GOT SENSOR?

Smart Phones

Smart Homes

Remote sensors for:

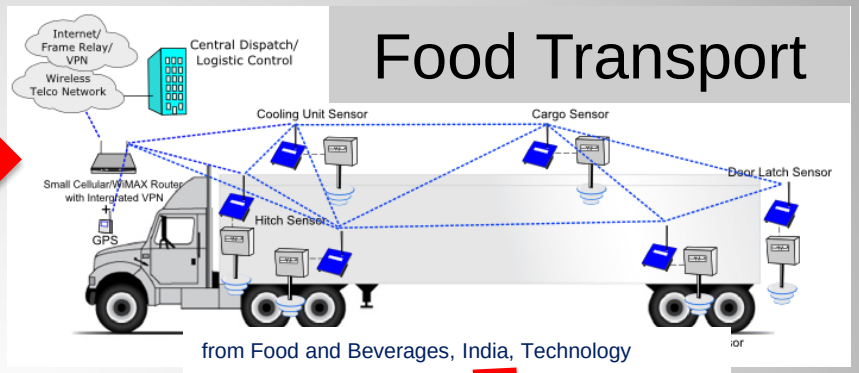
- **Smoke**
- **Heat**
- **Light**
- **Motion**

Smart food supply chain

ADI's platform-based **sensing, processing** and **communications solution** can precisely measure growing **conditions on the farm**, helping farmers make better decisions **throughout the growing cycle**.

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

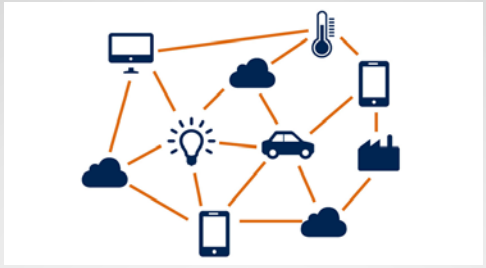
AIM Photonics Institute, Rochester, NY

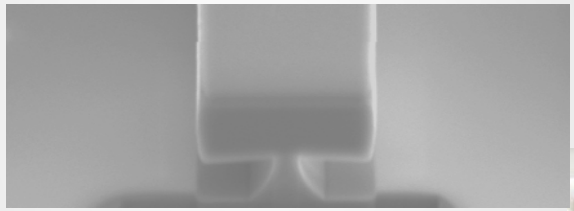
(With Juejun Hu and Lionel C. Kimerling)

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?

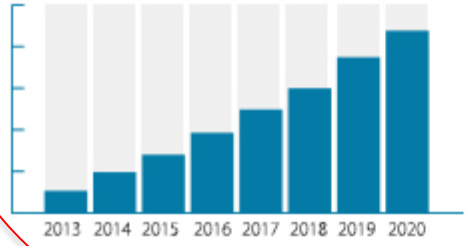
Global Photonics Sensors Market

Segmentation and Forecast, 2013 - 2020

https://www.alliedmarketresearch.com/photonics-sensor-market

Global Photonics Sensors Market

Global Photonics Sensors Market is expected to reach $15.2 Billion by 2020



Growing at a CAGR of 16.9% (2014-2020)

Global Photonics Sensors Market By Technology

- Fiber optic technology
- Laser technology
- Biophotonic technology

The comprehensive view on the % share of Technology segment (2020)

For More Details See Table of Contents

Global Photonics Sensors Market by Product Type

- Fiber optic sensors
- Image sensors
- Biophotonic sensors
- Other

The comprehensive view on the % share of Type segment (2020)

Global Photonics Sensors Market By Application

- Military
- Homeland security
- Industrial process
- Factory automation
- Civil structures
- Transportation
- Biomedical
- Micro fluidic
- Bio- environmental
- Wind energy turbines
- Other

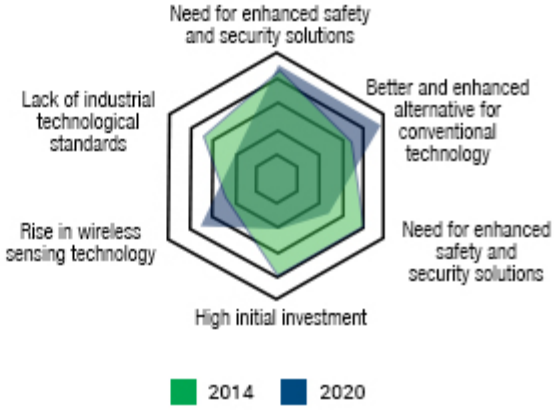
The comprehensive view on the % share of Application segment (2020)

Global Photonics Sensors Market by Geography

Europe is expected to be highest revenue generating region by 2020

North America, Asia Pacific, LAMEA

Top Impacting Factors



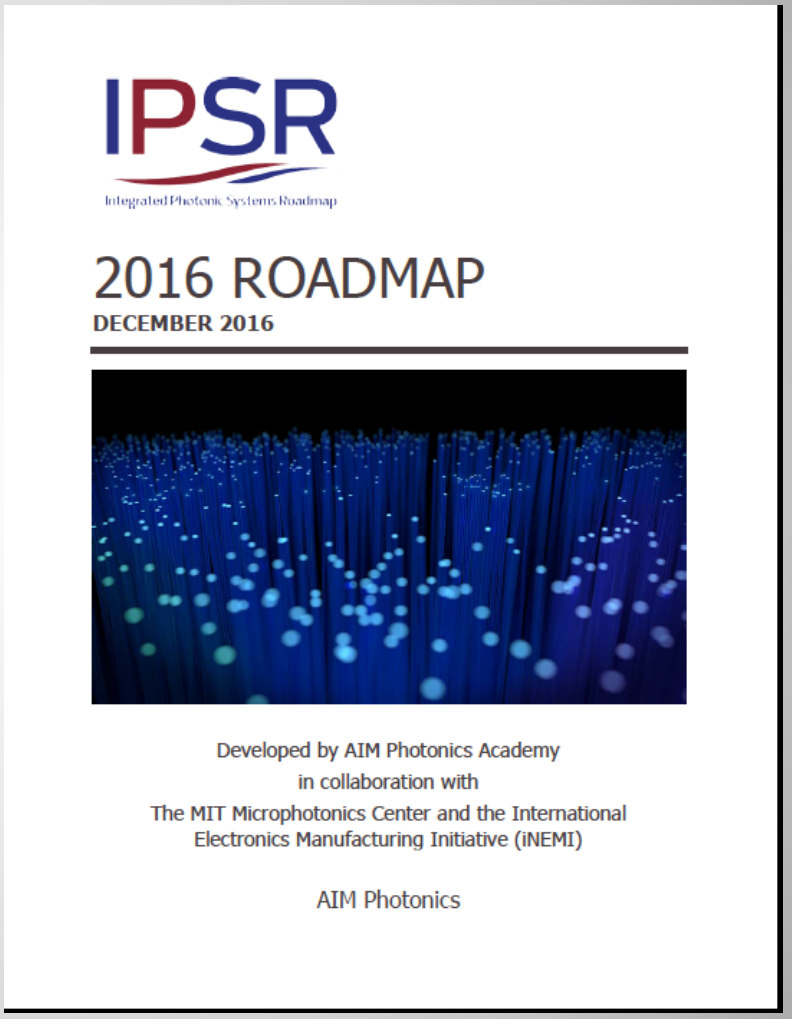
Content

- 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:

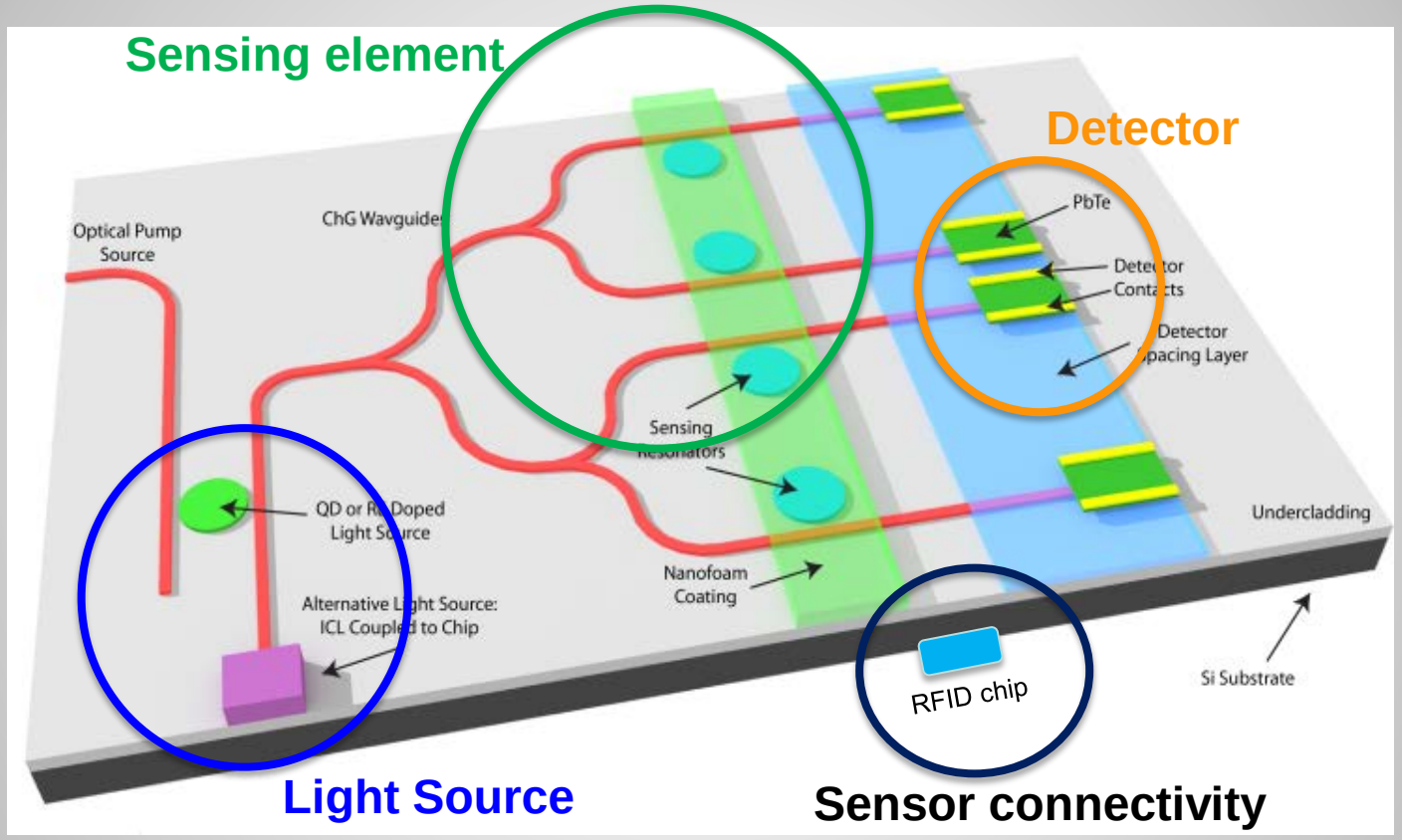
Telecommunications
LIDAR
Packaging
Testing
Integrated Photonic Sensors
(Technology, Components, Equipment, …Supply Chain)



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



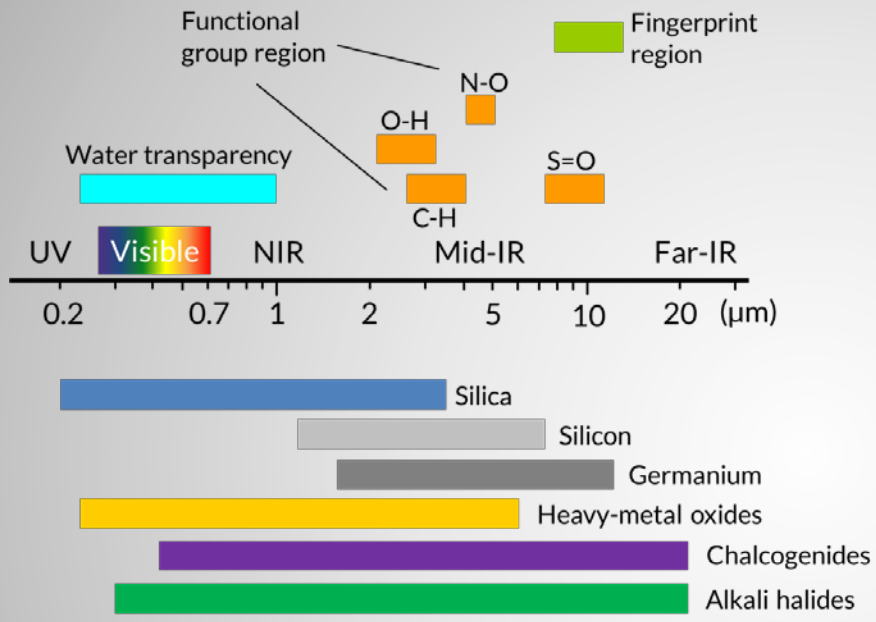
Sensor characteristics

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?

Sensor platform

Platform: Glass–on–Silicon Chalcogenide Glasses



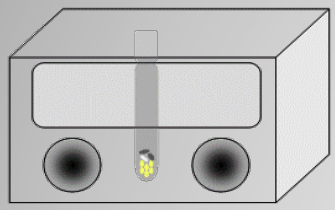
B	C	N	O	F	Ne
Al	Si	P	S	Cl	Ar
Ga	Ge	As	Se	Br	Kr
In	Sn	Sb	Te	I	Xe

Chalcogen elements

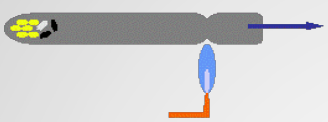
- **Wide IR transparency window**
- **Tunable optical properties**
- **Ease of fabrication**

Glass synthesis

Chalcogenide Glass Processing

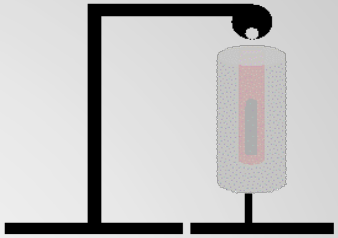


Weigh in Glove Box



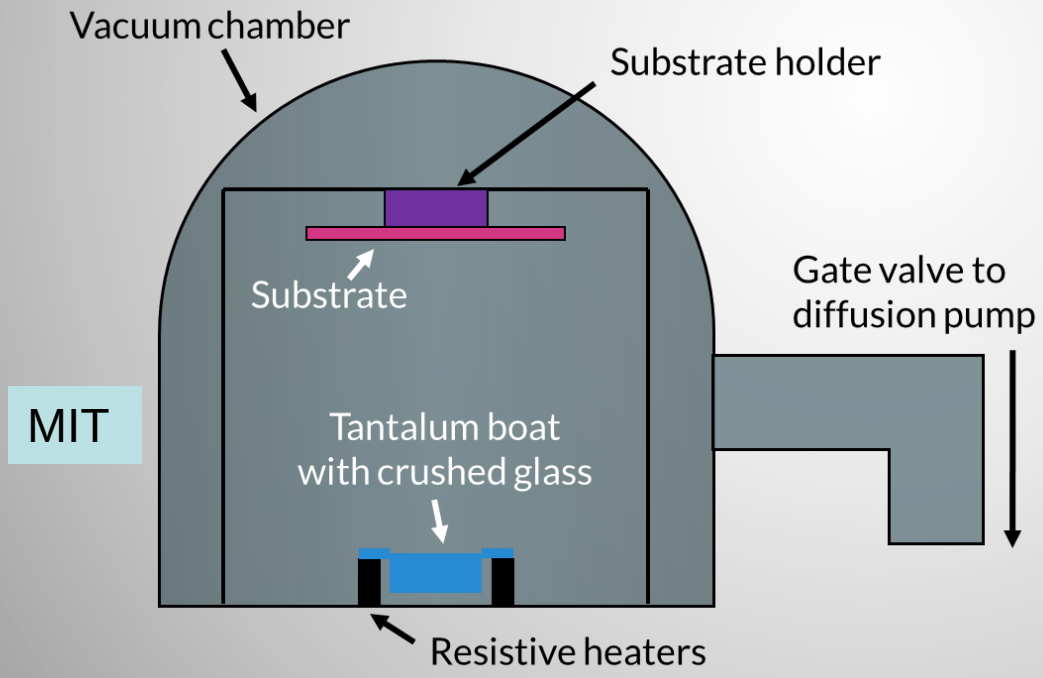
Vacuum @ 110 °C ~ 4 hrs
Seal with torch

Melting ~ 12 Hrs



Air quenching

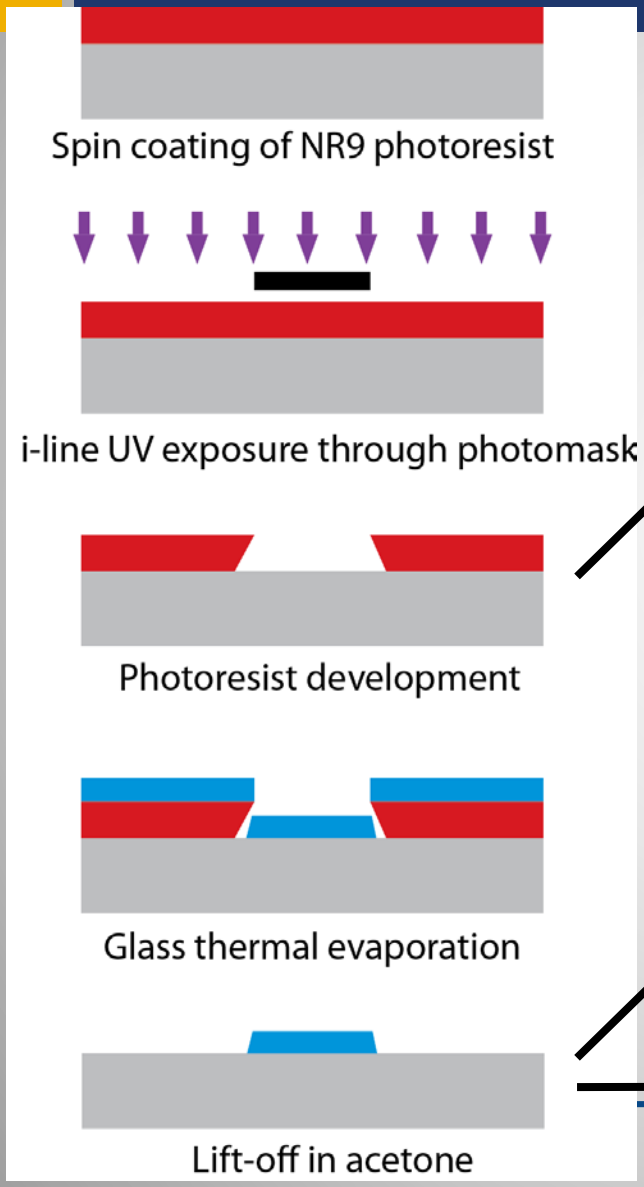
Annealing

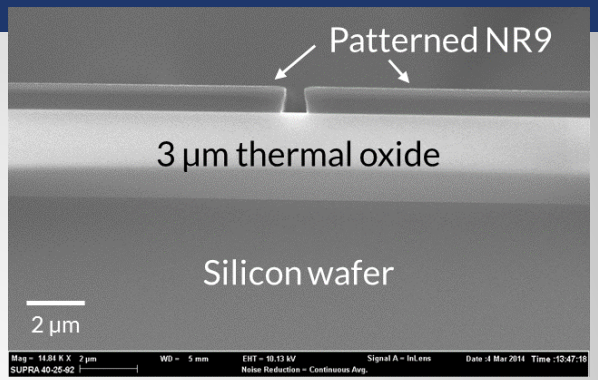


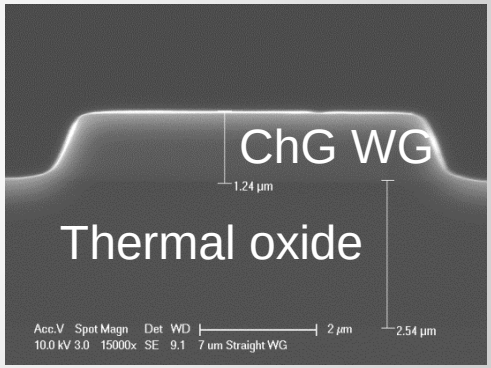
MIT

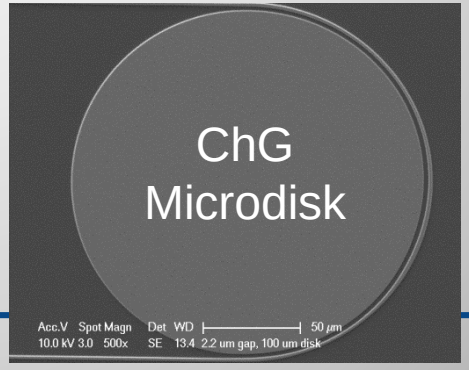
Kathleen Richardson, UCF

Lift-Off Fabrication Process





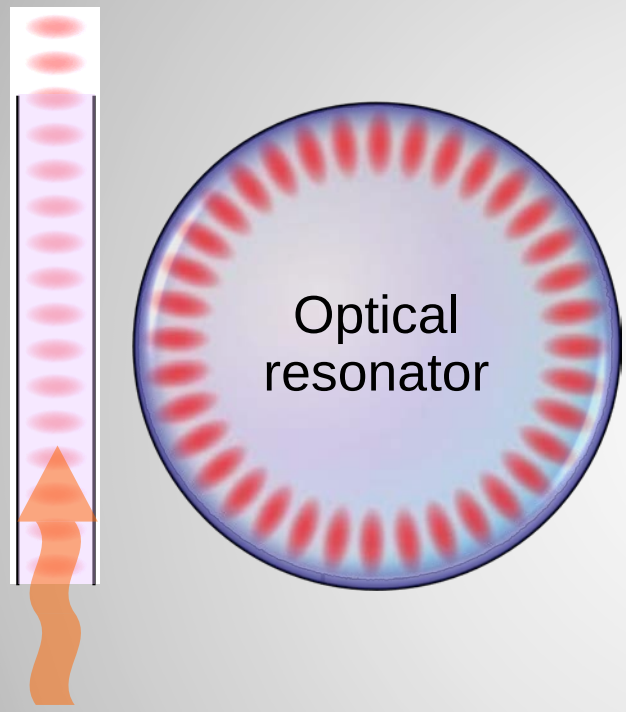




Sensing element

Sensing element: Resonator

Transmission



Light into waveguide

Resonant condition:

$$N \cdot \lambda_0 = n_{eff} L$$

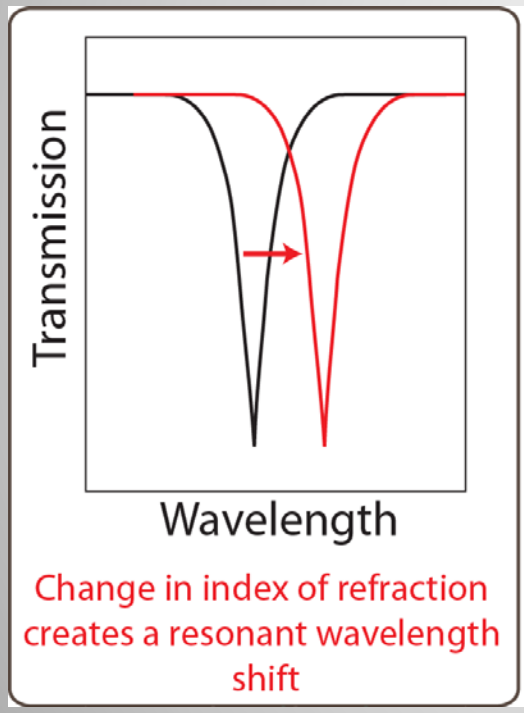
Interaction length ↑ : enhanced sensitivity

Sensing principle

Sensing Principle

Refractive index sensing

Cavity-enhanced absorption spectroscopy



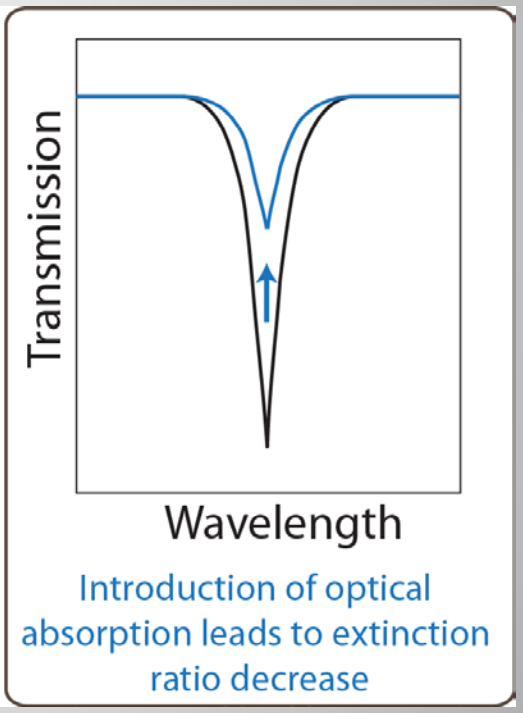
Change in index of refraction creates a resonant wavelength shift

Complex refractive index variations for sensing applications

$n + ik$

n: index of refraction

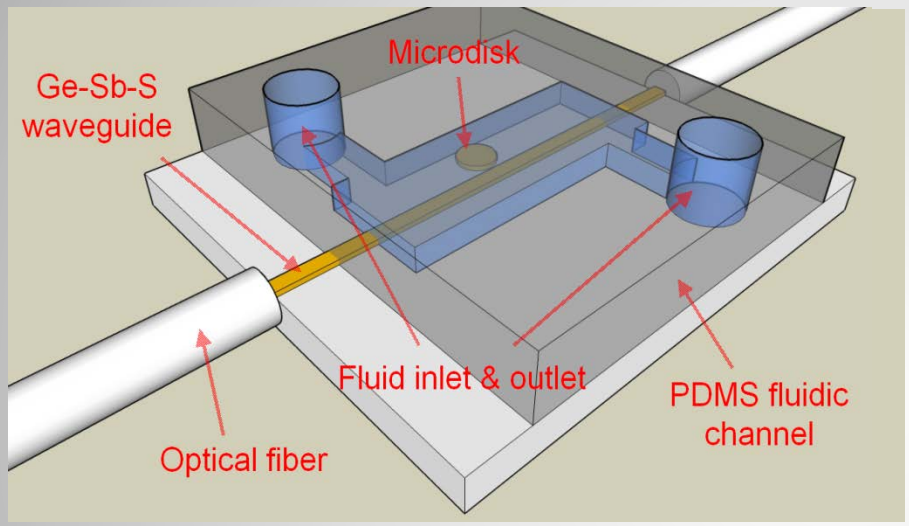
k: absorption coefficient

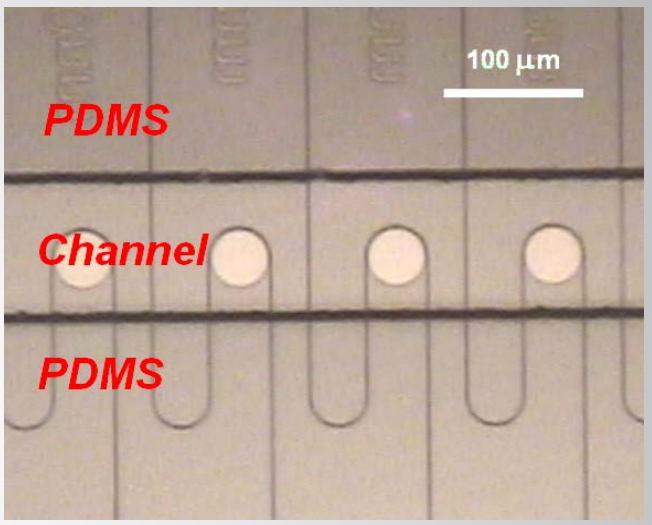


Introduction of optical absorption leads to extinction ratio decrease

Chemical delivery

Chemical delivery: Photonic-Microfluidic integration





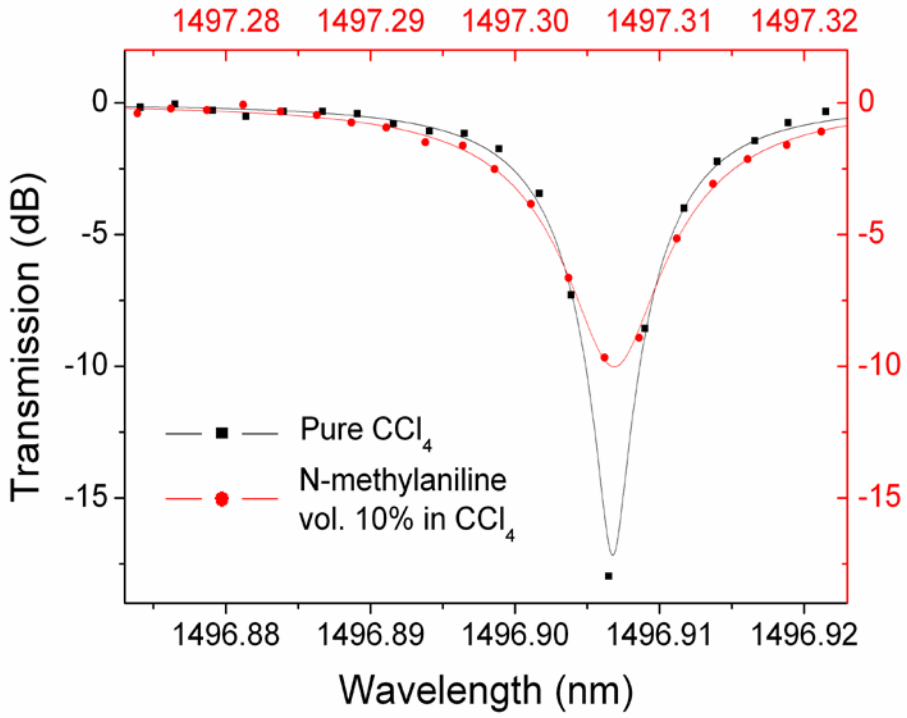
PDMS: POLY-DI-METHYL-SILOXANE

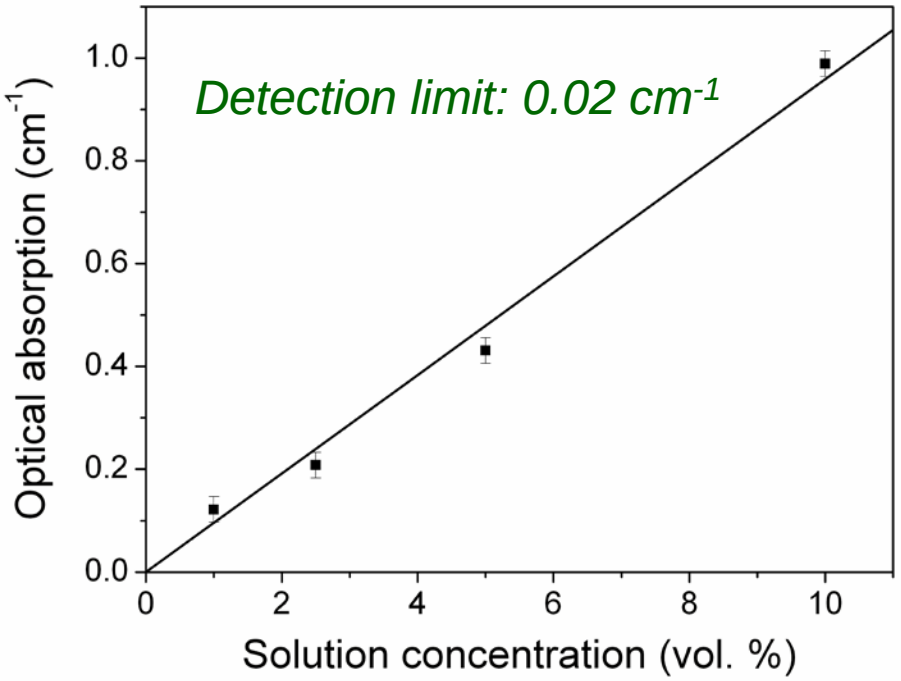
Photonic microfluidic integration enables:

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

Liquid sensing

Liquid sensing: N-Methylaniline in CCl_4



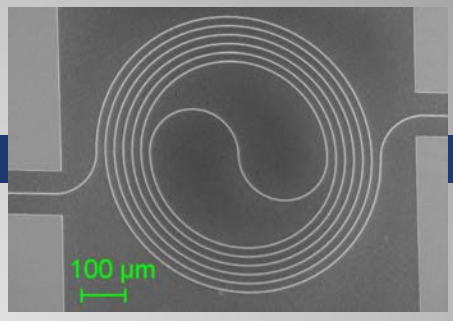


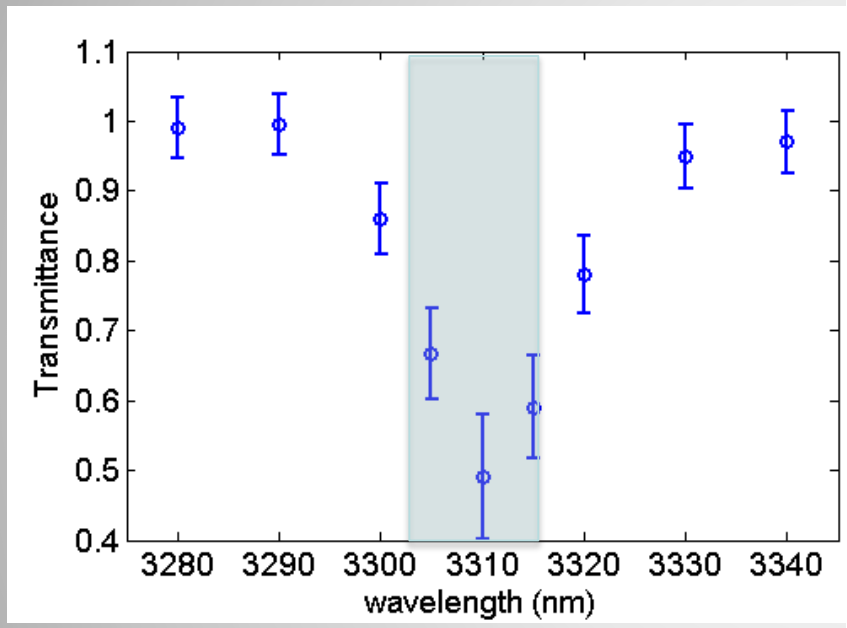
On-chip absorption spectroscopy to detect liquid N-methylaniline

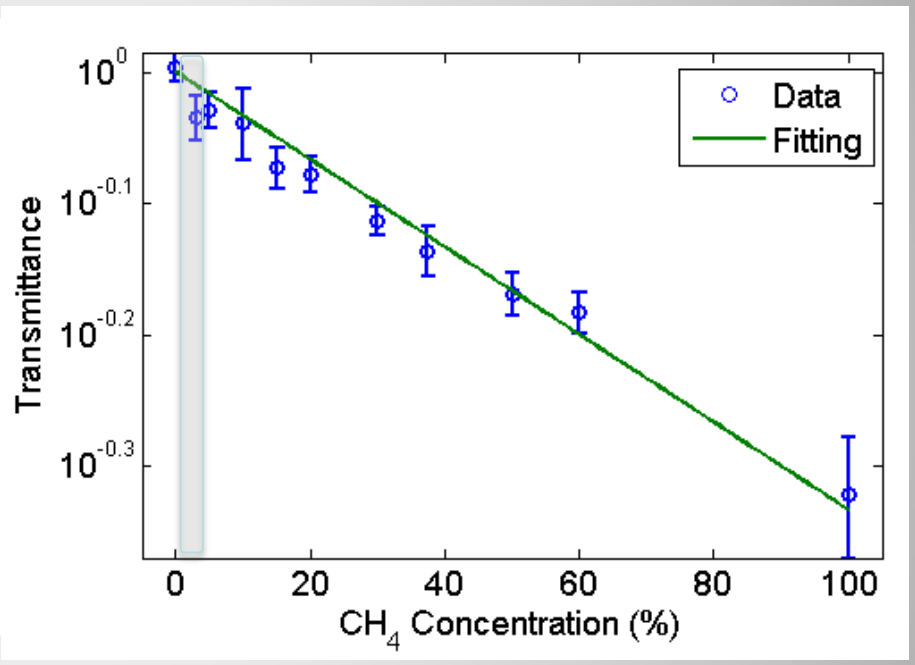
J. Hu *et al.*, *IEEE J. Lightwave Technol.* Vol. 27, No. 23, 2009

Gas sensing

On-chip methane gas sensing





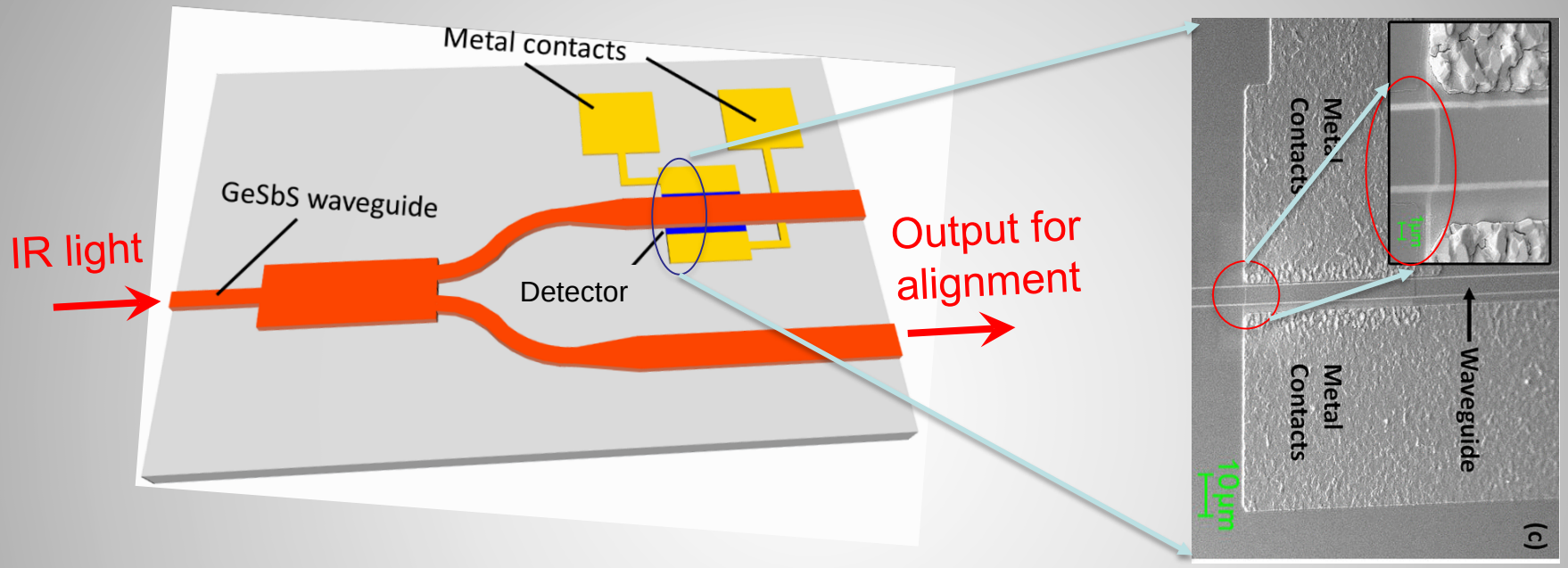


On-chip detection of methane gas using absorption

Zhaohong Han, et. al. Applied Physics Letters 108 (14), 141106, 2016

Waveguide-Integrated Detector

Waveguide-Integrated Detector

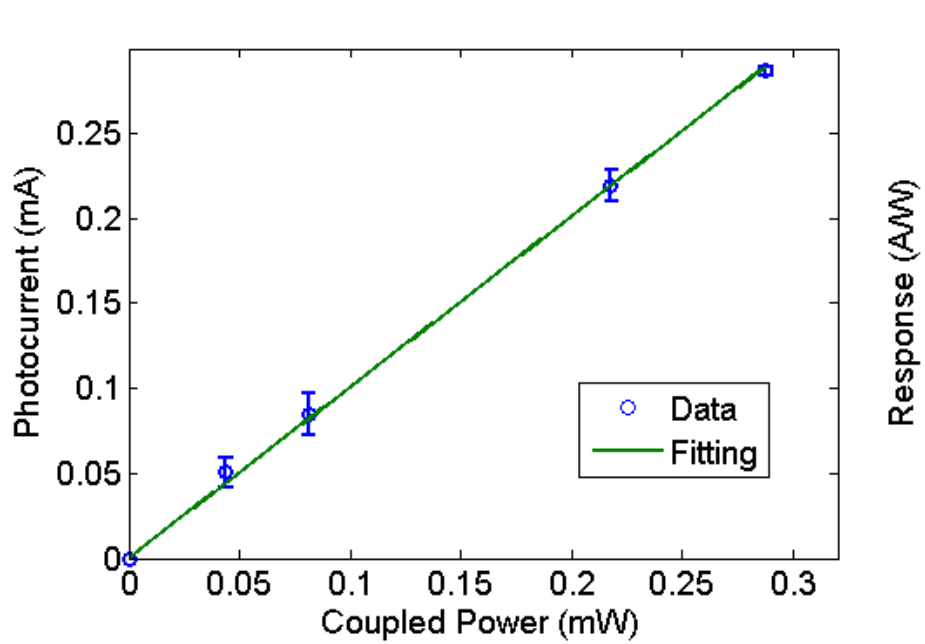


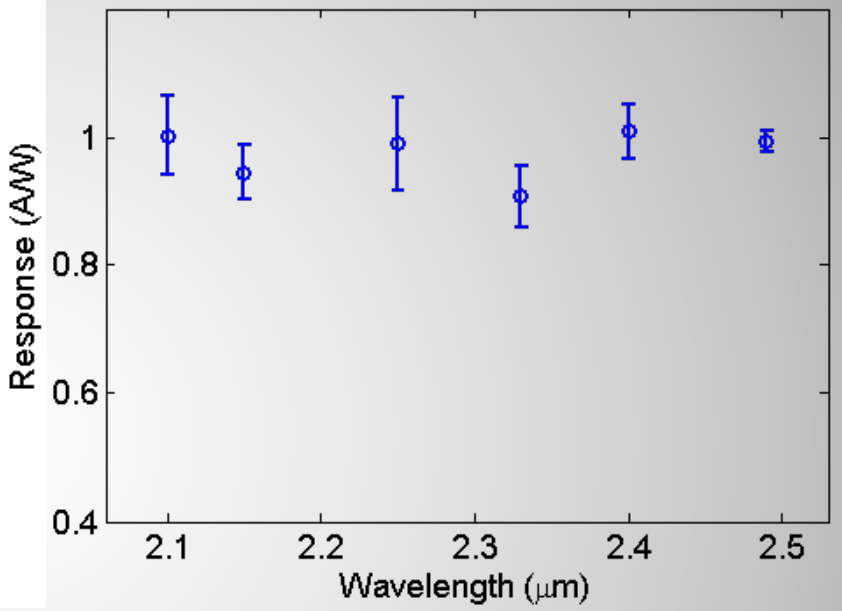
Waveguide integration:

- **Noise suppression**
- **IR photonic circuit**

Detector performance

Waveguide-Integrated Detector at RT



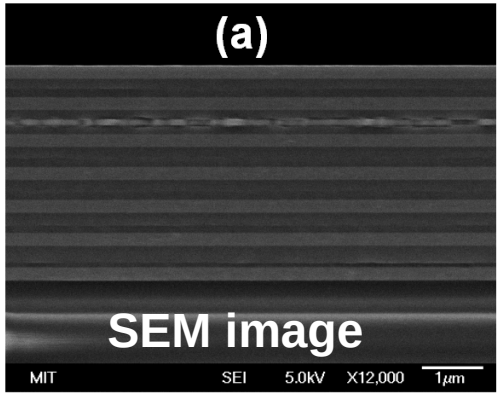


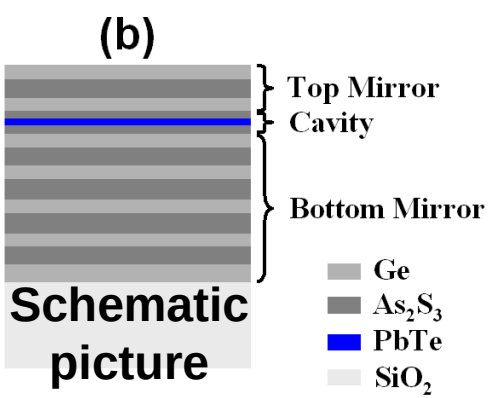
	Waveguide Integrated	Normal Incident
Responsivity (A/W)	1.0	0.017
External quantum efficiency	58%	0.94%
Temperature	Room Temperature	- 60 ºC

Resonance enhanced detector

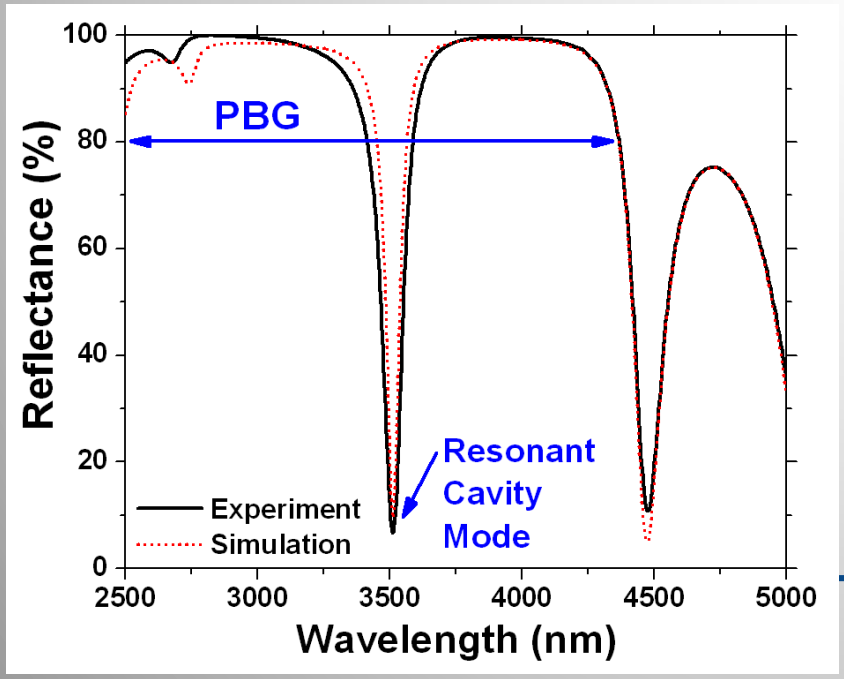
Zhaohong Han, et al. Applied Physics Letters 109 (7), 071111, 2016

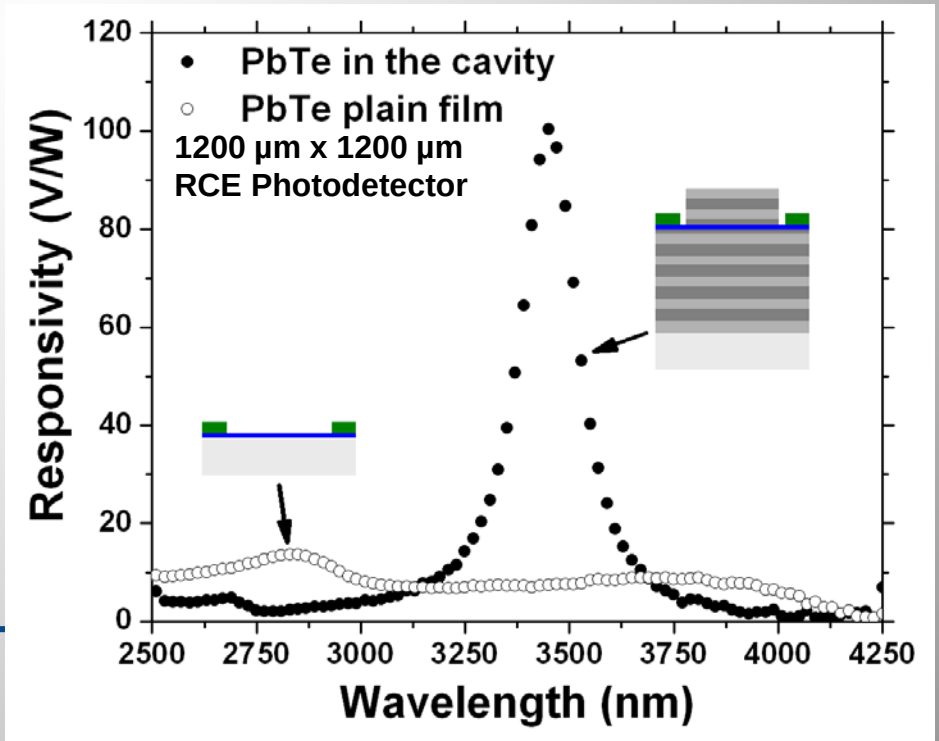
Enhanced Detection: PbTe Detector in a Resonant Cavity



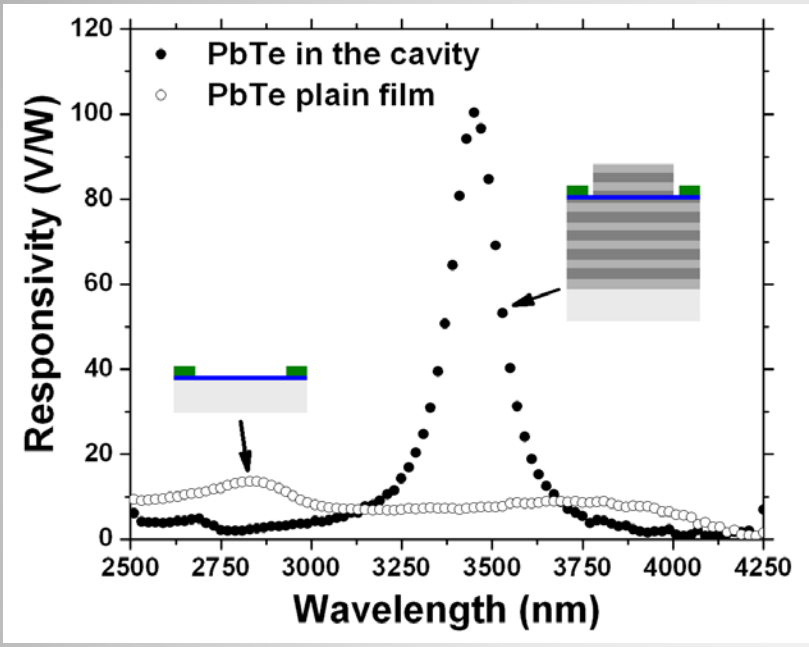


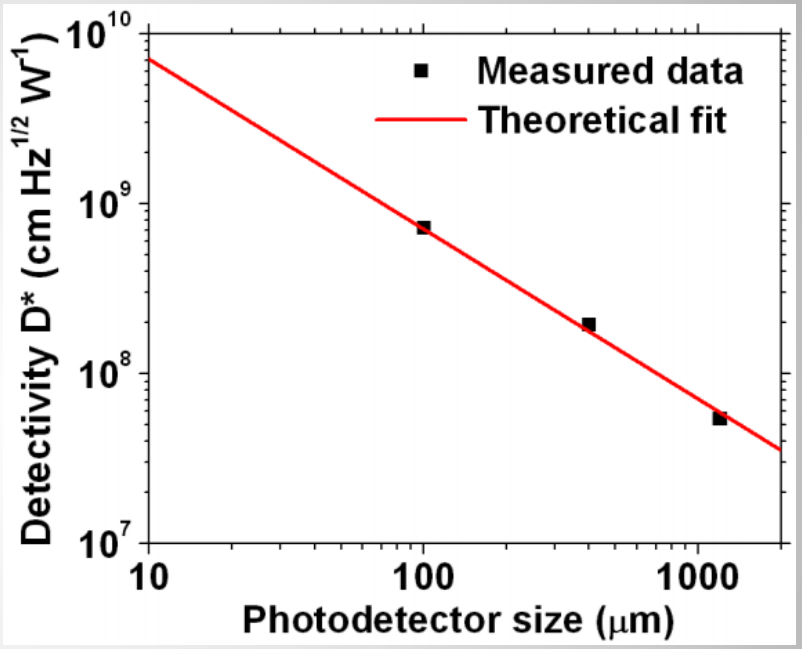
- Successful low-T fabrication process on Si: <150 °C
- Demonstrate 13.4X cavity enhancement
- Peak responsivity = 100 V/W





Resonant Cavity Enhanced IR Detector





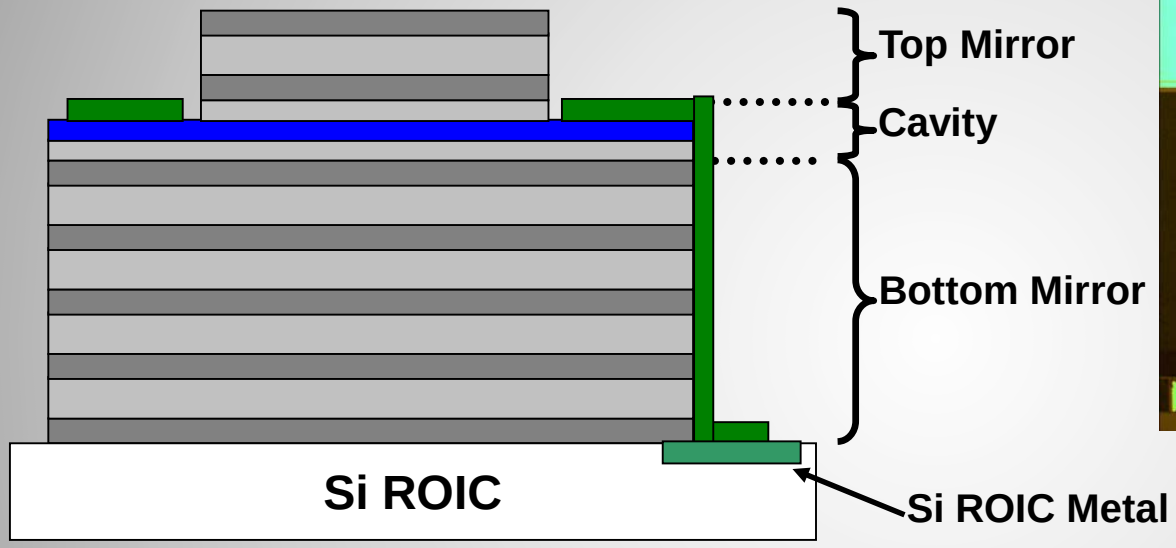
- **Enhanced detectivity inside a cavity**
- **Detectivity increases when photodetector size decreases**

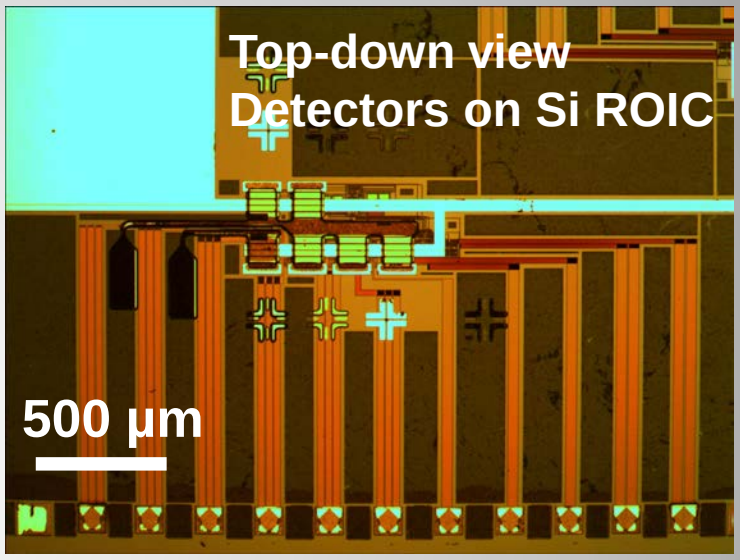
Jianfei Wang *et al.*, *Opt. Express* **18**, 12890-12896 (2010)

Prototype

Integrated detector on a silicon platform

Cross-sectional view of 1 photodetector

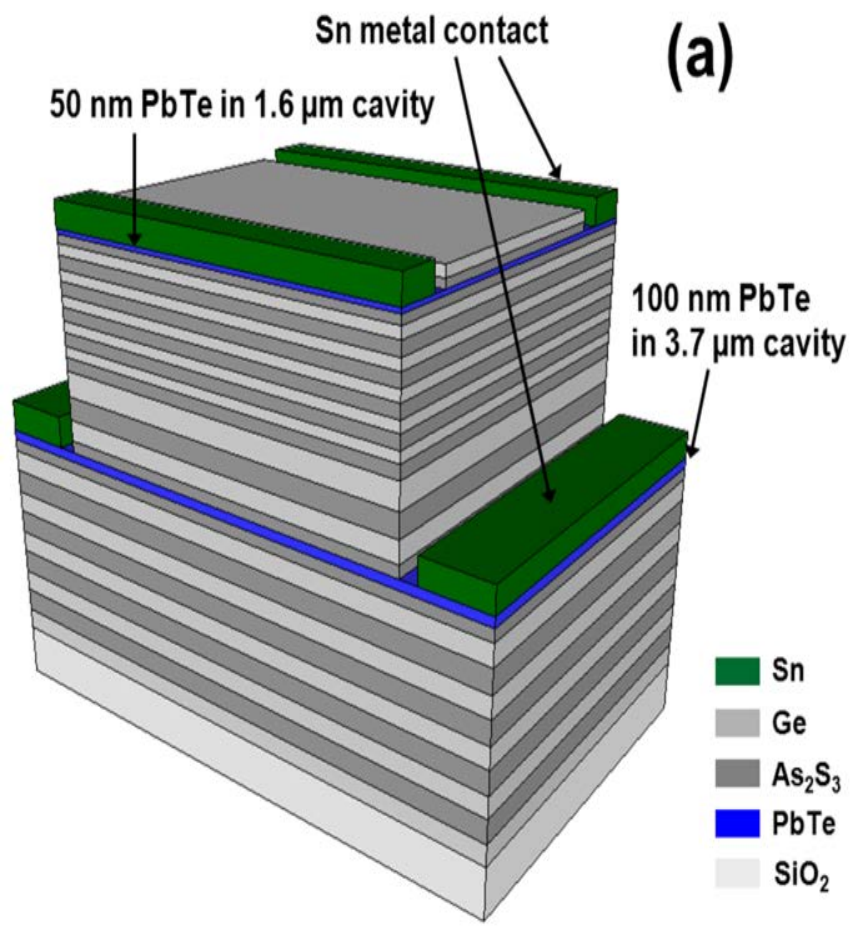


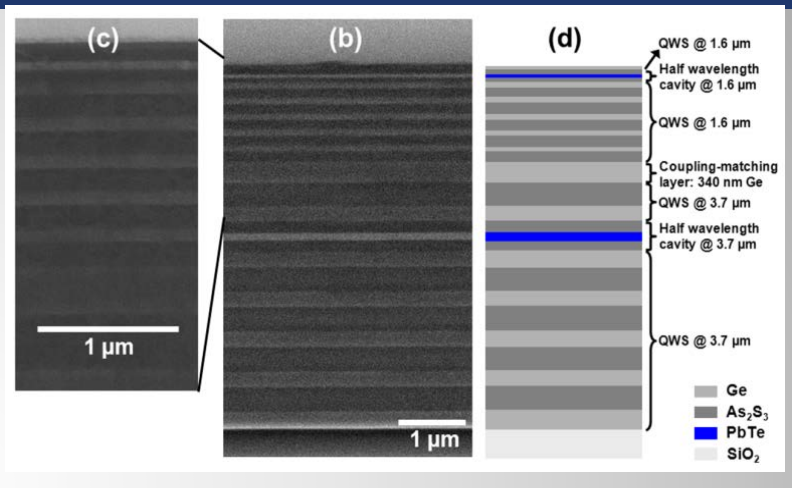


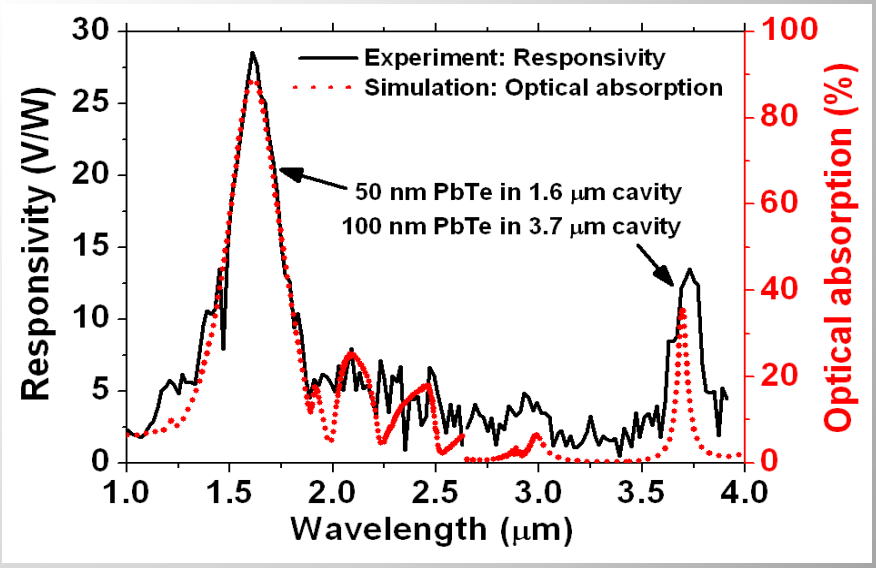
Successful fabrication of integrated prototype

Dual wavelength

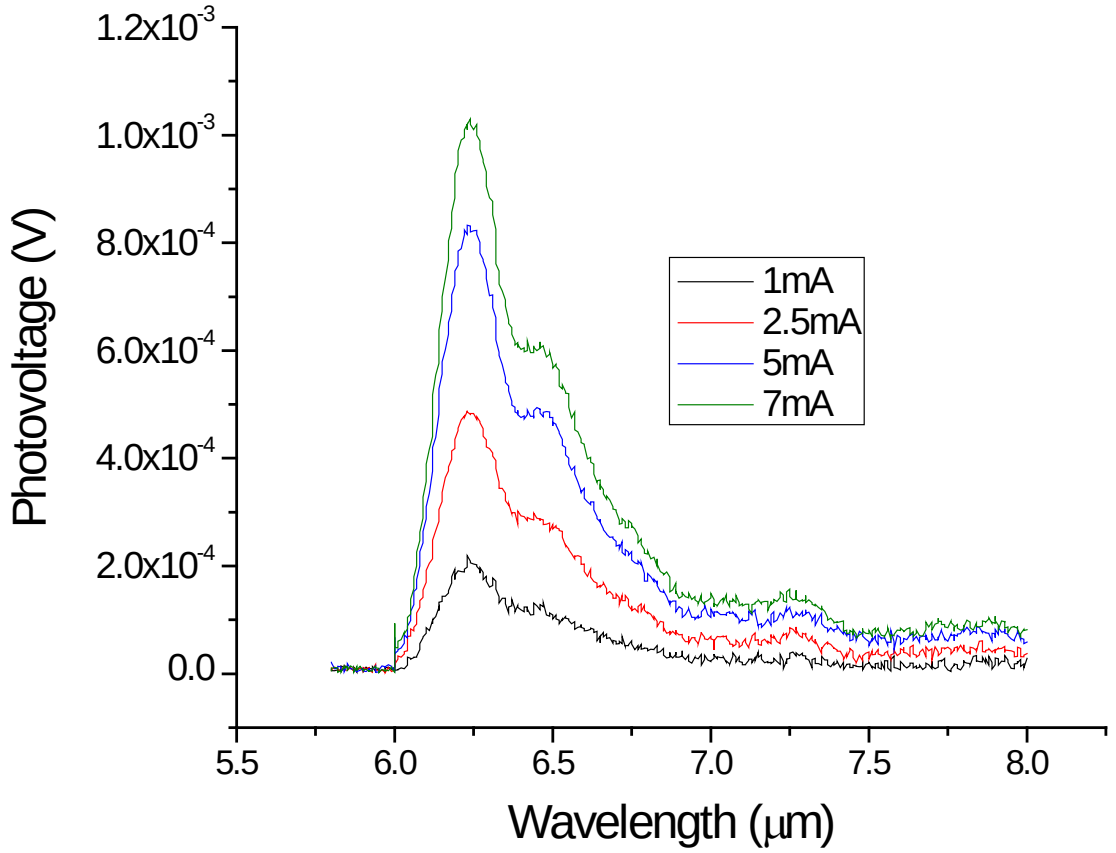
Dual wavelength detector pixel





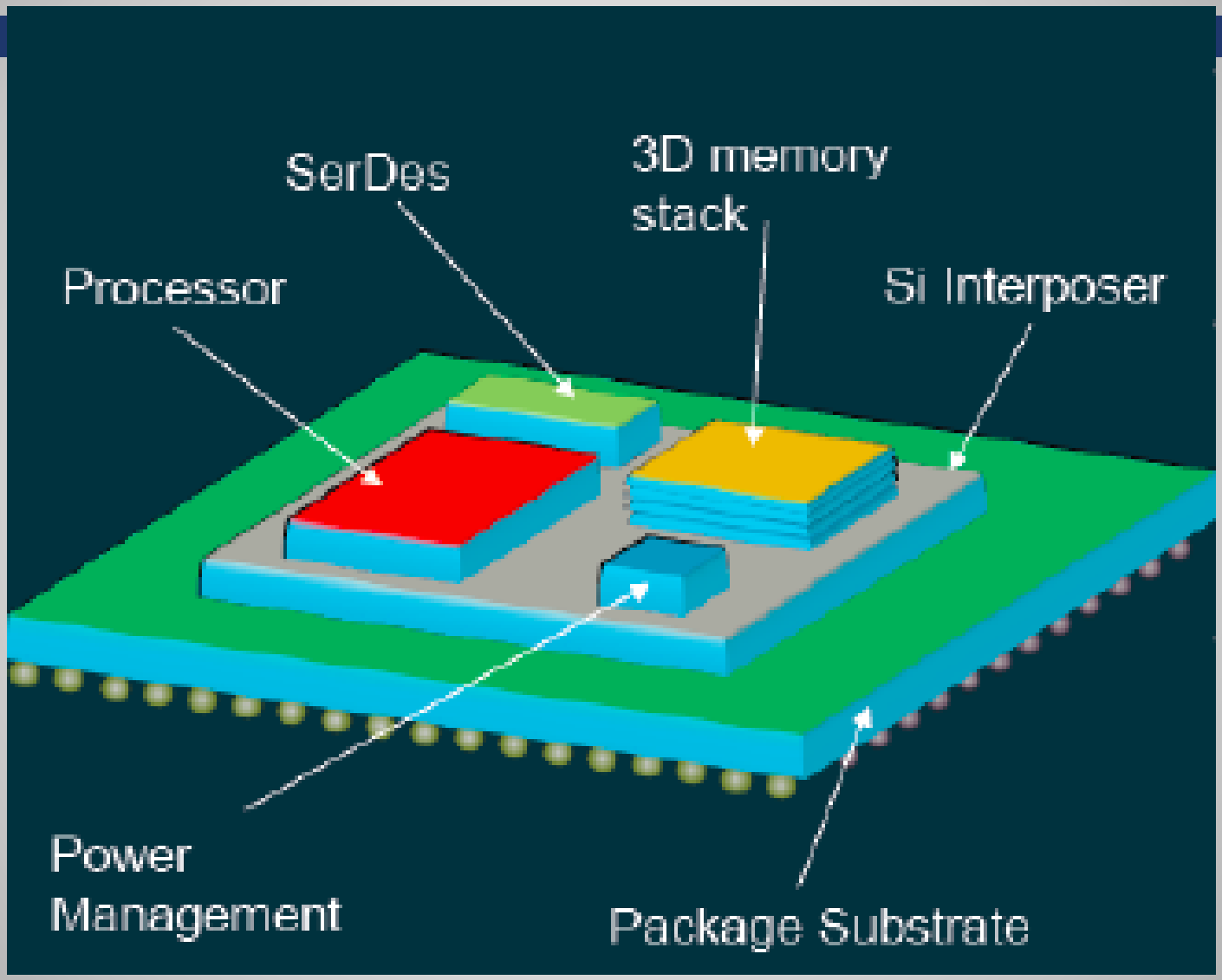


LWIR detection using PbSnTe



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

The Silicon Platform

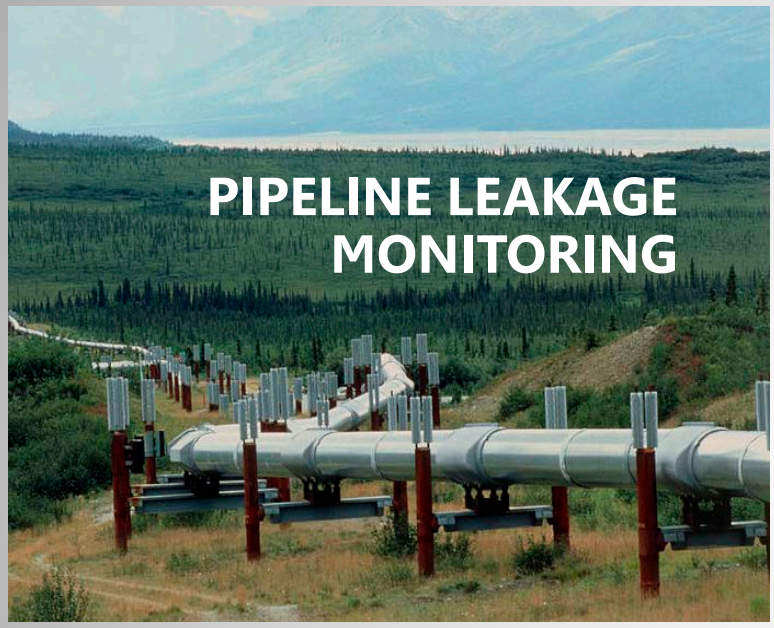


Three case studies:

- **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

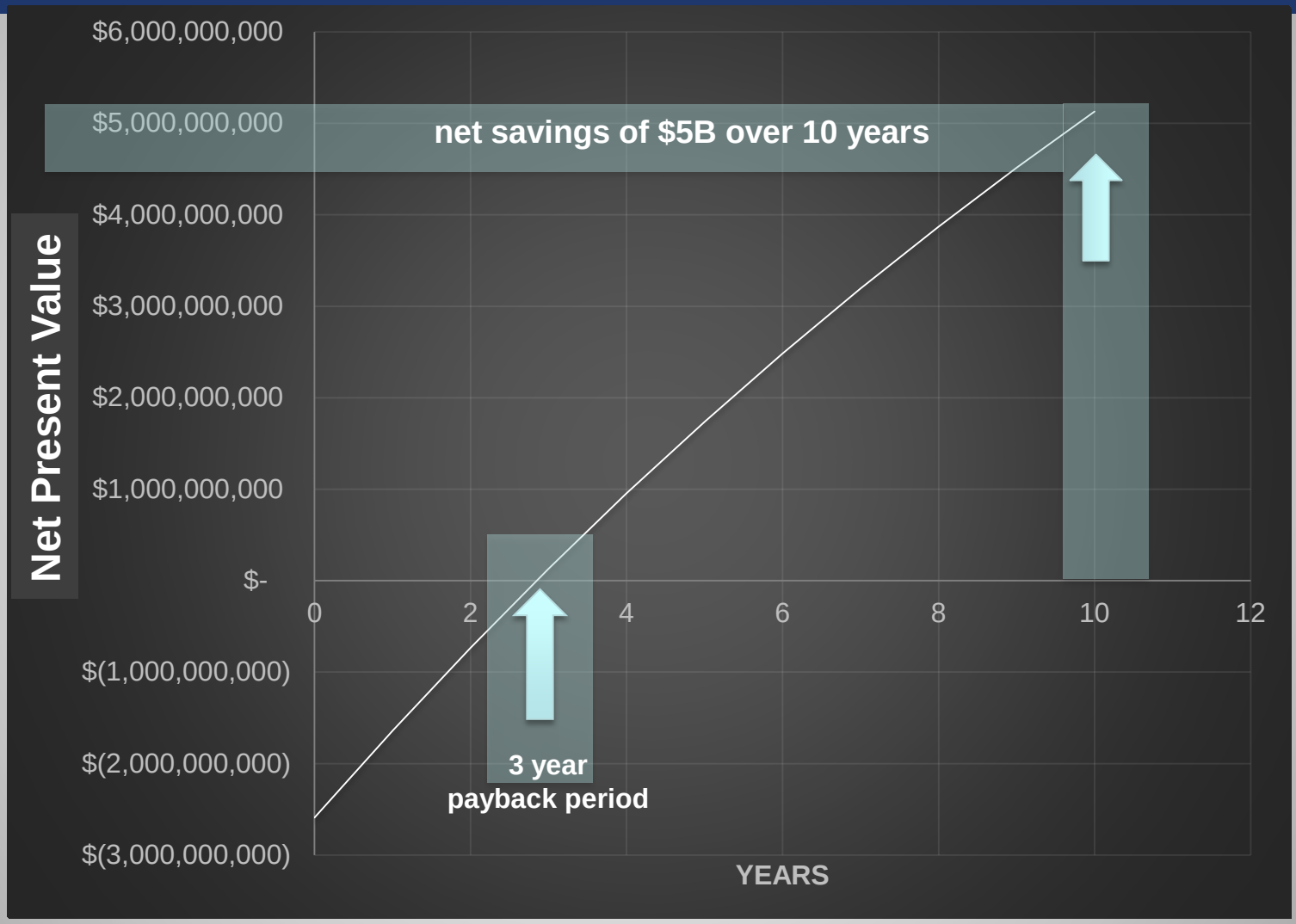
Oil and Gas Sensing



Requirements:

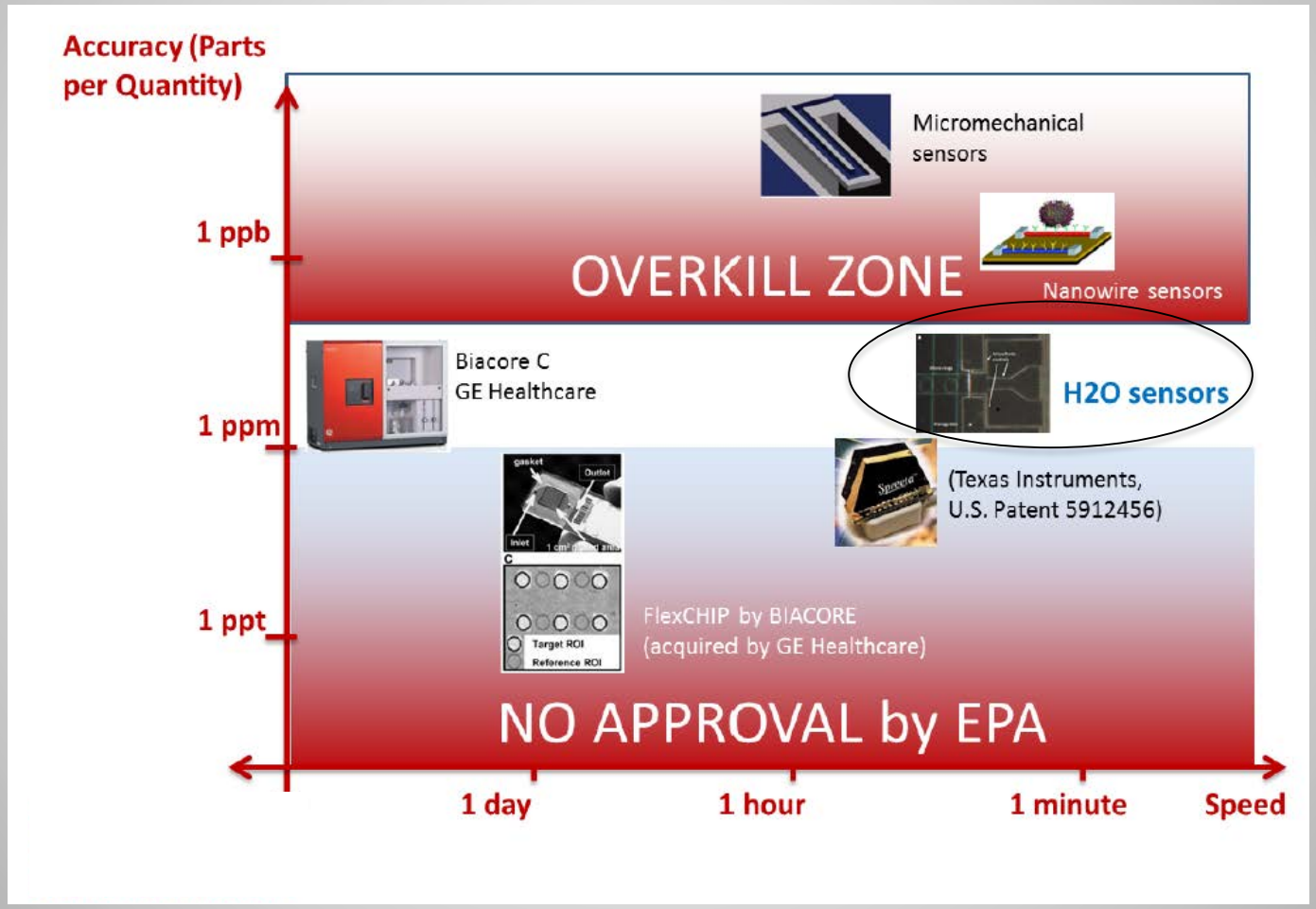
- **10-200 ppm sensitivity**
- **High selectivity and low false positive rate**
- **Low power consumption**

Pipeline leak detection with integrated photonic sensors can save billions $$

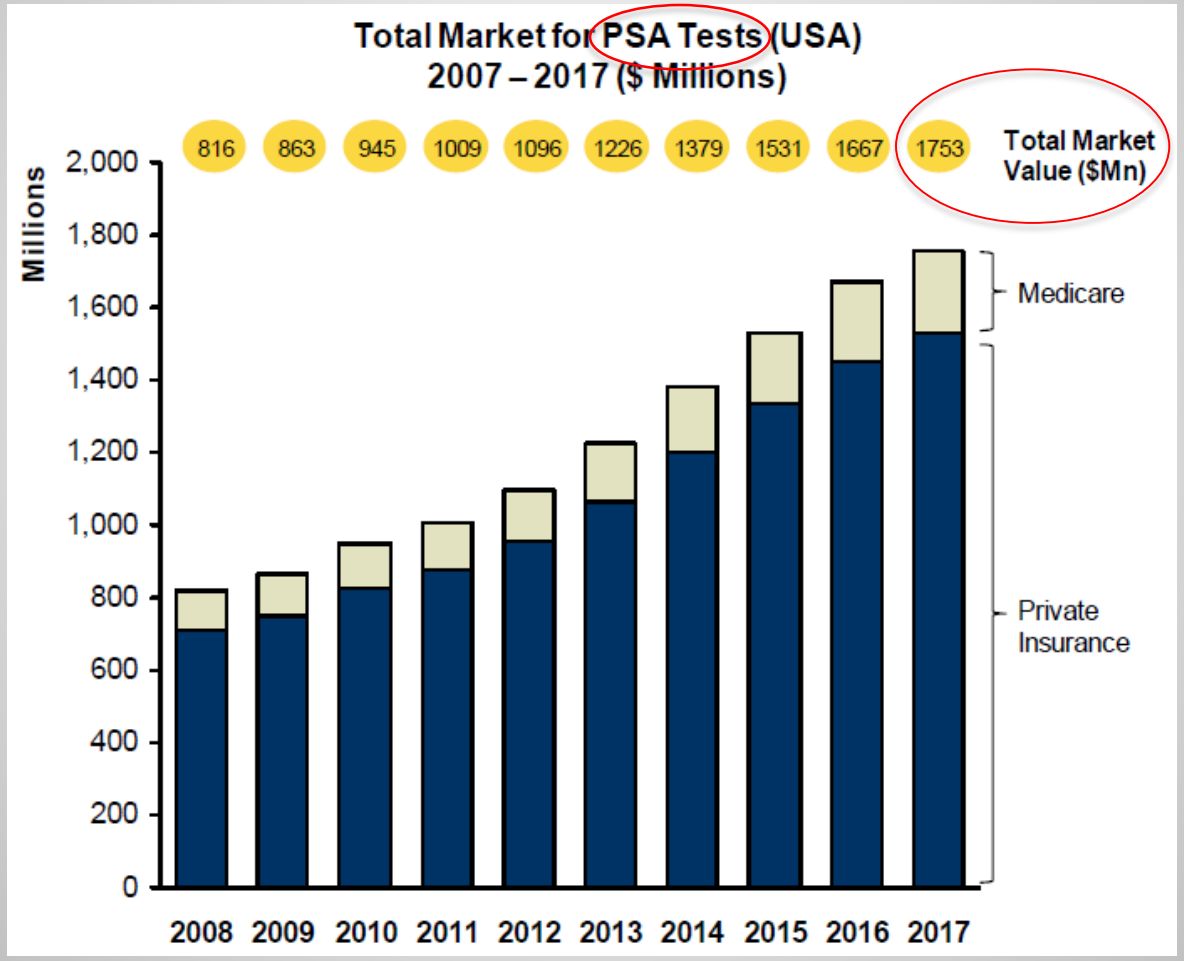


Based on assumptions from California Energy Commission Report
Natural Gas Leak Detection Sensor for Widely Deployable Networks" O. Herrera, M. Frish, D. Bamford, M. Laderer. Dec 2015.

Sensing water quality on airplanes

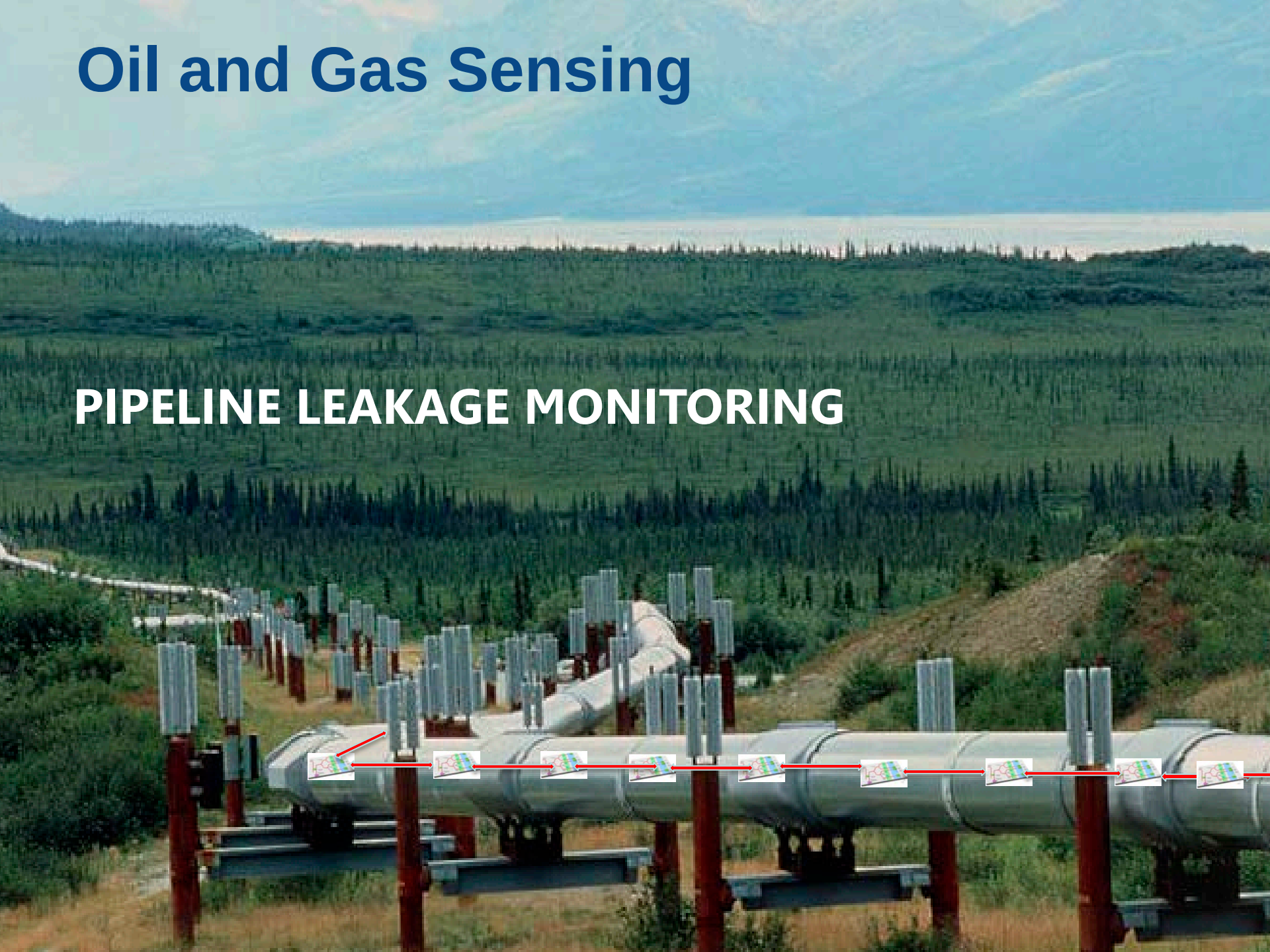


Medical diagnostics



Oil and Gas Sensing

PIPELINE LEAKAGE MONITORING



DEFINITELY GOT “INTEGRATED PHOTONIC” SENSORS