Optical Interconnect Technologies based on Silicon Photonics

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ABSTRACT

We discuss the principles of Optical interconnects, and discuss the potential of silicon photonics to provide all the necessary building blocks to construct dense, high-bandwidth, low-power optical links. We discuss waveguides, wavelength division multiplexing, modulators and photodetectors. We also take a look at the options for implementing light sources, a function which silicon cannot natively provide, with a focus on implementations in the IMEC silicon photonics platform.

INTRODUCTION

Optical communication is not new. The laser diode and the optical fiber have sparked a dramatic breakthrough for long-distance telecommunication. Optical fibers supported larger bandwidths over a long distance. Thus, optical links quickly became the backbone of the internet.

Given the fact that is most communication systems people start from an installed base and gradually expand it, it is clear that electrical communication is prevalent inside the closed 'box', while optical links are easier to connect boxes together. The notion of a box depends on the application, but in general the physical dimension of the box is shrinking. 40 years ago, optical links connected continents, but since then optical interconnects have penetrated metropolitan networks (box = town), access networks (box = building) and supercomputing infrastructure (box = rack). This expansion has been accompanied with a reduction in cost, size and power consumption of the photonic components in the optical link. More recently, optical links are being considered for board-to-board interconnects and even on-chip interconnects, where cores and memory could be considered as yet another set of boxes [1]

While light is just another form of electromagnetic radiation, its base frequency is in the order of several hundreds of THz: it can be used like a frequency carrier for a signal with lower bandwidth, which could still cover tens of THz. Also, optical fibers have extremely low propagation losses, allowing point-to-point links of over 100km. This gives optical communication a huge bandwidth×distance product. Also, the optical signals will not radiate and cause no electromagnetic interference and crosstalk.

While the bandwidth for optical signals is tens of THz, its use is limited by the electrical modulation and detection of the signals. Therefore, most telecom links adopt Wavelength Division Multiplexing (WDM): signals are encoded onto different carrier wavelengths, which are transmitted independently through the same physical channel, not unlike FM and TV channels share the same medium (air or cable). In WDM, the carriers are typically generated using lasers operating at different optical wavelengths. For fiber communication, these wavelengths are situated in the near infra-red, around 1300nm or 1550nm.

To build optical links, many different components are required, which will add significantly to the cost of the chips, modules or boards. Also, optical components come in many flavor and material systems, which are typically mutually incompatible, as well as incompatible with CMOS electronics manufacturing. The emerging exception is silicon photonics [2], where one of the drivers is exactly its compatibility with existing electronics manufacturing solutions. However, not everything is possible in silicon: efficient lasers turn out to be a major challenge.

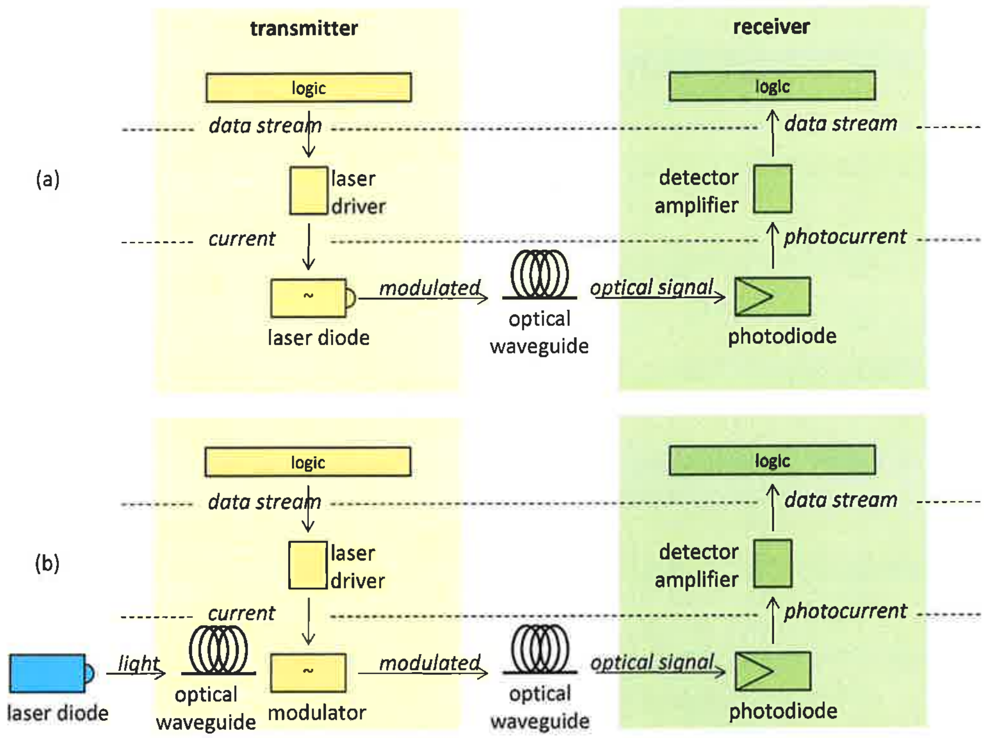

Figure 1: Optical links. (a) Using direct modulation on the laser. (b) Using a continuous wave light source and a separate modulator.

Over all different length-scales, we can see that optical links outperform electronic links when the bandwidth×distance product exceeds 100Gbps·m. That means that depending on the required distance and bandwidth, switching to optical interconnects will not necessarily result in reduced power consumption: While the actual transport of the light will most likely induce less power dissipation, there is additional power consumption for the laser(s) and the specific drivers. Also, these latter might result in floor space consumption just to support the link itself.

We will first describe the anatomy of a link to come to a list of all the required building blocks, and then apply that to the most promising technology to implement them, namely silicon photonics. With this technology base, we will cover the possible implementations for optical interconnect networks. Finally, we will go deeper into integration strategies.

ANATOMY OF AN OPTICAL LINK

Optical links consist of a transmitter, an optical medium, and a receiver. The anatomy of a basic optical links is sketched in Figure 1: An electrically modulated beam of light is sent through an optical waveguide to the receiver, where it is converted back to an electrical signal.

The simplest transmitter consists of a directly modulated laser, but this solution has disadvantages from an integration point of view. Instead, one can use an external laser, and use a separate modulator to imprint the signal onto the carrier.

In a WDM link, signals are encoded onto different wavelengths. There are different approaches to accomplish this: each wavelength has its own transmitter, and the signals are joined together in a multiplexer. At the receiver side the wavelengths are unraveled and converted each with their own photodetector.

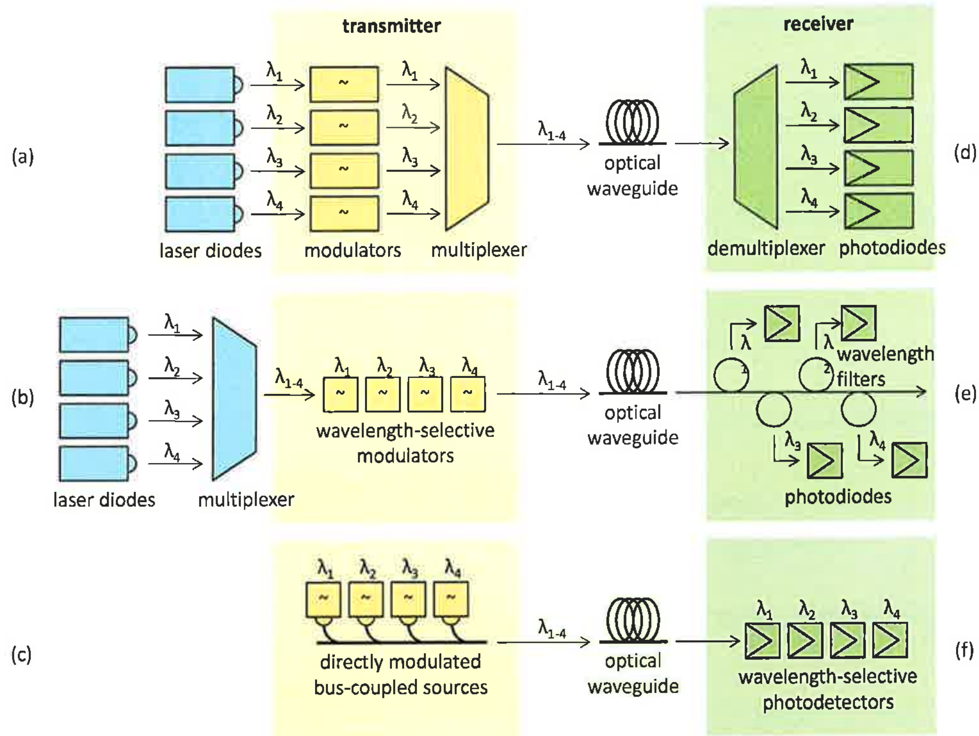

Figure 2: Point-to-point links using wavelength division multiplexing. The three transmitter and receiver configurations can be interchanged. (a) Using broadband modulators and a wavelength multiplexer. (b) Using wavelength-dependent modulators on a single bus. (c) Using directly-modulated sources on a bus waveguide. (d) Receiver using a demultiplexer and broadband photodiodes. (e) using a bus with single-wavelength filters and broadband photodiodes. (f) using wavelength-selective photodetectors on a bus waveguide.

Instead of a (de)multiplexer, one can use add/drop filters at the transmitter or receiver side to put a single wavelength signal onto a bus waveguide, or vice-versa extract it from the bus. One can even integrate the wavelength selective filter in the light source, modulator and/or detector.

SILICON PHOTONICS TECHNOLOGY

Silicon-based waveguide circuits have several advantages for applications in optical interconnects [3,4]: the material can be processed in using standard CMOS manufacturing tools, and can be used to monolithically integrate compact WDM filters, modulators and photodetectors. Only the light sources are currently not easy to integrate, so for such functions other materials, such as III-V semiconductors, need to be integrated.

Waveguides

Optical waveguides confine light in *core* with high refractive index surrounded by a *cladding* with a lower index. The confinement is stronger with a higher refractive index contrast, and in the silicon/oxide system this contrast is very high: this makes it possible to make waveguides especially small, with dimensions ranging from 300×300nm to 500×200nm, and guide light around tight bends of a few μm radius. Such waveguides are often called *photonic* wires. The silicon core needs to be of high optical quality, and surrounded by a lower-index cladding on all sides. *Silicon-on-insulator* (SOI) wafers are especially suited for this, but the buried oxide should be sufficiently thick too optically insulate the waveguide core from the silicon substrate [5]. An alternatives is deposited silicon: Poly-silicon has relatively high losses due to scattering at grain boundaries [6], but amorphous silicon is a good candidate [7].

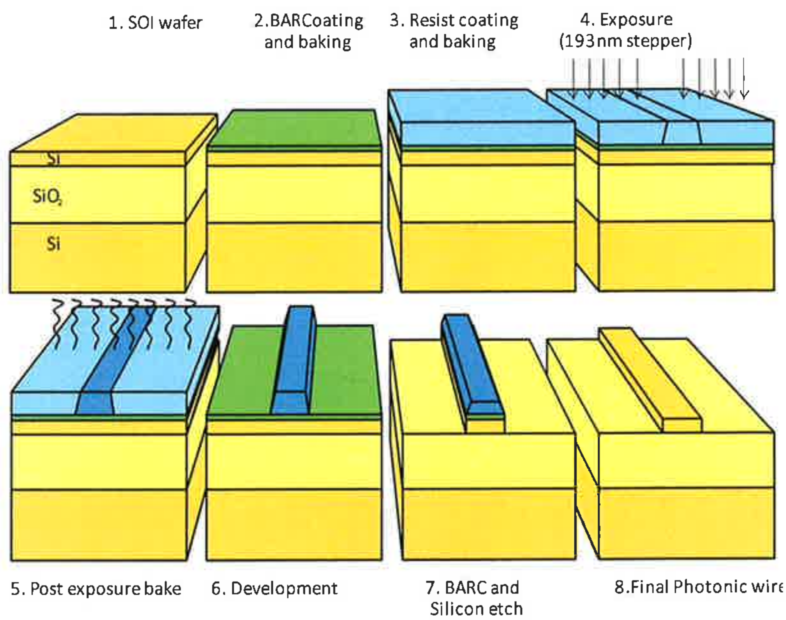

Figure 3: Fabrication process for Silicon waveguides.

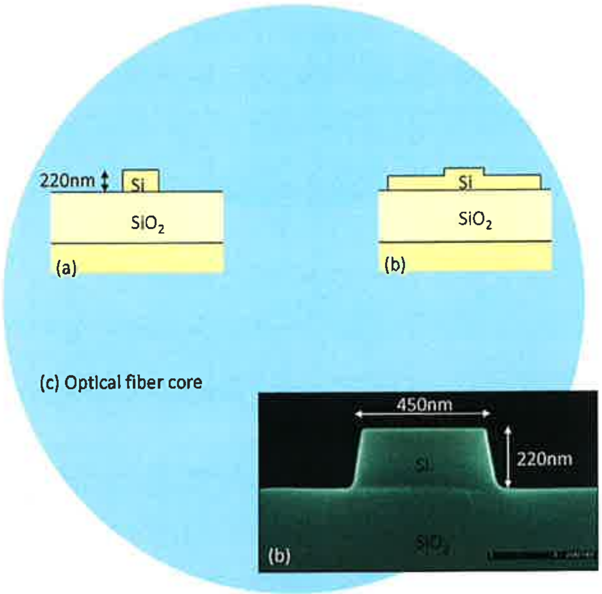

Figure 4: Silicon waveguides (a) Photonic wire with high contrast, (b) Rib waveguide with lower contrast, (c) To scale: core of a standard single-mode optical fiber, (d) Not to scale: SEM cross section of a photonic wire.

A typical fabrication process for silicon waveguides is shown in Figure 3. First the waveguide patterns are defined in the top silicon layer of an SOI wafer using a high-resolution lithography tool and dry etching.

One of the key performance metrics for waveguides is their propagation loss. In high-contrast waveguides losses are typically induced by scattering of light at sidewall roughness. Current state-of-the-art photonic wire waveguide now exhibit losses of about 1-2dB/cm: Over a length of 1cm they lose about 20% of the power [8]. This is already suitable for many applications. When longer propagation lengths are needed, photonic wires can be replaced by alternative geometries with lower propagation loss. Figure 4 shows a photonic wire waveguide to scale with an optical fiber. Lower loss can be achieved by broader waveguides: they have a lower intensity on the sidewalls, and losses as low as 0.3dB/cm have been demonstrated [9]. However, a wider waveguide supports more guided modes, which causes interference in bends. To preserve the single-mode behavior of the waveguide we use use a rib waveguide: The silicon is only partially etched, and this reduces the amount of sidewall surface as well as the index contrast. As a result, bends are not as tight as in wires, but it is possible to engineer a transition between the rib waveguide and the wire. Such rib waveguides have propagation losses as low as 0.27dB/cm [10].

Wavelength Filters and Multiplexers

In WDM links, many wavelength channels are multiplexed into a single waveguide. However, this requires wavelength selective filters which can extract one or more channels from a bus, or all-out demultiplexers which can separate all wavelength channels into their own waveguide. Such optical wavelength filters are based on interference: The optical signal is split over two or multiple paths with a delay line and then made to interfere: depending on the phase difference, the contributions in the paths will interfere constructively (high transmission) or destructively (low transmission). The wavelengths with constructive interference depend on the effective index in the delay line and the path length. The tight bends make silicon photonic wires attractive for wavelength filters: delay lines can be curled up in tight spirals, and ring resonators can be made extremely small [11], as shown in Figure 5. However, photonic wires are very susceptible to small geometry variations. In a delay-line filter, this will translate in unpredictable channel wavelengths. Photonic wire-based filters will therefore always need an additional tuning mechanism, but the tuning power consumption can be kept low with good process control.

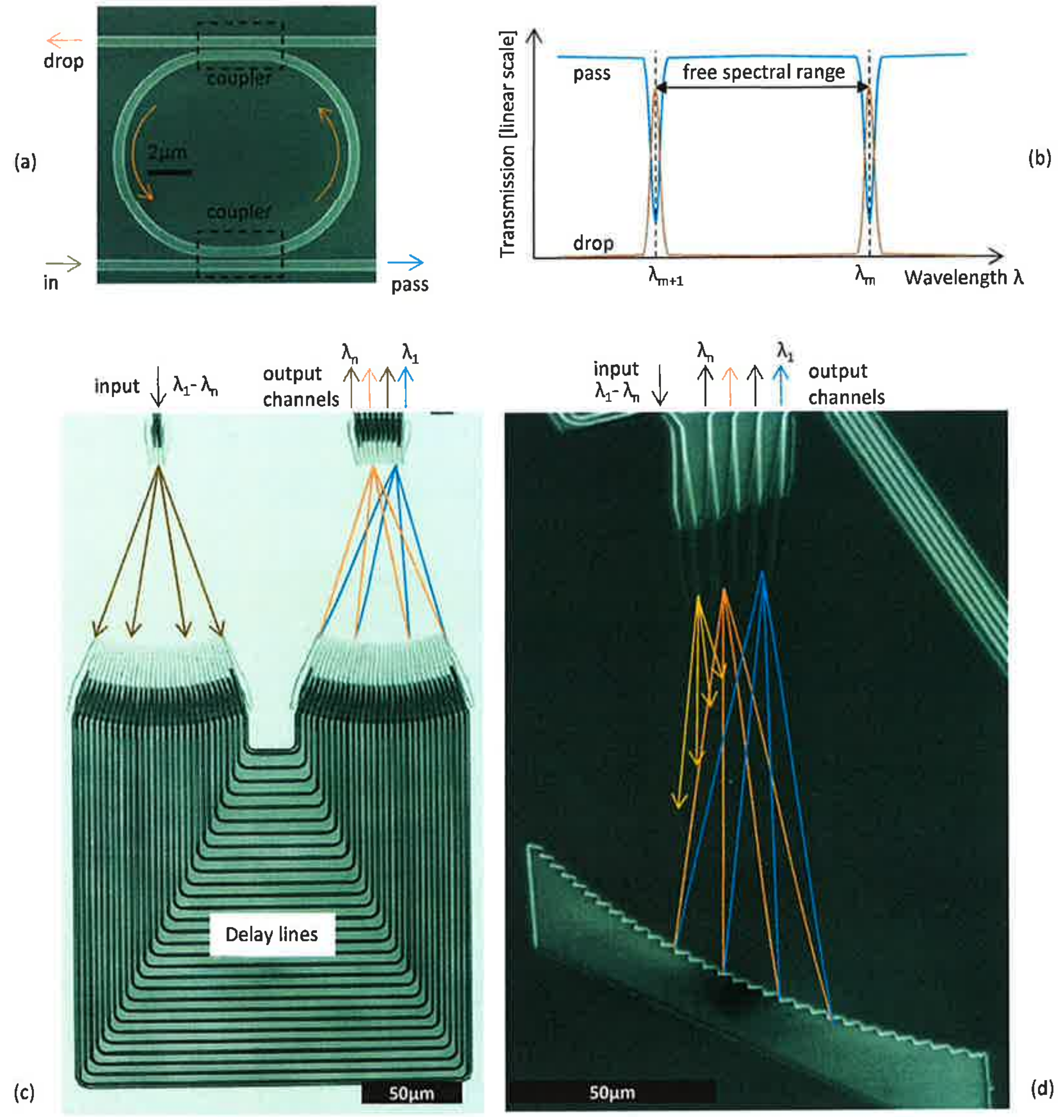

Figure 5: Silicon wavelength filters. (a) Microring resonator [12] with its transmission in drop and pass output, (c) Arrayed Waveguide Grating [13], (d) Echelle grating (Planar Concave Grating) [14].

Instead of using arrayed waveguides as delay, one can also implement the delay in the unpatterened *slab* area, as shown in Figure 5c [14]. By implementing reflectors at the correct distances, a set of phase delays is created. Just as with the AWG, the light will be refocused at different output positions depending on the wavelength. The advantage of such a *planar curved grating*, sometimes called *echelle grating*, is that the delay is not implemented as a waveguide, and therefore it is less susceptible to fabrication errors.

The silicon waveguides are sensitive to temperature: This makes it possible to thermally adjust the spectral characteristics of a wavelength filter or multiplexer, but this also generates problems, especially in the context of on-chip optical interconnects: the optical interconnect layer will be close to the electronics, and this will generate heat in an unpredictable way, with temperature swings of tens of degrees. This can seriously disrupt the operation of the WDM components. This can be solved by operating all photonic circuitry at an elevated temperature near the maximum operating point of the CMOS, and include heaters and monitoring circuits to keep the photonics at a stable temperature [3]. This has a significant detrimental effect on power consumption, and might also pose long-term reliability issues.

Modulators

Electrically modulating a signal on an optical carrier involves a modification of the effective index or the absorption of a waveguide: Either phase modulation or amplitude modulation can be used. The advantage of amplitude modulation is that it is straightforward to decode on the receiver side from the photocurrent of a photodetector. However, direct amplitude modulation is difficult in silicon: direct electro-absorption requires complex integration of SiGe and only works for a single wavelength.

Alternatively, phase modulation will encode a signal in the phase of the light. This makes more efficient use of the spectrum, and also the implementation of the modulator can be simplified, but the receiver side becomes more complicated, and will require an interferometer and multiple detectors. Phase modulation, i.e. modulating the refractive index, can be done through different mechanisms: mechanical, thermal, using electrical carriers, or direct electro-optic effects (e.g. Pockels effect in the $\chi^{(2)}$ material tensor).In this order, the effects have increasing operation speed, but decreasing magnitude. For multi-GHz signals, only the latter two mechanisms are useful.

The most practical modulation mechanism in silicon is through carriers[15]. The refractive index and the absorption of silicon depends on the concentration of electrons and holes [16]. As such, by injecting or extracting carriers in a waveguide it is possible to modulate a signal. The most efficient mechanism is majority carrier injection in a p-i-n diode in the waveguide core [17]. However, this mechanism is limited in speed by the recombination time of the carriers.

Alternatively, one can reverse-bias the junction. This effect moves around minority carriers, so it is much weaker, but potentially much faster, and limited by the carrier mobility and capacitance of the junction [18].

Instead of a junction, one can also use carrier accumulation in a capacitor [19]. The most promising geometry is the use of a layered capacitor. This involves somewhat more elaborate waveguide geometries, but enables very efficient capacitors with a thin oxide.

The effect of the capacitor can be enhanced by using electro-optic materials as the dielectric. In a *slot waveguide*, the silicon waveguide is intersected by a narrow slot, which can be filled with another material. If the material also has a low refractive index compared to silicon, there will be a very high confinement of the light in the slot. Such modulators have been demonstrated with an electro-optic polymer [20,21].

Even though the carriers induce an absorption, the main effect is a change in effective index. To convert a phase modulator into an amplitude modulator, it can be combined with an interferometer or a resonator. In an interferometer, the phase modulator induced a $0 - \text{to} - \pi$ optical phase shift to switch between high and low transmission. For carrier injection modulators, where the effect is quite strong, devices have been demonstrated with a length of only 150μm [17]. This is sufficiently small to be controlled as a lumped element. Carrier depletion modulators are potentially much faster, but also much weaker: the length scales up to millimeters. At these lengths, microwave travelling wave electrodes for high-speed modulation (up to 40Gbps) are needed. However, this needs proper termination, which will dissipate power, enough to dominate the power consumption of the entire link.

In a resonator, the phase modulator modifies the optical path length of the resonator, thereby changing the wavelength of the resonance. The resonator can be a small ring [22] which means that it can be driven as a simple lumped element. However, the transmission dip must be spectrally aligned with the operating wavelength. This will require good process control as well as an active tuning mechanism.

Photodetectors

In a photodetector, incident photons will generate free carriers which can be collected in a photocurrent. For telecom wavelengths, silicon is transparent, and this makes it unsuitable for photodetectors though. Germanium has the key advantage that it is already a material which can be integrated with silicon, and several foundries incorporate Ge or SiGe epitaxy in their fabrication cycle.

For efficient detection, the light-induced carriers must be efficiently collected, so they should not recombine at defects. As germanium epitaxy on silicon typically involves an interface layer with dislocations. So in the photodetector neither the light or the generated carriers should come into contact with such layers. Several integrated germanium photodetectors have been demonstrated [23,24] with good responsivity (order of 1A/W at 1550nm) and reasonably low dark current (a few nA).

Light Sources

One of the key issues with silicon photonics is the integration of the light source. Efficient semiconductor lasers require a direct-bandgap material, and silicon and germanium have an indirect bandgap. While an external laser can be used as an optical power supply, this limits the scalability and the topology of the link network. Also, in WDM systems an external laser for each wavelength is required. A better long-term solution is to integrate the laser on-chip. Flip-chip or other hybrid integration schemes can provide this, but this provides little added value compared to separate packaging. The laser can also generate additional thermal issues.

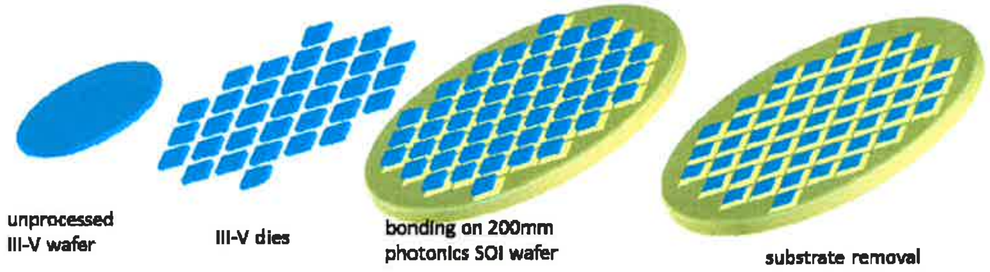

Figure 6: Integration of III-V semiconductor films on silicon photonics using die-to-wafer bonding

Ultimately, on should integrate the laser in the optical circuitry. This would require the integration of III-V semiconductors. Direct epitaxy of III-V materials on silicon has already been demonstrated, but this technology is far from the maturity required for laser-quality layer stacks. Therefore, the most commonly explored route is using a bonding approach: Dies of high-quality III-V material are bonded to a wafer with silicon photonic circuitry and subsequently thinned down to a film. The bonding can be either molecular bonding [25] or adhesive [26]. The III-V film is then processed into lasers using the same kind of tools used for the silicon processing. This approach makes it possible to integrate many lasers directly on the waveguide circuitry, and these lasers can be designed to emit the wavelength of choice, so the WDM source problem is reduced significantly.

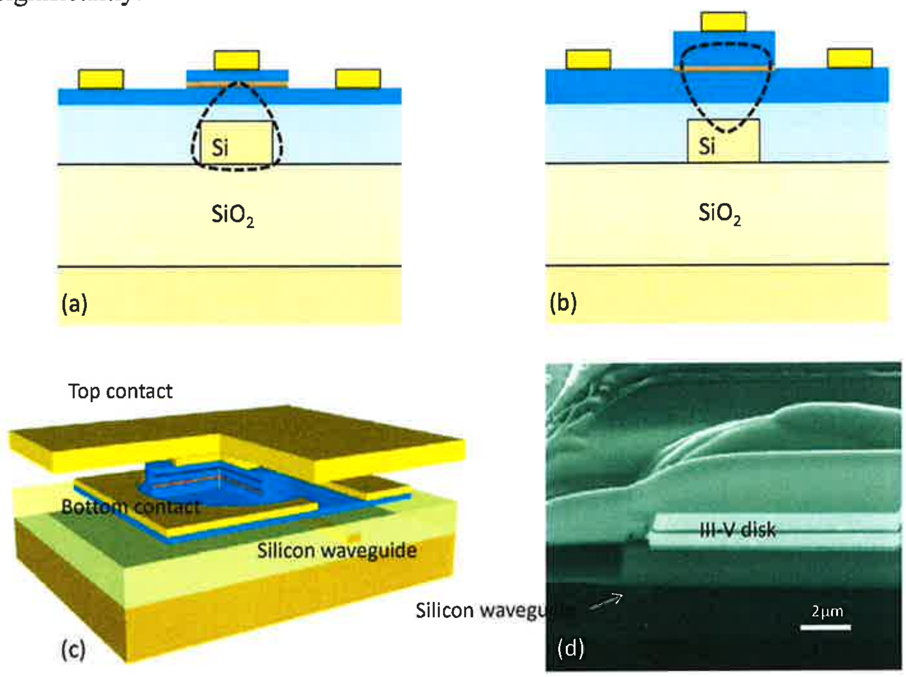

Figure 7: (a) Confinement of light largely in the silicon [25], (b) Confinement of the light largely in the III-V material[27], (c-d) Microdisk laser, with light coupled to an underlying silicon waveguide [28].

Having lasers directly integrated on the waveguides allows direct modulation of the laser: this obviates the need for an additional modulator, but the speed is limited by the carrier dynamics in the laser, so typically less than 10GHz. The integrated laser also have a topological advantage: no optical feed lines are required: the laser can be located exactly where the light is needed.

Apart from the additional process requirements (i.e. processing III-V materials in a silicon fab), the integrated lasers also introduce some operational issues. Semiconductor lasers tend to be very temperature sensitive: emission efficiency drops for higher temperatures, and as lasers generate quite a lot of heat in their own right, this leads to a severe thermal management problem

Depending on the application, different types of lasers can be used: Microdisk lasers are extremely small, with a footprint of only 15×15µm, and can be directly couples to a photonic wire waveguide [28]. Also, multiple of these waveguides can be integrated on the same bus waveguide [29]. However, given their small size, the output power is limited to 100-150µW. which could well be sufficient for on-chip interconnects.

For higher power levels, alternative laser geometries are needed: these have a larger footprint and are often more complicated to couple to a silicon wire waveguide. This can be solved by constructing geometries where a significant portion of the light remains in the silicon, with a small extension of the optical mode experiencing gain the in III-V material [25]. This implies a relatively large footprint to get sufficient power output. Alternative geometries confine as much light as possible in the III-V material, but this complicates the transition to the silicon wire [27].

INTEGRATION

The challenges in silicon photonics not only lie in the development of the individual component, but integrating them with sufficient performance into a complex circuit, and ultimately with electronics. This is a significant technical challenge, which involves process development, material science, packaging, system engineering, and codesign of the electrical, optical, thermal and mechanical properties.

Integrating photonic and electronic layers can be approached in different ways, which are most easily classified by the location in the electronics stack.

- **Front-end-of-line:** Using SOI technology, it is in principle possible to define both transistors and waveguides in the same stack [3].
- **Back-end-of-line:** The photonics on top of the metal interconnects, integrated in the wiring.
- **Backside**: The photonics on the backside is partially decoupled from the electronics.
- **3D integration**: 3D integration stacks the photonics on the electronics, largely decoupling the technologies, with dense interconnects between the layers.
- **Flip-chip integration:** Similar to 3D , but face-to-face, making further integration difficult.

All options have advantages and disadvantages, and several are being explored in the frame of the European project HELIOS.

CONCLUSIONS

Silicon photonics, with its high index contrast coupled to state-of-the-art silicon process technology, can be used to integrate all building blocks necessary to construct WDM links on a chip. Moreover, the compact photonic wires allow very dense circuitry and more complex functionality. However, there are significant challenges to implement silicon photonic optical interconnects. One is the large sensitivity to fabrication variation and operational conditions (especially temperature). Compensating for this is possible with active tuning en temperature control, but this can severely impact the power consumption of an optical link.

ACKNOWLEDGMENTS

Part of this work was supported by the European Union in the framework of the project FP7-HELIOS and FP7-WaDiMOS. Part of this work was performed as part of imec's Core Partner Program.

Wim Bogaerts is supported by the Flemish Research Foundation (FWO-Vlaanderen) for a postdoctoral fellowship. Thijs Spuessens was supported by Flemish Institute for the Promotion of Innovation through Science and Technology (IWT) with a specialization grant.

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Materials, Processes, and Reliability for Advanced Interconnects for Micro- and Nanoelectronics
April 26 - 29, 2011

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Terukazu Kokubo	JSR Tsukuba Research Laboratories
Shinichi Ogawa	National Institute of Advanced Industrial Science and Technology

* Invited paper

SESSION O1: Low-k Materials I
Chairs: Griselda Bonilla and Geraud Dubois
Tuesday Morning, April 26, 2011
Room 3000 (Moscone West)

8:45 AM *O10.1
Optical Interconnect Technologies Based on Silicon Photonics. Wim Bogaerts[1], Dries Van Thourhout[1], Philippe Absil[2], Shankar Kumar Selvaraja[1], Pieter Dumon[1], Hui Yu[1], Joris Van Campenhout[2], Thijs Spuessens[1] and Roel Baets[1]; [1]Information Technology, imec - Ghent University, Gent, Belgium; [2]Process Technology, imec v.z.w., Leuven, Belgium.

9:15 AM O10.2
Vertically Aligned Carbon Nanotubes as Flip Chip Interconnects. Dunlin Tan and Beng Kang Tay; School of Electrical & Electronic Engineering, Nanyang Technological University, Singapore, Singapore.

9:30 AM O10.3
Silicide Materials for Aligned Carbon Nanotube Synthesis in Interconnect Applications. Can Zhang, Feng Yan, Guofang Zhong, Bernhard C. Bayer, Bingan Chen, Stephan Hofmann and John Robertson; University of Cambridge, Cambridge, United Kingdom.

9:45 AM O10.4
Comparison of Electrical Characteristics of Multilayer Graphene and Multiwalled Carbon Nanotubes for Interconnect Applications. Neha Kulshrestha[1], Abhishek Misra[2], Reeti Bajpai[1], Kiran S. Hazra[1], Soumyendu Roy[1] and Devi Shankar Misra[1]; [1]Physics, Indian Institute Of Technology Bombay, Mumbai, 400076, India; [2]Electrical Engineering, Indian Institute Of Technology Bombay, Mumbai, Maharashtra, India.

10:00 AM BREAK

10:30 AM O10.5
Emerging Materials for Nanoscale Interconnects. Cengiz S. Ozkan, Ali Guvenc, Jian Lin, Miro Penchev, Jiebin Zhong and Mihri Ozkan; Mechanical Engineering, University of California at Riverside, Riverside, California.

10:45 AM O10.6
Stretchable Silicon Integrated Circuits with Graphene Interconnects. Won Ho Lee, Material Science and Engineering, Sungkyunkwan University, Suwon, Korea, Republic of.

11:00 AM O10.7
E-beam Deposited Tungsten Contacts for Nanocarbon Interconnect Test Devices. Nobuhiko Kanzaki, Shusaku Maeda, Patrick Whilhite, Toshishige Yamada and Cary Y. Yang; Santa Clara Univ., Santa Clara, California.

11:15 AM O10.8
A Simple Patterning Method of Solution-Processed ZnO Thin Film for the Flexible Transparent Thin Film Transistor. Kyongjun Kim, Si Yoon Park, Seung-Chul Yew, Ji hyun Lee, Sungyun Chung, Hanju Jo and Youn Sang Kim; Department of Nano Science and Technology, Graduate School of Convergence Science and Technology, Seoul National University, Suwon-si, Gyeonggi-do, Korea, Republic of.
