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# Intelligent thermopile-based vacuum sensor

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## Abstract

We report here the development of a simple and low-cost intelligent vacuum sensor based on multipurpose thermopile MEMS chips. Our devices have a $p^+$Si heater and two thermopiles with 30 $p^+$Si/Al thermocouples each. Thermal and electrical isolation is provided by a sandwich membrane (residual n-Si and sputtered oxide). The sensor utilizes for its intelligent mode of operation a modified version of an existing processing module we developed for our piezoresistive sensors.

*Keywords*: vacuum sensor; intelligent sensor; thermopile; pressure measurement

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## 1. Introduction

Sensors intended for measurements of pressures below atmospheric (vacuum sensors) are well-known and mature devices which find many important applications [1]. One especially important class among them is thermopile-based MEMS vacuum sensors [2], whose advantage is a very wide pressure range. The thermopile devices based on Seebeck effect are also utilized as e.g. gas flow sensors, vacuum detectors, thermal converters, etc. [1-3] finding a broad range of commercial applications [4,5]. Our multipurpose sensors have been successfuly demonstrated for the following applications: gas flow sensor, vacuum detector and thermal converter [3,4,6]. On the other hand, it is important for contemporary sensors generally to enable intelligent mode of operation, to ensure minimum costs of fabrication and application and maximum simplicity.

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This paper presents preliminary experimental results achieved in the realization of a simple and low-cost intelligent vacuum sensor. To this purpose we utilized our multipurpose thermopile MEMS chips and a processing module based on our intelligent control unit originally designed for piezoresistive sensors.

## 2. Intelligent thermopile - based vacuum sensor construction and principle of operation

Using technological procedure developed for IHTM piezoresistive pressure sensors, multipurpose thermal MEMS sensors with $p^+$Si/Al thermocouples were realized. As shown in Fig. 1, two thermopiles, with 30 thermocouples each, are positioned to the right and left from the heater located in the central part of the chip. "Cold" thermocouple junctions are placed on the rim in the vicinity of the $p^+$Si thermistors. The membrane area consists of sputtered oxide 1µm thick and partially etched residual n-Si of thickness $d_{\text{n-Si}}$. In order to improve performance, diced single chips were etched again and structures with different membrane thicknesses were fabricated.

Thermopile based vacuum sensor operation is based on dependence of the gas thermal conductivity on the pressure inside the housing. For a specific value of thermal conductivity $\lambda_{GAS}$ $(p, T)$, at a given pressure and ambient temperature, a temperature difference between hot and cold thermocouple junctions, $\Delta T$, is established. Due to thermoelectric conversion voltage is generated at the thermopile, $U$ $(p, T)$. When operating under constant current conditions, $I_{\text{const}}$, the temperature difference and the sensor output also depend on variations of the heater resistance with temperature, $R_{\text{H}}(T)$. Taking into account all of the mentioned influences, a general formula for the output sensor voltage can be written as

$$U(p,T) = N\alpha\Delta T\left(\lambda_{gas}(p,T), R_H(T) I_{const}\right), \tag{1}$$

where $N$ is the number of the thermocouples in the thermopile, while α is the Seebeck coefficient of the thermocouples. Without getting into details we will just point out that ambient temperature changes induce shift of the voltage/pressure curve as shown in Fig. 2.

### 2.1. Construction of the intelligent vacuum sensor

For the purposes of vacuum measurements, chips are mounted on TO-8 housing and welded in specially designed transducer housing as shown in Fig. 3. The process flange complies with the NW 16-KF vacuum standard. The sensor mount is compatible with the TO-8 housing.

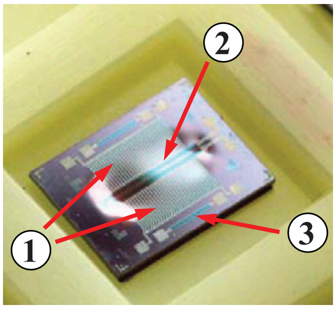

Fig. 1. Photograph of the multipurpose chip containing: two thermopiles with 30 $p^+$Si/Al thermocouples (1), $p^+$Si heater (2) and $p^+$Si thermistors (3).

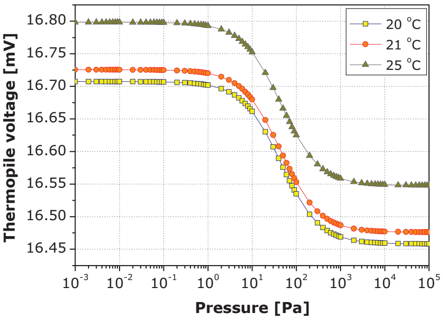

Fig. 2. Theoretical dependence of voltage of one thermopile of a sensor with residual n-Si thickness, $d_{\text{n-Si}} = 13.4$ µm, with constant current of 3 mA applied at $p^+$Si heater for different ambient temperatures.

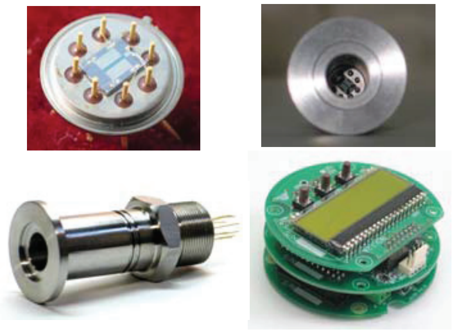

Fig. 3. Multipurpose thermal sensor for vacuum measurements mounted on a TO-8 housing and welded into a specially designed transducer housing and intelligent sensor control unit.

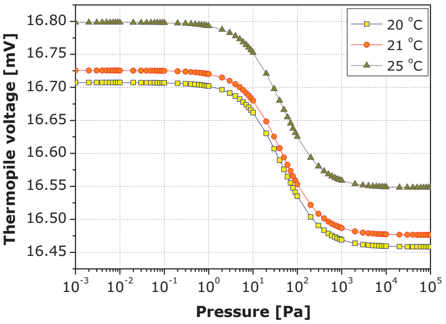

Fig. 4. Experimental (dots) and simulation (line) dependence of voltage at one thermopile on pressure for sensor with $d_{\text{n-Si}} = 2.9$ µm, obtained for 3 mA bias current at $p^{+}$Si heater.

Contact wires are bonded to pins of TO-8 housing and connected with the intelligent sensor control unit (Fig. 3), optimized for piezoresistive pressure sensors. The electronic unit of the intelligent sensor first performs A/D conversion, and then digital processing of signals from the vacuum sensor.

### 2.2. Software adaptation

We modified software originally optimized for our pressure transmitters to use with the intelligent thermal vacuum sensor. The blocks for physical signal processing, linearization and temperature compensation have been extensively modified. A different approach to A/D converter initialization was also necessary, since the output signal of a thermal sensor is different from that of a pressure sensor.

In the part of the code dealing with linearization, a polynomial up to 5th order was introduced based on fitting of experimental $U(p)$, output voltage being an independent and pressure a dependent variable

$$p(U) = P_0 + A_1\left(U + A_2U^2 + A_3U^3 + A_4U^4 + A_5U^5\right). \qquad (1)$$

A manual temperature compensation method was implemented. Voltage correction factor is interactively entered in the code. The polynomial coefficients are determined for measurements done at calibration temperature, $T_{\text{cal}}$. At an arbitrary temperature $T_1$, the output voltage will be higher ($T_1 > T_{\text{cal}}$) or lower ($T_1 < T_{\text{cal}}$) for each point in the pressure range, due to the shift of $U(p)$ curve. Therefore, instead of the voltage $U$, as read on display, it is necessary to use the corrected voltage value in the polynomial, $U \rightarrow U - \Delta U$, where $\Delta U$ is the correction factor calculated at the chosen pressure according to $\Delta U\big|_{T_1, p=const} = U\big|_{T_1, p=const} - U_{cal}\big|_{T_{cal}, p=const}$.

## 3. Experiment

The dependence of the output thermopile voltage on pressure was measured in a range of ($10^{-3}$ - $10^{5}$) Pa. Experimental and theoretical dependence for a sensor with $d_{n\text{-}Si} = 2.9$ µm are shown in Fig. 4. Our procedure consisted of two independent measurement sets, the first one for the range ($10^{-3}$ - 200) Pa, and the second one for (300 - $10^{5}$) Pa. In the first set, pressure was changed continuously by slowly letting the air into the system. In the second set, the pressure was generated and controlled by a Mensor APC 600 pressure calibrator.

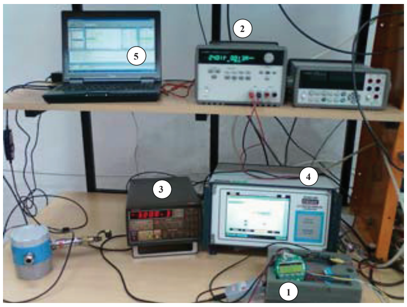

Fig. 5. Experimental setup: 1) electronics unit with alphanumerical display, 2) Agilent E3466A Dual Output DC Power Supply – electronics supply, 3) current source (Keithley 220) – sensors heater supply, 4) Pressure Calibrator Mensor APC 600, 5) laptop with special software and connected programmator.

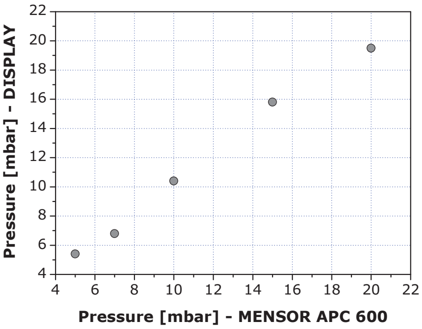

Fig. 6. Linear dependence of the pressure values read at the intelligent system display for the chosen pressures generated by Mensor APC 600 in the range (5-20) mbar.

Because of the quoted procedure, we performed the complete testing for p > 300 Pa where full control of pressure was assured. The experimental setup is shown in Fig. 5, while Fig. 6 shows the values measured by our intelligent sensor system and the corresponding values generated by the calibrator.

## 4. Conclusion

We presented a realization of a simple and low-cost intelligent vacuum sensor based on our multipurpose thermopile MEMS chips and an intelligent control unit originally designed for our piezoresistive pressure sensors. The adaptation of the software module was of key importance, since it ensured an extended mode of operation and multipurpose applicability of our vacuum measurement system. A fourth-order polynomial was used for the data processing. A special care has been taken to ensure an adequate temperature compensation. A linear dependence of pressure values read at the intelligent system display on pressures generated by pressure calibrator was observed.

## Acknowledgements

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