White Paper

The rise of Silicon Photonics

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A field that is constantly changing

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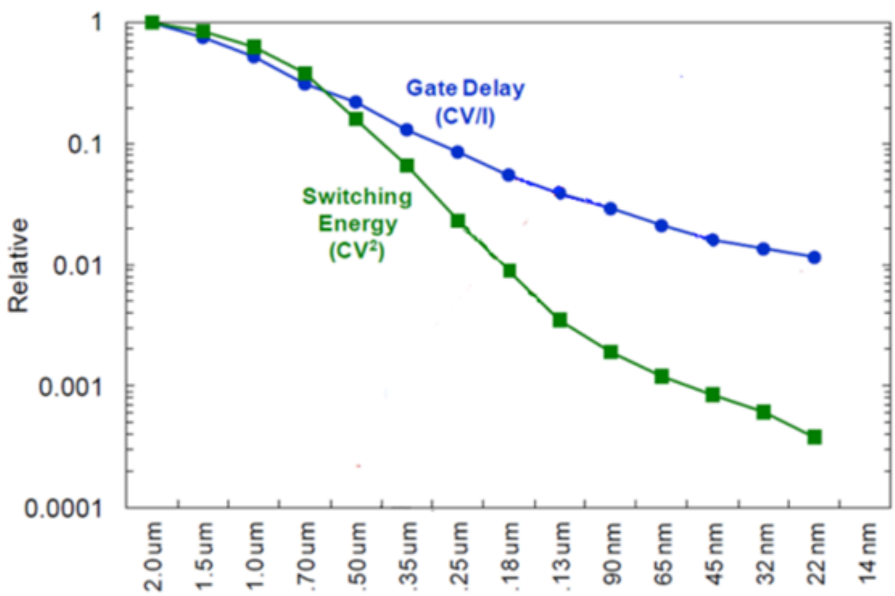
Electronics and photonics have been two worlds apart for many years; the first had an explosion that changed forever the way we live, the second became the de facto medium for the transport of information and the telecom and datacom industry: optical communication enabled the rise of internet and the steep price decline we all enjoyed, but it didn't reach the level of diffusion and the pace of integration and performance increase that the semiconductor business had.
The reasons for this difference can be summarized by the following table.

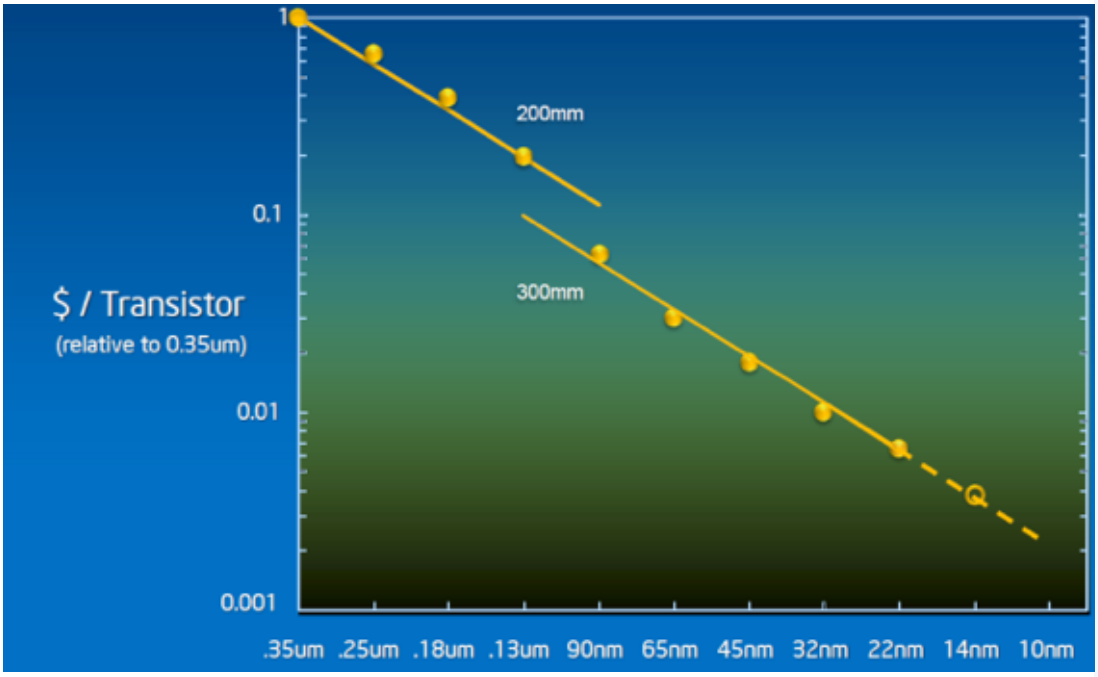
Enabling Technology	Optics	Semiconductor IC
Building block	Many (LD, PD, driver, modulator, etc.)	Transistor
Material	Many (InP, GaAs, InGaAs, Si, $LiNbO_3$,...)	Silicon
Prevalent MFG process	Many	CMOS

In a nutshell, the semiconductor business "kept it simple" while optics has always been a divided camp that failed to generate economy of scale. Silicon industry was able to build an ecosystem and focus investments in very precise directions: get things smaller, faster, cheaper, with the cheap came the mass application and the cycle fuelled itself. Just a couple of charts from Intel to better explain, the first indicates how much the power consumption of chips decreased over time (please note the scale is logarithmic and 1um happened around mid 80s).



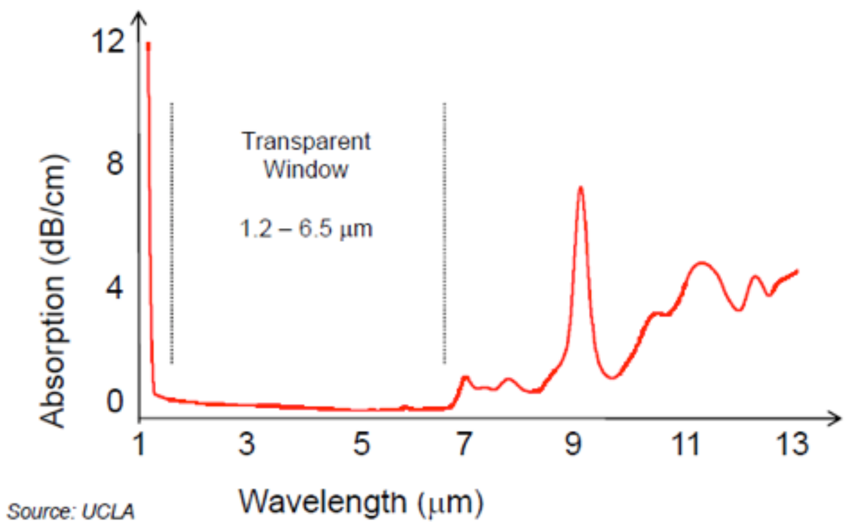
Left - Transistors parasitics over time

The second is the cost. Please note two things here: it starts from 0.35um, that is 1995 and the vertical scale is logarithmic as well. This means that the cost per transistor went down by more than 2 orders of magnitude!



Left - Cost per transistor progression

No wonder photonics is trying to jump on this train to leverage all the investments done by the semiconductor industry: from the business point of view, Silicon Photonics is the quest to leverage investment, infrastructure, tools and manufacturing processes of the CMOS Industry to put optics on a similar trajectory as ICs in terms of integration, manufacturability, scalability, power & cost.
Adding photonics to Silicon is a challenge for the IC industry to produce inexpensive and performing photonic devices out of Silicon. On the other hand, adding Silicon to photonics challenges the photonic industry to introduce in the production processes the same concepts (standardization, economy of scale, integration and roadmap) which make the success of the microelectronic industry.
Silicon is an optical material, in fact its absorption spectrum is transparent at optical wavelengths (1300nm-1500nm) used by single mode transmission.



Left - Silicon absorption spectrum

While the refration index of Silicon is 3.5, the one of SiO2 is 1.45, which allows to build very narrow waveguides. The most important problem to address is that Si has an indirect bandgap which means that is is not well suited for lasers, this problem will be examined at the end of this paper.

A Silicon photonics circuit will be like a conventional IC, with a photon supply unit. As a conventional IC has a DC electron supply and it manipulates electrons, with electrical I/Os, a Silicon photonics circuits will have a DC source of both electrons and photons (a laser) and will have both optical and electrical I/Os.

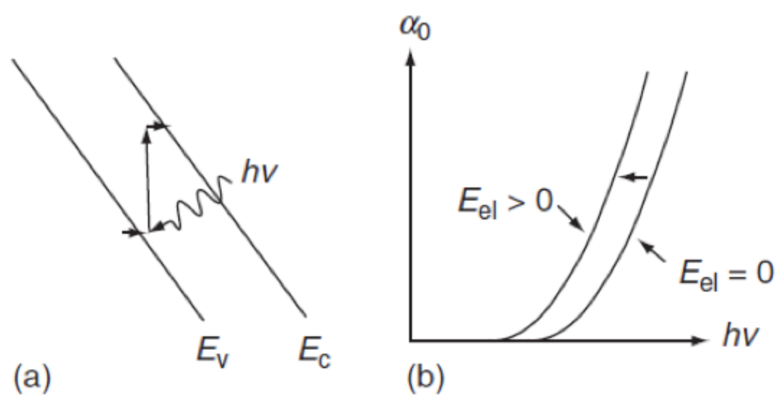
A comprehensive description of the physics of the light-matter interactions that take place when light is injected in Silicon chips is beyon the scope of this paper, indication on advanced readings are in the bibliography section. This paper will not describe as well techniques to get light in and out of the photonics circuits, which is a very broad topic.

Many different structures have been proposed to manipulate light in Silicon, including modulators, muxes, demuxes, couplers and almost all building blocks of photonics circuits, here we will give a brief description of only three of them: modulation of light, detection of light and lasers.

Modulation of light:

It is possible to implement in Silicon both electro-absorption (EAM) as well as Mach-Zehnder modulators, which are the two most used schemes in current transceivers.

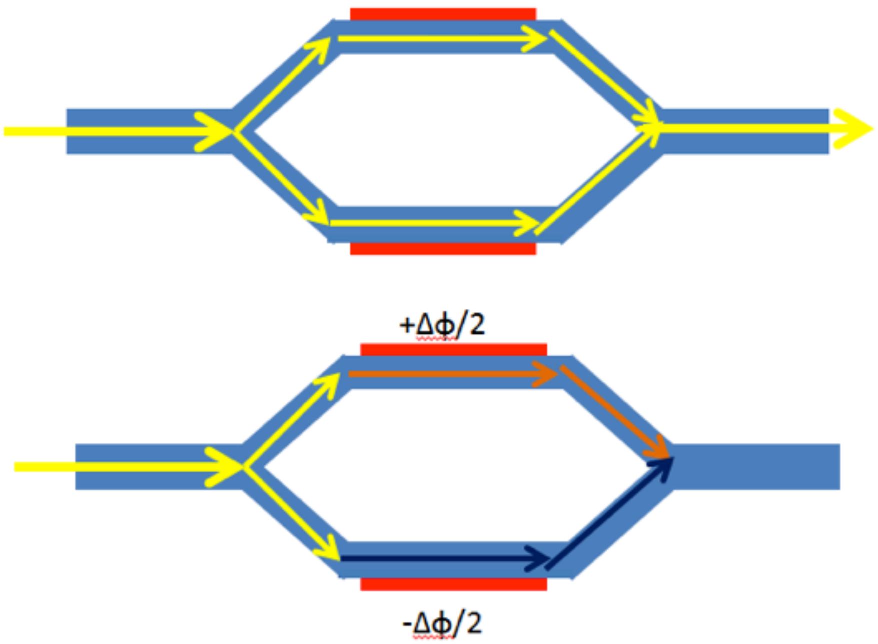
Being Silicon a semiconductor, it is possible to exploit physical properties of these material to modulate the absorption of light applying an electrical field. In fact when an electrical field is present, the energy bands of Si are distorted and electrons can tunnel across the bandgap, thus a lower energy than in band-to-band absorption is required. As explained in [2], the tunnelling process is strongly favoured if a photon, having energy close to bandgap, is absorbed. Such effect is more evident at wavelengths close to the bandgap.



(a) electric field tilts the band structure. When a valence electron absorbs a photon, it tunnels into the conduction band. (b) A red shift is observed.

The other important physical phenomenon affecting the Silicon refractive index is the free carrier absorption. Optical properties of Silicon are strongly modified by injection of charge carriers into an undoped material or by removal of free carriers from a doped one.

This principle can be used to build an optical modulator in Silicon, specifically a Mach-Zehnder interferometer (MZI). If light coming from a coherent source is split into two beams, and each follows a slightly different optical path, when recombining them, an interference pattern is obtained due to the phase change between both beams The MZI starts with a waveguide and then splits into two symmetric branches. After a certains distance, the two branches become parallel. The two branches join again in a straight waveguide. If the MZI is exactly symmetric and if the optical path on both branches is exactly equal, the input light splits at the first Y-junction into the two parallel branches and then recombines constructively into the final waveguide. If in one of the interferometer's arms the light suffers a phase shift of 180 degrees, at the end of the second Y-branch the light coming from the two branches will recombine in phase opposition and will give rise to destructive interference, with no light at the output. The phase shift in one arm is realized by applying a voltage across the waveguide. By designing the geometry, the electrode geometry, and the applied voltage, a total phase shift of 180 degrees can be obtained for a specific wavelength. The modulator can also be designed to apply half of the phase shift **$\Delta\varphi$** per each arm, with one arm applying a **$\Delta\varphi/2$** and the other **$\Delta\varphi/2$**.



Left - Mach-Zehnder modulator operation: electrical field changes the refraction index of the material being able to create distructive interference

Detection of light

Since Silicon is transparent at optical frequencies in the 1300nm-1500nm region, it is not well suited to build photodetectors. It has to be coupled with other materials still maintaining the possibility to nicely fit into a CMOS production process if we want Silicon photonics to be successful. Let's list what are the specification that we looks for:

- Compatibility with Silicon technologySilicon-based materials

- Large wafer scale technology
- Permit electronic integration (Transimpedance amplifier -TIA)
- Low cost integration schemes

- Broadband detection (1.3 -1.6 ↔m)

- High absorption coefficient

- Low dark current

- Depends on the electrical configuration and the quality of the absorbing layer.

- High bandwidth (frequency operation > 10 GHz)

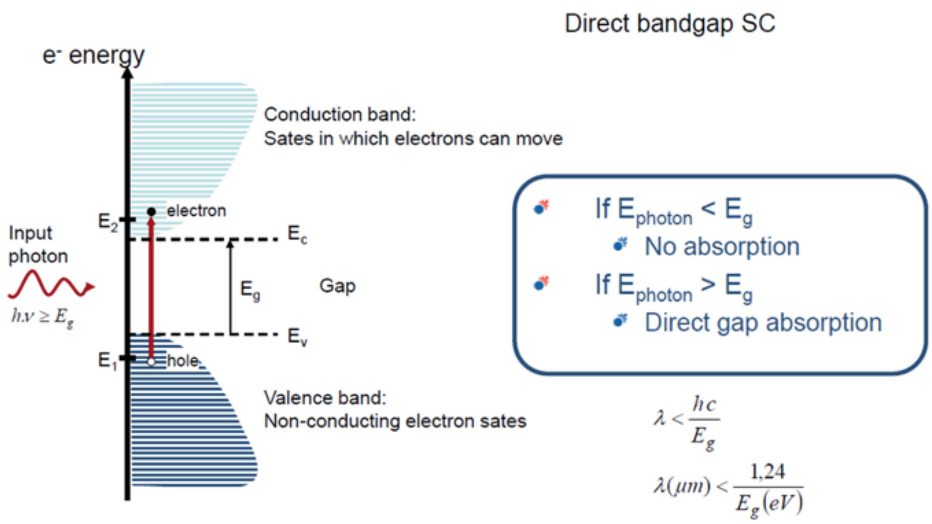
- Low carrier transit time
- Low RC constant -depend on the considered electrical

- High responsivity

- Determine the configuration to achieve the best light interaction with absorbing layer.

- Compactness

- Strong absorption coefficient in the complete wavelength range

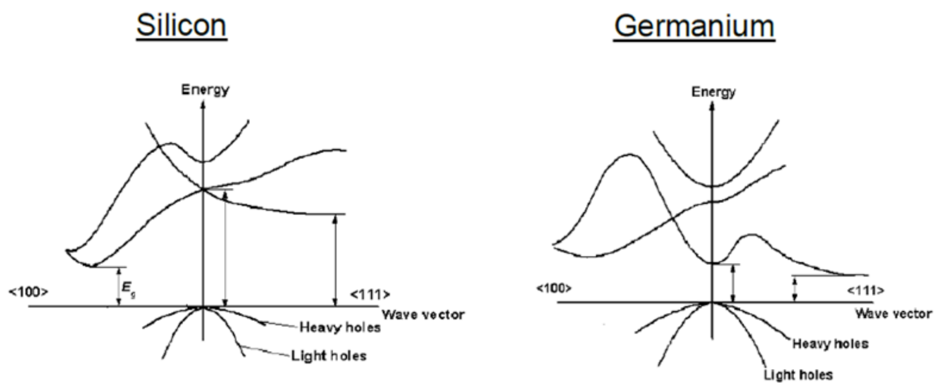


$$\lambda < \frac{hc}{E_g}$$

$$\lambda(\mu m) < \frac{1{,}24}{E_g(eV)}$$

Left - Absorption in direct bandgap semiconductors[3]

In this context, as material compatibility must be insured, the group IV Silicon–germanium technology is important due to the energy band engineering that it allows, with the integration of Si/SiGe heterostructures into the existing Silicon technology.



	Silicon	Germanium
Direct bandgap	> 3.4 eV (0.36μm)	0.80 eV (1.55μm)
Indirect bandgap	1.12 eV (1.10μm)	0.66 eV (1.88μm)

More suitable for visible absorption

Absorption up to 1.55 μm

Left - Comparison of Silicon and Germanium band structures[3]

Silicon-Germanium alloys can extend the absorption of lights towards longer wavelenghts, viceversa, pure Ge would allow the realization of high speed, low dark current devices, but themanufacturing processs would need to be adapted to grow Ge on Si (Efficient optical coupling of light into the absorbing region is important to guaranty a high yield. Surface- or waveguide illuminations have been proposed. For integration with optical micro-waveguides in a Silicon-compatible planar technology, the second option is preferred, while surface illuminated devices have less optical alignment problems.

Photodetectors can be built also integrating drect bandgap materials from the III-V group (InP, GaAs, etc.) wit Si, but given the process complications this is a less appealing solution.

Laser sources

The last and most complicated piece of the puzzle is the laser.

As already said, Si is an indirect bandgap semiconductor, so the probability for a radiative recombination is low, which means that the electron hole radiative lifetime is long, of the order of some milliseconds. If during this time both the electron and the encounter a defect or a trapping center, the carriers might recombine nonradiatively. Typical nonradiative recombination lifetimes in Si are of the order of some nanoseconds. This is the reason why Silicon is a poor luminescent material: the efficient nonradiative recombinations that depletes the excited carriers rapidly.

So far, in the commercial Silicon photonics modules that have started being produced, discrete laser chips are attached to the surface of the chip and light coupled with different techniques. These primordial methods allowed to bring devices to the market, but are far from optimal. In fact they are expensive, require special manufacturing equipments for alignment and do not offer high scalability.

A second approach consist on the use of III-V materials, currently widely used for laser devices in conjuction with Si. Three approaches are possible

- Flip-chip integration of opto-electronic components

- reliable
- allows testing of opto-electronic components in advance
- slow process (alignment accuracy)
- low density of integration

- Hetero-epitaxial growth of III-V on Silicon

- collective process, high density of integration
- mismatch in lattice constant, thermal coefficients
- contamination

- Bonding of III-V epitaxial layers

- fast integration process
- high density of integration,
- high quality epitaxial III-V layers

The last one has been recently explored using molecular bonding (van der Waals attraction between two surfaces) or adhesive bonding (using an adhesive as a bonding agent). Several startup are active in this area. The main attractions are the possibility of integration, the lack of alignment and the moderate final cost that can be achieved

The last method and the real "Holy Grail" of Silicon Photonics wil be the monolithic integration of source in the CMOS process, which will be - of course – the lowest cost solution. One very promising approach has been developed by Intel [4] which created a continuous wave (CW) Silicon Raman laser overcoming previous limitations that allowed only pulsed modulation. This device exploits Raman effect, a scattering process in which a lower energy (longer wavelenght) photon is release. This phenomenon is widely used in optical amplication for long haul systems.

Few recent works seems to question the belief that Silicon is not suited to build a laser, suggesting new structures and physical mechanism that could help achieve the scope [5,6]. All these results are very encouraging since the proposed systems have excellent electrical qualities as they are p–n junctions. The main problem with the bulk Si approach is related to the presence of a large enough gain to overcome possible free carrier losses, which needs to be better explored.

Thre is much more going on with Silicon Photonics than what we explained here, plus it is a field which is constantly changing, a very active and exciting development area, where new devices, techniques and studies are presented at every conference.

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