Near-Infrared Magneto-Refractive Effect for Antiferro-Magnetically Exchange Coupled Co/Ru Multilayer Film in Transmission Configuration

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A magneto-refractive effect in a near-infrared (IR) region was investigated with a transmission configuration (T-MRE) for antiferro-magnetically coupled Co/Ru multilayer films. Applying dielectric function analysis based on an expanded Drude model that takes spin-dependent scattering into account, it was found that (1) a \([Co(4 \text{ nm})/Ru(0.7 \text{ nm})]_{10}\) multilayer film took parallel to antiparallel magnetization states at \(H = 14 \text{ kOe}\) to 0 Oe, respectively, and (2) that T-MRE curves against \(H\) took the maximum in the near-IR region and the minimum in the middle wavelength IR region. (3) The magnitude and wavelength dependence of T-MRE were well fitted by using the expanded Drude model with \(\omega_p = 1.5 \times 10^{16}\), \(\text{SAL} = 0.66\), and \(\beta\text{SAL} = 0.125\), where \(\text{SAL}\) and \(\beta\text{SAL}\) were self-averaged relaxation time and spin asymmetry, and \(\omega_p\) was the plasma angular frequency of conduction electrons. (4) According to calculation based on the expanded Drude model, the T-MRE of \(\Delta T/\tau\) showed the maximum of 0.3% at around 700 nm, and in the longer wavelength region, it showed a saturated feature with a value of \(-1.3\%\) at around 3 \(\mu\)m.

Key words: magneto-refractive effect, spin-dependent scattering, expanded Drude model, dielectric constant spectrum

1. Introduction

Much attention has been paid to magnetic sensors with an optical probe (MSOP), since the sensor head can be relatively miniaturized and used under vacuum, liquid atmospheres through narrow space with an optical fiber. In order to realize MSOP with a simple optical system, an effect with light intensity change is more promising than that with light polarization change. Therefore, development of materials whose optical properties such as reflectivity and transmittance vary against magnetic field \((H)\) is eagerly required. Based on this point, we focused on magneto-refractive effect (MRE) for antiferro-magnetically coupled ferro-/ non-ferromagnetic multilayer films where we can expect linear response \(\Delta T/\tau\) with rotational magnetization process. Concerning MRE, theoretical studies were reported after 1995 and experimental researches after 2002. According to these papers and following reports, the main interest is how to measure large magnetoresistance (GMR) effect with contactless probe especially for Co-Ag related granular or Co/Cu related multilayer films, because the origin of both MRE and GMR is generally understood to be the spin-dependent scattering of conduction electrons. However, optical properties and transport properties are not completely the same; concerning the MRE with transmission configuration (T-MRE), there exists wavelength dependence, and it is desirable that total thickness of a multilayer film should be thin to obtain enough transmitted light intensity for detection, which is completely different situation for GMR. In this sense, material investigations of MRE itself have not sufficiently carried out. Therefore, in this study, we experimentally obtained MRE with the transmission configuration for Co/Ru multilayer films with RKKY-like interlayer exchange coupling\(^{7-8}\) as a typical multilayer system. Furthermore, we applied dielectric function analysis, and discussed material guide for enhancing T-MRE based on an expanded Drude model taking the spin-dependent scattering into account.

2. Experimental procedure

The multilayer films were fabricated by dc magnetron sputtering on glass substrates. A Ti(2 nm)/Ru(3 nm) layer was adopted as an underlayer for the purpose of adhesion of the film to the substrate and the control of crystalline sheet texture with atomic closed packed plane parallel to the film plane. A SiN with 10 nm thick was used as a capping layer to avoid oxidation. The stacking structure of the magnetic multilayer was \([Co(4 \text{ nm})/Ru(d_{Ru} \text{ nm})]_{10}\) with the repetition number \(N\) of 10 with changing \(d_{Ru}\) from 0 to 1.2 nm. Here, Ru was selected as a nonmagnetic layer material to stabilize antiparallel magnetical coupling state under zero field with a thinner film thickness than that of Cu by RKKY-like interlayer exchange coupling.

Magnetic properties were evaluated by the vibrating sample magnetometer with the maximum applied field \((H_{\text{max}})\) of 14 kOe. Optical properties were

![Fig. 1 Schematic of system for measuring spectroscopic magneto-refractive effect with transmission configuration. L1 to L4 are condensing and collimation lens.](image-url)
spectroscopically measured by the ellipsometer (M-2000, J. A. Woollam) with the wavelength region from 250 to 1700 nm. T-MRE was spectrometrically measured by a hand-made system with an electromagnet applying magnetic field (H) along the film plane direction as shown in Fig. 1. Here, the measurement wavelength (λ) range was 900–1650 nm limited by monochrometer (NIR-QUEST, Ocean Optics) and Hmax was 14 kOe.

3. Results and discussion

3.1 Magnetic properties

Figure 2 shows typical magnetic hysteresis loops with the Co/Ru multilayer films with the Ru thickness, dRu of (a) 0, (b) 0.2, (c) 0.4, (d) 0.6, (e) 0.7, (f) 0.8, (g) 1.0, and (h) 1.2 nm, respectively. In the loops of (a) and (b), steep magnetization process can be seen around H = 0 caused by magnetic domain wall motion with ferromagnetically interlayer coupling between Co layers. With increasing dRu, saturation field becomes beyond 14 kOe, due to the antiferro-magnetic interlayer coupling, while the wall motion magnetization process remains for the films with (c) and (d). Further increasing dRu at (e) to (h), wall motion process completely disappears and smooth rotational magnetization process with the scissors type is expected.

3.2 Optical properties and magneto-refractive effect

Transmittance (T) of the [Co(4 nm)/Ru(dRu nm)]10 multilayer films was measured and was found to be the magnitude of 0.5 to 1.7 % in the spectral range of 900–1650 nm (data not shown). In details, T monotonously increases with increasing λ, and T monotonously decreases with thickening dRu.

Figure 3 shows hysteresis curves in transmittance normalized by that of under H = 14 kOe at 1550 nm against H for typical samples with [Co(4 nm)/Ru(0, 0.4, 0.7 nm)]10, whose magnetic properties are shown in Fig. 2 (a), (c) and (e), respectively. Here, T-MRE was defined as difference in transmittance between that of under H = 14 kOe and 0 kOe normalized by that of under 14 kOe. As seen in Fig. 3 (a), no change in T against H was observed even though the sample shows magnetization process with ferromagnetic hysteresis shown in Fig. 2 (a). On the other hand, as seen in Fig. 3 (c) and (e), T changed symmetrically with the H = 0 axis. Compared with the transmittance hysteresis curves of (c) and (e), saturation feature under high H region cannot be observed in (c) but clearly observed in (e). These facts mean that the shape of transmittance curves of the present multilayer films reflects angles between magnetic moments of neighboring layers such as GMR effect rather than direction of magnetic moments as shown in Fig. 2.

Figure 4 shows the normalized transmittance map with [Co(4 nm)/Ru(0, 0.4, 0.7)]10 multilayer films (color...
on line). The vertical and horizontal axes indicate $\lambda$ and $H$. The white lines with $\lambda = 1550$ nm correspond to the curves shown in Fig. 3 (a), (c) and (e). As seen in Fig. 4 (a), no change can be seen, whereas in (b) and (c), the minimum and the maximum appears around $H = 0$. Focusing on $\lambda$ dependence of the sample (e), the minimum can be observed at $\lambda = 900$ nm. With increasing $\lambda$ up to 1100 nm, the magnitude of the minimum decreases. Further increasing of $\lambda$ over 1100 nm, this minimum changes into the maximum. The magnitude of the maximum enhances with increasing $\lambda$ in the present experimental range. In the following section, we select the sample (e), because we can realize parallel ($H = 14$ kOe) and antiparallel ($H = 0$ kOe) magnetization states in our experimental setup of T-MRE.

3.3 Dielectric function analysis with expanded Drude model

In order to understand the enhancement phenomenon and change in the extreme values from the maximum to the minimum in wavelength dependence of T-MRE, we carried out spectral analysis for dielectric function. According to M. Voparai et al. 4 dielectric function for a GMR multilayer film (self-averaging limit of dielectric constant $\varepsilon_{SAL}$), assuming the multilayer to be a single layer, is written by following formula:

$$
\varepsilon_{SAL} = 1 - \frac{\omega_p^2}{\omega^2} \left(1 - \frac{\beta_{SAL}^2}{\beta_{SAL}^2} \frac{\frac{M_p}{\tau}}{\frac{M_p}{\tau} + \frac{M_s}{\tau}}\right).$$

where $\beta_{SAL}$ and $\omega_p$ are self-averaged relaxation time and spin asymmetry, $\omega_p$ is the plasma angular frequency of conduction electrons, $\omega$ is the angular frequency of the incident light. $MM_s$ is the normalized magnetization and takes 1 for the parallel state (saturation) and 0 for the antiparallel state. In the eq. (1), the first term is the so-called Drude term and second one is an expansion Drude term taking spin dependent scattering into consideration. Here, eq. (1) is based on the form of complex refractive index of $N = n + ik$. By applying this equation, we can derive $\beta_{SAL}$ and $\omega_p$ from fitting analysis to optical and T-MRE spectra obtained by the experiment.

Figure 5 shows (A) Dielectric constants and (B) T-MRE spectrum for the [Co(4 nm)/Ru(0.7 nm)]10 multilayer film. Black solid lines mean experimental results, and broken lines with blue and red color are fitted results by using an oscillation model with the expansion Drude term. According to the ellipsometry, application of the oscillation model in fitting shown in Fig. 4 (A) revealed $\omega_p = 1.5 \times 10^{16}$ and $\beta_{SAL} = 0.125$. Next, T-MRE spectrum was fitted based on eq. (1) shown in Fig. 5 (B) through calculations of transmittance of parallel and antiparallel states, which resulted in $\beta_{SAL} = 0.125$.

Finally, we expected material guide to enhance T-MRE by calculation to expand spectral range. Figure 6 shows calculated T-MRE spectra for virtual multilayer films by changing (A) $\beta_{SAL}$ around 0.66 and (B) $\beta_{SAL}$ around 0.125. In the calculation, constant values of $\omega_p = 1.5 \times 10^{16}$ and $\beta_{SAL} = 0.125$ for (A) and $\omega_p = 1.5 \times 10^{16}$ and $\beta_{SAL} = 0.66$ for (B) are used. Here, $\omega_p = 1.5 \times 10^{16}$, $\beta_{SAL} = 0.66$ and $\beta_{SAL} = 0.125$ are the values obtained by fitted results as shown in Fig. 5. For all conditions, the sign of T-MRE of $\Delta T/T$ changes positive to negative with increasing $\lambda$. As seen in (A) for the condition of $\beta_{SAL} = 0.66$ which corresponds to the present [Co(4 nm)/Ru(0.7 nm)]10 multilayer film, $\Delta T/T$ shows the maximum of 0.3% at around 700 nm, whereas in the longer wavelength region, it shows the saturated feature to the value of -1.3% at around 3 µm. Therefore, the effect of the enhancement of the magnitude of T-MRE in Mid-wavelength IR region (negative sign) was found to be larger than that in Near IR region (positive sign). With increasing $\beta_{SAL}$, $\lambda$ where the sign of $\Delta T/T$ changes from the positive to the negative shifts toward the longer $\lambda$ side as shown in (A). In contrast, with increasing $\beta_{SAL}$, degree of enhancement increases as shown in (B). Therefore, considering of application of MRE, figure of merit can be increased by ferro/ nonferro-magnetic material combination, layer structure, and total thickness while realizing antiparallel magnetization states for thinner crystalline ferro/ non-ferromagnetic multilayers.

4. Conclusion

A magneto-refractive effect in a near-infrared (IR) region was investigated with a transmission configuration (T-MRE) for Co/Ru multilayer films. As results, It was found that (1) a [Co(4 nm)/ Ru(0.7 nm)]10
multilayer film with antiferro-magnetically coupling showed the magnitude of T-MRE of about \(-1\%\) at 1550 nm, (2) the magnitude and wavelength dependence of T-MRE were well fitted by an expanded Drude model with \(\omega_p = 1.5 \times 10^{16}\), \(\tau_{\text{SAL}} = 0.66\) and \(\beta_{\text{SAL}} = 0.125\), where \(\tau_{\text{SAL}}\) and \(\beta_{\text{SAL}}\) were self-averaged relaxation time and spin asymmetry, \(\omega_p\) was the plasma angular frequency of conduction electrons, and (3) according to calculation based on the expanded Drude model, the T-MRE of \(\Delta T/T\) showed a saturated feature with a value of \(-1.3\%\) at around 3 \(\mu\)m. Further increase of \(\Delta T/T\) in IR region is expected to enhance \(\beta_{\text{SAL}}\) of the multilayer.

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