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Automotive MEMS sensors based on additive technologies

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Abstract. The application of MEMS devices is one of the recent trends in sensor technology. However, traditional silicon MEMS have some intrinsic limitations, when applied to the monitoring of high temperature/high humidity processes. Thin ceramic films of alumina, zirconia or LTCC fixed on rigid frame made of the same ceramic material in combination with ink and aerosol jet printing of functional materials (heaters, temperature, pressure, gas sensitive elements) provides a cheap, flexible, and high-performance alternative for silicon MEMS devices used as gas sensors, gas flowmeters, lambda probes, bolometric matrices for automotive and general application.

1. Introduction

Recently, the main part of semiconductor and thermocatalytic gas sensors used in gas analytic instruments in the world is fabricated using thick film technology [1]. The application of this technology enables the fabrication of rather stable gas sensors, the elements of the sensor being fabricated by printing of conductive (Pt-based) or resistive (RuO$_2$ based) ink (paste) for the heater of the sensor and metal oxide semiconductor (doped SnO$_2$, ZnO, TiO$_2$ nanopowder) or thermocatalytic layer (Pt-Pd loaded Al$_2$O$_3$) ink for the sensing layer. The sensors produced by this technology are characterized by relatively high power consumption at working temperature. For example, the sensor described in [1] consumes ~ 280 mW at working temperature of 450ºC. This power consumption is related to the large size of the sensor made using thick film technology; the optimization of sensor layout permits to decrease power consumption down to ~ 100 – 120 mW, but a further decrease in power consumption seems to impossible within this approach.

Last years, this limitation was overcome by the application of silicon MEMS technology [2] used for the fabrication of sensor micro-hotplates. Using this technology, not only gas sensors were fabricated, it was applied for a large number of different devices, like flow meters, microbolometers, etc. At the moment, the main disadvantages of this technology are related with limited working and technological (necessary for the formation of sensing layers) temperature of the sensor and with the application of expensive and sophisticated equipment for the fabrication of sensors [3-8].

A possible solution of these problems was suggested in [9]. This solution consists in the application of ceramic MEMS substrates made of thin films of alumina, zirconia, or LTCC (thickness 10 – 20 µm) stretched on rigid frame made of the same material as the material of the membrane. This approach...
permits us to avoid problems related to the difference in expansion coefficients typical of silicon based MEMS. The advantages of this device layout become more pronounced if the functional elements of MEMS device are produced by aerosol or ink jet technologies providing flexibility of the technological process and low cost of the production. Indeed, the modification of sensor layout is related only to the modification of program controlling the printing process, and the ink, in contrast to sputtering process, is deposited only where it is necessary, but not everywhere in the sputtering chamber. In addition, the application of printing process enables the avoidance of photolithographic process and platinum etching.

These ceramic MEMS can operate at high ambient temperature and, in general, under harsh environmental conditions, and, therefore are very promising for automotive gas concentration and gas flow sensors. We consider the possibility to use the ceramic MEMS for most type of sensors used in the car industry: gas, flow, pressure, acceleration, IR, and other sensors.

2. Experiment

The basis of these MEMS devices is 12 µm thick alumina films made by anodic oxidation of aluminum. This possibility was discussed in publications [9,10]. Large area (>48×60 mm) films remain flat after annealing at 1000°C. Therefore, the application of thin alumina films enables the deposition and further annealing of almost any functional materials: platinum and ruthenium dioxide based heaters requiring annealing at ~ 850°C, sensing layers based on SnO₂, ZnO, TiO₂, etc., requiring formation temperature of ~ 700 - 750°C, high TCR materials for microbolometers.

Other possibilities for the fabrication of ceramic MEMS is given by thin slip cast HTCC based on yttria-stabilized zirconia and LTCC. These ceramic films can be 10-20 µm thick. An example of ceramic MEMS made of thin LTCC is presented in Fig. 1. This element was fabricated by slip casting of LTCC film (20 µm thick) followed by the co-pressing of this film with thick LTCC ceramics with a hole. In the next generation of the sensor, substrates, we will fabricate the whole substrate with such elements containing several hundreds of individual chips.

![Figure 1](image.png)

**Figure 1.** Top and bottom view of sensor chip made of 20 µm thick LTCC ceramics fixed on 0.5 mm LTCC frame.

Heating elements are fabricated by aerosol and ink jet printing using ink containing 3-5 nm particles of Pt as described in [10]. After drying and annealing, these prints give 20-40 µm wide lines stable at working temperature > 500°C.

An example of the microheater deposited on 12-micron thick aluminum oxide film is presented in Fig. 2. The size of the microcantilever triangle heater is of about 1 (base of the triangle) to 2 mm, the width of platinum lines is about 35 µm.
Figure 2. Platinum microheater fabricated using platinum aerosol jet printing over alumina membrane with a thickness of 12 μm. Heater size is of ~1 (base) × 2 mm. Hot area is located in the vertex of the triangle, where the line width is 35 μm.

After deposition, the ceramic membrane was cut by a laser beam (optic fibre laser with a wavelength of 1.06 μm and maximum power of 50 W normally used as a marker) to form sharp triangle cantilever with the hot area located in the vertex of the triangle. This sensor layout permits us to minimize heat losses from the hotplate due to minimization of thickness and area of heat conducting element. In addition, the application of cantilever type micro-hotplate improves the stability of microheater, because, in contrast to the whole membrane, heating of cantilever does not lead to bending of the hot element.

A sensing layer of the gas sensor was deposited by ink jet or using drop coating technique. Sensing material was prepared using tin (II) sulfate as a precursor, tin was oxidized in solution by hydrogen peroxide. The application of this procedure enables direct synthesis of powder with a specific area of about 100 m²/g (particle size of about 10 nm). The printable ink was prepared by mixing this powder with a solution of ethylcellulose in terpineol.

3. Results and discussion

We tested thermal properties of micro-hotplates based on thin alumina with Pt aerosol jet printed microheater.

Figure 3. Heating power of cantilever type gas sensor (Fig. 2) as a function of working temperature. The micro-hotplate consumes approximately 70 mW at working temperature of 450°C necessary for methane detection.

The heating power consumption of alumina MEMS is about 70 mW at permanent heating to 450 °C. The plot illustrating the power consumption as a function of working temperature is presented in Fig. 3. The temperature of the microheater was calculated using the value of TCR measured.
preliminarily in the furnace.

This value is the same as the power consumption of micro-hotplate fabricated using silicon MEMS technology [11] working at about 350 °C. At the same working temperature our ceramic MEMS micro-hotplate consumes ~ 55 mW, therefore the thermal efficiency of ceramic MEMS is at least not worse compared to silicon MEMS. Short thermal response time (<100 ms) of the microheater allows the fabrication of fast temperature sensors and enables the operation of gas sensors in pulse heating mode permitting, in turn, selective measurement of gases (CO and H₂, for example) and application of ceramic MEMS in mobile and autonomous instruments, because average power consumption of gas sensor in this case is below 1 mW. It was demonstrated that the detection limit of CO and hydrogen using this pulsing heating mode is about 1 ppm.

4. Conclusion

The application of ceramic MEMS with thin membrane element in combination with aerosol and ink jet technology of functional element printing enables flexible and cheap fabrication of various elements of electronics for harsh environment and automotive application.

The advantages of ceramic MEMS technology is most pronounced when these sensors are used for high temperature/harsh environment application. Indeed, the ceramic substrate used for such micro-hotplate is annealed at 1000 °C. Therefore any reasonable operation and technological temperature can not damage it.

Among these elements, which could be fabricated using a combination of ceramic MEMS and aerosol/ink jet technique are air quality sensors, lambda probes, gas flow sensors and other devices working at high temperature. This approach gives a possibility to fabricate sensors with characteristics exceeding the characteristics of silicon MEMS devices, but free of disadvantages of the last: ceramic MEMS is characterized by full compatibility of materials, high working temperature, and high-cost efficiency at medium scale production (up to several million units per year). The application of platinum ink jet printed conductive lines are characterized by good adhesion of platinum to alumina after annealing at a temperature of ~ 800 °C. Any other material but ceramics can not withstand this technological temperature. Decrease in production cost of printed micro-hotplates is related to a decrease in permanent production expenses: silicon MEMS technology needs not only expensive equipment but is also characterized but high service cost, which can not be attractive if the production scale is not extremely large.

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