Complete magneto-optical TE-TM mode conversion in Cd$_{1-x}$Mn$_x$Te waveguide for integrated optical isolator

M. C. Debnath*, V. Zayets, and K. Ando
Nanoelectronics Research Institute, National Institute of Advanced Industrial Science and Technology, Tsukuba central 2, Umezono 1-1-1, Tsukuba-shi, Ibaraki 305-8568, Japan

Received 12 September 2005, revised 14 October 2005, accepted 15 October 2005
Published online 9 March 2006

PACS 42.82.Et, 75.50.Pp, 78.20.Ls, 78.66.Hf, 85.70.Sq

Complete magneto-optical mode conversion was obtained in a 500 nm-thick graded-refractive-index Cd$_{1-x}$Mn$_x$Te waveguide grown on GaAs substrate. For the annealed waveguide, significant improvement of the complete mode conversion ratio was achieved up to 35 nm operational wavelength range. The Cd$_{1-x}$Mn$_x$Te waveguide also showed very low optical loss of 0.2 dB/cm, high magneto-optical figure-of-merit of more than 1000 deg/dB/kG and isolation ratio of more than 20 dB. This result is an important step toward achieving a practical integrated optical isolator.

1 Introduction

The optical isolator is an important integrated optic component in advanced fibre communication systems. Isolators are used to stabilize the laser diodes by protecting them from unwanted light reflections running back on the line. The operation of the waveguide optical isolator is based on the Faraday effect exhibited by the magneto-optical materials. In the present optical networks, oxide crystals of yttrium iron garnet such as Y$_3$Fe$_5$O$_{12}$ and (GdB)$_3$Fe$_5$O$_{12}$ are used as magneto-optical materials for the optical bulk isolators [1, 2]. Because most of the active optical elements such as isolators, laser diodes, modulators, optical amplifiers, etc. are grown on the semiconductor substrates, it is desirable to integrate monolithically all these optical circuits on the same substrate. However, because the growth of these oxide crystals on semiconductor substrate is impossible [3], alternative magneto-optical materials are highly desired for the future semiconductor optoelectronics devices. In this paper, we discuss a promising magneto-optical material for optical isolator, a diluted magnetic semiconductor (DMS) of Cd$_{1-x}$Mn$_x$Te [4].

Cd$_{1-x}$Mn$_x$Te has merit for integration of the optical isolator. A Cd$_{1-x}$Mn$_x$Te magneto-optical waveguide is compatible with AlGaInP:GaAs optoelectronic devices operating in a wavelength range of 600 - 800 nm. For longer wavelength ($\lambda = 800 - 1600$ nm) optoelectronic devices, Cd$_{1-x}$Mn$_x$Hg$_y$Te can be used [5, 6]. A high magneto-optical mode conversion ratio between transverse electric (TE) and transverse magnetic (TM) waveguide modes is indispensable for fabricating a waveguide isolator. Previously we showed that a Cd$_{1-x}$Mn$_x$Te waveguide with a graded-refractive-index structure could reduce the phase mismatch between TE and TM modes and attain the complete TE-TM mode conversion ratio with only 3 nm wavelength range [7, 8]. For practical use of a waveguide isolator, complete mode conversion in a wider wavelength range more than 20 nm is desirable. Therefore, we investigated the influence of the thermal annealing on Cd$_{1-x}$Mn$_x$Te waveguide and observed the complete mode conversion ratio in a wider wavelength range of 25 nm [9]. In this paper, we will discuss the detail results of the complete TE-TM mode conversion including the results of the optical loss, magneto-optical figure-of-merit, and isolation effect of the Cd$_{1-x}$Mn$_x$Te waveguide.

* Corresponding author: e-mail: m-debnath@aist.go.jp, Phone: +81-29-861-5080(ext. 55199), Fax: +81-29-861-3432

© 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
2 Experimental details

Cd$_{1-x}$Mn$_x$Te waveguides are grown on epi-ready GaAs (001) substrates by the molecular beam epitaxy (MBE) method employing the conventional cells for Mn and EPI SUMO cells for Zn, Cd and Te. The optimum growth conditions and the structure of the waveguide are described elsewhere [8,10]. For the present study, several Cd$_{1-x}$Mn$_x$Te waveguides with 1 µm-thick core layer ($x = 0.22$) and 0 - 500 nm-thick graded-refractive-index ($x = 0.22 - 0.26$) layers were grown at the substrate temperature of 300 °C. Since smaller step difference of the refractive index between the core and graded layers is expected to reduce the phase mismatch between TE and TM modes and increase the mode conversion ratio, we used the graded layers. After the growth, samples were annealed in the MBE chamber by increasing the substrate temperature between 400 °C and 450 °C under Cd flux for 5 - 10 minutes. From optical reflection measurements, the band gap of the waveguide core layer was estimated to be 690 nm for the waveguide without annealing. On the other hand, the band gap was slightly changed to 685 nm for the annealed waveguide indicating that Mn concentration in the core layer increased due to Mn diffusion in the core-graded layer during annealing.

Figure 1(a) shows the experimental set up to measure the optical propagation loss and the magneto-optical TE-TM mode conversion. A GaP prism was used to couple the laser light from a tunable Ti:sapphire laser ($\lambda = 680$ nm - 800 nm) into the Cd$_{1-x}$Mn$_x$Te waveguide. A CCD TV camera detected the light scattered from the film surface. A linear polarizer was placed in front of the TV camera with its polarization axis perpendicular to the light propagation direction. Figure 1(b) shows an image of the propagation with TE polarized input light at $\lambda = 750$ nm and $H = 0$ kG. Estimated optical loss of the waveguide mode is very low, less than 0.2 dB/cm. To evaluate the magneto-optical TE-TM mode conversion ratio, the TM polarized input light was excited and TE scattered light was detected by the CCD TV camera. A light streak with a periodically modulated intensity was observed at $H = 5.5$ kG and $\lambda = 735$ nm, due to the effect of Faraday rotation as shown in Fig. 1 (c). To measure the isolation effect, two GaP prisms were used for coupling the light into and from the waveguide [11]. The axes of polarizer and analyzer were adjusted so that the angle between them was 45°. In this way, the light passing through the waveguide in the reverse direction was blocked by the polarizer. To obtain high isolation effect, the angle of polarization rotation was also adjusted to 45° + $m$ 90°, where $m$ is a positive integer.

3 Results and discussion

Figure 2(a) shows the experimental results of the TE-TM mode conversion ratio of the two as-grown Cd$_{1-x}$Mn$_x$Te waveguides without graded layer (square) and the graded layer with thickness of 500 nm (circle). Data are shown as a function of light propagation length at $\lambda = 735$ nm and $H = 5.5$ kG. As
shown here, mode conversion ratio was only 15% for the waveguide without graded layer and this value reached to the maximum of 98% ± 2% for a waveguide with 500 nm-thick graded layer. Complete mode conversion ratio also obtained at λ = 740 nm for this graded-index waveguide The solid line of Fig. 2(a) was fitted by an analytical equation [12] that describes the relation of the mode conversion ratio, the Faraday rotation and the mode phase mismatch. Figure 2(b) shows the maximum mode conversion ratio as a function of thickness of the graded layers. With increasing the thickness of the graded layer, mode conversion ratio gradually increases and reached to the maximum value of 98% ± 2% for the waveguides with thickness of 400 - 500 nm. Analyses showed that increase of the mode conversion ratio was due to the reduction of the phase mismatch. The value of the phase mismatch was reduced by ten times for the waveguide with thicker graded layer as compared to a waveguide without graded layer. Thus, a graded-refractive-index layer at waveguide boundary play important role to reduce the mode phase mismatch and enhanced the mode conversion ratio [7, 8].

To obtain the complete mode conversion in the wider wavelength range, we studied the effect of thermal annealing on Cd$_{1-x}$Mn$_x$Te waveguides. Figure 3 shows the maximum mode conversion ratio as a function of wavelength of Cd$_{1-x}$Mn$_x$Te waveguide annealed at 425 °C. Complete mode conversion ratio was obtained between 730 and 765 nm and the operational wavelength range was enhanced up to 35 nm. This is our further improved result from a very good homogeneity waveguide sample with significant reduction of the phase mismatch between TE and TM modes. As shown in the inset of Fig. 3, the value of the phase mismatch was reduced to 50 deg/cm for the annealed waveguide (solid circles), which is five times smaller than that of a waveguide without annealing (open circles). This result indicates that the annealing redistributed Mn atoms along the waveguide thickness to give it a smoother refractive index distribution. Therefore, annealing reduce the mode phase mismatch significantly and expands the complete mode conversion for a wider wavelength range [9]. Further, because Cd$_{1-x}$Mn$_x$Te waveguide showed very low optical loss of 0.2 dB/cm and a high Faraday effect of 2000 deg/cm at H = 5 kG, we obtained high magneto-optical figure-of-merit [6] of more than 1000 deg/dB/kG at λ = 735 - 770 nm.
For the practical performance of an optical isolator, it is important to get an isolation ratio more than 20 dB. A high isolation effect can be achieved for a waveguide with high magneto-optical mode conversion ratio [13]. We define isolation ratio as the difference between forward and backward transmission of the two-prism coupling [11]. Figure 4(a) shows the transmission coefficient for forward (open squares) and backward (solid squares) propagations as a function of the magnetic field for light propagation length, \( L = 4 \) mm and \( \lambda = 740 \) nm. As indicated by arrows to the 45° and 45° + 90° of the polarization rotations which corresponds to the Faraday rotation angle for isolation peak, we can estimate the maximum isolation ratio at these peak to be 10 dB and 22 dB at 1.5 kG and 3.6 kG, respectively. Figure 4(b) plots the maximum isolation ratio as a function of wavelength. The value of the isolation ratio varies between 21 - 23 dB for \( \lambda = 725 - 745 \) nm and \( H = 1.5 - 5.5 \) kG. Because the present two-prism coupling efficiency is weak, even higher isolation ratio can be expected for strong prism coupling efficiency. Our results indicate that a Cd\(_{1-x}\)Mn\(_x\)Te waveguide isolator can deliver a high isolation ratio.

4 Conclusions

We found that graded-refractive-index of Cd\(_{1-x}\)Mn\(_x\)Te waveguides are very important to increase the mode conversion ratio. We also found that thermal annealing is very effective to obtain the complete mode conversion in a wider wavelength range. The annealing enhanced the operational wavelength range up to 35 nm, and the isolation ratio more than 20 dB was achieved at \( \lambda = 725 - 745 \) nm. This highly efficient Cd\(_{1-x}\)Mn\(_x\)Te waveguide demonstrate the feasibility of monolithically integrating of an optical isolator with other semiconductor optoelectronic devices.

Acknowledgements This work was supported in part as a NEDO project (No. 01A110b).

References