Spintronics, a technology that utilizes the spin degree of freedom of electrons, has been attracting much attention because of its use in devices such as spin transfer torque – random access memory (STT-RAM) and spin torque oscillators. The discovery of more phenomena related to spin current allows the development of spintronic devices, and such phenomena enable the basic technology that can be used to fabricate highly functional devices. In these phenomena, which include YIG in the spin Seebeck effect, the thermal generation of spin current involving CoFe₂O₄ and the spin Hall magnetoresistance effect, magnetic oxides play important roles. Therefore, the development of magnetic oxide thin films is needed in order to realize spintronic devices.

Spinel ferrites have been developed for use as electrodes in magnetic tunnel junctions (MTJs) and as tunnel barriers in spin filter junctions. Fe₃O₄, which is a ferromagnetic conductor, is the typical spinel ferrite so that a large number of research studies on Fe₃O₄ films have been reported so far. In particular, the metal-insulator transition at 120 K, which is called Verwey transition, has been still a matter of argument. Furthermore, the band calculations for this material predict that it is half-metallic, and therefore, researchers are seeking the way to use Fe₃O₄ as high-spin-polarized electrodes in an MTJ. On the other hand, CoFe₂O₄, which is a ferromagnetic insulator, can behave as a spin filter tunnel barrier easily allow epitaxial growth on MgO or Fe, being twice as large as that of MgO; therefore, the films can be integrated with Fe/MgO/Fe MTJs. The high Curie temperature of spinel ferrites enables their use in operations at room temperature (RT). Other oxides such as perovskite have also been intensively studied for their potential use as spintronic materials, even though their Curie temperatures are lower than RT.

In order to use oxides in spintronic devices, magnetic properties such as the coercive field (Hₑ) and the shape of the hysteresis loop must be highly controlled. In such metallic systems, magnetic properties are controlled by magnetic exchange coupling. Direct exchange coupling between a ferromagnetic metal and an antiferromagnetic metal is widely used in spin valve systems. Interlayer exchange coupling (IEC) is also extensively used in synthetic antiferromagnetic structures such as Co/Ru/Co systems. Few works, however, have examined multilayer systems involving oxides. The Fe₃O₄/MgO/Fe system has been reported to exhibit antiferromagnetic coupling, while the Fe₃O₄/MgO/Fe and γ-Fe₂O₃/MgO/Fe systems have been found to exhibit other types of coupling. The magnetic coupling in the Fe₃O₄/MgO/Fe system has also been previously investigated. Analogous to the metallic multilayer systems, hybrid multilayer systems having both a magnetic oxide and a nonmagnetic metal (NM) layer show various types of magnetic coupling.

In the present study, Fe₃O₄/Cr/Fe and Fe₃O₄/Pt/Fe hybrid systems were fabricated, and the magnetic characteristics of these systems were investigated. Since Fe/Cr/Fe is the typical system that exhibits the interlayer exchange coupling (IEC), the magnetic coupling in the Fe₃O₄/Cr/Fe system was a very interesting issue. For Fe₃O₄/Pt/Fe, we chose Pt as a non-magnetic layer because Fe/Pt/Fe was also reported to show IEC and Pt is hardly oxidized. If the IEC exists in the hybrid systems, the magnetic coupling would be expected to oscillate as a function of the NM layer thickness. On the other hand, the nonexistence of IEC would result in that the hysteresis loops were independent of the NM layer thickness. In this study, we found that the two systems exhibit completely different behaviors from observations on the magnetic coupling between the Fe₃O₄ and Fe layers.

We used Fe₃O₄ as a magnetic oxide layer because it is a highly spin polarized material, and reports confirm its epitaxial growth on MgO substrates. Samples were grown on MgO(110) substrates by using the reactive molecular beam epitaxy (MBE) method using oxygen to form MgO(110)/NiO(5 nm)/Fe₃O₄(60 nm)/Pt (tₚt of 0–10 nm)/Fe(5 nm)/Al₂O₃(2 nm) and MgO(110)/NiO/Fe₃O₄/Pt(0–10 nm)/Fe/Al₂O₃ film structures. The base pressure of the MBE chamber was 7 × 10⁻⁸ Pa. Before deposition, MgO(110)
single-crystal substrates were prebaked at 800 °C for 30 min. A NiO layer was inserted to prevent the diffusion of Mg from the MgO substrate into the Fe3O4 layer. The Fe3O4(110) layer was deposited on MgO(110) by using an Fe source at 300 °C in an oxygen atmosphere at 1 × 10⁻³ Pa. Next, the Ni layer (Pt or Cr) was grown at 130 °C in the form of a wedge (0–10 nm) by using a linear shutter. The Fe and Al2O3 layers were then deposited onto the Ni layer at RT. The epitaxial growth and surface morphology were confirmed by reflection high-energy electron diffraction (RHEED) and atomic force microscopy, respectively. The crystal structures were investigated by X-ray diffraction (XRD) measurements. The magnetization process was monitored from the longitudinal magneto-optical Kerr effect (MOKE) at RT at a wavelength of 650 nm.

Figure 1 shows the result of the RHEED and XRD measurements for the Fe3O4/Pt/Fe multilayers. Figures 1(a)–1(c) show the RHEED patterns of the Fe3O4, Pt, and Fe layers, respectively. The electron beam was incident along the MgO[100] direction. Spotty patterns [Figs. 1(a)–1(c)] indicate that the Fe3O4(110) and Pt layers grew epitaxially, although their surfaces were rough. According to the XRD profile at θ=2θ, Fe3O4 and Pt grew in the (110) direction. Since both the NiO and Fe layers were thin, the peaks for NiO and Fe were absent, although a small peak corresponding to Fe(211) appeared at 2θ=82°. The lattice parameters for MgO/NiO, NiO/Fe3O4, and Fe3O4/Pt are 0.421 nm, 0.418 nm, 0.8397 nm, and 0.392 nm, respectively; the lattice mismatch values for MgO/NiO, NiO/Fe3O4, and Fe3O4/Pt are −0.713%, 0.443%, and 6.63%, respectively.

The RHEED and XRD results for Fe3O4/Cr/Fe are shown in Fig. 2. Figures 2(a)–2(c) display the RHEED patterns of Fe3O4, Cr, and Fe, respectively. The surfaces of the Cr and Fe layers were rougher than those of the Fe3O4/Pt/Fe layer because their RHEED patterns were spottier than those of the sample with Pt. Fe3O4(110) peaks along with a Fe and a Cr(211) peak in the XRD profile indicate that Cr(211) grew on Fe3O4(110). The epitaxial growth of Cr(211) on MgO(110) is a well-known phenomenon. Moreover, the lattice parameter of Fe3O4 is twice that of MgO. Therefore, it is likely that Cr(211) grew on Fe3O4(110) epitaxially.

In order to investigate the magnetic properties of these materials, longitudinal MOKE was used to obtain the hysteresis loops of the Fe3O4(110)/[Pt(tPt) or the Cr(tCr)]/Fe(5 nm) system at RT. The wedge shape of the Pt or Cr layers enables the measurement of hysteresis at various Pt or Cr thicknesses in a substrate. The spot size of the MOKE was 0.1 mm, and the tPt and tCr values changed from 0 to 10 nm within 20 nm. The shapes of the hysteresis curves depended on the direction of the magnetic field (H). As shown in Fig. 3, the hysteresis curves when H was parallel to the MgO[-111] direction suggest a two-step magnetization process, while a single-step magnetization process was apparent when H was in the MgO[100] direction. In the two-step process, the abrupt magnetization switching of Fe and Fe3O4 occurred separately; a small switching field corresponds to the Hc value of Fe, and a large one corresponds to the Hc value of Fe3O4. In contrast, the magnetization switching of Fe3O4 progressed gradually because of crystal magnetic anisotropy when H was applied in the [100] direction; consequently, only the switching of the Fe layer was observed. Such magnetization switching was also observed by VSM measurements (not shown). The variation of the hysteresis depending on the H directions could be attributed to the crystal magnetic anisotropy of Fe3O4 and the anisotropic surface lattice of the MgO(110) substrates.

In Fig. 4(a), the hysteresis curves for various tPt are shown. At a tPt value of 0, the Hc value of Fe was much...
larger than that of bulk Fe because of the direct coupling between Fe$_3$O$_4$(110) and Fe. This coupling appeared to be ferromagnetic, as opposed to the Fe$_3$O$_4$(100)/Fe(100) antiferromagnetic coupling. Since the insertion of a thin nonmagnetic Pt layer ($t_{\text{Pt}} = 1.0$ nm) interrupted direct coupling, the $H_c$ value decreased abruptly after the insertion of the layer. In addition, the shape of the hysteresis loop at $t_{\text{Pt}}$ was different from that of the other loops, implying the existence of magnetic coupling. All hysteresis curves for the thicker Pt layers possess good squareness, and $H_c$ is nearly constant.

To investigate the properties of this relationship in greater detail, $H_c$ was plotted as a function of $t_{\text{Pt}}$ in Fig. 4(b). At a $t_{\text{Pt}}$ of 0, the $H_c$ value of Fe was enhanced significantly by direct magnetic coupling with Fe$_3$O$_4$(110). When $0 < t_{\text{Pt}} < 1.5$, the insertion of the Pt layer decreased the $H_c$ value by a large degree, and $H_c$ subsequently increased up to a $t_{\text{Pt}}$ of 2.5 nm, after which $H_c$ decreased and became constant. The behavior of this property seems to exhibit oscillation with damping.

Fig. 5(a) shows the hysteresis curves of the Fe$_3$O$_4$(110)/Cr/Fe system. At a $t_{\text{Cr}}$ of 0, the $H_c$ value exhibited a large field due to direct coupling and it decreased substantially with the insertion of the Cr layers, similar to that observed with Pt insertion. However, the behavior at $t_{\text{Cr}}$ greater than 2 nm differed from that observed with Pt insertion: the $H_c$ value of this system continued to increase up to a $t_{\text{Cr}}$ of 10 nm. As shown in Fig. 5(b), $H_c$ increased monotonically as a function of $t_{\text{Cr}}$ and reached 400 Oe at a final $t_{\text{Cr}}$ of 10 nm.

The $H_c$ value of the two samples exhibited very different dependences on the NM layer thickness, with one showing an oscillatory behavior and the other a monotonic increase. In the sample with an inserted Pt layer, the oscillation is reminiscent of the IEC metallic systems. In their investigation of the IEC in Co/Pt multilayers, Knepper and Yang found that the $H_c$ value of this system varied with the Pt thickness, 26 a behavior very similar to the variation in Fig. 4(b). Although the magnetic materials used in the two cases were different, the characteristics of the IEC remained dependent on the electronic properties of the nonmagnetic layer, 25 the Pt layer. Therefore, the IEC may be the origin of the observed variation of $H_c$ with $t_{\text{Pt}}$. 

![Fig. 2. In situ RHEED patterns of surfaces in the MgO(110)/NiO/Fe$_3$O$_4$/Cr/Fe layer: (a) Fe$_3$O$_4$, (b) Cr, and (c) Fe. (d) XRD pattern of the MgO(110)/Fe$_3$O$_4$/Cr/Fe layer at $\theta$=2$\theta$.](image)
On the other hand, the sample with an inserted Cr layer showed puzzling behavior. The monotonic increase in $H_c$ here is not characteristic of IEC. In a detailed investigation of the IEC for a Fe/Cr(211) multilayer grown on a MgO(110) substrate, Fullerton et al. observed a clear oscillation of the saturation fields, which disagrees with the results of the present study. The lattice distortion is therefore the probable origin for the increase in $H_c$. In order to confirm this theory, a MgO(110)/Cr($t_{Cr}$)/Fe trilayer was fabricated and MOKE measurements were performed. Since the lattice parameters of MgO and Fe$_3$O$_4$ are almost identical, we expected the Cr lattice on MgO to distort in the same way as on Fe$_3$O$_4$(110). As shown in Fig. 6, the magnetization of the Fe layer switched in a small magnetic field, and the $H_c$ value was almost independent of $t_{Cr}$. Therefore, the lattice distortion did not cause the increase in $H_c$. The interface effect (also known as the intermixing or proximity effect) was also unlikely to be the cause of the observed large $H_c$ because $H_c$ increased with increasing $t_{Cr}$. Furthermore, the interface effect is generally more applicable to thinner films. Thus, the cause of the increase in $H_c$ remains unclear; further investigation using both experimental and theoretical approaches is necessary in order to understand this phenomenon.

We investigated the magnetization characteristics of Fe$_3$O$_4$(110)/[Pt ($t_{Pt}$) or Cr($t_{Cr}$)]/Fe systems of various thicknesses of the NM layer, and we found that $H_c$ varied with $t_{Pt}$. In contrast, $H_c$ increased drastically with the use of Cr insertion layers. The observed increase in $H_c$ enables the control of the magnetic properties of the Fe layer in this hybrid system by varying the thickness of the Cr insertion layer. In order to understand the origin of this phenomenon, further experimental investigations on the multilayer’s structure and theoretical calculations for this material are necessary.

This work was partly supported by JSPS KAKENHI under Grant Nos. 15H05702 and 23686006, the Collaborative Research Program of Institute for Chemical Research, Kyoto University (Grant No. 2016-57), and the OPEN FACILITY, Hokkaido University Sousei Hall.