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Highly sensitive and fast response gas sensor based on a light reflection at the glass-photonic crystal interface

A.S. Kuchyanov*, P.A. Chubakov, A.I. Plekhanov

Institute of Automation and Electrometry SB RAS, 1, Acad. Koptyug Ave., Novosibirsk 630090, Russia

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ABSTRACT

We develop a versatile gas sensor based on the condition for total internal reflection at the glass-photonic crystal interface and corresponding detection scheme for rapid and precise measurement of vapors. The sensor consists of a vapor sensitive photonic crystal film as a Fabry–Perot etalon coated on a solid substrate (e.g., large face of a glass prism or glass slide). Such scheme and specific physicochemical properties of submicron silica particles provide photonic crystal sensor selectivity due to the capillary condensation of ammonia vapor with a sensitivity of 1 ppm with a response time of 100 ms.

1. Introduction

The latest gas sensors are making our lives safer, industrial plants more efficient, and driving less risky. Reliable, fast and small, they range from methane sensors that can spot defects in gas pipes to an alcohol tester in a cell phone. There are also very few methods today for measuring concentrations of other gases quickly and efficiently. But the devices are either too expensive and complicated to operate or, if they are simple and cheap, they do not yield reliable results. Optical techniques for the detection of liquid and gaseous analytes are of considerable interest for a wide range of applications [1]. As compared to electric analogs, they are not susceptible to electromagnetic interference and do not generate an electric field which may be undesirable in environmentally sensitive areas. The demand for portable and light-weight sensors is relentless in several industries, from consumer electronics and light-weight industrial sensing [2] to biomedical engineering such as point-of-care health monitoring [3] and the military. Increasing awareness and new regulations for safety and emission control have created a strong demand for compact/portable, reliable trace gas sensors (ppb concentration). However, due to the various limitations of current detection technologies, the gas detectors that meet these requirements are hardly available today. In particular, the detection of ammonia (NH_3) has attracted considerable interest in the environmental industry, explosives detection, and medical aspects. The allowed exposure limit in such environments is about 20 ppm. On the other hand, the fraction of exhaled NH_3 can be measured easily and has been recognized as a bio-marker for human physiological disorders. For example, a high correlation between blood urea nitrogen and breath ammonia level in kidney patients has been reported [4].

Optical sensors provide an attractive, stable, and economic alternative for portable applications. Thanks to recent advances in new optical materials optical sensors are expected to advance at a rapid rate. In recent years meaningful efforts have been made to design and develop optical sensors capable of monitoring an analyte in situ with minimal disturbance to the sample matrix. The efficiency of an optical chemical sensor depends strongly on the proper choice of indicators and the sensing platforms chosen to determine the analyte.

The integral features of optical chemosensor are determined by two main factors. These are the physicochemical properties of the sensor element and optical design. The physicochemical properties determine the optical parameters which vary due to an exposure to vapor analyte. These parameters are the refractive index and the size of which varies during swelling [5,6], the optical absorption coefficient and luminescence [7,8].

Silica photonic crystal (PhC) is a strong candidate to use as an optical chemical sensor due to its unique properties [9–11]. High internal surface area, high resistance to aggressive environment, biocompatibility and high surface quality are a few among them. An example of a three-dimensional (3D) PhC is synthetic opal fabricated in the close-packed structure where the nodes are spherical amorphous silica (SiO_2) particles of submicron size.

Recently, considerable attention has been devoted to the

* Corresponding author.
E-mail address: aleks@iae.nsk.su (A.S. Kuchyanov).

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applications of photonic crystals as optical chemical sensors[11–13]. Such materials have a high potential of application in sensing owning to their ability to respond to changes in the surrounding environment with a modification of their optical properties (reflectance or transmittance spectrum), generally caused by a variation of their refractive index or the thickness of the constituent layers, or both. Since self-assembled opal crystals themselves are relatively weak due to the fragile contact points between spheres within the structure, many structurally deformable photonic structures have been made from closed-packed or non-close-packed colloidal crystal arrays encapsulated within a hydrogel or polymer matrix that fills the void space surrounding the colloidal crystal [14,15]. The interaction between the polymer and vapor analyte causes a change in the reflection spectrum. By measuring the reflection spectrumshift, the concentration of the analyte can be quantified. Usually such spectral domain measurements involve a bulky spectrometer, and are often slow and limited by the spectral resolution of the spectrometer. A tunable diode laser has also been employed to measure sensor spectral shift but the tunable diode laser is expensive and has a limited tuning speed and range.

To increase the sensitivity of an optical chemical sensor a thin-film Fabry–Perot (FP) is used [16]. Thin layer of the polymer is chosen as the vapor sensing layer. In vapor sensing applications, a variation of sensing layer refractive index can be used to quantify the analyte. However, in a regular FP sensor, since the polymer thickness varies significantly, relating the intensity change to the change in thickness and/or refractive index of the polymer becomes quite challenging. This obstacle can be overcome by introducing another FP sensor, adjacent to the first one, with an additional thickness and under the assumption that the vapor causes the same polymer response in another FP [16]. The sensitivity of this sensor depends on the light incident angle, wavelength, reflectivities at the two interfaces, and the detector responsivity.

The main objective of our work was to use silica 3D PhC film as an optical chemical sensor for ammonia. The silica PhC film is chosen as the vapor sensing layer coated on a solid substrate (e.g., large face of a glass prism or glass slide). We used the condition for total internal reflection (TIR) to gain maximum sharpness of the interference pattern when the derivative of sensor response is maximal. This provides a detection limit of the vapor at approximately 1 ppm with a fast response time of 120 ms. Specific physicochemical properties of 3D PhC silica submicron particles provides a sensory selectivity due to the capillary condensation of vapor analyte.

2. Principle of sensor

The concept of an optical sensor, where a change in light properties is the transduction process, has been known for several decades.

The most commonly used optical sensors are based on thin-film FP interferometer [16,17] as shown in Fig. 1. The sensitivity of such optical chemo sensors besides its physical and chemical properties is determined by the sharpness of the interference pattern $F = 4R/(1 - R)^2$, depending only on its mirror reflection coefficient R. The reflection coefficient of the films at normal incidence is not more than 0.05. Attempts to increase the reflection coefficient using the high reflection coating leads to the fact that the analyte does not penetrate through the reflective coating of the sensing film. The use of a highly reflecting substrate improves the contrast pattern [17], but does not solve the problem fundamentally.

In this context we have used the condition for TIR to maximize reflectance. In this case, the coherent light is confined to propagate within the waveguide element (sensor film) in zigzag pattern where the light is reflected at each waveguide interface as shown in Fig.1. Thin-film interference occurs when incident light waves

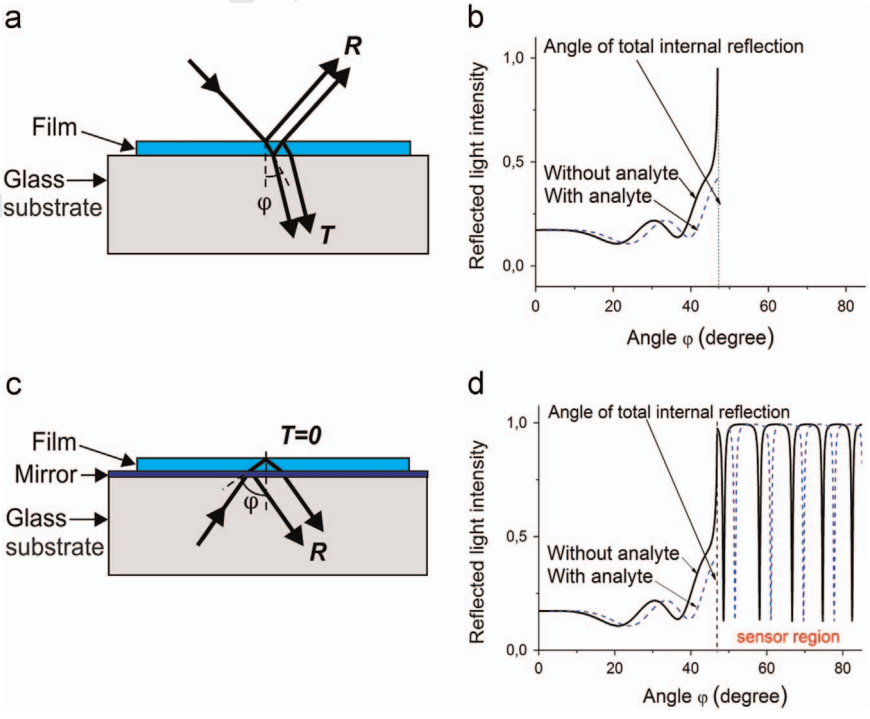

Fig. 1. Side view of a Fabry–Perot sensor. (a) Optical scheme, absorption of analytes by film results in a change in thickness and/or refractive index of the sensor film, which in turn leads to a change in the reflected light intensity as shown in (b) solid curve-without analyte; dotted line-after absorption of analyte. Side view of a Fabry–Perot sensor at the condition for total internal reflection. (c) Optical scheme, absorption of analytes by film results in a change in thickness and/or refractive index of the sensor film, which in turn leads to a change in the reflected light intensity as shown in (d)-solid curve-without analyte; dotted line-after absorption of analyte.

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