Hiroshima University

Monolithic Mach-Zehnder Optical Modulator on Silicon using $(Ba,Sr)TiO_3$ Sputter-Deposited at 450°C

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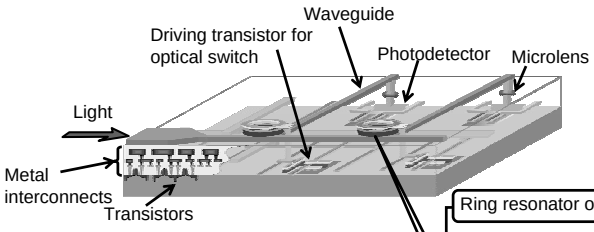
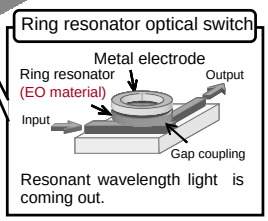
Target

LSI with optical global interconnection instead of metal interconnection



- Optical waveguides are monolithically integrated on LSI top layer.
- Optical switches are made of electro-optic (EO) material: $(Ba,Sr)TiO_3$ (BST).
- In fabrication, process temperature should not be over 450°C.

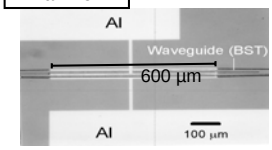


Why BST?

- BST have been already used as a dielectric film of the memory capacitors.
- BST has high EO coefficient.

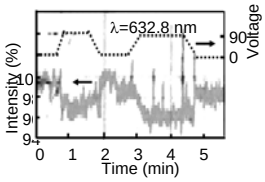
Mach-Zehnder interferometer using spin coated BST

Plan view



Annealing temperature: 550°C

Optical response of MZI

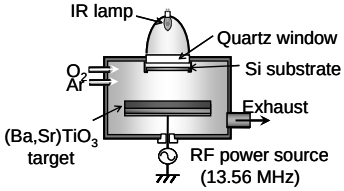


EO coefficient : 5.2 pm/V

Deposition Process

BST films were deposited by RF magnetron sputtering

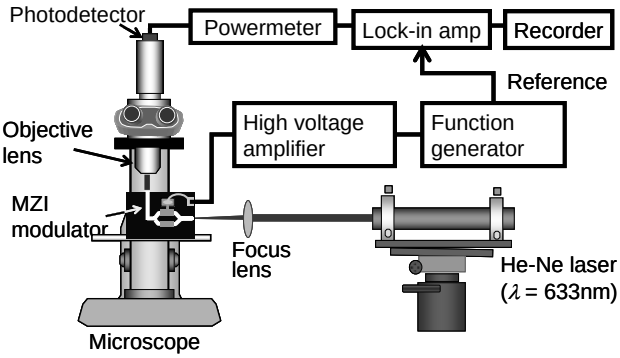
Sputtering machine



Condition

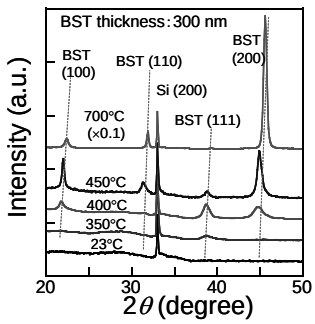
RF power	50 W
Base pressure	1.2×10^{-6} Pa
Sputtering gas	Ar : O_2 = 4 : 1
Pressure	2.0 Pa
Substrate temperature	23-700 °C
Deposition rate	1.0 nm/min

Optical Measurement System

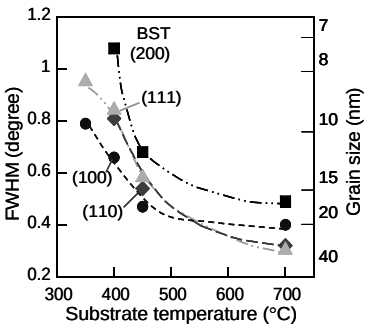


Crystallinity of Sputtered BST

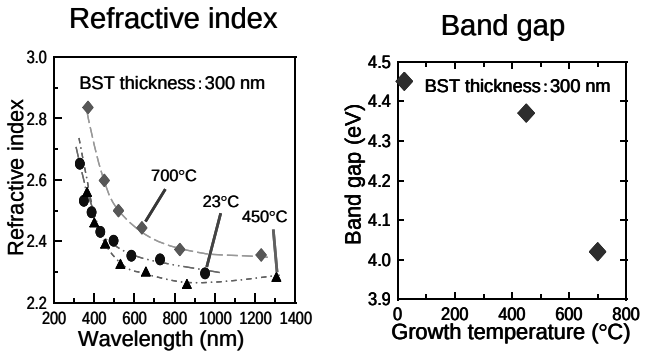
XRD spectra



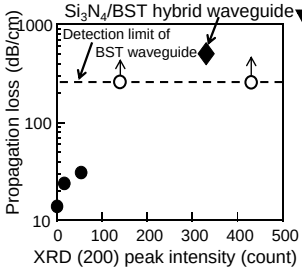
FWHM of XRD spectra and grain size of polycrystalline



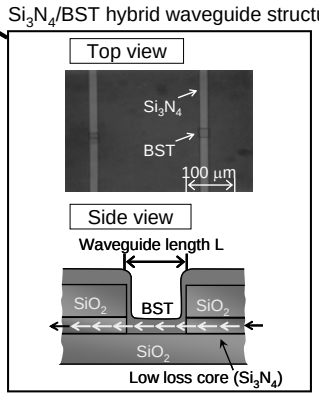
Optical Properties of BST films



Propagation Loss of BST Waveguide

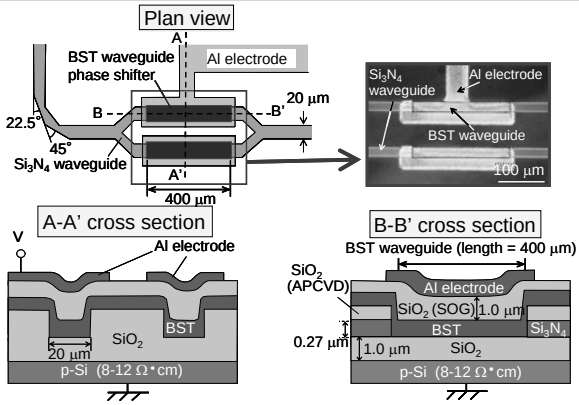


Propagation loss of the BST waveguides are rapidly increase with crystallinity



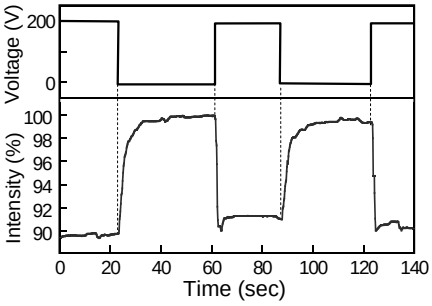
BST and Si_3N_4 waveguides are serially connected in horizontal direction.

Structure of BST Mach-Zehnder Interferometer



BST waveguide are used only for phase sifters (L= 400 μm)

Optical Response of MZI



BST conditions
- T_{sub} (deposition) : 450 °C
- Refractive index : 2.3

MZI parameter
- Phase shifter length : 400 μm
- Waveguide width : 20 μm
- Thickness : 0.27 μm

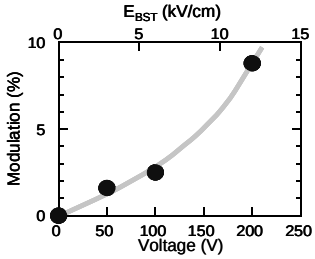
Measurement parameter
- Light source : He-Ne laser
- Wavelength : 633 nm

~10% modulation at V=200 V (E_{BST}=1.2×10^4 V/cm)

※E_{BST} mean "electric field in the BST film"

Voltage Dependence of Modulation

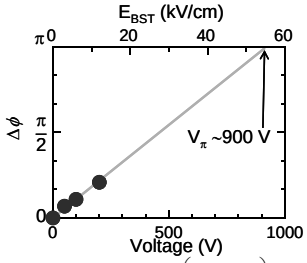
Modulation versus applied voltage



● Modulation(%) $= \frac{I_0 - I}{I_0} \times 100$

(I : Output intensity, I_0 : Initial output intensity)

Phase shift $\Delta\phi$ versus applied voltage



● $\Delta\phi = \cos^{-1}\left(2\frac{I_0}{I} - 1\right)$

performance index $V_\pi L$: ~ 36 V·cm

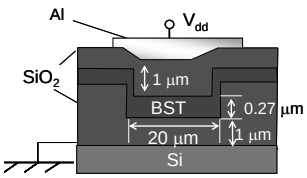
EO coefficient r: 25.2 pm/V

Comparing of Various EO Materials

Material	State	Substrate	EO coefficient (pm/V)
$KTa_{1-x}Nb_xO_3$	Bulk		600
$LiNbO_3$			30.8
$(Ba,Sr)TiO_3$	Film	Thermal SiO_2	25.2
$(Pb,La)(Zr,Ti)O_3$		ITO	102
$BaTiO_3$		MgO	22
$LiTaO_3$		Glass	0.32
$LiNbO_3$		(corning7059)	1.34

Future Work

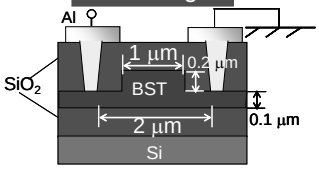
Present design



$V_\pi L$ ~ 28 V·cm

Electric field is applied to SiO_2 layer and BST layer.

New design



- Electric field is applied to BST directly.
- Scale down of device size.

$V_\pi L$ ~ 2.7 V·cm

c.f. Si MOS type MZI, $V_\pi L$ = 7.8 V·cm
Publication from Intel co. ltd.

A. Liu *et al.*, Nature 427 (2004) 615

Summary

- A monolithic Mach-Zehnder interferometer optical modulator was fabricated by using (Ba,Sr)TiO_3 (BST) sputter-deposited at 450°C.
- ~10% modulation at V=200 V (E_{BST}=1.2×10^4 V/cm) was achieved.
- EO coefficient of the BST sputter-deposited at 450°C is 25.4 pm/V.