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Observation of Magnetic Domain Structure in Room Temperature Ferromagnetic Semiconductor (Ti,Co)O_2

Shun Inoue[1], Tomoteru Fukumura[1] and Tetsuya Hasegawa[1,2]

[1] Department of Chemistry, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
Phone: +81-3-5841-7595 E-mail: s-inoue@chem.s.u-tokyo.ac.jp
[2] Kanagawa Academy of Science and Technology
3-2-1 Sakado, Takatsu-ku, Kawasaki-shi, Kanagawa 213-0012, Japan

1. Introduction

Ferromagnetic semiconductor is one of the promising spintronic materials [1,2]. (Ga,Mn)As is the representative ferromagnetic semiconductor [3], however, its low Curie temperature hampered the room temperature operation of the spintronic devices. Recently, oxide-based ferromagnetic semiconductors have been extensively studied [4], since some of them have quite high Curie temperature. Among them, (Ti,Co)O_2 has the Curie temperature of ~600 K [5], exhibiting both magneto-optical effect [6] and anomalous Hall effect [7] at room temperature, that systematically change with the carrier density. Recent study of electric field induced ferromagnetism at room temperature clarified the potential of this compound for the room temperature spintronic devices [8].

Generally, ferromagnets possess magnetic domain structures [9]. In (Ga,Mn)As, an ordinary stripe domain structure was observed [10], and the manipulation of the magnetic domain was successfully performed [11]. On the other hand, the magnetic domain structure in (Ti,Co)O_2 has not been clearly observed. Cho *et al*. failed to detect magnetic signals with magnetic force microscopy of polycrystalline (Ti,Co)O_2 thin films [12]. Hong *et al*. observed a magnetic image of (Ti,Co)O_2 epitaxial thin film, but the magnetic domain structure was unclear possible due to the rough film surface [13]. Yang *et al*. observed a magnetic signal of surface precipitations in (Ti,Co)O_2 epitaxial thin film [14].

In this study, we report the observation of magnetic domain structure in (Ti,Co)O_2 epitaxial thin films at room temperature with magnetic force microscope.

2. Experiments and results

Epitaxial thin films of anatase $Ti_{0.90}Co_{0.10}O_2$ (001) were grown on $LaAlO_3$ (100) substrates buffered with insulating anatase TiO_2 (5 unit cell thick) by pulsed laser deposition. A ceramic TiO_2:Co 10 at% target was ablated by KrF excimer laser (λ = 248 nm). The energy density and the repetition rate of the excimer laser were 1.5 J/cm^2 and 5 Hz, respectively. The growth temperature and the oxygen partial pressure were 600°C and 1×10^{-4} Torr for buffer TiO_2 and 250°C and $1 \times 10^{-7} - 5 \times 10^{-5}$ Torr for (Ti,Co)O_2, respectively. The lower oxygen partial pressure led to the higher electron carrier density, that promotes ferromagnetic exchange coupling in (Ti,Co)O_2. The crystal structure without any secondary phase was confirmed by x-ray diffraction measurement. Topographic image followed by magnetic image was observed by magnetic force microscope in a vacuum at room temperature.

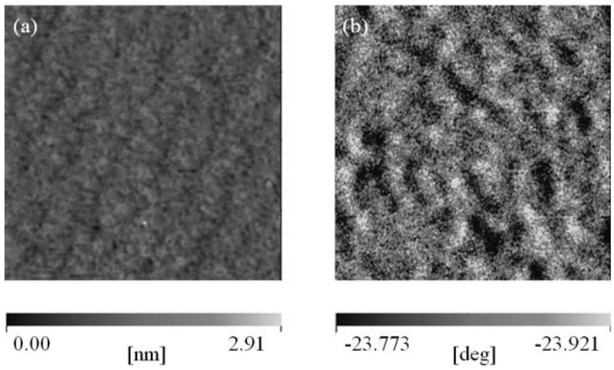

Fig. 1. Topographic (a) and magnetic images (b) of the same area in (Ti,Co)O_2 film. Scanned area was 2 μm × 2 μm.

Figure 1(a) shows a topographic image of $Ti_{0.90}Co_{0.10}O_2$ film, representing an atomically flat surface without any surface precipitation. Figure 1(b) shows a magnetic image of the same area. A maze-patterned structure is seen, as is usual in ferromagnets with perpendicular magnetization. An influence of the topographic image on the magnetic image was hardly seen, thus, the observed image corresponds to the magnetic domain structure. Each magnetic domain was approximately 200 nm wide. The similar domain width may rule out the possibility that the domain was formed from nanoclusters at surface.

The observed magnetic image has a weak contrast probably caused by the low stray field. The low stray field may be due to the much smaller surface magnetization than the bulk magnetization, as was observed by surface- and bulk-sensitive x-ray magnetic circular dichroism [15]. This small surface magnetization could be caused by a depleted carrier density at surface, where the surface depletion was observed by x-ray photoemission spectroscopy [16]. Accordingly, reducing the surface depletion will lead to clearer observation of the magnetic domain structure.

3. Conclusions

We observed the magnetic domain structure in anatase $(Ti,Co)O_2$ epitaxial thin films at room temperature with magnetic force microscope. The observed magnetic domain structure was a maze-like pattern, which is usually observed in ferromagnets with perpendicular magnetization. The regularly arranged magnetic domains may rule out the possibility of nanoclusters as the origin of ferromagnetism. The manipulation of the magnetic domain at room temperature will be an attractive application in the future.

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