Isolation effect in ferromagnetic-metal/semiconductor hybrid optical waveguide

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The isolation effect in a ferromagnetic-metal/semiconductor hybrid optical waveguide was experimentally studied. Optical transmission in a $Ga_{1-x}Al_xAs$ 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 $Ga_{1-x}Al_xAs$ buffer layer used between the waveguide core layer and Co layer. The physical origin of the isolation in this isolator structure was clarified.
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The optical isolator is an essential component of optical communication systems. It protects laser diodes and optical amplifiers from unwanted reflections. Several types of the waveguide optical isolators have been successfully demonstrated using magnetic garnet films grown on oxide substrates.[1–5] Because most active optical elements (such as laser diodes, optical amplifiers, modulators, and optical gates) are produced on GaAs or InP substrates, it is desirable to integrate monolithically all optical components on these semiconductor substrates. However, integration of the isolator is a difficult task. Garnet-made isolators have not been monolithically integrated with semiconductor optoelectronic devices, because these oxide crystals cannot be grown on semiconductor substrates. Several methods of integrating magneto-optical (MO) waveguide devices with semiconductor optoelectronics devices have been proposed. A direct bonding of garnet films was proposed onto InP substrate[6] and onto GaAs substrate.[7] Zayets *et al.*[8,9] fabricated a waveguide optical isolator with a MO film of a diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$ grown epitaxally on GaAs substrate.

Hammer *et al.*[10] proposed exploiting the MO properties of ferromagnetic metal to fabricate an integrated optical isolator. They showed theoretically that a non-reciprocal transverse-electric (TE)- transverse-magnetic (TM) mode converter can be obtained by using a semiconductor waveguide covered by a Fe layer. An optical amplification produced by the semiconductor waveguide compensated for the loss induced by the metal film. The magnetization direction was considered to be parallel to the light propagation (Faraday configuration). In this structure, phase matching and gain matching between TE and TM modes is crucial. For this purpose, they proposed a periodical reversal of magnetization of Fe, but this has not been experimentally realized. Zaets *et al.*[11] proposed a different structure for a ferromagnetic-metal/semiconductor hybrid isolator. In their proposed structure, the magnetization of the ferromagnetic metal was perpendicular to the light propagation direction and lay in the film plane (Voigt configuration). They showed theoretically that, in this case, a large difference exists in values of loss/gain for TM modes propagating in opposite directions. Thus, an amplifier covered with ferromagnetic metal can itself act as an optical isolator. This ferromagnetic-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.[11–14] Exploiting the unique nonreciprocal properties of the hybrid isolator to fabricate magnetically con trollable bistable laser diode was also proposed.[15] Van wolleghem *et al.*[16] 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.[18]

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 $Ga_{1-x}Al_xAs$ waveguide covered by Co. The $Ga_{1-x}Al_xAs$ 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

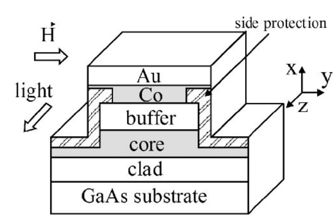

FIG. 1. $Ga_{1-x}Al_xAs$ optical waveguide covered with Co. Either SiO_2 or $Ga_{0.55}Al_{0.45}As$ was used as the buffer layer. Waveguide light propagates in the core layer and slightly penetrates into the Co layer.

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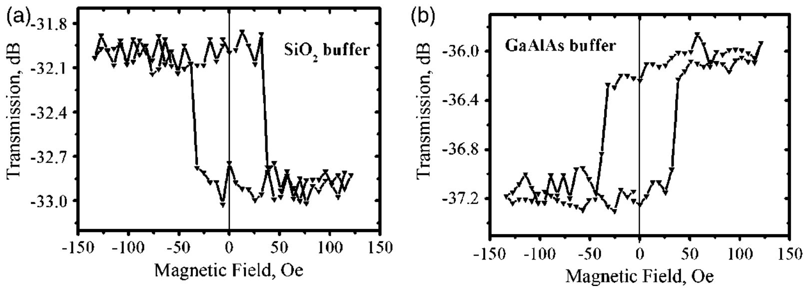

FIG. 2. Optical transmission in 1.1 mm long $Ga_{1-x}Al_xAs$ optical waveguides covered by Co at $\lambda = 770$ nm as a function of applied magnetic field (a) with SiO_2 as the buffer layer and (b) with $Ga_{0.55}Al_{0.45}As$ as the buffer layer.

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 ($\lambda = 770$ 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.[11] 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-inversion symmetry, the difference of transmission in the same direction of light propagation 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 a $Ga_{0.55}Al_{0.45}As$ 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 presented as

$$\mathbf{E} \sim e^{i(k_x x + k_z z - \omega t)} + \text{c.c.} \tag{1}$$

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:

$$\frac{E_z}{E_x} = -\frac{k_x}{k_z}. \tag{2}$$

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_x 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_x 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.[11] In addition, both the MCD and magnetoreflectivity contribu-

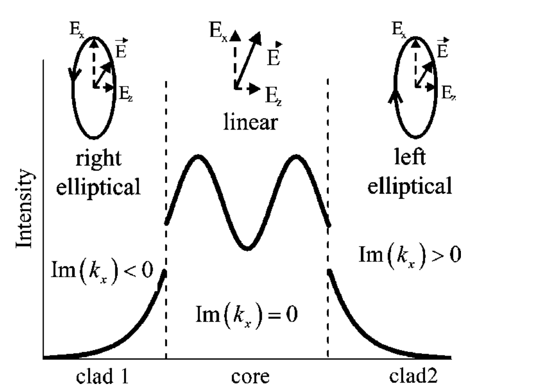

FIG. 3. Intensity distribution for the TM mode in an isotropic waveguide. Upper diagram shows the polarization of the light field as it observed along the y axis. The field is linearly polarized in the core, but it is elliptically polarized in clad layers.

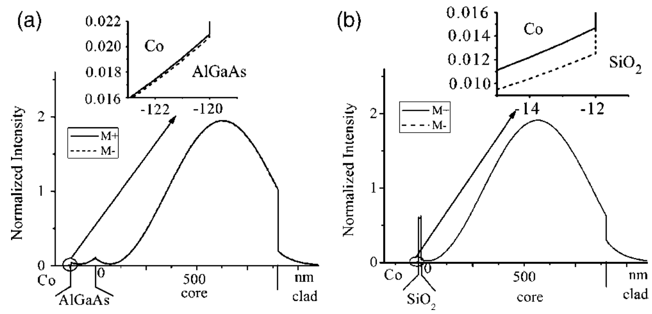

FIG. 4. Calculated intensity distribution of the TM mode along the waveguide thickness for the two opposite directions of magnetization in (a) waveguide with $Ga_{1-x}Al_xAs$ buffer and (b) waveguide with SiO_2 buffer.

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. The magnitude of the MCD contribution is almost the same for both waveguides. On the contrary, the magnitude of magnetoreflectivity contribution is significantly different (Fig. 4). That is the reason that opposite isolation directions were observed in the waveguides with SiO_2 and $Ga_{0.55}Al_{0.45}As$ buffers. For both waveguides, the sums of the MCD and magnetoreflectivity contributions are approximately equal to the FoM calculated from the rigorous solution of Maxwell equations. Therefore, we conclude that the MCD and magnetoreflectivity are two major contributions to the nonreciprocal loss in a waveguide covered by ferromagnetic metal.

In conclusion, we observed a clear hysteresis loop for the transmission of TM mode in $Ga_{1-x}Al_xAs$ 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 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.

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