



Micro-hot-plates without simply connected hot-spots and with almost-circular temperature distribution

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ABSTRACT

We have recently shown that the temperature distribution in micro-hot-plates with perfectly circular geometry can be accurately expressed in terms of modified Bessel functions. However, the geometry of practical micro-hot-plates cannot be perfectly circular due to several issues, including the presence of the electrical contacts; in fact, a typical manifestation of poor circular-symmetry is the occurrence of simply connected hot-spots. Here we systematically investigate all these issues and describe strategies for designing micro-hot-plates without simply connected hot-spots and with an almost circular temperature distribution. FEM simulations consistently confirm that our methodology reduces the temperature deviations from ideal circular symmetry down to levels which are unimportant for most applications (e.g. less than 2.5 °C for a micro-hot-plate operating at 800 °C). As a result of the excellent circular symmetry, the temperature distribution in the proposed micro-hot-plates, unlike previously reported devices, can be accurately expressed in terms of the modified Bessel functions, which is a key step toward the design of micro-hot-plates with unprecedented temperature uniformity or with desired temperature profiles.

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1. Introduction

Micro-hot-plates are micro-devices comprising resistive heaters integrated within a thin membrane; the low thickness of the membrane results in an increased thermal resistance between the heater and the substrate, so that high operating temperatures can be obtained with low power consumption [1]; moreover, since the micro-hot-plate can be heated without significantly increasing the substrate temperature, other devices on the same chip (electronic interface [2], other sensors/actuators and possibly, in the future, integrated energy harvesters [3–5]) can operate at much lower temperatures than the micro-hot-plate [6]. For these reasons micro-hot-plates are widely utilized in chemical gas sensors for metal-oxide gas sensing [7–9], infra-red emitters for optical gas sensing [10,11] and micro-reactors for chemical vapor deposition [6,12]; in almost all these applications, the uniformity of temperature distribution within the heater is decisive [13–15]. However, micro-hot-plates with simple meander shape heaters typically have a central hot spot [15] as, despite the asymmetry between the central part and the peripheral part of the heater, the power per unit area within the heater is almost constant.

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Though the temperature distribution can be easily made more uniform by using an heat-spreading plate [1,6,15], this solution increases both the cost and complexity of micro-fabrication. As another option which does not require any additional fabrication step and can also be combined with the heat-spreading plate for an even superior temperature uniformity, the heater geometry can be modified so that the power per unit area within the heater becomes significantly non-constant and can, therefore, somehow compensate for the asymmetry between the central and the peripheral parts; an effective implementation of this general solution is to use spiral heaters which give non-constant power per unit area. However, the accurate generation of the required distribution of the power per unit area requires an accurate and quantitative knowledge of the thermal losses in the different parts of the heater. Similarly, it has been proposed to use two distinct heaters for separately compensating the thermal losses inside and outside heater [16–18]; however, the accurate generation of the required compensating powers of the individual heaters requires an accurate and quantitative knowledge of the thermal losses in the interior and the exterior of the heater. Although FEM simulations can provide such information with reasonable accuracy, they do not provide sufficient insight for systematic design of the micro-heater. In fact, the systematic design of micro-heaters is inherently highly complex due to the presence of many free parameters. As a result, without an analytical model for the temperature distribution, designers can only improve the

temperature uniformity by trial-and-error, obviously resulting in largely sub-optimal designs due to the high number of free parameters.

For these reasons, in a previous manuscript [19] we have shown that the temperature distribution in a micro-hot-plate with perfectly circular geometry can be accurately expressed in terms of the modified Bessel functions; these analytical relations have almost the same accuracy as FEM simulations and can, therefore, be used for the systematic design of micro-hot-plates with uniform temperature distribution or with a desired temperature profile. However, perfect circular geometry was a prerequisite for the analysis reported in [19] because such a geometry, along with the typical (i.e. very small) membrane thickness, reduces the complex three dimensional temperature distribution to a much simpler one-dimensional problem. However, practical heaters may not be perfectly circular because the unavoidable electrical contacts somehow break the circular symmetry; such potentially very strong perturbation of the circular symmetry (see Section 3 on FEM simulations) is mainly caused by both the external contacts to the driving circuitry and by the internal contacts among the individual heaters (which is the case of a multi-heater micro-hot-plate design with any of the heater configurations: series or parallel). We stress that, since the importance of circular symmetry was recognized only very recently [19], the design of micro-hot-plates with almost circular symmetry is virtually unexplored.

Another key issue in micro-hot-plates design is minimizing simply connected hot and cold spots. Simply connected hot-spots can be defined as well localized, simply connected (i.e. there are no holes) regions at significantly higher temperature in comparison with their surroundings (e.g. due to an excessive local heat generation). Though generally not explicitly mentioned or discussed, hot-spots are well known by micro-hot-plates designers and can often be easily identified by inspection of the temperature distributions in micro-hot-plates, as for instance in [15,20–24]. In particular, an almost-constant power per unit area in regions whose surroundings are very different (e.g. in contrast to the central region, the peripheral parts of the micro-heater are adjacent to areas which are not directly heated, such as the bridges or membranes which connect the heater to the bulk) easily results in significant temperature differences, as in [15,20–22]. Alternatively, hot-spots can also arise in parts of the heater with substantially higher current flow as it was likely the case in the references [23,24]. In the case of multi-heater design [16–18] the electrical contacts can also be critical as, apart from breaking the symmetry due to their typically very high thermal conductivity (in striking contrast with the very low thermal conductance of the thermally insulating membrane), the current flow in the contacts will generate an undesirable heat, which may also give an hot-spot. Clearly, cold-spots can be defined in a dual manner and may be introduced by a locally insufficient heat generation. Despite its crucial importance, the minimization of simply connected hot-spots has not yet been systematically investigated in the literature. For instance, micro-heaters using a series [17,18,23] or a parallel [23] connection of different sub-heaters have been reported, but it has not been discussed if one option is better than the other in terms of hot-spots. We stress that a good circular-symmetry of the temperature distribution can only be obtained if, in particular, there are no simply connected hot-spots and/or cold-spots.

Here, we determine the guidelines for designing micro-heaters with an almost-circular temperature symmetry and, in particular, without simply connected hot-spots and cold-spots. FEM simulations confirm that our method allows one to design micro-heaters with a circular symmetry which is so good that the analytical relations found in [19] are still very accurate. The proposed design methodology, in conjunction with the model [19] may allow the

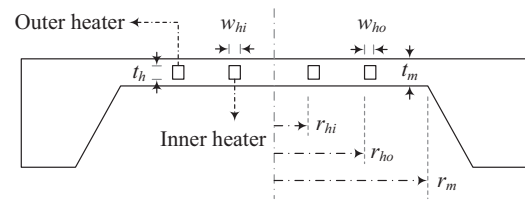


Fig. 1. Cross-sectional view of a micro-hot-plate (not in scale).

systematic design of micro-hot-plates with unprecedented temperature uniformity or with desired temperature profiles.

2. Strategies for the design of micro-hot-plates without simply connected hot-spots and with almost-circular temperature distribution

Here, we describe methodologies for designing a micro-heater structure with almost circular temperature distribution and, in particular, without simply connected hot-spots or cold-spots. First, in order to obtain a circular temperature distribution we adopt a multi-heater design [16–18] with the total heater made of a combination of circular heaters. For simplicity, here, we consider a micro-hot-plate with circular membrane and with only two circular ring-heaters, as schematically shown in Fig. 1 (cross section) where t_h and t_m are the thicknesses of the heater and of the membrane, w_{ho} and w_{hi} are the widths of the inner and outer heaters, r_{hi} , r_{ho} and r_m are the radii of the inner heater, outer heater, and membrane, respectively. We stress that though we consider only two circular ring-heaters, as we shall discuss later, our method can easily be applied to a generic number of heaters.

2.1. Temperature distribution in an hypothetical micro-hot-plate with perfectly circular geometry

In hypothetical micro-hot-plates with perfectly circular geometry the temperature can be accurately expressed in terms of modified Bessel functions [19]. With reference to Fig. 1, the device can be considered as composed by five regions: the central region inside the inner heater; the inner heater region; the intermediate region between the inner and outer heaters; the outer heater region; the external region, which is outside the outer heater. In [19], we assumed that, for both the inner and outer heaters, the temperature within an heater region is perfectly constant and determined the analytical expressions for temperature distribution in the central, intermediate and external regions [19] for two distinct design cases. Here, for conciseness, we only report the relations which correspond to the case of the inner and outer heaters temperatures equal to two arbitrary values, T_{hi} and T_{ho} , respectively, as this choice offers a better temperature uniformity if the both the temperatures (T_{hi} and T_{ho}) are equal (case (a) in [19]).

The temperature in the central region ($0 \leq r \leq r_{hi}$) is

$$T(r) = \frac{(T_{hi} - T_o)}{I_0(n_o r_{hi})} I_0(n_o r) + T_o \tag{1}$$

The temperature in the intermediate region ($r_{hi} + w_{hi} \leq r \leq r_{ho}$) is

$$T(r) = \left[\frac{[(T_{hi} - T_o)K_0(n_o r_{ho}) - (T_{ho} - T_o)K_0(n_o(r_{hi} + w_{hi}))]I_0(n_o r)}{[I_0(n_o(r_{hi} + w_{hi}))K_0(n_o r_{ho}) - I_0(n_o r_{ho})K_0(n_o(r_{hi} + w_{hi}))]} - \frac{[(T_{hi} - T_o)I_0(n_o r_{ho}) - (T_{ho} - T_o)I_0(n_o(r_{hi} + w_{hi}))]K_0(n_o r)}{[I_0(n_o(r_{hi} + w_{hi}))K_0(n_o r_{ho}) - I_0(n_o r_{ho})K_0(n_o(r_{hi} + w_{hi}))]} \right] + T_o \tag{2}$$

The temperature in the external region ($r_{ho} + w_{ho} \leq r \leq r_m$) is

$$T(r) = \left(\frac{(T_{ho} - T_a)[K_0(n_a r_m)I_0(n_a r) - I_0(n_a r_m)K_0(n_a r)]}{I_0(n_a(r_{ho} + w_{ho}))K_0(n_a r_m) - I_0(n_a r_m)K_0(n_a(r_{ho} + w_{ho}))} \right) + T_a. \tag{3}$$

$$n_o = \sqrt{\frac{2h_c + 8\sigma\epsilon T_h^3}{kt_m}}$$

$$n_a = \sqrt{\frac{2h_c}{kt_m}}$$

$$T_o = \left(\frac{2h_c T_a + 6\sigma\epsilon T_h^4 + 2\sigma\epsilon T_a^4}{2h_c + 8\sigma\epsilon T_h^3} \right)$$

I_i is the modified Bessel function of 1st kind and i th order [25], and K_i is the modified Bessel function of 2nd kind and i th order [25], whereas σ is Stefan's Boltzmann constant, ϵ is the average surface emissivity of membrane and h_c is the average convection heat transfer coefficient (average refers to the top and bottom surfaces which, in general, may have different emissivities and convection heat transfer coefficients), k is the thermal conductivity of membrane and T_a is the ambient temperature.

2.2. Possible causes of imperfect circular symmetry of the temperature distribution and strategies for minimizing deviations from circular symmetry and for avoiding simply connected hot-spots and cold-spots

In order to design a micro-hot-plate with almost circular temperature distribution and, in particular, without simply connected hot-spots or cold-spots, we will separately investigate all the possible causes of imperfect circular symmetry of the temperature distribution, namely the type of connection between the individual heaters (either series or parallel), the structure of the individual heaters (e.g. number of turns in the case of serpentes), the electrical contacts (both internal and external contacts), and the gaps and cuts.

2.2.1. Electrical connection among individual heaters

In multi-heaters designs hot-spots can easily arise from improper electrical connection between different individual heaters. A two-heater micro-hot-plate requires internal contacts between the individual heaters (in any of the configuration: series or parallel) and external contacts to the electronic interface of the micro-hot-plate; the contacts, which obviously do not have circular-symmetry, can perturb the circular symmetry either by their (typically high) thermal conductivity or by heat generation. In particular, the heat generation in the contacts often dominates and, besides breaking the circular-symmetry of the temperature distribution, easily introduces simply connected hot-spots at the junction between the contact and the heater (see also the discussion on FEM results in Section 3). Therefore, a proper design must minimize the heat generated within the electrical contacts. Accordingly, we prefer a series configuration of the individual heaters (shown in Fig. 2). In fact, every electrical contact, whose electrical resistance can be referred to as R_{CX} , is *in series* with the part of the heater which is internal to the contact and whose electrical resistance can be referred to as R_{ICX} . Therefore, the heat generated within the contact is negligible in comparison with the heat generated within the part of the heater internal to the contact if and only if R_{CX} is much smaller than R_{ICX} . However R_{CX} cannot be arbitrarily

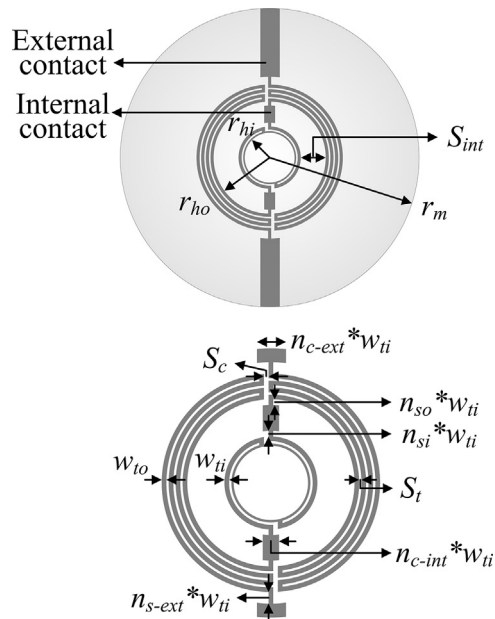


Fig. 2. Micro-hot-plate with two-heater geometry (top) and zoom of the central part of micro-hot-plate (bottom).

reduced (e.g. for external contacts, excessively thick and wide contacts would act as thermal short-circuits and degrade the thermal resistance between the hot-plate and the bulk); as a result, R_{ICX} must be sufficiently high, which in practice, taking into account the high electrical conductivities of typical heater materials and the limitations on the available area and on the minimum width, is substantially easier with series connections. The series connection is especially crucial for avoiding simply connected hot-spots at the external contacts which easily have a significant resistance due to their possibly very high length (especially if the radius of the membrane is very large in comparison to the radius of the active/heater region).

As is obvious, the series connection (i.e. higher total resistance) will require, in order to generate the power required for a desired hot-plate temperature, a larger supply voltage in comparison with the parallel connection (i.e. lower total resistance). Though this can be an issue for low voltage applications or may require, for instance, additional circuitry (e.g. charge pumps [26,27]) or even more robust processes, in this work we exclusively focus on how to minimize hot-spots and to minimally degrade the circular symmetry.

2.2.2. Structure of the individual heaters

Fig. 2 shows the proposed structure where, for simplicity, we only considered two-heaters simply referred to as the inner and outer heaters; r_{hi} , r_{ho} and r_m are the radii of inner heater, outer heater and membrane, respectively; w_{ti} and w_{to} are the track widths of inner heater and outer heater, respectively; S_{int} is the length of the intermediate region, S_t is the spacing between the tracks and S_c is the length of the cuts at the extremities of the tracks length; n_{c-int} and n_{c-ext} are the contact-width multiplicity factors for internal contacts and external contacts, respectively; n_{so} and n_{si} are the distance-to-junctions multiplicity factors for outer and inner edges of internal contacts, respectively, whereas, n_{s-ext} is the distance-to-junctions multiplicity factor for the external contacts.

As discussed above, the inner and outer heaters are connected in series. Since the outer heater has to compensate for significantly higher thermal losses than the inner heater in the series, for the series configuration (i.e. both heaters have the same current), the outer heater resistance must then be higher than the inner heater resistance. For this reason, in order to have a sufficiently higher

Table 1
Material properties.

Material	Thermal conductivity (W/(m K))	Resistivity (Ω m)	Temperature coefficient of resistance (1/K)	Surface emissivity
Silicon dioxide	1.4	–	–	0.5 [11]
Silicon nitride	20	–	–	0.9 [32]
Platinum	71.6	1.05×10^{-7}	3.927×10^{-3}	–

outer heater resistance with a reasonably narrow track width, the outer heater can be made by serpentine resistors which must ultimately be connected in series, and each serpentine resistor can be made of more turns; for instance, Fig. 2 schematically shows an outer heater made of two serpentine resistors, each with four turns (approximately an 8 times narrower track would be required for an outer heater with two single track resistors).

Fig. 2 also shows an inner heater made up of a middle ring (comprising two parallel track resistors) in series with two symmetrical tracks resistors (one on each side of the middle ring). As discussed above, the series connection is used for avoiding simply connected hot-spots in the contacts. However, though not essential for circular symmetry, here we also introduce an additional strategy for improving the temperature uniformity by inclusion of a middle ring with a parallel connection of two tracks having half of the inner heater track width, w_{ti} in order to keep the power produced per unit area almost constant within the inner heater region.

2.2.3. Electrical contacts

In order to further reduce the heat generation in the contacts in comparison with the heat generated in the heater, the contact width can be made larger than the inner heater track width. For clarity we define the contact-width multiplicity factor n_c , as the ratio between the contact width and the width of the track of the adjacent heater-ring internal to the contact. For instance, in our two-rings-heater the width of the external contacts can be made equal to $n_{c-ext} * w_{ti}$ and the width of the internal contacts equal to $n_{c-int} * w_{ti}$, as schematically shown in Fig. 2. Since the contacts cannot have a circular-symmetry, reducing the heat generated within the contacts, beside avoiding simply connected hot-spots, is also decisive for achieving a good circular-temperature-symmetry (see also the discussion on FEM results in Section 3).

In close proximity of the junction between contacts and heaters, the contact-width is not multiplied by the correspondent contact-width multiplicity factor as this would reduce the power generation in the junction regions in comparison to the other parts of the heater and result in a simply connected cold spot. In fact if, intuitively, we consider a very large contact-width it is clear that the very large contact-width would locally short-circuit a region of the heater. Therefore, the wider part of a contact is kept at a distance from the junction region and at smaller distance from the heater the track width is the same as the width of the correspondent heater. As schematically shown in Fig. 2, the distances between wider contacts and junctions can be synthetically expressed in terms of distance-to-junctions multiplicity factors, so that the wider part of the internal contacts can be kept at a distance of $n_{so} * w_{ti}$ from the outer heater and at a distance of $n_{si} * w_{ti}$ from the inner heater; likewise, the wider part of the external contacts can be kept at a distance of $n_{s-ext} * w_{ti}$ from the outer heater. The choice of the multiplicity factors is not critical as there is a range of values which results in excellent circular symmetry; however, for validation, FEM simulations can be used.

Another important concern, since the heater materials (e.g. platinum) generally have a much higher thermal conductivity than the membrane, is that the contacts tend to act as thermal short circuits in their area. Since thermal insulation between the heater and the bulk is crucial, this is especially important for the external contacts. In order to prevent this phenomenon, the wider part of the

contact must be kept at sufficient distance from the junction (i.e. by increasing $n_{s-ext} * w_{ti}$).

2.2.4. Gaps and cuts

As schematically shown in Fig. 2, the serpentine tracks introduce gaps (with spacing S_g) between adjacent tracks and moreover a circular micro-heater structure typically requires cuts (length S_c) at the extremities of the track lengths. Nevertheless, the gaps do not significantly deteriorate the circular structural symmetry as they are almost perfectly circular. Likewise, although cuts can be a source of temperature asymmetry in circular direction due to the absence of heat generation in a part (cuts) of the heater, this is a minor issue as the cut lengths can be made very small (in the micrometer range).

The heater geometry schematically represented in Fig. 2 is flexible as the turns (in serpentine tracks) can be increased or decreased to adjust the track widths of inner and outer heaters at desirable values depending on the application. Moreover, our structure can be utilized to realize any multi-heater-geometry (having more than two heaters) with good circular symmetry, with all the heaters connected in series. Each individual heater, apart from the innermost heater, will comprise two symmetrical serpentine tracks, similar to the outer heater schematically shown in Fig. 2; the innermost heater will have a middle ring (comprising two parallel tracks) with two symmetrical track resistors. All the inner heaters will contact the adjacent heaters with internal contacts which are wider than the heaters except in proximity of the junctions with the heaters. Similarly, the outermost heater will contact the supply with external contacts which are wider than the outermost heater except in proximity of the junction with the outermost heater.

The choice of all the multiplicity factors is typically not critical as there is a range of values which results in excellent circular symmetry; however, for validation, FEM simulations can be used.

3. FEM simulation

Here we verify that the design strategies introduced in Section 2 allow us to obtain excellent circular symmetry of the temperature distribution, prevent the occurrence of simply connected hot-spots, and allow to use the model [19] (found under the assumption of perfect circular symmetry) in practical micro-hot-plates. For validation, we utilize COMSOL for FEM simulations, with the Joule heating function of the heat transfer module. For meshing, we adopted the swept mesh method with the free triangular mesh at the source faces; importantly, we opted for a finer mesh within the heater and a coarser mesh in the external region as, firstly, not much detail is required in the external region and, secondly, this choice largely reduces the computation time. Regarding the boundary conditions, we replace the substrate with a temperature boundary condition $T = T_a$ [16] with $T_a = 20^\circ\text{C}$ and we utilize the convection heat transfer coefficient of $250 \text{ W}/(\text{m}^2 \text{ K})$ at the top surface and $150 \text{ W}/(\text{m}^2 \text{ K})$ at the bottom surface [28]. Though, for our validation test, we simply consider the values of convection heat transfer coefficient from [28], we mention this coefficient strongly depends on micro-hot-plate geometry, packaging and environment [29] and several methods have been reported in the literature for its prediction, mainly utilizing FEM simulations and/or experiments [17,29,30] so that for a practical design the heat transfer

Table 2
Micro-hot-plates parameters.

Parameter	Micro-hot-plate with narrow contacts	Micro-hot-plate with wide contacts
r_m	589 μm	611 μm
t_m	1.7 μm	1.7 μm
t_h	0.3 μm	0.3 μm
r_{hi}	55 μm	55 μm
r_{ho}	137 μm	137 μm
w_{hi}	4 μm	4 μm
w_{ho}	7 μm	7 μm
w_{ti}	2 μm	2 μm
w_{to}	1 μm	1 μm
S_{int}	78 μm	78 μm
S_t	1 μm	1 μm
S_c	1 μm	1 μm
n_{c-int}	1	12
n_{c-ext}	1	12
n_{so}	1	1
n_{si}	1	1
n_{s-ext}	10	10
Supply voltage, V_s	29.5 V	30.7 V

coefficient must preliminarily be determined. Regarding the materials, we consider a membrane consisting of stacked silicon dioxide and silicon nitride (with 0.35 μm silicon dioxide at the bottom and 1.35 μm silicon nitride); the heater is made up of platinum; the material properties are summarized in Table 1. The micro-hot-plates parameters are given in Table 2. Since the membrane is a stack of materials, our model determines the thermal conductivity of the region j using the expression [31]:

$$k^j = \frac{\sum_{i=1}^n \alpha_i^j t_i^j k_i^j}{t_e^j} \quad (4)$$

$$t_e^j = \sum_{i=1}^n \alpha_i^j t_i^j$$

where α_i^j is the ratio of the area of layer i in the region j to the total area of the region, t_i^j and k_i^j are the thickness and thermal conductivity, respectively, of layer i in region j and t_e^j is the effective thickness of region j .

Here, firstly, we analyze the circular temperature symmetry in a practical micro-hot-plate utilizing our novel micro-heater geometry. After verifying the excellent circular symmetry we demonstrate that the temperature in the proposed devices can be accurately expressed in terms of modified Bessel functions [19], similar to hypothetical perfectly circular devices.

3.1.1. Circular temperature symmetry in the micro-hot-plate

The combined use of all the design strategies proposed in Section 2 allows us to substantially reduce the deviations from circular symmetry of the temperature distribution. In order to quantitatively illustrate this result, we choose a representative design strategy, namely using, instead of electrical contacts with constant width (as in all previously reported micro-hot-plates), electrical contacts which are wider (in order to reduce the heat generated within the contact) apart in close proximity of the junctions (in order to not de-activate a significant part of the heater which would result in a cold-spot). As a result, Fig. 3 presents the FEM results for the surface temperature distribution for the proposed micro-heater structure, both with constant-width contacts (Fig. 3(a)) and with the proposed contacts (Fig. 3(b)). As evident, conventional constant-width contacts result in poor circular symmetry due to the undesired (non-circular) heat generation in the narrow contacts; we stress that if wider contacts are used, a significant

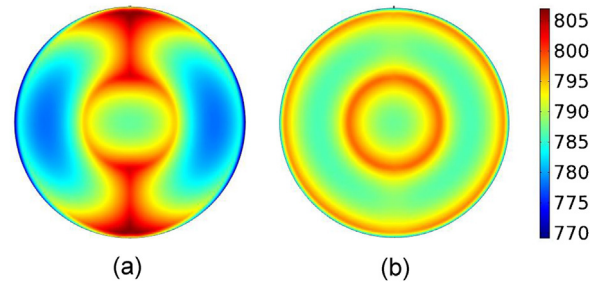


Fig. 3. Surface temperature distribution within the micro-heater structure (a) with narrow contacts and (b) with wide contacts.

part of the heater, at the junction with the contact, would be partially deactivated, resulting in a cold-spot, rather than hot-spot. In contrast, Fig. 3(b) shows an excellent circular symmetry; moreover, despite the unavoidable presence of temperature differences (perfect temperature uniformity is clearly impossible), there are no simply connected (i.e. without holes) hot-spots.

In order to more accurately evaluate the circular temperature symmetry, we may analyze, in both cases, the temperature along circumferences located inside the micro-heater; the maximum temperature difference along the circumference, ΔT_{max} can be taken as a concise parameter for quantifying the deviations from perfect circular symmetry along a certain circumference. Figs. 4–8 present the temperature along circumferences located in all the five regions of the micro-heater (ΔT_{max} is the maximum temperature difference along the circumference): circumference in the internal region with radius $r_{hi}/2$ (Fig. 4); circumference in the inner heater region with radius $r_{hi} + w_{hi}/2$ (Fig. 5); circumference in the intermediate region with radius $r_{hi} + w_{hi} + S_{int}/2$ (Fig. 6); circumference in the outer heater region with radius $r_{ho} + w_{to}/2$ (Fig. 7); circumference in the external region with radius $r_{ho} + w_{ho} + (r_m - r_{ho})/2$ (Fig. 8). Clearly, in the case of the conventional constant-width narrow contacts, the temperature peaks occur in correspondence with the electrical contacts which generate an undesired heat (left-side plots in Figs. 3–8). By contrast, due to much smaller contact resistances, these peaks disappear or, at least, are much smaller in the proposed micro-hot-plates (right-side plots in Figs. 3–8) which exhibit very small deviations from perfect circular symmetry (ΔT_{max} equal to 0.025 $^{\circ}\text{C}$, 0.65 $^{\circ}\text{C}$, 2.35 $^{\circ}\text{C}$, and 1.63 $^{\circ}\text{C}$ in the central, inner heater, intermediate, and outer heater regions, respectively); for most practical applications such small deviations are likely insignificant in comparison to the operating temperature (800 $^{\circ}\text{C}$). We mention that, for the proposed micro-hot-plates, circular symmetry is improved in the external region, which is outside the area of interest (ΔT_{max} equal to 8.18 $^{\circ}\text{C}$).

3.1.2. Comparison of model and FEM temperature distributions

Since the temperature distribution in the proposed micro-hot-plates has excellent circular symmetry, we expect the model found in [19] is still very accurate. In fact, Fig. 9 compares the analytical relations [19] and FEM simulations for the proposed micro-hot-plate. For completeness two different cases are considered for the FEM simulations: in the first case (green-triangle curve) the radiation heat transfer is ignored in the external region (i.e. radiation heat transfer is considered only within the micro-heater area) as assumed by our analytical model [19]; in the second case (black-circle curve) FEM simulations have been performed by taking into account radiation heat transfer everywhere (i.e. the most accurate possible FEM simulation). Due to the non-zero thickness, FEM temperatures are taken at the top surface of the membrane and T_{avg} (in Fig. 9) denotes the (spatial) average temperature within

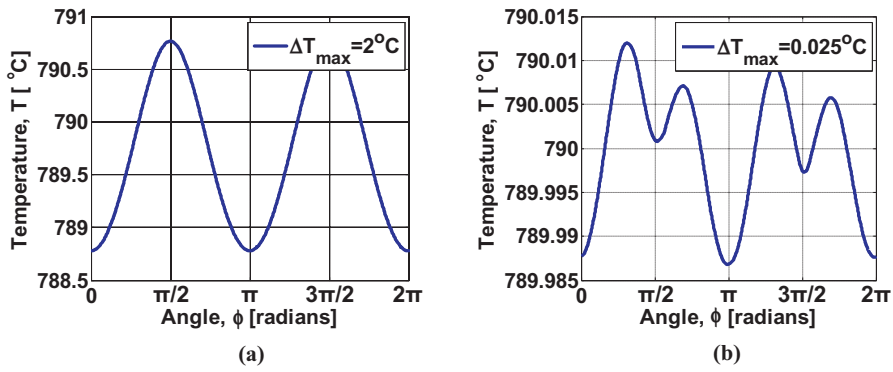


Fig. 4. Circular-temperature-plots in the central region at a radius of $r_{hi}/2$ in a micro-hot-plate (a) with constant-width narrow contacts and (b) with the proposed contacts.

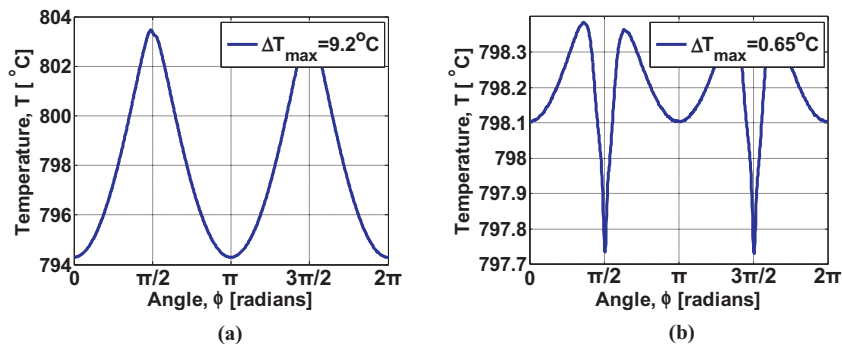


Fig. 5. Circular-temperature-plots in the inner-heater region at a radius of $r_{hi} + w_{hi}/2$ in a micro-hot-plate (a) with constant-width narrow contacts and (b) with the proposed contacts.

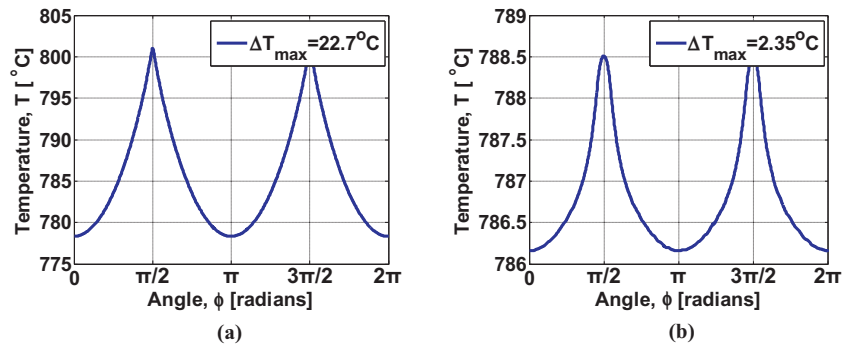


Fig. 6. Circular-temperature-plots in the intermediate region at a radius of $r_{hi} + w_{hi} + S_{int}/2$ in a micro-hot-plate (a) with constant-width narrow contacts and (b) with the proposed contacts.

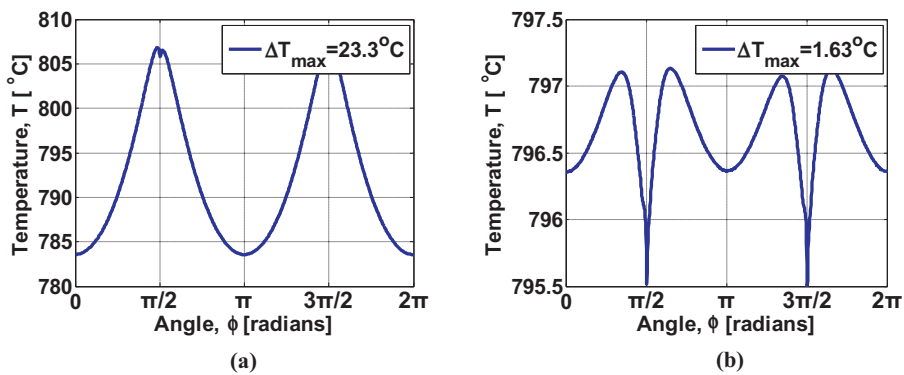


Fig. 7. Circular-temperature-plots in the outer-heater region at a radius of $r_{ho} + w_{to}/2$ in a micro-hot-plate (a) with constant-width narrow contacts and (b) with the proposed contacts.

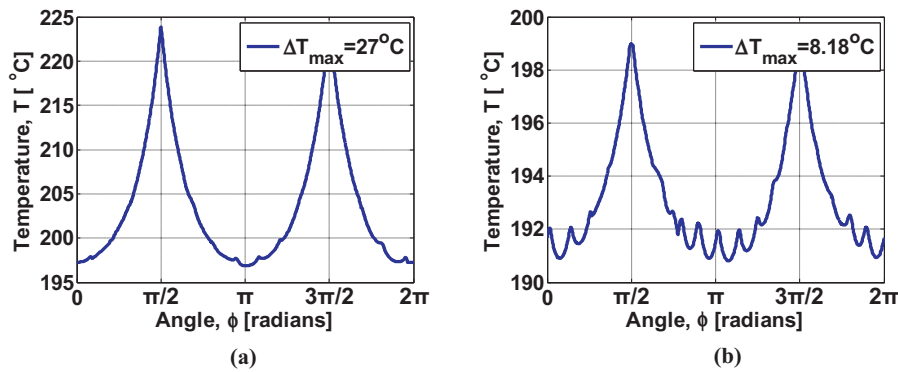


Fig. 8. Circular-temperature-plots in the external region at a radius of $r_{ho} + w_{ho} + (r_m - r_{ho})/2$ in a micro-hot-plate (a) with constant-width narrow contacts and (b) with the proposed contacts.

the micro-heater area. As evident, the analytical model [19] introduces a constant error (i.e. a shift of the curves) which is due to the assumption of constant temperature within the inner and outer heaters regions (which, clearly, is only an approximation [19]) and to the impossibility to easily include heat transfer radiation outside the micro-heater region (only within the micro-heater region the radiation heat transfer can be linearized by the first-order Taylor polynomial [19]). Nevertheless, such a constant shift is unimportant for studying with high-accuracy the temperature uniformity within the active area [19] as the temperature profile is almost perfectly preserved.

Overall, FEM results (Figs. 3–8) confirm that the proposed methodologies allow one to design micro-heaters without simply connected hot-spots, with excellent circular temperature symmetry and, therefore, with a temperature uniformity which can be accurately investigated in terms of modified Bessel functions [19]; these results may allow to designing micro-hot-plates with unprecedented temperature uniformity.

4. Conclusions

We have recently determined simple and compact analytical relations for the temperature distribution in a multi-heater micro-hot-plate with circular structural symmetry [19]. However, in real micro-hot-plates, the circular symmetry may not be perfect, for instance due to the electrical contacts; in particular, a typical manifestation of poor circular symmetry is the occurrence of simply connected hot-spots or cold-spots. Here, first, we have systematically investigated all the possible causes of imperfect circular symmetry, including simply connected hot or cold spots; afterwards, we have proposed strategies for designing micro-hot-plates with minimal perturbation of the circular symmetry and, in particular, without simply connected hot-spots and cold-spots. FEM simulations demonstrate that our approach allows the fabrication of micro-hot-plates with negligible deviations from ideal circular symmetry (e.g. less than 2.5°C for an operating temperature equal to 800°C) and, therefore, the analytical relations found for hypothetical perfectly circular micro-hot-plates can still be reasonably accurate for practical micro-hot-plates. In conclusion, the proposed design strategies along with our previous model [10] for temperature distribution constitute a powerful tool for designing micro-hot-plates with unprecedented temperature homogeneity.

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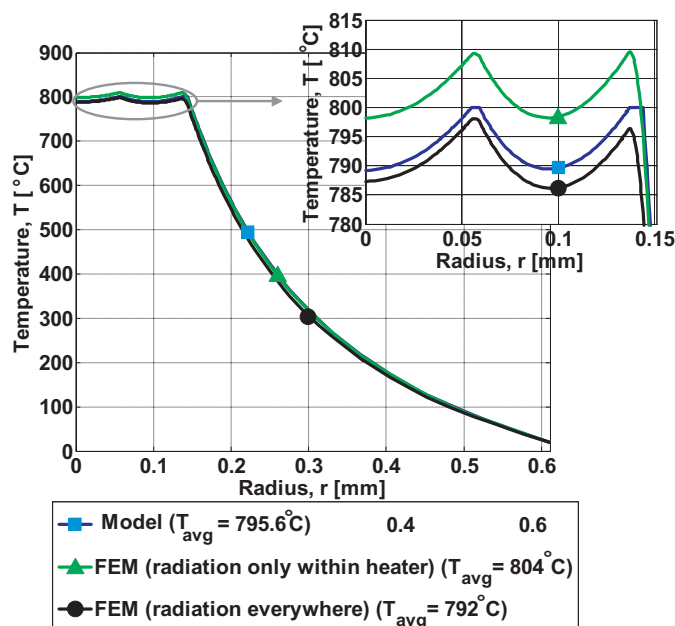


Fig. 9. Temperature distribution in the proposed micro-hot-plate according to FEM simulation and to the analytical model proposed in [19].

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