Sensors and Actuators A 279 (2018) 416–423

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Convective losses of thermal infrared emitters with cantilevered heating elements

T. Ott*, M. Schossig, G. Gerlach

Technische Universität Dresden, Institute of Solid-State Electronics, Mommsenstraße 15, 01069 Dresden, Germany

ARTICLE INFO

Article history:
Received 14 December 2017
Received in revised form 6 June 2018
Accepted 19 June 2018
Available online 26 June 2018

Keywords:
Convection losses
Modulation behavior
Thermal emitter
Infrared source
Thermal time constant
Thermal network model
Modulation depth

ABSTRACT

Non-dispersive infrared- (NDIR-) gas sensors usually consist of a thermal infrared emitter, a tube and a pyroelectric detector with a filter that is transparent to the characteristic wavelength of the gas to be detected. Since pyroelectric sensors are only sensitive to alternating radiation, the radiation must be modulated. This is easiest to achieve by electrical modulation of the emitter. Under this cyclic excitation the thermodynamic properties of the IR source affect the emitted infrared radiation and, in consequence, the sensor signal. Optimal gas sensor operations (e.g. with regard to gas measurement resolution) require to know which factors influence the thermodynamic properties of thermal emitters. In the course of miniaturization and with regard to portable use, gas measuring devices must also become more compact and energy-efficient. Consequently, the radiation source must have low power consumption and high (radiation) efficiency. The heating and cooling curves measured during electrical (square-wave) modulation contain all information about the thermal losses of real emitters and, therefore, about their energy efficiency as well. In this paper, a thermodynamic model of an infrared emitter will be introduced, which also includes all thermal losses (radiation, heat conduction and convection in the filling gas). The comparison of the measured and calculated heating and cooling curves allows to quantify the thermal losses of the emitter and to draw conclusions about its energy efficiency. As a result, this paper reveals that the majority of the electrical energy supplied is dissipated into the filling gas by convection and heat conduction, which significantly reduces the energy efficiency of the radiation source. Vacuum measurements confirm this assumption and support the model.

1. Introduction

1.1. Objective

Analytic models to describe thermodynamic properties of infrared (IR) emitters are to be found in [9,11]. To reproduce the temporal course of heating and cooling curves these models are based on time constants, which are usually used to characterize the thermal modulation behavior of IR sensors. As shown in this paper, time constants are, however, neither appropriate to reproduce the heating and cooling curves of IR emitters nor mathematically reasonable. This follows from the fact, that the radiation in the analytic model of IR sensors is negligible, while for IR emitters it is not at all due to high element temperatures. As a result, the differential equation to describe the thermal behavior of IR emitters is highly nonlinear.

The knowledge to determine the thermodynamic properties of IR emitters offers a multitude of optimization possibilities in the field of NDIR gas analysis. Here the trend is towards miniaturization and low energy consumption of gas measurement devices. In consequence, these devices require energy-efficient IR emitters. By varying the parameters of the thermal model the heating and cooling curves of IR emitters can be reproduced. This allows for conclusions at the nature of thermal losses of the emitter and, hence, their reduction, e.g. by customization of the heating element design or by using alternative gas fillings. Such an optimized IR emitter can be used in gas measurement devices of small size to monitor indoor air quality (e.g. detection of CO and CO_2), for smoke and fire detection (CO, CO_2) as well as to recognize gas leakage (detection of coolants and nitrogen oxides). For further information, see [12,13] and refs. therein.

1.2. Thermodynamic behavior of thermal IR sensors

The behaviour of thermal IR sensors under cyclic excitation is often described in sufficiently detailed manner by a simplified

* Corresponding author.
E-mail address: tobias.ott@tu-dresden.de (T. Ott).

https://doi.org/10.1016/j.sna.2018.06.039
0924-4247/

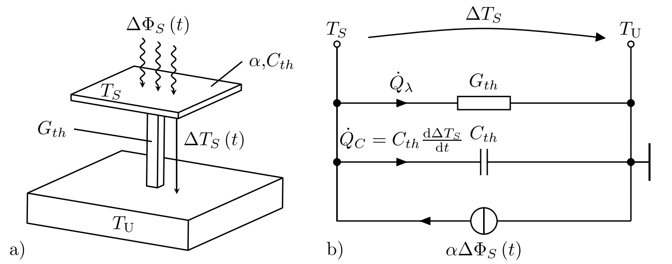

Fig. 1. Simple model of a thermal IR sensor with heat conduction via the clamping but without convection and heat conduction through the filling gas. (a) Principle with detector element (top), thermal isolation (middle) and heat sink (bottom); (b) thermal network model.

model according to Fig. 1. The physical system single element sensor is reduced to the sensitive element of the sensor with its connection to the heat sink on the housing. In order to model the flowing heat fluxes, a thermal network model of this structure is created in analogy to electrical networks (Fig. 1b). Subsequently, the inflow and outflow of heat fluxes are balanced and the resulting differential equation is solved. In order to provide a better understanding of the procedure for creating an analytical thermal model, the following section briefly describes the modeling of a thermal single element sensor system.

1.2.1. Heating

If the sensor is exposed to a cyclically alternating radiant flux, the temperature of the sensitive element changes depending on its thermal conditions. By balancing the heat fluxes from Fig. 1 the differential equation for the desired temperature change results

$$\alpha\Delta\Phi_S(t) = C_{th}\frac{\mathrm{d}\left[\Delta T_S(t)\right]}{\mathrm{d}t} + G_{th}\Delta T_S(t). \tag{1}$$

The model comprises the thermal heat capacity C_{th} of the sensitive element, the thermal conductance G_{th} between the element and the heat sink, the radiant flux $\alpha\Delta\Phi_S$ absorbed by the sensitive element with the absorption coefficient α and the resulting temperature change ΔT_S. With the initial condition

$$\Delta T_S(0) = 0 \tag{2}$$

Eq. (1) yields:

$$\frac{\mathrm{d}\left[\Delta T_S(t)\right]}{\mathrm{d}t} + \frac{G_{th}}{C_{th}}\Delta T_S(t) = \frac{\alpha_S\Delta\Phi_S(t)}{C_{th}}. \tag{3}$$

This system Eq. (3) is a linear differential equation of the first order. The excitation is considered idealized as a step on a radiation flow $\Delta\hat{\Phi}_S$, which in reality corresponds to the switching on of a radiation source without thermal inertia or the choppering of a constant light source

$$\Delta\Phi_S(t) = \Delta\hat{\Phi}_S\sigma(t), \tag{4}$$

with the Heaviside step function

$$\sigma(t) = \begin{cases} 0 & \forall\ t<0 \\ 1 & \forall\ t\geq 0 \end{cases}. \tag{5}$$

It follows that

$$\Delta T_S(t) = \frac{\alpha_S\Delta\hat{\Phi}_S}{G_{th}}\left(1-e^{-G_{th}/C_{th}t}\right) \qquad \forall t\geq 0. \tag{6}$$

For $t\to\infty$ the maximum temperature difference yields

$$\Delta\hat{T}_S = \lim_{t\to\infty}\hat{T}_S(t) = \frac{\alpha_S\Delta\hat{\Phi}_S}{G_{th}}. \tag{7}$$

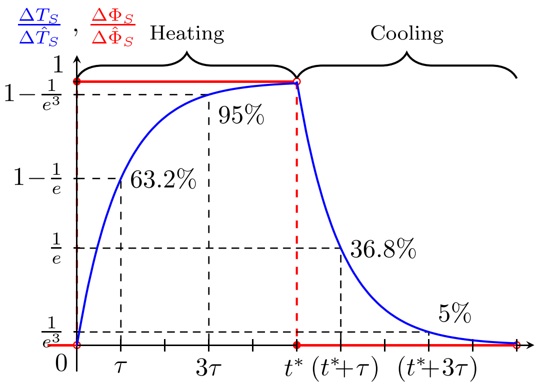

Fig. 2. Temporal course of heating ($t<t^*$) and cooling ($t\geq t^*$) of a LTI system and meaning of time constants.

1.2.2. Cooling

If the excitation is turned off, Eq. (1) becomes

$$\frac{\mathrm{d}\left[\Delta T_S(t)\right]}{\mathrm{d}t} + \frac{G_{th}}{C_{th}}\Delta T_S(t) = 0. \tag{8}$$

With the initial condition

$$\Delta T_S(0) = \Delta\hat{T}_S \tag{9}$$

it follows

$$\Delta T_S(t) = \Delta\hat{T}_S\ e^{-\frac{G_{th}}{C_{th}}t} \qquad \forall t\geq 0. \tag{10}$$

1.2.3. Thermal time constant

For first-order, linear, time-invariant (LTI) systems, which react to the Heaviside step function as per Eq. (5), it is reasonable to use a thermal time constant τ:

$$\tau = \frac{C_{th}}{G_{th}}. \tag{11}$$

The temperature increase of the sensor element is assumed as low and, therefore, the emitted radiation of the sensor element is negligible. Because of this, the simplified model of the single element sensor according to Eq. (1) is such a LTI system.

Inserting Eq. (11) into Eqs. (6) and (10), respectively, it results after rearranging for the temporal course of the temperature for the heating

$$\frac{\Delta T_S(t)}{\Delta\hat{T}_S} = 1-e^{-t/\tau} \tag{12}$$

and the cooling of the single element sensor:

$$\frac{\Delta T_S(t)}{\Delta\hat{T}_S} = e^{-t/\tau}. \tag{13}$$

The characteristic values for LTI systems arise for $t=\tau$ (heating)

$$\frac{\Delta T_S(t=\tau)}{\Delta\hat{T}_S} = 1-\frac{1}{e}\approx 63.2\%,$$

and for $t=t^*+\tau$ (cooling)

$$\frac{\Delta T_S(t=t^*+\tau)}{\Delta\hat{T}_S} = \frac{1}{e}\approx 36.8\%,$$

as shown in Fig. 2.

2. Non-linear model of thermal emitters

In the following a more detailed model will be derived, that consists not only of heat conduction, but also of radiation and heat convection.