Opportunities for photonic integrated circuits in optical gas sensors

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Abstract
In this article, the potential of photonic integrated circuits (PICs) for modern gas sensing applications is discussed. Optical detection systems can be found at the high-end of the currently available gas detectors, and PIC-based optical spectroscopic devices promise a significant reduction in size and cost. The performance of such devices is reviewed here. This discussion is not limited to one semiconductor platform, but includes several available platforms operating from the visible wavelength range up to the long wavelength infrared. The different platforms are evaluated regarding their capabilities in creating a fully integrated spectroscopic setup, including light source, interaction cell and detection unit. Advanced spectroscopy methods are assessed regarding their PIC compatibility. Based on the comparison of PICs with state-of-the-art bulk optical devices, it can be concluded that they can fill the application space of compact and low cost optical gas sensors.

1. Introduction
In the modern world, detection and sensing of gases are required for a multitude of applications. Examples of such applications can be found in the chemical industry for monitoring chemical processes [1], in climate research to identify climate-relevant gases [2], the agricultural industry to monitor emissions and stable conditions [3], or in the medical field, e.g. for breath analysis [4–6]. The applications determine the required sensitivities, and in the case of ammonia detection, Timmer et al provided an overview of the requirements [7]. In this case, sensitivities in the parts per billion (ppb) level are required for breath analysis applications, while higher concentrations in the parts per million level (ppm) find applications in environmental monitoring and leakage detection. Similar sensitivity requirements can be formulated for methane [8].

However, a high sensitivity, i.e. the ability to detect low concentrations, is not the only requirement for a gas detector. When measuring gas species in a mixture, selectivity is required. Selectivity describes the ability of the sensor to identify a specific gas in a mixture. While for environmental monitoring the response time is of no concern, safety applications might require a faster detection system. Energy consumption is of importance as well, especially for handheld systems. Longevity can be important when the detector cannot easily be replaced, as for example in space applications, even if the production costs of the sensor could be low.

Liu et al reviewed the state of the art gas sensing methods and classified them according to figure 1. The figure shows that, despite their benefits regarding selectivity, sensitivity, stability, and longevity, only a small fraction of the sensors in use are based on optical detection methods [9]. Optical detectors can also probe remote environments, and can take path-integrated data when measuring over long path lengths. Although there are optical high-performance sensors, the associated costs and difficulties in reducing the device size prohibit widespread applications. Photonic integrated circuits (PICs) promise to tackle both hurdles: cost and footprint.

PICs combine several functionalities on a substrate, e.g. lasers, modulators, detectors and amplifiers [10]. The development in the field was mainly driven by telecommunications applications, and a trend similar to the development in micro-electronics was predicted and seems to hold [11, 12]. With those applications in mind, mature PIC technology has converged to a limited set of platforms, most notably silicon photonics (Si-Ph), indium phosphide (InP) and silica or silicon nitride platforms (Si$_3$N$_4$), typically operating in the communications wavelength window of ~1200 to 1600 nm. As each of those platforms comes with certain benefits, much research has also been
guided towards their co-integration. For example, heterogeneously integrated InP-components embedded on a Si-Ph platform allow for active components, which would otherwise not be obtainable. Figure 2 shows the increase of complexity of some of those platforms over the last 30 years. The figure is adapted from [10], but we added two more data points corresponding to recent publications [13, 14].

An exploratory market study conducted by Tematys found a compound annual growth rate (CAGR) of 11% for compact spectrometer subsystems [15]. Specifically low-cost (<100$) micro spectrometers are of interest, as those allow spectroscopy in the everyday life, e.g. as part of gas sensor in the smartphone.

For the North American market, a study by Grand View Research predicted a distribution of the gas sensors market for 2019 as shown in figure 3 [16]. The study also predicted a growth, e.g. in the medical field with CAGR of ~5%. This reflects the growing need for gas sensors in our modern society.

This paper reviews how the maturity of the current PIC technology can be used to create powerful optical gas sensors. This is an active field of research, and first publications show the potential of this approach [17–19]. The research interest is also reflected in the number of scientific publications. Figure 4 shows the number of publications in the field of optical gas sensors, and the number of integrated gas sensors among those, using the refined search function. The data is obtained from Web of Science [20].

The paper is structured such that it first introduces the concept of an optical absorption measurement and how it can be used to extract the gas concentration in section 2. Section 3 will briefly introduce advanced methods to

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**Figure 1.** Classification of gas sensing methods. The majority of the detector obtain the gas concentration from a change of the electrical properties of the sensor under exposure to the gas, e.g. the electrical resistance, represented by the upper branch. The lower branch represents less common detection techniques, optical detection being one of them. © 2012 MDPI, CC-BY-4.0[9].

**Figure 2.** Increase of the number of components on PICs over the last three decades. The three major platforms, indium phosphide (blue), silicon photonic (green), and hybrid silicon (red) are shown. Adapted from [10], with two added data points [13, 14].
increase the sensitivity of the sensor. We will also show how those methods can be implemented on a PIC. Section 4 will evaluate which platforms can be used to create on-chip gas sensors. We also include information about how users can access the ecosystem of PICs and create PIC-based gas sensors, which is part of section 5.

2. Absorption and spectroscopy

Spectroscopy is a sensing method used to gain insights into matter. In the case of optical spectroscopy, electromagnetic waves interact with a sample [21, 22]. Ideally, the response of the matter, e.g. a change in transmission, is unique to the investigated sample. This work focuses on absorption spectroscopy of gases for different wavelength ranges. In such a setup, light is transmitted through a gas interaction region onto a detector. Depending on the gas, certain wavelengths of the light spectrum are absorbed. The concentration, temperature and pressure of the sample gas, as well as the optical path length through the sample, determine the strength of the absorption. This interaction probes, e.g. molecular transitions, and is very selective. Figure 5 shows the absorption of acetylene (C2H2) as found in laser wavelength reference cells, effectively providing a spectral fingerprint of the gas.

In this work, we consider the wavelengths that can be exploited with the use of PICs, i.e. the electromagnetic spectrum from 400 to ~14 μm [24]. The spectral data of several gases, including atmospheric composites, can be found on HITRAN [23]. These data can be used to link absorption signals to gas concentrations and to benchmark spectroscopic devices. A spectroscopic setup has to resolve the linewidths of the sample gas and be sensitive to detect the signal. An absorption line corresponds to a state transition in the molecule. For the short wavelengths from 200 to 400nm these are electronic transitions. The long wavelength range of 2.5–14 μm probes rotation and vibration states of the molecule or atom. The intermediate range, 700–2.5 μm, makes use of the higher harmonics of those transitions, typically with ~100 times weaker absorption strengths compared to the fundamental harmonic of the transition [8].

For PICs, two fundamental direct absorption measurement techniques exist. The first approach is using a tunable single-mode laser and a broadband photodetector for the measurement. As lasers are typically of a very narrow linewidth, this method can target narrow absorption lines as typically present in gases. A simple diode laser typically has a linewidth of a few MHz, while an absorption linewidth of ammonia at room temperature is
on the order of 10 GHz [18]. In addition, it is possible to use a single detector with a small dark current. This approach can be summarized under the tunable diode laser absorption spectroscopy (TDLAS) method.

The second approach is using a broadband lightsource and spectrometer, which, depending on the type of the spectrometer, can measure the whole spectrum simultaneously. With an angular dispersion spectrometer, detection arrays, such as cameras or moving apertures, need to be used. This approach is beneficial for very wide absorption lines, which would necessitate a wide tuning range of the laser, and is more common in measurements on liquids. Figure 6 illustrates the two different approaches. With frequency combs and mode-locked lasers, the benefits of both approaches can be harvested [6, 25–27]. Mode-locked lasers feature very well defined emission lines over a wide wavelength span, and can be considered an optical ruler. However, while mode-locked PICs or on-chip frequency combs have received much scientific attention, more development work is needed to make them realistic candidates for gas sensing [28–30].

PICs can also be used for indirect measurements, such as opto-chemical detection schemes, where a chemical reaction is optically probed to obtain a gas concentration. An example can be fluorescence measurements [31, 32]. In addition, bio-markers can be applied to change the refractive index in presence of an analyte, which can be measured using PICs [33, 34]. In photoacoustic spectroscopy, the absorption signal is
modulated and the matching acoustic wave is detected \([35–37]\). Popa and Udrea compared direct absorption and photo-acoustic compact spectrometers in a recent publication \([38]\).

This work predominantly focuses on the direct absorption measurement approaches, as the other mentioned methods are difficult to benchmark against each other.

3. Advanced spectroscopic methods

While the overall measurement scheme of a direct spectroscopic measurement is rather simple (source, interaction cell, detector), advanced methods exist to improve the Signal-to-Noise ratio (SNR). A small overview, not aiming for completeness, will be given here. A comprehensive study can be found in \([39]\). It is worth mentioning that PICs can incorporate all of the schemes mentioned here, with negligible impact on the footprint or cost of the devices. Hodgkinson and Tatam provided an extensive review of the optical spectroscopy methods, although they did not investigate the applicability to PIC-based sensors \([8]\).

3.1. Balanced detection

A balanced detection employs effectively two detectors instead of the minimal requirement of just one. One detector is used as an immediate reference signal. Typically, light is split into two arms, one containing the gas sample and the other a neutral background. A balanced detector measures the power difference between both arms. This eliminates noise originating from the light source, but effectively reduces the power in the gas cell and on the detectors, affecting their noise contributions. A comparison between the typical signals from a direct and a balanced detection scheme is shown in figure 8. A balanced detection scheme does not require additional fiber chip coupling when being implemented in the design. As shown in figure 7, the laser light can be split already on chip, before going to the interaction cell, which is a hollow core fiber in the figure, but could also be a fiber-coupled gas cell \([40–42]\). Chip-based balanced photodetectors have already been demonstrated \([43, 44]\).

3.2. Wavelength modulation spectroscopy (WMS)

In WMS, as a part of TDLAS, the laser light is modulated, mostly to eliminate low frequency noise contributions in the system \([45, 46]\). Fast modulation and a lock-in scheme effectively eliminate the 1/f-noise by moving the signal to a higher frequency. As such, it is predominantly useful in measurements where this noise exceeds white noise signals, which are frequency independent and not eliminated by WMS. A theoretical comparison of WMS and direct absorption spectroscopy (DAS) showed that, when using noisier equipment, WMS yields better signal to noise ratios, while DAS benefits from low-noise equipment more strongly \([47]\). As PICs are compatible with both, WMS and DAS, high-end applications relying on ultra-low noise equipment are feasible, as well as low end applications which can strongly benefit from the noise reduction techniques.

Figure 8 shows a comparison of the signal shape between a regular absorption measurement and a measurement relying on WMS.

3.3. Cavity-enhanced spectroscopy

When measuring trace gases, the interaction of gas sample and light is weak and long path lengths are needed for a detectable absorption signal. This is problematic for PIC-based interaction cells, as those devices are expected to be of small volume and the beam path needs to be folded or pass through the gas cell multiple times, as in, e.g. multi-pass cavities. An alternative approach is using resonant cavities \([48, 49]\). In such a cavity, the interaction...
length is not limited by the device size, but rather the losses and the quality of the waveguides and waveguide couplers. As high quality resonators have very narrow transmission bands, resonance and absorption wavelengths need to be matched. If the gas sample interacts with the light in the resonator, the quality factor (Q-factor) of the resonator is reduced, which can be monitored by an increase of the transmission linewidth. Figure 9 shows the comparison of both approaches, folded beam path and high-Q micro-ring resonator (MRR), for an on-chip CO2 sensor [50].

While not on-chip integrated gas cells, fiber based solutions can provide some of the benefits of integration [42, 51]. Fibers can be coiled to extend the propagation length in a given volume. It is also possible to create fiber-based resonator [52].

4. Platform and technologies

The available material platforms for PICs are almost as numerous as the applications they allow access to. While for telecommunication applications few selected platforms (Si3N4, Si and InP) are preferred, other technologies need to be considered when moving away from the standard telecommunication wavelength ranges. To maintain an overview of the technologies, we will group the available platforms regarding the wavelength ranges they provide access to. This is motivated by the fact that the different wavelength ranges target different transitions in atoms and molecules, and hence have individual applications. The downside of this approach is the overlap between the sections, as several platforms span more than one wavelength regime.

4.1. Visible light

The human eye can detect light in the visible wavelength range (VIS), which is spanning the wavelength from 390 to 760 nm [53]. This makes this region especially interesting for imaging applications, as a camera image would
be perceived as by the human eye. VIS light falls into an optical transmission window, i.e. atmospheric gases absorb very little of the radiation in this range \[54\]. For that reason it is of limited use for atmospheric and gas spectroscopy. It has importance in field of the quality control in agricultural industry, and has applications in the medical field and life sciences, although those are typically not gas measurements \[55, 56\].

CMOS (complementary metal-oxide-semiconductor) detector technology has reached a very high maturity and arrays of such detectors are already in use in cameras. Light sources, narrow and broadband, are also widely available. For the scientific market, light-emitting diodes (LEDs) can be purchased for less than 10 Euros \[57\]. Visible light LEDs are already found in basic household applications. Laser diodes can be in the same price range, but get more expensive if additional features, such as tunability, are desired. VIS PICs already found applications in optofluidics and biosensing, where refractive index sensing methods can be employed \[55, 58–60\].

Passive waveguide structures for PICs can be made in silicon nitride (Si$_3$N$_4$), which can be used in the wavelength range from 400 to 3700 nm \[61\]. The supported wavelength region of several waveguide materials in the visible range, up to the mid-infrared region, is shown in figure 10. Current research includes the use of lithium niobate (LiNbO$_3$), which is transparent at the VIS and mid-infrared wavelength regime \[62, 63\]. However, Si$_3$N$_4$ platforms are the only ones currently available for multi-project wafer (MPW) runs, supporting VIS waveguides. PIX4life, a European pilot line, is a driving force for PICs operating in the visible wavelength range \[64, 65\].
on a buried SiO2 layer. Due to the relatively high losses in InP waveguides and the high quality and the evanescent region, a Si-based PIC platform allows for low-loss waveguides with evanescent vertical coupling horizontally coupled using lensed detector and laser source operating at 1650 nm, were external devices. In this experiment, the light has been processed and environmental monitoring and an alternative to other proposed low-cost optical methane sensors, contrast to ppb-level concentrations with distributed devices detection PIC has been demonstrated by Tombez et al., where the interaction cell is provided by a Si waveguide. The high losses also prevent the use of on-chip resonant cavities for cavity enhanced spectroscopy. The availability of on-chip light sources and detectors as well as electro-optical modulators with bandwidths of more than 1 GHz lends itself to WMS and balanced detection schemes.

Lasers with tuning ranges of more than 70 nm allow to probe multiple species and absorption lines. Figure 12 shows the spectral coverage of the laser developed by Latkowski et al. The figure also shows that the laser is suitable for gas spectroscopy, but the detection levels have not been quantified. Different widely tunable laser structures have been demonstrated, with varying requirements on the clean room process flow.

Additional efforts have been made to stretch the limits of InP-based circuits to reach longer wavelength ranges. Latkowski et al. developed a single-mode laser operating between 2010 and 2045 nm. As with their former device, fine tuning allowing for gas detection was shown, but no sensitivity analysis was provided. The corresponding spectra are shown in figure 13. MPW runs are available for fabless users and are brokered via JePPIX.

There has been substantial work to integrate gas interaction cells on-chip. A methane (CH4) detection PIC has been demonstrated by Tombez et al., where the interaction cell is provided by a Si waveguide on a buried SiO2 layer. Figure 14 shows the PIC used in this experiment. The overall waveguide used in the evanescent field sensing experiment reached a length of 10 cm, with 25% of the modal power being in the evanescent region. A Si-based PIC platform allows for low-loss waveguides with evanescent fields in air. Both, detector and laser source operating at 1650 nm, were external devices. In this experiment, the light has been horizontally coupled using lensed fibers, but the Si-Ph platforms typically also support grating couplers for vertical coupling.

Measurements of CH4 concentrations in the sub-100 ppm have been demonstrated, in contrast to ppb-level concentrations with distributed devices. Such concentrations are already sufficient for process and environmental monitoring and an alternative to other proposed low-cost optical methane sensors,
while improvements of the detection levels will provide access to other markets [83]. Measurements in the liquid phase at higher concentrations have already been demonstrated [84]. Hence, PIC based sensors can find applications in high and low concentration environments, ranging from ppb-level concentrations to ppm and percent-level measurements.

PICs on Si₃N₄ feature very low optical losses, which can be used for creating long on-chip paths for the interaction cells and high-Q resonators [85]. High-Q resonators can be exploited for cavity enhanced spectroscopic setups. The feasibility of an acetone detection system using the Triplex technology, which is a Si₃N₄ waveguide layer stack, has been qualitatively demonstrated, although no quantitative analysis has been provided [86]. Similar to VIS PICs, NIR PICs found applications outside of gas spectroscopy, such as in medical imaging, biosensors and refractive index sensing [33, 36, 37, 87, 88].

Si-Ph and Si₃N₄ photonics platforms can be heterogeneously integrated with III/V materials, which can provide an on-chip light source [89–91]. That way, active components can be combined with low-loss optical waveguides. In addition to the heterogeneous integration, substantial research has been dedicated to the development of on-chip detectors within the Si-Ph platform. Germanium (Ge) detectors can be used for Si-Ph applications with similar responsivities as typically found in InP devices (∼1 A W⁻¹) [92, 93]. These devices operate at wavelengths around 1.5 μm, but with dedicated layer stacks, e.g. GeSn/Ge heterostructure, supported wavelength ranges can be extended to 2.2 μm [94]. On-chip detectors, when combined with wavelength selective elements, can be used for on-chip spectrometers. Such filters can be, e.g. ring resonators, arrayed waveguide gratings (AWG), or echelle gratings [95, 96]. Such sensors could be used for gas sensing using broadband illumination and a spectrometer. Recent research also investigates the use of graphene on PICs [97].

Monolithical integration of light sources and detectors with Si-Ph PICs has been demonstrated in lab, but it is currently not readily accessible for most users [98–102].
4.3. Mid-wavelength infrared (MIR)
Where the NIR region ends, the MIR region starts. The exact definitions of the MIR differ, and different standards and conventions exist. Here, the MIR extends from 2 to 8 μm. For many gases, the absorption line strengths are stronger in this wavelength region compared to NIR, where overtones of the MIR transitions have to be used for the measurements. In the case of methane, overtone lines are \( \sim 100 \) times weaker \([8]\). Unfortunately, this is offset by the lower performance of active optical components. The absorption strengths for five atmospheric gases within this wavelength range, and extending to the long-wave infrared, are shown in figure 15.

A few options for PIC compatible materials can be considered to create waveguides in this region, as shown in figure 16. Notably, Si and Silicon nitride, which are accessible via MPW runs, can be used. Silicon dioxide, a common cladding in Si-Ph, shows high losses for wavelengths longer than 3.5 μm. The wavelengths between 4 and 8 μm are therefore inaccessible in the standard Si-Ph processes \([103]\). Some of the current research is dedicated to the transfer of Si PICs to other substrates, the silicon-on-anything configuration presented by Chen et al being a noteworthy contribution \([104]\). The same publication showed absorption measurements at 5.2 μm. Si\(_3\)N\(_4\) waveguides combined with external laser source and detector were able to achieve a 5000 ppm CO\(_2\) sensitivity \([105]\). Other research investigated the use of germanium, sapphire, or air slots in the waveguide to target the longer wavelength ranges \([106–109]\). A variety of other materials has been used to create MIR thin film waveguides, which allowed for bio-sensing in liquids \([110]\).
Integrated optical light sources are typically based on quantum cascade or interband cascade lasers (QCL, ICL) \[24, 111\]. The heterogeneous integration of those devices with Si-Ph platforms allows for full on-chip gas detection systems \[112–114\]. The combination of high quality active and passive components allows the use of all the discussed advanced spectroscopic methods: balanced detection, WMS and cavity enhanced spectroscopy. Research has been conducted regarding the monolithic integration of active components, but has not reached the same level of maturity as the heterogeneous devices \[115\].

Hu et al reviewed the losses of waveguides within Si-Ph platforms in the MIR \[50\]. The majority of the devices operated in the wavelength range of 2–4 μm. They also outlined a possible PIC CO₂ sensor and predicted a detection level of ~20 ppm at 4.3 μm. PICs allow for complex waveguide structures, also in the MIR region. Therefore spectrometers and wavelength selective filters can be created \[116, 117\].

On-chip MIR detection can be achieved with GeSn detection systems, reaching maximum wavelengths around 2.3 μm \[118–120\]. Lead chalcogenides, such as PbS, PbS or PbTe, are alternative detector materials. In the case of PbTe, peak responsivities of 15 V W⁻¹ at wavelengths of up to 3.7 μm have been detected \[121\]. In those measurements, the responsivity has been increased using resonant structures. The same group reported responsivities of 100 V W⁻¹, again in resonance, at 3.5 μm \[122\]. With InAs/GaAs quantum dots, MIR detectors monolithically grown on Si substrates were able to detect signals up to 8 μm in wavelength, but no sensitivity has been reported \[123\].

Only recently an integrated circuit containing the gas sensing waveguide and an on-chip detector has been demonstrated \[19\]. However, to our knowledge, a fully integrated MIR gas sensor, including light source and detector, has not yet been demonstrated. Silicon-on-insulator and germanium-on-silicon platforms are subject to current research and promising candidates for future MIR spectroscopic systems \[124\].

4.4. Long wavelength infrared

In this work, the long wavelength infrared region constitutes of the wavelengths between 8 and 14 μm. This region falls into an atmospheric transmission window, i.e. has a high transmittance in atmospheric air. Hence, atmospheric gases are not easily detectable using this technology, ozone (O₃) being a noteworthy exception. As shown in figure 16, germanium is a suitable material choice for waveguides in this region. Possible waveguiding structures along with potential applications have been reviewed by Soref et al \[106\]. Hollow air core waveguides were among the investigated structures, which should allow for an easier implementation for gas sensor applications, due to the high overlap of field and gas. Suitable laser light can be generated with QCLs \[125\]. Overall, PIC based LWIR gas spectroscopic research has yet to see experimental verification.

5. Design process

PICs are manufactured in a clean room. As the costs of maintaining a clean room can easily exceed a company’s capital, MPW access, which distributes the costs over multiple users with smaller device numbers, enables research groups and smaller enterprises to obtain mature PICs \[11\]. Design, characterization, and packaging, are typically not taken care of by the foundry. We will give a brief overview of the process steps that go into developing a gas sensor, and which support can be obtained from the currently available PIC ecosystems.

5.1. Design phase

MPW foundries manufacture chips based on the mask files they receive. Process limitations, such as the smallest feature size, are part of the design rules that users need to follow. Mask file creation can be assisted with commercially available software, Synopsys and Mentor being notable developers. Those tools typically include a
design rule check to match the design with requirements of the foundry. Users are limited to a certain set of building blocks (BB). This generic approach can be compared to microelectronic circuit development. Figure 17 shows, how the BB approach in electronic circuits would find its match in the PIC world, and what the components would look like. A theoretical description of such BB as well as design examples can be found in [126]. Design houses can aid users in the layout process, bright photonics and VLC Photonics being two examples [127, 128]. Some MPW foundries offer custom wafer runs, in which the designer is granted more freedom in his design. Users can include custom BB, such as specialized waveguides, in the design. In the case of waveguides, opting for slot waveguides in contrast to ridge or rib waveguides can increase the proportion of the light that is not confined in the core of the waveguide, by a factor of three [129].

In Europe, JePPIX can provide access to the entire supply chain and brokers access to MPW runs [76]. With three MPW foundries, namely SMART Photonics, Fraunhofer HHI and LionIX International, Si$_3$N$_4$ and InP based PICs are supported [61, 75, 92, 130]. Rahim et al gave an overview of the existing open access platforms for Si-Ph PICs [131]. CMC Microsystems brokers MPW services to Canadian universities, research institutions, and industry [132]. Similarly to JePPIX in Europe, the American Institute for Manufacturing Integrated Photonics (AIM Photonics) offers support in fabrication, testing, and packaging of PICs [133].

5.2. Testing and verification
To verify the performance of the chip, light needs to be coupled out of the chip. This is typically done with fiber-chip coupling. Depending on the used technology, this can be done with vertical grating couplers and regular single-mode fibers. Other chip designs rely on edge coupling, which can necessitate using a lensed fiber, depending on the mode field diameter of the output waveguide. For multiple optical inputs or outputs, fiber arrays can be used.

Several on-chip components, e.g. SOAs, detectors, and modulators, require electrical contacts to be biased with an electrical current or voltage. In the laboratory, this can be done by probe needles and, depending on the platform, making use of the bottom contact of a conductive substrate, or using a top contact. For high-speed applications, ground-signal-ground probes are available. Increasingly complex circuits that require more and more contacts lead to the development of multi-contact needles or probe cards, which allow to simultaneously land multiple needles, but require the chip layout to be matched by, e.g. electrical routing on chip. Ideally, for the highest throughput, probing is done on the full wafer, and in an automated way.

5.3. Packaging
Once the functionality of the PIC is verified, the chip needs to be packaged. This refers to permanent optical and electrical contacts, as well as heat management. Figure 18 shows a generic packaging solution for InP based PICs [11]. Micro lenses can be used for optical coupling. Electrical coupling is typically done with wire bonding.

In the hybrid integration approach, light is coupled from chip to chip. This is done to combine active structures with, e.g. Si-Ph and Si$_3$N$_4$ circuits. Hybrid integration is still a topic of on-going research, but first MPW runs are offered, e.g. by LionIX [130, 134].

An alternative to wire bonding is flip-chip bonding, in which a flipped electrical circuit can be bonded to the top-side of a PIC [135–137]. This allows for higher integration density, as the vertical electrical contacting does not suffer from the limitations of wire bonding, in which the wires are typically connected to a printed circuit.
boards at the side of the chip. For many applications wire bonding is the current de facto standard for packaging of generic PICs.

A European pilot line, PIXAPP, has come to life to provide access to PIC assembly and packaging [138]. For users relying on the generic technologies approach, packaging in Europe is available, e.g. by Technobis, and is brokered by JePPiX [76, 139].

6. Conclusion

Optical spectrometers can be the solution to the increasing performance demands of modern gas sensors. Optical gas sensors show outstanding sensitivity, selectivity, and longevity, but are held back by their high costs in comparison to competing systems [9]. PICs promise to build on the strengths of optical detectors and potentially reduce their price and footprint. Despite these advantages, PIC-based gas sensing has not found its way out of the laboratory. We have reviewed the technology in this manuscript, and it can be concluded that photonic integration is ready for out-of-lab demonstrators. An example for such a demonstrator is the methane sensor developed by IBM research [17]. Other research focussed on the development of an integrated NH₃...
sensor [18]. As PICs are accessible via MPW foundries, users can pick and choose sensor layouts with reduced entry costs. Multiple semiconductor platforms are available, with InP, Si-Ph, and Si3N4 being supported by complete pilot lines to create commercial devices [140]. As such, the first commercially available PIC-based gas sensors are expected to hit the market in the near future. Currently, devices in the MIR and NIR range show the greatest potential. While the absorption of most relevant gases is higher in the MIR region, the high technical maturity and performance of PICs in the NIR region is capable of compensating the reduced signal strength. The CMOS-compatible NIR methane sensor reported by Tombez et al is an example for this [17]. The unavailability of suitable low-cost integrated laser sources in the MIR could result in a dominance of NIR-sensor systems in the near future. Further improvements on laser designs might change that in the long run, as the advantages in the NIR wavelength regime are based on technology, not on physical limitations. Figure 19 shows the relation between path length and the achievable minimal detection limit for a selection of published methane sensors. As PIC-based sensor systems, which are displayed in red and blue, are approaching the sensitivity of more established optical gas sensors, while still offering a more compact solution. This figure clearly shows the application space that can be filled by PIC-based gas sensors. It is worth mentioning that several applications do not require the most sensitive detection system. For such applications, other parameters, such as price, longevity, and footprint, can take a more dominant role, assuming that the adequate detection levels can be reached. It is exactly in these applications that PICs are the most promising candidate for future research and implementation. While in theory PICs are suitable for very sensitive measurements with extremely low concentrations, e.g. at the ~1 ppb-level for NH3, experimental verification for higher concentration levels, e.g. at the ~100 ppb-level for NH3, is an important milestone that should precede those developments.

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