Experimental Study of an Aluminum-Polysilicon Thermopile for Implementation of Airflow Sensor on Silicon Chip

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Abstract. A multi-directional airflow sensor has been realized. The essential part of the considered sensor is a thermopile configuration, which enables the measurement of flow speed and flow direction. The thermopile is a series arrangement of eight thermocouples. A thermocouple converts a difference in temperature into an electrical signal, by means of the Seebeck effect. The thermocouples are made of aluminum-N-type polysilicon junctions. The incoming flow is heated and the degree of heat transfer by convection to the flow, depends on the speed of the flow; the faster the flow the smaller the heat transfer, which leads to a smaller (Seebeck) output voltage of the thermopiles. After signal conditioning - i.e., filtering and amplification by means of an amplification system - the electrical output signals of the thermopiles are further signal-processed by applying analog-to-digital signal conversion, so that finally the flow speed and the flow direction can be properly displayed on a computer screen. The measured values of the Seebeck coefficient or thermopower (S) were in the range of: 0.43 to 0.68 mV/K which are in good agreement with the values found in the literature: 0.5 to 0.7 mV/K. Moreover, it was found that the flow speed U_∞ is proportional to the reciprocal value of the square of the output voltage of the outgoing thermopile.

Keywords: *airflow sensor; thermopile; Seebeck effect.*

1 Introduction

This paper reports the experimental characterization of thermopile *in situ* the flow sensor. It is used to measure the airflow by using thermoelectric principle in the thermopile, which is called the Seebeck effect.

Makinawa and Huijsing reported the implementation of the thermopile as wind sensor using a standard CMOS process [1]. The thermopile on the silicon chip

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consist of polysilicon p^+/aluminum junctions to measure air flow. A standard bipolar IC process also used to fabricate an integrated silicon thermal flow sensor using thermopile made of silicon-aluminum junction [2]. Both works developed a similar sensor construction, which is square formation and consist of four thermopile-heater pair. The system works by sensing the temperature difference between hot and cold junction caused by heat convection on the sensor surface 2D.

After considering the previous reported works, authors developed a new confiquration design of thermopile flow sensor using symetrical circle formation, which is believed to reduce the measuring mismatch and be operated in multidirectional measurement. The thermopile material used in the experiment is aluminum-N-type-polysilicon junction.

2 Principle of Operation

The physical principle of the semiconductor based wind flow sensor under study is the (forced) cooling of a heated surface by the convection of heat into the moving flow of mass.

The principle of operation is illustrated in Figure 1. An incoming flow of mass - after passing the incoming thermopile - absorbs heat by convection from a heated-smooth and flat surface [3]. The temperature of the heated flow is then measured by the outgoing thermopile. From this measurement the velocity of the flow can be determined. The heat that is transferred by convection from the heated surface into the fluid stream depends on the flow velocity. It is necessary for a proper operation of a thermopile section that the temperature difference between the "hot" and the "cold" junctions is well-defined.

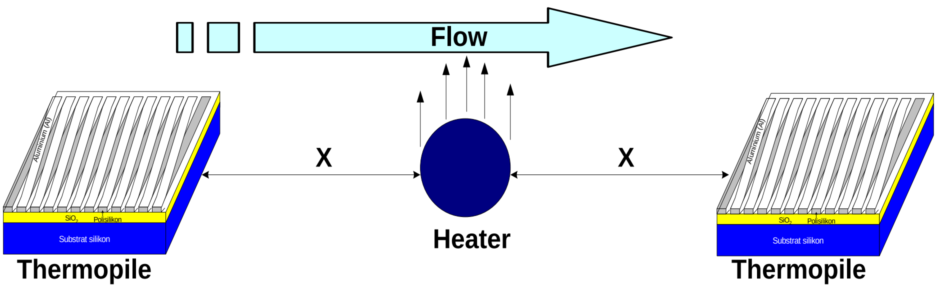


Figure 1 Set-up of the flow sensor. The thermocouple on the left is the incoming thermocouple and the thermocouple on the right is the outgoing thermocouple.

3 The Seebeck Effect

Consider a non electric-current carrying homogeneous metal or n-type semiconductor, to which a temperature gradient $\vec{\nabla}T$ is applied. Due to the temperature gradient electrons (thermally) diffuse from the hot end to the cold end, and carry their negative charge with them.

The accumulation of negative (electron) charge at the cooler end and the decreased concentration of negative (electron) charge on the heated end will ultimately lead to a back-flow of electrons in order to restore the unbalance in charge. The diffusion of electrons carrying heat would cease when the back-flow of electrons, due to an electric field $\vec{E}_S$, is just great enough to compensate for the tendency to diffuse due to the temperature difference. The electric field $\vec{E}_S$ thus represents the back-flow of electrons and can be considered as the source of an electromotive force (emf), of which the polarity is determined by the direction of the electric field $\vec{E}_S$. When finally the steady-state has been established in the semiconductor the electrons within it - on the average - are in dynamic equilibrium with the supply of heat [4]. The relation between the electric field, temperature gradient and coefficient is given by:

$$\vec{E}_S = S.\vec{\nabla}T \tag{1}$$

where S is the Seebeck coefficient, also called the thermopower. The electric field $\vec{E}_S$ provides a potential difference electromotive force V_S across the semiconductor. If two dissimilar conductors are welded together on one side and on other side the ends are open, a thermocouple is formed. A thermal sensor is obtained. In general materials used for a thermocouple design have to fulfill three design conditions [5]:

- a Seebeck coefficient S (thermopower)

$$S = \frac{dV_S}{dT} \tag{2}$$

  as large as possible,
- a low thermal conductivity λ, and
- a low electrical resistivity ρ.

The Thomson effect and Peltier effect are other important thermoelectric effects and both are strongly related to the Seebeck effect by the Kelvin relations of thermoelectricity. However, they are not considered in this paper, since for this application they can be regarded as secondary effects; hence both effects can be neglected.

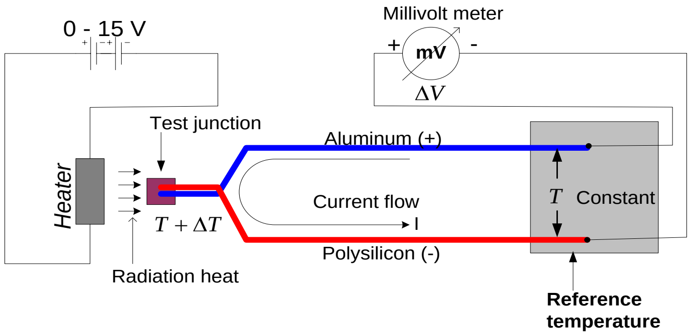
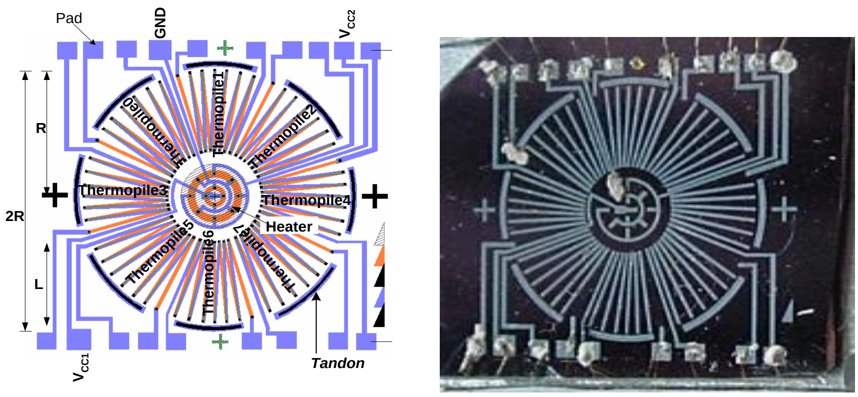


Figure 2 Principle of the thermocouple.

4 The Thermopile Design and Fabrication

The microelectronic wind meter is designed without moving part to measure wind speed and wind direction. A thermopile is a series arrangement of identical thermocouples (Figure 1 and Figure 2). The thermocouple functions as a sensor, where changes in heat are converted into an electrical signal, which are effectuated by the application of the Seebeck effect [5]. The thermocouple is the junction of a metallic conductor and a semiconductor. The length of a thermocouple is 5.2 mm. The Seebeck voltage V_S for thermocouple is given by [6]:

$$V_S = S \, . \, \Delta T, \tag{3}$$



(a) Sensor mask pattern (b) Fabricated sensor chip

Figure 3 Mask pattern and fabricated chip of thermopiles and heater with the size of the silicon chip is 23x23 mm.

For output voltage V_o of thermopile with **n** number of thermocouples, the equation (3) can be rewritten as below:

$$V_o = n \, . \, S. \, \Delta T \tag{4}$$

where ΔT is the temperature difference between the hot and the cold junction and S is the Seebeck coefficient.

In general, fabrication process of the thermopile as follow:

- Deposition of the polysilicon by LPCVD method,
- Diffusion of phosphorous doping to make N-type polysilicon,
- Metallization with aluminum by sputtering method.

In between those processes, four patterns of sensor mask were applied by lithography and etch techniques.

In Figure 3 the basic pattern of the flow sensor is displayed. It consists of a ring of thermopiles (each made of aluminum-polysilicon junctions) in 8 (fixed) sections. The heater, which provides the heated surface is placed in the center of the thermopiles.

In this flow-sensor study an incompressible laminar flow along a smooth flat plate is considered. The basic idea of the semiconductor-based multi-directional flow sensor (a thermal flow sensor) is, that it can measure, in one plane, the strength of the wind flow, and the direction of the wind in 8 (fixed) directions. A multi-directional measurement of the flow speed and flow direction is performed, in the sense that in a plane a number of flow directions and speeds can be determined, both speed are direction are determined by the output voltage of the outgoing thermopile. From this basic idea it is clear that the sensor must be centro-symmetrical. The thermopiles must be positioned in a circular array, around a circularly-shaped heater.

5 Results and Discussion

All the measurements in these experiments - performed *in situ* the flow sensor - are carried out using the set-up of Figure 1. In fact it is the objective that the output of the thermopiles should be caused by the flow speed alone, but the "pure" functioning of the thermopiles is influenced by the close presence of the heater. An important aspect for the performance of the measurements is the taking care of a proper wind guiding. The consequence is that the output voltage of the incoming thermopile is larger than that of the corresponding output of the outgoing thermopile. If no corrections are made, erroneous results can be obtained with respect to fact that the flow over the incoming thermopile is spreading over the heater area, so that only a fraction is seen by the outgoing thermopile. Further with respect to the measurements a distinction has to be made between zero-flow and non-zero flow measurements.

In Figure 4 the measured parameter relation is shown - under the zero flow condition - between the voltage difference across input of the heater as the input variable and the change in thermopile resistance and the change in heater temperature, both as the output variables. It was found that the heater temperature is proportional to square of heater voltage difference. The figure also shows an observed relation between the thermopile resistance and the heater temperature. The resistance of thermopile is increased with the increasing of the voltage (or power) of heater [6].

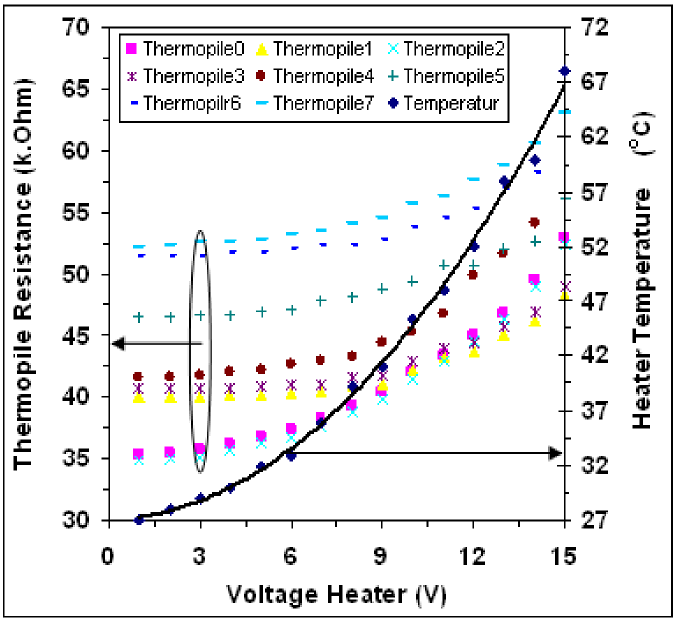


Figure 4 Temperature versus resistance thermopile (zero flow condition).

A study of thermoelectric effects [4] by applying solid state physics and transport theory of charged particles shows that there is a relation between the physical mechanism of the Seebeck effect and the doping concentration of the semiconductor part of the thermopile.

The resistance of the semiconductor part of the thermopile is a function of the temperature; and in particular, for a specific doping and temperature range its resistance can increase with increasing temperature [5]. Our experiments have shown that the curves for the thermopile resistance exhibits weak dependency on heater temperature. In the beginning, the curve shows a horizontal flat, which means electronic carriers in the thermopile have not been able to surpass the junction surface. It is due to thermal energy from heater is not sufficient yet to accelerate activities of the carriers. Figure 4 also shows a spreading of the curves for the resistance as a function of the voltage difference across the heater. This is due to the doping inhomogeneity in the silicon chip, wherein the chip size is relatively large: 23x23 mm.

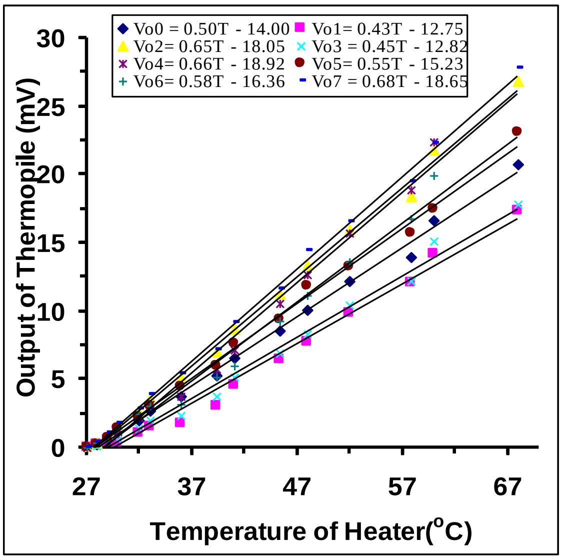


Figure 5 Heater temperature versus thermopile output at zero flow condition.

Figure 5 shows the relation between the output voltage of thermopiles and the heater temperature under zero flow condition. Linear relation between thermopile outputs and heater temperature were found due to the thermopile output relating to temperature difference (ΔT) between hot and cold junctions. In each thermopile, hot junctions refer to inner thermocouples near by the heater, on the other had, cold junctions refer to outer thermocouples which are far from the heater. During no airflow condition, hot junctions mainly receive the thermal energy through silicon substrate, compared to thermal transfer via convected air. If the heater temperature is increased, the temperature difference ΔT is also increased.

The measured values of the Seebeck coefficient or thermopower $S = \frac{dV_o}{dT}$ of the thermopile are obtained from the relation $V_o = \frac{dV_o}{dT}\Delta T$, are in the range of: 0.43 mV/K to 0.68 mV/K, which are in good agreement with the values found in the literature: 0.5 to 0.7 mV/K [6].

In Figure 6 the relation - with flow condition - between the thermopile output and the heater temperature is given. Linear relations are obtained, however, here also the spreading in doping causes spreading in the data curves. Several legends in Figure 6 refer to positions of thermopile in Figure 3a, i.e. thermopile3 at left side and thermopile 4 at right side. At zero flow condition, the output of thermopile 3 and thermopile 4 are V_3 and V_4, respectively. At constant airflow of 3 m/s, V_{33} is output voltage of thermopile 3 when airflow moves from left to right, and V_{34} is output voltage of thermopile 3 when airflow moves from right to left. Similarly, V_{43} is the thermopile 4 output when airflow from left to right, and V_{44} is thermopile 4 output with airflow from right to left.

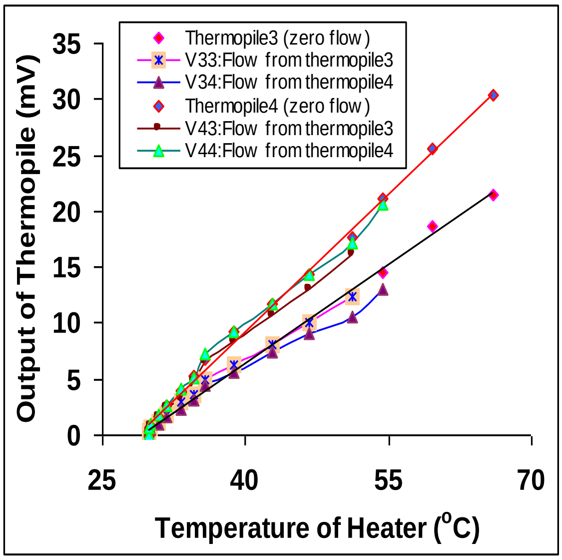


Figure 6 Thermopiles output v.s. Heater temperature.

When starting experiment at temperature 30°C, both thermopile 3 and 4 shows zero output. At zero flow condition, both thermopile output increased linearly with increasing temperature of heater. This is due to thermopile output is function of temperature. The line slope of output voltage of thermopile 4 is higher than that of thermopile 3 because of the thermopower of thermopile 4 is higher than that of thermopile 3. This is in a good agreement with data in Figure 5 (please see the legends).

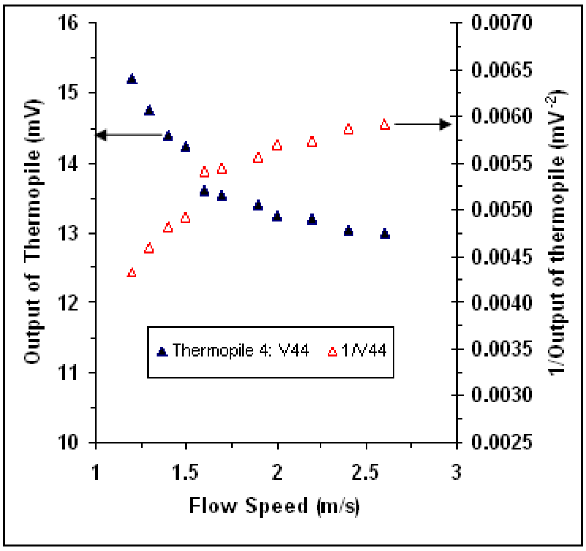


Figure 7 Output of a thermopile v.s. Flow speed.

At airflow of 3 m/s, it was found that $V_{33}>V_{34}$ and $V_{44}>V_{43}$. To explain this result, let take thermopile 4 at the right side of heater for example. When airflow moves from left to right, the airflow hit heater surface and the heater temperature was decreasing around 20-30% from its original value. Thermal energy was conveyed by the airflow to both hot and cold junction on the right direction of the heater. Because of the hot junctions near by the heater, it did not sense a significant temperature increment due to thermal conduction via silicon substrate was relatively high yet. On the other hand, the outer cold junctions received comparable additional thermal energy and experienced increasing temperature significantly. Hence, temperature difference between hot and cold junctions became smaller. In case of airflow moves from right to left, the outer cold junctions detect cooler air and experience decreasing temperature significantly. However, hot junctions did not sense comparable decreasing temperature due to they located nearby heater. Hence, temperature difference between hot and cold junctions increased significantly. These explains how the output voltage of thermopile (V_{44}) when incoming airflow blows its outer cold junction first were higher than that (V_{43}) of when it was blown by airflow direction from heater.

In Figure 7, the measurement of thermopile output as a function of airflow speed is shown. The starting experiment to measure the airflow was setup of heater voltage at 12 V (or temperature at 66^oC) and the airflow moved from right to left. It was shown that the output voltage of thermopile 4 at lower airflow is higher than those of at higher airflows.

When airflow coming from right, the temperature of outer cold junction significantly decreased, however, hot junction temperature slightly decreased only due to strong heater influence. By increasing airflow, cold junction temperature further decreased slightly, but hot junction temperature decreased significantly. This is due to air mass absorbed heat from heater surface and reduced the heater temperature, resulted in decreasing temperature at hot junctions significantly. As a result, temperature different between hot and cold junction became smaller and finally output voltage of thermopile decreased.

In Figure 7 is shown at right side the reciprocal value of the output voltage of thermopile 4. Flow speed U_∞ is proportional to the reciprocal value of the square of output voltage of the thermopile [7]. In one journal paper reported that the flow speed square root is proportional to the reciprocal of the temperature different, wherein the output voltage of thermopile is linear relation to the temperature different [8]. In general these show that our results are closed to their reports.

This study also showed that with a modest facility for IC fabrication and available signal-processing components, a modern flow sensor can be realized.

6 Conclusion

Thermopiles made of aluminum-n-type polysilicon junctions have been successfully designed and fabricated on silicon chip as temperature sensor to measure multi-directional wind flow. The measured values of thermopower (S) or Seebeck coefficients are in the range of: 0.43 mV/K to 0.68 mV/K. The flow speed U_∞ is proportional to the reciprocal value of the square of the output voltage of thermopile.

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