A pneumatic infrared detector with capacitive read-out circuit

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Abstract
A concept for a new miniaturized Golay cell IR detector with capacitive read-out circuit is presented. The expected (theoretical) performance is calculated and principle of operation could be proven with a first prototype. Necessary steps for its improvement are described.

Keywords: *Golay cell, infrared sensor, thermal detector*

1 Introduction

Common types of thermal infrared (IR) sensors are thermopiles, bolometers, pyroelectric detectors, and Golay cells. Although the three former types have been miniaturized by using silicon micromachining and thin-film technology, the Golay cell has not been improved very much recently. Some miniaturized Golay cell IR detectors have been developed using silicon micromachining technology together with a tunneling displacement transducer [1] or a capacitive detector [2] as read-out mechanism. The main advantages of a capacitive detection system over a tunneling displacement transducer are its simple realization and evaluation making it ideal for low-cost applications. Beyond, the low-frequency stability of tunneling displacement transducers is always uncertain [3] and they show serious problems in terms of reliability. Otherwise, miniaturization of the Golay cell has been limited by the performance of miniature capacitive displacement transducers. In this paper, a concept for a new miniaturized Golay cell IR detector is described which does not use silicon as material for the gas chamber in order to improve the sensors thermodynamics. We will also demonstrate that a capacitive detection is still very attractive in terms of detectivity.

2 Device structure and thermal modeling

The first prototype of the proposed miniaturized Golay cell detector is a hybrid device (Fig. 1). It basically consists of a sealed cavity made up of lithium tantalate (LT) and a capacitive displacement transducer. The dimensions of the gas chamber are approximately (2.5 x 2.5 x 0.03) mm^3. In the gas chamber infrared radiation is absorbed by a silver-black coating resulting in a heating of the gas and, consequently, an increase of gas pressure. This pressure rise causes a membrane deflection which is detected capacitively by a parallel plane capacitor with an active area of (2 x 2) mm^2. The membrane is made up of a 1 µm thin polymer foil spanned over a silicon frame giving a resulting deflection area of (2.5 x 2.5) mm^2. It is covered with a thin gold film serving as upper electrode of the capacitor. The counterpart electrode consists of a simple metal block. The bottom electrode has the same thickness as the silicon frame so that the capacitor gap is defined by the silicone joint which is formed by capillary forces and bonds the detector

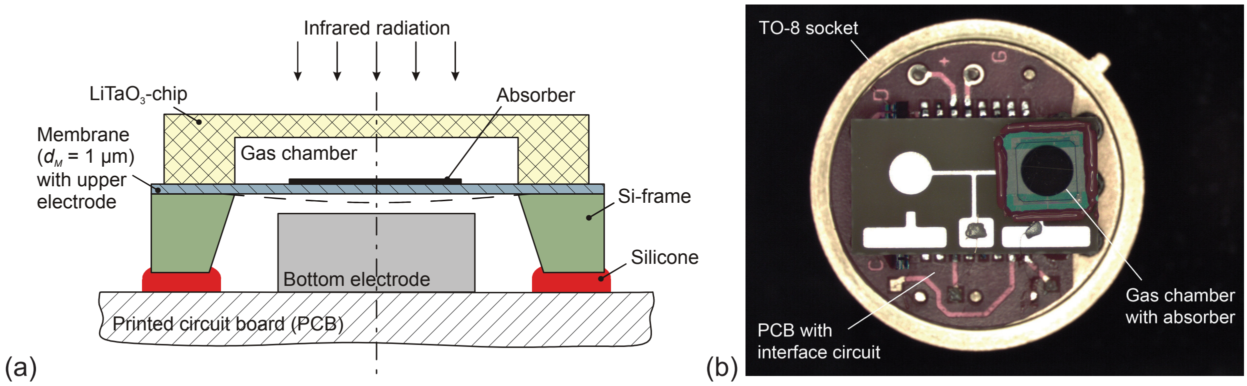

Fig. 1: (a) Drawing of the structure of the miniaturized Golay cell detector and (b) picture of the prototype assembled in a TO-8 package.

onto a printed circuit board (PCB). For the manufactured prototypes the spacing is in the range of (5…10) µm giving a typical capacitance of (3.5…7) pF.

The magnitude of the detector signal is proportional to membrane displacement resulting from gas expansion due to the absorption of radiant energy. The relationship is described by the expression for energy conservation

$$P_{abs}(t) = p \cdot \frac{dV}{dt} + H_{th} \cdot \frac{dT}{dt} + \frac{1}{R_{th}} \cdot (T - T_0) \tag{1}$$

where $P_{abs}(t)$ is total IR power absorbed, t is time, p is instantaneous gas pressure, V is the instantaneous volume of the gas, H_{th} is the heat capacity of the absorption compartment, R_{th} is the thermal resistance between the absorption compartment and its environment, T is instantaneous gas temperature, and T_0 is the temperature of environment (i.e. the heat sink). The first term in equation (1) describes the gas expansion work rate which has to be as large as possible in order to get a maximum membrane displacement. Consequently, the second and third term, which describe the storage of power in the absorption compartment and the total heat loss rate to environment, respectively, have to be minimal. Thus, a small gas volume and use of materials with a low thermal conductivity are beneficial.

Based on the resistance and the capacitance of the different parts of the sensor structure a thermal model was developed which may be simplified by accepting the following approximations (Fig. 2):

(i) The thermal resistance of absorber, membrane, and LT window can be neglected due to their low film thickness.

(ii) The heat capacity of trapped air, absorber, and membrane may be ignored because they are much less than that of the lithium tantalate chip, $H_{LT\text{-}v}$ and $H_{LT\text{-}h}$, respectively.

(iii) The thermal resistance from the LT frame to ambient air due to convection is extremely high so that the silicon frame is regarded as heat sink for lateral heat conduction.

The effective temperature change ΔT of the gas in the cell can be calculated from the thermal model and is given by

$$\Delta T = \frac{\Delta P_{abs}}{\dfrac{1}{R_{gap}} + \dfrac{1}{R_{gas-v} + \dfrac{1}{\dfrac{1}{R_{to\ air}} + j\omega H_{LT-v}}} + \dfrac{1}{R_{gas-h} + \dfrac{1}{\dfrac{1}{R_{LT-h}} + j\omega H_{LT-h}}}} . \tag{2}$$

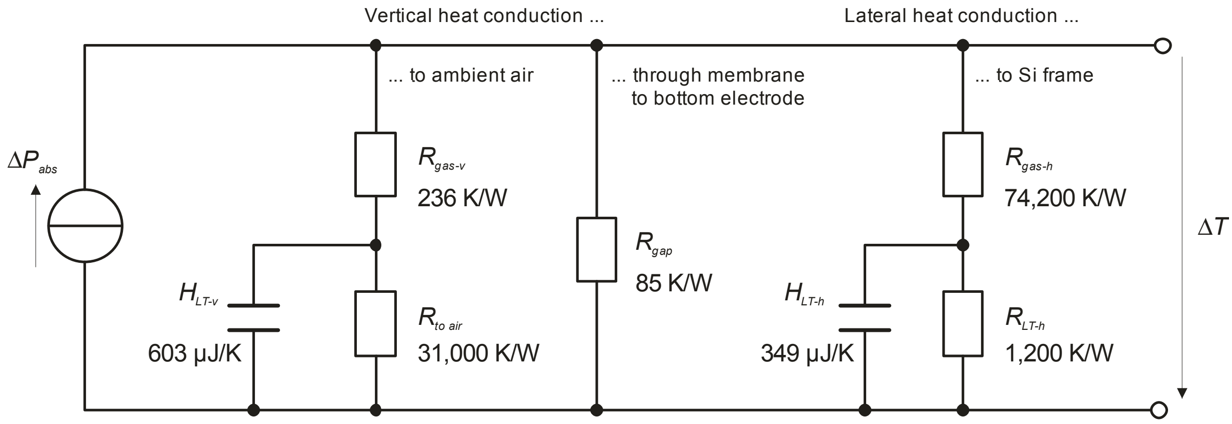

Fig. 2: Simplified thermal model of miniaturized Golay cell IR detector with thermal resistances $R_{th\text{-}gas\text{-}v}$ and $R_{gas\text{-}h}$ of gas, $R_{to\ air}$ of convection to ambient air, R_{gap} of capacitor gap, and $R_{LT\text{-}h}$ of LT frame.

For the static response we find the approximation

$$\Delta T_{static} \approx \Delta P_{abs} \cdot R_{gap} \tag{3}$$

because most of the heat is lost through the membrane to the bottom electrode. Here, R_{gap} denotes the thermal resistance of the capacitor gap. The thermal resistance is given by

$$R_{th} = \frac{l}{\lambda \cdot A} \tag{4}$$

where λ is thermal conductivity, A is cross-sectional area, and l is length. The heat capacity is given by

$$H_{th} = \rho \cdot c \cdot V \tag{5}$$

where ρ denotes density and c is specific heat capacity.

The resulting deflection w of the square-shaped membrane which is fixed at all edges can be calculated by Ritz's method [4] with

$$w(x,y) = \frac{0.383 \cdot \Delta p}{16 \cdot a^4 \cdot D} \cdot \left(x^2 - \frac{a^2}{4}\right)^2 \cdot \left(y^2 - \frac{a^2}{4}\right)^2 \tag{6}$$

where a is the edge length and D the bending stiffness of the membrane. The volume change ΔV and capacitance C are calculated from the deflection shape $w(x,y)$ as

$$\Delta V = \int_{-a/2}^{a/2} w(x,y)\, dxdy \tag{7}$$

and

$$C = \varepsilon_0 \varepsilon_r \int_{-a/2}^{a/2} \frac{dxdy}{\left[d_{gap} - w(x,y)\right]}\ . \tag{8}$$

For the given dimensions of the detector it can be shown that the relative pressure change is negligible compared to the relative volume change [1]. This means that bending stiffness D and, consequently, thickness d_M of the membrane hardly influence the sensor performance.

3 Capacitive read-out circuit

There are many possibilities for the measurement of capacitance. The easiest are based on relaxation oscillators that measure the decay time of a *RC* filter. In order to digitize the output of a capacitive sensor capacitance has to be converted into a voltage first, followed by a regular ADC.

In our work, we use a 24-bit capacitance-to-digital converter AD7745 from Analog Devices. This interface circuit is based on a sigma-delta core which directly converts a capacitance into a digital word, at high resolution (2 aF $Hz^{-1/2}$), high linearity (±0.01 %), and high accuracy (±4 fF) [5]. Such a sigma-delta converter consists of a switched-capacitor modulator, whose operation is based on balancing an unknown charge with a known reference charge of variable polarity, and a digital filter. All necessary functions such as sensor excitation, temperature sensor, voltage reference, etc. are included. This circuit has a 2-wire, I^2C-compatible serial interface and allows assembly of the complete infrared detector together with signal evaluation into a TO-8 package (Fig. 1b).

The resolution of the AD7745 is limited by noise which varies with selected conversion time t_C and voltage V_{exc} across the capacitance to be measured (see Fig. 3a). The conversion time defines the output data rate of the read-out circuit and, consequently, defines the maximum operation frequency of the detector. For the minimum conversion time of 11 ms the corresponding output data rate is 90.9 Hz. This limits the maximum operation frequency of the detector to about 30 Hz.

Environmental temperature variations can cause capacitor offsets which are commonly prevented by constructing a pneumatic leak between the sealed cavity and the capacitor. However, the AD7745 can be configured for differential mode allowing the use of a second, identically constructed but passive working Golay cell to avoid these influences without the need for a pneumatic leak.

4 Theoretical performance

The expected responsivity *S* of the Golay cell prototype can be calculated by

$$S = \frac{\Delta C}{\Delta P_{abs}} \tag{9}$$

and gives a maximum value of 4.8 aF/µW for steady illumination (see Fig. 3b). The minimum RMS noise of the capacitive interface circuit occurs at the highest conversion time of 110 ms and has a value of 4.2 aF. Hence, the calculated minimum noise equivalent power (NEP) for the prototype is $8.7 \cdot 10^{-7}$ W leading to a maximum specific detectivity D^* of $4.3 \cdot 10^{5}$ cm $Hz^{1/2}$ W^{-1} which is a quite moderate performance. In order to achieve an adequate specific detectivity of 10^9 cm $Hz^{1/2}$ W^{-1} a responsivity of 11 fF/µW is needed. For this purpose, the thermal resistance R_{gap} has to be improved currently limiting the detector performance. This can be done by constructing the bottom electrode of the capacitor as a thin membrane with an isolation gap beneath. A further improvement can be achieved with a reduction of the capacitor gap and a larger height of the gas chamber. For a target capacitor gap of 2 µm and a chamber height of 200 µm this isolation gap has to be at least 200 µm in order to achieve the needed responsivity.

5 Experimental results

The noise measurements were performed in a sealed and shielded metal box. For the measurement of responsivity the detector prototype was illuminated by a red LED of 660 nm wavelength with an irradiance of 50 µW/mm^2. The results are shown in Fig. 3.

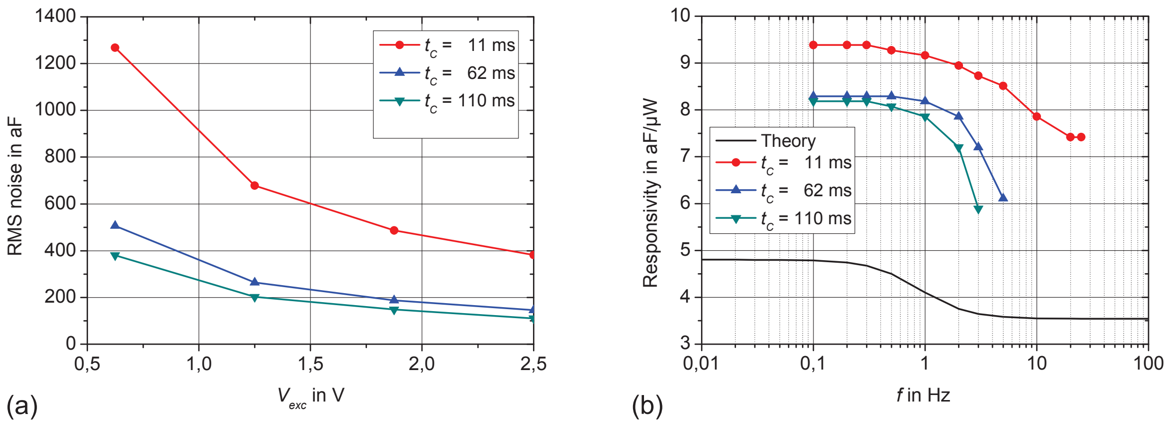

Fig. 3: Measured (a) RMS noise and (b) responsivity of the miniaturized Golay cell prototype for different conversion times t_C of the read-out circuit.

The RMS noise increases with the reduction of conversion time and excitation voltage. Therefore, the maximum excitation voltage $V_{exc} = V_{DD}/2 = 2.5$ V was used for all measurements. The measured RMS noise is about 10 to 25 times higher than that of the AD7745. Consequently, the read-out-circuit does not limit the detector performance.

The frequency-dependent run of the measured responsivity is in agreement with that calculated from the thermal model but the absolute values differ by a factor of about two. This is owed to measurement uncertainties as well as to the simplified assumptions for the thermal model. As mentioned before, the conversion time limits the maximum operating frequency of the detector by acting as a low-pass filter. This explains the higher responsivity values for lower conversion times as well as the drop in responsivity at frequencies near the maximum operating frequency.

From the measured noise and responsivity values a minimum NEP of $1.4 \cdot 10^{-5}$ W and a maximum specific detectivity of $4 \cdot 10^{4}$ cm Hz$^{1/2}$ W^{-1} is obtained. This quite low value of detectivity and large value of NEP result from the rather low thermal resistance R_{gap} currently limiting the detector performance. However, this D^* value is one order of magnitude higher than that of the miniaturized Golay cell reported by Yamashita et al. [6].

6 Conclusion and outlook

A new concept for a miniaturized Golay cell IR detector with capacitive displacement transducer was presented. The principle of operation could be proven with a first prototype. The detector performance is quite low but not limited by the read-out circuit. Next steps will deal with the thermal, geometrical and electrical optimization of the Golay cell. Especially, the thermal resistances of the vertical heat conduction paths have to be improved. Moreover, a smaller capacitor gap is beneficial for a high responsivity. The used sigma-delta interface circuit offers a very attractive method for the precise measurement of capacitance that is directly converted into a digital word. It can be placed together with the Golay cell into a small transistor housing and requires only four electrical connections, two for the I^2C-compatible serial interface and two for the power supply. Finally, a capacitive detection is still very attractive for a Golay cell infrared detector.

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