Fabrication of circular Si waveguides on bulk Si substrate by KrF Excimer Laser System for Optical Interconnect

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Outline

- Integration of electronics and photonics on a single chip
  - Data transmission
  - Power dissipation
  - Incompatibility between electronics and photonics
- The method to produce Si waveguides on non-SOI substrates
  - Deep RIE etching
  - Laser reformation
  - Oxidation
- Fiber-like optical mode
- Summary
Colossal amount of data!

• The collective knowledge accumulated by mankind since the beginning of history to 2000 A.D. is estimated to be around five exabytes \((5 \times 10^9\) gigabytes). A further 487 exabytes of data was generated in 2000–2009, and that by now we are producing around 2,500 exabytes of data every year. (Data reported by Microphotonics Center at the Massachusetts Institute of Technology, USA.)

• A major portion of this is driven by web-based multimedia such as social-networking sites, which require significant bandwidths to transport and store images.
Energy usage

• Internet usage and data storage are both currently growing at a rate of ~50% per year.

• By 2018, the energy used as a result of Internet traffic may comprise 10% of the world’s total energy usage.

• This power dissipation is significantly contributed by interconnects and increases super-linearly as clock speed increases.
Power dissipation ceiling

- Moore’s Law is being threatened by the rapid increase in the power dissipated from electronic chips as devices reduce in size and increase in speed.
- Thermal budge causes performance saturation in single-core processors.
- Power-efficient performance has therefore required the use of multicore processors which exploit multi-threaded architecture to hide memory latency.

(The right figures are ref. from Kaveh Azar, the history of power dissipation, http://www.electronics-cooling.com/2000/01/the-history-of-power-dissipation/)
Optical transmission

• Optical interconnection is also expected to provide much larger bandwidth density for buses and networks than electrical interconnection. Wavelength-division multiplexing (WDM) technology provides a way to further increase data capacity.

• In addition, silicon photonics that utilizes scalable CMOS technology may offer a highly integrated photonics transmission platform for such applications.

R. Colin Johnson, IBM Preps Optics to Replace Copper Interconnects (2010-03-11), http://www.smartertechnology.com/c/a/Technology-For-Change/IBM-Preps-Optics-to-Replace-Copper-Interconnects/
Power consumption (mW) in electrical and optical interconnects

- The power consumption of both the electrical and optical interconnects increases due to the higher signal switching frequencies and greater leakage current. Optical interconnect consumes less power than electrical interconnect for all of the technology nodes.

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<tr>
<td>Technology node</td>
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<td>65 nm</td>
<td>45 nm</td>
<td>32 nm</td>
<td>22 nm</td>
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<tr>
<td>Transmitter</td>
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<td>1.9</td>
<td>3.4</td>
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<tr>
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<td>2.4</td>
<td>3.7</td>
<td>6.2</td>
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<td>16.9</td>
<td>21.7</td>
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</table>

(Ref. from G. Chen et al., “Predictions of CMOS compatible on-chip optical interconnect,” INTEGRATION, the VLSI journal 40 (2007) 434–446)
Si photonics based on SOI substrate

- Boasting low-cost substrates and mature manufacturing infrastructure, silicon photonics represents a path toward mass manufacturing of discrete optical components, as well as integrated transceivers for synchronous optical network, gigabit Ethernet, and optical backplane markets.

The strong confinement of light in silicon-insulator (SOI) materials enables silicon light guides to be scale down to ultra-small cross-sections (0.1um²).

Richard Osgood, “Silicon photonic wire use for on-chip communication and control,” SPIE Newsroom 2008

F Y Gardes et al., “Sub-micron optical waveguides for silicon photonics formed via the Local Oxidation of Silicon (LOCOS),” Proc. of SPIE Vol. 6898

Low-loss waveguides on SOI substrate

- Hydrogen annealing at 1100°C
- RMS roughness is reduced to 0.26 nm

- Oxidation-induced improvement for Si wire waveguides
- RMS roughness is reduced to 0.5 nm


- Wet chemical method to smooth sidewall
- RMS roughness is reduced to 0.7 nm
Incompatibility using a SOI substrate

- One of the main drawbacks of the integration of optics on the transistor layer is the need for extensive cladding material, typically a few micrometers of silica surrounding the silicon core waveguide.
- In electronics, however, only a small layer of SiO$_2$ is needed.
- Having more than a few hundred nanometers of SiO$_2$ underneath the Si waveguide creates incompatibility with the CMOS transistor layer, which necessitates thermal conduction through the silicon substrate.

Require different thickness of oxide layer in electronics and photonics!
Use a high-power laser to reform Si ridges

- A method to fabricate Si/SiO2 waveguides from bulk silicon using laser reformation technique is presented.
- The main process is to melt the Si ridges into the circular-profile structure by excimer laser and then oxidize it. This causes a structure with a wider upper part and a narrower bottom part. After uniformly oxidizing the structure, Si waveguides can be formed on the top.
Creating a high-aspect-ratio fin

• The geometry of the Si ridges before laser illumination is crucial for the profile transformation.

• Low-power reactive-ion-etch (RIE) using SF6 and CHF3 gases was applied to create extremely high-anisotropic Si ridges.

\[
\text{SF}_6 : \text{CHF}_3 = 6 : 50 \quad \text{SF}_6 : \text{CHF}_3 = 7 : 50 \quad \text{SF}_6 : \text{CHF}_3 = 8 : 50 \quad \text{SF}_6 : \text{CHF}_3 = 8 : 50
\]

~50nm
Profile transformation in different widths

Laser reformation

Irregular profile transformation
Thermal conduction

The molten depths can be determined by heat transfer equation, which includes wavelength, pulse duration, incident angles, and energy densities as the parameters. Assuming absorbed light is totally converted to heat, the heat generation rate per unit area (W/cm²) at the illuminated surface is derived from the Fresnel formulas for the regime of strong absorption as the following equation.

The calculated molten depth is useful in the profile transformation analysis and in the selection of energy densities in laser reformation.

\[
g(t) = \frac{E \beta(t)}{\tau_d} \cos \theta_i \left( r_\perp \frac{n_2}{n_1} \right) \left[ \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_i + (n_2 + i\kappa_2) \cos \theta_i} \right]^2 + r_{\parallel} \frac{n_2}{n_1} \left[ \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_i + (n_2 + i\kappa_2) \cos \theta_i} \right]^2 \right\}
\]
Circular profile after illumination

- A ridge perfectly transformed into a circular-profile structure.
- Surface tension supported and formed this structure during the silicon was melted.
- The surface of the reformed structure was extremely smooth, which is advantageous to the reduction of scattering loss.
There was wavy morphology after laser illumination.

The P-R instability was more severe in the narrower ridges.
Enlarge the size of Si ridges

- To avoid P-R instability, we deliberately enlarge the size of Si ridges.
- The ridge with the width of 500nm transformed into an approximately circular profile. However, there are still ups and downs.
- The ridge with the width of 600nm transformed into an ellipse-like profile. Nevertheless, the profile is quite uniform in the light transmission direction.
Oxidation (1)

- The difference between upper width and bottom width of the reformed structure determines the diameter of the waveguide core after oxidation.
- The finally oxidation process have to be controlled accurately. Twice oxidations were applied to completely isolate the upper Si core.
Oxidation (2)

- The profile would further change after oxidation.
- In this case, the oxidation time is not enough to completely oxidize the neck of the structure. This may cause serious light leaking into the substrate.
Discussion

- The Si waveguide core was isolated from the Si substrate. The core diameter is about 400nm. The distance between Si waveguide and Si substrate can be further increased.
The Optical mode is like that of optical fiber

- The structure can be formulated by applying conventional fiber principle.
- It shows the potential of the coupling loss reduction with fiber since the cross section is matched.

Wavelength: 1550nm
Index of Core ($n_1$): 3.45
Index of Cladding ($n_2$): 1.45
Core diameter ($a$): 300nm

$$V\text{-number} = k_0^2a^2(n_1^2-n_2^2) = 1.9035 < 2.405 \Rightarrow \text{single mode}$$
Design using optical fiber formulation

Single mode waveguide can be achieved under the condition of the Si/SiO$_2$ waveguide with the Si core diameter below 380nm.
Summary

- An incompatibility for the integration of optics and electronics on a single chip occur due to large difference of oxide layer. Here, a novel method to fabricate Si/SiO₂ waveguides from non-SOI substrate using laser reformation technique is demonstrated.

- Under proper illuminating condition, the Si ridges would be melted and reshaped to circular-profile structure. An optical fiber-like formulation can be easily applied to this structure. The process provides a new platform to design optoelectronic devices on a single chip.