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Large Faraday effect in a short wavelength range for disordered zinc ferrite thin films

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We have prepared a zinc ferrite (ZnFe$_2$O$_4$) thin film 85 nm thick deposited on a silica glass substrate by using a radio frequency sputtering method. Faraday effect measurements have been carried out not only for as-deposited but also for annealed thin films. The thin film annealed at 300 °C as well as the as-deposited thin film exhibit a large Faraday rotation angle at a wavelength of around 390 nm. In particular, the thin film annealed at 300 °C manifests the largest Faraday effect among the present thin films; the rotation angle of 1.65°/µm is attained at a wavelength of 386 nm. The thin films 1.08 µm thick exhibit a large magnetization at room temperature, and the dependence of the magnetization on the external magnetic field is suggestive of a ferrimagnetic behavior. © 2006 American Institute of Physics. [DOI: 10.1063/1.2199727]

The stable phase of zinc ferrite (ZnFe$_2$O$_4$) possesses a normal spinel structure, in which antiferromagnetic order results due to Fe$^{3+}$ ions in octahedral sites (B sites) below about 10 K, i.e., Néel temperature. But a nonzero magnetization can be observed at room temperature when ZnFe$_2$O$_4$ is quickly cooled from elevated sintering temperatures. In particular, an unusually large magnetization is observed at room temperature for a superfine particle of ZnFe$_2$O$_4$, a rapidly quenched ZnFe$_2$O$_4$, and a gas phase-derived thin film of ZnFe$_2$O$_4$. The large magnetization is attributable to such a structure that a site exchange between Zn$^{2+}$ in the A site (tetrahedral site) and Fe$^{3+}$ in the B site takes place, and that the strong superexchange interaction between Fe$^{3+}$ ions in A and B sites leads to a ferrimagnetic order at least for localized magnetic moments even above the room temperature. We recently reported that the ZnFe$_2$O$_4$ thin film prepared by a sputtering method manifests a large magnetization at room temperature, and the dependence of magnetization on the external magnetic field is suggestive of a ferrimagnetic behavior.

The as-deposited and annealed thin films were subjected to an x-ray diffraction analysis with a Cu $K_α$ radiation (Rigaku RINT2500) to ascertain that the thin film is composed of a single phase of ZnFe$_2$O$_4$. The microstructure of the thin film was observed by means of transmission electron microscopy (TEM) with Philips CM200 at 200 kV. Optical absorption spectra were obtained for the thin films at room temperature using a spectrophotometer (JASCO, V-570). A variation of the Faraday rotation angle with a wavelength was explored by using a commercially available measurement system for Faraday and Kerr effects (JASCO, Model K-250). A dc magnetic field of 1.5 T, the direction of which was perpendicular to the film surface, was applied. The measurements were performed at room temperature. Magnetization as a function of external magnetic field was measured at 300 and 5 K by using a superconducting quantum interference device magnetometer (Quantum Design, MPMS2). The magnetic field was varied from −5 to 5 T.

Figure 1 shows the magnetization as a function of the external magnetic field at 5 and 300 K for the as-deposited and annealed ZnFe$_2$O$_4$ thin films 1.08 µm thick. The annealing was carried out at 300 °C. The magnetization of the as-deposited ZnFe$_2$O$_4$ thin film is 23 emu/g at 300 K when the external magnetic field is 5 T. This value is somewhat smaller than that reported previously. This is because the sputtering conditions such as kinds of glass substrate, atmosphere during sputtering, gas pressure, rf output power, and so forth are different. A similar phenomenon that magnetic properties such as magnetization are very sensitive to the preparation conditions was reported for ZnFe$_2$O$_4$ thin films prepared by pulsed laser deposition. The large magnetization at 300 K is imposed to the site exchange between Zn$^{2+}$...
ions in A sites and Fe$^{3+}$ ions in B sites, as described above.

It is found in Fig. 1 that the magnetization of the ZnFe$_2$O$_4$ thin film annealed at 300 °C is larger compared with the as-deposited thin film at both 5 and 300 K; the values of magnetization at 5 T are 39 and 47 emu/g for as-deposited and annealed thin films, respectively, when the temperature is 5 K. Although the reason why the annealing at 300 °C enhances the magnetization of the sputtered ZnFe$_2$O$_4$ thin film still remains open, we suggest a couple of possibilities. Figure 2 depicts a plane view TEM image of the as-deposited ZnFe$_2$O$_4$ thin film. The micrograph seems to indicate that the thin film is composed of concentrated crystalline nanoparticles dispersed in an amorphous matrix. The diameter of the crystalline particles is about 8–15 nm, coincident with the value estimated from x-ray diffraction lines, i.e., 5 nm or so.\(^\text{14}\) The presence of an amorphous phase formed via a rapid quenching process provided by the sputtering is a main reason why the present ZnFe$_2$O$_4$ thin film exhibits magnetization somewhat smaller than the value previously reported. Furthermore, it is speculated that ZnFe$_2$O$_4$ crystals in which Fe$^{3+}$ and Zn$^{2+}$ ions are randomly distributed are precipitated in the amorphous phase by the annealing at 300 °C; the volume fraction of the crystalline phase is increased by the annealing. Thus, the possible precipitation of ZnFe$_2$O$_4$ crystalline phases, which possess a large magnetization due to the disordered distribution of Fe$^{3+}$ and Zn$^{2+}$ ions, in the amorphous phase may lead to the enhancement of the magnetization caused by the annealing at 300 °C. Another possibility is the variation of the distribution of Fe$^{3+}$ ions in the spinel structure of ZnFe$_2$O$_4$ nanoparticles with the annealing at 300 °C. The magnetization of ZnFe$_2$O$_4$ strongly depends on the deviation in the site occupation from the normal spinel structure. A fraction of Fe$^{3+}$ ions which occupy the A sites has a great influence on the resultant magnetization.

As reported previously, the sputtered ZnFe$_2$O$_4$ thin films exhibit a magnetic transition like those of cluster spin glasses.\(^\text{15}\) We have preliminarily confirmed that the present thin films manifest similar features. Namely, the magnetic susceptibility takes a maximum at a certain temperature in the temperature dependence of susceptibility when the zero-field cooling is carried out. By contrast, the susceptibility increases monotonically with a decrease in temperature when the field cooling is performed. Such a cluster spin glasslike behavior partly stems from the disordered distribution of Fe$^{3+}$ and Zn$^{2+}$ ions in the spinel structure of ZnFe$_2$O$_4$. In such a structure, magnetic clusters composed of Fe$^{3+}$ ions are present and bring about the cluster spin glasslike transition. Namely, a superparamagnetic blocking of the clusters accompanied with intercluster interactions takes place. In addition, the nanoparticles of which the thin film is composed, as shown in Fig. 2, can contribute to the superparamagnetic blocking as well. At the transition, the magnetic interaction among the nanoparticles plays an important role because the nanoparticles are present so closely to each other. Thus, magnetic properties such as cluster spin glasslike transition and large magnetization at room temperature are soundly explained in terms of the disordered distribution of Fe$^{3+}$ ions over the A and B sites in the spinel structure as well as the microstructure of the thin film. The cationic distribution may be estimated from mutual zero-field and in-field low-temperature Mössbauer measurements.

Figure 3 illustrates optical absorption spectra for ZnFe$_2$O$_4$ thin films 85 nm thick. The spectra for the as-deposited thin film and those after annealing at 300 and 800 °C are shown. All the spectra manifest an intense absorption in a wavelength range shorter than about 500 nm; an absorption peak is clearly observed at about 310 nm. The absorption coefficient at around 310 nm is smaller for an-
nealed thin films than for the as-deposited film and is apt to decrease gradually as the annealing temperature increases. Considering that MgFe$_2$O$_4$ and LiFe$_2$O$_4$ exhibit an optical absorption band starting at 2 eV, which is assigned to the $d \rightarrow s$ transition and a similarity in the crystal structure between those ferrites and ZnFe$_2$O$_4$, we can speculate that the absorption in a wavelength range from 300 to 400 nm is attributed to the $3d^5 \rightarrow 3d^44s^1$ transition of Fe$^{3+}$ ions, where the 4s orbital of Fe$^{3+}$ is thought to contribute to the conduction band.

In Fig. 4 is shown the variation of the Faraday rotation angle with wavelength for as-deposited and annealed ZnFe$_2$O$_4$ thin films. The Faraday effect is evidently observed for the as-deposited thin film and those heat treated at 300 and 400 °C. By contrast, the Faraday rotation angle is very small for the thin film annealed at 800 °C. The absolute value of the Faraday rotation angle manifests its maximum at around 380–390 nm. The maximum of the absolute value of the Faraday rotation angle is 300 °C manifests the maximum rotation angle of 1.65°/μm at a wavelength of 386 nm.

In conclusion, we found that large Faraday effect takes place in a short wavelength range such as 390 nm for ZnFe$_2$O$_4$ thin films prepared by the sputtering method. In particular, the thin film annealed at relatively low temperatures such as 300 °C as well as the as-deposited film exhibit a large Faraday rotation angle; the thin film annealed at 300 °C manifests the maximum rotation angle of 1.65°/μm at a wavelength of 386 nm.

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