

Integrated Capacitors using LTCC

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Abstract

With the continuous increase of the semiconductor resolution accompanied by higher integration levels, passive components tend to determine more and more the size of electronic modules. One trend, to minimise the area required for these passives, is to shrink the component size down to the 0201-outline. However, the number of solder or conductive epoxy interconnects remains the same and the placement accuracy needs to be higher requiring more sophisticated and expensive placement tools. Therefore it would be most desirable to integrate as many passives as possible into the substrate.

A multilayer substrate based on LTCC offers the opportunity to print passive components like resistors, inductors or capacitors on internal layers. This paper focuses on printed capacitors in LTCC for use as decoupling capacitors in a microwave application. 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 systems available having a permittivity in the range from approx. 6 to 9. 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. The paper shows results obtained with two different capacitor materials. 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 material combination for high-rel applications. Microwave measurement of scattering parameters are used to demonstrate the high-frequency capability of these capacitors.

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

Introduction

The growing market for multimedia applications like Video-on-Demand or Highspeed Internet Access requires fast transmission velocities with a wide band width straight to the end user (customer). Without a change in the infrastructure like fibre to home this is only achievable with terrestrial Point-to-Multipoint wireless systems like LMDS (Local Multipoint Distribution System) or MVDS (Microwave Video Distribution System) working beyond 20 GHz. The heart of such a system consists of a microwave circuit containing a receive/transmit channel and a local oscillator. Modern high resolution screen printing techniques make cost efficient manufacturing of circuit carriers possible. This enables the penetration into the consumer market.

Usually a set of electrical, mechanical and thermal properties is required to realise such circuits. Standard thick film technology cannot provide a viable solution. Low Temperature Cofired Ceramics (LTCC) however, can fulfil all requirements necessary. The LTCC substrate can even be used as the bottom of the device housing. RF-feed throughs with non-galvanic interconnections to the antenna and electrical connections to the digital control board are integral parts of the multilayer package. In order to allow cooling of power circuits LTCC can be provided with thermal vias or cavities decreasing the thermal resistance to the heat sink. Fig. 1 shows a demonstrator for a 28 GHz LMDS based on LTCC.

The MMICs require decoupling capacitors for operation in the direct vicinity. These capacitors are usually wire-bonded disc capacitors of the MIM-type. Components and their assembly add considerable costs to the electronic module. It would therefore be desirable to integrate these capacitors in LTCC with reasonable effort.

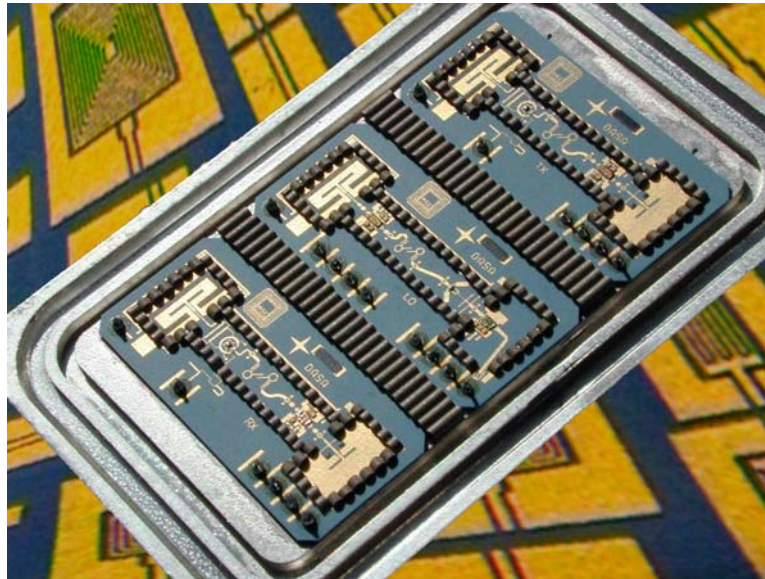


Fig. 1: LMDS Modul for 28 GHz (Design: EADS Deutschland GmbH)

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 mm^2). An increase of this value can only be achieved by either reducing the distance between the electrodes or increasing the permittivity.

$$C = \epsilon_0 \cdot \epsilon_r \cdot \frac{A}{d} \quad (\text{Eq. 1})$$

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. 3a)
- c) Filling of holes with high-k-material (Fig. 3b)
- d) Locally printing high-k-paste (Fig. 3c)

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. 4).

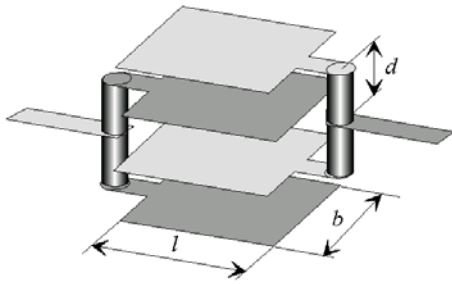


Fig. 2: LTCC multilayer capacitor

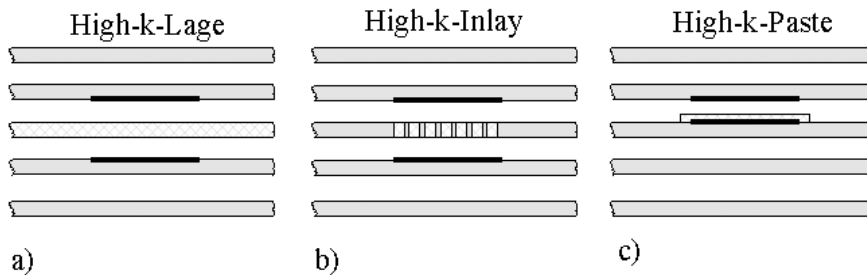


Fig. 3: Methods to increase the density of capacitance

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

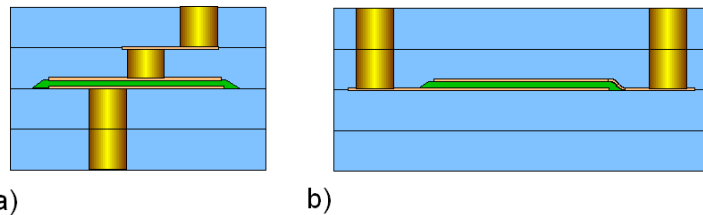


Fig. 4: Contact solutions for plate capacitors a) central b) peripheral

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. In addition, a second high-k-paste (DP5516) developed for thick film capacitors has been considered as a candidate to obtain even a higher density of capacitance. However, this paste is not a recommendation from the paste supplier.

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 aller Lagen

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, (passivation) the cofire solution can be obtained with a minimum effort.

No.	High-k-Mat.	Electrode material	k-value [1 MHz]	tan δ	class	Density of cap. pF/mm ²	Area for 50pF
01	5674	Ag (tbd)	60 – 80	<0.008	X7P	18	2.8mm ²
02	5516	PtAg	1200-1500	<0.03	X7S	260	0.2mm ²

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 independent 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.

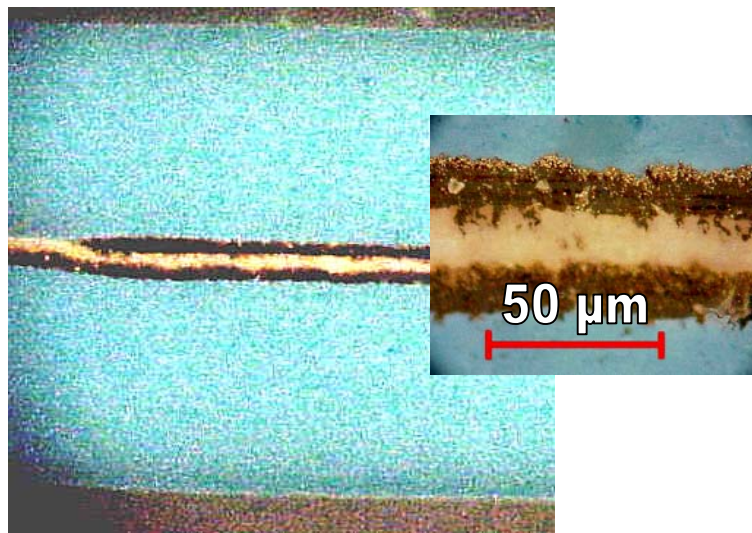


Fig. 5: Cross section of a 4-layer structure of 951A2 with an embedded capacitor

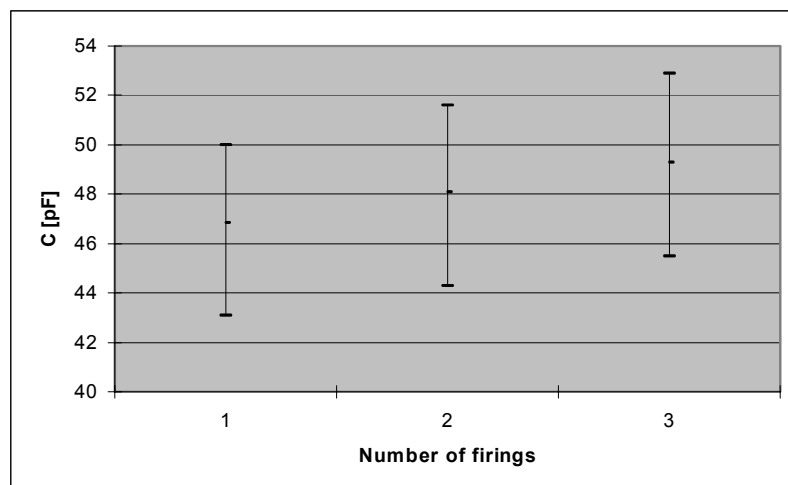


Fig. 6: Influence of the number of firings on the capacitance (min,mean,max for Ag-paste A)

Paste B, a fritless Ag-paste showed less interactions with the high-k-dielectrics in general. However, in combination with the 5516-paste from firing to firing, intermittent opens were detected. Fig. 7 shows a cross section of such a capacitor on the edge of the dielectrics. The delamination has caused opens in the connection to

the plate in the peripheral design used for this test (Fig. 4b). A possible reason for the delamination could be the strong shrinkage mismatch between the tapes and the capacitor paste. This effect became visible by measuring the overall shrinkage of the test coupon. The high load of the capacitor paste (about 50% coverage) reduced the shrinkage from 12.8% (unmetallised) to 10.8%. Therefore, this paste was not considered anymore.

Fig. 7: Cross section showing the edge of the capacitor (electrodes not visible) made of 5516



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. 8).

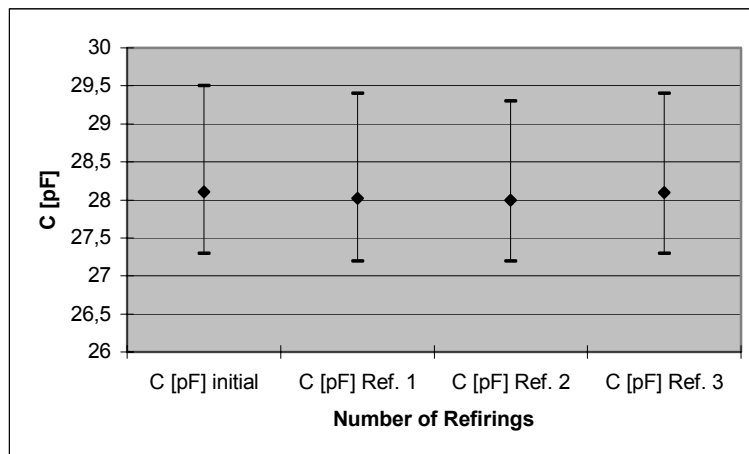


Fig. 8: Stability of capacitance vs. refirings

Qualification of this system was performed on a new test structure suitable for various test conditions. Fig. 9 shows the qualification test pattern. Three capacitors with different plate areas are connected in parallel (1x1mm², 2x2mm², 4x4mm²). 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/mm². 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.

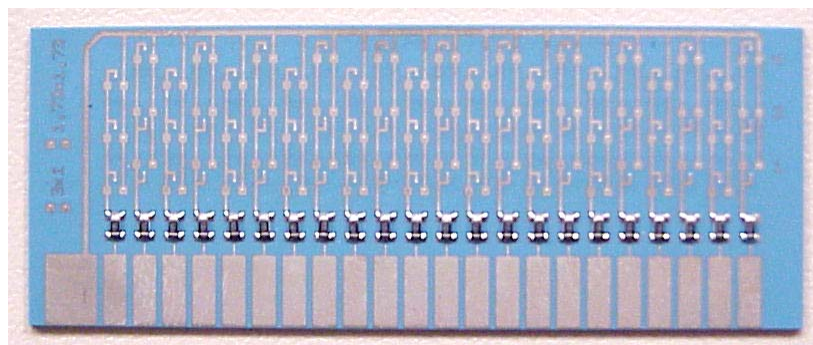


Fig. 9: Qualification test coupon

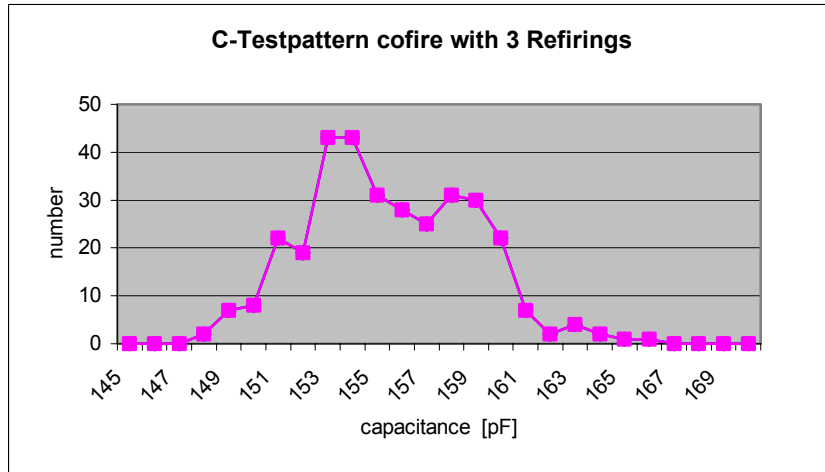


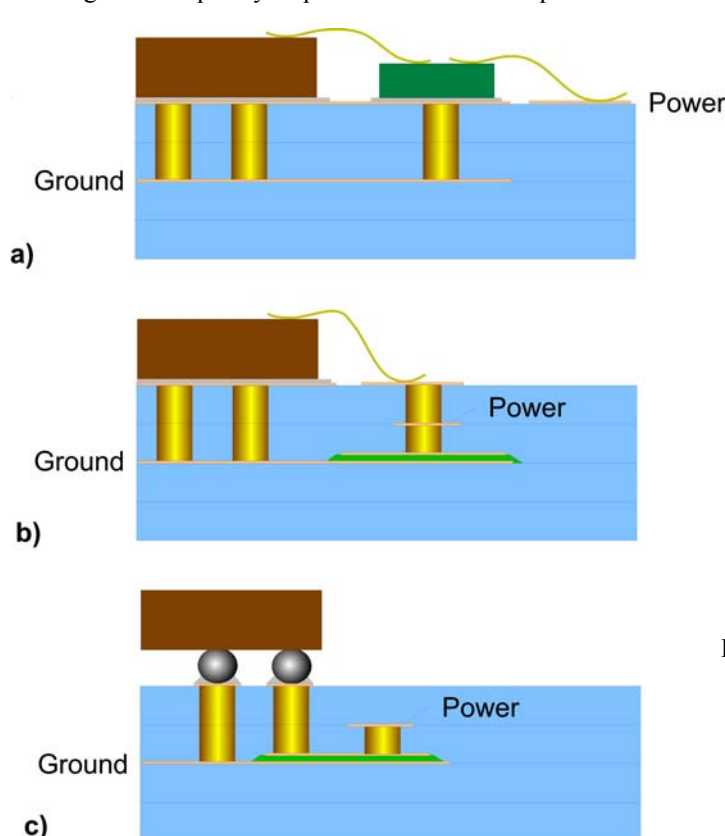
Fig. 10: Distribution of capacitance values

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. 11a. Two wire bonds are necessary to connect the MMIC. A possible approach with an embedded capacitor is shown in Fig. 11b. 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.11c). 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. A further test coupon was designed to evaluate their rf-behaviour. It could be demonstrated that the via connection to the upper plate has a considerable influence on the self resonant frequency. Fig. 12 shows measurement results of forward transmission parameter S21 for two 50 pF capacitors. 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: Arrangement of decoupling capacitors in microwave applications
a) traditional (chip & wire)
b) embedded capacitor + chip & wire,
c) embedded capacitor + FlipChip

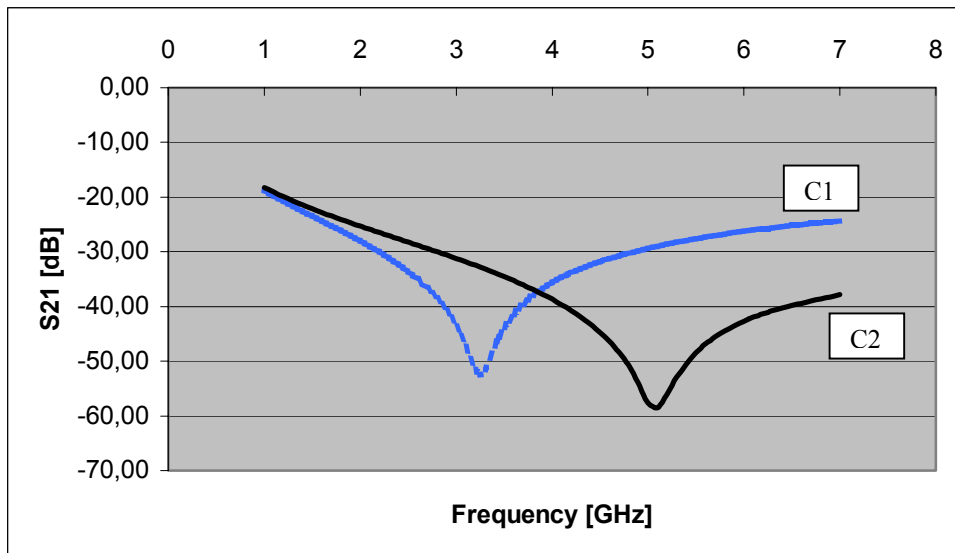


Fig. 12: Transmission behaviour of embedded capacitors with single (C1) and double (C2) via connections to the surface (shunt capacitor)

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 authors would like to thank their project partners at EADS Deutschland GmbH for their support in designing and measuring the rf-test structures. 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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