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RESEARCH ARTICLE

Embedded thick-film resistors applied in low temperature co-fired ceramic circuit substrates

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Abstract

The materials that are used to create low temperature co-fired ceramics (LTCC) circuits (produced from green tape and various pastes) can be processed by the equipment of the conventional thick-film technology (screen printing machine, drying and burning ovens). The equipment needed to produce multilayer boards (sinter press, tools, punching machine or Nd-YAG laser) can be purchased with a little investment. At the same time the high temperature co-fired ceramics (HTCC) technology requires completely new equipment, so the changeover is harder and more expensive. An LTCC test-circuit was designed and realized by using the thick-film technology equipment at the Department of Electronics Technology, BME. The surface and embedded resistors were made from thick-film paste. In the course of the realization and with circuit measurements it could be determined what have to be considered at the pre-calculation of the resistor values.

Keywords

LTCC manufacturing · thick-film · embedded resistor · glass ceramics

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1 Introduction

Nowadays the integration and miniaturization of passive circuits have lagged significantly in developments in electronic circuits.

There was a growing need of a technology, where – as in the HTCC (High Temperature Co-fired Ceramics) technology – multilayer routings and ceramic structures could be made, but at the same time the equipment of thick-film technology could be used for production. LTCC technology evolved from HTCC technology combined the advantageous features of thick-film technology. The aim was to produce a low loss, high operational speed and highly integrated carrier with the equipment of thick-film RC circuits. That is how the LTCC (Low Temperature Co-fired Ceramics) technology came into existence.

Since the mid 1990s LTCC have successfully entered the market. The LTCC technology has provided a much needed advance in the miniaturization of devices, however materials used in the past required firing temperatures that were too high to allow the use of highly conductive and low loss materials essential for superior performance. In addition, a serial processing was required in the circuit construction, resulting in long manufacturing times. Hence LTCC materials found limited applications. In the last few years the increase in the level of functions required of wireless communications has necessitated the use of higher frequency ranges. Also demands of consumers for faster, smaller, and cheaper communication devices have put pressure on the wireless communications market to integrate passive elements and resulted in significant advances in manufacturing and properties of 3D LTCC circuits. All layers can be now processed in parallel, reducing the production cost and time [1, 2].

Currently, thick film printing is still the most commonly used technique to pattern LTCC substrates. Thick film printing is a well-established technology that is suitable for high volume production at relatively low cost.

The base materials of the green tape (raw ceramic sheet) are ~45% aluminium-trioxid (Al_2O_3); ~40% cordierite ($2MgO_2$-Al_2O_3-$5SiO_2$), or MgO mixed with SiO_2 and ~15% Pb_2O_5 and Ba_2O_3 additives, in other words the recrystallized glass and additives have appeared along ceramic dust. These materials have

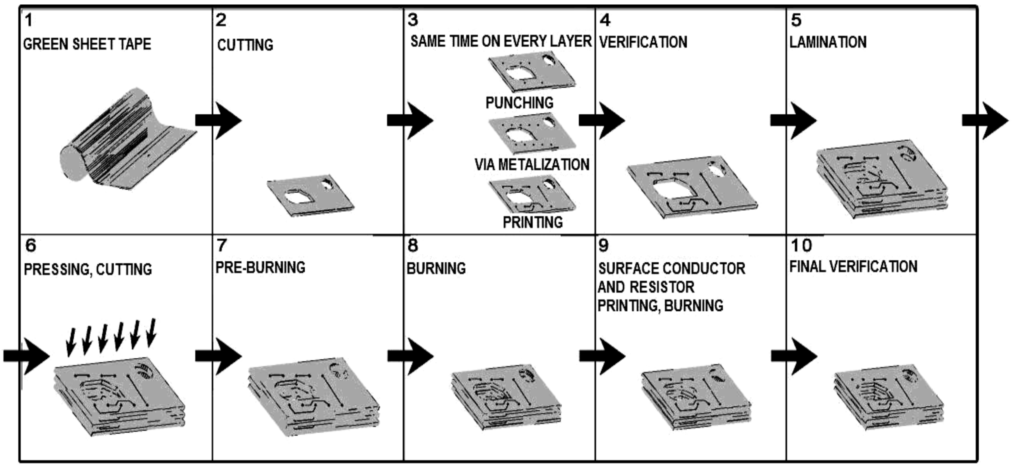


Fig. 1. Main steps of LTCC manufacturing [6]

greater permittivity compared to other organic materials. The ingredients containing glass are responsible for the density of the substrate after co-firing. Too little glass causes reduction of the density, too much glass results in bubble-formation in the course of firing organic materials.

The low firing temperature of the glass ceramics allows the construction of conductive materials (Au; Ag; PdAg; CuO), resistive and dielectric composition into embedded layers. The inorganic ingredients of the compositions dissolve into the green sheet in a sort in the course of firing and the green sheet shrinks. The manufacturers fit their compositions to the thermal expansion of their own green sheets, so at sintering they shrink together.

LTCC allow three-dimensional circuits to be constructed within a ceramic block that enables burying of passive elements: resistors; inductors and capacitors; in addition it is possible to create thick-film circuits on their surface. The process flow is similar to the manufacturing technology of hybrid integrated RC circuits, the equipment used for thick-film process can be used for LTCC production after minor modifications. Fig. 1 shows the main steps of the LTCC manufacturing, Fig. 2 shows the structure of a complex circuit realized with the technology [3–5].

The LTCC substrate can be fired at a relative low temperature (T≈850 ˚C) in an oxygen-rich environment due to low alkali glass dust, so thick-film pastes and materials can be used that are not applicable to HTCC boards because of the high firing temperature. The manufacturing of LTCC substrate is almost equal to manufacturing of thick-film substrate and the changeover does not need a huge investment. Unlike in the thick-film technology – where the different layers have to be printed and fired after each other – the LTCC technology allows all of the layers to be processed at the same time before lamination. Pastes using to LTCC technology are usually colloidal structures and consist of three main components:

– Functional phase dust
– Dust using adhesives: glass (pl. borosilicate-glass) or metal-oxide
– Organic compound adapting pastes to screen-printing (dissolvent and organic adhesives such as terpineol and texanol) [8]

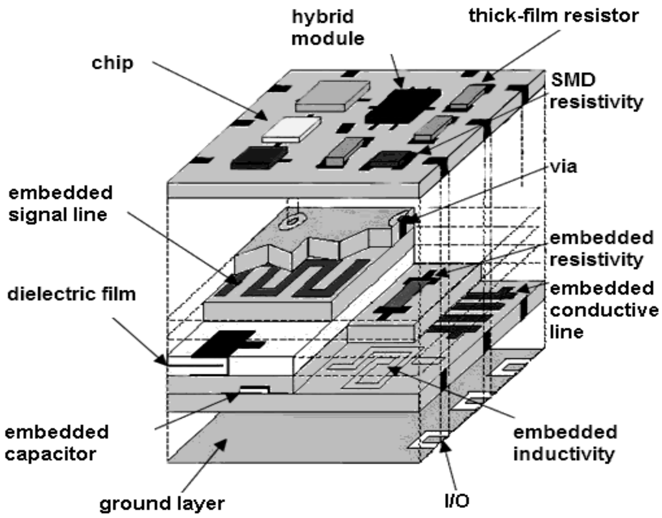


Fig. 2. Complex LTCC circuit structure [7]

The main requirements to embedded resistors in LTCC technology are electrical and mechanical parameters. The parameters above of the resistive layers on green sheet depend on the sort of printing process, and drying and firing profile.

Conductive materials in resistive paste

At an early stage pastes were made of mostly the mixture of Pd and Ag. In this case the heat profile had to be kept accurate otherwise the ratio of phases (specific resistivity as well) seriously changed. The specific resistivity of Pd-Ag resistive pastes in a mildly reduced atmosphere changes too, the resistance-range is limited and the thermal coefficient of film resistors is rather high.

Ruthenium oxide based pastes took out Pd-Ag functional phase pastes. The oxides of ruthenium have semiconductive characteristics, however the thermal coefficient is positive which refers to metallic conduction. In resistive compositions NiCr, CrSi, NiP, TaN are used beyond RuO_2.

Along the common resistive compositions a paste based on Pyrochlore (DuPont) appeared, it is more stable and has lower ESD sensitivity than RuO_2[8, 9]. Table 1. shows the main parameters of inorganic conductive materials of LTCC resistivity.

Resistive compositions

The resistive compositions developed for the LTCC technology are produced in decadic scales of its sheet resistance (1 Ω, 10 Ω, …, 100 kΩ, 1 MΩ). Often there is a need of an intermediary value. This can be achieved by the appropriate mixture of the consecutive composite decades. If the composition sequence is made by two different materials, the manufacturer has to tell the margin of the two materials to avoid the mixture of them.

There are some resistive compositions that cannot be fired in an oxygen-rich environment (Table 1). Currently DuPont and Ferro deal with making resistive compositions for LTCC technology.

2 Designing and implementing LTCC circuit containing buried resistors with thick-film equipment

The equipment available for the technological process is the following:

- THEME product, TES/S25 type screen printing automata device
- Collin P200E press
- DEK 248 type stencil printer
- AVIA 4500-355 Coherent product laser

Before the topological design the following technical parameters have to be fixed: the size of the circuit, the placing of the positioning apertures and the preliminary computing of the film resistance. First, an alignment device was designed, which is suitable to aligning the green glass-ceramic sheets in the course of pressing. Fig. 3 shows the dimensions of the device.

The material of the alignment device is Al-Si-Mg hard alloy, which is easy to work. The surface of the plates was polished in order to avoid the damage of the raw glass-ceramic substrate during the lamination of the aligned green sheets. The two plates were drilled together, 8 pieces of 15mm height and 3mm diameter taps were fixed in the holes of either plate. For the correct positioning markings were scratched in both plates.

Four distinct test circuits were placed on a raw substrate of 60.5×60.5 mm dimensions. The designed structure has three layers: the upper contains the test points and the middle layer contains the buried resistors. The bottom layer is a so-called sacrificed layer which has significance in the process of laminating and co-firing.

2.1 Planning of resistors

After choosing a paste with the adequate sheet resistance, the value of the resistor is determined by the shape of the composition carried up (the width, the length and the thickness). In general, the paste properties are specified for a layer-thickness of 18-25 μm. If this thickness is kept, the value of the resistance can be estimated with certain tolerance after co-firing.

In general, in the course of planning the resistance values are designed below their final desired value of about 40-70%, because increasing the value of the film resistance is much easier than decreasing it with subsequent adjustment. The value of the buried resistance can be calculated with scheme (1):

$$R = \delta \cdot \frac{l}{d \cdot \upsilon} = R_{\mathrm{sq}} \cdot \frac{l}{d}[\mathrm{ohm}] \tag{1}$$

where δ is the specific resistance [ohm·mm]; l is the length of the paste, [mm]; d is the paste width, [mm]; υ is the paste thickness and $R_{sq} = \delta/\upsilon$ is the sheet resistance. Another important parameter of the film resistors is the thermal coefficient (TCE):

$$TCE = \frac{1}{R} \cdot \frac{dR}{dT}[1/^{o}\mathrm{C}], \tag{2}$$

where R is the resistance value at 25˚C, dR is the difference between the resistance values measured at the highest and the lowest temperature, and dT is the difference of the measuring temperatures. For the expected correct functioning of the LTCC substrates, frequently a small or a given value of TCE in the R network is necessary. The TCE values of the film resistances are determined by the heat-dilatation of the layer and substrate. The dependence of the resistance value by the potential is expressed with potential factor (VK):

$$VK = \frac{1}{R} \cdot \frac{dR}{dU}[1/\mathrm{V}], \tag{3}$$

where R is the resistance value at a given potential, dR is the difference between the resistance values measured at the highest and the lowest potential, and dU is the difference of the measuring potentials. One important functional parameter is the stability of the resistors, which gives the fluctuation of the resistance with time (%). The dependence of this factor with the time is nonlinear, because this fluctuation caused by the oxidation and the changes in the structure of the layers.

One characteristic of the layer resistors is the power density (power per surface unit), what determines the temperature of the layer for a given substrate, then it can decisively influence the stability of the resistors. If the power parameters are known (Eq. (1)) the longer size of the resistors is determined with Eq. (4), while the shortest size with Eq. (5):

$$l = \sqrt{\frac{P \cdot Ri}{q \cdot R_{sq}}}[\mathrm{mm}], \tag{4}$$

$$d = \frac{d \cdot R_{sq}}{Ri}[\mathrm{mm}], \tag{5}$$

$$\frac{P}{P_f} = l \cdot d, \tag{6}$$

Tab. 1. Inorganic conductive materials of LTCC resistivity [10]

Material	Burning atmosphere	Resistivity/sq; Resistivity/sq; [ohm]	Thermal Thermal coefficient [ppm/°C]	Specific resistivity of conductors; (25 °C) [ohm]
Ag/Pd(PdO)	Air	1 – 1 M	±250 – ±300	$4{\cdot}10^{-5}$
RuO_2; IrO_2	Air	10 – 10 M	±50 – ±300	$4{\cdot}10^{-5}$
$Pb_2Ru_2O_6$; $SrRuO_3$; $Bi_2Ru_2O_7$	Air	10 – 1 M	±50 – ±300	$2.3{\cdot}10^{-2}$
LaB_6	Nitrogen	10 – 10 K	±100	$1.7{\cdot}10^{-5}$
SnO_2	Nitrogen	5 – 1 M	±250	n.a.

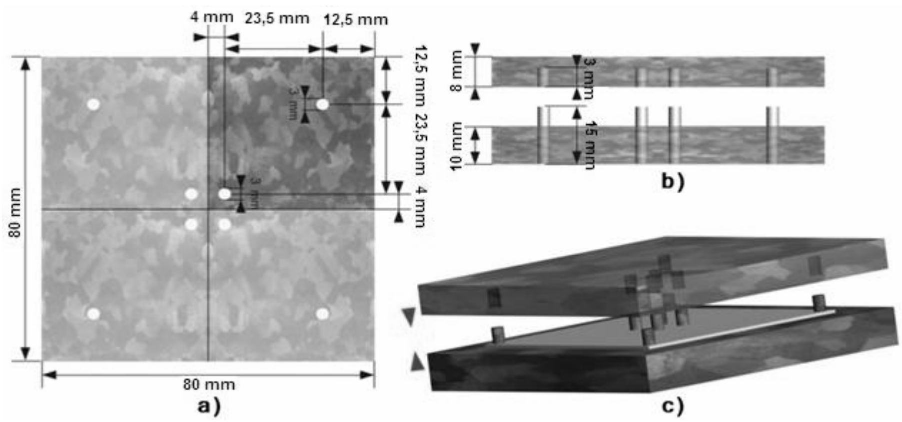


Fig. 3. Alignment device a. plan; b. side-view; c. perspective

where d is the shorter size of the resistor, l is the longer size, P is the dissipated power of the resistor at environment temperature, P_f is the specific power, R_i is the unadjusted value of the resistance, R_{sq} is the sheet resistance, q is the surface power density at the maximal environment temperature. If the values of l or d are below the technical minimum (in case of screen printing this minimum is 200 μm), these values have to be increased at least to this minimum, and after it the other parameter too. For size greater than 5 mm, the morphology of the substrate is important too. The dimensions of the resistor are optimal, if l/d is near 1, and the shortest size is between 1 mm and 3 mm. The minimal dimensions depend on thermal considerations and the carrying-up technology of the layers [8, 11, 12].

DuPont 2031 paste with sheet resistance of 1 kohm was chosen. The recommended thickness of the paste after firing is 27 μm. The manufacturer recommends Ag/Pt or Ag/Pd conducting paste to decrease the undesirable reactions which can occur at overlapping. The designed film resistances have simple rectangle and cylindrical shapes. The resistance values were calculated previously providing a fixed film thickness of 27 μm. In case of rectangle resistors l/d was kept between 0.2 and 0.5, while in case of the cylindrical resistors this interval was exceeded. The scale of post adjustment can be much bigger for the cylindrical resistors than the rectangle resistors. The unadjusted values of the cylindrical resistors were calculated using expression (7):

$$\frac{R}{R_{sq}} = \frac{l-l_t}{d} + \frac{l_t}{d+d_t} + \frac{2}{\pi}\cdot\left[\frac{2d\cdot(d+d_t)+d_t^2}{d\cdot(d+d_t)}\cdot\ln\left(1+2\frac{d}{d_t}\right) - 2\ln\frac{4d\cdot(d+d_t)}{d_t\cdot(2d+d_t)}\right] \quad (7)$$

where l is the longer size of the rectangle resistor without cylinder, d is the shortest size of the same, l_t is the height of the cylindrical part, d_t is width of the cylindrical part. The third component of the above formula gives the variation of the number of effective squares caused by the inhomogeneous current distribution caused by size jumping.

Trimmed intervals were calculated for all resistor shapes. In case of the cylindrical resistors the maximal number of the equivalent squares at the M-shaped cutting was calculated. In case of the Y-shaped cutting of the rectangle resistor equations (8) and (9) belong to Fig. 5 were used, where the cutting size is maximized to 2/3 of the width of layer. Fig. 4 shows the calculations in detail [8].

$$R = R_n\cdot\frac{\omega_L}{\pi} = \frac{R_n}{\pi}\cdot \operatorname{arch}\frac{2\,\mathrm{ch}(\pi\cdot L/d)+1-\cos(\pi\cdot b/d)}{1+\cos(\pi\cdot b/d)} \quad (8)$$

$$\Delta N = \frac{1}{\pi}\cdot\operatorname{arch}\frac{2\,\mathrm{ch}(\pi\cdot L/d)+1-\cos(\pi\cdot b/d)}{1+\cos(\pi\cdot b/d)} - \frac{L}{d} \quad (9)$$

The disadvantage of perpendicular trimming is that longer trimming causes extreme resistance sensitivity. In case of laser

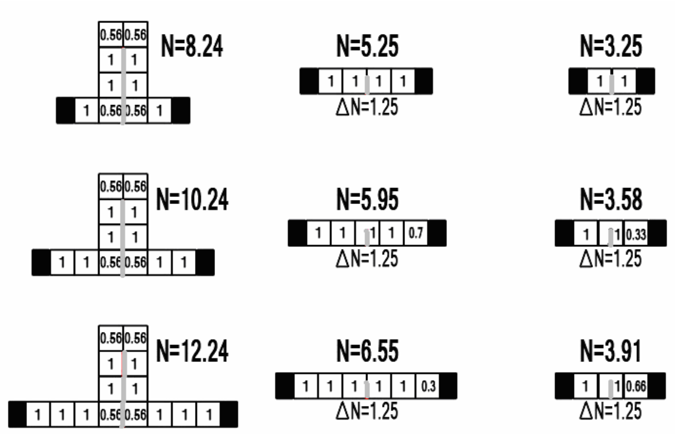


Fig. 4. The equivalent square numbers of the trimmed film resistors

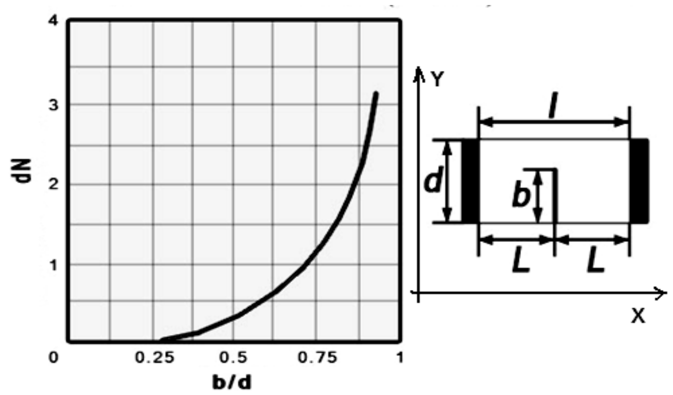


Fig. 5. Change of sheet resistance in the function of the parameters of laser trimming

trimming, the value of resistance can only be increased, and the tolerance is below ±0.25%. The laser beam damages the material in addition the channel current is constricted. This fact is important at the reliability analysis.

2.2 Making a test circuit

The unburnt glass-ceramics worked by laser

The intended topology was created on DuPont 951 type green glass-ceramic substrate. The next phase of the implementation was parceling these unburnt sheets and the punching of the necessary positioning holes, windows and via apertures. The green sheet was punched with AVIA 4500-355 Coherent product frequency-tripled Nd:Yag laser [13]. Before working the test circuit, a test punching was made at diverse adjustments. In Fig. 6 there are 180 test-punching with 200 μm diameter examined the shape and the edge of these pieces by an optical microscope.

The parameters of the laser during the test cutting are the following:

– Repetition frequency (10 kHz, 50 kHz, 100 kHz)

– Drift speed of the beam (10 mm/s, 100 mm/s, 1000 mm/s)

– Repetition number of the impulse (1×…20×)

The exaggeratedly high frequency of the impulse causes considerable melting of the glass-dust in the LTCC substrate, on the

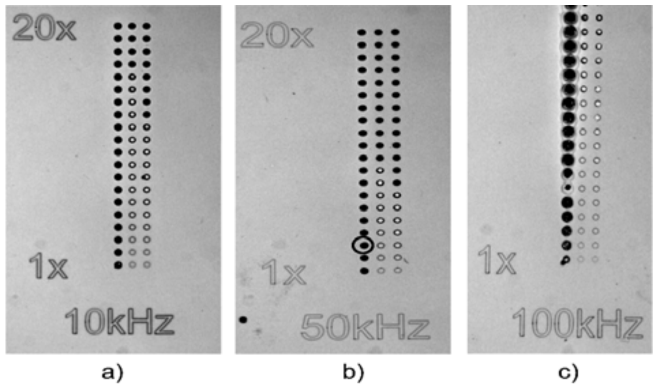


Fig. 6. Vias made by laser at diverse adjustments
a. 10 kHz repetition frequency b. 50 kHz repetition frequency c. 100 kHz repetition frequency

other hand the fast drift of the beam do not cut deep enough in the material. On Fig. 6. in the left row the drift speed was 10 mm/s, in the middle row was 100 mm/s and in the right row, the speed was 1000 mm/s. From 180 holes only 73 were adequate. (The hole is circle, the laser totally cut across the material, the roughness of the edge is within ±10 μm and the melted glass-dust does not decrease the diameter of the hole.) The good holes are prepared with the following parameters (Fig. 7):

– Repetition frequency: 50 kHz

– Drift speed of the beam: 10 mm/s

– Repetition number of the impulse: 3

– Power: 4.2 w

– Thermal track parameter: 3200 K

Experiences show that using laser, the top and the bottom side diameters of the holes are distinct (the difference is ∼50 μm). This difference arises from the focusing of laser. (This fact is important because in case of ∼100 μm diameters the bottom diameter is only 50 μm) [14]. The green sheets were fixed to the work-table with metal frame. The polyester of the substrate was not removed, because it protects the substrate against the deposition of the arising fine impurities during the working. Fig. 8 shows the state of the sheets after the working.

The sheet labeled 1 is the upper layer. Via connections are on this layer between the pads and the interior resistance (and conducting) layers, the positioning and trimming apertures. The buried resistors and wires will be printed on the sheet labeled 2. On this layer and on the sacrificed (labeled 3) layer only the positioning holes had to be punched. Fig. 7 shows the test holes of adequate quality.

The eight positioning holes are of 3 mm diameter, the diameters of the vias are of 600 μm, while the windows size is 6.2×4.2 mm. It was important, that the width of the window was at least the width of the parallel connected tophat resistors and the length of the window was at least the longer size of the film resistor (the maximal width is 6 mm, the longer resistor is 4 mm).

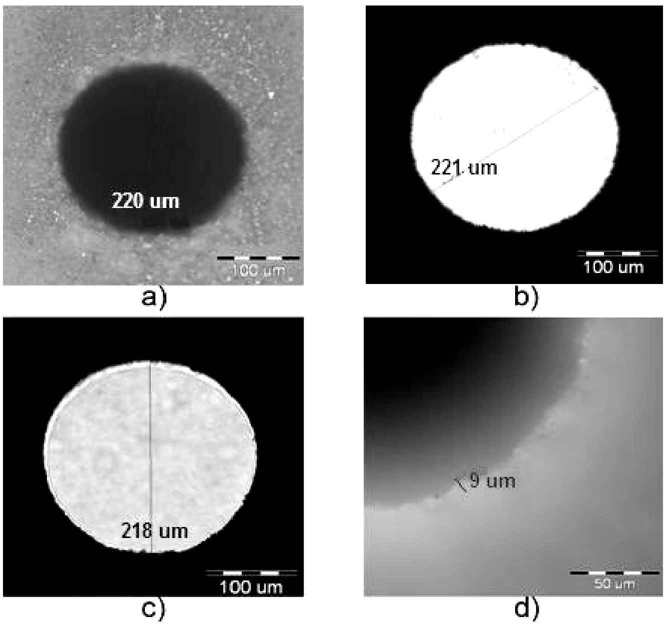


Fig. 7. Results of laser punching with proper parameters a.) Plan of 200 μm diameter hole, lighted from above; b.) Plan of the same hole, lighted from under; c.) worm's-eye view of 200 μm hole, lighted from under; d.) Raggedness of the edge of 200 μm diameter hole

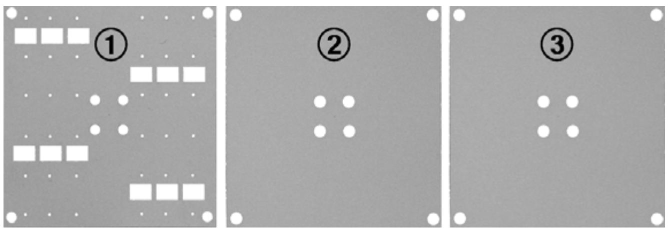


Fig. 8. Plan of green sheets after laser punching

Via filling with stencil printing

The next technological step was via filling. In this process via holes formed in the green sheet are filled with the conductor. In general, a squeegee is used to fill the holes with the conductor. It is desirable to fill via holes in the green sheet uniformly with the conductor. DEK 248 stencil printer was used for via filling and the DuPont 6141 paste. In the process of via filling it is desirable to take into account the squeegee pressure, the squeegee speed, the squeegee angle and the squeegee-substrate distance. In Table 2 the LTCC technological prescriptions of printing, our best adjustments and the maximal parameters of the DEK 248 stencil printer were compared.

The third column of the table shows that the original squeegee angle does not conform to the technological prescription of the angle consequently the squeegee had to be modified. Using the planning files, apertures were made on the stencil mask with the Nd:Yag laser, nevertheless my apertures were 20% greater than the apertures of the substrate, therefore the imprint became greater and in this way much more paste got through the apertures.

On the vacuum table of the DEK 248 stencil printer there are 6 air-vacuum tubes, by which the paste satisfactorily fills the via holes. On the test circuit there are 36 holes to fill, so the suction effect of the vacuum tubes must be concentrated to these holes. Hence, a vacuum table shown in the Fig. 9 was created.

The bottom FR4 isolating sheet contains 6 holes, which fit in the 6 tubes of the stencil table. On the table there are two FR4 isolating frames. The three FR4 substrates were attached together and the inner part was filled with cellulose without threads in order to avoid arising dent in the sieve and the substrate by the vacuum. The texture of the sieve was previously stretched on the upper frame [16]. The substrate was fixed to the table with special glue (3M 8952). The glue had to be thin, not too strong but hard enough to keep the sheet at its place. After some attempt, with the above devices the holes were filled, and after it the substrate was put into the stove according to the prescriptions of the paste. Fig. 10 shows the filled via holes.

Printing the conducting and resistive layers

After the process of via filling, the next step in the LTCC technology is the printing of the conductive and resistive layers. For this, a screen printing machine used in thick-film technology was used for printing the wiring pattern on the green sheet.

Screen printing

The screen printing is a method in which a gap is set between the mask and the green sheet and when the squeegee passes over the mask, the conductive paste is pushed through the openings in the mask onto the green sheet. The squeegee pushes the paste through the openings of the mask so that the paste is applied to the green sheet. At the same time moving along the squeegee, the bolting-cloth is released from contact with the substrate. THIEME product TES/S25 type automata printer was used for screen printing.

The mask determines the surface shape and the thickness of the printed layer. Using the three films of topological plan an emulsion layer was carried up on the polyester sieve [16]. During screen printing the layers which are not actually needed were covered with glue. To forming masks SAAT product direct emulsion was used. The emulsion over mesh (EOM) was 20 μm. The mesh number of the texture was 305. The thread thickness of the polyester texture was $\sim$35 μm, while the squared opening size was about 42 μm$\times$42 μm. The thickness of the sieve together with the emulsion was averagely 84 μm. Thickness of the printed layer is hardly influenced by the thickness of the mask. This thickness was calculated according to Fig. 11. The figure shows, that in case of polyester threads intersect each other have to calculate not with $2{\cdot}d$, but with $1.6{\cdot}d$, due to the deformation of polyester texture. The gap between the used direct emulsion and the substrate was 20 μm (EOM, in the figure "e"), and the emulsion thickness on the other side of the mask was $h - 1.6{\cdot}d - e = 8$ μm. The theoretical thickness is: $a{\cdot}d + e = 76$ μm.

Tab. 2. Parameters of stencil printing

	Recommended setup	Own setup	DEK 248 printer
Squeegee pressure	0.17 kg/cm	14 kg (0.46 kg/cm)	0 – 15 kg
Aperture-carrier distance	$< 150\mu$m	0 (contact printing)	0 – 1000 μm
Squeegee press-angle	$<$ 45 degrees	$\sim$ 40 degrees	90 - 60 degrees
Printing speed	50 – 150 mm/s	50 mm/s	7 – 70 mm/s

Fig. 9. Structure of vacuum table

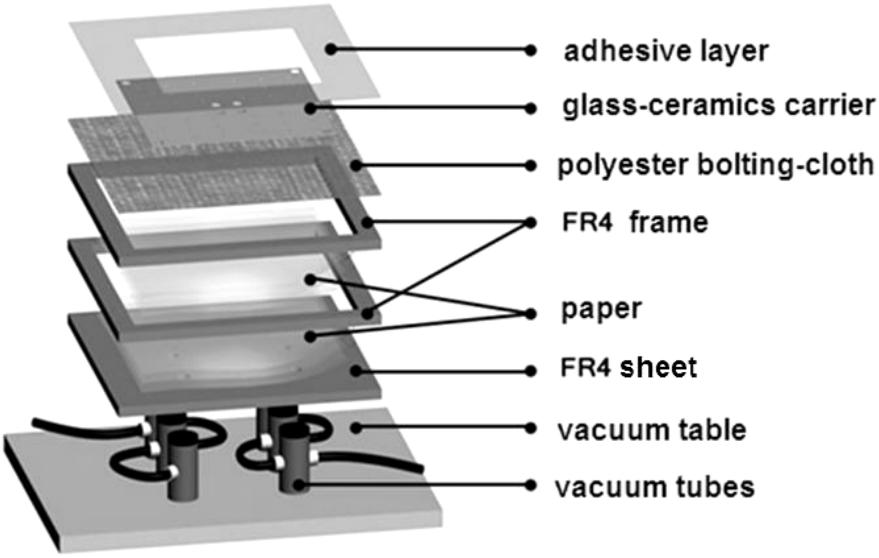
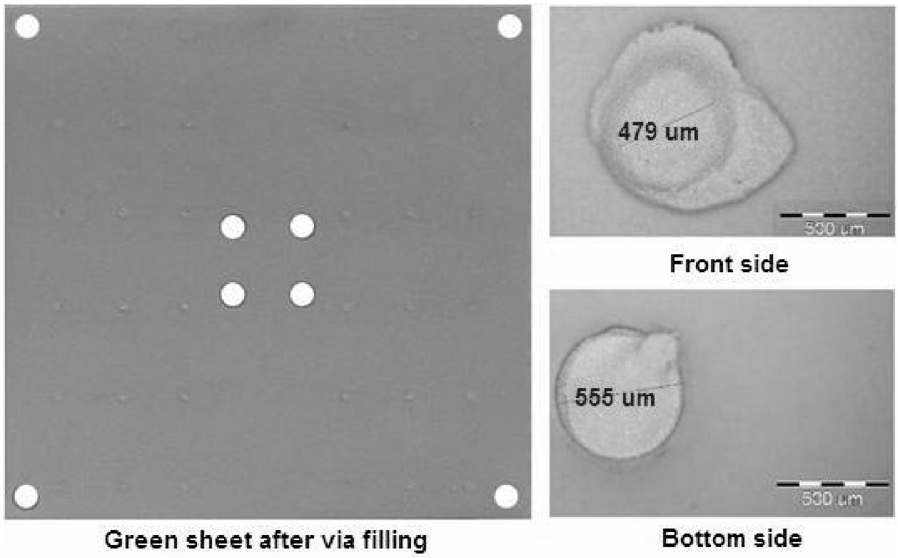


Fig. 10. Filled via holes on testboard



Printing

In the LTCC technology the green glass-ceramic substrates are spooled and in this form are transported and stored. During the fabrication, the glass-ceramic mixture is carried up on the thin ($\sim$30 μm) polyester foil. This foil protects the substrate against rupture before using it. Moreover, the foiled side of the raw substrate is less rough and impure than the free side, because during the fabrication the glass-ceramic mixture is ductile about 2 weeks and thus in the adequate position the material filled totally the gap between it and the polyester foil [17]. Before screen printing the foil from the substrate was removed and was put on the vacuum table of the screen printer. The margins of the substrate were fixed with adhesive tape. The positioning was done manually, with the help of the 16 positioning symbols and the 8 positioning holes each of 3 mm diameter. Table 3 illustrates the adjustments suggested by the literature, the best adjustments found and the maximal parameters of the device. After printing the substrate was dried for 10 minutes in the stove at 120°C temperature.

DuPont 6145 type conductive paste based on Ag was used for the test circuit. First, the conductive layer was printed (Fig. 8, 2nd substrate) on the middle layer, then – after drying it – the resistive layer was printed, which was followed again by a drying phase. The pad layer was printed on the substrate after laminating, because the process of laminating can damage the printed conductive material on the upper layer.

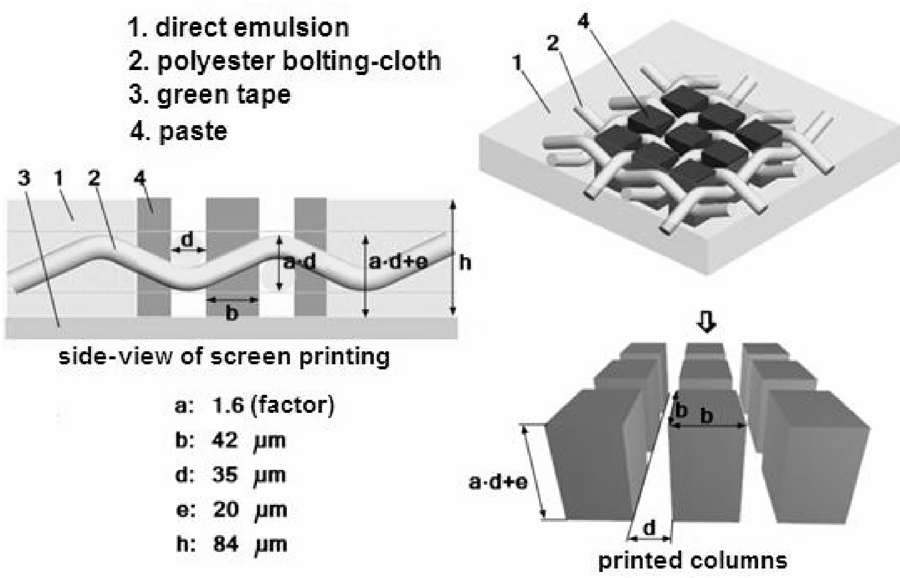


Fig. 11. Calculating of paste thickness from parameters of emulsion and bolting-cloth

Tab. 3. Parameters of screen printing

	LTCC technology	Own setup	TES/S25 printer
Squeegee pressure	0.17 kg/cm	3 bar	0-7 bar
Bolting-cloth-carrier distance	$<$ 1000 μm	800 μm	0-7000 μm
Squeegee press-angle	$\sim$ 60 degrees	$\sim$ 60 degrees	$\sim$ 60 degrees
Printing speed	50-150 mm/s	50 mm/s	10-300 mm/s

The thickness of the buried resistors was one of the important parameters, so the thickness of a single printing was examined by an optical microscope. Fig. 12a shows the printed conductive and resistive layers, while Fig. 12 b shows the printed pad layer on the upper layer.

On the vacuum table of the screen printer the positioning was helped by the positioning symbols on the polyester foil. After the printing of the conductive layer on the substrate, the positioning of the resistive layer was helped by 16 “x” positioning symbols. The positioning was precise, when the brown symbols of the conductive layer were totally covered by the black symbols of the resistive layer. The wiring patterns and resistive imprints were controlled by microscope.

Fig. 13a shows the imprints of the conductive and the resistive layer in the case of a cylindrical resistor. Because the viscosity and the content of the DuPont 2031 resistive paste (the black layer) differs from the DuPont 6145 conductive paste (the grey layer), consequently the printed layers differ too. The conductive paste distribution is uniform, whereas the resistive layer is not there. It can be seen in the enlarged parts: the resistive paste has ribbed margin, while the conductive paste has linear margin. During the printing process the paste with small viscosity produces blank regions at the crossings of the texture (this is the so-called pinhole effect).

Fig. 13b shows the thickness of the single printed conductive and resistive layers before laminating and co-firing. The thickness of the single printed conductive layer is 15 μm ($\pm$5 μm), while the average thickness of the resistive layer is 24 μm ($\pm$5 μm). These values differ from the calculated values, because practically the paste gets stuck in the texture of the sieve (the sort of stucking depends on the viscosity of the paste). The EOM value of the direct emulsion (20 μm) approaches better the real thickness, but this is not homogeneous on the total surface of the bolting-cloth.

The thickness of the resistive layer in case of single printed imprint was not thick enough, because during the laminating process the substrate is shrinking in the Z direction, and during the firing this process intensifies further. In the course of co-firing process the glass components of the substrate diffuse into the material of the resistor, which decrease also the real thickness of the resistive layer, and increases the value of the sheet resistance. For this reason, another test circuit was made which is similar to the original, the only difference is that after the first printing-drying phase another layer was printed on the resistive layer. In this way, the pinhole effect was eliminated and the thickness of the resistive layer was increased.

Another important effect is the deformation of geometry during the printing process. It can be seen on Fig. 14. The green rectangle indicates the aperture. In the course of printing the resistive layer, the surface of the substrate is not uniform due to the already printed conductive layer. The height of the bolting-cloth was adjusted to the substrate, but the conducting layer (because of its thickness) came nearer to the sieve. As a result of it, the resistive layer is defective above the conductive layer (1). As the squeegee passes over the conducting layer, it arrives at a cave of 15 μm depth, which can not be followed by neither the device

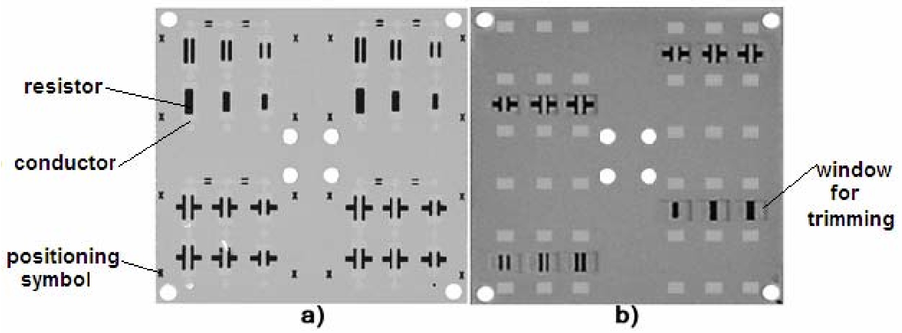


Fig. 12. Results of screen printing a. wiring and resistors on middle layer; b. pad layer on via holes of laminated structure

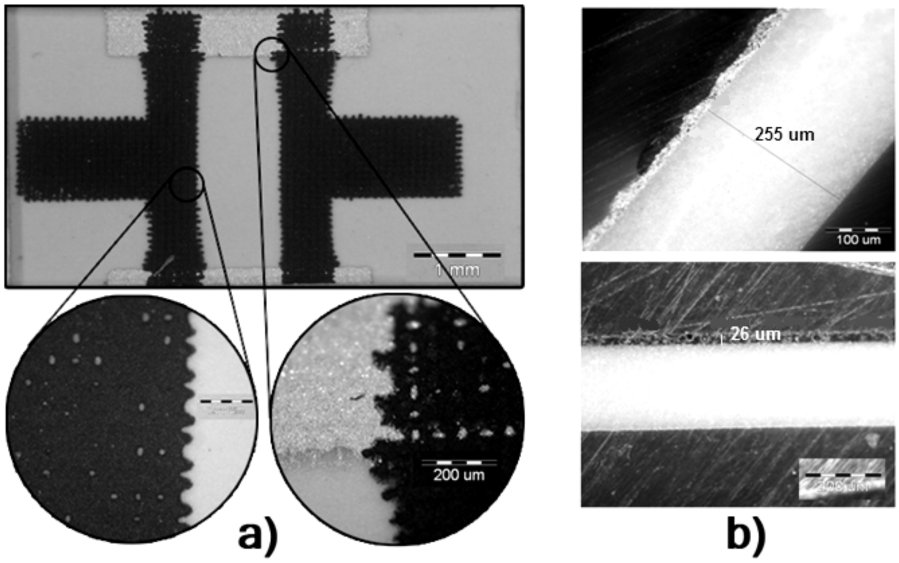


Fig. 13. Printing examined by microscope a. plan about the margins of the resistors; b. thickness of imprints measured in polished section

nor the bolting-cloth. In this place the paste fill the cave, but here the aperture do not contact the substrate, the filling will not be regular (2), the geometry get out of shape. The same thing happened when the squeegee approaches the conducting layer on the other side. The resistor width suited to the aperture can be carried out only by convenient distance ($>300\mu$m) from the ends of the resistor (3). The thickness of the layer resistors here will be suited to the adjustments, also.

Laminating

Collin product, P200E type, uniaxial press was used for lamination. The mechanically prepared and printed substrates were attached together before laminating with the alignment device. Fig. 15a shows that three layers of the measuring circuit were pressed: the 1st layer containing via holes, the 2nd layer with the resistors and wires and one sacrificed layer. The role of the last layer is to achieve the adequate thickness of the structure. The three layers, each of 250 μm thickness, are enough thick for, that during co-firing the substrate do not undulate in the height direction. It is important that during the aligning process, the green glass-ceramic does not contact the material of the alignment device. To achieve this, the protecting foil of the bottom sacrificed layer was not removed, while above the upper layer a polyester foil with adequate tap openings was put.

The plates of the device before laminating were heated at 70˚C at the pressure of 210 bar, because this is the prescribed value in the literature. Unfortunately, the value indicated by the manometer is not the direct real pressure of the plates. Before laminating the thickness of the aligned LTCC substrate was about 756 μm, which after laminating became 705 μm, that is a shrinkage of 6.74 % in the direction of the thickness. (The thickness was measured in 10 distinct places).

During lamination, the phenomenon of delamination can take place, which may have the following causes:

- Aligned substrates were not adequately cleaned
- Adhesion of the conducting and resistive layers to the substrate were not adequate
- Plates of the press were not parallel
- Jointing of the alignment device was not good.

One of the most characteristic mistakes – that could be observed during laminating – was under the upper layer of the trimming windows. This was caused by the fact that the contact of the substrate and the alignment device was only one-sided during pressing in this place. The solution of the problem is to use water-pillowed plates to pressing the substrate.

The laminated structure was checked by X-ray equipment. The positioning precision during the printing and the aligning process was acceptable (via holes were above the conducting layer). After laminating the pads were printed on the upper layer of the structure.

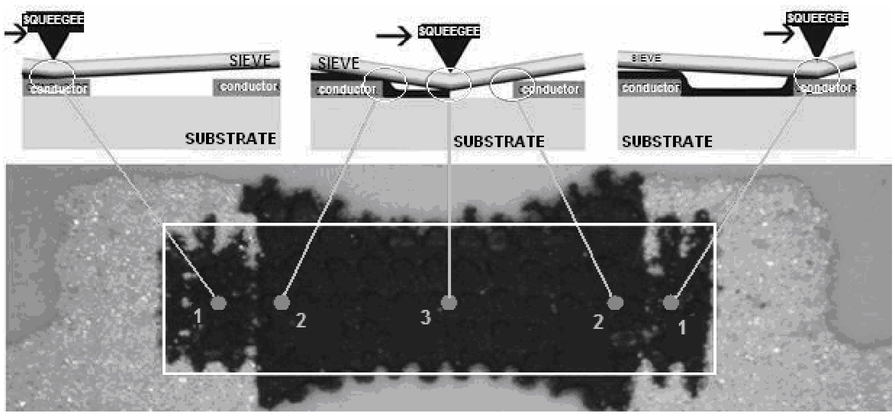


Fig. 14. Deformated rectangular film resistor with dimension of 200 x 1000 μm

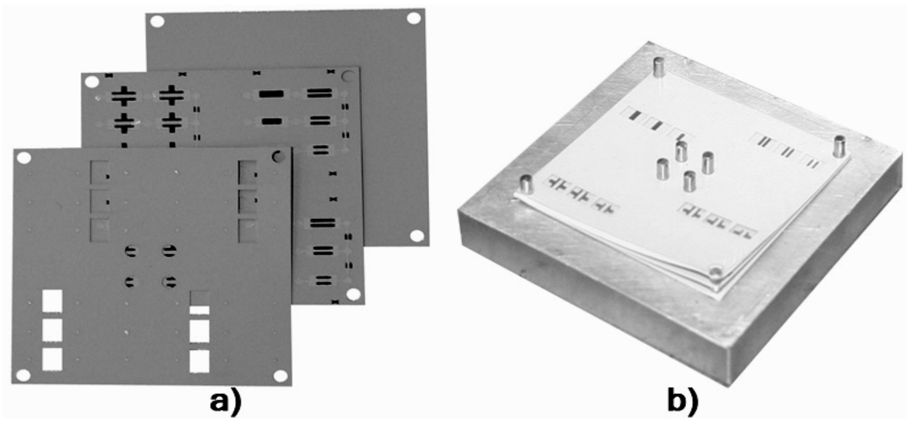


Fig. 15. Aligning a. layers before aligning; b. layers on alignment device

2.3 Co-firing

The last step of the technology was the co-firing of the substrate. During this process the organic compounds evaporate from the substrate, moreover the glass-matrix melts and converges, then the substrate shrinks and its structure solidifies. For the firing of the raw glass-ceramics Denkal 3-K/1160 type stove was used. The literature prescribed the following technological conditions:

– Plane and small unevenness firing surface

– Continuous controlling of the temperature

– Maximum 15˚C/min heating speed

Excluding the first condition, the other two parameters are satisfied by this stove. The controlling of the temperature was manual. Because the bottom of the stove is not uniform, a special (with melting point 1280˚C) ceramic plate of 15 cm$\times$20 cm size was used as firing surface. The temperature of the stove was measured with an external thermo-element, whose thermal point was fixed above the LTCC substrate.

For the DuPont Green tape 951 the prescribed heat profile suggests that in the 12th minute the temperature has to rise to 50˚C from the ambient value. It has to be followed by a 14˚C/min slanted heating period, which stops at 410˚C. Between 180. . . 415˚C the solvents and other organic components evaporate from the substrate, so adequate air flowing has to be guaranteed. In the next 20 minutes the temperature has to be kept between 410. . . 420˚C, followed a 9˚C/min slanted heating period, hence after 50 minutes the temperature achieves 850˚C. It is important to keep this precisely for 30 minutes, because at this temperature the glass is melting and the substrate gains his final size and structure. The last cooling down period was not kept, but there was not any negative consequence for this in the literature.

2.4 Post-cut by laser

After co-firing the test circuits were separated with laser (Fig. 16.). In this way, the circuits can be examined separately and a polished section was prepared for different investigations of the layer resistance.

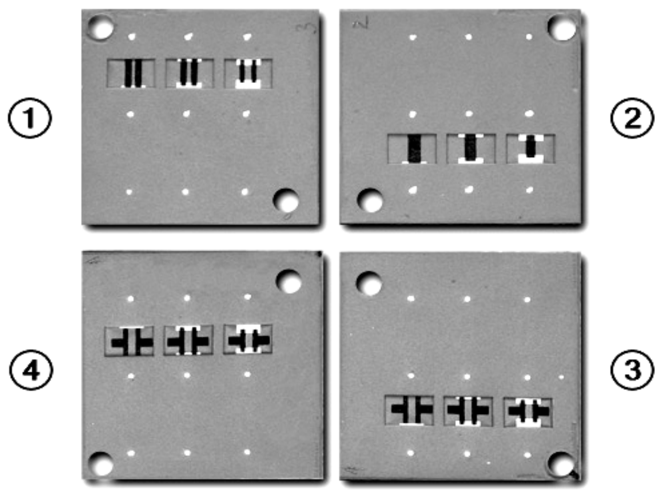


Fig. 16. Post-cutted test circuit

The parameters of the laser during the cutting of the co-fired substrate were the following:

– Repetition frequency: 10 kHz

– Drift speed of the beam: 200 mm/s

– Repetition number of the impulse: 250

– Pumping current: 100 %

– Thermal track parameter: 3200K.

Because the thickness of the co-fired substrate was 700 μm, it had to be cut in two steps. First, the focus of the laser was adjusted at 700 μm from the table, after incision this distance was decreased to 500 μm and at this height substrate was incised again. After cutting the substrate could be carefully snapped.

2.5 The examination of the substrate

Co-firing examination

After co-firing the three-layered structure shrunk 15.4% (from 60.5 mm to 51.183 mm) in the X-Y direction and the thickness shrunk 19.1% (from 755 μm to 610 μm). This corresponds to the prescribed interval given by the literature (12%-16% for X-Y direction and 15%-25% for the thickness shrinking). On the one circuit single resistive layer was printed, on the other structure double resistive layer were printed. In the last case the double printed layers were squeezed through.

The examined width of the resistive layers was about 520 μm before co-firing, after co-firing became 448 μm, which means 13.85% shrinking. After co-firing polished sections of resistive layers were prepared and the thickness could be measured. In case of the single printed resistors, the thickness was about 13 μm ($\pm$3 μm), while in case of the buried resistors the thickness was about 10 μm ($\pm$3 μm). The problem was the dispersion of the buried resistors. The thickness of the double printed, co-fired resistive layer was 33 μm ($\pm$5 μm), which approaches the value of the literature. The thickness of the co-fired conducting layer was about 13 μm ($\pm$5 μm), on the overlapping places also. In the case of double printing the thickness was also 13 μm ($\pm$5 μm), hence the overlapping does not influence the thickness of the conducting layer. The average thickness of the overlapping in the single printing case was 30 μm ($\pm$10 μm), while in the double case it was 50 μm ($\pm$10 μm).

Measuring the values of the film resistance

After co-firing the film resistance was measured with Agilent product 4338B resistance measuring device. Fig. 17 summarizes the average values of the cylindrical resistors, while the Fig. 18 summarizes these values for rectangular resistors.

The measurements show that where a window was opened above the resistive layer, the value of resistors approached to the previous calculated value. Without a window, the values of the resistors significantly deviated from the Graddy-HYDE program calculated values. It has happened because of the melting and convergence of the glass component into the DuPont 2031 paste during co-firing, interrupting this way the conducting net. If the resistive layer is buried between raw glass-ceramic sheets, the conducting layer reacts with the melted glass on both sides, the real functional thickness of the layer decreases and the sheet resistance increases: the insulating particles get in between the greater granular resistive particles and in this way interrupt the conduction in the layer [15]. DuPont 2031 resistive paste is not satisfactory for realization of the buried resistors in the LTCC substrate, although if it is considered, that the value of the embedded resistors will be eight or nine fold of the calculated value, this paste can be useable for it. Among resistive pastes recommended for the LTCC technology this effect can be moderately observed.

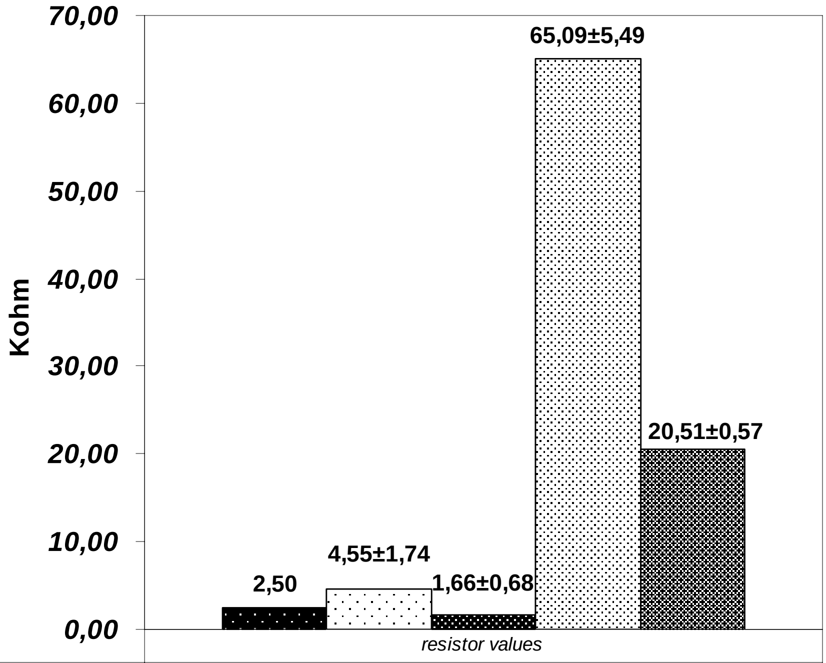
The increasing of the resistance value during co-firing is an important fact in case of planning buried resistive layers. During the screen printing process if the double of the prescribed thickness is printed, then after co-firing the reached value of the resistance approaches the calculated value. Exaggeratedly thin ($<15\mu$m) resistive layer causes thermal and electrical instability of the resistance, on the other hand exaggeratedly thick layer (>50 μm) the resistor can break into pieces during the co-firing. In the case of the double printed ($\sim$34 μm) structure, where the thickness approaches much better the planned thickness (27 μm), the measured value of the resistance was near the calculated value and after laser adjustment the stability increased.

3 Conclusion

LTCC technology enables burying of passive elements: resistors; inductors and capacitors. The equipment used for thick-film process can be used for LTCC production after minor modifications.

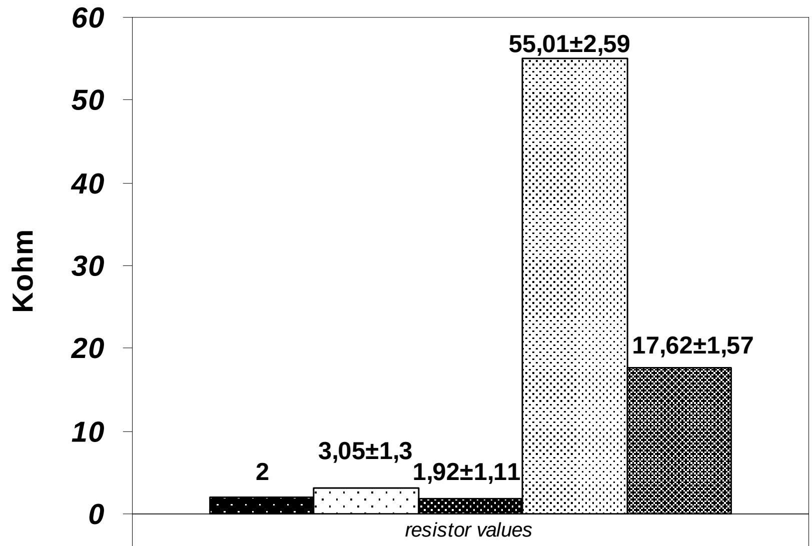
The increasing of the resistance value during co-firing is an important fact in case of planning buried resistive layers. During the screen printing process if the double of the prescribed thickness is printed, then after co-firing the reached value of the resistance approaches the calculated value. In case of embedded resistors the glass component melts and convergences into the resistive paste during co-firing, interrupting this way the conducting net. If the resistive layer is buried between raw glass-ceramic sheets, the conducting layer reacts with the melted glass on both sides, the real functional thickness of the layer decreases and the sheet resistance increases: the insulating particles get in between the greater granular resistive particles and in this way interrupt the conduction in the layer. Exaggeratedly thin resistive layer causes thermal and electrical instability of the resistance, on the other hand exaggeratedly thick layer the resistor can break into pieces during the co-firing. In the case of the double printed structure, where the thickness approaches much better the planned thickness, the measured value of the resistance was near the calculated value and after laser adjustment the stability increased.

Fig. 17. Measured and calculated values of cylindrical resistors



	resistor values
■ *calculated*	*2,50*
□ *1xprinted, surface*	*4,55*
▩ *2xprinted, surface*	*1,66*
⊡ *1xprinted, embedded*	*65,09*
▩ *2xprinted, embedded*	*20,51*

Fig. 18. Measured and calculated values of rectangular resistors



	resistor values
■ *calculated*	*2*
⊡ *1xprinted, surface*	*3,05*
▩ *2xprinted, surface*	*1,92*
⊡ *1xprinted, embedded*	*55,01*
▩ *2xprinted, embedded*	*17,62*

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