Nanotechnology Commercialization Success Story

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Description of the nanotechnology-enabled product or service

Through the AFOSR MURI research center on silicon nanomembranes, we built a myriad of sensing devices for Lidar[1-3], early cancer detection[4-8], drug screening[9-10], heavy metal detection[11-12], air-and water-pollution sensing[13-16], 40 Gbit/sec EO modulator [17] and wide band RF sensors [18-20]. The nanotechnology developed herein is based on photonic crystal waveguide (PCW) nanostructures and has a feature size down to 50 nm. When properly designed, PCWs can trap a photon using bandgap-engineered point and line defects to form waveguides and waveguide cavities. This principle is shown in Fig.1 with semiconductor single crystal as a reference. The first is dealing with Schrodinger Equation and the 2nd Maxwell Equations. We can manipulate the defect nano-structure such that speed of light can be drastically reduced which provides a much longer interaction between photons and the analytes. Due to the slow light effect and highly mode overlapped structure, the device we built is more sensitive than any existing devices in the market with a much smaller form factor as shown in Fig 2 where a silicon nanosensing chip (1mmx 3mm in size for up to 64 biomarker detections) for early cancer detection was made. Furthermore, it is an OPEN sensing platform suitable for any analytes as long as the signature of the detection is defined by photons. Up to this point, we have demonstrated following pivotal milestones using silicon nanomembranes:

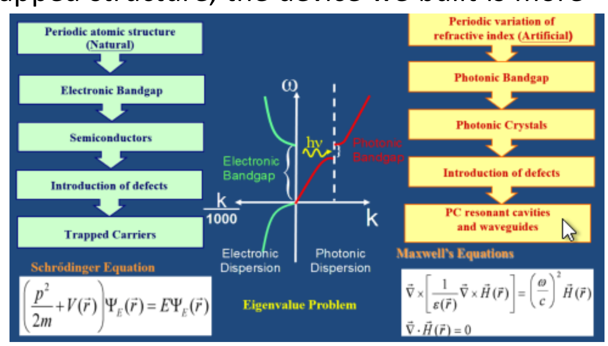

Figure 1 the working principle of Photonic Crystal governed by the Maxwell Equations in a similar way of semiconductor governed by Schrodinger equation

1. Early Breast Cancer biomarker detection
2. Early Lung Cancer Biomarker Detection
3. Early Pancreatic cancer detection
4. Ultra-sensitive EM wave sensing
5. Heavy Metal (Cd, Uranium) detection
6. Air- and Water-pollution sensing
7. Chemical warfare sensing
8. 3D laser beam steering for Lidar applications
9. Drug screening for three antibiotics : vancomycin, gentamicin and tobramycin
10. 40 Gbit/sec high speed modulator with low power consumption

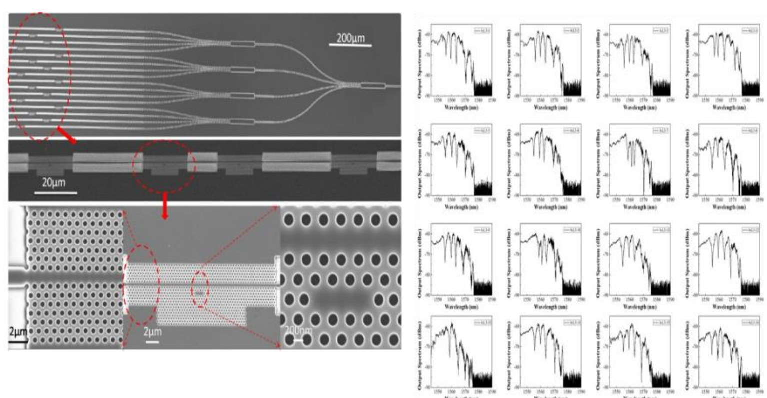

Figure 2 A Silicon nanomembrane based cancer detection chip (1mmx3mm in size) that can detect 64 biomarkers together. The whole process only requires one lithography mask which ensure cost-effectiveness for mass production

All these platforms are with sensitivity higher than existing devices and systems. It is an open platform suitable for any analyte detection with unprecedented sensitivity due to the slow light effect inherited in the nanomembrane nanostructures together with the high overlap integral of the guided mode and the analyte of interest. Fig.3 shows a hand-held system we developed and was selected by Smithsonian Magazine as one of the most promising commercializable projects in the nation.

The video clip can be found in:

https://www.youtube.com/watch?v=qasB2eJvAhI

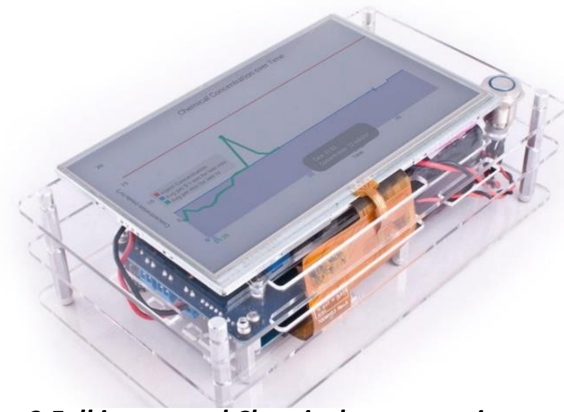

Figure 3 Full integrated Chemical sensors using semiconductor nanomembrane devices. The article published by Smithsonian Magazine can be found in *http://www.smithsonianmag.com/innovation/made-college-seniors-these-seven-products-give-glimpse-into-future-180955280/?no-ist*

Success Stories

It is an open platform as long as the signature of sensing is photon-based. We are in the process of building hand-held and desktop systems with automation functions. We have a commercial order from a major aerospace company to build several packaged EM wave sensors (~350,000). We will deliver this device to AFRL for further testing also. The prototype unpackaged EM-wave sensing device based on the on-chip slow light photonic crystal waveguide is shown in Figure 4. A bow tie antenna is implemented on top of the slotted PCW waveguide as depicted. For the bio- and chemical-sensing platform, we are building both desk top and hand-held system. The desk top system can provide higher accuracy while the hand-held system can provide portable system in any places with blue tooth communication channel through smartphones. The desktop

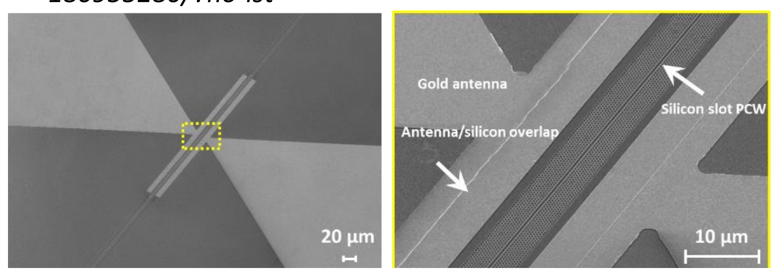

Figure 4 Si Nanomembrane PCW infiltrated with EO polymer for EM-wave sensing.

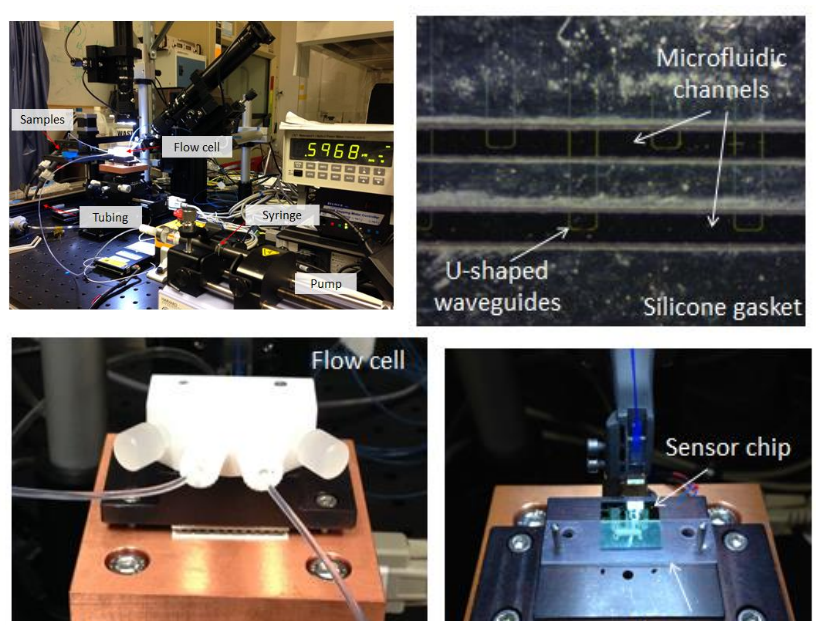

Figure 5 Automatic desktop system with all accessories with control and readout by a PC (not shown). Microfluidic channel and the U-shaped Silicon membrane waveguide are clearly shown on right top panel.

system with automation function is shown in Fig. 5 where the microfluidic channels for biomarker supplication and U-shaped silicon nanomembrane waveguides are clearly shown in Figure 5. All the other components are also depicted in the figure. We have on-going collaborations with several medical schools including MD Anderson Cancer Research Center, Medical University of South Carolina and The UT Medical University in Houston. Various cancer biomarkers are provided including mRNA. Early detection results have been confirmed for breast cancer, lung cancer and pancreatic cancer. We try to make all basic research elements ready by demonstrating a working prototype with high sensitivity without compromising specificity while maintaining cost-effectiveness for ownership. A new company Alfa Sensors is formed to further commercialize the silicon nanomembrane based products. Strategic partners from private sectors are explored to further commercialize this technology. Up to now, 10 US patents have been granted for this nanotechnology as summarized in Table 1. And several patent applications are still under evaluation.

Table 1 Summary of US patents that have been granted as of today

Patent #	**Title of the patent**	Status
1	"Photonic Crystal Microarray Device for Label-free Multiple Analyte Sensing, Biosensing and Diagnostic Assay Chips," Patent 8293177 (Issued: 10/23/2012) US Patent and Trademark Office (2009).	Granted
2	"Photonic Crystal Slot Waveguide Miniature On-Chip Absorption Spectrometer," Patent 8282882 (Issued: 10/09/2012) US Patent and Trademark Office (2010).	Granted
3	"Method for Label-Free Multiple Analyte Sensing, Biosensing and Diagnostic Assay," Patent Application # 13607791, US Patent and Trademark Office (2012).	Granted
4	"Method for the Chip-Integrated Spectroscopic Identification of Solids, Liquids, and Gases," Patent Application # 13607792, US Patent and Trademark Office (2012).	Granted
5	"Packaged chip for multiplexing photonic crystal waveguide and photonic crystal slot waveguide devices for chip-integrated label-free detection and absorption spectroscopy with high throughput, sensitivity, and specificity," Patent Application # 13607801, US Patent and Trademark Office (2012).	Granted
6	"Photonic Crystal MicroArray Layouts for Enhanced Sensitivity and Specificity of Label-Free Multiple Analyte Sensing, Biosensing and Diagnostic Assay," Patent Application # 13607793, US Patent and Trademark Office (2012).	Granted
7	"Fabrication Tolerant Design for the Chip-Integrated Spectroscopic Identification of Solids, Liquids, and Gases," Patent Application # 13607794, US Patent and Trademark Office (2012).	Granted
8	"Multimode Interface Coupler for Use with Slot Photonic Crystal Waveguides," Provisional Application 61/092,672 (2008).	Granted
9	"Broadband, group index independent, and ultra-low loss coupling into slow light slotted photonic crystal waveguides", PCT Conversion, WO 2013/048596 A2 (2012)	Granted
10	"Subwavelength grating coupler", Provisional Application 61/770,694 (2013).	Granted

Another success story is in the laser beam steering (LBS) device for LIDAR application. It has both civilian and military opportunities. Si nanomembrane based LBS is an approach particularly beneficial for air-borne and space-borne systems since it does not provide any moving parts while maintaining low payload with very large steering angle without significant side lobes. We have an on-going collaboration with Princeton Infrared Technologies Inc. (http://www.princetonirtech.com/)

To further provide system integration, a photodetector array is planned to be wafer-scale integrated with all beam steering function without any moving parts. A 17 million dollar proposal has been submitted to DARPA a week ago for further evaluation. Within USA, only a few research universities have the capability building a system that DARPA wants. These include UT Austin, MIT (Mike Watts), UC Berkeley (Ming Wu) and UCSB (John Bower). Currently packaged LBS system supported by AFOSR MURI program (**AFOSR (Dr. Pomrenke, Contract No. FA 9550-08-0394)** is shown in Figure 6. 6(a) is the packaged device where a silicon nanomembrane is shown on top of a silicon chip with all needed wire bonding for electrical current injection. 6(b) is the experimental result of the 2D beam steering without significant side-lobe. And (c) is the confirmation of Gaussian shape beam profiles at the far field.

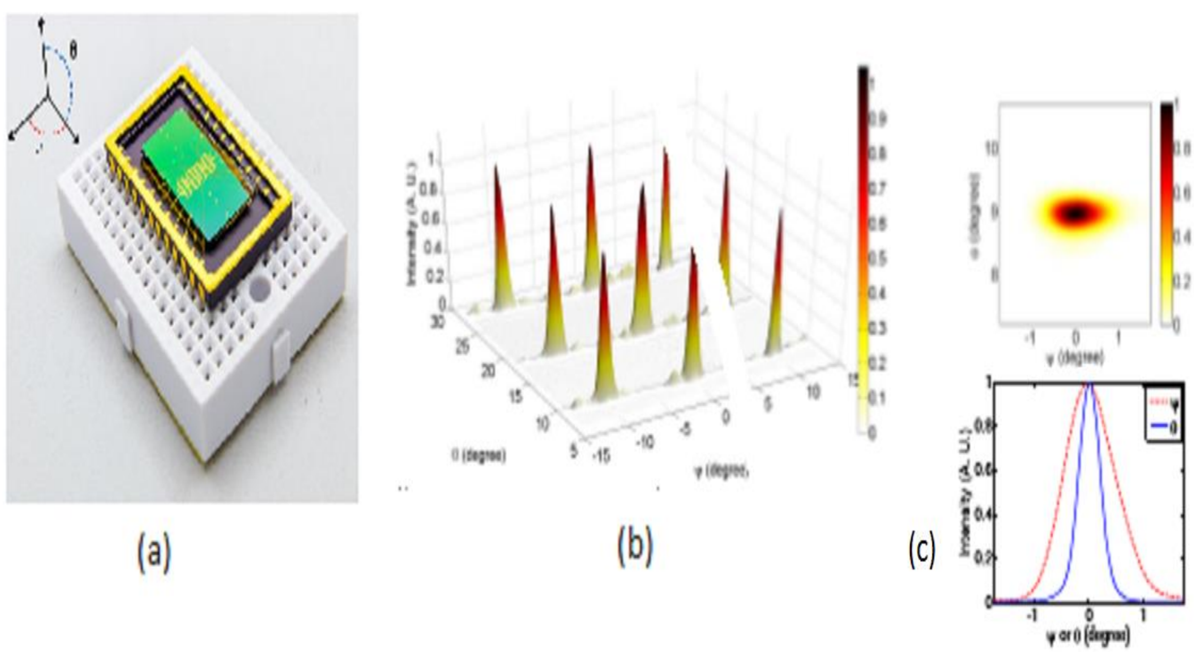

Figure 6 (a) Packaged silicon nanomembrane device with current injection pads. (b) The far field beam steering pattern at nine different angles and (c) Mode profile confirming the Gaussian beam profiles

We presented the nanotechnology research results in various domestic and international conference. In 2013 Photonics West (SPIE), our nanotechnology has been selected by a panel of investors as one of the top 10 photonics ideas that have highest commercialization potential. We have also received several best paper awards in the international conferences. And several plenary and keynote speeches are also delivered in many international conferences

Role of the U.S. Government in commercial success

The role of US government play a major role in supporting the semiconductor based nanomembrane nanotechnology. Role of the Federal Government has been led by AFOSR (Dr. Pomrenke, Contract No. FA 9550-08-0394) through a 4.75 million dollar MURI program in Silicon Nanomembranes from 2008 to 2013. The five year program provides us with the scientific and technology infrastructure through which a large number of supports from industry and federal government followed. These include Boeing, MD Anderson Cancer Research Center, Medical University of South Carolina, DOE, NIH, Army, Navy, EPA, and NSF. The story of success can be easily explained by viewing Figure 7. Federal support started from the 2008 AFOSR MURI program which functions as the root for the fruition of many related nanotechnologies including Optical phased array for Lidar, biosensing for early cancer detection and drug screening, air- and water-pollution sensing, EM wave sensing, and heavy water detection. The total funding from AFOSR/AFRL, Army, Navy, DOE, NIH and EPA have added up to over 10 million dollars. For the nanofabrication of all silicon nanomembrane devices, we employ the NSF NNIN facility in UT Austin which provided tremendous help. The NSF NNIN facility in UT has all the nano- and micro-fabrication and lithography tools (http://www.mrc.utexas.edu/nnci) where all our devices are fabricated using this facility. The most valuable equipment is the e-beam lithography where feature size as small as 50 nm can be precisely fabricated. Also, AFRL will send engineers to our research center this spring (2016) to get familiar with how we test our EM wave sensing devices. We will deliver a packaged silicon nanomembrane based EM wave sensor operating at Ka-band for further evaluation in AFRL in Dayton, Ohio.

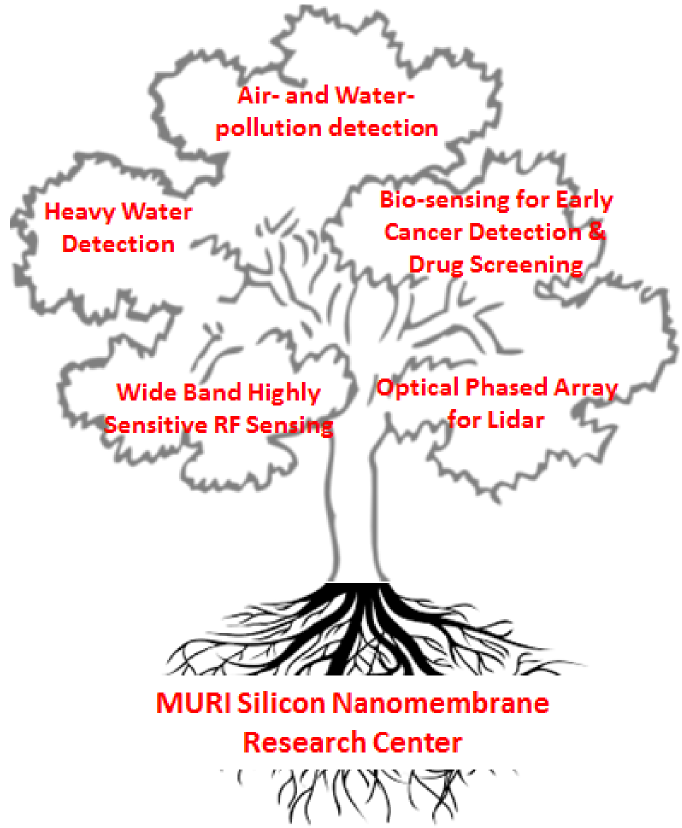

Figure 7 Federal support started from the 2008 AFOSR MURI program which functions as the root for the fruition of many related nanotechnologies including Optical phased array for Lidar, biosensing for early cancer detection and drug screening, air- and water-pollution sensing, EM wave sensing, and heavy water detection. The total funding from AFOSR/AFRL, Army, Navy, DOE, NIH and EPA have added up to over 10 million dollars

Figure 8 A full packaged device for EM wave sensing to be delivered to AFRL