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Miniaturized Photoacoustic CO_2 Sensors for Consumer Applications

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Abstract:
We present a sensor concept for a photoacoustic CO_2 sensor with potential for consumer application mass market. The system consists of an IR-source and a silicon microphone as detector in a sealed detection chamber with integrated target gas. The detection chamber serves as gas selective filter of the sensor. A detailed simulation model allows prediction of system behavior and the investigation of relevant parameters for a further miniaturization process. All active components are silicon based. A full integration in silicon MEMS technology is possible. Sensor prototypes and characterization measurements are shown. The presented system shows high potential for integration and miniaturization.

Key words: gas sensor, photoacoustic, carbon dioxide, consumer applications, MEMS

Introduction

The measurement of CO_2 gains high importance on today's gas sensor market. In scientific research there is also a high significance for new CO_2 sensing methods. Especially the indoor air quality monitoring is a large field for CO_2 sensors. Increased CO_2 levels indoors means less air quality and can even negatively influence human's health. Furthermore the work performance of employees at workplaces or students in schools is impaired. The indoor CO_2 concentration directly correlates with the number of people present and requires adequate rates of air-ventilation. In public buildings, public transportation, cars or even in every closed room the CO_2 concentration is strongly influenced by high variation in the number of present people. These broad applications for indoor air quality monitoring provide a huge market with high quantities for CO_2 sensors. To serve this market a selective, low-cost sensor for CO_2 is needed with low energy consumption simultaneously. There are two main options for applications in monitoring CO_2 indoors. One option is the fixed installation of sensor systems in all relevant environments or rooms. Another option is the usage in portable consumer products like smartphones or tablets. This would imply much higher quantities of sensors.

The consumer application market is mainly driven by the price of a single sensor system. Furthermore the volume of the sensor system has to be very small with minimized power consumption in parallel.

We present a miniaturized photoacoustic gas sensing method for CO_2 with the potential for further miniaturization and potential for high quantities and low price solutions for the consumer market.

In 1938, E. Lehrer and K.F. Luft demonstrated that absorbed electromagnetic energy of IR-active gases can be measured by means of acoustic detection [1]. The effect was firstly discovered by A.G. Bell in 1880 [2]. Conventional absorption spectroscopy is based on excitation by electromagnetic radiation with intensity I_0 and the measurement of reflected or transmitted light intensity I [3]. The so-called photoacoustic spectroscopy exhibit a strong sensitivity to traces of IR-active gases present in the air. An advantage of this measurement method is to measure the absorbed energy directly [4]. The photoacoustic measurement method is suitable for CO_2 as strong IR-active gas to build miniaturized selective gas sensors.

Photoacoustic gas sensors, fabricated on silicon substrates provide compatibility with common microelectronics and microelectromechanical systems (MEMS) with the possibility to use common assembly and packaging technologies. These approaches enable low cost fabrication of photoacoustic sensor elements coupled with reduced size and power consumption. Finally, the development of “smart sensors” incorporating “on chip”-electronics for data acquisition and signal processing also becomes possible.

Theory

Basis of the sensor principle is the photoacoustic effect. The working principle and theoretical background of the effect are discussed in detail in [5]. The resulting pressure signal can be calculated from the absorption strength and knowledge concerning the IR-light source. We use data from HITRAN [6] to calculate the transmission profile T(λ) of a certain gas concentration on a defined absorption length including absorption line intensities and broadening with changing environmental conditions. In the calculations we estimate an ideal black body radiator as broadband IR-source to describe the used thermal emitter. The black body radiator is estimated as ideal with a certain temperature. Quantized absorbed photon energy levels cause oscillations and vibrations in molecules. This quantized absorption lines give a specific “fingerprint” to each IR-active molecule. Absorption of radiation in a medium shows exponential dependence between radiation intensity and absorption distance. It is described by Beer-Lamberts-law. The energy levels of IR radiation are not high enough to cause electronic transitions, but characteristic vibrations are excited. To get the power P_{ges} that is absorbed by an absorbing gas, the integral of the multiplied power profile of the infrared source P(λ) with the absorption profile A(λ) = 1-T(λ) can be calculated.

$$P_{ges} = \int_{\lambda_1}^{\lambda_2} A(\lambda) \cdot P(\lambda)\, d\lambda \qquad (1)$$

Estimating ideal performance and neglecting all loss mechanisms (reflections, scattering, heating) all absorbed energy results in increased internal energy of the gas. If a modulated IR source is used, the pressure variations are periodic as well [7]. To determine the energy ΔQ that is inserted in the gas volume, modulation frequency f and duty cycle v of the IR-source have to be taken into account. We assume for our system a rectangular function with 0.5 duty cycle, to have 50% of the time power entering and a frequency of 13 Hz:

$$\Delta Q = \frac{P_{ges} \cdot v}{f} \qquad (2)$$

Under the assumption of an ideal gas, the heat capacitance for an ideal gas C_V is constant. With this parameter the temperature difference ΔT for each on-phase of the emitter can be calculated.

$$\Delta T = \frac{\Delta Q}{C_V} \qquad (3)$$

With the ideal gas equation we can calculate directly a pressure difference Δp:

$$\Delta p = \frac{n \cdot R \cdot \Delta T}{V} \qquad (4)$$

To operate described calculations for a certain sensor setup, specific data has to be imported from HITRAN [6]. A numerical integration approximation has to be done over the wavelength region to calculate formula (1). There should be taken into account that the proposed setup hast two absorption chambers, so that two absorption profiles have to be regarded for each concentration step.

Sensor Principle

In application we use a 2-chamber sensor setup. Having a non-resonant operation mode because of the electronic modulation of the IR-emitter, the pressure wave has to be measured in a closed volume for detection. We use a hermetically sealed detection chamber with enclosed target gas inside. The target gas appears as indirect selective gas filter. The measurement chamber is placed in front of the detection chamber and contains the ambient air to be measured. This chamber is implemented open to the ambient air. The working principle is visualized in Figure 1.

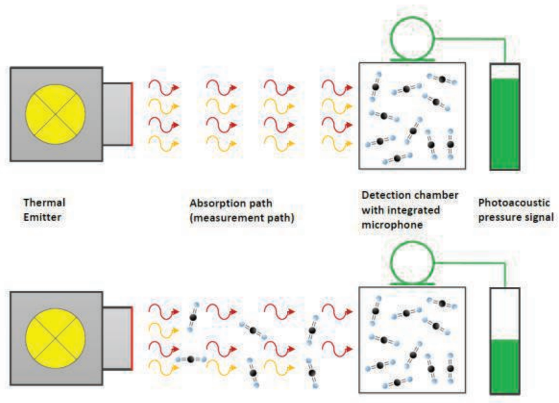

Figure 1: Visualized sensing principle of the setup with two chambers and a thermal emitter.

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If there is an increased CO_2 concentration in the measurement chamber, an increased pre-absorption occurs. Due to this fact the intensity in the detection chamber is decreased. We have an indirect measurement method of the ambient CO_2 concentration.

Simulation Model

To predict the system behavior and the effect of size reduction a detailed simulation model was investigated. Considering all above-mentioned formulas, we developed a detailed mathematical model which includes all boundary conditions as number of absorption chambers, absorption lengths, housing materials and environmental conditions. The simulation model demonstrates the influences of modified size related parameters like absorption length or total chamber volume. Figure 2 shows the simulated sensor response for several defined CO_2-concentrations in the measurement chamber for a certain setup.

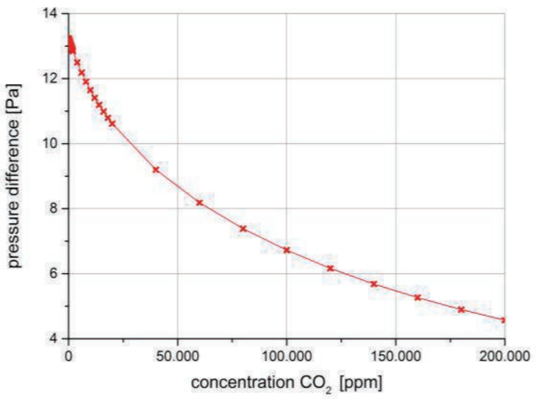

Figure 2: Simulated pressure signal inside the detector chamber. The measurement chamber is simulated with a length of 5 mm.

The detection chamber is simulated with 100% CO_2 filling. There can be seen the typical exponential behavior of an absorption based measuring principle. The absorption data is imported from HITRAN [6]. The simulation model is used as tool to dimension sensor setups and predict the system behavior.

Experimental

First implemented prototype setup can be seen in Figure 3. It is developed according the concept shown in figure 1. The setup has a size of 20 x 20 x 20 mm³. The system consists of an aluminum housing with sapphire windows between the measurement and detection chamber. As pressure sensor we use a microphone as it is used in cell phones (SMM310, Infineon).

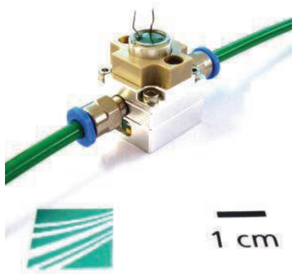

Figure 3: First developed prototype of the photoacoustic gas sensor.

The system shows good work performance with a resolution better than 100 ppm in the measurement range up to 5000 ppm. Further development of this setup is described in [8] in detail.

Another realized sensor setup with variable absorption length can be seen in figure 4. The measurement chamber is constructed with variable absorption length inside the tube. The detection chamber is realized in a hermetically sealed TO-housing, as it is detailed described in [9]. A broadband thermal emitter is used as IR-source (Hawkeye, IR66). Two peripheral gas connectors allow filling gas mixtures into the measurement cell at a gas test stand. Various characterization measurements have been performed with this setup. Long-term behavior, detection limit, resolution and cross-sensitivities to other gases are investigated [9].

Figure 4: Developed characterization setup to evaluate detector unit performance. The measurement chamber length is realized variable inside the tube.

A characterization measurement with this setup can be seen in figure 5. In this measurement the measurement path is defined as 5 mm. The concentration steps are 100 ppm from 1000 ppm up to 2000 ppm CO_2 in N_2. The baseline is stable and the resolution is smaller than 100 ppm.

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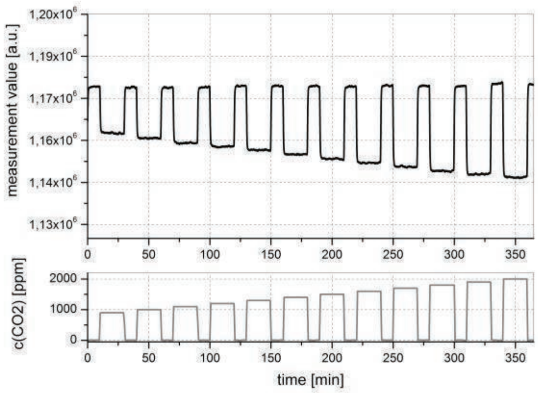

Figure 5: Measurement from 1000 – 2000 ppm CO_2 in N_2 in 100 ppm steps.

To determine CO_2 concentrations from the measured pressure signal, a calibration process is needed. In the range from 0 – 1000 ppm CO_2 the calibration measurement is done with 5 fixed-point measurements with defined concentrations. This calibration is repeated 10 times to verify reproducibility of the setup. Further the calculated calibration curve is verified with simulations. As it can be seen in figure 2, the sensor response can be approximated linearly in the region 0 – 2000 ppm. The pressure signal is linearly amplified and converted before the digitalization. Figure 6 shows the sensor response of a measurement after the implemented calibration algorithm. The red curve shows the defined gas concentration in the measurement chamber delivered from the gas test stand at Fraunhofer IPM. The blue curve shows the signal which is measured by the sensor. It can be seen that the calibration curve fits well for the investigated measurement range.

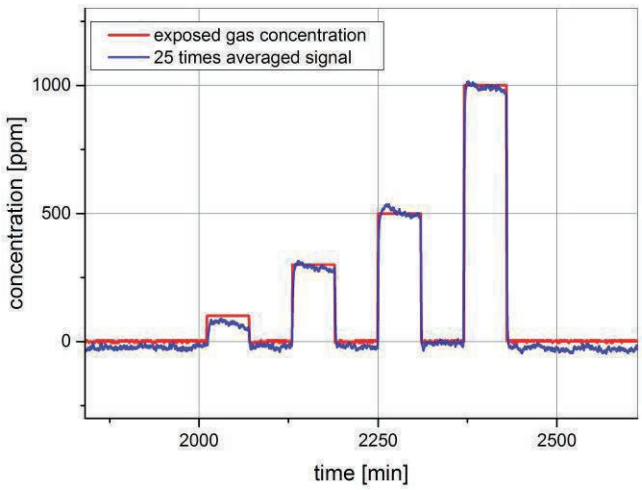

Figure 6: Measurement from 0 – 1000 ppm in 250 ppm steps of CO_2 in N_2. The red curve shows the defined gas concentration delivered from the gas test stand at Fraunhofer IPM. The blue curve shows the sensor response.

Conclusion and Outlook

A photoacoustic sensor setup with two chambers for real-time measurements is presented. Implemented sensor prototypes are shown. The prototypes are investigated with characterization measurements. A simulation model to predict system behavior under varying boundary conditions is presented. The measurements show stable measurement results with sufficient resolution (better 100 ppm) for CO_2. The measurement range is chosen for indoor air monitoring (0 – 2000 ppm). The sensor principle shows great potential for miniaturization. The detector is a simple microphone as it is used in cell phones.

The full integration of the sensor in silicon microtechnology is planned by using MEMS fabrication processes because all relevant sensor elements (detector, emitter, optics, housing) can be fabricated using silicon micromachining. Potential for further miniaturization is shown and limitations concerning sensitivity (absorption length) and pressure signal (chamber volume) are investigated. The biggest challenge is the fabrication of a hermetically sealed detection chamber with enclosed target gas. Market potential, economic expectations and quantities are considered. For usage in consumer applications especially the price of one sensor system is the dominating parameter.

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