Parametric Design Optimization of a CMOS-MEMS Infrared Thermopile for Biomedical Applications

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Abstract

A design optimization of a CMOS-MEMS thermopile was developed using a previously validated model and parameters that govern the behavior of the sensor. Those parameters are classified as fabrication process, material and design dependent. Several analyses were made in order to find parameter-specific design optimization rules. The most relevant results were found for the design dependent parameters, the ones with the most ease of handling. It was shown for a previously fabricated thermopile, that by applying the proposed design optimization rules, the sensitivity would increase by a factor of 28. It was also shown that a thermopile with an area 147 times smaller could be fabricated without any loss of sensitivity. The proposed design will be fabricated to build a spectrophotometer for non-invasive glucose measurement in biomedical applications.

Keywords: Design optimization, CMOS-MEMS thermopile, bridge-MEMS, cantilever-MEMS

Resumen

La optimización del diseño de una termopila CMOS-MEMS fue desarrollada usando un modelo previamente validado y parámetros que gobiernan el comportamiento del sensor. Dichos parámetros se clasifican como dependientes al proceso de fabricación, a los materiales y al diseño. Diversos análisis fueron realizados para encontrar reglas de optimización del diseño específicas a los parámetros. Los resultados más relevantes fueron encontrados para los parámetros dependientes al diseño, cuya manipulación es la más sencilla. Se demostró que para una termopila previamente fabricada, aplicando las reglas de optimización propuestas, la sensibilidad aumentaría por un factor de 28. También se demostró que una termopila con un área 147 veces más pequeña podría ser fabricada sin pérdidas de sensibilidad. El diseño propuesto será fabricado para construir un espectrofotómetro para la medición no invasiva de glucosa en aplicaciones biomédicas.

Palabras clave: Optimización de diseño, termopila CMOS-MEMS, puente-MEMS, viga-MEMS

Introduction

A CMOS-MEMS thermopile model and simulation demonstrated to accurately describe the behavior of an infrared (IR) thermopile based on a cantilever structure [1], as the one shown in Figure 1. The parameters that affect the sensitivity of the thermopile are described by the sensitivity equation expressed in terms of the ratio of signal voltage (*U*) to incident radiation power (*P*) as follows:

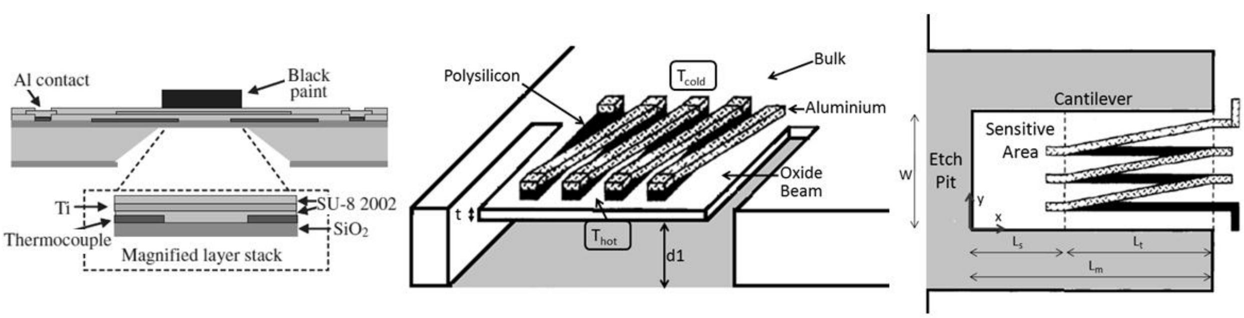
$$S = \frac{U}{P} = \frac{\varepsilon_t z \alpha}{\left[4(\varepsilon_t + \varepsilon_b)\sigma T_e^{\,3} + \gamma\right] W_m L_s + W_m k \left(\frac{c_m t_m + c_t t_t}{t_m + t_t}\right)\left(t_m + \frac{V_t}{W_m L_m}\right) coth\left(k(L_m - L_s)\right)} \quad (1)$$

where z is the number of thermocouples connected in series, α the Seebeck's coefficient or thermoelectric force, T_e the environmental temperature, ε_t the emissivity of the upper face of the membrane (thermocouple material), ε_b the emissivity of the lower face of the membrane (bulk material), σ the Stefan-Boltzmann constant, W_m the width of the membrane, L_s the length of the sensitive area, L_m the length of the beam, t_m the thickness of the membrane, t_t the thickness of the thermocouples, V_t the volume contribution of the thermocouples, c_m is the thermal conductivity of the membrane, c_t is the thermal conductivity of the thermocouples, γ is the heat transfer coefficient defined as:

$$\gamma = c_g\left(\frac{1}{d_1} + \frac{1}{d_2}\right) \quad (2)$$

where c_g is the thermal conductivity of the gas atmosphere, d_1 is the distance between the membrane and the bottom of the etch pit and d_2 is the distance between the membrane and the package cap; and *k* is a parameter defined as:

$$k = \sqrt{\frac{4(\varepsilon_t + \varepsilon_b)\sigma T_e^{\,3} + \gamma}{\left(\frac{c_m t_m + c_t t_t}{t_m + t_t}\right)\left(t_m + \frac{V_t}{W_m L_m}\right)}} \quad (3)$$



(a) Schematic (b) Lateral view (c) Superior view

Figure 1. Schematic image of an IR thermopile [2] and some geometric parameters [3]

These variables can be classified in 3 different groups: fabrication process dependent parameters, material dependent parameters and geometry dependent parameters. In order to increase the sensitivity of the device by optimizing the design, these variables had to be analyzed.

Optimization of the parameters

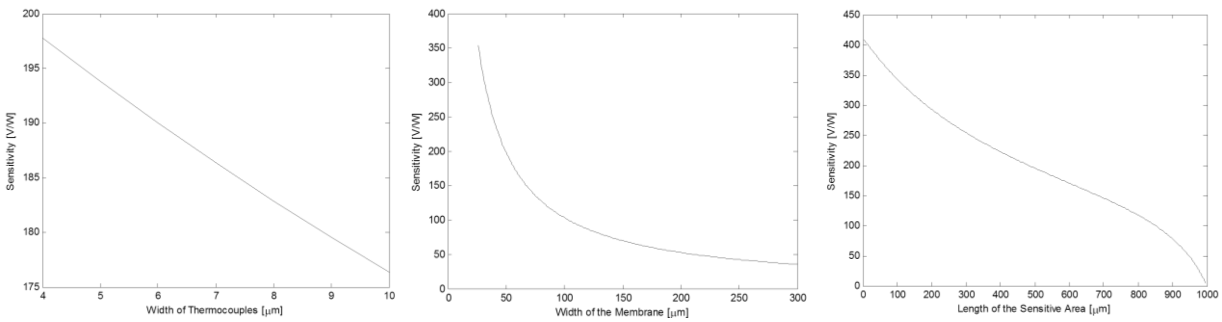
Fabrication process dependent parameters. Since these variables depend solely on the chosen fabrication process, there is not really any optimization that can be done to them. The only way to achieve a better sensitivity through the indirect manipulation of these parameters is by selecting the fabrication process with the best characteristics for this specific application. The parameters that depend on the fabrication process are: the distance between the cantilever and the bottom of the etch pit d_1, the distance between the cantilever and the package cap d_2, the thermal conductivity of the gas atmosphere c_g, the thickness of the thermocouples t_t, the thickness of the membrane t_m and the width of the thermocouples W_t.

It is easy to see why the first three parameters depend solely on the fabrication process, but that may not be the case with the rest of the previously mentioned parameters. Thicknesses and widths seem to belong to the geometry dependent parameter class, but that is actually not the case. It was already demonstrated that the thinner the thermocouples and the membrane, the larger the temperature difference [1]. Also, previous modeling and simulation efforts [1, 3] show that a large temperature difference translates into a large output voltage, which in turn translates into a higher sensitivity. Because of this, the membrane and the thermocouples will be designed as thin as the fabrication process allows them to be and not with a specific designer defined value. Thus, the geometry dependency for both of these parameters disappears.

The width of the thermocouples is another parameter that could depend on the geometry instead of on the fabrication process, but similar to the thicknesses of the thermocouples and the membrane, the slimmer the thermocouples, the higher the sensitivity. This characteristic is shown in Figure 2, where it can be seen that the highest sensitivity is achieved with the smallest value for the width of the thermocouples. Thus, the critical dimension of the process ("the absolute size of a minimum feature in an IC or a miniature device, whether it involves a line width, spacing, or contact dimensions" [4]), referring to the line width particularly, will be used for the width of the thermocouples, eliminating the geometry dependency for this parameter as well. In Figure 2, by assuming the curve as linear, a slope with a value of -3.57 is obtained. This indicates that for every extra micrometer that the thermocouples are widened, 3.57 V/W are approximately loss in sensitivity. This simulation was made using the analytical model from Equation (1) and the values shown in Table I, varying the width of the thermocouples from 4 to 10 µm.

Table I. Parameters for the simulation in which the width of the thermocouples was varied

Parameter	Value	Parameter	Value	Parameter	Value
ε_t	1	t_m	$0.5\ [\mu m]$	α	$309.64\ [\mu V \cdot K^{-1}]$
ε_b	0.5	t_t	$0.5\ [\mu m]$	W_m	$50\ [\mu m]$
T_e	$300\ [K]$	L_t	$650\ [\mu m]$	W_t	4 to 10 $[\mu m]$
c_m	$20\ [W \cdot K^{-1} \cdot m^{-1}]$	L_s	$250\ [\mu m]$	d_1	$350\ [\mu m]$
c_t	$34\ [W \cdot K^{-1} \cdot m^{-1}]$	L_m	$900\ [\mu m]$	d_2	∞
c_g	0.0262	z	2		



(a) (b) (c)

Figure 2. Sensitivity vs. (a) width of the thermocouples, (b) width of the membrane, and (c) length of the sensitive area

Material dependent parameters. The parameters that depend on the selection of the materials are: the Seebeck coefficient α, the emissivity of the sensitive area on the lower face ε_b , and the emissivity of the sensitive area on the upper face ε_t. The Seebeck effect was discussed in previous work [1], where it was made obvious why the Seebeck coefficient depends on the chosen materials. However, this parameter could also be classified as fabrication process dependent. Since an intention in making the thermopile IC compatible exists, the material selection for the thermocouples must be restricted to the materials available in the IC fabrication process. This restriction of materials makes the Seebeck coefficient not only material dependent, but also fabrication process dependent. Moreover, all the material dependent parameters that affect the sensitivity of the thermopile are, in some way, also dependent on the fabrication process. Thus, achieving a larger sensitivity through the manipulation of these parameters is very complex.

Geometry dependent parameters. The parameters of the thermopile that can most easily be manipulated in order to optimize the design, increasing the sensitivity, are the geometry dependent parameters. The geometry dependent parameters of the thermopile are: the width of the membrane W_m, the length of the sensitive area L_s, the length of the thermocouples L_t, the length of the membrane L_m and the number of thermocouples z. As is it shown in Figure 2, as the membrane widens, the sensitivity decreases. It is important to clarify that in the simulation carried out to obtain this curve, the number of thermocouples remains fixed. The rest of the parameters were set to the values shown in Table I, with the exception of the width of the thermocouples, set to 4 μm and the width of the membrane, varied from 26 to 300 μm. However, widening the membrane can help in enhancing the performance of the thermopile, because as the membrane widens, the maximum number of thermocouples that can fit increases.

The maximum length of the thermocouples and of the sensitive area is restrained by the length of the membrane and by each other. Regarding fabrication, the sum of both of these lengths must be equal or smaller than the length of the entire membrane. Because of this, an analysis has been made to optimize the design of the thermopile by finding the best length of the thermocouples to length of the sensitive area ratio in terms of sensitivity. Using the proposed analytical model, a simulation was made using the parameters shown in Table II, varying the length of the sensitive area from 4 to 996 μm and defining the length of the thermocouples as the length of the membrane minus the length of the sensitive area.

Table II. Parameters for the simulation in which the length of the thermocouples and the length of the sensitive area were varied

Parameter	Value	Parameter	Value	Parameter	Value
ε_t	1	t_m	$0.5\ [\mu m]$	α	$309.64\ [\mu V \cdot K^{-1}]$
ε_b	0.5	t_t	$0.5\ [\mu m]$	W_m	$50\ [\mu m]$
T_e	$300\ [K]$	L_t	$L_m - L_s$	W_t	$4\ [\mu m]$
c_m	$20\ [W \cdot K^{-1} \cdot m^{-1}]$	L_s	4 to 996 $[\mu m]$	d_1	$350\ [\mu m]$
c_t	$34\ [W \cdot K^{-1} \cdot m^{-1}]$	L_m	$1000\ [\mu m]$	d_2	∞
c_g	0.0262	z	2		

The simulation results are shown in Figure 2. It is worth clarifying that the curve for the output voltage would look identical to the curve of the sensitivity shown, as long as the power of the IR radiation source was maintained constant. A similar analysis has been made by other authors [3], in which the value of the irradiance was fixed and not the power of the source. Such analysis implies that as the length of the absorbing area changes, the power of the source must change too, in order to maintain a fixed value for the irradiance, and this is not convenient in an optimization analysis.

The previous results show that the sensitivity decreases as the ratio of the length of the sensitive area to the length of the thermocouples increases. This implies that when designing, the largest sensitivity is achieved with the maximum length of the thermocouples to length of the sensitive area ratio that the critical dimensions of the fabrication process allow. However, the implications that such configuration have on the response time must also had to be analyzed. To do so, a transit analysis simulation on COMSOL was done, in which thermopiles with the parameters used for the previous simulation were designed. The designed thermopiles had thermocouples with lengths that vary from 250 to 650 μm, with a 50 μm increase between each thermopile. The designed thermopiles with the shortest and longest thermocouples are shown in Figure 3.

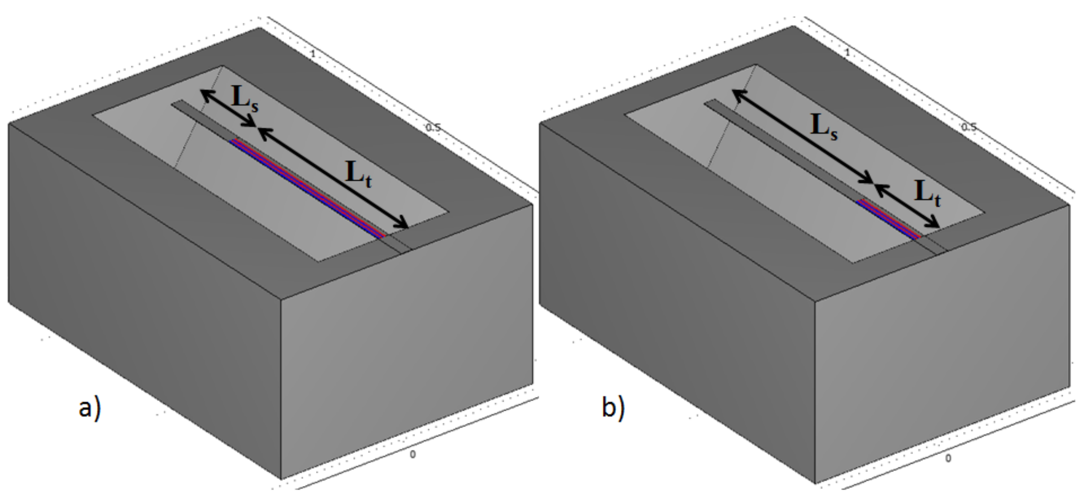
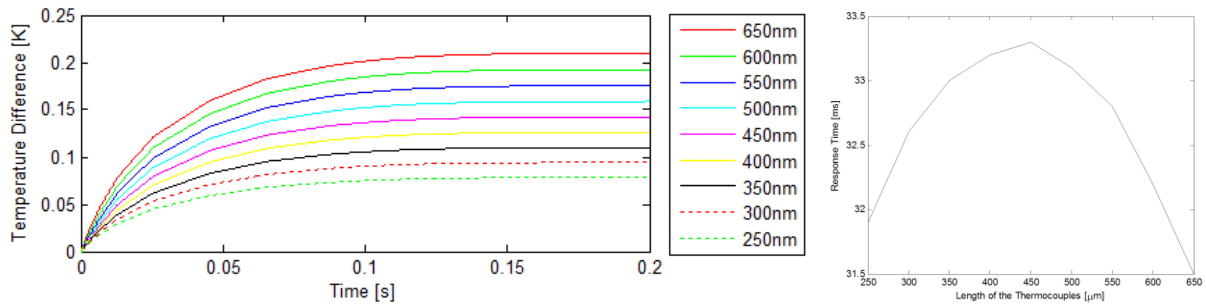


Figure 3. Thermopiles designed using COMSOL, with (a) thermocouples length of 650 μm and sensitive area length of 250 μm; (b) thermocouples length of 250 μm and sensitive area length of 650 μm

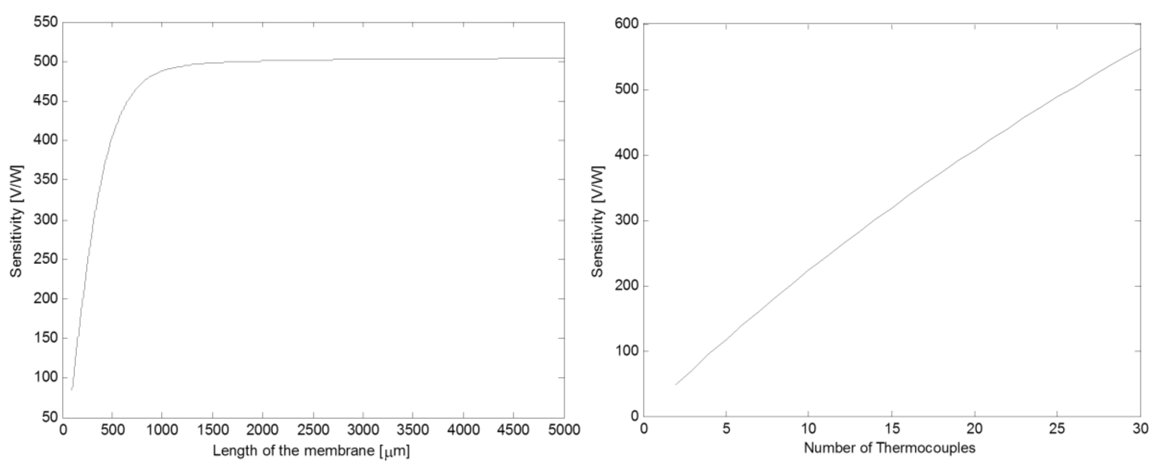
The curves shown in Figure 4 represent the signal obtained for each thermopile. After acquiring that data, the response time for each signal was determined. The response time is defined as the time it takes for a signal to achieve 0.6321 times the maximum value of the signal. Figure 4 shows that the maximum response time occurs when the length of the thermocouple equals the length of the sensitive area. The smallest values for the response time appear when the thermocouples are either the shortest or the longest within the simulation. Thus, lengthening the thermocouples not only increases the sensitivity, but also reduces the response time. However, it can be seen that the actual time that can be reduced or increased by manipulating these parameters does not exceed a couple of milliseconds.



(a) (b)

Figure 4. (a) Temperature difference between the hot and cold junctions for different lengths of thermocouples, and (b) response time vs. length of the thermocouples

The length of the membrane L_m enhances the sensitivity indirectly, because as the membrane lengthens, so can the thermocouples. However, increasing the length of the membrane is not necessarily practical, because as the membrane grows larger, so does the dimensions of the device. Also, as it can be seen in Figure 5, the increase in sensitivity is limited to a certain length of the thermocouple. For this specific simulation, such value was found at a length of approximately 1.5 mm. This result corresponds to a simulation performed using the parameters shown in Table III, where the length of the membrane was varied from 100 to 5000 μm and where the length of the thermocouples was defined as the length of the membrane minus the length of the sensitive area, fixed to 4 μm.



(a) (b)

Figure 5. Sensitivity vs. (a) the length of the membrane and (b) number of thermocouples

Table III. Parameters for the simulation in which the length of the membrane L_m was varied

Parameter	Value	Parameter	Value	Parameter	Value
ε_t	1	t_m	$0.5\ [\mu m]$	α	$309.64\ [\mu V \cdot K^{-1}]$
ε_b	0.5	t_t	$0.5\ [\mu m]$	W_m	$36\ [\mu m]$
T_e	$300\ [K]$	L_t	$L_m - L_s$	W_t	$4\ [\mu m]$
c_m	$20\ [W \cdot K^{-1} \cdot m^{-1}]$	L_s	$4\ [\mu m]$	d_1	$350\ [\mu m]$
c_t	$34\ [W \cdot K^{-1} \cdot m^{-1}]$	L_m	100 to 5000 $[\mu m]$	d_2	∞
c_g	0.0262	z	2		

The number of thermocouples is not only geometry dependent, but it also depends at some point on the fabrication process. A simulation was performed, where the number of thermocouples was varied from 2 to 30, and a membrane width of 362 μm was considered in order for up to 30 thermocouples, with a spacing of 2 μm, to fit in the membrane. The values of the rest of the parameters used in this simulation are the same as the ones shown in Table III, fixing the length of the thermocouples at 994 μm, and the length of the sensitive area at 4 μm. The sensitivity can be improved by increasing the number of thermocouples, as shown in Figure 5. However, there is a limit for the maximum number of thermocouples that can fit in a membrane with a specific width, which depends on the critical dimensions of the fabrication process for the spacing and line width. The critical dimension for the spacing defines the minimum distance between legs of the thermocouples, and the critical dimension of the line width defines the minimum width of the thermocouples.

The maximum number of thermocouples that can fit in a cantilever membrane with a specific width W_m, depends solely on the minimum spacing s and the minimum line width l_w, critical dimensions of the fabrication process, and can be represented as:

$$z_{max} = \left\lfloor \frac{W_m - s}{2(l_w + s)} \right\rfloor \tag{4}$$

As it can be seen, the width of the membrane is the only geometry dependent term in such equation. Thus, for a membrane with a specific width, a parameter that is geometry dependent, the maximum number of thermocouples may seem to depend on the fabrication process exclusively. This equation assumes that a minimum spacing s exists not only between the legs of the thermocouples, but also at both sides of the membrane. This situation is better represented in Figure 6, where the blue and red highlighted structures represent the n-poly-Si and p-poly-Si legs of the thermocouples respectively; the gray structure represents the non-coated part of the membrane and the black area represents the black coated sensitive area, which forms part of the membrane. In that same figure, it can also be noticed that there will be some unused space in the membrane if the width of the membrane is not designed for a specific number of thermocouples according to Equation (4).

The maximum number of thermocouples achievable seems to be a fabrication process dependent parameter, but there is a geometry dependency. In order to increment the maximum number of thermocouples, exceeding the value obtained with Equation (4), there are two viable options, either to widen the membrane or to use a bridge structure instead of the cantilever structure used up to this point.

Unfortunately, both options have drawbacks. Since the final goal of this sensor is to be part of a microspectrophotometer, and the wider the membrane, the bigger the device, it is not ideal to just widen the membrane to obtain a better sensitivity by increasing the maximum number of thermocouples. Also, widening the membrane translates into a larger thermal conduction area, ergo, the sensitivity increases at a slow rate when this parameter is modified. On the other hand, by using a bridge structure, the maximum number of thermocouples would approximately double, but the length of their legs would be approximately half of the original length. Making the thermocouples shorter would translate into a sensitivity reduction, since as stated previously, the larger the thermocouple, the larger the sensitivity. Thus, an analysis had to be made to better understand the trade-off between the length and the number of thermocouples.

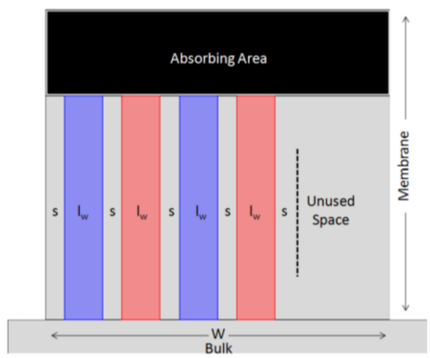


Figure 6. Top-view of the membrane of a cantilever thermopile showing the line width and spacing

Bridge vs. Cantilever structures

The reason why a thermopile with a bridge structure can approximately double the number of thermocouples from a thermopile with a cantilever structure resides on the possibility to place thermocouples in both sides of the bridge, in contact with the bulk. As it is shown in Figure 7, a bridge structure needs a thermocouple to cross the bridge in order for the thermal series connection to maintain. It is because of this particular thermocouple, that the maximum number of thermocouples between a bridge and a cantilever structure does not exactly double. Depending on the width of the membrane and the critical dimensions mentioned previously, there will either be $2z + 1$ or $2z - 1$ thermocouples, where z is the number of thermocouples in the cantilever structure.

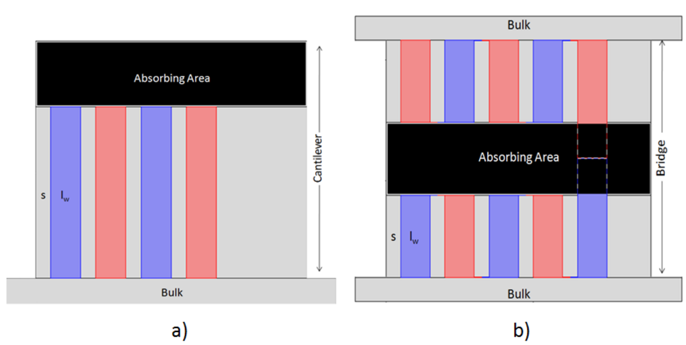


Figure 7. Top-view of a thermopile (a) based on a cantilever structure and (b) based on a bridge structure

A bridge structure can be analyzed as a cantilever structure with a sensitive area half as long and $2z \pm 1$ thermocouples using the proposed analytical model. Six n-poly-Si/p-poly-Si thermopiles based on a Si_3N_4 bridge structure, as the one shown in Figure 8, were designed using COMSOL. Each thermopile had a different thermocouple thickness, ranging from 300 to 800 µm, with 100 µm increases between each. The values of the geometry parameters used for this simulation are shown in Table IV.

Table IV. Values of the geometry parameters used in the COMSOL® design of the bridge based thermopiles

Parameter	Value [µm]	Parameter	Value [µm]	Parameter	Value [µm]
W_m	36	L_t	341	t_t	0.3 to 0.8
W_t	4	L_s	300	d_1	400
L_m	982	t_m	0.8	d_2	∞

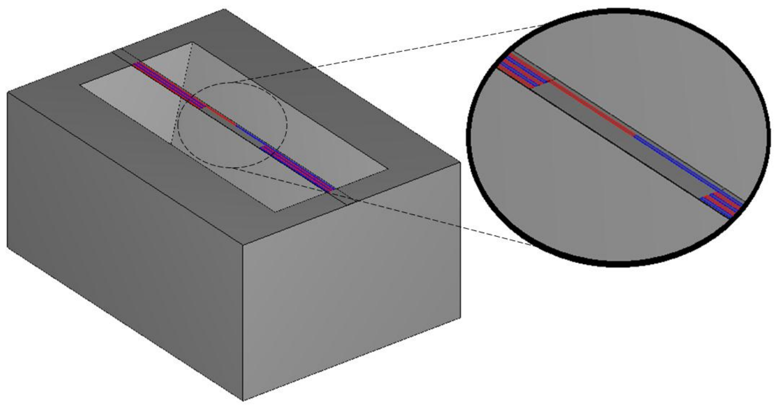


Figure 8. Thermopile based on a bridge structure designed using COMSOL. In the zoomed image, the thermocouple junction at the sensitive area is shown

Another simulation was carried out using MATLAB, using the geometry parameters from the COMSOL simulation. A detailed list of the values fixed for the different parameters is shown in Table V. It is important to notice that in this simulation, the values for the lengths of the sensitive area and the membrane are defined as half the lengths used in the finite element analysis. This is done because, as it was already stated, to fit a bridge structure in the analytical model, it must be considered as a cantilever structure with half the length of the bridge structure.

Table V. Parameters for the bridge structure simulation where the thickness of the thermocouples was varied

Parameter	Value	Parameter	Value	Parameter	Value
ε_t	1	t_m	$0.8\ [\mu m]$	α	$309.64\ [\mu V \cdot K^{-1}]$
ε_b	0.5	t_t	0.3 to $0.8 [\mu m]$	W_m	$36\ [\mu m]$
T_e	$300\ [K]$	L_t	$341\ [\mu m]$	W_t	$4\ [\mu m]$
c_m	$20\ [W \cdot K^{-1} \cdot m^{-1}]$	L_s	$150\ [\mu m]$	d_1	$400\ [\mu m]$
c_t	$34\ [W \cdot K^{-1} \cdot m^{-1}]$	L_m	$491\ [\mu m]$	d_2	∞
c_g	0	z	5		

For the analytical model to accurately represent the behavior of the thermopile based on a bridge structure, changes had to be done. The volume contribution of the thermocouples was originally defined as:

$$V_t = 2zW_tL_tt_t \tag{5}$$

but, for a bridge structure, the volume contribution of the thermocouples had to be expressed as:

$$V_t = zW_tL_tt_t \tag{6}$$

since the number of thermoelements (a single leg of the thermocouple) in one side of the bridge is exactly z, while in the case of the cantilever structure, the number of thermoelements in the membrane is $2z$.

The results of the temperature difference obtained with both analyses are shown in Figure 9. There was a maximum error between both methods of 3.8%, proving that the analytical method does accurately explain the behavior of a thermopile based on a bridge structure. After normalization, both methods responded to a change in the thickness of the thermocouples in an almost identical manner, with a maximum error of 2.02%.

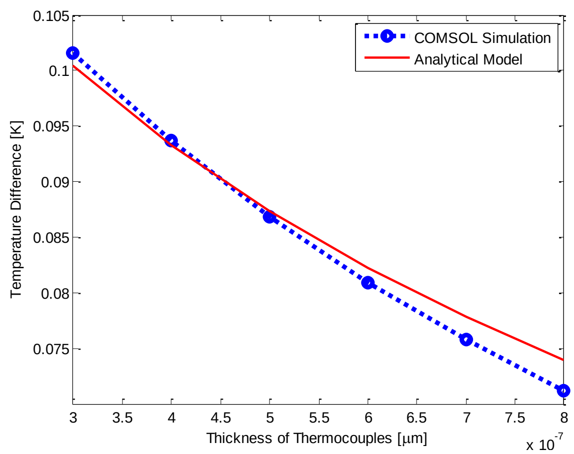


Figure 9. Temperature difference vs. thickness of the thermocouples in a bridge structure

To determine in which structure, if any, a larger sensitivity can be achieved with the same geometric restrictions, a couple of simulations were made. For the first simulation, the available length of the membrane was set to 1 mm. The lengths of the thermocouples and of the sensitive area, for the cantilever structure, were fixed at 996 µm and 4 µm, respectively. For the bridge structure, on the other hand, the length of the thermocouples was fixed at 448 µm and the length of the sensitive area at 4 µm. However, in the analytical model, a value of 2 µm for the length of the sensitive area in the bridge structure was used, because of the aforementioned restrictions. Since what is being analyzed, is the trade-off between increasing the number of thermocouples, and shortening them, this analysis was made for a wide range of number of thermocouples. In order to do so, the width of the membrane was varied from 26 to 1000 µm, fitting from 2 to 83 thermocouples in the cantilever structure. The bridge structure fitted either $2z + 1$ or $2z - 1$ thermocouples, and the cantilever structure z thermocouples. If there was enough remaining space in the cantilever membrane for an extra thermoelement and the width of the minimum spacing to fit, then the bridge structure had $2z + 1$ thermocouples, otherwise it had $2z - 1$ thermocouples.

The results for this simulation, shown in Figure 10, demonstrate that for a specific length of the membrane, designing a bridge structure results in a larger sensitivity than designing a cantilever structure. The reason for the sawtooth shaped curves is explained, considering that for the number of thermocouples to increase from z to $z+1$, the membrane must widen by a specific value. Before such value is reached, the membrane keeps widening, but it does not increase its number of thermocouples, therefore, the sensitivity starts to decrease until it reaches the point at which another thermocouple can be added and then, the sensitivity increases abruptly.

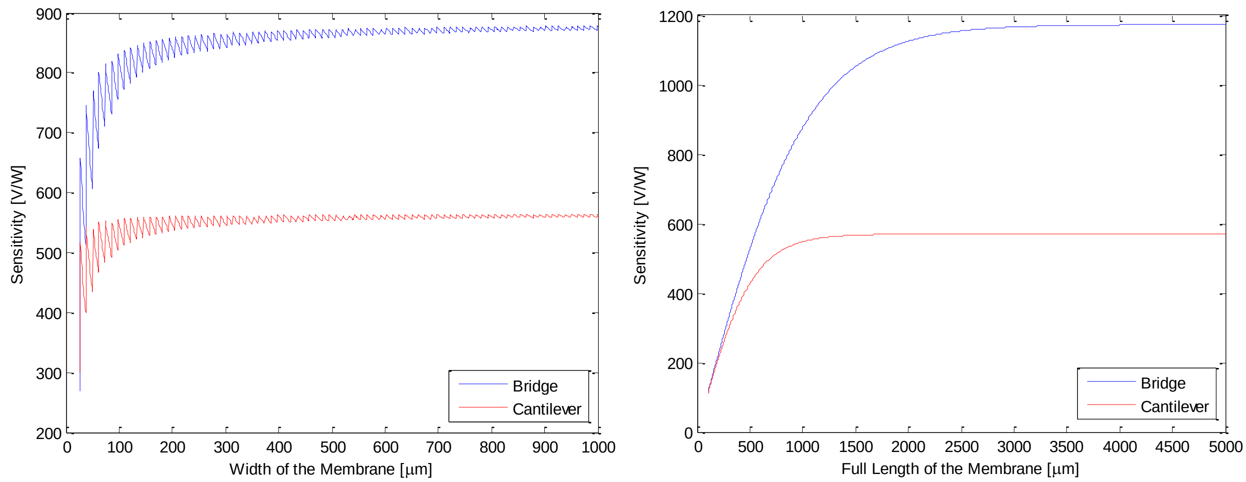


Figure 10. Sensitivity vs. (a) width of the membrane, and (b) length of the membrane

For the second simulation, instead of varying the width of the membrane (and therefore, the number of thermocouples) and fixing the length of the membrane, the width of the membrane was fixed at 200 μm and the length of the membrane was varied from 100 to 5000 μm. A membrane width of 200 μm fits 16 thermocouples for the cantilever structure and 33 thermocouples for the bridge structure, assuming a thermocouple width of 4 μm and a minimum spacing of 2 μm. Also, for the cantilever structure, the length of the sensitive area was fixed at 4 μm and the length of the thermocouples was defined as the length of the membrane minus the length of the sensitive area. For the bridge structure, the values of the lengths were defined as half their counterparts in the cantilever structure. The results of this simulation are shown in Figure 10, where it is demonstrated that the bridge structure achieves a larger sensitivity than the cantilever structure when there is a fixed membrane width. Thus, independently of the situation, designing for a thermopile based on a bridge structure seems to result in a larger sensitivity than designing for one based on a cantilever structure. This means that the number of thermocouples has a larger weight, regarding sensitivity, than the length of the thermocouples.

The optimization methods presented before can significantly increase the sensitivity of a thermopile. Using the thermopile designed by Wu et al. [5] as an example this is demonstrated. The parameters of such thermopile are shown in Table VII, in which the values marked with an asterisk are not specified by the authors, but assumed according to typical values. While the sensitivity reported for this device is of

289 V/W, the value obtained with the proposed analytical value is of 267 V/W, implying that one or more of the assumed values is not completely accurate. However, this small discrepancy is not relevant for the purpose of this analysis. By modifying the geometry dependent parameters only, assuming a typical 0.35 μm CMOS process, a significant increase in sensitivity can be achieved. The width of the thermocouples is changed to 0.35 μm with a spacing of 0.45 μm. Therefore, the number of thermocouples that fit in the membrane increases to 22. Also, the length of the sensitive area is assumed as 0.5 μm and the thermocouples length as 490.5 μm. Even though this material is deposited during the post-processing stage, such value was assumed according to typical values for metals deposited in a 0.35 μm CMOS process. After modifying these values and simulating using the proposed analytical model, a sensitivity of 4107.1 V/W was observed, a value 14 times larger than the one reported. Moreover, if the thicknesses of the membrane and of the thermocouples, fabrication process dependent parameters, were also changed to typical values of the process being assumed (0.29 and 0.282 μm, respectively), the sensitivity would almost double, reaching a value of 8048.5 V/W.

Table VI. Parameters of the bridge structure simulation where the thickness of the thermocouples was varied

Parameter	Value	Parameter	Value	Parameter	Value
$\boldsymbol{\varepsilon}_{\mathrm{t}}{}^{*}$	1	$\boldsymbol{t_m}$	$0.8\ [\mu m]$	α^*	$309.64\ [\mu V \cdot K^{-1}]$
$\boldsymbol{\varepsilon}_{\mathrm{b}}{}^{*}$	0	$\boldsymbol{t_t}$	$0.3\ [\mu m]$	W_m	$36\ [\mu m]$
$\boldsymbol{T_e}$	$300\ [K]$	$\boldsymbol{L_t}$	$341\ [\mu m]$	W_t	$4\ [\mu m]$
$\boldsymbol{c_m}^*$	$20\ [W \cdot K^{-1} \cdot m^{-1}]$	L_s	$150\ [\mu m]$	d_1	$525\ [\mu m]$
$\boldsymbol{c_t}^*$	$34\ [W \cdot K^{-1} \cdot m^{-1}]$	L_m	$491\ [\mu m]$	d_2	$300\ [\mu m]$
$\boldsymbol{c_g}^*$	0	z	2		

Sensivities so large may not necessarily be needed, but these results have other implications. If the reported sensitivity of 289 V/W was wanted for any particular reason, the dimensions of the sensor could be decreased by applying the proposed optimization scheme. Considering the same parameters used above, and changing the length and width of the membrane to 20 μm and 6 μm, respectively, a sensitivity of 290 V/W is obtained. This means that the dimensions of the sensor can be decreased from 17676 μm^2 to 120 μm^2 without having any loss of sensitivity.

Based on this optimization scheme, on the values of a typical 0.35 μm CMOS fabrication process, and assuming a desired sensitivity of 5000 V/W, a design for a thermopile is proposed. Structurally, the thermopile consists of a SiO2 membrane on a Si bridge with an Au-black thin film as the absorbing material. It was considered that the values of the minimum spacing and line width of poly-Si in these kinds of processes are usually around 0.45 μm and 0.35 μm respectively, that the typical value of the minimum line width of metals (the absorbing material in this case) is 500 nm, and that the minimum thicknesses of poly-Si, SiO2 and metals have typical values of 282 nm, 290 nm and 665 nm, respectively. For a thermopile with these characteristics to achieve a sensitivity of 5000 V/W, a membrane length and width of 101.33 μm and 4.45 μm respectively, are proposed. This sensitivity is achieved considering a vacuum packaging, in which case the values of d_1 and d_2 are negligible. Also, the value of the relative Seebeck coefficient for the n-poly-Si/p-poly-Si junction is assumed as 309.64 μV/°C.

Conclusions

A scheme to perform a design optimization of a CMOS-MEMS thermopile has been presented using parameters that govern the behavior of the sensor. The parameters that affect the sensitivity of the thermopile were classified as: fabrication process dependent, material dependent, and geometry dependent. Optimization of the sensitivity through the modification of the fabrication process dependent parameters is only possible if there are several processes to choose from, in which case, an analysis using the proposed model can be made in order to find the best option for the specific design. The parameters that constitute this category are: the distance between the cantilever and the bottom of the etch pit d_1, the distance between the cantilever and the package cap d_2, the thermal conductivity of the gas atmosphere c_g, the thickness of the thermocouples t_t, the thickness of the membrane t_m and the width of the thermocouples W_t. From Equation (1) it was easy to observe that the larger the first two parameters, the larger the sensitivity. Also, decreasing the value of the thermal conductivity of the gas atmosphere by creating a vacuum increases the sensitivity, and causes the values d_1 and d_2 to be negligible. Decreasing the thicknesses of the thermocouples and of the membrane and designing for slimmer thermocouples also enhance the performance of the device.

The material dependent parameters were demonstrated to be also fabrication process dependent, since the range of materials to choose from directly depends on the fabrication process being used. Therefore, the same implications as the ones stated for those variables, applies to the material dependent parameters. The only material dependent parameters are: the Seebeck coefficient α, the emissivity of the sensitive area on the lower face ε_b , and the emissivity of the sensitive area on the upper face ε_t.

The geometry dependent parameters are the most easily modified when designing thermopiles. It was demonstrated that, for any fixed membrane length, it is optimal to design the sensitive area as short as the fabrication process allows it to be. Therefore, the length of the thermocouples should be almost as long as the membrane. Previous work stated that lengthening the thermocouples increased the response time, but the obtained results did not agree with that asseveration. Actually, it was proved that the largest response time was obtained when the lengths of the thermocouples and of the sensitive area were equal, and that the difference between the smallest and the largest response time was smaller than 2 ms.

The maximum number of thermocouples that can fit in a membrane with a specific width depends on the fabrication process, and the more thermocouples, the larger sensitivity. A way of increasing the number of thermocouples without widening the membrane is by designing a bridge structure, instead of the more conventional cantilever structure. However, for a fixed membrane length, that would imply shortening the thermocouples by half. It was demonstrated that doubling and shortening the number of thermocouples has a greater impact in the sensitivity than having longer and fewer thermocouples. Therefore, the bridge structure is better, in terms of sensitivity, than the cantilever structure.

It was demonstrated that, using the optimization scheme mentioned, the sensitivity of a previously designed thermopile could be increased up to 28 times. Also, the dimensions of such thermopile could be decreased from 491 x 36 μm, to 20 x 6 μm without having any loss of sensitivity. The optimized design is being proposed for fabrication into a miniaturized spectrophotometer device [6, 7].

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