Organizational Interplay in the Development of Silicon Photonics

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Introduction

The field of photonics covers the generation, guidance, processing, and detection of optical signals (that is, light). Its initial development saw competition between academia and industry as research groups across America sought to create the first laser. Richard Maiman's demonstration of a ruby-based laser in 1961 spurred continuous research and development in photonics through contemporary times. This has led to a broad set of applications including the transcontinental optical fibers which allows for the high bandwidth internet we enjoy today (Bromberg, 2008). These developments have connected academic research with industrial research and development as well as 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 with projected growth to $735,100 million by 2024.

Integrated photonics is the development of photonic components and circuits onto chips resembling a computer processor. Silicon is a choice material for integrated photonics as it allows for device fabrication in the same CMOS microelectronics foundries used to mass-produce microelectronics. The low cost of silicon wafers coupled with silicon's high manufacturing yield and extant production infrastructure makes silicon photonics cheap compared to its alternatives, such as photonics built on expensive indium phosphide wafers. However, silicon's lack of an electro-optical effect prevents the creation of silicon lasers, modulators, and optical amplifier which are necessary components for photonics. Thus, the development of silicon photonics required a large investment in developing photonic components which are compatible with silicon. The development of such components has required industrial and academic research and development with investment from both industry and government sources.

A burgeoning specialization 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 with a higher degree of contrast than traditional approaches. This technique is particularly useful in the imaging of brain blood vessels as it does not require an invasive 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 for detecting neurological pathway deficiencies including Alzheimer's disease and ischemic stroke.

Photoacoustic microscopy is currently limited by piezoelectric transducers, the state-of-the-art technology in ultrasonic detection. 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.

Path Dependence in the Development of Integrated Photonics

The groups involved in the development and production of integrated photonics create a complex system involving research, investment, and manufacturing, termed an innovation ecosystem. The current state, as well as future research directions, of this complex system are best understood through an analysis of the historical underpinnings of the technology as well as the groups contributing to it. The main framework for analyzing this innovation ecosystem 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 and the inertia that constrains future changes. 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 (2006) further distinguishes between path dependence, state dependence, and “phat” dependence. Path dependence refers to cases which depend on the full history of choices, state dependence to cases which depend on segments of the history of choices, and phat dependence to cases which depend on parts of the history of choices but not necessarily the order of the choices.

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 creates an obvious starting point for analyzing the historical and contemporary development of silicon photonics. Silicon is a flawed source for a photonics platform. If development of integrated photonics were to start in a world without the existence of silicon microelectronics foundries, the field of silicon photonics likely would not exist at all. Rather, silicon photonics was born from pre-standing infrastructure and its possibility to produce cheap photonic integrated circuits. In Page's terms, this is a phat dependence with lock-in – silicon photonics is and always will be dependent on its beginnings in repurposing silicon foundries. The history and future of silicon photonics, then, is altered by this starting point. An understanding of the extent phat dependence has affected the development of silicon photonics will provide a vantage point for evaluating the direction of future research.

From this vantage point, path dependence also provides a framework to understand the different groups involved in developing silicon photonics. The concept of a cheap photonics platform is appealing to industry for profits, the government for military applications, and researchers for the technical challenge and potential applications. However, the specialized nature of silicon photonics limits the interested constituents. Existing private industry interest in silicon photonics will likely be limited to companies who already have investment and connections in silicon infrastructure. These companies will then be interested in simple adaptations to their infrastructure for producing integrated photonic circuits. New private industry may start from individuals with specialized expertise in certain aspects of silicon photonics. On the other hand, government investment and expenditures in silicon photonics may be for military applications either directly or indirectly benefiting private industry. Through all of this, academics drive development of these technologies with research grants. The development of this complex system of organizations saw influence from the unique histories of its constituent organizations, providing a state dependence for the current interest in silicon photonics. That is, the development of silicon photonics is dependent on the groups who invest in it who have been influenced by their past experiences with silicon photonics. Understanding this system overtime will provide an outlook for silicon photonics and its implementation in society.

Case Context

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 critical technology.

Later, 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 with path dependence shows the benefits and potential constraints of further investments in silicon photonics. The concept of silicon photonics is based in sound decision making, but it is not necessarily the best path forward for integrated photonics. Fuchs and colleagues (Fuchs et al., 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 (2011) 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

This research seeks to answers: How do academia, industry, government, and other organizations contribute to the research and development of silicon photonics? Silicon photonics has and continues 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 the development of 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 silicon 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, more affordable, and more informative medical imaging.

Methods

This question will be addressed through interviews with experts in the field of silicon photonics and a subsequent review of prior literature on the development of silicon photonics focusing on the interactions between different players involved in the development of integrated photonics. I interviewed six people: Dr. Joe Campbell, Lucien Car III Professor of Electrical Engineering at the University of Virginia with research interests in optoelectronics and silicon photonics and former employee of AT&T Bell Laboratories; Dr. Andreas Beling, Associate Professor of Electrical Engineering at the University of Virginia with research interests in silicon photonics and previous experience at the Heinrich-Hertz-Institut in Berlin, Germany; Dr. Keren Bergman, Charles Batchelor Professor of Electrical Engineering at Columbia University with research interests in silicon photonics and optical interconnects; Dr. Jagdeep Shah, former Bell Labs employee and DARPA project manager with research interests in silicon photonics and quantum information; Dr. Robert Leheney, former DARPA project manager with experience applying photonics to the telecommunications market; and Dr. Daniel Radack, former DARPA project manager with expertise in microtechnology and semiconductor fabrication and integration including photonics applications. Transcripts from these interviews are available in Appendix A. From these interviews and separate research, I constructed a selection of case studies on silicon photonics including: its scientific origins and seminal literature from Miller, Kogelnik, and Soref; external investing agencies the American Institute for Integrated Photonics (AIM Photonics), the Defense Advanced Research Projects Agency (DARPA), and Interunivesrity MicroElectronics Center (IMEC); silicon photonics industry players Acacia Communications, Infinera, Intel, Cisco, silicon foundries, Facebook, Microsoft, Apple, Google, and Nvidia; and academic players including those interviewed as well as John Bowers, Professor of Electrical Engineering and Materials Science at the University of California, Santa Barbara and former employee at AT&T Bell Labs and Honeywell.

Across these case studies, I will specifically seek the historic interactions between private industry, the government, and academic research and how these past interactions influence the contemporary development of the silicon photonics market. Using this data set, I will perform a case comparison between 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 towards the greater silicon photonics market.

Results

The data set showed clear interactions between academia, industry, government, and other organizations in the development of silicon photonics. These interactions can largely be categorized into investments, supply chains (or lack thereof), and a partially revolving door of employees. Academic research has garnered modest investment from private industry and major government investments as well as spun off start-offs which are taken over by private industry giants while simultaneously sending students to industry. Private industry players in silicon photonics exist and conduct some of their own scientific research while also accepting other funding sources and working with (or often outright purchasing) suppliers. Finally, government investment as well as several other non-profit organizations have provided funding for the research and integration of existing silicon photonics infrastructure while concurrently pushing towards the development of new cutting-edge technology.

Historical Conception of Silicon Photonics

Miller (1969) published the first review of the possibility of integrated optics, that is doing photonics on a chip using fabrication techniques developed for microelectronics, in the internal AT&T Bell Labs technical journal. He listed plausible theory and fabrication techniques for dielectric waveguides, integrated lasers, optical modulators, and optical filters. While the paper was entirely theoretical and displayed no results, it did coin the term "integrated optics" and laid out the backbone for the integrated photonics concept we know today. Later, Kogelnik (1977) published a review of the early experimental results in integrated optics based on Miller's framework at the first conference for Fiber and Integrated Optics. Miller further offered new applications in optical signal processing on a much smaller scale than currently possible.

Early work in integrated optics focused on creating photonics on indium phosphide wafers as photonic technologies had previously been developed around the high efficiency photodetectors available on indium phosphide platforms at telecommunication wavelengths (1550nm). Richard Soref, a research scientist at the US Air Force Research Lab, saw the lack of infrastructure and fabrication techniques available to mass-produce indium phosphide integrated photonics. Instead, Soref foresaw the possibility for integrated photonics on a silicon platform which could be mass-produced in the silicon foundries already used for microelectronics. He proposed silicon-on-insulator waveguides, which are now the standard waveguide used in silicon photonics. He also foresaw applications in sensors, integration with microwave systems, and quantum information (Rubenstein, 2016). About Soref, Campbell (personal communication, January 27, 2020) said, "He [Soref] imagined photonic integrated circuits (PICs) and silicon photonic integrated circuits (silicon PICs). Industry and academia didn't pay him much attention as there were no lasers, modulators, or detectors developed for silicon." Silicon photonics remained an idea until academic research could create the photonic components necessary to compete in some market with other photonics platforms.

US Investments in Foundry Silicon Photonics

Past its conception, silicon photonics developed through investments in fundamental research for silicon photonics technologies. Bergman (personal communication, February 25, 2020) on the topic of initial investment in silicon photonics noted, “Foundry integrated photonics started a while ago. Initial support in the US came almost entirely from a government push through DARPA and the DoD. Essentially, the field of silicon photonics is so open that no private industry has enough money to invest in the ecosystem. Even still, the ecosystem is far from closing and funding largely comes from government agencies.” Early investments for silicon photonics were relatively non-existent as neither the technology nor development infrastructure existed.

Seeing its potential uses, the US Government’s Defense Advanced Research Projects Agency (DARPA), a subsidy of the Department of Defense (DoD), added much of the initial and recent funding. Shah (J. Shah, personal communication, March 30, 2020) noted, “In the Early 2000’s, I proposed DARPA’s first major project in silicon photonics. My argument in the proposal was that silicon is not a ‘good’ photonic material, but the infrastructure based on it allows for the integration of electronics and optics. At first, it wasn’t clear if you could make high performance components in a commercial fabrication facility on silicon. The initial funding was put in place to produce high quality devices to allow for the eventual realization of silicon photonics systems.” DARPA’s initial interest in silicon photonics came from the potential from integration of silicon microelectronics with optical technologies. This investment had the intention of developing the technology for silicon photonics with consideration for production of defense applications rather than marketable scaling.

On the topic of the position DARPA takes in its investments, Radack (D. Radack, personal communication, March 30, 2020) noted, “DARPA funds critical mass experiments. They try to stay a couple steps ahead on real problems towards advancing understanding for the community. This appears at conferences and similar which indirectly benefits private industry when they see these results – in essence DARPA is providing funding for risk.” As mentioned by Bergman, the early stages of silicon photonics saw a potential with huge investments – in its early role, DARPA took on some of the risk to develop the technologies, but not create an ecosystem.

DARPA has continued to invest in silicon photonics technologies. Beling (personal communication, February 26, 2020) noted the recent pushes in silicon photonics by DARPA: “Some money has also come from DARPA. For example, a recent request for proposal dubbed LUMOS has offered funding for research developing microwave photonics, photonic integrated circuits which operate in the visible spectrum, and gain in silicon-based photonic integrated circuits. It’s almost funny – these are fundamental scientific problems which you’d think should have been solved 20 years ago for silicon photonics to continue.” Lasers for Universal Microscale Optical Systems (LUMOS) seeks to integrate several different integrated photonics platforms, including silicon, with new optical materials towards creating new accessible and manufacturable systems (DARPA, 2019). DARPA’s support of photonics has historically been rooted in its potential applications in data processing and sensing for scalable military applications.

The US Government has more recently invested in silicon photonics through the American Institute for Manufacturing Integrated Photonics (AIM Photonics). About AIM, Bergman (personal communication, February 25, 2020) said, “Around 5 years ago, the US government pushed for a centralized place for integrated photonics with the AIM Photonics (the American Institute for Manufacturing Integrated Photonics). The funding came almost entirely from the government, both at the federal level and from the state of New York, and the institute is based in Albany, New York. My group [the Lightwave Research Laboratory at Columbia University] was one of the leading academic partners. AIM partially sought to reproduce the centralized structure for foundry fabrication seen in both IMEC and IME. Economically, AIM provided the upfront costs to build the infrastructure for fabricating wafers on an industry scale. They specifically used 300mm silicon wafers, the state-of-the-art in CMOS (complementary metal oxide semiconductor) fabrication creating the more advanced photonics foundry in the world. Private industry and academics are able to order small portions of a wafer for fabrication, called a multi-project wafer (MPW). AIM’s infrastructure has vastly lowered the cost of fabricating silicon integrated photonics for all forms of research and development in the US.” Campbell (personal communication, January 27, 2020) noted, “The effort [AIM Photonics] focused on making a well-documented and widely available platform for integrated photonics with additional support for packaging devices.” AIM Photonics was established in 2015 from a \$100mil federal grant as a part of the US Government’s “Manufacturing USA” push to develop public-private relations towards the development of manufacturing advanced technologies. Additional funding was sourced from the New York state government, which houses AIM through the cleanroom at SUNY Albany and a developing packaging institute in Rochester, New York (2015). The initial 5-year contract sought to combine these AIM facilities with existing academic and private-industry silicon photonics infrastructure at over 30 members including Infinera and Intel. In this sense, the government's vested interest was in creating a starting point for the scaling of silicon photonics.

Beling (personal communication, February 26, 2020) noted the shortcomings of the initial AIM funding: "In principle, the institute should have been self-sustaining monetarily after the initial investment. Instead, as we near the end of the contract, the packaging facility has not been finished and industry partners have largely stayed out of the institute. It's hard to blame them – why would private industry open their foundries up to competitors? Now the question AIM faces is how to continue with the government funds used up and an unsustainable model." AIM's initial contract did not necessarily meet its goals; however, it did provide a starting point for understanding the industry; centralized infrastructure for manufacturing silicon photonics does not exist as the private industry does not demand it. This is especially noted by the lack of large microelectronics foundries joining AIM.

International Investments in Foundry Silicon Photonics

Outside of the US, silicon photonics has received support from the Interuniversity Microelectronics Center (IMEC). Beling (personal communication, February 26, 2020) noted, "Silicon photonics in Europe has had support from IMEC largely since its inception. They have focused on pilot prototyping new uses for silicon photonics towards commercial applications in Europe. This is quite different from the US where the electronics industry has almost entirely stayed out of silicon photonics." IMEC, led by the European Union cooperative research and development center, is a research hub for the field of nanoelectronics founded in 1984. Based in Belgium, IMEC also has campuses in the Netherlands, China, India, Japan, and the United States which hold clean room spaces for the research and manufacturing of new nanoelectronics. IMEC was an early player in silicon photonics and was able to use its previous expertise in CMOS manufacturing to produce its own manufacturing base for silicon photonics in its Belgium facilities (IMEC International, 2020). IMEC has recently opened a new design facility for photonics in Orlando which will spread their silicon photonics manufacturing capabilities to the US (IMEC International, 2019).

Silicon Photonics Industry

Private industry for silicon photonics has developed as the underlying technology and market demand advances. Acacia Communications Inc. has developed as a leader in commercial silicon photonics through their sales of silicon optical interconnects. Acacia was founded in 2011 by Mehrdad Givehchi, Benny P. Mikkelsen, and Christian J. Rasmussen from the idea of developing the integration of CMOS silicon signal processing with silicon photonics for high-bandwidth data transfer and using private investments. The founders worked on business operations and hired Chris Doerr, a research scientist who had spent 20 years at AT&T Bell Labs developing integrated photonics, as their lead scientist. Acacia's efforts have drastically shrunk optical interconnects while also allowing cheap and simple integration with other components in fiber-optical communications networks (Shanmugaraj, 2017). On Chris Doerr, Beling (personal communication, February 26, 2020) noted, "I knew Chris and he has largely disappeared since joining Acacia – his publications are largely patent applications and he isn't an invited speaker at conferences anymore." Since leaving his previous roles in research, Doerr's focus has shifted to creating products for Acacia rather than fundamental research (Crew, 2017).

Acacia has listed its future goals for silicon photonics as creating optical interconnects with smaller form factors, higher density, and lower power towards higher capacity data links. They are also looking towards new applications of integrated photonics in light detecting and ranging (LIDAR), 3D sensing, deep learning, and unforeseen possibilities (Shanmugaraj, 2019). In July 2019, Cisco announced it was acquiring Acacia for approximately $2.6 billion. Acacia had formerly acted as a supplier to Cisco's for optical interconnects used in data centers. This acquisition will close in the latter half of 2020. Cisco cited a desire to integrate their systems to "simplify operations and reduce network complexities" as their reason for acquiring Acacia. This was announced almost concurrently with Cisco's acquisition of Luxtera, another silicon photonics start-up founded by Professor Axel Scherer and some of his students at the California Institute of Technology (Cisco Press Release, 2019). Separate from initial interest in silicon photonics for high-volume manufacturing, Cisco's interest in silicon photonics comes from its potential for energy efficient data centers.

Infinera, another private company specializing in silicon photonics, was founded in 2000 as Zepton Networks by Drew Perkins, Jagdeep Singh, and David Welch. The founders had previously worked together at Spectra Diode until its acquisition in 2000. Perkins and Singh acted as operational managers while Welch was a primary researcher in optical interconnect technology. Through two rounds of private funding, they amassed $86 million. The funding phase was entirely secret, but investor Tony Sun from Venrock cited Zepton's distinguished intellectual property as a key differentiator for funding (Harvey, 2001). Infinera specializes in creating ultrafast optical networks on integrated chips. Their initial work used the communications industry standard material platform indium phosphide, and they used their initial success to fund the creation of silicon integrated photonic circuits which they specialize in today (Greene, 2007). Infinera is known to be very secretive with their technology and manufacturing methods. Infinera Director of Solutions and Technology Geoff Bennet has claimed, "Vertical integration is more valuable than ever" (Bennett, 2019).

On the topic of Infinera, Campbell (personal communication, January 27, 2020) stated, “They joined AIM, but ironically their foundry and methods are not available outside of the company. They also won’t give you the time of day – they operate through trade secrets. I have sat on several conference committees which have refused Infinera presentations as they have previously used academic conference to show product launches rather than science.” Similarly, Beling (personal communication, February 26, 2020) noted, “they [Infinera] don’t want to talk about their technology if they don’t have a product to sell.” While Infinera has internal research and development efforts, they keep their findings and infrastructure secret in the interest of future profit.

Intel, a large player in microelectronics, holds interest in silicon photonics for integration with their microelectronics products. Campbell (personal communication, January 27, 2020) noted, “Intel has used its large capital from electronics to invest in creating their own private integrated photonics foundry, but have lagged behind these new smaller companies in terms of innovation and products”. Their first foray into silicon photonics came in 2007. That year, a presentation at the Nature Photonics Conference by Dr. Mario Paniccia noted the potential for silicon optical interconnects to remove bandwidth limitations in future tera-scale servers. They particularly emphasized the potential for fabricating this technology with existing CMOS infrastructure. The presentation then went on to discuss Intel’s advancements in hybrid laser integration, waveguide fabrication, electro-optical modulation, photodetection, assembly, and integration with CMOS noting that the first step was creating innovation to prove the viability of silicon photonics (Nature Photonics, 2007). Intel now produces and distributes silicon optical transceivers which are targeted for use in optical interconnects for data communications. Intel currently does not offer any other silicon photonics products, and its scientists have not published in a major journal since 2011.

External Industry Interest in Silicon Photonics

Many contemporary technology companies without backgrounds in microelectronics have found recent interest in silicon photonics technologies. Beling (personal communication, February 26, 2020) noted, “Some large data companies, including Facebook, Google, Microsoft, and Nvidia, have recently found interest in user-level silicon photonics for their data centers and products. But their interest lies on the user-level, not the device level, and the technology is not fleshed out enough for large investment and interest in this yet.” Google, Apple, Facebook, Amazon, and Microsoft have been developing data centers to handle the high network traffic they experience while also maximizing internal security. As a result, they are pushing for silicon photonics as they see benefits in making their data centers much more power efficient (Ward-Foxton, 2019). Facebook scientists claim integration of optics and switching technology could reduce power consumption in data centers by up to 20%, however the silicon photonics market has not expanded enough to have the automation necessary for the mass-production of creating a data center (Curtis, 2019).

Graphics processing company Nvidia acquired Israeli-American optical interconnect producer Mellanox in 2019 to improve the efficiency of the data centers and processing for their graphics processing products. Mellanox had previously obtained this technology from their acquisition of Kotura in 2013. Bergman (personal communication, February 25, 2020) noted, “We currently have a partnership with Nvidia. Nvidia is known for making graphics processing units, but have interest in silicon photonics for future scaling of their systems. They invest in my group both monetarily and with effort from their employees, and my students have also worked at Nvidia on internships and jobs after graduation." In this respect, Nvidia has interacted with both academic players and other private industry to develop their silicon photonics interests in a way very similar to Cisco.

Academic Involvement in Silicon Photonics

Academia's role in silicon photonics can generally be difficult to trace. Campbell (personal communication, January 27, 2020) noted, "In general, modern academic and industry goals are disconnected as academia seeks to produce papers and students while industry seeks to produce products." In the context of silicon photonics, this leads to a disconnect in the usefulness of products created. Bergman (personal communication, February 25, 2020) noted "There is currently no automated method to align systems of optical fibers … there is very little automation in silicon integrated photonics fabrication, and consequentially most components are hand assembled." For the mass production of silicon-photonics, the automation of fiber alignment is necessary, but this is not something academics would pursue as high-impact research.

Campbell (personal communication, January 27, 2020) further noted, "Academics usually get to industry in one of two ways: leaving academics for industry, and usually never coming back, or starting a company on the side with their research… These research-oriented divisions of private industry are largely gone, and academic research now largely stays in universities." One good example of this is John Bowers, Professor of Electrical Engineering and Materials Science at the University of California, Santa Barbara. Bowers has founded several start-ups out of his academic research lab, the most recent of which was Aurrion. Bowers founded Aurrion with his graduate student Alex Fang in 2008. Their goal was to address the market need for heterogenous integration of lasers with silicon photonics integrated circuits. The research towards this technology was funded largely by the DoD and DARPA with additional development funding in subcontracts from aerospace companies. Initial manufacturing was then made possible by angel investors and strategic corporate investors. In an interview, Bowers explicitly mentioned DARPA's insistence for the creation and publication of photonic integrated circuits improving over previous technology as the main driver leading to Aurrion. By 2016, Aurrion held over 70 patents and was acquired by Jupiter Networks (Chang, 2016). While Bowers could start a private industry company, he returned to his academic role rather than continue the private company.

Further, the focus of academic researchers often leads to the need for a unique idea and research, ostensibly to fund and publish high-impact research and to obtain faculty positions; however, this creates a strife in the industry. On this, Beling (personal communication, February 26, 2020) noted, "For example, Mike Watts, a founding partner of AIM and a professor at MIT, owns the company which makes the process development kit (PDK) for AIM's foundry. How is that fair? The SUNY facility used for the foundry was recently built before AIM started – for them, AIM is essentially free funding … A recent invited lecturer here [the University of Virginia], Professor Hong Tang from Yale University, talked about using an aluminum nitride platform for integrated nonlinear photonics. Others are pushing for thin-film lithium niobate and silicon nitride platforms based on their research. While this makes sense in some respect – silicon's crystal structure gives it no nonlinear effects – the different special applications pushed by academics also create diverging interest in scaling a single platform like silicon." Academic research, while pushing fundamental technology, is limited by funding sources and the need for unique research. To this end, and much like industry interests, unified silicon integrated photonics manufacturing infrastructure does not have wide-scale support from academia. Rather, it has support from the limited set of academics doing research it would benefit.

Microelectronic Foundry Involvement in Silicon Photonics

Soref noted that the potential for mass-production of silicon photonics was the fundamental reason for developing the platform in the first place. However, no CMOS foundries are a member of AIM Photonics. Some microelectronics foundries, including Synopsys (Synopsys, 2020) and Taiwanese Semiconductor Manufacturing Corporation (Fibre Systems, 2018) have process development kits (PDKs) available for producing silicon photonic circuits in their foundries. These PDKs are not standardized, however, and are not designed for mass-production. To that, Beling (personal communication, February 26, 2020) noted, “Towards scaling, the question is how many foundries do we need? We want a result like CMOS microelectronics, but the market is not developed like that yet.” While the goal of silicon photonics may have been mass production, the market for high-volume photonic component production does not exist yet. Foundries will stay largely uninterested in silicon photonics until new high-volume applications for photonics become possible on a silicon platform.

Foundry involvement seems to be at odds with government investments in silicon photonics. On this, Leheney (R. Leheney, personal communication, March 30, 2020) noted, “Every dollar invested by the government was in the belief that a useful technology would come out of it. There is a problem in that academics and their research outcomes do not necessarily convert to manufacturing capabilities. These technologies have to enter the marketplace at some point. The market’s goal of getting the promised performance at a price point where the market runs with it is not necessarily in-line with the government’s interest in the performance of technology.” While government investment has garnered useful technologies for silicon photonics, these technologies have not created a mass-production market because it was not their goal in the first place.

Discussion

The study demonstrates clear connections between the investments made by multiple organizations involved in silicon photonics. However, it also shows that the divergent intent of these organizations has led to an incoherent silicon photonics market. The concept of silicon photonics in CMOS microelectronics foundries created a phat (time independent) dependence; Soref envisioned silicon photonics to utilize the existing infrastructure for manufacturing silicon microelectronics. Despite this, there has been no significant inertia to the mass-production of silicon photonics. The mass production of silicon photonics is impeded by a lack of market drive, private industry trade secrets, and divergent funding goals extant in the silicon photonics microeconomy. Instead, a path dependence has appeared in parallel: the integration of silicon photonics with CMOS microelectronics driven by a new market for efficient data centers. The historical development of silicon photonics technology has led to new market interests.

The broad topic of organizational interplay in silicon photonics has shown key themes in the photonics market. All research bodies seek investment, but several routes for funding now exist including government sources (DoD, DARPA, AIM, and similar), angel investors, and internal corporate investments. While academics fight for government funding, they also broaden the scope of these technologies with the original ideas they push for funding. Meanwhile, private industry has shown a new preference to avoid government funding in favor of generating more profits with trade secrets and patents. Private industry further has a notion of supply chains whereby companies purchase silicon photonic components from other companies including from academic spin-offs, but also a trend towards vertical integration and the outright purchase of suppliers. Perhaps the largest evidence of interplay is in the overturn of personnel, whereby students from academia leave for private industry and government roles. However, an increasing trend shows personnel staying in either academia or industry for a career.

Path dependence for the mass production of silicon photonics is not currently developed as the process development kits (PDKs) are not widely available to support the mass-production of silicon photonics in these foundries. Even if they did, the technologies available in silicon photonics do not create the market demand for high-volume production that would garner foundry interest. This is evident from the lack of foundry involvement in AIM and the lack of a standardized silicon photonics PDK available for microelectronics foundries. With low volume production, it is not possible to generate positive externalities (revenue streams, in the immediate sense) and therefore there is no increasing returns, self-reinforcement, or positive feedback. The technology has also not had the chance to lock-in as the academics develop unique research in exotic materials such as aluminum nitride, lithium niobite, and silicon nitride photonics in place of silicon. Meanwhile, silicon photonics companies hide their own research under trade secrets until the technology can create a marketable product and perhaps patents as seen in Acacia Communications and Infinera. The current influence towards centralized silicon photonics manufacturing infrastructure comes from US Government funding through DARPA (LUMOS) for new technologies and Manufacturing USA (AIM) for manufacturing capabilities and is aimed at mass-production of low-volume military-use integrated photonics. In this sense, academics and private industry are actively working against the original path dependence for their own limited interests. Government investments in new technologies have not yet generated a viable market needed for cheap production of silicon photonics as a marketable product is not their goal, but instead would be a happy side-effect.

A potential new path forward in silicon photonics appears to be in the utilization of silicon photonics for high efficiency data interconnects to support the data centers of technology giants. Intel manufactures these optical interconnects and sells these to select private industry customers. Apple, Facebook, Google, Microsoft, Cisco, and Nvidia have outright bought start-ups specializing in technology related to optical interconnects (including Acacia and Aurrion) towards producing their own communication link and, in the case of Nvidia, have also worked closely with academic collaborators to produce more advanced technologies. These companies seem to be following Infinera's belief in vertical integration for silicon photonics. This is distinctly against the historical path of microelectronics, wherein private foundries separately developed and invested in research towards new applications and technologies which will ultimately benefit the foundries. This new path benefits individuals (both academic and industry) and does not develop a major commercial market. This market further runs counter to silicon photonics development in Europe where IMEC has brought together CMOS and silicon photonics production to a greater degree, but not necessarily to a self-sustaining market. While the European market adequately fulfills its current needs, it does not realize mass production as envisioned by the US Government through its manufacturing initiatives.

To this end, a new path dependence is appearing in the US market for silicon photonics. One direction is funded by private industry for low-volume silicon photonics insertion into select products while Manufacturing USA is trying to fund mass produced silicon photonics infrastructure for primarily military use. This creates a complex future for silicon photonics; mass-production is dependent on creating new technologies to use silicon photonics, but competing forces fund niche markets for unique silicon photonics products. In other words, the US Government is almost solely funding the mass-production facilities for silicon photonics originally envisioned, but they do not yet have the sufficient external market demand to make it financially viable. From this viewpoint, a critical failure can be seen in Manufacturing USA and AIM Photonics. The US government's historical position in developing manufacturing infrastructure for microelectronics has been in taking risk to develop new technologies which might be marketable. AIM Photonics has attempted to force market interest in silicon photonics by funding several conflicting bodies. The program does not have the funding, time scale, or market interest to achieve its goal of a self-sustaining silicon photonics foundry, and most importantly the program is not working in-line with the new path dependence for silicon photonics.

The nature of this study is relatively limited. For one, actual research developments by private industry are not well published and are usually hidden behind products. Similarly, DARPA does not publish detailed records of silicon photonics investments and I was unable to find open literature information. I was able to talk to several academics to establish trends, but many more exist with their own unique research interests and resulting opinions on silicon photonics. For example, my data heavily skews towards interest in optical interconnects (Keren Bergman's research), but I did not interview anyone researching non-linear integrated photonics using non-silicon platforms. I was not able to establish meaningful contact with private industry; Acacia Communications was too busy with recent conferences and Infinera would not respond to emails (in-line with their trade secrets). I also interviewed former DARPA employees and did not establish contact with government employees involved in AIM Photonics. To that end, my work is biased towards the specific views of certain academics. Their opinions are supported by data, but the data may not be exhaustive. A better interview set could have been made with enough time to make connections through, for example, conferences. The interviews were not recorded and instead were reconstructed from notes.

This research will guide my future engineering practice. Seeing the grand scheme of investment in academic research shape both where I will go in my career and the decisions I will make as I enter industry. Funding for research projects often appears arbitrary, but it is rooted in both past decisions and evolving current interests. Seeing the need for a research project can be almost as important as the actual research. In advancing a career, it is necessary to both have work which reflects positively on you while also having the skills to advance new fields as they appear. In particular, I chose to attend a graduate program focusing on quantum engineering because I found the field of photonics overly bureaucratic after completing this paper.

Conclusions

This work shows a clear split in the future direction of silicon photonics. The original sensor-based products have not established the market volume necessary to interest silicon foundries investments. Private industry is investigating silicon photonics for power-efficient data centers through integration with CMOS silicon microelectronics information processing and storage. US Government resources are still being spent on finding technologies useful to their unique needs and ways to mass-produce silicon photonics, but industry demand does not yet exist for this nascent technology.

An expanded study should focus on a more quantitative analysis of all facets of photonics research and the photonics market. Further study needs to be put into the viability and practicality of other photonics platforms (aluminum nitride, lithium niobate, silicon nitride) and their integration into silicon products before locking into silicon photonics technologies. Meanwhile, the expanse of applications in these separate fields must be studied. This research is largely funding-driven, and this funding should be re-focused towards technology which promises both functionality, affordability, and scalability. This analysis has shown that investment exists for industry-focused uses of photonics, but high-volume photonics manufacturing will require a large external investment that must be set in the right direction for success. In a broader scope, the study of industrial research business structures in a post-Bell Labs world would further elucidate the different interactions between government and private industry and the resulting silicon photonics economic market.

In the grander scheme, silicon photonics will not completely replace standard III-V semiconductor devices as it lacks the sufficient range of bandgap engineering for many photonics applications. However, it can support many applications with product development kit availability. Future integration of exotic materials with silicon through heterogeneous integration technologies holds a promising future for silicon photonics.

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Appendix A - Interviews

Dr. Joe Campbell Interview Transcript, January 27th, 2020

Turflinger: Where did the initial interest come for silicon photonics?

Campbell: The money historically came from 2 sources: industry and the department of defense. The big pioneer was Richard Soref from the Air Force Research Lab in the 1980s. He imagined photonic integrated circuits (PICs) and silicon photonic integrated circuits (silicon PICs). Industry and academia didn't pay him much attention as there were no lasers, modulators, or detectors developed for silicon. However, the development of the optical telecommunications industry started the development of these components. Bell labs and Intel had a vested interest in developing integrated circuits which could cheaply interact with their fiber optic communications networks. Despite this development, integrated photonics did not take off until the early 2000s when photodetectors, transceivers, lasers, and modulators were developed on an integrated platform. Even still, these components were not developed in the high density envisioned for silicon photonics until fairly recently. Now, there are many companies with their hands in silicon photonics, some large and some small.

Turflinger: Speaking on the funding you mentioned, where is the funding coming from and where is it going?

Campbell: The government is still investing in integrated photonics. There is currently a request for proposal from the Defense Advanced Research Projects Agency (DARPA) for photonic integrated circuits which provide hundreds of devices and high-performance function on a single wafer. Similarly, the Department of Defense currently has a request for proposal to create tunable microwave sources stable to the attosecond with photonic integrated circuits. There are also programs through the US Navy, Army, and Air Force. In those contexts, the government agencies have a product in mind and source funding for someone to make it happen. This money largely went to academics. In general, the photonic industry has not given large investments to academics as occurred with the electronics industry. A large portion of photonics researchers came from AT&T Bell Labs with their fiber optical communications division. When Bell Labs was dissolved, many of these scientists left for academia which most resembled Bell Labs in terms of work. For example, John Bowers went from Bell Labs to working for the DoD at Honeywell. He then took his connections in the government and started his lab at UC Santa Barbara working on silicon photonics. He has since spawned several startups from the science he has developed in academia.

On the subject of government investment, the American Institute for Manufacturing Integrated Photonics (AIM Photonics) is one of the current driving forces of research. It was funded as a result of a desire for a centralized foundry which can provide integrated photonic devices. With hundreds of millions of funding from both the US government and the state government of New York, the AIM foundry was established at the State University of New York Albany (SUNY Albany) along with around 30 academic partners, including us [University of Virginia]. The effort focused on making a well-documented and widely available platform for integrated photonics with additional support for packaging devices. This has provided a place for both industry and academics to fabricate silicon photonic integrated circuits for their research.

Turflinger: What are some of the private-industry players in integrated photonics?

Campbell: Infinera has created high-level photonic integrated circuits using private investment. They joined AIM, but ironically their foundry and methods are not available outside of the company. They also won't give you the time of day – they operate through trade secrets. I have sat on several conference committees which have refused Infinera presentations as they have previously used academic conference to show product launches rather than science. Acacia also found success using private funding to create an integrated photonics company as a spin-off of Bell Labs in Holmdel, New Jersey. Their initial products used known Indium Phosphide (InP) platforms, then using profits created new products with the same components re-done on silicon. Intel has used its large capital from electronics to invest in creating their own private integrated photonics foundry, but have lagged behind these new smaller companies in terms of innovation and products. Across these, the private industry players in integrated photonics tend to use trade secrets rather than patents. In that regard, private industry tends towards producing technology for profits rather than for science.

On the international front, there is a larger platform for collaboration in the Interuniversity Microelectronics Centre (IMEC) in Europe, which has its own foundries, and investment from semiconductor juggernauts including Taiwanese Semiconductor (TSMC) and Singapore's semiconductor industry. The idea for AIM was largely copied from these.

Turflinger: On that note, how do academics connect to industry?

Campbell: Academics usually get to industry in one of two ways: leaving academics for industry, and usually never coming back, or starting a company on the side with their research. It is very rare for individuals to go from private industry back to research. This largely trends with the focus of academia and industry. In the 80s and 90s, academics shifted their focus even more towards research as companies including RCA, Westinghouse, Xerox-Palo Alto, and IBM created a demand for research scientists. These research-oriented divisions of private industry are largely gone, and academic research now largely stays in universities. In general, modern academia and industry goals are disconnected as academics seeks to produce papers and students while industry seeks to produce products. Academics are able to pay their bills on government contracts and their overheads.

Dr. Keren Bergman Interview Transcript, February 25th, 2020

Turflinger: Where did the initial interest come for silicon photonics?

Bergman: Foundry integrated photonics started a while ago. Initial support in the US came almost entirely from a government push through DARPA and the DoD. Essentially, the field of silicon photonics is so open that no private industry has enough money to invest in the ecosystem. Even still, the ecosystem is far from closing and funding largely comes from government agencies.

Around 5 years ago, the US government pushed for a centralized place for integrated photonics with the AIM Photonics (the American Institute for Manufacturing Integrated Photonics). The funding came almost entirely from the government, both at the federal level and from the state of New York, and the institute is based in Albany, New York. My group [the Lightwave Research Laboratory at Columbia University] was one of the leading academic partners. AIM partially sought to reproduce the centralized structure for foundry fabrication seen in both IMEC and IME. Economically, AIM provided the upfront costs to build the infrastructure for fabricating wafers on an industry scale. They specifically used 300mm silicon wafers, the state-of-the-art in

CMOS (complementary metal oxide semiconductor) fabrication creating the more advanced photonics foundry in the world. Private industry and academics are able to order small portions of a wafer for fabrication, called a multi-project wafer (MPW). AIM's infrastructure has vastly lowered the cost of fabricating silicon integrated photonics for all forms of research and development in the US.

Turflinger: What problems does the manufacturing of silicon integrated photonics face?

Bergman: Most importantly, the infrastructure for packaging is still relatively non-existent. In microelectronics, there is a massive market for both the software to design integrated circuits as well as foundries to produce and package them, but silicon integrated photonics is far too young to have such a streamlined set of tools. To that end, the goal is to get the photonics manufacturing industry to the level of microelectronics and CMOS, but photonics does not have the same massive market that electronics does. Photonics does not yet have the range of applications nor the scalability microelectronics does. For example, there is currently no automated method to align systems of optical fibers and there is not a practical way to integrate lasers with silicon integrated photonic circuits. There is very little automation in silicon integrated photonics fabrication, and consequentially most components are hand assembled. On account of this, the current applications have largely been in the limited market of transceivers.

Turflinger: What other collaborations have you seen in silicon integrated photonics?

Bergman: We currently have a partnership with Nvidia. Nvidia is known for making graphics processing units, but have interest in silicon photonics for future scaling of their systems. They invest in my group both monetarily and with effort from their employees, and my students have also worked at Nvidia on internships and jobs after graduation.

In general, most successful collaborations are partnerships between some combination of the government, a company, and a university. I've seen many start-ups coming from academia. Recently, a start-up came out of Columbia University focusing on LIDAR based on technology they had developed with government funding. A close friend spent time in academia, left to work on silicon photonics at Intel, and has recently left to work on a start-up on silicon photonics technology. John Bowers has produced several start-ups out of his lab at UC Santa Barbara. Many of these start-ups have private funding to start the companies. Before the 2000s, Stera and Infinera are two stand-out examples of companies in integrated photonics.

Dr. Andreas Beling Interview Transcript, February 26th, 2020

Turflinger: Where has the funding been for silicon photonics?

Beling: A lot of the investment at the moment has been in AIM, the American Institute for Manufacturing Integrated Photonics, from a contract starting around 5 years ago. The federal government invested $100 million through the office of scientific research with additional investments from local institutes around New York. The initial proposal had a cohort of industry and academic partners, including us [the University of Virginia]. A process design kit (PDK) was created such that any member could pay for their chips to be fabricated in the "AIM foundry" – the clean room at SUNY Albany. In addition, partners would open their foundries to similarly allow for their chips to be fabricated at other existing facilities. All of the fabrication infrastructure already existed, and some of the money was invested into developing a new packaging facility for these chips in Rochester, NY. In principle, the institute should have been self-sustaining monetarily after the initial investment. Instead, as we near the end of the contract, the packaging facility has not been finished and industry partners have largely stayed out of the institute. It's hard to blame them – why would private industry open their foundries up to competitors? Now the question AIM faces is how to continue with the government funds used up and an unsustainable model.

Some money has also come from DARPA. For example, a recent request for proposal dubbed LUMOS has offered funding for research developing microwave photonics, photonic integrated circuits which operate in the visible spectrum, and gain in silicon-based photonic integrated circuits. It's almost funny – these are fundamental scientific problems which you'd think should have been solved 20 years ago for silicon photonics to continue.

Turflinger: On that note, what has silicon photonics shown versus, say, indium phosphide-based photonics?

Beling: Indium phosphide integrated photonics has been used for decades since it integrates easily with lasers and detectors used in the telecommunications industry. In that respect, it has been argued that the expansion of foundries to 4'' indium phosphide wafers would lower costs for telecommunications more than silicon photonics as the volume of production is very small. Now, of course, it's a different story when you come to the concept of photonic data centers with huge volumes of interconnects to be fabricated. AIM initially claimed they would focus on silicon photonics, but later mixed in indium phosphide wafers to try to increase volume to little avail.

Turflinger: What industry involvement in silicon photonics have you seen?

Beling: Intel has created some silicon photonics products over the past couple of years. They have largely produced products for data communications which have been funded almost entirely by internal research and development funding. They produced some academic papers near the beginning of their foray into silicon photonics. Intel, as well as some other companies including Sun Microsystems, received government funding for research into silicon photonics, but federal funding requires publications and output. To these large companies, they do not want to talk about their research until they have a product to sell.

Some large data companies, including Facebook, Google, Microsoft, and Nvidia, have recently found interest in user-level silicon photonics for their data centers and products. But their interest lies on the user-level, not the device level, and the technology is not fleshed out enough for large investment and interest in this yet.

Infinera was one of the first examples of the recent examples in private integrated photonics industry. Privately funded entirely by the selling of Spectra Diode, they produced indium phosphide based integrated photonics for telecommunications applications. Around 10 years ago, they started to also produce silicon photonics. Infinera has largely functioned through trade secrets and not academic publication – again, they don't want to talk about their technology if they don't have a product to sell. Somewhat similarly, Acacia was founded around 10 years ago and through private investment has created their own market for silicon photonics in data centers. They hired a lead scientist, Chris Doerr, out of academia. I knew Chris and he has largely disappeared since joining Acacia – his publications are largely patent applications and he isn't an invited speaker at conferences anymore.

Turflinger: How has the US compared to the international development of silicon photonics?

Beling: Silicon photonics in Europe has had support from the Interuniversity Microelectronics Centre (IMEC) largely since its inception. They have focused on pilot prototyping new uses for silicon photonics towards commercial applications in Europe. This is quite different from the US where the electronics industry has almost entirely stayed out of silicon photonics. The Institute for Microelectronics (IME) in Singapore has similarly invested in silicon photonics. Out of this, many foundries including Taiwanese Semiconductor and Singapore Semiconductor offer a process design kit (PDK) for fabricating silicon photonic integrated circuits. These are not standardized like they are in microelectronics, however, and are very small in scale. Most importantly, there is still no foundry-available integration of silicon photonics with CMOS circuitry, which was originally the entire point of silicon photonics.

In the US, DARPA's LUMOS hopes to create the push required to get foundries involved. At the moment, foundries are not pushing silicon photonics as there is not a high-volume market for it to be profitable for them yet.

Turflinger: What other roles have you seen academics play in silicon photonics?

Beling: John Bowers at UC Santa Barbara has founded 3 or 4 companies off of his research. The most recent one, Aurrion, produced components heterogeneously integrating silicon photonics with indium phosphide photonics. They were later acquired by Jupiter Networks. One of his older start-ups was acquired by Intel. One similar start-up out of UVa was Face Sensitive Innovations. Most academic interactions with industry are one way – either a professor or their students leaving academia for industry or starting a company and eventually selling it off. Doing both academic research and operating a business together is difficult as the goals are fundamentally different – academia wants research and publications while industry wants a marketable product.

Turflinger: What do you think the bottom line is for silicon photonics in the US?

Beling: Silicon photonics won't happen without a market. In its recent history federal funding has attempted to push that, but it isn't quite there yet. AIM is largely run by the DoD and academics – but where are the industry partners? Academics have their own agendas for pushing their research as important. For example, Mike Watts, a founding partner of AIM and a professor at MIT, owns the company which makes the PDK for AIM's foundry. How is that fair? The SUNY facility used for the foundry was recently built before AIM started – for them, AIM is essentially free funding. To that end, silicon photonics is currently largely academic research pushed by government funding. This won't last forever, and with the recent end of the initial AIM contract hopefully they learned something.

On a different front, other academics are also pushing different photonics platforms for their own uses. A recent invited lecturer here [the University of Virginia], Professor Hong Tang from Yale University, talked about using an aluminum nitride platform for integrated nonlinear photonics. Others are pushing for thin-film lithium niobate and silicon nitride platforms based on their research. While this makes sense in some respect – silicon's crystal structure gives it no nonlinear effects – the different special applications pushed by academics also create diverging interest in scaling a single platform like silicon.

Towards scaling, the question is how many foundries do we need? We want a result like CMOS microelectronics, but the market is not developed like that yet. At the moment, we do not see industry investments in academics with their own money. The most we have seen is industry passing on government funding to us.

One recent attempt at a large industrial partner has been Huawei, who has bought several labs and companies in silicon photonics in Europe. Their current ban in the US has prevented further spreading though.

Dr. Jagdeep Shah, Dr. Robert Leheney, and Dr. Daniel Radack Interview, March 30th, 2020

Turflinger: Where did the government's early interest in silicon photonics come from?

Shah: In the Early 2000's, I proposed DARPA's first major project in silicon photonics. My argument in the proposal was that silicon is not a "good" photonic material, but the infrastructure based on it allows for the integration of electronics and optics. At first, it wasn't clear if you could make high performance components in a commercial fabrication facility on silicon. The initial funding was put in place to produce high quality devices to allow for the eventual realization of silicon photonics systems.

Leheney: One of DARPA's first interests in silicon photonics was interconnects for high performance computing. This interest pre-dated silicon photonics back to the 1970s. The DoD was interested in any way for computers to work more efficiently. For example, there was interest in replacing heavy coaxial cable systems in aircraft with light fiber. Unfortunately, this still hasn't happened.

Radick: The answer might be different for other government funders including the National Science Foundation, Department of Energy, and others, but DARPA usually provides the most government funding for technological developments. Initial investments in photonics sought to make better laser telecommunication devices and miniaturize solid-state technologies in networks and aircraft. This included a large amount of investments for higher bandwidth and lower loss components. With silicon photonics, the thought was advances in semiconductors and processing could overcome the material limitations of silicon.

Turflinger: How does the government see their advancements in technology connecting to academic research and industry?

Leheney: Every dollar invested by the government was in the belief that a useful technology would come out of it. There is a problem in that academics and their research outcomes do not necessarily convert to manufacturing capabilities. These technologies have to enter the marketplace at some point. The market's goal of getting the promised performance at a price point where the market runs with it is not necessarily in-line with the government's interest in the performance of technology.

Radack: To DARPA, research leads to potential applications in a military system. There are several answers why such technologies don't work in a market. There needs to be more technology beyond an academic paper – in the case of silicon photonics, this includes design tools and packaging.

Turflinger: Where do you see industry playing a part in all of this?

Leheney: There are three groups. One is the industrial base of defense contractors. These obviously pay lots of attention to DARPA's interest. Another is small businesses who have low research funding. They are attracted to the fact that DARPA doesn't take ownership of a technology like a company would, although they do take intellectual property. Finally, there are large companies, including Intel, Google, formerly Bell Labs, IBM, and others, who at least formerly had many smaller and less funded internal research groups. These groups were able to take government money to expand to technologies beyond their internal role. For example, I invested in a small group at IBM who focused on transistors to make silicon germanium semiconductors. These were useful in radio-frequency applications which IBM did not have interest in, but the group was able to use our funding to expand IBM into this field.

Radack: DARPA funds critical mass experiments. They try to stay a couple steps ahead on real problems towards advancing understanding for the community. This appears at conferences and similar which indirectly benefits private industry when they see these results – in essence DARPA is providing funding for risk. More recently, DARPA has funded IR Las to produce integrated photonics for light detection and ranging (LIDAR).

Leheney: In general, DARPA’s philosophy is to have program managers, with expertise in different technologies, find and propose areas that need investment. The difficult step in this is transitioning to a commercial market – most DARPA projects fail at this, but it is not their goal.