Wafe bonding and its application to integrated optical isolator

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Abstract: An optical isolator composed of a semiconductor guiding layer is studied. The isolator employing a nonreciprocal phase shift was fabricated by using wafer bonding technique. The nonreciprocal phase shift was measured in the fabricated device.

Introduction

An optical isolator is indispensable in protecting optical active devices from unwanted reflected light. When we consider to integrate an optical isolator with a laser diode, issues to be solved include how to integrate dissimilar crystals. Also, the device structure must be fully compatible with fabrication processes. In order to integrate magnetooptic crystals with III-V semiconductors, we developed the wafer direct bonding. As a device structure, the optical isolator employing a nonreciprocal phase shift [1] is promising. The isolator employing this effect has the advantages of single polarization operation, which results in large fabrication tolerance, and relatively easy magnetization control.

In this paper, we report the wafer direct bonding of garnet crystals with III-V semiconductors and the experimental results of the optical isolator having a semiconductor guiding layer.

Device structure

A schematic drawing of the optical isolator composed of a GaInAsP guiding layer is shown in Fig.1. A magnetooptic garnet crystal directly bonded onto the GaInAsP guiding layer provides the nonreciprocal phase shift. The nonreciprocal phase shift is experienced by TM modes traveling in a magnetooptic waveguide in which the magnetization is aligned transversely to the light propagation direction in a film plane.

The isolator consists of three-guide tapered couplers [2], non-reciprocal phase shifters in the two arms and a reciprocal phase shifter in one of the arms. The reciprocal phase shift is achieved by an optical path difference between the two arms of interferometer. External magnetic fields, which align the magnetization, are applied to two arms in anti-parallel directions in order to reduce the device size by providing a nonreciprocal phase shift in a push-pull manner.

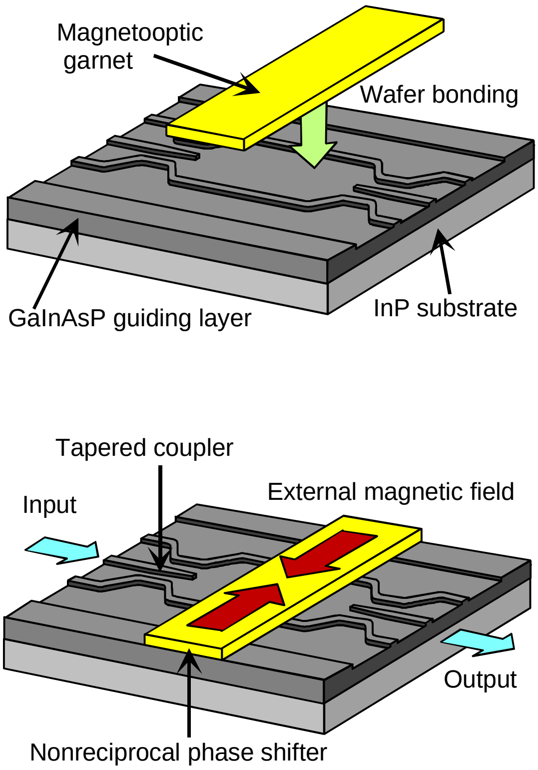

Fig.1 Optical isolator, employing nonreciprocal phase shift, fabricated by wafer bonding

The operation of isolator is based on the

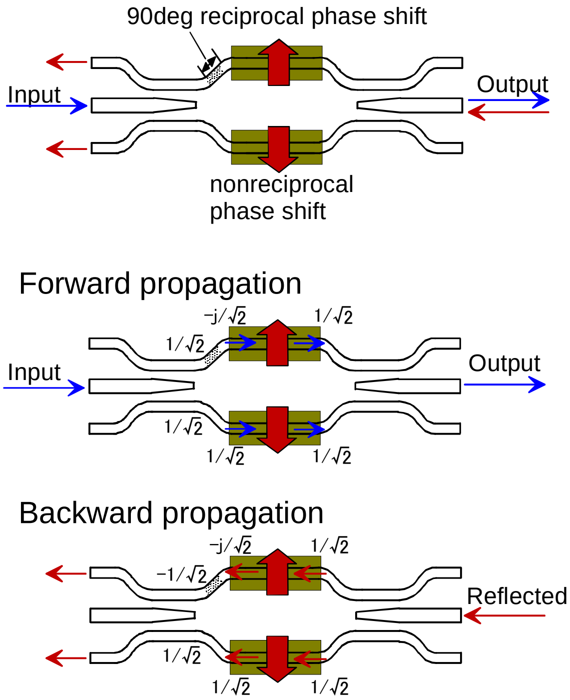

Fig.2 Operation principle of optical isolator employing nonreciprocal phase shift.

interferometric nature of the device as shown in Fig.2. That is, the interferometer is designed so that light waves propagating in two arms becomes in-phase and out-of-phase for forward and backward propagation, respectively. For the forward propagation, 90° reciprocal phase difference is canceled by -90° nonreciprocal phase difference. Since the nonreciprocal phase shift changes its sign by reversing the propagation direction, the phase difference becomes 180° for the backward propagating light. By virtue of the characteristics of the tapered coupler, the waves in phase opposition is not coupled into the central waveguide. Thus, the device operates as an isolator.

A Ce-substituted yttrium iron garnet $(Y_2Ce_1)Fe_5O_{12}$ was grown on (111)-oriented $Gd_3(Sc_2Ga_3)O_{12}$ substrates by sputter epitaxy, and is used as an upper cladding layer of the nonreciprocal phase shifter. The Faraday rotation coefficient of Ce:YIG was –4500 deg/cm at a wavelength of 1.55µm. The nonreciprocal phase shift was calculated for a Ce:YIG / GaInAsP / InP magnetooptic waveguide at 1.55µm. From the calculation, a propagation distance of 6.2mm is required to

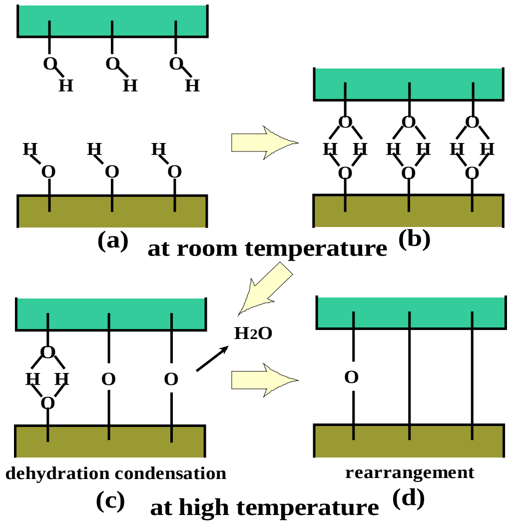

Fig.3 Schematic illustration of wafer direct bonding.

Table 1 Contact angles after pretreatment. The smaller contact angle indicates a more hydrophilic suface.

Treatment	Contact angle (deg)		
	GaInAsP	InP	Ce:YIG
without treatment	66.6	53.6	83
Deionized water [RT]	51.7	51.0	54
H_3PO_4 [RT]	48.0	10.7	<5.0
H_3PO_4 [100℃]	—	—	<5.0
HCl: H_3PO_4 (1:3) [RT]	50.5	—	—
H_2SO_4:H_2O_2:H_2O (5:1:1) [RT]	—	10.8	—
H_2SO_4:H_2O_2:H_2O (1:1:50) [RT]	37.3	—	—
O_2 plasma (2-3Pa, 10W, 30sec)	14.8	—	—
O_2 plasma → Water dip 10min	<5.0	5.6	<5.0

obtain the 90° nonreciprocal phase shift for 0.4µm-thick GaInAsP guiding layer.

Wafer bonding

Since the nonreciprocal phase shift is brought about by an evanescent field penetrated into the Ce:YIG cladding layer (n=2.22), tight contact between the guiding and cladding layers is required to be realized wholly over the nonreciprocal phase shifter. The Ce:YIG cladding layer was contacted with a GaInAsP (λ_g=1.25µm, n=3.36) guiding layer by wafer bonding.

The wafer bonding has been studied in

various wafer combinations, e.g. Si/Si, GaAs/Si, InP/GaAs [3]-[5]. We have developed this technique for the wafer combination of garnet crystals and III-V semiconductors. The mechanism of wafer bonding used in this study is explained in Fig.3. In order to achieve the successful bonding, it is important to make wafer surfaces hydrophilic by the treatment prior to bonding. We investigated appropriate surface treatments for garnet crystals and GaInAsP [6]. The wafers were treated in various chemical solutions. Also, O_2 plasma activation process was investigated. The plasma with 10W RF power was applied for 30sec in 2.7Pa O_2 pressure. The hydrophylicity of surface was evaluated through a contact angle measurement. The results are shown in table 1. Immersing Ce:YIG into H_3PO_4 was effective to make its surface hydrophilic. For GaInAsP, no suitable chemical treatment was found in our experiment. Exposing to O_2 plasma was remarkably effective to obtain hydrophilic GaInAsP surfaces. This treatment was also effective in case of Ce:YIG.

By using these conditions, Ce:YIG was successfully bonded onto GaInAsP waveguides at room temperature. The bonded sample was annealed at 220℃ in H_2 ambient for 90min. In the annealing process, the sample was pressed with a load of 320g/cm^2.

Experimental results

The three-guide tapered coupler designed for 1.55μm wavelength was fabricated with waveguide parameters shown in Fig.4. The rib waveguides were formed in the GaInAsP layer by E-beam lithography and CH_4/H_2 RIE.

Coupling characteristics of the tapered coupler were measured. The branching ratio of the light waves incident on the central waveguide (port C in Fig.4) was measured. The unbalance of the branching ratio was within 1% in a wavelength range of 1.50-1.58μm.

Also, the coupling characteristics of the tapered coupler were measured at 1.55μm using an experimental set-up shown in Fig.5. Lightwaves of equal amplitude were launched into two side waveguides (ports A and B) simultaneously through a silica waveguide

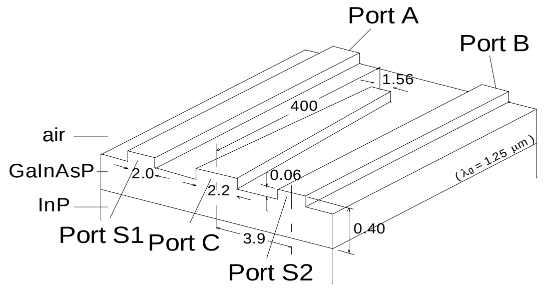

Fig.4 Waveguide parameter of three-guide tapered coupler (unit: μm)

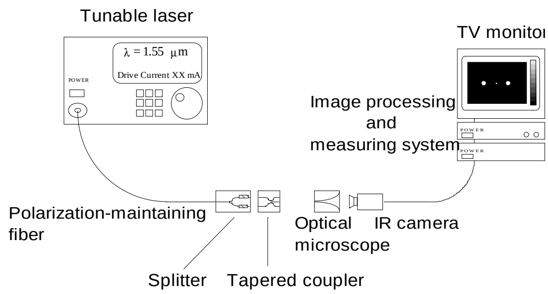

Fig.5 Experimental setup for measuring the coupling characteristics of three-guide tapered coupler

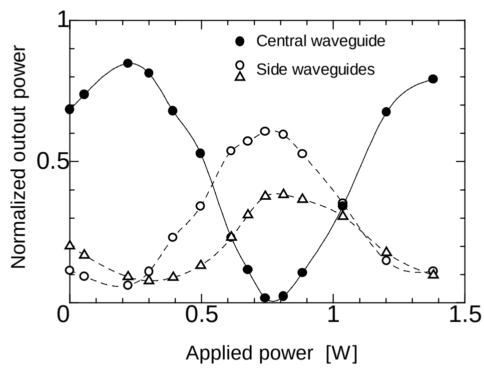

Fig.6 Measured coupling characteristics of three-guide tapered coupler

splitter. The phase difference of the launched waves was varied through a refractive index change produced by a thermo-optic effect in one branch. Measured coupling characteristics are shown in Fig.6. Output power from every port is normalized by the total output, and is plotted as a function of electric power applied to produce the thermo-optic effect. The phase difference between two input lightwaves is proportional to the applied power. It is observed that the amount of power transferred to the central

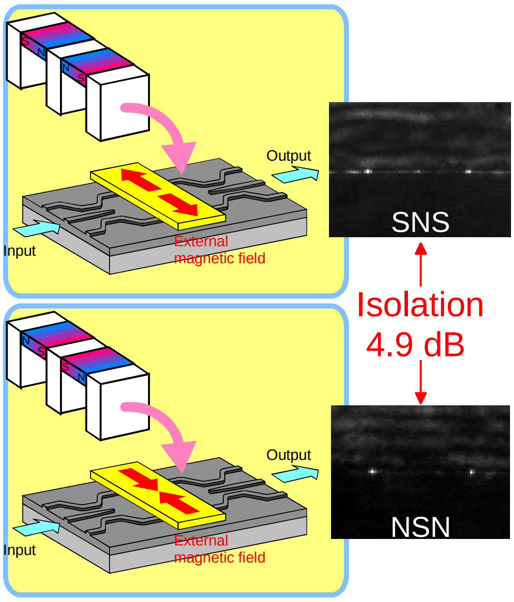

Fig.7 Isolator operation obtained by reversing the direction of external magnetic fields.

waveguide varies sinusoidaly depending on the phase difference between the two waves launched into side waveguides. This is consistent with theoretical prediction. When the applied power is 0.22W, the output from the central waveguide is at a maximum. The output from the central waveguide becomes minimal at the applied power of 0.74W. Judging from the measurement of power output from the central waveguide, the isolation ratio of 17dB is expected at 1.55μm, when the nonreciprocal and reciprocal phase shifters work ideally.

A complete structure of isolator was fabricated to evaluate the nonreciprocal phase shift. The Ce:YIG upper cladding layer was contacted with the GaInAsP guiding layer by wafer bonding. Before contacting wafers, the surface of Ce:YIG was slightly etched with H_3PO_4. The contact surface of GaInAsP waveguide was exposed to weak O_2 plasma.

Using a pair of miniature magnets, external magnetic fields were applied to the two arms of the interferometer in anti-parallel directions. Since reversing the direction of external magnetic field is equivalent to reversing the propagation direction, we measured the isolation of the device by reversing the direction of external magnetic field. When the direction of magnetic field was reversed, the output from the device was changed by virtue of the nonreciprocal phase shift as shown in Fig.7. The isolation ratio of 4.9dB was measured.

From this result, the nonreciprocal phase shift was estimated to be 24°. This value would be improved further by realizing a tight contact between the GaInAsP guiding layer and the Ce:YIG cladding wholly over the nonreciprocal phase shifter.

Conclusions

The isolator composed of the semi-conductor guiding layer was demonstrated for the first time. The coupling characteristics of the tapered coupler, which is one of principal components in the interferometric isolator, were measured. The nonreciprocal phase shift was observed in the fabricated device. The isolation ratio of 4.9dB was achieved in the isolator. The result obtained exhibits the feasibility of wafer direct bonding to such a kind of application in integrated optics.

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