Results in Optics 9 (2022) 100317

Contents lists available at ScienceDirect

Results in Optics

journal homepage: www.elsevier.com/locate/rio

From Lab-on-chip to Lab-in-App: Challenges towards silicon photonic biosensors product developments

Andreas Mai [a,b,*], Christian Mai [a], Patrick Steglich [a]

[a] IHP - Leibniz-Institut fuer innovative Mikroelektronik, Im Technologiepark 25, Frankfurt (Oder), 15236, Germany
[b] Technische Hochschule Wildau, Hochschulring 1, Wildau, 15745, Germany

ARTICLE INFO

Keywords:
Silicon photonic sensors
Integrated optical sensors
Photonic integrated circuits
Optical ring resonators
Photonic biosensor
Refractive index sensing
Interchangeable sensor chip

ABSTRACT

This work presents and evaluates different approaches of integrated optical sensors based on photonic integrated circuit (PIC) technologies for refractive index sensing. Bottlenecks in the fabrication flow towards an applicable system are discussed that hinder a cost-effective mass-production for disposable sensor chips. As sensor device, a waveguide coupled micro-ring based approach is chosen which is manufactured in an 8” wafer level process. We will show that the co-integration with a reproducible, scalable and low-cost microfluidic interface is the main challenge which needs to be overcome for future application of silicon technology based PIC sensor chips.

1. Introduction

Photonic integrated circuit (PIC) technologies are widely used for applications in communication but have additional great potential for the realization of optical sensor development for cost-effective disposable sensor solutions with various applications in environmental monitoring, food analysis and point-of-care-testing (Steglich et al., 2019). Such sensors have the potential for the simultaneous analysis of various substances (Wang et al., 2020) and physical parameters such as temperature (Mai et al., 2019) and stress (Lu and Lee, 2009). Basic principle of these sensors is the interaction of an evanescent decoupled light wave close to a waveguide. These PIC based device technologies provide a scalable platform for label-free sensing of various substances (Luan et al., 2018) as well as temperature sensing (Dickmann et al., 2021). Recent advances in the design of sub-wavelength grating waveguides (Kita et al., 2018) and coherent phase detection (Molina-Fernández et al., 2019) have led to a high sensitivity and demonstrate their high performance. Due to the fact that sensor application means a defined interaction of the device with the bio-chemical environment recent approaches usually use passive photonic devices. Hence, the PIC-based sensor chips are realized without or very limited possibilities of co-integration with electrical driven components, like photodetectors, and an on-chip data processing is usually excluded. Moreover, scalable on-chip light sources are still not available through open-access silicon photonics platforms (Rahim et al., 2019) and an external light source is required. In order to use an external light source like a tunable laser or a super luminescence diode, the photonic sensor can be integrated in conjunction with grating coupler for an effective fiber-to-chip light coupling (Bondarenko et al., 2021). Beside this high potential of the sensor chip technology a remaining challenge is an effective co-integration with the necessary fluid environment. Different chip based integration of microfluidic components had been presented so far. However, ability of scaling and compact integration are still a missing piece from a Lab-on-chip concept to an towards an applicable Lab-in-App system.

In this paper we will present the main reasons hinder a compact integration of optical, electrical and bio interface. In the first section, we will show and discuss general aspects and necessary steps in the fabrication and value chain for a chip based photonic sensor. The second part discuss challenges for the co-integration of passive and active PIC sensors with a microfluidic environment and presents an integration method enabling a compact co-integration. We present in part three a system integration concept for this sensor chip and show first proof of concept results for the entire system.

2. Fabrication and value chain of PIC sensor

The use of silicon photonic waveguides as refractive index sensor is commonly known for several years. Advances in silicon technology thereby push the developments towards a widely accessible research platform and many application scenarios had been identified so far (Steglich et al., 2019). In general there are different steps which needs to be considered with the fabrication chain from a chip towards an applicable sensor. Surface functionalization on wafer level

---

* Corresponding author at: IHP - Leibniz-Institut fuer innovative Mikroelektronik, Im Technologiepark 25, Frankfurt (Oder), 15236, Germany.
E-mail address: mai@ihp-microelectronics.com (A. Mai).

https://doi.org/10.1016/j.rio.2022.100317
Received 18 May 2022; Received in revised form 11 October 2022; Accepted 30 October 2022

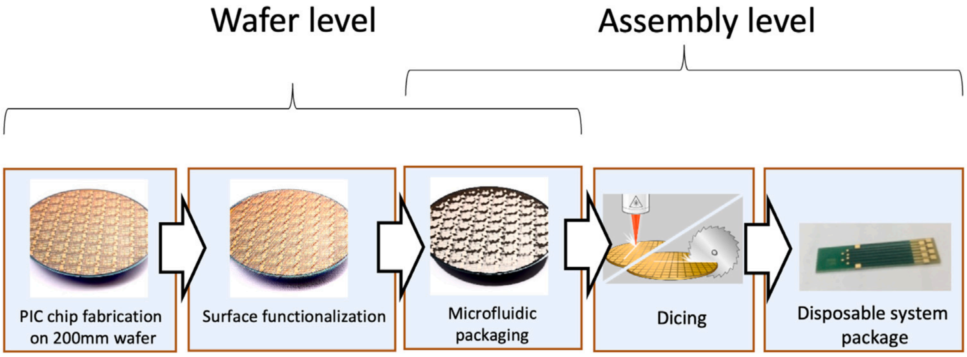


Fig. 1. Photonic sensor fabrication chain from chip technology towards disposable sensors. Co-integration of the sensor chip can applied either by on-wafer integration techniques or during the system assembly. Both approaches have to face the challenge of local and high density integration on the electronic–photonic chip interface.

and the conjunction with an appropriate microfluidic environment for commercial purposes are two main key points within this chain. But usually the attempt applying these steps are pre-defined by the underling chip technology and especially the microfluidic integration can be implemented either on wafer level or during the assembly of the systems as shown in Fig. 1.

If you use a standard photonic-integrated-circuit technology (PIC) consisting of passive photonic components as waveguides e.g. as micro-ring resonator and coupling structures. The working principle of such resonators is based on a refractive index change (Steglich et al., 2022). At this point, we should distinguish between two cases. First, if the refractive index of the surrounding material changes, we speak about refractive index sensing in bulk material or surface sensing in case of specific detection of molecules at the surface of the waveguide. Second, if the refractive index of the optical waveguide is changed, we speak about thermal or stress sensing, depending on either the refractive index change originates from a temperature change or from the applied stress inside the silicon waveguide, respectively. Temperature sensing is highly efficient in silicon-based PICs due to its large thermo-optical effect (Weituschat et al., 2020). In all aforementioned cases, the detection principle relies on the change of the effective refractive index of the optical waveguide which causes a change of the resonance condition that can be detected by tracking the resonance peak position or by measuring the intensity at a fixed wavelength. The peak position is usually tracked by using a broad light source in combination with an optical spectrum analyzer, while the intensity can be measured by employing a laser with a photodiode. However, you have to provide increased effort during the assembly of the sensor system due to the required integration of the opto-electrical interface, data recognition by a photodetector and additional data evaluation in an external read out circuit (ROC) as shown in Fig. 2. Thanks to advances in the integration of on-chip Ge-photodetectors which can work in conjunction with Si photonic passive elements (Lischke et al., 2015) an on-chip data conversion simplify the system integration due the avoidance of a optical output. However, a missing step to drop down the cost and requirements for sensor system realization is the monolithic co-integration of photonic devices in an electronic CMOS or BiCMOS platform, respectively. As shown in 2 thereby the complexity of chip integration increases as well as the costs and hence needs to be considered with respect to the system integration costs to find best performance vs. cost trade-off for the entire system.

As a consequence, the main challenge of photonic biosensors and their use in real point-of-care applications lies in the monolithic integration of grating coupler, photodiode and microfluidics to reduce the complexity of chip-integration and, hence, fabrication costs. Usually all three components are placed on the same side of the chip, occupying a relatively large area, which increases fabrication costs drastically. This leaves the high potential of silicon photonic sensors unleashed.

To overcome this issue, we propose and investigate a cost-effective optofluidic system by integrating monolithically a microfluidic channel into a PIC technology in conjunction with a easy to fabricate microfluidic interconnection, consisting of a replaceable sample substrate.

3. Chip integrated photonic sensor approaches and bottlenecks

To understand the necessity for such a compact integration approach we need to figure out the bottlenecks of alternative approaches. For all variants the fabrication of photonic biosensor is realized on a 200 mm silicon-on-insulator technology platform as part of a SiGe-BiCMOS process line. While the photonic biosensor is structured from the top of the wafer, the later presented microfluidic channel is locally introduced by a backside release process using a combination of dry and wet etching (Steglich et al., 2020). Other bottlenecks within the fabrication flow and measurement set-up are challenges in light source, detection technique and light coupling. Towards disposable sensor chips, the use of a single wavelength light source in combination with a chip-integrated photodiode is preferable since optical spectrum analyzer are expensive and cannot be miniaturized currently. As mentioned before, such a configuration can be used for intensity measurements. However, the main drawback of intensity measurement is the small detection range. Currently, approaches to track the peak position with a laser and photodiode is realized with a tunable laser, which is expensive and requires much space. To avoid this, a tunable optical filter is placed in front of the optical sensor (Moldenhauer et al., 2017). In this way, a broadband light source such as a superluminescent diode can be used because only certain wavelengths with sharp linewidth can pass the optical filter. The transmitted center wavelength can be tuned, so that the working principle of a tunable laser is achieved. The advantage of a tunable filter is mainly referred to the fact that it can be realized by integrating an additional add-drop ring resonator that is thermally tuned using the relatively large thermo-optical effect in silicon. Metal plates in the back-end of line can be employed as heater. Another bottleneck is related to the light coupling from the external light source into the chip. Single mode optical fiber having a mode field diameter of 10.4 μm and a numeric aperture of 0.14 are typically used. Due to these characteristics, the optical fiber needs to be placed above chip with a distance of about 3 μm, making the fiber alignment challenging. Therefore, precision 3D translational stages are used. However, the alignment procedure is time consuming and the tolerance against misalignment is small. Current research is focused on the development of cost-effective fiber-to-chip packaging methods to overcome this issue (Wan et al., 2019; Nauriyal et al., 2019).

3.1. Photonic sensor chips with top-side functionality

For the most simple approach to use a PIC sensor a technology can be used which just patterned the photonic layer. Fig. 3 shows an example of such a Si PIC micro ring resonator. The microfluidic structures needs to be placed on top and therefor with an appropriate

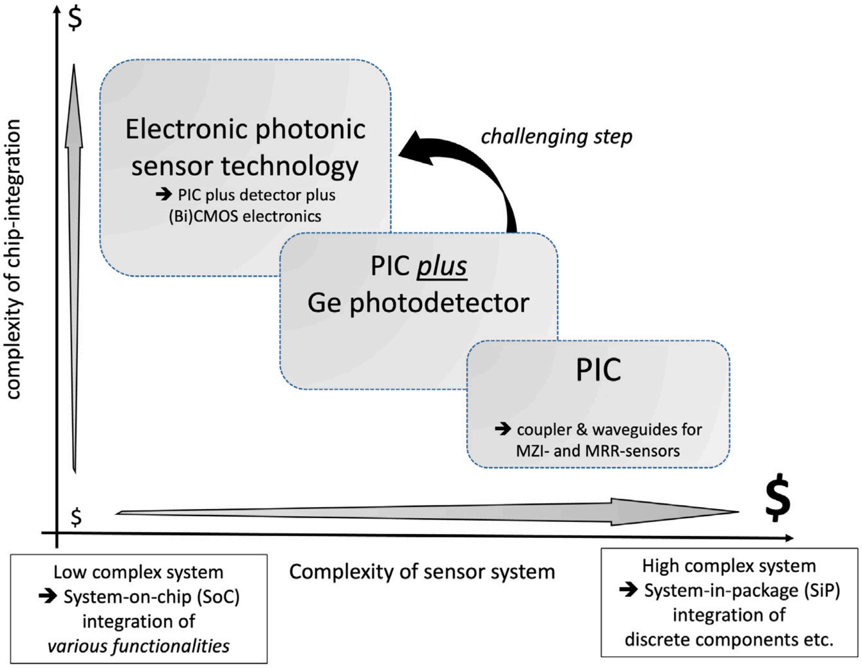


Fig. 2. Different photonic sensor integration concepts with respect to their complexity of chip technology versus requirements for package integration. Simple chip designs based on photonic-integrated-circuit (PIC) technologies consist only on passive components and require higher effort and cost intense package and assembly techniques. (MRR = Micro Ring Resonator, MZI = Mach–Zehnder Interferometer). System complexity and cots can be significantly reduced towards electronic–photonic sensor technology consisting integrated microfluidic and CMOS electronics.

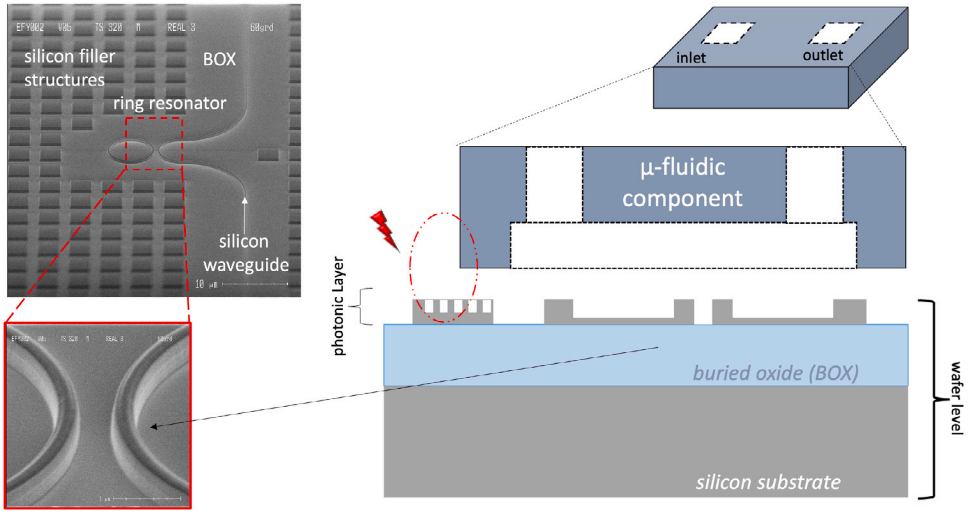


Fig. 3. Schematic cross-section of a single photonic sensor layer with required microfluidic module. Only passive photonic components are used and optical input is required from top without interacting with micro-fluidic module (right). The scanning electron microscopy image shows an example of a photonic ring-resonator structure with silicon-on-insulator dummy structures realized by state-of-the art PIC technology (left).

distance to coupling structures. This limits the density of integration and moreover the aforementioned bottlenecks with respect to light source integration and possible thermal tuning of the add-drop ring resonator is excluded due to the absence of any interconnect layer on the chip. Additionally two optical interfaces needs to be realized during the assembly.

To overcome partially these limitations a PIC platform with at least one interconnect layer and integrated photodetectors can be used as shown in Fig. 4. Here the process is stopped after patterning of the first aluminum based interconnect layer. A CMOS standard tungsten base contact formation is used to enable the low ohmic contact to the monolithically integrated photodetector (Mai et al., 2019c). As shown in Fig. 4 exemplary the isotropic release of the sensor area as the last step can cause detachment of the metal interconnect layers. Therefor large areas of active and dummy filler free metal layers needs to be considered which finally also hinder a compact integration and in case of large sensor areas e.g. for multiplexing arrays, the stability of semiconductor process.

However, these example show that PIC technology has a high potential for disposable sensor applications. However, the main bottleneck

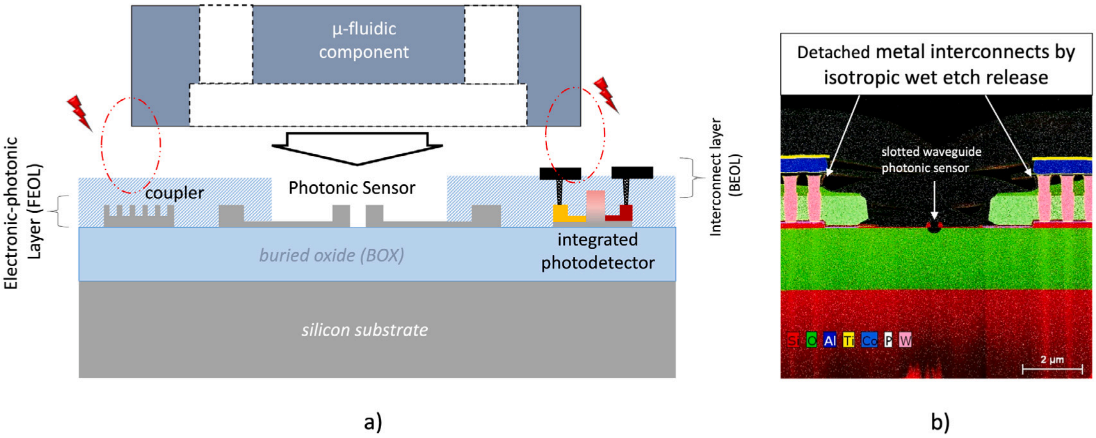


Fig. 4. Photonic sensor consisting of waveguide sensor element and on-chip active devices as Ge photodetector. Local and compact microfluidic integration is limited due to necessity of access to standard metal pads and optical coupling structures (a). EDX/TEM image (b) of a front-side electro-optic sensor waveguide with close metal interconnects. Isotropic release of the photonic element can cause detach of interconnect layers and therefor limits the density of integration.

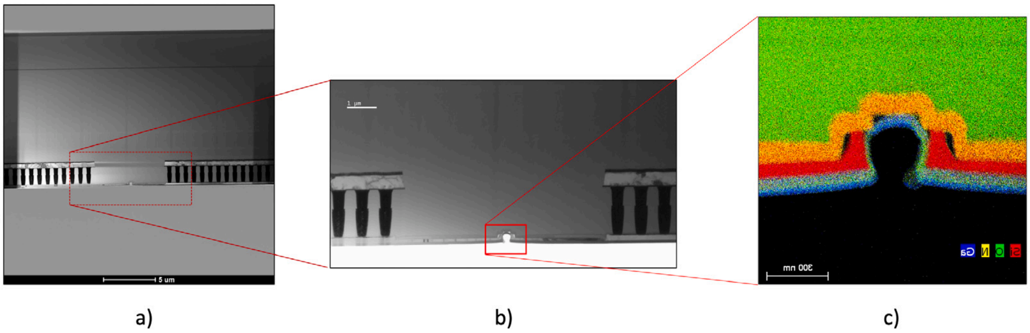


Fig. 5. TEM cross section with backside opening of photonic sensor regions (a). This integration approach enables a zero-change of front end technology and separates the fluidic interface from the electronic and photonic layers. Therefor high density co-integration of electronic–photonic is possible. Enlarged TEM (b) and EDX (c) images of a slotted waveguide as photonic sensor and locally released from wafer backside.

for cost-effective and reliable sensor integration is the co-integration of light-source (optical fiber), electrical signal supply and microfluidic from same interface.

3.2. *Photonic sensor chips with back-side etching*

To overcome the bottleneck of compact microfluidic integration on a chip with standard interconnects and optical coupling structures an integration approach in a Si CMOS/PIC environment was developed using a local backside release method to enable the access to the sensor slot-waveguide devices. For the local-backside-etching of the 760 µm thick silicon substrate a deep reactive ion etching (DRIE) process in conjunction with a hard mask was used with a very high selectivity of silicon dioxide to silicon (selectivity SiO_2:Si of 1:200). This guarantees a very controlled stop on the buried oxide (BOX). In comparison to Adamopoulos et al. (2021b) where a similar approach was used in an electronic–photonic integrated circuit (EPIC) process sharing photonic devices within a CMOS platform we chose a combination of RIE and wet etching to remove the BOX additionally. We used this combination to avoid damages of the waveguide if only RIE would be used but moreover to increase the sensitivity of the waveguide sensor. Drawback of a pure chemical wet etching is an extended process time due to low etch rates of the BOX. Fig. 5 shows a fabricated photonic sensor-chip fully released from the wafer backside. A comprehensive description of the fabrication process can be found elsewhere (Mai et al., 2019a,b; Steglich et al., 2021). By releasing the sensor chip form the backside of the wafer an approximately 16 µm thick layer remains consisting of a maximum 70 nm thick silicon layer and several interlayer dielectric (ILD) as well as aluminum and tungsten based interconnect layers. Following the existing design rules of metal e.g. densities in the BEOL we observe no mechanical instability of the released areas so far.

This chip integration approach enables a direct functionalization of the waveguide and a strong interaction of the evanescent field with the fluid and contained substance to analyze. Moreover an adaptation of the electro-optical chip design on the wafer front side is not necessary. For previously discussed front side integration of the microfluidic above the sensor element you have to relax and expand the optical and electrical interconnects to enable a save front side release of the sensor area and a microfluidic system integration. In particular for a co-integration into EPIC platforms this means higher cost for the entire chip and system. Instead the novel concept enables an integration with an obviously decreased form factor for the sensor chip.

4. Sensor system integration and results

The presented approach allows a separation of the microfluidic from the optical interconnections. Here, fiber-to-chip light coupling is used on the top side of the sensor chip, and the microfluidic interconnection formed by an interchangeable sample substrate with an integrated fluidic access, meaning there have to be at least two separate components. This allows to change between multiple chip samples and to apply various functionalization steps. We decided on a tray-drawer type design with a movable inner holder, where the photonic chip is attached to its underside and that slides into a fixed, outer holder.

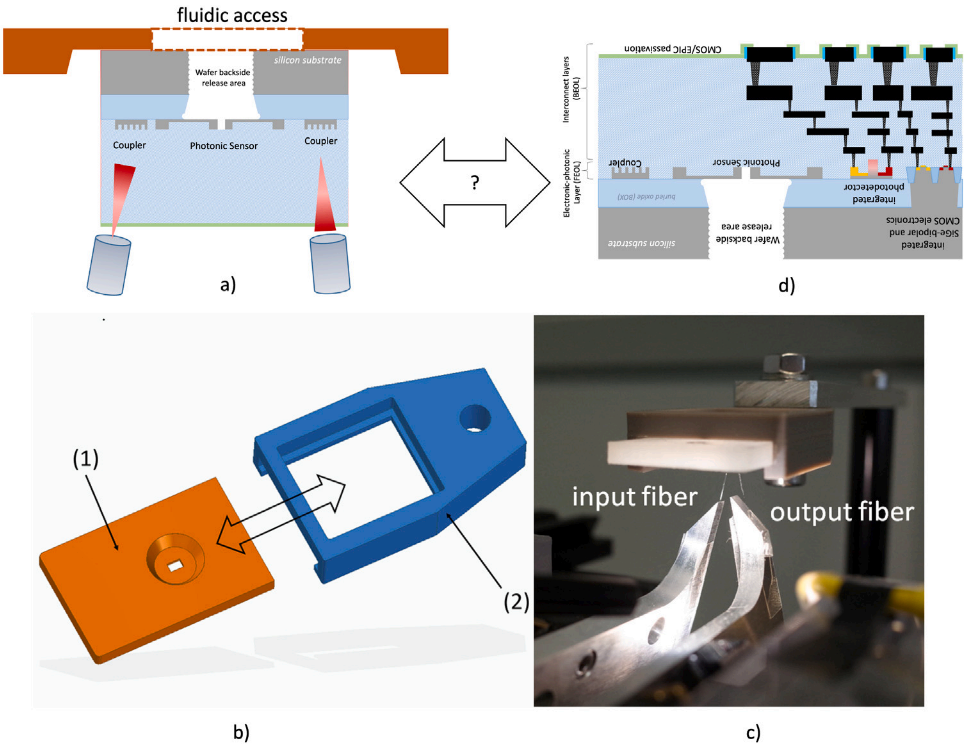


Fig. 6. Schematic assembly of the PIC sensor chip placed on a disposable sample holder (left) (a,b). Optical in- and output is enabled by a fiber coupled measurements set-up using GRIN fibers (c). Using appropriate system integration techniques with optical cpoupling and electrical interconnects enables a direct use of an EPIC integrated sensor chip allowing an on-chip date evaluation (d).

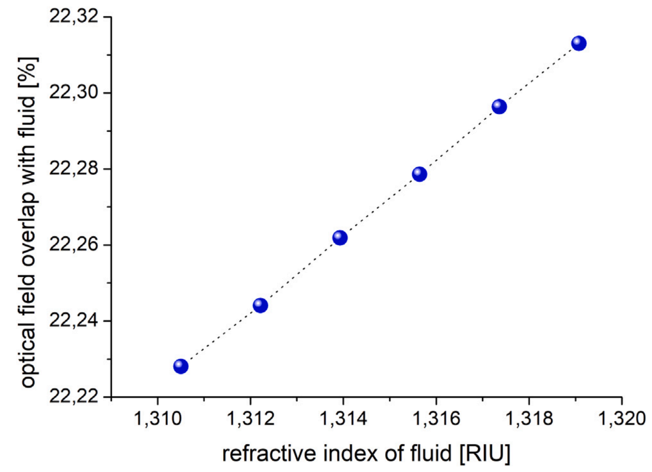


Fig. 7. Calculated optical field overlap with fluid with a backside released strip-loaded slot waveguide.

As a microliter container for the liquid chemical reagents is required, conical frustum-shaped mold was chosen, which is recessed into the inner holder, where it is flush to its brim. A cutout on the underside enables the sensing interface of the photonic sensor to be filled with the liquid reagents.

Fig. 6 shows the fabricated sample holder. This fabrication enables a mass production based on various polymer substrates. Despite the fact that we use just a passive chip without embedded Ge-PD for this study similar approaches could be applied to combine a sensor chip e.g with wire bonded electrical connections to the sample holder — similar as an USB stick.

As mentioned before the slot waveguide provides a higher optical field overlap with the fluid compared to strip or rib waveguides (Steglich, 2018). We have computed this field overlap for a backside released slot waveguide with air cladding and plotted the results in Fig. 7. However, to avoid excessive optical losses due to enhanced scattering at the slot waveguide sidewalls, we combine the slot waveguide with a rib waveguide, so that a ring resonator with narrow bandwidth can be realized. An APEX AP3350A tunable laser-source (TLS) controlled by the APEX AP1000 mainframe platform is used as light source, operating in the optical C-band. A Thorlabs IO-H-1550FC optical isolator and FPC561 polarization controller follow the outputs of the light source, minimizing reflections and optimizing the polarization for the internal grating couplers of the photonic chip. An external Thorlabs DET08CFC/M photo detector and KeySight 34461A digital multimeter are used on the detector side.

Results for the temperature sensitivity are shown in Fig. 8. We deduced a temperature sensitivity of $S_T = (92 \pm 0.6)$ pm/°C from this graph. This value is slightly higher compared to the same device that is released from the top (Mai et al., 2019).

As proof on concept, we used NaCl dispersed in DI water at different weight percentages. The refractive index n_f of the NaCl solved in DI water at a wavelength of 1550 nm can be calculated by

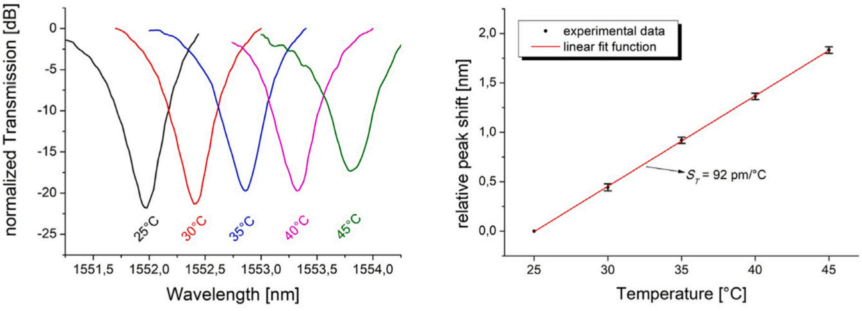
$$n_f\ (\text{wt\%}) = 1.3105 + 0.17151 \times \frac{C\ (\text{wt\%})}{100}, \tag{1}$$

where C (wt%) represents the concentration in weight percentage (Su and Huang, 2007; Tu et al., 2012). We injected four different concentrations ranging from 0wt% to 3wt%. The overall photonic device sensitivity is defined as (Steglich et al., 2019)

$$S = \frac{\Delta\lambda_{res}}{\Delta n_f}, \tag{2}$$

where $\Delta\lambda_{res}$ and Δn_f are the change of the resonance wavelength position and the change of the refractive index of the fluid (NaCl in DI water).

We have measured the resonance wavelength position as a function of the refractive index of the fluid. Fig. 9 shows the experimental results. From the slope of the linear fit we revealed a ring resonator



a)

b)

Fig. 8. In (a): normalized resonance peaks of the ring resonator at several temperatures. In (b): temperature sensitivity ST of the ring resonator, deduced from the mean resonance peakshift, resulting in a highly linear trend of S_T = (92 ± 0.6) pm/°C.

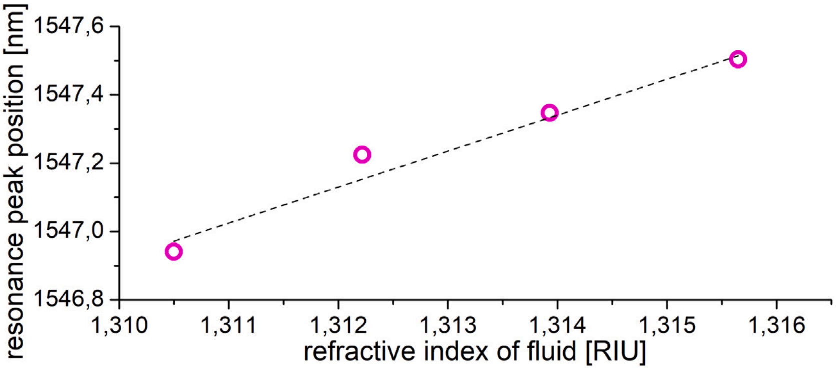


Fig. 9. Resonance peak position of the photonic sensor as function of the refractive index of the fluid (NaCl in Di water). A ring resonator sensitivity of 100 nm/RIU is deduced from the linear fit function.

Table 1
Benchmarking of different integrated photonic sensor platforms.

Ref.	PIC technology			ePIC	Sensor
	Material	Passive components	integr. PD	compatibility	sensitivity
Castelló-Pedrero et al. (2021)	SiN	**Yes**	No	No	***High***
Griol et al. (2019)	SiN	**Yes**	No	No	**Moderate**
Steglich et al. (2017)	Si	**Yes**	No	No	**Moderate**
Laplatine et al. (2018)	Si	**Yes**	**Yes**	No	***High***
Adamopoulos et al. (2021a)	Si	**Yes**	**Yes**	**Yes**	Low
This work	Si	**Yes**	**Yes**	**Yes**	**Moderate**

sensitivity of about 100 nm/RIU. Our results indicate the feasibility of the proposed back-side integration approach in conjunction with the disposable sensor assembly system. Table 1 benchmarks different technology platforms with respect to their complexity and compatibility for compact (e)PIC sensor systems.

5. Conclusion

We have presented recent developments on wafer level integrated photonic sensors with special emphasis on current bottlenecks and perspectives. A novel integration approach using the advantage of a backside released PIC-sensor technology offers a great potential for future low cost package integration of this sensors chips. The revised integration approach enable a direct combination with an EPIC environment and provide the possibility to co-integrate a read-out circuit for the sensor system with a small form factor on the same chip. Moreover the presented accessibility of the silicon sensor interface enables an increased sensitivity of the chip with respect to existing non-zero change (E)PIC platforms. Finally the presented approach overcome the different discussed bottlenecks and preliminary experimental results showing the potential for a disposable sensor assembly towards point-of-care applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Adamopoulos, C., Buchbinder, S., Zarkos, P., Bhargava, P., Gharia, A., Niknejad, A., Anwar, M., Stojanović, V., 2021a. Fully integrated electronic–photonic biosensor for label-free real-time molecular sensing in advanced zero-change CMOS-SOI process. IEEE Solid-State Circuits Lett. 4, 198–201. http://dx.doi.org/10.1109/LSSC.2021.3124234.

Adamopoulos, C., Zarkos, P., Buchbinder, S., Bhargava, P., Niknejad, A., Anwar, M., Stojanović, V., 2021b. Lab-on-chip for everyone: Introducing an electronic-photonic platform for multiparametric biosensing using standard CMOS processes. IEEE Open J. Solid-State Circuits Soc. 1, 198–208. http://dx.doi.org/10.1109/OJSSCS.2021.3118336.

Bondarenko, S., Hülsemann, M., Mai, A., Steglich, P., 2021. Fiber-to-chip light coupling using a graded-index lensed fiber collimator. Opt. Eng. 60 (1), 014105.

Castelló-Pedrero, L., Gómez-Gómez, M.I., García-Rupérez, J., Griol, A., Martínez, A., 2021. Performance improvement of a silicon nitride ring resonator biosensor operated in the TM mode at 1310 nm. Biomed. Opt. Express 12 (11), 7244–7260. http://dx.doi.org/10.1364/BOE.437823, URL https://opg.optica.org/boe/abstract.cfm?URI=boe-12-11-7244.

Dickmann, W., Weituschat, L.M., Eisermann, R., Krenek, S., Postigo, P.A., Kroker, S., 2021. Heat dynamics in optical ring resonators. In: Bodermann, B., Frenner, K. (Eds.), Modeling Aspects in Optical Metrology VIII, Vol. 11783. SPIE, International Society for Optics and Photonics, 1178309. http://dx.doi.org/10.1117/12.2592552.

Griol, A., Peransi, S., Rodrigo, M., Hurtado, J., Bellieres, L., Ivanova, T., Zurita, D., Sánchez, C., Recuero, S., Hernández, A., Simón, S., Balka, G., Bossis, I., Capo, A., Camarca, A., D'Auria, S., Varriale, A., Giusti, A., 2019. Design and development of photonic biosensors for swine viral diseases detection. Sensors 19 (18), http://dx.doi.org/10.3390/s19183985, URL https://www.mdpi.com/1424-8220/19/18/3985.

Kita, D.M., Michon, J., Johnson, S.G., Hu, J., 2018. Are slot and sub-wavelength grating waveguides better than strip waveguides for sensing? Optica 5 (9), 1046–1054.

Laplatine, L., Luan, E., Cheung, K., Ratner, D.M., Dattner, Y., Chrostowski, L., 2018. System-level integration of active silicon photonic biosensors using fan-out wafer-level-packaging for low cost and multiplexed point-of-care diagnostic testing. Sensors Actuators B 273, 1610–1617. http://dx.doi.org/10.1016/j.snb.2018.07.025, URL https://www.sciencedirect.com/science/article/pii/S0925400518312620.

Lischke, S., Knoll, D., Mai, C., Zimmermann, L., Peczek, A., Kroh, M., Trusch, A., Krune, E., Voigt, K., Mai, A., 2015. High bandwidth, high responsivity waveguide-coupled germanium pin photodiode. Opt. Express 23 (21), 27213–27220.

Lu, T.W., Lee, P.T., 2009. Ultra-high sensitivity optical stress sensor based on double-layered photonic crystal microcavity. Opt. Express 17 (3), 1518–1526.

Luan, E., Shoman, H., Ratner, D.M., Cheung, K.C., Chrostowski, L., 2018. Silicon photonic biosensors using label-free detection. Sensors 18 (10), 3519.

Mai, A., Bondarenko, S., Mai, C., Steglich, P., 2019. Photonic thermal sensor integration towards electronic-photonic-IC technologies. In: ESSDERC 2019 - 49th European Solid-State Device Research Conference (ESSDERC). pp. 254–257. http://dx.doi.org/10.1109/ESSDERC.2019.8901718.

Mai, C., Steglich, P., Mai, A., 2019a. Adjustment of the BEOL for back side module integration on wafer level in a silicon photonic technology. In: MikroSystemTechnik 2019. VDE/VDI, pp. 1–4.

Mai, A., Steglich, P., Mai, C., Simon, S., Scholz, R., 2019c. Electronic-photonic wafer-level technologies for fast prototyping and application specific solutions. In: Photonics & Electromagnetics Research Symposium. pp. 249–255, Spring (PIERS-Spring), Rome, Italy.

Mai, C., Steglich, P., Mirko, F., Mai, A., 2019b. Back-side release of slot waveguides for the integration of functional materials in a silicon photonic technology with a full beol. IEEE Transactions on Components, Packaging and Manufacturing Technology 2020 vol.10 no. 9, 1569–1574.

Moldenhauer, L., Lipka, T., Venegas-Rojas, D., Igeta, K., Trieu, H.K., 2017. Optofluidic a-si:H-based photonic lab-on-chip with dispersion engineered resonance spectra. IEEE Photonics Technol. Lett. 29 (4), 412–415. http://dx.doi.org/10.1109/LPT.2017.2651980.

Molina-Fernández, Í., Leuermann, J., Ortega-Moñux, A., Wangüemert-Pérez, J.G., Halir, R., 2019. Fundamental limit of detection of photonic biosensors with coherent phase read-out. Opt. Express 27 (9), 12616–12629.

Nauriyal, J., Song, M., Yu, R., Cardenas, J., 2019. Fiber-to-chip fusion splicing for low-loss photonic packaging. Optica 6 (5), 549–552.

Rahim, A., Goyvaerts, J., Szelag, B., Fedeli, J.-M., Absil, P., Aalto, T., Harjanne, M., Littlejohns, C., Reed, G., Winzer, G., Lischke, S., Zimmermann, L., Knoll, D., Geuzebroek, D., Leinse, A., Geiselmann, M., Zervas, M., Jans, H., Stassen, A., Domínguez, C., Munoz, P., Domenech, D., Giesecke, A.L., Lemme, M.C., Baets, R., 2019. Open-access silicon photonics platforms in Europe. IEEE J. Sel. Top. Quantum Electron. 25 (5), 1–18. http://dx.doi.org/10.1109/JSTQE.2019.2915949.

Steglich, P., 2018. Silicon-on-insulator slot waveguides: Theory and applications in electro-optics and optical sensing. Emerg. Waveguide Technol. 187–210, IntechOpen.

Steglich, P., Bondarenko, S., Mai, C., Paul, M., Weller, M.G., Mai, A., 2020. CMOS-compatible silicon photonic sensor for refractive index sensing using local back-side release. IEEE Photonics Technol. Lett. 32 (19), 1241–1244. http://dx.doi.org/10.1109/LPT.2020.3019114.

Steglich, P., Hülsemann, M., Dietzel, B., Mai, A., 2019. Optical biosensors based on silicon-on-insulator ring resonators: A review. Molecules 24 (3), 519.

Steglich, P., Paul, M., Mai, C., Böhme, A., Bondarenko, S., Weller, M.G., Mai, A., 2021. A monolithically integrated micro fluidic channel in a silicon-based photonic-integrated-circuit technology for biochemical sensing. In: Baldini, F., Homola, J., Lieberman, R.A. (Eds.), Optical Sensors 2021, Vol. 11772. SPIE, International Society for Optics and Photonics, 1177206. http://dx.doi.org/10.1117/12.2588791.

Steglich, P., Rabus, D.G., Sada, C., Paul, M., Weller, M.G., Mai, C., Mai, A., 2022. Silicon photonic micro-ring resonators for chemical and biological sensing: A tutorial. IEEE Sens. J. 22 (11), 10089–10105. http://dx.doi.org/10.1109/JSEN.2021.3119547.

Steglich, P., Villringer, C., Pulwer, S., Heinrich, F., Bauer, J., Dietzel, B., Mai, C., Mai, A., Casalboni, M., Schrader, S., 2017. Hybrid-waveguide ring resonator for biochemical sensing. IEEE Sens. J. 17 (15), 4781–4790. http://dx.doi.org/10.1109/JSEN.2017.2710318.

Su, H., Huang, X.G., 2007. Fresnel-reflection-based fiber sensor for on-line measurement of solute concentration in solutions. Sensors Actuators B 126 (2), 579–582.

Tu, X., Song, J., Liow, T.-Y., Park, M.K., Yiying, J.Q., Kee, J.S., Yu, M., Lo, G.-Q., 2012. Thermal independent silicon-nitride slot waveguide biosensor with high sensitivity. Opt. Express 20 (3), 2640–2648. http://dx.doi.org/10.1364/OE.20.002640, URL http://www.opticsexpress.org/abstract.cfm?URI=oe-20-3-2640.

Wan, C., Gonzalez, J.L., T. Fan, A.A., Gaylord, T.K., Bakir, M.S., 2019. Fiber-interconnect silicon chiplet technology for self-aligned fiber-to-chip assembly. IEEE Photonics Technol. Lett. 31 (16), 1311–1314.

Wang, J., Snachez, M., Yin, Y., Herzer, R., Ma, L., Schmidt, O.G., 2020. Silicon-based integrated label-free optofluidic biosensors: Latest advances and roadmap. Adv. Mater. Technol. 5 (6), 1901138.

Weituschat, L.M., Dickmann, W., Guimbao, J., Ramos, D., Kroker, S., Postigo, P.A., 2020. Photonic and thermal modelling of microrings in silicon, diamond and GaN for temperature sensing. Nanomaterials 10 (5), 934.