THE INFLUENCE OF GEOMETRY AND ELECTRICAL RESISTANCE OF THE THERMOELECTRIC LEGS IN THE μ-TEC DESIGN

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În aceasta lucrare sunt prezentate diferite tipuri de geometrie pentru termo-elementele folosite în micro-cooler-e (μ-TEC), care sunt făcute pe filme de silicon policristaline nanoscalare. Tehnica folosită pentru a obține aceste termo-elemente este aceea a depunerii unui strat de poli-silicon înăuntrul reactoarelor LPCVD. Performanța micro-cooler-elor μ-TEC este influențată de geometria de suprafață a termo-elementelor, a grosimii stratului şi a rezistivității materialului. În această lucrare sunt prezentate performanțele obținute pe patru tipuri diferite de geometrie a termo-elementelor menționate anterior.

In this paper, there are presented different types of geometries for the thermo elements used in micro-coolers (μ-TEC), which are made on nanoscale polycrystalline silicon films. The technique used to obtain these thermo elements is that of doped poly-silicon deposition within LPCVD reactors. The μ-TEC's performances are influenced by the surface geometry of thermo elements, the layer thickness and the material resistivity. In the present paper, there are presented the performances obtained on four different types of geometries for the thermo elements mentioned above.

Keywords: μ-TEC, thermo elements, thin films

1. Introduction

Most of the electronic and optoelectronic components dissipate a large amount of heat on a small surface, which adversely affects their performance [1, 2]. To reduce overheating, a potential solution could be the use of micro-

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thermoelectric coolers (μ-TEC) [1, 2, 3, 4]. The yield's of a thermoelectric device is determined by the material used in its manufacture. The most recent studies have shown, through experimental results, that the figure of merit had increased in special thermoelectric materials [3, 4, 5].

The thermoelectric element is integrated in the membrane holder for the cooling section, as it can be seen in Fig. 1. By supplying the system, the cold point of the membrane becomes a cooler and the frame take's the radiator function.

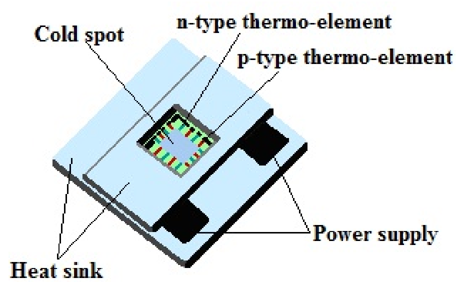


Fig. 1. Thermoelectric micro-cooler

2. The implementation of μ-TEC experimental model

In Fig. 2 it can be observed an in-plane representation, as well as a transversal representation, of the micro-cooler presented in Fig. 1.

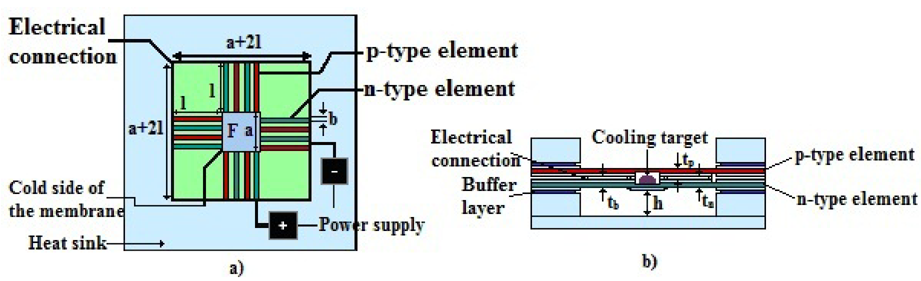


Fig. 2. μ-TEC: a) in-plane representation; b) transversal representation

The micro device consist in four pairs of thermoelectric legs, with b being the width and l being the length, which are connected in series, being extended from the cold point of the membrane (T_c temperature) around the cold membrane (F) toward the end of the frame (T_∞ temperature). The thermoelectric legs are made from poly-silicon material of n-type (t_n thickness) and p-type (t_p thickness), with a buffer layer from $SiO_2/Si_3N_4/SiO_2$ with a total thickness of t_b. The substrate used is made from single crystal silicon of n-type, with <111> orientation, which represent the hot spot (T_∞). The electrical connections are made from Cr/Au/Cr and there are used as bonding layer either in the hot region or in the cold one. This layer can't be transferred between the two regions, and for this reason it will be neglected within this model. Joule heat is released at the junction of this connection due to the electrical contact resistance (r_{ec}), which can degrade the performance of the micro devices. This aspect is taken into account at the model design.

The thermoelectric leg thickness is limited by the thin films growth technologies, being in the range of μm or even smaller [6, 7]. Therefore, the temperature distribution along the thickness direction can be ignored. In addition, due to the μ-TEC symmetrical design, the analysis of a single pair of legs, presented in Fig. 3, is enough to highlight its performance.

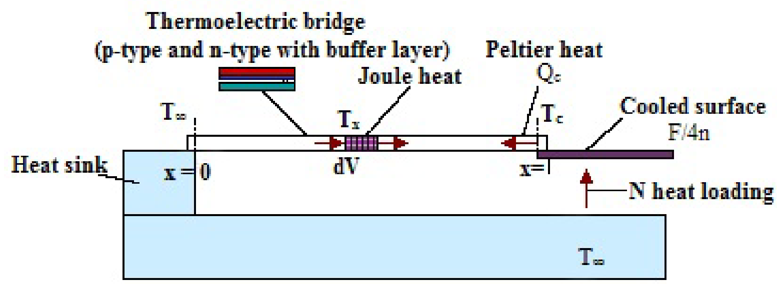


Fig. 3. The schematic diagram of μ-TEC

A uniform temperature T_c it is supposed on the cooled surface (F/4n), because Si has a high thermal conductivity. While the current passes through the thermoelectric legs, at the cold junction, namely (x=1), Peltier heat Q_c is generated, which is given by the relation:

$$Q_c = (\alpha_n - \alpha_p) I T_c \tag{1}$$

where α_n and α_p are the Seebeck coefficients for the n-type thermoelectric legs and respectively p-type. Considering Joule heat, the thermoelectric leg resistance is:

$$R = \left(\frac{\rho_n}{t_n} + \frac{\rho_p}{t_p} \right) \frac{l}{b_{eg}} \tag{2}$$

where ρ_i is the resistivity and b_{eg} is the equivalent width of the thermoelectric leg which will be defined later.

The equation which oversees the model of a pair of legs (Fig. 3) is:

$$\lambda_f t_f b_{eg} \frac{d^2[T(x) - T_\infty]}{dx^2} + \frac{I^2 R}{l} - (2\beta + 8\varepsilon k T_\infty^3) b_{eg} [T(x) - T_\infty] = 0 \tag{3}$$

where $\lambda_f t_f = \lambda_n t_n + \lambda_p t_p + 2\lambda_b t_b$. λ_i indicates the thermal conductivity; t_i indicates the thickness; while *n*, *p*, and *b* indices represent the n-type thermoelectric legs, respectively p-type, and the buffer layer. The 3rd term from Eq. (3) describes the amount of absorbed heat through convection and radiation, with the coefficient of heat transmission $\gamma = 2\beta + 8\varepsilon k T_\infty^3$, where β is the coefficient of native convection for environmental air, ε is the thermoelectric leg emissivity and k is the Stefan-Boltzman constant. The coefficient of thermal conduction isn't included because the temperature distribution near the hot frame, along the thermoelectric leg, is larger than the environment temperature, which could have as consequence a better performance due to the heat reflux. When the condition $[T(x) - T_\infty] / T_\infty \langle\langle 1$ is satisfied, the approximate thermal radiation coefficient is $\varepsilon k [T(x)^4 - T_\infty^4] \approx 4\varepsilon k T_\infty^3 [T(x) - T_\infty]$.

The two frontier conditions for Eq. 3 are:

- The hot side is maintained at the environment temperature

$$[T(x) - T_\infty]|_{x=0} = 0 \tag{4}$$

- The thermal equilibrium at the cold junction (x=1) drive to:

$$\lambda_f t_f b_{eg} \frac{d[T(x) - T_\infty]}{dx}|_{x=1} = -(Q_c - N - I^2 R_{ec}) - \gamma_F \frac{F}{4n}[T(l) - T_\infty] \tag{5}$$

where N is the heat derived from the cooled target, R_{ec} is the electrical contact resistance at junction, defined as r_{ec} (in Ω/m^2), depending on the contact area (A_c) and $\gamma_F = \frac{\lambda_{air}}{h} + 2\beta + 8\varepsilon_F k T_\infty^3$ which represents the coefficient of heat transfer from the layer toward the cooled area, and ε_F is the cooled membrane emissivity.

The analytical solution is given by:

$$(T_c - T_\infty)\left[\frac{\lambda_f t_f b_{eg}}{l}\frac{s}{f(s)} + \gamma_F \frac{F}{4n}\right] = -[(\alpha_n - \alpha_p) I T_c - N] + I^2\left\{R\left[\frac{g(s)}{sf(s)}\right] + R_{ec}\right\} \text{.....(6)}$$

where $s = l\sqrt{p}$, *with* $p = \gamma / \lambda_f t_f$; f(s) and g(s) functions being defined as:

$$f(s) = \tanh(s) \tag{7}$$

$$g(s) = 1 - \frac{1}{\cosh(s)} \tag{8}$$

These two functions depend on the thermoelectric leg length (1) and the ratio of transfer coefficient (p). The optimum current for the maximum temperature difference and the maximum cooling capacity can be determined from Eq. (6) and it is given by:

$$I_{opt} = \frac{(\alpha_n - \alpha_p)T_c}{2\overline{R}} \frac{sf(s)}{g(s)} \tag{9}$$

where $\overline{R} = R\left[\frac{g(s)}{sf(s)}\right] + R_{ec}$. By replacing Eq. (9) within Eq. (6), the maximum temperature difference ΔT_{max} can be obtained in the absence of heat load (N) and the maximum cooling capacity N_{max} can be obtained when there are no temperature differences along the entire μ-TEC.

$$(T_c - T_\infty)_{max} = -\frac{(\alpha_n - \alpha_p)^2 T_c^2}{4\overline{R}} \frac{sf(s)}{g(s)} \left[\frac{1}{\frac{\lambda_f t_f b_{eg}}{l} \frac{s}{f(s)} + \gamma_F \frac{F}{4n}} \right] \tag{10}$$

$$N_{\max} = \frac{n(\alpha_n - \alpha_p)^2 T_\infty^2}{\overline{R}} [\frac{sf(s)}{g(s)}] \tag{11}$$

Eq. (6) ÷ (11) can be used in the μ-TEC optimal design to obtain maximum temperature differences with high cooling capabilities.

If the buffer layer, the electrical contact resistance and the heat dispersion are neglected, then Eq. (10) and (11) can be rewritten as follow:

$$\Delta T_{\max} = -\frac{ZT_c^2}{2} \tag{12}$$

$$N_{\max} = \frac{\alpha_n^2 T_c^2}{\rho_n} \frac{t_n P}{l} \tag{13}$$

We notice that these results are of an ideal thermoelectric system.

3. Resolving the model

The electrical contact resistance has an important role within the μ-TEC design. The overall electrical resistance, along both the cold and hot regions ($\overline{R}$), the resistance per square is used to observe the yield reduction of μ-TEC devices. Generally, r_{ec} is of $10^{-6} \div 10^{-8}$ Ω/cm^2 order supposing an A_c=50 μm^2 contact surface.

Table 1

Influence of the electrical contact resistance

$l(mm)$	Resistance ratio ($R\left[\frac{g(s)}{sf(s)}\right]$)	$R_{ec}\ in\ \overline{R}$ (%)
0,3	48,2	0,0008 – 0,08
0,5	50,9	0,00079 – 0,079
1,0	51,2	0,00078 – 0,078

Normally, $R_{ec} \langle\langle\ \overline{R}$, thus the electrical contact resistance can be neglected if the thermoelectric leg resistance is very high at the thin films level of a μ-TEC.

To simplify the model it is assumed that we have the same material properties and same dimensions for the n and p-type thermoelectric legs, namely: $\rho_n = \rho_p$, $\lambda_n = \lambda_p$, $\alpha_n = -\alpha_p$ *şi* $t_n = t_p$. Thus, Eq. (2) and Eq. (9) ÷ (11) can be written as:

$$R = \frac{2\rho_n l}{C_3 b t_n} \tag{14}$$

$$I_{opt} = \frac{\alpha_n T_c}{R}\frac{sf(s)}{g(s)} = \frac{\alpha_n T_c}{2\rho_n}\frac{C_3 b t_n}{l}\frac{sf(s)}{g(s)} \tag{15}$$

$$\Delta T_{max} = -\frac{ZT_c^2}{4}\left[\frac{1}{\left(1+\frac{\lambda_b t_b}{\lambda_n t_n}\right)\frac{g(s)}{f^2(s)} + \frac{\gamma_F}{\lambda_n t_n}\frac{C_1 C_2 a^2}{2C_3}\frac{l}{P}\frac{g(s)}{sf(s)}}\right] \tag{16}$$

$$N_{\max} = \frac{\alpha_n^2 T_c^2}{2\rho_n}\frac{C_3 t_n}{C_2}\left(\frac{P}{l}\right)\left[\frac{sf(s)}{g(s)}\right] \tag{17}$$

where $Z = \alpha_n^2 / \rho_n \lambda_n$ is the figure of merit, C_1, C_2 and C_3 are the coefficients given by the geometrical shape and the thermoelectric legs position. From Eq. (14)-(16) it is noticed that:

(1) ΔT_{max} is proportional with ZT;

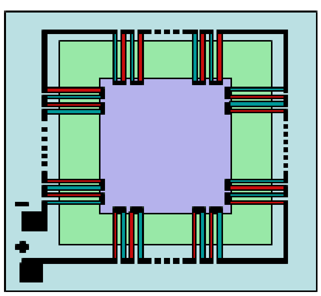
(2) It is possible that a square shape for the cooled surface to not be the most appropriate solution, thus C_1 is used to define the ratio of the cooled surface against a square shape with fixed side (a), thus, apparent that $F = C_1a^2$. For example, if the cooled area has a round shape then $C_1 = \pi/4$;

(3) The distance between the thermoelectric legs is a very important parameter. Thereby C_2 is used to define the spacing of thermoelectric legs on each side of the cooled surface, resulting that $a = C_2n_b$. For example, if the distance between two thermoelectric legs is equal with the thermoelectric leg width, then $C_2 = 2$.

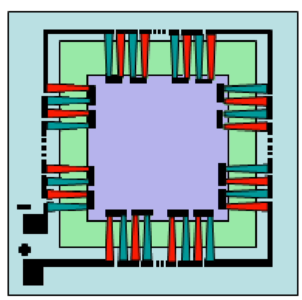
In principle, the thermoelectric legs can have any shape. To simplify the analyses it is assumed that the width *b* and length *l* of the thermoelectric legs are fixed, while their width b_2 is near of the hot frame. It is defined $C_3 = (b+b_2)/2b$, used to determinate the equivalent width $b_{eq} = C_3b$, to convert the top surface ($A_{top}=C_3bl$) and cross section ($A_{cross}=C_3bt_f$) of the thermoelectric legs.

4. Results and discussions

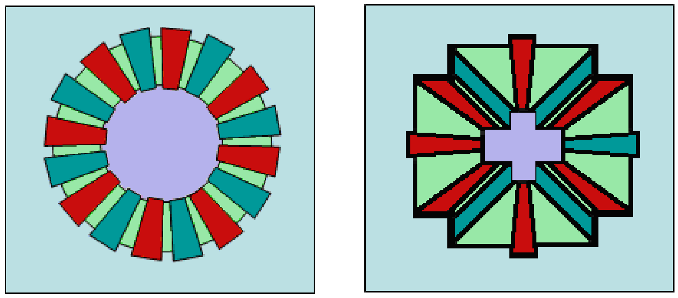
4 different geometries of thermo elements were resolved (Fig. 4).



a) $C_1= 1, C_2= 2, C_3= 1$



b) $C_1= 1, C_2= 2, C_3= 2$



c) $C_1 = \pi/4$, $C_2 = 2$, $C_3 = 2$ d) $C_1 = 5/9$, $C_2 = 2$, $C_3 = 2$

Fig. 4. Different geometries of μ-TEC (a÷d)

a) thermo-elements rectangular geometry and the square shape of the cooled surface;
b) thermo-elements triangular geometry and the square shape of the cooled surface;
c) thermo-elements conic geometry and the circular shape of the cooled surface;
d) thermo-elements truncated cone geometry and the cross shape of the cooled surface

From the experimental point of view, the μ-TEC was made on a single crystalline silicon substrate. The substrate, in wafer shape, has a thickness which ranges from 300μm to 500μm with a (111) crystal orientation. It is a very good thermal conductor, helping to dismiss the heat released in the cooling process. Alternatively, other materials (glass, sapphire or alumina) can be used. In addition to this substrate, another important element is represented by a membrane composed of three insulating layers, two of silicon nitride and one of silicon dioxide. This membrane carries out two functions: electric insulator and, in the same time, thermal insulator. It must be thin enough to allow the heat flow minimization which passes towards the substrate, and does not contribute to the thermoelectric conversion.

The thermo elements pair was fabricated from polycrystalline silicon doped with boron for the p-type thermo elements and with phosphorus for the n-type thermo elements, all depositions being made through LPCVD process.

The n and p-type thermo elements are disposed around this membrane and are interconnected with the help of a metallic layer from chromium and gold.

In table 2, there are presented data's with respect to the use of parameters for the μ-TEC fabrication.

Table 2

Parameters and properties of materials used in the computation of a μ-TEC

a (mm)	1
$t_n = t_p$ (μm)	0,4
l (mm)	0,3; 0,5; 1
h (mm)	0,5
4n	20
T_∞ (K)	300
$\alpha_n = -\alpha_p$ (μV/K)	200

$\rho_n = \rho_p$ (10^{-5} Ωm)	0,6
$\lambda_n = \lambda_p$, λ_b, λ_{air} (W/m·K)	2; 2; 0,042
ZT_∞	1
ε, ε_F (worst case)	1
β (W/m^{2}K)	5
r_{ec} (Ωm^2)	10^{-10}
k (W/m^{2}K^4)	$5{,}67 \cdot 10^{-8}$

The coefficient of heat transfer γ_F can be calculated by thermal conduction, native convection and thermal radiation. The value of γ_F can range from 10 to 100 W/m^{2}K or even more, which can damage the system. The γ_F control can be achieved by introducing a space (h). In table 3, there can be noticed the values for the coefficient of heat transfer, depending on the air space (h).

Table 3

The coefficient of heat transfer

h (mm)	λ_{air}/g	2β	$8\varepsilon_F kT^3_\infty$	γ_F (W/m^{2}K)
0,5	84	10	12,5	108,5
1	42	10	12,5	64,5

In the charts from Figs. 5 and 6, there are compared the performances of μ-TEC used in vacuum with those of μ-TEC used in the environment (γ_F = 110).

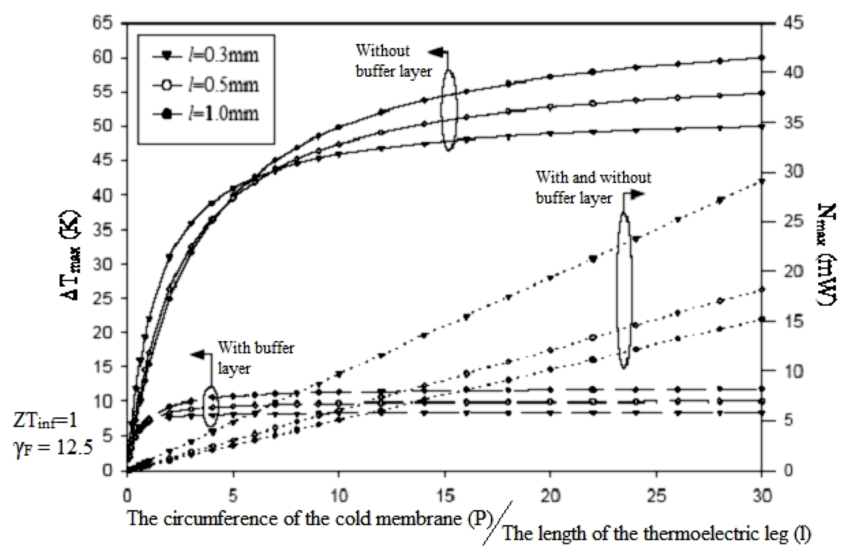


Fig. 5. The performance of a μ-TEC depending on P/l in vacuum

As it can be noticed from Figs. 5 and 6, considering the fixed length of the thermoelectric leg for each curve, the maximum temperature difference (ΔT_{max}) and the maximum cooling capacity (N_{max}) proportionally increase with the cooled surface. N_{max} is achieved in the moment in which there is no temperature difference, and depends only by the thermoelectric leg resistance. The buffer layer does not affect N_{max} because there isn't any thermoelectric phenomenon, but the thermal conduction from the buffer layer is taken into account. By comparing two sets of curves (with or without buffer layer), it can be noticed that the effect of the buffer layer is to decrease ΔT_{max}. If a high ΔT_{max} is necessary then the buffer layer must be removed during the fabrication process. ΔT_{max} is also influenced by heat loss at ambient exploitation.

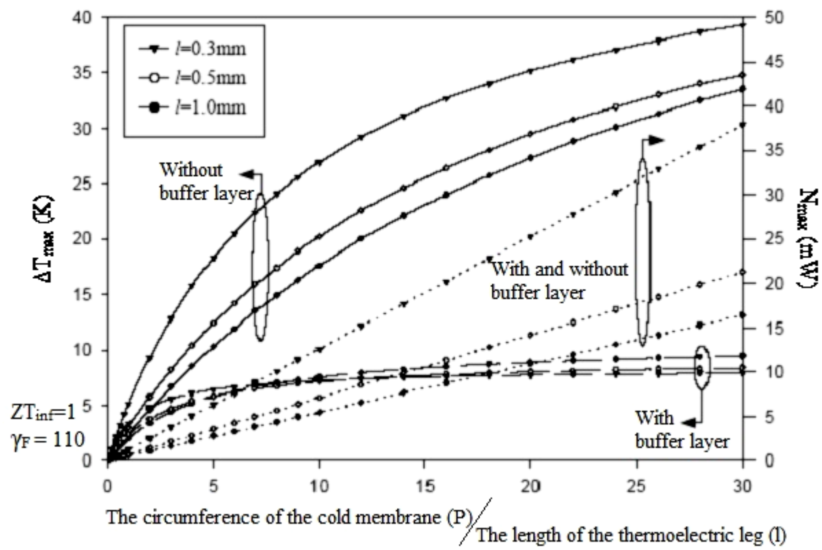


Fig. 6. The performance of a μ-TEC depending on P/l in the environment

Fig. 7 shows the performance differences of a μ-TEC in ambient for l = 0.5 mm.

For finding the optimal geometry of the thermoelectric leg and the cooling surface, there are used three parameters (C_1-C_3). The S point indicates the optimal case without any air space (C_2=1) between the thermoelectric legs, where P/l =4 mm / 0.5 mm = 8. The relative quantity (C_1C_2/C_3) in the temperature flow term from the Eq. (16), should be minimized for obtaining the ΔT_{max}. In Eq. (17) there also exists the parameter (C_3/C_2), which should be minimized for finding N_{max}.

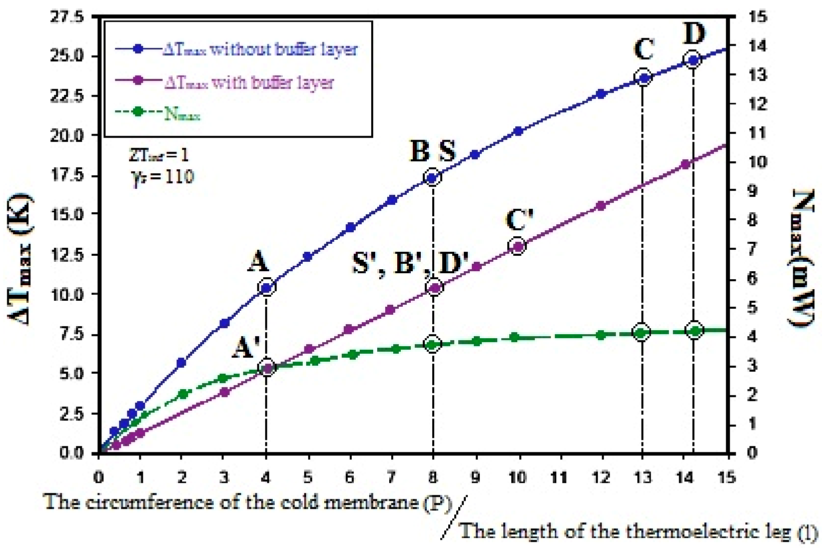


Fig. 7. The μ-TEC performance variation used in the environment for l = 0,5

By choosing the model from Fig. 4, the performance of the new μ-TEC model can be obtained by calculating the new ratios $(P/l)_{nou1} = (P/l)_{vechi} / (C_1C_2/C_3)$ for the ΔT_{max} curves and a new ratio $(P/l)_{nou2} = (P/l)_{vechi} (C_3/C_2)$ for N_{max}, as shown also by the A÷D points for ΔT_{max} and A`÷D` for N_{max}. Due to the equal width of the space and the legs, $C_2 = 2$, the performance should degrade from S to A point. The B÷D indicates the performance increase by adjusting the shape of the thermoelectric legs and the cooling surface. In any case, because N_{max} depends only by C_3/C_2, the points S`, B` and D` show the same performance.

5. Conclusions

The development of a model for μ-TEC design must consider the effects of heat looses and the shape of the thermoelectric legs. It had been shown that a μ-TEC buffer layer and also the effect of heat transfer can degrade its performance. The electrical contact resistance can be neglected because the resistance of the thermoelectric legs is very large in thin-film based μ-TEC. Based on the model and the experimental result presented, there can be obtained high performance μ-TEC. Any of the c) or d) models from Fig. 4 can represent the optimal choice for a μ-TEC development.

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