Cross Talk among Pyroelectric Sensitive Elements in Thermal Imaging Device

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Abstract: The two-dimensional modeling of the non-stationary thermal state and voltage responsivity of the sensitive elements usually used in solid-state pyroelectric focal plane arrays are presented. Temperature distributions under periodical thermal excitation and the response of the thermal imaging device, which is composed of the pyroelectric sensitive elements mounted on a single silicon substrate, are numerically calculated. The sensitive element consists of a covering metal layer, infrared polymer absorber, front metal contact, sensitive pyroelectric element, the interconnecting column and the bulk silicon readout. The results of the numerical modeling show that the thermal crosstalk between sensitive elements to be critical especially at low frequency ($f < 10$ *Hz)* of periodically modulated light. It is also shown that the use of our models gives the possibility to improve the design, operating regimes and sensitivity of the device.

Cross Talk, Pyroelectric, Thermal Imaging, Modeling, Simulation, Device

1. INTRODUCTION

Solid state pyroelectric focal plane arrays sensitive to 8 – 14 μm radiation and operating at the ambient temperature are used widely for thermal imaging [1,2]. The main requirements, that multi-element pyroelectric structures have to meet, are to obtain high detectivity of the element combined with a high density of elements per unit of area and minimal inter-element coupling in the design of element and array as well as in their operation. Some of our results on the thermal modeling and dynamic response analysis of a single pyroelectric sensitive element are presented in [3]. The resolution of imaging devices based on pyroelectric radiation detector arrays is controlled to a large extent by electrical and thermal crosstalk between separate elements of the array fabricated, as a rule, on a single silicon substrate [4]. Attempts to increase the device resolution by means of increasing the number of elements per unit area lead to the appearance of spurious signals from elements adjacent to those illuminated. Thus, the development of the multi-element pyroelectric arrays meets with the conflicting demand for the high level of the integrity and small inter-elementary crosstalk. Perfect thermal insulation of each element (pixel) offers the possibility to minimize the heat flow to adjacent elements and, as a result, to reduce the crosstalk to an acceptable value.

The main goal of this paper to provide a short description, of the modeling and the comparative analysis of the dynamic voltage response and thermal crosstalk in the group of sensitive elements that are usually used in pyroelectric linear and matrix arrays. To achieve this goal, it is sufficient to consider a group of three elements. If only one element of the array (first element) is under the irradiation, one can expect that the thermal crosstalk will lead to the increase of temperature in the nearest adjacent pixel (second element) and may be in the third one in this line. All other elements arranged on relatively far distances from the first pixel practically do not change their temperatures. Changing different parameters of mathematical model (physical properties of used materials, sizes of all layers in sensitive element, spacing between the detector elements in array and so on), one can select the most promising numerical values of these parameters and essentially improve the design, operating regimes and sensitivity of the device.

2. MODEL

The principal scheme of the group of three sensitive elements deposited on a single silicon substrate is shown in Fig.1.

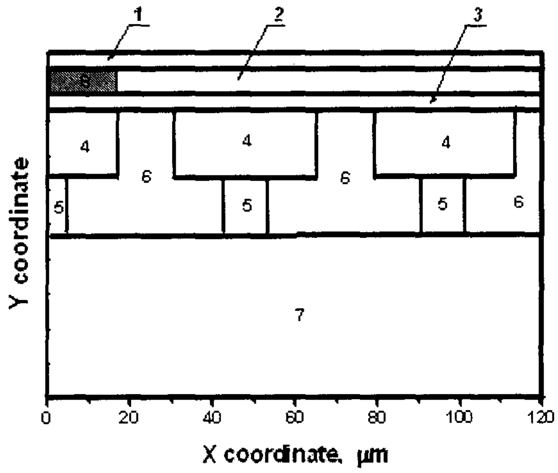

Fig. 1. The principal scheme of a group of sensitive elements of pyroelectric detector. 1 - covering metal layer, 2 - the layer of infrared absorber, 3 - front metal contact, 4 – pyroelectric.
crystal, 5 - interconnecting column, 6 - air volumes, 7 - silicon substrate, 8 - the part of the layer of infrared absorber under the irradiation.

The top metal layer 1 is thin and semi-transmissive. It forms an antireflection coating and is used as a mechanical support for very thin multilayered system. The periodically modulated infrared light is absorbed in the marked area of the polymer layer 2, where it is converted to heat. The thin metal layer 3 contacts with the front side of pyroelectric element 4 and serves as a reflector for infrared and a common front electrode. The interconnecting column 5 can be fabricated from metal or polymer. Signal electrode and local interconnect are very thin, have extremely small thermal resistance and are not shown in the figure. The air fills in volume 6 between sensitive elements. The back electrode (not shown) is deposited to the underlying side of silicon substrate 7. Physical properties of all materials used in device are given in [3, Table 1], typical thicknesses of layers in y-direction are presented in Fig.1 [3].

It is easy to see that only a half of the first element is under consideration. It means that the line x=0 is not only the ordinate axis, but is also the axis of symmetry. The part at x<0 is a looking-glass reflection of the part at x>0. As a result, the heat flow q(x,y) across this line is strictly equal to 0. The heat flow across external horizontal boundaries of a system at y=0 and $y=y_{max}$ is equal to 0 because of a thermal insulation of the device. The situation is more complicated at the right vertical boundary at $x=x_{max}$. There is no insulation layer at this boundary and no reason to suppose that q(x,y)=0. Nevertheless, we supposed that the last equality is correct from the following physical consideration. The thickness of the silicon substrate in the y-direction δySi = 1000 μm is much greater then the thickness of any other layer in the x-direction but the thermal resistance of silicon substrate δySi/KSi ≈ $6 \cdot 10^{-6}$ m2K/W is much less than the sum of thermal resistances of pyroelectric crystals and air volumes in x-direction 2.5δxp/Kp + 2.5δxair/Kair ≈ $1480 \cdot 10^{-6}$ m^2K/W. The heat flow at the boundary $x=x_{max}$ will be much less than that at the boundary $y=y_{max}$ but we trust that the approximation will be negligibly small. The error connected with this approximation leads to an increase in the temperature wave amplitude in all sensitive elements under consideration. However, the condition q(x,y)=0 at $x=x_{max}$ will be exactly correct if one can suppose that the third sensitive element is the last one in its line and the boundary $x=x_{max}$ is thermo-insulated.

The main and practically only physical process of heat transfer between contacting layers within the device is heat conduction. Heat transfer by convective flow of air in "empty" volumes of the structure and radiation from more hot upper layers to the surface of the silicon substrate are negligibly small because of the micron size of all the layers and the small absolute values of oscillating temperature. Periodical change of pyroelectric crystal temperature leads to the periodic variation of its polarization and the increase of the photocurrent of the sensor. The temperature field inside the device can be determined by using a numerical solution of heat conduction equations with corresponding boundary conditions. Details of the mathematical model and formulas for the heat conductions are presented in [3]. At every moment in time, it was found that the average temperature of each pyroelectric crystal was

$$g_m(t) = \langle (T_p^m(x,y,t)) \rangle = \frac{1}{H_x H_y} \iint_{H_x H_y} T_p^m(x,y,t)\, dxdy \qquad (1)$$

and the voltage responsivity of each unloaded pixel was

$$Sm = \frac{pHy \max (g_m(t))}{\varepsilon \varepsilon_0 q_V} \qquad (2)$$

Here: Tp is the temperature of pyroelectric crystal; t is time; x , y are the coordinates; qV is the volume density of internal heat generation within infrared absorber layer; m is the number of sensitive element; Hx , Hy are the pyroelectric crystal sizes in both coordinate directions; p is the pyroelectric coefficient, ε, ε0 are the dielectric constants of the material and vacuum, respectively.

The procedure for a numerical solution of a similar problem for a single sensitive element is discussed in [3]. Simulation results of this paper show that the mathematical model under consideration can be applied for a quantitative description of the problem.

3. RESULTS AND DISCUSSION

Fig. 2 demonstrates the typical temperature distribution in the group of sensitive elements for the moment of time corresponding to the maximum of temperature wave in the infrared absorber layer. More exactly, this group is shown in Fig. 1. A temperature field is built for the case when interconnecting columns are fabricated from metal. It is easy to see in the upper picture that the zone of heat generation is located directly over first sensitive element. In accordance with the conditions of thermo-insulation, all isotherms are perpendicular to outer boundaries, x=0, x=xmax and y=0. Some isotherms are not smooth enough on a large scale because of a limited number of mesh points. Heating of the upper three-layered sandwich structure is not uniform. The first semi-transmittive metal layer has essentially a higher temperature than the front electrode which contacts the array of pyroelectric elements. Most of the heat generated in the infrared absorber goes through the front electrode, air, sensitive elements and interconnects into the silicon substrate. The lower picture in Fig. 2 shows that the most intensive heating is realized in the direction "pyroelectric – air – substrate"; intermediate heating – in direction "air – substrate"; and the least intensive – in the direction "pyroelectric – column - substrate". It is because of the high heat capacity of the metal column that leads to a relatively slow processes of heating and cooling of the interconnection

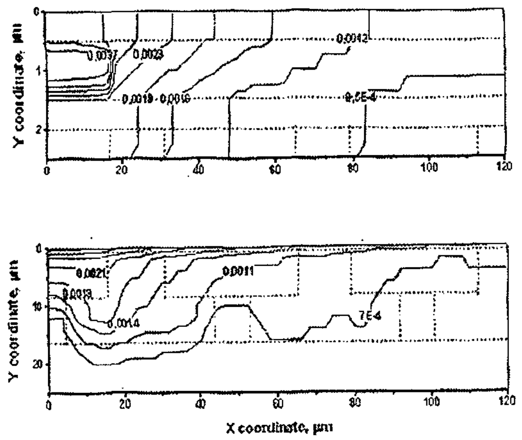

Fig. 2. Temperature field (solid lines) in the group of sensitive elements (dashed lines) at the moment of time t=0.2084 s corresponding to the maximum of temperature wave in the part of the layer of infrared absorber. The upper picture is an extension of the lower one in the y-direction. The modulation frequency f=30 Hz, voltage responsivities R1=4111.0, R2=2406.7, R3=1611.3.

Fig. 3 shows voltage responsivities of three sensitive elements versus frequency of light modulation in the actual frequency range. For all elements, the voltage responsivity decreases with the increasing of the frequency. At low frequencies, $f < 10$ Hz, the thermal crosstalk is extremely high; elements 2 and 3 give high-level spurious signals that practically can be interpreted as equal to an order of magnitude of the real signals. Thermal crosstalk decreases with frequency and at high frequencies, spurious signals are essentially smaller than the real one. This fact can be explained taking into account peculiarities of the temperature wave attenuation in a medium. For example, in one-dimensional case of a half space, the depth of wave penetration is proportional to $f^{-0.5}$. This tendency has place in our more complex two-dimensional case too. As also easy to see in Fig. 3, due to high conductivity of interconnecting column, quasi-stationary oscillatory regime (see [3]) begins in all sensitive elements at the same time.

Analogous results in the case when the interconnecting columns are fabricated by using a nonmetallic material are shown in Fig. 4. The responsivity falls smoothly with frequency and has much higher values than the ones for elements with metal interconnects. At low frequencies, crosstalk is extremely high and decreases with frequency. Relatively low conductivities of interconnections lead to different frequency dependencies of tS. The longer the distance between the zone of heat generation and the sensitive element, the longer is the time period tS.

Analysis of curves 3 – 5 in Figs. 3, 4 shows that the use of a thin interconnecting column fabricated from insulating material will lead to essential increasing the voltage responsivity.

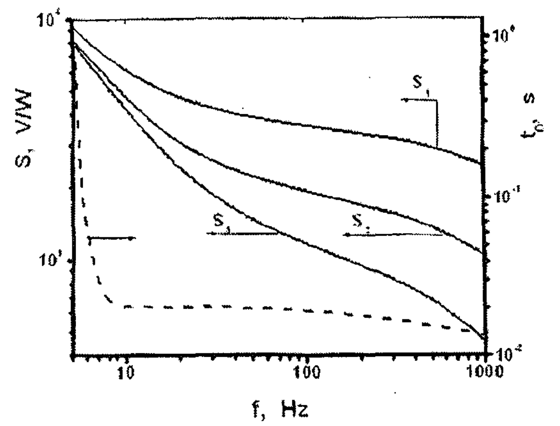

Fig.3. Responsivities of three sensitive elements (solid curves) and time period of coming quasi-stationary regime (dash curve) versus frequency of light modulation in the case of interconnecting metal columns. Numbers of curves correspond to the numbers of elements.

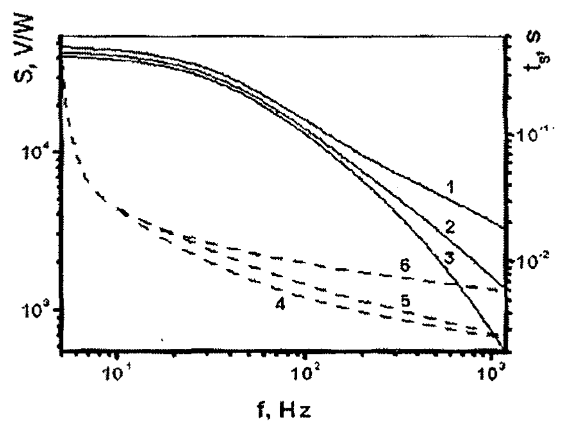

Fig.4. Responsivities of three sensitive elements (solid lines) and time period of coming quasi-stationary regime (dash curves) versus frequency of light modulation in the case of interconnecting polymer column. Curves 1,4 correspond to the sensitive element No 1, curves 2,5 – to the element No 2 and curves 3,6 – element No 3.

4. CONCLUSION

Main results on the two-dimensional modeling of the non-stationery thermal state and voltage responsivity of a group of sensitive elements usually used in solid-state pyroelectric focal plane arrays are presented. Transient two-dimensional temperature fields in such devices, time of coming of quasi-stationery oscillatory regime, dynamic responsivity and so on are calculated numerically. It is shown that both maximal responsivity and thermal crosstalk in this group is observed at low frequencies of light modulation $f < 10$ *Hz*. In the actual diapason of frequency, the duration of transient processes in the array with metal interconnects is 0.01 – 0.7 s and with polymer ones – 2 10^{-3} – 0.2 s. It is shown that use of such kind of models gives the possibility to improve the design, operating regimes and sensitivity of the device.

References

[1] C.M. Hanson, “Hybrid pyroelectric-ferroelectric bolometer arrays”, in *Uncooled Infrared Imaging Arrays and Systems, Semiconductors and Semimetals*, vol. 47, Academic Press, pp. 123-174, 1997.

[2] B.M. Kulwicki, A.Amin, H.R. Beratan, C.M.Hanson "Pyroelectric imaging", in *Proceedings of the Eighth IEEE International Symposium on Applications of Ferroelectrics*, Greenville, SC, USA, August 30- September 2, pp. 1-10, 1992.

[3] Y.S. Yoon, V.B. Samoilov, S.V. Kletsky, “Dynamic response analysis of pyroelectric sensitive element for thermal imaging”, *IEEE Transactions on ultrasonics, ferroelectrics and frequency control*, to be published.

[4] M.D. Kladkevich, V.B. Samoilov, L.V. Shchedrina, “Imaging devices based on pyroelectric radiation detector arrays”, *Ferroelectrics*, vol. 168, pp. 261-271, 1995.