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Multipurpose MEMS thermal sensor based on thermopiles

Danijela Randjelović [a,*], Anastasios Petropoulos [b], Grigoris Kaltsas [c,b], Miloš Stojanović [d], Žarko Lazić [a], Zoran Djurić [a], Milan Matić [a]

[a] IHTM, Institute of Microelectronic Technologies and Single Crystals, University of Belgrade, Njegoševa 12, 11000 Belgrade, Serbia
[b] IMEL/NCSR Demokritos, P.O. Box 60228, 15310 Aghia Paraskevi, Athens, Greece
[c] Technological Educational Institution (TEI) of Athens, Department of Electronics, 12210 Egaleo, Athens, Greece
[d] ENIGMA Instrument, Studentski trg 19/III, 11000 Belgrade, Serbia

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Abstract

This paper presents design, fabrication and experimental results of multipurpose thermopile based sensor which is compatible with technological processes already developed at IHTM-IMTM for fabrication of pressure sensors. Thermal isolation is assured using back etching of bulk silicon. Thermopiles have multilayer structure and sandwich membrane consists of layer of residual n-Si and sputtered oxide. Post-etching technique was developed and functional structures with membranes below 3 μm were fabricated. Steady state and transient behaviour of fabricated structures were anticipated by applying two-zone 1D analytical model and FEA Comsol simulation. Sensors were tested as ac–dc transfer devices, gas flow meters and vacuum detectors.

Keywords: Thermopile; Micromachining; Analytical and FEA modelling; Thermal converter; Flow meter; Vacuum detector

1. Introduction

Principle of operation of thermopile based MEMS sensors relies on detection of thermal gradient established on the chip. Depending on output signal, this type of sensors can be divided in two groups: (1) output signal is equal to the sum of thermopile voltages placed on the chip (thermal converters [1–3], vacuum detectors [4], IR detectors [5–7], chemical sensors [8]), (2) output signal is equal to the difference of thermopile voltages (flow sensors [9–11], accelerometers, inclinometers [12,13]).

This paper presents a multipurpose sensor with thermopiles. Section 2 of this paper covers design and modelling of the device. Design and fabrication technology are presented in Section 2.1. The structure is designed with two independent thermopiles in order to enable different applications where output signal can be either the sum or the difference of the two Seebeck voltages. Two types of sensors with p^+Si/Al thermocouples were fabricated – type »P« with p^+Si heater, and type »A« with Al heater. Sensors with different membrane thickness were obtained using wet post etching method. Section 2.2 gives analytical and FEA simulation results for stationary and transient regime. Experimental results and discussion are presented in Section 3. Tests cover thermal characterization of steady state response of structures with different membrane thicknesses, ac–dc transfer (thermal converter), gas flow measuring and vacuum detection. Experimental and theoretical results are compared and analytical model is applied for estimation of membrane thickness of fabricated sensors.

2. Design and modelling

2.1. Design and fabrication of the device

Design of multipurpose sensor based on Seebeck effect is based on characterization results obtained for test structure [14]. Similar devices have been proposed in the literature [1,2] from other groups. The main idea was to obtain structure with enhanced performance which is fabricated using technological processes already developed at IHTM-IMTM for fabrication of piezoresistive pressure sensors. The specific technology was chosen because it is mature enough and well established for

* Corresponding author. Tel.: +381 11 2638 188; fax: +381 11 2182 995.
E-mail address: danijela@nanosys.ihtm.bg.ac.yu (D. Randjelović).

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industrial use. It provides reliable and reproducible results and has the potential to be integrated with the corresponding readout electronics.

The chip area which is of the identical size as test structure (3.6 mm × 4.8 mm) contains two independent thermopiles with 30 multilayered p$^+$Si/Al thermocouples placed symmetrically relative to the central heater (p$^+$Si or Al). Two lateral p$^+$Si thermistors are placed on the rim for monitoring of the cold junctions temperature. Central area of the chip is sandwich membrane consisting of sputtered oxide 1 μm thick and a thin layer of n-Si (thickness, $d_{\text{n-Si}}$).

Each thermopile has separate contact pads in order to enable sensor applications were difference of Seebeck voltages between left and right thermopile presents output signal. When the structure is functioning as thermal converter, the two thermopiles should be connected in series.

We used double side polished n-type Si wafers with ⟨1 0 0⟩ orientation, nominal thickness of 385 μm and nominal resistivity 3–5 Ω cm. The first part of thermocouples, lateral thermistors and heater of P-type sensors are formed during the shallow diffusion process. In order to achieve thermal and electrical isolation between p$^+$Si and Al thermocouple lines and to avoid redistribution of the dopants it was not possible to use thermal oxide. Sputtered oxide had to be chosen instead. Al layer is also sputter deposited as the second part of thermocouples, contact pads and heater of A-type sensors. Quality of the fabricated chips and uniformity of their parameters were checked using prober Karl Suss AP4.

Designed structures contain thermocouples with multilayer structure where Al and p$^+$Si lines are placed one over another. These lines are thermally and electrically isolated by a layer of sputtered SiO_2. Simulation results show that sensor sensitivity can be significantly improved by reducing the n-Si membrane thickness. The highest influence on sensor performance is accomplished after complete removal of the residual n-Si. At that point, membrane of pure oxide is obtained with p$^+$Si lines surrounded by air. Realization of this kind of structures is performed using post-etching bulk micromachining techniques. Fig. 1 shows sensor with boss after complete removal of n-Si. Etching was performed in aqueous KOH solution at room temperature. This kind of etching was performed on structures with NiCr/Au thermocouples and NiCr heater. During etching process, it was not necessary to protect the upper side of the chip because gold used as metallization is resistant to KOH solutions.

Sensors of »A« and »P« type have Al metallization for which isotropic etching is more suitable. The best results are obtained when aqueous solution of HF and nitric acids is used. During the process it is necessary to protect the upper side of the chip which contains areas where oxide is exposed. Picein was used as a protection barrier. Using this procedure, structures with membrane thicknesses below 3 μm were fabricated. Experimental results presented in the Section 3 shows that functionality of the structures was completely maintained while sensor performances were noticeably improved.

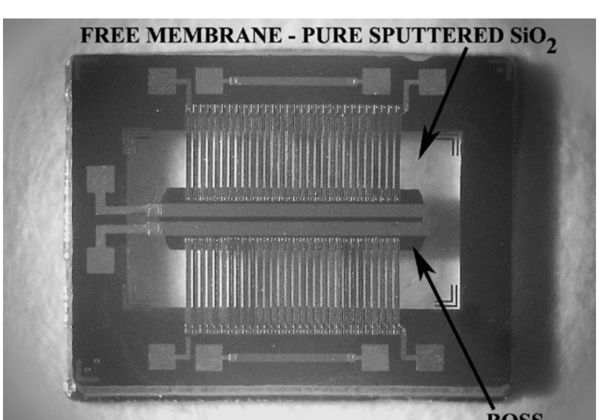

Fig. 1. Thermal sensor with “boss” structure, NiCr heater and NiCr/Au thermocouples after complete release of oxide membrane using bulk micromachining.

2.2. Modelling–simulation of the device

Since the operation of thermopile based sensors relies on formation of temperature gradient on the chip, we applied analytical and numerical methods to analyse spatial and time dependence of temperature profile formed on the chip for different heating powers and membrane thicknesses.

2.2.1. Steady-state simulation

Combining principles of analytical modelling of thermopile based sensors [15–19] designed structure was analysed using appropriate two-zone model. The same structure can be divided in three zones also, but the two-zone model was chosen as a simpler while retaining the calculation accuracy. Using the symmetry of the sensor, it is sufficient to analyse only one half of the structure, taking care about corresponding input and output values of the sensor as a whole. Simulation shows that instead of analysing the whole membrane area it is sufficient to take into account only the part defined by upper and lower edges of the heater (Fig. 2). It is assumed that the surrounding bulk rim

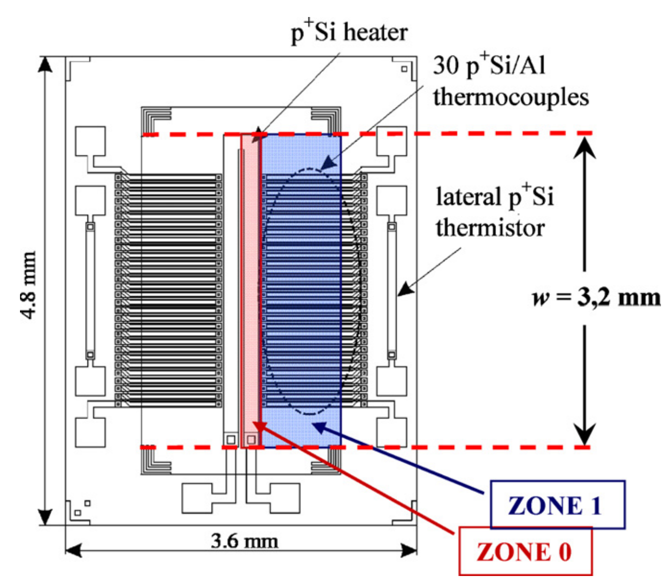

Fig. 2. Partition of sensor in zones 0 and 1, membrane area of interest is marked with dashed lines.