Між подвійним електричним шаром зарядів та шаром магнітних зарядів існує взаємозв'язок, при змінах в одному шарі проходить перебудова іншого.

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NONLINEAR DISCRETE ELEMENTS IN ELECTRO-THERMAL MODEL OF THICK-FILM MULTILAYER STRUCTURE

The complexity of heat exchange mechanisms and difficulties in accurate determination of their coefficients make the thermal analysis a complicated problem at the beginning of the design process. In reality, only numerical calculations and specialised simulation programs can solve the systems of differential equations with very complicated boundary and initial conditions. The paper presents some aspects of describing of thermal model of the thick-film microcircuits with equivalent models (based on RC elements).

Комплексність механізму теплообміну і складності під час визначення коефіцієнтів процесу роблять тепловий аналіз однією з важливих проблем при розробці електронних приладів. Насправді тільки числові методи і спеціальні програми моделювання можуть розв'язати системи диференціальних рівнянь з ускладненими крайовими і початковими умовами. Наведено кілька аспектів опису теплової моделі товстоплівкових мікросхем з еквівалентними моделями на базі RC елементів.

Introduction

Temperature plays a very important role in proper operation of microelectronic circuits. It determines exploitation parameters and – in the most cases – life of circuit or whole system. From this reason, taking into consideration the thermal problems is strongly recommended on the beginning of design process.

The thick-film microcircuits are very complicated objects to their formal description from point of view of heat transfer. The complexity of heat exchange mechanism makes the mathematical analysis only approximation of the real-world conditions. In reality, only numerical calculations can solve the systems of differential equations with very complicated boundary and initial conditions.

The paper presents the method of temperature field simulation using electro–thermal analogy. Using the mathematical analogy of equations (in stationary and dynamic states) which describe the temperature field and electric potential field, it is possible to create the electrical equivalent circuit of thermal system [1-6].

Electro-thermal modelling procedure

The thermal behaviour of multilayer structure can be described in terms of thermal capacity C_{th}, which is directly proportional to the relevant volume V, to the density of the material and to the specific heat c. The applicable equation is as follows:

$$C_{th} = c \cdot \rho \cdot V \tag{1}$$

To calculate the voltage change ΔU it is necessary to use the quantity-of-charge equation for a capacitance C. This can be described by formula:

$$U \cdot C = I \cdot t = Q \tag{2}$$

where U is voltage, C – electrical capacitance, I – electrical current, t – time and Q means electrical charge.

By analogy, the quantity-of-heat equation can be expressed:

$$\Delta T \cdot C_{th} = P \cdot t = Q \tag{3}$$

Where the current I=Q/t represents a transport of charge per unit of time and the power dissipation P represents the transport of thermal energy per unit of time. So, the temperature change ΔT can be described by equation (4):

$$\Delta T = \frac{P \cdot t}{C_{th}} \tag{4}$$

The thermal capacities calculated from the material properties and the volume are connected in parallel with the thermal resistances. For calculating the components of a network it is necessary to know the thickness d, the cross-sectional area A and the thermal conductivity λ, in order to obtain the appropriate thermal resistance R_{th}:

$$R_{th} = \frac{d}{\lambda \cdot A} \tag{5}$$

In accordance with the analogy to electrical systems, the temperature response of structure element (in pulse operation) can be analysed like a voltage increase across an RC section which is being fed by a current pulse generator. The following relationships described such analogy:

$$U(t) = R \cdot I \cdot \left(1 - e^{\frac{t}{R \cdot C}} \right) \tag{6}$$

and for the increase in temperature:

$$T(t) = R_{th} \cdot P \cdot \left(1 - e^{\frac{t}{R_{th} \cdot C_{th}}} \right) \tag{7}$$

The created in this way thermal equivalent RC elements network can be simulated in any simulator of electric or electronic circuits [7].

Modelling examples

The PSPICE program allow to take into account the mathematical relations - describing particular single element – using ABM (Analogue Behavioural Modelling) options. They are based on controlled voltage and/or current sources with special declarations. They make possible to simulate of the analysed circuit in time domain as well as in wide frequency range or with parametric assumptions [8]. The example 1D distributed RC thermal line (towards in X-axis) is presented in Fig.1.

The calculations (in PSPICE program) were carried out for two cases. First, thermal resistance Rth was modelled in the standard form as linear resistor with value independent on voltage (temperature). In the second case, thermal resistances in above mentioned model were simulated as voltage – dependent resistors (varistors).

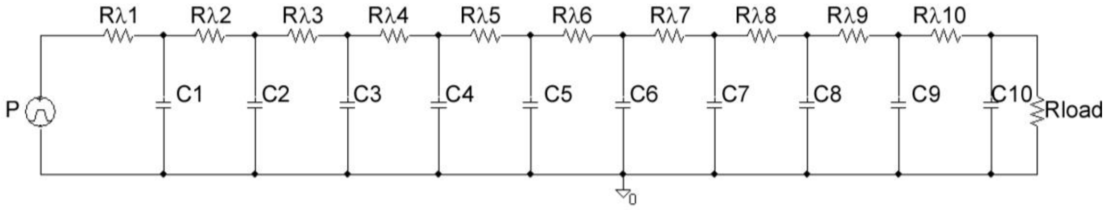

Fig.1. 1D distributed RC thermal line (towards in X-axis).

They were modelled in PSPICE program as special created "subcircuits" using controlled sources (ABM options). They took into account third order approximation of the λ and α parameters. The example PSPICE netlist of such model is as follows:

```
.subckt lambda_substrate 10 20; Al2O3 99,5%
R1 10 30 1;
E1 30 20 poly(2) 10 30 40 50 0.0 1 0.0 0.0 -1
R3 40 50 600; geometrical constant
R4 50 0 10000meg
G2 40 50 value={1/(-2.64e-8*V(10,20)*V(10,20)*V(10,20)+
+1.095e-4*V(10,20)*V(10,20)-0.147*V(10,20)+71.514)}
.ends
```

The modelling results (obtained from PSPICE program using third order polynomial approximation) of the thermal properties of thick-film components are shown in Fig. 2 and 3. In those figures the voltage (on X axis) correspond with temperature.

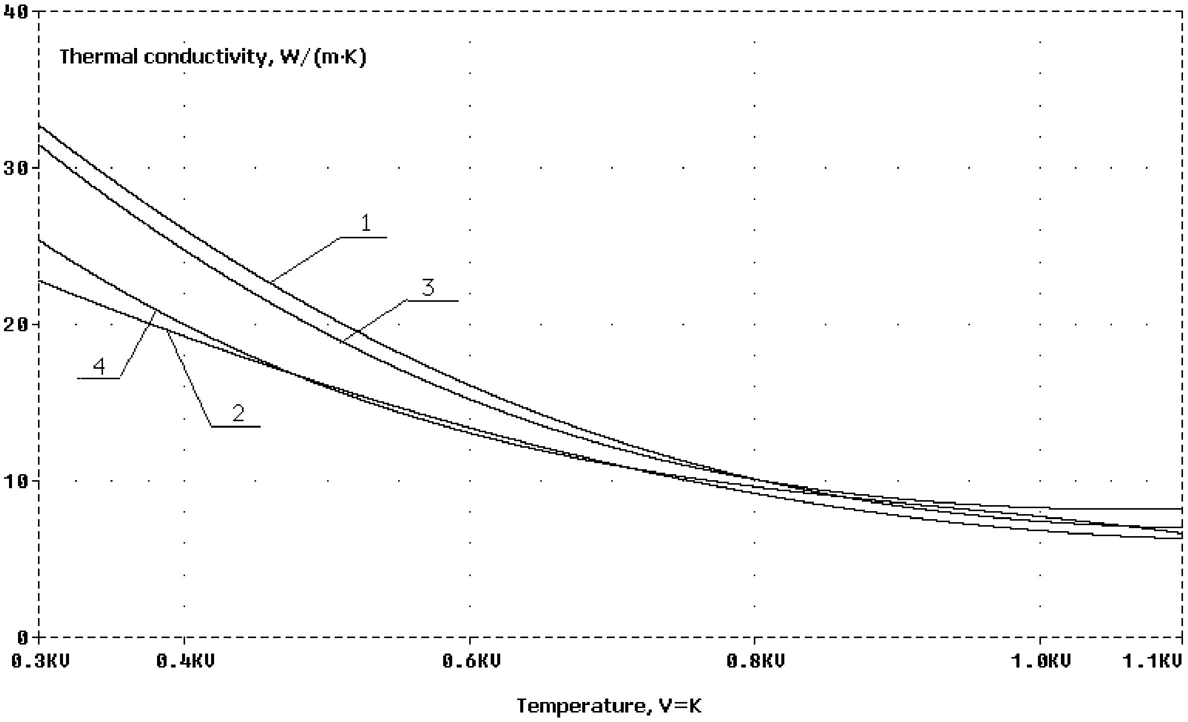

Fig.2. Modelling of the thermal conductivity vs. temperature of ceramic substrate:
1 - 99.5% Al_2O_3, 2 - 98% Al_2O_3, 3 - 96% Al_2O_3, 4 - 94% Al_2O_3.

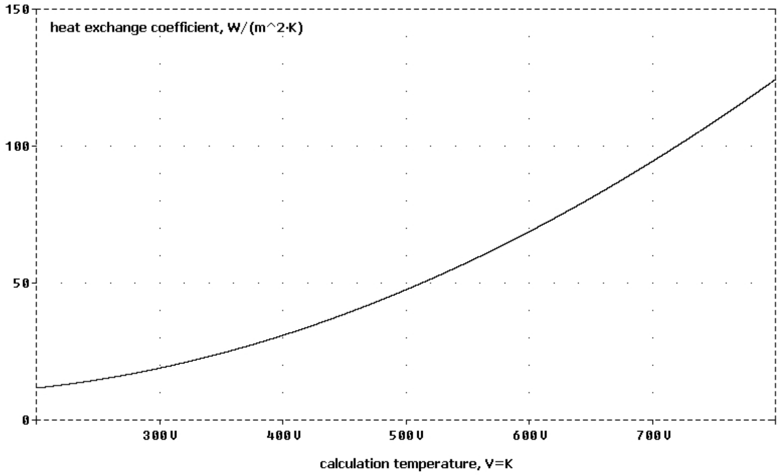

Fig.3. Modelling of the total coefficient of heat exchange with air vs. calculation temperature for characteristic dimension equal 0.006m.

The temperature courses in particular points of RC network obtained from PSPICE simulation are presented in Fig.4 and Fig.5.

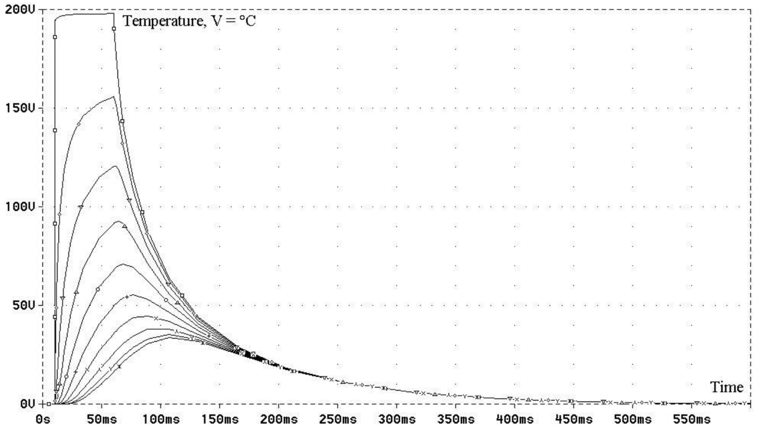

Fig.4. Transient response of the substrate - thermal stimulation RC model (thermal resistances modelled as linear resistors).

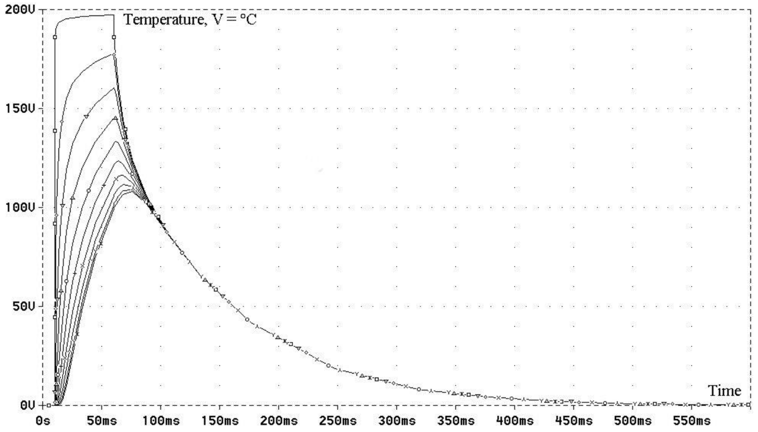

Fig.5. Transient response of the substrate - thermal stimulation RC model (thermal resistances modelled as varistors.

The example calculations have been provided for test circuit consist of: Al_2O_3 ceramic substrate (96% - dimensions: $12 \cdot 10^{-3}$ m × $10 \cdot 10^{-3}$ m) with single resistance heater (RuO_2 - dimensions: $7 \cdot 10^{-3}$ m × $7 \cdot 10^{-3}$ m) placed $2 \cdot 10^{-3}$ m from the substrate edge. For comparison, the calculations were also realized in another specialised ANSYS program (Finite Element Methods). The results are shown in Fig. 6 and 7.

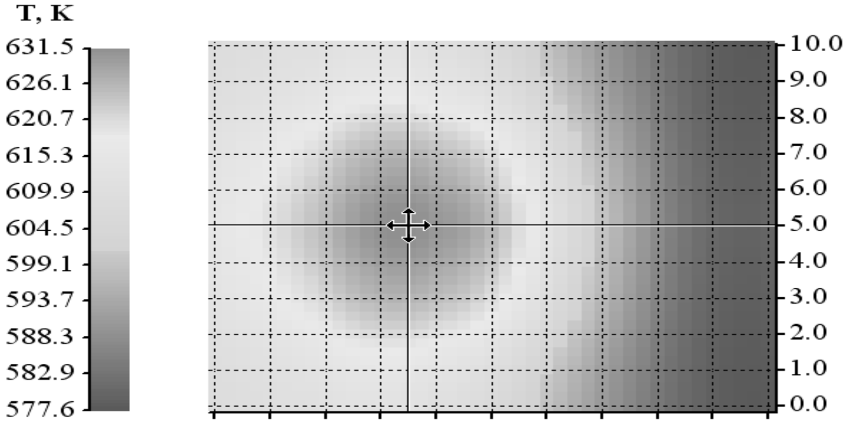

Fig.6. EQ Term simulation of ceramic substrate with single heater – RC model (2D).

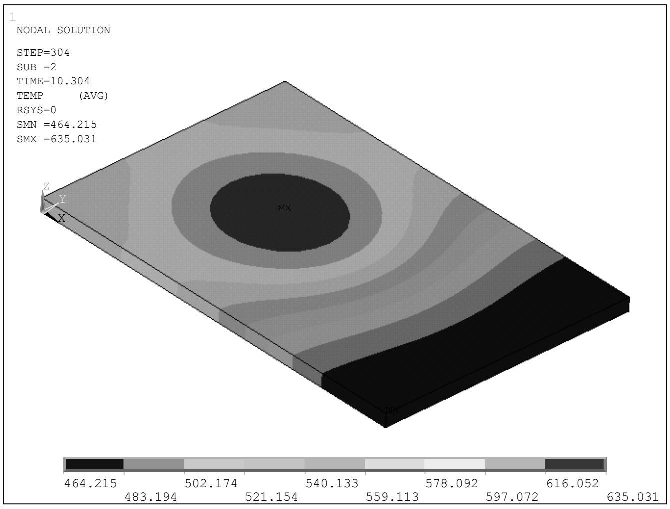

Fig.7. ANSYS simulation of ceramic substrate with single heater (view from heater side).

CONCLUSIONS

The presented method of the thermal modelling of substrate can be also applied for each thick-film components but the very good knowledge about their thermal parameters is required.

The proposed method of temperature simulation using equivalent RC models based on Beuken theory is very useful (and much more easier) for designers of the electronic equipment. The big advantage of such method is possibility of its application not only for thick-film microcircuits. The main disadvantage is necessity of well knowing of the complete thermal characteristic of the analysed object (thermal properties and adequate coefficients).

The results of simulations - in dynamic states - using ANSYS program (with much more complicated substrate and resistive layer models) show the good agreement with calculations using RC models (EQ Term program).

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