White Paper
Research at Intel

A Hybrid Silicon Laser

Silicon photonics technology for future tera-scale computing

Mario Paniccia
Director, Photonics Technology Labs
Victor Krutul
Director, Photonics Technology Strategy
Richard Jones
Senior Optical Researcher
Oded Cohen
Senior Process Development Engineer
Intel Corporation

John Bowers
Professor, Electrical & Computer Engineering
Alex Fang
Electrical & Computer Engineering
Hyundai Park
Electrical & Computer Engineering
University of California, Santa Barbara

Introduction

On September 18, 2006, Intel and the University of California, Santa Barbara (UCSB) announced the demonstration of the world's first electrically driven hybrid silicon laser. This device successfully integrates the light-emitting capabilities of indium phosphide with the light-routing and cost advantages of silicon. The researchers believe that with this development, silicon photonic chips containing dozens or even hundreds of hybrid silicon lasers could someday be built using standard high-volume, low-cost silicon manufacturing techniques. This development addresses one of the last hurdles to producing low-cost, highly integrated silicon photonic chips for use inside and around PCs, servers, and data centers.

This paper explains how the hybrid silicon laser works, how it is a key enabler for silicon photonics, and how the resulting integrated silicon photonic chips could someday enable the creation of optical "data pipes" carrying terabits of information. These terabit optical connections will be needed to meet the bandwidth and distance requirements of future servers and data centers powered by hundreds of processors.

The Announcement

The demonstration of the first electrically pumped hybrid silicon laser addresses one of the last remaining obstacles of integrated silicon photonics—namely, developing a low-cost light source on silicon. Previously, getting laser light to a silicon photonic chip was done using one of two approaches: attach and align individual prefabricated lasers directly to a silicon waveguide or have a high-powered external laser source placed off the chip and then route the light into the silicon chip using an optical fiber. Both approaches are expensive and not practical for high-volume production.

This new laser is termed "hybrid" because it combines two materials: silicon and an indium phosphide-based material. The indium phosphide-based material is a compound semiconductor that is widely used today to produce commercial communication lasers.

There are two key aspects to this development:

- A novel design that uses an indium phosphide-based material for light generation and amplification bonded to a silicon waveguide that forms the laser cavity and determines the laser's performance.
- A unique manufacturing process that creates a "glue" that fuses these two materials together. This glue layer is a mere 25 atoms thick.

In this process, the indium phosphide-based wafer is bonded directly to a pre-patterned silicon photonic chip. This bonding does not require alignment of the indium phosphide-based material to the silicon waveguide chip. When a voltage is applied to the bonded chip, the light generated from the indium phosphide-based material couples directly into the silicon waveguide, creating a hybrid silicon laser.

This bonding technique can be performed at the wafer or die level, depending on the application, and could provide a solution for large-scale optical integration onto a silicon platform.

Silicon Photonics Overview

Silicon is the principal material used in semiconductor manufacturing today because it has many desirable properties. For example, silicon is plentiful, inexpensive, easy to work with, and well understood by the semiconductor industry. Intel, in particular, has developed some of the most advanced silicon fabrication technology available today. Due to the company's leadership in this area, it has long invested in research to "siliconize" other technologies, such as optical communications. This field—known as silicon photonics—aims to provide inexpensive silicon building blocks that can be integrated to produce optical products that solve real communication problems for consumers.

Silicon is an especially useful material for photonics components due to one key property: it is transparent at the infrared wavelengths at which optical communication operates. Therefore, while silicon is opaque to the human eye, it appears clear as glass to a laser operating at infrared wavelengths.

The hybrid silicon laser announcement[1] builds on our previous research, namely the first demonstration of an optically pumped hybrid silicon laser[2] in 2005, and the first demonstration of continuous-wave optically pumped operation[3] in 2006.

The announcement also builds on Intel's other accomplishments in its long-term research program to siliconize photonics using silicon and silicon manufacturing processes. In 2004, Intel researchers were the first to demonstrate a silicon-based optical modulator with a bandwidth in excess of 1GHz. In 2005, researchers demonstrated data transmission at 10Gbps using a silicon modulator. Also in 2005, Intel researchers were the first to demonstrate that silicon could be used to amplify light, and they produced a continuous-wave laser on a chip based on the Raman effect. In 2006, Intel researchers demonstrated world-class performance in silicon-germanium photo-detectors.

The Silicon Laser Challenge

A key challenge facing the silicon photonics community is a fundamental physical limitation of silicon: namely, silicon cannot efficiently emit light. While it is capable of routing, modulating, and detecting light, silicon has needed an external light source to provide the initial light.

These external light sources are generally discrete lasers and require careful alignment to the silicon waveguides. The problem is that accurate alignment is difficult and expensive to achieve. Even submicron misalignment of the laser to the silicon waveguide can render the resulting photonic device useless.

A long-standing quest in silicon photonics has been the creation of a laser source that can be manufactured directly on the silicon photonic chip, in high volume, and whose emitted light is automatically aligned with the silicon waveguide.

To solve this problem, Intel has partnered with Professor John Bowers at UCSB, who has more than 25 years' experience working with indium phosphide-based materials, lasers, and other compound semiconductor materials. During the past few years, he has developed a variety of novel photonic devices, including very high-speed lasers, modulators, and photo-detectors. Also, he has integrated them in advanced transmission systems at data rates as high as 160Gbps. In parallel, he has been developing wafer-bonding techniques to enhance the performance of these materials.

The Hybrid Silicon Laser

Figure 1 is a cross-section of the hybrid silicon laser, showing the indium phosphide-based gain material (orange) that generates the laser light bonded on top of a silicon waveguide (gray).

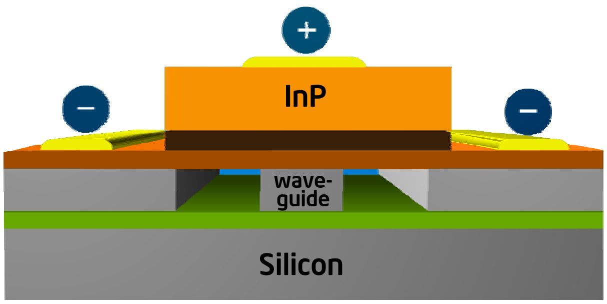

Figure 1. Cross-section schematic of a hybrid silicon laser.

The silicon substrate, which is marked in gray at the bottom of Figure 1, is the base upon which the other items are placed. On this substrate rests the silicon waveguide. Both the substrate and the waveguide are manufactured using standard silicon fabrication processes.

Both the silicon wafer and the indium phosphide-based wafer are then exposed to an oxygen plasma, which leaves a thin coating of oxide on each of the two surfaces that acts as a glue layer. The oxide layer is only 25 atoms thick, yet it is strong enough to bond the two materials together into a single component.

The oxygen plasma that is used for this layer is similar in concept to the plasma used in fluorescent light bulbs and modern high-definition plasma TV screens. Plasma is a gas that has been electrically charged. While fluorescent bulbs are based on plasma that derives from neon or argon gases, the hybrid laser relies on oxygen plasma to coat the components and make them bond.

When the silicon and the indium phosphide-based material are heated and pressed together, the two oxide layers fuse them together.

Electrical contacts, shown in yellow in Figure 1, are then patterned onto the device. As shown in Figure 2, when a voltage is applied to these contacts, electrons flow from the negative contacts toward the positive contact. When these electrons encounter holes in the semiconductor lattice, they emit a photon (a particle of light). The ability to generate light this way is a property of indium phosphide and other compounds (known as direct bandgap semiconductors). Silicon is a poor light emitter because it generates heat, instead of light when electricity is applied—hence the need for the indium phosphide-based material.

As shown in Figure 2, the light generated in the indium phosphide-based material passes directly through the glue layer into the silicon waveguide below, which acts like the laser cavity to create the hybrid silicon laser.

The design of the individual silicon waveguides is critical to determining the performance of the hybrid silicon laser, and will allow future versions to be built that generate specific wavelengths.

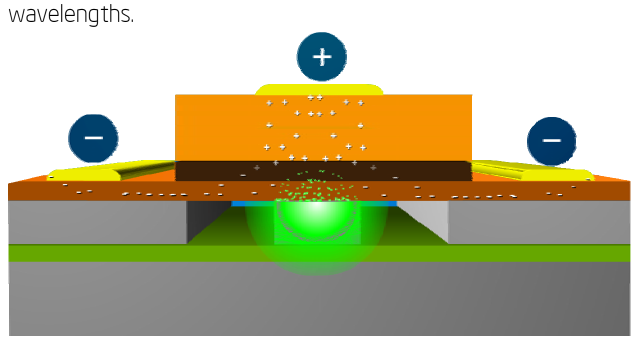

Figure 2. When voltage is applied to the contacts, current flows, and the electrons (-) and holes (+) recombine in the center and generate light.

Benefits and Potential Applications

The principal benefit of the hybrid silicon laser is that silicon photonics components no longer need to rely on aligning and attaching discrete lasers to generate light into a silicon photonic chip. In addition, dozens and maybe even hundreds of lasers can be created with a single bonding step. This has several advantages:

- The laser is compact so it allows many lasers to be integrated onto a single chip. This first demonstrated hybrid silicon laser is only about 800 microns long. Future generations will be significantly smaller.
- Each of these lasers can have a different output wavelength by simply modifying the silicon waveguide properties without having to modify the indium phosphide-based material.
- The materials are bonded with no alignment and are manufactured using high-volume, low-cost manufacturing processes.
- The laser is easy to integrate with other silicon photonic devices to produce highly integrated silicon photonic chips. An example of this is shown in Figure 3.

Figure 3 shows what a proposed terabit integrated optical transceiver could look like. It consists of a row of small, compact hybrid silicon lasers, each generating laser light at a different wavelength (color). These different wavelengths are then directed into a row of high-speed silicon modulators that encode data onto each of the different laser wavelengths. An optical multiplexer would combine these individual data streams together into one output fiber. One of the benefits of optical communications is that all of these signals can be simultaneously sent down a fiber without interfering with each other. If 25 hybrid silicon lasers were integrated with 25 silicon modulators, each running at 40Gbps, the result would be 1 terabit per second of optical data transmitting from a single integrated silicon chip.

With this highly integrated silicon photonic transceiver, it is possible to imagine a future world in which most computing devices are endowed with high-bandwidth optical connectivity. Be they servers, desktops, or smaller client devices, all devices will have access to substantially greater bandwidth at a lower cost.

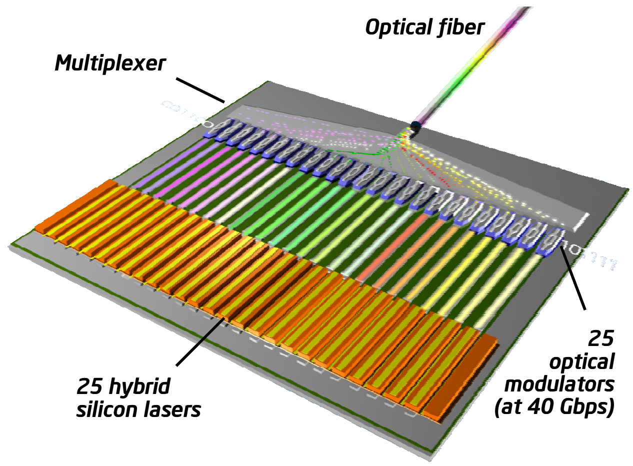

Figure 3. Concept of a future integrated terabit silicon optical transmitter containing 25 hybrid silicon lasers, each emitting at a different wavelength, coupled into 25 silicon modulators, all multiplexed together into one output fiber.

An integrated photonic chip, like the one shown in Figure 3, is expected to play an important role in the Intel® Tera-scale Computing Research Program, which seeks to leverage multi-core processing by keeping all processor cores as busy as possible. Given the high capacity of these cores and the plans to place 10s to 100s of cores into one future chip, the data demands will be substantial. As a result, tera-scale servers might one day require optical communication to deliver the bandwidth and large volumes of data needed for processing with multiple cores. A key technology for enabling optical communication could be silicon photonics—with the hybrid silicon laser playing a central role.

Summary

Intel is actively continuing its research work in silicon photonics in the hope of building smaller, faster, and less expensive optical components that fulfill the goal of universal, ubiquitous, low-cost, high-volume optical communications. The announcement from UCSB and Intel demonstrating the first electrically powered hybrid silicon laser is another example of progress toward this overarching goal. The research collaboration has been able to successfully combine the light-emitting capabilities of indium phosphide and the light-routing capabilities of silicon. The researchers believe that with this development, silicon photonic chips containing dozens or even hundreds of hybrid silicon lasers could someday be built using standard high-volume, low-cost silicon manufacturing techniques. This development addresses one of the key hurdles to producing low-cost, highly integrated silicon photonic chips for use inside and around PCs, servers, and future data centers.

Acknowledgements

The authors would like to Kevin Teixeira, Manny Vara, Russ Hodgin, and Sean Koehl for contributions to this whitepaper. UCSB and Professor Bowers would like to thank Dr. Jag Shah and DARPA for funding this research.

Learn More

Find out more about the hybrid silicon laser.
www.intel.com/research/platform/sp/hybridlaser.htm

Silicon Photonics.
www.intel.com/go/sp

Professor John Bowers' research and UCSB.
www.ece.ucsb.edu/uoeg

The Intel® Tera-scale Computing Research Program.
www.intel.com/go/terascale

References

1. "Silicon Evanescent Lasers and Amplifiers," J.E. Bowers, Alexander W. Fang, Hyundai Park, Richard Jones, Oded Cohen, Mario J. Paniccia, 2006 IEEE/LEOS Group IV Photonics Conference, Ottawa, Canada, September 13-15, 2006.
2. "Hybrid silicon evanescent laser fabricated with a silicon waveguide and III-V offset quantum wells," H. Park, A. W. Fang, S. Kodama, and J. E. Bowers, *Optical Express,* 13, 9460-9464, November 2005.
3. "A continuous wave hybrid AlGaInAs-silicon evanescent laser," Alexander W. Fang, Hyundai Park, Richard Jones, Oded Cohen, Mario J. Paniccia, and John E. Bowers, *IEEE Photonics Technology Letters* 18, 1143-1145 (2006).