Laser forming of LTCC Ceramics for Hot-Plate Gas Sensors

Jaroslaw Kita[1*], Frank Rettig[1], Ralf Moos[1], Karl-Heinz Drüe [2], Heiko Thust [2]
[1] University of Bayreuth, Chair of Functional Materials,
Universitätsstr. 30, D-95440 Bayreuth, Germany
Phone +49 921 7401, Fax +49 921 7405, email: Jaroslaw.Kita@Uni-Bayreuth.de
[2] Technical University of Ilmenau, Microperipheric Group,
Max-Planck-Ring 14, D-98693 Ilmenau, Germany
Phone: +49 3677 69 26 04 Fax +49 69 12 04
*-Corresponding author

Abstract

Hot-plate LTCC gas sensors combine advantages of silicon structures (low power consumption) and typical ceramics gas sensors (stability and reliability). Such elements can be integrated in MEMS packages as well as in ceramic sensor arrays. Moreover, they can be produced in small series with relatively low cost. One important key in hot-plate design are properly formed beams. This paper presents possibilities and problems related to laser forming of LTCC ceramics for hot-plate gas sensors. Influence of beam width on power consumption and temperature distribution is discussed. Possibilities to achieve beam width as narrow as possible are practically tested by laser cutting. Obtained results are very promising for future work and for possible application of LTCC ceramics in such type of gas sensors.

Key words

LTCC, low temperature cofired ceramics, ceramic hot-plate, gas sensor

1. INTRODUCTION

Design of modern electronic devices requires consideration of four important properties. They must be small, fast, low cost and low power devices. These requirements are valid for gas sensor design as well. Thick-film semiconductor gas sensors can be characterized as low cost sensors. However, power consumption is still far from expectations. The reason is not only the platinum heater dimension but also the substrate material. Usually alumina ceramics are applied to thick-film gas sensors substrate. This has many advantages. One of them is high thermal conductivity which allows obtaining a uniform temperature distribution in the gas sensing layer area. High thermal conductivity of alumina causes, however, relatively high power consumption. Heat is distributed along the whole substrate, not only in the area of the gas sensing layer.

The first logical step in decreasing of power consumption is the change of the substrate material. Low Temperature Cofired Ceramics (LTCC) seems to be appropriate for sensor construction. All materials known from thick-film technology can be used on LTCC substrate in the co-firing or post-firing process. First gas sensors in LTCC technology were reported in [1]-[3]. The results were very promising and deserved continuation of this work. Thermal conductivity of LTCC ceramics is about 3 W/m·K. This allows reducing power consumption up to 70 % only by changing the substrate material (for the same sensors dimensions – work temperature above 250°C) [4]. However, temperature distribution is unfavorable in comparison with alumina substrates. This can be avoided either by optimization of the heater meander or by forming the LTCC substrate [5].

Easy structuring of unfired LTCC tape enables the design of novel sensor substrates with respect to low power consumption. Very promising are ceramic hot-plate gas sensors [1], [2]. The construction resembles that of silicon hot-plate gas sensors [6], but in contrast to silicon structures, ceramic hot-plates can be produced in small series at relatively low cost. First results of investigations have been very promising. This paper continues investigations on ceramic hot-plate substrates for semiconductor gas sensors.

2. SENSOR DESIGN

Basic construction of ceramic hot-plates is very similar to silicon ones (Fig. 1). It consists of a small hot-plate (3.24 mm^2), four suspended beams and a frame. Platinum heater and contacts were printed by the standard screen-printing method. After lamination, structures were co-fired according to manufacturer’s recommendation.

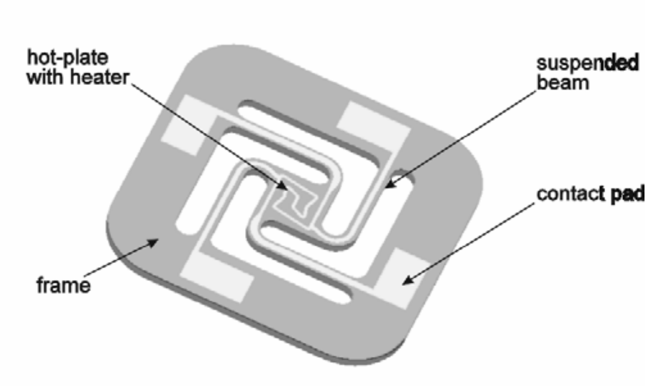

Fig. 1. Construction of hot-plate gas sensor

In the first design, suspended beams were 500 µm wide and conductors on the beam were 300 µm wide, respectively. The power consumption was about 630 mW (at 400°C). There are different ways and possibilities to minimize power consumption for the presented structure. One of them is decreasing the cross-section area of the beams. This can cause a reduction of heat transferred through the beams to the frame. In order to verify this assumption, simulations of sensor substrates with different beam widths were performed. All presented results of simulations were computed with the ALGOR FEM-Analysis software. The simulation was verified by infrared camera measurements. Simulated profiles agreed very well with measured ones [1], [2].

3. MODELING A SENSOR SUBSTRATE

In simulation, three different sensor substrates were tested. Structures were indicated as HP_0x3, HP_0x4 and HP_0x5 for structures with suspended beam widths 0.3, 0.4 and 0.5 mm (before firing), respectively. All others dimensions of the structure remained unchanged. Shrinkage of the tape was taken into account in the simulation process. For the selection of beam width practical considerations were taken into account. Narrower beams, e.g. 0.15 mm, are difficult to produce in LTCC technology and are mechanically not stable. In addition to that, line widths below 100 - 150 µm cannot be obtained by standard screen-printing.

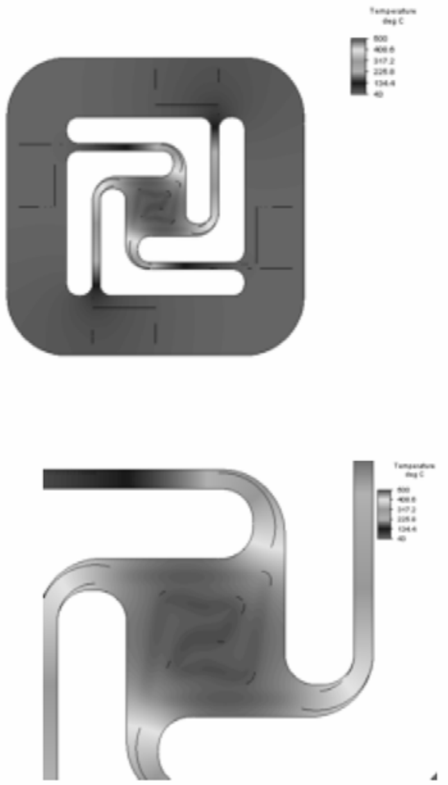

Fig. 2. Temperature distribution on sensor substrate (top) and hot-plate area (bottom) for structure HP_0x3

Fig. 2 shows the temperature distribution of the whole substrate and of the hot-plate area (in this case, as an example, for structure HP_0x3, max. temp. 500°C). As can be expected, the frame is cold in comparison with the hot-plate. Temperature of the frame does not exceed 45°C, whereas maximum temperature of the hot-plate is equal to 500°C. Temperature distribution on the hot-plate is acceptable due to the double spiral heater. Similar results were obtained for other beam widths. Decreasing of beam widths does not affect significantly temperature distribution in the gas sensing layer area (area of the hot-plate; a little bit smaller than heater size). For working temperature of 500°C the uniformity of temperature distribution in the desired region was about ± 1.5% (Fig. 3).

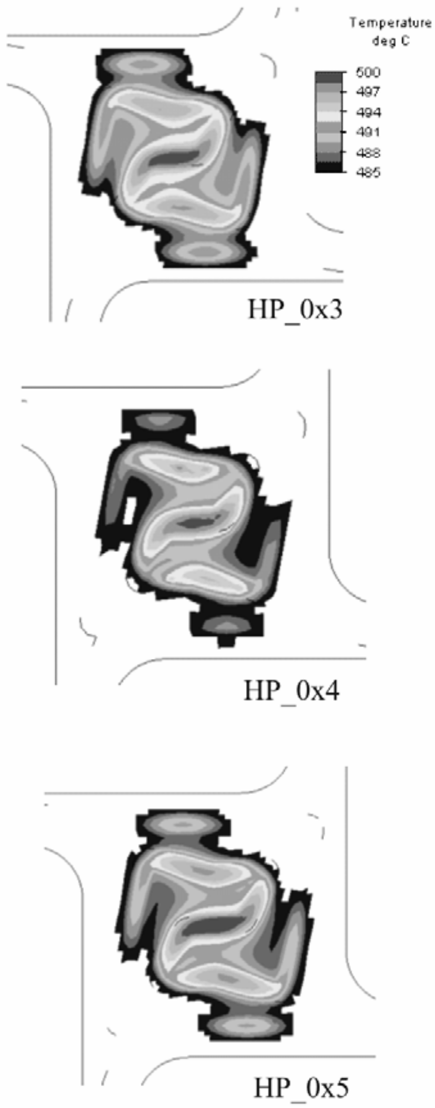

Fig. 3. **Comparison of temperature distribution on the hot-plate area for different beams widths**

However, power consumption decreases with decreasing beam width as shown in Table 1. Smaller beams are affected more on heat transferred by conduction in ceramics. Convection changes only slightly because the vertical walls convection coefficient (80 W/m^2·K) remains the same and the change of substrate area is relatively small – about 2%.

Table 1. Power consumption of hot-plate substrates with different beam widths

	T_{max} = 400°C	T_{max} = 500°C
Sample		
HP_0x3	598 mW	771 mW
HP_0x4	617 mW	796 mW
HP_0x5	682 mW	949 mW

Non-linearity in power consumption between structures is probably caused by influence of beam width on radiation, which increases very fast with temperature. Differences in power consumption between structures 0x5 and 0x3 are about 13.5% (at 400°C) and 19% (at 500°C), respectively.

Performed simulations showed that it is possible to minimise power consumption without significant changes in temperature distribution by decreasing beam width. Next step is to verify whether it is possible to produce very fine structures with beams width down to 0.3 mm.

4. LASER FORMING OF LTCC CERAMICS

There are different methods of forming of LTCC ceramics: drilling, punching, etching, laser cutting. Punching is an easy method of structuring, however very inflexible in laboratory. Laser cutting seems to be more suitable than the other methods. For cutting of unfired ceramics, a frequency-tripled Nd-YAG UV laser (λ = 355 nm) was used. Laser beam diameter was about 25 µm. Two types of LTCC tapes were used: DP 951 AT (DuPont) and CT 2000 (Heraeus). The tape thickness was 96 µm and 99 µm, respectively.

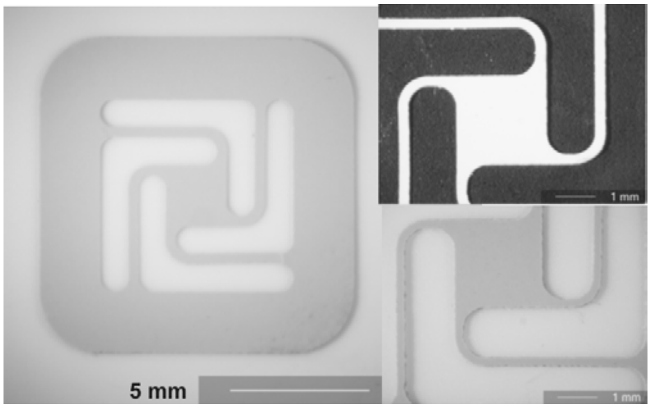

Fig. 4. Examples of laser cut green LTCC tapes: left: whole structure (beam width – 0.4 mm); right - CT 2000 (top) and DP 951 (bottom) - designed beam width – 0.3 mm.

Initial tests were carried out with tapes without printed electrodes and heaters to avoid shrinkage mismatches between thick film and ceramics. In both tapes it was possible to cut 0.3 mm beams (Fig. 4). After laser parameter optimisation, clean cuts were achieved. After cutting, structures were fired according to manufacturer's recommendation. Fired structures are shown in Fig. 5. During firing shrinkage of the tape occurs, as it is characteristic for LTCC. For DuPont tape shrinking is about 12.7% in X-Y axes and for Heraeus tape about 14.4%. Beam width after firing was between 0.21 and 0.46 mm. After firing small deformations of beams were observed (Fig. 5). This phenomenon goes along with the shrinkage process and the mechanical stress that occurs. Although deformations are not significant, it is very difficult to print conductors on such fine beams. Therefore, in a second optimisation step conductors (heater, electrodes) were printed first and afterwards tapes were laser-structured.

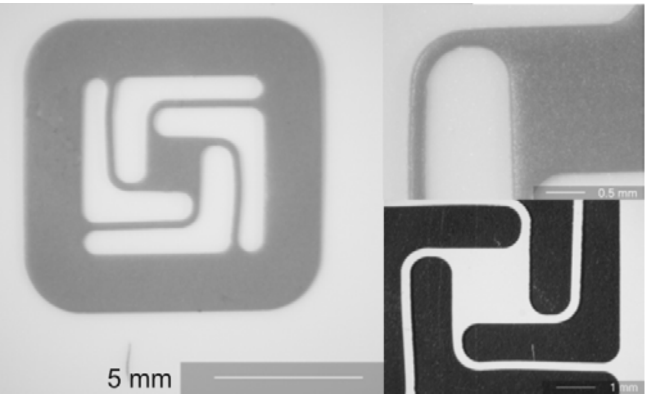

Fig. 5. Hot-plate structures after firing: whole substrate HP0x4 (right), HP0x3 DP 951 (top left) and CT 2000 (bottom left).

The quality of the tapes that were cut after the heaters were printed is very good (Fig. 6). Small displacements of printed structure were observed, but laser cut did not affect the conductors.

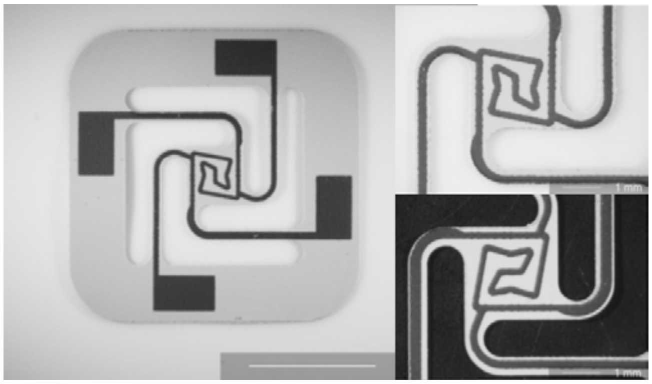

Fig. 6. Hot-plates HP0x4 with printed heater: DP 951 (top right and left) and CT 2000 (bottom left).

Examples of structures after firing are shown in Fig. 7. In the case of DuPont LTCC small beam deformations were observed. Structures made out of CT 2000 tape looked better and shape of beams remained practically the same. One can notice that quality of fired substrates made out of DP 951 and CT 2000 tapes is acceptable and structures of the both suppliers are suitable for further tests.

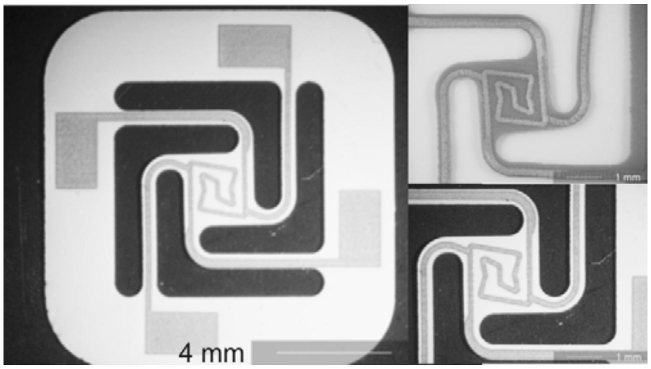

Fig. 7. Fired hot-plates HP0x4 with printed heater: CT 2000 (bottom right and left) and DP 951 (top right).

5. PROBLEMS WITH FINE-LINE STRUCTURING

Fine line structuring is a difficult technology due to small dimensions of produced elements. Even small differences in dimensions or positioning e.g. 50 µm play an important role. As mentioned above, structure was designed with beams width 0.3, 0.4 and 0.5 mm. Measurements of unfired and structured tapes exhibit differences between projected and obtained beam widths. In Table 2 results of measurements of unfired and fired samples were compiled.

Table 2. Projected and obtained beams widths for DP 951 and CT 2000 tapes

Projected beam width [µm]	Obtained width in DP 951 [µm]		Obtained width in CT 2000 [µm]	
	unfired	fired	unfired	fired
300	234	208	261	231
400	342	297	354	313
500	416	370	465	407

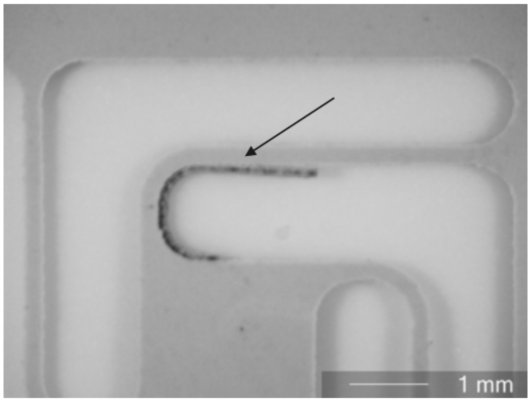

Fig. 8. Burned part of ceramics adhered on the beam after the laser cut process (arrow)

The differences can be due to different tape compositions, influence of laser beam diameter (position of the laser is calculated for the middle of laser beam), inappropriate focusing or too high applied laser power. When laser power is to high or focusing is inappropriate, then the laser cut trace is wider compared with optimal cutting parameters. The so-called debris region (region covered with laser-ablated material where it is non-irradiated by the laser beam) [7] is more pronounced. This part of ceramics remains after the cut process but it is often burned, not stable and easy to remove as shown in Fig. 8. Finally, the beam can be narrower than designed. Shrinkage is little bit smaller but very close to values given in datasheets of the tapes. There were only small differences in shrinkage between beams with or without printed conductors.

6. CONCLUSION

In this paper possibilities of power consumption reduction in ceramic hot-plates gas sensors were pointed out. FEM-Analysis based on measured data showed that decreasing beams cross-section causes reduction of heater's power about 15-20% without significant temperature distribution changes in hot-plate area. LTCC tapes were structured successfully with UV laser. Minimal obtained beams width was about 200 or 230 µm (after firing). From practical point of view structuring tapes with printed structure is recommended. In the next step, long-term stability of such structures will be tested.

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