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A Simple Fabry-Perot-Based Germanium Bolometer for CO2 Monitoring: Simulation and Measurement

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Abstract

We report on the design of a simple germanium bolometer designed as a Fabry-Perot absorbing structure, which can be used for monitoring, e.g., CO\textsubscript{2}, where no additional filter is required. CO\textsubscript{2} absorbs IR radiation in a major band centered around 4.26\mu m. The selectivity of the whole sensor-configuration is mainly accomplished by the wavelength-response associated with the Fabry-Perot structure involved. The analysis shows, that the designed bolometer has an adequate response-function for the measurement of CO\textsubscript{2} concentration. Combining this analysis for the bolometer with ray tracing simulations for a connected sample chamber yields the response for an entire IR-absorption sensor system, which is in good agreement with measurements.

Keywords: gas monitoring, infrared, bolometer

1. Introduction

Non-dispersive infrared (NDIR) gas sensors are used in various applications, e.g., monitoring of air quality in office buildings, which is a big market for low cost sensors. Such NDIR gas sensors consist of basic building blocks i.e., an IR-source, an optical path with reflecting walls containing the sample gas, and an IR-detector in combination with a gas-specific filter (see Fig. 1). Commercially available systems use thermopile or pyroelectric detectors fabricated with, e.g., a narrowband interference filter as detecting device. In this paper we present a much simpler design of an absorbing device which requires just a few layers and can be manufactured effortlessly. The main part is the combination of the two mirrors and a germanium dielectric layer, which represent a Fabry-Perot structure. This structure filters the targeted CO\textsubscript{2}-specific absorption wavelength\textsuperscript{1} (4.26\mu m) out of the spectrum of the total IR-radiation impinging on the bolometer. The absorbed radiation heats up the structure, which can be measured by the change of the electrical resistance of a defined layer.

There are two main advantages of germanium as dielectric layer: at first its high index of refraction (n_{Ge} \approx 4 for mid infrared)\textsuperscript{2} which allows for a design with a thinner layer. The second advantage lies in the possibility to use this material itself as the active sensing layer because of its high (negative) temperature coefficient of resistance\textsuperscript{3} (TCR).

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2. Design of the Fabry-Perot Structure

The Fabry-Perot structure basically consists of a semitransparent metal mirror on the top, the dielectric germanium layer, and a second metal mirror on the bottom (see Fig. 2).

The major part of the IR-absorption takes place in the top metal mirror. For our application we can neglect the absorption within the germanium layer due to very small extinction factor of germanium in the mid infrared region (extinctions coefficient \( k < 10^{-4} \)).

2.1. Design of the Layers

The following design considerations apply for the different layers shown in Fig. 2:

- For optimum absorption, the thickness of the top metal mirror has to be chosen in such a way that its resistance matches the vacuum-impedance
  \[ Z_0 = \sqrt{\mu_0 / \varepsilon_0} = 377 \Omega \]
  where \( \mu_0 \) is the vacuum permeability and \( \varepsilon_0 \) is the vacuum permittivity. Simulations show that 15 nm is a good value for this parameter when titanium is used as absorbing material.
- The thickness of the dielectric layer has to fulfill the condition \( d = (2m+1) \cdot \lambda / 4 \) for maximum absorption of radiation with wavelength \( \lambda \), where \( m \) is the order of the absorption-peak. We decided to use the first order absorption \( \rightarrow d = 3 \cdot \lambda / 4 \) which, considering the vacuum-absorption-wavelength for the detection of CO₂ (4.26 µm), yields a thickness around 800 nm.
- The thickness of the second metal mirror is not very critical in the design; it has to be just thick enough to prevent transmission through itself and to bear the mechanical stress of the bonding process. We use gold because of its good IR-reflection and aging properties with a thickness of about 120nm.
- To prevent diffusion of gold atoms into germanium, a 5 nm titanium layer is used which is sufficient at room temperature.
Independent from the substrate material, glass or silicon, a thin undercoating layer made of e.g. 10 nm chromium is also necessary to ensure a good adhesion on the substrate.

2.2. Simulating the Absorbing-Structure

Since the center wavelength associated with a Fabry-Perot structure depends on the incidence angle of the radiation upon the device surface, it is necessary to consider the influence of this parameter in the simulation of the design. The simulated absorption of such a system is shown in Fig. 3.

![Simulated absorption of a bolometer assembled similar to Fig. 2. The absorption depends on the IR-wavelength and the incidence angle of the IR-radiation.](image)

3. Fabricated Sensor

All layers were manufactured in a physical vapor deposition device (PVD) under high vacuum. Except for the dielectric germanium layer, the associated coating parameters (e.g. coating rate or surface roughness) for the deposition process are unproblematic. For a high selectivity of the total sensor system, a high TCR is required. The parameters used for the germanium evaporation process and the roughness of the substrate material directly affected the density of the amorphous germanium and consequently the TCR of the bolometer. A list of experimentally obtained values for TCR is given in Table 1. The values correspond to common ones reported in the literature. In Fig. 4 electron microscope pictures of the fabricated germanium bolometer are shown.

| Substrate material and coating parameter | TCR [K⁻¹] |
|-----------------------------------------|-----------|
| high coating rate for germanium on glass | -0.007    |
| low coating rate for germanium on glass  | -0.012    |
| low coating rate for germanium on silicon| -0.02     |

![Electron microscope picture of the utilized germanium bolometer. On the left hand side a profile of the total sensor is depicted and on the right hand side the structure of the amorphous germanium layer is presented.](image)
3.1. Simulation and Measurement of the Total Sensor System

To compare the theoretical performance to experimental data, an absorption system featuring a sample cell has been implemented (see Fig. 5). Besides the bolometer as IR-detector, the sample cell consists of a commercial broadband IR-emitter and a gold-plated optical path with circular diameter. The measurements were made with defined CO$_2$ concentrations in N$_2$.

![Fig. 5: Sketch of the whole experimental setup of the CO$_2$ monitoring including broadband IR-source, optical path and bolometer. In this case the length of the sample cell is 55mm, its diameter is 10mm.](image)

The theoretical predictions (the sample cell has been modeled using a ray-tracing model$^6$) are in good agreement with the measured data as displayed in Fig. 6. Further calculations show a cross-selectivity to other gases like carbon monoxide and water vapor. Minimizing this effect is one of the main parts of our current work.

4. Conclusion

We demonstrated the feasibility of a simple design for an IR-absorption sensor based on a Fabry-Perot structure including a germanium bolometer for the measurement of CO$_2$ concentrations. The design and the fabrication of the different layers have been discussed. Measurements with a sample cell showed a good agreement with $d = (2 \cdot m + 1) \cdot \lambda / 4$ simulations. The presented bolometer structure can be used for building simple gas sensor systems for mass-market applications.

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