Modeling of a bimetallic MEMS-based infrared detector

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Abstract. In work techniques of calculations of the key parameters of the bimetal capacitive IR detectors matrix are presented. Sensitivity characteristics of the bimetal detector were calculated and prototype model of detector in the form of bimetallic console was produced. The possibility of use of capacitive MEMS-receivers on basis of bimetallic effect as an alternative to pyroelectric and microbolometer IR detectors is shown.

1. Introduction
Currently, the market for relatively inexpensive infrared cameras is dominated by devices based on microbolometer matrices. In our opinion, the improvement of characteristics and the expansion of their functionality is based on the use of new materials in these devices. An example is the work on creating matrices with ferroelectric detectors [1, 2], as well as structures in which the matrix pixels are made of bimetallic materials. A principle of operation of MEMS bimetallic infrared detectors is based on change of bimetallic plate capacitance when the plate is heated with radiation. Theoretical evaluation of the detector parameters and results of the prototype models experimental studies [3, 4] showed that this kind of detector demonstrates low noise, high sensitivity, and therefore lower for detectors noise equivalent delta temperature (NEDT ~ 5…10 mK) in the wavelengths range 8…14 μm. Compatibility with standard silicon technology defines relatively low cost of such detectors production for a monolithic array configuration while simultaneously achieving high reliability characteristic for all MEMS. This work is dedicated to the development of methods for such device modeling using specialized CAD software.

2. Design of Bimetallic IR Detector
Change of z coordinates of the bimetallic plate center in the course of heating (temperature sensitivity) is calculated by Equation [1]:

\[
\frac{dz}{dT} = \frac{3L^2}{8t_1} \left( \alpha_1 - \alpha_2 \right) \frac{8(1 + x)}{4 + 6x + 4x^2 + nx^3 + \frac{1}{nx}},
\]

where \( \alpha_1 \) and \( \alpha_2 \) – thermal expansion coefficients of the respective layers; \( t_1 \) and \( t_2 \) – layers thickness, \( L \) – length of bimetallic console, \( x = t_2/t_1 \) – ratio of the bimetal layers thicknesses, \( n = E_2 / E_1 \) – ratio of Young's modules for the correspondent materials.

When developing detector design, the detector pixel parameters were defined taking into account the following considerations:
– difference between thermal expansion coefficients of the bimetallic layer materials should be as large as possible;
– the material thicknesses should meet requirements of standard silicon technology for production of integrated circuits;
– ratio of the bimetal material thicknesses should correspond to the maximum sensitivity;
– the material of the thermal insulating elements should have low thermal conductivity;
– length of the bimetal element should be maximized within the selected topology design;
– high absorption should be provided in the range of far infrared atmospheric transmission band (8…14 μm);
– pixel design should provide high mechanical strength;
– films of the materials used should have low internal stresses and good adhesion to each other;
– materials used should be fully applicable in standard technological processes of integrated circuits production.

Based on these criteria, in this work, a bimetal pair Al/Si3N4 was selected as a sensitive element of the detector. Other parameters of the bimetallic pixel: the area of the pixel – 50x50 μm²; the length of the bimetallic element – 52 μm; the length of the heat-insulating element (supporting console) – 47 μm; the thickness of the Al layer – 0.5 μm; the thickness of the SiO2 layer varied within 0.2…0.5 μm; the height of the initial gap of the sensing capacitor – 0.5 μm.

3. Results of device modeling
CAD software [5], which is a versatile tool for analysis and design of MEMS devices, was used for modeling of bimetallic IR detector. The modeling purpose was to study mechanical behavior of the device exposed to external flux of radiation, and also study of the temperature distribution in the model volume and corresponding change of electrical capacitance of the sensing capacitor based on this device, for different geometrical characteristics.

When the 3D model was synthesized, CAD used both standard procedures from the built-in libraries of technological operations of microsystem technology and prospective procedures for the formation of sacrificial layers from organic materials [6, 7]. To improve expression (1) and define the detector characteristics, temperature distribution in the detector volume and temperature distribution change in time in the course of heating with radiation were calculated of this CAD, for given boundary conditions, using a mesh method for thermal problems. The results are illustrated in Figure 1 and Figure 2, which show the results of calculating the transition function of the mean temperature $T_{av}$ of a bimetallic element when a constant heat flux of 1 W/m² is switched on and the results of simulation of the temperature distribution of the receiver in a stationary mode.

**Figure 1.** Average temperature of the bimetal element versus time of exposure to heat flux.

The characteristic heating time (thermal constant, tau), determined from the simulation results, is 8 ms for this design.
Figure 2. Distribution of the temperature in a bimetallic receiver when heated by radiation in a stationary mode.

The detector sensitivity to radiation was calculated in the next stages of modeling:

\[
S_C = \frac{1}{C_0} \left( \frac{dC}{dT} \right) \approx \frac{1}{z_0} \left( \frac{dz}{dT} \right)
\]

where \(z_0\) – initial value of the distance between the plates of the sensing capacitor (in this model, \(z_0 = 0.5 \mu m\)); \(C_0\) – corresponding value of the bimetallic plate electrical capacitance relative to the substrate (see Figure 3). It is shown that the relative change of applicate of the detector pixel center is 0.072 μm/W, and the radiation converter sensitivity \(S_C\) for this design variant is 14.4 %.

In the modeling, analysis of the device frequency characteristics was performed as well. Frequency parameters of the detector being a mechanical oscillator are very important for selection of the sensing voltage frequency and evaluation of thermomechanical noise. A model used the boundary condition in the form of variable electrostatic forces between the plates of the sensing capacitor that occurs when vibrations due to sinusoidal electric voltage with amplitude of 5 V are excited was used for calculation of the resonant frequency. Modeling results are given in Figure 3.

The resonant frequency of this device is about 23 kHz. Subsequent evaluations showed that at frequency of the sensing voltage more than 170 kHz, and in presence in the sensing circuit of additional RC damping filter [4], thermodynamic mechanical noise has virtually no effect on the output characteristics of the device.

The analysis of the limiting parameters of sensitivity was carried out according to the classical technique [8, 9], in which, with known characteristics of the optical path for a given transfer function of the device, a scene temperature equivalent to the noise source noise density (NETD) is determined. The spectral densities of the noise components due to thermodynamic fluctuations during heat transfer, thermomechanical oscillations, noise of readout circuit were calculated for the given characteristics of the system (optical force F:1, surface absorption coefficient 0.9, spectral range 8...14 μm, operating voltage 5 V, etc.).
The results of calculations of the components of NETD, depending on the ratio of the thicknesses $t_1$ and $t_2$ of the bimetallic pixel layers ($m = t_1 / t_2$) are summarized in Figure 4.

**Figure 3.** Frequency characteristic of the bimetal detector.

**Figure 4.** Dependences of the NEDT components of a bimetallic receiver on the design parameters: $\text{NEDT}_{\text{TF}}$ – the contribution of thermal fluctuation noise; $\text{NEDT}_{\text{TM}}$ – the contribution of mechanical noise; $\text{NEDT}_{\text{ROIC}}$ – the contribution of the noise of the electrical circuit of reading; $\text{NEDT}_{\text{TOTAL}}$ – total value of temperature difference equivalent to noise.

**4. Prototype model of bimetal infrared detector pixel**

The model of the prototype MEMS bimetallic console IR detector was made by ion etching technology using Quanta 200 3D equipment. The equipment combines a scanning electron microscope and a thermionic cathode intended for formation of a focused ion beam that enables applying and removing of the materials, and it also contains system for energy dispersive microanalysis and analysis of crystalline materials texture.

To obtain the cantilever structure, substrate of low resistance silicon coated with a layer of silicon dioxide with a thickness of about 1 micron was applied. A layer of platinum in the form of a pad with
dimensions of 20×20 µm² and outgoing stripes with width of 1 µm and length of 20 µm was deposited on oxide using Quanta 200 3D equipment. Ion etching under the platinum layer was carried out at the angle of 52° that was preconditioned by technical characteristics of the equipment. As a result, the structure shown in Figure 4 was produced. The platinum layer and substrate form a bimetallic capacitor with capacitance which changes at heating. Preliminary results of the temperature coefficient measurements for capacitance of such bimetallic detector structure prove the above modeling results.

5. Conclusion
Technique for calculations of the basic parameters of the bimetal capacitive IR detectors matrix pixel was developed. Sensitivity characteristics of the bimetal Al/SiO₂ detector with the pixel size of 50x50 µm² were calculated. It was shown that the thermal constant is 7.3 ms for this design variant of detector matrix pixel that allows obtaining of high-quality image with a standard frame rate. In this case, calculated value of the bimetallic detector sensitivity is 14 % that is much larger than similar characteristics of bolometric and pyroelectric detectors for which the sensitivity is less than 2 %/K.

The bimetallic IR detectors elements producibility was studied with application of electron and focused ion beam equipment Quanta 3D. A prototype model of detector in the form of bimetallic console with length of 20 µm and width of 1 µm, consisting of Pt (1 nm) and SiO₂ (1 µm) layers, was produced.

The results of the characteristics analysis for the model of bimetallic IR detector matrix pixel show the prospect of development of such type of thermal detectors. Simplicity of the MEMS bimetallic IR detector design and also application of materials which are fully compatible with standard silicon manufacturing techniques for integrated circuits production should provide lower cost of such devices in comparison with pyroelectric and microbolometer IR detectors. Higher sensitivity and availability of manufacturing processes for capacitive MEMS sensors based on bimetallic effect enables their use as an alternative for pyroelectric and microbolometer IR detectors.

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