Magneto-optic Effect in Amorphous Bi$_3$Fe$_5$O$_{12}$ Waveguide Sputtered at Room Temperature

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1. Introduction
In the state-of-the-art LSI, the signal delay in the global metal interconnection limits the processing speed of the LSI. In order to overcome this problem we are studying optical interconnection in LSI (see Fig. 1) [1-3].

Especially for the low-operation voltage and compactness, we have proposed the ring resonator optical switch using MO material as shown in Fig. 2. The operation voltage of 0.45mV is estimated for the ring resonator made of Bi substituted Y$_3$Fe$_5$O$_{12}$ film with a radius of 12μm and using the 18 turn coil. From the simulation we have found that the resonance peak splits to double peaks by applying the magnetic field (Fig. 3). The switching gain more than 10 dB can be obtained when Bi substituted Y$_3$Fe$_5$O$_{12}$ film is used [4]. The interesting finding is that the polarizer is not necessary although the conventional MO devices need the polarizer. In order to integrate the optical switches on Si LSI, it is necessary to realize the devices at process temperature below 450°C [5].

In this paper, we have investigated the magneto-optic effect of the MO material, Bi$_3$Fe$_5$O$_{12}$ (BIG) deposited by RF sputtering at room temperature. As a result, a relatively large Faraday effect was observed even for the amorphous film.

2. Experiment
The Bi$_3$Fe$_5$O$_{12}$ (BIG) film was deposited by RF sputtering at room temperature in Ar+O$_2$ mixture plasma. The schematic apparatus is shown in Fig. 4 and the typical sputtering condition is summarized in Table 1. The optical waveguides were fabricated using contact optical lithography and wet-chemical etching in the diluted HCl solution (Fig. 5). The amorphous BIG film is easily etched in the diluted HCl solution while the crystallized film (deposited at >500°C) can not be etched. The schematic and pictures of the fabricated BIG waveguides are shown in Fig. 6. The BIG film is only used for a short length (4-1000 μm), and the other part of the waveguide is consisted with the Si waveguide. The measurement system for the Faraday effect is shown in Fig. 7.

3. Results and Discussions
3.1 X-ray diffraction measurement
Figure 8 shows the x-ray diffraction (XRD) spectra for sputtered BIG at various temperatures. The BIG (004) peaks are observed for the films deposited at temperatures higher than 515°C. The (004) peak intensity is plotted as a function of the deposition temperature in Fig. 9, which shows that the XRD peak intensity increases with growth temperature. At room temperature the amorphous BIG film is deposited.

3.2 Faraday effect
First we have evaluated the light propagation loss of the amorphous BIG waveguide. Figure 10 shows the output light intensity from the waveguide with the different BIG length. From this figure the light propagation loss of 100dB/cm is obtained. Next, we have measured the Faraday effect of the amorphous BIG film using the measurement apparatus shown in Fig. 7. The input light is TE mode and the angle of the output polarizer is set so as to obtain a highest sensitivity to the rotation of the polarization plane by the Faraday effect. The result is shown in Fig. 11 where the 3.2% light modulation is achieved at an external magnetic field of 0.2T (magnetic field is parallel to the light propagation direction). Figure 11 shows the magnetic field dependence of the output intensity, where only a part of the hysteresis curve is shown. When the direction of the magnetic field is reversed the output light intensity was changed in the opposite direction (decreased when the magnetic field is applied). Table 2 shows magneto-optic properties of various MO materials. It is found that the Faraday rotation angle of amorphous BIG is comparable to that of some epitaxial material (Y$_3$Fe$_5$O$_{12}$) [6].

4. Conclusions
We have fabricated amorphous BIG waveguides by RF sputtering at room temperature and, for the first time, evaluated the Faraday effect. The output light intensity is modulated by 3.2% at applied magnetic field of 0.2T. The Faraday rotation angle was found to be relatively large even though the film is amorphous.

References
Fig. 1: LSI with optical interconnection, which operates at >10 GHz and is the target of this research.

Fig. 2: Ring resonator optical switch using magneto-optic material.

Table 1: Sputtering conditions.

Table 2: Magneto-optic properties of various MO materials.

Fig. 3: Simulated resonance characteristics of the ring resonator using magneto-optic material. Resonance peak splits to two peaks when magnetic field is applied.

Fig. 4: Sputter deposition of Bi$_3$Fe$_5$O$_{12}$ film.

Fig. 5: Fabrication process of BiFe$_3$O$_{12}$ (BIG) Waveguide.

Fig. 6: (a) Schematic view of BIG waveguide and its photograph, (b) SEM photograph of cross section of BIG waveguide and (c) photograph of fabricated BIG waveguides.

Fig. 7: Measurement apparatus for Faraday effect of BiFe$_3$O$_{12}$ (BIG) Waveguide.

Fig. 8: XRD spectra for sputtered BIG at various temperature.

Fig. 9: Crystallinity of BIG film versus growth temperature.

Fig. 10: Propagation loss of amorphous BIG waveguide.

Fig. 11: Measured Faraday effect of BIG film sputtered at room temperature. 3.2% modulation is achieved at an external magnetic field of ~0.2T.