The isolation effect in ferromagnetic-metal/semiconductor hybrid optical waveguide was experimentally studied. Optical transmission in a Ga$_{1-x}$Al$_x$As waveguide covered by Co was found to depend on the magnetization of the Co. The isolation direction was different for a waveguide with a SiO$_2$ buffer layer and for a waveguide with a Ga$_{1-x}$Al$_x$As buffer layer used between the waveguide core layer and Co layer. The physical origin of the isolation in this isolator structure was clarified.

The purpose of the present study is to demonstrate the isolation effect in a waveguide covered by ferromagnetic metal, to study its properties, and to explain its physical origin. The directional dependence of absorption by the metal is a reason for isolation in this structure. The optical gain is used only to compensate for the loss. To avoid side effects due to optical amplification, in the present work we studied a passive waveguide covered by a ferromagnetic metal.

Figure 1 shows the structure of a Ga$_{1-x}$Al$_x$As waveguide covered by Co. The Ga$_{1-x}$Al$_x$As waveguide was grown with molecular-beam epitaxy on a GaAs (001) substrate. Following a 2500 nm thick Ga$_{0.55}$Al$_{0.45}$As clad layer and a 900 nm thick Ga$_{0.7}$Al$_{0.3}$As core layer, a buffer layer of 12 nm thick SiO$_2$ or 120 nm thick Ga$_{0.55}$Al$_{0.45}$As was grown. The 10 µm wide 600 nm deep rib waveguide was wet etched. A 100 nm of Co layer and a 100 nm of Au layer were deposited on the buffer layer. A protection layer of 100 nm thick SiO$_2$ with metal/semiconductor hybrid isolator can be beneficial for monolithic integration of the optical isolator with semiconductor optoelectronic devices, because of its simple structure and simple fabrication process.

The isolation effect in this hybrid isolator was studied theoretically in optical amplifiers covered by Co, Fe, FeCo, and MnAs. Exploiting the unique nonreciprocal properties of the hybrid isolator to fabricate magnetically controllable bistable laser diode was also proposed. Van wolleghem et al. experimentally observed nonreciprocal amplified spontaneous emission in a semiconductor optical amplifier covered by FeCo. Optical isolation was experimentally observed in an InGaAsP optical amplifier covered by Fe (Ref. 17) and in a GaAlAs passive waveguide covered by Co.

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8 μm wide window was used to avoid light absorption at the sidewalls of the waveguide (Fig. 1).

For the evaluation of nonreciprocal loss, laser light (λ=770 nm) was coupled into the waveguide with a polarization-maintaining fiber. The output light was detected by a charge coupled device (CCD) camera. A polarizer was placed in front of the CCD camera. The magnetic field was applied perpendicularly to the light propagation direction and in the film plane with an electromagnet.

Figure 2 shows the transmission coefficient of the TM mode as a function of applied magnetic field for the waveguide with SiO$_2$ buffer and the waveguide with Ga$_{0.55}$Al$_{0.45}$As buffer. A clear hysteresis loop of the transmission coefficient was observed with a coercive force of 35 Oe. The same value of coercive force of the Co layer was measured with a superconducting quantum interface device. The transmission coefficient of TE mode showed no dependence on the magnetic field as was predicted theoretically. The observation of the hysteresis loop of the transmission coefficient of TM mode proves the TM mode transmission depends on magnetization of the Co. Considering time-reversal symmetry, the difference of transmission for two opposite directions of magnetic field is equal to the difference in transmission for opposite directions of light propagation in one direction of magnetic field. Therefore, the amplitude of the hysteresis loop of the transmission corresponds to the isolation provided by the waveguide.

As can be seen from Fig. 2, the isolation direction for a waveguide with a SiO$_2$ buffer is different from that for a waveguide with Ga$_{0.55}$Al$_{0.45}$As buffer. Therefore, the isolation direction depends not only on the magnetization direction of the ferromagnetic metal, but on the waveguide structure as well.

We explain these results by considering two contributions to nonreciprocal loss. The first contribution is magnetic circular dichroism (MCD) in the ferromagnetic metal, which states that elliptically polarized light is absorbed differently by MO media for two opposite directions of its magnetization. For TM mode, the light is linearly polarized inside the waveguide core, but it is elliptically polarized inside the ferromagnetic metal. To prove that, let us consider a simple waveguide, which consists of an isotropic core and two isotropic clad layers. Axis directions are shown on Fig. 1. Figure 3 shows the field distribution in this waveguide for TM mode. The light is confined inside the core layer and its amplitude exponentially decreases in the clad layers. The electrical field in each layer can be derived as

\[ \mathbf{E} \sim e^{i(k_x x + k_z z - \omega t)} + \text{c.c.} \]

By substituting Eq. (1) into Maxwell’s equations, the ratio between the XZ components of the electrical field of the TM mode can be derived:

\[ \frac{E_z}{E_x} = -\frac{k_y}{k_z}. \]

Since \( k_z \) is the mode propagation constant, its value is real and the same for all layers. For the core layer, the field is harmonic, so its \( k_y \) value is also real and the ratio (2) is real as well. Therefore, the polarization in the core layer is linear. For clad layers, the field exponentially decreases, so its \( k_y \) value is imaginary and the value of the ratio (2) is imaginary as well. Therefore, the polarization in the clad layer is elliptical in the XZ plane and the absorption of the waveguide mode by the clad made of ferromagnetic metal depends on the magnetization direction due to the MCD effect.

The magnetoreflectivity at the buffer-metal interface is the second contribution to the nonreciprocal absorption in the waveguide. Due to magnetoreflectivity, the amount of the light penetrated into the metal depends on its magnetization. Since the light absorption by a metal is directly proportional to the amount of the light inside the metal, the absorption for a waveguide mode is different for opposite magnetizations due to the magnetoreflectivity. Figure 4 shows the calculated field distribution in waveguide with the SiO$_2$ buffer and in waveguide with the Ga$_{0.55}$Al$_{0.45}$As buffer for opposite magnetizations M+ and M−. For both waveguides, the amount of the light penetrated into the metal is higher for M+ magnetization. Therefore, the light absorption in case of M+ magnetization will be higher than for M− magnetization for both waveguides.

To estimate the performance of a hybrid optical isolator, we defined the figure-of-merit (FoM) for this isolator as a ratio of the nonreciprocal absorption to the total absorption by the metal. The mode propagation constants, nonreciprocal loss, and the FoM were rigorously calculated from a direct solution of Maxwell’s equations for the planar waveguide. In addition, both the MCD and magnetoreflectivity contribu-
tions to FoM were roughly estimated by estimating the light energy dissipation resulting from each contribution. For the waveguide with SiO$_2$ buffer, the FoM was calculated to be 7.95%, where the MCD and magnetoreflectivity contributions were estimated as $-8.01\%$ and 15.86%, respectively. For the waveguide with Ga$_{0.55}$Al$_{0.45}$As buffer, the FoM was calculated to be $-7.19\%$, where the MCD and magnetoreflectivity contributions were estimated as $-8.01\%$ and 1.11%, respectively. The sign of the contributions is different for both waveguides. On the contrary, the magnitude of the MCD contribution is almost the same for both waveguides. The demonstration of optical isolation, even in a passive waveguide without any loss compensation, reveals a high feasibility of semiconductor-ferromagnetic-metal-hybrid isolator for future integrated optoelectronics circuits.

In conclusion, we observed a clear hysteresis loop for the transmission of TM mode in Ga$_{x}$Al$_{1-x}$As waveguide covered by Co as a function of magnetic field applied perpendicularly to the light propagation direction and in the film plane. TM-mode transmission in this waveguide depends on the magnetization of Co and the optical isolation effect occurs in the optical waveguide covered by a ferromagnetic metal. The isolation direction is different for the waveguide with a SiO$_2$ buffer and waveguide with a Ga$_{0.55}$Al$_{0.45}$As buffer. We found two contributions from different signs to nonreciprocal loss. Because of the different magnitudes of these contributions, the isolation direction is opposite in these two waveguides. The authors thank Dr. S. Yuasa and X. Wen for their help and discussions.

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FIG. 4. Calculated intensity distribution of the TM mode along the waveguide thickness for the two opposite directions of magnetization in (a) waveguide with Ga$_{1-x}$Al$_x$As buffer and (b) waveguide with SiO$_2$ buffer.