Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 188-189

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Enhancement of Magneto-Optic Effect in Magneto-Optic Waveguide with Low Refractive Index Undercladding Layer

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1. Introduction

In optical communication systems, optical waveguide isolators are important optics components, which protect optical active devices from unwanted reflection. We have studied an optical isolator with a semiconductor guiding layer for integrating a semiconductor laser diode and an optical isolator [1].

Figure 1 shows the optical isolator, employing a nonreciprocal phase shift, fabricated by wafer bonding technique. The nonreciprocal phase shift is experienced by TM modes traveling in the magneto-optic waveguide where the magnetization is aligned transverse to the light propagation direction in the film plane. A Ce-substituted yttrium iron garnet (Ce:YIG) was connected with a GaInAsP guiding layer by wafer bonding technique. Faraday rotation coefficient of Ce:YIG was approximately –4500 deg/cm at a wavelength of 1.55 μm. An evanescent field penetrating into the Ce:YIG cladding layer gives rise to the magneto-optic effect. As shown in Fig. 1, the optical isolator includes an optical interferometer. Owing to the nonreciprocal phase shift, the constructive interference and the destructive interference occur for the forward-traveling wave and the backward-traveling wave, respectively. The nonreciprocal characteristics were observed in the magneto-optic waveguide with the Ce:YIG / GaInAsP / InP structure [1].

However, in the magneto-optic waveguide with the Ce:YIG / GaInAsP / InP structure, there existed small fraction of the evanescent field due to small refractive index of Ce:YIG compared with that of InP. The refractive indices of Ce:YIG and InP are approximately 2.2 and 3.17, respectively, at a wavelength of 1.55 μm. The required propagation distance for the nonreciprocal phase shifter became large. An undercladding layer with lower refractive index is effective for enhancement of the magneto-optic effect.

In this paper, we report on surface micromachining for enhancement of the magneto-optic effect in the optical isolator employing the nonreciprocal phase shift.

2. Experimental Results

Figure 2 shows the fabrication process of the magneto-optic waveguide with the Ce:YIG / GaInAsP / AlInAs-oxide structure by means of surface micromachining. A GaInAsP guiding layer and an AlInAs layer were grown on an n-InP substrate by metal organic vapor phase epitaxy. The thickness of the GaInAsP and the AlInAs layer were 400 nm and 1000 nm, respectively. The rib waveguide was formed by use of reactive ion etching with CH_4:H_2 gas. Two deep grooves were also fabricated beside the rib waveguide by use of reactive ion etching with CH_4:H_2 gas. The AlInAs layer was oxidized at 530°C for 2 hours under carrier N_2 gas bubbled through H_2O [2]. In order to avoid the deterioration of the GaInAsP guiding layer, a SiO_2 protection layer was deposited on the GaInAsP guiding layer during the selective oxidation. The AlInAs layer was slightly etched by H_2SO_4:H_2O_2:H_2O (1:1:5) prior to the SiO_2 deposition in order to prevent the SiO_2 from covering the AlInAs side facets. The magneto-optic waveguide is obtained by wafer bonding between a Ce:YIG cladding layer and the GaInAsP guiding layer.

The magneto-optic waveguide with the air bridge structure was also effective for enhancement of the magneto-optic effect. The GaInAsP waveguide with the air bridge structure was fabricated by selective wet etching of the AlInAs-oxide layer by HF prior to wafer bonding between GaInAsP and Ce:YIG.

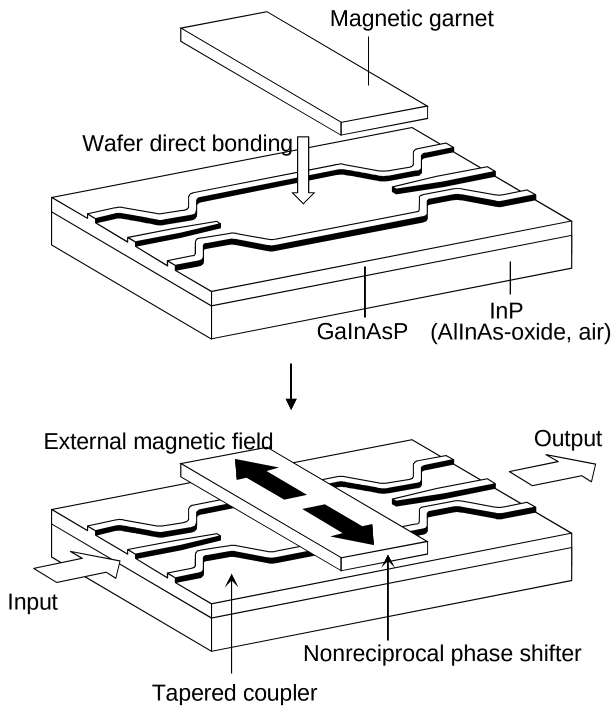

Fig. 1 Optical isolator, employing nonreciprocal phase shift, fabricated by wafer bonding.

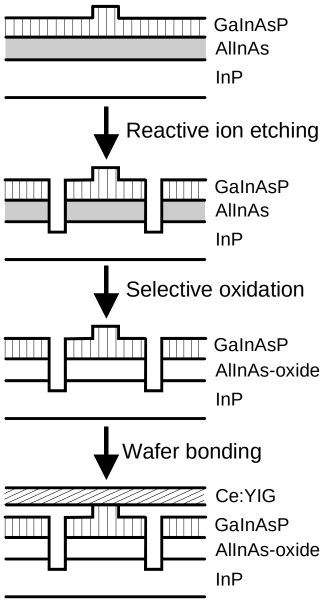

Fig. 2 Fabrication process of Ce:YIG / GaInAsP / AlInAs-oxide waveguide.

Figure 3 shows the SEM image of the GaInAsP rib waveguide with the AlInAs-oxide cladding layer. Light waves at 1.55 μm were launched into the GaInAsP rib waveguide. Near field pattern observed at the output facet indicated that the light waves could be guided in the waveguide. The refractive index of the AlInAs-oxide was measured by Fabry-Perot cavity resonance method. The 200-μm long GaInAsP waveguide with the AlInAs-oxide cladding layer was obtained by cleaving the sample. The amplified spontaneous emission from an erbium-doped fiber amplifier was launched into the waveguide. From the resonance pattern, the effective refractive index of the waveguide n_{eff} is given by

$$n_{eff} = \frac{\lambda^2}{2\Delta\lambda L} \qquad (1)$$

where $\Delta\lambda$ is a measured period of the resonant wavelength, L is a propagation distance and λ is a wavelength concerned. The refractive index of the AlInAs-oxide was estimated from n_{eff} by a commercially available mode solver. The refractive index of the AlInAs-oxide obtained by selective oxidation at 530°C was estimated to be approximately 2.45, at a wavelength of 1.55 μm, which was markedly reduced from 3.22, the refractive index of AlInAs.

The GaInAsP waveguide with the air bridge structure was successfully obtained by HF wet etching against the AlInAs-oxide.

Figure 4 shows the calculated nonreciprocal phase shifts in the magneto-optic waveguide with the Ce:YIG / GaInAsP / InP (AlInAs-oxide, air) structure. In case of the AlInAs-oxide or air cladding layer, the maximum nonreciprocal phase shift is more than ten times larger than that of the waveguide with the InP cladding layer. Larger nonreciprocal phase shifts can be attributed to the increase in the electromagnetic field penetrating into the Ce:YIG cladding layer.

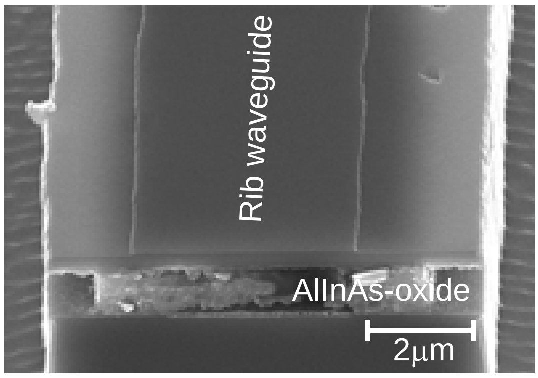

Fig. 3 SEM image of GaInAsP rib waveguide with AlInAs-oxide cladding layer.

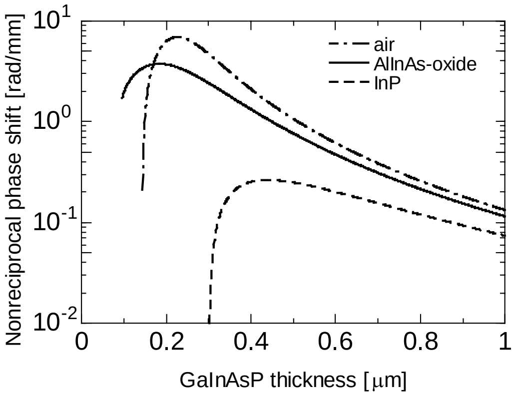

Fig. 4 Calculated nonreciprocal phase shift depending on GaInAsP thickness at a wavelength of 1.55 μm.

4. Conclusions

The magneto-optic waveguide with the low refractive index under cladding layer was investigated in order to enhance the magneto-optic effect. The GaInAsP rib waveguide with the AlInAs-oxide or air cladding layer was fabricated. It was confirmed that the nonreciprocal phase shift was more than ten times larger when the waveguide had the AlInAs-oxide or air cladding layer.

Acknowledgments

We would like to thank to Dr. Naito, Professor Emeritus, for continuous encouragement. We would like to appreciate Nippon Sheet Glass Co., Ltd for supplying GaInAsP / AlInAs wafer. This work is partly supported by NEDO within the framework of the “Photonic Network Project”.

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