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Sensitivity Comparison of Integrated Mid-Infrared Silicon-Based Photonic Detectors †

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Abstract: Integrated silicon photonics in the mid-infrared is a promising platform for cheap and miniaturized chemical sensors, including gas and/or liquid sensors for environmental monitoring and the consumer electronics market. One major challenge in integrated photonics is the design of an integrated detector sensitive enough to detect minimal changes in light intensity resulting from, for example, the absorption by the analyte. Further complexity arises from the need to fabricate such detectors at a high throughput with high requirements on fabrication tolerances. Here we analyze and compare the sensitivity of three different chip-integrated detectors at a wavelength of 4.17 μm, namely a resistance temperature detector (RTD), a diode and a vertical-cavity enhanced resonant detector (VERD).

Keywords: silicon photonics; mid-infrared detectors; cavity-enhanced resonant detector; integrated photonics

1. Introduction

Photonic sensors based on mid-infrared absorption spectroscopy are promising for chemical sensing due to the high selectivity achieved by probing molecular-specific vibrational absorption features. For field-analysis and portable-electronics applications, one major requirement is the capability to develop miniaturized, fully integrated photonic sensors with a high sensitivity and a small footprint. There are, however, still several challenges for highly integrated photonic sensors including the lack of cheap and powerful narrowband sources in the mid-infrared (quantum-cascade lasers are currently costly and make use exotic materials difficult to integrate into silicon photonics), and the poor sensitivity of typically uncooled detectors needed for low-power applications.

Here we focus on the spectral region around 4.2 μm relevant for CO_2 detection. In our previous work we showed the feasibility of CO_2 detection via evanescent-field absorption in slab and strip silicon waveguides, both using an external quantum-cascade laser or an integrated broadband thermal light source [1–3]. While our earlier work relied on an external MCT detector detecting gas-induced changes in light intensities, this work focuses on the development of integrated thermal detectors for mid-infrared radiation operating at room temperature. Different concepts of miniaturized mid-infrared detectors have already been proposed [4–7]. While high sensitivity can be achieved, such detectors are based on heavy-metal semiconductors such as PbTe or $Ge_3Sb_2Te_6$, and are thus rather complex to fabricate. In this work, we focus on detectors fabricated using standard MEMS processes, which are therefore easy to produce and integrate in existing fabrication technologies on a high throughput format. Three detector concepts are benchmarked against each other, namely: a resistance-temperature detector (RTD), a planar p-n diode, and a vertical-cavity enhanced resonant detector (VERD) based on the design of a vertical-cavity resonant thermal emitter [8,9].

2. Materials and Methods

Figure 1 shows microscope pictures of the three fabricated detectors. The RTD (Figure 1a) is a wire of n-type amorphous silicon (n-Si). The diode (Figure 1b) consists of a similar structure as the RTD with a p-n junction located in the middle of the wire. Both structures were fabricated in front of a slab waveguide at a distance of 1 μm from the waveguide. The solid substrate under the detector structure was removed and the structures lie on a 140 nm thick silicon-nitride membrane. Both RTD and diode are broadband thermal detectors. Thermal absorption is read-out resistively for the RTD or by changes in current at a constant bias voltage (1 V) for the diode.

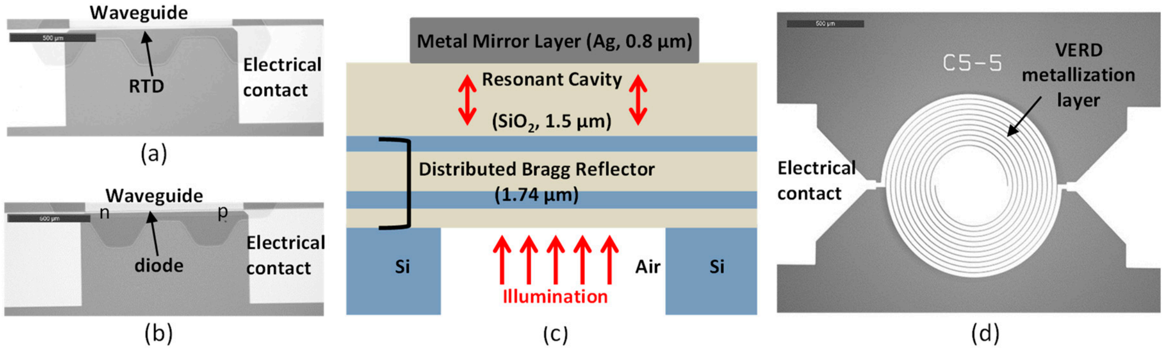

Figure 1. Overview about different detector designs. (**a**) RTD, based on a n-Si wire; (**b**) Diode: p-n junction on a Si wire (**c**) VERD: Schematic cross-section through the layer stack and (**d**) silver meander structure for resistance measurements.

The VERD consists of alternated Si/SiO_2 layers with a structured metallization layer on top (Figures 1c, 1d). The fabrication and optimization details are provided elsewhere [9]. Briefly, the structure function is analogous to that of a Fabry-Perot resonator, with a SiO_2 cavity, whose thickness determines the central operating frequency, and a thin layer stack of Si and SiO_2 beneath it, forming a distributed Bragg reflector. Being highly reflective and slightly absorptive, the metal layer (Figure 1d) functions simultaneously as the second mirror of the Fabry-Perot resonator and as a detector. In contrast to the RTD and the diode, the VERD structure works as a narrowband detector whose central frequency and bandwidth are determined by the cavity thickness and the distributed Bragg reflector (i.e., design parameter). The VERD is thermally decoupled from the substrate via a backside etch and the change in temperature of the metal layer due to absorption of the mid-infrared radiation is read out resistively.

For each structure the temperature coefficient in the linear regime until 100 °C was determined and was 3.84 Ω/K for the RTD and 0.077 Ω/K for the VERD. Different U-I curves were recorded for the diode and the temperature coefficient for 1 V bias was extracted and found to be 1.51 A/K.

The responsivity and the sensitivity of the three devices were quantified by a continuous wave external-cavity quantum-cascade laser (QCL), tuned to a central wavelength of 4.17 μm. For the RTD and the diode the laser light was coupled to a 500 μm-long slab-waveguide using a fiber and a grating etched on the top surface of the slab (Figure 2a). The detector response was monitored as a function of the laser power and time. For the VERD structure, which is not yet integrated with the waveguide, the laser light is out coupled from the fiber, collimated and refocused onto the sensor surface through the Si/SiO_2 layer stack (Figure 2b).

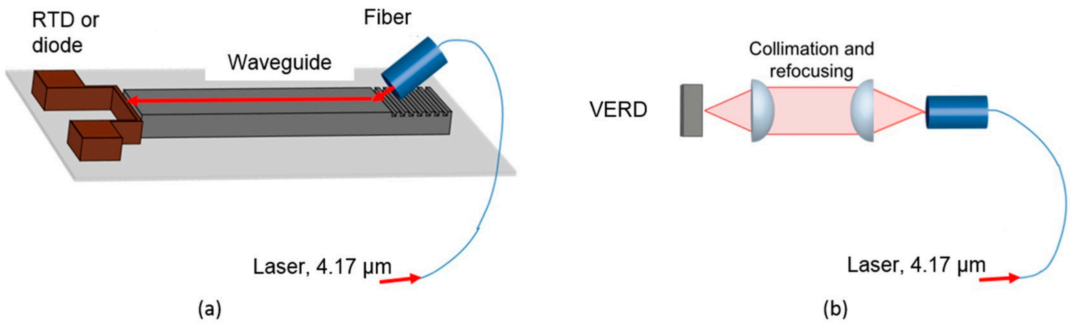

Figure 2. Schematic view of the experimental setup for characterization of (**a**) the integrated RTD and diode structures in front of a waveguide and (**b**) the VERD structure.

3. Results and Discussion

Figure 3 shows the recorded temperature profile for each structure as a function of incident power and time. To evaluate the responsivity of each detector, which is reported in Figure 3, the change in signal is plotted as a function of the laser power and a linear fit is used to determine the slope. The noise-equivalent power (NEP) is obtained by measuring the noise level at 1 Hz bandwidth for our detection scheme with a sourcemeter (Keithley SMU 2450). Power levels for the VERD are higher since the light is irradiated by free-space rather than through a (slightly) absorptive waveguide [10]. Using an integrated detection scheme the NEP is expected to further improve for all detectors.

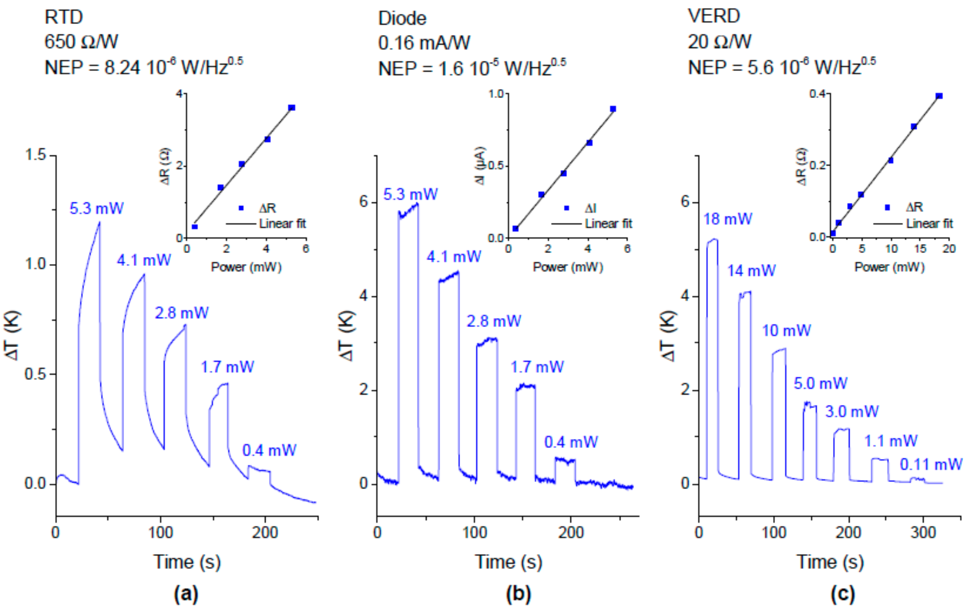

Figure 3. Temperature change of the three detectors illuminated by mid-infrared light at 4.17 µm. (**a**) RTD, (**b**) diode and (**c**) VERD. The experimentally determined responsivity and noise-equivalent power (NEP), including the current readout noise of our instrument, is indicated in each panel. The detectivity is expected to improve significantly by on-chip readout due to a reduction of the noise level.

The diode shows the highest light-induced temperature jump but also the highest noise, which might be partly due to the small measured current. Operation at higher voltages, however, is not recommended as it shows a reverse temperature-current dependence and significant non-linear response. Consequently, both resistive detectors outperform the diode due to the much lower NEP.

While the RTD shows very slow response times, with thermalization times exceeding 20 s, both diode and VERD react to the laser light on a sub-100 ms time scale and have faster recovery times. Additional preliminary measurements reveal that only a fraction of the measured RTD response (decreasing from about 75% to about 55% with increasing laser power) arises from direct light absorption, while the remaining signal arises from a slower temperature change of the membrane.

Therefore, the diode and VERD are better detector candidates for field applications, where a quick response to light changes and short acquisition times are required. Additionally, different from the RTD, these structures can be employed to detect modulated signals, making the final device less prone to thermal drifts and other low-frequency noise sources.

4. Conclusions

In this work we present a quantitative comparison between three integrated detector structures for mid-infrared photonic applications. In contrast to other detector structures our designs are solely based on standard MEMS processes. Our results show that the VERD is the most promising detector structure, since it combines a quick response time with a low detection limit and has, additionally, an integrated wavelength-filter function.

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Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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