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Research paper

Nano-porous aluminum oxide membrane as filtration interface for optical gas sensor packaging

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ABSTRACT

Packaging and filtration is critical for photonic gas sensors as they are vulnerable to contaminations of dust and moisture in the ambient air. In this work, we present a prototype of packaging using nano-porous anodized aluminum oxide (AAO) as filtration interface for an optical CO_2 gas sensor based on evanescent fields of silicon waveguides. An acrylate-type package housing for the AAO membrane was designed, manufactured and assembled via implementing additive manufacturing technologies including 3D-printing and inkjet printing. Simulation and experimental results for the corresponding package shows a minimal influence of response time while providing a significant filtration performance.

1. Introduction

Recently, inorganic nano-porous materials, especially anodic aluminum oxide (AAO) gained considerable attention in environmental and biomedical applications [1–3]. The AAO membranes are self-organized, highly ordered nanomaterials with regular pore size, uniform pore density and high porosity over a large scale. Moreover, nano-porous AAOs are electrically insulating, chemically stable, and biocompatible. Free standing nonporous AAO membranes with uniform pore structure across the entire thickness are ideal candidates for contamination barriers. Such a barrier is crucial for those gas sensors where the reaction interface is sensitive to contamination and eventually their performance is deteriorated when they are exposed to ambient conditions. Approaches were already presented for liquid-tight filtering of the gas sensors [4], minor air isolation of the sensor by introducing gas inlet and outlets [5, 6], and warming up the sensor platform by integrated heater in the package [7]. In the present work, the package is developed for an optical carbon dioxide sensor [8], where the gas interacts with the evanescent field of a silicon waveguide. Since the optical response of such a device is very sensitive to the change of the refractive index at the interface of the waveguide, contaminations can cause misinterpretation of the outcome of the system. Therefore, such a contamination filtering is necessary in order to assure a long life-time of the sensor. Among all current technologies, additive manufacturing is regarded as an effective approach for fast, precise, and adaptive microfabrication of complex 3D structures. Hybrid prototypes composed of several materials with specific functions can be manufactured with minimal material loss, low failure cost and fast customization [9, 10].

Here, a packaging prototype is designed for the gas sensor with nano-porous AAO membranes as dust and moisture filtration interface. The mole diffusion of the carbon dioxide over the designed packaging is computed with commercial computational fluid dynamics (CFD) program ANSYS FLUENT. The designed package housing is printed with a multi-jet 3D printer using acrylate-type material and bonded to the sensor chip by inkjet printing technique.

2. Material and methods

2.1. Optical gas sensor

The platform considered for measuring CO_2 concentration is an optical guiding system, shown schematically in Fig. 1a. The system is excited and its output is collected by two fibers through in and out coupling of light mediated by two terminal gratings. This system functions in a range around the free space wavelength of 4.26 µm, which is the center of the mid-infrared absorption band of CO_2 [11]. The physical principle of the sensor structure is evanescent field absorption in the functional frequency of the guiding system. A numerical study on dielectric waveguides for evanescent field gas sensing, including a more detailed description of the sensing principle, can be found elsewhere, e.g. in [12, 13]. In short, due to the small cross-section of the waveguide compared to the wavelength, a significant portion of

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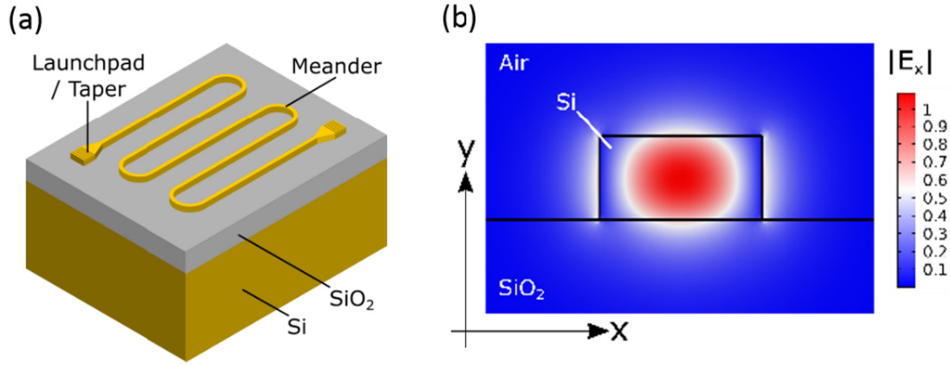

Fig. 1. (a) Schematic representation of a meander Si strip waveguide on a SiO_2 thin film, (b) the calculated distribution of the absolute value of the electric field (*x*-component of the fundamental mode) at the cross section of the waveguide at the free space wavelength of 4.26 µm.

the electromagnetic mode propagates outside of the waveguide. In Fig. 1b, the simulation results, depicting the dominant component of the fundamental electromagnetic mode (the *x*-component) at the cross section of the waveguide are shown. The evanescent field propagates in the air region and interacts with the absorbing medium, in our case CO_2 gas, and therefore the power reaching to the end of the waveguide gets attenuated. In order to incorporate a long interaction path of the waveguide into a small area, a meander-shaped silicon waveguide was used. A study on similar waveguides concerning their intrinsic losses as well as their gas sensing capability can be found in [8].

2.2. Packaging methodology

A schematic demonstration of the dedicated package for the optical gas sensing is shown in Fig. 2b, where 50% of the packaging top surface was covered with a porous AAO membrane, to act as a filter to let air and other gases pass and prevent contaminations in forms of particles down to certain dimensions to enter the sensing area. The commercially available AAO membranes normally offer thorough pores, with almost homogenous pore diameters. The density and the pores diameter are dependent on the anodization conditions and are in general well-controlled. For the current work, the membranes were purchased from Smart Membranes. As shown in Fig. 2a, the geometrical properties of the AAO membranes can be presented with the pore radius (r_0), the membrane thickness or pore length (L), and the inter-pore distance or periodicity (d_0). The holes of these membranes are arranged with a hexagonal periodicity. The porosity (φ) indicates the opening area on the membrane surface, and for our case of a hexagonal lattice can be calculated as:

Table 1
Geometric and diffusion parameters of the studied AAO membranes.

Porous membrane	r_0 [nm]	d_0 [nm]	L [µm]	φ (%)	$D^{eff} \times 10^6$ [m²/s]
AAO-1	20	125	50	9.3	0.3587
AAO-2	35	125	50	28.4	1.6411
AAO-3	40	100	50	38.7	3.6496

$$\varphi = \frac{2\pi}{\sqrt{3}}\left(\frac{r_0}{d_0}\right)^2 \quad (1)$$

The geometrical parameters of the studied AAO membranes are listed in Table 1.

2.3. Modelling the diffusion

In order to evaluate the delay introduced by the filter and also, to understand the effect of the two extra channels in the prototype system, the gas diffusion through the membrane and the holes are modeled. For simulating the mass diffusion, different CO_2 concentrations in air are considered. For a problem consisting of different gases, the binary mass diffusion coefficient ($D_{i,j}$) of the component *i*th in the component *j*th is described by Chapman-Enskog theory [15] as:

$$D_{i,j} = \frac{0.00186T^{\frac{3}{2}}}{p\sigma_{ij}^2\Omega_D}\left(\frac{1}{M_i} + \frac{1}{M_j}\right)^{\frac{1}{2}} \quad (2)$$

where p is the pressure in Atmospheres, T is the absolute temperature in Kelvin, M_i is the molecular weight of the *i*th species, and $\sigma_{i,j}$ is the

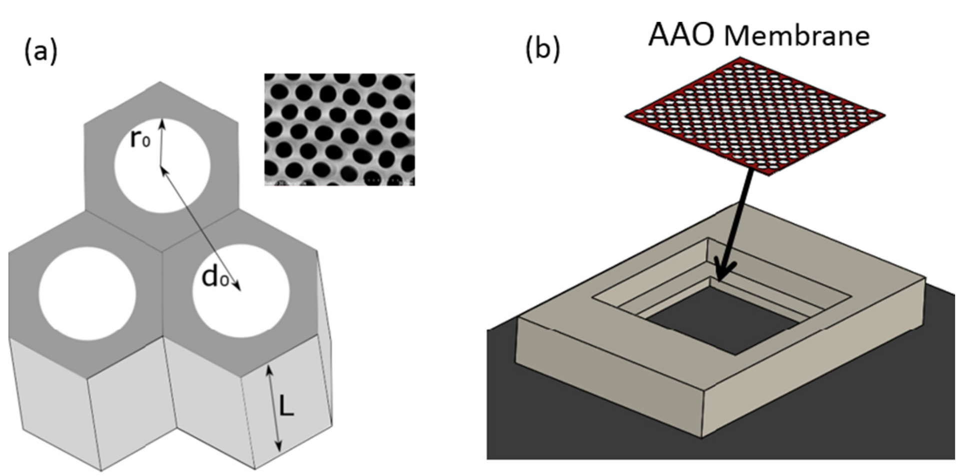

Fig. 2. (a) Schematic representation of the hexagonal lattice of the AAO membrane, inset: the SEM image of such a membrane [14], (b) a schematic representation of the package for the optical gas sensor.