a high purity (>99%). On the other hand, material K15 were prepared from Al_2O_3, Ca–Al–B–Si–O glass and Ba–(Sm, Nd)–Ti–O powder calcined at 1200 °C. The Al_2O_3 powder and Ca–Al–B–Si–O glass are common to both materials. The ingredients of these materials were mixed with an organic solvent and an organic binder to make a slurry. Green tapes were cast by doctor-blade tape casting. After the tapes were formed, they were cut to the desired sheet size and via holes were punched in the sheets. Conductive silver paste was then filled in the via holes. After that, conductors and resistors were screen-printed on the surface of the sheets. The printed sheets were stacked in the desired order into blocks and constraining sheets made of Al_2O_3 powder and an organic binder,

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Table 1
Dielectric properties of K8 and K15 materials

	K8	K15
ε (3 GHz)	8.7	15.1
Q (3 GHz)	330	940
TCC −25 to 20 °C	+130 ppm/ °C	−15 ppm/ °C
TCC 20–85 °C	+140 ppm/ °C	−5 ppm/ °C

were added to the tops and bottoms of the stacked blocks in order to apply the constrained sintering.[1,2] The stacked blocks were then laminated under optimal pressure and temperature. The laminated blocks were fired at 870 °C in air atmosphere. After sintering, the constraining layers were removed by sand-blasting with ceramics powder and the resulting blocks were plated with nickel and gold. Before singulation, SMDs or bare chips were mounted on the surfaces of the blocks if necessary.

2.2. Measurements

The dielectric properties, ε_r and Q, were measured by the perturbation method using two facing circular resonators with air gap and unperturbed resonant frequency at 3 GHz. The thickness of the measured specimens was about 620 μm. The temperature coefficients of capacitance (TCC) of each sample were measured at 1 MHz by using an LCR-meter at temperatures between −25 and 85 °C. The resistances of the buried resistors were measured using an IR-meter.

The mechanical flexural strengths of the sintered specimens were measured by three-point bending test. The thermal-expansion coefficients and the sintering-shrinkage curves at temperature from RT to 600 °C and RT to 900 °C, respectively, were obtained by thermal mechanical analysis (TMA).

The microstructures of the sintered LTCC materials were examined by scanning electron microscopy (SEM) and energy-dispersive X-ray spectrometry (EDX). The crystal structures of the sintered LTCC materials were examined by X-ray diffraction analysis (XRD).

3. Results and discussion

3.1. Dielectric properties

Table 1 lists the dielectric properties of materials K8 and K15. K8 has low ε_r. On the other hand, K15 has high ε_r, high Q and near-zero TCC which are suitable properties for capacitors.

Fig. 1 shows a cross-section of the K8/K15 co-fired substrate. No delamination is observed in the specimen. Buried capacitors on the K8 and K15 interface were laser-trimmed and, as shown in Fig. 2, the insulation characteristics of the materials were not deteriorated after laser trimming. Though it is well known that insulation of Ba–(Sm, Nd)–Ti–O ceramics is easily deteriorated by laser processing, no deterioration in insulating properties was found in this case. It is assumed that the glass matrix surrounding the Ba–(Sm, Nd)–Ti–O crystals maintains the insulation characteristics.

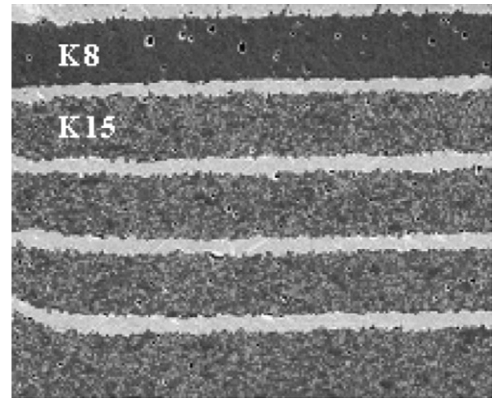

Fig. 1. Cross-section of K8/K15 co-fired substrate.

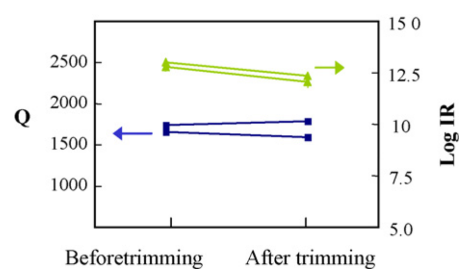

Fig. 2. Q and IR behavior before and after laser trimming.

3.2. Mechanical properties

Table 2 lists the mechanical properties of materials K8 and K15. The flexural strength of K15 is lower than that of K8 material but is average for LTCC materials. When K15 is applied to the internal layers co-fired with the outer layers of K8, as expected, the composite substrates maintain high mechanical strength equivalent to that of K8.

3.3. Properties of buried resistors

The resistors were buried in the K8/K15 and K8/K8 interfaces. Using three kinds of resistive paste, we formed resistors

Table 2
Mechanical properties of materials K8 and K15

	K8	K15
Flexural strength (monolithic)	350 MPa	260 MPa
Flexural strength (composite)	–	350 MPa (surface K8, inner layer K15)
Thermal expansion coefficient	7.6 ppm/K (from RT to 600 °C)	7.6 ppm/K (from RT to 600 °)
Density	3.21 g/cm^3	3.56 g/cm^3

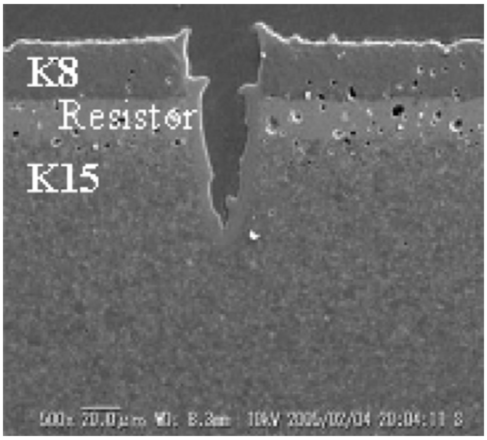

Fig. 3. Cross-section of buried resistors and laser trimming.

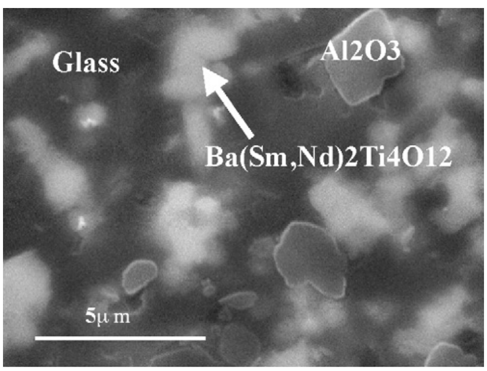

Fig. 4. SEM image of K15 substrate.

with resistances from 10 to 1000 Ω, at two interface positions without forming any defects (like delamination). The buried resistors were trimmed, as shown in Fig. 3, using a YAG laser. No change in the quality of the resistor materials before and after trimming was observed in resistance measurements or EDX.[3]

3.4. Microstructure of K15

Fig. 4 is an SEM image of the K15 substrate. Ba–(Sm, Nd)–Ti–O and Al_2O_3 crystals are dispersed in a glass matrix. Fig. 5 is an XRD pattern of K15. Al_2O_3 and $CaSiO_3$ (wollastonite) were detected as main phases in K8. And Al_2O_3, $CaSiO_3$, Ba–(Sm, Nd)–Ti–O, and $CaTiO_3$ were detected in K15. $CaTiO_3$

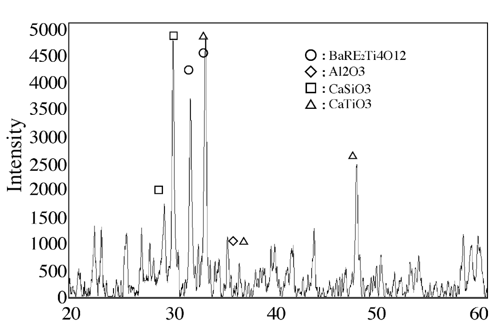

Fig. 5. XRD diffraction pattern of K15 substrate.

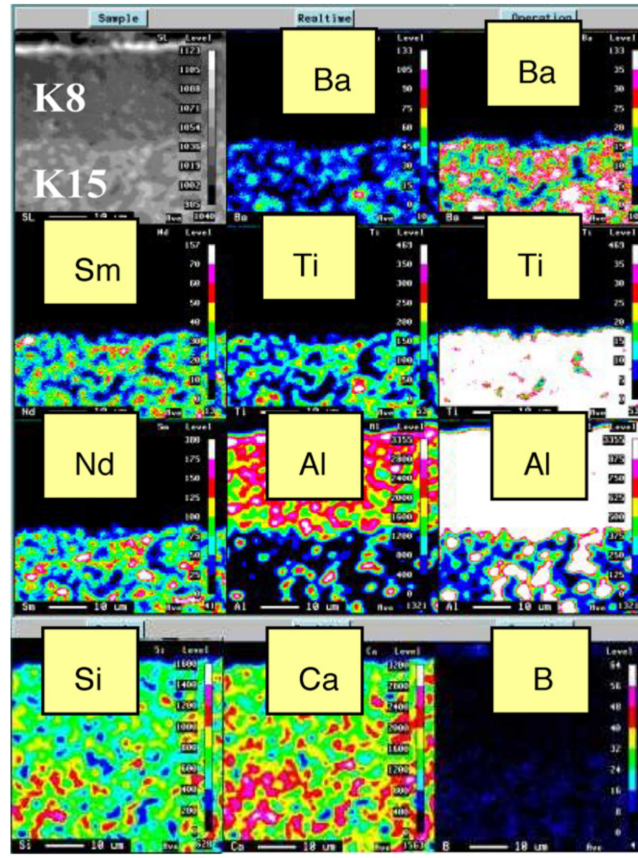

Fig. 6. EDX-mapping of co-fired substrate.

is generated by the reaction of glass with Ba–(Sm, Nd)–Ti–O and has a very negative TCC. On the other hand, the TCCs of glass, Al_2O_3 and $CaSiO_3$, are positive, so those ingredients in K15 are considered to precisely compensate each other in producing near-zero TCC of K15.

3.5. Reactions and mechanical stress of both LTCC materials

Fig. 6 shows a SEM image and an EDX-mapping analysis of the co-fired substrates. Both materials, K8 and K15, contain common glass and Al_2O_3, so it is clear that mutual diffusion of these elements was not detected. The diffusion of specific elements, namely, samarium, neodymium, barium, and titanium contained in K15 was also not detected because of the stability of Ba–(Sm, Nd)–Ti–O particles.

Fig. 7 shows shrinkage curves of both materials during free sintering (non-constrained sintering). The start temperatures are almost the same, and the shrinkage behaviors of both materials are very close. The reason for this is that both materials contain common glass, and the difference in the composition of both materials is small (that is only the filler contents differ).

Thermal-expansion coefficients (TECs) of K8 and K15 are listed in Table 2. Ba–(Sm, Nd)–Ti–O has a high TEC (10 ppm/K), but K15 contains more glass (low TEC) than K8 and is highly crystallized ($CaSiO_3$; low TEC), therefore the deviations of TECs from that of K8 in the ingredients of K15 cancel

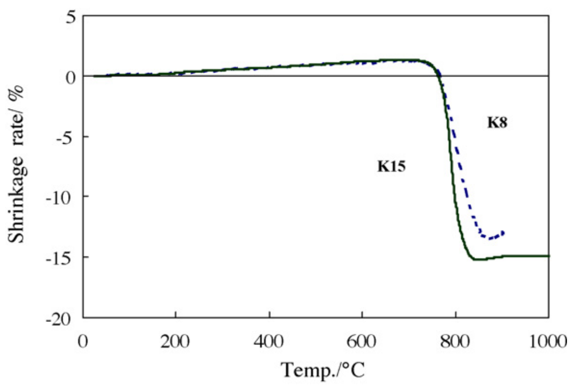

Fig. 7. Shrinkage-curves of K8 and K15 substrates.

each other out. As a result, K15 has almost the same TEC as K8. This means that the TECs of both materials are well matched, and stress and delamination between co-fired materials is completely suppressed.

3.6. Co-fired substrate

Fig. 8 shows a cross-section of two types of asymmetric layer structure composed of co-fired materials. In both structures, K8 and K15 have the same TEC, so no delamination or warpage occurs. This allows substrates with various geometric structures to be designed. Constrained sintering technique also makes it easier to co-fire the different materials and to improve dimensional accuracy significantly. (Dimensional tolerance is reduced from ±0.3% by normal sintering to ±0.05% by constrained sintering.) In the case of this LTCC system, capacitors with high-Q and near-zero TCC can be miniaturized by using K15 and a low-TCR resistor can be buried and trimmed by YAG-laser in substrate. Nickel and gold electrodes can be plated on the surface of silver electrodes and no damage to the substrates occurs.

3.7. Future targets for LTCC system

Though a new high-ε_r material was introduced in the previous section, further miniaturization requires the development of material with much higher ε_r and lower TCC.[4] Moreover, a new magnetic material with high-μ that can be co-fired with a low-ε_r base material is desired. These materials will enable us to realize further miniaturization and integration, and expand the functions of substrates. What's more, if thinner layers can be formed in substrates, they will bring equivalent effects to those brought by high-ε_r materials.

Cost reduction is a key issue regarding current and future LTCC substrates. Enlarging substrates is one way to reduce cost, and thinner substrates is another. As the former needs larger equipment with big investments and increases dimensional distortion, it does not always result in much cost reduction. Care should be taken before choosing the former approach. Thinner and large substrates raise the concern of a lack in mechanical toughness. To solve this problem, improvements of toughness, especially drop-impact and twist resistance, are key issues regarding low-profile substrates. If this situation is ameliorated, low-cost and toughness can be achieved simultaneously. Not only material strength but also the structures of layers and electrodes should be taken into account.

For miniaturization, fine line wiring is also required. Current screen-printing technologies have limits around several dozen microns, and further improvements are required for screen printing or quite a different method for forming fine wiring patterns is required.

To realize miniaturized substrates with lower profile and lower area, cavities with higher dimensional precision are required. Though ICs have been mounted on the surface or in the cavity of LTCC substrates up till now, they will confront the limits of dimensional precision soon. Cavities in which ICs can be mounted with higher dimensional precision can break through these limits. To realize them, the constrained sintering technique should be also combined with the above-described technologies.

4. Summary

A new material, K15, which is composed of Ba–(Sm, Nd)–Ti–O and Al_2O_3 fillers and Ca–Al–B–Si–O glass, has high ε_r (15.1), high Q (900 at 3 GHz) and low TCC (−10 ppm/K). This material can be co-fired with the base material K8. The material K8 is composed of Al_2O_3 filler and Ca–Al–B–Si–O glass and has low ε_r of 8.7 at 3 GHz. Buried and co-firable (with K8 and K15) resistor material, which is composed of RuO_2 and glass, was trimmed by a YAG-laser. The substrates which are co-fired with these materials have no defects like warpage, delamination and cracks, and are very stable chemically and mechanically. The LTCC substrates hold great promise for the development of functional substrates and module products to meet increasing demands for miniaturization.

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