Available online at www.sciencedirect.com
ScienceDirect
Journal of Magnetism and Magnetic Materials 310 (2007) 2161–2163
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Nonreciprocal propagation of light without external magnetic fields in a semiconductor waveguide isolator with a MnAs layer

T. Amemiya[a,c,*], H. Shimizu[a,c], P.N. Hai[b,c], M. Tanaka[b,c], Y. Nakano[a,c]

[a]Research Center for Advanced Science and Technology, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan
[b]Department of Electronic Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[c]Japan Science and Techonology Agency, SORST, Japan

Available online 27 November 2006

Abstract

A 1.5-μm, TM-mode waveguide optical isolator was developed for use in photonic integrated circuits. It consists of an InGaAlAs-based optical waveguide with a ferromagnetic MnAs layer and makes use of nonreciprocal propagation loss of light induced by the magnetized MnAs layer. With a large-remanence MnAs layer grown with the Mn-template epitaxy method, the isolator successfully showed an 8.7 dB/mm isolation ratio without external magnetic fields.

PACS: 85.79.Sq

Keywords: Waveguide optical isolator; Nonreciprocal loss; MnAs; Epitaxial ferromagnet; Template effect; Magnetic anisotropy

An important element for developing photonic integrated circuits is small-sized waveguide isolators that can be monolithically combined with other waveguide-based optical devices. One promising way of creating such waveguide isolators is by using of the nonreciprocal loss phenomenon observed in an optical waveguide with a magnetized layer [1–3]. We fabricated a prototype of a waveguide isolator based on this phenomenon and obtained an isolation ratio of 8.8-dB/mm for 1.5 μm-band TM mode [4]. Our device consisted of a semiconductor optical amplifier (SOA) covered with a ferromagnetic manganese–arsenide (MnAs) layer. MnAs can be epitaxially grown on GaAs substrates without producing undesirable solid-phase reaction at the interface [5]. MnAs is a suitable ferromagnetic material for our device because it can make a low-resistive contact on the SOA waveguide, as compared with ordinary ferromagnetic metals such as Fe [6]. Although its Currie temperature is a little low, about 40 °C, it can be used stably in photonic integrated circuits because photonic integrated circuits are generally used under temperature control to operate laser diodes stably.

Our prototype device, however, needed a permanent magnet to apply a magnetic field to its MnAs layer and, therefore, took a lot of space. This was caused by the fact that an MnAs layer grown on the SOA waveguide was of poor crystalline quality and therefore showed a soft hysteresis curve with small remanence. Applying an external magnetic field was indispensable for the sufficient magnetization of the MnAs layer.

To solve this problem, we tried to improve the quality of the MnAs layer by using the Mn-template epitaxy method [7]. We found that MnAs layers grown with this method were of good crystalline quality and had a desirable hysteresis with enough remanence to operate our device at zero magnetic fields. We made a waveguide isolator with this improved MnAs layer and confirmed the successful operation without external magnetic fields. The following provides details on this improved device.

Fig. 1 shows a cross section of our device designed for 1.5 μm-band, TM-mode operation. Light passes through the SOA perpendicular to the figure (*z* direction). The SOA consists of a tensile-strained InGaAs/InGaAlAs multiple quantum well sandwiched between two InGaAlAs guiding

*Corresponding author. Research Center for Advanced Science and Technology, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo, 153-8904, Japan. Tel.: +81 3 5452 5155; fax: +81 3 5452 5156.
E-mail address: ametomo@hotaka.t.u-tokyo.ac.jp (T. Amemiya).

0304-8853/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmmm.2006.11.039

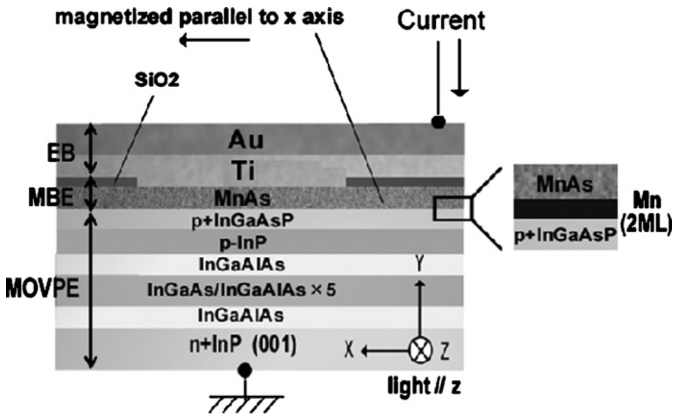

Fig. 1. Cross section of our waveguide isolator, consisting of an InGaAlAs-based SOA and a ferromagnetic MnAs layer.

layers. The upper guiding layer is covered with an InP cladding layer, an InGaAsP contact layer and the ferromagnetic MnAs layer. An Au/Ti double metal layer forms a top electrode to supply bias current to the SOA.

To operate the device, the MnAs layer is magnetized perpendicular (x direction) to the propagation of light. Under these conditions, the propagation loss of TM-polarized light is larger for backward propagation ($-z$ direction) than for forward (z direction). This nonreciprocal loss is caused by the magneto-optic transverse Kerr effect. The SOA compensates for the forward propagation loss and is operated so that the net loss for forward propagation will be zero. The MnAs layer is a key component of the device: it functions as a ferromagnetic body that induces the nonreciprocity, and as a metallic electrode that provide a bias current to the SOA.

We made a sample device on an n-type InP subatrate as follows. The SOA structure was the same as that of our previous devices [4] and grown by metal–organic vapor phase epitaxy. On the InGaAsP contact layer, we grew the MnAs layer using molecular-beam epitaxy. In general, it is difficult to grow a good crystalline MnAs layer on a substrate that contains P atoms as the InGaAsP layer does. To overcome this problem, we grew a MnAs layer by using the Mn-template epitaxy method [7]. Before the growth of MnAs, the sample was heated to 600 °C with the existence of As flux to clean the surface of the sample. Then the substrate was cooled to 180 °C, and As flux was shut off. After that, two monolayers of Mn were first deposited on the surface of the InGaAsP contact layer; depositing a few monolayers of Mn is the point of the Mn-template epitaxy method. On this surface, at the temperature of 200 °C, Mn and As fluxes were supplied simultaneously to grow a 130 nm-thick MnAs layer, with a growth rate of 80 nm/h. The X-ray diffraction (XRD) $\theta-2\theta$ scan was measured for the above MnAs thin film grown on the InGaAsP contact layer. A strong $(1\,\bar{1}\,0\,0)$ MnAs peak and small $(1\,\bar{1}\,0\,1)$ and $(1\,\bar{1}\,0\,2)$ MnAs peaks were observed. After the MnAs growth, we fabricated the gain guiding waveguides structure of Fig. 1.

The MnAs layer showed strong anisotropy. Fig. 2 shows the magnetization curve of the MnAs layer measured at 25 °C. For a magnetic field applied along the [0 1 1] direction of the InP substrate, the MnAs layer showed a hard hysteresis with a remanence of 450–500 emu/cm^3 and a coercive force of 33.2 mT, which is twice as large as that of our previous devices (17 mT) [4]. In contrast, for a magnetic field along the $[0\,1\,\bar{1}]$ of the InP, only a soft hysteresis with small remanence was observed. Therefore, to operate the device without external magnetic fields, we formed the waveguide stripe parallel to the $[0\,1\,\bar{1}]$ direction of the InP substrate and magnetized the MnAs layer along the [0 1 1] of the InP (x direction in Fig. 1).

We measured the nonreciprocical transmission of light in the device. To generate TM-polarized light, we used a wavelength-tunable laser with a polarization controller. The light was of wavelength 1.54 μm and of intensity 5 dBm. We transferred the light into and out of the device with lensed optical fibers. The output light from the device was measured with an optical spectrum analyzer. The device was 0.4 mm-long and kept at 15 °C. The bias current for the SOA was set to 100 mA. The MnAs was magnetized before measurements. Fig. 3 shows the results with an external magnetic field of 0.1 T (Fig. 3a) and without magnetic fields (Fig. 3b). With the external magnetic field, the output intensity changed by 3.71 dB by switching the direction of light propagation; therefore an isolation ratio was 9.3 dB/mm (= 3.71 dB/0.4 mm). Without magnetic fields, the change in output intensity decreased slightly but maintained a value of 3.47 dB. The isolation ratio of 8.7 dB/mm (= 3.47 dB/0.4 mm) was obtained successfully without external magnetic fields.

Fig. 4 plots the intensity of transmitted light for forward and backward propagation, together with the isolation ratio, as a function of SOA bias current from 30 to 100 mA. The SOA gain was saturated at 100 mA. The isolation ratio is almost constant within this current range, but the

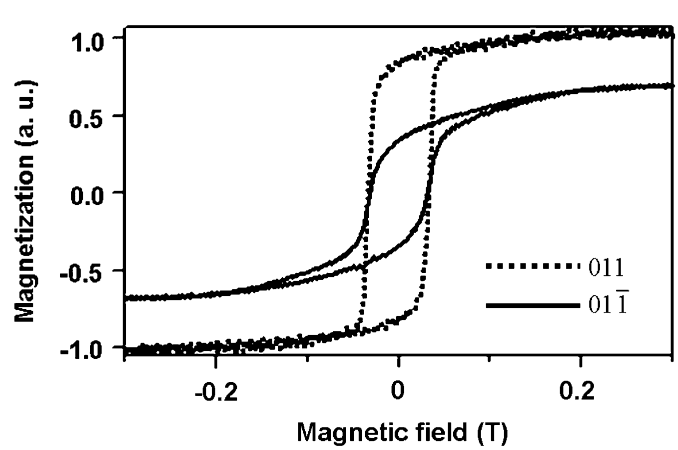

Fig. 2. Magnetization curves for the MnAs layer, with a magnetic filed applied in the [0 1 1] direction (dashed line) and the $[0\,1\,\bar{1}]$ direction (solid line) of the [1 0 0]-oriented InP substrate.

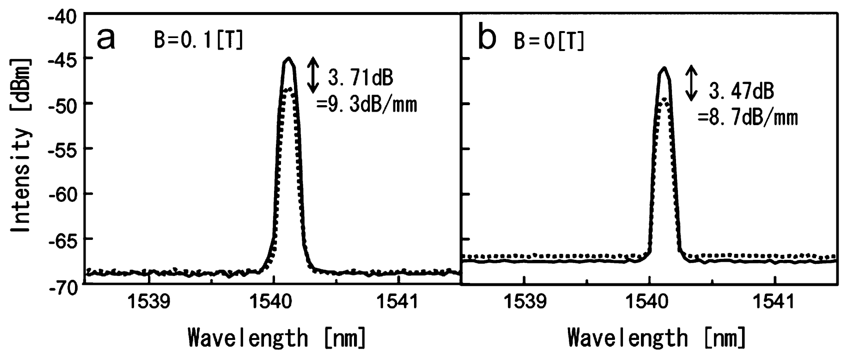

Fig. 3. Nonreciprocal transmission in the device for 1540 nm, TM-mode light: (a) with a 0.1 T external magnetic field and (b) without external magnetic fields. Solid lines are for forward propagation and dashed lines for backward propagation.

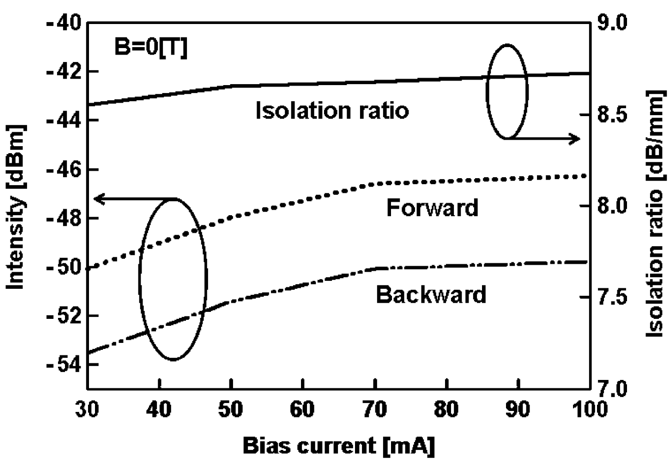

Fig. 4. Forward and backward transmission and isolation ratio as a function of SOA current, without external magnetic fields.

forward propagation loss was rather large. The large loss was caused by the fact that the intrinsic propagation loss in the device was about 25 dB, larger than we had expected. The gain in the SOA was insufficient to compensate for the sum of the intrinsic propagation loss plus measurement system loss (total loss in lensed-fiber couplers, circulators, and switches: about 30 dB in total). To reduce the forward propagation loss, we are now developing an improved device consisting of an index-guiding, high-gain SOA waveguide.

References

[1] W. Zaets, K. Ando, IEEE. Photon. Tech. Lett. 11 (1999) 1012.
[2] H. Shimizu, Y. Nakano, IEEE. J. Lightwave Tech. 24 (2006) 38.
[3] W. Van. Parys, B. Moeyersoon, D. Van. Thourhout, R. Baets, M. Vanwolleghem, B. Dagens, J. Decobert, O.L. Gouezigou, D. Make, R. Vanheertum, L. Lagae, Appl. Phys. Lett. 88 (2006) 071115.
[4] T. Amemiya, H. Shimizu, Y. Nakano, P.N. Hai, M. Yokoyama, M. Tanaka, Appl. Phys. Lett. 89 (2006) 021104.
[5] M. Tanaka, J.P. Harbison, T. Sands, T.L. Cheeks, G.M. Rothberg, J. Vac. Sci. Technol. B 12 (1994) 1091.
[6] T. Amemiya, H. Shimizu, Y. Nakano, in: Proceedings of the 17th International Conference on Indium Phosphide and Related Materials, 2005, pp. 303–306.
[7] M. Tanaka, J.P. Harbison, G.M. Rothberg, Appl. Phys. Lett. 65 (1994) 1964.