Embedded Capacitors for LTCC applications above 20 GHz

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Abstract

Low Temperature Cofired Ceramics becomes more and more accepted for RF- and Microwave Circuitry. Reason for this is the combination of electrical, mechanical and thermal properties as well as the enhanced capabilities for real three dimensional designs. In the lower Gigahertz-range this material is ideally suited for passive integration of lumped elements. This has been demonstrated on a variety of applications like Bluetooth and filter modules. This contribution focusses on receive-/transmit modules for LMDS (Local Multipoint Distribution System) or MVDS (Microwave Video Distribution System) working at frequencies from 20 to 60 GHz.

Initially, the following pre-requisites were identified: multilayer connectivity, a sufficiently low millimeter-wave loss, good thermal management capabilities high module reliability, and compatibility with soldering, conductive epoxy and wire bonding – all this while maintaining low overall weight and cost. A typical unit contains three individual chains – Receive-, Local Oscillator and Transmit-Channel. Integrated hermetic waveguide-to-microstrip transitions provide mm-wave input and output terminals. The narrowest lines on the LTCC substrate are 50 microns wide and are obtained by screen-printing.

MMICs require decoupling capacitors in their direct vicinity. These capacitors are usually wire-bondable disc MIM-capacitors which are rather expensive (component + assembly cost). DuPont's Green Tape™ 951 system offers the opportunity to realize passive components like resistors, inductors or capacitors on internal layers. The latter could be used to replace the discrete decoupling capacitors in the next generation of LMDS-modules. Embedded capcitors can also be helpful in the transition from a wire bond solution to a flip chip approach.

In order to achieve a high capacitance density the dielectric thickness of a plate capacitor should be as thin as possible and the permittivity of the dielectrics should be as high as possible. These requirements are difficult to achieve with the tape available having a permittivity of about 7.8. Thinning the tape thickness has its limits in the manufacturability due to the incompatibility to installed tape handling systems.

The best approach in terms of manufacturability is to print a thin layer of high-k-material between electrodes on internal layers. Tolerances, design constraints and the impact of the "foreign" material on the laminate shrinkage and substrate topology will be discussed. Reliability testing successfully performed on test structures show the capability of one metal/dielectrics combination for high-rel applications. A special test coupon has been designed, manufactured and measured to evaluate the wide band behavior and to establish a suitable electrical model for simulations.

Key words: LTCC, Embedded Components, Passive Integration, Capacitors, High-k-Material, Microwave Application

Integrated Capacitor solutions in LTCC

Parallel plate capacitors are determined by the area *A* of the electrodes (plates), their distance *d* and the material (permittivity ε_r) between them (Eq. 1). The density of capacitance is related to a defined area in or on the circuit (e.g. 1 mm²). An increase of this value can only be achieved by either reducing the distance between the electrodes or increasing the permittivity.

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d} \qquad \textbf{(Eq. 1)}$$

In a multilayer circuit additional layers might be used to build a multilayer capacitor. However, this will mainly be a trade-off between functionality and costs.
The general approaches to increase the capacitance are:

a) Adding of layers (Fig. 2)
b) Insertion of one layer of high-k-tape (Fig. 2a)
c) Filling of holes with high-k-material (Fig. 2b)
d) Locally printing high-k-paste (Fig. 2c)

Type a) was not a solution due to the fixed number of layers in the application. Inserting an entire tape layer of high-k-material requires a tape which should meet the following requirements:

- matched shrinkage to base tape during firing
- tape sinters hermetically to avoid moisture penetration into the package
- matched TCE to base tape
- no material interactions with the base tape dielectrics (both ways)
- compatibility to conductor and via-paste systems
- compatibility to general tape processing methods (handling etc.)

Tapes showing these properties are still under development and were not commercially available within the project time frame [1]. A solution to locally insert high-k-material has been introduced earlier [2]. This so-called tape insert array method eliminates some of the requirements mentioned above. However, the processing method is rather complex and was therefore not introduced into series production. The most promising method considered is type d) [3]. The electrodes are printed on the top of the first tape and on the rear site of the second layer. A high-k-paste is printed over the first electrode twice isolating electrode 1 from electrode 2 in the layer stack. Electrical connections to both electrodes can be realised by vias placed directly in the center of the plates or by conductor traces leaving the electrodes within the plane (Fig. 3).

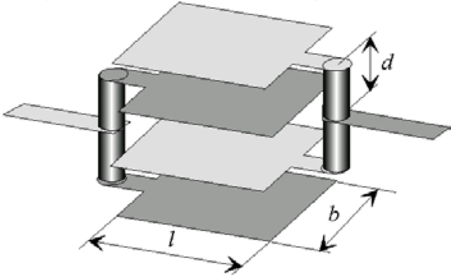

Fig. 1: LTCC multilayer capacitor

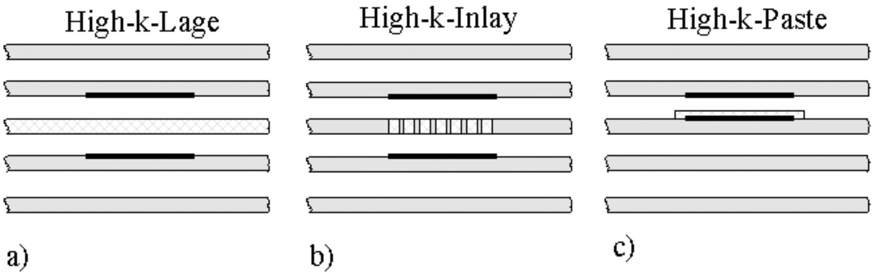

Fig. 2: Methods to increase the density of capacitance

The printing solutions addresses both variables in the capacitor design. The thickness of the dielectrics is minimised and the permittivity is increased.

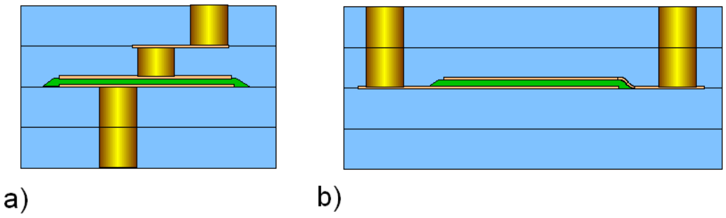

Fig. 3: Contact solutions for plate capacitors a) central b) peripheral

This approach requires a high-k-paste with the following features:

- matched shrinkage to tape during sintering
- pin hole free printability
- controlled thickness (for low capacitance variations)
- compatible to electrode and via materials
- stability to refirings

Furthermore, the whole capacitor should not lead to a remarkable topology on the LTCC surface after firing. This method should therefore not be applied on tapes thinner than 130 µm or on tapes with a low compressibility. Warpage of the circuit due to a slight mismatch of the shrinkage or the TCE can be prevented by arranging the capacitors always symmetrically in the package.

Printed capacitors using Green Tape™ 951

Recently, a high-k-paste (DP5674) has been introduced for the 951 tape system. A summary of data is listed in Table 1.

The capacitor is made the following way:

- PD bottom electrode together with the conductor lines on side 1 of layer n
- *PD High-k-paste on side 1 of layer n*
- *PD High-k-paste on side 1 of layer n*
- *PD top electrode on side 2 of layer n+1*
- Cofiring of all layers

P = Print, D = Dry, italic printed tasks are additional steps compared to the standard processing.

Compared to a postfire capacitor which requires additional firings, prints, and materials, (passiviation) the cofire solution can be obtained with a minimum effort.

No.	High-k-Mat.	Electrode material	k-value [1 MHz]	tanδ	class	Density of cap. pF/mm²	Area for 50pF
01	5674	Ag (tbd)	60 – 80	<0.008	X7P	18	2.8mm²

Table 1: cofire high-k-paste data

The first investigation focussed on the material compatibility metallisation to high-k-paste. Two silver based pastes were used in the test coupon. Paste A turned out to be incompatible with the dielectrics. The failures independend on the high-k-paste applied were:

- initial shorts (after cofiring)
- increasing number of shorts after refirings
- capacitance increased with the number of refirings

Cross sectioning revealed the reason for these effects (Fig. 5). The plates are very thick and show a tendency to migrate into the dielectrics. The penetration of silver is accelerated by temperature, which was the reason for the increasing capacitance observed after refirings (Fig. 6). The effective thickness of the dielectrics is reduced by the growing amount of silver in the dielectrics.

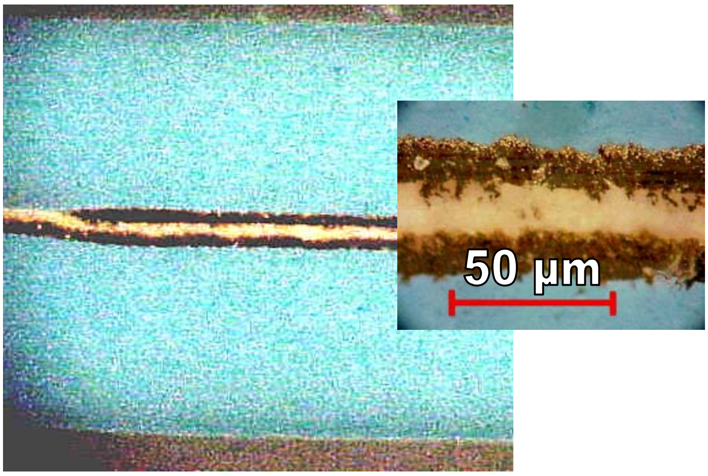

Fig. 5: Cross section of a 4-layer structure of 951A2 with an embedded capacitor

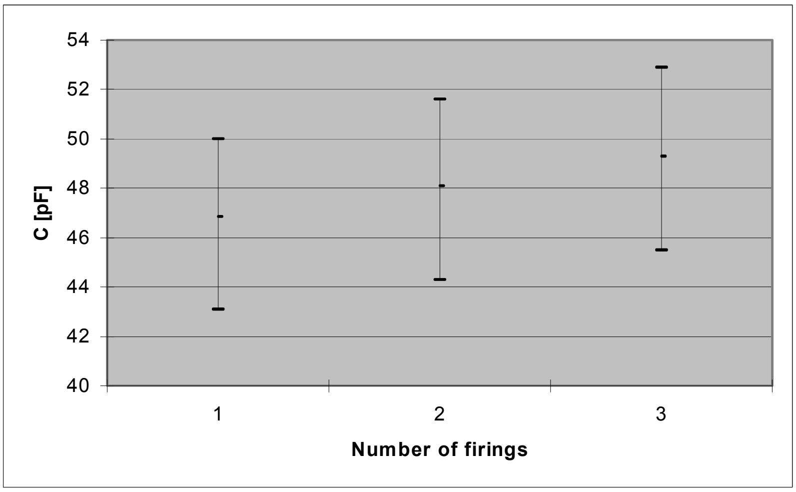

Fig. 6: Influence of the number of firings on the capacitance (min,mean,max for Ag-paste A)

Paste B, a fritless Ag-paste showed less interactions with the high-k-dielectrics in general. The material combination Ag-paste B and DP 5674 lead to an overall shrinkage of 12.2%. The initial yield for fully populated substrates with 380 single capacitors in a matrix was > 98% and was stable after refirings (Fig. 7).

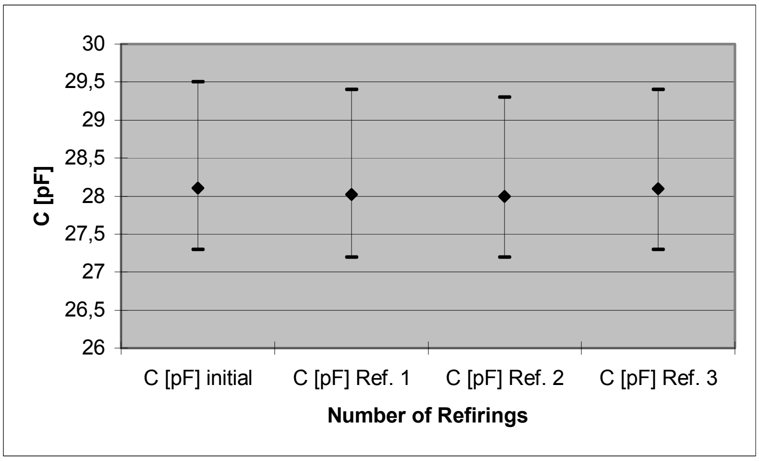

Fig. 7: Stability of capacitance vs. refirings

Qualification of this system was performed on a new test structure suitable for various test conditions. Fig. 8 shows the qualification test pattern. Three capacitors with different plate areas are connected in parallel ($1x1mm^2$, $2x2mm^2$, $4x4mm^2$). 22 groups were placed on one coupon. The series resistors are used for limiting the maximum current in case of shorted capacitors in the biased humidity test. For pre-conditioning these substrates were refired 3 times to simulate postfire steps and went through reflow soldering and cleaning. Fig. 10 shows the distribution of capacitance values for 16 test coupons. The density of capacitance was calculated to $22pF/mm^2$. Table 2 shows the qualification conditions applied and the test results. The defined target value for capacitance change was 5%. All capacitors passed this requirement.

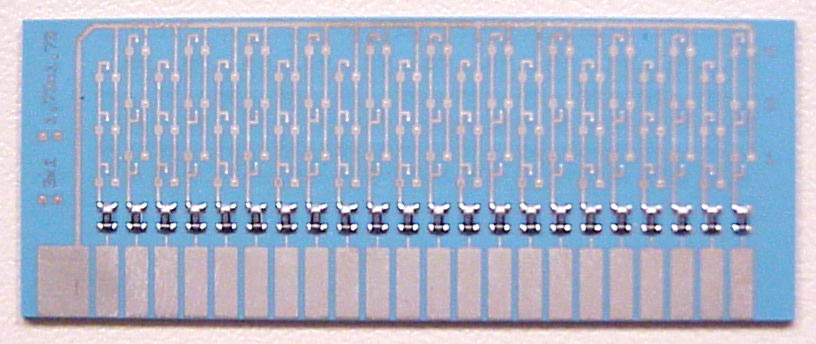

Fig. 8: Qualification test coupon

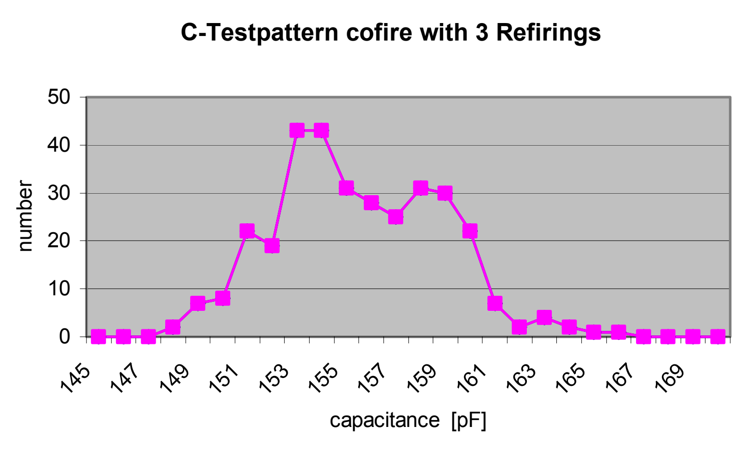

Fig. 9: **Distribution of capacitance values**

Test	Condition	Max. Deviation from initial value	Evaluation
Biased humidity test	1000h 85°C/85%r.F., 10V –	-0,89%	Pass
Temperature storage	1000h, 125°C	+0,7%	Pass

Table 2: Qualification tests for embedded capacitors

Decoupling capacitors for microwave circuits

In typical microwave applications the power connections of MMICs contain decoupling capacitors. The usual value for these capacitors is 40 ... 100 pF. In order to reduce parasitic effects (wire bond inductance etc.) these capacitors are located in the direct vicinity of the IC. A standard solution with a disc capacitor is shown in Fig. 10a. Two wire bonds are necessary to connect the MMIC. A possible approach with an embedded capacitor is shown in Fig. 10b. Only one wire is necessary for the connection. Even a better solution is the combination of a buried capacitor and the use of FlipChip technology, which is considered for future applications (Fig.10c). Although the frequency requirements of these capacitors are more relaxed than in the signal path of the circuit, they should work over a wide frequency range.

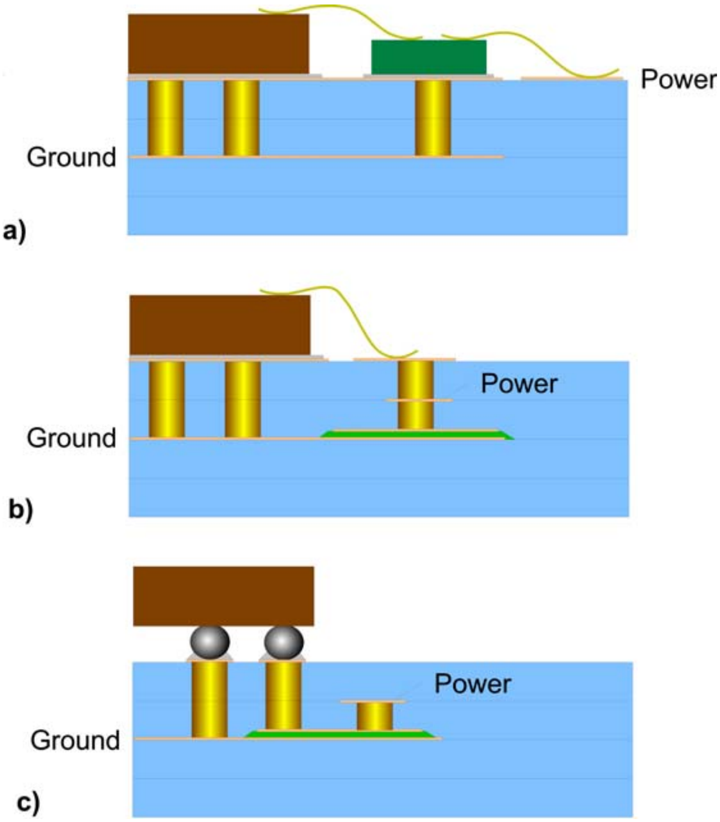

Fig. 10: Arrangement of decoupling capacitors in microwave applications
a) traditional (chip & wire)
b) embedded capacitor + chip & wire,
c) embedded capacitor + FlipChip

A further test coupon was designed to evaluate the rf-behaviour. It could be demonstrated that the via connection to the upper plate has a considerable influence on the self resonant frequency. Fig. 11 shows the via-arrangements applied. Measurement results of the forward transmission parameter S21 for two 50 pF capacitors can be seen in Fig. 12. The worst behavior was obtained by the via solution from Fig. 11c (results not shown in the diagram). Capacitor 2 is connected by 2 vias in parallel, whereas capacitor 1 has only one. The increased self resonant frequency is due to the decreased parasitic inductivity (20pH vs. 45pH).

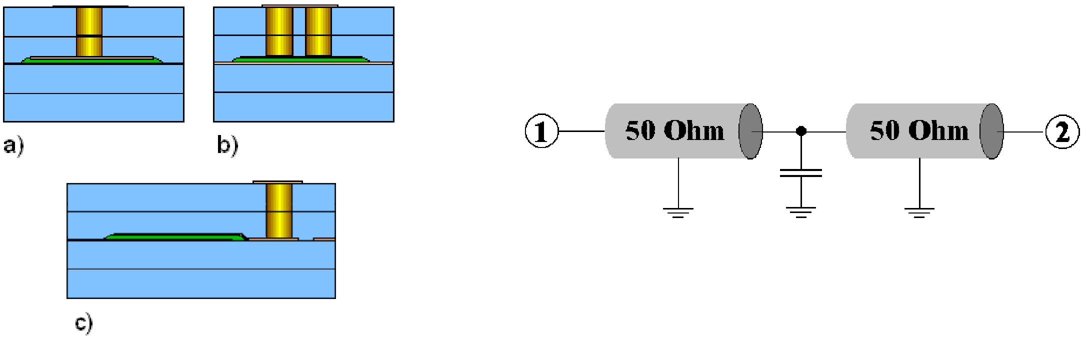

Fig. 11: Via-connections to the upper capacitor plate and electrical model (lower plate is made by the ground plane)

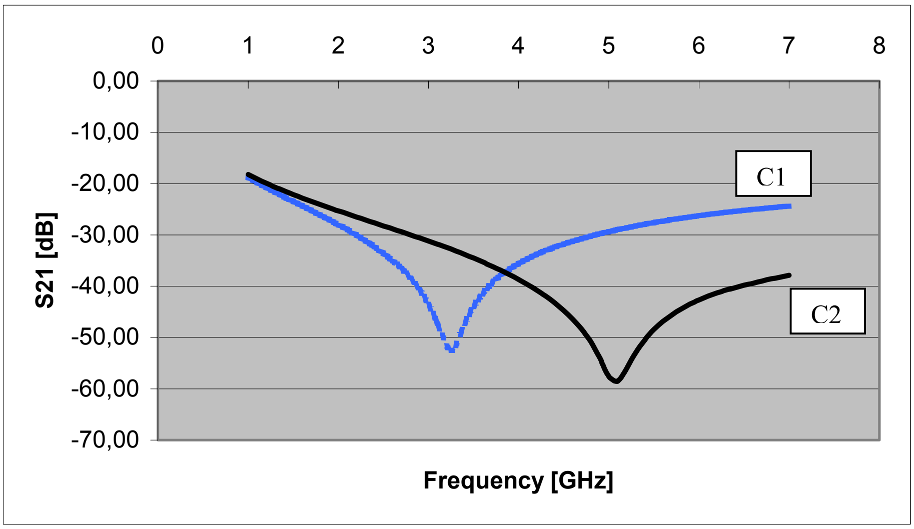

Fig. 12: Transmission behaviour of embedded capacitors with single (C1) and double (C2) via connections to the surface (shunt capacitor)

Conclusions and Acknowledgements

LTCC offers a suitable performance for microwave applications. Embedding of passive components will lead to a higher scale of integration and to improved electrical properties. The buried capacitors investigated in this contribution were able to demonstrate their manufacturability, reliability and rf-performance. They can be applied in future microwave products and are compatible with both the traditional chip & wire approach and FlipChip technology. The work carried out in this project is funded by the BMBF within the program "Mikrosystemtechnik 2000+" under the contract number 16SV1067/5.

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