Sensors and Actuators B 213 (2015) 53–58

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Influence of emissivity tailoring on radiative membranes thermal behavior for gas sensing applications

Anthony Lefebvre[a,b,*], Daniele Costantini[b], Giovanni Brucoli[b], Salim Boutami[a], Jean-Jacques Greffet[b], Henri Benisty[b]

[a] Univ Grenoble Alpes F-38000 Grenoble, France, CEA, LETI, MINATEC Campus, F-38054 Grenoble, France
[b] Laboratoire Charles Fabry, Institut d'Optique, CNRS, Univ Paris Sud, 2, Avenue Augustin Fresnel, 91127 Palaiseau cedex, France

ARTICLE INFO

Article history:
Received 2 October 2014
Received in revised form 2 February 2015
Accepted 3 February 2015
Available online 19 February 2015

Keywords:
Infrared
Gas sensing
CO_2
MEMS
Membrane
Hotplate
Emissivity
Metamaterial

ABSTRACT

Suspended micro-hotplates acting as infrared emitting sources are privileged energy-efficient sources for intended use in optical gas sensors. For such sources, the main constraints are the maximum operating temperature and the battery-limited available energy per measurement. Using simulations that take into account the dynamics of heating through the spatio-temporal radial profile, we first demonstrate how to design a thermally efficient membrane complying with these specifications. Once nonspecific thermal leaks are minimized, we show a further increase of the wall-plug efficiency by tailoring the membrane spectral emissivity with a metasurface in order to match the absorption spectrum of a gas of interest, e.g. CO_2 in this study. We consider the effects of an array of plasmonic resonators on the overall efficiency, and show non-trivial favorable effects on the thermal balance of the system.

1. Introduction

Optical gas sensors have many advantages when compared to competing approaches such as metal-oxide-semiconductor, catalytic or electrochemical sensors: they achieve high sensitivity and selectivity, they have virtually unlimited lifetime and they are not subject to poisoning [1]. The only drawback is their price, which arises from their relative complexity. In these sensors, one measures the transmission of infrared (IR) radiation emitted by a dedicated source through the gas of interest. Due to the unique molecular absorption fingerprint exhibited by most gases in the IR range, the power attenuation measured by a detector provides the gas concentration according to Beer-Lambert law:

$$P = \int_{\Delta\lambda} P_0(\lambda) 10^{-\varepsilon_{\mathrm{mol}}(\lambda) l c} d\lambda \tag{1}$$

where P is the measured power, $P_0(\lambda)$ is the reference spectral power in the absence of gas, l is the path length through the gas, and ϵ_{mol} and c are respectively the molar absorptivity and concentration of the gas. The sensitivity of the measurement depends on the signal-to-noise ratio, while its reliability depends on the cross-talk caused by interfering gases in the targeted line. The detector is e.g. a pyroelectric sensor, a thermopile or a bolometer. The source is either a quantum cascade laser for high-cost/high-precision sensors, or a blackbody-like source in cheaper devices. In this case, it is often designed as a suspended microbridge, micromembrane or microhotplate, using Micro-Electro-Mechanical Systems (MEMS) technology. This allows the source to be thermally insulated from the substrate, increasing its efficiency. Although these structures were first demonstrated in the 1980s [2,3], a lot of work is still in progress on this topic, particularly regarding temperature homogeneity [4–6]. Ali et al. provided an extensive review of latest achievements concerning micromembranes [7].

Although increasing the temperature of the membrane is the easiest way to improve the dominance of radiative flux over other losses (conduction, convection), there is an upper limit set by technological constraints in order to avoid premature degradation. The device lifetime is mostly limited by electromigration effects likely to disrupt conductive paths, and by thermomechanical fatigue, leading to arm's rupture. The former are avoided by limiting the current density in the conductive tracks, while the latter depends

* Corresponding author. Tel.: +33 438784094.
E-mail address: anthony.lefebvre@cea.fr (A. Lefebvre).

http://dx.doi.org/10.1016/j.snb.2015.02.056
0925-4005/

on the membrane thermal expansion [8]. Thermal deformations can be lessened using non axisymmetric suspension arms, used for example in bolometers [9]. The source is thus operated at this limit temperature in the following calculations. In order to design a battery-powered, long-lasting, efficient source, available energy is restricted for each measurement. As a result, dynamics matter: a basic trend is for instance that the larger the membrane, the more power it demands, and the shorter the time it can be powered on before the allocated energy is exhausted. It turns out that getting the best detection under such constraints is no simple design exercise. In the following, we show how to find the best compromise in order to maximize the wall-plug efficiency for the detection of a specific gas, with the CO_2 example in mind. We also give an insight into the thermo-optical mechanisms governing this kind of devices, and the influence of emissivity tailoring on overall efficiency. Practical figures are given for a 5 mJ allocated energy per measurement, and a 650 °C maximum membrane temperature, corresponding to a realistic, low-consumption gas sensor discussed in more details in Section 3.

2. Modeling

We consider a rather generic wafer-level suspended microhotplate, for example the one developed by Barritault et al. [10], shown in Fig. 1a, made of resistive metallic tracks inside a dielectric ring-shaped shell in a series/parallel arrangement (clear wire-like areas in Fig. 1a). Heating is achieved via Joule effect, and the rather narrow mechanical suspension reduces thermal losses to the substrate. Temperature homogeneity inside the disc is guaranteed by the use of electrically isolated heat-spreading areas surrounding the heating wires and made of the same stack. In order to reduce computation time and to retain generality, we consider a model (Fig. 1b) based on three straightforward simplifications:

- The membrane thickness is much smaller than the central disk radius, implying that the heat distribution is constant along the vertical axis.
- The central disk of radius R consists of a single material, due to the presence of heat-spreading spacers actually made of the same stack of materials as the wires, covering most of the disk.
- The system is modeled as fully axisymmetric: even the arms can be homogenized around the central disk, considering effective thermal conduction characteristics based on the relative fraction of their intersection with the perimeter of the membrane. Their outer boundary at radius R_{out} can be also considered as thermalized with the substrate holding the membrane. Metallic tracks azimuthal dependence is neglected. The trends we find should not be sizably affected by this level of detail.

The obtained one-dimensional bi-material model associated to a variable r in the interval $[0, R_{out}]$ is illustrated on Fig. 1b.

Let us now treat this model: a subsequent approximation that holds for most reasonable combination of the above choices is that the arms contribution to the overall radiative flux is negligible due to their small surface and low temperature. As a consequence, they can be considered as a simple thermal leakage resistance Z_a, defined by:

$$Z_a = \frac{L_a}{k'_a} = \frac{L_a}{k_a \dfrac{N_a w_a}{2\pi R}} \quad [\mathrm{K.W^{-1}.m^2}] \tag{2}$$

where N_a, L_a and w_a are respectively the number, length and inner arc width of the arms and k'_a is the equivalent thermal conductivity, obtained from the arms thermal conductivity k_a weighted by the relative fraction of their subtended inner arc with the perimeter of the membrane, $N_a w_a/2\pi R$. In the following calculations, Z_a is kept constant by increasing the inner arc width of the arms w_a at the same rate as the radius of the membrane, and keeping their length unchanged. One can check that this is a consistent way to preserve the mechanical resistance of the structure. Heat equations are then expressed as:

$$\rho C_p \frac{\partial T(r,t)}{\partial t} = k\left[\frac{\partial^2 T(r,t)}{\partial r^2} + \frac{1}{r}\frac{\partial T(r,t)}{\partial r}\right] - \frac{1}{e}\left\{\varphi_{\mathrm{rad_{top}}}[T(r,t)] + \varphi_{\mathrm{rad_{bot}}}[T(r,t)]\right\} + P(r,t) \tag{3}$$

with

$$\varphi_{\mathrm{rad_{top/bot}}}[T(r,t)] = \pi\int_0^\infty \varepsilon_{\mathrm{top/bot}}(\lambda)\{I[\lambda, T(r,t)] - I(\lambda, T_{\mathrm{sub}})\}d\lambda \tag{4}$$

where ρ is the mass density, C_p is the specific heat capacity, k is the thermal conductivity, $\varepsilon_{top/bot}$ is the emissivity of the top or bottom surface of the membrane, and I stands for the spectral radiance of the blackbody, given by Planck's law. Convection losses are neglected as the source is encapsulated under vacuum. The source power $P(r,t)$ is constant over the central disk of the membrane (practically, this assumption depends on the exact wire pattern, and boils down to a tractable electrical problem). Initially, the whole membrane is at the substrate temperature T_{sub} and the model's boundary conditions are given by:

$$-k\frac{\partial T(0,t)}{\partial r} = 0 \tag{5}$$

$$-k\frac{\partial T(R,t)}{\partial r} = \frac{1}{Z_a e}(T(R,t) - T_{sub}) \tag{6}$$

Eq. (5) comes from the axisymmetry, and Eq. (6) is a Robin condition taking into account the arms thermal resistance (with T_{sub} the substrate temperature being the actual boundary condition at the attached end of the arms). From the computed spatio-temporal temperature profile, we define the efficiency of the source as the ratio of the energy $E_{rad,top}$ radiated by the top surface over the total energy (radiated and conducted E_{cond} to the substrate):

$$\eta = \frac{E_{\mathrm{rad,top}}}{E_{\mathrm{rad,bot}} + E_{\mathrm{rad,top}} + E_{\mathrm{cond}}} \tag{7}$$

with

$$E_{\mathrm{cond}} = \int_0^{t_f} \frac{(T(R,t) - T_{\mathrm{sub}})}{Z_a} N_a w_a e \,\mathrm{d}t \tag{8}$$

and

$$E_{\mathrm{rad,top/bot}} = \pi\int_0^{t_f}\int_0^R\int_0^\infty \varepsilon_{\mathrm{top/bot}}(\lambda)[I(\lambda, T(r,t)) - I(\lambda, T_{\mathrm{sub}})]\mathrm{d}\lambda\, r\mathrm{d}r\,\mathrm{d}t \tag{9}$$

where t_f is a long time at which we consider that the membrane is back to the substrate temperature. In the case of a blackbody, $\varepsilon_{top} = \varepsilon_{bot} = 1$, which is not very favorable as all the radiation emitted by the bottom surface is lost in this model. We shall also define a spectral efficiency η_λ akin to Eq. (7) but taking into account only the radiation in a specific wavelength range in Eq. (9).

3. Case study

3.1. Blackbody emitter

In order to demonstrate the main results of this study, we model a membrane similar to the one developed by Barritault et al. [10].