Silicon Based On-chip Optical Interconnects: The Rationale and Implementation

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Abstract—**The reasons why optical interconnects play a significant role on the chip are briefly introduced. The implementation of the silicon-based optoelectronics is discussed based on some recent pioneer work done by Intel, including the generation, modulation and detection of light to communication.**

Index Terms—**optical interconnects, on-chip, optoelectronics, silicon photonics**

I. Introduction

THE continuing exponential reduction in feature sizes on electronic chips leads to ever large numbers of faster devices at lower cost. However, the electrical interconnections do not scale to keep pace as the transistors get faster. Though there are other approaches to electrical interconnects that may help well, optics is arguably a very interesting physical mean of interconnection that can in principle address most, if not all, of the problems met in electrical interconnections. The potential benefits of optical interconnects are briefly introduced in the first part of this paper.

Although theoretically attractive, implementing optical interconnects to silicon based chips still faces many technical challenges. The monolithic integration of electronics and optics on silicon chips is possible but with numerous obstacles. The related issue known as silicon photonics, including the generation, modulation and detection of light is discussed in the second part of this paper based mainly on the recent leading work done by Intel.

II. Potential Benefits of Optics

A. Scaling of Interconnects

For an electrical interconnect with an effective cross-sectional area *A* and length *l*, it has the "Aspect Ratio" limit defined as A/l^2 [1]. This limit is due to the fact that almost all the conventional electrical lines possess resistance and can be modeled as "resistive-capacitive" (*RC*) lines, which results in the rise-time scaling problem. From a simple calculation [2], we can intuitively understand this problem.

Consider the wire has a capacitance per unit length C_i and a resistance per unit length R_i. The total *RC* time constant of the wire is then $R_i C_i l^2$. Now if we shrink the line in all the dimensions by some factor *s*, the resistance per unit will be increased to R_i/s^2 and the length of the line will be shrunk to sl, while the capacitance per unit remains the same. Therefore the total *RC* time constant of the shrunk line is $(R_i/s^2)C_i(sl)^2 = R_i C_i l^2$, the same as before. This means the on-chip wires are not keeping up as the transistors on a chip in general get faster as the technology dimension shrinks. From other points of the view, the total resistance $R \propto l/A$, the total capacitance $C \propto l$, hence the bit-rate capacity *B*, which is $\propto 1/RC$, is limited by $B \propto A/l^2$.

However, optical interconnects do not suffer from this limit by the fact that there is essentially no distance-dependent optical loss over the scale of a machine or even a computer room with optical interconnects. So we can expect an aggregate bandwidth for data transmission with optical interconnect, which is too costly for a copper-based solution.

B. Other Benefits

1) Timing Accuracy: The predictability of timing of optical signals could be physically possible to eliminate synchronizing circuits in interconnect links, which reduce the power dissipation and the chip area for clock distribution.

2) Design Simplification: a). Optical interconnects provide voltage isolation because of the quantum nature of optical sourcing and detection: optical detectors essentially count photons, not measure voltages. b). Wave reflection and impedance matching are essentially absent in optical interconnects due to the intrinsic phenomenon of quantum impedance conversion of all optoelectronic devices. c). Optical interconnects could avoid inductive crosstalk since the absence of pin inductance existing in electrical interconnects. d). The carrier frequency of optics is so high that optical interconnect is almost frequency independent. These characteristics all result in the design simplification of optical interconnects.

III. Implementation of Silicon Opto-electronics

When come to the details of the implementation of that optical interconnect, it is not that easy as one thought. The architecture, the transmission medium, the integration platform, and finally the level of integration [3] are all issues should be considered. Here we discuss three blocks of the

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Manuscript received December 12, 2006.

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technology based on the recent leading work done by Intel to gain primary knowledge of the whole process.

A. Si-based Light Source

Achieving a silicon laser has been one of the most challenging goals in silicon photonics due to bulk silicon's indirect band-gap. Recently, Intel developed a Raman Silicon Laser, shown in Fig. 1, using stimulated Raman scattering (SRS) to demonstrate light amplification and lasing in silicon [4]. Raman scattering is a nonlinear optics effect. In order to obtain a large optical gain due to SRS in silicon, it is preferable to use a silicon waveguide configuration. The S-shaped curve is also designed to increase the interaction length but keep the device compact. The optical coatings applied to the facets act as reflectors to achieve lasing. The reflectivity of the front dichroic coating is about 71% for the Raman wavelength of 1,686nm and about 24% for the pump wavelength of 1,550 nm. The back facet has a broadband high reflectivity coating of about 90% for both pump and Raman wavelengths (Fig. 1a).

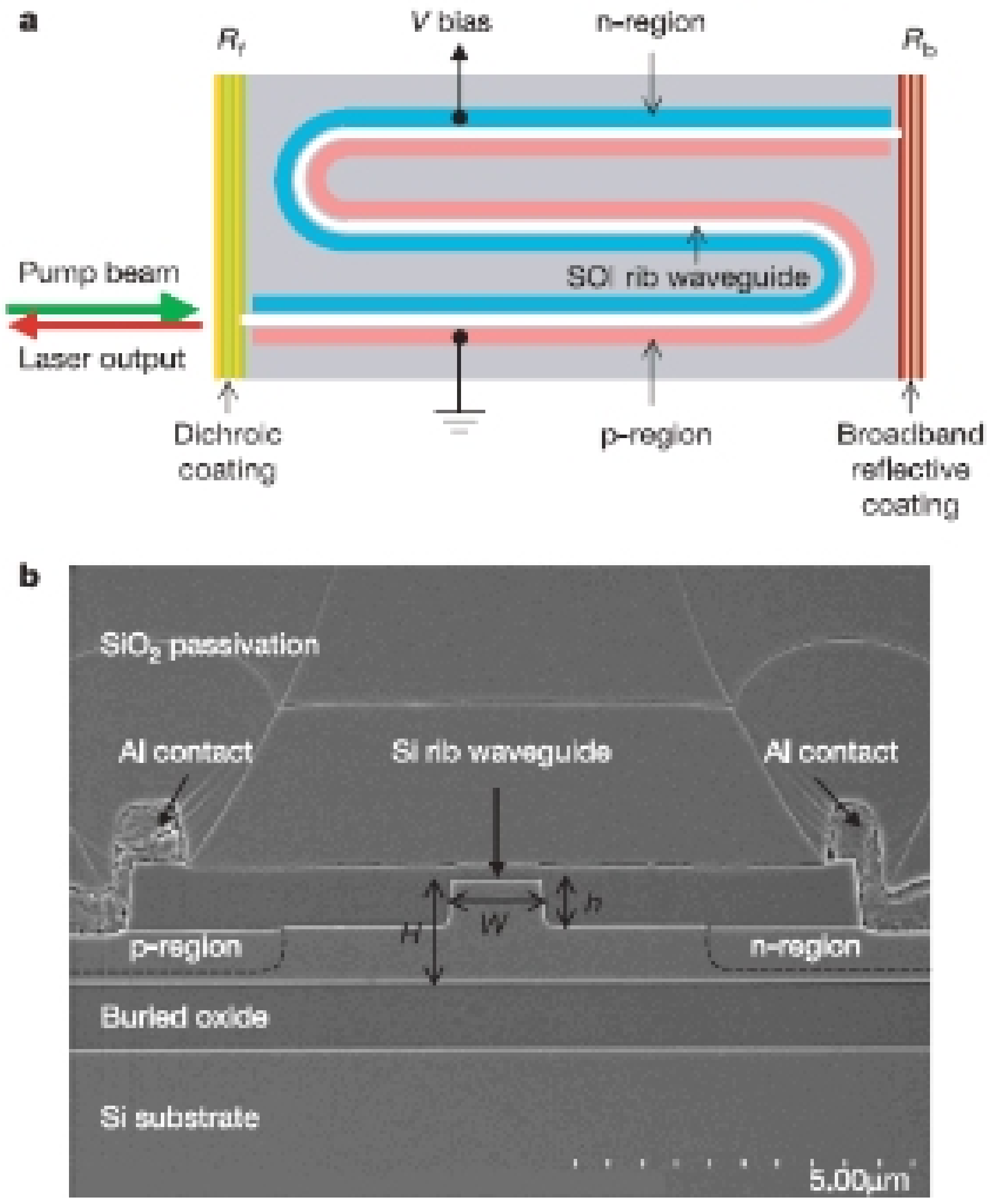

Fig. 1. Raman Silicon Laser. **a**, Schematic layout of the Si-waveguide laser cavity with optical coatings applied to the facets. **b**, Scanning electron microscope cross-section image of a Si rib waveguide with a p-i-n structure. [5]

The reversed bias to the p-i-n diode embedded in the silicon waveguide is to eliminate the two-photon absorption -induced free carrier absorption (TPA-induced FCA), which exaggerated the nonlinear optical loss.

Stable single mode continuous-wave laser output with side-mode suppression of over 55 dB and line-width of less than 80 MHz is achieved. The demonstration of a Raman Silicon Laser represents a significant milestone for silicon-based optoelectronic devices.

B. Silicon Optical Modulator

A high-speed silicon modulator is achieved by using a novel phase shifter based on a metal-oxide-semiconductor (MOS) capacitor embedded in a passive silicon waveguide Mach-Zehnder Interferometer (MZI), shown in Fig. 2.

A positive drive voltage, V_D, is applied to the p-type poly-silicon causing a thin charge layer to accumulate on both sides of the gate oxide. The voltage-induced charge density change ΔN_e (for electrons) and ΔN_h (for holes) is related to the drive voltage by [3]

$$\Delta N_e = \Delta N_h = \frac{\varepsilon_0 \varepsilon_r}{e t_{ox} t}[V_D - V_{FB}] \qquad (1)$$

where ε_0 and ε_r are the vacuum and low frequency relative permittivity of the oxide, e is the electron charge, t_{ox} is the gate oxide thickness, t is the effective charge layer thickness, and V_{FB} is the flat band voltage of the MOS capacitor.

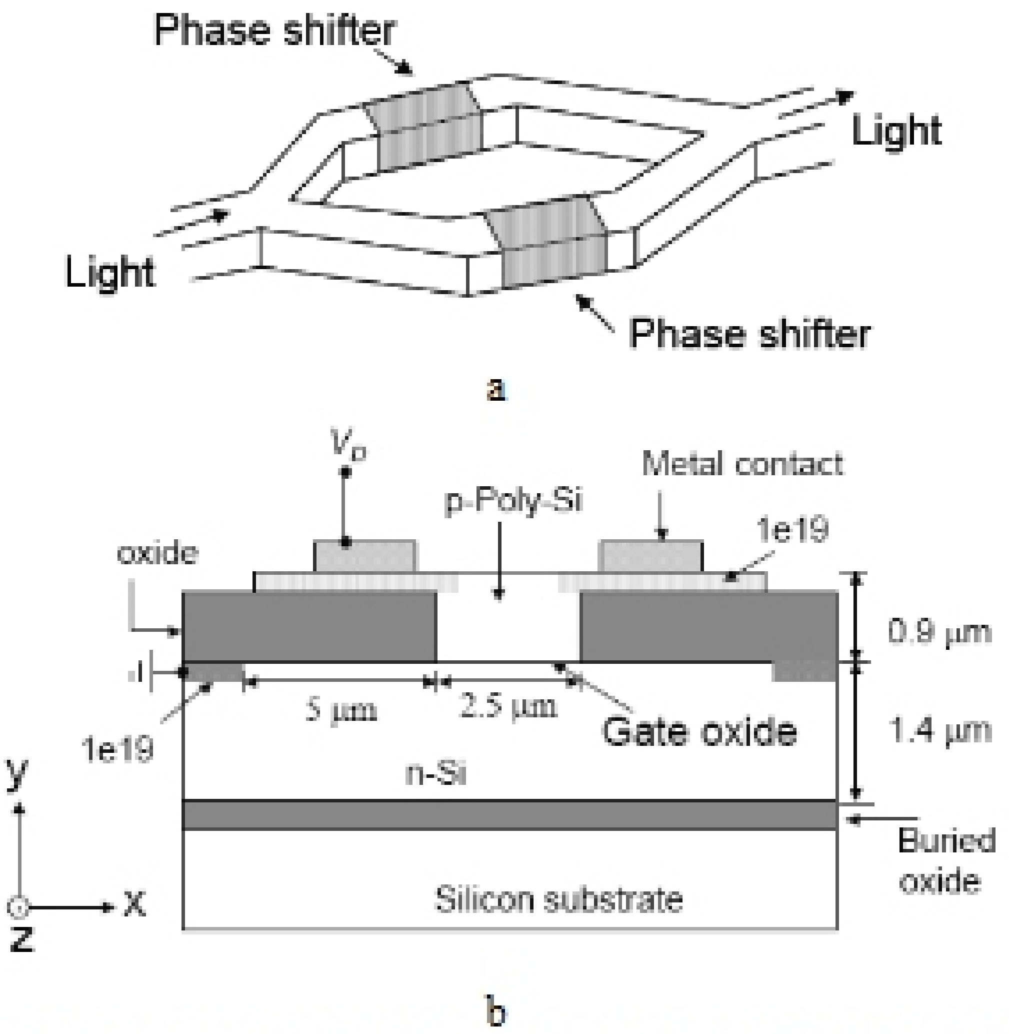

Fig. 2. Silicon Modulator. **a**, MZI with two phase shifter sections. **b**, The cross-sectional view of a MOS capacitor waveguide phase shifter in SOI. [3]

The free carrier plasma dispersion effect results in the change of refractive index induced by the accumulated charges in the silicon. The relation is given by [3] from experiment data

$$\Delta n_e \propto \Delta N_e \qquad (2)$$

$$\Delta n_k \propto (\Delta N_k)^{0.8} \quad (3)$$

The change in refractive index eventually causes a phase shift in the optical mode by

$$\Delta\phi = 2\pi\Delta n_{eff} L/\lambda \quad (4)$$

where L is the length of the phase shifter, λ is the wavelength of light in free space, and Δn_{eff} is the effective index change in the waveguide.

Because charge transport in the MOS capacitor is governed by majority carriers, device bandwidth is not limited by the relatively slow carrier recombination processes of pin diode devices. Therefore, this capacitor-based design can achieve an enormous bandwidth that is unprecedented in a silicon-based modulator. Fig. 3 shows that the phase shifter has an intrinsic bandwidth of approximately 2.5GHz.

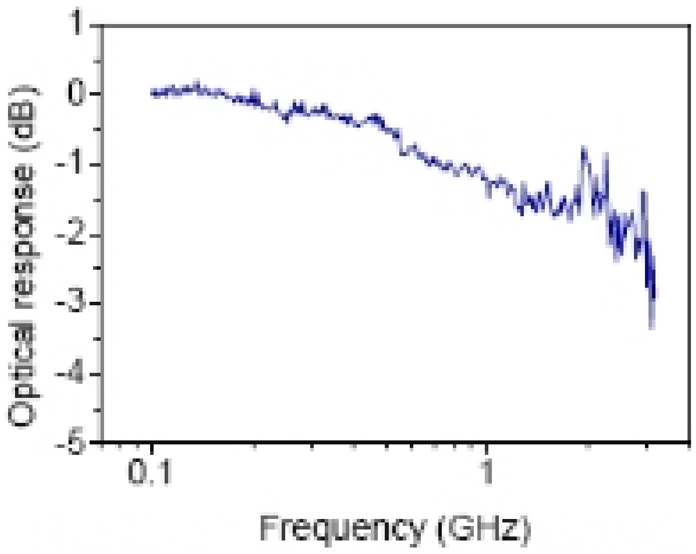

Fig. 3. Optical response of the phase shifter. [3]

C. Si-based Photodetector

In the optical domain of infrared wavelength (1.3μm – 1.6μm), silicon is an exceptional medium for guiding optical data. So most communication-grade semiconductor lasers are operating in this region, where, however, silicon is a poor detector.

Fig. 4 shows the absorption coefficient of pure silicon at the wavelength of 1.3μm and 1.55μm is extremely small, but if we introduce germanium to silicon, the detectable wavelength region of SiGe would cover those two wavelengths.

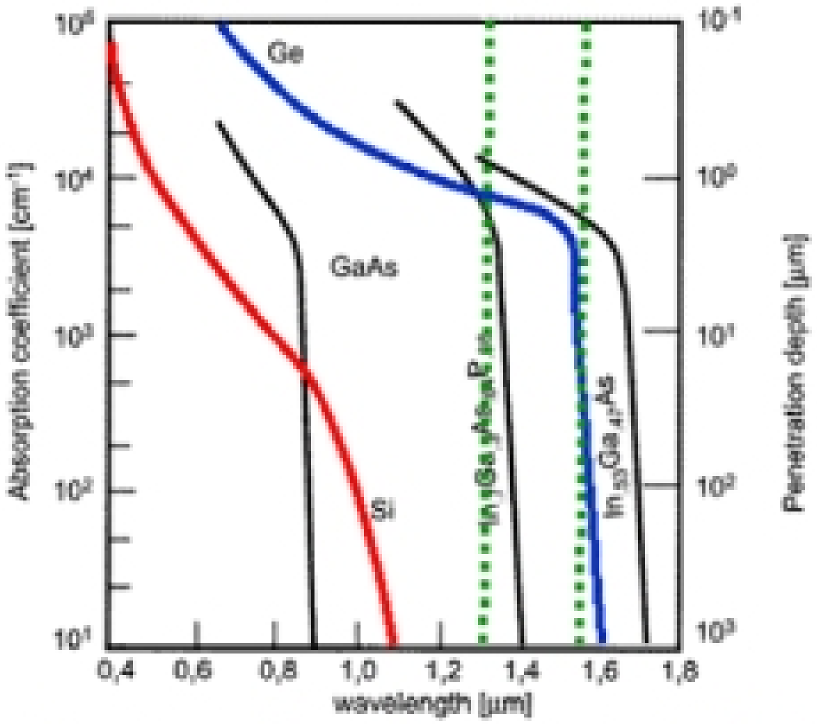

Fig. 4. Absorption coefficient and penetration depth of various bulk materials. The green lines mark the important wavelengths for telecommunications of 1.310 and 1.550 μm. [3]

The same SOI platform as the modulator work is used to make SiGe waveguide-based photodetectors, as shown in Fig. 5. The SiGe multiple quantum wells (MQW) layer is on top of a p-Si rib waveguide. The light illuminates the device from the side to maximize the absorption of the light and minimize the transit time of the device. The responsivity of the device can be improved through a combination of increasing the number of quantum wells and changing the placement of the SiGe in the waveguide.

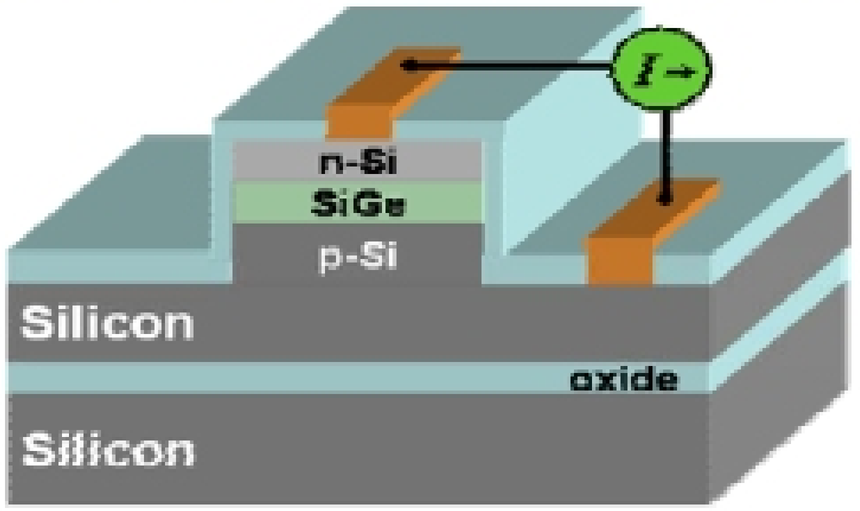

Fig. 5. SiGe waveguide-based photodetector on a SOI wafer. [3]

IV. CONCLUSION

The concept of optical interconnect brings a brilliant future for the dense interconnects to the silicon chips. And the recent achievement in Intel of the silicon laser, silicon optical modulator and silicon-based photodetector shows the potential of monolithic integration of silicon-based optoelectronics.

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