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Optofluidic biosensors with Si-based photonic integrated circuit technology

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Summary:
This study reports a cost-effective optofluidic system achieved by monolithically integrating a microfluidic channel into a photonic integrated circuit technology. Alongside a photonic biosensor based on a silicon micro-ring resonator, we present findings on the feasibility and reproducibility on wafer-level of the integrated optofluidic system. The photonic biosensor is fabricated on a 200 mm silicon-on-insulator technology platform. While the photonic biosensor is structured from the top of the wafer, the microfluidic channel is introduced locally through a backside release process, utilizing a combination of dry and wet etching. In this way, the photonic biosensor in the front-end of line as well as the metal interconnects in the back-end of line can be fabricated in a mature photonic integrated circuit technology within a small area saving extensive costs for production.

Keywords: Photonic Biosensor, Photonic Integrated Circuits, Lab-a-Chip, Refractive Index Sensing

Introduction

Optical biosensors play a pivotal role in real-time monitoring of biomolecular markers, making them indispensable for a multitude of applications in various crucial domains such as healthcare, food diagnostics, environmental monitoring and water analysis [1]. Particularly in the context of high-content diagnostics, where a comprehensive characterization of analytes is essential rather than their mere quantification, optical biosensors offer unparalleled potential. Due to their high sensitivity and modular design, fast adaptation to a variety of analytes is highly beneficial. For over three decades, direct-optical biosensors such as surface-plasmon resonance (SPR) spectroscopy have been regarded as gold standard in the pharmaceutical-driven research and quality control processes. This is primarily attributed to their remarkable capability to swiftly and sensitively provide high-content data, a critical advantage in the field with significantly more information compared to classical immunoassays like lateral flow immunochromatographic assay (FPIA). Simultaneously, the realm of biosensing has witnessed a dynamic evolution over the last 15 years with the intensive development of silicon-based photonic integrated circuits (PIC) driven by a trend of miniaturization and cost reduction [2]. Initially recognized and extensively utilized in the realm of telecommunications only, these PICs have undergone significant adaptation, refinement and diversification for integration into biosensing applications, marking a transformative phase in biosensor technology. Photonic biosensors constructed from silicon, the most abundant and processed semiconductor, exhibit considerable promise as key components in lab-on-a-chip solutions. However, until now their widespread adoption faced a significant hurdle - the intrinsically complicated structure of the measurement system, encompassing optical, electrical and microfluidic connections [3]. The current state of the art for further processing of these photonic chips is marked by its complexity and high cost, limiting its use to academia only and rendering it impractical for mass production. Addressing these gatekeeping challenges, we propose a novel approach involving the monolithic integration of microfluidics from the chip's rear surface. This innovation facilitates a simple yet cost-effective and mass-producible method for chip advancement. Leveraging a modified CMOS process flow, we employ localized backside etches to expose the photonic sensor structures on the die, enabling the seamless integration of four photonic biosensors, detection photodiodes and the custom microfluidic into a compact chip. Our

experimental endeavors have convincingly demonstrated the viability of this monolithic integration. This breakthrough holds immense potential, potentially revolutionizing the manufacturing and deployment of silicon photonic biosensors, thanks to the newfound prospects of mass production.

Fabrication

The photonic chip discussed in this study was created using Photonic Integrated Circuit (PIC) technology at IHP in Germany. The fabrication process uses standard 200 mm silicon-on-insulator (SOI) wafer, featuring a 220 nm crystalline silicon layer atop a 2 μm buried oxide layer. This crystalline silicon layer is meticulously structured using deep ultraviolet (DUV) lithography, specifically KrF (krypton fluoride) and an i-line lithography with 250 nm resolution, which is compatible with the CMOS-baseline technology. A detailed description of the fabrication process can be found in Ref. [4]. In terms of the microchip architecture, the back-end of line (BEOL) comprises three thin and two thick metal layers. This structural configuration is important as it significantly enhances the functionality and performance of the microchip. Moreover, it must be highlighted that the outcomes and findings presented in this study are not limited to the discussed PIC technology at IHP; they are equally applicable and relevant to electronic-photonic integrated circuits (EPIC) technologies.

To obtain the finished sensor, the chip is then placed on a printed circuit board (PCB) with electric contact pads and prestructured microfluidic channels, as shown in Fig. 1. In this way, we conveniently achieve electrical, optical and microfluidic interconnections on a plug-and-play level using standard procedures from microelectronic industries. This novel approach allows for mass production by a higher degree of integration and miniaturization and gives perspective to digital rapid tests in laboratory quality for point-of-care applications.

Experimental Set-Up

In the experimental set-up for measurements of the transmission spectra of the ring resonator, a tunable external cavity laser (Yenista TUNICS T100S-HP) serves as light source. The tunable laser is used to scan the wavelength dependent behavior of the ring resonator. A fiber-grating-coupler set-up is used to couple the light into the chip. The laser is connected to the input fiber, while an integrated Ge-photodiode provides the output signal. Due to the polarization dependence of the grating coupler, the polarization of the input light was adjusted in such a way that highest transmission is achieved by using a paddle style fiber polarization rotator (Thorlabs FPC031).

Photonic Biosensor

Designing sensors tailored to specific applications often involves a delicate balance between sensitivity and optical losses, traded off against each other within the constraints of the current fabrication process.

We employ a ring resonator as sensor transducer element. Reducing the line width (FWHM) of the ring resonator enhances the detection limit but necessitates minimizing optical losses within the ring resonator. Conversely, lower losses result from strong confinement inside the silicon waveguide, leading to reduced interaction with the fluid and, consequently, diminished ring resonator sensitivity.

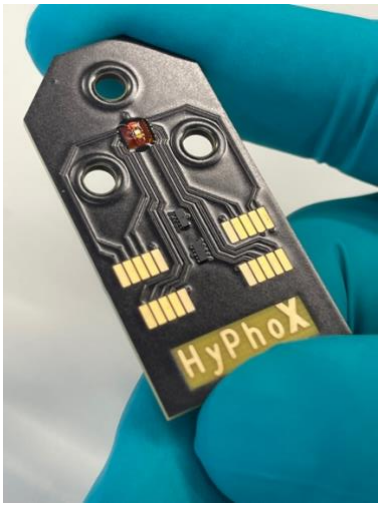

Fig. 1: Photonic biosensor chip placed on top of a PCB. Metal wire bonds connect the integrated Ge-photodiode with the PCB.

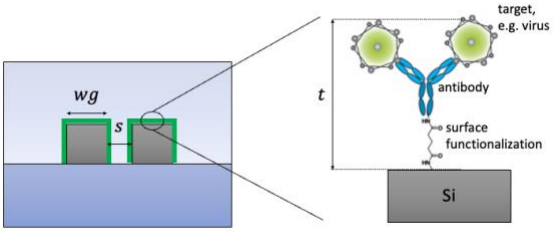

Fig. 2: Schematic cross-section of a slot waveguide and the surface with antibodies as capture molecules.

One strategy to find a compromise is the use of a partially slotted ring resonator, combining a rib waveguide with a slot waveguide [5]. A schematic cross-section of the slot waveguide is shown in Fig. 2. The slot waveguide is covered with antibodies as capture molecules, which requires a silane as surface

functionalization. We calculated the surface sensitivity to evaluate the performance of this kind of waveguide. Fig. 3 shows that the surface sensitivity decreases with higher slot widths. A slot width below 100 nm is recommended to keep high sensitivities but it should be noted that such slot widths are challenging in terms of fabrication tolerances.

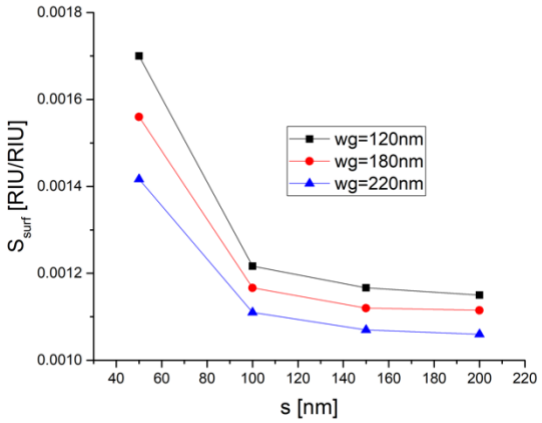

Fig. 3: Surface sensitivity as function of the slot width.

The slot waveguide incurs higher optical losses due to random line-edge sidewall roughness scattering but offers heightened sensitivity suitable for sensing applications. In our approach, we employ a rib waveguide alongside a strip-loaded slot waveguide. Fig. 4 shows the full width at half maximum (FWHM) of the resonance peaks. This data was deduced from wafer-level measurements. The low variance demonstrates the wafer-scale fabrication stability.

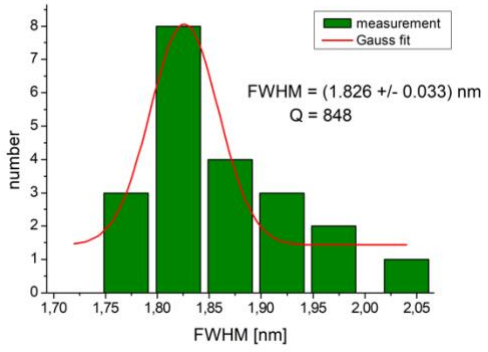

Fig. 4: Full width at half maximum (FWHM) of the partially slotted ring resonator. Each data point corresponds to one sensor chip. The data was collected on a full wafer.

We also investigated wafer-scale measurements on the integrated Ge-photodiode. Fig. 5 shows the responsivity defined as the photocurrent per laser power. We received a mean value of 0.606 A/W by taking into account nine sensor chips distributed over the full wafer.

The responsivity is deduced from the responsivity curve, as shown in Fig. 5. The slope of this curve is the responsivity of the photodiode. The low standard deviation below 5 dBm laser power indicates a low noise of the full system, including laser source.

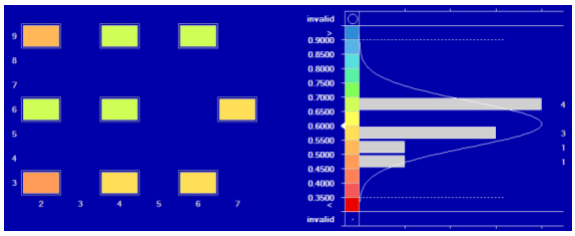

Fig. 5: Full wafer map of the integrated Ge-photodiode responsivity.

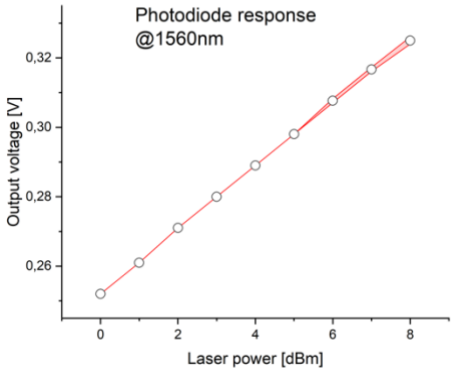

Fig. 6: Typical responsivity curve of an integrated Ge-photodiode. The responsivity is deduced from the slope of this curve. The orange line corresponds to the standard deviation.

The typical dark current of such an integrated Ge-photodiode is shown in Fig. 6.

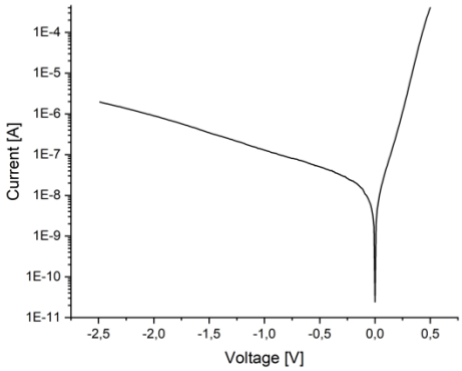

Fig. 7: Dark current of integrated Ge-photodiode.

To assess the sensor viability, we conduct a homogeneous sensing experiments using NaCl in deionized water at various weight percentages, as shown in Fig. 8, to evaluate the sensitivity.

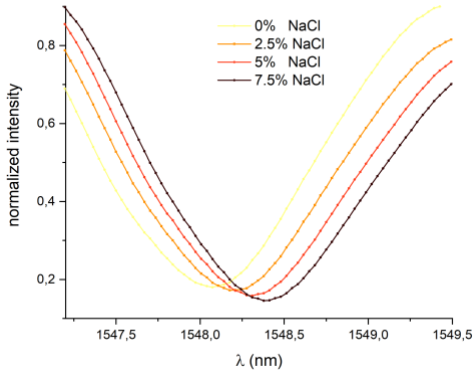

Fig. 8: Resonance peak position for different concentration of NaCl in deionized water at various weight percentages.

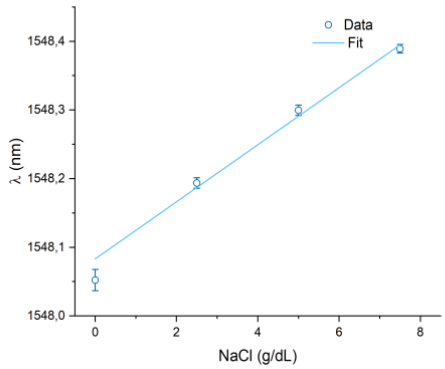

Fig. 9: Center wavelength position of each peak as a function of the NaCl concentration.

From Fig. 8 we deduced the center wavelength position of each peak as a function of the NaCl concentration, as plotted in Fig. 9. The slope of this graph gives a sensitivity of 0.04 nm/(g/dL).

Conclusion

We have demonstrated a photonic integrated biosensor in a silicon-based 200mm wafer-scale production. The performance evaluation was carried out at wafer-level and our results demonstrate a high reproducibility of the sensor device. In a proof of principle experiment we demonstrated a sensitivity of 0.04 nm/(g/dL) for bulk refractive index sensing. Further investigations are required for the specific detection of molecules. In this work we have demonstrated a wafer-scale analysis of the sensor elements, which represents the fundament for reliable and mass-producible photonic biosensors.

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