Characterization of 1.55-μm Infrared Light Propagation in SOI Waveguide

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1. Introduction

Recently, optical wiring has been extensively studied due to its inherent no RC-delay in metal wiring. Therefore, the light waveguide is expected to be integrated on Si LSI.

In this study, waveguide structure, which is able to be integrated on Si LSI, is examined. As a substrate, silicon on insulator (SOI) is used, which is widely put to practical use in advanced LSI's. Examined structures are those with bend and MOS ones with aluminum gate as a reflective material.

While, an optical modulator of MOS structure was proposed by the authors based on free carrier absorption [1]. Recently, an MOS modulator based on permittivity change was successfully proposed [2].

2. Experimental

The SOI waveguides are fabricated on {110} SOI wafer. Thickness and resistivity of the SOI layer are 1.4 μm and 10 Ω-cm, respectively. BOX layer is 1.0-μm in thickness. Two kinds of waveguide structures are investigated as shown Fig. 1. Those are formd by TMAH anisotropic etching or ECR dry etching. In case of TMAH, {111} side walls are delineated vertically because the etch rate of {110} to {111} exceeds 130 [3], as shown in Fig. 2.

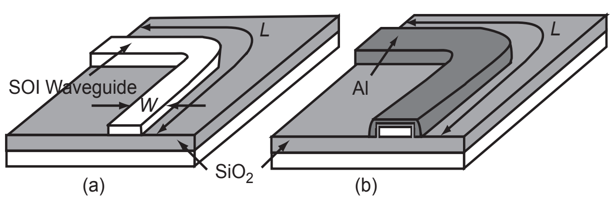


Fig. 1 Two kinds of waveguide structures : (a) air / SOI and (b) Al / 50-nm thick SiO_2 / SOI.

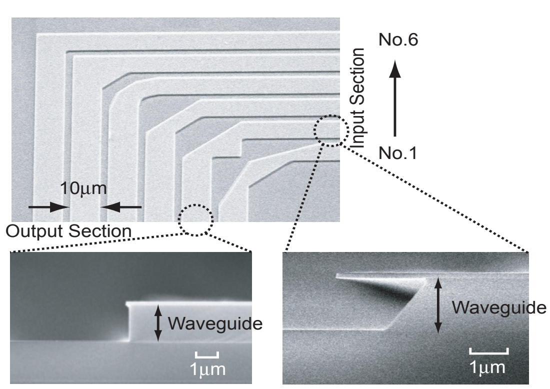


Fig. 2 Characterized six bends delineated with TMAH etchant.

3. Results and Discussion

1) Loss Measurement for Six Bend Shapes

Propagation characteristics at 1.55-μm wavelength are measured by six bends, already shown in Fig. 2. The results are shown in Fig. 3. While, simulation is done for these structures using FDTD with PROLOG simulator. An example is shown in Fig. 4 for No. 4 bend. Evaluated values are summarized in Table I on an assumption that absorption in straight portion is equal for six bends.

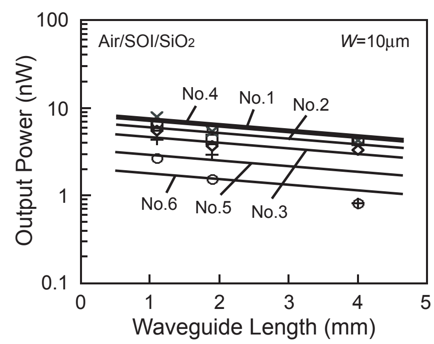


Fig. 3 Propagation characteristics for six bend shapes at 1.55-μm wavelength.

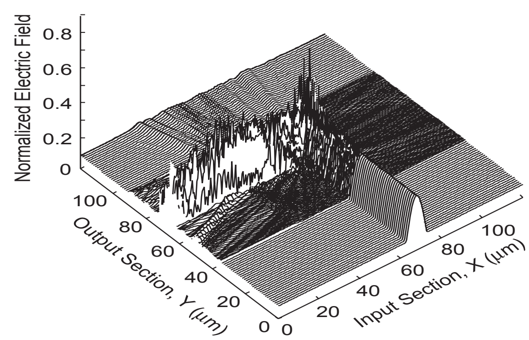


Fig. 4 Simulated propagation for No.4 bend of 10-μm width, using FDTD with PROLOG at 1.55-μm wavelength.

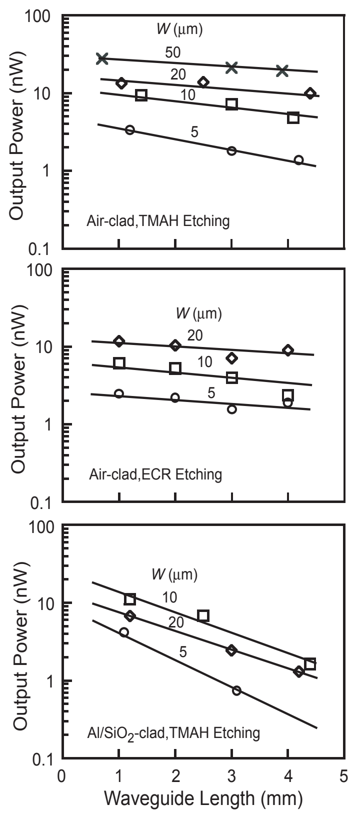
Table I Evaluated absorption coefficient and transmission for six bend shapes.

Bend Shapes	Measured Values		FDTD Simulation
	Absorption Coefficient α (/mm)	Transmission	Transmission
No.1	0.15	0.21	0.96
No.2	0.15	0.19	0.02
No.3	0.15	0.16	0.56
No.4	0.15	0.22	0.91
No.5	0.15	0.08	4×10^{-5}
No.6	0.15	0.06	0

2) Structure Dependence of Propagation Loss

Figure 5 indicates the propagation difference for air clad or Al/50-nm thick SiO_2 clad, and sidewalls etched by TMAH or ECR.

The total optical loss may be affected by six factors such as (1) free carrier absorption, (2) sidewall roughness, (3) bend shape (4) coupling loss at input and output sections, (5) absorption by aluminum, and (6) optical mode, as shown in Fig. 6, in waveguide.



(a) Air-clad waveguide etched by TMAH.

(b) Air-clad waveguide etched by ECR.

(c) Al/SiO_2-clad waveguide etched by TMAH.

*Smaller output power for 20-μm width may be caused by smaller input power due to poor coupling.

Fig. 5 The comparison of propagation characteristics among three different structures.

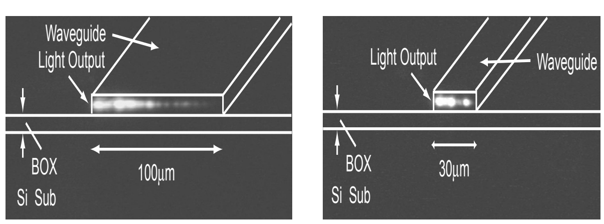


Fig. 6 Infrared microscope output patterns of 1.55-μm infrared light for 100-μm wide and 30-μm wide SOI waveguides.

To summarize the results, evaluated absorption coefficients are illustrated in Fig. 7. It is very obvious that Al electrode causes propagation loss due to free carrier in the electrode. Based on the results and simulation of reflection of plane wave, it is estimated that certain free carrier concentration gives optimum propagation, shown in Fig. 8 in case of ITO (Indium-Tin-Oxide).

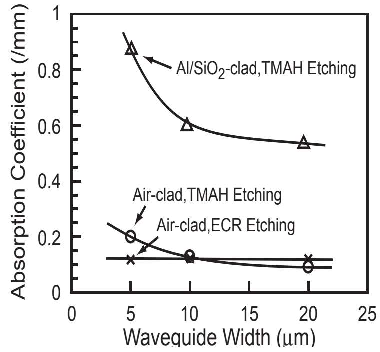


Fig. 7 Absorption coefficient summarized for two kinds of waveguide structures and etching techniques.

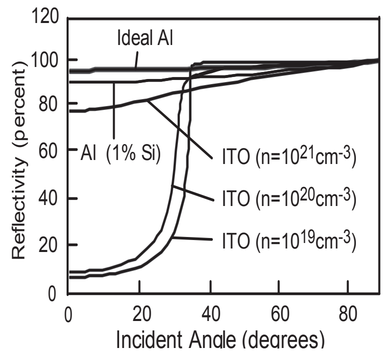


Fig. 8 Reflectivities for various metalic materials, *n* is electron density.

4. Conclusion

Integrated SOI waveguide structures are investigated in this study. Although highly reflective metal layer is expected to be suitable, light loss is given rise to with Al. Therefore, it is simulated that there exists optimum carrier concentration for maximum propagation. ITO may be suitable for its flexibility to choose the concentration.

Futhermore, light propagation mode should be considered to make accurate simulation in wider waveguide in paticular.

Acknowledgements

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References

[1] T. Furukawa, and H. Sunami, Extended Abstracts, JSAP Autumn Meeting, Abs. #6p-ZK-1, p. 94, 2000.
[2] A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu and M. Paniccia, *Nature*, Feburary 12, pp. 615-618, 2004.
[3] T. Furukawa, H. Yamashita, and H. Sunami, *Jpn. J. Appl. Phys.*, Vol. 42, Part 1, No. 4B, pp. 2067-2072.

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Introduction

Background

RC delay

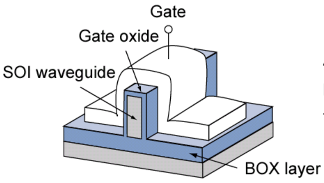
Power consumption

⇒ Optical wiring

Aim

To fabricate the optimum SOI waveguide structure

Application Device



Expectation

Waveguides,

to be integrated on Si LSI

⇒SOI waveguide, and bend structure

to improve propagation characteristics

⇒TMAH* etchant

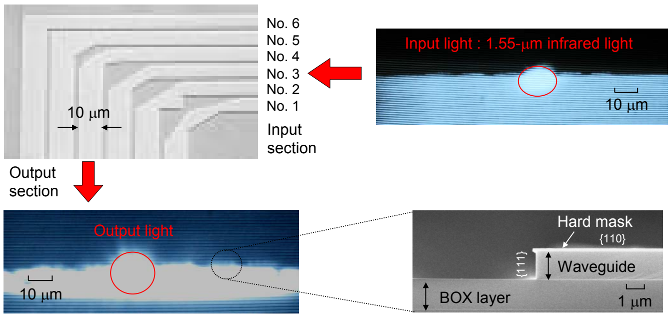
* tetra methyl ammonium hydroxide

An optical modulator of MOS structure based on free carrier absorption:

T. Furukawa and H. Sunami:

Ext. Abstr. JSAP, (61st Autumn Meet. 2000).

Fabricated SOI Waveguides with Bend Structure

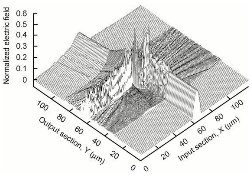


Waveguide structures are delineated vertically by TMAH.

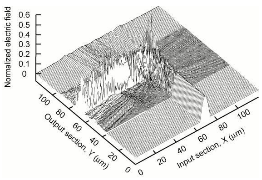
→Sidewall roughness is expected to be much smaller.

Simulated Propagation

FDTD analysis with PROLOG at 1.55-μm wavelength



(a) No. 3 bend structure



(b) No. 4 bend structure

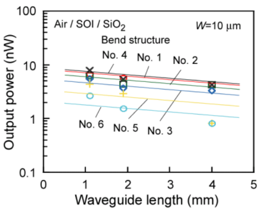
-Assumption-

- Total reflection occurs at the top and bottom surfaces
- Input light is expressed with Gaussian function

-Waveguide parameters-

- width : 10 μm
- core : Si, refractive index, n= 3.4
- clad : air, n=1.0

Propagation Characteristics for Bend



Bend structure W=10μm	Measured values: Absorption coefficient α (/mm)	Measured values: Transmission	FDTD simulation: Transmission
No. 1	0.15	0.21	0.96
No. 2	0.15	0.19	0.02
No. 3	0.15	0.16	0.56
No. 4	0.15	0.22	0.91
No. 5	0.15	0.08	4×10^{-5}
No. 6	0.15	0.06	0

* It is assumed that propagation characteristics with straight portion absolutely equal for six bends.

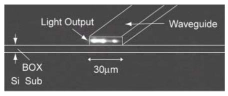
Total optical loss

(1) Free carrier absorption in silicon (2) Sidewall roughness

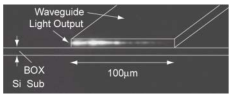
(3) Bend structure (4) Coupling loss at input and output sections

(5) Optical mode

Optical mode of output light



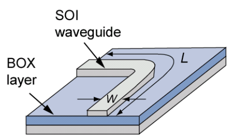
(a) bend structure ; No. 4 width ; 30 μm



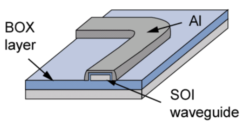
(b) bend structure ; No. 4 width ; 100 μm

Propagation Characteristics for Waveguide Structure

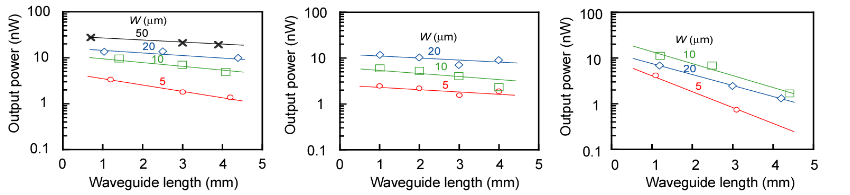
Fabricated waveguides



(a) Air-clad waveguide etched by TMAH or (b) Air-clad waveguide etched by ECR



(c) Al-clad waveguide etched by TMAH



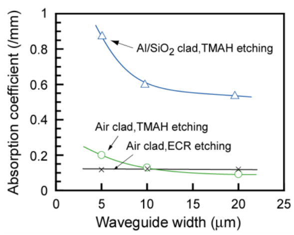
(a) Air-clad waveguide etched by TMAH (b) Air-clad waveguide etched by ECR (c) Al-clad waveguide etched by TMAH

- Fig. (a) and Fig. (b) are propagation characteristics in comparison of etchant.
- Fig. (b) and Fig. (c) are propagation characteristics in comparison of clad.

In case of Al-clad, another loss factor is,

(6) Absorption for propagation reflection by clad material.

Summarized Absorption Coefficient

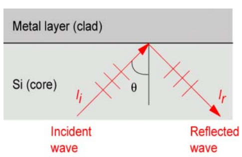


-Common parameter-

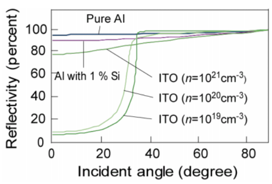
- Bend Structure : No. 4
- Waveguide height : 1.4 μm
- Light length : 1.55 μm

Al clad caused propagation loss due to free carrier absorption.

Reflectivities for various metallic materials



Simulation model of one time reflection of plane wave



* Al with 1 % Si is used in this study

ITO (Indium Tin Oxide) may be suitable

- High reflectivity
- Flexibility of choice of carrier concentration

Conclusion

- Integrated SOI waveguide structure are investigated.
- SOI waveguide transmits 1.55-μm infrared light with very small propagation loss.

Issue

MOS waveguide structure with aluminum gate gives rise to propagation loss due to free carrier absorption.

Further Study

It is necessary to control the carrier concentration with an optimum metallic material for MOS-type waveguide.

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