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CO_2 monitoring using a simple Fabry–Perot-based germanium bolometer

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ABSTRACT

We report on the design, simulation and experimental characterization of a simple germanium bolometer utilizing a Fabry–Perot absorbing structure, which can be used for monitoring, e.g., CO_2 where no additional filter is required. CO_2 absorbs IR-radiation in a major band centered around a vacuum wavelength of 4.26 μm. The selectivity of the whole sensor-configuration is mainly accomplished by the wavelength-response associated with the Fabry–Perot structure. The analysis shows, that the designed bolometer has an adequate response-function for the measurement of CO_2 concentration. Combining the 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 proven to be in good agreement with measurements.

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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. Common 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 filter selecting spectral components which are specific for the gas to be detected (see Fig. 1). Commercially available systems use thermopile or pyroelectric detectors combined with, e.g., a narrowband interference filter as detecting device. In this paper, we present a much simpler design of an absorbing device (bolometer) which requires just a few layers and can be manufactured a lot easier. It is based on the combination of two mirrors and a germanium dielectric layer, which represent a Fabry–Perot structure. This structure filters the targeted CO_2-specific absorption wavelength [1] (4.26 μm in vacuum and 4.26 μm/n in a media with refraction index n) out of the total IR-radiation spectrum impinging on the device. The absorbed radiation heats up the structure, which can be measured by the change of the electrical resistance of a defined layer (bolometer principle).

There are two main advantages of using germanium as dielectric layer. Firstly, it features a high index of refraction n, which enables a design with a thinner layer. In particular, for monocrystalline germanium we have $n_{Ge} \approx 4$ in the mid-infrared radiation [2]; polycrystalline and amorphous germanium show a slightly smaller index of refraction due to voids. 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 (TCR) [3].

2. Design of the Fabry–Perot structure

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

The mechanism is based on generating a standing wave pattern of the fields at selected resonance wavelengths λ (the wavelengths in the specific medium, not in the vacuum), in our case we use those λ where the thickness of the germanium corresponds to odd multiples of λ/4. In the resonance case large amplitudes of the electromagnetic field build up leading to increased IR-absorption where the major part of the absorption takes place in the top metal mirror. For monocrystalline germanium the absorption within the dielectric layer would be negligible due to its very small extinction factor in the mid infrared region [2] (extinction coefficient $k < 10^{-4}$). This is based on the reason that the energy of IR light is to small to shift electrons from the valence to the conductance band. In our application we use amorphous germanium where dangling bounds (i.e. "voids" produced by germanium atoms, where at least one of the possible four bindings is not bonded to a neighbor [4]) create additional states and yield a smaller bandgap which leads to a small additional IR-absorption in the germanium layer.

The absorption leads to an increase in temperature of the entire structure, which can be sensed using the temperature coefficient of resistance (TCR) of the heated materials. Since semiconductors

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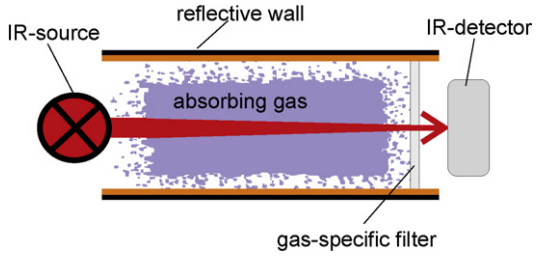

Fig. 1. Sketch of a common NDIR gas sensor with its basic building blocks: IR-source, optical path containing the sampling gas, filter, and IR-detector.

have a much higher (but negative) TCR than metals we measure the resistance of the dielectric layer in order to gain sensitivtiy with respect to CO_2 concentration. For that reason the conductive layers have to be patterned such that the measurement current flows through the germanium layer [3].

2.1. Design of the layers

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

- In [5] it is shown, that for optimum absorption the sheet resistance of the top metal mirror of such a Fabry–Perot structure has to match the vacuum-impedance.

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377\,\Omega \tag{1}$$

  where μ_0 is the vacuum permeability and ϵ_0 is the vacuum permittivity. Since the thickness of the top metal layer approaches a few nanometers, the electrical resistivity of the bulk material is no longer an appropriate physical description [6]. In [6] numerical calculations for such a three layer structure based on the Drude model are made. Those calculations turned out, that the optimum absorption by the use of titanium as absorbing material takes place at a thickness of about 15 nm.
- The thickness of the dielectric layer d has to fulfill the condition

$$d = (2 \cdot m + 1) \cdot \frac{\lambda}{4} \tag{2}$$

  for maximum absorption of radiation with wavelength λ, where m is the order of the absorption-peak. We decided to use the first order absorption $\left(\rightarrow d = 3 \cdot \lambda/4\right)$. For this calculation it is important to translate the CO_2-absorption band in vacuum to the corresponding wavelength in germanium ($\lambda_{Ge} = \lambda_{Vacuum}/n_{Ge} = 4.26\,\mu m/4 = 1.07\,\mu m$). The combination of the first order absorption together with the wavelength in germanium yields to a thickness d around 800 nm.
- The thickness of the second metal mirror is not very critical in the design; it has to be 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 120 nm.
- To prevent diffusion of gold atoms into germanium, a 5 nm titanium layer is used above the gold layer, which is a sufficient diffusion barrier at room temperature.
- Regardless of the used substrate material, glass or silicon, a thin undercoating layer made of e.g. 10 nm chromium is also necessary to improve adhesion to the substrate.

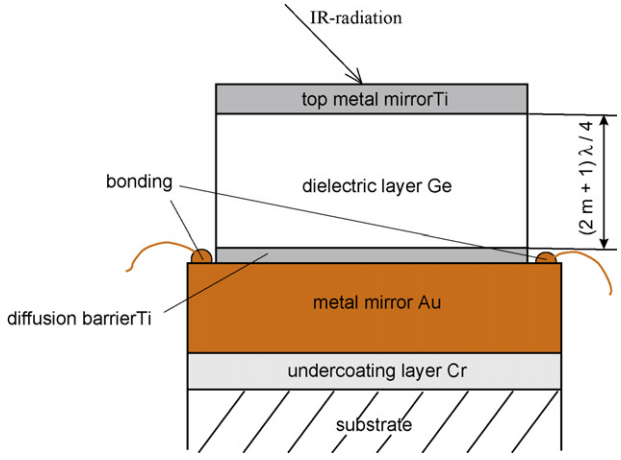

Fig. 2. Sketch of the implemented Fabry–Perot structure (dimensions not to scale). The thickness of the germanium layer corresponds to the infrared absorption wavelength required for the CO_2 detection.

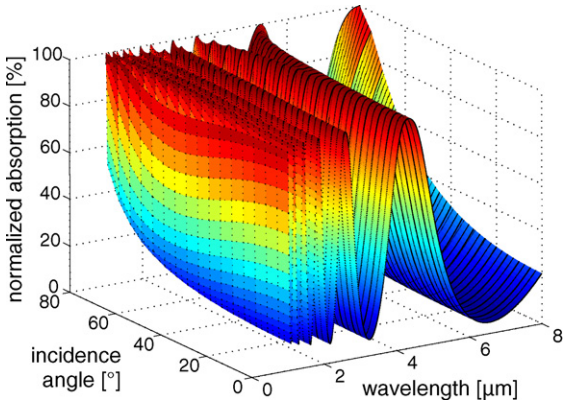

Fig. 3. Simulated absorption of a bolometer assembled similar to Fig. 2. The absorption depends on the IR-wavelength and the incidence angle of the IR-radiation.

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 also consider the influence of this parameter in the simulation of the complete system [7] by means of, e.g., the enhanced transmittance matrix approach [8]. The simulated absorption of such a system is shown in Fig. 3. It can be seen, that especially for radiation with a very flat incident angle (towards 90°), the wavelength-dependent absorption characteristics are changing drastically.

3. Spectral characteristics of the complete sensor system

For calculating the total IR-absorption versus wavelength characteristics for a particular combination of IR-source and IR-absorber, it has to be considered that two parameters of the IR-source and one of the IR-absorber are wavelength-dependent. The two factors for the thermal IR-source are the blackbody radiation and material-depending emissivity at a defined temperature [9] (we use 600 K). For our prototype system, we use a commercial source (SHA1037 from LaserComponents [10]). Note that the approach described in this paper is also feasible for other emitters if the associated characteristics are adapted accordingly. For the IR-absorber, i.e. our bolometer, the intentionally designed wavelength-dependent absorption (as discussed in Section 2.2) has to be considered. The characteristics for these the three parameters and the resulting transfer function vs. wavelength is shown in Fig. 4. In this picture the area below the curve of the resulting total IR-absorption is proportional to the achieved detector signal of the bolometer if no absorbing medium is inserted between the

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