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Silicon Photonics – Optics to the Chip at Last?

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1. Introduction

Optics dominates long distance communications, but will it ever be useful on silicon chips or their successors? In this paper, we will discuss why we might be interested in the use of optics for such shorter interconnections, what technology we might need, and what new technological opportunities are emerging that could make such use practical or even ubiquitous.

Optics for use in handling information has been about now for several decades, with clear successes in optical fiber communications and in removable disk storage (Compact Discs and DVDs, for example). Early interest in optics for logic faded as integrated circuits advanced and limitations in energy for optical logic became clearer[1], but optics for communication and interconnect has become increasingly interesting. There, optics is competing against copper, not silicon. Basic issues of physics favor optics for communication anywhere a high density of information has to be communicated over any substantial distance[2,3].

2. Problems of wires

The physical problems and limitations of electrical wired interconnects are many and substantial. They perform increasingly poorly at higher frequencies, showing both signal attenuation and distortion. One surprising aspect of the performance that it is essentially scale invariant: that is, once one has filled all the available space with wires, then, at least for on simple on-off signaling, one cannot get any more information down the wiring system either by miniaturizing it or by making it bigger (see Fig. 1)[4]. This argument is straightforward to derive for "RC" line from the resistance and capacitance of wires, but, surprisingly, it also applies to "LC" wires or transmission lines. It leads to a capacity limit $B \propto A/\ell^2$ bits/second, where A is the total cross-sectional area of the wiring system and ℓ is the wire length. The proportionality constant is ~ 10^{16} for "RC" lines (as typically found on chip) and ~ 10^{15} for "LC" lines. Hence, wire capacity in large dense systems can suddenly become a problem at all size scales, including long on-chip lines and between chips. We routinely run into this limit in long on-chip wires and in coaxial cables, for example. Optics completely avoids this scaling limit, and is therefore particularly attractive wherever we require dense high speed wiring of any substantial relative length[4].

Wires also have unavoidably low impedances (e.g., 50 ohms) and/or high capacitances per unit length (e.g., several pF/cm); impedance and capacitance both scale only ~ logarithmically with the ratio between conductor size and conductor spacing, and so there is little that can be done to change such numbers substantially. Low impedance and high capacitance both contribute to substantial power dissipation. With sufficiently well integrated optoelectronic devices, optics might be able to solve that power dissipation problem also[5], through a process that can be called quantum-impedance conversion, a process that is actually inherent in any optical link.

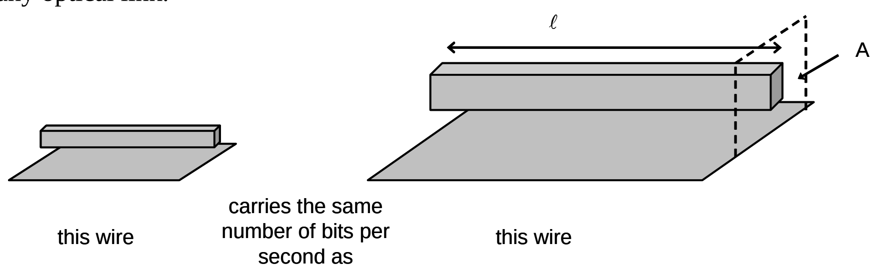

Fig. 1. Illustration of the scaling of the capacity of wires for simple on-off signaling. Scaling a wire in all three dimensions leaves its information capacity the same, though scaling transistors in the same way makes them faster. Hence wiring progressively becomes the problem.

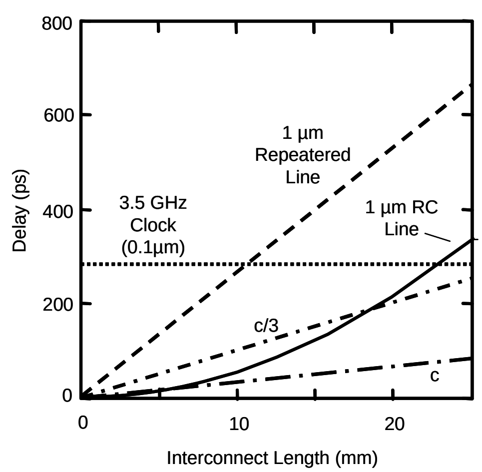

Fig. 2. Delay on repeatered lines on chip compared with delay from propagation at the velocity of light (*c*) [3].

Even on chips themselves, where repeaters can be incorporated to break wires into shorter lengths to mitigate the above scaling problem, there are problems with wires. The effective propagation velocity of signals on chips, for example, is generally much slower than the velocity of light (see, e.g., Ref. [3]), as shown in Fig. 2.

Another major feature of optics is its ability to deliver very precise timing to electronic circuits, based on the relative ease with which short optical pulses can be generated and propagated over substantial distances. Clocking[6] of digital logic circuits with sub-picosecond precision has been demonstrated[7], and optics has been used to trigger analog-to-digital converters with timing precision as good as 80 fs[8].

3. Technologies for optical interconnects to chips

Despite physical advantages, and despite growing problems with interconnection at all levels, optics has never made any impact at the level of integrated circuits. Why? As discussed above, the physical arguments for using optics especially off chip are particularly strong, with possible substantial reductions in power and increases in communication density, but the cost targets are daunting for introducing a new technology such as optics. The practical targets for power dissipation are also very severe.

Given the increasing dominance of power dissipation as the limit to the performance of information processing machines, optics must certainly use no more power than the electrical systems it would replace, and likely must promise significantly lower powers if it is to convince engineers to adopt it. A not unreasonable starting target for off-chip interconnects would be something ~ 1 mW/Gb/s (1 pJ/bit) for the total optical link if it is to replace electrical chip-to-chip or chip-to-board technologies. Then 100 links each running at 10 Gb/s would consume 1 W. For long on-chip optical interconnects to be clearly superior to current electrical systems, dissipations ~ 100 fJ/bit for the entire link are likely required. (Short optical interconnections on chip likely do not make much sense since wires are extremely good at such connections.)

Both the cost and the power requirements mean that for such applicaitons the optoelectronic devices are going to have to be very well integrated with the electronics. For example, if a link is to dissipate no more than 100 fJ/bit, and the components such as detectors, modulators, and driver transistors are to swing through the supply voltage of 1 V, based on the energy to charge such a capacitance the total capacitance involved in the link could not possible exceed 100 fF, and would likely have to be lower because there will be other sources of energy dissipation in the system. Capacitances of this order or smaller absolutely require very well integrated technologies. Prior optoelectronic technologies for communications have never been integrated well with silicon. Silicon itself is a frustrating optoelectronic material, because of its indirect gap. III-V materials, which give good optoelectronic devices, are not easy to integrate with silicon processes.

The idea of on-chip optics on silicon is gaining momentum in research, however. Significant advances have been made recently in silicon optical systems (waveguides, couplers), and in active optoelectronic devices (modulators)[9-12]. Recently, quantum-confined Stark effect (QCSE) electroabsorption[13] has been observed in Ge quantum wells grown on silicon-germanium buffers on silicon substrates, in processes that are likely compatible with silicon CMOS manufacture[11,12]. Fig. 3 shows electroabsorption spectra for such wells, showing clear strong shifts of the absorption with field, as required for compact optical modulators. This mechanism is likely the strongest high-speed optical modulator mechanism known, and is routinely used with III-V materials to make optical modulators integrated with lasers for telecommunications. The importance of the observation, at telecommunications wavelengths near 1.5 microns, of the QCSE in Ge is that it may finally allow Group IV optoelectronics with performance comparable with III-V's, avoiding the difficult materials integration issues of attempting III-V integration on Si. Hence, there is now serious hope for a very high-performance Group IV CMOS-compatible optoelectronics technology capable of low-cost, low-power optoelectronics for interconnects and other applications.

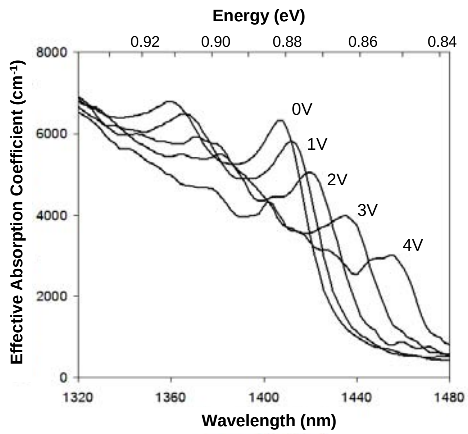

Fig. 3. Effective absorption coefficient spectra of Ge/SiGe (10nm Ge well and 16nm Ge/$Si_{0.15}Ge_{0.85}$ barrier) quantum wells on a relaxed $Si_{0.1}Ge_{0.9}$ buffer[11,12]

The other required aspects for low-cost optical connections off of silicon are also becoming more realistic. Serious attempts are being made at commercializing optoelectronic chips made entirely in a CMOS platform, such as recent demonstrated work by Luxtera Inc. A possible path for the introduction of optics to silicon is the progressive evolution of integrated optoelectronics on silicon for telecommunications and data communications transceivers, leading to technology we may be able to use for other applications, such as possibly optical interconnects on chip.

At the same time, radical ideas are emerging from nanophotonics, in dielectrics, semiconductors, and now also nanometallics, all in principle compatible with CMOS. With such nanotechnologies, it is possible to make optical devices much more compact than before, and to contemplate completely new kinds of structures, such as miniaturized wavelength[14] or mode[15] splitters, miniaturized metallic optical antennas[16] and 50 nm sized waveguides[17,18] that could concentrate and guide light into high-speed, low-capacitance photodetectors the same size as current transistors. Fig. 4 shows a recent structure used to demonstrate photodetection enhanced by a metallic nanostructure[16], in this case a sub-wavelength C-shaped aperture in a gold film on Ge.

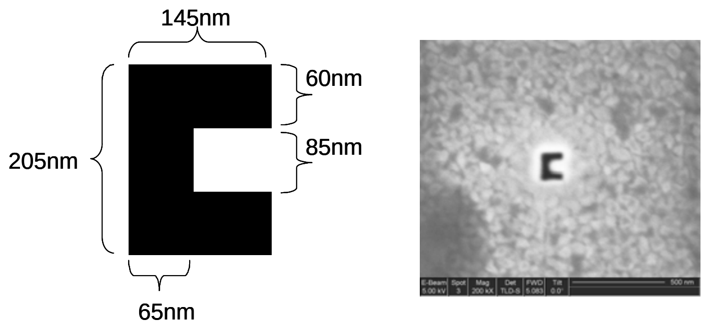

Fig. 4. Schematic of a nanoaperture in a gold film on germanium (left) and picture of the fabricated structure (right). For light shining on the top of this structure, the metallic structure acts like an antenna to generate an intense local spot in the middle of the C-aperture. The photocurrent per unit active volume here is enhanced by ~ x 10 compared to the corresponding current in a simple piece of Ge illuminated by the same intensity of light.[16]

4. Conclusions

Optics has many strong physical reasons for seriously considering it for interconnects, now possibly all the way to silicon chips themselves. The implementation of optics for such interconnects is very challenging, but recent breakthroughs are very promising for the ultimate construction of an integrated, low-cost, low-power technology. Advances also in nanophotonics structures, themselves enabled by the nanotechnologies of silicon electronic manufacture, offer additional exciting opportunities for optics and optoelectronics well beyond even current devices.

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