

Analytical tool for electro-thermal modelling of microbolometers

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Abstract

In this paper we present a tool which incorporates an analytical model of a microbolometer. Within the tool the user can freely change the input parameters such as dimensions and material properties and immediately obtain output parameters such as responsivity, thermal time constant etc. Moreover, the tool can be used to compute the transient thermal response of the microbolometer for a given radiation power and bias current. The model was validated against the results obtained from ANSYS for several different devices and the maximal relative error in transient temperature response was found to be only 3%.

1. Introduction

Microbolometers are an example of Microelectromechanical Systems (MEMS), used to measure electromagnetic radiation. The operation principle is quite simple: a material with high temperature coefficient of resistance (TCR) is exposed to the incoming radiation, it heats up and therefore changes its resistance. Such resistance change can be then measured and the power of the incoming radiation can be calculated. Microbolometers are mostly used to measure infrared radiation in thermal imaging. Currently, many manufacturers offer thermal cameras based on microbolometer arrays [1-3]. Nevertheless, this field still needs research so that cameras can have a better resolution and work with higher frame rate. Therefore, a multi-domain simulation of phenomena occurring in microbolometers is necessary.

Finite Element Method (FEM) – based tools like ANSYS[8] and COMSOL[9] are commonly used for simulating such devices. However, very often during the early design phase the exact device dimensions, shape or even used materials are not yet known and it is the role of the designer to find the optimal/desired parameters. Therefore, it may be very time consuming to use FEM analysis at this stage, especially if the device geometry has to be repeatedly changed and transient analysis with many time points has to be used. Hence the need arises for simpler and, more importantly, faster model. Thanks to such a model, it is possible to rapidly sweep through a wide range of parameters, obtain preliminary results and, in general, significantly reduce the design space. Obviously, after finding the optimal/desired parameters using the simpler model, the obtained results should be validated using detailed FEM simulation.

In the paper, we thoroughly describe such a model and validate it against results obtained using FEM simulation. We perform the validation for various device dimensions and different materials in the electrical, thermal and coupled electro-thermal domain. The validation is based on comparing the transient thermal response obtained from Ansys and from our model. The presented comparisons show that the model correctly predicts the thermal behaviour of the device for a wide range of input parameters. Based on this validation, weak points of the model are identified and corrective measures are applied. The perspectives for model development are also given, with special emphasis put on the need for incorporating the mechanical domain into the model.

2. General microbolometer architecture

The description of the structure of a microbolometer may be found in literature [4-6], so only a short summary will be presented here. Various microbolometer implementations vary in shape, but a general device structure always remains the same: a square-shaped bridge suspended over the substrate, supported by relatively thin legs. Thin supports are necessary to thermally separate the bridge from the substrate. A microbolometer contains two specific type of materials: one active material with a high TCR, and an insulator. Usually the thin layer of active material is located between two membranes made from insulator. To maximize the resistance change of the thin active layer due to temperature, it is sometimes serpentine-shaped (see Fig. 1). The insulating membrane allows increasing the receptive area of the device and at the same time it does not change its electrical behaviour. It also strengthens the structure from the mechanical point of view.

The specific microbolometer structure which is analyzed in this paper is shown in Fig. 1. Although all dimensions are treated like input parameters in our work, for the model validation (see section 5) it was assumed that the general structure remains the same. Of course, the fact that the model was not validated for other types of structure does not mean that it will not work in such cases; simply, the model would need to be tuned to adequately describe the new device shape.

Let us now describe the structure and specify the parameters which will be later used as inputs to our model. First, the active material layer is assumed to have the same width and thickness in every point of the device. Other two parameters describing this layer are its total size and the size of its inner serpentine part (Fig. 1).

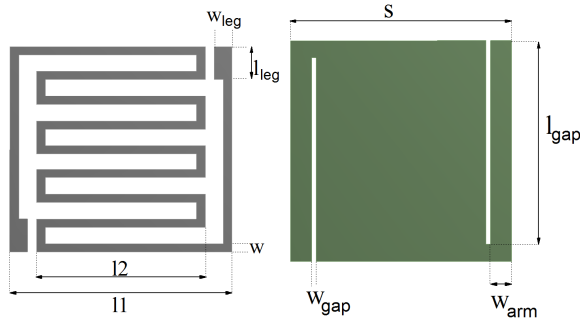


Fig. 1. Shape of the active layer (left) and the insulating membrane (right).

Note that it is also assumed that the number of serpentine turns stays the same. The necessary material properties of active layer are its electrical resistivity, thermal conductivity and TCR. Second, the insulating membrane is assumed to cover the entire structure and to have gaps along supporting arms. It is described by its total size, gap width and length and arm width (arm length is supposed to be equal to the total membrane size). The necessary material properties of insulating layer are its thermal conductivity, density and specific heat. All above-mentioned parameters and their symbols used later in this paper are summarized in Table 1.

Table 1. List of geometrical and material parameters

Name	Symbol
Active layer size	$l1$
Active layer inner size	$l2$
Active layer width	w
Active layer height	h
Leg length	l_{leg}
Leg width	w_{leg}
Leg height	h_{leg}
Membrane size	s
Top membrane height	h_t
Bottom membrane height	h_b
Gap length	l_{gap}
Gap width	w_{gap}
Arm width	w_{arm}
Electrical resistivity of active material	r
Thermal conductivity of active material	κ_a
Temperature coefficient of resistance of active material	α
Thermal conductivity of insulating material	κ_i
Density of insulating material	ρ
Specific heat of insulating material	c

3. Microbolometer model

The purpose of our model is to allow fast analysis in the early stage of the design process, allowing the designer to sweep across a wide range of parameters. Therefore, it was decided to use a simple RC equivalent circuit model [7] (see Fig. 2). Although such an approach constitutes a significant simplification with respect to

FEM-based simulation, it will be shown in section 5 that the resulting error is quite small. In exchange, the model has the advantage of allowing the designer to analytically calculate the temperature of the microbolometer at every time point. Let us now describe in detail how all output parameters of the microbolometer are obtained.

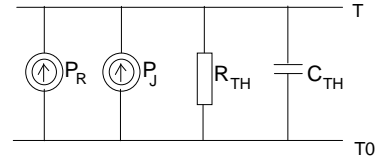


Fig. 2. Microbolometer model. P_R – radiation power, P_J – Joule heat power, R_{TH} – thermal resistance, C_{TH} – thermal capacity

Electrical domain.

We assume here that the resistivity of the insulator is much higher than that of the active material. Consequently, the bias current only flows through the active layer and only in this body Joule heat is generated. The main parameter in this domain is the resistance of the active layer. To obtain this parameter, it is first necessary to calculate the total length of active layer using appropriate dimensions from the Table 1. Once total length is calculated, the electrical resistance can be easily obtained using the well-known formula:

$$R = r \frac{l_a}{w_a h_a} \quad (1)$$

where r is the resistivity of the material, l_a is its length, w_a is its width and h_a is its height. From the electrical resistance and assuming the bias current is known, one can derive the Joule heat dissipated in the active layer using $P=I^2R$ relationship. Thus, the first parameter (P_J) of the circuit presented in Fig. 2 is obtained.

Thermal domain.

The calculation of thermal parameters is more complex because both active and insulating layer has to be taken into consideration. Fortunately, there are some assumptions than can be made which greatly simplify the following analysis. Let us look at the results of the steady-state thermal analysis performed in ANSYS (Fig. 3).

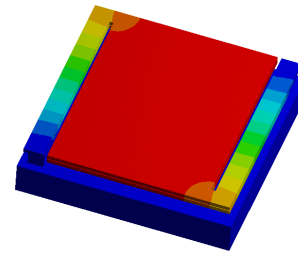


Fig. 3. Steady-state thermal simulation of a microbolometer performed in ANSYS.

We can see that the temperature of the substrate is practically equal to the ambient temperature. The second observation is that the temperature of the membrane is distributed almost uniformly in the membrane. Therefore, the temperature drop only occurs along the supporting arms. In other words, the thermal resistance of the arms is much higher than the thermal resistance of the membrane and the substrate. Therefore, in the model, only the thermal resistance of arms is necessary. Note that each arm is composed of three layers: bottom membrane, active layer and top membrane.

$$R_{TH} = \frac{1}{\kappa w_{arm} h_{arm}} \quad (2)$$

In this case, the total resistance of three layers is obtained by first calculating the thermal resistance of each layer (see Eq. 2) and then deriving the total thermal resistance as a parallel connection of three individual resistances. The appropriate dimensions of the arms needed for Eq. 2 are calculated based on the parameters shown in Table 1.

When it comes to thermal capacity, necessary for transient simulation, it can be calculated using the formula Eq. 3:

$$C_{TH} = \rho c V \quad (3)$$

To calculate the volume V in Eq. 3, we assume in our model that the volume of the active layer is significantly smaller than that of insulating membranes and is therefore neglected. Consequently, only the volume of membranes needs to be calculated. Again, we use the geometrical dimensions from the Table 1 to calculate the total membrane volume. Thus, we obtain two other parameters of the model, the thermal resistance R_{TH} and the thermal capacity C_{TH} .

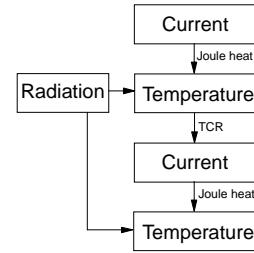


Fig. 4. Coupling between electrical and thermal domain based on one iteration step

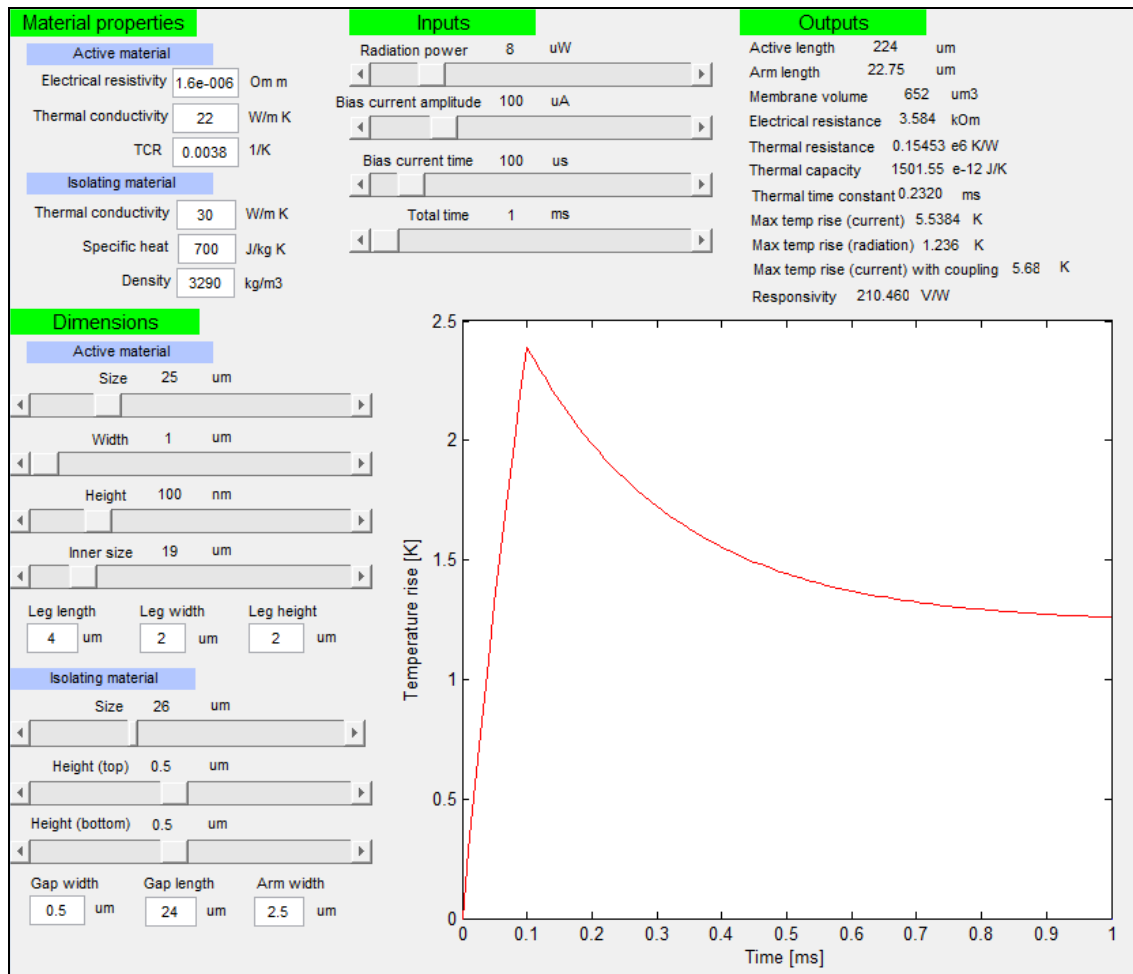


Fig. 5. A screenshot of the modelling tool developed in Matlab.

A careful reader may have noticed that so far in our model we ignored the coupling between thermal and electrical domain. Note that the thermal domain influences the electrical domain because the resistance of the active layer is a function of temperature. This effect in principle cannot be neglected because the materials used in microbolometers have relatively high TCR which means that the resistance can change significantly with temperature. Typically, in complex tools this problem is solved iteratively, however, after thorough analysis, it was discovered that in the case of a microbolometer, one iteration step already gives acceptable results. The reason is that the temperature change of the device is quite small, in the range of several degrees. Thus, such an approach (shown in Fig. 4) was implemented in our model. In short, we first calculate the resistance in room temperature, next the temperature change due to current and radiation is calculated. This new temperature is then used to calculate a new value of electrical resistance, which is in turn used to calculate the final temperature.

4. Modelling tool

The tool which uses the model described in the previous section was written in Matlab. The screenshot of the program is shown in Fig. 5. A user has the possibility to choose all material properties (like electrical resistivity, thermal conductivity, specific heat, TCR, etc.) and all geometrical dimensions of the device (total size of the device, the size of particular layers, the sizes of legs and arms, etc.). He can also define simulation inputs (bias current, current pulse time, radiation power, etc.). Based on these data, the tool calculates output parameters such as electrical resistance, thermal resistance, thermal capacity, thermal time constant, responsivity, etc. and, most importantly, shows the microbolometer's transient temperature response. Therefore, it is possible for example to quickly see what will be the maximum temperature reached by the microbolometer for a given radiation power, current pulse amplitude and current pulse time. Note that for the reason of convenience, sliders were added to the tool to control some inputs; since outputs and the graph are updated on-the-fly, a user can rapidly assess the influence of a parameter on output values just by moving the slider.

5. Validation of the model against FEM simulation

Since the model comprises many parameters, it would be difficult to compare the model with ANSYS for a wide range of all parameters. Therefore, it was decided to perform the comparison for several specific microbolometer structures. The transient temperature response was chosen as a method of comparison. We designed different geometries in ANSYS, used various material properties and simulation inputs (bias current and radiation power) and ran transient thermal simulations for each device. Then, the same devices were modeled in our tool and the results were compared. Although we performed the simulations for many structures, here we

present the analysis for five sample devices, whose parameters are given in Table 2.

Table 2. Parameters of five simulated devices

	Parameters
1	$l_1=25 \mu\text{m}$, $l_2=19 \mu\text{m}$, $w=1 \mu\text{m}$, $h=100 \text{ nm}$, $l_{leg}=4 \mu\text{m}$, $w_{leg}=2 \mu\text{m}$, $h_{leg}=2 \mu\text{m}$, $s=26 \mu\text{m}$, $h_r=0.5 \mu\text{m}$, $h_b=0.5 \mu\text{m}$, $l_{gap}=24 \mu\text{m}$, $w_{gap}=0.5 \mu\text{m}$, $w_{arm}=2.5 \mu\text{m}$, $r=1.6 \cdot 10^{-6} \Omega\text{m}$, $\kappa_a=22 \text{ Wm}^{-1}\text{K}^{-1}$, $\alpha=0.0038 \text{ K}^{-1}$, $\kappa_i=30 \text{ Wm}^{-1}\text{K}^{-1}$, $\rho=3290 \text{ kg/m}^3$, $c=700 \text{ Jkg}^{-1}\text{K}^{-1}$ $I_{bias}=100 \mu\text{A}$, $t_{pulse}=100 \mu\text{s}$, $P_R=8 \mu\text{W}$
2	All dimensions from device 1 scaled 2x, material properties without change, $I_{bias}=200 \mu\text{A}$, $t_{pulse}=200 \mu\text{s}$, $P_R=10 \mu\text{W}$
3	$l_1=25.5 \mu\text{m}$, $l_2=15.5 \mu\text{m}$, $w=1.5 \mu\text{m}$, $h=50 \text{ nm}$, $l_{leg}=6 \mu\text{m}$, $w_{leg}=1.5 \mu\text{m}$, $h_{leg}=2 \mu\text{m}$, $s=26.5 \mu\text{m}$, $h_r=0.3 \mu\text{m}$, $h_b=0.3 \mu\text{m}$, $l_{gap}=24 \mu\text{m}$, $w_{gap}=2.5 \mu\text{m}$, $w_{arm}=2.5 \mu\text{m}$, $r=1.6 \cdot 10^{-6} \Omega\text{m}$, $\kappa_a=22 \text{ Wm}^{-1}\text{K}^{-1}$, $\alpha=0.0038 \text{ K}^{-1}$, $\kappa_i=30 \text{ Wm}^{-1}\text{K}^{-1}$, $\rho=3290 \text{ kg/m}^3$, $c=700 \text{ Jkg}^{-1}\text{K}^{-1}$ $I_{bias}=100 \mu\text{A}$, $t_{pulse}=100 \mu\text{s}$, $P_R=8 \mu\text{W}$
4	All dimensions from device 3, $r=3 \cdot 10^{-6} \Omega\text{m}$, $\kappa_a=40 \text{ Wm}^{-1}\text{K}^{-1}$, $\alpha=0.01 \text{ K}^{-1}$, $\kappa_i=15 \text{ Wm}^{-1}\text{K}^{-1}$, $\rho=2000 \text{ kg/m}^3$, $c=500 \text{ Jkg}^{-1}\text{K}^{-1}$ $I_{bias}=50 \mu\text{A}$, $t_{pulse}=100 \mu\text{s}$, $P_R=10 \mu\text{W}$
5	All dimensions from device 3 scaled 1.5x, $r=3 \cdot 10^{-6} \Omega\text{m}$, $\kappa_a=40 \text{ Wm}^{-1}\text{K}^{-1}$, $\alpha=0.01 \text{ K}^{-1}$, $\kappa_i=15 \text{ Wm}^{-1}\text{K}^{-1}$, $\rho=2000 \text{ kg/m}^3$, $c=500 \text{ Jkg}^{-1}\text{K}^{-1}$ $I_{bias}=150 \mu\text{A}$, $t_{pulse}=100 \mu\text{s}$, $P_R=15 \mu\text{W}$

It should be emphasized that version 14 of ANSYS Workbench that we used does not directly support transient coupled electro-thermal simulation, so a workaround was necessary. The detailed description of our approach is however beyond the scope of this paper. In short, we performed iterative transient thermal analysis and for each step the inputs were calculated manually based on the outputs from the previous step. The figures 6 and 7 show the results of the performed simulations both in Matlab using our model and in ANSYS. The comparison was performed for a constant radiation power and a short pulse of bias current. On the y axis, the maximal temperature rise (with respect to the ambient) is shown.

It can be seen that the model is quite accurate: the maximal encountered error was equal to 3%, in the case of device 5. After a thorough analysis of all simulations results, it was discovered that the main source of error is probably the simplified calculation of the thermal resistance of supporting arms. Thus, if needed, the model could likely be improved by implementing a more complex thermal resistance modelling. A potential improvement might consist of using two thermal resistances with slightly different values, one resistance for calculating the temperature rise caused by the bias current and the second one for calculating the temperature rise from incoming radiation.

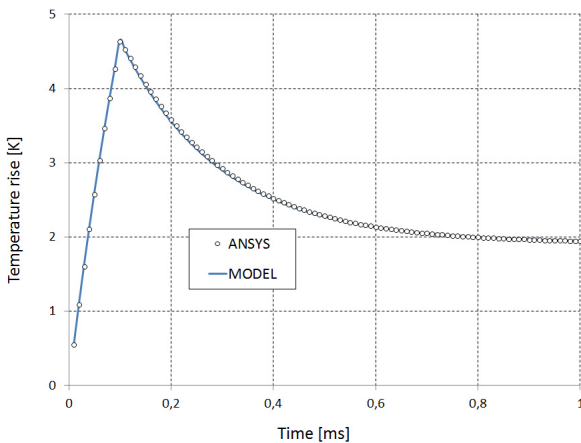
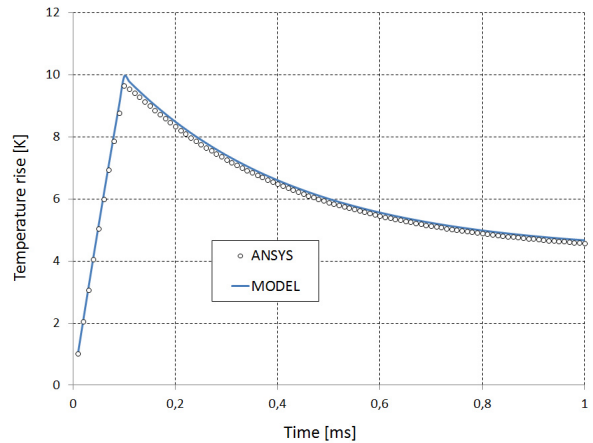
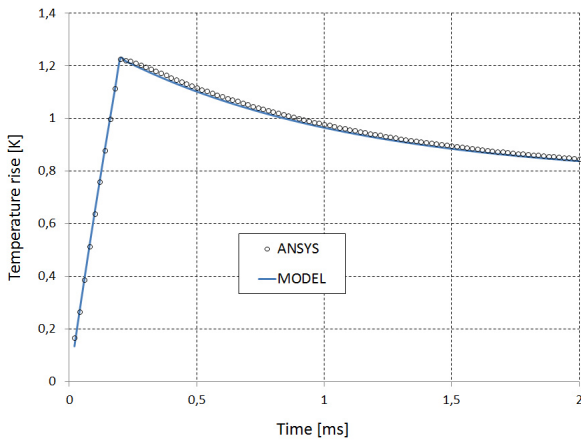
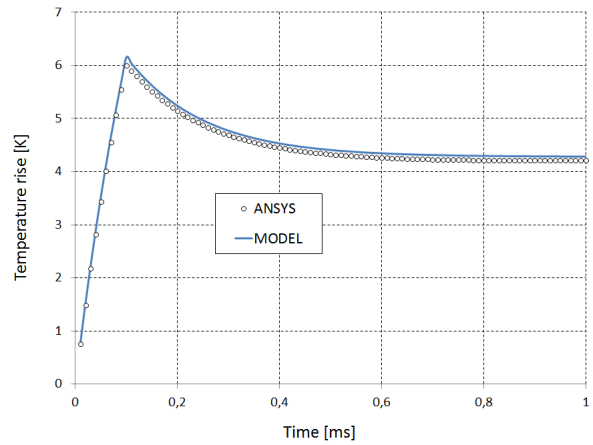
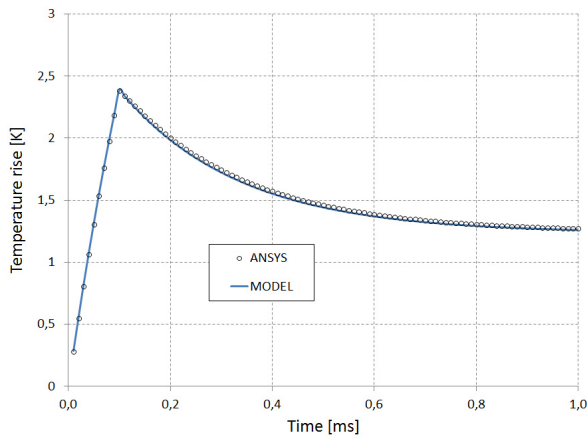


Fig. 7. Comparison of our model with ANSYS for devices 4 (top) and 5 (bottom)

Fig. 6. Comparison of our model with ANSYS for devices 1 (top), 2 (middle) and 3 (bottom)

6. Conclusions and perspectives

It has been shown that despite its simplicity, our thermo-electric model of a microbolometer provides the results very similar to those obtained using relatively time-consuming FEM analysis. The disadvantage of the model is that its mathematical formulas depend on pre-defined shape of the device so if it is changed, the model requires a slight tuning. However, it may generally be expected that the RC equivalent circuit model will work correctly also for other types of microbolometer shapes.

In the future, the model will be expanded to include the mechanical domain which will allow the user to assess the structural integrity of the device under mechanical and thermal stress.

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