A Study on Microbolometer Electro-thermal Circuit Modelling

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***Abstract*—Electro-thermal models are commonly used in simulations and designing MEMS devices, also in case of microbolometers. These models allow to estimate sensors performance before fabrication that consequently impacts on fabrication cost. Coupling of electric and thermal domains and building appropriate model for carrying out simulations are crucial to detect all phenomena having impact for Readout Integrated Circuit. This article brings closer to the subject matter of circuit modelling (willingly implemented in MATLAB/SIMULINK or PSPICE tools) and to its theoretical background.**

***Keywords*—microbolometer, circuit modelling, electro-thermal modelling**

I. INTRODUCTION

Infrared radiation microdetectors are commonly used by many scientists all over the world, because of its wide range of application. Microbolometers are good example of resistive detectors. They belong to large family of MEMS devices, designed for infrared radiation detection, i.e. measuring electromagnetic radiation. The principle of operation bases on resistance change due to electromagnetic radiation emitted by every object with a non-zero temperature (black body radiation). At ambient temperature the maximum intensity of object radiation is at a wavelength of about 10µm. This corresponds with the atmospheric transmission window between 8 and 14µm for infrared (IR) radiation [1].

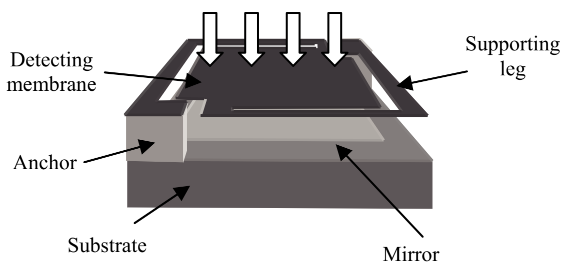

Fig.1. Microbolometer structure.

Attractiveness of this kind of sensor comes from conditions under which it can successfully work, especially operating temperature and ambient light. Microbolometers can operate at room temperature and their sensitivity allows to measure even in complete darkness. Very important capability is also technology of fabrication, which makes possible to create complex and cheap devices that can integrate electronics (ROIC), have low weight, low power consumption, large spectral response and long term operation compared to photon-based detectors [2].

A typical microbolometer consists of following parts: a membrane thermally isolated from its surroundings by beams, anchors and a substrate (Fig. 1). The membrane is the main part which detects radiation. It consists of two protective layers and active sensing layer. Membrane is hung on beams (supporting legs) fixed to the substrate (silicon based). It allows to avoid destruction of detector because the membrane deforms under heating. Beams have additionally important function. They are electrically connected to the readout integrated circuit. Resistive absorbing conductor is fixed at the end of beams that allows applying the current. To make the detector more efficient, a mirror is placed under the membrane that reflects the radiation (Fig. 2). The device is also packaged in vacuum to eliminate the thermal convection loss through the air. The ROIC elements used for signal processing are placed on the substrate. They are responsible for converting the detector temperature to an electrical signal. All of these elements are made in a CMOS technology.

II. THEORY BACKGROUND OF THERMAL DETECTION

Fig. 2. presents the principle of microbolometer operation. Incident radiation falling on detecting layer cause the temperature rise $\Delta T=E/C$. This rise continues until both radiation power in absorber and power flowing into the heat sink are equal. Absorber with specific heat capacity C and absorption η cumulates heat energy which next affects directly absorber resistance and causes changes in current flow.

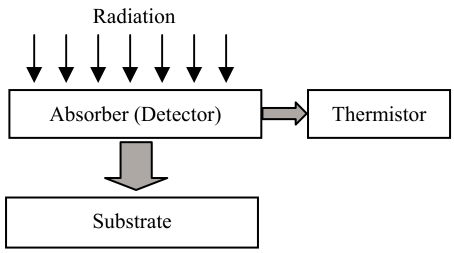

Fig. 2. Bolometer - principle operation.

As one can see, the most important in microbolometer is heat flow between particular elements. Simple microbolometer thermal *model* consists of radiation power, detector and substrate was presented in paper [3].

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Fundamental equation for IR detectors describing above phenomena is the heat flow equation. This relationship describes the temperature change due to radiation power (1). The equation takes into consideration heat (thermal) capacity C of active part of microbolometer as well as thermal conductance G of supporting beams[4]:

$$C\frac{d(\Delta T)}{dt}+G(\Delta T)=\eta P_0 e^{j\omega t} \qquad (1)$$

where P_0 is amplitude of absorbing IR radiation power; η is absorbance of sensitive layer; ω is angular frequency of IR radiation modulation; ΔT is temperature change of detecting layer. Solving the equation (1) gives the rise in the detector element temperature[5]:

$$\Delta T=\frac{\eta P_0}{G\sqrt{1+\omega^2\tau^2}} \qquad (2)$$

where, $\tau = C/G$ - thermal response time, time constant (self-heating effect of absorbing layer is neglected). The thermal capacity of the bolometer can be calculated by [6]:

$$C=\sum_i^n V_i\rho_i c_i \qquad (3)$$

V_1, V_2, ... ρ_1, ρ_2 ..., c_1, c_2,... are the volumes, densities, mass specific heats (respectively) of bolometer membrane material layers (including absorption layer). Thermal capacity expresses detecting area of microbolometer as a thermal mass which can absorb heat energy [7].

Linear dependency between resistance and temperature can be expressed in following formula[8]:

$$R=R_0\left[1+\alpha\left(T-T_0\right)\right]=R_0\left(1+\alpha\Delta T\right) \qquad (4)$$

where, α is the temperature coefficient of resistance (TCR), R_o is the resistance at the temperature T_0. We can assume that the resistance changes linearly with temperature (for most metals), i.e.:

$$\Delta R=\alpha R_0\Delta T \qquad (5)$$

Taking into consideration (2) and (6) and output voltage signal V_{out} we obtain responsivity $\Re$:

$$\Re=\frac{I_{bias}\Delta R}{P_0}=\frac{\eta I_{bias}\alpha R_0}{G\sqrt{1+\omega^2\tau^2}} \qquad (6)$$

where I_{bias} is the bias current of microbolometer.

As we can see in (6) $\Re$ is proportional directly to the temperature coefficient of resistance and inversely (highly) proportional to the thermal conductance [5]. Conductance is connected directly with heat loss, TCR next influences operational characteristics. IR detector is also characterized by detectivity with the following formula[9]:

$$D=\Re\frac{\sqrt{\Delta fA}}{V_{noise}} \qquad (7)$$

where, Δf is the detector noise bandwidth, A is the detector area, V_{noise} is the total detector noise.

III. Electrical and Thermal Consideration

There are some fundamental considerations which have strong impact on microbolometer performance and must be taken into account during modelling and simulation process. In Table I there are these considerations presented.

TABLE I. PERFORMANCE CONSIDERATIONS OF MICROBOLOMETERS

Consideration	Description
Joule effect	Self-heating effect due to current flow influences resistivity of microbolometer.
Material properties	Active absorbing layer physical properties, especially mechanical (Young modulus), thermal (TCR), electrical (resistivity).
Thermal isolation	Thermal isolation absorbing layer from the substrate layer. It is dependent on geometry and construction of microbolometer.
Time constant	Tells about the time needed to read the correct value by readout circuit in case of instantaneous changes of infrared radiation.
Noises	Noise level generated during operation and signal processing in CMOS Integrated circuits.

The performance of microbolometer detectors depends mainly on following thermal parameters such: temperature coefficient of resistance, TCR (α), thermal conductance of the support structure from element to the substrate (G_{TH}), thermal capacity (C_{TH}) and time constant (τ). Model of microbolometer has to include all of these parameters.

A. Material Properties

Since the microbolometer is complex device, to achieve require mechanical, thermal and electrical performance individual parts are built of various materials.

Thermosensing material should have a large temperature coefficient of resistance TCR. A large TCR means that a small change in temperature in the sensing material will result in a large change in resistance. This affects resolution of microbolometer.

Although there are many materials commonly used in microbolometer fabrication - Titanium (Ti) [9], Vanadium Oxide (VO)[10], Yttrium barium copper oxide (YBaCuO, YBCO)[11], GeSiO [12], poly SiGe[13], BiLaSrMnO and others - the most attractive among them are semiconductor (amorphous silicon α-Si, poly-Si, Si-Ge)[4], because they have a higher temperature coefficient of resistance (TCR) than other materials.

B. Thermal Isolation

High performance of operational IR detector is achieved thanks to the design that decreases the heat loss in the structure. In such detectors three heat transfer mechanism can occur. These are: convection, conduction and radiation. Convection can take place when the heat transfer occurs in surrounding environment. Conduction is present in supporting legs handling active film and heat flows along them from absorption to substrate layer. Radiation depends on mutual influence surroundings and absorption film.

The most meaningful heat loss happens by the conduction through the supporting legs of absorber membrane to the substrate[4]. This conduction phenomenon is critical when neighbor detectors are very close and transfer heat can occur between them. The less important is convection, which can be considerably minimized by vacuum detector encapsulation.

As presented on Fig 1. thermally isolation active film detector from its surrounding is achieved thanks to two thin beam (legs) application.`

IV. Modelling and Simulations

Microbolometers used for thermal imaging applications need integrated circuit (ROIC) to process signal from detector and transform it to useful information signal. To design correctly such electronic compatible and optimized circuit, the appropriate simulations should be done before fabrication.

There are many tools capable to model and carry out circuit simulation of MEMS devices. The most popular are MATLAB/SIMULINK and PSPICE packages. Using such software one can apply many alternative approaches comparing results and finally obtain model which is as closely as possible to real device. Final verification can be done by carrying out simulation with Finite Element Method (e.g. ANSYS, COMSOL).

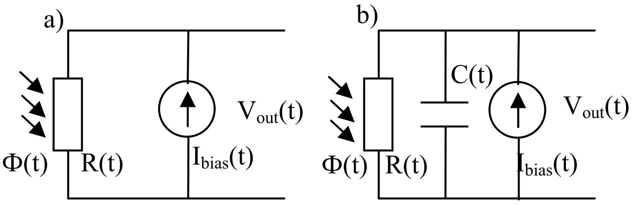

Fig. 3. Microbolometer simple circuit models: a) without heat capacitance [15], b) with heat capacitance [19].

A. Simple Circuit Model

The simplest dynamic circuit model of microbolometer (Fig. 3a), found in literature [16] consists of resistor (detector) and current source (bias), where *Φ(t)* is radiation flux, $I_{bias}(t)$ is bias current, $V_{out}(t)$ is output voltage[17]. However, model presented in Fig. 5a. does not reflect effect of thermal capacity. To take into consideration this effects in circuit model, it is necessary to connect additional capacitor *C* in parallel (Fig. 3b)[18]. This quantity can be calculated using (3).

Resistance of detector can be found by calculating total resistance of absorbing conductor taking into account TCR parameter agreeing to well-known formula (8):

$$R = \rho \frac{d}{A} \tag{8}$$

where ρ is resistivity, A – section area, d – length of conductor.

Effective thermal resistance is complex quantity. One has to remember that detecting layer placed between two protective layers is built of various materials. This resistance cannot be neglected thus total thermal resistance [19]:

$$R_{TH} = \frac{1}{G_{TH}} = \frac{L_{leg}}{K_{leg} W_{leg} t_{leg}} = \sum_i \frac{L_i}{K_i W_i t_i} \tag{9}$$

where K_{leg} is thermal conductivity, W_{leg}, L_{leg}, t_{leg} are supporting legs dimensions: width, length and thickness respectively. The quantities with i indexes are referred to particular layers of supporting legs Consequently, we have to calculate the effective thermal resistance of a block composed of two materials. It can be shown that in such a case, the effective thermal resistance can be calculated as a parallel connection of the thermal resistances of both materials[19].

Besides thermal capacitance, it is desirable to put additional resistance represents the losses through radiation with a thermal conductance G_{rad} (especially when thermal conductance G_{leg} value approaches to radiation conductance G_{rad}). G_{rad} can be obtain by multiply derivative the total exitance of a blackbody by multiplying by the bolometer area $2A_d$ (because both the top surface and the bottom surface of the bolometer are radiating) [23]:

$$G_{rad} = 2 A_d \frac{d\eta\sigma T^4}{dT} \tag{10}$$

B. Voltage Bias and Joule Effect

As it mentioned earlier microbolometer operation is based on resistance change. This requires DC bias current to be applied to the device which allows to read the change in resistance due to the radiation. High responsivity is achieved by use of large current flow (6). Unfortunately, higher current bias strengthen self-heating effect (Joule heating effect), which next has negative impact on final measurement [21]. Hence, (1) it has to be corrected with factor P_{JH} (dissipated Joule heat) on the right side in the following formula [22]:

$$C \frac{d(\Delta T)}{dt} + G(\Delta T) = P_{JH} + \eta P_0 e^{j\omega t} \tag{11}$$

Decrease Joule heat emission imposes DC bias current to be pulsed. Joule heating potentially can produce thermal energy which will affect the performance parameters of the device – *NETD* (noise equivalent temperature difference), thermal conductance and responsivity (via I_{bias}) and also the operation of the readout circuit. It is important to highlight to get optimum performance of detector it is necessary to look into temperature distribution and response of the detector under different thermal condition and loads - it should be carried out in initial stage of designing process. Additionally, an impact on *NETD* can take place also by increasing the pulse width. However, characterizing the thermal behavior for different loads of a given microbolometer device (also when Joule heating is minimized) is very important to understand its performance and reliability and should be carry out at the beginning of designing. The thermal characteristic of the device itself also changes the physical properties of the multilayered structure which in turn affects the performance and lifetime of the microbolometer [23].

One of the simplest model with Joule heating effect presented in literature contains two sources and RC elements (Fig. 4) [14]. It was developed to make analysis in initial design process. Joule heating and radiation in that model was simulated using controlled current sources *(P_{Joule}, P_{rad})* [24].

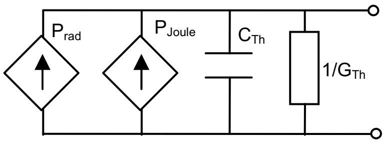

Fig. 4. Circuit model of microbolometer with Joule-heating effect[14].

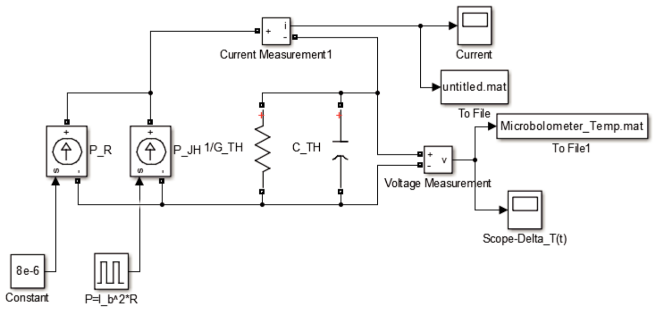

Fig. 5. Implementation simple circuit model of microbolometer in SIMULINK.

Basic model presented in Fig. 4. was implemented by authors in MATLAB/SIMULINK package (Fig. 5). This model was biased with pulse generator with constant amplitude. Other power source (radiation) was taken as a constant value $8*10^{-6}$. Parameters like: *R*, G_{TH}, C_{TH} used in this model were calculated using formula (3),(8),(9). Verification its functionality and reliability was committed comparing results obtained in publication [14].

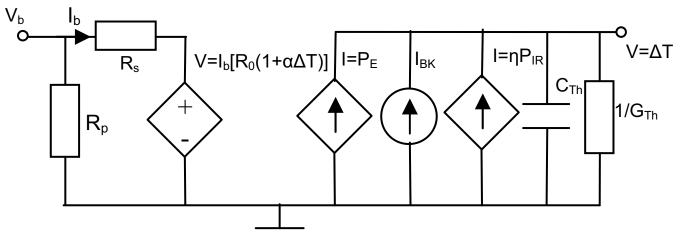

Fig. 6. Microbolometer model proposed in [25].

More complex model was presented in [25]. Authors stated that to do bias properly current optimization the model needs to incorporate electro-thermal effects and one cannot reflect all phenomena with resistor-based only microbolometer. Proposed model shows that responsivity depends on TCR, thermal conductance (*G*) and time constant (τ) and it should not to avoid impact on these quantities. Experimental and simulation results were similar, thermal parameters mentioned above follow expected results so it verified proposed model.

This model takes into consideration Joule effects, resistivity in contacts R_s and R_p and temperature independent series resistance. Current brought about Joule heating is described as $I=P_E$, which next $P_E=V_BI_B$. Radiation power is presented as controlled current source $I=\eta P_{IR}$. To reflect initial temperature value, there is additional current source I_{BK} placed in parallel.

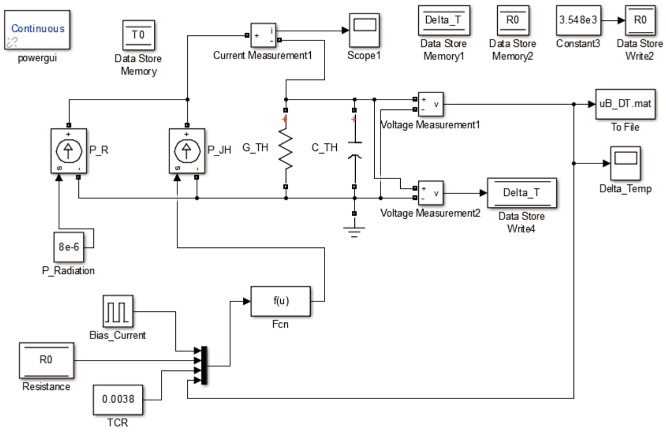

Fig. 7. Implementation complex circuit model of microbolometer in SIMULINK.

Model presented in Fig. 6. was implemented in SIMULINK package (without R_s and R_p) – Fig. 7. Voltage source is replaced with direct connection output model signal to input user-defined function block *Fcn* to implement dependency *R(T)*.

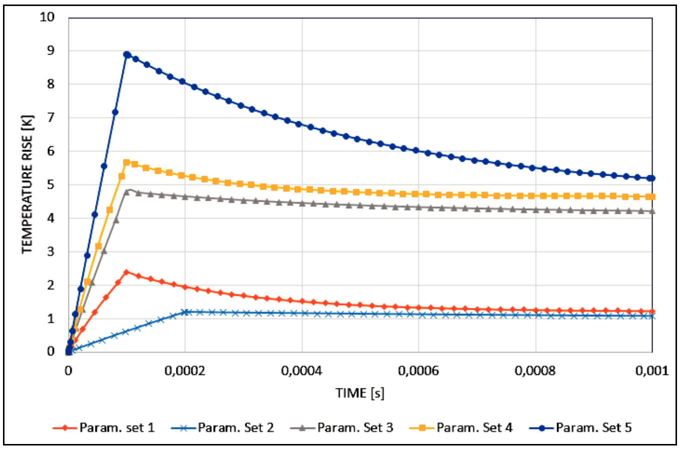

Fig. 8. Temperature rise our model simulated microbolometer in SIMULINK.

Some simulations were performed with this SIMULINK model. First of all verification of reliability was done. We used five parameters sets taken from publication and presented in Table II - [14].

Comparative simulation shows that results are very similar to these in [14], what confirms that model was created appropriately (Fig. 8).

We also performed simulations with parameter set 1 and changed bias current. Simulation performed in this model shows strong dependency between temperature rise and current bias – Fig. 9. Above I_b=100mA due to self-heating effect the temperature dramatically grows what affects measurement process. One way to reduce this impact is changing microbolometer dimensions. One can see on Fig. 8 that with I_b=200mA applied dimensions increase helps significantly (set 2) - temperature rise drops at the peak from 8.5K to 1.2K.

TABLE II. PARAMETERS SET USED IN SIMULATIONS.

Initial parameters sets					
	Set 1	Set 2	Set 3	Set 4	Set 5
l_1 [μm]	25	50	25,5	25,5	38,3
l_2 [μm]	19	38	15,5	25,5	23,3
w [μm]	1	2	1,5	1,5	2,25
h [μm]	0,1	0,2	0,05	0,05	0,075
l_{leg} [μm]	4	8	6	6	9
w_{leg} [μm]	2	4	1,5	1,5	2
h_{leg} [μm]	2	4	2	2	3
s [μm]	26	52	26,5	26,5	39,8
h_t [μm]	0,5	1	0,3	0,3	0,45
h_b [μm]	0,5	1	0,3	0,3	0,45
l_{gap} [μm]	24	48	24	24	36
w_{gap} [μm]	0,5	1	2,5	2,5	3,75
w_{arm} [μm]	2,5	5	2,5	2,5	3,75
r [Ωm]	$1,60 \cdot 10^{-6}$	$1,60 \cdot 10^{-6}$	$1,60 \cdot 10^{-6}$	$3 \cdot 10^{-6}$	$3 \cdot 10^{-6}$
κ_a [$Wm^{-1}K^{-1}$]	22	22	22	40	40
α[1/K]	0,0038	0,0038	0,0038	0,01	0,01
κ_i [$Wm^{-1}K^{-1}$]	30	30	30	15	15
ρ [kg/m^3]	3290	3290	3290	2000	2000
c [$Jkg^{-1}K^{-1}$]	700	700	700	500	500
Calculated parameters					
R_{TH}[K/W]	$1,89 \cdot 10^5$	$9,44 \cdot 10^4$	$4,14 \cdot 10^5$	$4,64 \cdot 10^5$	$3,09 \cdot 10^5$
C_{TH}[J/K]	$1,56 \cdot 10^{-9}$	$1,25 \cdot 10^{-8}$	$9,70 \cdot 10^{-10}$	$4,21 \cdot 10^{-10}$	$1,42 \cdot 10^{-9}$
R[Ω]	$3,51 \cdot 10^3$	$1,75 \cdot 10^3$	$4,11 \cdot 10^3$	$7,71 \cdot 10^3$	$5,14 \cdot 10^3$

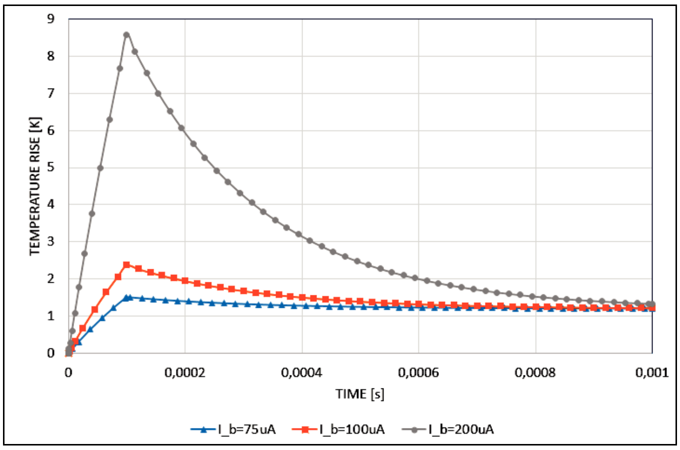

Fig. 9. Implementation complex circuit model of microbolometer in SIMULINK.

C. *Noise Sources*

Although above model seems to be close to complete, it does not contain some important negative effects – noises. It is all the more crucial when we realize the scale of this problem.

There are several uncorrelated sources to bolometer noise: the Johnson noise (or thermal noise), the *1/f* noise (also called flicker noise), and the background noise. The extended model necessary for analyzing impact noises on microbolometer performance was presented in [26]. Authors took particular consideration on noises taking place in microbolometer:

- background radiation noise – can be simulate with random noise voltage source,
- temperature fluctuation noise, caused by any uncontrolled temperature fluctuation, influences directly into output noise – can be implemented as a random voltage source connected in series with element,
- Johnson noise – main noise source in microbolometer - generated by the electron thermal vibration inside an electrical conductor - can be implemented as a random voltage source or random current source,
- flicker noise (*1/f* noise) - noise brought about the non-ideal of the material surface conditions – can be implemented as random voltage source connected in series with element.

This model was verified by authors, thus in conclusion, using similar approach there is possible to use controlled and uncontrolled voltage and current sources to implement any other identified noises in future modelling.

V. CONCLUSIONS

Good knowledge about heating transfer mechanisms is basis in optimization MEMS structure as well as in obtain better performance. To achieve desired performance level sensor has to be designed along with ReadOut Integrated Circuit. This approach allows to focus on key dependences that influence whole microbolometer performance. Using modelling and simulation methods one can describe them. Circuit models of MEMS devices are very popular among scientist because they are easy-to-implement and results are close to FEM simulations.

As we can see there are some various circuit model applied in research and published. This depends on author needs and researched phenomena. Analysis of publications shows that it is possible to create complex model consisting most of key aspects of microbolometer operation.

We presented two microbolometers models created in MATLAB/SIMULINK which were verified. Results are promising and give foundations for microbolometer optimization – geometry, material properties and bias parameters. These models will be further expanded and compared with Finite Element Analysis models.

Despite continuous research, modeling, and improve microbolometers, they have not yet reached maximum performance level. Scientists still work on reducing negative phenomena, like noises, improve detectivity, optimize time constant. It will allow in future to "see" more smaller object by thermal camera than nowadays. Development of microbolometer modelling is crucial especially scientists efforts are currently concentrated on infrared imaging application, automotive safety (e.g. driver's night vision), some medical and military applications, industrial process control, person detection, person counting, and consumer products (mobile phones).

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