High Temperature Operation of TM-mode Nonreciprocal-Loss Waveguide Optical Isolator with Ferromagnetic MnSb

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ABSTRACT
A TM-mode waveguide optical isolator consisting of a semiconductor waveguide combined with a ferromagnetic MnSb layer was developed. An isolation ratio of 12 dB/mm was achieved at a wavelength of 1.54 μm and a temperature range of 20-70 °C.

1 INTRODUCTION

One of indispensable elements for developing photonic integrated circuits is waveguide optical isolators that can be monolithically combined with other waveguide devices such as lasers, amplifiers, and modulators. A promising way of creating such devices is by using the nonreciprocal propagation loss, a magneto-optical phenomenon where——in a semiconductor optical waveguide combined with a magnetized ferromagnetic layer——the propagation loss of light is larger in backward than in forward propagation [1, 2].

The key to developing isolators based on this phenomenon is using an appropriate material for the ferromagnetic layer because the ferromagnetic layer has to meet a dual requirement of producing a large magneto-optical effect and of providing a low-resistance contact for a semiconductor waveguide. We previously made a prototype device that consisted of a semiconductor optical-amplifying waveguide (SOA waveguide) combined with a ferromagnetic manganese-arsenide (MnAs) layer [3]. MnAs can be grown epitaxially on GaAs, InP, and related semiconductors [4]. With this prototype device, we obtained an isolation ratio of 9.8 dB/mm for 1.5-μm-band TM mode.

The prototype was, however, unable to operate at high temperatures because the Currie temperature of MnAs is quite low, only about 40°C. Moreover the isolation ratio of 9.8 dB/mm is not enough for practical use. To overcome these problems, we took up manganese antimonide (MnSb). MnSb is a ferromagnetic, intermetallic compound with a nickel-arsenide structure the same as MnAs and is another strong candidate for the ferromagnetic layer in our device because of a larger magneto-optical effect and higher Currie temperature (T_c=587°C) than those of MnAs. We recently developed an epitaxy technology to grow MnSb layers on an InGaAs layer (a top of the SOA waveguide) [5]. Using this technology, we made a waveguide isolator that can operate at high temperatures. The following sections provide the details on this waveguide isolator.

2 DEVICE STRUCTURE

The structure of our TM-mode waveguide isolator is shown in Fig. 1. The device consists of a SOA waveguide covered with a ferromagnetic MnSb layer. Light passes through the SOA in the direction perpendicular to the figure (z direction). To operate the device, an external magnetic field is applied so that the MnSb layer will be magnetized perpendicular to the propagation of light, as indicated by the arrow in the figure (x direction). This produces a difference in propagation loss of TM-polarized light between forward (z direction) and backward propagation (-z direction); the propagation loss is larger for backward propagation than for forward. This nonreciprocal loss shift is caused by the magneto-optic transverse Kerr effect. The SOA compensa-tes for the forward propagation loss; it is operated so that the

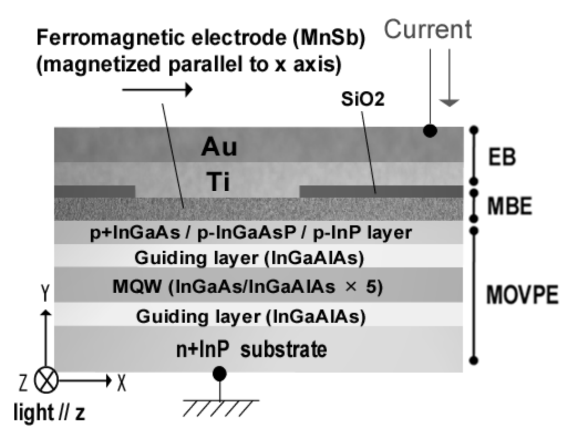

Fig. 1 Schematic cross section of the TM-mode waveguide isolator. The MnSb layer is magnetized along *x* direction. Light passes perpendicular to the figure (z direction).

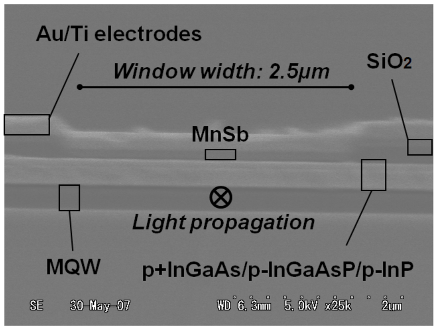

Fig. 2 Cross section of the waveguide isolator observed with a scanning electron microscope (SEM).

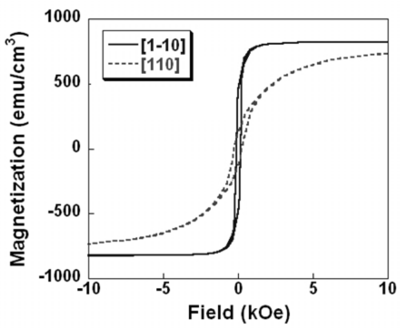

Fig. 3 Magnetization curves of the MnSb layer, with a magnetic filed applied in the [011] direction (dashed line) and the [01–1] direction (solid line) of the [100]-oriented InP substrate.

net loss for forward propagation will be zero. Under these conditions, the device can act as an optical isolator.

3 FABRICATION OF DEVICE

The substrate was a highly doped, [100]-oriented n-type wafer of InP. The SOA region was grown with metal organic vapor phase epitaxy (MOVPE). The MQW was composed of five tensile-strained InGaAs wells and six compressive-strained InGaAlAs barriers sandwiched between InGaAlAs guiding layers——the structure same as that of our previous device [3]. After that, a p-InP (0.25-μm thick) and a p-InGaAsP (0.15-μm thick) cladding layers and a highly-doped p-InGaAs contact layer were grown on the upper guiding layer. The InGaAsP-InP double cladding layer was used to achieve large optical confinement in the MnSb layer and strong interaction between light in the SOA and the magnetization vector in the MnSb layer.

After the formation of the SOA, a 160-nm MnSb layer was grown on the surface of the InGaAs contact layer by means of molecular-beam epitaxy (MBE) [5]. A 20-nm thick InGaAs layer was first grown at a substrate temperature of 450 °C. Then the MnSb layer was grown at 250 °C with a growth rate of 80 nm/h. During the growth, RHEED images exhibit a streaky feature except for the initial stage of the growth.

After the growth, a SiO2 layer was deposited on the

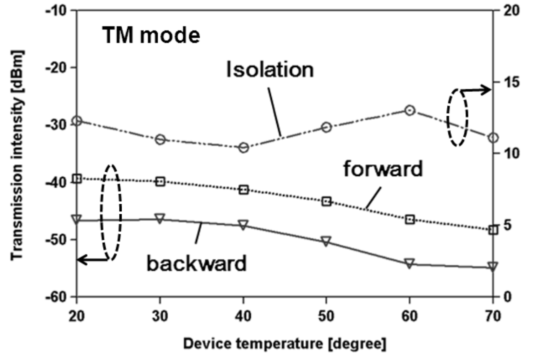

Fig. 4 Temperature dependence of the optical transmission and the isolation ratio. The waveguide isolator was operated with an 80 mA current and magnetized with a 1 kOe external field.

MnSb layer with magnetron sputtering, and a stripe window of 2.5-μm width was opened using wet chemical etching. A-100 nm Ti layer and a 200-nm Au layer were then deposited on the surface to make an electrode, using electron-beam evaporation. Figure 2 is a cross section of the device observed with a scanning electron microscope.

The MnSb layer on the InGaAs contact layer showed strong magnetocrystalline anisotropy, as depicted in Fig. 3, and was easily magnetized along the [01-1] direction of the InP substrates with a remanence of 850 emu/cm^3, which is larger than that of MnAs (about 500 emu/cm^3). Therefore, we formed the waveguide stripe parallel to the [011] direction and applied an external magnetic field to the [01-1] direction (x-direction in Fig. 1).

4 DEVICE OPERATION

We measured the transmission characteristics of the device. The light from a tunable laser was transferred into and out of the device through end-fire coupling. The device was 0.6-mm long and as cleaved. During measurement, the device was driven with a current of 80 mA, and magnetized with an external field of 1 kOe. Figure 4 shows the temperature dependence of the isolation ratio and the transmission intensity for the TM mode. The wavelength of incident light was fixed to 1.54 μm——the wavelength at which the SOA exhibited a gain peak. At temperatures from 20 °C to 70 °C, we obtained an isolation ratio of 12 dB/mm——a larger value than that of our previous device with MnAs. This large isolation ratio and the high temperature performance are produced by the large magneto-optical effect and the high Currie temperature of MnSb.

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