LEAD FREE DIELECTRIC AND MAGNETIC MATERIALS FOR INTEGRATED PASSIVES

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Dielectric and magnetic materials were developed for use as integrated passive components in LTCC packages. These materials were tested with standard commercially available ESL LTCC tapes as well as those available from Dupont, Motorola and Ferro. ESL conductors were evaluated with all systems and include low cost, high conductivity silver and silver alloys appropriate for high frequency applications. The tapes and pastes were fired using the profiles recommended by the respective tape vendors. All of the ESL compositions are lead free.

The magnetic tapes in the study show permeabilities of 50 to greater than 1200 and were originally developed for use in LTCC transformers and inductors. They are shown here to be capable of decreasing the size of inductors buried in LTCC's. Capacitor tapes and pastes with dielectric constants ranging from 50 – 250 tested as buried capacitors under various processing conditions and temperature coefficients are within the limits of XR7 standards. The compatibility of these inductor and capacitor materials with LTCC tapes from ESL and other vendors is established by evaluating electrical and structural properties.

Introduction:

Indications are that there will be a continuing demand for electronic systems that are less expensive, more reliable, less lossy and capable of providing increased functionality. In addition to these needs, that never seem to be completely satisfied, we believe that many system customers will be asking that their requirements be met with lead-free materials. There is a concern that lead can be leached from discarded electronic equipment and get into the water supply and thus create problems in our ecosystem.

Currently the listed needs, apart from the lead-free materials requirement, are being met by an approach that involves squeezing highly integrated ICs and miniaturized passive components together on a substrate of reduced size. This approach, however, has limitations. One problem is that passive components, which in most cases outnumber the ICs, are reaching a size where difficulties in handling and testing are having an adverse effect on cost and reliability. Another problem is that there is no surface left onto which components can be squeezed.

Designers are turning to approaches that make use of the third dimension, i.e., involve burying components. This paper will discuss an LTCC approach where some or all of the passive components can be buried in the interior of the module leaving room on the surface for ICs which can provide the desired added functionality and increased reliability due to a reduction in the number of solder joints. LTCC technology is especially well suited to the integration of passive components with the package (module) because; (1) its layer by layer build-up scheme provides a number of surfaces on which to deposit components, (2) the LTCC materials are fired at temperatures close to those used to fire thick film passive components, and (3) LTCC host materials not only form an excellent base for the component, they also form a good protective coating.

The LTCC approach also has the necessary flexibility to meet the on-going system needs. Loss can be reduced by proper layout of high conductivity metals and low loss ceramics while the need for low cost is achieved by parallel processing of low cost materials. The concern about lead being leached from discarded electronic equipment is handled through the use of lead free materials.

Materials and Processing

The robust set of conductors and dielectric tapes and pastes developed to make the integrated passive parts are listed in Tables 1 and 2. These lead free materials are compatible and cofireable for use in multilayer applications. The conductor system is based on silver which provides high conductivity, low cost, and good solderability. Compatible Au, Pd/Ag and Pt/Ag, pastes are also available where special properties are needed. A wide range of LTCC dielectrics are also available. These include K values up to 16 for size reduction capability.[1]

The loss characteristics of these LTCC structural tapes were determined using ring resonator structures. The details of the process and measurement technique are described in an earlier publication [2]. Silver conductors were used for all test parts. Hold time at peak temperature was varied from 15 minutes to 90 minutes. The heating rate from 450 to 875 was varied from 2°C/minute to 15°C/minute. These parameters were found to have no effect on loss characteristics.

Figures 1 shows loss characteristics for all four LTCC tapes as compared to FR-4. These low and intermediate K dielectric tapes show better loss characteristics than FR-4 and have the additional advantages of higher thermal conductivity and the ability to accommodate multilayer structures.

Table 1
Lead Free, Cofireable Conductors

Designation	Description
903-CT-1	High Conductivity Ag
903-CT-1A	Ag Matched for Shrinkage
953-CT-1G	Low Cost Pt/Ag
963-G	Solderable Pd/Ag
902-G	Ag via fill
962-G	Via fill Ag/Au transition
903-CT-A	Solderable top layer Ag
953-AG	Leach Resistant Pt/Ag
803-MG	Wire Bondable Au
Solder	95.5 Sn-3.8Ag- 0.7 Cu
9904 Ag*	Top layer photoimageable
8804 Au*	Top layer photoimageable

* post fireable only

Table 2
Lead Free, Cofireable Dielectric

Designation	Description	
41110	K - 4	LTCC Tape
41020	K - 7.5	LTCC Tape
41050	K - 13	LTCC Tape
41060	K - 16	LTCC Tape
41240	K - 50	Capacitor Tape
41250	K - 100	Capacitor Tape
41260	K - 250	Capacitor Tape
4162	K - 50	Capacitor Paste
4163	K - 100	Capacitor Paste
4164	K - 250	Capacitor Paste
40010	μ - 200	Ferrite Tape
40011	μ - 50	Ferrite Tape
40012	μ - 500	Ferrite Tape

Buried Capacitors

Lead free capacitor tapes were developed with a range of K values up to 250. They were tested by embedding them in the four lead-free LTCC host tapes in Table 2 and firing at peak temperatures of 850 - 875 °C. Hold times at peak ranged from 12 to 60 minutes. These same capacitor tapes were also buried in DuPont 951, Motorola T-2000 and Ferro A-6 and except for A-6 fired at a peak temperature of 875°C. The Ferro A-6 was fired at 850°C. All the profiles used were those recommended by the tape vendor. The ESL 41240 (K-50), ESL 41250 (K-100) and ESL41260 (K-250) tapes were compatible with all the host LTCC tapes. The configuration used for testing these capacitor tapes is shown in Figure 2.

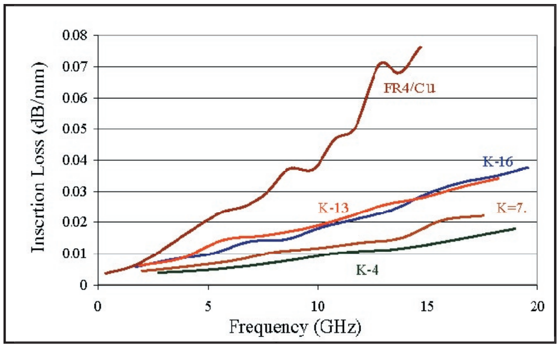

Figure 1
Loss vs. Dielectric Constant

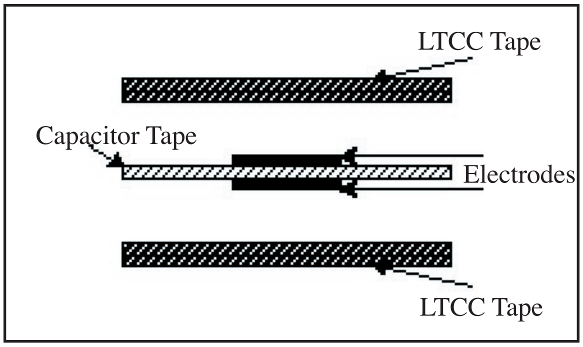

Figure 2
Buried Capacitor Configuration

Resulting dielectric constants are shown in Figure 3. Dissipation factor was approximately 1% for most combinations and tended to be lower for the lower K tapes. Temperature variations (TCC) were consistent with X7R characteristics. K values were calculated from measured capacitance values and thickness determined by cross-sectioning the parts. Interface regions were examined for voids and delamination to determine interaction between materials. From this we have determined that the buried capacitor tapes are physically and chemically compatible with a number of commercial LTCC host materials available from different vendors in the marketplace. All the combinations of capacitor and LTCC tapes yielded values for dielectric constant, dissipation factor, and delta C with temperature that were consistent with expected values.

The same electrode was used for all of these test samples, 953-CT-1G (a Pt/Ag conductor with resistivity <6 mohms/square, designed for use with LTCC tapes). It is important to note that the conductor metallurgy can make a difference as seen in Figure 4 where Ag, Pt/Ag and Pd/Ag are compared. These capacitors were buried in ESL 41060-70C (K-16) LTCC tape.

Capacitor tapes have the advantage of uniform thickness which is important for design considerations. Capacitor pastes, however, can be applied in smaller areas as needed. Therefore, capacitor pastes based on the above tape compositions were also buried in these LTCC tapes to establish compatibility. The data obtained on paste buried in LTCC was limited. Table 3 shows some results obtained for capacitor paste buried in ESL 41050-70C (K-13) LTCC tape. A Pt/Ag electrode (953-CT-1G) was used for these experiments.

Figure 5 shows a part prepared by Motorola (3) for evaluation of ESL 4164 (K=250 paste) buried in DuPont 951. Data obtained for this part is shown in Table 4. The silver used was 953-CT-1G and the firing conditions were those recommend for the 951 tape. The

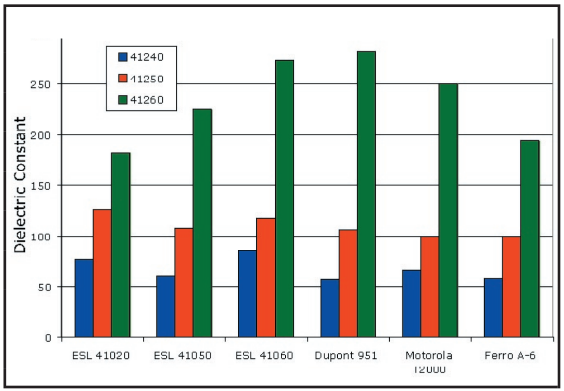

Figure 3
Lead Free Capacitor Tapes Buried in Various LTCC Hosts

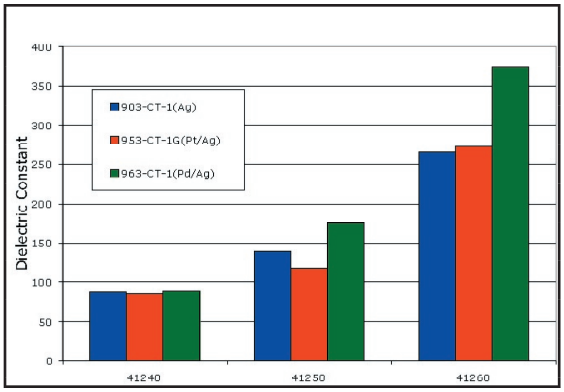

Figure 4
Effect of Electrode Composition on the Properties of Buried Capacitor Tapes

Table 3

Capacitor Pastes Buried in K-13 LTCC Tape

Buried Capacitor Paste	Time at 875°C (min)	Dielectric Constant K	Dissipation Factor DF	Insulation Resistance IR	Maximum |ΔC| 55 to 125°C
4162	15	54	0.3%	8x10^{11}	0.8
4163	15	84	0.8%	8x10^{10}	9.2
4164	15	242	2.5%	1x10^{11}	17.5

Table 4

4164 Paste Buried in Dupont 951 Tape

Pad Size	Capacitance (pF)	K
30 x 30	43.9	213
40 x 40	75.6	207
50 x 50	113.2	198
60 x 60	160.0	195

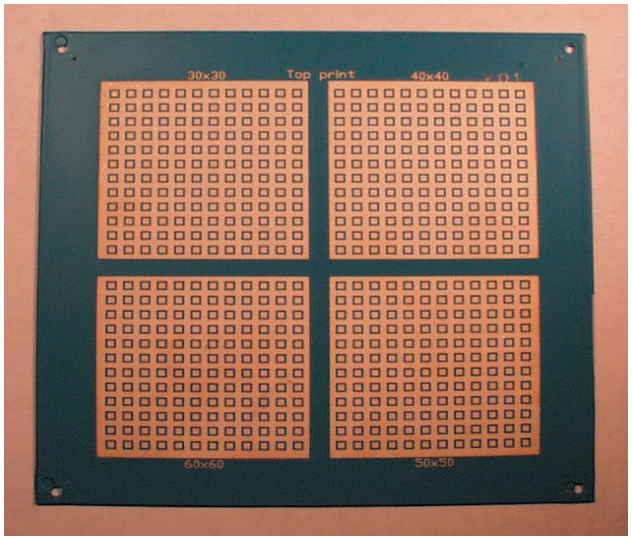

Figure 5
4164 Paste Buried in Dupont 951

part (6” x 6”) is flat and shows no adverse reaction between the materials from different manufacturers. Warping due to shrinkage mismatch was eliminated by symmetrical design. In a test where only one side was completely covered with capacitor paste with none on the other side, warpage was observed. The amount of warping will depend on the specific design and can be minimized or eliminated with symmetrical placement of constrained shrinkage technology. The high values realized for the dielectric constant provide a route to obtaining small area buried capacitors.

The availability of both high K lead free tape and paste provides the designer with options to take advantage of the uniformity of tape thickness and/or the ability to print paste only where it is needed. Further development of these materials is proceeding for specific customer applications for buried components and will be reported in future papers.

Buried Inductors

Inductors represent another component that designers would like to see removed from the premium surface positions and buried in the interior of the part. This can be done by printing an inductor configuration with thick film conductive coils on standard LTCC dielectric layers. Our objective was to enhance the inductance of such structures by using low temperature cofiring ferrite tapes as the covering dielectric layers. This could result in considerable savings in space and cost.

Permeability of the new tapes was calculated from inductance measurements made on fired toroids formed from laminates of each tape. Grain size measurements was obtained from fracture surfaces on these parts. The permeability vs. firing temperature for the ESL

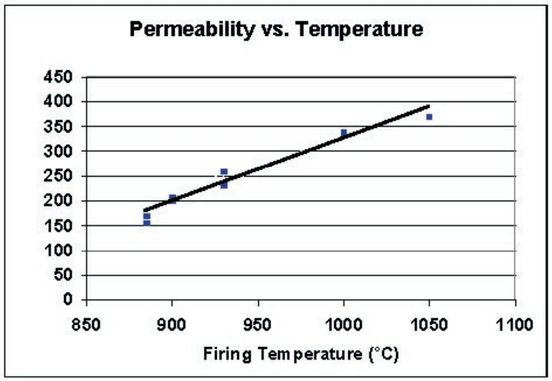

Figure 6
Permeability vs. Firing Temperature

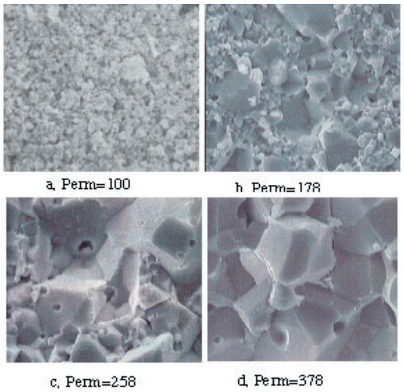
a, Perm=100
b, Perm=178
c, Perm=258
d, Perm=378

Figure 7
Permeability vs. Grain Size

40010 (μ=200) ferrite tape developed for use in LTCC applications is shown in Figure 6. Similar variation with firing temperature is observed with the ESL 40012 (μ=500) tape. Values of permeability >700 are achieved at temperatures compatible with silver conductors (930°C). Permeability of 1100 was obtained with parts fired at 1030°C. All these lead-free tapes exhibit the expected grain size vs. permeability behavior shown in Figure 7 for the ESL 40010 (μ=200) tape. Figure 8 is a photomicrograph of ferrite grains that have been fired at a temperature which yields a permeability value of 1215.

Compatibility testing of the magnetic tape involved sandwiching a conductive silver spiral in ferrite tape layers which were in turn placed in LTCC tape products from ESL, DuPont and Ferro. A typical schematic of this part is shown in Figure 9. Figure 10 presents data showing the increase in inductance resulting from the presence of ferrite tape buried in the LTCC bodies. Examination of the microstructure of these composite structures indicate good compatibility between the LTCC tapes and the ESL ferrite tape. Voids delamination and reaction layers were not observed.

Increasing thickness or the number of ferrite layers increases the inductance. These tapes have been used to manufacture surface mount transformers and inductors (4). Increasing inductance due to ferrite presence will yield smaller, lighter parts than typical wire wound components. Figure 11 shows comparable transformers made by wire wound and LTCC processing showing that size reduction and shape uniformity are possible with LTCC tape materials and processing.

In order to evaluate the effect of ferrite thickness on inductance, parts were fabricated with spirals buried in tapes with nominal permeability values of 200 (ESL 40010) and 500 (ESL 40012). Inductance should increase with thickness of the ferrite tape up to a point where

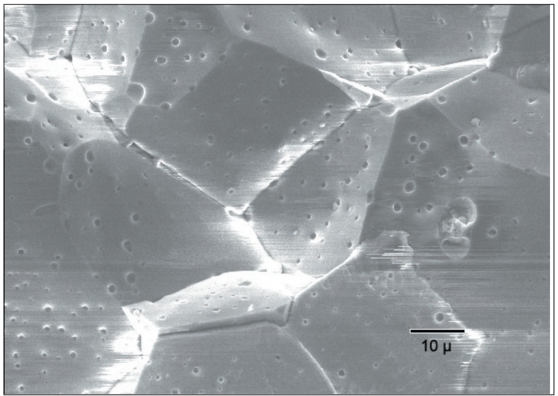

Figure 8
Ferrite Grains With Permeability 1215

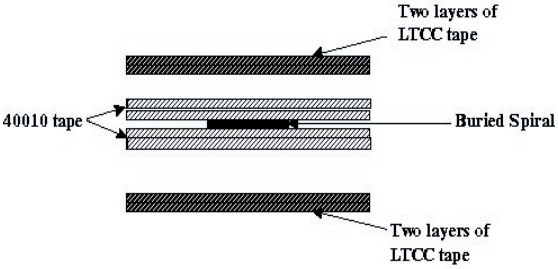

Figure 9
Spiral Buried in LTCC

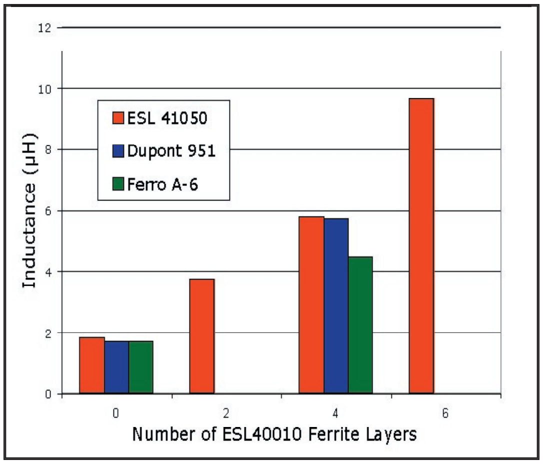

Figure 10
Inductance Enhancement from Ferrite

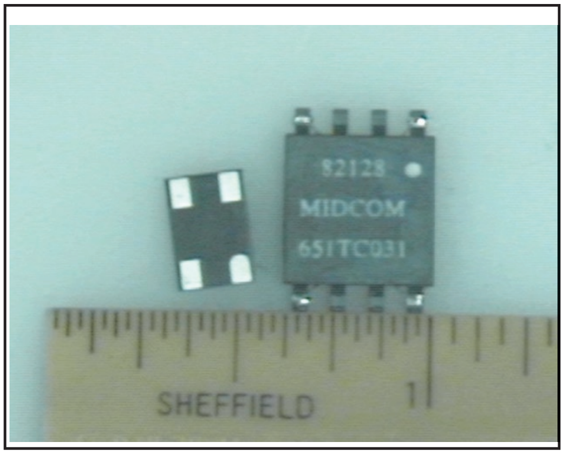

Figure 11
Comparison of Transformers Made by
LTCC and Wire Wound Technologies

the ferrite could be considered infinite in thickness. (5) At this point, the inductance would be the inductance of the spiral in air times the permeability of the ferrite. This theoretical value for "infinite" thickness is of the order of 2.5 - 5.0 mm for a spiral on top of a slab of magnetic material. Figure 12 shows inductance values increasing in value linearly with thickness for our buried spirals. The µ=500 (ESL 40012) tape yields higher values than the µ=200 (ESL 40010) tape as expected. The effective permeability can be increased by raising the peak firing temperature as shown in Figure 6. The calculated value(6) for inductance of the spiral in air is 1.8 µH.

Further work is directed at combining magnetic and high K dielectric materials to form modules such as filters. An example of a composite microstructure is shown in Figure 13. The compatibility of the magnetic tape with other dielectric systems is reinforced by the data presented in Figure 9 which shows consistant values for inductance for all tape systems tested.

Summary:

Materials systems were developed for:

- LTCC tapes with loss characteristics better than those achievable with FR-4/Cu technology. The tapes have K values from 4 to 16 which can provide increased signal velocity, better isolation or size reduction with proper material selection.
- Capacitor tapes and pastes suitable for embedding in a variety of LTCC tapes from different

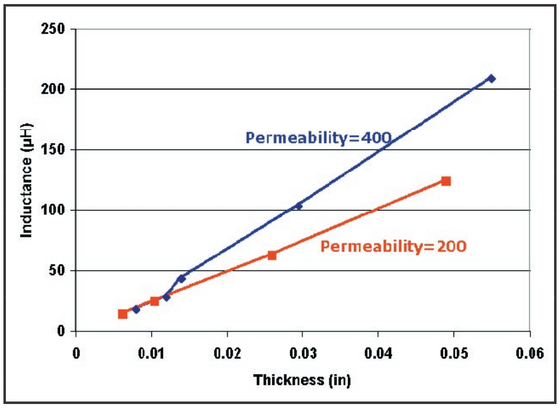

Figure 12
Inductance vs. Thickness of Ferrite Tape

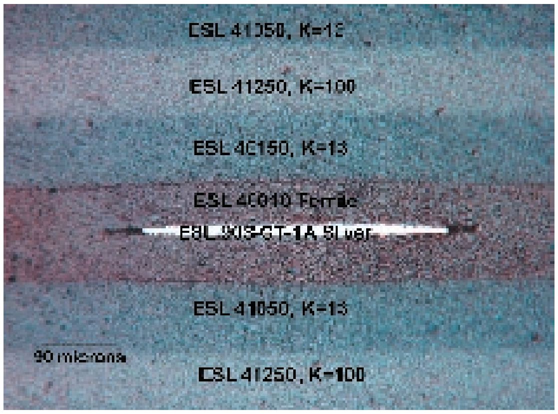

Figure 13
ESL 40010 Ferrite & ESL 41250 Capacitor
Tape Buried in ESL 41050 LTCC Tape

tape manufacturers (ESL, DuPont, Ferro and Motorola).

- A complete lead free materials system including LTCC tape, compatible conductor, embeddable capacitor tapes and pastes, ferrite tapes and solder.
- A wide range of cofireable, low cost, low loss silver based conductors.
- Materials amenable to low cost parallel processing.
- Embeddable capacitor tapes with a K value range of 13-250.
- Inductance enhancing LTCC compatible ferrite tapes with permeabilities attainable from 50 to >1100.

References:

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