LOW PROFILE LTCC TRANSFORMERS

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There is a growing need for transformers that are small, low cost, low profile and surface mountable. In addition they must meet safety requirements while maintaining the efficiency of the existing product. This paper discusses an approach designed to meet these requirements. It involves parallel LTCC processing of ferrite tape and low temperature (850-950˚C) cofiring of the screen printed silver primary and secondary coils resulting in a small, low profile, highly reliable product.

INTRODUCTION

The current trend in IC manufacturing is to lower costs with more integration. Even so there is still a large number of passive components needed to support these ICs. For example, the modern computer modem has been reduced to two ICs plus about 125 passive components. Among the largest of these parts are high dielectric breakdown transformers. Although transformers have been decreasing in size over the years as power requirements decrease and operating frequencies increase, the basic wire wound technology/construction has not changed substantially since Michael Faraday's discovery in 1831.

Currently the need for size reduction is being addressed through the use of small wire wound toroidal cores. Hand winding is required for the very small toroidal cores in which there is the greatest interest. The fact that fabrication by automated means is precluded because of their size and shape has a negative impact on their cost. This paper will discuss overcoming the size, high cost, odd shape and hand winding limitations using LTCC technology(1) to cost effectively embed screen printed inductive elements in a flux enhancing ferrite matrix.

LTCC TECHNOLOGY

Ferrite sheets are the "building blocks" from which the magnetic matrix is formed. The tape from which the sheets are cut is generally 2 to 15 mils thick and 5 to 12 inches wide. It is prepared from a slurry of magnetic powder, thermoplastic resin, solvent and surfactants. The slurry is cast on a polymer carrier film moving under a doctor blade, the height of which determines the tape thickness. The required thickness uniformity is achieved by optimizing the slurry properties and the tape casting parameters (speed, temperature and airflow). Heaters in the casting equipment expedite the removal of the solvent converting the cast slurry into a flexible ceramic tape.

Firing the LTCC tape at elevated temperatures (850°C-1000°C) promotes sintering of the powder particles and converts the tape into a dense ferrite body. The primary and secondary coils of the transformers are formed by screen printing thick film conductor on tape sheets cut from the tape roll. These sheets are aligned with other sheets, laminated together and fired. This results in a dense monolithic body. Other components can be incorporated into the part by following a similar procedure with the appropriate materials. The buried components are connected to the other circuit elements through punched and filled via holes and screen printed metallization.

LTCC TRANSFORMERS - DESIGN CONSIDERATIONS

The design of transformers in LTCC ferrite tape presents several challenges to the traditional ways of thinking and designing transformers.

<u>Ferrite Effects</u>

Embedding the inductive coils in ferrite tape is like winding with magnetically shielded wire. A transformer functions because the magnetic flux lines created by one winding cross or link to another winding. If you bury the wire coil in magnetically conductive material, the flux will concentrate near the wire and not reach out and link with other turns or windings. Effective use of the embedded coil approach requires the designer to deal with this phenomena.

The ferrite is there to enhance the flux transfer from primary to secondary coil, but it also provides electrical insulation between the coils, the value of which depends on its composition, processing and coil layout/ design. Unfortunately the ferrite compositions having the best IR values usually don't have the best magnetic properties. Trade-offs are required.

<u>Winding Resistance</u>

Low coil resistance is important in order to achieve the desired properties. This need argues for designs that use high conductivity metals of large cross sectional areas. Silver, copper and gold provide the highest conductivity. Gold's cost generally rules it out.

The required inert atmosphere firing for copper raises its manufacturing cost, makes the vehicle burnout more difficult and can adversely effect the properties of the ferrite, so it is rarely used. Silver is the usual choice for LTCC applications. Lower resistance can also be achieved by increasing the cross sectional area of the coil. However, it is important to realize that excessive increases can cause warping and cracks due to shrinkage mismatch and stress.

<u>Magnetic Flux Paths</u>

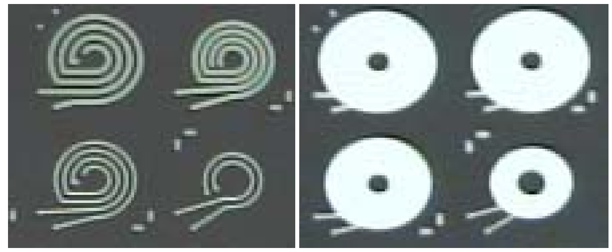
One of the problems with which a designer has to deal is the presence of the nontraditional magnetic flux paths in the transformer made using LTCC processing. An approach used to handle this problem involves calculating the reluctance of all paths within the structure including those around each conductor in the windings. This becomes complicated quite quickly but can be done by arranging the paths in a matrix form and using a program such as MATLAB to do the calculation.

Finite element modeling software like Ansoft's Maxwell has also been used to get the desired flux path information. This approach yields information on inductance values consistent with experimental results. It has also provided pictorial maps of the flux density.

In a traditional transformer the magnetic path is defined by the core shape, its size and cross sectional area. The windings are well defined and completely separate from the core. Normally they are formed on a coil former or bobbin and then placed on the core. With LTCC ferrite tape the windings and core are fully integrated. In the traditional transformer, the air, insulation and windings present a higher reluctance path for the flux than the core. Hence the flux concentrates in the core. This core magnetic path envelops the entire winding, thus insuring effective coupling. According to Faraday's law, the voltage induced in a loop or loops of wire (coil turns) is related to the amount of flux passing through the interior of the loop. The flux is directed to pass through the turns by the core; for example, the center leg of an E-core. In the LTCC transformer the core is intimate with the windings and thus a low reluctance path is available right next to the wire. Since flux will seek the path of least reluctance, it will not pass through the other turns of the winding. Flux that does not couple by passing through the other winding turns is lost and referred to as leakage inductance.

This problem has been solved (as revealed in US patent 6,198,374) by placing a lower permeability material between the windings on the ferrite tape. This lower permeability material helps direct and control the flux paths so that more flux passes through the winding loops substantially increasing transformer efficiency.

Figure 1A shows a few of the many different interdigitated primary and secondary winding loops that might be printed on a layer of ferrite tape. In this configuration the flux is not directed and will tend to take the low reluctance path next to the printed winding.



1A 1B

Figure 1

Figure 1B shows a configuration in which a donut of low permeability dielectric has been printed over the winding loops. (Shown as light area in the figure) This has the effect of redirecting the flux through the desired center core (shown in dark) area.

<u>Layer to Layer Connection</u>

Another design consideration is the area used to interconnect and couple the winding loops. Since minimum size and cost are key considerations, any way to reduce the area is beneficial.

A design, which effectively copes with this need, is revealed in US patent 6,054,914. It discusses locating the interconnection vias in the center core area of the transformer. This reduces size and provides more efficient use of the available area without adversely affecting the final performance of the transformer. It is incorporated in the LTCC transformers discussed in this paper.

MATERIALS DEVELOPMENT

The LTCC transformer required the development of a materials system that could be fired at low temperatures and result in dense, flat, crack-free parts. Compatible magnetic tapes, dielectric pastes, conductors and via fill pastes were needed. NiZn ferrite was chosen as the magnetic material because of its high resistivity and relative ease in processing.[2] The highest permeability of this material is generally obtained when it is fired at temperatures >1000˚C. The choice of silver based materials for the conductor and via fill was made not only to meet the need for low cost and high conductivity, but also because of its ability to lower the firing temperature and facilitate grain growth in the ferrite.[3] Even though the use of silver limits the firing temperatures to less than 950˚C (MP silver = 962˚C), excellent magnetic properties can be obtained.

The choice of material for the dielectric was based on the need for compatibility with the ferrite tape and silver conductors, its contribution in raising the breakdown voltage (BDV), its effectiveness in providing the needed reluctance and its ability to achieve these functions after being cofired with the other materials. Permeability and Q are also affected by the dielectric composition selected.[4] Testing of a variety of materials resulted in the material choices listed in Table 1.

A portion of a fired transformer is shown in Figure 2. Note that the ferrite has fired into a monolithic

Table 1

Designation	Material	Form	Function	Resistance/-Resistivity
40010	NiZn ferrite	LTCC tape	Magnetic matrix	10^{8}-10^{11} Ω
4926-JH	Dielectric	TF paste	Redirect flux & increase BDV	10^{12} Ω
903-CT-1A	Silver conductor	TF paste	Form buried inductors	3 mΩ/sq
902-CT	Silver conductor	TF paste	Via fill	4 mΩ/sq

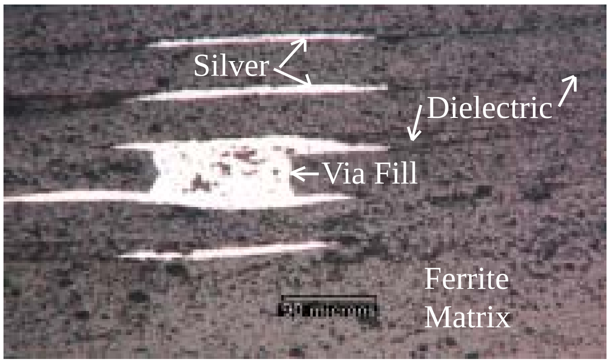


Figure 2

body containing the silver traces and vias and dielectric films. No delamination, or cracking is evident after cofiring.

The firing conditions affect the properties of the ferrite matrix as shown in figures 3 -5. Figure 3 shows the effect of temperature profile on permeability. Although higher permeability can be obtained at higher temperatures, we are limited to about 950°C as noted

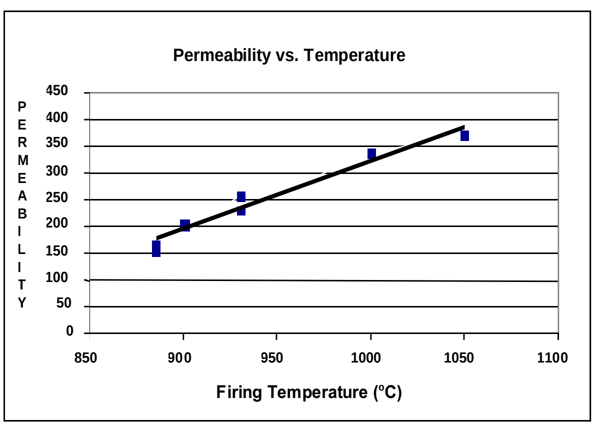


Figure 3

above. Permeability is optimized when the grain structure is large and uniform.[5] Figure 4 shows the relationship between grain structure and permeability. Breakdown voltage also varies with firing conditions. Figure 5 shows the effect of peak firing temperature on the breakdown voltage of interdigitated lines separated by 0.010" and covered with a dielectric paste. There is

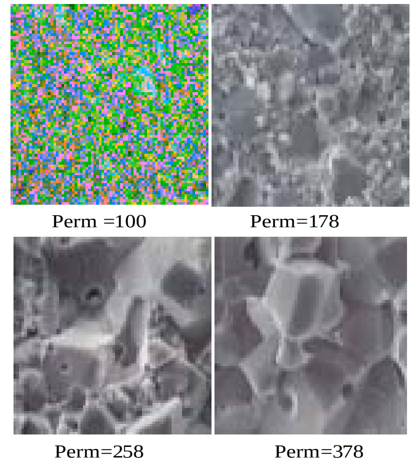


Figure 4

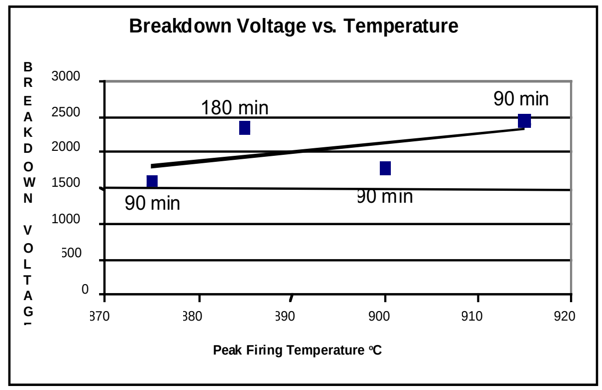


Figure 5

also a relationship between insulation resistance and breakdown voltage. This is shown in Figure 6.

As noted earlier, the principle functions of the dielectric in these low profile transformer applications

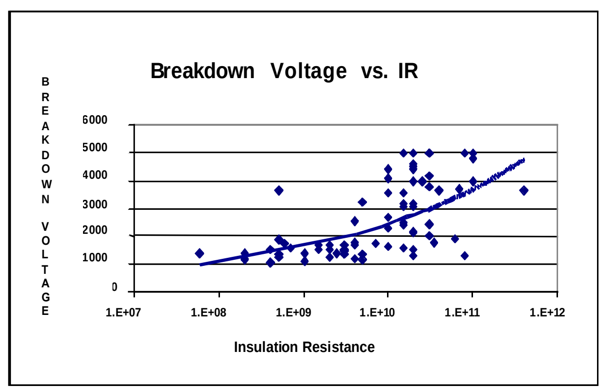


Figure 6

are to redirect the flux by increasing the reluctance in selective locations and to raise the breakdown voltage. It also increases the insulation resistance. The values achieved depend not only on the dielectric composition, but on the firing profile as shown in Table 2. The IR and BDV were measured on the 10 mil line and space interdigitated pattern while the inductance values were obtained from a spiral pattern deposited in the middle of a 10 layer ferrite stack. Table 2 illustrates property differences that result when the interdigitated and spiral patterns are covered with a layer of dielectric.

Table 2

Dielectric Layer	**No**		**Yes**	
Firirng Temperature/ Time at Peak	885°C/ 3 hrs	930°C/ 3 hrs	885°C/ 3 hrs	930°C/ 3 hrs
Insulation Resistance	1×10^{8}	6×10^{9}	2×10^{10}	3×10^{10}
BDV (volts AC)	2500	4400	<5000	>5000
Inductance	34μH	44μH	12μH	16μH

Technology Implementation

A number of transformers have been designed and built to test the applicability of the approach and determine the limits of LTCC technology for making transformers. As noted earlier transformer fabrication involves printing planar inductors such as those shown in Figure 1A on ferrite tape sheets, depositing the low permeability dielectric on the inductor loops, printing the interconnect metallization including via fill, registering the patterned tape layers, laminating and firing. The material/processing we developed was used to meet the requirements of digitally interfaced telecom analog modems. These transformers can provide low power and clock signals across a 1500 VAC barrier and meet IEC 60950 dielectric breakdown specifications. Its low profile (less than 0.050"), small size and cost effective manufacturing compare favorably with traditional hand wound toroidal transformers mounted in plastic headers used for the same application. The robust structure of the LTCC part is easily manipulated by SMT equipment and there is no fear of broken wires due to shipping or handling. In Figure 7, the smaller four pad LTCC transformer is shown next to the wire wound device which it replaces. The wire wound device is 0.075" in height.

The LTCC manufacturing technology was also applied to a series of demonstration transformers designed for low power switching applications in the 250 KHz to 2

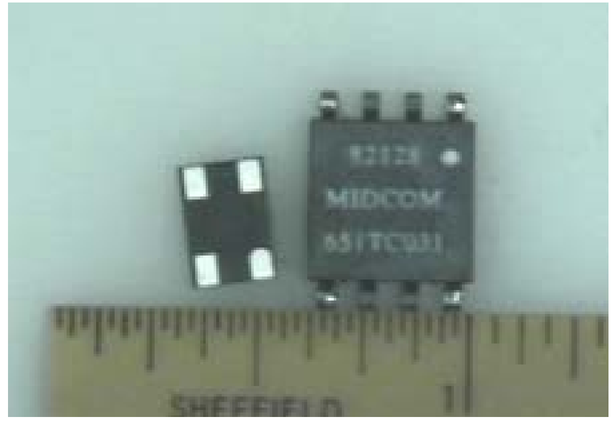


Figure 7

MHz frequency range. Some of these LTCC demonstration transformers are shown in Figure 8, along with three multilayer capacitors built using the same technology. (This is the first step in making small, low profile transformer/capacitor integrated parts.)

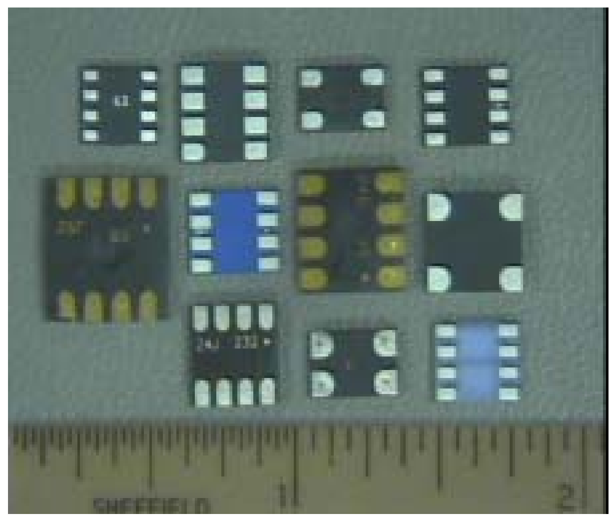


Figure 8

Transformers with turn ratios from 1:1 to 1:4, all with split primary and secondary windings, allow for series, parallel or center tapped connections to be made. These transformers can also be used as inductors, including use with limited DC bias. Table 3 lists some of the characterizing parameters of these LTCC magnetic devices.

Table 3

Part No.	Turns Ratio	Pri Res.Ω ± 20%(1-4)	Sec Res.Ω ± 20%(5-8)	Pri Ind.μH ± 20%(1-4)	Sec Ind.μH ± 20%(5-8)	Leakage Ind. μH	CouplingK
95006	1:1	0.75	0.75	19.0	19.0	2.6	0.93
95007	1:1.5	0.75	2.15	20.0	47.5	2.2	0.94
95008	1:2	0.75	1.35	15.0	57.5	1.6	0.95
95009	1:2	0.75	3.65	20.0	82.0	1.9	0.95
95010	1:2.5	0.75	3.00	16.0	98.5	1.6	0.95
95011	1:3	0.75	4.30	16.0	145.0	1.5	0.95
95012	1:3.5	0.75	5.65	17.0	210.0	1.4	0.96
95013	1:4	0.75	7.10	17.0	270.0	1.4	0.96

Additional characteristics of the ferrite tape used to make prototype transformers are shown in figures 9-11. They indicate the effect of frequency, magnetizing force, and temperature on permeability. The range of magnetic devices to which this technology can be applied is expected to grow as additional ferrite compositions become available.

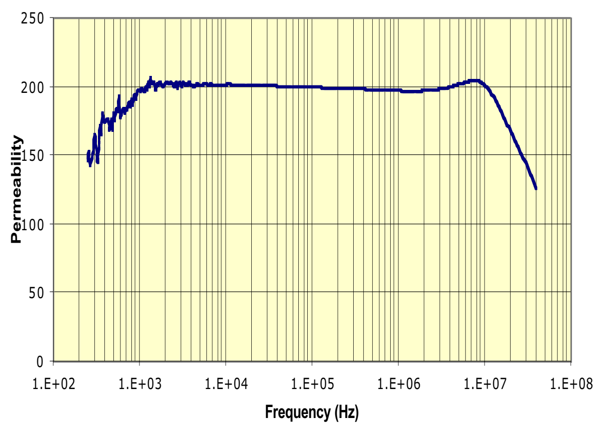


Figure 9
Permeability vs. Frequency

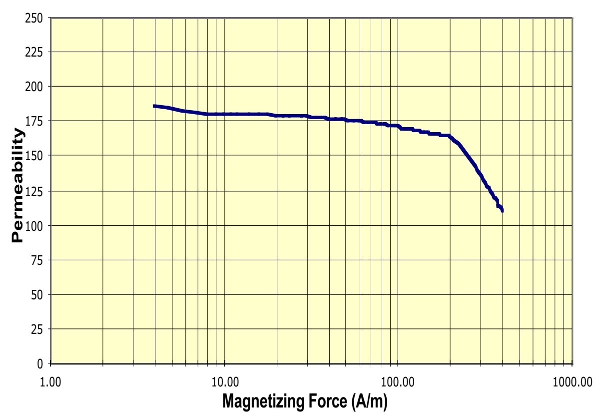


Figure 10
Permeability vs. Magnetizing Force

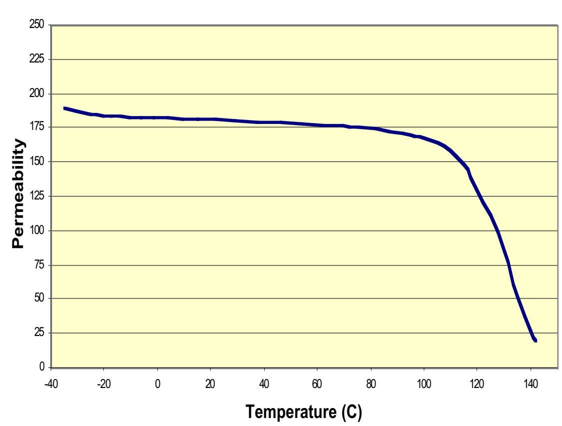


Figure 11
Permeability vs. Temperature

Summary

The primary goal of this work was to develop a scheme for producing small, low profile transformers. They had to be reliable, easily mountable, low cost and not require hand winding. A secondary goal was that the scheme would be applicable to other magnetic components and compatible with passive components. A materials set was formulated which allowed the primary goal to be met using LTCC processing customized to the application, adjusted to limit interactions and focused to accentuate key magnetic and dielectric properties.

Reducing the transformer size required more efficient use of space. This was achieved by imbedding the inductive elements in the ferrite matrix and by making element to element connections in the inner core. Use of a patented design allowed connections to be made this way without degrading the magnetic properties. A high reluctance dielectric layer deposited on the screen printed primary and secondary windings provided the increased insulation strength needed as size is reduced and elements get closer together. This layer also acts to direct flux, thus providing the added benefit of increased efficiency of the transformer. The reduced size, weight and uniform shape of the LTCC parts are more compatible with SMT pick and place equipment.

Reliability testing is underway, but historically LTCC processing applied to a compatible set of materials has a proven track record of reliability. The work also provided a reasonable expectation that our secondary goals can be achieved with further development.

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