Epitaxial $NiFe_2O_4$ films grown on Si(111) substrates

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Recently, electrical spin injection/detection via Si have been studied using multi-terminal devices with Fe/MgO junctions and a Si channel, since Fe(001)/MgO(001)/Si(001) structures are expected to have a high spin filter effect that is yet unclear. For actual Si-based spintronic device applications, it is needed to achieve much larger spin injection efficiency than that of the present value (7.5% for Fe/MgO/Si[1]) by advancing physical understanding concerning spin injection/detection. For this purpose, the spin filter effect of ferrite with inverse spinel crystal structure, such as $CoFe_2O_4$(CFO) and $NiFe_2O_4$(NFO), is promising [2,3]. In this study, growth, structure, and magnetic properties of epitaxial NFO films on Si(111) substrates are investigated to establish the growth conditions primarily for structures without SiO_x that would be unwanted for spin injection/detection. The reason why NFO was selected is that X-ray photoelectron spectroscopy (XPS) cannot reveal the formation of SiO_x in CFO/Si structures since the binding energy of 3s Co overlaps that of 2p Si originating from SiO_x.

To exclude the formation of a SiO_x interlayer and to solve the large lattice mismatch between NFO and Si, a γ-Al_2O_3 buffer layer was formed by the similar procedure in ref. [4] (Fig. 1): The epitaxial growth of γ-Al_2O_3 was performed by thermal reaction of a 0.5-nm-thick Al layer and a HCl-oxidized Si substrate, which was confirmed by reflective high-energy electron diffraction (RHEED) patterns after annealing at 820°C for 30 min. Then, a 1-2 ML Al_2O_3 layer was epitaxially grown at substrate temperature Ts = 780°C using the pulsed laser deposition (PLD) method with a single-crystalline Al_2O_3 target under the O_2 pressure of of 1×10^{-5} Pa. This 1.0-nm-thick buffer layer had a flat surface (RMS ~0.15nm), and did not have both SiO_2 and residual Al from XPS. Then, 3-nm-thick NFO films were grown by PLD at Ts (=150–650°C) under the O_2 partial pressure P_{O2} (= 2×10^{-4}–2×10^{-2} Pa) and Ar pressure 10 Pa.

When a sintered NFO target was used, XPS revealed the SiO_2 formation for any growth condition. Here, we describe the results of samples formed with a metal $NiFe_2$ target. In Fig. 2, the SiO_2-free and SiO_2-present growth conditions are represented by open and closed circles, respectively (Typical XPS spectrum of 2p Si is shown in Fig. 3.). In the SiO_2-free growth conditions, the RHEED patterns of NFO were streaky with a (1×2) reconstruction pattern (Fig. 4) and six-fold rotational symmetry. From X-ray reflective diffraction (XRD) patterns, the epitaxial relationship of one domain was [11-2]NFO(111) //[11-2]Si(111), whereas that of another domain rotated by 30° in the (111)NFO plane, as previously reported[5]. The surfaces of these samples had condition-independent RMS values of ~0.33nm. Using a SQUID magnetometer, we measured the hysteresis loop at 300 K of the SiO_2-free samples, and found that the saturation magnetizations and coercivities were 145-200 emu/cc and ~90 Oe, respectively, indicating that the epitaxial NFO films are applicable to spin-filter junctions.

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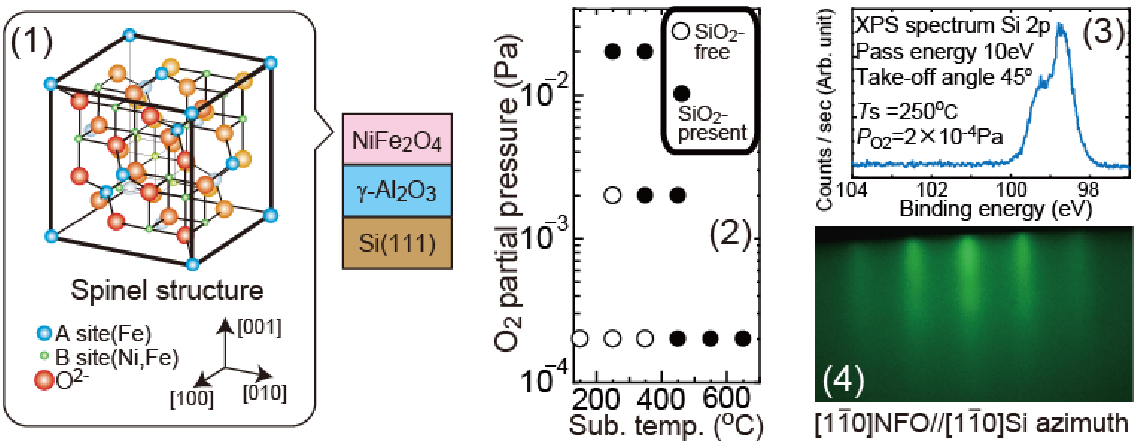

Figures (1)Layer structure of the sample and inverse spinel crystalline structure of NFO. (2) SiO_2-free growth conditions(Open marks). (3) Typical XPS spectrum of 2p Si. (4) RHEED pattern of NFO.