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.

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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
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_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 ⟨100⟩ 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 SiO2. 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.

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

Fig. 2. Partition of sensor in zones 0 and 1, membrane area of interest is marked with dashed lines.
is efficient heat sink which maintains constant cold junctions temperature equal to ambient temperature, $T_a$.

Fig. 3 shows that right half of the structure is divided into two zones, zone 0 (heater area) and zone 1 (thermocouples plus area between hot junctions and outer heater edge). Width of these areas is $w = 3.2$ mm, length $l_0 = 0.18$ mm, while $l_1$ depends on $d_{n-Si}$ and equals 0.805 mm for $d_{n-Si} = 20$ μm. Each zone has its own coordinate system and temperature $T_i$ ($i=0$, 1). Zone 0 is characterized by generated heat flux, $q_0$, while between zones 0 and 1 there exists thermal energy transfer characterized by flux $q_{01}$.

During analysis, each zone “i”, containing $n$ layers of different materials “l”, with thickness $d_i^l$ and thermal conductivity $\lambda_i^l$ is replaced with the equivalent one, which has homogenous structure and is characterized by the following parameters:

- equivalent thickness:
  
  $$d_i^e = \sum_{i=1}^{n} k_i^l d_i^l$$  
  
- equivalent thermal conductivity:
  
  $$\lambda_i^e = \frac{1}{d_i^e} \sum_{i=1}^{n} k_i^l d_i^l \lambda_i^l$$

In previous relations, the coefficient of “coverage”, $k_i^l$, is defined as a ratio of area covered by elements fabricated of material “l” in a zone “i” to the area of zone “i”.

Zone 0 contains one half of the heater and represents active-heat generating region. Using heat transfer theory [20], heat balance equation for zone 0 ($0 < x_0 < l_0$) can be written in the form

$$\frac{\partial^2 \theta_0}{\partial x_0^2} - m_0^2 \theta_0(x_0) = -\frac{\phi_0}{\lambda_0 d_0}, \quad m_0 = \sqrt{\frac{A_0}{\lambda_0 d_0}},$$

where $\phi_0$ is heat energy density, $\theta_0 = T_0(x_0) - T_a$, $d_0$ and $\lambda_0$ are equivalent thickness and thermal conductivity of zone 0 given by Eqs. (1) and (2). Coefficient of total convective and radiative losses for zone 0 is given by relation

$$A_0 = h_0 + 4 \sigma B (\varepsilon_0 w + \varepsilon_0 l) T_a^3$$

where $h_0$ is convection coefficient, $\sigma B = 5.67 \times 10^{-8}$ W/(m² K⁴) is Stefan–Boltzmann constant, $\varepsilon_0 w$ and $\varepsilon_0 l$ are emissivities of the upper and lower surface of zone 0.

Following boundary conditions are valid for zone 0:

$$-\lambda_0 \frac{\partial \theta_0(x_0)}{\partial x_0} \bigg|_{x_0=0} = 0, \quad -\lambda_0 \frac{\partial \theta_0(x_0)}{\partial x_0} \bigg|_{x_0=l_0} = q_{01}. \tag{5}$$

General solution of the partial differential equation given by Eq. (3) is of the form

$$\theta = C_1 e^{m x} + C_2 e^{-m x} + C_3.$$ \tag{6}

Using the two boundary conditions, final expression for temperature rise in zone 0 is obtained

$$\theta_0(x_0) = \frac{\phi_0}{A_0} \left[ 1 - \frac{ch(m_0 x_0)}{sh(m_0 l_0)} B^{-1} \right],$$

where parameters $\theta_1$, $m_1$, $A_1$ and $\lambda_1$ are defined analogously to those of zone 0. Using the general solution (Eq. (6)) and boundary conditions

$$-\lambda_1 \frac{\partial \theta_1(x_1)}{\partial x_1} \bigg|_{x_1=0} = q_{01}, \quad \theta_1(x_1)|_{x_1=l_1} = 0,$$

expression for temperature rise in zone 1 is obtained

$$\theta_1(x_1) = \frac{\phi_0 \lambda_0 m_0}{A_0 \lambda_1 m_1} B^{-1} sh[m_1(l_1 - x_1)] \frac{ch(m_1 l_1)}{ch(m_1 l_1)}.$$ \tag{10}

Temperature gradient on the chip, $\Delta T$, is obtained as temperature difference between hot, $T_h = \theta_1(\Delta l)$, and cold junctions, $T_c = \theta_1(l_1)$:

$$\Delta T = T_h - T_c = \frac{\phi_0 \lambda_0 m_0}{A_0 \lambda_1 m_1} B^{-1} sh[m_1(l_1 - \Delta l)] \frac{ch(m_1 l_1)}{ch(m_1 l_1)},$$ \tag{11}

Since distance hot junctions-heater, $\Delta l$, is much smaller than $l_1$, the following approximation can be used

$$\Delta T = T_h - T_c = \frac{\phi_0 \lambda_1 m_1}{A_0 \lambda_0 m_0} \frac{ch(m_0 l_0)ch(m_1 l_1) + 1}{ch(m_1 l_1)} \tag{12}.$$
through conduction was the main mechanism that the model took into consideration. A constant power was applied to the heater. Results of numerical modelling are also shown in Figs. 4 and 5 as dotted lines.

The dies are considered to be mounted on a PCB substrate surrounded by air at an initial temperature of 300 K. The dimensions of the sensor elements as defined in Fig. 2 were accurately transferred into the model. Sensor components of sizes varying by orders of magnitude co-exist in the same mesh structure, which is an asset regarding the complicity of the model, but also a prohibiting factor regarding its expansion in three dimensions. In order to perform non-stationery analytical modelling it is much more convenient to analyse the structure in zones. In order to perform non-stationery analytical modelling in stationary regime is performed by dividing the structure: analytical modelling in stationary regime is performed by dividing the structure:

\[ T(x, t) = \sum_{n=1}^{\infty} \left( \frac{1}{\sqrt{\lambda_m I_0}} \right) \frac{1}{(m_1 + 1)} \left( \cos(m_1 x) \right) \cos(\omega_n x) \]

where \( \lambda_m \) and \( I_0 \) are thermal conductivity and cross-sectional area of the heater, respectively.

The obtained results indicate the temperature distribution in the upper surface of the heater as a function of the power generated at the heater and the residual n-Si thickness. A typical result of temperature distribution graphical presentation in Comsol is illustrated in Fig. 6. The generated power upper limit is 50 mW for the Al heater case and 150 mW for the p⁺Si heater case, while the thickness of the residual n-Si ranges from 20 μm down to about 0 μm (ideal case). As an overall estimate, they appear to be in very good agreement with the analytical solution, especially for large values of the residual n-Si thickness as shown in Figs. 4 and 5.

2.2.2. Transient simulation

Thermal sensor structure is relatively complicated and analytical modelling in stationary regime is performed by dividing the structure in zones. In order to perform non-stationery analytical modelling it is much more convenient to analyse the structure as a whole and introduce equivalent parameters (equivalent length, \( l_0 + l_1 \), equivalent thickness, \( d_e \), etc.) [17]. Heat equation of equivalent structure which is cooled after heat source is turned off is a partial differential equation with two independent variables: distance \( x \), and time \( t \).

\[ \frac{\partial^2 T(x, t)}{\partial x^2} - \frac{A_e}{\lambda_e d_e} (T(x, t) - T_0) = \frac{1}{\epsilon_e c_e} \frac{\partial T(x, t)}{\partial t}, \]

where \( A_e \) is equivalent thermal diffusivity equal to

\[ A_e = \frac{\lambda_e}{\epsilon_e c_e} = \frac{\rho_0 \lambda_0 \epsilon_1 l_1}{l_0 \epsilon_0 + l_1} \]

with \( \rho_0 \) and \( \lambda_0 \) equivalent thermal diffusivities of zones 0 and 1 calculated analogously to expression (2).

Following boundary conditions are valid for the analysed structure:

\[ \frac{\partial T(x = 0, t)}{\partial x} = 0, \quad T(l_0 + l_1, t) = T_0. \]

Initial condition

\[ T(x, t = 0) = f(x) \]

is obtained using results of stationary model (Eqs. (7) and (10)).
where expression $B$ is defined by Eq. (7) and

$$\omega_n = \frac{(2n - 1)\pi}{2(l_0 + l_1)}, \quad n = 1, \ldots, \infty$$

(18)

while $\tau_n$ is thermal time constant given by

$$\tau_n = \left[ a_x \left( \omega_n^2 + \frac{A_x}{\lambda_x a_x} \right) \right]^{-1}.$$

(19)

Integrals $I_1$, $I_2$ and $I_3$ are given below together with their solutions

$$I_1 = \int_0^{l_0} \cos(\omega_n x) \, dx = \frac{\sin(\omega_n l_0)}{\omega_n}$$

(20)

Integral $I_2$

$$I_2 = \int_0^{l_0} \cosh(m_0 x) \cos(\omega_n x) \, dx$$

$$= \frac{\omega_n \sin(\omega_n x) \cosh(m_0 x) + m_0 \cos(\omega_n x) \sinh(m_0 x)}{(m_0^2 + \omega_n^2)}$$

(21)

Integral $I_3$

$$I_3 = \int_{l_0}^{l_0 + l_1} \sinh(m_1 (l_0 + l_1 - x)) \cos(\omega_n x) \, dx$$

$$= \frac{\omega_n \sin(\omega_n x) \sinh(l_0 + l_1 - x)}{(m_1^2 + \omega_n^2)}$$

(22)

Using first order approximation, thermal time constant of sensors with Al and p+Si heater was estimated as Fig. 7 indicates. Fig. 8 shows spatial and time temperature distribution of temperature rise on surface of A-type sensors for various thicknesses of residual n-Si.

Fig. 7. Thermal time constant of A- and P-type sensors calculated using analytical model in transient regime.

Fig. 8. Spatial and time temperature distribution of temperature rise on a half of the chip for a sensor of A-type with n-Si membrane of thickness 20, 10, 5 and 0 μm.
3. Experimental results and discussion

In this section experimental results are given covering steady-state behaviour (thermal characterization, influence and estimation of membrane thickness, response time), ac–dc transfer and gas flow measurement.

3.1. Steady-state performance

Static sensitivity of the fabricated structures with different thickness of residual n-Si was obtained as a ratio of output Seebeck voltage and applied heating power. Measurements were performed under constant current condition provided by Keithley 220 Programmable current source. Output Seebeck voltage was measured using Agilent 34410A Digital multimeter. For A-type sensors input current was in the range 0–100 mA. For P-type sensors input current range was determined after measurement of time stability of output Seebeck voltage for different applied currents. It was concluded that output signal is stable up to 5 mA input current. The maximum applied power was 50 mW and 150 mW for devices with Al heater (5 Ω) and p⁺Si heater (5.8 kΩ) respectively.

Fig. 9 presents measured Seebeck voltage of the left thermopile of A-type sensors with different thicknesses of residual n-Si. Lines representing Seebeck voltage as a function of input power obtained using 1D analytical model for structures with residual n-Si thickness 3, 5, 10, 20 µm are also shown. Temperature variation of heater resistance was neglected.

Results of analytical modelling were applied for determination of residual n-Si thickness of fabricated sensors. Lines in Fig. 10 represent theoretical dependences of sensitivity, $S$, on residual n-Si thickness ($d_{n-Si}$) obtained using 1D analytical model for A- and P-type sensors. Sensitivity of the whole sensor, $S$, was calculated by taking into account twice higher voltage developed at both thermopiles. Using experimentally obtained sensitivities of sensors, $S_{exp}$, and theoretical dependence $S(d_{n-Si})$ and solving numerically equation

\[
S(d_{n-Si}) = S_{exp}
\]  

thickness of residual n-Si was calculated for each sensor. Fig. 10 also shows sensitivities of tested sensors placed at appropriate points on theoretical dependence of sensitivity line depending on residual n-Si thickness of tested A- and P-type sensors.

The dependence of the sensitivity on ambient temperature was also studied. For this purpose sensor was placed in the Heraeus VÖTSCH VMT 08/64/S temperature test chamber with temperature control ±0.5 °C. Fig. 11 shows measured static sensitivity of A- and P-type sensors as a function of input power at ambient temperatures in the range 20–60 °C. Temperature change of sensitivity can be calculated as slope of $S(T)$ lines. Sensor with the thinnest membrane (P2) has $\Delta S/\Delta T = 5.2 \text{ mV/(W °C)}$ while sensor P1 has $\Delta S/\Delta T = 1.7 \text{ mV/(W °C)}$. When relative temperature change ($\Delta S/\Delta S(T)$) is calculated it is obtained $2.15 \times 10^{-3} \text{ °C}^{-1}$ for P2 and $2.8 \times 10^{-3} \text{ °C}^{-1}$ for P1. TCR of p⁺Si heater is 0.001 °C⁻¹.

Fig. 9. Output voltage of a thermopile with 30 p⁺Si/Al thermocouples as a function of power developed at Al heater for different thicknesses of residual n-Si. Lines represent results obtained using 1D model and symbols are experimental values measured for four A-type sensors.

Fig. 10. Experimentally obtained sensitivities of fabricated A- and P-type sensors marked on theoretical $S(d_{n-Si})$ curve obtained using analytical model.

Fig. 11. Temperature dependence of sensitivities of A- and P-type sensors with thickest and thinnest membranes (A1, A4) and (P1, P2).
For A-type sensors absolute and relative temperature change of sensitivities are: A4: 5 mV/(W°C), 2.7 \times 10^{-3} °C^{-1}, A1: 1 mV/(W°C), 2.8 \times 10^{-3} °C^{-1}.

As in all other thermoelectric sensors, Johnson noise is dominant

\[ V_n = (4k_B T R_{tp} \Delta f)^{1/2} \]

where \( k_B = 1.38 \times 10^{-23} \text{ J/K} \) is Boltzmann constant. For A- and P-type sensors at ambient temperature (\( T = 300 \text{ K}, \Delta f = 1 \text{ Hz} \)) and thermopile resistance of \( R_{tp} = 140 \text{ kΩ} \), \( V_n = 48.1 \text{ nV} \) was calculated.

Thermal time constant of sensors was obtained by supplying a series of voltage impulses (impulse width 100 ms, and a very long period) generated with Hewlett–Packard 8002A Pulse Generator while thermopile voltage was stored using Tektronix TDS3000B Digital Oscilloscope. Analysing the response time of A-type sensors with four different membrane thicknesses it was concluded that thermal time constant variations are negligible and approximatively equal 4 ms.

### 3.2. Evaluation as thermal converter

AC performance of fabricated structures was characterized by comparison with PTB 90 Ω multijunction thermal voltage converter [1,2] using experimental setup for manual ac–dc transfer. Sinusoidal voltage was generated using Agilent 33220A arbitrary function generator, while Agilent E3466A Dual Output DC Power Supply provided dc voltage. Input ac or dc voltage selected by the transfer switch was simultaneously applied at parallel connection of referent-PTB converter and IHTM structure under test. Output thermal voltages of the two converters were measured with two Keithley 181 nanovoltmeters. Measurements were performed in the frequency range (50 Hz–200 kHz). ac and dc inputs were subsequently applied at heaters of the two thermal converters with 90 s waiting time.

Due to high heater resistance of P-type structures (5.8 kΩ) they are not suitable for ac–dc transfer. Here we present results of tests performed using A-type structure with residual membrane thickness of approximately 5 μm.

Measurement sequences were performed in 12 points at ac and dc input at each frequency. When 1 kHz sine input and 0.6 V dc voltage were applied at PTB 90 Ω TC for ac input average thermal voltage of 35.90642 mV was obtained with standard deviation 3.5 μV, while for dc input for the same parameters values of 35.89633 mV and 3.0 μV were obtained, respectively.

Taking into account thermal voltages measured simultaneously in the same sequence at both reference and tested converter, ac–dc transfer difference of the IHTM TC A1 was calculated with respect to PTB 90 Ω TC at several frequencies in the range of interest. Results for 1 kHz are shown in Fig. 12 with average value of 306 ppm and standard deviation 26 ppm. Ac–dc transfer difference calculated for each chosen frequency in the range (50 Hz–200 kHz) is presented in Fig. 13. It can be concluded that due to very fast response time of the IHTM TC A1 (about 5 ms) ac–dc transfer difference does not drop below 200 ppm. The best behaviour is obtained in the sub-range (1 kHz–20 kHz) where ac–dc transfer difference varies within the range of 100 ppm.

Important conclusions were deduced from experiments performed in the domain of thermal converters which will serve as a base for future work. Compared with commercial component developed at PTB which has operating range (10 Hz–1 MHz), current design should be improved towards increasing thermal time constant in order to widen operating frequency range and lower ac–dc transfer difference. For this purpose “boss” structures with higher thermal mass will be used.

### 3.3. Evaluation as flow sensor

The evaluation of the sensor under flow was performed in a specially designed experimental set-up, which is described in detail elsewhere [10]. Pure nitrogen was used in all the experiments conducted. The sensor was wall mounted in a square, 25 mm² cross sectional tube. The length of the tube was 1.5 m in order to obtain fully developed flow throughout the entire laminar region. A Brooks mass flow controller was used to form the reference flow in the range 0–10 SLPM, which corresponds to 0–6.7 m/s flow velocities in the specific experimental set-up.

![Fig. 12. Ac–dc transfer difference of IHTM TC A1 with Al heater obtained with respect to PTB 90 Ω TC for measurements performed in 12 points.](image1.png)

![Fig. 13. Ac–dc transfer difference of IHTM TC A1 with Al heater determined with respect to PTB 90 Ω TC in the frequency range (50 Hz–200 kHz).](image2.png)
The calorimetric principle of operation was implemented for flow evaluation [21]. Power was applied to the p⁺Si heater and the flow induced temperature difference in two points situated symmetrically on both sides of the heater was extracted through the thermopile voltage difference. The device was operated in constant temperature mode. A Keithley 220 current source and a Keithley 2000 multimeter were used for the heater temperature stabilization. The instruments were connected to a PC through a GPIB interface and the stabilization was performed with a specially designed algorithm in LabView package. The input of the program was the predefined sensor operation power. The specific power was applied to the heater and the corresponding resistance was monitored. The heater resistance was changing (due to heating) and when the variations were less than 2%, the corresponding resistance value was locked. Thereafter, the heater voltage was continuously monitored and the current that should be applied to the heater so as to stabilize the resistance was extracted and re-applied. Two more Keithley multimeters were used for monitoring the output of each thermopile. All the values were stored for further manipulation.

Fig. 14 represents the thermopile difference as a function of flow velocity, for various initial power values applied to the heater. The corresponding Reynolds numbers are also indicated in the same figure. According to the theory [20] the thermopile response should be a linear function of the square root of the flow velocity. The specific dependence is verified in Fig. 15, where the sensor response as a function of the square root of flow velocity is illustrated. A deviation from the square root law is observed for flow velocities above 5.5 m/s, which corresponds to Reynolds number ~1800. This effect is attributed to the transition from laminar to turbulent region. From Fig. 15 the sensitivities can be extracted which are 0.98, 1.22 and 1.45 mV/(m/s)¹/₂ for 65, 80 and 95 mW respectively. In all the cases the normalized sensor sensitivity with respect to power is 15.2 mV/(m/s)¹/₂ W, which is almost six times higher compared with test structure [14] and falls in the range of optimized MEMS flow sensors such as one developed at IMEL (12.39 mV/(m/s)¹/₂ W) [11].

3.4. Evaluation as vacuum detector

Evaluation of A- and P-type sensors as vacuum detectors was performed by measuring output Seebeck voltage at room temperature under constant current supply. Sensor was packaged on a TO housing which was mounted on a vacuum system. Heaters were connected at current source Keithley 220 while the sum of the thermopiles output voltages was measured by Agilent 34410A digital multimeter. Multimeter was used for automatic data logging during a measuring sequence which comprised of measuring Seebeck voltage at atmospheric pressure and in vacuum (10⁻² mbar) during at least 90 s.

Fig. 16 represents the typical »step« response observed for all sensors when sensor ambient is suddenly evacuated. The specific data on Fig. 16 were measured for A-type sensor with residual
n-Si thickness of 10.6 μm for current supply of 100 mA. For P-type sensors current of 3 mA was applied.

Difference between output voltage measured on the left thermopile when sensor is in vacuum and at atmospheric pressure showed that voltage rise increases with decreasing of residual n-Si thickness. For both sensor types voltage rise was about 0.1 mV for sensors with the thickest membranes while reaching 1.2 mV for sensors with the thinnest membranes. When relative voltage change is calculated linear dependence on residual n-Si thickness is obtained (Fig. 17).

Conduction component of heat exchange is dominant in the presented sensor design, which limits the performance of the vacuum detector. Maximum change of thermopile voltage in the specific pressure range is about 10 times lower compared with thin-film thermal vacuum sensors reported in literature [4]. For this type of application better response would be obtained with structures with completely removed residual n-Si where effect of conduction through the sensor is minimized.

4. Conclusions

Thermopile based sensors presented in this paper were fabricated using the already existing technological processes developed at IHTM-IMTM for MEMS pressure sensors. Fabricated structures contain multilayer p+Si/Al thermocouples and p+Si or Al heater. Sandwich membrane consists of sputtered SiO₂ and residual n-Si layer. Wet post-etching technique was developed and sensors with membranes below 3 μm were fabricated. Steady state and transient sensor behaviour were anticipated using analytical and numerical models. Thickness of the membranes was estimated by comparison of experimentally obtained static sensitivity and theoretical dependence sensitivity– membrane thickness, calculated using analytical model. Thermal characterization was performed. Thermal time constant was measured. Fabricated structures were tested as ac–dc transfer devices, gas flow meters and vacuum detectors. Ac–dc transfer performance of fabricated structures was tested using manual method by comparison with PTB 90 Ω multijunction thermal voltage converter. The ac–dc transfer difference was calculated for each chosen frequency in the range (50 Hz–200 kHz). Due to very fast response time of the sensors the ac–dc transfer difference does not drop below 200 ppm. The best behaviour was obtained in the sub-range (1 kHz–20 kHz) where the ac–dc transfer difference varies within the range of 100 ppm. During flow measurements the device was operated in constant temperature mode. For flow velocities up to 5.5 m/s gas flow was laminar and linear thermopile response as a function of the square root of the flow velocity was observed. Normalized sensor sensitivity with respect to power is 15.2 mV/(m/s)1/2 W, and falls in the range of optimized MEMS flow sensors. During vacuum measurement sensors were operated in constant current mode. For all sensors step response was observed when ambient pressure changes from atmospheric to vacuum. It was concluded that structures with thinner residual n-Si are more sensitive to changes of ambient pressure while relative change of Seebeck voltage depends linearly on residual n-Si thickness.

Acknowledgements

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References

[14] D. Randjelović, G. Kaltas, Ž. Lazić, M. Popović, Multipurpose thermal sensor based on Seebeck effect, in: Proceedings of 23rd International Con-
Biographies

Danijela Randjelović was born in Surdulica, Serbia in 1970. She received her Dipl-Ing and MSc degrees in electrical engineering from the Faculty of Electrical Engineering, University of Belgrade, Serbia, in 1995 and 2002, respectively. Since 1996 she is with IHTM-IMTM employed as a research scientist. She was working in the fields of semiconductors physics and photonic crystals. Her current research interests are: analytical modelling of thermal sensors, design, fabrication and characterization of thermopile-based MEMS sensors and atomic force microscopy. She is currently pursuing her PhD degree in the field of multipurpose thermopile-based MEMS thermal sensors.

Anastasios Petropoulos was born in Athens, Greece in 1978. He received his BSc in Physics from the University of Athens in 2004 and his MSc in Nanoelectronics from the University of Leeds in 2005. He is currently pursuing his PhD at NCSR Demokritos, Athens, with concerning research interests the fabrication and modelling of thermal sensors and microfluidics.

Dr. Grigoris Kaltsas received his BSc degree in Physics from National University of Athens in 1993. He joined the Institute of Microelectronics of NCSR “Demokritos” in 1993 as a PhD student. He received his PhD in 1998 from the National Technical University of Athens. He is now Associate Professor in the Department of Electronics at the Technological Educational Institution of Athens. He has worked in the field of silicides from 1993 to 1994 and then on fabrication and characterization of integrated thermal sensors using porous silicon technology. His research interests are: thermal integrated sensors, integrated flow and gas sensors, silicon micromachining techniques, MEMS modelling and simulation, porous silicon technology and microfluidic devices fabrication and characterization.

Miloš Stojanović was born in Belgrade, Serbia in 1965. He received the Dipl-Ing degree in electrical engineering from the Faculty of Electrical Engineering, University of Belgrade, Serbia, in 1992. The activity in power and energy measuring systems was in co-operation with Institute Mihajlo Pupin, Belgrade, through development and implementation of electrical quantities transducers. He is in the field of precision measurements with his own private company, ENIGMA Instrument. Since 1997 he is collaborating with PTB institute in Germany as a guest-scientist, developing high-end instrumentation for ac–dc transfer.

Žarko Lazić was born in Belgrade, Serbia in 1959. He received his Dipl-Ing degree in electrical engineering from the Faculty of Electrical Engineering, University of Belgrade, Serbia, in 1984. He is a researcher at the IHTM-IMTM where he is leading various processes of planar technology and characterization of semiconductor devices.

Prof. Dr. Zoran Đurić received his PhD in electrical engineering in 1972 from the Faculty of Electrical Engineering, University of Belgrade, Serbia, after obtaining Dipl-Ing in engineering physics (1964) and Mag. Sci. (1967), both from the same university. Since 1967 he is in the field of microelectronics and optoelectronics. His main fields of interest are microsystem and nanosystem technologies, including MEMS and NEMS-based sensors, detectors and actuators and their building blocks. Prof. Đurić proposed a new type of infrared detectors (EMCD) and authored generalized theories of ISOVPE and LPE epitaxial techniques on HgCdTe. Prof. Đurić is science adviser, the director of the HTM-IMTM and full professor at the Faculty of Electrical Engineering in Belgrade.

Dr. Milan Matić received his PhD in Physics from Faculty of Electrical Engineering, University of Belgrade, in 1978, after obtaining Dipl-Ing degree in electronics from the same faculty in 1968. He was the director of the Atomic Physics Laboratory in Vinca 1978–1982. Since 1983 he joined IHTM where he is working as a senior scientist in the field of semiconductor sensors, infrared detectors and MEMS pressure piezoresistive sensors and transmitters.