Fabrication of Epitaxial Fe$_3$O$_4$ Film on a Si(111) Substrate

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The application of magnetic oxides in spintronics has recently attracted much attention. The epitaxial growth of magnetic oxide on Si could be the first step of new functional spintronics devices with semiconductors. However, epitaxial spinel ferrite films are generally grown on oxide substrates, not on semiconductors. To combine oxide spintronics and semiconductor technology, we fabricated Fe$_3$O$_4$ films through epitaxial growth on a Si(111) substrate by inserting a γ-Al$_2$O$_3$ buffer layer. Both of γ-Al$_2$O$_3$ and Fe$_3$O$_4$ layer grew epitaxially on Si and the films exhibited the magnetic and electronic properties as same as bulk. Furthermore, we also found the buffer layer dependence of crystal structure of Fe$_3$O$_4$ by X-ray diffraction and high-resolution transmission electron microscope. The Fe$_3$O$_4$ films on amorphous-Al$_2$O$_3$ buffer layer grown at room temperature grew uniaxially in the (111) orientation and had a textured structure in the plane. When Fe$_3$O$_4$ was deposited on Si(111) directly, the polycrystal Fe$_3$O$_4$ films were obtained due to SiO$_2$ on Si substrate. The epitaxial Fe$_3$O$_4$ layer on Si substrates enable us the integration of highly functional spintronic devices with Si technology.

In the field of spintronics, spin injection and transport phenomena have attracted much attention owing to the possibility of producing novel functional devices$^1$–$^3$. In particular, the combination of spintronics and semiconductors is a promising technology for the development of the next stage of spintronic devices, e.g., spin-FET or logic devices$^4$–$^6$. The spin injection technique, in which the spin-polarized currents are injected from ferromagnetic metals into conventional semiconductor materials$^7$–$^{10}$, has been intensely investigated for the preparation of spintronic devices. As a result, researchers have succeeded in nonlocal detection$^7$ or the observation of the Hanle effect$^1$, which demonstrates the spin state in the semiconductor; thus, the behavior of the spin current in the semiconductor can be determined$^8$. Recently, graphene has also been the subject of spin injection because the spin diffusion length in such light elements is expected to be long owing to small spin–orbit interaction$^9$–$^{10}$. The source of the spin current plays an important role in obtaining high-efficiency spin injection. Magnetic oxides are one of the most promising spin source candidates. However, ferromagnetic metals have been used so far because of convenience during fabrication. Magnetic oxides possess unique properties$^{11}$–$^{14}$; Fe$_3$O$_4$ or (LaSr) MnO$_3$ have a half-metallic state, which provides highly spin polarized current$^{15}$, and NiFe$_2$O$_4$ or CoFe$_2$O$_4$ are magnetic insulators, which means that they could work as a spin filter tunnel barrier$^{16}$–$^{18}$. NiFe$_2$O$_4$ is another candidate as the spin filter barrier. It is the spinel type ferrimagnetic insulator that is obtained by over oxidation of Fe$_3$O$_4$. Recently, NiCo$_2$O$_4$ with spinel structure was discovered to exhibit large magnetoresistance effects$^{20}$. Therefore, the combination of magnetic oxides and semiconductors enables us to produce new functional devices. Some research groups fabricated the magnetic oxide on oxide semiconductor, Nb:SnTiO$_3$, and investigated the transport characteristics including spin transport of the junctions$^{19}$, $^{21}$. However, epitaxial growth of magnetic oxide on Si, which is the most important semiconductor, has not been established because the surface of Si is easily oxidized by the oxygen atmosphere during the evaporation of the magnetic oxides$^{22}$.

In this study, we grew Fe$_3$O$_4$ epitaxially on a Si(111) substrate by the insertion of a ultrathin γ-Al$_2$O$_3$ buffer layer. Fe$_3$O$_4$ is the ferrimagnetic conducting oxide with spinel crystal structure. At 120K, Fe$_3$O$_4$ shows phase transition called Verwey transition, at which the electric resistivity increases drastically and the crystal symmetry decreases from face-centered cubic to monoclinic$^{23}$–$^{25}$. Fe$_3$O$_4$ is expected to be half-metallic theoretically, meaning to have a spin polarization of 100%$^{15}$, and a spin polarization of more than 80% was observed experimentally using a spin-resolved photoemission spectroscopy$^{26}$. An ultrathin γ-Al$_2$O$_3$ layer was inserted to prevent surface oxidation.

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oxidation of Si during the Fe$_3$O$_4$ growth. γ-Al$_2$O$_3$ is an aluminum oxide with the same spinel structure as Fe$_3$O$_4$ and the lattice constant of γ-Al$_2$O$_3$ is 7.91 Å, which is three halves of that of Si with lattice mismatch of −2.9%$^{27}$. From the viewpoint of the crystal structure, Fe$_3$O$_4$ and γ-Al$_2$O$_3$ seems to grow on Si epitaxially.

γ-Al$_2$O$_3$ (111) epitaxial growth on Si(111) was reported by two research groups recently. Jung et al. formed a γ-Al$_2$O$_3$ (111) layer by annealing an Al layer on protective Si oxide, which was carefully oxidized to be reduced by the Al layer$^{28}$. Merckling et al. fabricated γ-Al$_2$O$_3$ (111) by the deposition of an Al$_2$O$_3$ source under ultra-high vacuum$^{29}$. In the former method, it is difficult to optimize the oxidation of the Si layer and the thickness of Al film. In contrast, the latter method is simple if an ultra-high vacuum system is accessible.

In this study, the epitaxial γ-Al$_2$O$_3$ buffer layers were prepared using an ultra-high vacuum system and the Fe$_3$O$_4$ layer was fabricated by reactive molecular beam epitaxy. We investigated the crystal structure, magnetic and electric properties of the Fe$_3$O$_4$ layer on Si(111) with an epitaxial γ-Al$_2$O$_3$ buffer layer, an amorphous-Al$_2$O$_3$ buffer layer, and without a buffer layer. We succeeded in the fabrication of high quality Fe$_3$O$_4$ films on Si(111) substrates. The buffer layer had a significant effect on the crystal structure of the Fe$_3$O$_4$ layers.

Results and Discussion

Epitaxial growth. The γ-Al$_2$O$_3$ and Fe$_3$O$_4$ layers were grown by molecular beam epitaxy method. The structures of the samples were (a) Si(111)/γ-Al$_2$O$_3$ 2.4 nm/Fe$_3$O$_4$ 50 nm/amorphous-Al$_2$O$_3$ 2.0 nm, (b) Si(111)/amorphous-Al$_2$O$_3$ 2.4 nm/Fe$_3$O$_4$ 50 nm/amorphous-Al$_2$O$_3$ 2.0 nm and (c) Si(111)/Fe$_3$O$_4$ 50 nm/amorphous-Al$_2$O$_3$ 2.0 nm, as shown in Fig. 1 (hereafter referred to as (a) EPI, (b) AMO and (c) W/O), respectively. After treatment of the Si substrate, we confirmed that the in-situ reflection high energy electron diffraction (RHEED) pattern of the Si substrate had a (7×7) streak pattern (Supplementary Fig. S1). This means that the surface of Si was clean and flat. Figure 2(a) and (b) show the RHEED pattern of γ-Al$_2$O$_3$ and Fe$_3$O$_4$ in EPI. The direction of the incident electron beam was [11-2]. The RHEED patterns of γ-Al$_2$O$_3$ and Fe$_3$O$_4$ were clear streak patterns indicating that γ-Al$_2$O$_3$ and Fe$_3$O$_4$ grew epitaxially. Therefore, the γ-Al$_2$O$_3$ film was considered to play a role of a buffer layer for epitaxial growth of Fe$_3$O$_4$. The surface roughness of γ-Al$_2$O$_3$ and Fe$_3$O$_4$ estimated to be very small in value by atomic force microscope (AFM) (shown in Supplementary Fig. S2).

Figure 2(c) and (d) show the RHEED pattern of amorphous-Al$_2$O$_3$ and Fe$_3$O$_4$ in AMO. The amorphous-Al$_2$O$_3$ layer was deposited at room temperature. After the deposition of Al$_2$O$_3$, as shown in Fig. 2(c), the Si (7×7) streak pattern turned into a halo pattern, which indicated that the Al$_2$O$_3$ layer was amorphous. Figure 2(d) shows the RHEED pattern of Fe$_3$O$_4$ on the amorphous-Al$_2$O$_3$. A ring and streak pattern was observed, which implied the presence of a polycrystalline surface. Thus, the epitaxial γ-Al$_2$O$_3$ played a crucial role in the formation of epitaxial Fe$_3$O$_4$ on the Si substrate.

Figure 2(e) and (f) show the RHEED pattern of the Si substrate and Fe$_3$O$_4$ in W/O. The surface of the Si substrate exhibited a diffused streak pattern owing to the introduction of oxygen gas, which oxidized the Si surface. In Fig. 2(f), the RHEED pattern of Fe$_3$O$_4$ on SiO$_x$ shows a halo pattern, which indicated that spinel-type Fe$_3$O$_4$ was not formed.
X-ray diffraction. To confirm the crystallization, the θ–2θ X-ray diffraction (XRD) measurements were carried out on three samples, as shown in Fig. 3(a). The diffraction pattern of Fe₃O₄ on a γ-Al₂O₃ buffer layer in EPI (red line) exhibited four peaks (18.3°, 37.2°, 57.2°, 79.4°), which were in agreement with the diffraction patterns of Fe₃O₄ (111), (222), (333) and (444) planes. This indicated that the Fe₃O₄ film was (111)-oriented without other orientations or phases. The lattice constant measured by XRD was estimated to be 8.39 Å. The lattice constant of the in-plane direction was estimated to be 8.23 Å (Supplementary Fig. S3), which is smaller than the bulk lattice parameter. Therefore, the Fe₃O₄ was considered to be compressed in-plane.

To investigate the in-plane epitaxial relationship, we conducted φ-scan measurements of Si(311) and Fe₃O₄ (4-40), as shown in Fig. 3(b). The six peaks of Fe₃O₄ (4-40) appeared at 60° intervals, indicating the presence of two 180° rotated domains in the Fe₃O₄ layer. The epitaxial relationships were [11-2]Fe₃O₄(111) and [-1-12] Fe₃O₄(111) parallel to [11-2]Si(111), as exhibited in Fig. 3(c). In addition, the peaks of the Fe₃O₄ film were broader than that of the Si substrate. There was a lattice mismatch of 5.7% at γ-Al₂O₃/Fe₃O₄.

The θ–2θ XRD diffraction pattern of Fe₃O₄ in AMO (blue line) exhibited four peaks, which was identical with the diffraction pattern of Fe₃O₄ in EPI. Therefore, the Fe₃O₄ in AMO was also (111)-oriented. However, the RHEED pattern in Fig. 1(d) implied the presence of a polycrystalline structure. Furthermore, the Fe₃O₄(4-40) diffraction peak was not observed in the φ-scan measurement. Therefore, we concluded that the Fe₃O₄ had a textured structure and the growth direction was (111).

The θ–2θ XRD diffraction pattern of Fe₃O₄ in W/O (green line) exhibited small peaks related to Fe₃O₄(311), (400), (422) and unknown peaks. In a previous study, the XRD of Fe₃O₄ on SiO₂ indicated that the Fe₃O₄ layer was polycrystalline and contained other phases.

Figure 2. RHEED patterns: (a) γ-Al₂O₃ and (b) Fe₃O₄ film on γ-Al₂O₃ in EPI, (c) amorphous-Al₂O₃ and (d) Fe₃O₄ on amorphous-Al₂O₃ in AMO, (e) Si surface before depositing Fe₃O₄, and (f) Fe₃O₄ on Si substrate in W/O.
To investigate the crystallinity of the Fe$_3$O$_4$ layer in detail, we carried out X-ray reciprocal space mapping around the symmetric (222) diffraction for Fe$_3$O$_4$ in EPI and AMO (Fig. 3(d)). The symmetrical scan showed that the Fe$_3$O$_4$(222) spot on amorphous-Al$_2$O$_3$ was larger than the Fe$_3$O$_4$ spot on γ-Al$_2$O$_3$, which means that the Fe$_3$O$_4$ in AMO had an angle distribution in the growth directions. Although the reason for the (111) oriented Fe$_3$O$_4$ growth on amorphous-Al$_2$O$_3$/Si(111) was unclear, two possibilities exist that could explain this growth. The first is a reduction in the total anisotropy energy related to the surface energy and interface energy. The difference between AMO and W/O could be attributed to the difference of the surface and interface energy of amo-Al$_2$O$_3$.
and amo-SiO. The second possibility is that the amo-Al2O3 maintains a crystal structure of Si locally because the amo-Al2O3 layer was very thin. Fe3O4 could utilize such a microcrystal-like region as a growth nucleus.

Transmission electron microscope observation. We conducted cross-sectional transition electron microscopy (TEM) analysis to confirm the crystallinity and compositions of the materials. Figure 4 shows the cross-section TEM images in which the electron beams were incident along the Si [1-10] zone axis. In Fig. 4(a), the TEM image shows that the Fe atoms of Fe3O4 were orderly aligned; thus, the Fe3O4 film was epitaxial. The electron diffraction (ED) of Fe3O4 in EPI shown in Fig. 4(b) was in good agreement with the simulation of spinel structure. The left side in Fig. 4(a) shows the epitaxial relationship on [11-2]Fe3O4(111)/[11-2]Si(111), whereas the center of image shows the epitaxial relationship on [-1-12]Fe3O4(111)/[11-2]Si(111), which were consistent with the results of the φ-scan measurements in the XRD. In addition, the spacing of the (111) planes were estimated at 4.87 Å from the high angle annular dark-field scanning (HAADF) image (Supplementary Fig. S4(c)), which were almost the same as the out-of-plane lattice constant (4.84 Å) determined by XRD in Fig. 3(a) and that of bulk Fe3O4 (4.85 Å). In contrast, the TEM image of Fe3O4 in AMO shown in Fig. 4(c) demonstrated that the structure was polycrystalline and grain boundaries were clearly observed. The ED image in Fig. 4(d) consisted of the diffraction from the grains with some crystal orientations. In the low magnification TEM image (supplementary Fig. S4(b)), some grains with a size of 15–30 nm appeared.

With respect to the buffer layer, the thickness of γ-Al2O3 was estimated from the HRTEM image (Fig. 4(a)) to be approximately 1 nm, which was thinner than the nominal value measured by the crystal oscillator in the chamber. The reason for this difference in thickness was unclear; however, it could be due to the fluctuation of the crystal oscillator or re-evaporation of Al2O3 because the γ-Al2O3 was grown at a high temperature (900°C). We could see the amorphous layer under the γ-Al2O3 layer, which was determined to be a SiOx layer by HAADF and Energy dispersive X-ray spectroscopy (EDS) mapping images (Fig. 5). The SiOx layer was considered to form during the growth of Fe3O4 because the Fe3O4 was grown in 4 × 10⁻⁴ Pa O₂ gas. It was reported that Si was oxidized through the γ-Al2O3 layer of less than 2.0 nm by introducing oxygen (>10⁻³ Pa)³². To confirm that, we fabricated a γ-Al2O3 (7.5 nm) film on Si(111), and carried out XRD and TEM observations (supplementary Fig. S5(a) and (b)). The γ-Al2O3 grew epitaxially on Si and we found no amorphous layer at the Si(111)/γ-Al2O3(7.5 nm) interface.
Magnetic characteristics. The magnetic character of Fe₃O₄ is one of its fundamental properties. The magnetization curves at room temperature for the Fe₃O₄ films on γ-Al₂O₃ layer are shown in Fig. 6(a). The directions of the magnetic field were in-plane [11-2], in-plane [1-10] and out-of-plane [111]. The hysteresis curve along [11-2] was the same as that along [1-10] and the Fe₃O₄ film had in-plane magnetization. The saturation magnetization (Mₛ) was 480 emu/cm³ for all magnetic field directions. The remanent magnetization (Mₚ), the coercive field (H_c), and the remanent ratio (M_p/Mₛ) in the in-plane field were 280 emu/cm³, 500 Oe, and 0.48, respectively, and those for the out-of-plane field were 47 emu/cm³, 225 Oe, and 0.08, respectively. The hysteresis loops for Fe₃O₄ in EPI, AMO, and W/O are illustrated in Fig. 6(b). Fe₃O₄ in EPI had the largest H_c and Mₛ among the three samples. The Mₛ of Fe₃O₄ in EPI was the same as the value of bulk Fe₃O₄. Although the reason for small magnetization for AMO and W/O has not been clear so far, the antiphase boundary or disordered structure at grain boundary could be responsible for it³³,³⁴.

Transport characteristics. Figure 7 shows that the dependence of the resistance on temperature for the Fe₃O₄ film in EPI. As is well-known, Fe₃O₄ is an electric conductor at room temperature and the resistivity increases exponentially with decreasing temperature. The resistivity of the film at 300 K was 2.5 × 10⁻⁴ Ωcm, which is lower than the bulk value (5 × 10⁻³ Ωcm)³⁵. The dlogR/dT plots (inset) show a valley at approximately 120 K. This anomaly corresponds to a Verwey transition³⁶, which is a famous phase transition in Fe₃O₄. The Verwey transition has been reported to sharply change the resistivity by approximately one digit³⁶; however, the transition is easily disappeared by impurities or structure defects³⁴,³⁸. As the Fe₃O₄ in EPI possessed magnetic and electric characteristics that were comparable to bulk Fe₃O₄, the Fe₃O₄ on γ-Al₂O₃ buffer layer was very good quality.
Conclusions
We fabricated an epitaxial Fe$_3$O$_4$ film on a Si substrate by inserting an γ-Al$_2$O$_3$ buffer layer. From the XRD measurement and TEM observation, the γ-Al$_2$O$_3$ buffer layer contributed to the growth of epitaxial Fe$_3$O$_4$(111) on Si(111). In contrast, the Fe$_3$O$_4$ film on an amo-Al$_2$O$_3$ buffer layer had an (111)-orientation with a textured structure. The Fe$_3$O$_4$ on γ-Al$_2$O$_3$ had magnetic properties corresponding to the bulk Fe$_3$O$_4$, furthermore the resistivity exhibited a Verwey transition at 120 K. The results indicate that the heterostructure of Si substrate/γ-Al$_2$O$_3$/Fe$_3$O$_4$ could be used as a part of magnetic tunnel junctions or spin injection devices and will allow us to integrate spintronic devices including Fe$_3$O$_4$ electrode, e.g., spin-FET or magnetic tunnel junctions, on Si.

Methods
Preparation of the samples. Before deposition, the Si substrate was cleaned by a standard Radio Corporation of America clean and hydrofluoric (HF) acid solution and annealed at 900°C under a vacuum of <10$^{-6}$ Pa. The γ-Al$_2$O$_3$ buffer layer was formed by evaporating the Al$_2$O$_3$ source material at 900°C and annealing at 900°C for 30 minutes. In previous reports, γ-Al$_2$O$_3$ was grown at >850°C and under a vacuum of <10$^{-6}$ Pa. The growth conditions we used for γ-Al$_2$O$_3$ were in the range of the report. In Si(111)/amo-Al$_2$O$_3$/Fe$_3$O$_4$, the amo-Al$_2$O$_3$ was grown at room temperature under a vacuum of <3 $\times$ 10$^{-6}$ Pa. Then, the Fe$_3$O$_4$ film was formed by reactive deposition at 300°C under a O$_2$ atmosphere of 4.0 $\times$ 10$^{-4}$ Pa. All the samples were fabricated under the same growth conditions to investigate the dependence of the quality of Fe$_3$O$_4$ films on the buffer layer.

Measurements. The epitaxial growth and crystal structure were confirmed by RHEED, XRD (XRDCorporation of America clean and hydrofluoric (HF) acid solution and annealed at 900°C under a vacuum of <10$^{-6}$ Pa), and TEM (FEI Titan3 G2 60-300). Cross-sectional samples for TEM were prepared by using conventional mechanical polishing and dimpling techniques. The magnetic properties of Fe$_3$O$_4$ were measured by vibrating sample magnetometer (VSM) and the electrical properties were measured by direct current (DC) measurements.

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Author Contributions

N.T. and T.N. conceived and designed the experiments using the help of other authors. N.T., T.N., Y.Y., T.Y. and T.S. performed the sample preparation, XRD measurements, magnetic and electrical measurements. T.H., A.H., N.T. and T.N. performed TEM observations. All the authors contributed to analysing and interpreting the data, and to writing the manuscript.

Additional Information

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