SENSORS

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EXECUTIVE SUMMARY

Silicon photonics based integrated chemical and biological (chem-bio) sensors will enable applications that are currently not possible or are cost prohibitive. These applications range from consumer medical and food markets to defense and industrial markets. Technical barriers to market entry that affect all these industries include the requirement of low-Cost, Size, Weight and Power (CSWaP), which ultimately drives the technology requirement for highly integrated photonic circuits, including but extending well beyond conventional passive devices.

The integration of active components such as light sources, optical detectors and optical modulator structures on passive silicon photonic (Si-photonic) devices can enable the market to realize and commercialize highly integrated-low CSWaP chem-bio sensors. Recent advances in optical components in the UV, Near InfraRed (NIR), Mid InfraRed (MIR) and LongWave InfraRed (LWIR) regimes are enabling highly sensitivite sensors. These advances must coincide with rapid New Product Introduction (NPI) cycles to reduce the time to market for users of integrated chem-bio sensors.

The realization of low CSWaP designs, fast NPI cycles and custom wavelength tunability of integrated Si-photonic packages across the electromagnetic spectrum will allow quick time to market of chem-bio sensors.

CURRENT STATUS

The market for chem-bio sensors is projected to reach a combined value of $50.4B in 2021 with a compound annual growth rate (CAGR) of 11.3%. While significant development and maturity have been demonstrated in various aspects of active component integration at various wavelengths, the current manufacturing capabilities haven't addressed the market challenges presented for photonic sensors.

MAIN CHALLENGES

There are many challenges related to introducing low CSWaP microfluidic and biosensors to the market. These challenge areas include the development of appropriate sensor architecture, design of the photonic sensing element, the development of the microfluidic assembly and the final packaging of the device.
Sensor architecture challenges include the integration of wavelength specific features and active devices into a low CSWaP package. Multi-spectral sources, detectors, low-loss passive waveguides, and chemical concentrators for some applications must be integrated while maintaining optical specifications over a variety of environments. Development of wavelength specific passive devices includes ring resonators, Mach Zehnder Interferometers (MZIs), photonic crystals, and spiral waveguides. Sensor architecture challenges also include microfluidic specific elements such as integration and design of different materials.

Challenges pertaining to the Photonic Sensing Element are specifically addressed towards the photonic process design kit (PDK)improvements required for quick design turn around, interface definitions which include input, output, and interface standards as well as overall specifications and testability of the sensing element arrangement.

NEEDS

Needs 2020-2025

- Low CSWaP sensors
- Si based waveguides with Ge detectors
- Interposer-based lasers (1.3um to 1.5um)
- Sensors Process Design Kit (PDK) and Design Rule Check (DRC)
- Automated Arrayed Waveguide Gratings (AWGs) in mature PDKs

Needs 2025-2030 years

- Wider spectral bandwidth sources
- Integrated detectors
- Monolithic Short wavelength, Mid-IR, Long-IR, & Multi-spectral sources on Si
- Low-loss passive waveguides; Passive waveguides suitable for integration with microfluidics Flourescence detection (VIS)
- Integrated Mid-IR & Long-IR detectors
- Monolithic multiplexing & de-multiplexing for all spectral regions
- Resonant enhancement of sensing & detection
- 3-5um spectrometers
- Testing and packaging capabilities

Needs 2030-2040

- Chip designs suitable for high-yield manufacturability with low cost & ultra-small packaging
- Monolithic tunable sources on Si
- Multiple wavelength passive waveguides
- Chemical concentrators to enhance sensitivity over given pathlength
- Broadband beam combining
- Monolithic/ hybrid intergation of multiple light sources
- Integrated spectroscopy, refractive index (RI) and flourescence sensors in Si
- Metamaterial enhancement of chem/bio detection sensitivity
- Dual frequency-comb spectrometers integrated on a chip
- Photonic module standardization - instances of plug and play light sources, sensor modules and detectors

INTRODUCTION

Technology platforms in the photonic sensors market are application driven. The market is quite segregated with long R&D and NPI (New Product Introduction) cycles, because of immaturity of the technology, development cost, and in some instances, regulatory hurdles. We can expect that as technology advances and development costs drop, this cycle will shorten. A gamut of applications is expected to arise during the coming five years due to the increased usage of sensors. Numerous examples of market drivers that contribute to growth are described in the Product Emulator Groups (PEGs) document. Here we outline the technology development needs for photonic sensing applications, with four applications using input from the PEGs listed below:

- IIoT chapter– Wearable sensors
- IIoT chapter – Gas sensing
- Aerospace chapter – Water quality monitoring
- Biophotonics and medical chapter– Early detection of prostate cancer

MATERIALS

Initial sensor designs will focus primarily on operation at telecom or near-telecom wavelengths. As such, these sensors can be fabricated from silicon or silicon nitride. For monolithically integrated sensor systems, detection will be accomplished via Ge photodiodes, likely integrated with on-chip spectrometers fabricated from silicon or silicon nitride. However, much higher sensitivity will be attainable following extension into the midwave infrared (mid-IR). This will require waveguides made from materials such as SiN (up to about 5 µm) or germanium, (up to about 15 µm) and also new materials such as InGaAs, Pb chalcogenides, InP-based quantum cascade structures, or GaSb-based interband cascade structures for detectors. The academic literature describes several materials systems for on-chip sources, including InAs quantum dots, interband cascade lasers (ICLs), and quantum cascade lasers (QCLs) for the mid-IR.

DESIGN TOOLS

Computational tools needed for the design of integrated photonic sensor chips will be similar to those employed in other integrated photonics market areas. Additional tools will be required to design laser sources and detectors, and environmental interfaces, including microfluidics systems and air sampling design.

DESIGN VERIFICATION TESTING (DVT) AND TEST, INSPECTION, MEASUREMENT (TIM)

Design Verification Testing (DVT) must be planned and performed appropriately to ensure operational success to the Photonic Integrated Circuit (PIC) specifications. Both wafer scale and die level testing of sensors will be analogous to other photonic devices. The design verification testing can include optical figures of merit, epitaxial tolerance verification and test structure specific samples. DVT testing is imperative for a successful sensor launch. DVT analysis can also include yield measurements, known good die metrics and failure analysis to aid in the Design for Manufacturing phase.

DESIGN FOR MANUFACTURING (DFM)

As part of the overall design, key manufacturing and test elements such as Design for Test (DfT) and Packaging (DfP) and Manufacturing (DfM) must be considered in early stages. The photonic sensor specifications should address the transition from research and development to manufacturing transitions and their corresponding considerations. Principally research and development will test the sensor functions and DVT items. DFM is the stage where the design now has to consider Si-Yield, defect appropriation, test locations, appropriate test structures, and size reduction efforts. On top of these efforts is the logistic and PIC backlog appropriation considerations for commercial success. Education and training will inform this activity to enable a successful program. Six Sigma methodology used to determine Critical to Quality parameters (CTQ's), provides a focus on the most critical elements of the design. When coupled with appropriate process measurements it will provide vital information throughout the manufacturing process. In the case of multiplexing, yields must be high for every step to provide highest Rolled Throughput Yield of the photonic sensor.

ROADMAP OF QUANTIFIED KEY ATTRIBUTE NEEDS

Using the example of manufacturing an integrated photonic chem-bio sensor, Table 1 presents a roadmap for targeting key attributes.

Table 1. *Roadmap for targeting key attributes required in chemical and biological sensors*

Quantified Key Attribute Needs	**2020 Roadmap**	**2025 Roadmap**	**2030 Roadmap**	**2040 Roadmap**
Sensing mechanism	Absorption spectroscopy and surface capture; single point, time of flight; Refractive Index	Include detection of changes in fluorescence or colorimetry (visible); Raman Spectroscopy	Absorption spectroscopy, Changes in RI and fluorescence, polarization etc.	Improvements on techniques from the past decades - for example, novel technologies using NIR for spectroscopy with better instrumentation; New ideas on physical sensing; Low-cost materials.
Analyte to be detected by sensor	Chemicals with absorption in the 1300 to 1550 nm wavelength range; biomolecules at moderate abundance (≥ ng/mL)	Much more sensitive detection in the mid-IR (MWIR) and longwave-IR (LWIR);	Broad wavelength tunability on the same chip, for detecting many analytes with the same sensor; biomolecules at low abundance (fg/mL)	Single biomolecule detection (improvements in mass transport for rare analytes); versatility in pivoting to serving societal sensing needs (such as coronavirus)
Labelled or Label-free sensing	Label-free (chemical); labeled or label-free (bio)	Add Functionalization which may be required (eg. AB-Antigen pair) or other labelling – and the required facilities for this task	Label-free, labelled, and mass-enhanced	Multi-modal sensing
Material System	Si or silicon nitride waveguides with Ge detectors	Si, SiN, Ge, chalcogenide, or III-V passive waveguides.	Multiple passive waveguides operating in different spectral bands on the same chip.	Multiple sensing modalities on the same chip
Analyte delivery	Etching down to silicon or silicon nitride waveguide level, and analyte delivery via microfluidics, ink-jet printing etc.	Coating with chemical sorbents to enhance sensitivity.	Developing packaging capabilities for analyte delivery and encapsulation, microfluidics	On-chip optical forces to enhance delivery; Improved materials for microfluidics.

Light Source	Interposer-based lasers. Backup: VCSELs emitting in the 1300 nm to 1550 nm range. SOA (broad-band)	On-chip lasers (1310 nm, 1550 nm), Frequency comb sources, Mid-IR ICLs and QCLs, LWIR QCLs; sources for high-energy/short wavelength (< 900 nm)	More choices in hybrid and integrated light sources across several wavelength ranges. Multiple integrated sources operating in different spectral bands; Multiple integrated ICL and QCL for on-chip dual-comb spectroscopy	On-chip higher power and tunable light sources
Detector	Multiple Ge detectors (with different sensitivities). High sensitivity, low-frequency Ge detector particularly important.	Multiple silicon detectors (with different sensitivities). Interband and quantum cascade detectors, silicon bolometers, for the mid-IR and LWIR; in-plane resonant-cavity Mid-IR and LWIR detectors	On-chip and hybrid Si, Ge and other material system (3-5 µm) photodetectors and imagers with application-specific sensitivities. Multiple detectors operating in different mid-IR and LWIR spectral bands operating on same chip. Resonant cavity detectors for higher sensitivity.	Resonant cavity detection, multi-wavelength detectors integrated with spectrometers, non-cryogenic and on-chip detection
Spectrometer	Automated AWG design. Standard AWG as part of the PDK. FTIR (MZ- or ring resonator based). Focus on telecom and datacom bands	Add wavelength regions (3-5 µm); increase resolution. Alternative spectrometer designs (echelle gratings). Mid-IR and LWIR spectroscopy, via wavelength selectivity by source, sensor resonator, and/or resonant cavity detector	Broaden wavelength range; add 8-12 µm wavelength region. Integrated spectroscopy in multiple spectral bands, with wavelength multiplexing and demultiplexing via echelle gratings and/or arrayed waveguide gratings (AWGs)	On-chip spectrometers using dFT, Resonant cavity spectrometry; temperature-independent spectrometers
Filters	Ring resonators	Photonic crystal, Tunable filters; polarization filtering (including tunability)	Coating-based; Optical isolators on-chip	Narrow-band and broad-band integrated filters using Bragg gratings for example, MEMS-based turnability; manufacturing-tolerant filter designs; environmentally insensitive filters
Sensor I/O	Edge coupler (25, 50, 127 µm pitch) Grating coupler	Tunable gratings	Multimode waveguides	Implantable sensors; hollow waveguide; alternative structures for improved sensitivity
Integration level	Hybrid with flip-chip bonding	Hybrid with flip chip bonding and some monolithic where needed	Hybrid and monolithic capability. TSVs specific to sensing such as ability for high-density multi-level vertical packaging	Low-cost of manufacture with foundry level processing, “smart sensors” with full ROIC integration as

				well as separate hybrid integration
Coupler	In-plane	In-plane or grating	In-plane or grating with varied material systems	Zero-loss couplers
Resolution	Application-specific	Application-specific	Application-specific	Application-specific
Solved Applications	Prototype sensors in biomedical, chemical, and environmental sensing	Point-of-Care photonic sensor systems for diagnostics	Long-term, minimal maintenance remote sensing, like oil pipeline leak detection, industrial pollution monitoring, environmental monitoring, agricultural monitoring etc.	Implantables for the medical field, Low power sensing systems for spacecrafts

CRITICAL (INFRASTRUCTURE) ISSUES

In addition to the markets for chemical and biological sensors discussed above, the need for autonomous systems that interrogate their surroundings toward an ever expanding and holistic realization of the Internet of Things (IoT) continues to drive data rates and information content beyond simple point and line sensors. Indeed, volumetric photonic solutions provide the primary means that can support a cost-effective expansion of embedded sensing into automotive, integrated building, residential, and aerospace systems. To that end, it is essential to develop a suite of low cost, agile, sensor manufacturing platforms that simultaneously incorporate: photonic based sensing, reconfigurability, platform reuse, self-diagnostics, wireless communication and agile power.

Central to sensor development are the needs for combined designs of not only the sensing element, but also the means for packaging and powering the device. Consequently, a System In Package (SiP) approach, complete with wireless communication and agile power should be a primary aim of the sensor roadmapping process. Packaging needs will also vary considerably depending on the particular application, complexity, and form factor of the sensor. As such, the diversity of the application space and technical solutions to those applications constitutes a key issue. Identification of broadly applicable, common platform technologies must be a priority, because they enable standardization, which is typically desirable for use in diverse markets. When applications need anything beyond what is standardized, new platforms can be added.

TECHNOLOGY NEEDS

PRIORITIZED RESEARCH NEEDS (AFTER 2025)

Sources: Chemical (including gas sensing) and physical metrology are the two primary means of photonic based volumetric sensing that will evolve and expand during the next few years. While metrology often can be achieved using single wavelength optical sources, chemical sensing requires specification and quantification and thus needs a wider spectral bandwidth than afforded by a single wavelength source. The optical source must be semi-continuously tuned to both a reference line and throughout a spectral band, or emit in a broadband for coupling with an on-chip spectrometer. While an off-chip source may be employed initially, tunable and/or broadband on-chip sources emitting in single or multiple spectral bands will become manufacturable over the coming years. Integrated detectors are also critical if we are to detect small sensor signals at low cost.

Different sensing modalities including refractometry, absorption, Raman, fluorescence and others, and different use cases, including disposable vs. reusable, stipulate distinctive requirements on light sources. Light sources used in conjunction with single-use sensor chips can be off-chip lasers and technical solutions that already have been developed by companies like Genalyte Inc. for efficient optical Input-Output (I/O) interfaces. On-chip source integration for reusable sensors remains a major unresolved challenge. Specific technical challenges include:

Wavelength coverage beyond telecommunication windows

Flip-chip bonding of InP based lasers provides access to the 1550 nm telecommunication wave band. For Raman spectroscopy shorter excitation wavelength is preferred to enhance signal strength (which scales with λ^{-4}) provided that fluorescence is suppressed. Visible or Near InfraRed (NIR < 1 μm) light source integration with silicon nitride waveguides is not available. For absorption spectroscopy the absorption lines and fingerprints of most chemical and biological species are located in the Mid-InfraRed (MIR) (2.5 μm - 25 μm) regime, where waveguide-integrated sources are developing rapidly. The recent demonstrations of QCLs and ICLs integrated on Si [2,3] may offer a viable solution.
Broadband spatially coherent sources are essential for absorption spectroscopy. Infrared spectroscopy requires a combination of broad spectral coverage and high spatial coherence compatible with single-mode photonics, for proper analysis of samples. While these sources are not commercially available yet, IR LEDs, amplified spontaneous emission devices, frequency combs, and super-continuum sources are promising solutions. An alternative to broadband spatially coherent sources is a broadly tunable laser, or more likely, multiple lasers emitting in different spectral bands integrated on the same chip.

Detectors

Integrated interband and quantum cascade detectors may be formed using the same wafer material as the lasers, or other integrated detectors such as silicon bolometers may be employed.

Robust spectrometers

Broadband spectroscopy may be performed by tuning the wavelength of one or more lasers, employing sensing resonators operating at different wavelengths (each of which is tunable over a narrow range), and/or employing one or more in-plane resonant-cavity detectors. These may be used in conjunction with AWGs or echelle gratings to multiplex and/or demultiplex the beams propagating in passive waveguides on the chip.

Scalable methods for post-fab chemical functionalization

Contact-based chemical and biological sensors require that the sensor surface be coated with a chemical able to provide specific or semi-specific capture of the target of interest, the recognition elements. For example, in the context of biological sensing, this recognition element may be an antibody specific for a target antigen. Biological recognition elements such as antibodies are susceptible to inactivation by heat, drying, or other environmental factors, requiring careful handling and post-deposition stabilization. In some cases, artificial antibodies are built from a molecular library (APTAMER database), and can outperform natural antibodies. Confinement of the recognition element to micron or sub-micron features may be required, and multi-target (multiplex) sensors will require selective functionalization of different areas of the sensor surface. While currently available piezoelectric dispense technologies can address some of these needs, they are typically limited to feature sizes of > 50 μm. Photolithographic patterning of nucleic acids (DNA) is well developed, but has not been commercially extended to other classes of molecules.

Integration with environmental sampling systems and microfluidics

In extrinsic sensors, it will be necessary to equip the sensor with a subsystem able to sample the environment, as in air monitoring systems, or to deliver a sample, such as a biological fluid. Many commercial and research-scale technologies are available in both these areas, but as yet there has been little work done in the context of co-manufacturing them with integrated photonic sensors. Hybrid extrinsic and intrinsic based sensors will require technologies to easily incorporate both.

Interface technologies for disposable components

The cost of integrated photonic sensors is particularly problematic in the biomedical / diagnostics realm, where competing technologies center on disposable components with profit margins on the order of pennies per unit. Such technology solutions that allow integration of integrated photonic systems with disposable components are a significant need.

Data analysis, storage, and transmission

Standardized formats and protocols for data compression, storage, transmission and analysis would accelerate significantly the integrated photonic sensors industry by allowing diverse sensor types to function within a unified ecosystem.

PRIORITIZED DEVELOPMENT & IMPLEMENTATION NEEDS (BEFORE 2025)

Photonic sensors are required for a variety of applications. First, a micro sensor can be considered a sensor system including all the support for converting the raw sensor data such as temperature and O_2 level into actionable information. Generally, a micro sensor system should be compact and embeddable as opposed to a piece of test equipment. Compact would translate into a reduction in Cost, Size, Weight, and Power (CSWaP). The types of host or delivery methods will be those needed for a compact solution. The host may be a human where the micro sensor is used to detect biological conditions.

A delivery method may be a small Unmanned Aerial System (UAS) where the micro sensor is used to determine chemical environments. The conditions and environments of interest include: 1) human biological, 2) environmental biological, 3) environmental chemical, and 4) environmental physical.

- A typical human biological sensor would be a micro sensor attached to the human that could be used to determine the host human’s operating condition. These conditions could include glucose, oxygen, heart rate, blood pressure, and sweat characteristics.
- Wireless interfaces will need co-development with photonics whether for use in biosensors (both in-body or on-body) or in chemical sensors.
- An environmental biological sensor would be a micro sensor that could be attached to any object and would be used to determine the presence of biological warfare agents (anthrax, cyanide, etc.).
- An environmental chemical sensor would be a micro sensor that could be attached to any object and would be used to determine the presence of chemicals (CO_2, fuels, explosives, gases, etc.) used to determine the presence of objects of interest.
- An environmental physical sensor would be a micro sensor that could be attached to any object and would be used to determine physical conditions including positional data, temperature, shock, vibration, radiation, RF spectrum, etc.

  Photonic micro sensors have the potential to be deployed in either an embedded or standoff mode. As an embedded sensor they are inserted into the environment they are intended to monitor. However, in a standoff mode there is the ability to detect the environment from a distance. The standoff mode has several advantages. The use of a photonics transmission that can be reflected off an object or environment and returned for standoff analysis eliminates the burden of host attachment or environmental physical insertion. There is a broad need for micro sensors to detect various conditions, and hopefully integrated photonics technology can address some or all these needs.

GAPS AND SHOWSTOPPERS

TECHNO-ECONOMIC CHALLENGE

The cost-benefit analysis of integrated photonics is justifiable only when the manufacturing volume is large enough. In many instances, however, the sensor market is highly fragmented with specialized sensor devices dedicated to one or a small number of applications. Penetration of integrated photonics is therefore likely limited to two possible use cases: (1) applications with massive volume using low-cost single-use sensor chips or sensors integrated with consumer electronic devices such as smart phones and wearable electronics, or (2) applications with a medium-to-high volume but can afford a higher premium cost, making multi-project wafer runs an economically viable manufacturing solution. Many sensors for industrial process monitoring fall in the latter category. Identification of these applications remains a challenge for the sensor community because integrated photonic sensing is still a largely nascent concept in many industrial sectors.

On-chip sources

The above discussion of techno-economic challenge applies to on-chip sources. More details can be found in the chapter on Monolithic Integration.

Passive components

The spectral diversity mandated for different sensing applications presents a severe technical barrier towards standardization for MPW shuttles and for scalable manufacturing. On one hand, different materials and device architectures are needed for optical transmission at different wavelengths. For instance, silicon nitride is used for device operation in the visible range while suspended silicon or silicon germanium and germanium waveguides are essential for optical transmission beyond the transparency window of silicon dioxide ($\lambda > 4$ µm). On the other hand, even for devices using the same material system, operation bandwidth can be limited by the single-mode wave guiding condition.

Photodetectors

Attaining broadband spectral coverage is important for on-chip photodetectors. Polycrystalline lead-chalocgenide based on-chip photoconductors have successfully been demonstrated in methane gas sensor systems [7]. In the crystalline space, this is more challenging. While silicon and germanium are excellent detector materials in the visible and NIR, MIR detector integration often involves III-V and II-VI alloys with large lattice mismatch as well as Coefficient of Thermal Expansion (CTE) mismatch with silicon. Fortunately, both interband cascade and quantum cascade structures are suitable for processing lasers and detectors from the same wafer material. Both monolithic [4] and heterogeneous integration [5] are currently being pursued to resolve the integration challenge. Configurations such as resonant cavities that enhance the sensitivity are needed to preclude the need for cryogenic cooling, which would substantially restrict potential applications.

Spectrometers

Spectrometers are essential components for infrared and Raman sensors, and they can also function as standalone devices for applications ranging from flame monitoring to food quality control. The primary limitations of on-chip spectrometers compared to their conventional bulk counterparts based on discrete optics include: 1) low signal-to-noise ratio (SNR); and 2) limited spectral channel number. Since on-chip spectrometers rely on single-mode waveguide input, the optical throughput is fundamentally limited by thermodynamics (unless used in conjunction with a spatially coherent light source). The use of on-chip detectors with small active volume [6] suppresses detector noise and partially compensates for the low SNR, although alternative strategies to further boost the SNR are mandated. Placing a detector closer to the sensing element can minimize overall insertion loss, enabling higher sensitivity [7].

The spectral channel number N connects the spectral resolution $\delta\lambda$ (minimum resolvable wavelength difference) and spectral bandwidth $\Delta\lambda$ (operational wavelength range) through $\Delta\lambda = N \cdot \delta\lambda$. In state-of-the-art on-chip spectrometers the spectral channel number (typically ~ 100 or less) is far inferior compared to those of commercial spectrometers (usually > 1,000). Further, the spectral channel number scales linearly with system footprint and complexity in current on-chip spectrometer designs and is therefore not sustainable. Hence, as mentioned previously, wavelength selectivity for spectroscopy may be imposed at the source, sensor, and/or detector segment of the integrated system.

However, a recent design of an on-chip spectrometer [8] structure consists of an interferometer whose arms comprise a series of cascaded optical switches connected by waveguides of varying lengths. Unlike prior on-chip spectrometers where the arm length is changed by tuning the waveguide effective index, the approach here is to modify the optical path through which light propagates using the cascaded switches. Direct modification of the waveguide path is a far more effective approach for changing the optical path length than is index modulation, thus enabling much improved spectral resolution. Additionally, better environmental performance has been achieved via direct modification instead of tuning via index changes.

Integration

Various levels of integration are possible with photonic devices. As indicated above components such as sources, simple passive devices, photodetectors, and spectrophotometers all can be integrated into the device. From the simplest passive sensor to the most sophisticated active sensor, each can satisfy unique application needs ranging from high volume, low cost solutions to fully standalone devices suited for certain added value applications.

Photonic devices integrating only sources, passive devices and detectors can in themselves be useful. An example of this selective integration could enable a compact read head for application such as handheld devices and can provide cost effective solutions to help mitigate consumable cost and improve overall reliability by reducing the complexity of each individual sensor element. As examples of partial integration, an on-chip sensing element with a waveguide-integrated detector has been demonstrated [7], as has a detector with a Read-Out-Integrated Circuit (ROIC) [6].

Packaging

Major issues here will be to determine the special requirements for sensor packaging and the categories of sensors addressed. One common challenge for all sensor packaging is that sensor photons need to interact with the external environment to sense it, and yet the sensor must be robust against environmental degradation. For example, a gas or liquid sample must have a pathway to reach the sensor within the packaging, but not damage any other on-chip photonic devices used such as light sources, detectors, filters etc. The photon source will eventually be inside the package but currently it remains outside. In the future, active elements like the source and detector may be separated for applications where disposable parts (too costly to dispose sources and detectors) are preferred. Currently off-chip sources are being considered for use in chem-bio sensing systems. To monitor/control the package temperature and the temperature of the photonic sensing element, either a non-optical Micro-Electro-Mechanical-System (MEMS)-based temperature sensor or a photonic device such as a ring resonator can be employed.

Access for fluidics and/or gas handling in and out of the package

For practical use of the sensors, access for fluids (both in and out) will be needed. In extrinsic sensors, the package has an opening and in others microfluidic channels will handle gas and liquid delivery to the sensor element. Gas entry must be separated from the balance of the system and materials used in the package must be compatible with the system requirement. Most of the microfluidic parts will be silicon or glass for bio sensing, where fluids are typically bio fluids. For gas and chemical sensing, in general, caustic/toxic materials will require specially coated surfaces. In gas sensors, bio fouling does not represent a significant problem but toxicity can be a challenging issue, so coatings such as Teflon and parylene have been used. Photonic designs can also aid in simplifying packaging requirements. For instance, waveguides are typically designed to avoid interaction of evanescent light with the microfluidic channel walls (for example widening the waveguide at the intersection of the microfluidics with the waveguides will retain the mode within the waveguide, minimizing evanescence [9]). Sensor chips can have light sources, sensors and detectors on the same sub mounts. Bonding to sub mounts or Printed Circuit Boards (PCBs) require pick and place die-bonding methods. Tools already used in electronic packaging can be adapted to photonics with small modifications. Vendors like MRSI Systems (MA), Palomar Technologies (CA) and Finetech (NH) have already begun adapting their die placement tools for photonic applications. Westbond supplies wire bonders useful for connectorizing active devices.

Thermal management requirements (range of temperature, environmental temperatures in the use case, accuracy and stability of temperature in any part of the sensor)

Thermal management will be very important as sensors are packaged in a heterogeneously integrated complex Si platform. Often, they will be held at ambient temperature, but heaters may be needed for calibration and/or regeneration of sensors. Many sensors also require precise thermal regulation to prevent signal drift. Heater power supplies will be determined by heat capacity of the sample flow. In the future, when MIR sensors are a part of foundry capabilities, cooling to -60°C may be needed, perhaps provided by thermo-electric coolers (TECs). In this case, a power source for a two-stage TEC will be needed to dissipate heat from the detectors. However, these power sources generate heat that will need to be sinked with on-chip air or water-cooling.

Mechanical requirements in use case environments

One must consider a variety of environments. For example, some sensors will have vibrational environmental concerns. Humidity can play a role in gas (not liquid) sensor measurements, for which we may need an active control. Non-disposable sensors will require repeated cleaning mechanisms.

Cost targets

Sensor type with a typical full chem-bio sensor system costing ~$200 determines cost targets. Cost must necessarily be very low (much less than $ 1) if disposable sensors are a requirement. Military and space have much less price sensitivity but require high performance sensors with a long lifetime.

New materials for in-body bio sensing

Materials for use in in-body biosensing applications require Food and Drug Administration (FDA) approval. For instance, in-vivo sensors will need to be safe as ingestible and implantable photonic devices.

Sensors needing FDA approval

What kind of protective material coatings are required to protect patient as well as device? Biocompatible polymers or porous membranes may fit the bill, but have their own issues of lifetime in vivo and fouling (preventing access to the sensor). These will need to be evaluated.

Porous membranes

Manufacture of these porous membranes is not easy. For instance, to oxygenate blood, the membrane must pass gases but not fluids, and such membranes typically have a finite lifetime.

RECOMMENDATIONS ON POTENTIAL ALTERNATIVE TECHNOLOGIES

Competing technologies include MEMS devices, and existing sensor and analytical systems. Advantages of integrated photonic sensors over these technologies have been detailed above; the primary advantages of existing technologies at least in the near term will be market familiarity and cost. Integration of MEMS or "low tech" existing technology may be feasible in some instances, and such integration may help drive costs down while accelerating market adoption.

EDUCATION AND TRAINING

DESIGN PROCESS

Education and training in the integrated photonics sensors industry needs to begin with the design process. Familiarity with layout and simulation tools, as well as the use of foundry PDKs, will be essential. Designers will also need to consider application-specific performance criteria in formulating their designs. Current PDKs are typically optimized for datacom and telecom applications. PIX4life in Europe offers PDKs for biosensing. A generalized sensors PDK that includes chemical and bio-sensing applications would be helpful. The choice of sensing components in the PDKs will depend on wavelengths used and sensing modality selected. Design enablement includes Electronic Photonic Design Automation (EPDA) software that can do multiphysics simulations (e.g., photonic interaction with analyte solution) as well as PDKs. [Please refer to the EPDA chapter].

In addition to training in PIC design and providing an understanding of the underlying physical and optical properties, successful design and implementation of integrated photonics sensors will require at least passing familiarity with the field of sensor applications.

TESTING OF PROTOTYPES

Education centers and programs need to serve as bridges to test prototypes of diverse photonics-based sensors. Cross-training in materials science, chemistry, biology, biophysics and biomedical engineering will be desirable for these activities. Training in Testing, Assembly and Packaging (TAP) will be invaluable, since sensor PICs have different TAP requirements compared to standard datacom and telecom chips. From the interaction between academia and industry new proposals will be presented to adapt to the theoretical, practical and commercial needs of the sensors.

INFORMING STANDARDS FOR MASS PRODUCTION

Finally, a well structured education and training strategy will inform industry and standardization agencies about performance, reproducibility and efficacy of diverse photonic prototypes as compared to other methods. Such data will drive photonic sensor adoption in specific applications.

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APPENDIX

BACKGROUND

Properties of light that are typically monitored are wavelength, refractive index, phase change, number of photons (intensity of light), polarization and spin. Monitoring changes in these properties of light enable the sensing of chemicals or biomolecules, stress, shape deformation, pressure, distance, temperature and vibration, to name a few. Such light sensors can be fiber-based, free space, or can use integrated photonics.

This chapter of the roadmap will focus specifically on the sensing of biological molecules and chemicals using integrated photonics. The other sensor types and markets like aerospace, automotive and the (Industrial) Internet of Things will be expanded upon in future editions. A few examples of the possible markets for integrated photonic sensors are detailed in Table 2.

***Table 2**. Biosensor and chemical sensor market segments showing example target analytes.*

Market Segment	**Example Target Analytes**
Industrial	For process control & workplace safety, any industrially relevant analytes, especially dangerous ones (Volatile Organic Compounds (VOCs), CH_4, NH_4, etc.)
Defense	Explosives (TNT, PETN), compounds used in chemical weapons (HCN, mustard gas), nuclear processing byproducts (HF)
Transportation	Oxygen, Fuel (hydrocarbons), pollutants (NO_x, SO_x, CO_2)
Air Quality/Environmental Monitoring	Pollutants (CO_2, NO_x, SO_x, Ozone), CO, greenhouse gases (CH_4), particulates
Water Quality	Pollutants (nitrates, phosphates, heavy metals), bacteria, chem/bio warfare agents
Food	Organic compounds that indicate food state/quality; common food-borne pathogens; DNA and protein markers of genetically modified foods
Medical	Oxygen, glucose, proteins, nucleic acids and other biomarkers for diagnostics; “non-chemical” health indicators (respiration, cardiovascular system, temperature, activity), virus sensing and decontamination
Consumer	Pollutants (Ozone, NO_x, SO_x, CO_2), health indicators (compounds in sweat, glucose levels)

Integrated photonics is very well positioned to take advantage of this explosion in the use of sensors for different applications. Large volume production will be realized with the advent of chip-scale sensors. Low CSWAP and low maintenance are required of this chip-scale sensor, because a system incorporating the sensor, for example a cellphone, must retain its size, battery life, cost, and usability. At this time, only MEMS and integrated photonics can rise to the occasion, as shown in Table 3.

***Table 3.** Comparison of several common biosensor and chemical sensor technologies.*

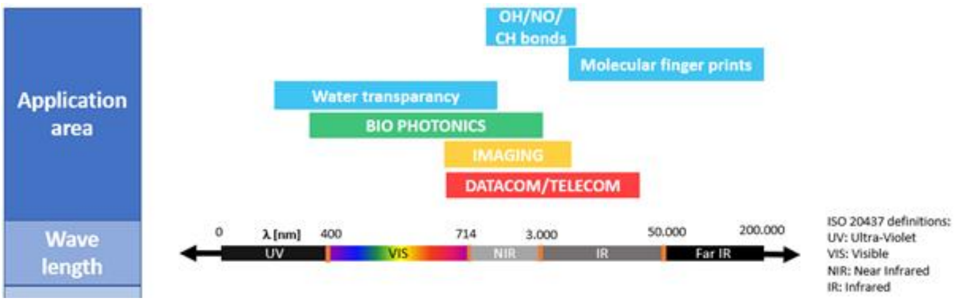
Sensor Technology	**Size**	**Cost**	**Power Consumption**	**Maintenance/ Calibration**
Integrated Photonics	Chip-scale	Promises to be very low at scale	Very low	None for consumer
MEMS	Chip-scale	Very low at scale	Very low	None for consumer
Metal Oxide Semiconductor (MOS)	Chip-scale	Very low	Can require heating (energy intensive)	None for consumer
Electrochemical	Handheld	Very low	Very low	None for consumer
Catalytic/Pellistor	Handheld	Very low	Requires heating (energy intensive)	Requires calibration before measurement
Non-Dispersive Infrared (NDIR)	Handheld	Moderate	Very low	None for consumer
Photoionization Detection (PID)	Handheld	Moderate	Very low	Requires calibration before measurement

Luminescent	Handheld	Moderate	Very low	Requires labels on analyte
Fiber Optic	Handheld	Moderate	Very low	None for consumer

Comparing MEMS and integrated photonics, the latter promises better reliability since MEMS sensors typically have moving parts. Some types of photonic sensors for chem/bio applications also have inherent "fingerprinting" selectivity because of the unique absorption spectra of chem-bio analytes.

SITUATIONAL (INFRASTRUCTURE) ANALYSIS

Functional requirements



GaSb substrates with Interband Cascade Laser (ICL)-based sensors will have far lower power consumption than Quantum Cascade Laser (QCL)-based sensors.
Also, interband cascade detectors are more sensitive than quantum cascade detectors.

Figure 1. *Overview of markets and materials for sensing as a function of wavelength. Adapted from reference [1]*

TECHNICAL REQUIREMENTS

The development of label–free chemical and biosensors using photonic technologies will require the successful integration of technology and manufacturing processes. Key development aspects include:

1. **Sensing Elements:** Micro-fabrication of optical sensing devices on silicon wafers, with or without component integration. For active sensing these may integrate optical sources (various spectral bands), passive sensing waveguides, detectors, and possibly tunable sources, multi-spectral sources, frequency comb sources, and/or microfluidics onto the same ultra-compact semiconductor chip.
2. **Development and Fabrication of Microfluidics Elements:** For precise sample delivery and fluid (gas, water, or biological sample) management
3. **Manufacturing and Integrated Packaging including:**
   a. Precision optical sensing elements
   b. Application of biomaterials to devices
   c. Production of microfluidic assemblies
   d. Precision integrated packaging (integration of photonic sensor, microfluidics and external structural/housing)
   e. BioSafety Level 2 (BSL-2) laboratory availability for testing biological samples, and analogous facilities for testing hazardous chemical samples (gases or liquids)
4. **Ancillary capability:** Analytical testing to demonstrate performance against predicate devices

The design, fabrication, assembly and testing of photonic sensor devices must consider many critical factors. As discussed above, chem-bio sensor applications are very broad, with a significant range of sample types, sensitivity and specificity requirements, and stringent precision and accuracy of the analytical measurement goals. These devices must have high reliability and no undetectable failure modes when produced at high production volumes. The ability to get a sample of high quality to the photonic sensing element, under various sample and environmental conditions, becomes an integral part of the design and development process. In many cases the solution involves microfluidics and the integration of photonic sensor elements to microfluidic structures, packaged in an integrated assembly at low production cost.

Chemical and biosensors may be considered active or passive. Passive sensors rely on supporting instrumentation to provide the needed illumination, detection and analytical processing. Active sensors integrate much of this capability within the sensing element itself via monolithic integration. The application determines the approach to use. Considerations such as total test cost, the maturity and availability of technologies needed to implement sensing, size of the consumable and instrument, and test throughput are important in this determination. The advancement of technology and manufacturing capability over time enables the ability to integrate more functionality into active photonic sensors. If costs of active elements, such as sources and detectors, fall over time, then it is reasonable to assume a logical progression from passive to active devices.

Sensors can also be categorized as multiplexed/multi-modal or non-multiplexed. A sensor dedicated to a single analyte is considered non-multiplexed, or “singleplex”. Its design and manufacture are simplified since no interaction between detection channels needs to be considered. Its manufacturing yield is not impacted by a failure of adjacent detection zones as in a multiplexed sensor. However, the non-multiplexed sensor suffers from higher costs since the cost of the sensor cannot be amortized over multiple tests. Multiplexed sensors can measure a number of different analytes in a single device simultaneously, making them particularly suited for detection of specific diseases that require a number of discrete analyte measurements for proper determination. Failure of a single test within a multiplexed sensor can destroy the utility of the entire device in many cases. To guard against this loss of device value, redundancies can be built into the multiplexed sensor system. Redundancies can also be used to duplicate sensors, leading to an increased confidence in measurements. To retain competitive costs, a sensor system must have high manufacturing yields.
Biological sensors are typically classified as “labeled” or “label-free”. Label-free sensors directly detect the presence of the target analyte either spectroscopically, or by specific capture of the target analyte via a physisorbed or covalently attached capture molecule yielding a change in the local refractive index. Labeled sensors detect a fluorescent or luminescent signal produced by a helper molecule (such as an antibody) on binding to the target analyte.

Chemical and biological sensors can be further classified as disposable, “one time use” or continuously reusable. Reuse of a sensor typically requires regeneration and/or decontamination. For gas sensing this may be a simple function of heating the device to release adsorbed material, or purging a microfluidic channel with an inert gas or liquid between measurements. Such a sensor system (typically a chemical sensor) must maintain reliable operation over its lifetime. However, for biosensors, and particularly with regard to biosensors used with human samples, decontamination requires significant wash protocols at best, and is difficult in practice. Degradation of sensor performance through its life adds to analytical error, making “one time use” sensors preferable in many biosensor applications.

When analyzing biological fluids, sample acquisition may also play an important role. Point of Care (POC) diagnostics may require the acquisition of a whole blood sample from a simple finger stick. Separation of plasma from whole blood is an added feature to consider, and impacts final packaging considerations. For gas sensors, integration with an atmospheric sampling system that is capable of processing medium to large volumes of air may be needed, depending on the application and analyte sensitivity requirements.

A list of design considerations for sensors follows. In large part these are common to both chem and biosensors:

1. **Sensor Architecture: depends on sample property to be sensed, and the approach to sensing**
    a. **Photonic Source and Detector Types:** One or more integrated active semiconductor (or other) source(s) and/or detector(s), meeting required specifications for spectral band, linewidth, and tuning range, source output power, detector sensitivity, source power and wavelength stability, frequency response, means for propagating beam from source to photonic sensing element to detector
    b. **Analyte requirements:** Sensitivity, Specificity, Sample Size
    c. **Photonic Sensing Element Type:** Examples include but are not limited to spiral waveguides, ring resonators, Mach-Zehnder interferometers, 2D photonic crystal
    d. **Microfluidics:** PDMS (polydimethylsiloxane), Glass, Silicon, Micro-molding, Hot Embossing
    e. **High Level Interfaces:** Physical alignment, fluidic, Input/output
    f. **Physical Design:** Size, tolerances, materials

2. **Photonic Sensing Element**
    a. **Photonic Sensor**: Requirements, design, modeling
    b. **Design Kit**: Capability
        - Existing capability
        - Added capability required
    c. **Photonic Manufacturing Plan**
    d. **Key Interfaces:** Depending on the level of integration (i.e. component based to monolithic), these include
        - Input illumination source
        - Output light detection
        - Fluidics Input to sensor element
        - Fluidics Input to packaged device
        - Alignment and test features
        - Assembly equipment interface
        - Functionalized coating/ Concentrator layer/ Bio materials deposition/
        - Transitory shipping/packaging interfaces
    e. **Specifications:**
        - Manufacturing specification
        - Test specification
        - Release specification

3. **Microfluidics Assembly**
    a. **Microfluidics Assembly:** Requirements, design, prototyping
    b. **Manufacturing Development and Manufacturing Plan:** Examples include
        - Stamper development: Design, stamper manufacture, release process
        - Disk molding
        - Chip punching and taping
        - Biomaterial deposition

c. **Key Interfaces:** Definition
   - Fluidics Input to sensor element
   - Fluidics Input to packaged device
   - Alignment and test features
   - Assembly equipment interface
   - Bio materials deposition
   - Transitory shipping/packaging interfaces
   - Wireless link between sensor and remote data collection system

d. **Specifications:**
   - Manufacturing specification
   - Test specification
   - Release specification

4. **Final Packaging**

a. **Housing:** Requirements, design, prototype

b. **Manufacturing Development and Manufacturing Plan:** Final Assembly
   - Pick and Place assembly
   - Ultrasonic welding
   - Final Packaging

c. **Key Interfaces:** Definition
   - Housing to Sensor assembly
   - Alignment and test features
   - Assembly equipment interface
   - Labeling interfaces
   - Transitory shipping/packaging interfaces

d. **Specifications:**
   - Manufacturing specification
   - Test specification
   - Release specification

Infrastructure requirements depend on the specific market application. A flexible approach is required with the ability to provide scale-up as needed. Local suppliers in the area can be utilized to support early feasibility needs and can be instrumental in future manufacturing planning.

MANUFACTURING PROCESSES

For the most part, manufacturing processes for sensors will largely follow processes developed for other, more mature industries such as microelectronics fabrication, with two exceptions. First, the operation of both chemical and biological sensors requires exposure of relevant sensor elements to the environment. As such, robust processes for trench production that do not contribute to optical losses are required. Second, the requirement of some sensor applications for novel materials and material configurations in order to access specific wavelength ranges may require specialized equipment.

Wafer-scale photonic sensor manufacturing technology is anticipated to essentially build on advancements in other areas such as computing and telecommunications, with the exception that the breadth of materials and manufacturing protocols are likely to be broader to support criteria specific to sensors. The requirements diverge considerably from the telecom/datacom model in post-fab die modification, such as deposition of biological capture molecules/chem-bio functionalized coatings, and in integration processes. With regard to the latter, for a Test, Assembly, and Packaging (TAP) facility, currently available manufacturing needed for heterogeneous integration of glass substrates such as optical interposers or microfluidic test cells with photonic chips involves a relatively small group of tools.

MANUFACTURING EQUIPMENT

The list of manufacturers below is not intended to be comprehensive. In several cases, other manufacturers also produce equipment with similar capabilities. Rather, these are provided as representative examples.

Fab processes

Lithography

Contact Aligner: Suss MicroTec MA/BA Gen4 or EVG 6220 with front and backside align capability and bonding jig compatibility and possible Nano imprint requirement

Laser Writer: Suss MicroTec LI Series direct write GaN laser system for greyscale litho would be very useful for quick turn designs but secondary to the contact aligner.

Photoresist spin/spray coat/develop: Suss MicroTec ACS200 or EVG101. Spin apply and spray coating will be needed to handle high aspect ratio substrate topography

Inspection and Metrology: Keyence 3D microscope VHX-900F for large area deep pattern inspection and large depth of field. Filmetrics F40UVX film thickness unit with extended wavelength range 190-1700nm for thick photoresist and photonic uses. A small Hitachi or JEOL Scanning Electron Microscope will be needed for resist sidewall pre/post etch as well as bonding inspections and cross sections.

Photoresist Strip and Precleans: Wet benches will be needed for solvent strips, acid strips and precleans. A dedicated set of tanks will be needed for bonding precleans to ensure minimum particle defects. Modutek, Reynolds and Santa Clara Plastics can provide options. Single wafer acid/base and solvent processors can also be obtained from Suss MicroTEC and EVG.

A small oxygen plasma strip unit such as YES CV200 or Plasma Etch PE100 is suited for tougher cross-linked resists.

Bonding

Suss MicroTec and EVG both supply bonders that mate with the aligners from lithography. The Suss XB8 bonder and EVG 500 series are good matches for full wafer-scale bonding. EVG also supplies a 540C2W that can perform wafer to wafer as well as chip to wafer bond. The SET FC150 is another choice for photonic chip bonding into the glass substrate while OAI also supplies aligners and bonders.

Oxidation

High Quality dry (low and high stress) and wet oxidation processes will require PECVD. An oxidation tube furnace will be needed for growing thick (wet) oxides on silicon wafers and to finalize high temperature bonds with high temperature anneal activation. However, fully active Si photonic chips with metal and Ge detectors will not go above 400 ºC. The addition of a bonded III-V laser will lower the temperature ceiling even further. Furnaces can be supplied by Tystar, Thermco or ASM.

Etch

The Deep Reactive Ion Etching (DRIE) system will need to be able to handle deep Si etching using the BOSCH process at depths of several hundred microns. A deep Si dioxide or glass etch also will be needed. The Plasma Therm Versaline and Oxford Plasma Pro systems are good options. These systems also can be enhanced with extra CVD deposition of oxides and nitrides for more flexibility.

Thin Films

In some cases, metal films such as Ti, Ni, Au and InSn may be needed for interconnect on a glass substrate and flip chip mounting of the photonic chip. Electrom beam evaporation is the preferd method when compared to sputtering. Temescal supplies the 2800 series with good capability.

Dicing

Wafer and substrate dicing will be needed. Disco sells the DAD3000 series and ADT 7000 Series.
Veeco also manufactures dicing equipment. Laser dicing and other "stealth" methods able to produce chiplets without Si particle contamination will be needed.

Optical Testing

If the product sensor does not have on-chip or interposer-based source and detector, then off-chip optical testing will be needed using various optical fibers, coherent and non-coherent sources and detectors as well as many free space optics components for re-imaging. Fixturing such as optical stages, micromanipulators, optical tables and microscopes will be required. Optical characterization equipment such as spectrum analyzers, power meters and mode field imagers/ wavefront sensors will be required alongside the appropriate software to drive the equipment.

Post Fab Manufacturing Processes

Functionalization

For many sensors, treatment of the sensor element with chemicals to enhance analyte capture or to provide specificity for an analyte is essential. In some cases, it may be possible to add these treatments at wafer scale, via CVD, spin-coating, or photolithographic patterning. Many capture reagents for sensors including antibodies that provide specificity for bio sensing are expensive and fragile; therefore, they are more likely to be added to the device after dicing, in a packaging facility. Equipment used in this context is discussed below.

Post-Fab Functionalization

Chemical functionalization of sensors for specific analyte capture post-dicing may require a first salinization treatment to render the surface capable of covalent capture of a biomolecule such as an antibody. In most cases, chemical functionalization may be accomplished via CVD/ALD (chemical vapor deposition/atomic layer deposition), using tools such as the commonly available YES Eco-Coat vapor deposition oven from Yield Engineering Systems. For precise deposition of chemicals with micron resolution, piezoelectric (ink-jet) spotting is the current industry standard. Manufacturers include Scienion, A.G.; the SciFlexArrayer SX and S100 are production-level tools. Other manufacturers in this area include BIoDot and Arrayjet. Printing with higher resolution is currently accessible using dip-pen nanolithography, a derivative of atomic force microscopy. Commercial systems are available from Nanomics Imaging, Ltd. and others, but are relatively low-throughput.

Fabrication of microfluidic channels

While laboratory prototype microfluidic systems frequently are fabricated in polydimethylsiloxane (PDMS), lack of manufacturing scalability for this material coupled with its permeability (a problem with gas sensing) and susceptibility to fouling, a problem with bio sensing, means that commercial systems typically will use microfluidic channels fabricated from glass, silicon or plastic. The microfluidics industry is growing rapidly, meaning that numerous suppliers are available.

While integration of microfluidic channels with sensor chips is possible using a "cover and clamp" strategy, robust bonding methods are needed to provide integrated devices. In most cases, for bio-sensors, these bonding methods will need to be low temperature, as capture elements such as antibodies are highly sensitive to elevated temperatures.