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The thermopile: An anisotropic temperature sensor

Suvhashis Thapa[a], Siva Mahesh Tangutooru[b], Eric J. Guilbeau[b], Niel D. Crews[a,*]

[a] Institute for Micromanufacturing, Louisiana Tech University, Ruston, LA, United States
[b] Center for Biomedical Engineering and Rehabilitative Science, Louisiana Tech University, Ruston, LA, United States

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ABSTRACT

This article discusses the operation of thermopiles when used under non-isothermal baseline conditions. Although isothermal baselines are the common thread among existing thermopile applications, this article demonstrates that these sensors can also be used to detect subtle thermal events that are superimposed over much larger steady-state or transient temperature gradients. The larger temperature variation will not contribute to the transduced voltage as long as specific thermal symmetry conditions are matched with a specific thermopile design. This article discusses this sensing anisotropy that corresponds to certain thermopile designs, and experimental results are presented which demonstrate the relative performance under several thermal conditions. Thermopile performance characteristics of baseline voltage, baseline drift and noise, and signal sensitivity have been compared experimentally for isothermal and high gradient conditions. When symmetry conditions were met, certain thermopile geometries exhibited a sensing anisotropy of more than 1000:1.

1. Introduction

A thermopile is a temperature or radiation sensor that is formed by placing multiple thermocouples in series. The result is a series of wires or traces with alternating material properties. In the presence of a temperature gradient, an electric potential (ΔV) forms in each trace that is a function of the temperature difference (ΔT) between interconnects and the Seebeck coefficient (S) of the material itself:

$$\Delta V = S\Delta T \tag{1}$$

The total voltage transduced in a circuit will be the sum of all these individual voltages:

$$\Delta V = \sum_i S_i(\Delta T)_i \tag{2}$$

By selecting materials with dissimilar Seebeck coefficients, alternating positive and negative temperature differences (see Fig. 1) can transduce a cumulative voltage. Common thermopile material pairs include p-type silicon ($S = 450\ \mu V/K$) with n-type silicon ($S = -450\ \mu V/K$), antimony ($S = 48.9\ \mu V/K$) with bismuth ($S = -73.4\ \mu V/K$), and chromium ($S = 21.8\ \mu V/K$) with nickel ($S = -19.5\ \mu V/K$) [1]. For example, the thermopile geometry shown in Fig. 1 – were it to have an arbitrary (n) number of traces[1] of each material – would transduce a cumulative voltage potential (ΔV) given by:

$$\Delta V = n(S_A(T_2 - T_1)) + n(S_B(T_1 - T_2)) = nS_r\Delta T \tag{3}$$

where S_r, the "relative Seebeck coefficient", is defined as $S_A - S_B$.

Since voltage is transduced according to the temperature differential (ΔT) across the thermopile, an isothermal condition ($T_1 = T_2$) would result in no voltage change, regardless of the temperature of the thermopile. This characteristic, a type of common mode signal rejection, is the basis of virtually all current and historical implementations of thermopile sensing. Of the extensive body of thermopile literature that reaches back even into the 19th century [2], a common thread (to the extent that the authors of this present work have been able to ascertain) of these implementations has been the following methodology:

- A thermopile is maintained under *isothermal* conditions. Whether the temperature is controlled or floating, ramped or constant, the baseline condition is one in which all junctions are at a single temperature.
- The system is designed such that a thermal perturbation induce by some stimulus (chemical, radiological, biological, etc.) will occur in the vicinity of a set of thermopile junctions (often identified as "measuring junctions"), while the other junctions (known as "reference" junctions) remain at or near the baseline temperature.

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* Corresponding author.
E-mail address: ncrews@latech.edu (N.D. Crews).

[1] In this article, n is referred to as the number of traces of each material. Elsewhere in the literature, n is defined the number of junction pairs. In general, the number of traces of each material is equivalent to the number of junction pairs. However, the definition used in this article is more appropriately derived from the Seebeck effect, which is material-specific rather than interface-specific.

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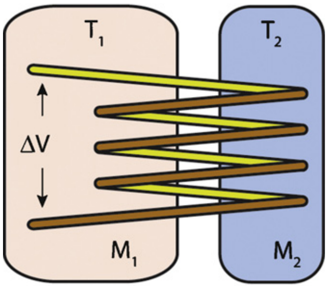

Fig. 1. Diagram of a thermopile consisting of eight traces of alternating material, placed between two temperatures. If the Seebeck coefficients of the two materials are unequal, a voltage will be transduced in the circuit. Because of the alternating arrangement of junctions, they can be divided into two groups, shown here as $M1$ and $M2$. Often, these groups are identified as reference and measuring junction groups.

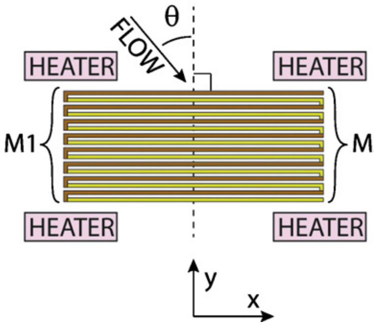

Fig. 2. By placing heaters near the thermopile junctions, the transduced voltage is a sinusoidal function of the direction of the flow across the device [10]. Thermopile voltage is zero when flow is at either $\theta = 0^\circ$ or 180°. The dotted vertical line indicates the line of symmetry between junction of group $M1$ and of group $M2$.

- The thermal event transduces a voltage in the thermopile that is used to signal, locate, quantify, or characterize the stimulus.

From this common foundation, tremendous strides that have been made in recent years in such areas as sensitivity [3], versatility [4], speed [5,6], and the miniaturization [7,8] of thermopile systems.[2] Although thermopile research is currently a vibrant research area, there is almost complete silence in the realm of thermopile application under non-isothermal baseline conditions. A notable exception occurred in the late 20th century, through a partnership between Bastiaan van Oudheusden of Delft University of Technology and Alexander van Herwaarden of Xensor Integration (Delft, The Netherlands). Their pioneering work in the use of silicon thermopiles as flow sensors [9] involved a unique emphasis on temperature gradients. By placing heaters near the thermopile junctions, temperature gradients would be present across the sensor according to the speed and direction of the flow [10]. These gradients caused a voltage in the thermopile whose value was a sinusoidal function of the angle of the flow with respect to the thermopile axis of symmetry (as indicated in Fig. 2). In other words, when the flow was directly perpendicular to the thermopile ($\theta = 0^\circ$), voltage was zero. The voltage would increase with the angle, reaching a maximum at $\theta = 90^\circ$, then decrease to zero at 180°, then to a minimum at 270°, and back to zero at 360°. Since a principle direction of this prior work was toward the sensitive quantification of flow speed, the authors focused their application on the configuration with a flow angle of $\pm 90^\circ$. Also, by placing multiple thermopiles orthogonally, the researchers were able to create a robust 2-D flow sensor [11].

The focus of this article is on one promising aspect of thermopile behavior that was indirectly validated as part of this prior work. When the temperature gradients over the two sets of thermopile junctions (labeled M1 and M2 in Fig. 2) were identical, no voltage was transduced in the thermopile. Such was the case only when the flow was directly perpendicular to the thermopile. This current article explores the thermopile configurations where, in a similar way, non-isothermal conditions can yield a zero voltage background condition. Experimental conditions are discussed and evaluated in which such thermopiles exhibit a high degree of sensing anisotropy. In other words, extreme temperature variations across a thermopile can be made invisible to the sensor as long as symmetry conditions are met, while *at the same time*, subtle thermal events lacking such symmetry produce clearly measurable voltage signals.

2. Theory

There are several conditions under which a thermopile will theoretically exhibit perfect sensing anisotropy. For this discussion of orientation-specific temperature distributions, the aim will be sensitivity toward a horizontal temperature gradient, and insensitivity toward a vertical[3] temperature gradient.

Case 1. Completely axisymmetric thermopile configuration (see Fig. 3a)

Performance: CANNOT detect any vertical gradients; CAN detect non-axisymmetric horizontal gradients; CANNOT detect axisymmetric horizontal gradients.

Consider a thermopile with a vertical line of symmetry, such as the schematic shown in Fig. 3a. In the presence of any purely vertical temperature gradient, the thermopile voltage – the sum of the voltages from each trace from both sides of the line of symmetry – is given as:

$$\Delta V_V = \underset{\text{LEFT OF CENTERLINE}}{\left[S_A \sum_{i=even}^{n/2} (T_{i+1} - T) + S_B \sum_{i=odd}^{n/2} (T_{i+1} - T) \right]} + \underset{\text{RIGHT OF CENTERLINE}}{\left[S_A \sum_{i=even}^{n/2} (T_i - T_{i+1}) + S_B \sum_{i=odd}^{n/2} (T_i - T_{i+1}) \right]} \quad (4)$$

where each T_i value is the temperature at the precise vertical location of a thermopile junction. Because of geometric symmetry, the temperature difference term is $(T_{i+1} - T_i)$ for each trace on the left hand side of the line of symmetry, and $(T_i - T_{i+1})$ for the "mirrored" trace on the right hand side of the line of symmetry. Therefore, Eq. (4) simplifies to:

$$\Delta V_V = S_A \left(\sum_{i=even}^{n/2} \left[\underset{\text{LEFT}}{(T_{i+1} - T_i)} + \underset{\text{RIGHT}}{(T_i - T_{i+1})} \right] \right) + S_B \left(\sum_{i=odd}^{n/2} \left[\underset{\text{LEFT}}{(T_{i+1} - T_i)} + \underset{\text{RIGHT}}{(T_i - T_{i+1})} \right] \right) = 0 \quad (5)$$

Eqs. (4) and (5) do not include the voltage contribution of the bottom trace in Fig. 3a. There will in fact be no contribution, since

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[2] The references indicated here are by no means exhaustive. Rather, these citations are indicators to the interested reader of some research groups that are advancing the cutting edge of thermopile science and technology.

[3] In this text, "horizontal" refers to a temperature gradient in which $\delta T/\delta x \neq 0$, $\delta T/\delta y = 0$ (refer to Fig. 2 for the x and y coordinates. A "vertical" temperature gradient is therefore when $\delta T/\delta x = 0$, $\delta T/\delta y \neq 0$.