Thermal annealing of magneto-optical (Cd,Mn)Te waveguides for optical isolators with wider operational wavelength range

M. C. Debnath,[a] 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

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We obtained significant improvement of magneto-optical performance by thermal annealing of the graded-index $Cd_{1-x}Mn_xTe$ waveguide. For a waveguide annealed at 425 °C, complete mode conversion was achieved in a wavelength range between 710 and 735 nm, which is an expansion of more than eight times that of a waveguide without annealing. The annealed waveguide also showed very low optical loss of 0.2 dB/cm and a high magneto-optical figure-of-merit of more than 1000 deg/dB/kG. In addition, an isolation ratio of more than 20 dB was obtained at $\lambda = 715-735$ nm in magnetic fields, $H = 1.6-5.1$ kG. This result is an important step toward achieving a practical integrated optical isolator. © *2005 American Institute of Physics*.
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The optical waveguide isolator is an important component in advanced fiber communication systems. In high-bit-rate optical networks, isolators are used to stabilize laser diodes by protecting them from unwanted light reflections running back on the line. The operation of the isolator uses the inherent time-inversion asymmetric dielectric function exhibited by the magneto-optical materials. In the present optical networks, oxide crystals of iron garnet such as $Y_3Fe_5O_{12}$ and $(GdBi)_3Fe_5O_{12}$ are used as magneto-optical material for optical bulk isolators.[1–3] Most of the active optical elements of such isolators, laser diodes, modulators, optical amplifiers, and optical gates are grown on semiconductor substrates; therefore, integrating all of these monolithically on the same substrate is desirable. However, because the growth of the oxide crystals on semiconductor substrate is impossible,[4] alternative magneto-optical materials are highly desired for future semiconductor optoelectronics devices. In this letter, we discuss another promising magneto-optical material for optical isolators, a diluted magnetic semiconductor (DMS) of $Cd_{1-x}Mn_xTe$.

$Cd_{1-x}Mn_xTe$ is an attractive magneto-optical material for integrating optical isolators and circulators. $Cd_{1-x}Mn_xTe$ has several merits for integration. It can be grown epitaxially on GaAs or InP substrate; it is transparent, and it exhibits 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 ions.[5] Furthermore, a $Cd_{1-x}Mn_xTe$ magneto-optical waveguide would be compatible with AlGaInP:GaAs optoelectronic devices operating in a wavelength range of 600 to 800 nm. For longer wavelength ($\lambda = 800-1600$ nm) optoelectronic devices, $Cd_{1-x-y}Mn_xHg_yTe$ can be used.[6,7] A high magneto-optical mode conversion ratio between transverse electric (TE) and transverse magnetic (TM) waveguide modes is indispensable for fabricating a waveguide isolator with high performance.[8] Recently, we successfully attained a complete mode conversion ratio in a $Cd_{1-x}Mn_xTe$ waveguide with a graded-refractive-index structure.[9,10] However, the operational wavelength range was only about 3 nm with a mode conversion ratio larger than 98% and a isolation ratio more than 20 dB. To achieve a waveguide isolator for the practical use, obtaining a high-mode conversion ratio and high-isolation ratio in a wider wavelength range more than 20 nm is desirable. For this purpose, we have investigated the influences of the post-growth annealing of the $Cd_{1-x}Mn_xTe$ waveguide on the mode conversion ratio. In this letter, we also report the low optical propagation loss, high magneto-optical figure-of-merit, and isolation effect of the annealed $Cd_{1-x}Mn_xTe$ waveguide.

$Cd_{1-x}Mn_xTe$ waveguides are grown on epi-ready GaAs (001) substrates with a molecular beam epitaxy (MBE) system using high-purity (6N) elemental sources of Mn, Zn, Cd, and Te. The optimum growth conditions and the structure of the waveguide are described elsewhere.[10,11] Previously we showed that graded-refractive-index clad layers are important for the $Cd_{1-x}Mn_xTe$ waveguide because the smaller step difference of the refractive index between the core and graded layers reduces the phase mismatch between TE and TM modes and increases the mode conversion.[9–11] For the present study, several $Cd_{1-x}Mn_xTe$ waveguides with 1 μm-thick core layer ($x = 0.225$) and 5000 Å-thick graded-refractive-index ($x = 0.225-0.26$) layers were grown at the substrate temperature of 300 °C. 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 minutes, typically. 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 the Mn concentration in the core layer increased due to Mn diffusion in the core-graded layer during annealing.

Figure 1(a) illustrates the experimental set up we used to evaluate the optical propagation loss and the TE-TM waveguide mode conversion ratio. A GaP prism was used to couple the laser light from a tunable Ti:sapphire laser ($\lambda = 680-800$ nm) into the $Cd_{1-x}Mn_xTe$ 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

[a]Author to whom correspondence should be addressed; electronic mail: m-debnath@aist.go.jp

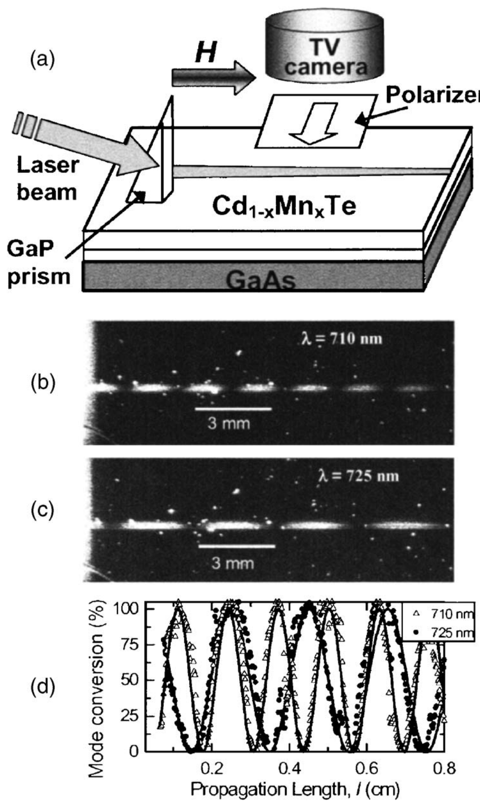

FIG. 1. (a) Experimental set up used to evaluate optical propagation loss and the magneto-optical TE-TM mode conversion. Spatially modulated light streak for TM-mode excitation at $\lambda=710$ nm (b) and $\lambda=725$ nm (c) under magnetic field 5.5 kG of the $Cd_{1-x}Mn_xTe$ waveguide annealed at 425 °C. (d) Mode conversion ratio as a function of light propagation length at $\lambda=710$ nm (triangles) and $\lambda=725$ nm (circles).

polarization axis perpendicular to the light propagation direction. To evaluate the magneto-optical TE-TM waveguide mode conversion, a magnetic field up to 5.5 kG was applied parallel to the light propagation direction. We observed a light streak with a periodically modulated intensity due to the effect of Faraday rotation on both the TE- and TM-mode excitations. Figures 1(b) and 1(c) present images of the spatially modulated light streak for two different wavelengths, $\lambda=710$ nm (b) and $\lambda=725$ nm (c) at $H=5.5$ kG under the TM-mode excitation of the $Cd_{1-x}Mn_xTe$ waveguide annealed at 425 °C. The period of the oscillation was shorter for the wavelength closer to the band gap of the core layer [Fig. 1(b)] because the Faraday rotation was larger.[12] Figure 1(d) shows the intensity for those two modulated streaks as measured along the light propagation length. As shown in Fig. 1(d), the mode conversion ratio reached to the maximum (100%) for both wavelengths, $\lambda=710$ nm (triangles) and $\lambda=725$ nm (circles). The solid line of Fig. 1(d) was fitted by an equation[13] that describes the relation of the mode conversion ratio, the Faraday rotation, and the mode phase mismatch. According to the equation, to increase the mode conversion ratio, the Faraday rotation should be increased and the mode phase mismatch should be reduced.

Figure 2 shows the maximum mode conversion ratio as a function of wavelength at $H=5.5$ kG for the $Cd_{1-x}Mn_xTe$ waveguide annealed at 425 °C (solid circles) and the waveguide without annealing (open circles). The complete mode conversion obtained for only a 3-nm wavelength range (725 to 728 nm) for the waveguide without annealing. On the other hand, the complete mode conversion obtained for the waveguide annealed at 425 °C was between 710 and 735 nm. Annealing expanded the operation wavelength range by more than eight times. To the best of our knowledge, this is the best result to date for the complete mode conversion of a DMS waveguide. We also observed an improvement in the complete mode conversion ratio for the annealing temperatures between 400 °C and 450 °C. Figure 3(a) shows the operation wavelength range for the complete mode conversion at five different annealing temperatures 400 °C, 415 °C, 425 °C, 440 °C, and 450 °C, in addition to an as-grown temperature of 300 °C. The operation wavelength range depended on the annealing temperature. The best annealing temperature was 425 °C where the operation wavelength range was enhanced up to 25 nm. Analyses showed that the annealing reduced the absolute value of the phase mismatch between TE and TM modes, and this increased the mode conversion ratio. On the other hand, the annealing did not change the Faraday coefficient. Figure 3(b) shows the phase mismatch as a function of wavelength for the $Cd_{1-x}Mn_xTe$ waveguide with annealing (circles) and without annealing (squares). The value of the phase mismatch was reduced to less than 100 deg/cm for the annealed waveguide, and this value is five times smaller than that of the waveguide without annealing. This result indicates that the annealing redistributed Mn atoms along the waveguide thickness to give it a smoother refractive index distribution.

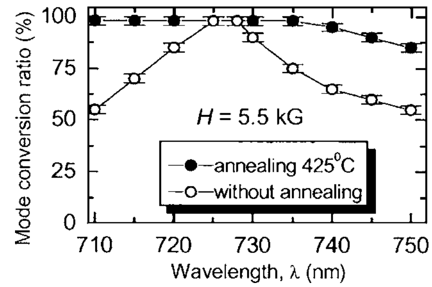

FIG. 2. Maximum mode conversion ratio as a function of wavelength of $Cd_{1-x}Mn_xTe$ waveguide without thermal annealing (open circles) and with annealing at 425 °C (solid circles).

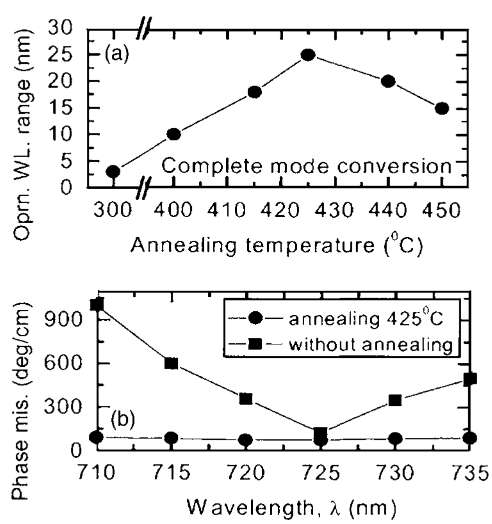

FIG. 3. (a) Operational wavelength range for the complete mode conversion at five different annealing temperatures from 400 °C to 450 °C including the as-grown temperature of 300 °C. (b) Phase mismatch of the $Cd_{1-x}Mn_xTe$ waveguide with annealing at 425 °C (circles) and without annealing (squares).

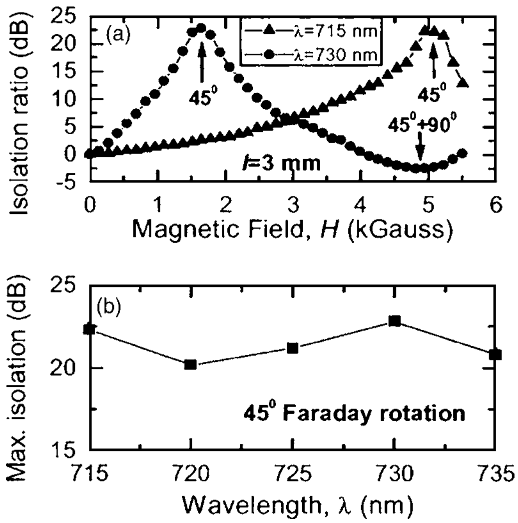

FIG. 4. (a) Isolation ratio as a function of magnetic field at $\lambda = 715$ nm (triangles) and $\lambda = 730$ nm (circles). (b) Maximum isolation as a function of wavelength.

During annealing, Mn atoms diffuse out of the core layer to the graded-index layer. A similar phenomenon was reported in CdTe/CdMnTe quantum well systems where thermal annealing induced interdiffusion between the well and the barrier material.[14] In $Cd_{1-x}Mn_xTe$ waveguides, the refractive index distribution is homogeneous within the graded-index layer as a result of annealing. Thus, annealing plays a significant role in reducing the mode phase mismatch and enhances the mode conversion ratio for a wider wavelength range. These annealed waveguides also showed a very low optical loss of 0.2 dB/cm. Because the $Cd_{1-x}Mn_xTe$ waveguide exhibited a high Faraday effect of 2000 deg/cm at 5 kG, we obtained the high magneto-optical figure-of-merit[6] of more than 1000 deg/dB/kG at $\lambda = 715-750$ nm.

Figure 4 shows the isolation ratio as a function of magnetic field and wavelength of $Cd_{1-x}Mn_xTe$ waveguide annealed at 425 °C. A high isolation effect can be achieved for a waveguide with high magneto-optical mode conversion ratio.[15] We define isolation ratio as the difference between forward and backward transmission of the two-prism coupling.[8] Figure 4(a) shows the isolation data at $\lambda = 715$ nm (triangles) and $\lambda = 730$ nm (circles) for the light propagation length, $l = 3$ mm. The isolation peaks at the 45° Faraday rotation shifted to a higher magnetic field for a shorter wavelength as indicated by the up arrows. At $\lambda = 715$ nm, the maximum isolation ratio of 23 dB was obtained at a 45° Faraday rotation in 5.1 kG. On the other hand, at $\lambda = 730$ nm, the isolation ratio showed the maximum of 23 dB at 1.66 kG and the minimum, −3 dB, at 4.8 kG. This corresponds to the 45° and 45° +90° of the Faraday rotation, respectively. Because $Cd_{1-x}Mn_xTe$ is a paramagnetic material and its Faraday rotation coefficient is linearly proportional to the applied magnetic field, different peak of the isolation ratio appeared in different magnetic fields. Figure 4(b) shows the maximum isolation as a function of wavelength. The maximum isolation was extracted from the 45° Faraday rotation and appeared in the magnetic fields 1.6–5.1 kG. The value of the isolation ratio varies between 20 to 23 dB for the wavelength, $\lambda = 715-735$ nm. These results indicate that a $Cd_{1-x}Mn_xTe$ waveguide isolator can deliver a high isolation ratio.

In conclusion, thermal annealing of a graded-index $Cd_{1-x}Mn_xTe$ waveguide was found to be very effective for attaining the complete mode conversion in a wider wavelength range. The annealing enhanced the operational wavelength range up to 25 nm, and an isolation ratio more than 20 dB was achieved at $\lambda = 715-735$ nm. This highly efficient annealed $Cd_{1-x}Mn_xTe$ waveguide demonstrates the feasibility of monolithically integrating of an optical isolator with other semiconductor optoelectronic devices.

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