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We fabricated TM mode InGaAlAs/InP active waveguide optical isolators based on the magnetically induced nonreciprocal loss. We used epitaxially grown MnAs thin films as ferromagnetic electrodes of the semiconductor active waveguide optical isolators. We demonstrated TM mode nonreciprocal propagation (8.8 dB/mm) at 1540 nm with an excellent ferromagnetic electrode contact, which has greater semiconductor active waveguide optical isolator performance than that of our previously reported devices with Ni/Fe polycrystalline electrodes. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2220016]

Optical isolators are indispensable components in optical transmitter modules and photonic integrated circuits to prevent undesired reflection of light. *Integrable* semiconductor waveguide optical isolators are strongly desired, because conventional "free space" optical isolators are quite incompatible with InP-based optoelectronic devices, such as semiconductor laser diodes. It is very difficult to monolithically integrate Faraday rotators with InP-based waveguide devices. Therefore, various waveguide optical isolators have been studied.[1–4] However, most of the previous works are based on ferrimagnetic garnets, and still incompatible with InP optoelectronics.

A semiconductor waveguide optical isolator based on the nonreciprocal loss is one of the most promising waveguide optical isolators. They consist of semiconductor optical amplifier (SOA) waveguides with a laterally magnetized ferromagnetic metal upper electrode (Voigt configuration). The nonreciprocal loss is based on the transverse magneto-optic Kerr effect inside the magneto-optical planar waveguide. For TM mode light, the nonreciprocal loss is brought about by the reflection of light at the interface between the ferromagnetic upper electrode and the SOA waveguide. There is a difference in the TM mode complex reflection coefficient (both the amplitude and phase change) at the laterally magnetized ferromagnetic upper electrode/SOA waveguide interface between the forward and backward propagating light. In other words, the backward propagating light suffers from stronger absorption loss by the ferromagnetic metal than does the forward propagating light. The SOA gain compensates for the forward propagation loss. Under these conditions, this SOA waveguide works as an optical isolator.[5,6]

Recently we demonstrated 14.7 dB/mm TE mode nonreciprocal propagation at 1550 nm in an InGaAsP/InP active waveguide optical isolator.[7,8] Other groups reported TM mode nonreciprocal propagation in an InGaAlAs/InP SOA with $Co_{50}Fe_{50}$ electrodes (8.1 dB/mm at 1300 nm),[9,10] and in

a GaAs/GaAlAs passive waveguide with Co (1 dB/mm at 770 nm).[11] However, their operation wavelengths are not 1550 nm, where monolithically integrable optical isolators are strongly desired. Therefore, we demonstrated 6.7 dB/mm TM mode nonreciprocal propagation in an InGaAlAs/InP SOA with Ni/Fe electrode at 1530 nm.[12] However, the optical isolation was not enough, the insertion loss was large, and the contact resistance between the Ni/Fe polycrystalline upper electrode and the SOA contact layer was high. In these waveguide optical isolators above, ferromagnetic metals work as magneto-optical materials and upper electrodes. Therefore the ferromagnetic metals must provide large nonreciprocal loss and low-resistive electrode contact for the p^+InGaAsP layer. However, elemental ferromagnetic metals such as Ni and Fe are not always suited for this purpose. For example, Fe brings Schottky contacts although the magneto-optic effect of Fe is strongest among transition metals. Upon annealing to decrease the contact resistance, undesirable nonferromagnetic compounds such as FeAs are produced at the electrode interface, hence reduces the nonreciprocal loss. To solve these problems, we fabricated TM mode semiconductor active waveguide optical isolators with epitaxially grown MnAs ferromagnetic electrodes. Atomically flat and thermodynamically stable interfaces can be obtained between MnAs and GaAs.[13] Therefore, epitaxially grown MnAs thin films are suitable for realizing stable ferromagnetic electrode with low contact resistance.

As mentioned above, the ferromagnetic MnAs thin films can be epitaxially grown on the SOA waveguides as top electrodes in semiconductor active waveguide optical isolators. On the other hand, by depositing ferromagnetic metals at one of the SOA waveguide sidewalls and applying magnetic field vertically, it is possible to realize TE mode nonreciprocal propagation.[7,8] Therefore, by depositing two ferromagnetic layers on a single SOA waveguide (upper and side), we can realize polarization insensitive semiconductor active waveguide optical isolators. In the polarization insen-

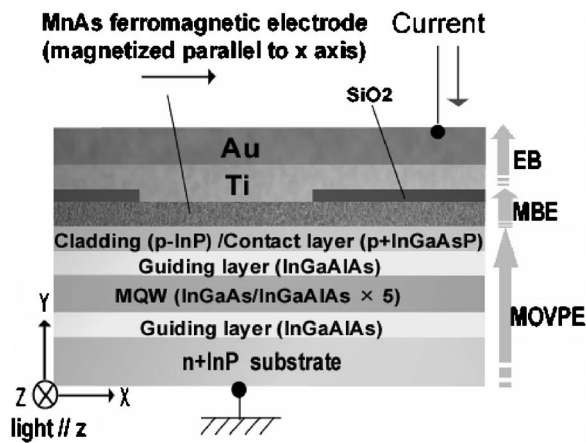[a)]FAX: +81-3-5452-5156; electronic mail: ametomo@hotaka.t.u-tokyo.ac.jp

FIG. 1. A schematic image of our TM mode semiconductor active waveguide optical isolator using an epitaxially grown MnAs ferromagnetic electrode.
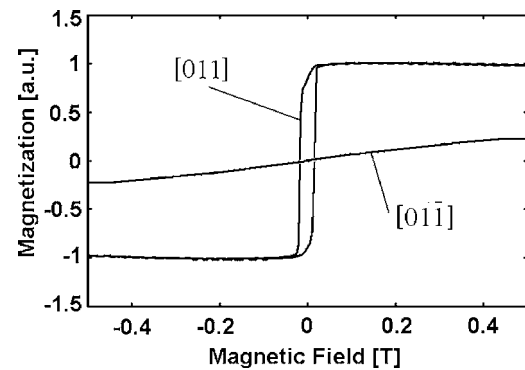

FIG. 2. The magnetization characteristics of the MnAs electrode of the fabricated semiconductor active waveguide optical isolator at room temperature.

sitive semiconductor active waveguide optical isolators, the polarization dependence of the modal gain and the absorption loss from the ferromagnetic layers bring the polarization dependent loss, which can be determined by proper design of the SOA active layer and the ferromagnetic metal layer structure.

Figure 1 shows a schematic image of our TM mode semiconductor active waveguide optical isolator based on the nonreciprocal loss. The device is composed of the SOA waveguide and the ferromagnetic metal upper electrode. The operation wavelength range is 1530–60 nm. The SOA layer stack was composed of a n^+ InP substrate, a 0.2-μm-thick n-InP buffer layer, a 0.1-μm-thick InGaAlAs (band gap wavelength $\lambda_g=1.1$ μm) lower waveguide layer, five tensile strained InGaAs quantum wells (−0.4%, 13 nm) with six compressively strained InGaAlAs barriers (+0.6%, 8 nm, $\lambda_g=1.2$ μm) for the TM mode amplification, a 0.1-μm-thick InGaAlAs ($\lambda_g=1.1$ μm) upper waveguide layer, a 0.2-μm-thick p-InP cladding layer, and a 0.25-μm-thick p^+ InGaAsP ($\lambda_g=1.4$ μm) contact layer. The photoluminescence peak wavelength of the multiple quantum well (MQW) was 1540 nm. The p-InP upper cladding layer is thin (0.2 μm) to obtain a larger optical confinement factor in the epitaxially grown MnAs thin film ferromagnetic upper electrode, and a large nonreciprocal loss. MnAs is a ferromagnetic compound metal with hexagonal NiAs structure and has a Curie temperature of 40 °C. MnAs thin films can be epitaxially grown on (100) GaAs and InP substrates by molecular-beam epitaxy (MBE).[13–15] External magnetic field was applied perpendicular to the light propagation direction and parallel to the MnAs thin film (x direction of Fig. 1).

We fabricated the prototype device of Fig. 1. The SOA layer structures were grown by metal-organic vapor phase epitaxy (MOVPE). After taking the substrates out of the MOVPE reactor, we introduced them to the MBE chamber for the growth of MnAs thin films. Before growing MnAs thin films, the substrate was heated up to 500–600 °C for thermal cleaning. Then the substrate was cooled to 200 °C and the growth of MnAs thin films was started with the growth rate of 80 nm/h. The MnAs layer thickness is 100 nm. Figure 2 shows the magnetization characteristics of our MnAs thin film at room temperature. The magnetization was measured by alternating gradient force magnetometry (AGFM). When the applied magnetic field was along the

[011] of the InP, the MnAs thin film showed almost perfectly square hysteresis characteristics. The coercive field is as low as 0.017 T, which can be easily applied by permanent magnets. However, when the applied magnetic field was along the [01$\bar{1}$] of InP, no hysteresis loop was observed and the magnetization did not saturate even at 0.5 T. This strong uniaxial magnetic anisotropy of the MnAs electrode is consistent with MnAs thin films grown on (100) GaAs or InP substrates.[14,15] We thus fabricated the waveguide stripes parallel to the [01$\bar{1}$] of the InP substrate, and the magnetic field was applied parallel to the [011] of the InP substrate (x direction of Fig. 1). We fabricated 5.5-μm-widestripe window openings by photolithography for gain guiding waveguide. Then, Ti/Au thin films were deposited by an electron-beam evaporator for the upper electrode. Figure 3 shows the cross sectional image of the fabricated device by scanning electron microscopy. It is clear that we fabricated the designed waveguide structure of Fig. 1.

We measured the propagation characteristics of the fabricated device under a 0.1 T permanent magnetic field at 15 °C. The device was cleaved to 0.6 mm long and facets were left uncoated. The bias current was 100 mA. An external magnetic field was applied by a permanent magnet along the [011] of the InP substrate. The laser diode light was of wavelength 1540 nm, of intensity 5 dBm, and coupled in and out of the device through the lensed optical fibers. The transmitted light was examined with an optical spectrum analyzer to separate out the transmitted light from the amplified spontaneous emission of the SOA. The required voltage for
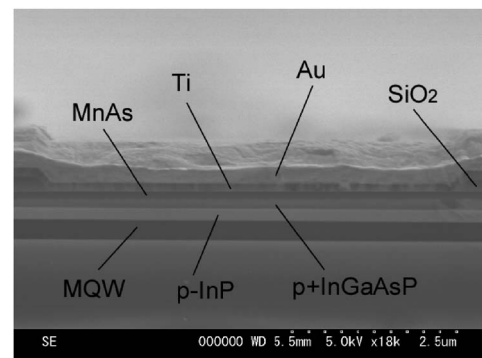

FIG. 3. A cross-sectional scanning electron microscope image of the fabricated TM mode InGaAlAs/InP semiconductor active waveguide optical isolator.
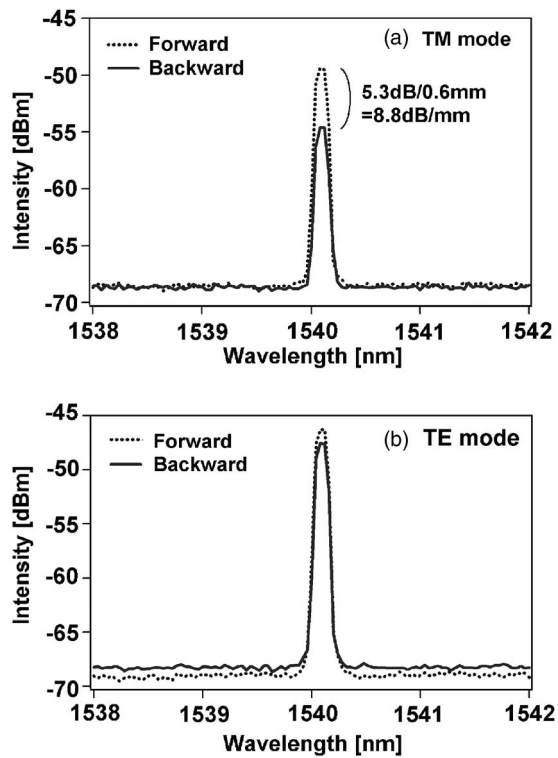
FIG. 4. The measured nonreciprocal propagation characteristics of the fabricated waveguide optical isolator for the 1540 nm (a) TM and (b) TE modes at a 100 mA bias under a magnetic field of 0.1 T.

100 mA bias current was 1.5 V, which is much lower than that of active waveguide optical isolators with polycrystalline ferromagnetic electrodes.[12] Figure 4 shows the propagation characteristics for (a) the TM and (b) TE modes at 1540 nm. In the TM mode, the output light intensity changed by a difference of 5.3 dB/0.6 mm=8.8 dB/mm between the forward and backward traveling light. On the other hand, the output intensity change was very small for the TE mode. Because this device operates in TM mode in principle, this polarization dependence is clear evidence of the expected nonreciprocal loss. At this stage, the forward propagation loss is large ($\sim$50 dB), as shown in Fig. 4. The origins of the forward propagation loss are (1) the absorption loss from the MnAs electrode ($\sim$25 dB), (2) the coupling loss between the lensed optical fiber and the waveguide (10 dB/facet), (3) weak lateral optical confinement due to the gain guiding structure, and (4) insufficient SOA gain (9 dB/0.6 mm =15 dB/mm) to fully compensate for the absorption loss from the MnAs electrode. By using larger SOA gain materials and index guiding waveguide structure, it is possible to reduce the forward propagation loss.

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