Semiconductor waveguide optical isolators incorporating ferromagnetic epitaxial Mn*X* (*X*=As or Sb)

T. Amemiya[1], Y. Ogawa[2], H. Shimizu[3], M Tanaka[4], H. Munekata[2], and Y. Nakano[1]

1: Reserach Center for Advanced Science and Techonology, Univ. of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan
2: Imaging Science and Engineering Laboratory, Tokyo Inst. of Tech., 4259-G2-13 Nagatsuta, Midori-ku, Yokohama, 226-8502, Japan
3: Dept. of Electrical and Electronic Engineering, Tokyo Univ. of Agri. and Tech., 2-24-16 Nakacho, Koganei, Tokyo, 184-8588, Japan
4: Dept. of Electronic Engineering, Univ. of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
E-mail: ametomo@hotaka.t.u-tokyo.ac.jp

Abstract: TM-mode waveguide optical isolators consisting of semiconductor waveguides with ferromagnetic Mn*X* (*X*=As, Sb) layers were developed. The device with a MnSb layer had an isolation ratio of 12 dB/mm in the wavelength range 1530-1555 nm.

OCIS codes: (230.3810) Magneto-optical systems; (250.5980) Semiconductor optical amplifiers.

1 Isolators that make use of nonreciprocal loss phenomenon in magneto-optic waveguides

An important element for developing photonic integrated circuits is waveguide isolators that can be monolithically combined with other waveguide-based optical devices. One promising way of creating such waveguide isolators is by using *nonreciprocal propagation loss*, a magneto-optic phenomenon where——in an optical waveguide with a magnetized ferromagnetic metal layer——the propagation loss of light is larger in backward than in forward propagation [1]. Making use of this phenomenon, we are developing TE- and TM-mode waveguide isolators for use in the 1.5-μm telecommunication band [2, 3]. The following provides the outline of our TM-mode isolator.

The TM-mode device consists of a III-V semiconductor optical-amplifier (SOA) waveguide combined with a ferromagnetic layer. In this device, the ferromagnetic layer has to function as (i) a magneto-optic layer that induces the nonreciprocity, and as (ii) a low-barrier electrode that provodes a driving current for the SOA. As an appropriate material that can meet these requirements, we used manganese compounds, Mn*X* (*X*=As or Sb), instead of ordinary ferromagnetic metals. Mn*X* materials are a ferromagnetic, intermetallic compound with a nickel-arsenide structure and can be grown epitaxially on III-V semiconductors [4, 5]. They produce a large magneto-optic effect comparable with ordinary ferromagnetic metals and make a low-barrier contact for III-V semiconductors.

2 Prototype device with ferromagnetic MnAs

First, we made a device with a MnAs layer because the epitaxy technology of MnAs on III-V semiconductors was well established [4]. Figure 1(a) shows a cross section of the device. The device consists of an MOCVD-grown, InGaAlAs/InP SOA waveguide covered with a MBE-grown MnAs layer [3]. To operate the device, an external magnetic field of 0.1 T was applied so that the MnAs layer would be magnetized perpendicular to the propagation of light, as denoted by the arrow in the figure (*x* direction). A TM-mode light was transferred into and out of the device by end-fire coupling from a tunable laser through a polarization controller. During measurement, the device was set at 20 °C. Figure 1(b) is a plot of the isolation ratio, as a function of wavelength from 1530 to 1550 nm (the device was 0.65-mm long). The output ntensities for forward and backward propagations are also plotted (including the loss in the measurement system). In this range of wavelengths, the device had an isolation ratio of 7.2 dB/mm. The device was able to operate at temperatures lower than 30°C because the Currie temperature of MnAs is 40°C.

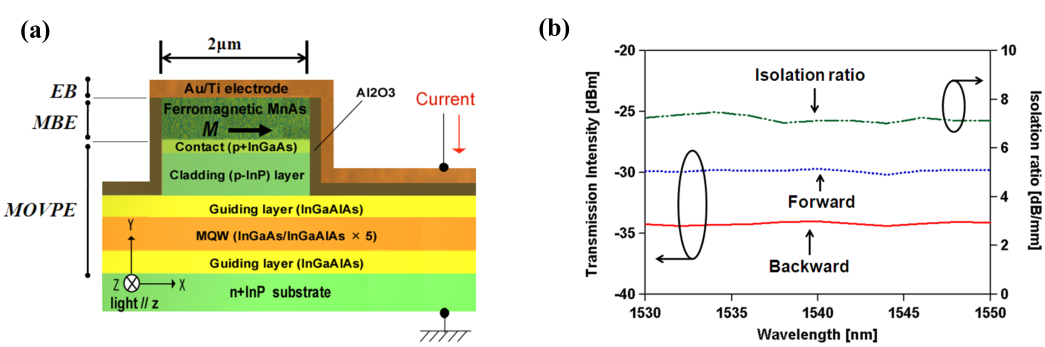

Fig. 1 (a) Schematic cross section of the TM-mode waveguide optical isolator with a ferromagnetic MnAs layer. (b) Transmission intensity and isolation ratio of the device as a function of wavelength.

978-1-55752-859-9/08/$25.00 ©2008 IEEE

3 Developing devices that can operate at higher temperatures——the use of ferromagnetic MnSb

Encouraged by this result, we then made an improved device that used MnSb instead of MnAs. The MnSb device was expected to operate at temperatures higher than room temperature because of the high Currie temperature, 314°C, of MnSb. In addition, MnSb has a larger magneto-optical effect (i.e., a large off-diagonal element of the dielectric tensor) and a larger saturation magnetization than those of MnAs; therefore the effect of the nonreciprocal loss phenomenon was expected to be greater. To make the device, we developed a MBE method to grow MnSb layers epitaxially on III-V semiconductor substrates [6].

A cross section of the device with a MnSb layer is shown in Fig. 2. The structure of the SOA region was the same as that of the MnAs device. In this improved device, we inserted an InGaAsP-InP double cladding layer between the SOA and the MnSb. This two-layer structure gives a good balance between optical confinement in the SOA waveguide and the extension of light into the MnSb layer.

Figure 3(a) shows the temperature dependence of the isolation ratio and the transmission intensity at 1.54-μm wavelength, measured for TM-polarized light (the device was 0.6-mm long). The isolation ratio was 11-12 dB/mm over the temperature range between 20 and 70°C, which is larger than that of the MnAs device (7.2 dB/mm at 20°C). The large isolation ratio and high temperature capability are due to the strong magneto-optic effect and high Currie temperature of MnSb. The transmission intensity gradually decreased with an increase in temperature, as shown in Fig. 3(a), because the TM-mode gain of the SOA waveguide decreased and its peak shifted towards a longer wavelength side with an increase in temperature. Figure 3(b) shows a plot of the output intensity for forward and backward propagation and isolation ratio as a function of wavelength from 1530 to 1555 nm, measured at 20 and 70°C. In this range of wavelengths, the isolation ratio was almost constant and independent of temperature.

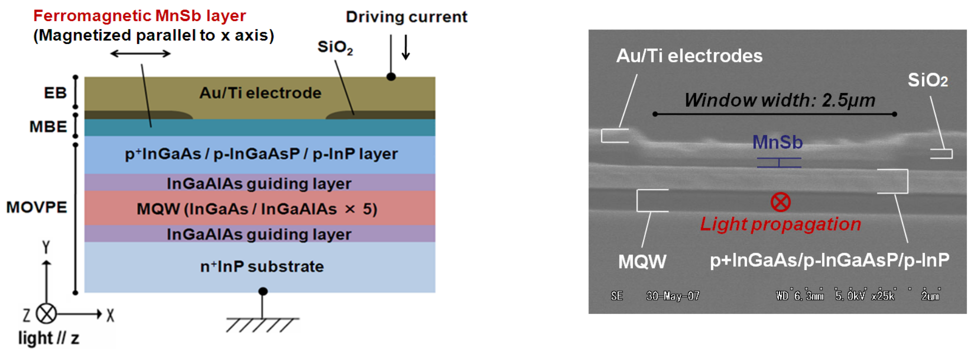

Fig. 2 (Left) Schematic cross section of the improved TM-mode waveguide optical isolator. The MnSb layer is magnetizated along *x*-direction. Light passes perpendicular to the figure (z-direction). (Right) Cross section of the device observed with a SEM.

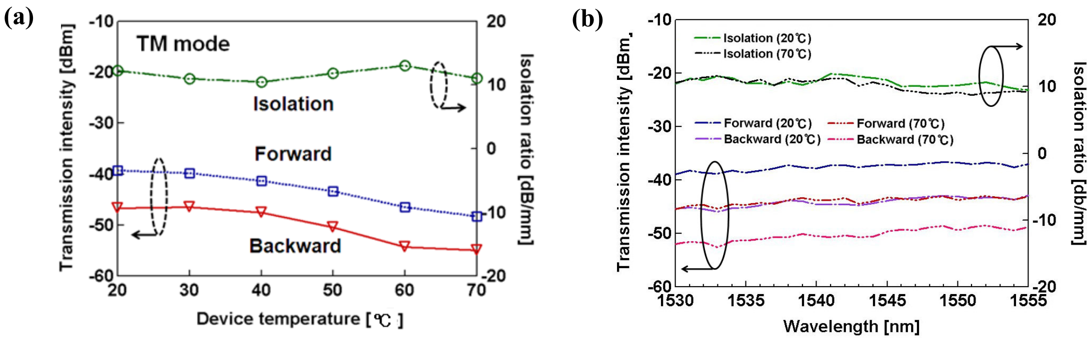

Fig. 3 (a) Temperature dependence of the isolation ratio and the transmission intensity at 1.54 μm wavelength measured for TM-polarized light (the device was 0.6-mm long). (b) Transmission intensity and isolation ratio as a function of wavelength.

References

[1] W. Zaets and K. Ando, IEEE Photonics Technol. Lett. **11**, 1012 (1999).
[2] H. Shimizu and Y. Nakano, IEEE J. Lightwave Technol. **24**, 38 (2006).
[3] T. Amemiya, H. Shimizu, P. N. Hai, M. Yokoyama, M. Tanaka, and Y. Nakano, Appl. Opt. **46**, 5784 (2007).
[4] M. Tanaka, J. P. Harbison, T. Sands, T. L. Cheeks, and G. M. Rothberg, J. Vac. Sci. Technol. B **12**, 1091 (1994).
[5] H. Akinaga, K. Tanaka, K. Ando, and T. Katayama, J. Cryst. Growth **150**, 1144 (1995).
[6] Y. Ogawa, T. Amemiya, H. Shimizu, Y. Nakano, and H. Munekata, in Proc of the 34th Int. Symposium on Compound Semiconductors (ISCS-2007).