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Thermal-electrical Design Improvements of a New CMOS Compatible Pyroelectric Infrared Sensor Based on HfO_2

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Summary:

The pyroelectric properties of doped hafnium dioxide (HfO_2) are utilized to create a new CMOS compatible infrared sensor element suitable for mass production. In this paper, we propose a new sensor design with the goal of maximizing the temperature sensitivity and optimizing the thermal time constant. Furthermore, a thermal-electrical model of a complete pyroelectric detector is developed to estimate the signal and noise behavior.

Keywords: HfO_2, pyroelectric sensor, CMOS, thermal-electrical model, temperature sensitivity

Introduction

The demand for low cost and high-performance infrared detectors is constantly growing, for example in the area of gas sensing and flame detection. Especially pyroelectric detectors offer a high detectivity for measuring infrared radiation [1]. For a few years, the pyroelectric behavior of HfO_2, deposited on a silicon membrane, has been profoundly studied [2]. The potential advantages, compared to the widely used lithium tantalite (LT), are low cost, because of the CMOS compatibility and a high performance considering a low thermal capacitance and high thermal isolation. The generated pyroelectric current corresponds to the following Eq. (1). Trenches, which are shown in Fig. 1, enable a 3D-structuring of HfO_2 for a larger effective electrical surface *A* and a higher resulting current.

$$I_{pyro} = p \cdot A \cdot \frac{dT}{dt} \qquad (1)$$

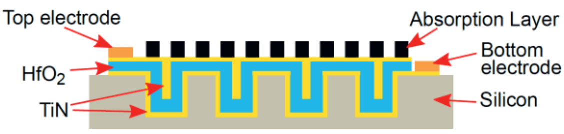

Fig. 1: Cross-section of the structured membrane.

Additionally, a plasmonic absorber replaces a conventional black layer like a metal or polymer coating. This ensures CMOS compatibility of the whole pyroelectric sensor.

The contributions of this paper are the optimization of a new sensor design with respect to a high sensitivity and an appropriate time constant. Besides, the overall pyroelectric performance is evaluated with a new extended *SPICE* model.

Optimization of the New Sensor Design

According to Eq. (1), the pyroelectric coefficient *p* is a material specific parameter and is independent of the sensor design. But both the effective surface area *A* and the temperature change *dT / dt* depending on the incident radiation power can be optimized. A suitable design of the new sensor element, plotted in Fig. 2, is a thin membrane with beams to an outer frame.

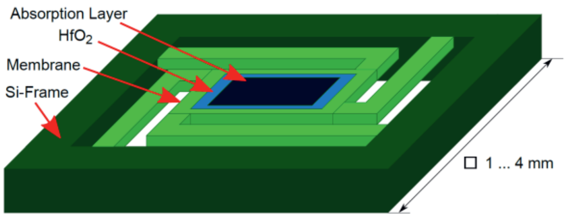

Fig. 2: Proposed design of the sensor element.

The stack including HfO_2 and silicon is structured with etching processes limiting the minimum physical dimensions of gaps, widths and heights. Moreover, the mechanical stability must be guaranteed.

In Fig. 3, *COMSOL Multiphysics™* is used to simulate the temperature distribution (left) and the average temperature behavior in the membrane in the time domain (right). The sensor geometry can be optimized for several parameters. For instance, the relative impact of varying the membrane thickness is shown in Fig. 4 for a radiation intensity of 5 W/m². In summary, there is a tradeoff between the temperature sensitivity, time constant and further constraints, like the mechanical stability and maximum layout dimensions.

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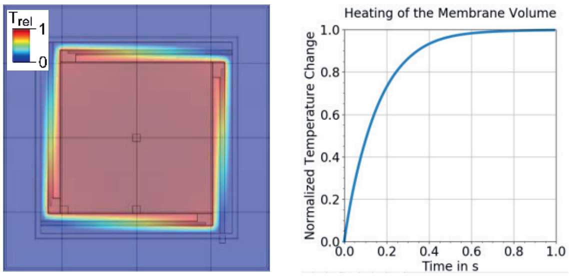

Fig. 3: Steady state of the FEM heat simulation of the sensor element (left) and average temperature settling curve of the membrane (right).

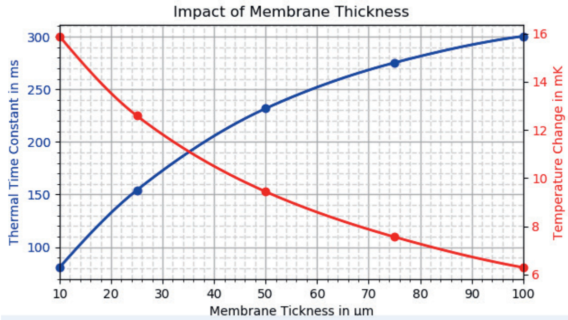

Fig. 4: Dependency of the thermal time constant and temperature change on the membrane thickness.

Thermal Electrical Model for Pyroelectric System

An alternative approach to examine the thermal behavior is to use the thermal electrical analogy and develop a *SPICE* model, proposed in [3]. Spatially concentrated elements, in the form of resistances, connect the heat source with the ambience. The finite element method (FEM) simulation is used to identify the dominating conducting paths, like beams and air gaps, and validate the implemented *SPICE* model. Figure 5 illustrates some of the important thermal resistances for the heat conduction in the simplified sensor. Thermal convection and radiation can be neglected because of a small membrane area and tiny temperature differences.

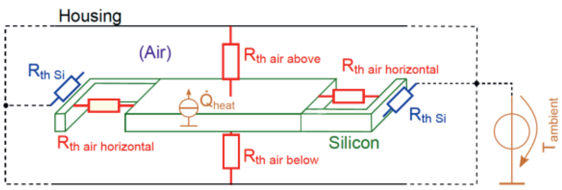

Fig. 5: Spatially distributed thermal resistances.

A new parametrized *SPICE* model has been developed, which can map thermal 3D structures. It requires only a short calculation time and can perform frequency and parameter sweeps, but still differs only few percent from the FEM analysis. In addition, the model can be extended by an electrical circuit to investigate the overall behavior of the pyroelectric detector. The improved model, which is shown in Fig. 6 (top), combines a thermal 3D-system and a readout circuit including substantial noise sources, like tan(δ)-noise of the pyroelectric material.

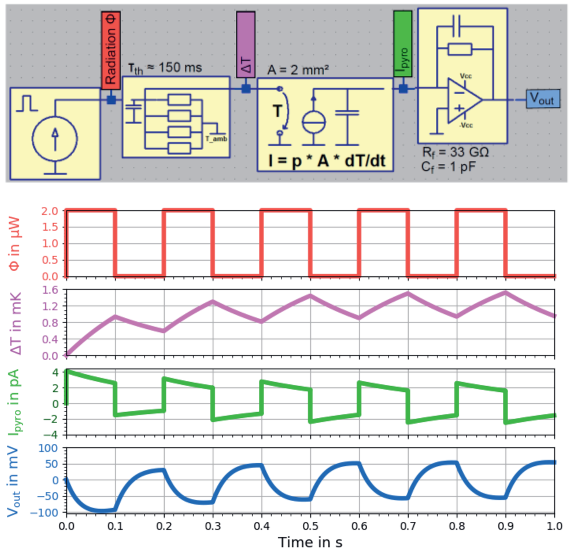

Fig. 6: SPICE model of a LT current mode detector (top) and the simulated pyroelectric signals in the time domain during thermal settling (bottom).

For model validation, a typical LT current mode detector is studied. Figure 6 (bottom) demonstrates the rectangular incident radiation as excitation of the model and the output voltage.

Conclusion

A new sensor design based on HfO_2 has been proposed. Different layouts and parameter combinations have been examined to optimize the temperature sensitivity and achieve a suitable thermal time constant in the order of 100 ms. The pyroelectric coefficient of HfO_2 is lower than that of LT, but due to a higher temperature sensitivity and effective area extension by 3D-structuring, a higher pyroelectric current can be obtained. Furthermore, a new *SPICE* model has been realized to estimate the overall performance of a pyroelectric detector combining both a 3D thermal system and an electrical readout circuit.

Acknowledgment

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