Ceramic Tapes for Wireless Applications

R.L. Wahlers, S.J. Stein, M.A. Stein, A.H. Feingold & P.W. Bless
Electro-Science Laboratories
Presented at ACerS, 2000

The rapidly growing wireless industry needs new high performance materials to build low loss, high density, thermally stable integrated packages. This paper describes cofire and transfer ceramic tapes developed to meet these needs. Low loss gold and silver based compositions for screen print and photoimaging technologies are used for top and inner layer conductors. Size reduction using buried passive components and techniques for reducing cross talk are discussed. Design, processing and material interaction effects on dielectric constant and loss characteristics are presented for frequencies up to 20 GHz.

Introduction

The wireless telecommunications industry is growing at a rapid pace. Applications include automotive (safety, control and entertainment), global positioning system mapping (GPS), multifunctional portable phones, home entertainment and office voice, video and data transmission through wireless local area networks (WLAN). New materials are required to meet the increased speed and multifunctionality needed in these systems. Their GHz operating frequencies necessitate the use of dielectric matrix materials with low loss and low dielectric constants. Low loss is critical in applications requiring long battery life. Low K is needed for isolating signal traces and for high signal propagation rates. Polymer based circuit boards offer low K but suffer from poor thermal conductivity and, in some cases, lossy behavior at high frequencies (1). Ceramic substrates like alumina meet many of the requirements but have relatively high dielectric constants and suffer from the general requirement that refractory metal conductors must be used in multilayer configurations. In the frequency range of most telecommunications applications, where conductor losses dominate, the higher resistivity of these materials is undesirable.

The solution proposed in this paper involves burying passive components in low firing ceramic tape. Burying the surface-occupying passive components frees up surface space for additional functions. It also increases the number of circuits per substrate which lowers system cost. Use of tape having low loss and low K values provides the dielectric properties needed in the matrix.

Ceramic Tape System

Figure 1 gives an outline of the two approaches used in building up the multilayer tape modules along with the advantages associated with each. In the cofire tape approach green tape sheets each with its appropriate screen printed circuitry are laminated together and cofired. The transfer tape process, on the other hand, involves sequential firing of individual layers laminated to a ceramic substrate such as alumina. The cofire approach allows for a single burnout/firing cycle thereby improving cost savings, especially as the number of layers increases. Technological challenges are greater with cofire tape, however, since all materials must be matched in coefficient of thermal expansion and shrinkage during firing to avoid warpage of the final package. The transfer tape approach more closely resembles conventional thick film processing and offers more flexibility in the selection of materials, largely because planar shrinkage is effectively constrained by the ceramic substrate. Processing costs necessarily increase with the number of fired layers.

Transfer Tape	**Cofire Tape**
Processing (Sequential)	**Processing (Parallel)**
Tape sheets cast	Tape sheets cast
Lamination to substrate	Metallization
Metallization	Component formation
Component formation	Lamination of layers
Advantages	**Advantages**
Strength	Low labor
Heat dissipation	Single fire
Zero shrinkage (XY)	Layer capability
Multiple fire	Sheet inspection

Figure 1. Approaches for building multilayer tape modules

The properties of the tapes, conductors, and buried components discussed in this paper are given in Tables 1-3. Table 1 lists the properties of two tape chemistries in both cofire and transfer formats. The “111” composition is distinguished by a very low dielectric constant (K) around 4 to facilitate high signal propagation rates, excellent isolation and low insertion loss. The “101” composition possesses a still low K of about 7 while offering some advantages in materials compatibility.

Table 1. Tape Properties

Tape Designation	Dielectric Constant	Insertion Loss*	Peak Temperature	Furnace Type
111-TT	~4	~0.004 dB/mm	850°C	Belt
101-TT	~7	~0.006 “	“	“
111-CF	4.2	0.0038 “	850/875°C	Box
101-CF	7.3	0.0057 “	“	“

* Measured at 3 GHz

The conductors used in this study are shown in Table 2. They were formulated to provide low loss, ohmic contact, shrinkage match to the tape matrix and minimal interaction with the components. Metallurgies include Ag, Pd/Ag and Au. The Ag and Au conductors are also available in photoimageable versions for high frequency applications requiring fine lines and precise edge definition.

Table 2. Conductors

Designation	Metallurgy	Processing	Firing Temperature
Ag-1	Ag	Screen Printed	850-875°C
Pd/Ag-1	Pd, Ag	"	"
Au-1	Au	"	"
Ag-PI	Ag	Photoimaged	"
Au-PI	Au	"	"

Table 3 lists the designations and properties of the capacitors which were embedded in the tape matrix. For the capacitor tape, nominal stand-alone K and DF values along with conductor and firing temperature recommendations are listed. The reported properties/processing of the capacitor pastes are those related to conventional use as thick film inks fired on 96% alumina. These values may be compared with the buried component values reported later in the paper. Deviations from the numbers in Table 3 serve as an indication of the degree of interaction between the capacitors, conductors and tape.

Table 3. Properties of Capacitor Materials

Capacitor Product Number	Dielectric Constant (K)	Dissipation Factor (DF, %)	Electrode Metallurgy	Firing Temperature (°C)
4113	110	<0.5	Pd/Ag	930-980
4117	300	"	"	"
4151	300	<2.0	Ag, Pt/Ag	850-930
4152	1,000	"	"	"
4153	2,400	"	"	"
41210-70C*	100	<2.5	Pd/Ag	850

* Cofire Tape

Firing temperatures for the tapes fall into the range of 850-875°C which allows for a greater selection of materials based upon conventional thick film pastes. This temperature range, below the melting point of pure silver, accommodates the use of high conductivity, air firable precious metal conductor systems. Conventional thick film tunnel kilns are appropriate for transfer tape firing while programmable box furnaces are preferred for cofire tapes which require a longer cycle containing adequate burnout time in the 450°C range. Figure 2 outlines these firing schedules.

Firing Conditions

Belt Furnace (Transfer Tape)

580°C peak / 50 minute cycle (burnout)
850°C peak / 45 minute cycle (sintering)

Box Furnace (Cofire Tape)

5°C/minute to 450°C
Hold at 450° for 60 minutes
5°C/minute from 450° to peak temperature*
Parts cool with furnace

***Peak Temperatures of 850 & 875°C**

12 minute hold time at 850°C
30 minute hold time at 875°C

Figure 2. Firing conditions of dielectric tapes

A ring resonator pattern was used to measure the insertion loss and dielectric constant versus frequency of the dielectric tapes. The specifics of test part preparation and measurement methods used in this technique are described in another publication (2). The loss versus frequency characteristics of the 111-CF and 101-CF tapes are plotted in Figure 3. Their values are close in the low frequency region with the superiority of the low K 111-CF composition becoming evident at higher frequencies. Ag-1 silver was used for the ground plane and top layer ring pattern for both parts. Firing was done in a box furnace at a peak temperature of 850°C. Comparison of the loss vs. frequency curves of 111-CF with silver on alumina and copper on FR-4 can be seen in Figure 4. The loss of 111-CF is close to that of silver/alumina and clearly better than that of copper/FR-4.

Buried Components

Embedding passive components in the tape matrix can provide a significant amount of surface space on which additional functions can be placed. Component counts indicate that 90% or more of the components used in wireless applications are passives (3). The majority of these are de-coupling capacitors with tolerances in the 5-10% range. Since this performance is obtainable with buried capacitors the potential for saving space with buried components is great.

Buried resistors and capacitors, especially when cofired, are subject to physical and chemical interactions with the surrounding tape layers. Values and tolerances are affected, sometimes dramatically so. Significant work is involved in selecting and developing passives which approach their conventional counterparts. High range resistors are particularly problematic because of their sensitivity to glass diffusion from the dielectric tapes. Buried resistors with tolerances of 20-30% are still the norm. Generally, it can be said that the materials used for buried passives are still evolving.

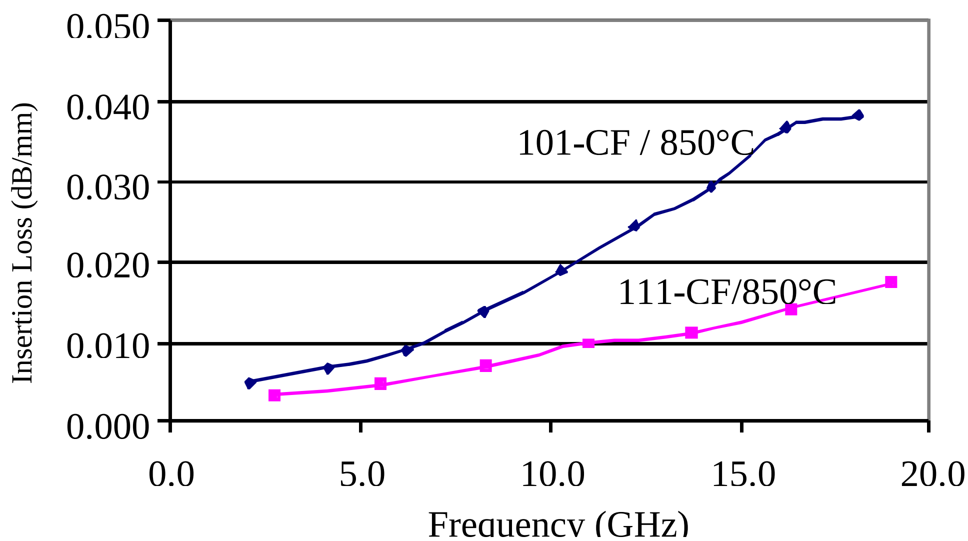

Figure 3. Loss versus frequency of 111-CF and 101-CF

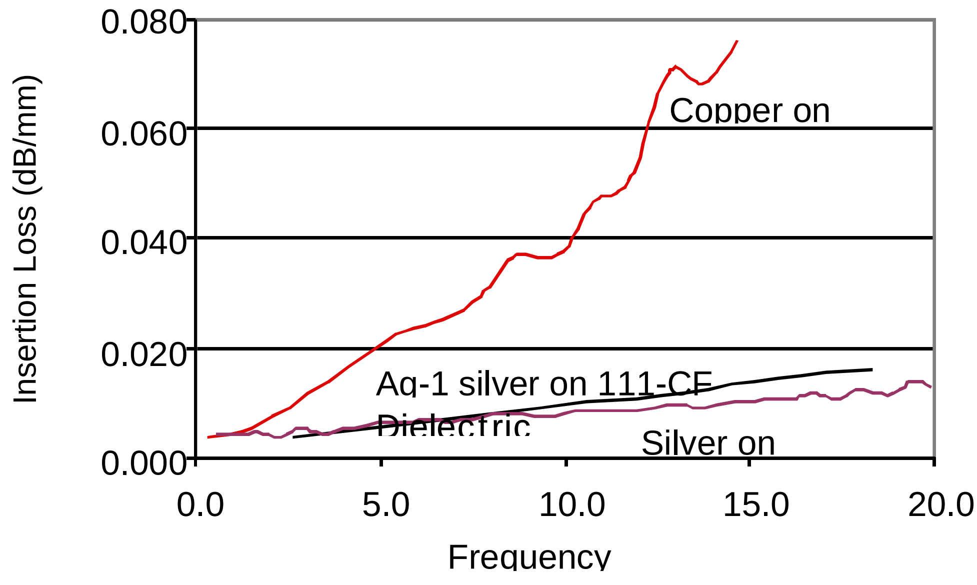

Figure 4. Loss comparisons to alumina and FR-4

Capacitors

The simplest method for producing capacitors involves using the dielectric tape itself as the capacitor and printing the appropriately sized electrodes to achieve the capacitance desired. Buried capacitors constructed in this way with 101-CF and both Ag and Pd/Ag conductors can be cofired at 875°C to produce flat packages with TCCs within ±2.2% from –55 to +125°C (EIA classification X7C).

Table 4. Buried High K Capacitor Tape

Matrix Tape	K	DF (%)	ΔC (%, -55°C)	ΔC (%, 125°C)
111-CF	50	1.2	-6.1	3.9
101-CF	79	1.2	-11.5	13.5

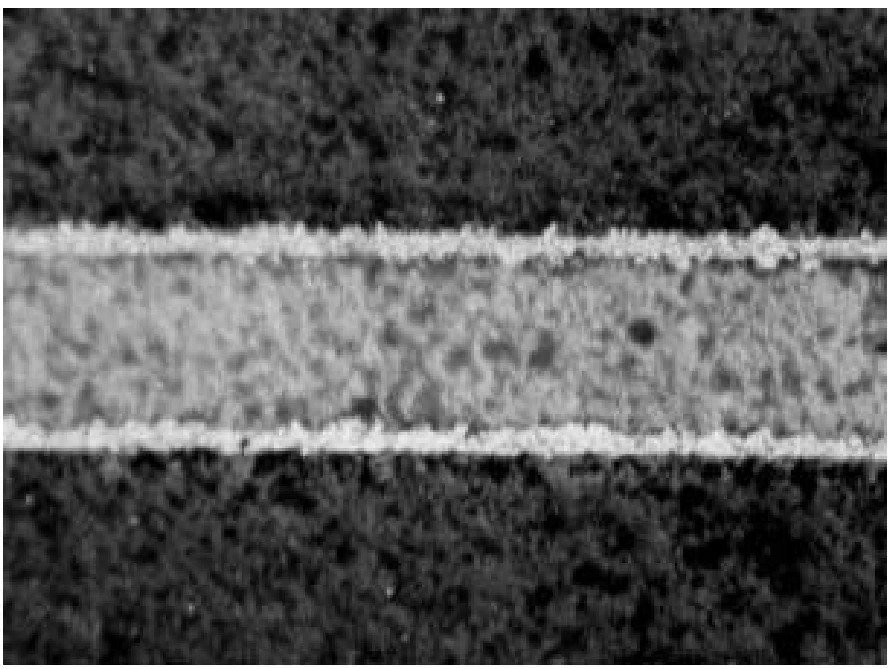

Figure 5. SEM of K-100 tape buried in 111-CF tape

Higher values can be achieved by substituting a ferroelectric based tape composition for the capacitor layer. The K 100 tape was cofired at 850°C with Pd/Ag electrodes in 101-CF and 111-CF with the results shown in Table 4. Dielectric constants are reduced by about 20-50% from the nominal value of 100 in these buried cofired composites because of interactions with the contiguous low K tape layers. Dissipation factors are maintained at low values around 1.2%. Temperature characteristics are X7R or better depending upon the surrounding matrix. The interaction between the capacitor tape and the host tapes is likely that of glass diffusion into the capacitor layer. This interaction does not appear to have any deleterious effects on the bonding between the tapes. Figure 5 is a photomicrograph of the K 100 tape with Pd/Ag-1 electrodes buried in 111-CF. No delamination is evident and boundaries are clearly defined. Fired film thickness of the single capacitor tape layer is approximately 95 μm.

Maintaining planarity with buried components is often difficult for screen printed capacitors where multiple layers of dielectric and conductor are usually required. One approach which minimizes this problem is the use of an interdigitated electrode pattern followed by a layer of dielectric to fill in the spaces between conductor lines. The result is a nearly planar capacitor in which the capacitance becomes a function of line dimensions and, inversely, of spacing. Figure 6 is a photomicrograph of interdigitated Ag electrodes with 40μm lines and 60μm spaces obtained by photoimaging. These dimensions result in an eightfold increase in capacitance over those obtainable with the 250μm capability of standard thick film techniques. Table 5 shows the effect of line and space dimensions on capacitance. It should be pointed out that these interdigitated capacitors are inherently asymmetric in the z direction and careful selection of materials is required to avoid possible warpage.

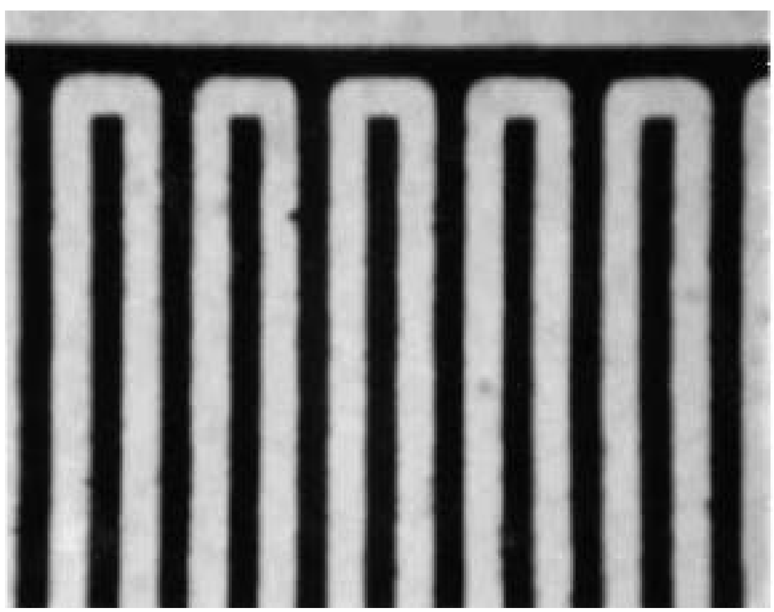

Figure 6. SEM of photoimaged electrode pattern (40μm lines, 60μm spaces)

As an indication of future developments, Figure 7 shows an SEM of a photoimaged Ag conductor which had been processed on a K 4, screen printed multilayer dielectric (ESL 4911). Line width is 8μm on a 50μm pitch. At present, line definition is not optimized at this level of resolution but improvement would be expected to occur with processing on the smoother dielectric tapes.

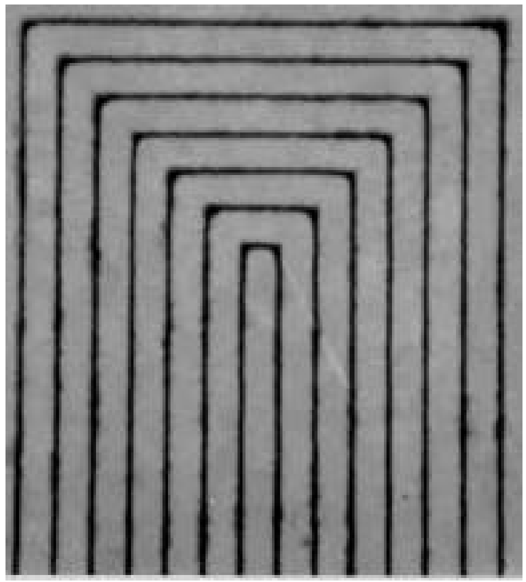

Figure 7. SEM of photoimaged Ag conductor (8μm lines on 50μm pitch)

Capacitors were also prepared in more conventional fashion using a parallel plate arrangement of Pd/Ag electrodes and two dielectric layers buried in both 101-CF and 111-CF. All layers were cofired at 850°C. The capacitor dielectrics tested were ESL 4113 and ESL 4117. The results are listed in Table 6. Electrode size was $1mm^2$ and the capacitance density ranged up to about 3000 pF per cm^2 of electrode area. Dielectric constants are reasonable but below the values obtained in standard thick film processing which has the advantage of separate firing schedules for all layers and lack of intimate contact with low K glass phases.

Table 5. Buried Interdigitated Capacitors

Conductor Processing	Line Width (μm)	Line Height (μm)	Line Spacing (μm)	Capacitance Increase Over SP-Std
Screen Print (SP-Std)	250	15	250	SP-Std
Screen Print	125	10	125	2.67X
Photoimaged	40	6	60	8.33X

Table 6. Screen Printed Capacitors Buried in Cofire Tape

Capacitor/Tape	K	DF (%)	ΔC (%, -55°C)	ΔC (%, 125°C)
4113 / 111-CF	73	0.5	-1.1	0.6
4113 / 101-CF	75	1.1	-9.1	5.0
4117 / 111-CF	103	0.3	2.0	-1.0
4117 / 101-CF	129	1.7	-2.0	1.2

Table 7. Screen Printed Capacitors Buried in Transfer Tape

Capacitor/Tape	Temp (°C)	K	DF (%)	ΔC (%, 125°C)
4113 / 111-TT	850	46	1.5	-3.2
"	930	114	1.0	-1.1
4113 / 101-TT	850	114	1.4	13.6
"	930	142	1.1	-0.4
4117 / 111-TT	850	63	4.6	3.6
"	930	301	1.5	-8.8
4117 / 101-TT	850	247	1.5	-5.9
"	930	400	1.2	-8.5
4153 / 111-TT	850	53	0.6	-4.4
"	930	57	1.0	-8.2
4153 / 101-TT	850	43	2.0	-8.9
"	930	862	1.5	-35.7

Separate firing of layers is possible with the transfer tape method and two approaches were tried. In the first, the dielectrics and electrodes were printed and fired on tape coated alumina followed by lamination and firing of a top tape layer. All firings were performed at 850°C. In the second, thick film dielectrics and conductors were fired onto terminated alumina substrates at temperatures higher than that used for subsequent firing of the tape. The ability of transfer tape processing to allow higher firing temperatures of the capacitors prior to their being buried means that the capacitors will achieve higher fired densities and higher K values while minimizing interactions with the glassy matrix of the tape. Table 7 shows the results of these approaches. Terminations were Ag-1 in all cases and the matrix tapes were 101-TT and 111-TT. The data for the 850°C firings represent properties obtained using tape coated alumina (first approach) and the data for the 930°C firings represent capacitors prefired onto alumina (second approach). The general conclusions are that prefiring the capacitors at a higher temperature can dramatically raise the dielectric constant but that interactions with the matrix can still be significant. The nature of the interaction depends upon the chemistries involved. Among the capacitor dielectrics tested, ESL4153 shows the greatest variability with K values ranging from 43 to 862 depending on processing details. Generally, however, the highest K values are achieved with the transfer tape method.

Resistors

Resistors are arguably the most process sensitive of thick film materials and initial attempts to bury resistors in dielectric tapes resulted in sometimes dramatic changes in value and temperature characteristics. Undesirable physical and chemical reactions such as blistering could occur when resistors were buried in tapes. Cofiring the materials often exacerbated the problems. Rational approaches aimed at improving the compatibility of the compositions have yielded some positive results. Table 8 lists the resistor properties of a nominal 1KΩ, 100ppm/°C resistor modified for tape use and buried in cofire and transfer tapes with Ag and Pd/Ag conductors. Buried in 101-CF the resistor gave values similar to those that would be expected on bare alumina. The resistance values were higher and the TCR values more negative when this same resistor was buried in transfer tape of a similar composition. The larger changes in the latter are likely the result of the additional firings associated with the transfer tape process.

Table 8. Resistor Buried in Dielectric Tapes

Matrix Tape	Conductor	Resistance (KΩ)	CTCR (ppm/°C)	HTCR (ppm/°C)
111-TT	Ag-1	13.4	-751	-439
“	Pd/Ag-1	11.5	-747	-423
101-TT	Ag-1	8.3	-680	-403
“	Pd/Ag-1	5.3	-548	-313
101-CF	Ag-1	1.26	-183	-181
“	Pd/Ag-1	0.78	-25	-26

Conclusions

The rapidly growing wireless communications industry is placing demands on the materials and packaging industries to provide microwave circuits with high performance in small sizes and at low cost. One promising way to accomplish this goal involves the burying of passive components in low K dielectric tapes. The advantages of this approach include space and cost savings, good thermal dissipation, environmental protection of the buried components, reduction in the number of soldered connections, mechanical robustness and good high frequency performance. We have described a set of materials comprising low K tapes, compatible Ag, Pd/Ag and Au conductors and capacitors and resistors that can be buried in the tapes to form planar, dense structures in either the cofire or transfer tape formats.

References

(1) Skurski, M.A., Smith, M.A., Draudt, R.R., Amey, D.I., Horowitz, S.J., and Champ, M.J., Microwaves & RF, Feb, 1999, pp. 77-86

(2) A.H. Feingold, C. Huang & S.J. Stein, Low K, Low Loss, Low Fire Tape System `for Microwave Applications Proceedings of IMAPS Europe, Prague, June, 2000

(3) T.G. Reynolds, The Application of LTCC Technology to Improved Integrated Passive Components, LTCC Wireless Workshop, NIST, Nov, 1999