Bonded Photonic Structure Incorporated into a Chip

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Outline

1. Optical Interconnection
2. Interconnect Era
3. Nanophotonics
4. Si Photonics for Photonic NW: or vice versa
5. Summary
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Optical Interconnects in Electronics

Penetration of high data capacity optical communication from long-haul to short-distance interconnect.

- Telecommunication: km
- Between Computers: m
- Between Boards: cm
- Between Chips: mm

Larger Market

Smaller Distance
On-Bord Optical Interconnection

Short Electrical Signal lines

Optical Fibers

Photoelectric Devices

- 10Gbps x 4 Ch Transceiver
- 14mm x 14mm

Courtesy of K. Kurata
Optical Interconnection between CPU & Memory in HPC

- Small size of 5 mm$^2$, 20 Gbps x 12ch OE/EO converters with a water-cooling module
- ~1000-channel OE converter is attached around CPU
- High reliability VCSEL ($\lambda = 1.07 \mu m$) is developed

Courtesy of K. Kurata
Replacement of Electrical Interconnect to Optical One

External EO/OE Module

Optical Interconnect Using Photonic SiP

LSI On-chip Optical Interconnect

50-200 mm

5-10 mm

<5 mm

Courtesy of Y. Hashimoto & S. Yanagimachi

Electrical Interconnect

Optical Interconnect

Optical Connector

LSI

EO/OE

Waveguide

Fiber

3D LSI

Empowered by Innovation

NEC
Cross Point for On Board Interconnection

75 cm @ 6 Gbps

Optics gives lower power consumption for back plane (~1 m)

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In 2012, a 1-mm-long interconnect’s latency will be 100 times larger, and its binary switching energy will be 30 times larger, than a corresponding transistor. 

Dynamic power is larger than heat removal capacity

N. Magen et al, *SLIP 04*
Electrical Interconnect

20 mm-interconnects with repeaters

M. Mizuno et al., ISSCC 2001
Electrical Interconnect

Bill Dally, ISSCC 2005

<table>
<thead>
<tr>
<th>Operation</th>
<th>Energy (130 nm, 1.2 V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32-bit ALU operation</td>
<td>5 pJ</td>
</tr>
<tr>
<td>32-bit register read</td>
<td>10 pJ</td>
</tr>
<tr>
<td>Read 32 bits from 8K RAM</td>
<td>50 pJ</td>
</tr>
<tr>
<td>Move 32 bits across 10 mm chip</td>
<td>100 pJ</td>
</tr>
<tr>
<td>Move 32 bits off chip</td>
<td>1300 to 1900 pJ</td>
</tr>
</tbody>
</table>

High Power Consumption by Interconnect
From Electrical To Optical

Electrical Interconnect

Circuit

Cu/Low-k, Repeaters

Optical Interconnect

Light Source

Driver

Modulator

Optical Waveguide

Amp

Photodiode

Circuit

Advantages: No repeaters, Small delay, Small jitter, Immune to EMI, High data capacity, …
Reduce overhead by introducing micro EO and OE devices @10 Gbps.

Current

Target

Optical Interconnect

Electric Interconnect

hp65(2007)

hp22(2016)

1pJ / 1bit

1W / 1Tbps
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Size Comparison: Light vs. Electron

Wavelength of **light** (visible - near IR)

\[ \sim 1000 \text{ nm} \]

De Broglie wavelength of **electron**

\[ \sim 0.1 \text{ nm} \ (100 \text{ V}) \]

\[ \frac{1}{2} \sim \frac{1}{5} \]

\[ \frac{1}{5} \sim \frac{1}{100} \]

Si Photonics

Photonic Crystal

Surface Plasmons

Near-Field

materials
+ metamaterial

Empowered by Innovation

NEC
Contour map of light power (in Z direction)

SiON Waveguide

Ag electrode embedded in Si

Input light (TM polarized)

1.1 μm

Si nano-photodiode

Contour map of electric field

Z' (μm)

Coupling length ~10 μm


SiON Waveguide

Si plasmon photodiode

Pad

2 μm
Bonding Optical Interconnect on LSI

Optical Interconnect Chip (front side for bonding)

Optical Interconnect Chip (front side for bonding)

Optical Signal

SiON waveguide

Si nano-photodiode

LSI chip

Bonded Structure (Cross-Section)

Si nano-photodiode

Flip-Chip Bonding with LSI Chip

Face-to-face bonding gives short vias $\rightarrow$ >10 GHz

Large tolerance for alignment compared with optical via

- Large tolerance for alignment ($\pm 5 \, \mu m$)

Diagram showing:
- Optical Interconnect Chip
- Si Nano-Photodiode
- SiON Core
- Cu-via
- LSI Chip
- Flip-Chip Bonding
- AuSn Bump
- SiO$_2$

15 $\mu m$
5-GHz optical pulses triggered the LSI circuits

Pulses from Light Source (5GHz)

Optical Interconnect Chip

Output signal from electronic circuit

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Optical Switch

World’s smallest 1 x 4 Optical Switch Chip (190×75 μm²)

Input light

Output light

1×4 Optical SW Module

Courtesy of T. Chu
**One-Chip Colorless MUX/DEMUX Using Si Photonic Circuit**

Using Si waveguides, an AWG and switches were integrated into a chip. Low-power and quick reconfiguration of optical paths within a 2-mm device was demonstrated.

S. Nakamura, et al., ECOC2008, Tu.4.C.6
More than 50% of production cost for state-of-the-art LSIs comes from interconnect. … T. Shibata (Toshiba) 2008.

- On-chip optical WDM
  (Wavelength Division Multiplexing)
  - Data transfer rate increase (\(\sim\) one order)
  - Reduction of pin #

- On-plain crossing by optical waveguides
  - Less interconnection layers
  - Less crosstalk
Optical Ring Bus Connecting Chip & Memories

- Memory array
- SDRAM with opt. I/F
- Optical clock
- Multiple wavelength light sources
- Serial to parallel conversion
- Clock synchronization
- MUX
- DEMUX
- Bank 1, Bank 2, Bank 3, Bank 4
- Multi-bank memory I/F
- IP's via NoC
- Write
- Read
3-D Integration + Optical Interconnect

Integrated Optical Layer / LSI Chip
(Optical Clocking)

On-Chip WDM

Input WDM Signal

Output WDM Signal

3-D Integrated LSI
On-Chip Optical Network

- **Functional Block (Core)**
- **Waveguide**
- **Micro-node**
  - PD
  - Mod/ SW
  - AWG/ Filter
- **Adjacent Chip**
- **WDM Signal**
  - (Data + Clock)
WDM Circuit with Si Nano Photodiode

SiON Waveguide for On-chip WDM

Branching Structure

Si Nano Photodiode
10 GHz signal from WDM signal was extracted by the integrated demultiplexer and Si nano photodiode. Crosstalk noise; less than -10dB.
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• We proposed an approach for on-chip optical interconnect suitable for 3-D integration.

• Flip-chip bonding of an optical interconnect chip with a LSI reduces the electrical path enough to obtain high speed response of >10 GHz.