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Magneto-optical mode conversion in $Cd_{1-x}Mn_xTe$ waveguide on GaAs substrate

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Magneto-optical mode conversion was achieved in a waveguide of diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$ grown on GaAs substrate. Mode conversion ratio up to 34% under a magnetic field of 5.5 kG was obtained. $Cd_{1-x}Mn_xTe$ waveguide showed low optical loss, 4 dB/cm, and high magneto-optical figure-of-merit, 15 deg/dB/kG at $\lambda = 790$ nm. This result shows the feasibility of monolithical integration of an optical isolator with semiconductor optoelectronic devices. © *2000 American Institute of Physics.* [S0003-6951(00)04437-5]

Optical isolators and circulators are indispensable components for high-speed optical network systems. Isolators stabilize laser oscillation by preventing the backward traveling light from re-entering into the laser cavity. Circulators separate output and input ports in bi-directional data transmission systems. These time-inversion asymmetric functions can be realized only by the magneto-optical effect. In present optical networks, ferrimagnetic garnet oxide crystals such as $Y_3Fe_5O_{12}$ (YIG) and $(GdBi)_3Fe_5O_{12}$, are used for the discreet optical isolators and circulators. Waveguide optical isolators based on these films have been also reported.[1–5] However, a monolithic integration of the garnet-film isolators and circulators with semiconductor optoelectronic devices has not been realized, because these oxide crystals can not be grown on semiconductor substrates. Several methods have been proposed to realize the integration of magneto-optical waveguide devices with semiconductor optoelectronics devices. Yokoi and Mizumoto[6] and Levy *et al.*[7] proposed a direct bonding of the garnet waveguide onto a semiconductor substrate. Hammer *et al.*[8] and Zaets and Ando[9] proposed a hybrid structures of semiconductor optical amplifier and ferromagnetic metal films. In this letter we discuss another promising way of the integration, i.e., a magneto-optical waveguide made of diluted magnetic semiconductor.[10]

Diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$[11,12] is very attractive as a magneto-optical material for integrated optical isolators and circulators. $Cd_{1-x}Mn_xTe$ shares the zinc-blende crystal structure with the typical semiconductor optoelectronic materials such as GaAs and InP; its film can be thus grown directly on GaAs substrate. $Cd_{1-x}Mn_xTe$ also exhibits a huge Faraday effect (its Verdet constant is typically 50–200 deg/cm/kG)[13,14] near its absorption edge due to the anomalously strong exchange interaction between the sp-band electrons and the localized d electrons of Mn^{2+}. Furthermore, the tunability of its absorption edge from 1.56 to 2.1 eV with Mn concentration[11] makes the $Cd_{1-x}Mn_xTe$ magneto-optical waveguide compatible with AlGaInP:GaAs optoelectronic devices operating in the wavelength range of 600–800 nm. For longer-wavelength ($\lambda = 800-1600$ nm) optoelectronic devices, $Cd_{1-x-y}Mn_xHg_yTe$[15,16] can be used. Bulk optical isolators using these materials are now commercially available.[15] $Cd_{1-x}Mn_xTe$ waveguide grown on GaAs substrate has been demonstrated.[10] However optical loss of the waveguide was too high (~ 70 dB/cm) and its magneto-optical figure-of-merit was too low (~ 1.8 deg/dB/kG) to perform magneto-optical mode conversion experiments. In this letter we report an experimental demonstration of magneto-optical conversion between transverse electric (TE) and transverse magnetic (TM) waveguide modes in a low-optical-loss $Cd_{1-x}Mn_xTe$ waveguide grown on GaAs substrate.

$Cd_{1-x}Mn_xTe$ single crystal films were grown with molecular beam epitaxy (MBE) employing conventional CdTe, Cd, MnTe, and ZnTe effusion cells. The optical loss of the $Cd_{1-x}Mn_xTe$ waveguide was successfully reduced by the following growth procedure.[17] GaAs (001) substrate was thermally cleaned at 400 °C under atomic hydrogen flux[18] to remove gallium oxides from GaAs surface. Next, GaAs surface was covered with a 5-nm-thick amorphous Cd layer at substrate temperature of 50 °C to prevent the formation of the undesired Ga_2Te_3 compound, which causes a high density of threading dislocations and stacking faults in the film.[19–21] When the substrate temperature was increased to 250 °C and the reflection high energy electron diffraction (RHEED) pattern indicated that GaAs surface was covered approximately with a 0.8 monolayer of Cd, the growth was started. After a 2 monolayer thick ZnTe was deposited on that surface to initialize the (001) growth, a 1 μm thick CdTe buffer layer, a 3-μm-thick $Cd_{0.85}Mn_{0.15}Te$ waveguide cladding layer, a 200-nm-thick $Cd_{1-x}Mn_xTe$ ($x = 0.15-0.09$) graded layer, a 1.2-μm-thick $Cd_{0.91}Mn_{0.09}Te$ waveguide core layer, and a 200-nm-thick $Cd_{0.85}Mn_{0.15}Te$ top cladding layer were grown. The surface reconstruction was $c(2\times2)-(2\times1)$ intermediate structure during CdTe growth and (2×1) during $Cd_{1-x}Mn_xTe$ growth. There are two reasons why we used $Cd_{0.85}Mn_{0.15}Te$ layers as cladding layers. Since GaAs is an optical absorber with a higher refractive index than that of $Cd_{1-x}Mn_xTe$,[10] a single $Cd_{1-x}Mn_xTe$ layer on GaAs does not work as a waveguide. One needs transparent waveguide cladding layers with smaller refractive index. $Cd_{0.85}Mn_{0.15}Te$ satisfies these conditions because $Cd_{1-x}Mn_xTe$ with higher Mn concentration has a smaller

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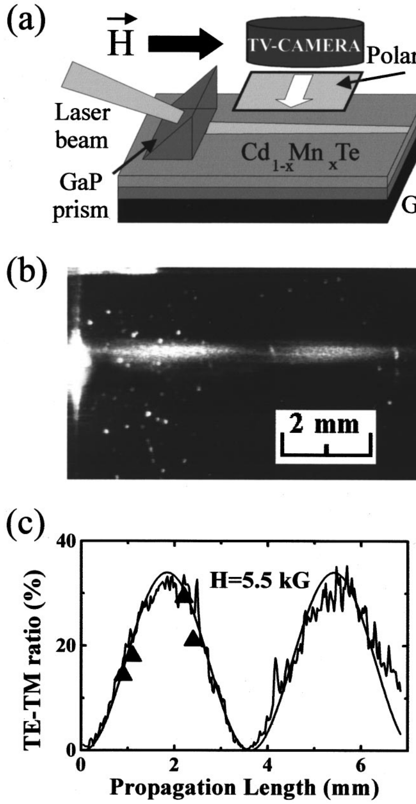

FIG. 1. (a) Experimental setup to evaluate optical propagation loss and TE–TM waveguide mode conversion at $\lambda = 790$ nm. (b) A spatially modulated light streak appears when a magnetic field of 5.5 kG is applied parallel to light propagation direction. Input light is TM polarized. (c) TE–TM conversion ratio as a function of propagation length. Solid line is calculated data from Eq. (1). Triangles are data measured by coupling out the waveguiding light by the second GaP prism and measuring the rotation angle of its polarization plane.

refractive index and wider optical band gap.[10–14] The second reason is to reduce the difference of the phase velocity (phase mismatch), $\Delta\beta$, between TE and TM waveguide modes. As described later, $\Delta\beta$ reduces the mode conversion ratio. A smaller refractive index difference between the waveguide core and cladding layers is desired to reduce $|\Delta\beta|$.

Figure 1(a) illustrates an experimental setup to evaluate optical propagation loss and TE–TM waveguide mode conversion. A GaP prism was used to couple the laser light ($\lambda = 790$ nm) into the $Cd_{1-x}Mn_xTe$ waveguide. A cooled charge-coupled device (CCD) TV camera collected light normally 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. With this configuration, only the TE mode component of waveguiding light can be detected by the TV camera. Optical propagation loss was evaluated by exponential fitting of the decay of the scattered light intensity as a function of the propagation length with TE-polarized input light and without applying a magnetic field. Estimated optical loss of the waveguide mode was 4 dB/cm, which is 17 times smaller than the previously obtained value.[10] Such a small optical loss leads to the high magneto-optical figure-of-merit of 15 deg/dB/kG, which is sufficient for use in magneto-optical devices.

For the evaluation of the magneto-optical TE–TM waveguide mode conversion ratio, the TM polarized input light was excited. In the absence of a magnetic field, no scattered light streak was seen because there was no TE-mode component in the waveguiding light. When a magnetic field was applied parallel to the light propagation direction, a light streak with a periodically modulated intensity was observed [Fig. 1(b)]. This is due to the appearance of the TE waveguide mode component by the Faraday effect. The oscillation is damped with propagation length due to the optical loss of waveguide mode. In all our experiments we limited the magnetic field strength up to 5.5 kG, which is almost the maximum available value by permanent magnets.

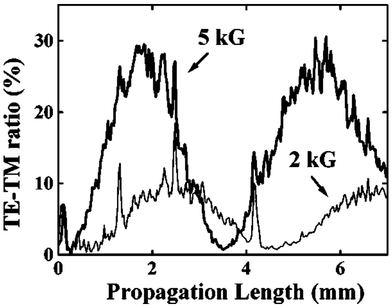

FIG. 2. TM–TE mode conversion ratio as a function of propagation length measured under magnetic fields of 5 and 2 kG.

TE–TM waveguide mode conversion ratio R induced by the Faraday effect is expressed as a function of optical propagation length L as[22]

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

where $\Theta_F = V \cdot H$ is the Faraday rotation per unit length, V is the Verdet constant, H is the magnetic field strength, and $\Delta\beta$ is the phase mismatch between TE and TM modes.

Figure 1(c) shows the TE–TM conversion ratio as a function of propagation length under a magnetic field of 5.5 kG. The mode conversion ratio was also measured by coupling out the waveguiding light by the second GaP prism and measuring the rotation angle of its polarization plane. The data obtained by this method are shown by closed triangles in Fig. 1(c). The best fitted curve with Eq. (1) [a solid curve in Fig. 1(c)] was with $V = 56$ deg/cm/kG and $\Delta\beta = 852$ deg/cm. The phase mismatch $\Delta\beta$ calculated from the thickness and refractive indexes of the waveguide layers with the assumption of strain-free layers was $\Delta\beta = 870$ deg/cm,

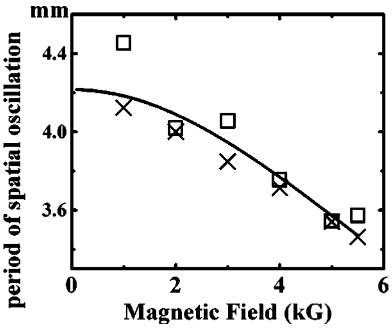

FIG. 3. Period of spatial oscillation of TE–TM mode conversion as a function of the applied magnetic field. Crosses show data for the magnetic field applied parallel to light propagation direction and squares for the magnetic field in the opposite direction. The solid line is a fitted curve.

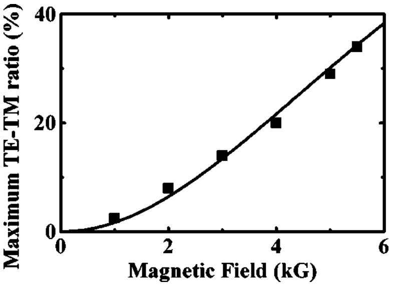

FIG. 4. Maximum TE–TM conversion ratio as a function of applied magnetic field. Squares are measured data and the solid line is a fitted curve.

which well agrees with the experimentally obtained value. The value of Verdet constant V is a reasonable value in $\mathrm{Cd}_{1-x}\mathrm{Mn}_x\mathrm{Te}$.[13]

Figure 2 shows the TE–TM mode conversion as a function of light propagation length for two different values of applied magnetic field: 5 and 2 kG. The stronger magnetic field induced the larger TE–TM mode conversion ratio and the shorter period of the spatial oscillations. Magnetic field dependence of the period is shown in Fig. 3. According to Eq. (1), the period of spatial oscillation of TE–TM mode conversion ratio should be inversely proportional to $\sqrt{(V\cdot H)^2+(\Delta\beta/2)^2}$. Indeed, the calculated values with $V=56$ deg/cm/kG and $\Delta\beta=852$ deg/cm (solid curve in Fig. 3) are in excellent agreement with those measured. Figure 4 compares the measured maximum TE–TM conversion ratio as a function of magnetic field with those calculated from Eq. (1) using $V=56$ deg/cm/kG and $\Delta\beta=852$ deg/cm. The maximum TE–TM mode conversion ratio was 34%. In order to increase the conversion ratio, the Verdet constant of the core layer should be increased and/or the magnitude of the phase mismatch $|\Delta\beta|$ should be decreased. The Verdet constant of diluted magnetic semiconductors sharply increases with approaching to absorption edge.[11–16] Therefore, by tuning the band gap of waveguide core layer closely to the laser wavelength a significant increase of Verdet constant can be expected. The value of $|\Delta\beta|$ can be reduced by the smaller refractive index step between the core and cladding layers. Improvement of stability and controllability of molecular beam fluxes during the film growth will enable one to achieve a higher mode conversion ratio.

In conclusion, we have obtained a magneto-optical TE–TM mode conversion in a waveguide of the diluted magnetic semiconductor, $\mathrm{Cd}_{1-x}\mathrm{Mn}_x\mathrm{Te}$, grown on GaAs substrate. The maximum TE–TM conversion ratio under the applied magnetic field of 5.5 kG was 34%. These results show a viability of monolithic integration of diluted-magnetic-semiconductor-based optical isolators and circulators with other semiconductor optoelectronic devices.

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