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Computation of current response of a bimorph pyroelectric infrared detector

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Recently, it has been proposed that bimorph detector structure has potential to demonstrate better pyroelectric performance than monomorph. In this context, a one-dimension thermal diffusion equation has been solved for an n-layered structure for pyroelectric bimorph films. In such a system performance of any number of layers of a detector structure can be derived, predicted, and optimized using these computations. Using viable bimorph element sensor configurations and materials parameter, the calculated and predicted current responsivity and other parameters are presented. It is predicted that greater enhancement of the bimorph current responsivity relative to that of monomorph with the well-known pyroelectric materials require higher modulating frequency or thicker bottom (lower) pyroelectric layer of the bimorph detector structure.

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1. Introduction

The pyroelectric thin-film detector is a thermal transducer based on pyroelectric effect. When the detector is exposed to infrared radiation, it absorbs radiation, its temperature rises, changing the spontaneous polarization which leads to photocurrent. There is a growing demand for miniaturized piezoelectric, pyroelectric, and other devices [1-3]. Size reduction is driven predominantly by demand for enhanced device performance, reduced manufacturing cost, and better response time. The applications for infrared imaging are numerous and include military night vision, security surveillance, fire detection, medical diagnostics, and automotive vision enhancement, imaging systems for cars, ships, aircraft, and others. Pyroelectric infrared sensing devices have several main advantages over photon infrared sensors made by Si, GaAs or MCT materials, which are based on the photo-quantum-effect which require cooling: i.) sensitivity over a very large spectral bandwidth, ii.) sensitivity over a very wide temperature range without the need of cooling, iii.) low power requirements, iv.) relatively fast response, v.) generally low cost of materials, vi.) detection is limited , being a passive device, vii.) temperature range of operation can be changed in certain materials by the variation of the amount of its constituents (such as Lead zirconate titanate, Potassium titanate niobate and others), and viii) suitable for space applications because of light weight; consuming less power having no bulky cooling equipment. Thin and Thick film technologies offer many advantages over the bulk crystalline materials and ceramics in ferroelectric micro-system devices. For example, the low heat capacity of a thin film reduces the thermal loss to its ambient surrounding, thus increases its pyroelectric response and sensitivity. The pyroelectric film also offers the possibility of easily making 2D arrays, which greatly enhances the device density. The application of pyroelectric materials in film form for use as radiation detectors is expected to considerably simplify the technology for detector production and to promise further increase in pyroelectric detector performance. Thin and thick film geometries are convenient for device design and have the potential to be integrated into a standard process of silicon chip fabrication. In order to produce integrated pyroelectric devices, deposition of film directly on substrate is required. Available pyroelectric materials for use in infrared detector fabrication are triglycine sulfate (TGS), lithium tantalate (LT), lead titanate (PT), lead zirconate titanate (PZT), P(VDF-TrFE), the deuterated TGS (DTGS) and modified TGS and others [4-8]. To fabricate an integrated detector, it is essential to understand both thermal and electrical performance of the system. A thermal analysis is a critical part in the designing of a pyroelectric infrared detector structure. Theoretical studies on pyroelectric materials have shown that materials with higher figure-of-merit are not likely to be found [9]. One of the ways to improve pyroelectric performance is to fabricate non-homogeneous materials like 0-3 connectivity composites so as to decrease dielectric constant [10] and hence increase the figure-of-merit (p/ε'; p-pyroelectric coefficient; ε'-dielectric constant). Other proposed approaches to improve pyroelectric response have been to: (i) fabricate an integrated pyroelectric system on silicon substrate; and (ii) use bimorph configurations with two pyroelectric materials stacked together [11]. Alexe and

Pintilie [11] proposed a novel non-homogeneous structure for pyroelectric infrared detection: a pyroelectric bimorph (*two stacked pyroelectric materials*) similar to one shown in Fig. 1 and Fig. 2. The authors found out voltage response theoretically for both bimorph on heat sink and in suspended configuration. It was shown that larger (four times) voltage response is possible in bimorph structure rather than homogeneous pyroelectric structure of single layer. Later, Lang and Alexe [12] investigated theoretically and experimentally bimorph structure on a substrate and verified the predictions of Alexe and Pintilie [11]. They found in *Pt: PLZT :PZT:Pt:SiO*$_2$ type structure that the *voltage responsivity* of bimorph was 40% higher than that of PLZT monomorph and six times larger than PZT monomorph. The enhancement was principally due to smaller capacitance of the bimorph that each of the mono-layers of two layers acts in series. Furthermore, it was also mentioned that both the layers have to be pyroelectric materials and classic definition of material figure-of-merit (p/ε'; p-pyroelectric coefficient; ε'-dielectric constant) for high voltage responsivity is not valid for non-homogenous case. There have been several studies in the past on the heat flow and performance of a monomorph detector structure and others [13-20], including the effect of the substrate [19-20] on the performance of monomorph pyroelectric detector structure.

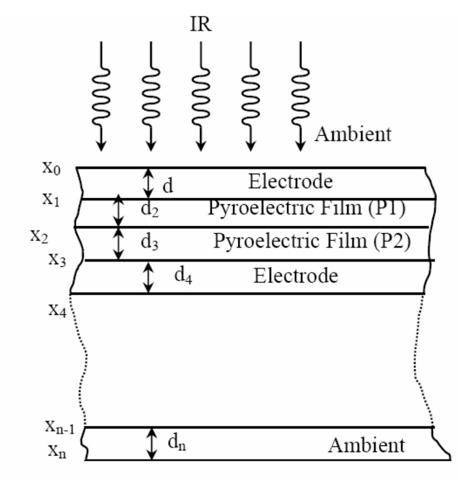

Fig. 1. A cross section of an n-layer detector structure.

In this article, an effort has been made to theoretically obtain the *current responsivity* of a bimorph-integrated structure on silicon substrate using one-dimensional heat conduction equation. It is proposed that at high modulating frequencies as required for laser power measurements, one can enhance the current responsivity by variation of thickness and thermal conductivity of the bottom pyroelectric layer in bimorph. A comprehensive thermal analysis of a n-layer structure, including the simulated response of a *Pt:PT-PZT:Pt:Si* based thin film bimorph detector structure is presented. A one-dimension heat conduction model is used to analyze the influence of following parameters on an integrated bimorph detector system: thickness of top and bottom layer of bimorph pyroelectric element; and thermal conductivity of bottom pyroelectric layer. The results are compared with typical mono-morph detector structure.

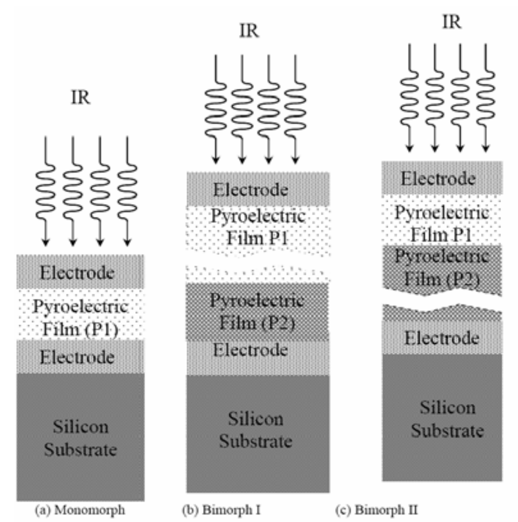

Fig. 2. Configuration of a monomorph and bimorph integrated detector structures (P1: top pyroelectric layer of PT; P2: bottom pyroelectric layer of PZT)

2. Thermal analysis

The detector structure consisting of n-layers used in the thermal analysis is shown in Fig. 1, which consists of n layers. It is assumed that infrared radiation is modulated sinusoidally by a mechanical chopper at an angular frequency, ω, which falls on the front surface of an upper layer and is converted to thermal energy that is then conducted to the bulk of the pyroelectric layers. A One-dimensional heat conduction equation is employed with an assumption that the lateral dimensions are considerably large when compared to the thickness of the total composite structure. Thus, the lateral heat flow is neglected.

The Thermal Diffusion Equation for an nth Layer is:

$$\frac{\partial T_n(x,t)}{\partial t} = \frac{K_n}{c_n \rho_n} \frac{\partial^2 T_n(x,t)}{\partial x^2} \tag{1}$$

where c_n is specific heat, ρ_n is density, and K_n is thermal conductivity of nth layer.

Let $T_n(x,t) = T_n(x)\exp(j\omega t)$. Using the boundary conditions, such as heat current density is continuous at each interface, a solution the heat conduction (1) is given by:

$$T_n(x) = A_n \cosh a_n(x_n - x) + B_n \sinh a_n(x - x_{n-1}) \tag{2}$$
$$(\text{for } n^{th} \text{ layer, } x_n \geq x \geq x_{n-1})$$

Now assuming the second layer is a pyroelectric layer with a thickness d_2, the spatial average of the temperature in the pyroelectric layer is calculated as:

$$\overline{T}(t) = \frac{1}{d_2}\int_{x_1}^{x_2} T_2(x,t)dx \tag{3}$$

The pyroelectric current is:

$$I_o = pA\frac{\partial \overline{T}}{\partial t}, \tag{4}$$

where p is the pyroelectric coefficient of upper layer and A is the area of the pyroelectric element. The Current Responsivity is defined as:

$$RI(\omega) = \frac{jpA\omega\overline{T}}{P}, \tag{5}$$

where P is the incident power. $\overline{T}$ was evaluated out analytically using standard methods and calculated by using MATLAB.

The above relations are valid under following assumptions and limitations:

1. The constants such as specific heat and thermal conductivity are independent of time, temperature, and space.
2. Each layer in the integrated system is considered to have thermal uniformity
3. The system is under stationary periodical condition.
4. The pyroelectric coefficient of only upper layer is considered for modeling because at high modulating frequency, thermal waves subsequently produced shall penetrate the upper layer completely but penetrate lower layer partially so that the effective pyroelectric coefficient of bimorph shall be dominated by the upper layer [11] in bimorph detector structure.
5. The heat flow at the interfaces of each layer is continuous.

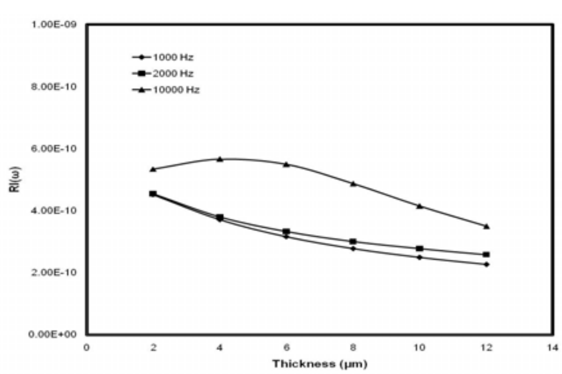

Fig. 3. Current Responsivity (RI (ω)) versus thickness of pyroelectric layer with modulating frequency as parameter in mono-morph pyroelectric system

3. Results and discussion

Current responsivity, *RI (ω),* is determined numerically using the configuration of a viable detector system described in Fig. 2 and physical parameters tabulated in table 1, with the above cited formula. Three types of structures were studied: monomorph (thickness of the single PT layer is varied); bimorph-I (thickness of the bottom PZT layer was held constant at 1 micron and thickness of top (P1) pyroelectric layer was varied); and bimorph-II (thickness of the top PT layer was held constant at 1 micron and thickness of the bottom (P2) PZT layer was varied). Finally the effect of thermal conductivity of the bottom layer on *RI (ω)* is also estimated. The results of the analysis are shown in figures 3–6. The thickness of the substrate (Si) is assumed to be 20 microns. Figure 3 illustrates the effect of thickness of pyroelectric PT element in monomorph on the current responsivity as a function of thickness of the layer at different modulating frequencies. It is found that *RI (ω)* decreases substantially with the increase of the thickness as expected. This behavior is due to the fact that the thinner the layer, the lesser the heat in the film and thereby a higher *RI (ω).* Fig. 4 (Bimorph-I) illustrates the current responsivity versus thickness of upper layer with chopping frequency *(ω)* as the parameter. Fig. 5 (Bimorph-II) illustrates the current responsivity versus thickness of lower layer with chopping frequency as the parameter. *RI (ω)* decreases slightly with an increase in the bottom layer's thickness except at 10 kHz. At the frequency of 10kHz, it first increases substantially with increase in the thickness with maxima at about 6 microns and then it remains almost constant. However, it is worth mentioning that at lower frequencies, *RI (ω*) does not change with increase in the thickness of bottom layer with particular frequencies. Thus, this kind of bimorph structure shall also be useful where constant *RI (ω)* is required, where there is a variation in the thickness of lower layer, due to processing/ manufacturing constraints. Figure 6 shows the variation of *RI (ω)* with thermal conductivity of bottom layer with modulating frequency as a parameter. The thermal conductivity values of pyroelectric materials used for calculations were: 0.223 W/mK (P(VDF-TrFE)); 0.263 W/mK ((P(VDF-TrFE)-PT); 0.72 W/mK (DTGS); (PT); 1.45 W/mK (PZT); and 3.5 W/mK (LT). A substantial decrease in *RI (ω)* with an increase of thermal conductivity of bottom layer for modulating frequency of 10 kHz was obtained. In other cases the (at lower frequencies), *RI (ω)* remains almost constant. In other words, with decrease in thermal conductivity, the pyroelectric response increases. This increase is due to the fact that the low thermal conductivity of layer reduces the heat loss. At lower frequencies, *RI (ω*) remains almost constant. The table 2 summarizes the results of this investigation. From the data it is inferred that a greater enhancement of the bimorph current responsivity relative to that of monomorph with these materials require higher modulating frequency or thicker lower layer. At 10 kHz, 2-3 times increase in *RI (ω) is* predicted. Thus, by choosing proper selection of pyroelectric material with low thermal conductivity (and modulating frequency) of bottom layer (P2), one can obtain higher pyroelectric performance in terms of current responsivity. From this study, it is predicted that material with low thermal conductivity (in our case P (VDF-TrFE), 0.223W/mK) operating at 10 kHz shall giver higher *RI (ω)* than monomorph. Further studies shall be performed to verify some of the results presented.

Table 1. Values of Parameters used in the Current Responsivity Computation [20-22].

Material	Thermal conductivity (W/mK)	Density (kg/m^3)	Specific heat (J/kg.K)	Thickness (x 10^{-6}m)	Pyroelectric Coeff. (μC/m^{2}K)
PZT (P2)	1.45	7300	425	1.0-12.0	350
PT (P1)	1.76	6900	363	1.0-12.0	400
Pt	69.5	21450	134	0.1	-
Si	148.0	2330	712	20.0	-

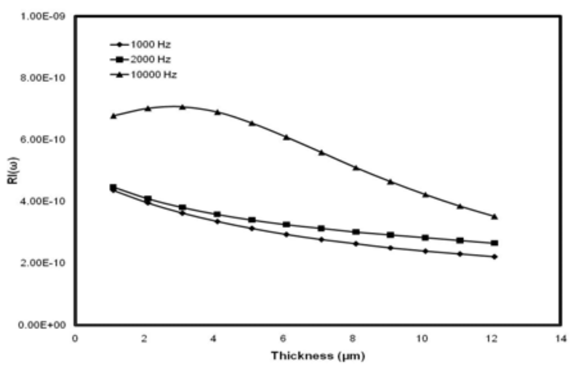

Fig. 4. Current Responsivity (RI (ω)) versus thickness of upper pyroelectric layer with modulating frequency as parameter in bimorph (I) pyroelectric system.

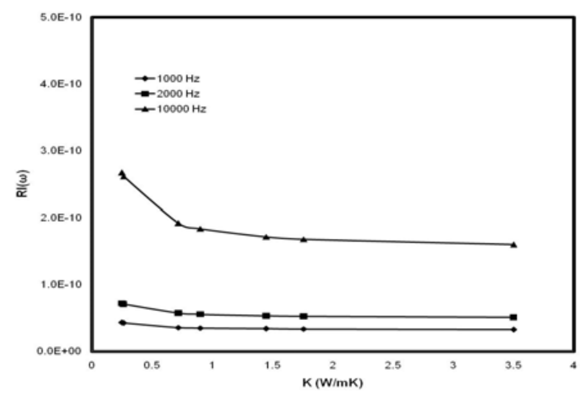

Fig. 6. Current Responsivity (RI (ω)) versus thermal conductivity of lower pyroelectric layer with modulating frequency as parameter in bimorph (II) pyroelectric system.

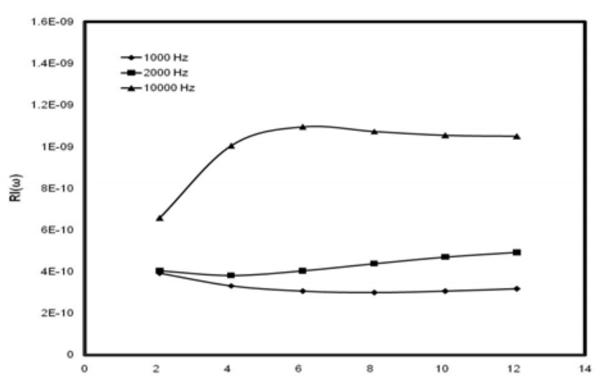

Fig. 5. Current Responsivity (RI (ω)) versus thickness of lower pyroelectric layer with modulating frequency as parameter in bimorph (II) pyroelectric system.

4. Conclusions

(i). The current responsivity, *RI (ω),* of three pyroelectric detector configuration was calculated by solving a one-dimensional thermal diffusion equation for a multi-layer system.

(ii). Preliminary results indicate that the thicknesses and thermal conductivity of the bottom layer in pyroelectric bimorph structure are very important factors, which affect the performance of a detector as shown in the Fig. 3 to Fig. 5. It is predicted at high modulating frequencies, it is possible to obtain 2-3 times *RI (ω)* in bimorph detectors than in mono-morphs.

(iii). The results obtained are encouraging for the development of Pt:PT:PZT:Pt:Si films based integrated bimorph detector. Further, enhancement of *RI (ω)* shall be observed with the introduction of an insulating layer of material such as Polyimide, SiO_2, or Si_3N_4 between lower electrode (and using micro-machined silicon substrate) and substrate as predicted in the past [15] (iv). The analysis presented, algorithms and MATAB 6.0 computer program are applicable to multi-layer systems with any number of layers. This facilitates the design of an integrated pyroelectric detector system and provides a guide for the design and fabrication of a detector system such as selection of thickness and pyroelectric material of bottom layer.

(v) It is concluded that greater the enhancement of the bimorph detector on a substrate, the better the current responsivity relative to that of monomorph with the well-known pyroelectric materials studied that require higher modulating frequency or thicker bottom pyroelectric layer of bimorph.

Acknowledgements

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