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Characterization of a Vertical-Cavity Enhanced Detector for Narrowband Detection in the Mid-Infrared †

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Abstract: In this work we present the experimental characterization of a vertical-cavity enhanced resonant detector (VERD) optimized for detection in the mid-infrared. We demonstrate that the VERD shows a 7.1 times higher absorption and responsivity at 4.26 μm compared to a bare metal absorber. As such this design can be easily optimized and integrated to specifically enhance the absorption around the design wavelength.

Keywords: detector; photonic crystal; mid-IR; bragg reflector

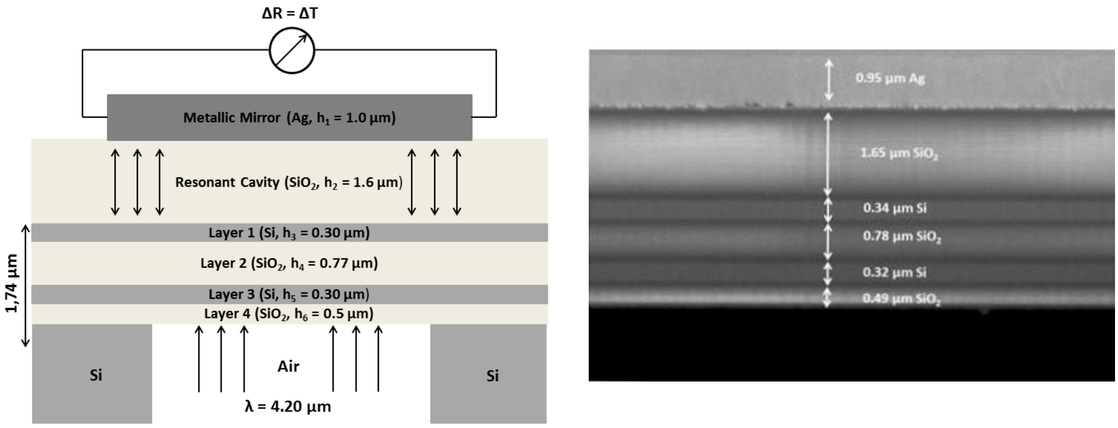
1. Introduction

Various gases have specific absorption peaks in the infrared spectral region due to the existence of different vibrational and rotational modes of the molecules. These characteristic fingerprints can be utilized to reliably detect their presence and concentration within the environment using photonics-based sensors. There is an increased interest to shrink such sensors achievable by, for example, the use of waveguides for evanescent-wave absorption sensing or photoacoustic spectroscopy [1,2]. Photoacoustic sensors, for example, rely on the specific absorption of electromagnetic radiation by gaseous molecules generating, due to periodic temperature variations acoustic waves, detectable by a microphone [3]. Similarly, in absorption based photonic sensors the frequency of incident radiation is matched to a specific corresponding mode of the analyte molecule. These sensors have the advantage that a primary effect (i.e., absorption) is measured rendering them much faster when compared to photoacoustic devices. For absorption based sensors there is, however, a need to tune the operating frequency of the sensor for selectivity. This can either be done on the emitter or the detector side. On the emitter side quantum cascade lasers (QCL), for example, can be used. QCLs are, however, often hard to integrate due to compatibility of exotic materials with classic Si-based-photonics. A simple alternative for integrated photonic based sensors can be achieved by filter structures in form of a Bragg mirror (e.g., silicon/silicon dioxide) tailored for permeability at a specific wavelength termed vertical-cavity enhanced resonant thermal emitter (VERTE) as proposed by I. Celanovic et al. [4]. Briefly, a VERTE-consists of a resonant cavity sandwiched between a silver layer and the Bragg mirror. Our group further optimized this structure and an experimental characterization of the VERTE structure is described elsewhere [5]. Based on

Kirchhoff's radiation law "a good absorber must also be a good emitter and vice versa". The VERTE could potentially also be used as an absorption based sensor, here termed vertical-cavity enhanced resonant detector (VERD). In this work we present the experimental characterization of the VERD structure which was optimized for the CO_2 absorption as a detector. Our results indicate a significant enhanced absorption resulting in ~7.1 times higher responsivity compared to a bare metal surface.

2. Methods

The detector concept is composed of a thin dielectric cavity sandwiched between a Bragg reflector of alternating silicon and silicon dioxide layers on the front side and a thin partially reflective silver mirror on the backside (Figure 1). The Bragg reflector induces interference between multiple reflected beams at a specific wavelength given by the resonant cavity and maximum electromagnetic field intensity is achieved. The thin silver layer on the backside of the cavity acts as a highly reflective, slightly absorptive mirror forming the cavity. For thermal insulation the substrate is locally removed under the VERD. The absorption of the incoming radiation leads to an increase in temperature which can be read out by a silver meander structure and the change in resistance is proportional to the average device temperature. Different meander shapes were tested (Figure 2a–d). Each structure was mounted on an optical setup and a QCL was irradiated via a fiber onto the VERD at different power levels and responsivity of the VERD was quantified by change in device's average temperature by irradiation either the bare silver structure or through the layer stack (Figure 2e). While the overall absorption area is largest for the rectangular structures the round meander structures performed best, most probably due to the Gaussian beam shape leading to a higher average power density for these structures. In addition a solid silver surface is in the center of the circular structures, further enhancing absorption at the peak beam intensity.



(**a**) (**b**)

Figure 1. Schematic of the VERD structure (**a**) and an example FIB cross section through the fabricated device indicating the individual layer thicknesses (**b**).

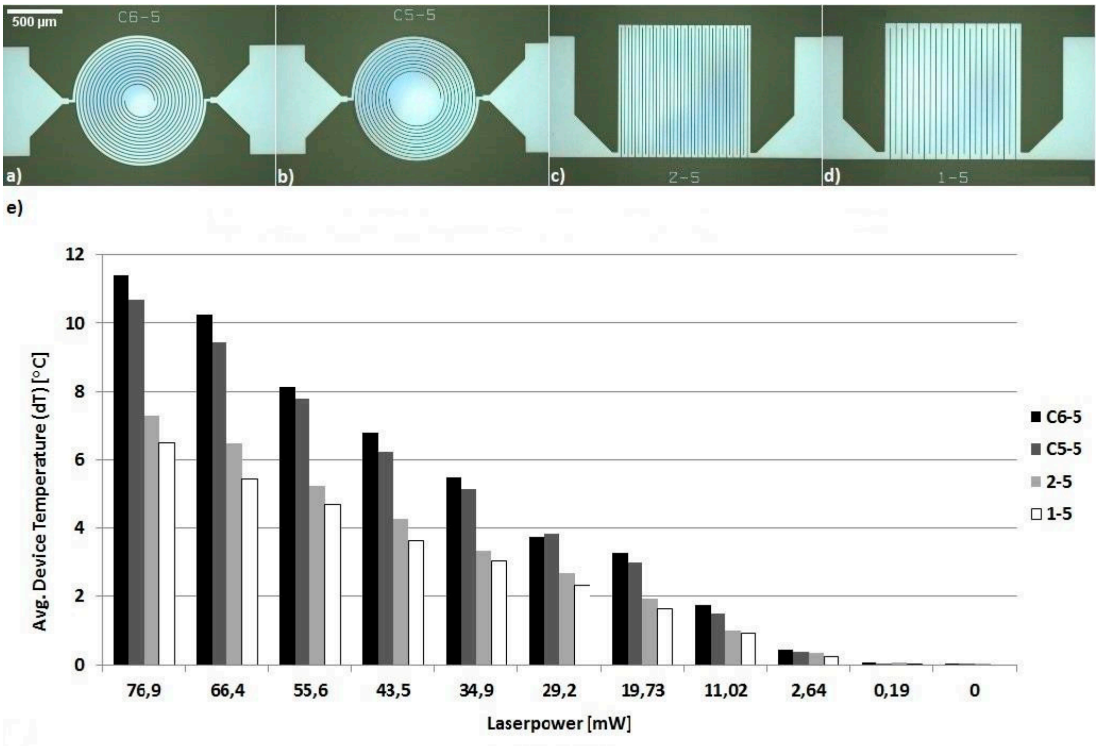


Figure 2. Different silver meander structures investigated (**a**–**d**). Responsivity of the four different structures at 4.17 µm.

3. Results and Discussion

To characterize the enhancement of the absorption due to the VERD the structure was irradiated at 4.26 µm either through the Bragg mirror stack (front side) or onto bare silver surface (backside)—while the average temperature was recorded for the best performing structure (C6-5, Figure 3). The VERD shows a quicker and higher response profile compared to the bare silver surface. Further responsivity was extracted for both structures by comparing the temperature change resulting from a given laser power (Figure 3c). Responsivity for the VERD was determined to be 149.5 mK/mW compared to 21 mK/mW for the bare silver surface, resulting in a 7.1 times enhancement. Note that absorbance of the metal surface could also be enhanced by, for example, choosing a different metal with a refractive index that has a higher imaginary part. There is, however, an intrinsic tradeoff since the Q-factor of the cavity is dependent on the reflectivity of the mirrors placed on both sides. Higher absorption values in the metal would ultimately de-tune the cavity leading to a broadening of the absorption spectrum and an increase in full—width half max (FWHM) of the VERD structure [6]. Thus, depending on the application one has to find a balance between absorption and reflectivity of the metal use. Further, by modifying the cavity thickness one can optimize the proposed design to be sensitive to a specific wavelength. Taken together these results demonstrate the feasibility of the VERD structure optimized for 4.26 µm. Given the simplicity of the design and the fabrication steps needed, we believe that the VERD is a promising candidate for integrated photonic sensors operated in the mid-infrared.

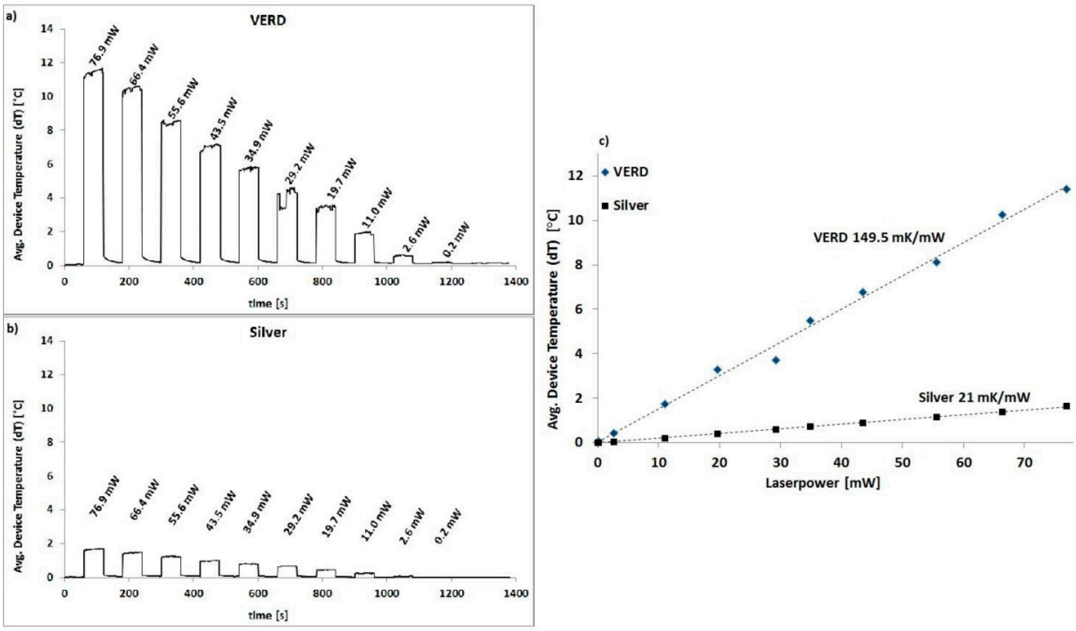


Figure 3. Heating characteristics of the VERD (**a**) and bare silver surface (**b**) of the best performing meander structure C6-5. (**c**) Extracted responsivity expressed as average device temperature increase in dependence of laser power.

4. Conclusions

In this work we show the experimental characterization of a VERD structure as a detector for Si based photonic sensors operating in the mid-infrared. We report a 7.1 times absorption enhancement indicating their feasibility as an integrated mid-IR detector.

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