SILICON PHOTONICS
THE STATE OF THE ART

Edited by

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To Alison, Hannah and Matthew for making it all worthwhile.
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Foreword

Civilized society has traditionally measured progress by the materials used to fashion structures and implements. However, the Ages of Stone, Bronze and Iron have now been followed by the Information Age where bits are the implements and knowledge is the product. During the last decade, silicon photonics has emerged as a viable alternative to compound semiconductor materials platforms and as the only solution to mega-unit volume manufacture of photonic integrated circuits. A twenty-year gestation period for novel research concepts to become pervasive commercial products is typical. With silicon photonics scheduled for high-volume market applications in the 2010–2015 window, products and advanced prototypes have already entered the market. Now, more than ever before, is the time to document the science and technology for a knowledge base to launch the new era.

The Information Age is progressing in four consecutive phases of development: telecommunication; computation; imaging; and learning. In the telecommunication phase, smoke signals became Morse code telegraphy, then copper-based, analog voice transmission, and finally digital voice/video/data content. The emergence of digital electronics in the computation phase drove early electronic switching for voice, and later massive bandwidth demand for data communication. As the imaging phase began, the advent of image communication with the World Wide Web created further bandwidth demand. The learning phase is incubating with interactive computation and imaging activities that drive even higher bandwidth requirements, and that will ultimately eliminate software with neural architectures of distributed information and adaptive intelligence.

The hallmark of the Information Age has been unparalleled growth in both content and components. About thirty years ago, I attended a strategy session of my employer, AT&T Bell Laboratories. The question under consideration was whether optical fiber transmission media would ever be commercially viable. After considerable comparison of various figures-of-merit, the decision was that the current transition for twisted-pair copper to coaxial cable would more than account for the anticipated growth in the voice market (now known as POTS, ‘plain old telephone service’). The analysis was correct, but we did not ask the right question. In 2000, twenty-five years later, a joint MIT–industry team founded the Communication Technology Roadmap, http://mph-roadmap.mit.edu, to consider the technology supply chain issues that were created by the enormous growth of telecommunications and the limits of component supply and performance. The erbium-doped fiber amplifier had enabled an information capacity scaling of optical networks with wavelength division multiplexing (WDM) to provide for ten years of growth before the year had ended. The inconsistencies of the network-build cycle time, the technology-development costs and the consequent need for consolidation among the >700 companies with product offerings that once were served by one company led, by the end
of the next year, to the ‘bursting of the telecom bubble’. Demand for components disappeared with bandwidth in excess; hardware became a commodity; and tens of thousands of optical communications specialists had no place to practice. Would we ask the right question this time?

History suggested that the proper question should be (to paraphrase Tolstoy), ‘How much bandwidth does a person need?’ The best subject for analysis was a typical teenaged student who was reported to be watching television, talking on a cellphone, working on a computer, playing a digital game and when asked ‘What are you doing?’, replied ‘My homework!’.

A quick calculation showed that one megabit-per-second could exceed all of the data needs of this individual. We quickly realized that we had asked the wrong question again. A new transformation had occurred. People were not the only consumers of information; machine-to-machine communication for commerce and data storage was dominant. This change in network use drove demand for ‘shorter-reach’ bandwidth at the network edge. Premium ‘long-haul’ services had become a commodity, and the new communication value point was with servers and storage.

The first release of the Communication Technology Roadmap in May of 2005 posted as its primary conclusion,

Photonics technology will be driven by electronic–photonic synergy and short (<1 km) reach interconnection. This direction will ignite a major shift in leadership of the optical component industry from information transmission (telecom) to information processing (computing, imaging).

The lesson of the Information Age has been that the best measure of progress is the rate of change. The telecom, optical component paradigm is customized, discrete components with fiber ‘pigtails’ and a total addressable market that peaks at a few hundred thousand units per year. The new need is tens of millions of standardized components per year with low cost and high functionality that is enabled by large-scale integration. As an example, one server machine in 2010 will deliver 6 PFLOP ($6 \times 10^{15}$ floating-point operations) performance that is enabled by the parallelism of interconnected computational units. One such server cluster will require $\sim2.5$ million optical interconnects at 10 Gb/s with a budget of $20–40M$ for optical transceivers. The optical transmission needs of a single data center dwarf the earlier vision for telecom. This emerging demand for high-volume production at low cost of standard components with integrated functionality is the demand pull for silicon photonics.

The mere existence of a ‘state of the art’ for silicon photonics is both logical and illogical. The commercial success of fiber optic communication systems is based on the transparency of silica (SiO$_2$). Planar lightguide circuits (PLCs) based on doped-silica waveguides were the first stage of transformation of fiber optics to a planar platform. It would seem natural to exploit the materials compatibility of the Si/SiO$_2$ materials systems for photonics, since many of the planar processing issues have already been solved for electronic integrated circuit chips. In addition, silicon presents a high-thermal-conductivity substrate; it is transparent at $\lambda = 1550$ nm; and its refractive index can be actively modified by free-carrier injection or temperature change; and it has a high refractive index ($n = 3.5$) that enables scaling to dimensions of $\lambda/n$ ($\sim500$ nm for silicon waveguides).

However, silicon photonics is a misnomer to those specializing in active photonic devices: light emitters, photodetectors, modulators; since silicon has an indirect gap band structure that offers weak interaction between electrons and photons. In addition, the design principles of the highly successful fiber platform are based on optimized single devices and materials
diversity... the diametric opposite of the materials and process integration mindset of CMOS circuit design and fabrication. Now the perennial question of electronics has been transposed to photonics: ‘Will silicon, once again, render III–V compounds to being the materials of the future?’

Has photonic technology advanced on the silicon platform? This question is a good one, and it can be answered affirmatively. The chapters in this book’s presentation of the state of the art document that progress. If the driver for silicon photonics is high performance/cost enabled by monolithic device integration, then the key metrics to follow are speed, power and footprint. The high index contrast of the Si/SiO2 materials system allows record reduction in photonic device footprint with new performance achievement. Micrometer-dimensional silicon ring resonator devices provide optical filter response with wide (>20 nm) free spectral range (FSR). Monolithic, waveguide-integrated germanium photodetectors convert 1550 nm light to electrical current with >95% quantum efficiency and >10 GHz bandwidth, simultaneously. Optical modulators have been reduced to small sizes whose low capacitance dissipates record low power. Integrated data links have been created in low-cost, CMOS technology process flows. These demonstrations are creating a standard set of materials, processes, and design/fabrication tools. With photonic capability throughout the interconnection hierarchy, from chip to board to box, the effortless parallelism of optics has become an architectural necessity. As the electronic chip industry encounters scaling roadblocks in power density, bandwidth and latency, a realization is emerging that integrated silicon photonics is the only option for continued exponential increase in chip performance with time. For server cluster interconnection the expectations are low cost, low power, less space/Gb/s, lower shielding costs, and improved cable management.

Where does silicon photonics face its most difficult challenge? This is also a good question, and its answer could determine the ultimate viability of a commercial silicon photonic technology. Practitioners of the seminal III–V materials platform would answer that an efficient light emitter is missing. Those from the silicon electronics side would ask for more standardization in design and processing. One can envision a discrete optical power supply chip that provides photons to photonic integrated circuits in the same fashion that electrical current is supplied to electronic chips. It is clear that wavelength division multiplexing is critical to the performance advantage of optics over electronics for short-reach applications. The optical power supply of the future will deliver greater than fifty wavelengths of light for WDM and pulses of light for global synchronization. The materials platform for this optical power supply will be determined and implemented within the next decade.

How important is the standardization barrier? Standardization is critical for component vendors to grow the market, and it is critical for the silicon platform to achieve economies of scale. The first release of the Communications Technology Roadmap described a photonics component industry dynamic that has since been dubbed ‘the death spiral’. The scenario goes as follows. Faced with a decreasing sales volume, Company A attempts to secure its near-term viability by customizing products for a current customer. The rationale is that at least that customer will be secure, because Company A is the only source for the customized component. A byproduct of this strategy is that the rest of the market has not designed for that particular customization, and the total addressable market for that product from Company A decreases. Revenues decrease; investment in research and development decrease; and competitiveness to participate in the next generation of technology is decreased. The only way to win through customization is to increase the variety of product offerings and lose the economies of scale.
Standardization leads to consolidation of the industry to a smaller number of vendors in the short term, but to a healthier industry in the long term. Customization (proliferation of variety in product offerings) leads to the ‘death spiral’ for which each company’s total addressable market decreases in the short term with consequent decreasing revenues, research and new products. If the silicon photonics platform becomes ubiquitous, as it has for electronics, it will offer a common set of components that will serve not only one application, but multiple applications in multiple markets.

Standardization of the silicon photonics platform is essential. An integrated circuit chip represents >$100M in development costs that must be recovered by rapid deployment to the market with high volume sales. The low-cost manufacturing infrastructure for silicon chips requires that a standard set of tools and processes be employed. Mere substitution of silicon for the diversity of materials used in the optoelectronics industry is not a viable option. The huge investment over the past two decades in silicon fabrication knowledge and infrastructure must be leveraged to give silicon photonics a scalable advantage in both factors of the performance/cost metric.

What are the performance metrics for success? Electronic–photonic convergence is the technology train on which the emergence of silicon photonics is riding. Power efficiency, bandwidth, latency, footprint and functionality create the systems performance boundaries. The critical devices for an integrated microphotonic chip are the waveguide, the modulator and the photodetector. High index contrast is essential for electronic–photonic convergence to enable dimensional scaling to >10^6 devices/chip. The Si/SiO₂ system gives a refractive index ratio of 3.5/1, the highest index contrast ever employed in a photonic integrated circuit. An operating wavelength of \(\lambda = 1550\) nm is ideal for this system, because it is transparent, because germanium photodetectors and modulators are capable and compatible and because it conforms to the silica fiber transparency minimum. For electronic–photonic circuits of high complexity, silicon waveguides should operate with propagation loss \(\sim 0.1\) dB/cm. Waveguide-integrated germanium photodetectors exhibit the best performance of any comparable optoelectronic device at 1550 nm. The small size, capacitance and transit distance of the device enable high speed at low applied voltage. The capability of controlled evanescent coupling of light from the waveguide to the detector (absorption along the detector length) yields an extended spectral width for photodetection at theoretical responsivity (\(\sim 1.2\) A/W). For the most demanding, next-generation applications, the waveguide-integrated photodetector should deliver a bandwidth \(\times\) external quantum efficiency \(\sim 75\) GHz. The optical modulator is the most power demanding of the integrated optoelectronic devices. Mach–Zehnder interferometric devices are large with high capacitance and high power dissipation. Ring resonator devices are small, but they must be tuned for wavelength stability. Waveguide integrated electro-absorption devices offer the best combination of small size and spectral stability, but insertion loss must be carefully managed. For advanced computational and imaging applications, the waveguide integrated modulator should be capable of \(3dB\) bandwidth >25 GHz, with a switching power <150 pJ, with an extinction ratio >5.

Silicon photonics enables electronic–photonic convergence. This new functionality is not simply breaking the bandwidth barrier. It is design freedom for the information appliance. It enables a distributed footprint with minimal latency penalty. It is freedom from electromagnetic interference. It is design simplicity, aesthetics and new form factors. It is power efficiency and enhanced connectivity through WDM. Two essential topics are not covered in this state-of-the-art compendium, because no known solutions exist. They are chip packaging and integrated