Highly efficient (Cd,Mn)Te waveguide for integrated magneto-optical isolator

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Graded-index clad layers with different thickness were used to increase the magneto-optical TE-TM mode conversion efficiency in $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide. Almost complete mode conversion efficiency of $98\% \pm 2\%$ was achieved for the waveguide with 4000-5000 Å thick graded layer at $\lambda = 740$ nm and $H = 5.5$ kG. The high mode conversion efficiency is due to the strong reduction of the phase mismatch between TE and TM modes. The waveguide also showed low optical loss below 1 dB/cm, high magneto-optical figure-of-merit above 500 deg/dB/kG and an isolation ratio of 18 dB at $\lambda = 740$ nm. Highly efficient present $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide demonstrates the feasibility of monolithical integration of an optical isolator with semiconductor optoelectronic devices.

Key words: diluted magnetic semiconductor, $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide, optical isolator, mode conversion efficiency, phase mismatch, figure-of-merit, isolation

1. Introduction

Optical isolator is an important optical component in the optical communication systems. Isolators are used with discrete active optical elements of laser diode, modulator, optical amplifier, optical gate, etc. In the high bit rate fiber transmission systems, isolators are applied to stabilize the laser diodes by protecting them from unwanted light reflections running back on the line. Compact isolator is available in the bulk forms¹⁾ but the waveguide optical isolator, which is expected to be compatible with integrated optics and less expensive, has not been developed well. 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 (YIG) such as $\text{Y}_3\text{Fe}_5\text{O}_{12}$ and $(\text{GdBi})_3\text{Fe}_5\text{O}_{12}$ are used as magneto-optical materials for the optical bulk isolators. Waveguide optical isolators based on these films have been already reported²⁾⁻⁴⁾. Because most of the active optical elements are grown on the GaAs or InP 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 impossible⁵⁾, alternative magneto-optical materials are highly desired for the future semiconductor optoelectronics devices. In this paper we report another promising magneto-optical material of $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$, known as diluted magnetic semiconductor (DMS).

$\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ is an attractive magneto-optical material for the applications of the optical isolator⁶⁾. $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ has several merits for the integration. It can be grown epitaxially on GaAs or InP substrate, it is transparent, and it shows a large Faraday effect near its absorption edge due to the strong exchange interaction between the *sp*-band electrons and the localized *d* electrons of Mn ions⁷⁾. Because of the tunability of its absorption edge from 1.56 to 2.1 eV by changing the Mn concentration, $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ can be used for magneto-optical devices operating in the wavelength range of 600 - 800 nm. For longer wavelength ($\lambda = 800$ - 1600 nm) optoelectronic devices, $\text{Cd}_{1-x}\text{Mn}_x\text{Hg}_y\text{Te}$ can be used⁸⁾. In $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide, we reported the mode conversion efficiency between transverse electric (TE) and transverse magnetic (TM) was only 34% and magneto-optical figure-of-merit 15 deg/dB/kG⁹⁾, which was not sufficient for the practical purposes. For the practical application of the waveguide isolator; the increases of the TE-TM mode conversion efficiency above 95% and the figure-of-merit above 100 deg/dB/kG are essential.

TE-TM mode conversion efficiency R induced by the Faraday effect is expressed as a function of optical propagation length L as¹⁰⁾

$$R = \frac{\Theta_F^2}{\Theta_F^2 + (\Delta\beta/2)^2} \sin^2 \left[\sqrt{\Theta_F^2 + (\Delta\beta/2)^2} L \right], \quad (1)$$

where $\Theta_F = V \cdot H$ is the Faraday rotation per unit length, V is the Verdet constant,^{6), 11)} H is the magnetic field strength, and $\Delta\beta$ is the phase mismatch between TE and TM modes. To achieve the high mode conversion efficiency, it is necessary to increase Θ_F and reduce the absolute value of $\Delta\beta$. In DMS, Θ_F exponentially increases when the optical wavelength approaches the band gap^{11) -12)}. On the other hand, the absolute value of $\Delta\beta$ can be reduce in a waveguide with graded-index clad layers. Recently, we have succeeded to increase the mode conversion efficiency up to $98\% \pm 2\%$ by using a $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ core layer sandwiched by two graded-index $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ layers^{13) -14)}. As shown in this work, this enhancement was due to the decrease of the absolute value of $\Delta\beta$. In order to clarify the mechanism of the reduction of the phase mismatch, magneto-optical waveguide mode conversion in the $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide was investigated as a function of the graded-index layer thickness. We also report the low optical propagation loss, high magneto-optical figure-of-merit and an isolation effect of the $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide.

2. Experimental details

$\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguides are grown on epi-ready GaAs (001) substrates by the molecular beam epitaxy method employing the conventional cells for Mn and Zn and EPI SUMO cells for Cd and Te. Fig. 1 shows the $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide structure on GaAs (001) substrate. The optical loss of the $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide was successfully reduced by the following growth procedure¹⁴. At the beginning, GaAs substrate was thermally cleaned at 480 °C under atomic hydrogen flux to remove oxides from GaAs surface. Before initiate the growth, GaAs substrate was kept for 30 minutes under Cd flux to prevent the formation of the undesired Ga_2Te_3 compound. Substrate temperature and growth rate are 300 °C and 6 Å/sec, respectively. The growth was monitored *in situ* by the surface sensitive diagnostic method of the reflection high-energy electron diffraction (RHEED). At first, two successive buffer layers of 10-nm thin ZnTe and 1-μm thick CdTe layers are grown to release the lattice mismatch. Then a 1-μm thick first $\text{Cd}_{0.66}\text{Mn}_{0.34}\text{Te}$ waveguide clad layer, a 2-μm thick second $\text{Cd}_{0.73}\text{Mn}_{0.27}\text{Te}$ clad layer, a bottom $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ ($x = 0.27-0.23$) graded layer, a 1-μm thick $\text{Cd}_{0.77}\text{Mn}_{0.23}\text{Te}$ waveguide core layer, and a top $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ ($x = 0.23-0.29$) graded layer are grown. Graded layers with different thickness of 0 Å, 1000 Å, 2000 Å, 3000 Å, 4000 Å, and 5000 Å are inserted between the core layer and air and between the core and clad layers. For both graded layers, Mn concentration was changed linearly with thickness. During CdTe and $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ growth, the RHEED pattern showed the $c(2\times 2)$ - (2×1) surface reconstruction which indicates the optimum condition to grow the waveguide structure.

Fig. 1 Graded-index clad layer of $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide structure on GaAs (001) substrate. Refractive index (n) of the core and graded layers are shown in the right side diagram.

Waveguide core layer was grown by choosing the band gap for 685 nm which is the limit of our excitation source of the laser beam. As shown in Fig. 1, the refractive index (n) of the core layer is high. Therefore, light is confined in the core layer as indicated by the arrows. Difference between refractive indices of the core and clad layers induces the phase mismatch $\Delta\beta$, and reduce the conversion efficiency (Eq. 1). Since smaller step difference of the refractive index between the core and graded layers is expected to reduce the phase mismatch and increase the mode conversion efficiency, we used the graded layers.

Figure 2(a) shows the experimental set up to measure the optical propagation loss and magneto-optical TE-TM mode

Fig. 2 (a) Experimental set up to evaluate the optical loss and the magneto-optical TE-TM mode conversion. (b) Streak of the waveguiding light in a low optical loss $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide at $\lambda = 740$ nm and $H = 0$ kG. Input light is TE polarized. (c) A spatially modulated light streak at $\lambda = 740$ nm and $H = 5.5$ kG. Magnetic field is applied parallel to the light propagation direction. Input light is TM polarized.

conversion. A GaP prism was used to couple the laser light from a tunable Ti: sapphire laser ($\lambda = 680 \text{ nm} - 800 \text{ nm}$) into the $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide. The light scattered from the film surface of the waveguide was detected by a CCD TV camera. A linear polarizer was placed in front of the TV camera with its polarization axis perpendicular to the light propagation direction. With this configuration, only the TE mode component of the waveguiding light can be detected by the TV camera. Fig. 2(b) shows an image of the propagation at $\lambda = 740 \text{ nm}$ and $H = 0 \text{ kG}$ for the $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide with $4000 \text{ \AA}$ thick graded layer. Optical propagation loss was determined by exponential fitting of the decay of the scattered light intensity as a function of the propagation length with TE polarized input light. Estimated optical loss of the waveguide mode was less than 1 dB/cm . Because $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ is a semiconductor, optical loss increases near the absorption edge of the waveguide core layer. In spite of this, present waveguide showed considerably low optical loss. For the evaluation of the magneto-optical TE-TM mode conversion efficiency, the TM polarized input light was excited and TE scattered light was detected by the CCD TV camera. When a magnetic field was applied parallel to the light propagation direction, a light streak with a periodically modulated intensity was observed due to the effect of Faraday rotation as shown in Fig. 2 (c). TE-TM mode conversion was measured with several wavelengths and magnetic fields up to 5.5 kG . To measure the isolation effect, two GaP prisms were set to different light propagation length for coupling the light into and from the waveguide. 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 $45^\circ + k \cdot 90^\circ$, where k is a positive integer.

3. Results and discussion

Figure 3(a) shows the experimental results of the TE-TM mode conversion efficiency of the three waveguides with $0 \text{ \AA}$ (without graded-index layer, triangle), $1000 \text{ \AA}$ (square) and $4000 \text{ \AA}$ (circle) thick graded-index layers. Data are shown as a function of propagation length at $\lambda = 740 \text{ nm}$ and $H = 5.5 \text{ kG}$. As shown here, mode conversion efficiency was only 15% for the waveguide without graded-index layer. We found that the value of the mode conversion efficiency gradually increases with increasing the thickness of the graded-index layer¹⁴⁾. Mode conversion of 45% was achieved for a waveguide with $1000 \text{ \AA}$ thick graded layer, and this value was strongly enhanced to the maximum value of $98\% \pm 2\%$ with an insertion of $4000 \text{ \AA}$ thick graded layer. This is the highest value of the mode conversion efficiency in the DMS waveguide. The solid line of Fig. 3(a) was fitted by Eq. (1). From the fitting, Faraday rotation and mode phase mismatch can be determined with high accuracies. Fig. 3(b) shows the maximum mode conversion

efficiency as a function of wavelength of the waveguide with $4000 \text{ \AA}$ thick graded layer at $H = 5.5 \text{ kG}$. Both wavelength and magnetic field influenced on the mode conversion efficiency of the present $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide. Highest mode conversion was achieved at $\lambda = 740 \text{ nm}$. As shown in the inset of Fig. 3 (b), magnetic field induced sharp increase of the mode conversion efficiency and reached the maximum value of $98\% \pm 2\%$ at 5.5 kG .

Figure 4 shows the maximum mode conversion efficiency and mode phase mismatch as a function of thickness of the graded layers under the magnetic field of 5.5 kG . Square and circle represent the mode conversion efficiency and mode phase mismatch, respectively. With increasing the thickness of the graded-index layer, the phase mismatch decreases and mode conversion efficiency increases. The increase of the mode conversion efficiency is due to the strong reduction of the phase mismatch. The phase mismatch was reduced by 10 times for the waveguide with thicker graded layer as compared to a waveguide without graded layer.

Fig. 3 (a) TE-TM mode conversion ratio as a function of propagation length at $\lambda = 740 \text{ nm}$ and $H = 5.5 \text{ kG}$. Triangle, square and circle represents the experimental data of the $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide with $0 \text{ \AA}$, $1000 \text{ \AA}$ and $4000 \text{ \AA}$ thick graded layer, respectively, where solid lines are fitted by the Eq.(1)¹⁴⁾. (b) Maximum mode conversion ratio as a function of wavelength of $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide with $4000 \text{ \AA}$ thick graded layers at $H = 5.5 \text{ kG}$. Inset shows maximum TE-TM ratio as a function of applied magnetic field.

Fig. 4 Graded layer thickness dependence of the mode conversion ratio (square) and the mode phase mismatch (circle) in $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide at $H = 5.5 \text{ kG}$ ¹⁴⁾.

For the reduction of the phase mismatch, the stress-induced optical birefringence and the growth-induced optical birefringence ¹⁵⁾ also play important roles in the garnet-based waveguide isolators. Present $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide on GaAs substrate was completely relaxed and the stress- and growth- induced birefringences had no roles for the reduction of the phase mismatch. We found that $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide without graded-index layer has an experimental value of the phase mismatch of 1000 deg/cm, which agrees with the theoretical value calculated by ignoring the effect of the stress- and growth- induced birefringences. In the $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide, only the graded-index layer seems to work for the reduction of the phase mismatch. If we consider the waveguide mode as a plane wave reflected between the boundaries of the waveguide, the phase mismatch between TE and TM polarized modes exists due to the polarization dependence of the Fresnel reflection coefficient. It is bigger for a bigger refractive index step at waveguide boundaries. At the boundary, if there is a graded change of refractive index through some thickness instead of sharp step, the polarization dependence of the reflection coefficient should diminish. Thus graded-index clad layers at waveguide boundary can reduce the phase mismatch and enhanced the mode conversion efficiency ¹⁴⁾.

Figure 5 shows the magneto-optical figure-of-merit as a function of wavelength for the $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide with 5000 Å thick graded layer. The figure-of-merit was defined as a Faraday rotation per unit optical loss ⁸⁾. The value of the figure-of-merit varies in the range of 200-900 deg/dB/kG for the wavelength regions of 715-755 nm. The higher figure-of-merit is due to the higher value of the Faraday rotation and lower value of the optical loss. As shown in the upper

Fig. 5 Magneto-optical figure-of-merit as a function of wavelength in $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide with 5000 Å thick graded layer ¹⁴⁾. Upper inset shows Faraday rotation and lower inset shows the optical loss as a function of wavelength.

inset of Fig. 5, the Faraday rotation exponentially increases as the wavelength approaches the band gap of the waveguide core layer. Such tendency is common for DMS. On the other hand, optical loss of the present waveguide is small. The value of the optical loss varies in the range 0.5 - 6 dB/cm as shown in the lower inset of the Fig. 5. Although optical loss increases near the absorption edge of the waveguide core layer, this value is reasonable to get the high figure-of-merit. At $\lambda = 740 \text{ nm}$ where mode conversion efficiency was maximum, the figure-of-merit was measured to be more than 500 deg/dB/kG ¹⁴⁾. Similar results also obtained for all others graded-index layer waveguides. This value of figure-of-merit is feasible for use in the magneto-optical devices.

Figure 6 shows the isolation ratio as a function of magnetic field at $\lambda = 740 \text{ nm}$ for the $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide with 4000 Å thick graded layer. Isolation results represent for the two light propagation lengths, $L = 3.5 \text{ mm}$ (circle) and $L = 1.5 \text{ mm}$ (square). For $L = 3.5 \text{ mm}$, the 45° Faraday rotation angle reached the maximum at 1.1 kG with an isolation 6 dB and the 45°+ 90° Faraday rotation angle reached the minimum at 3.2 kG with an isolation - 1.5 dB, as indicated by the up and down arrows, respectively. Moreover, this isolation trend approached to the 45°+180° Faraday rotation angle higher than the magnetic field 5.5 kG. At 5.5 kG, highest isolation ratio obtained to be 18 dB. The isolation ratio is directly related to the mode conversion efficiency. Since mode conversion efficiency is higher for the higher magnetic field ¹³⁾⁻¹⁴⁾, the isolation at 5.5 kG is

Fig. 6 Isolation ratio as a function of magnetic field in $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide with 4000 Å thick graded layer. Circle and square represents the isolation data for the light propagation length, $L = 3.5$ mm and $L = 1.5$ mm, respectively. For $L = 3.5$ mm, highest isolation 18 dB was obtained.

higher than those of 1.1 kG. For the short light propagation length of 1.5 mm (square), only 45° Faraday rotation angle peak was observed at $H = 2.5$ kG. It needs higher magnetic field more than 5.5 kG to reach the isolation for the $45^\circ+90^\circ$ and the $45^\circ+180^\circ$ Faraday rotation angle. We estimated numerically that $98\% \pm 2\%$ of mode conversion was sufficient for fabrication of an optical isolator with an isolation we have obtained (18 dB).

4. Conclusions

In conclusion, we found that graded-index clad layers are very effective to increase the mode conversion efficiency and reduction for the mode phase mismatch. Mode conversion efficiency reached to the maximum value of $98\% \pm 2\%$. Highly efficient $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ waveguide also

showed low optical loss less than 1 dB/cm, figure-of-merit more than 500 deg/dB/kG and an isolation ratio 18 dB at $\lambda = 740$ nm. This result is an important step to achieve a monolithic integration of DMS based optical isolators with other semiconductor-based optoelectronic devices.

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