Original citation:
Hopper, R., Ali, S., Chowdhury, M. F., Boual, S., De Luca, A., Gardner, J. W. (Julian W.), 1958- and Udrea, F.. (2014) A CMOS-MEMS thermopile with an integrated temperature sensing diode for mid-IR thermometry. Procedia Engineering, Volume 87 . pp. 1127-1130. ISSN 1877-7058

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 87 (2014) 1127 – 1130

Procedia Engineering

www.elsevier.com/locate/procedia

EUROSENSORS 2014, the XXVIII edition of the conference series

A CMOS-MEMS Thermopile with an Integrated Temperature Sensing Diode for Mid-IR Thermometry

R._Hopper[1], S. Ali[1], M. Chowdhury[1], S. Boual[1], A. De Luca[2], J.W. Gardner[1, 3], F. Udrea[1, 2]*

[1]Cambridge CMOS Sensors, Deanland House, Cowley Road, Cambridge CB4 0DL, United Kingdom
[2]Department of Engineering, University of Cambridge, 9 JJ Thomson Avenue, Cambridge CB3 0FA, United Kingdom
[3]School of Engineering, Warwick University, Coventry CV4 7AL, United Kingdom

---

Abstract

In this paper, we describe an infrared thermopile sensor comprising of single crystal silicon p+ and n+ elements, with an integrated diode temperature sensor fabricated using a commercial SOI-CMOS process followed by Deep Reactive Ion Etching (DRIE). The chip area is 1.16 mm × 1.06 mm. The integrated diode, being on the same substrate, allows a more localized measurement of the cold junction temperature compared to a conventional external thermistor. The use of single crystal silicon allows good process control and reproducibility from device-to-device in terms of both Seebeck coefficient and sensor resistance. The device has a measured responsivity of 23 V/W, detectivity of 0.75×10^8 cm√Hz/W, a 50 % modulation depth of 60 Hz and shows enhanced responsivity in the 8 – 14 µm wavelength range, making it particularly suitable for thermometry applications.

Peer-review under responsibility of the scientific committee of Eurosensors 2014

Keywords: Thermopile; mid-infrared; detectors; cmos; thermometry

---

1. Introduction

Thermopile infrared (IR) sensors are widely used as the sensing devices for non-contacting infrared (IR) thermometers [1] and non-dispersive (NDIR) gas sensors [2]. Devices fabricated using CMOS processes have good reproducibility, are mass producible and provide low unit cost [3]. Micromachining of the silicon substrate can be used to form a membrane with a high thermal resistance, in order to enhance infrared heating of the thermopile

---

* Corresponding author. Tel.: +44-1223-395-551
E-mail address: richard.hopper@ccmoss.com

Peer-review under responsibility of the scientific committee of Eurosensors 2014
doi:10.1016/j.proeng.2014.11.363

elements. For thermometry applications, it is important to determine the thermopile's cold junction (ambient) temperature. This is normally achieved using an external thermistor but at increased system cost. In this paper, we present a CMOS based p+ and n+ type single crystal silicon/tungsten thermopile with an integrated on chip diode sensor for cold junction temperature monitoring.

Our device was fabricated using a commercial SOI-CMOS process, followed by Deep Reactive Ion Etching (DRIE) to form the membrane. During CMOS processing, a thin SOI-layer is used to form the single crystal silicon p+ and n+ elements of the thermopile and the temperature sensing p+/p-/n+ diode. Tungsten metal forms the interconnects for the diode, as well as between the silicon p+ and n+ elements. The substrate was back etched using DRIE to form a SiO_2 membrane 600 µm in diameter and ~5 µm thick, see Figs. 1 & 2. The thermopile array consists of 40 thermocouples arranged on the membrane and surrounding silicon substrate.

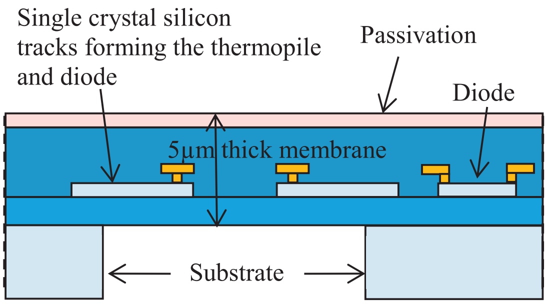

Fig. 1: Cross-sectional view of the p+ and n+ single crystal Si/W thermopile infrared sensor

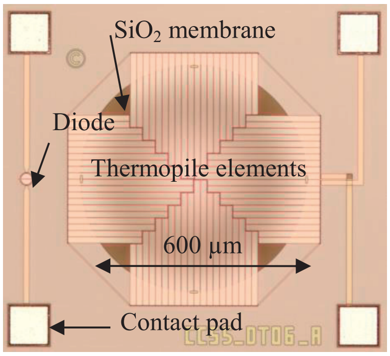

Fig. 2: Optical image of the p+ and n+ single crystal Si/W thermopile infrared sensor. The chip area is 1.16 mm × 1.06 mm.

The electrical resistance of the sensing elements is *ca*. 65 kΩ. The infrared absorption spectrum of the sensor is shown in Fig. 3. The SiO_2 layers provide relatively high optical absorption (> 50 %) in the 8 to 14 µm thermometry waveband. The responsivity R of the thermopile was measured at 23 V/W and the specific detectivity D^* 0.75 × 10^8 cm √ Hz/W. The frequency response is shown in Fig. 4. The 50 % modulation depth frequency is relatively high for this type of device at 60 Hz.

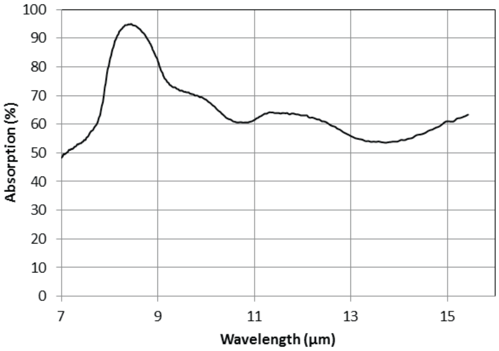

Fig. 3: Infrared absorption spectra of the p+ and n+ single crystal Si/W thermopile sensor measured using an FTIR system.

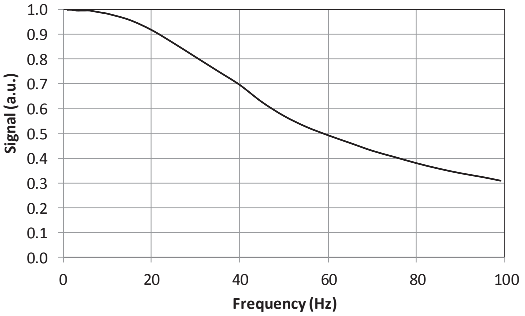

Fig. 4: Frequency response of the p+ and n+ single crystal Si/W thermopile sensor measured using a chopped IR signal from a blackbody source in atmosphere.

A calibration curve for the temperature sensing diode was obtained by measuring its forward voltage drop over a temperature range of 16 to 55°C and has a temperature coefficient of 1.0 mV/°C. The device has potential for many thermometry applications where the integrated diode could replace an external thermistor for cold junction (ambient) temperature monitoring. In the next sections we describe the methodology, experimental results, and finally draw conclusion on the accuracy and make suggestions for further work for thermopile with integrated temperature sensing diode.

2. Experimental setup

The test setup for the experimentation is shown in Fig. 5. Here we measured and compared results of constant current and constant voltage of diode biased mode.

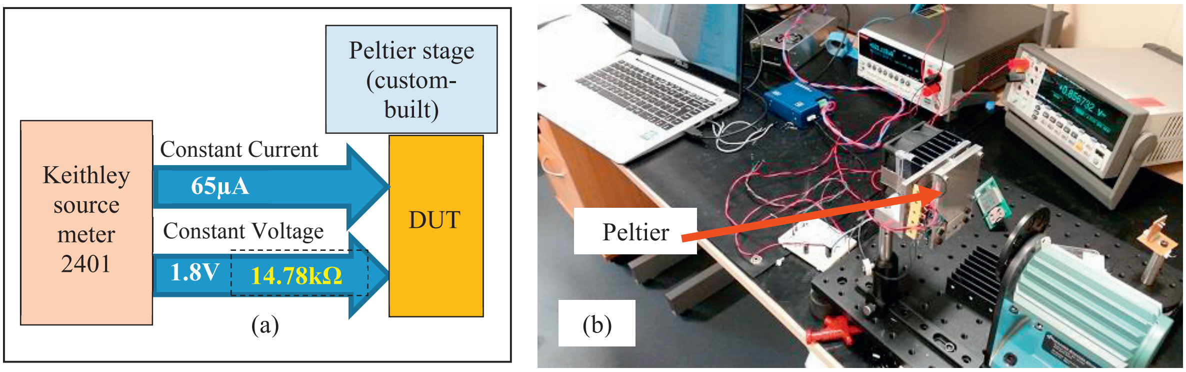

Fig. 5 (a) Constant current or voltage setup; (b) Experimental test arrangement.

From the above setup, we estimate precision on measurements for: voltage to be ± 40µV, with accuracy of ± 1mV; temperature measurement: ± 0.01ºC, with accuracy of ± 0.5ºC. We characterized a set of 10 devices. In constant current mode, the bias current was 65µA. In constant voltage mode, the voltage was set at 1.8V (which is typical for mobile phone) where the DUT current was measured with 14.78KΩ sense resistor. Temperature cycling was done covering the range 15 to 55ºC, where we looked at the aspects of linearity, repeatability and variability between samples to sample. Laboratory ambient temperature was 27 ± 0.45ºC during the measurements.

3. Measurement results

Fig. 6(a) shows the diode as a function of device temperature obtained with constant current (source) and constant voltage modes. Excellent linearity is displayed by the device with both circuits, the regression linear curve being characterised by a regression coefficient $R^2 > 0.9998$. A simple constant voltage + resistance circuit is suitable to 'sense' the diode.

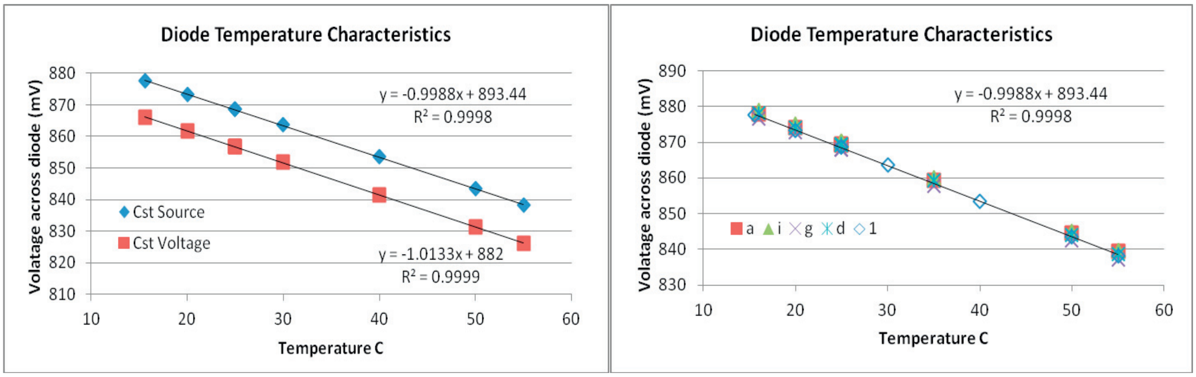

Fig. 6: (a) Diode forward voltage vs. temperature; (b) thermally cycled test for variability.

It was also noted that measurements from both, constant current and constant voltage (Fig. 6(a)) produced similar temperature coefficient values. Four additional devices were thermally cycled and again show excellent linearity as show in Fig. 6(b).

3.1 Analysis of results

The measurement results were analysed and regression parameters were evaluated on the samples tested to determine the relative accuracies between the devices. The diode voltage temperature coefficient is on average found to be −1.004 mV/ºC. The diode voltage at a current drive of 65 µm is on average 869 mV. The variability on the temperature coefficient is about ±1%. For a measured voltage of 867 mV for example, the spread of temperature would be 27°C ±0.9ºC. This demonstrates that a calibration procedure is required to use the diode as a sensor in the voltage correction of the detector output.

Five devices were measured and the variability on a single device at 25ºC on a given setup with 65 µA forward current was below 0.012%, as shown below in Table 1.

Table 1: Diode forward voltage measurement variability

Variability on 3 measurements at 25ºC (start, middle, end of thermal cycle)					
	a	**i**	**g**	**d**	**1'**
Mean	869.3	870.3	868.0	869.3	868.6
St dev	0.0635	0.0379	0.1058	0.1060	0.0058
CoV (%)	0.007%	0.004%	0.012%	0.012%	0.001%

The repeatability of the measurements across one sample was below 0.02% and across 10 samples was 0.1%.

4. Conclusions and further work

The diode voltage-temperature characteristics were investigated for a set of thermopile devices at temperatures from 16 to 55 ºC. Excellent linearity on all devices was found with a constant current source, as well as with a simple constant voltage source and resistor circuit. The precision on the diode sensing measurement was excellent (< 0.012%). However some variability was observed across the devices such that it was found that a calibration procedure will need to be adopted if the diode is to be used to sense the device temperature to compensate for the thermopile voltage. For example, the accuracy error on a measured temperature of around 27ºC is currently estimated ±0.9ºC across devices. Variability over 10 devices, show a repeatability of 0.1%. An extension to this study should consist in evaluating the stability and ageing of the diode sensing on the device in operation, thermal coupling between sensing diode and thermopile, characterisation of the diode up to 225ºC (as the process used for the thermopile has been qualified for high temperature operation) and comparison of diode vs thermistor.

Acknowledgements

We would like to acknowledge this work for the support of EU FP7 program (MSP project – 611887)

References

[1] Suman S, Gaitan M, Joshi Y and Harman G G, Wire-bonding process monitoring using thermopile temperature sensor, IEEE Trans. Adv. Package. 28 (2005) 685–93

[2] Yoo K P, Kwon K H, Min N K, Kim S D and Choi W S, A front-side dry-etched thermopile detector with 3–5 µm infrared absorber and its application to novel NDIR CO2 gas sensors, Proc. IEEE Int. Conf. Sensors (Puglia, Italy) (2008) 894–7

[3] A. Graf, M Arndt, M Sauer1 and G Gerlach, Review of micromachined thermopiles for infrared detection, IOP Meas. Sci. Technol. 18 (2007) R59–R75.