(Cd,Mn)Te/(Cd,Zn)Te quantum well waveguide optical isolator with wide wavelength operational bandwidth

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(Received 20 April 2007; accepted 25 June 2007; published online 23 July 2007)

The authors developed a magneto-optical (Cd,Mn)Te/(Cd,Zn)Te quantum well waveguide and demonstrated that the Faraday rotation in the waveguide was slightly dependent on the wavelength. For a waveguide with a quantum well width of 20 Å, constant Faraday rotation and a small amount of wavelength dispersion were simultaneously achieved in a wide 25 nm wavelength range at room temperature. Thus the broadband waveguide optical isolator is operated over a wide bandwidth of 25 nm. This result shows that it is feasible to monolithically integrate an optical isolator made of diluted magnetic semiconductor with semiconductor optoelectronic devices. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2759465]

Optical waveguide isolators are an indispensable component in high-speed optical network systems. Isolators are used to stabilize the laser diodes by protecting them from unwanted light reflections running back along the line. They function by utilizing the nonreciprocal nature of the magneto-optical Faraday effect. In present optical networks, ferrimagnetic garnet oxide crystals, such as $Y_3Fe_5O_{12}$ (YIG) and $(GdBi)_3Fe_5O_{12}$, are used in magneto-optical materials for discrete optical isolators.

Because most of the active optical elements (e.g., laser diodes, optical amplifiers, modulators, and optical gates) are produced on GaAs or InP substrates, it is advantageous to monolithically integrate all optical circuits on these types of substrate. Waveguide optical isolators based on oxide films have already been reported.[1–6] However, these garnet-film isolators have not been monolithically integrated with semiconductor optoelectronic devices because oxide crystals cannot be grown on semiconductor substrates. To fabricate optical integrated circuits, integrating optical isolators with the circuits is one of the most difficult tasks.

Diluted magnetic semiconductor of (Cd,Mn)Te was proposed as a magneto-optical material to be used in integrating optical isolators with semiconductor optoelectronics.[7] (Cd-,Mn)Te can be grown directly on GaAs and InP substrates because they share a common zinc-blende crystal structure. (Cd,Mn)Te also exhibits a huge Faraday effect near its absorption edge.[8] Furthermore, the tunability of its absorption edge between 1.56 and 2.1 eV by varying the Mn concentration makes the (Cd,Mn)Te magneto-optical waveguide compatible with (Al,Ga,In)P:GaAs optoelectronic devices operating in the wavelength range of 600–800 nm.[9] For longer-wavelength ($\lambda = 800-1600$ nm) optoelectronic devices, (Cd,Hg,Mn)Te can be used.[10]

(Cd,Mn)Te waveguide optical isolator has been fabricated on GaAs substrate and high isolation ratio and low optical loss were demonstrated.[11,12] However, its operational bandwidth is narrow (i.e., only about 5 nm), which is a significant obstacle to its practical application. The reason for the narrow bandwidth is the large variation of the Faraday rotation in (Cd,Mn)Te for different wavelengths.[8,9,11] The large Faraday effect in (Cd,Mn)Te originates from the anomalously strong exchange interaction between the *sp*-band electrons and the localized *d* electrons of Mn^{2+}.[8] Because of its excitonic nature, the Faraday effect in (Cd,Mn)Te is very high for wavelengths near its semiconductor band gap, and the effect sharply decreases for longer wavelengths.[13] The optical isolator uses the 45° rotation of the linearly polarized light due to the Faraday effect.[9,14] As the Faraday rotation in (Cd,Mn)Te changes with wavelength, the rotation angle of the polarization plane deviates from 45° resulting in severe performance degradation of the isolator. Because Faraday rotation of paramagnetic (Cd,Mn)Te is proportional to the applied magnetic field, it is possible to compensate for the large wavelength dependence of the Faraday rotation in (Cd,Mn)Te by tuning an external magnetic field for each operated wavelength. Using this field tuning method, a 35 nm operational wavelength range was demonstrated in the (Cd,Mn)Te waveguide isolator.[15] However, such tuning is not practical for real applications because a practical isolator needs a permanent magnet with fixed magnetic field.

To overcome the large wavelength dependence of Faraday rotation in (Cd,Mn)Te and to fabricate a broadband waveguide isolator that has a permanent magnet, in this letter we have proposed a (Cd,Mn)Te quantum well (QW) waveguide structure. The Faraday effect in a (Cd,Mn)Te QW is greater than that of bulk (Cd,Mn)Te. Further, it is not as dependent on the wavelength size.[16] However, due to the two-dimensional nature of QW, its optical properties become significantly different for light polarized in the plane of the QW and perpendicular to the QW. Therefore, for a waveguide composed of only a single QW, there is a big difference between propagation constants of transverse electric (TE) and transverse magnetic (TM) modes. Due to this difference, which is called TE-TM mode phase mismatch $\Delta\beta$, linearly polarized light can be easily converted to elliptically polarized light, which reduces the performance of the isolator.[17] Therefore, a waveguide composed of only a single QW cannot be used for the isolator application.

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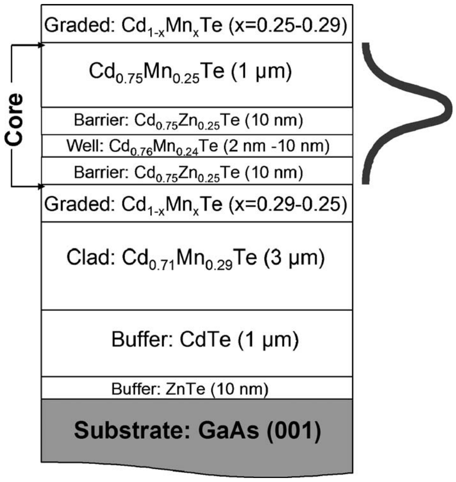

FIG. 1. Structure of a (Cd,Mn)Te waveguide with (Cd,Mn)Te/(Cd,Zn)Te QW. The waveguiding light intensity distribution is shown in the right side.

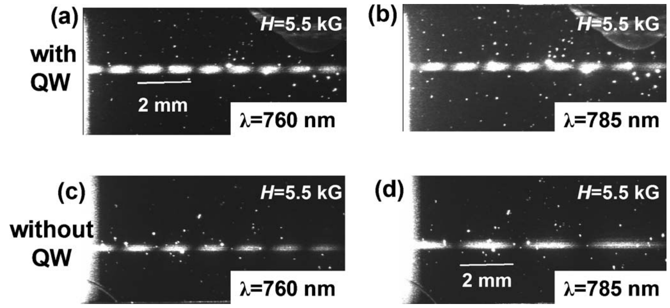

FIG. 2. Spatially modulated light streak from waveguide TE mode for waveguide with a 20-Å-thick (Cd,Mn)Te/(Cd,Zn)Te QW [(a) and (b)] and waveguide without QW [(c) and (d)] at λ=760 nm [(a) and (c)] and λ=785 nm [(b) and (d)] under magnetic field of 5.5 kG at room temperature.

Mode conversion efficiency R between the TE and TM modes induced by the Faraday effect is expressed as a function of optical propagation length L as[18]

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

where $\Theta_F=VH$ is the Faraday rotation per unit length, V is the Verdet constant, and H is the magnetic field strength. As described above, in order to keep the linearly polarized state of the waveguiding light, $\Delta\beta$ should be ideally zero, which is equivalent to complete mode conversion, i.e., $R=1$. Larger Θ_F is also useful to keep the linear polarization and to make the propagation length to obtain the 45° rotation shorter. Therefore, in order to make a high performance isolator, we need a large, wavelength independent Θ_F and small $\Delta\beta/\Theta_F$. For that purpose, we proposed using an optical waveguide that combines (Cd,Mn)Te bulk material and single QW.

Figure 1 shows the (Cd,Mn)Te/(Cd,Zn)Te QW waveguide structure. The waveguide was grown by molecular beam epitaxy on a GaAs(001) substrate. There are two buffer layers of ZnTe (10 nm) and CdTe (1 μm) and a $Cd_{0.71}Mn_{0.29}Te$ (3 μm) waveguide clad layer. The waveguide core layer was sandwiched between two $Cd_{1-x}Mn_xTe$ (0.5 μm) graded layers in order to reduce TE-TM mode phase mismatch.[11,12,17] The waveguide core consists of a $Cd_{0.76}Mn_{0.24}Te/Cd_{0.75}Zn_{0.25}Te$ single QW and a 1-μm-thick $Cd_{0.75}Mn_{0.25}Te$ layer, where the $Cd_{0.76}Mn_{0.24}Te$ well layer varies between 20 and 100 Å and the $Cd_{0.75}Zn_{0.25}Te$ barrier layer is 100 Å.

Magneto-optical measurements were carried out at room temperature and in magnetic fields up to 5.5 kG. A GaP prism was used to couple the laser light from a tunable Ti:sapphire laser (λ=680–800 nm) into the waveguide. The light scattered normally to the waveguide surface was detected by a highly sensitive camera to obtain the TE-TM mode conversion efficiency R.[7,12] To evaluate the optical isolation, another GaP prism was used to couple the light out. In this case, the input and output polarizers were used with the angle between their axes set to 45°.[14,15]

Figure 2 shows spatially modulated light streak of the waveguide mode at two different wavelengths (760 and 785 nm) for the waveguides with and without QW. By putting a linear polarizer between the waveguide surface and the camera, only the TE polarization component of the waveguide light is detected. High contrast between the minima and maxima of the light intensity oscillations shows that complete mode conversion is attained for both waveguides. The distance between peaks corresponds to 180° of the rotation. For the waveguide without QW [Figs. 2(c) and 2(d)], there is a big difference of the rotational period for these two wavelengths. However, for the waveguide with QW [Figs. 2(a) and 2(b)], such a difference was not seen. This means that, for the waveguide with QW, the Faraday rotation at these two wavelengths is the same. Also, in the waveguide with QW, the oscillation period is much shorter than that of the waveguide without QW. This corresponds to the larger Faraday rotation in the waveguide with QW. We analyzed the above light propagation data by using Eq. (1) to estimate R, Θ_F, and $\Delta\beta$.

Figure 3 shows the Faraday rotation Θ_F as a function of wavelength for the waveguides with thin 20 Å QW (solid circles) and without QW (open circles). For the waveguide without QW, the Faraday rotation sharply decreases as wavelengths become longer. This wavelength dependence is the same as that of bulk (Cd,Mn)Te. In the contrary, for the waveguide with QW, the Faraday rotation is high, 2000 deg/cm, and it is almost constant in a wide 25 nm wavelength range. Within this operation range, the QW waveguide shows ten times smaller variation of Faraday rotation than that of the waveguide without QW. By calculating the field distribution of the waveguide mode, it was revealed that only a small amount of light field is confined inside the QW. However, as can be seen in Figs. 2 and 3, our wave-

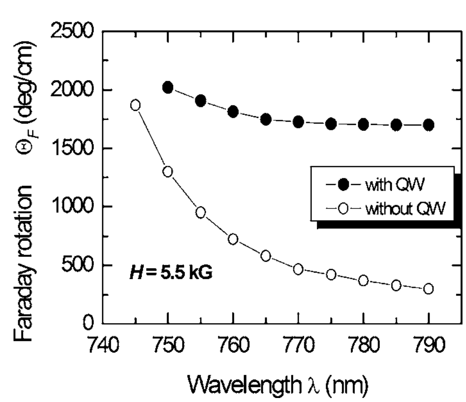

FIG. 3. Faraday rotation Θ_F as a function of wavelength in waveguide with a 20-Å-thick (Cd,Mn)Te/(Cd,Zn)Te QW (solid circles) and for waveguide without QW (open circles) under magnetic field of 5.5 kG at room temperature.

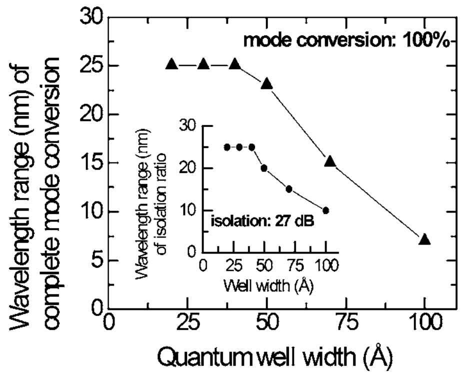

FIG. 4. Wavelength range, within which the complete mode conversion is obtained at $H=5.5$ kG and room temperature, as a function of QW width in the waveguide with single (Cd,Mn)Te/(Cd,Zn)Te QW. The Inset shows the isolation ratio.

guide structure with QW shows the larger Faraday rotation and lower wavelength dispersion than a waveguide without QW. These results can be attributed to the longer lifetime of electron in QW, the increase of the exciton oscillator strengths in the well layer,[19] and the stronger spin-exchange interaction.[16] Variation of strain and dislocation density inside the whole waveguide core induced by the insertion of the QW are another possible reasons for the results above.

TE-TM mode conversion efficiency is closely related to the performance of the waveguide optical isolator. For practical applications, the mode conversion efficiency should be at least 95% to achieve a high isolation ratio of 25 dB.[2,14,15] Figure 4 shows the wavelength range within which more than 95% conversion efficiency was obtained for the waveguide with single QW as a function of well width. For well widths of 20–40 Å, the operational wavelength range is as wide as 25 nm. However, for thicker well widths of 70–100 Å, the operational wavelength range sharply decreases. Analysis showed that the expansion of the wavelength range for thinner QW waveguides was due to the reduction of the mode phase mismatch $\Delta\beta$, to as low as 50 deg/cm, whereas this value rose to more than 500 deg/cm for thicker QW waveguides. Thinner QW waveguides have high $\Theta_F(\approx 2000$ deg/cm$)$ and small $\Delta\beta(\approx 50$ deg/cm$)$, resulting in a smaller $\Delta\beta/\Theta_F$ ratio. The value of $\Delta\beta/\Theta_F$ was much larger for thicker QW waveguides and those without QW waveguides. This is the reason why thinner QW waveguides provided a wider operational wavelength range of complete mode conversion, as shown in Fig. 4. From this result we conclude that, for the practical optical isolator application, only waveguides with single QW thinner than 40 Å can be used.

We also investigated the waveguides with double and multiple QW structures. However, the mode phase mismatch of these structures was too large to obtain a complete mode conversion efficiency. The directly evaluated isolation ratio was 27 dB with a 25 nm wavelength range for a QW waveguide thinner than 40 Å, as shown in the inset of Fig. 4. This waveguide also showed a low optical loss of less than 0.5 dB/cm and a high magneto-optical figure of merit of more than 2000 deg/dB/kG.

In conclusion, we found that a thin (Cd,Mn)Te/(Cd,Zn)Te single QW significantly improves the Faraday rotation in (Cd,Mn)Te magneto-optical waveguide. For a waveguide with 20 Å thin QW, high and almost constant Faraday rotation was observed in a wide 25 nm wavelength range at room temperature. This QW waveguide also had a high Faraday rotation of 2000 deg/cm, a high isolation ratio of 27 dB, a low optical loss of 0.5 dB/cm, and a high magneto-optical figure of merit of 2000 deg/dB/kG in a wide 25 nm wavelength range. These values are comparable to that of commercial discrete isolators. These results show a feasibility of monolithically integration of the optical isolator with semiconductor optoelectronics.

This work was partly supported by the New Energy and Industrial Technology Development Organization (NEDO).

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