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High-sensitive pyroelectric detectors with internal thermal amplification

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Abstract

A novel procedure for increasing the sensitivity of pyroelectric detectors and its mathematical and physical analysis are presented. Due to a 3-dimensional pattern that is etched into the sensitive element lateral heat flux spreading is used to improve the responsivity. Here, the effect is used, that very thin regions between thicker regions show a faster heating due to incident radiation and, hence, lead to an additional heat flow from this intermediate regions to the sensitive element. The analysis allows the description of the thermal and electrical behavior of the sensitive element depending on the dimensions of the pattern and the modulation frequency.

Keywords: Pyroelectric detector; thermal simulation; patterned layers; high responsivity

1. Introduction

Pyroelectric detectors are widely used in many applications like pyrometry, spectrometry, gas analysis, and security technology. For many of these applications a high responsivity and a high detectivity are required.

In order to get maximum responsivity, several approaches were already investigated, for example the use of thermal absorber layers, the appropriate choice of pyroelectric material or special construction techniques to reduce the heat conduction value [1,2].

This paper investigates another method for increasing responsivity and detectivity. It describes a 3-dimensionally structured thermal element that has locally reduced passive areas and thicker electrically active areas. So far, only the reduction of the whole element thickness d_a was investigated that leads to a reduced heat capacity of the element and therefore to a higher temperature change due to the absorbed heat flow. But simultaneously, the electrical capacity of the element increases which again decreases responsivity. Therefore, the responsivity does not change at all in particular for modulation frequencies over 10 Hz.

The new structure uses the advantages of the higher detectivity of thinner elements and the higher responsivity of thicker elements. First simulation and measurement results depending on construction parameters will be presented.

2. Idea and Simulation

The work investigates a novel approach for increasing the responsivity of pyroelectric detectors in voltage mode by structuring the sensitive area with a 3-dimensional pattern. The pattern is etched into the sensitive area of the

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detector, leading to thicker electrically active areas, and to much thinner electrically passive areas (Fig.1). The locally reduced thickness of the detector leads to a temperature gradient in the sensitive element which results in a heat flow from the passive to the active areas and causes a temperature rise in the active areas compared to non-structured elements. Due to this effect the output signal of the sensor can be increased in contrast to an unstructured sensor at constant incident radiation [3].

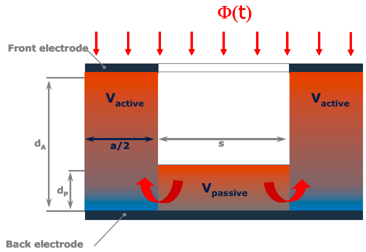

Fig.1. Cross-section of the structured sensitive element with electrically thicker active and thinner passive areas; resultant heat flow from the passive to the active area (red arrows). *s* is the width of the passive region.

2.1. Thermal analysis – analytical and finite element model

The thermal analysis was performed both analytically and numerically with a finite element model. The analytical calculations are based on the combination of the well-known partial differential equation for heat flow considering vertical and lateral heat conduction [2] which was adapted to the new structures by an average element thickness. A second compact model was also implemented that considers the ratio between the remaining pyroelectric material and the removed parts. Depending on this ratio the material parameters were adapted to the 3-dimensional pattern.

The finite element model was implemented in ANSYS® 11.0. In order to investigate the principle thermal procedures within the sensitive element and to keep the computing time justifiable, only a part of the 3-dimensional pattern was simulated. Furthermore, the surrounding chip material and the sensor housing were neglected. The simulated element part is considered thermally isolated from the rest of the sensitive element. The incident radiation is modelled by a periodic heat flux at the surface of the element.
Figure 2a shows the transition from the sensitive element to the FE-model. Figure 2b presents the simulated temperature distribution in the active and passive area.

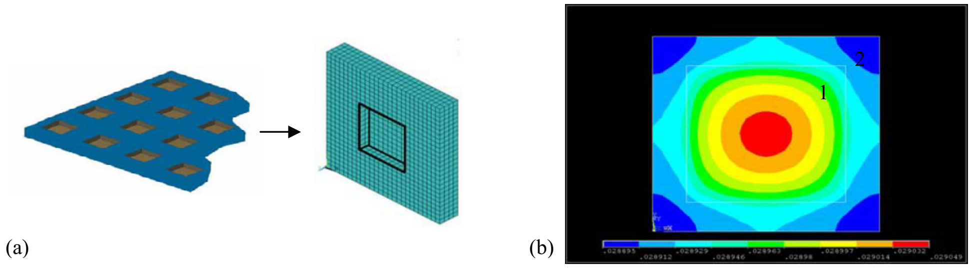

Fig.2. (a) Transition from the 3-dimensional structured sensitive element to the FE-model. (b) Temperature distribution in the active (2) and passive area (1).

2.2. Electrical Analysis

The 3-dimensional etched pattern in the thermal element causes a change of the electrical capacity of the element. Therefore, an electrical transfer function was defined to describe the relation between the sensor voltage output u_s to the temperature amplitude T_p in the active volume of the sensitive element. The electrical transfer function is calculated by

$$ETF = \frac{u_S}{\hat{T}_P} = \frac{A_{FE} \cdot p \cdot \omega}{\sqrt{(\frac{1}{R})^2 + \omega^2 \cdot C^2}}$$

with A_{FE} as sensitive area, p as pyroelectric coefficient, ω as modulation frequency, R as resistance and C as the capacity of the sensor.

3. Results and Discussion

The basis for the thermal and electrical simulation is a single-element detector based on lithium tantalate ($LiTaO_3$) with a thickness d_a of 5µm and a sensitive element size of 1 x 1 mm². The etched holes are filled with air.
With the aid of the simulation results the responsivity and electrical transfer function were investigated depending on the thickness d_p of the passive areas, and the width s of the etched structures.

3.1. Thermal simulations

The relative temperature amplitude plotted against the structure size s for different element thicknesses d_a in the passive regions is shown in figure 3. It is obviously that the thinner the passive areas and the higher the structure width are, the higher is the reachable temperature amplitude in the active regions. This is because of the lower thermal mass. The temperature amplitude can be increased by more than 150% referred to an unstructured sensor. Figure 4 presents the plot of the temperature amplitude (node temperature) against time at different locations in the element (nodes).

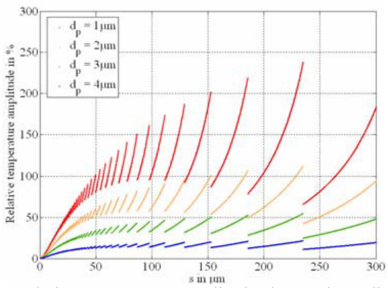

Fig.3. Relative temperature amplitude change depending on the structure size s and the thickness of the passive area d_p.

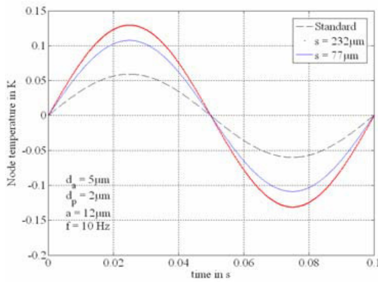

Fig.4. Node temperature of a standard unstructured sensor in comparison to different structure sizes s at the same location (node).

3.2. Electrical transfer function

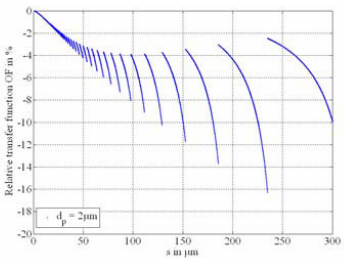

Fig.5. Relative transfer function change *ETF(s)/ETF(0)* depending on the structure size s and a thickness d_p of 2µm in the passive areas.

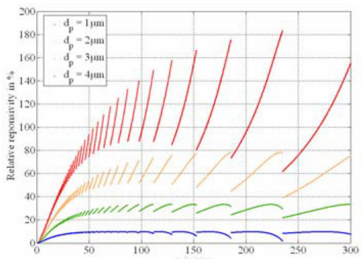

Fig.6. Relative responsivity change *R(s)/R(0)* referred to an unstructured sensor depending on the structure size s and the thickness d_p of the passive areas.

Figure 5 shows the change of the transfer function *ETF* depending on the structure width *s*. The discontinuities in the plot follow from the integer number of etched holes. The transfer function is independent of the etch depth of the structure, because only the area of the active region has an influence on the electrical capacity. By reducing the sensitive area the transfer function of a structured element is always worse than that of an unstructured element because of the smaller effective area and the lower electrical capacity.

3.3. Responsivity

Figure 6 presents the relative increase of the responsivity normalized on the responsivity of an unstructured sensor. The 3-dimensional pattern increases the responsivity up to 150%. The achievable increase depends on the structure width *s*, the element thickness d_a and the thickness d_p of the passive areas.

3.4. Comparison between measurement and simulation

First sensors with structured elements were fabricated and the responsivity was measured. The structure width *s* was 77µm. Figure 7 shows that the measurement and simulation results are in a good agreement. It can be seen that the structured sensors show responsivity exceeding that one of unstructured sensors by a factor of 2,5.

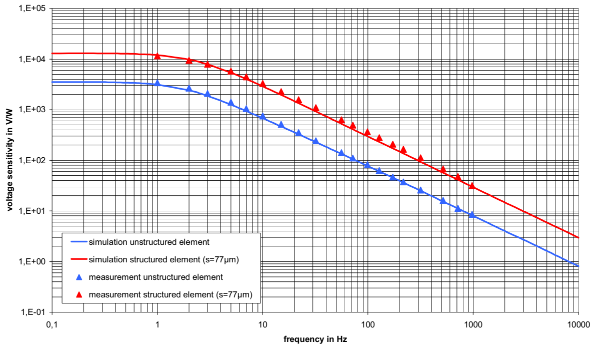

Fig.7. Measured (triangles) and simulated (lines) frequency-dependent sensitivity of single-element detectors with (red) and without (blue) surface pattern.

4. Conclusion

It could be shown that the 3-dimensional pattern has an important influence on the sensor parameters. Depending on the structure width and other geometrical parameters, the achievable responsivity can be increased by more than 150% in contrast to unstructured detectors. Further investigations will be done to analyze the influence of filling material in the etched holes to increase the absorption.

Acknowledgement

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