Optical Interconnection in Silicon LSI

Shin Yokoyama, Yuichiro Tanushi, and Masato Suzuki
Research Center for Integrated Systems
Hiroshima University, Japan
http://www.rcis.hiroshima-u.ac.jp/rcns/

I. Introduction
II. Ring Resonator Optical Switches using Electro-Optic (EO) Material (Ba,Sr)TiO₃ (BST)
III. Mach-Zehnder Modulator using EO Material
IV. Optical Switches using Magneto-Optic Material
V. Optical Switches using Si Ring Resonator
VI. Summary

Why Optical Interconnection? (①Ultra High Frequency)

Why Optical Interconnection?
②Small Size
Optical Waveguide
Coaxial Transmission Line

Present Status of Usage of Optical Communication

Optical Interconnection is introduced in Cellular Phone

Oct. 1, 2005
Asahi Newspaper
Si Ring Resonator Optical Switch

Carrier injection into pin junction causes modulation of refractive index.

Shift of Resonance Wavelength

Operation at 1.5 Gbit/s


Outline

I. Introduction

II. Ring Resonator Optical Switches using Electro-Optic (EO) Material (Ba,Sr)TiO₃ (BST)

III. Mach-Zehnder Modulator using EO Material

IV. Optical Switches using Magneto-Optic Material

V. Optical Switches using Si Ring Resonator

VI. Summary

I. Introduction

II. Ring Resonator Optical Switches using Electro-Optic (EO) Material (Ba,Sr)TiO₃ (BST)

III. Mach-Zehnder Modulator using EO Material

IV. Optical Switches using Magneto-Optic Material

V. Optical Switches using Si Ring Resonator

VI. Summary

Change in Clock Frequency of CPU

Jump by Optical Interconnection

Power (dB)

10G
100M
1G
100M
10M
10G
1993 1995 1997 1999 2001 2003 2005
Year

Target: Optical Global Interconnection in Si LSI

- Ring resonance type switch is used for miniaturization.
- Electro-optic (EO) material (Ba,Sr)TiO₃ (BST) is used for optical switches.
- Optical switches are integrated on the top layer (process temp.<450°C)

Optical Switches using Ring Resonator

Resonance Characteristics

Resonance: \( \lambda = \frac{2\pi n_{eff} R}{m} \)

EO Effect: \( \Delta\lambda = 2\pi R \cdot \Delta n_{eff} = 2\pi R \left( -\frac{1}{2} n_{ref}^2 r E \right) \)

Switching Gain: 17 dB

Switching Gain of 17 dB at \( \Delta n_{eff} = 5\times10^{-4} \)

Ring Radius: 12 \( \mu \)m

Width of Waveguide: 2 \( \mu \)m

Gap: 0.1 \( \mu \)m

1G
10M
100M
10G

Resonance peak becomes sharp with increasing in round time of the light.

Operation Speed of Ring Resonator Switch

Factors
- Polarization Time of EO Material
- RC Time Constant of Device
- Resonance Time of Ring

Resonance time determines the switching speed. ~ 100 GHz at R=12 μm

Outline
I. Introduction
II. Ring Resonator Optical Switches using Electro-Optic(EO) Material (Ba,Sr)TiO₃ (BST)
III. Mach-Zehnder Modulator using EO Material
IV. Optical Switches using Magneto-Optic Material
V. Optical Switches using Si Ring Resonator
VI. Summary

(Ba,Sr)TiO₃ Film Formation by Spin-Coat

Spin-Coat
Repeat, 80 nm/cycle ▶ Final Thickness 500 nm
Drop Source Liquid
Rotation
600 rpm, 10 s
2000 rpm, 20 s
Low Temp. Bake
180°C, 10 min
High Temp. Bake
450°C, 30 min

Post Anneal for Crystallization 450~750°C

Annealing Behavior
XRD Spectra

Surface Roughness

Poly-Crystallized at >550 °C
Roughness increases with Temp.
550°C Annealed Film is used.
**Fabricated Mach-Zehnder Optical Modulator**

**Plan View**

- **Input**: 633 nm
- **Output**: 0.6 mm

**Plan View Photograph**

**Cross Section**

- **Monolithic Integration on Si Substrate**

---

**First Demonstration of Monolithic Optical Modulator using EO Material**

**Measurement System**

- **Optical Modulation by 2-3% at 90V (E=1.7x10⁶ V/cm)**
- **Process Temp. of 550°C ≥ 450°C Too High**


---

**Mach-Zehnder Optical Modulator**

**Mach-Zehnder Interferometer (MZI)**

- **Input Light**
- **Output Light**
- **Electro-Optic Material (Ba,Sr)TiO₃ (BST)***
- **Ever Introduced in Si Process**
- **Spin-Coat Easy Fabrication**
- **Sputter Low Temperature Good Crystallinity**

---

**Sputter Deposition of (Ba,Sr)TiO₃ Film**

- **RF Power Source**
- **13.56 MHz**

<table>
<thead>
<tr>
<th>RF Power</th>
<th>50 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Pressure</td>
<td>1.2 x10⁻⁶ Pa</td>
</tr>
<tr>
<td>Sputtering Gas</td>
<td>Ar : O₂ = 4 : 1</td>
</tr>
<tr>
<td>Pressure</td>
<td>2.0 Pa</td>
</tr>
<tr>
<td>Substrate Temperature</td>
<td>23-700°C</td>
</tr>
<tr>
<td>Deposition Rate</td>
<td>1.0 nm/min</td>
</tr>
</tbody>
</table>

---

**Crystallinity and Optical Property**

**XRD Spectra for Sputtered BST**

- **Thickness: 300 nm**
- **BST (200)**
- **10 mm**
- **400 mm**
- **600 mm**

- **Light Propagation Loss versus Crystallinity**

- **High Crystallinity causes Loss of Light Propagation**
- **Deposition at 450°C → 470 dB/cm**
- **Acceptable Temp. after Metallization**

---

**Mach-Zehnder Modulator using Sputtered BST**

- **Si₃N₄ and BST series connection is used because of high propagation loss of BST.**
- **Loss of BST phase shifter (400 μm) is ~19dB.**

---

*Images and diagrams are not included in the text representation.*
Optical Modulation of Mach-Zehnder Modulator using Sputtered BST

Device
- Dep. Temp. = 450°C
- Ref. Index of BST = 2.3
- Length of BST WG = 400 μm
- Width of WG = 20 μm
- Thickness of BST = 0.27 μm

Measurement
- Input: He-Ne laser (633 nm)
- Modulation by ~10% at 200 V (E=1.2x10^5 V/cm)

Low temperature formation of 450°C, acceptable for the process after metallization.

Sub-Summary and Improvement Plan

<table>
<thead>
<tr>
<th>Spin-Coat BST</th>
<th>Sputtered BST</th>
<th>Plan (Sputtered BST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance Index</td>
<td>60</td>
<td>36</td>
</tr>
<tr>
<td>Distance between Al Electrodes</td>
<td>15 μm</td>
<td>2.27 μm</td>
</tr>
<tr>
<td>EO Coeff. (pm/V)</td>
<td>5.2</td>
<td>25.2</td>
</tr>
<tr>
<td>Dep. Temp.</td>
<td>550 °C</td>
<td>450 °C</td>
</tr>
</tbody>
</table>

- Al direct contact to BST
- Miniaturization

Ring Resonator Optical Switches using Magneto-Optic Material

Low Voltage Operation <0.1 V

Electric Field
- \( E_x = \frac{1}{\sqrt{2}} (E_{xL} - iE_{xH}) \)
- \( E_y = \frac{1}{\sqrt{2}} (E_{yL} + iE_{yH}) \)

Power
- Not Polarized Light: \( P \propto |E_x|^2 + |E_y|^2 \)
- Polarized Light: \( P \propto |E_x|^2 - |E_y|^2 \)

Polarizer is not necessary.

Various Electro-Optic Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Phase</th>
<th>Substrate</th>
<th>EO Coeff.(pm/V)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNbO_3</td>
<td>Bulk s-Cryst.</td>
<td>30.8</td>
<td>CZ</td>
<td></td>
</tr>
<tr>
<td>KTaO_3 × NbO_2</td>
<td>Bulk s-Cryst.</td>
<td>600</td>
<td>CZ</td>
<td></td>
</tr>
<tr>
<td>LiNbO_3</td>
<td>Poly Film</td>
<td>Glass</td>
<td>1.34</td>
<td>RF Sputter (275°C)</td>
</tr>
<tr>
<td>BaTiO_3</td>
<td>Epitaxial Film</td>
<td>MgO × Cryst.</td>
<td>22</td>
<td>MOCVD (725°C)</td>
</tr>
<tr>
<td>LiTaO_3</td>
<td>Poly Film</td>
<td>Glass</td>
<td>0.32</td>
<td>RF Sputter</td>
</tr>
<tr>
<td>(Pb,La)(Zr,Ti) O_3</td>
<td>µc Film</td>
<td>ITO</td>
<td>102</td>
<td>Aerosol Dep. (300°C)</td>
</tr>
<tr>
<td>(Ba,Sr)TiO_3</td>
<td>Poly Film</td>
<td>Thermal SiO_2</td>
<td>5.2</td>
<td>Spin-Coat (550°C, annealed)</td>
</tr>
</tbody>
</table>

Faraday Effect of Magneto-Optic Material

Sputtered Bi_2Fe_5O_12 (BIG) at Room Temp. (Amorphous)

~2% modulation is achieved at an external magnetic field of ~0.2T.

Outline

I. Introduction
II. Ring Resonator Optical Switches using Electro-Optic (EO) Material (Ba,Sr)TiO_3 (BIG)
III. Mach-Zehnder Modulator using EO Material
IV. Optical Switches using Magneto-Optic Material
V. Optical Switches using Si Ring Resonator
VI. Summary
Outline

I. Introduction
II. Ring Resonator Optical Switches using Electro-Optic (EO) Material (Ba,Sr)TiO₃ (BST)
III. Mach-Zehnder Modulator using EO Material
IV. Optical Switches using Magneto-Optic Material
V. Optical Switches using Si Ring Resonator
VI. Summary

Principle of Si Ring Optical Switch

- Refractive index is changed by carrier injection.
- Stack type optical switch is proposed.

Fabricated Si Ring Resonator

- Si nitride waveguide
- Gap : 0.2 μm

Summary

- (Ba,Sr)TiO₃ (BST) Optical Switch:
  - Low temperature (450°C) monolithic fabrication technology was developed.
  - Optical modulation of ~10% was achieved by Mach-Zehnder modulator.

- Bi₅Fe₃O₁₂ (BIG) Optical Switch:
  - Ring switch without polarizer was proposed and the characteristics were simulated.
  - Modulation of ~2% was achieved using amorphous BIG film.

Si Optical Switch:
- Stack type ring switch was proposed and ~3% modulation was demonstrated by optical pumping.

~3% of modulation is achieved by Si ring resonator optical switch.

Realization of optically interconnected LSI by improving the device properties.