MODERN THICK-FILM AND LTCC PASSIVES AND PASSIVE INTEGRATED COMPONENTS

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Key words: LTCC technologies, modern passives, thick-film, passive integrated components, modern electronic circuits

Abstract: The dimensions of modern passives and passive integrated components should be reduced significantly in the nearest future. The aim of this paper is to present current situation in the area of discrete, integrated and integral passives made using thick-film or Low Temperature Co-Fired Ceramic (LTCC) technologies. The role of these components in modern electronic circuits is discussed too. The concept of such passives is very simple and they are very cheap in mass production. But from materials science point of view they are complicated, non-equilibrium systems with physical and electrical properties dependent on microstructure, which is determined in turn by proper arrangement of raw materials properties and conditions of fabrication process.

The material, technological and constructional solutions and their relation with electrical and stability properties are analyzed in details for thick-film and LTCC micropassives - microresistors, microcapacitors, microinductors and microvaristors - both described in the literature as well as fabricated and characterized at the Faculty of Microsystem Electronics and Photonics, Wroclaw University of Technology. Moreover the relations between minimal geometrical dimensions, technological accuracy and limitations on the one hand and electrical properties and stability behavior on the second hand are presented and discussed.

Moderne pasivne in integrirane pasivne komponente izdelane z debeloplastno in LTCC tehnologijo

Kjučne besede: LTCC tehnologije, moderne pasivne komponente, debeloplastne pasivne integrirane komponente, moderna elektronska vezja

Izvleček: Velikosti modernih pasivnih in integriranih pasivnih komponent moramo v bližnji prihodnosti še dodatno zmanjšati. Namen tega članka je predstaviti trenutno situacijo na področju diskretnih, integriranih in integralnih pasivnih komponent, narejenih s pomočjo debeloplastnih filmov ali LTCC tehnologij. Omenjamo tudi vlogo the komponent v modernih elektronskih vezjih. Koncept teh pasivnih komponent je zelo enostaven, v široki potrošnji pa so zelo poceni. Toda s stališča materialoznanstva pa gre za zapletene, neravnovesne sisteme, katerih fizikalne in električne lastnosti so odvisne od mikrostrukture, ki je na drugi strani določena z lastnostmi osnovnega materiala in pogojev proizvodnega procesa.

V prispevku analiziramo material, tehnološke in konstrukcijske rešitve ter njihov vpliv na stabilnost in električne lastnosti debeloplastnih in LTCC pasivnih komponent. - mikroupori, mikrokondenzatorji, mikroinduktivnosti in mikrovaristorji - oboje opisano v literaturi, kakor tudi proizvedeno in okarakterizirano na Fakulteti za Mikrosisteme, elektroniko in fotoniko na Univerzi Wroclaw. Obravnavamo tudi povezavo med minimalnimi dimenzijami, tehnološko točnostjo in omejitvami na eni strani in električnimi lastnostmi in zanesljivostjo na drugi strani.

1. Introduction - characterization of modern passives

Electronic devices, components, circuits and systems should be faster, smaller, lighter and cheaper. Proper functionality of modern electronic circuits demands both active devices and passives (primarily resistors, capacitors and inductors, but also nonlinear resistors - thermistors and varistors, potentiometers, transformers, filters, fuses, mechanical switches and electromechanical relays).

About 10^{12} of passives, which undergo deep technological and constructional transformation, are used by electronic industry every year and the world wide market in this segment is equal to about 35 billions of US dollars. Around 1980's the through-hole packaging moved towards surface mount technology (SMT). Wirewound components were replaced gradually but rapidly by surface mount ones and about 90% passives is SMT adapted at present.

According to the classification of National Electronics Manufacturing Initiative (NEMI, USA) the following generation of passives can be distinguished /1-4/:

- Discretes - traditional single purpose surface mount or through-hole passives,
- Arrays - multiple passive components with identical function in a single SMT case,
- Networks - multiple passive components of more than one function in a single SMT case, usually 4 to 12 elements,
- Integrated - a package containing multiple passive elements of more than one function and possibly a few active elements in a single SMT or Chip Scale Package (CSP),
- Integral - passives embedded in or incorporated on the surface of an interconnecting substrate,
- On-chip passives - passive components that are fabricated along with the active ICs as a part of semiconductor wafer.

The requirements for passives are dependent on type of circuits (Table 1).

Table 1. Typical passive components requirements for various electronic circuits (based on /5/)

Analog and mixed-signal circuits		
Application	Value range	Tolerance [%]
Resistors	10 Ω– 100 MΩ	1 – 10
Signal capacitors	10 pF– 10 nF	5 – 10
Decoupling capacitors	0.01 – 0.1 μF	10 – 20
EMI filter capacitors	1 – 10 nF	10 – 20
Choke inductors	1 – 10 μH	10 – 20
RF and microwave circuits		
Application	Value range	Tolerance [%]
Terminating resistors	20 – 100 Ω	1 – 10
Signal resistors	10 – 100 Ω	1 – 10
Signal capacitors	1 – 20 pF	5 – 10
Decoupling capacitors	0.01 – 0.1 μF	10 – 20
Choke inductors	1 – 10 μH	10 – 20
Signal inductors	1 – 20 nH	1 – 10

The average linear dimension (Table 2) and complexity of passives was decreased during recent years much less than characteristic dimension and complexity of integrated circuits. This is the reason why the ratio between passives and active devices is increased almost all the time.

Table 2. Percentage contribution of package sizes of passive components (based on /6/)

Year / Pack. size	1980	1990	2000	2010
1206	89.5	13.0	5.0	1.0
0805	10.5	78.0	22.0	2.5
0603		9.0	60.0	20.0
0402			13.0	60.0
0201				15.0
01005				1.5

Further miniaturization of passives reaches the equipment barrier - for example modern pick-and-place machines are not adjusted for accurate placement of 01005 components. Therefore an old idea of planar arrays and networks was reanimated.

Four 0603 capacitors, together with solder pads and technological margins, need 17.5 mm^2 area. But array of 4 identical capacitors placed in one 1206 structure needs only 7.75 mm^2 of printed circuit board area. Moreover, considering the necessary technological margins, the contribution of area (volume) of active layer in relation to nominal device dimensions is decreased for smaller packages. For example, this is 43% in 1206 multilayer ceramic capacitors and only 19% in 0402 ones. Moreover passive arrays and networks are characterized by smaller serial inductance and better frequency behavior as well as lower assembly cost and higher circuit reliability.

The integration of passives is the best solution for very high component density with increased electrical performance, improved reliability, reduced size and weight as well as lower cost. This process causes reduction or elimination of discrete SMT components and the same reduction of overall part count, elimination of solder joints, improvement of wireability and frequency behavior due to elimination of parasitic inductance. The above advantages are possible thanks to multichip module (MCM) technologies /7,8/ - an extension of hybrid technologies permitting a higher packaging density than can be assures by other approaches.

The signal transmission lines in MCM are placed at many levels and the ratio of bare VLSI circuits' area (mounted on MCM surface) to MCM area is greater than 20%. Therefore MCM can transmit signals with frequency higher than 100 MHz. There are three kinds of MCM technology:

- MCM-D, where interconnections are formed in a similar manner as in thin-film circuits, i.e. by depositing alternate layers of conductors and dielectrics onto an underlying substrate,
- MCM-L, where multilayer structures are formed by lamination of printed circuit board materials with etched patterns in copper foils and metalized vias,
- MCM-C, where multilayer structures are made by co-firing of ceramic or glass/ceramic tapes, similar to thick-film process. This means that vias are punched in green tapes and then filled with conductive electronic paste. The individual layers are screen-printed to create desired metallization patterns. Several such prepared tapes are laminated at elevated temperature and then co-fired at proper temperature to form a monolithic structure.

Modern MCM substrates consist not only interconnections but also many integral (embedded) passives. In this manner they fulfill the demands for the next generation of packaging needs. For example, integral passives significantly reduce inherent parasitics connected with the current discrete passive packages.

This paper concentrates on author and his co-workers activity in the area of thick-film and LTCC passives.

2. Fabrication of thick-film and LTCC fine lines

In thick-film and LTCC technologies screen-printing is the most reliable and cost-effective process for film deposition on tape or ceramic substrates. The standard screen-printing resolution (line width and line-to-line space) is equal to 100-125 μm /9/. The fine line print resolution is limited both by ink rheology as well as by screen properties (mesh size, wire thickness, calendaring and angle of the screen fabric in the frame) and the current achievable print resolution is about 50 μm for curved structures and 30-40 μm for straight lines /10,11/.

There are also other techniques developed for deposition of fine lines - in general they are based on printing processes, like printing through etched solid metal masks, offset printing (eg. gravure-offset printing /12/, where as narrow as 25 µm wide conductors have been printed), stamping or pad printing.

Next techniques are based on combination of standard screen-printing with photolithography. This attempt is present in photosensitive inks, where pattern is defined after film drying /13,14/ – this method enables to produce fine lines narrower than 20 µm in the case of Hibridas-like materials. Also standard screen-printing can be connected with photoetching, where patterns are defined after firing of the layer. There are also tests with diffusion patterning /15/ or nanoinprint technologies /16/.

There are also a group of methods involves the deposition of thick-films by capillary action from a precious stylus (nozzle) that also serves as the ink reservoir. Three methods are used to deposit inks through the writing orifice:

- Hydraulic positive displacement pumping synchronized with substrate stage motion (direct write printing) where standard inks can be applied,
- Non-contact electrostatic thick-film printing where ink is ejected by a high electrostatic field applied between the nozzle and the substrate,
- Drop-on-demand ink-jet printing, in which drop-lets of ink are jetted from small aperture directly to a specified position by application of a voltage pulse to a piezoelectric material that is coupled directly or indirectly to the printed fluid; typically drop-on-demand systems are able to produce droplets of diameter between 25 and 100 µm /17/; the ink-jet process made it possible to metalize fine lines with line/space = 30/30 µm /10/.

Investigation of author and his PhD and MSc students in this area /18,19/ was devoted to preparation of set-ups for exposure and development of miniature photoimageable thick films, self-building of apparatus for deposition of thick-film with the usage of ink-jet technique, elaboration of technology of stamping and geometrical characterization of lines obtained in these techniques and set-ups. Our Fodel made lines had minimal width of about 50 µm, ink-jet printed lines – 90 µm and stamped lines – 80 µm. Examples of stamped 80 µm lines are shown in Fig. 1.

4. Laser-shaped micropassives

Many laser applications, especially related to complete microcircuit size reduction and packaging density increase are reported in the literature (please see eg. /20-24/). This chapter presents the systematic studies of fabrication as well as geometrical, electrical and stability properties of thick-film or LTCC micro-resistors, microcapacitors and microinductors made with the aid of laser-shaping.

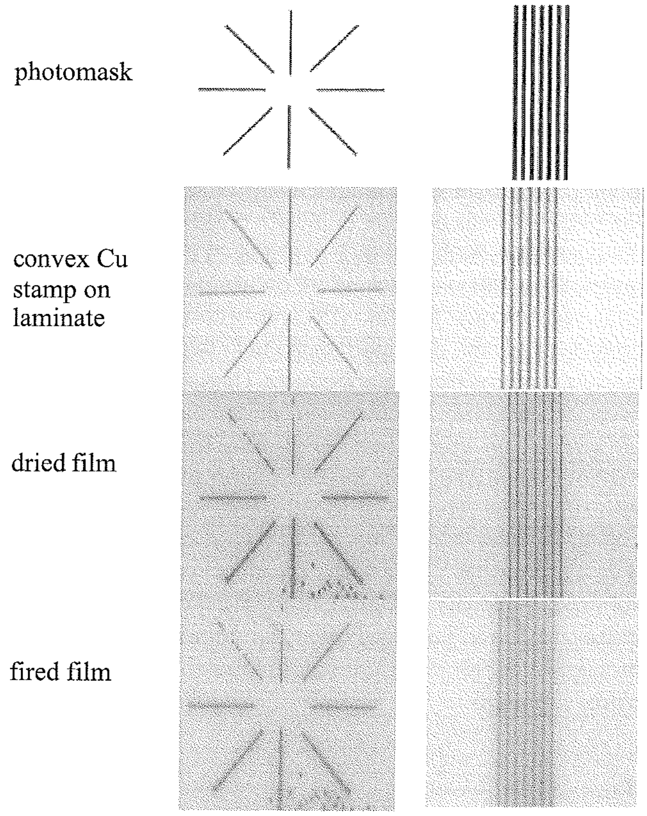

Fig. 1. Quality of 80 µm PdAg lines made by stamping method with the aid of convex Cu stamp

Micropassives were patterned by means of three lasers:

- Nd:YAG laser - arc lamp pumped Nd:YAG (cur-rent industrial standard in LTCC and thick-film technology); the Aurel NAVS-30 Laser Trimming and Cutting System (Aurel, Italy) with pulse Nd:YAG laser (1064 nm wavelength) and special software was used,
- frequency-tripled Nd:YAG laser (third harmonic generated with two extra-cavity LBO-crystals, beam length of 355 nm) - Microline 350L laser system (LPKF, Germany) equipped with an arc lamp pumped Nd:YAG-laser with Q-switching; the resulting beam is guided by two galvanoscan-ners on a *f*-Θ lens; the typical repeating precision of the *x-y*-stage was 1 µm and typical laser spot velocity on the surface between 1 and 400 mm/s,
- KrF excimer laser - LPX 210 Lambda Physik model, wavelength λ = 248 nm, 30 µm laserspot diameter on the surface, repetition rate - 200 Hz, energy density on the surface - 40 J/cm^2, shaping by scanning with 1 pulse per µm.

The laser parameters in every case depend on patterned material. In case of fired thick-film conductive layers relatively low energy laser beam is needed to avoid injury of the substrate.

4.1. Thick-film and LTCC microresistors /21, 25-27/

Laser-shaped microresistors were made on alumina (96% Al_2O_3) or LTCC (DP 951 tape from DuPont) substrates. The distance between electrodes, i.e. proper resistor length, was created by laser cutting of conductive films. Nd:YAG laser was used for cutting of dried conductors and because of various behavior of cut films during firing, the real notch width was dependent on conductor metallurgy. The spaces equal to 109, 120 and 96 µm have been received for 80 mm designed distance in the case of PdAg-, Au- or Ag-based films, respectively. These differences between particular conductors are larger than for laser cut performed on fired ones. Therefore frequency-tripled Nd:YAG laser was used for fabrication of microresistors with regulated length (30 to 300 µm), created by laser cutting of fired PdAg-, Au- or Ag-based conductive films (Fig. 2). Next DP 2021 (100 ohm/sq.) or DP 2041 (10 kohm/sq.) ink was screen-printed and fired. To compare these structures standard ones the screen-printed resistors with 300 to 1800 µm length were prepared on the same substrate.

Microresistors with constant length and regulated width down to 30 µm were made by proper cutting of 1×1 mm^2 fired resistors (Fig. 2) - this shaping method permits to eliminate conductor distance beyond resistor width.

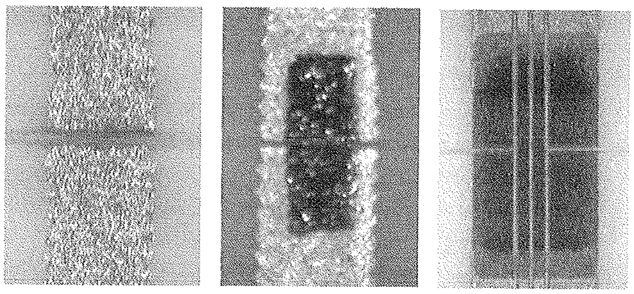

Fig. 2. Conductive path with laser made gap, gap filled with screen-printed resistive ink and top view of resistors with regulated width

Laser profilometer was used for three-dimensional characterization of investigated structures. A typical cross-section profile is shown in Fig. 3. The thickness of resistive film is not identical at every point. The mean thickness of these films is about 10 µm, both on alumina and LTCC substrates. The depth of laser kerf is dependent on scribed material and kind of substrate - the same pulse energy of laser gives much deeper notches in LTCC substrates in comparison with alumina ones. Moreover it is much more difficult to cut fired conductive films than resistive ones.

Example of sheet resistance (R_{sq}) versus resistor length dependences is shown in Fig. 4. The sheet resistance is increased with resistor length. The increase level is dependent on kind of resistive film. Resistors with regulated width exhibit hot temperature coefficient of resistance (HTCR) practically independent of their width (Fig. 5).

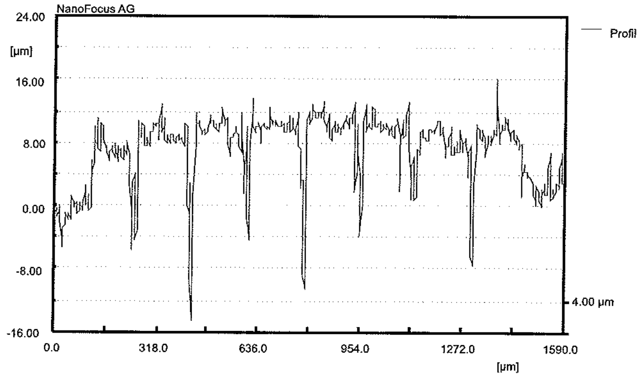

Fig. 3. Profile through six 800x170 μm^2 laser-shaped resistors (DP2031/LTCC substrate)

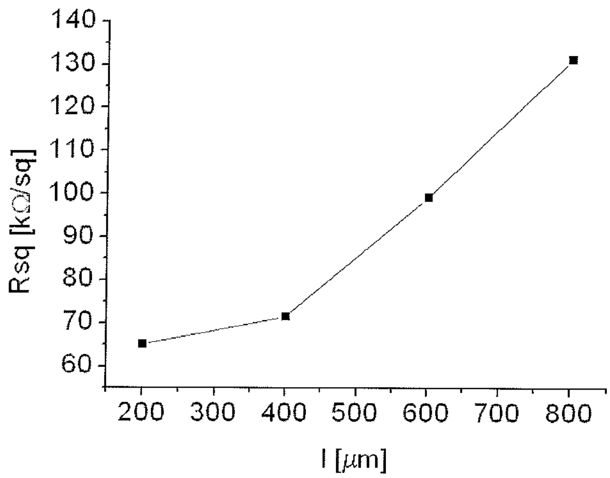

Fig. 4. Sheet resistance of R8951/Al_2O_3 resistors vs. resistor length

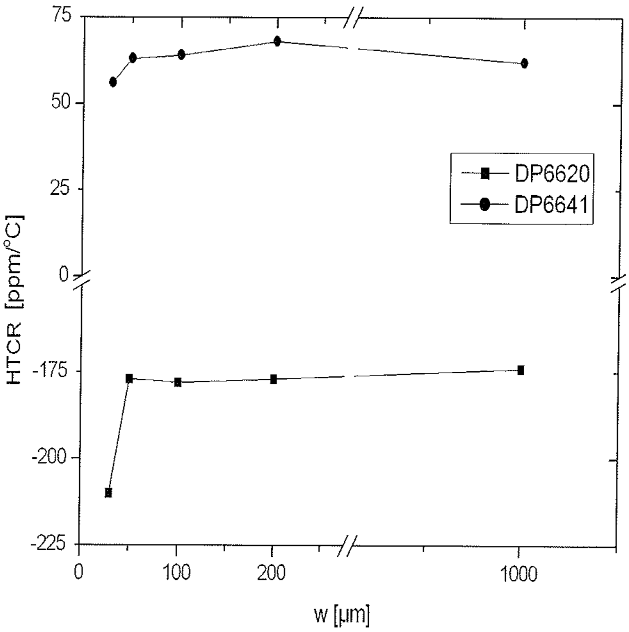

Fig. 5. HTCR as a function of resistor width

Long-term stability was characterized based on resistance drift induced by long-term thermal ageing at three different temperatures- 150°C, 200°C and 250°C. The samples were kept at every temperature for about 300 hours. Some examples of fractional resistance changes are shown in Fig. 6. Insignificant resistance changes are observed in general. Resistors with Au-based terminations have better stability as those with Ag- or PdAg-based contact layers. Longer and wider resistors exhibit smaller resistance drift. This means that ageing processes within resistor volume give smaller fractional resistance changes than those appearing at the resistor/conductor interface. Screen-printed resistors exhibit similar stability level under the same ageing conditions /28,29/. This suggests that laser affected zone, appearing during shaping, is very small and can be neglected during analysis of electrical and stability properties for structures with resistor width larger than 150 μm.

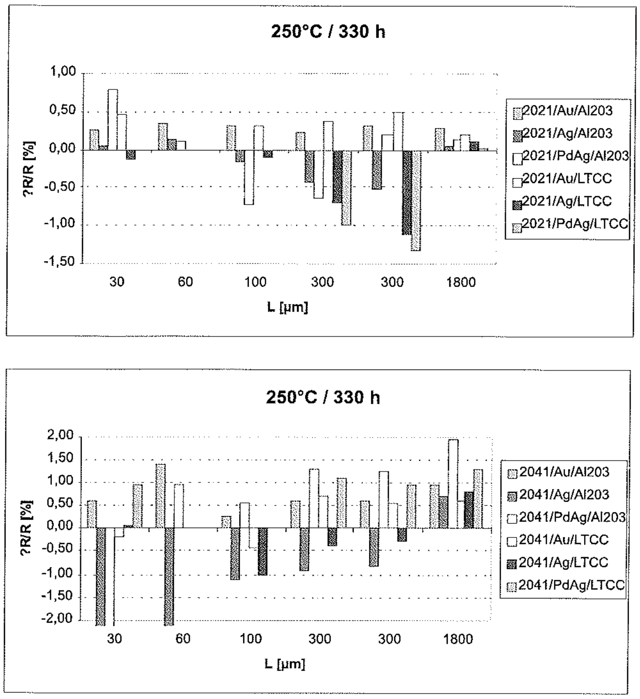

Fig. 6. Long-term stability of laser-shaped microresistors - resistive ink DP 2021 (top) and DP 2041 (bottom)

4.2. Thick-film and LTCC microcapacitors /30,31/

Capacitance density of thick-film components ranges from few pF/mm^2 up to few nF/mm^2. This is a result of relatively large thickness of dielectric layer - it must be printed at least twice for prevention from shorts. Thus, considering area occupied, only small and medium capacitances are achievable in thick-film technology. Multilayer LTCC structures allow circuit integration and miniaturization. But LTCC process differs from typical thick-film one, what results in significant difference of component properties.

Below fabrication and electrical as well as stability characterization of 2.5×2.5 mm^2 comb laser-shaped planar capacitors (Fig. 7) is presented. Basic electrical properties of components were measured as a function of frequency and temperature. Two dielectric inks - ESL4164 (K = 250) and DP5674 (K = 50÷80) were used. PdAg-based ESL963 and DP6146 conductive inks served for electrodes. Moreover Ag-based ESL9912-A conductive ink was applied in combination with both dielectrics for surface capacitors. Each capacitor layer on alumina and post-fired LTCC substrate was fired at standard 850°C/60 min. profile after printing. Two prints were used for all capacitors except buried planar ones.

Finger electrodes (50/50 and 75/75 μm line/space) were formed by Nd:YAG frequency-tripled laser. In addition standard Nd:YAG laser was used to cut 120/80 μm electrodes in dried conductive inks both for surface and buried capacitors.

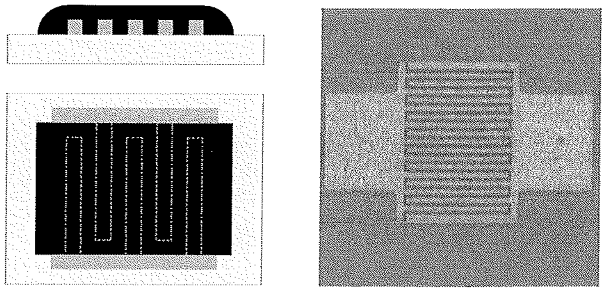

Fig. 7. Planar comb capacitor configuration

The frequency (1 kHz÷30 MHz i.e. from acoustic to UHF frequency range) and temperature (25°C÷145°C) characteristics of comb capacitors were measured and analyzed. Some examples of capacitance versus frequency characteristics (compared with fitting results) are shown in Fig. 8.

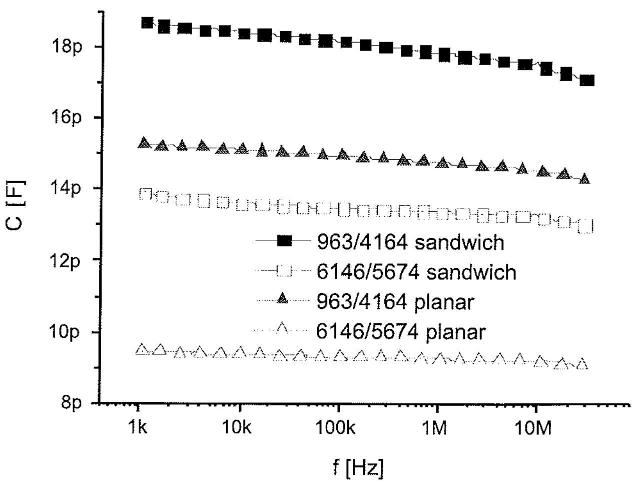

Fig. 8. Capacitance vs. *frequency (sandwich buried 0.5×0.5 mm^2 capacitors and comb planar ones, LTCC substrate)*

4.3. Thick-film and LTCC microinductors /32,33/

Modern circuits operate at higher and higher frequencies. Therefore inductors are used more frequently. Such thick-film passives also can be laser-shaped. Air-cored, one-side ferrite covered and planar inductors with conductive tracks (silver ink ESL 9912-A with 14-16 μm thickness) embedded in ferrite material (Fig. 9) in three different shapes (meander inductors with 100 μm conductor width/50 μm conductor spacing, and square spiral ones with 100 μm conductor width/50 μm conductor spacing or 50 μm width/50 μm spacing) were designed and laser-shaped (by frequency-tripled Nd:YAG laser). Next their elect-rical and stability properties were investigated. The inductors of meander form consist of 17 sections whereas those of rectangular form of 5 (for 100 μm track width/50 μm spacing) or 8 turns (for 50 μm track width/50 μm spacing). The size of the fabricated inductors was about 2.5x2.5 mm^2.

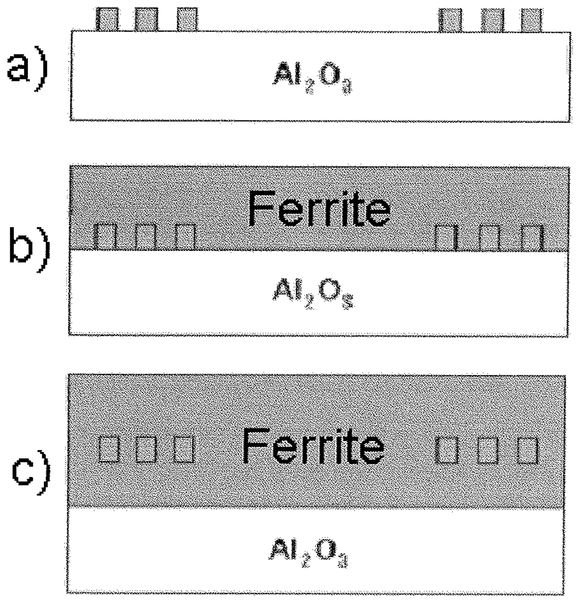

Fig. 9. Schematic cross-sections of realized inductors

Next ferrite layer, based on ESL 40011 magnetic tape /34/, was prepared in the following way - the organic medium was removed from the magnetic tape by firing at 550°C, the remaining part was thoroughly powdered and mixed with typical ethylcellulose-terpineol binder to obtain an appropriate thick-film ink. This ink was screen-printed below or onto planar inductors through proper screen and fired in 850°C/60 min cycle.

Inductance, resistance and quality factor, Q_L were determined in a wide frequency (10 kHz - 110 MHz) and temperature (20°C - 250°C) range and analyzed as a function of inductor geometry (shape and width of conductive tracks) and presence/absence of magnetic core. The stability properties, i.e. fractional inductance and resistance changes after long-term thermal ageing at elevated temperature (150°C and/or 250°C, 250 hours each) were also investigated and analyzed.

The inductances of structures with ferrite layer were from the range 29-31 nH for 100/50 μm meander inductors, 91-102 nH for 100/50 μm and 179-232 nH for 50/50 μm spiral square inductors. The inductances of air-cored inductors were from the range 10-13 nH for 100/50 μm meander inductors, 55-60 nH for 100/50 μm and 137-143 nH for 50/50 μm spiral square inductors This means that the inductance is increased for 1.6-2.9 times for one-side ferrite covered inductors (Fig. 10).

Ag-based spiral square inductors have the quality factor $Q_L = \omega L/R$ from the range 15 to 18 at 90 MHz frequency, independently on kind of substrate. However *Q*-factor of inductors with ferrite layer becomes lower in higher frequencies (about 1.5 - 5.3 for 90 MHz) than for air-cored coils. It might be caused by loses of magnetic field energy for induction of eddy currents in ferrite.

The stability properties, which are not analyzed too often for such components, i.e. fractional inductance and resistance changes after long-term thermal ageing at elevated temperature (150°C and/or 250°C, 250 hours each) were also investigated. The inductors are very stable - long-term thermal ageing did not change inductance level and caused only small resistance increase in the whole frequency range - this is con-nected with good temperature stability of applied thick-film conductors (Fig. 11). Therefore ageing pro-cess practically do not affect $Q_L = f(\omega)$ dependence.

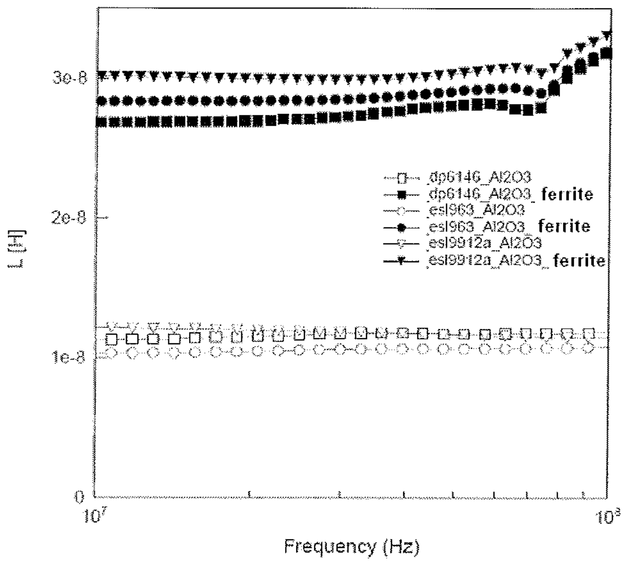

Fig. 10. Inductance vs. *frequency for meander air-cored and with ferrite layer inductors on alumina substrates*

The impedance spectra of inductors with ferrite core were also measured in temperature range from 30 to 210°C. As is shown in Fig. 12 decrease of inductance in higher temperature was observed. At temperature above 180°C the value of inductance is almost the same as for air-cored structures. This indicates that the Curie point (temperature above which core loses its characteristic ferromagnetic ability) was crossed. Parasitic resistance proves typical for metals linear increase with temperature - is a strong function of temperature and is slightly affected by thermal ageing.

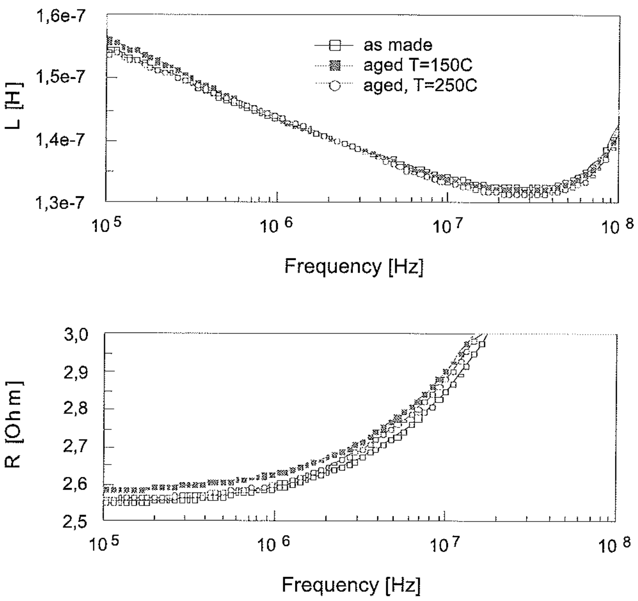

Fig. 11. Behavior of inductance and parasitic series resistance of Ag-based thick-film inductors after long-term thermal ageing

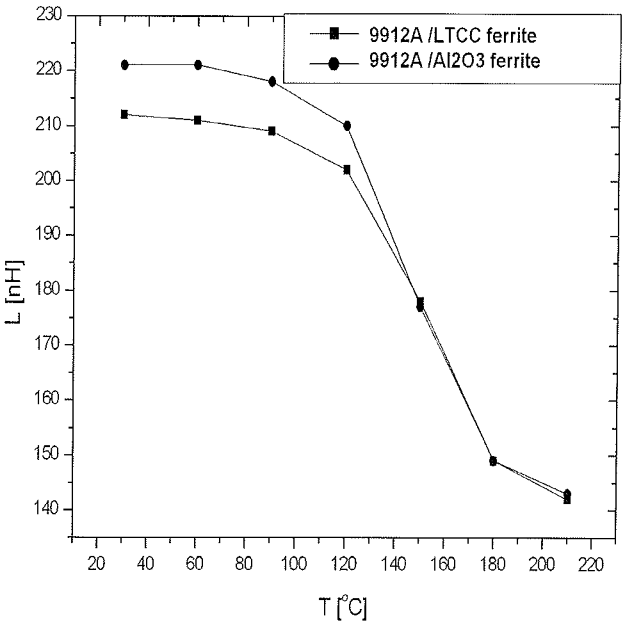

Fig. 12. Inductance vs. temperature for Ag-based square inductors with ferrite layer on different substrates

5 Fodel microresistors

So far various photosensitive conductor and dielectric inks are commercially available. But such resistive compositions are still only at the research and development stage. For example Du Pont mentioned about Fodel photopatternable resistive inks /35/. We investigated the fabrication and preliminary electrical characterization of microresistors made of experimental DP E-93350-153 (1 kohm/sq.) Fodel resistive ink (based on RuO_2) and Ag-based DP6453 Fodel conductor, both from Du Pont. Screen-printed or fully photopatternable test resistors with designed dimensions from 50x50 to 800x200 μm^2 were made and tested. Results related with geometrical, electrical and stability properties of microresistors were described in /28,36,37/. During examinations the following were found:

- The 3D geometry of microcomponents is strongly affected by applied fabrication method. The screen-printed resistors are wider whereas the Fodel one - narrower than designed. To obtain assumed planar dimensions the technological offset should be included into the design procedure. Moreover microresistors made in Fodel process have much smoother surface.
- Microresistors made in full Fodel process exhibit weaker dependence of sheet resistance on resistor length and better long-term stability.
- In spite of significantly reduced dimensions (even down to 50x50 μm^2) the R(T) characteristics of microresistors are typical for thick-film resistors with resistance minimum at certain temperature. The minimum shifts towards lower temperatures when the resistor aspect ratio is decreased.
- Much better reproducibility of this technology leads also to much better pulse behavior of Fodel microresistors (increase of critical electrical field and surface power density approximately by 20-30% in comparison with standard ones).
- The long-term stability of 200x200 μm^2 Fodel microresistors was similar to typical thick-film resistors. The 100x100 and 50x50 μm^2 microresistors exhibited somewhat worse long-term stability (after 500 h ageing at 150°C the resistance increased by about 1.0 - 1.5%).

Probably the problems with long-term stability were the reason that Fodel resistive system was not commercialized and photosensitive resistive inks are still at the research and development stage in laboratories of ink manufacturers.

6 Microvaristors

ZnO-based varistors are widely used for overvoltage protection of electronic circuits. High firing tempe-rature (1150°C÷1300°C) has to be applied in order to obtain satisfactory nonlinearity properties of such devices. However recently various thick-film varistor ceramics and structures possessing nonlinearity coefficient from the range 20-35, but fabricated in the temperature range between 850°C and 1000°C, were presented /38-45/.

Our varistor ink was prepared from ZnO-based powder consisting of ZnO (97.54 mol.%) and such additives as $BaBiO_3$ (0.7 mol.%), $Bi_4Ti_3O_{12}$ (0.16 mol.%), Sb_2O_3 (0.125 mol.%), MnO_2 (0.125 mol.%), NiO (0.5 mol.%), Cr_2O_3 (0.5 mol.%), and Co_3O_4 (0.35 mol.%). Next 1 wt% of Bi_2O_3

was added to improve sintering process of such ink /12/. Three conductive inks - DP6146 (PdAg), DP9894 (Pt) and ESL8880-H (Au) - were used for electrodes. Alumina and fired LTCC tape (DP951) served as substrates. Two varistor configurations were designed - planar with finger-like electrodes with 0.25 mm spacing and 2 mm wide varistor layer and sandwich one (with dimensions of 0.5×0.5 or 2×2 mm^2 - Fig. 13).

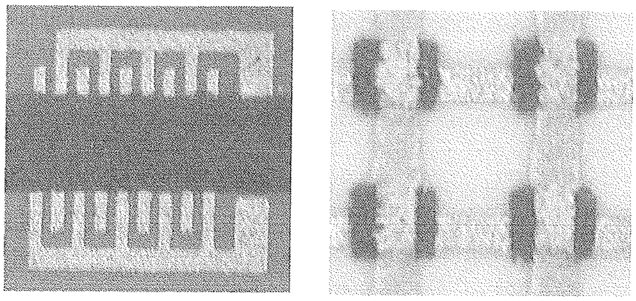

Fig. 13. Planar and sandwich varistor configuration

I-V characteristics of varistors were measured with pulse generator (0.1 ms pulses duration, 1 s interval). Obtained curves were fitted using $I = kV^{\alpha}$ formula and the nonlinearity coefficient α and characteristic voltage V_{1mA} were calculated (Fig. 14).

Electrical properties of varistors were significantly dependent on technology. The strongest factor was electrode material. Nonlinearity coefficient α in the range of 9÷23 was obtained for Pt terminations, 3÷8 for PdAg and 3÷11 for Au ones. Structures on LTCC substrate exhibited higher nonlinearity in comparison with those on alumina, especially in the case of Pt metallurgy. Moreover platinum terminations made *a* dependent on firing profile; in the case of Au and PdAg electrodes nonlinearity changed weakly. In general sandwich varistors showed higher α. The distribution of *a* values was about 25% for sandwich varistors and 10% for planar ones.

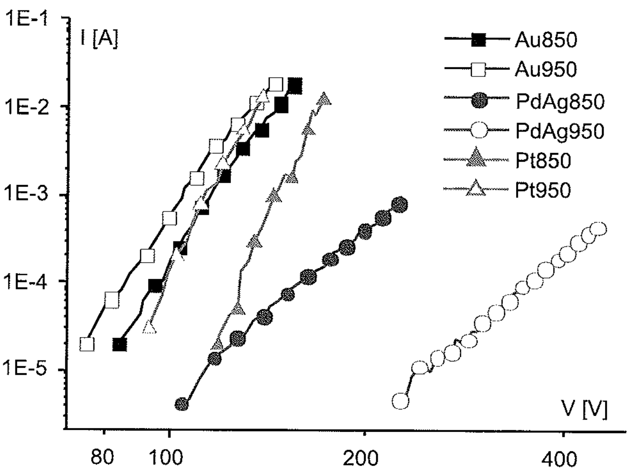

Fig. 14. I-V characteristics of planar varistors on LTCC substrate

Wide range of characteristic voltage, V_{1mA} (10÷200 V for sandwich varistors and 100÷460 V for planar ones), strongly affected by electrode metallurgy, was obtained. Its value was weakly correlated with *a*.

The stability of thick-film and LTCC varistors is not described yet. This is why we decided to characterize long-term thermal and electrical ageing and pulse durability of such devices.

Varistors were thermally aged at 150°C for 250 h. Examples of their *I-V* characteristics, measured before and after ageing, are shown in Fig. 15.

Generally thermal ageing slightly deteriorated varistors properties - small decrease in *a* and 10÷15% decrease in V_{1mA} was observed in most cases.

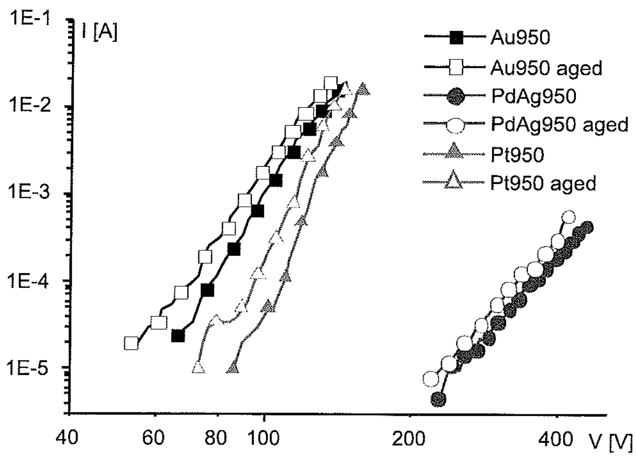

Fig. 15. I-V characteristics of planar varistors on LTCC substrate fired at 950°C before and after ageing

Sandwich varistors with easy solderable PdAg electrodes were chosen for long-term electrical ageing. They were loaded with 100 μA current for 250 h at room temperature. Varistors made on alumina practically were not affected by electrical load. Also α value for LTCC components remained unchanged. Only their *I-V* characteristics shifted toward lower voltages. Changes were in the range from a few to about 40 V.

Durability of varistors to high voltage pulses was also investigated. Components were subjected to series of 1000 pulses with 10 mA amplitude and 5 ms duration each. Test was done at room temperature. Examples of changes in I-V characteristics for as-fired and pulse exposed varistors are shown in Fig. 16. Varistors showed good durability. Generally small drop in α were found, although in some cases its value remained the same or even increased. V_{1mA} changes were very small, either positive or negative. Structures with Au electrodes were the most reliable, no breaks during test occurred.

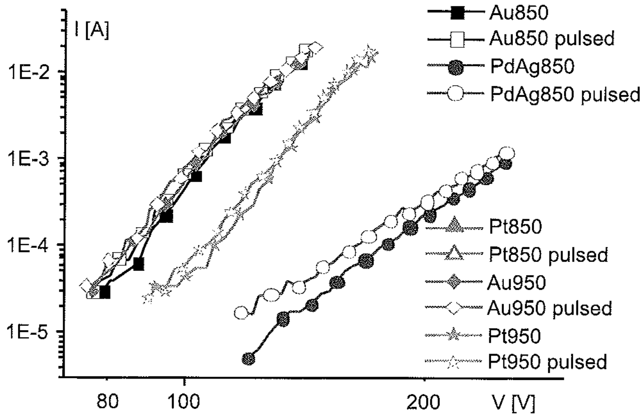

Fig. 16. I-V characteristics of planar varistors on LTCC substrate before and after exposure

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