Compact Thermal Modeling of Microbolometers

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Abstract

This paper presents an approach to dynamic thermal modeling of micromachined microbolometers. Firstly, all the important factors influencing temperature of infrared radiation sensing elements are identified in repeated numerical thermal simulations performed for a detailed device model, where temperature values were computed for time instants equidistantly spaced on the logarithmic time scale. Secondly, based on the simulation results all the important time constants contained in these dynamic thermal responses were properly identified what allowed the derivation of compact thermal models in the form RC equivalent circuits containing a limited number of stages. The resulting compact thermal models are suitable for the direct implementation in SPICE or any other multiphysics simulation environment.

1. Introduction

Various Micro-Electro-Mechanical Systems (MEMSs) are now commonly encountered in numerous everyday use machines and equipment, e.g. accelerometers present in cars and phones. Another MEMS device is a micro-bolometer which is used for sensing infrared radiation. Formerly, mainly because of their price, they were used predominantly in military applications, however now they became affordable and soon they could be even integrated as standard devices with portable devices allowing low-cost thermal imaging [1]-[2].

Considering that the operating principles of particular MEMS devices involve different electrical, mechanical, chemical and thermal phenomena, the simulation of these devices requires dedicated multiphysics tools. Such tools are offered various providers, e.g. by Ansys, Coventor or Comsol, but usually solutions are obtained after time consuming simulations of detailed system models what is not suitable for analyses of large sensor arrays.

Moreover, MEMS devices are usually integrated with electronic readout circuits, thus it would be advantageous to have the possibility of running simulations in standard circuit simulators, such as SPICE, using a compact model. This approach was already adopted in a few papers where compact model parameters were found based on complex geometrical calculations [3]-[4].

Thus, here we propose to derive compact models from device temperature responses. The next section is devoted to a brief description of microbolometer construction and its operating principles as well as the presentation of the particular structure used here for thermal simulations. The experimental part of the paper contains detailed analyses of simulation results and provides indications for further development of microbolometer models.

2. Microbolometers

Microbolometers are basically radiation sensors based on resistive principle in which radiant energy influences the resistance of the radiation sensing material. When the radiation absorption characteristics of the active material has its maximum in the infrared wave range, such sensors can be used to measure temperature. Since the amount of radiation is converted into the change of resistance the materials of choice should have quite high temperature coefficient of resistance but at the same time they should be compatible with MEMS technology. Therefore, typical materials used in practice are amorphous semiconductors, various metals and their oxides.

Except for the proper choice of active material, the device sensitivity can be increased by maximizing the temperature rise value for a given radiation intensity. This, as shown in Fig. 1, could be realized assuring high sensor thermal resistance manufacturing it as a very thin membrane suspended on cantilevers over semiconductor wafer surface. Additionally, this solution guarantees low thermal capacitance of the entire sensor structure and consequently quick response times. Moreover, when the membrane is suspended at the height of a few of microns, it forms with the substrate a resonant cavity reflecting radiation back from the wafer towards the sensor and consequently further increasing its sensitivity [5]-[6].

Microbolometer structures are usually etched on the semiconductor surface forming large matrices of sensors, known as infrared Focal Plane Arrays (FPAs), which are integrated in one piece of semiconductor substrate with their Readout Integrated Circuit (ROIC) and hermetically sealed in vacuum packages [7].

Taking into account that state-of-the-art FPAs contain hundreds of thousands of individual devices their detailed models cannot be effectively employed for simulations at the system level and then some appropriate reduced models have to be used. Furthermore, since the operation of microbolometers is highly temperature dependent their simulation requires accurate thermal models which would allow relatively fast but reliable determination of sensor key parameters, such as current or voltage responsivity.

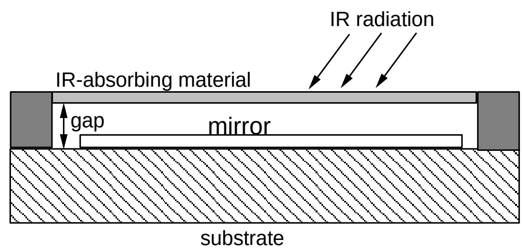

Figure 1: Simplified cross-section of a microbolometer.

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3. Experimental Results

For thermal simulations a sensor structure with 25 μm pitch was chosen. The membrane was suspended 2 μm above the wafer surface. The radiation absorbing element was a 70 nm thin winding titanium resistor sandwiched between 500 nm silicon nitride layers. The detailed model of this structure was created in the Ansys environment.

Initially, the goal of simulations was to determine the actual influence of individual factors affecting the sensing element temperature. Namely, three main heat generating factors were considered: incident infrared radiation, Joule heating by current flow in the sensing resistor and heating by the power dissipated in the ROIC electronics beneath the membrane.

During the simulations temperature values computed for logarithmically spaced time instants so as to capture all the thermal time constants contained in the dynamic responses. The results of these simulations are presented in Fig. 2 applying logarithmic time scale for both axes. Furthermore, the curves, in order to render possible their comparison, were normalized do as to obtain the same maximal temperature rise value.

As can be seen, when the heat source is located in the membrane, the solid and the dashed curves after 10 μs are identical. The difference in the beginning of the heating time might be attributed to the fact that the Joule heat is dissipated directly in the sensor whereas the incident radiation has to diffuse first through the top nitride layer.

When the membrane is heated from beneath by the ROIC, the heating curve looks entirely different reaching its final value only after a few milliseconds. This, in turn is caused by the fact that diffuses mainly to the substrate heating its thermal capacitance and only partly reaches the membrane.

More detailed analyses of these heating curves carried out applying a method similar to the multipoint moment matching technique described in [8, 9] allowed the precise determination of the thermal time constants present in the transient responses. The results of these analyses for each of the curves are given in Table 1 providing the values of thermal time constant and their corresponding thermal capacitances and resistances.

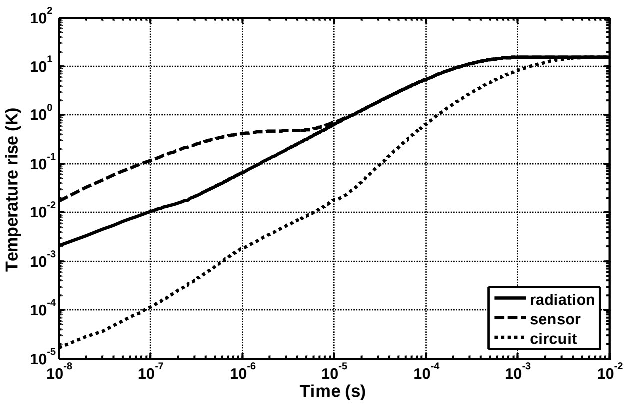

Figure 2: Normalized heating curves simulated with full distributed model.

When the first two cases are considered, there exists one dominant time constant at 232 μs which correspond to the thermal resistance of 155 kK/W and the thermal capacitance of 1.53 nJ/K. Usually in literature, e.g. in [1] or [3], microbolometers are also characterized by a single thermal time constant reflecting the thermal capacitance of the membrane and the resistance of its supporting beams. These data obtained from Ansys simulations, also provided in the table, are very close to the ones obtained from the analyses of the heating curves.

Except for the dominant thermal time constants in the microsecond range there exist also time constants of the order of nanoseconds but their contributions to the total temperature rise are insignificant and could be neglected, even when analysing the Joule heating because the typical electrical pulse width during the sensor readout is around 100 μs.

The thermal parameters given in the table for the first two cases represent the RC values of the Foster ladder, which cannot have direct physical interpretation because capacitances are not directly connected to the thermal ground node, i.e. ambient temperature, but it facilitates the computation of the temperature response according to the following formula:

$$T(t) = P \sum_{i=0}^{n} R_{thi}\left[1 - \exp\left(-t/\tau_{thi}\right)\right] \qquad (1)$$

Each thermal time constant τ_{th} in the above equation is the product of thermal resistances R_{th} and capacitances C_{th} whereas P is the dissipated power.

When the influence of power dissipation in the ROIC is considered, the thermal model is different because heat only partially flows into the membrane, but the majority of it diffuses into the semiconductor substrate. Thus, the correct thermal model consists of two parallel RC ladder branches.

Table 1: Thermal parameters of reduced models.

Radiation heating		
Time constant (s)	Resistance (K/W)	Capacitance (J/K)
.2.27E-08	3.72E+01	6.11E-10
2.36E-04	1.55E+05	1.53E-09
Sensor bias current heating		
Time constant (s)	Resistance (K/W)	Capacitance (J/K)
3.06E-07	3.69E+03	8.29E-11
2.36E-04	1.55E+05	1.53E-09
ROIC electronics heating		
Time constant (s)	Resistance (K/W)	Capacitance (J/K)
1.49E-03	5.74E-03	2.59E-07
2.36E-04	1.55E+05	1.53E-09
Ansys		
Time constant (s)	Resistance (K/W)	Capacitance (J/K)
2.32E-04	1.55E+05	1.50E-09

Consequently, the thermal model parameter values given in the table correspond to two parallel RC stages. One of them represents the previously discussed dominant time constant related to the membrane whereas the other one reflects the presence of the large silicon substrate. Then, the formula to compute the time response of the system takes the following form:

$$T(t) = P \; \frac{R_{ths} R_{thm}}{R_{ths} + R_{thm}} \times \times \left[1 - \exp\left(-t \Big/ \frac{(C_{ths} + C_{thm}) R_{ths} R_{thm}}{R_{ths} + R_{thm}} \right) \right] \quad (2)$$

where the indices *s* and *m* denote the substrate and the membrane respectively.

The value of the substrate thermal capacitance given in the table coincides very well with the one calculated theoretically for the volume of silicon considered in the simulation. However, it should be mentioned that in order to accelerate the simulations the structure included only the silicon volume under one sensor. If the total substrate volume were considered, the value of the capacitance would be much larger. Thus, depending on the cooling applied to the substrate, there might be cases when the consideration of more time constants is necessary.

The next stage in the numerical experiments was the computation of thermal responses based on the previously identified compact thermal models. For each of the cases considered here, the heating curves calculated from the compact models (dashed lines) were compared in Figs. 3-5 with the original Ansys simulations results (solid lines) obtained for the full distributed model.

The simulation accuracy with these extremely simple models was satisfactory and the simulation error with respect to the results from the detailed model did not exceed 10 % for all time instants. This is an important observation from the practical point of view because microbolometers are usually probed with short current pulses in order to avoid excessive sensor self-heating and increase its detectivity.

Another important benefit from using compact models is significantly shorter simulation time. The computation of results in Ansys took almost half an hour whereas the results from the compact model are available after just a few seconds. Besides, the preparation of the detailed model also requires significant amount of time, even for an experienced user.

4. Conclusions

This paper presented the analyses of microbolometer temperature responses to various factors influencing the temperature of the radiation sensing element. The results proved that in most practical cases the commonly used approximate thermal model consisting of just one thermal resistance and one thermal capacitance might be accurate enough.

However, the determination of exact model parameter values requires the knowledge of internal structure of the sensor and is subject to the availability of the detailed model. The main advantage of the approach adopted here is that basically the detailed model is not necessary for the generation of the compact model. Namely, though the analyses presented here were carried out on simulated data, the method allows the creation of a compact model also from measured dynamic responses. This solution can be also beneficial in cases when manufacturers do not want to reveal their confidential data.

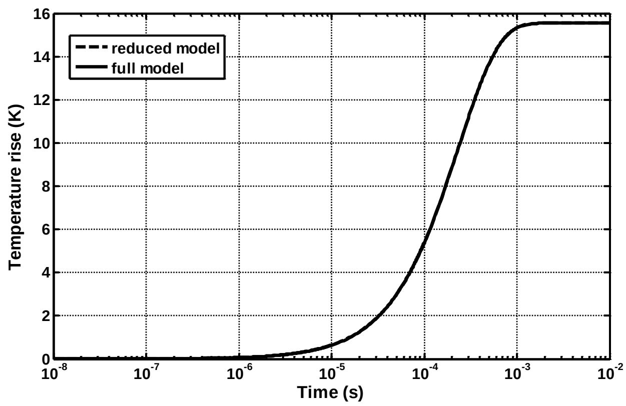

Figure 3: Simulated heating by radiation.

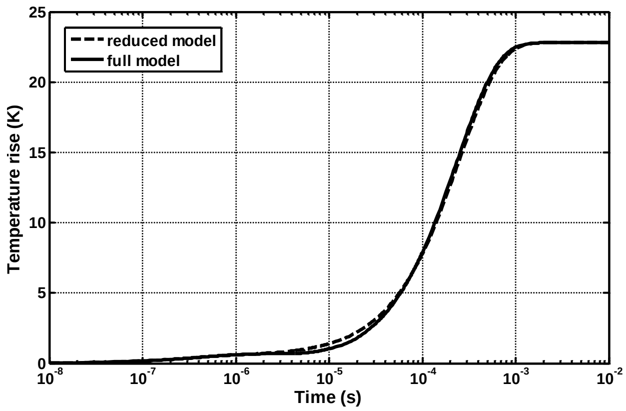

Figure 4: Simulated heating by sensor current.

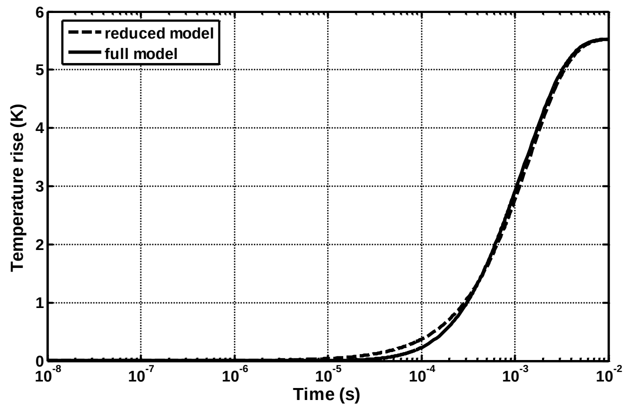

Figure 5: Simulated heating by ROIC.

Moreover, this behavioural approach to the generation of compact models based on the analysis of measured responses allows the determination of exact mathematical dependencies between qualities of various nature without any prior knowledge on investigated phenomena, what unfortunately often is the case in multiphysics simulations of MEMS devices.

Acknowledgments

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