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Magneto-Optical (Cd,Mn)Te/(Cd,Zn)Te Quantum Well Waveguide with Broadband Operation Optical Isolator

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1. Introduction

Optical waveguide isolator is an important integrated component in the optical communication systems. Isolators are used to stabilize the laser diodes by protecting them from unwanted light reflections running back on the line. Diluted magnetic semiconductor of (Cd,Mn)Te is promising magneto-optical material for optical isolator. We demonstrated the bulk (Cd,Mn)Te waveguide isolator on GaAs substrate [1,2]. However, the operational bandwidth of this isolator was narrow, i.e. only about 5 nm. The narrow bandwidth is a significant obstacle for the practical application of the isolator. The reason for the narrow bandwidth is large variation of the Faraday rotation in the (Cd,Mn)Te with wavelength. To overcome the large wavelength dependence of Faraday rotation of (Cd,Mn)Te and to fabricate a broadband waveguide optical isolator, we propose a novel quantum well (QW) structure of (Cd,Mn)Te/(Cd,Zn)Te. We demonstrate that Faraday rotation in this QW waveguide is as high as 2600 deg/cm and almost constant in wide 30-nm wavelength range. We also report similar wavelength range of high isolation ratio of 30 dB. Using this QW waveguide we fabricated broadband optical isolator.

2. Experimental

(Cd,Mn)Te/(Cd,Zn)Te QW waveguide was grown on epi-ready GaAs substrate (001) by molecular beam epitaxy method. Two buffer layers of ZnTe (10 nm) and CdTe (1 μm) are followed by a $Cd_{0.71}Mn_{0.29}Te$ (3 μm) waveguide clad layer. Waveguide core layer was sandwiched between two $Cd_{1-x}Mn_xTe$ graded layers (0.5 μm) in order to reduce the mode phase mismatch between two waveguide modes of transverse electric (TE) and transverse magnetic (TM) [1,2]. The waveguide core consists of a (Cd,Mn)Te/(Cd,Zn)Te single QW and a 1-μm-thick $Cd_{0.75}Mn_{0.25}Te$ layer. Several QWs are grown with 20Å-thick of $Cd_{1-x}Mn_xTe$ well by varying Mn from 0.21 to 0.28 and 100Å-thick of $Cd_{1-y}Zn_yTe$ barrier by varying Zn from 0.22 to 0.30.

Magneto-optical measurements were carried out at room temperature with wavelengths λ = 680 – 800 nm and magnetic fields up to 5.5 kG. For evaluation of Faraday rotation in the waveguides, a GaP prism was used to couple the laser light into the waveguide. The light scattered normally to the waveguide surface was detected by high-sensitivity camera and the effective Faraday rotation, TE-TM mode phase mismatch were measured. For evaluation of optical isolation, another GaP prism was used to couple light out. In this case the input and output polarizers were used with the angle between their axes adjusted to 45 degrees.

3. Results and discussion

Due to the two-dimensional excitonic nature of QW, the Faraday effect in (Cd,Mn)Te QW is significantly larger than in bulk (Cd,Mn)Te and it decreases for longer wavelength more gradually than in bulk (Cd,Mn)Te. Figure 1 shows the Faraday rotation as a function of wavelength with three (Cd,Mn)Te/(Cd,Zn)Te QW waveguide samples for different Mn concentration as indicated by solid mark of triangles (Mn = 0.21), squares (Mn = 0.24), and circles (Mn = 0.28) and the waveguide without QW by open squares for comparison. For the waveguide without QW, the Faraday rotation sharply decreases as wavelength changes out from the bandgap. This wavelength dependence is same as that of bulk (Cd,Mn)Te [1]. In contrary, for the waveguide with QW, the Faraday rotation is almost constant in the wavelength at λ = 760 nm -790 nm. Moreover, Faraday rotation increases significantly with increasing the Mn concentration from 0.21 to 0.28 in the well layer. We obtained high Faraday rotation of 2600 deg/cm for Mn = 0.28 in QW

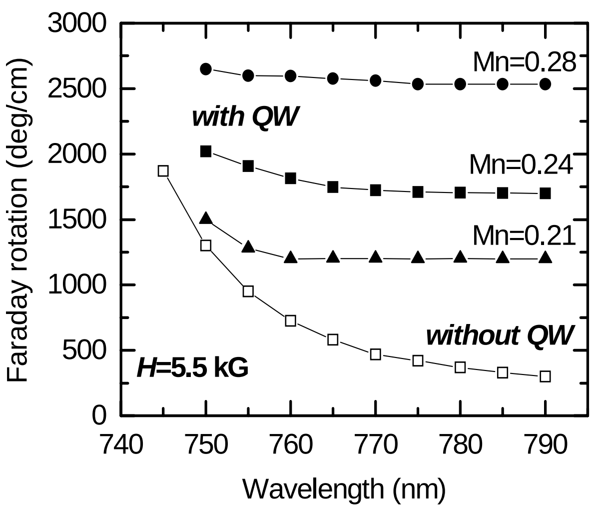

Fig. 1 Faraday rotation as a function of wavelength with 20Å-thick (Cd,Mn)Te/(Cd,Zn)Te QW for three different Mn samples (solid marks as indicated) and for waveguide without QW (open squares as indicated) under magnetic field of 5.5 kG.

waveguide and it is almost constant in wide 30-nm wavelength range. Within this operation range, QW waveguide shows fifteen times smaller variation of Faraday rotation than that of the waveguide without QW. Such low variation of Faraday rotation is desirable for optical isolator application. Therefore, QW waveguide has advantage for tuning the optical isolator at both short and long wavelengths. From a calculation of the field distribution of waveguide mode, only small amount of light field is confined inside QW. However, as it can be seen from Fig. 1, thin QW and high Mn concentration significantly influence the effective Faraday rotation in the waveguide. The Faraday rotation in QW is much larger and constant with wider operational wavelength range. These results can be attributed to longer life time of electron in QW, the increase of the exciton oscillator strengths in the well layer and stronger spin-exchange interaction between *sp*-band electrons and the localized *d*-electrons of Mn ions. Variation of strain and dislocation density inside the whole waveguide core induced by the insertion of the QW is another possible reason.

For the practical performance of an optical isolator, it is important to get an isolation ratio more than 25 dB. A high isolation effect can be achieved for a waveguide with high magneto-optical mode conversion ratio [3]. We found that QW waveguide thinner than 40Å can only contribute the complete mode conversion with 25-nm operational wavelength range because of the significant reduction of TE-TM mode phase mismatch of below 50 deg/cm [4]. Figure 2 shows the isolation ratio as a function of the magnetic field for light propagation length, L = 2 mm and λ = 750 nm of $Cd_{0.76}Mn_{0.24}Te/Cd_{0.75}Zn_{0.25}Te$ QW waveguide. Up and down arrows indicating the 45º and 45º + 90º of the polarization rotations that corresponds to the Faraday rotation

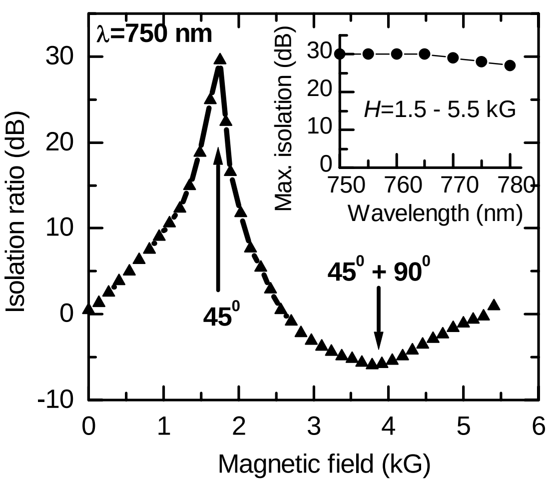

Fig. 2 Isolation ratio as a function of magnetic field at λ = 750 nm and L = 2 mm with 20Å-thick $Cd_{0.76}Mn_{0.24}Te/Cd_{0.75}Zn_{0.25}Te$ QW waveguide. Inset shows the maximum isolation as a function of wavelength.

angle for isolation peak at H = 1.75 kG and H = 3.8 kG, respectively. We obtained high isolation of 30 dB at 45º Faraday rotation. Inset of Fig. 2 plots the maximum isolation ratio as a function of wavelength for the same QW waveguide. The value of the isolation ratio is almost constant of 30 dB for wide 30-nm operational wavelength range. Our results indicate that (Cd,Mn)Te/(Cd,Zn)Te QW waveguide can deliver a high isolation ratio. We also obtained low optical loss of below 0.2 dB/cm and high magneto-optical figure-of-merit of more than 2000 deg/dB/kG from this QW waveguide.

4. Conclusions

In conclusion, it was found that (Cd,Mn)Te/(Cd,Zn)Te single QW significantly modify Faraday rotation with increasing Mn in the well. For a $Cd_{0.72}Mn_{0.28}Te/Cd_{0.70}Zn_{0.30}Te$ QW waveguide, the larger Faraday rotation of 2600 deg/cm and lower wavelength dispersion was observed in wide 30-nm wavelength range. QW waveguide also showed high isolation ratio of 30 dB, low optical loss of 0.2 dB/cm, and high magneto-optical figure-of-merit of 2000 deg/dB/kG in broad 30-nm operational wavelength range. These values are comparable or better than that of commercially used discrete isolator. These results show feasibility of monolithically integration of the optical isolator with semiconductor optoelectronics.

References

[1] V.Zayets, M. C. Debnath, and K. Ando, Appl. Phys. Lett. **84** (2004) 565.

[2] M. C. Debnath, V.Zayets, and K. Ando, Appl. Phys. Lett. **87** (2005) 091112.

[3] M. C. Debnath, V.Zayets, and K. Ando, phys. stat. sol. (c) **3** (2006) 1164.

[4] M. C. Debnath, V.Zayets, and K. Ando, manuscript preparation for Appl. Phys. Lett.