Fabrication and Read-out of Integrated Photonic High Frequency Acoustic Wave Detectors
(Technical Report)

Organizational Interplay in the Development of Silicon Photonics
(STS Topic)

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On my honor as a University Student, I have neither given nor received unauthorized aid
on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

The field of photonics covers the generation, guidance, processing, and detection of optical signals. Its initial development saw competition between academia and industry as groups across America sought to create the first laser. Following Richard Maiman's demonstration of a ruby-based laser in 1961, continuous research and development in photonics has led to a broad set of applications including the transcontinental optical fibers which allow for the high bandwidth internet we enjoy today (Bromberg, 2008). These developments have connected academic research, industrial research and development, and government funding and policy towards creating smaller and more affordable products. Industry Reports (2019) valued the global photonics market in 2018 at $546,700 million and predicted it will grow to $735,100 million by 2024.

Integrated photonics is the development of photonic components and circuits onto chips resembling a computer processor. Silicon is usually the choice material for integrated photonics as it allows for device fabrication in widely available CMOS microelectronics foundries. The development of silicon photonics greatly reduced the cost of creating photonic circuits; however, silicon's distinct optical properties required a large investment in re-developing photonic components with silicon. Silicon photonics development sparked industry demand for lower production cost photonic circuits driving new academic research.

A burgeoning technology in photonics is photoacoustic microscopy. Ultrasonic waves (sound waves with frequencies greater than 20 kilohertz) are characteristically released from soft tissues when they are blasted with light of a specific wavelength. These ultrasonic waves can be measured and reconstructed to produce images of the tissues they came from with a high contrast. This technique is particularly useful in the imaging of brain blood vessels as it does not require an invasive implanted contrast agent as is needed for x-rays, computed tomography (CT), or magnetic resonance imaging (MRI). Song Hu (2010) extended photoacoustic microscopy to optical resolution, 5-microns, and demonstrated it with the imaging of a single capillary in a mouse's brain. He has then used this system to demonstrate applications in detecting neurological pathway deficiencies including Alzheimer's disease and ischemic stroke.

Photoacoustic microscopy is currently limited by the state-of-the-art technology in ultrasonic detectors, piezoelectric transducers. Piezoelectric transducers measure the charge generated when a piezoelectric material is strained by an acoustic wave. These detectors are large, expensive, and not easily integrated into scalable sensor arrays. Consequently, current photoacoustic microscopy on mice requires anesthetizing the subject for alignment with the detectors (Hu, 2010). This is problematic as anesthesia slows blood flow thereby altering the images produced. Silicon photonics offers an attractive starting point for replacing these sensors due to its low cost, micron-scale size, and potential for array integration with optical multiplexing. Further, it would allow direct integration of the sensor with contemporary photonic circuit fabrication infrastructure for the mass production of these sensors. The research and development of this contemporary silicon phonics platform sees contributions from academia, industry, government, and other organizations.

Technical Topic

Initial attempts at a photonic ultrasonic sensor start with high quality factor optical micro-ring resonators. These resonators are micron-scale rings (either circular or elliptical) which create light interference patterns. This interference pattern allows most incident light to transmit unattenuated, but certain resonant wavelengths are "trapped" in the ring and are not transmitted. A membrane is then cut into the chip such that the micro-ring resonator and the input and output waveguides are embedded in a microns-thick material (see Figure 1).

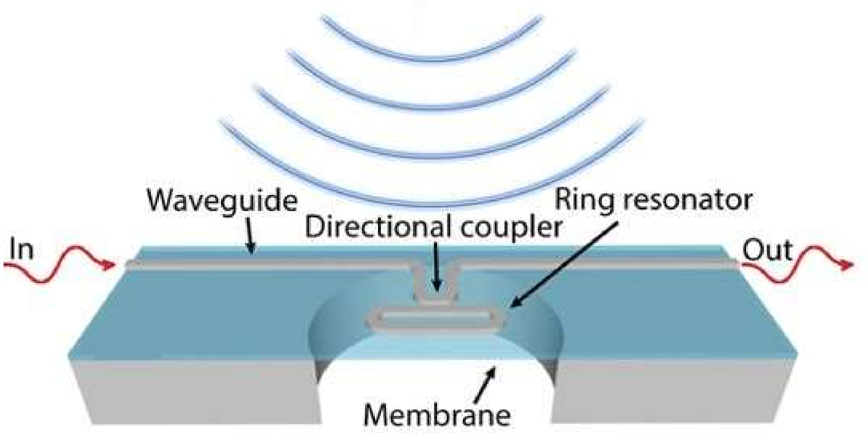

Figure 1. Ultrasonic sensor sketch. The red "In" and "Out" lines represent optical signals entering and leaving the resonator respectively. The blue wave fronts represent incident acoustic pressure fronts. The blue slab represents the photonic circuit packaging while the gray slab represents the carrying substrate. (Image source: Leinders et al., 2015)

An incident sound wave pressure front will strain this membrane altering the geometry and dielectric constant of the material. This will shift the resonance frequency of the resonator (see Figure 2).

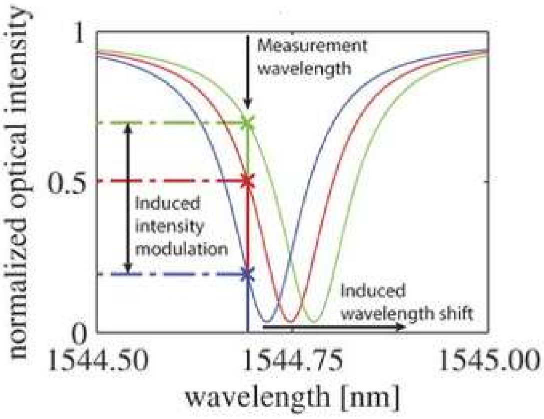

Figure 2. Acoustic Wave Resonance Frequency Shift. The blue line is the unperturbed resonance curve, the red and green lines are the resonance curves with increasing pressure fronts straining the membrane. (Image source: Leinders et al., 2015)

If the input to this resonator is light of a wavelength near the resonant frequency (like the starred point on the blue curve in Figure 3), a certain amount of light will be transmitted. An acoustic pressure front will then change the transmitted light (like the starred points on the red and green curves in Figure 3) a set amount dependent on the pressure strength. This change in transmitted light can then be measured with a photodiode as an acoustic wave amplitude. Therefore, this system can be used as an acoustic sensor by measuring the change in transmitted light over time.

A sensor of this type was first fabricated and tested by Maxwell and colleagues (2008). They created a polystyrene polymer mold substrate to support a 4-micron thick silicon dioxide photonic circuit. The mold had holes aligned with the resonator to create the membrane as an empty spot in the mold. This sensor demonstrated a bandwidth spanning the optical frequencies. Thus, the group demonstrated the ability to detect ultrasonic signals, however the sensor fabrication required expensive and specialized polymer molding. A group at Northwestern University later fabricated a similar sensor but extended the bandwidth to 150MHz, covering the full range of ultrasonic waves used in photoacoustic microscopy (Li, Dong, Zhen, Zhang, & Sun, 2014).

To overcome the issue of fabrication, a group at Delft University sought to fabricate an ultrasonic detecting micro-ring resonator on industrial-grade silicon wafers. These sensors matched and exceeded the state-of-the-art piezoelectric transceivers in terms of sensing performance in a 65 times smaller footprint (Leinders et al., 2015). However, their fabrication required specialized dicing blades and laser etches to cleanly fabricate a membrane out of the silicon, so it was not directly compatible with silicon foundries.

Our project seeks to extend the work at Delft University to an industrial-grade CMOS fabrication process. To start, the micro-ring resonators will be sourced from silicon-on-insulator (SOI) foundry-fabricated chips. These structures house a 7-micron thick silicon dioxide photonic circuit on a 700-micron thick silicon substrate for mechanical stability and dielectric constant matching. We will then etch a vertical hole through the silicon substrate to the silicon dioxide to create a membrane over the resonator and waveguides. The fabricated sensor can then be characterized for bandwidth and stability using a tunable laser and a spectrum analyzer.

Designing the fabrication process flow for the sensor is a non-trivial task. Microelectronic circuit fabrication techniques are isotropic. This means that features cut into the material will broaden over deep material etches, such as the 700-micron silicon etch required here. This will damage the mechanical stability and potentially overlap features of the completed chip. To combat the isotropic nature of ICP RIE, the Bosch process can be used. The Bosch process, patented in 1996 by Bosch Corporation, alternates between isotropic inductively coupled plasma reactive ion etching (ICP RIE) using sulfur hexafluoride and a passivation with octafluorocyclobutane to create anisotropic vertical etches (Laermer & Schilp, 1996). This process can be completed with a thick photoresist feature mask such as AZ9260 which can be deposited at thicknesses as large as 24-microns. Our initial testing shows AZ9260 etches at a rate 50 times slower than silicon in the Bosch process. Thus, etching 700-microns of silicon will etch 14-microns of AZ9260, and the remaining 10-microns of AZ9260 can be removed with acetone. This process can be completed in the University of Virginia's Microelectronics Laboratory (UVML), but more importantly it utilizes tools available in a CMOS-foundry. Demonstration of this process flow would therefore extend micro-ring resonator ultrasonic sensors from a university clean room to an industrial scale in which they could be mass produced and easily integrated with photonic integrated circuits.

This technical project acts as a liaison between academic research and industrial applications. Previous implementations of photonic ultrasonic sensors have shown promise, but they have been limited by obscure, expensive, and unscalable fabrication techniques. This is a part of the long-standing development of integrated photonics. The contributions of photonics from groups with different interests has led to new research in reconfiguring the benefits of photonics to scalable means.

STS Topic

As my technical project focuses on making a scalable solution using silicon photonics, my sociotechnical research will examine how different organizations contribute to the development of integrated photonics.

The main framework for developing the contributions of different organizations to integrated photonics will be the concept of path dependency. Page (2006) describes path dependency as a set of four conditions: increasing returns, self-reinforcement, positive feedback, and lock-in. These conditions provide vantage points for understanding the historical dependence of the current state of a choice and its future equilibrium points. Increasing returns shows increasing benefits each time the choice is made. Self-reinforcement shows a choice creating positive externalities put in place by the choice. Positive feedback shows a choice creating positive externalities when chosen by others. Finally, lock-in shows a choice becoming better than its alternates because a sufficient number of other people have previously made this choice. Page further distinguishes between path dependence, state dependence, and phat dependence. These differentiate between choices dependent on the full history, segments of the history, and parts of the history but not necessarily their order respectively.

Page further cautions that path dependency is not necessarily induced by positive returns as commonly conjectured in prior literature. In fact, positive returns can act as a distractor from the positive and negative extremities which actually cause the path dependence of a choice. Page supports this with the historical examples of employers offering healthcare following the New Deal on account of negative extremities induced on companies who do not offer healthcare. He further cautions that path dependence does not lead to deterministic outcomes, but rather more likely outcomes. This is supported by legal proceedings where previous rulings hold power, but can also be overruled. Page extends this argument with his own dynamic and static economic models which he supports with data from known processes including the Polya Process. This model can be used to show current inefficiencies in a market on account of historical events (Page, 2006).

Path dependence is inevitable in silicon photonics as the technology hinges on previous developments and infrastructure for silicon microelectronics. This provides a phat dependence with lock-in as the starting point rests on the choice of silicon for electronics decades ago. Rickman (2014) argues that research in silicon photonics is inherently more difficult than other forms of photonics, but it is desirable on account of the infrastructure for silicon already available in foundries. He displays this with a case study on one of the early silicon photonics companies, Bookham Technology Ltd. Bookham initially relied on a collaboration with Surrey University to produce the first silicon waveguides. Silicon photonics could not exist without a way to guide light between components, but specialized knowledge and facilities were required to realize this necessary technology. Bookham found a market for their silicon photonics in telecommunications, but eventually saw investments dwindle during the burst of the dot-com bubble in 2001 and discontinued silicon photonics research. In 2006, an offshoot of Bookham's silicon photonics division was founded as Kotura Inc. Kotura received initial funding from the US government through DARPA and is now poised to provide infrastructure for the continued expansion of internet traffic (Rickman, 2014). Through this, contributions to silicon photonics from industry, academia, and government are displayed. They are further related by a path dependency beyond the initial choice in silicon microelectronics. The researchers at Surrey University were enabled by investments from Bookham. The technology they developed was continued and eventually discontinued with telecommunications investment. It then saw renewed research and development with government interest.

Analysis through path dependence shows the benefits and potential hang-ups of silicon photonics. The concept is based in sound decision making, but it is not necessarily the best path forward. Fuchs and colleagues (Fuchs, Kirchain, & Liu, 2011) argue that indium phosphide-based systems are preferential for most industry applications of integrated photonics compared to silicon photonics. They advanced this with a model developed by SEMATECH in the 1980s modified with contemporary cost data for the fabrication of transceivers on both silicon and indium phosphide. Their model found that indium phosphide-based chips would be cheaper to produce in low-volume quantities as compared to the equivalent silicon chips. Using this, Fuchs and colleagues further argued that existing infrastructure for silicon has created a lock-in. The adaptation of infrastructure for fabrication of indium phosphide has not been largely considered despite its high potential revealing an inefficiency in the market.

The relatively independent development of semiconductor research has led to several organizations outside of industry, academia, and government. Koch and colleagues (2016) announced the formation of the American Institute for Manufacturing Integrated Photonics (AIM Photonics) to help alleviate this discrepancy. AIM Photonics draws resources, expertise, and investment from industry, academia, and government to fulfill the common goal of advancing US capabilities in integrated photonics manufacturing. They hope the shared infrastructure will mature the market by allowing products to be tailored to a customer. This model comes from similar previous successes in the microelectronics industry including Semiconductor Research Corporation (SRC) (Koch et al., 2016). These organizations further draw on path dependency as their existence rely on a phat dependency of previous players in semiconductors attempting to combine their research interests, efforts, and infrastructure.

Research Question and Methods

This research seeks to answers: how do academia, industry, government, and other organizations contribute to the research and development of integrated photonics? Silicon and integrated photonics have and continue to receive investment from these different groups. The segmented investments lead to knowledge and infrastructure which is not necessarily complete and further may be leading towards technologies inefficient for the market. Analysis of the players, their past choices, and their current state will shed new light on dealing with the unique challenges of integrated photonics. The potential for better collaboration as well as new technologies to develop could deliver benefits to society. In the case of my technical project, this could be better and more affordable and informative medical imaging.

This question will be advanced through a review of prior literature on the development of photonics as a whole as well as the interactions of different players involved in the development of integrated photonics. I will specifically investigate Semiconductor Manufacturing Technology (SEMATECH), Semiconductor Research Corporation (SRC), Optoelectronics Industry Development Association (OIDA), AIM Photonics, and National Nanotechnology Initiative (NNI) as they comprise the current models for external organizations combining research across academia, industry, and government (National Research Council, 2013). I will also conduct interviews with professors at the University of Virginia with expertise in the field of silicon photonics and whom I have built a relationship with. This will provide additional insights into interactions stemming from academia to industry and government.

Using this data set, I will perform a case comparison to piece together the historical narrative of integrated photonics. I will further analyze these sources for bias inherent in long-time researchers in the field through their past work and current positions. This method will elucidate the current state of integrated photonics through an understanding of the different players and how they work together.

Timeline and Expected Outcomes

The technical component of my project seeks to fabricate an ultrasonic sensor which is cheaper, more easily mass produced, and more easily integrated into large sensor arrays by the end of the fall semester. Its production will lead to more affordable and better medical imaging and subsequent better healthcare. The successful completion of this technical project will see publication in a conference paper. The mass production of the sensor will serve as evidence of the immediate benefits of silicon photonics and its continued research and development.

The STS deliverable will focus on viewing the contributions of different groups to integrated photonics through the lens of path dependency. The sources for the case studies and interviews will be compiled in the first month of next semester (January through mid-February). These collected cases will then be analyzed including finding related sources to consider in the next month (February through mid-March). From here, the paper will be synthesized for final completion in early May. This paper will lead to a better understanding of the current state of integrated photonics and allow for a more informed path forward in new research. It will provide information to help guide my future career in research.

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