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Towards Integrated Plasmonic Gas-Sensors in the MWIR †

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Abstract: Optical measurement approaches have proven to provide intrinsic selectivity and the sensitivity, required for the development of integrated gas sensors. In an on-going project, we work towards a Si-photonics non-dispersive infrared gas sensor and are investigating the possibility of the incorporation of IR-active plasmonic materials, which could allow to increase sensitivities and reduce size of such sensors. Here we present the basic concept and discuss in some detail first results concerning fabrication and characterization of the plasmonic properties.

Keywords: NDIR gas sensor; hybrid plasmonic-photonic crystal waveguide; silicon photonics; IR plasmonics

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1. Introduction

Integrated environmental sensing for personal health care monitoring is a topic of increasing interest and has triggered much research towards full integrated sensor solutions. In this context optical spectroscopic measurement approaches in the infrared can provide intrinsic selectivity and sensitivity, as required for the development of integrated gas sensors. In an ongoing project, we work towards a Si-photonics non-dispersive infrared gas sensor and are investigating the possibility of the incorporation of IR-active plasmonic materials, which could allow to increase sensitivities and reduce the size of such sensors. Here, we will first present the overall idea, which consists in the combination of pillar photonic crystal waveguides with plasmonic elements in order to provide maximal interaction with gaseous analytes [1]. Then, we describe the characterization of the very first test structures, which were fabricated. Reflectivity measurements on grating structures allow the detailed characterization of the plasmon resonances, which can also be related to theoretical estimations and FEM simulations.

The basic concept, which we investigate here in the context of a miniaturized sensitive integrated gas sensor, is based on the idea of combining plasmonic propagation bound to a conductive surface with propagation within a pillar type photonic crystal (PhC) structure based waveguide [2], which enables slow group velocity, wavelength selectivity and strong interaction with the gas to be measured. The conceptual structure is shown in Figure 1.

The photonic crystal waveguide is based on dielectric pillars made from Si. Since the gas can freely penetrate between the pillars, strong overlap between the photonic mode and the analyte is expected. Furthermore, the slower light propagation effectively increases interaction time and thus sensitivity. However, detailed simulations reveal, that conventional two-dimensional dielectric PhC waveguides would require a prohibitively high aspect ratio in order to efficiently confine the guiding mode in the vertical direction. By combining a PhC waveguide and surface plasmon polaritons (SPPs), the proposed system efficiently confines the optical mode vertically while benefiting from the lateral confinement enabled by PhC structures.

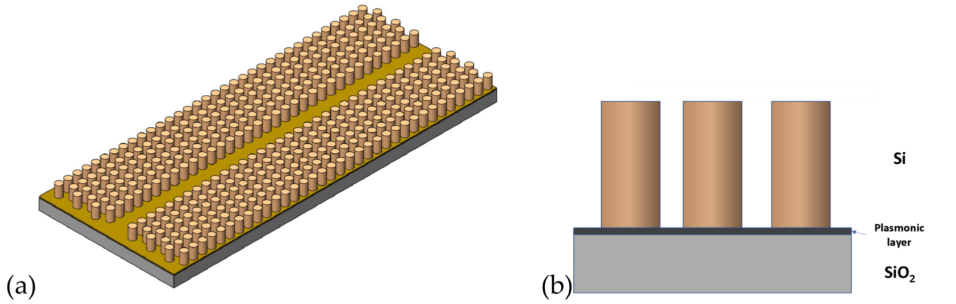

Figure 1. Scheme of the concept: A pillar type photonic crystal with a line defect as a waveguide structure is placed on a conductive layer. Pillars are made from Si. The plasmonic layer is deposited on SiO_2 (a) overview, (b) cross section with layer stack

Within this work, we wanted to demonstrate the feasibility of fabrication as well as to characterize possible plasmonic materials to be used.

2. Materials and Methods

Fabrication of the structures

In the initial tests, two structures were realized. On the one hand, fabrication of the pillar type PhCs was established and on the other hand we fabricated simple test-structures, in order to be able to validate the SPP-properties of different plasmonic materials.

The proposed structures were fabricated on 8-inch silicon (Si) substrates in the clean-room facilities of Infineon Technologies Austria AG in Villach. An oxide layer with a thickness of about 2 µm was deposited to decouple the waveguide from the substrate. Then a doped polycrystalline Si layer was deposited via low pressure chemical vapor deposition (LPCVD) on top. Afterwards the structures were etched using a standard Bosch etch process [2]. For the pillars, the Si-layer had a height of roughly 4 µm and the etch process was performed over the whole thickness. For the grating structures, a Si-thickness of 600 nm was chosen and by varying the etching times, gratings with different depths were prepared. For tests with metals, the plasmonic material with a thickness of about 100 nm was added by a sputtering process to ensure good sidewall coverage.

More details on the fabrication process are given in [4]. Representative SEM images of the structures are shown in Figure 2.

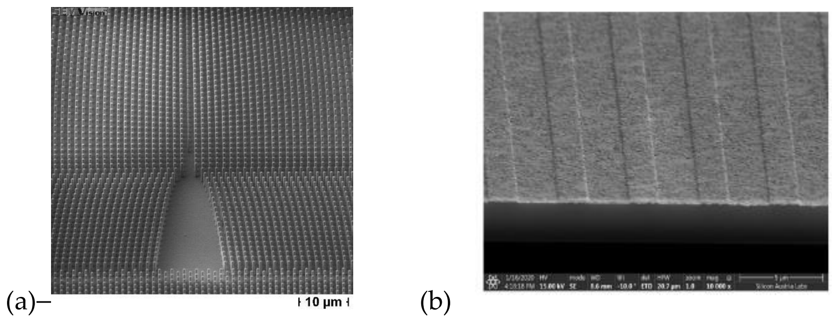

Figure 2: (a) SEM picture of the PhC-waveguide including the taper structure (b) SEM image of the grating structure

Plasmonic characterization

Characterization of the plasmonic properties was done with reflective measurements on the grating structures. The schematic set-up is shown in Figure 3(a). The beam of a Quantum Cascade laser (QCL, MIRcatTM, DRS Daylight Solution), which was tunable in the range around 4.2 µm, was guided to the grating-sample and the intensity of the reflected beam was measured with an MCT detector. The sample was mounted on a rotation stage, in order to adjust the incoming angle of the beam. The laser was linearly polarized with the polarization perpendicular to the grooves of the grating.

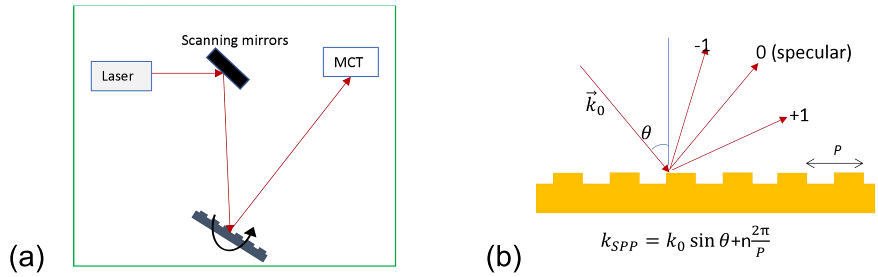

Figure 3. (a) Scheme of the measurement setup for reflectivity measurements (b) Geometry for the reflection at the grating. The wavevectors for incoming beam and several orders of reflection (+1, -1, 0) are plotted. Coupling to the surface plasmon mode occurs when the resonance condition is fulfilled.

Measurements were typically performed for different angles in the range from 24°-30° and over a wavelength range of 4.0 µm-4.3 µm. The reflected intensities were referenced to the reflection spectrum obtained from a flat Au-coated Si substrate.

3. Results and Discussion

The measurements reported here were performed on a shallow grating with a depth of 50 nm, coated with a 100 nm Ag-layer. Results are shown in Figure 4. A clear resonance dip from the plasmon resonance can be observed, the position of which varies continuously with the reflection angle.

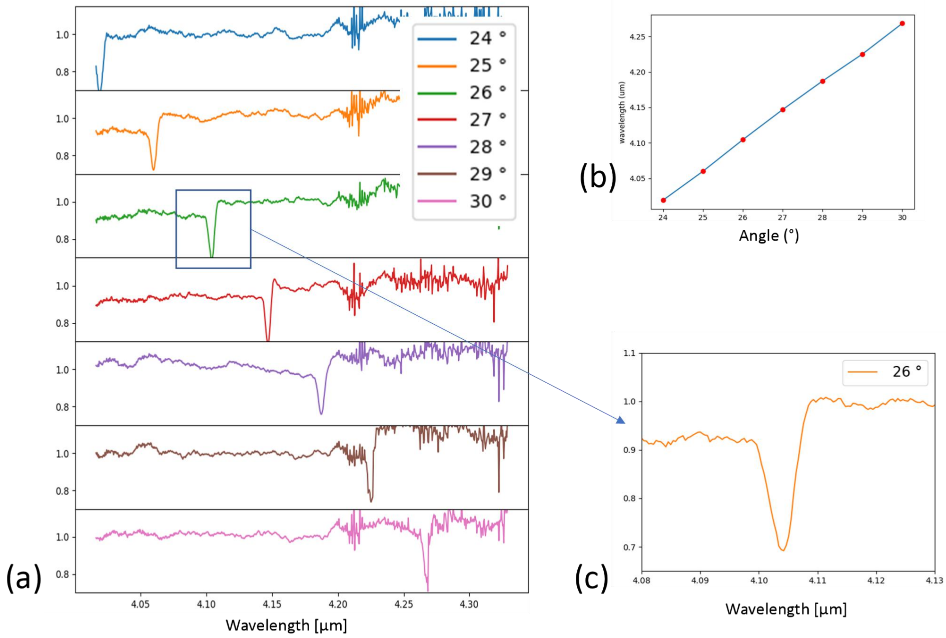

Figure 4. (a) First results from reflectivity measurements of Ag coated grating structures for different angles of incidence. (b) The extracted position of the SPP

resonance as a function of angle. (c) Zoom out of the SPP resonance for incidence angle of 26° reveals narrow resonance dip (FWHM less than 5 nm)

On the long wavelength side, starting at a wavelength from around 4.2 µm the data is quite noisy, which is caused by the absorption band of CO_2, which peaks at around 4.26 µm. Since measurements were performed in ambient air, with an overall pathlength of about 100 cm, the absorption caused by CO_2 is significant. Nevertheless, in this region it is possible to follow the SPP resonance dip.

The position of the resonance as a function of incidence angle is shown in Figure 4(b) and closely follows the theoretical prediction except for a constant offset, probably caused by uncertainties in the zero calibration of the angle. Figure 4(c) shows a zoom on the SPP resonance for the case of 26° incidence angle. It has a width of less than 5 nm. This is in good agreement with simulations, which predict about 2-3 nm width for a grating depth of 50 nm and which can also well describe the shape of the signal.

Overall, the results predict good performance for Ag layers in the mid-IR range. In addition, more detailed investigations including different metals and structures have meanwhile also been performed [5,6]

4. Conclusions

We have reported very first results in the context of a novel integrated sensing concept, which combines PhC-waveguides with SPP propagation. Reflection measurements on Ag-coated grating test structures revealed narrow SPP resonances which is in good agreement with simulation, indicating favorable properties for mid-IR plasmonic sensors. We are confident, that approaches incorporating plasmonic structures will significantly extend the range of possibilities in the field of integrated infrared sensors.

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Conflicts of Interest: The authors declare no conflict of interest.

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