GOT SENSOR?
Smart Phones

- Accelerometer
- Gyroscope
- Magnetometer
- Barometer
- Proximity
- Light sensor
- Touch screen
- WiFi
- Bluetooth
- GSM/CDMA Cell
- NFC: Near Field
- Camera (front)
- Camera (back)

14 sensors!
Smart Homes

Remote sensors for:

- Smoke
- Heat
- Light
- Motion
Smart food supply chain

Food Growth
from Analog Devices

Food Transport
from Food and Beverages, India, Technology

Food Distribution
from Matrix Product Development

Food Consumption
The Mid-IR Silicon Photonics Sensor Platform

Anu Agarwal

MIT Microphotonics Center, Cambridge MA
AIM Photonics Institute, Rochester, NY

(With Juejun Hu and Lionel C. Kimerling)
Content

- Sensor Applications
- Sensor Markets
- What does this mean for you?
- What do we do?
- Why does it matter?
Integrated Photonic Sensor Applications
Content

- Sensor Applications
- Sensor Markets
- What does this mean for you?
- What do we do?
- Why does it matter?
Integrated Photonic Systems Roadmap 2016

Photonic Systems:

Telecommunications
LIDAR
Packaging
Testing
Integrated Photonic Sensors (Technology, Components, Equipment, …Supply Chain)
Content

- Sensor Applications
- Sensor Markets
- What does this mean for you?
- What do we do?
- Why does it matter?
Anatomy of an Integrated Photonic Chemical Sensor
Lab-on-a-chip
Chemical Sensor Characteristics

- What is our sensor platform?
- How do we interrogate the sensor?
- What do we detect?
- How do we deliver the chemical contaminant to our sensor?
- What parameters do we optimize?
Platform: Glass–on–Silicon Chalcogenide Glasses

- Wide IR transparency window
- Tunable optical properties
- Ease of fabrication

Chalcogen elements

Glass synthesis
Chalcogenide Glass Processing

Vacuum @ 110 °C ~ 4 hrs
Seal with torch

Melting ~ 12 Hrs

Air quenching

Annealing

Weigh in Glove Box

Vacuum chamber

Substrate holder

Gate valve to diffusion pump

Tantalum boat with crushed glass

Resistive heaters

Kathleen Richardson, UCF
Lift-Off Fabrication Process

Spin coating of NR9 photoresist

i-line UV exposure through photomask

Photoresist development

Glass thermal evaporation

Lift-off in acetone

Patterned NR9

3 μm thermal oxide

Silicon wafer

Thermal oxide

ChG WG

ChG Microdisk

Sensing element
Sensing element: Resonator

Resonant condition:

\[ N \cdot \lambda_0 = n_{eff} L \]

Sensing principle

Interaction length \rightarrow enhanced sensitivity
Sensing Principle

Refractive index sensing

\[ n + ik \]

Complex refractive index variations for sensing applications

- \( n \): index of refraction
- \( k \): absorption coefficient

Cavity-enhanced absorption spectroscopy

Chemical delivery

- Change in index of refraction creates a resonant wavelength shift
- Introduction of optical absorption leads to extinction ratio decrease
**Chemical delivery: Photonic-Microfluidic integration**

Photonic microfluidic integration enables:

- Minimal sample amount requirement: < 0.1 mL
- Integration of multiple functionalities on a single chip: chemical sampling, separation, purification

**PDMS: POLY-DI-METHYL-SILOXANE**
Liquid sensing: N-Methylaniline in CC\textsubscript{4}

Detection limit: 0.02 cm\textsuperscript{-1}

On-chip absorption spectroscopy to detect liquid N-methylaniline

On-chip methane gas sensing

On-chip detection of methane gas using absorption

Waveguide-Integrated Detector

Waveguide integration:
- Noise suppression
- IR photonic circuit

Detector performance
Waveguide-Integrated Detector at RT


<table>
<thead>
<tr>
<th></th>
<th>Waveguide Integrated</th>
<th>Normal Incident</th>
</tr>
</thead>
<tbody>
<tr>
<td>Responsivity (A/W)</td>
<td>1.0</td>
<td>0.017</td>
</tr>
<tr>
<td>External quantum efficiency</td>
<td>58%</td>
<td>0.94%</td>
</tr>
<tr>
<td>Temperature</td>
<td>Room Temperature</td>
<td>-60 °C</td>
</tr>
</tbody>
</table>

Resonance enhanced detector
Enhanced Detection: PbTe Detector in a Resonant Cavity

- Successful low-T fabrication process on Si: <150 °C
- Demonstrate 13.4X cavity enhancement
- Peak responsivity = 100 V/W
Resonant Cavity Enhanced IR Detector

- Enhanced detectivity inside a cavity
- Detectivity increases when photodetector size decreases

Integrated detector on a silicon platform

Cross-sectional view of 1 photodetector

Top-down view
Detectors on Si ROIC

Successful fabrication of integrated prototype

Dual wavelength
Dual wavelength detector pixel

(a)

- 50 nm PbTe in 1.6 μm cavity
- 100 nm PbTe in 3.7 μm cavity
- Sn metal contact

(c)
(b)
(d)

Experiments: Responsivity
Simulation: Optical absorption

50 nm PbTe in 1.6 μm cavity
100 nm PbTe in 3.7 μm cavity

LWIR detection using PbSnTe

With addition of Sn we have demonstrated a resonant cavity detector at longer IR (6 µm)

Zens et al., IPR 2011, SMD5, OSA/ANIC/IPR/Sensors/SL/SOF/SPPCom/2011
The Silicon Platform

Silicon photonics is "future-proof".
Three case studies:

- **Oil and Gas – Pipeline leakage monitoring**  
  (Joseph De Wolk, Will Wolfe, Preston Kutney, Ozzie Ortiz)

- **Mobile Water – Airplane water quality monitoring**  
  (Bessma Aljarbou, Dina Amin, Atif Javed, Mehmed Onbasli, Lee Swanson)

- **Medical Device – PSA test for prostate cancer**  
  (Jennifer Fremont-Smith, Holly Goodwin JJ Hu, Gary Mullen Stewart Sidhu)

By students at MIT’s Sloan School of Management
Oil and Gas Sensing

Requirements:
- 10-200 ppm sensitivity
- High selectivity and low false positive rate
- Low power consumption
Pipeline leak detection with integrated photonic sensors can save billions $$

Based on assumptions from California Energy Commission Report
Sensing water quality on airplanes

**Accuracy (Parts per Quantity)**

- 1 ppb
- 1 ppm
- 1 ppt

**Speed**

- 1 day
- 1 hour
- 1 minute

**OVERKILL ZONE**

- Micromechanical sensors
- Nanowire sensors
- H2O sensors

**NO APPROVAL by EPA**

- Biacore C
- GE Healthcare
- FlexCHIP by BIACORE (acquired by GE Healthcare)

(Texas Instruments, U.S. Patent 5912456)
Medical diagnostics

Total Market for PSA Tests (USA)
2007 - 2017 ($ Millions)

- Medicare
- Private Insurance

Total Market Value ($Mn)

2008: 816
2009: 863
2010: 945
2011: 1009
2012: 1096
2013: 1226
2014: 1379
2015: 1531
2016: 1667
2017: 1753

Millions
DEFINITELY GOT "INTEGRATED PHOTONIC" SENSORS