Vacuum 101 (2014) 118–124

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Intelligent thermal vacuum sensors based on multipurpose thermopile MEMS chips

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ARTICLE INFO

Article history:
Received 17 November 2012
Received in revised form
24 July 2013
Accepted 26 July 2013

Keywords:
Thermopile
Vacuum sensor
Intelligent sensor
Pressure measurement
Digital signal processing

ABSTRACT

Realization of intelligent thermal vacuum sensors based on multipurpose thermopile microelectromechanical (MEMS) chips is presented in this work. These vacuum sensors satisfy the main requirements for contemporary sensors, they are cost-effective in both fabrication and operation, and simple to use. Intelligent devices based on two types of thermal sensors, A-type with Al heater, and P-type with p^+Si heater, were developed. Both types have 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 intelligent functionality is achieved by using a signal processing unit the authors developed earlier for pressure sensing based on their proprietary Si piezoresistive pressure sensing elements. The main issues which were of key importance for realization of intelligent vacuum sensors are addressed in this work: design and fabrication of the intelligent vacuum sensors, adaptation of the software module, linearization of the input signal using digital signal processing and temperature compensation. A three-stage test procedure is presented. The A-type sensor, with a thinner membrane, achieved 19 times better thermopile voltage-pressure sensitivity compared with the P-type sensor, with a thicker membrane. Since the estimated noise level of the measuring system is comparable with the useful signal of the P-type device, the improved voltage-pressure sensitivity provides a better resolution and signal to noise ratio of the intelligent vacuum measuring system.

1. Introduction

Vacuum covers the range below atmospheric pressure, therefore vacuum sensors actually measure pressure. So far, different solutions for such sensors have been presented in literature [1–9]. This work is focused on thermopile-based vacuum sensors [3–9]. This type of vacuum sensors offers applicability in a very wide pressure range. On the other hand, microelectromechanical system (MEMS)-based thermopile devices using the Seebeck effect cover extremely broad spectrum of applications such as e.g. flow sensors, thermal converters, IR detectors, bio- and chemical sensors, accelerometers, inclinometers, gas type sensors, gas mixture composition sensors, etc. [10–18]. Several devices were developed to commercial level [6,18,19]. Experimental verification of the following applications of multipurpose sensors used in this work have been performed: gas flow sensor, helium sensor, vacuum detector and thermal converter [20–23].

On the other hand, the contemporary sensors are expected to be cost-effective in both fabrication and operation, and to be as simple to use as possible. The latter can be achieved through the intelligent sensor concept [24–26], whose fundamental aspects are digital signal processing and digital communication. This paper presents experimental results achieved in the realization of simple and low-cost intelligent vacuum devices based on two types of multipurpose thermopile sensors (A-type and P-type) [20]. To this purpose a signal processing unit was developed based on the unit originally designed for piezoresistive sensors [26]. Preliminary results regarding the development of the intelligent vacuum sensor based only on the P-type chip are given in Ref. [24]. Further research activities included evaluation of the intelligent vacuum sensor with an incorporated A-type sensing element which has a thinner

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http://dx.doi.org/10.1016/j.vacuum.2013.07.044

membrane. The obtained experimental results together with a comparison of the performance of both types of intelligent vacuum sensors are given in this work. The influence of the sensing element geometry on the performance of the intelligent system is thoroughly discussed.

Several research groups reported wide operating ranges of vacuum sensors. Berlicki [8] developed a thin-film vacuum sensor with a NiCr heater and a GeAu–Ni thermopile with an operating range of (10^{-2}–10^5) Pa. The commercial vacuum Si sensor XEN-TCG3880 developed by Xensor Integration [19] achieves the same operating range with the best features in the sub-range (10^0–10^3) Pa. It should be noted that the widest operating range so far has been achieved not with thermopile based-sensors but using two other solutions. Kimura et al. [27] developed a Silicon-On-Insulator (SOI) vacuum sensor consisting of a microheater and three p–n junction diodes serving as thermistors. Such a configuration is applicable in the range (2×10^{-3}–10^5) Pa. Heimann Sensor GmbH [28] offers a commercial vacuum measuring device in the widest range of (10^{-3}–10^5) Pa based on a combination of two Si sensors with Wheatstone bridges.

A logical further step in the development of the thermopile-based vacuum sensors was the introduction of intelligent sensor control, the trend readily observable in practically all classes of sensors. The expected benefits surely include compensation of parasitic values through software signal processing (e.g. signal linearization and temperature compensation) and ensures additional functionalities like multivariability, self-diagnostics, communication, etc. As far as the authors are informed, very little work has been done in this direction on the thermopile-based vacuum sensors. Since one of the goals is to develop a cost-effective and versatile solution, the authors' approach was to start from an already existing system developed for intelligent pressure sensors and to customize it in order to ensure an enhanced operation of vacuum sensors.

This paper reports on the development of a thermopile-based cost-effective intelligent vacuum sensor. Two types of thermal sensors were used, one with an Al heater, another with a p^+Si heater. The consideration includes the design of multipurpose thermal MEMS sensors, the operation of a thermopile based vacuum sensor, the design of the intelligent vacuum sensors, adaptation of the software module, linearization of the input signal using digital signal processing and temperature compensation. A three-stage test procedure is presented and the improvements of thermopile voltage-pressure sensitivity are considered.

2. Design and realization of intelligent sensor

2.1. Multipurpose thermal MEMS sensors

Multipurpose thermal MEMS sensors with p^+Si/Al thermocouples were realized using a technological procedure developed for piezoresistive pressure sensors manufactured at the Institute of Chemistry, Technology and Metallurgy (IHTM) [20]. Fig. 1a shows a photograph of a sensor with marked main elements, while Fig. 1b shows a sensor mounted on an eight-lead transistor outline package (TO-8) metal base for the purposes of vacuum measurement.

Two thermopiles consisting of arrays of 30 thermocouples are placed symmetrically to the right and the left of the heater. The "hot" thermocouple junctions are located near the heater on a thermally isolating membrane consisting of sputtered oxide 1 μm thick and partially etched residual n-Si of thickness $d_{\text{n-Si}}$. The "cold" thermocouple junctions are placed on the rim. Either Al or p^+Si was used as the material for heater fabrication, thus forming sensors of A-type or P-type, respectively. After completing the fabrication procedure on the whole wafers, structures with membranes of around 20 μm were obtained. The thickness of the thermally isolating area was reduced by applying a post-etching bulk micromachining technique at the diced single chips. Functional structures with different membrane thicknesses were fabricated.

The sensors were fabricated using double side polished n-Si (100) wafers with a nominal thickness of 385 μm. The size of the multipurpose chip is 4.8 mm × 3.6 mm, the length of the p^+Si and Al stripes is 1090 μm, while their widths are 60 μm and 40 μm, respectively. The thickness of the p^+Si elements obtained using Boron diffusion was estimated to be 0.3 μm. The sputtered Al lines are 0.7 μm thick.

2.2. Principle of operation of a thermopile based vacuum sensor

Thermopile-based vacuum sensors measure pressure of the gas inside the housing. The operation of such sensors relies on a three-step detection process. First, at a given pressure and ambient temperature, the surrounding gas gains a specific value of thermal conductivity λ_{GAS} (p, T). Second, taking into account all relevant parameters of the sensor at given conditions and λ_{GAS} (p, T), a certain value ΔT of temperature difference between hot and cold thermopile junctions is reached. In the third step, thermoelectric conversion occurs, inducing establishment of Seebeck voltage $U(p, T)$ at the thermopile contacts. In this work the constant current operating mode is used. In that case, it is necessary to take into account variations of the heater resistance with temperature, $R_H(T)$.

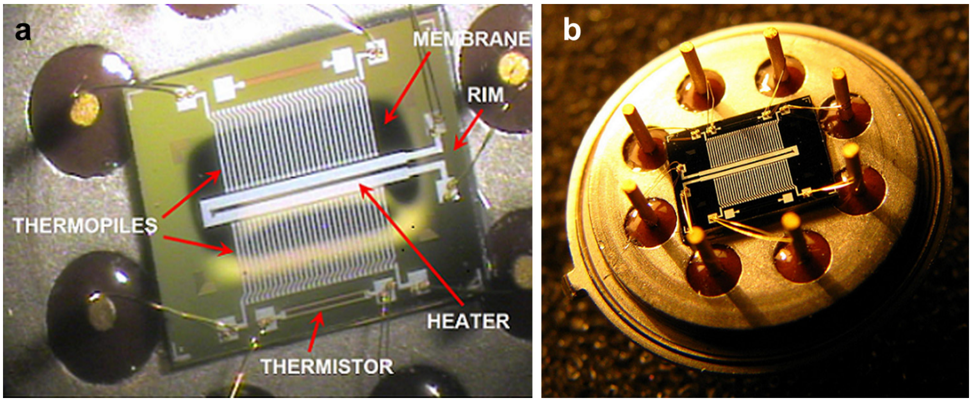

Fig. 1. Photographs of the multipurpose chip (4.8 mm × 3.6 mm): (a) the main sensor elements: two thermopiles with 30 p^+Si/Al thermocouples, p^+Si or Al heater and p^+Si thermistors, (b) sensor mounted on TO-8 housing. Cold thermopile junctions are placed on the rim while hot junctions are close to the heater on the central membrane area.