Thick-Film and LTCC Passive Components for High-Temperature Electronics

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Abstract. *At this very moment an increasing interest in the field of high-temperature electronics is observed. This is a result of development in the area of wide-band semiconductors' engineering but this also generates needs for passives with appropriate characteristics. This paper presents fabrication as well as electrical and stability properties of passive components (resistors, capacitors, inductors) made in thick-film or Low-Temperature Co-fired Ceramics (LTCC) technologies fulfilling demands of high-temperature electronics. Passives with standard dimensions usually are prepared by screen-printing whereas combination of standard screen-printing with photolithography or laser shaping is recommenced for fabrication of micropassives. Attainment of proper characteristics versus temperature as well as satisfactory long-term high-temperature stability of micropassives is more difficult than for structures with typical dimensions for thick-film and LTCC technologies because of increase of interfacial processes' importance. However it is shown that proper selection of thick-film inks together with proper deposition method permit to prepare thick-film micropassives (microresistors, air-cored microinductors and interdigital microcapacitors) suitable for the temperature range between 150°C and 400°C.*

Keywords

High-temperature electronics, thick-film technology, LTCC technology, passive component, long-term stability.

1. Introduction

An increasing interest in high-temperature electronics (i.e. electronics operating above "traditional" temperature range which is equal to +125 °C for military electronics or +150 °C for automotive electronics) has been observed in recent years [1]. Some applications, for example electronics for oil and gas exploration and production, distributed controls for aircraft, industrial processes control or even space exploration, operate at much higher temperatures [2], [3]. The progress in technology of wide-bandgap semiconductors (SiC, GaN) permits to fabricate a new class of active electronic devices that can work in harsh environment involving high temperature [4], [5]. These facts cause also development of passive components. The dimensions of modern passives and passive integrated components used in high-temperature circuits should be reduced significantly in the nearest future in order to significantly reduce the size, weight and cost of the electronic systems and to improve their reliability. Therefore the relations between minimal geometrical dimensions, technological accuracy and limitations as well as electrical properties become more and more important.

Thick-film and LTCC (Low Temperature Co-fired Ceramics) technologies are well-known and relatively low-cost fabrication method of passives [6-10]. Thus, they represent promising fabrication techniques to meet the demands for miniaturizing devices operating at high temperature. This paper presents manufacturing process and chosen electrical and stability properties of thick-film and LTCC resistors, capacitors and inductors in a wide temperature range.

2. Fabrication of Thick-Film and LTCC Micropassives

There are various deposition technologies for deposition of thick films on tapes or ceramic substrates – some information about this can be found e.g. in [11], [12]. The passives described in this paper were made using standard screen-printing (with resolution i.e. line width and line-to-line space equal to 100-125 µm – Fig. 1a), combination of standard screen-printing with photolithography, where photosensitive inks are necessary and pattern is defined after film drying – Fig. 1b (see e.g. [13-15]) or laser shaping – Fig. 1c. Micropassives were patterned by means of four lasers:

- Nd:YAG laser - arc lamp pumped Nd:YAG (current 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), 70-80 µm laser beam and special software was used [16],

- 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 with 25 µm laserspot diameter on the surface is guided by two galvanoscanners on a *f-Θ* lens; the typical repeating precision of the *x-y*-stage was 1 µm and typical laser spot velocity between 1 and 400 mm/s [9], [17], [18],
- KrF excimer laser - LPX 210 Lambda Physik model, wavelength $\lambda = 248$ 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 [19],
- Nd:YAG picoseconds laser - Duetto from Time-Bandwidth - working on fundamental or frequency-tripled wavelength; the laser delivers 10 ps length pulses with repetition frequency in the range from 50 kHz to 8 MHz (the maximum energy for fundamental wavelength in a single pulse is 200 µJ at 50 kHz); the laser micromachining was performed at repetition frequency of 200 kHz and the laser beam spot diameter was conforming with the structure gaps 30 µm; for wider gaps (50 µm) two folding tracks were generated [20].

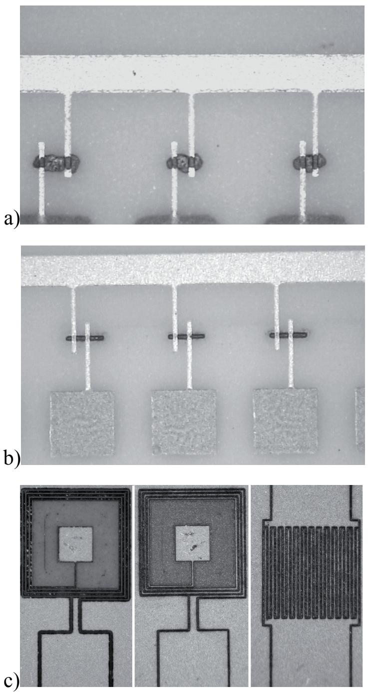


Fig. 1. a) Screen-printed microresistors; b) microresistors made of photosensitive conductive and resistive inks, c) laser-shaped planar inductors and interdigital capacitor (substrates – alumina or DP951 tape from Du Pont).

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

Confocal laser scanning microscope was used for three-dimensional characterization of investigated structures. Typical cross-section profiles are shown in Fig. 2. It is visible that the thickness of resistive/conductive film is not identical at every point. The average thickness of these films is about 10 µm, both on alumina and LTCC substrates. The laser kerf is V-shaped. Its depth is dependent on type of resistive/conductive material and substrate - the same pulse energy of laser gives much deeper notches in LTCC substrates (about 15 µm) in comparison with alumina ones (about 2 µm). The width of finger varies from about 30 µm in the top to about 40 µm in the bottom of layer. However, this method offers good repeatability of structuring.

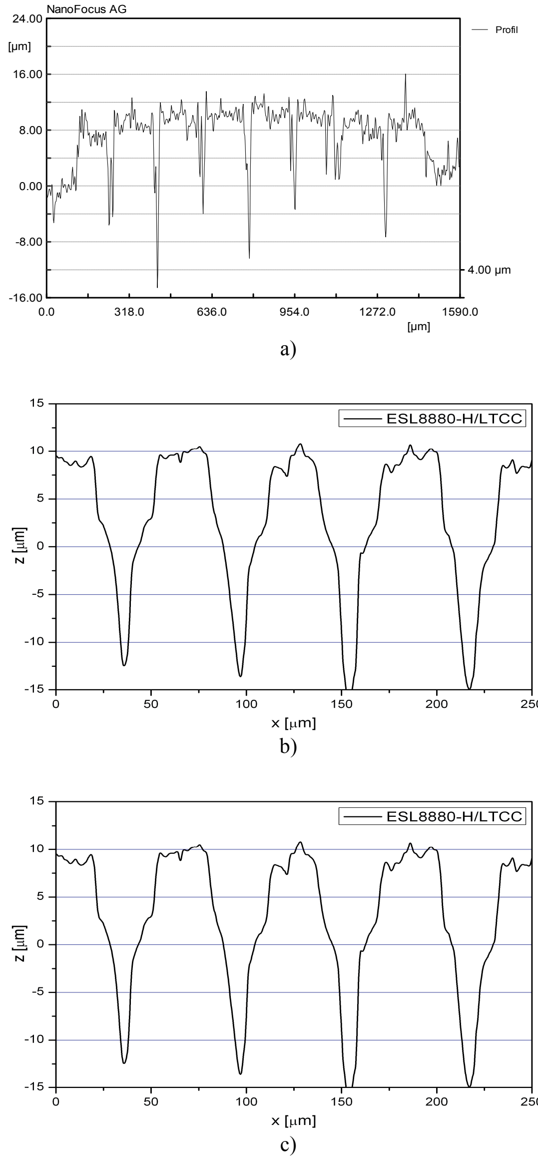


Fig. 2. Cross-section of laser-shaped resistor ladder (a), 30/30 µm capacitor on LTCC substrate (b), and 30/30 µm capacitor on alumina substrate (c).

3. High-Temperature Properties of Thick-Film and LTCC Resistors

Standard firing process in thick-film and LTCC technologies take place at 850-900°C. But in order to assure possible operation temperature up to 500°C the typical lead borosilicate glass should be replaced by CaO-BaO-B_2O_3-SiO_2-Al_2O_3 one [21] which exhibit significant increase of glass softening temperature.

Every thick-film ink consists of four subsystems – functional phase, glass, organic vehicle and modifiers and has to be deposited on proper substrate. During firing there are physicochemical, thermodynamical and mechanical interactions inside mentioned subsystems or among them, substrates and terminations. The knowledge about such interactions permits to obtain passives with assumed exploitation parameters [22-24]. For example, change of firing profile, topology and/or terminations' metallurgy of test components lead to change of resistance-temperature characteristics of specified resistor (Fig. 3). And it is clear that high-temperature thick-film resistors should posses the characteristic minimum of resistance at higher temperature in comparison with those operating within "traditional" temperature range.

But of course proper long-term stability at elevated temperature seems to be the most important parameter for possible application in high-temperature electronics. The authors of this paper have many years experience in investigation of this parameter as a function of various constructional and technological parameters of thick-film resistors.

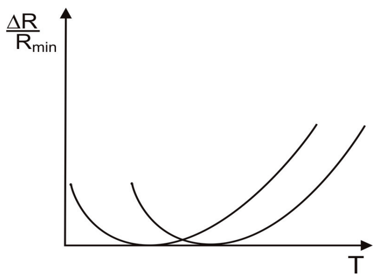


Fig. 3. Typical shape of $R(T)$ dependence for thick-film resistor.

The relative changes in resistance ($\Delta R/R_o$) and changes in the Hot Temperature Coefficient of Resistance ($HTCR = (R_2 - R_1)/R_1(T_2 - T_1)$ where R_2 is resistance at $T_2 = 125°C$, R_1 is resistance at $T_1 = 25°C$ and $\Delta HTCR = HTCR(t) - HTCR(0)$ where $HTCR(t)$ is Hot Temperature Coefficient of Resistance after t hours ageing process at given conditions, $HTCR(0)$ – the same parameter before ageing process) as a function of exposure time and temperature are the most often analyzed parameters in this case. One can find information about long-term stability behavior of thick- and thin-film resistors [22], [25-32] but there is not too much data for LTCC resistors [18], [33-36].

The percentage resistance change, $\Delta R/R_0$ was found to be a function of time and temperature. In general to fit the temperature-time dependence of the resistance changes this relation may be described by the following equation

$$\frac{\Delta R}{R_0} = \sum_i A_i t^{n_i} \exp(-\frac{E_i}{kT}) \qquad (1)$$

where E_i is the activation energy, n_i is the time dependence, A_i is the pre-exponentional constant of a particular ageing mechanism [27]. If a single mechanism dominates the analytical equation between the fractional changes in resistance, time and temperature can be written as [22], [27]

$$\frac{\Delta R}{R_0} = At^n \exp(-\frac{E}{kT}) \, . \qquad (2)$$

Based on n values we can conclude that the rate of resistance changes is somewhere between $t^{1/5}$ and $t^{1/2}$ law. For example, during ageing of self-made $CaIr_xTi_{1-x}O_3$ or IrO_2-based thick-film resistors a positive time–dependent resistance drift has been shown below 300°C and values of n equal to 0.40-0.55 for the structures based on IrO_2, 0.31-0.45 for the $CaIr_{0.75}Ti_{0.25}O_3$-based films and 0.30-0.34 for the resistors with $CaIr_{0.5}Ti_{0.5}O_3$ have been obtained by the least-squares method [22]. In this case the initial base materials affect the long-term stability of resistors. Diffusion mechanisms ($n = 1/2$) dominate in IrO_2-based resistors whereas the changes due to the stress relief within the resistor volume ($n = 1/3$) are significant for films prepared in active chemical process; the stress relief becomes predominant mechanism when the Ti content is increased. Compositions based on mixed ternary oxides $CaIr_xTi_{1-x}O_3$ are characterized by better long-term stability at elevated temperature (above 300°C). Thanks to glass transformation they can operate successfully up to 400°C while the resistors with IrO_2 are satisfactory to 300°C.

But modern passives should be much smaller, cheaper and integrated. Fig. 4 presents schematic cross-section through surface and buried thick-film (or LTCC) resistor and its DC electrical equivalent circuit. The temperature causes changes not only in resistor volume (R_b) but also in interface region between resistive film and terminations (R_k). The changes of R_k, difficult to describe by (1), become more and more important for miniaturized components.

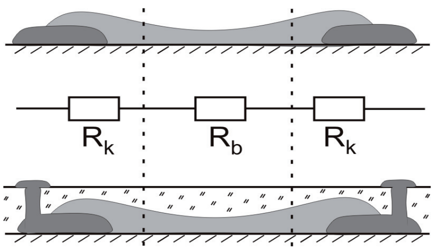


Fig. 4. Surface and buried resistor and it's DC electrical equivalent circuit.

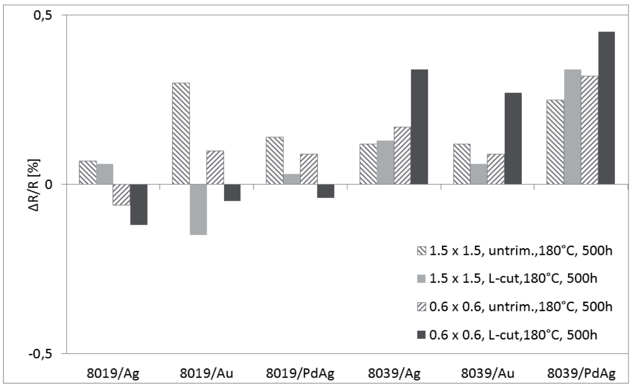
The example of long-term stability behavior of untrimmed and laser-trimmed resistors with various planar dimensions and contact metallurgy are summarized in

Fig. 5. Most of untrimmed resistors exhibit very small positive resistance drifts after long-term thermal ageing in 180°C. Stability of laser-trimmed structures is somewhat worse. Increase of ageing temperature leads in principle to negative resistance drift, larger for smaller structures [30].

The influence of termination metallurgy on long-term high-temperature behavior was confirmed in [18]; resistors with Au terminations have better stability than those with Ag or PdAg contact layers. Moreover longer and wider resistors exhibit smaller resistance drift.

According to [33] the standard long-term thermal ageing test (500 h or 1000 h at 150°C) is unselective for modern thick-film or LTCC resistors because the relative changes in resistance are within the ±0.2% range, independently on technological variants. Therefore the step-ageing profile (after 200 h ageing at specified temperature as well as resistance and *HTCR* measurements, in next step the temperature was raised by about 50°C and the same samples were held in these new conditions for next 200 hours) was used for analysis of the relative changes in resistance and changes in the HTCR versus storage time and temperature [34], [35]. The above ageing procedure was repeated for 96, 162, 207, 253, 300 and 350°C and the results were collected in Tab. 1.

The embedded resistors were somewhat more stable than surface ones. The buried CF021 (100 ohm/sq.) and CF041 (10 kohm/sq.) resistors were extremely stable - they exhibit fractional resistance changes within the ±0.3% range and changes in HTCR less than 20 ppm/°C, independently on processing conditions and ageing temperature. Surface resistors exhibit slightly larger changes of fractional resistance and HTCR but still they are enough stable and can be recommended for work at significantly high temperature (up to 300-350°C). Similar stability level is characteristic for DP2041. Only surface resistors from ESL 3414B ink (which is not designed for Du Pont ceramic tapes) exhibit significantly larger changes – up to 3% in relative resistance and 50 ppm/°C in *HTCR* after ageing at 300°C.



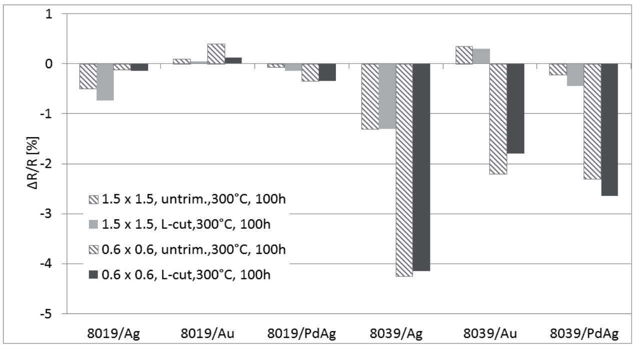


Fig. 5. Long-term stability of untrimmed and laser-trimmed DP8019 and DP8039 thick-film resistors with various planar dimensions and contact metallurgy (ageing conditions – 180°C/500 h or 300°C/100 h).

Ageing conditions		**200 h / 96°C**	**200 h / 162°C**	**200 h / 207°C**	**200 h / 253°C**	**200 h / 300°C**	**200 h/ 350°C**
Resistors/firing conditions	**Changes**						
DP2041, surface /875°C,15 min	***ΔR/R₀* [%]**	+0.02	+0.12	+0.37	+0.73	+0.50	-1.73
	***ΔHTCR* [ppm/°C]**	-5	+7	+7	+15	+5	-6
DP2041, buried /875°C,15 min	***ΔR/R₀* [%]**	-0.02	+0.05	+0.02	+0.06	-0.28	-1.06
	***ΔHTCR* [ppm/°C]**	-3	-6	+1	-7	+5	0
CF041, surface /875°C,15 min	***ΔR/R₀* [%]**	+0.02	+0.09	+0.12	+0.41	+0.49	+0.10
	***ΔHTCR* [ppm/°C]**	-3	-4	-2	-3	-3	-20
CF041, buried /875°C,15 min	***ΔR/R₀* [%]**	-0.03	-0.02	-0.01	+0.06	-0.02	-0.10
	***ΔHTCR* [ppm/°C]**	-2	-3	-7	-5	+2	+6
ESL3414B, surf. /875°C,15 min	***ΔR/R₀* [%]**	+0.32	+0.41	+1.54	+2.33	-1.20	-17.00
	***ΔHTCR* [ppm/°C]**	-32	+2	+13	-14	+39	+41
ESL3414B, buried /875°C,15 min	***ΔR/R₀* [%]**	-0.17	+0.11	+0.27	-0.38	-1.49	-3.19
	***ΔHTCR* [ppm/°C]**	+11	+6	+2	+18	+7	+10

Tab. 1. Relative changes in resistance and changes in *HTCR* in thermally aged LTCC resistors.

Recently thermal ageing behavior was checked for microresistors with regulated length made on LTCC (DP951, 300 μm thick) substrates by combining of standard screen-printing and photoimageable techniques [36]. Conductive paths were prepared from Ag65 photosensitive ink [37]. The distance between electrodes, i.e. proper resistor length was designed as 90, 120 and 300 μm. The 200 μm width resistors from DP2021 (DuPont, 100 ohm/sq.) or R490A (Heraeus, 10 ohm/sq.) pastes were screen-printed through 325 mesh screen. The conductive and resistive pastes were co-fired at 850ºC. The HP Agilent 34970A multimeter, interfaced to PC for data acquisition and presentation, was used for measurements of dynamic resistance changes directly at elevated temperature (so-called *in-situ* measurements of long-term stability [38]). The test structures were placed on hot plate equipped with spring probe needles and digital temperature controller. They were step-aged at 300°C, 400°C and 500°C for minimum 72 hours. The data were collected every 15 minutes. The dynamic resistance changes are shown in Fig. 6. The elevated temperature caused decrease of resistance for the DP2021 resistors. The observed drift was about -1.75% at 300°C. However, keeping at 400°C caused more significant changes of resistance up to -7%. The R490A resistors exhibit resistance drift of about ±2% at 300°C and 400°C.

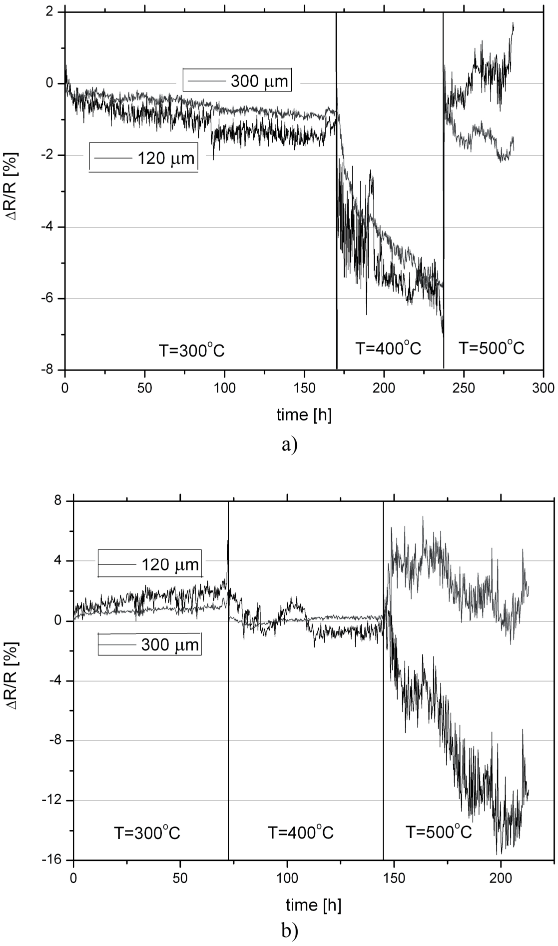


Fig. 6. Relative resistance changes for DP2021 (a) and R490A (b) resistors.

It was proved in [39] that 1/*f* noise is dominant in the low frequency range independently of the trimming method. The noise intensity of unaged structures is comparable for all resistors made of the same ink and of identical planar dimensions. After long-term thermal ageing the current noise of untrimmed and laser trimmed resistors does not change. But after this process the noticeable increase of current noise index is observed in high voltage trimmed resistors.

An interesting result was presented in [36] where pulse durability of components was compared for various ambient temperature (between room temperature and 500°C) – Figs. 7 and 8. Generally, a decrease of allowable electric field with the temperature increase was observed. However, at elevated temperature they were comparable. Moreover, shorter components exhibited higher durability to voltage pulses.

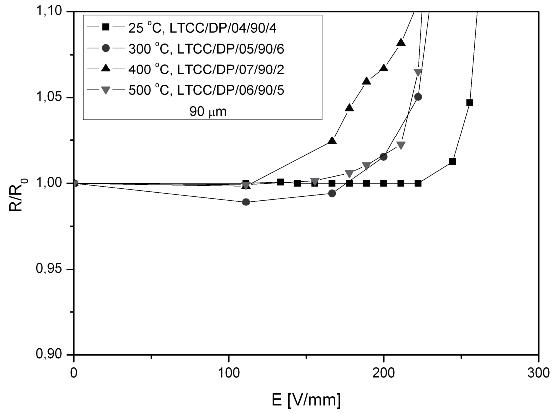


Fig. 7. Relative resistance changes versus electric field for DP2021 (pulse duration 20 μs).

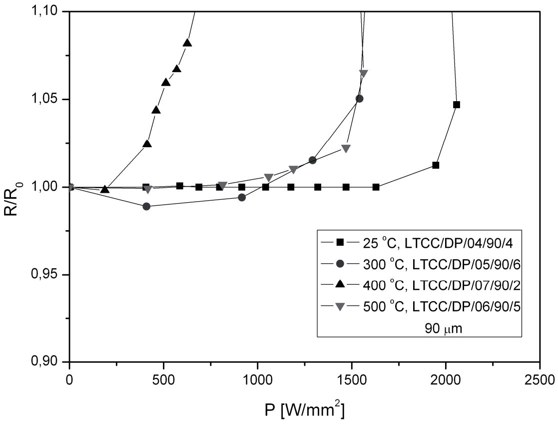


Fig. 8. Relative resistance changes versus surface power density for DP2021 (pulse duration 20 μs).

The data from this section show chosen electrical properties of thick-film resistors in high-temperature range. However one should pay attention that since today many parameters are not reported or reported only incidentally. For example nobody reported noise properties of such resistors in temperature from the range 150-500°C. Similarly there is no information about nonlinearity properties (expressed e.g. by third harmonic index) in above mentioned temperature range. Also reliability behavior of high-temperature components under pulse or cyclic operation modes should be deeply investigated (the second mode is important in thermal printheads, heaters for gas sensors or in creation of chemical or biochemical reactors).

4. High-Temperature Properties of Thick-Film and LTCC Capacitors and Inductors

The schematic construction of inductors and capacitors made in film technologies is shown in Figs. 9 and 10 whereas the examples of laser shaped comb capacitor and planar inductor are visible in Fig. 1c. To obtain larger capacitance or inductance ferroelectric or ferromagnetic materials are recommended (Fig. 11). However since today there are no such materials prepared in the ink forms with Curie temperature of about 500°C.

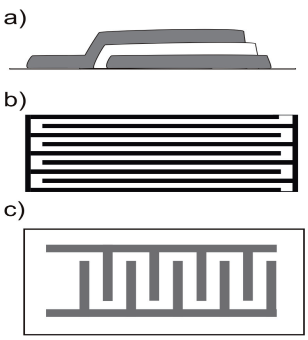


Fig. 9. Capacitor: a) sandwich structure, b) multilayer, c) interdigital (a and b – cross-section, c – top view)

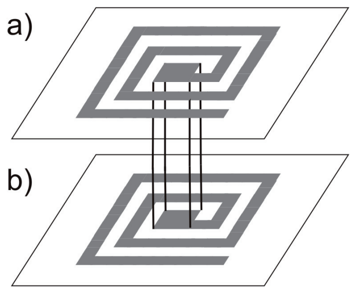


Fig. 10. Inductor: a) planar, a+b) multilayer.

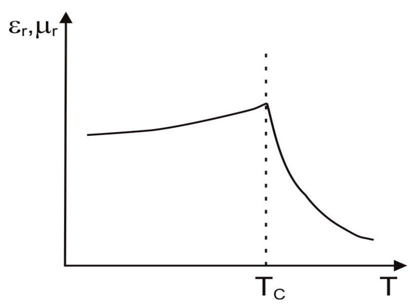


Fig. 11. Transition ferro-para in dielectric or magnetic materials (T_C – Curie temperature).

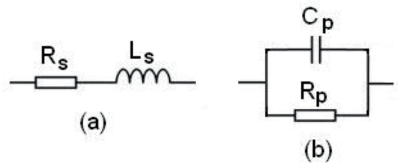


Fig. 12. Equivalent circuit of inductor (a) and capacitor (b).

The electrical measurements of square planar inductors and interdigital capacitors (fabricated on the 3×3 mm^2 area) were made in the frequency range from 10 kHz to 110 MHz using HP Agilent 4292A impedance analyzer for temperature from 25°C up to 450°C [20]. The values of their parameters were described using electrical equivalent circuits given in Fig. 12. Fig. 13 and 14 present changes of serial inductance and resistance of 3-turns laser-shaped inductor made of DP6145 silver-based ink at different temperature. The small changes of inductance (about -5%) were observed whereas resistance depends strongly on temperature. It is caused by typical for metals increase of resistance (temperature coefficient of resistance for this ink is equal to 3170 ppm/°C). Moreover, above 10 MHz the skin effect occurs causing increase of conductor effective resistance. The increase of resistance causes simultaneous decrease of inductor quality factor, $Q_L = \omega L/R$ of component. 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 [17], [40], [41]. 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 connected with good temperature stability of applied thick-film conductors. Therefore ageing process practically does not affect $Q_L = f(\omega)$ dependence. One should expect, that air-cored thick-film inductors will be stable over a temperature range of 25 to 500°C, similarly like thin-film spiral ones [42].

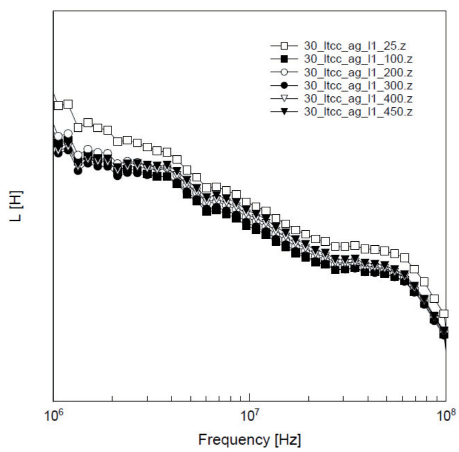


Fig. 13. Inductance changes at different temperatures for 30/30 μm inductor, DP6145, LTCC.

Thick-film capacitors' capacitance density 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 and LTCC technologies. For example comb capacitors made of ESL963 or DP6146 (PdAg-based) conductive inks and covered by ESL4164 ($\varepsilon_r = 250$) or DP5674 ($\varepsilon_r = 50 \div 80$) dielectric layer were aged at two temperatures – 150°C or 250°C for 275 h [9]. Most of samples showed satisfactory stability with capacitance changes smaller than ±3%.

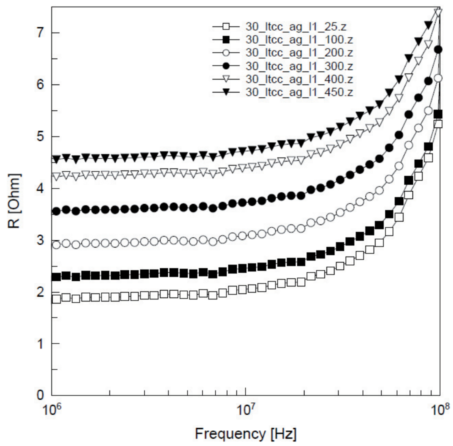


Fig. 14. Series resistance changes at different temperatures for 30/30 µm inductor, DP6145, LTCC.

The behavior of as-made and thermally aged capacitors in a wide temperature and frequency range was described by simple electrical equivalent circuit (Fig. 15) - the model includes serial resistance of terminations, R_s and two parts consisted of parallel resistance and constant phase element (Constant phase elements (CPE) has admittance described by relation $Y = Q(j\omega)^n$, where ω is angular frequency, j imaginary unit, Q, n are constants). They are related to electrode/dielectric interface (R_1 and CPE_1) and bulk dielectric material (R_2 and CPE_2), respectively. Different properties of those regions are modeled by *CPE* parameters, especially value of exponent n. It is nearly 1 for dielectric material (*CPE* practically is a pure capacitance) and about 0.6÷0.8 for electrode/dielectric interface [43]. Bulk material section of model is predominant in low frequency range. Interface region and serial resistance influence are important at higher frequency, affecting mainly dissipation factor value. Both temperature and thermal ageing affect strongly on that part of the model.

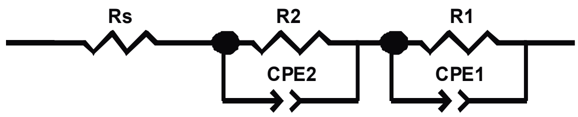


Fig. 15. Generalized equivalent circuit for microcapacitors.

Influence of thermal ageing on values of model elements is shown in Tab. 2. Larger changes were observed for parameters connected with electrode/dielectric interface region. However still "bulk" part of the electrical equivalent circuit plays the main role. While Q_2 altered slightly larger changes are obtained for R_2 resistance, n_2 exponent remains practically the same after ageing. Otherwise n_1 were much affected, except for planar structures. Also R_1 changed significantly compared to R_2.

Substrate	Sample history	R_s [Ω]	R_1 [Ω]	Q_1 [s^{n1}Ω]	n_1	R_2 [Ω]	Q_2 [s^{n2}Ω]	n_2
LTCC postfired	unaged	0.58	7.66×10^{-3}	8.66×10^{-8}	0.778	2.67×10^{-9}	4.61×10^{-11}	0.997
	aged 150°C	0.81	3.42×10^{-3}	1.23×10^{-7}	0.775	2.02×10^{-9}	4.44×10^{-11}	0.997
	unaged	0.56	6.80×10^{-3}	8.26×10^{-8}	0.779	1.47×10^{-9}	4.49×10^{-11}	0.997
	aged 250°C	0.89	3.25×10^{-3}	1.33×10^{-7}	0.774	2.19×10^{-9}	4.30×10^{-11}	0.997
Alumina	unaged	0.66	1.07×10^{-4}	5.81×10^{-8}	0.768	2.29×10^{-9}	3.03×10^{-11}	0.997
	aged 150°C	1.47	4.53×10^{-3}	8.42×10^{-8}	0.773	2.03×10^{-9}	2.99×10^{-11}	0.997
	unaged	0.57	8.37×10^{-3}	8.74×10^{-8}	0.759	2.03×10^{-9}	3.59×10^{-11}	0.997
	aged 250°C	1.45	8.60×10^{-3}	4.90×10^{-8}	0.806	1.77×10^{-9}	3.43×10^{-11}	0.998

Tab. 2. Thermal ageing effect on model parameters for planar ESL4164/ESL963 comb capacitors.

5. Conclusions

This paper presents in details material, technological and constructional solutions and their relation with electrical and high-stability properties of thick-film and LTCC passives – both described in the literature as well as screen-printed standard sized resistors as well as laser shaped microresistors, interdigital microcapacitors and air-cored microinductors, fabricated and characterized by authors at the Faculty of Microsystem Electronics and Photonics, Wroclaw University of Technology. In the case of resistors/microresistors long-term stability at elevated temperature (up to 500°C) has been analyzed as a function of various constructional and technological parameters of thick-film resistors, e.g. kind of resistor functional phase, its planar dimensions and contact metallurgy. The relative changes in resistance ($\Delta R/R_o$) during *ex-situ* or *in-situ* stability measurements, changes in the Hot Temperature Coefficient of Resistance after *ex-situ* long-term thermal ageing and pulse durability of components for various ambient temperature have been used for characterization of high-temperature properties of these components.

The electrical measurements of as-made and long-term high-temperature aged square planar inductors and interdigital capacitors (fabricated on the 3×3 mm^2 area) were made in the frequency range from 10 kHz to 110 MHz using HP Agilent 4292A impedance analyzer for temperature from 25°C up to 450°C. Their properties were described using proper electrical equivalent circuits. In the case of air-cored microinductors only small changes of inductance were observed in the whole temperature range whereas resistance of inductor depends strongly on temperature.

The model describing behavior of as-made and thermally aged capacitors in a wide temperature and frequency range includes serial resistance of terminations and two parts consisted of parallel resistance and constant phase element (related to electrode/dielectric interface and bulk dielectric material, respectively). Bulk material part of the model is predominant in low frequency range and interface region together with serial resistance - at higher frequency. After high-temperature thermal ageing larger changes are observed for parameters connected with electrode/dielectric interface region. However still "bulk" part of the electrical equivalent circuit plays the main role.

The above presented results prove that proper selection of thick-film inks together with proper deposition method permit to prepare thick-film micropassives (microresistors, air-cored microinductors and interdigital microcapacitors) suitable for the temperature range between 150°C and 400°C. However there are some properties which have to be investigated in future from the point of view of high-temperature passives.

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