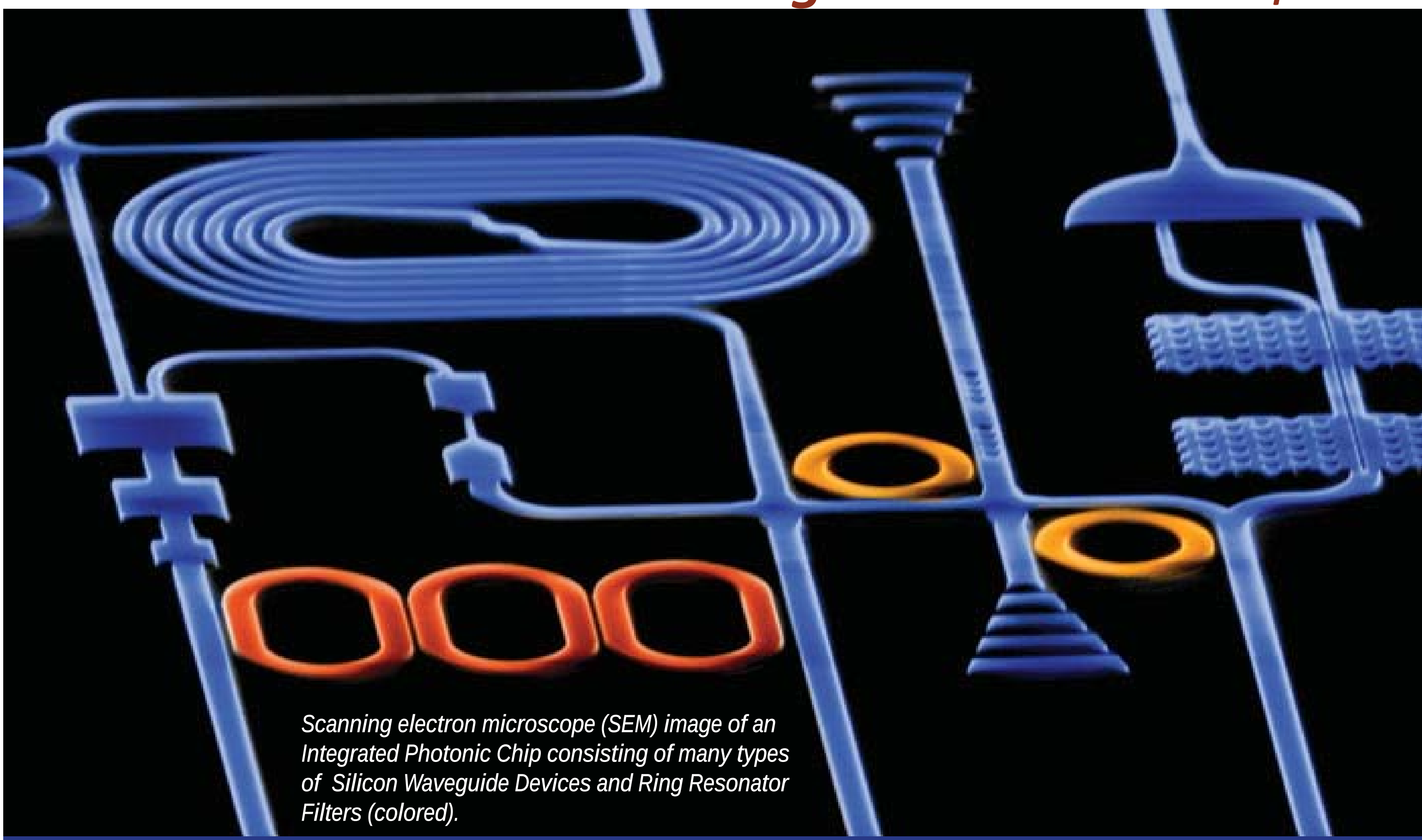
THE Rochester Engineer

PUBLISHED BY
ROCHESTER ENGINEERING SOCIETY

www.roceng.org

SEPTEMBER 2015

The Next Revolution: Integrated Photonics | 6



Scanning electron microscope (SEM) image of an Integrated Photonic Chip consisting of many types of Silicon Waveguide Devices and Ring Resonator Filters (colored).

Also in this Issue:

TheLimitedMonopoly.com
Website Launched
| 17

The Next Revolution: Integrated Photonics

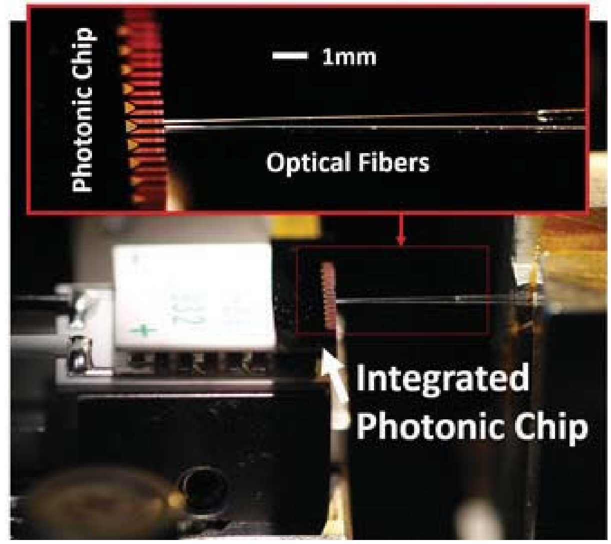
by Stefan Preble, Microsystems Engineering, Kate Gleason College of Engineering, RIT

The recent establishment of the American Institute for Manufacturing Integrated Photonics (AIM Photonics), headquartered in Rochester, will bring the nation's leading companies, universities and federal research institutions together to realize the scalable manufacturing of integrated photonic circuits. The institute will leverage the rich history of optics and imaging in Rochester and its skilled workforce to lead to a bright future where photonics is as commonly used as electronics. However, what exactly is integrated photonics and what are its applications? Here an overview is given by Professor Stefan Preble, director of the Nanophotonics Group and faculty of the Microsystems Engineering Program at the Rochester Institute of Technology.

Integrated Photonics is the intersection of microelectronics and photonics. Microelectronics has been the driver of technology and the world's economy for several decades. Its success is a direct result of the integrated circuit where billions of electrical components (transistors, wires, resistors, capacitors, etc.) are seamlessly integrated together on silicon wafers using manufacturing processes that have followed the scaling trends of Moore's law. Photonic technologies are now at a point similar to where microelectronics was at in the early 1970's - where just a relatively small number of components were tediously integrated together. However, by leveraging the manufacturing equipment and techniques that made microelectronics a success, it is now beginning to be possible to realize the same economies of scale to make integrated photonic circuits. Furthermore, since similar manufacturing technologies are being used, photonics and electronics can be directly integrated together to make both the electronic and photonic elements of the circuits function better - not only reducing size, weight and power but enabling entirely new applications, many of which have not been envisioned.

In order to understand integrated photonics a general overview of photonics is needed. Photonics is the study of the generation, manipulation and detection of light. Light is made up of photons, similar to how electric current is made up of individual electrons. However, photons have the distinct advantage that they travel at the speed of light and don't consume any power during their propagation. For example, photons routinely travel across the entire universe (albeit after approximately thirteen-billion years) with just the energy required to initially produce them. Photons are also very efficient information carriers. They are an electromagnetic wave (just like a radio wave) that oscillates at very high frequencies, on the order of 200 THz (200×10^{12} Hz), and as a result can easily encode terabytes/second of information in their amplitude, phase and/or polarization.

There have been many platforms for photonics over the decades, such as fiber optics where discrete components (lasers, the actual fiber optic cable which transmits light, and detectors) are separately manufactured and put together. In the 1990's the first steps towards integrated photonics were made with the development of planar lightwave circuits (PLCs), based on glasses that are patterned using photolithography or directly written by modifying the material



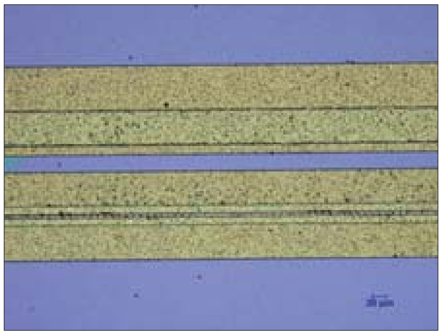
Integrated Photonic Chip Connected to Two Optical Fibers [Source: RIT & Michael Fanto, Air Force Research Laboratory]

using lasers. PLCs are still commonly used today and allow light to be guided and manipulated to interfere with itself, enabling switches and filters. However, the PLC platform illustrates the challenges of realizing truly integrated photonics. Specifically, the large size of the glass waveguides limits the ability to scale the circuit's complexity (because of the limitations of total internal reflection) and more importantly, it is challenging to integrate the lasers and detectors on the same PLC chip because of the dissimilar material and manufacturing platforms.

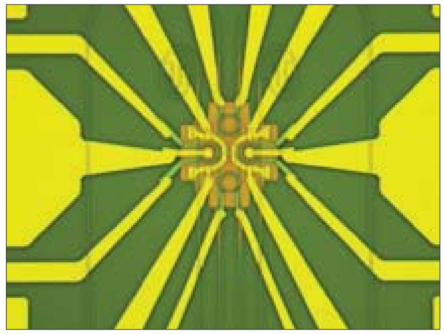
In the early 2000's the promise of silicon as an integrated photonics platform emerged. It is ideal for manufacturing since silicon wafers are also used to make the vast majority of integrated electronic circuits. Early on though it was not clear how well silicon would work for photonics - but after multiple breakthroughs over the past decade it's proven to excel at controlling light. Specifically, silicon is excellent at guiding light in "photonic wires", known as waveguides (fiber optics are another type), because it has a very high refractive index (n~3.5) that tightly confines light (due to the scaling of wavelength by the refractive index of a material $\lambda_{waveguide}$- λ/n) and easily supports total internal reflection - even for a ~90 degree bend.

Consequently, it is possible to realize very complex integrated photonic circuits that are now rapidly growing in density. Furthermore, silicon is transparent at the same wavelengths used for fiber optics (λ ~1300-1600nm), enabling direct interfacing of silicon photonic chips with optical fibers, which is key for many applications. However, for silicon to be the integrated photonics platform of the future, it also needed the ability to generate, control and detect light.

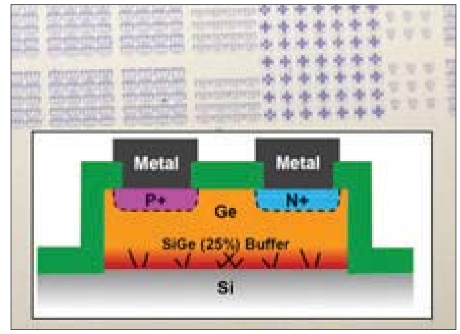
Silicon itself cannot generate light because it is an indirect bandgap semiconductor, which means that it produces *phonons* (heat)



III-V Laser on Silicon
RIT & Wei Guo, U. Mass. Lowell



Silicon Electro-Optic Modulators
RIT

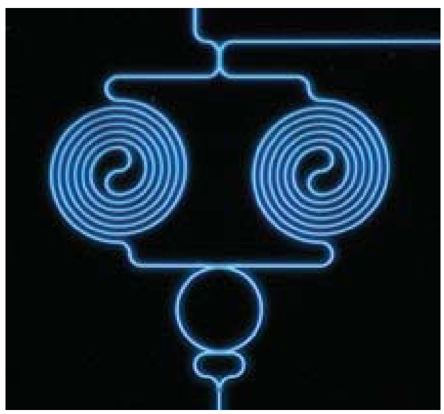


Germanium Photodetectors
RIT & SEMATECH

instead of *photons*. In contrast, many III-V semiconductors (named from the groups on the periodic table), such as GaAs and InP, are direct bandgap semiconductors and can easily be made into lasers. Fortunately, it is now cost effective to bond III-V lasers directly onto silicon through advances in manufacturing technology. III-V's can also be used to detect light but the most commonly used detector material is germanium because it is straightforward to grow on silicon and is already used to make silicon transistors operate faster while using less power.

It is also now possible to actively encode information on light by combining photonics and microelectronics. Light is sensitive to the same electrons and holes that microelectronic devices excel at controlling. Specifically, free-carriers change the refractive index and absorption of silicon. As a result, by combining silicon photonic waveguides with PN diodes it is possible to change the transmission of the light electrically. These electro-optic modulator devices are now able to switch the light on/off at staggeringly high rates of >40gigabits/second, while using incredibly low amounts of energy of <1femtoJoule and has the potential to approach the same energy used by just a few state-of-the-art transistors.

It is clear now that silicon photonics will be able to realize very complex photonic circuits. In just the last few years the number of devices that have been integrated together has rapidly grown to over ten-thousand, and the natural application of these integrated photonic circuits is high bandwidth communications. Particularly, since data centers are expected to consume a few percent of the entire power generated in the United States and a vast majority of that power usage is used to simply move data around. Consequently, the integration of all of the previously used discrete components onto silicon photonic chips will yield dramatic reductions in power along with orders of magnitude improvements in bandwidth. This revolution is really akin to the improvements seen in computers, where cell phones now have the same performance as the discrete-component supercomputers that took up entire warehouses decades ago.



Silicon Photonics for Quantum Computing [RIT & Air Force Research Laboratory]

Silicon photonics is also likely to lead to many new applications, some of which can be imagined now. Circuits are already being developed for processing analog radio-frequency signals, particularly for the frequencies ranges that are difficult to control electrically (~GHz – THz). These are likely to yield ultra-stable oscillators, analog communication systems or high sensitivity Terahertz imagers (like the ones currently used in airports but with improved sensitivity). It is also possible to steer light beams emitting from the chip by controlling the relative phase of the light (e.g. phased arrays), which will be particularly useful to robotics or self-driving cars. Photons can also be used to realize sensors, which when implemented with other biological or chemical technologies, can be used to detect minute changes in the environment, which will benefit fields from healthcare to security. And one of the ultimate goals of photonics has always been to realize an optical computer. While this still remains very far off due to limitations of photons (they do not interact strongly with each other), there are future computing technologies that photons may benefit, such as, quantum computing.

It is clear that the benefits of integrated photonics are enormous – particularly once the technology fully adopts the scalable manufacturing that made integrated electronics so successful. However, challenges remain - the biggest being the ability to cost effectively package photonic chips. Packaging currently accounts for most of the cost because optical fibers must be precisely positioned to the waveguides using time consuming procedures. However, solutions based on microfabrication are now being realized and will dramatically improve packaging throughput and realiability.
As a result it is likely that integrated photonics will yield its promise and become ubiquitous in the coming future.

As the integrated photonics efforts in the Rochester Region grow, there will be tremendous opportunities for research, innovation, education, and commercialization. Partnerships in the engineering community are being established through the NY universities (RIT, UR, and SUNY Polytechnic Institute), various regional industry groups, and professional engineering societies (like the RES, the IEEE Photonics Society, the IEEE Electron Device Society, and the OSA), which will ensure a variety of opportunities for involvement.

Stefan Preble is an Associate Professor at the Rochester Institute of Technology in Microsystems Engineering and Electrical & Microelectronic Engineering.