# Materials for Capacitive and Inductive Components Integrated with Commercially Available LTCC Systems


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

*The magnetic tapes in the study show permeabilities of 50 to 1100 and were developed for use in discrete LTCC transformers and inductors. They are shown here to be capable of decreasing the size of inductors buried in LTCC's in that the inductance of such devices is much higher than inductors be made from commercial LTCC tapes. 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 X7R 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:

A prior paper [1] reported on a K-100 capacitor tape which was compatible with a variety of LTCC tapes. Its sensitivity to temperature was low, (XR7), and it exhibited stable properties over a wide firing temperature range. It is, however, based on a leaded system which is of growing environmental, health and business concern .

In light of this growing concern, we developed a lead free system to meet ecological and technical requirements of industry. We also believed that there were other issues (increased functionality, smaller size, lighter parts, lower loss, and cost reduction) that needed to be improved in the development of the materials system. Increasing the functionality can be accomplished by burying some or all of the capacitors and inductors and putting more ICs on the vacated surface of the package.

## Procedure and Results

Conductors and dielectric tapes and pastes developed to meet these needs 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.[2]

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 [3]. 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 also varied from 2°C/minute to 15°C/minute. These parameters were found to have no effect on loss characteristics. The firing profiles were varied to determine how process variations necessary to optimize properties in multilayer packages with buried components would effect loss characteristics of the LTCC body tapes.

Figure 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. These curves were obtained using typical firing profiles and did not change when the firing profile was varied.

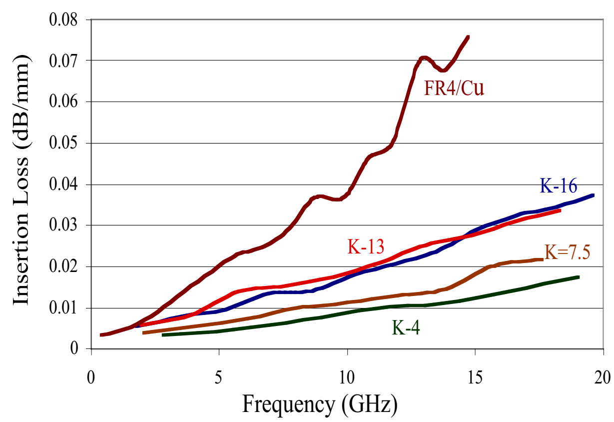


Figure 1
Loss vs. Dielectric Constant

## Buried Capacitors

Lead free capacitor tapes and pastes were developed with a range of K values up to 250. All of them were

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 | Pd/Ag Solderable Electrode |
| 902-G | Ag via fill |
| 962-G | Via fill for 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-3.8% Ag- 0.7% Cu |
| 9904 | Top layer photoimageable Ag* |
| 8804 | Top layer photoimageable Au* |

* post fireable only

embedded in the four lead-free LTCC host tapes in Table 2 and fired 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 ESL41240 (K=50), ESL41250 (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. Resulting dielectric constants are shown in Figure 3. Dissipation factor was approximately 1% for most combinations and tend to be lower for the lower K tapes. Temperature variations (TCC) were consistant with X7R characteristics. K values were calculated from measured capacitance values and thicknesses determined by cross-sectioning the parts. Interface regions were also examined for voids and delamination to determine interaction between materials. From this we have determined that the buried

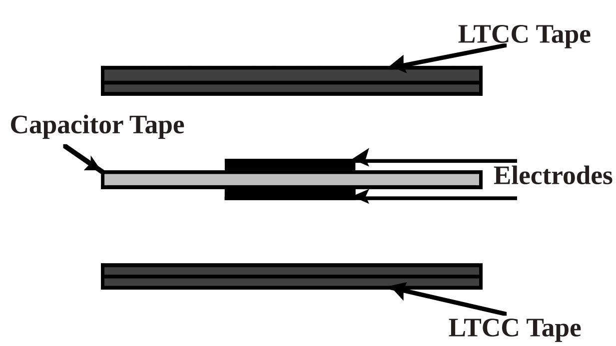


Figure 2
Buried Capacitor Configuration

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 |

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, dissapation factor and delta C with temperature that were consistant 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. The capacitors were buried in ESL41060-70C (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

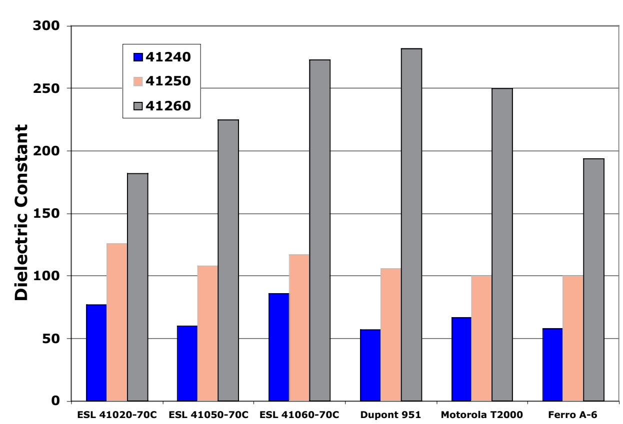


Figure 3
Lead Free Capacitor Tapes Buried in Various LTCC Hosts

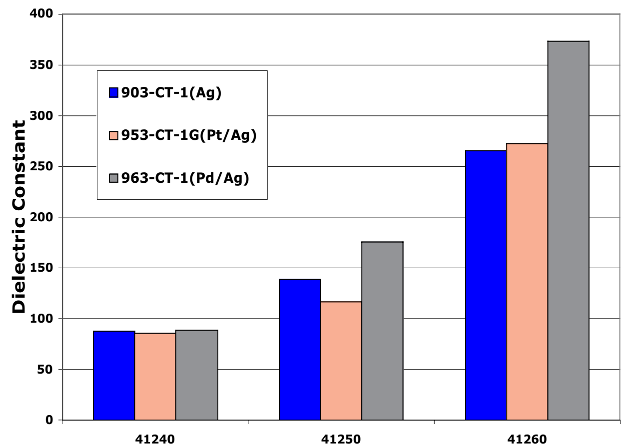


Figure 4
Effect of Electrode Composition of the Properties of Buried Capacitor Tapes

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

Table 3
Capacitor Pastes Buried in ESL 41050-70C (K=13) LTCC

| Buried Capacitor Paste | Time at 875°C (min) | Dielectric Constant K | Dissipation Factor DF | Insulation Resistance IR | Maximum $\lvert\Delta C\rvert$ 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 |

tape. A Pt/Ag electrode (953-CT-1G) was used for these experiments.

Figure 5 shows a part prepared by Motorola [4] for evaluation of 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 part (6" x 6") is flat and shows no adverse reaction between the materials from

Table 4

| ESL 4164 Paste Buried in Dupont 951 Tape | | |
|---|---|---|
| Pad Size(mm) | Capacitance (pF) | K |
| 7.62 x 7.62 | 43.9 | 213 |
| 10.16 x 10.16 | 75.6 | 207 |
| 12.70 x 12.70 | 113.2 | 198 |
| 15.24 x 15.24 | 160.0 | 195 |

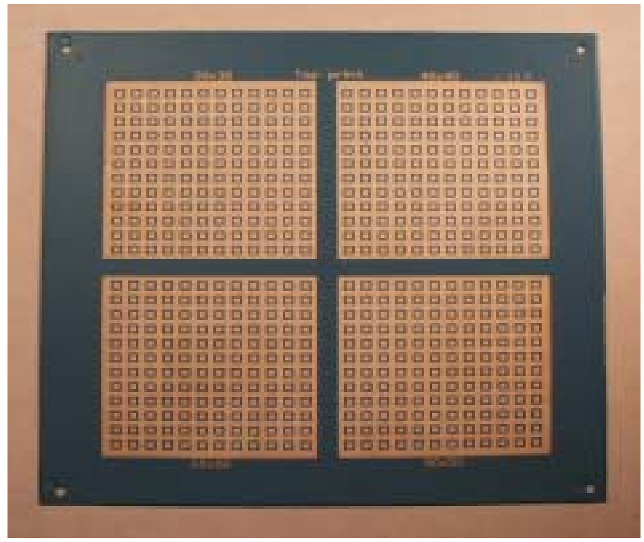

Figure 5
4164 Paste Buried in Dupont 951

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, the warpage was observed. The amount of warping will depend on the specific design and can be minimized or eliminated with symmetrical placement or constraind shrinkage technogy. 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 determine if the inductance of such structures could be enhanced by using a low temperature co-firing ferrite tape as the 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 ESL40010 ($\mu$=200) ferrite tape developed for use in LTCC applications is shown in Figure 6 . Similar variation with firing temperature is observed with the ESL40012 ($\mu$=400) tape. Values of permeability >700 are achieved at temperatures compatible with silver conductors (930°C). Permeability of 1100 was obtained with toroids fired at 1030°C. All these lead-free tapes exhibit the expected grain size vs. permeability

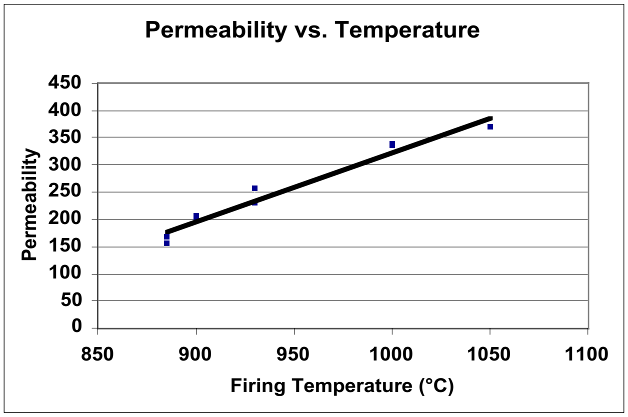


Figure 6

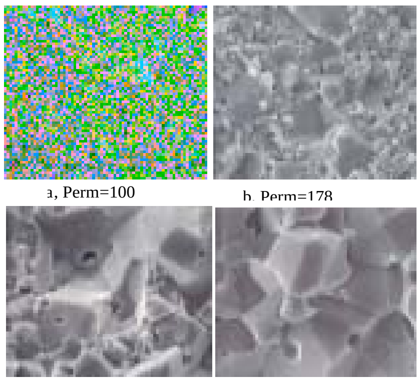


Figure 7
Permeability vs. Grain Size

behavior shown in Figure 7 for the ESL40010 (μ=200) tape.

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 8. Figure 9 presents data showing the higher 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 the number of ferrite layers increases the inductance. These tapes can also be used to manufacture surface mount transformers and inductors [5]. Increasing inductance due to ferrite presence will yield smaller, lighter parts than typical wire wound components. Figure 10 shows

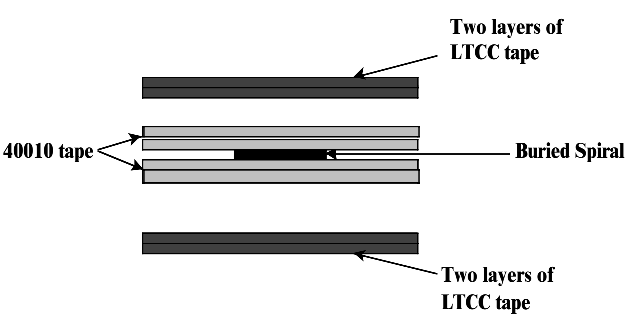


Figure 8
Spiral Buried in LTCC

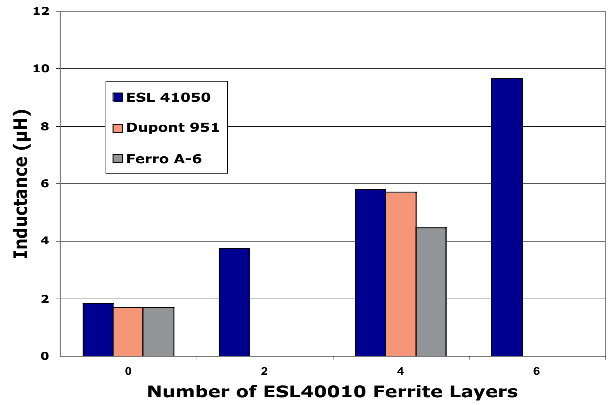


Figure 9
Inductance Enhancement from Ferrite

examples of transformers, inductors and capacitors made from the ESL tapes.

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 (ESL40010) and 400 (ESL40012). Inductance should increase with thickness of the ferrite tape up to a point where the ferrite could be considered infinite in thickness. [6] At this point, the inductance would be the inductance of the spiral in air times the permeability of the ferrite. This theoretical value

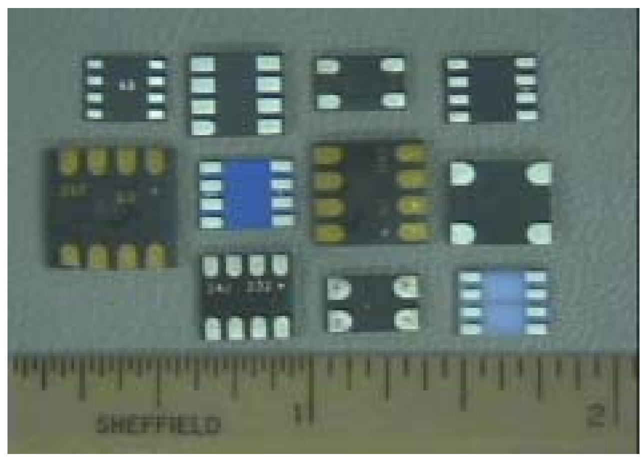

Figure 10
Low Profile LTCC components

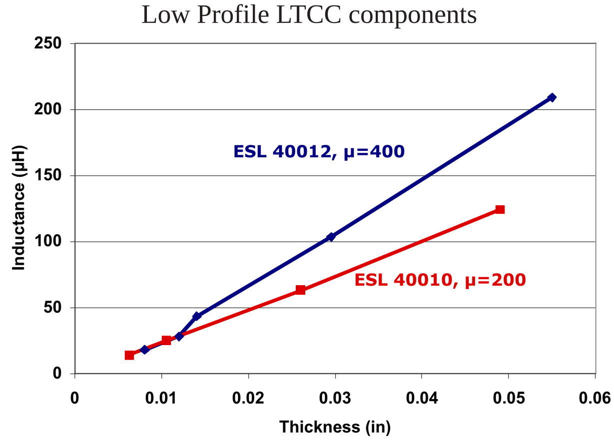


Figure 11
Inductance vs. Thickness of FerriteTape

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 11 shows inductance values increasing in value linearly with thickness for our buried spirals. The $\mu$=400 (ESL40012) tape yields higher values than the $\mu$=200 (ESL40010) tape as expected. The effective permeability can be increased by raising the peak firing temperature as shown in Figure 6. The calculated value[7] for inductance of the spiral in air is 1.7 $\mu$H.

Further work is directed at combining magnetic and high K dielectric tape and paste materials to form modules such as filters. An example of a composite LTCC microstructure of this kind is shown in Figure 12. The physical 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.

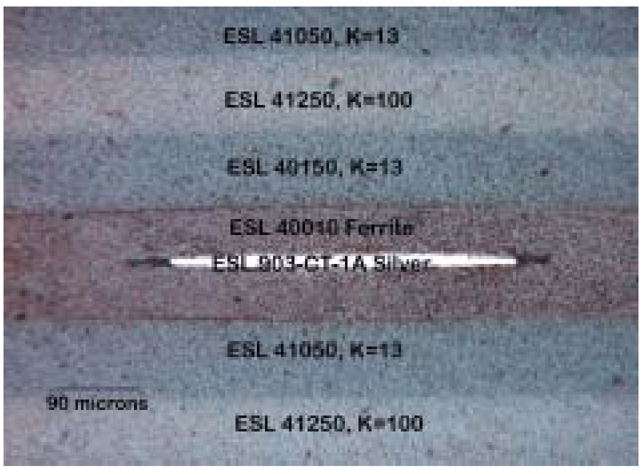


Figure 12
ESL 40010 Ferrite &ESL 41250 Capacitor Tape Buried in ESL 41050 LTCC Tape

**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 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:**

1) A.H. Feingold, M. Heinz, and R.L. Wahlers; *Compliant Dielectric and Magnetic Materials for Buried Components;* Proceedings of IMAPS Denver, 2002 pp 65-70

2) A.H Feingold, R.L. Wahlers, and S.J. Stein; *Lead Free Dielectric Tape System for High Frequency Applications;* Proceedings of IMAPS Baltimore, October 2001

3) A.H. Feingold, C. Huang, and S.J. Stein,; *Low K, Low Loss, Low Fire Tape System for Microwave Applications;* Proceedings of IMAPSEurope Prague June 2000; pp.163-168

4) Motorola; Private Communication

5) R.L. Wahlers, C.Y.D. Huang, M.R. Heinz, A.H. Feingold, J. Bielawski and G. Slama; *Low Profile Transformers;* Proceedings of IMAPS Denver, 2002, pp 76-80

6) W.A. Roshen; *Effect of finite Thickness of Magnetic Substrate on Planar Inductors;* IEEE Transactions on magnetics, vol 26, No. 1 January 1990, pp 270-275

7) F.S. Burkett, *Improved Designs for Thin Film Inductors;* Proceedings of the 1971 ECC Conference, pp 184-194