Magnetic Properties of Fe(001) Thin Films on GaAs(001)
Deposited by RF Magnetron Sputtering

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Abstract. Fe thin films, down to 6 nm thick, were prepared on GaAs(001) substrates by RF magnetron sputtering. The x-ray diffraction (XRD) analyses show that the epitaxial thin films of Fe(001) were grown with cube-on-cube orientation on GaAs(001). Magnetic properties were investigated by vibrating sample magnetometry (VSM) and ferromagnetic resonance (FMR) spectroscopy. The magnetization curves obtained by applying in-plane magnetic fields indicate that easy (hard) direction is along [100] ([110]) and the saturation magnetization is close to the bulk values. The in-plane magnetic anisotropy measured by FMR shows four-fold symmetry, as expected for bcc Fe. We did not observe the in-plane uniaxial magnetic anisotropy reported on the MBE-grown Fe films on GaAs substrates.

1. Introduction
The magnetic and transport properties of magnetic metal/semiconductor structures are of scientific and technological importance in view of developing magnetic/semiconductor hybrid (spintronic) devices. Fe thin films on GaAs substrates are intensively studied as a model structure since they are well-known materials in magnetic/semiconductor engineering with small lattice mismatch ($a_{GaAs} \approx 2 \times a_{Fe}$). Most of the Fe/GaAs structures have been deposited by molecular beam epitaxy [1, 2, 3, 4], and the epitaxial growth of Fe on GaAs has been reported. Another approach, i.e., sputtering is also important, as it is conventionally used for wide variety of magnetic film deposition. However, we can find a small number of previous works on the crystallographic [5, 6] and the magnetic [7] properties of Fe/GaAs structures fabricated by sputtering. In this report we present our study on the magnetic properties of Fe(001) thin films deposited on GaAs(001) substrates by RF magnetron sputtering. The crystallographic quality of Fe films was analyzed by XRD and the magnetic properties were studied by VSM and FMR.

2. Growth and structure

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The Fe films of thickness 6 - 100 nm were prepared on epi-ready n-GaAs(001) wafers (Wafer Technology) at room temperature (RT) using a 3N Fe target by RF magnetron sputtering. The base pressure of the growth chamber was 0.8 - 1.0 \times 10^{-4} \text{ Pa}, and the Ar gas pressure during the deposition was kept at 0.8 Pa. The GaAs substrates were heated to 550 °C to remove a surface oxide layer prior to the deposition. The growth rate of Fe was 0.03 nm/s. The thicker film (100 nm) was used for XRD analyses in order to obtain the data with sufficient signal intensities. For magnetic properties by VSM and FMR, we show the data of thinner films (6, 12, 25 nm) below as we are interested in the magnetic properties of thin films.

The crystal structure of a 100-nm thick Fe film on GaAs(001) was analyzed by XRD using Cu Kα lines. First the crystallographic quality and orientation of the Fe film were investigated by pole figure measurements. In Fig. 1, the pole figure profile with a diffraction angle fixed at 2θ = 44.4° is plotted. Four-fold diffraction spots are observed at polar angle ψ = 45° which correspond to the diffractions from GaAs{220} and Fe{110} bcc. These two spots are very close because of the small difference in lattice constants (a_{GaAs} = 0.56530 nm and 2 \times a_{Fe} = 0.57328 nm). The enlarged profile in the inset shows that the spot from Fe(011) is observed, separated from the strong spot of GaAs(022). No circular streaks were observed due to misaligned Fe{110} plane. This result indicates that the Fe film is epitaxially grown on GaAs substrate with the crystallographic orientation relationship with respect to a GaAs(001) substrate being Fe(001)[100]bcc//GaAs(001)[100].

The lattice spacing of the Fe(001) film on the GaAs(001) substrate was investigated by out-of-plane θ-2θ scan and in-plane θ_{f}-2θ_{f} scan. The out-of-plane diffraction spectrum is shown in Fig. 2 (a). (The diffraction was measured with off-set 0.4° to mitigate the intense signal from the GaAs substrate.) An Fe(002) peak is observed adjacent to a diffraction from GaAs(004). (Small peaks on the left shoulder are due to a Cu Kβ line and a WL line from a contamination.) Other Fe lines, e.g., Fe(011) at 44.7°, were not detected. After peak separation the lattice spacing in the direction normal to the film surface was estimated to be 0.2920 nm, expanded by 1.8% relative to the bulk lattice spacing. The in-plane diffraction spectra with the scattering vector parallel to a GaAs[400] axis and a GaAs[220] axis are plotted in Figs. 2 (b) and (c), respectively. The diffractions from Fe(200) and
Fe(110) are not distinctly separated from GaAs peaks; it is likely that Fe(200) overlaps with GaAs(400) in Fig. 2 (b), and Fe(110) overlaps with GaAs(220) in Fig. 2 (c). However, as shown in the inset of Fig. 2 (c), the diffraction from Fe(220) is separated from GaAs(440). The in-plane lattice spacing was estimated to be 0.2844 nm by peak separation. In the film plane the Fe thin film is compressed by 0.8% compared with the bulk lattice constant of Fe, but it is larger than the half of GaAs lattice constant, 0.28265 nm.

Out-of-plane and in-plane dispersions of crystalline orientations were investigated by measuring rocking curves of the Fe(002) out-of-plane XRD peak (Fig. 2 (d)), and the Fe(220) in-plane XRD peak (Fig. 2 (e)). The FWHM line width $\Delta \theta_{50}$ was 1.7° for Fe(002) plane, and $\Delta \theta_{50} = 1.8°$ for Fe(220) plane. The observed width is larger than those reported previously for dc-sputtered Fe films on GaAs [5] or ion-beam sputtered films [6].

3. Magnetic properties

The magnetization curves of Fe thin films with various thicknesses were investigated by VSM at RT. The representative data with the in-plane field at [100]$_{Fe}$ and [110]$_{Fe}$ for a 25 nm film are shown in Fig. 3. The saturation magnetization ($M_s$) of $1.7 \times 10^3$ emu/cm$^3$, and the shape of loops with a [100]$_{Fe}$-direction (110]$_{Fe}$-direction) being an easy direction (a hard direction), are identical to the well-known data for a bulk Fe single-crystal specimen [8]. For the thinner films, 6 and 12 nm in thickness, and for the thicker film, 100 nm in thickness as used for XRD analyses, the identical shape of loops was observed.

There are many studies on the magnetic anisotropy of thin films of Fe grown on GaAs(001) substrates by MBE. They reported the in-plane uniaxial magnetic anisotropy (UMA); a [110]$_{Fe}$-direction was an easy direction and [1-10]$_{Fe}$ was a hard direction [9, 10]. Its origin is still controversial. UMA decreases with film thickness, and it is likely that the anisotropy originates from the interfacial effect between Fe and GaAs. FMR spectroscopy is one of the important methods to study magnetic anisotropy. However, care should be taken to interpret the data. In order to obtain the data that could be unambiguously analyzed, the external magnetic field should be so high that sample magnetization was saturated (parallel to the external field) and a sample was of single domain [11]. We investigated the in-plane magnetic anisotropy of Fe thin films using a conventional FMR spectrometer at a microwave frequency 35 GHz (Q-band) and at RT. The external field was in the plane of films and its

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**Figure 2.** (a) Out-of-plane and (b), (c) in-plane XRD spectra of an Fe film grown on a GaAs(001) substrate. The in-plane XRD measurements were performed by making the scattering vector parallel to (b) the GaAs[400] or (c) the GaAs[220] direction. Rocking curves observed for (d) the Fe(002)$_{bcc}$ out-of-plane and (e) the Fe(220)$_{bcc}$ in-plane XRD peaks. The intensities in (a)–(c) are shown in a logarithmic scale and in (d) and (e) in a linear scale.
direction was varied from 0° ([100]_Fe) to 360°. (See the inset of Fig. 4) The in-plane angle dependence of resonance fields for 6-nm and 12-nm Fe films are plotted in Fig. 4. In our measurements the resonance field (H_r) was large enough to saturate the in-plane magnetization of samples. In the MBE grown Fe thin films UMA becomes conspicuous in thinner samples, e.g., in an 8 nm Fe film in [10]. In the present case, from the angular dependence of H_r in Fig. 4, the four-fold in-plane anisotropy of films is clearly shown, as expected for cubic lattice of Fe. The in-plane four-fold anisotropy constant K_1 was estimated from H_r in FMR and M_s observed in VSM measurements [11, 12]. We obtained K_1 = 3.9 x 10^5 erg/cm^3 for the 12-nm Fe film. We did not observe uniaxial component even in the 6-nm film. This observation was also confirmed in our VSM measurements. The magnetization curve with the external field in [110]Fe-direction is identical to that in [1-10] Fe (not shown). The different kinetics of crystal growth or the surface preparation of GaAs substrates in MBE and RF magnetron sputtering may result in the different in-plane magnetic anisotropy. Considering that the UMA is of interfacial origin [13], it is likely that the uniaxial component could be seen in sputter-deposited films if they were much thinner.

4. Conclusion
In conclusion, we have grown epitaxial Fe(001) thin films on GaAs(001) substrates by RF magnetron sputtering. The crystal structure was confirmed by XRD measurements, including pole figures, out-of-plane θ-2θ scan and in-plane θ_L-2θ_L scan, and rocking curves. The magnetization curves measured by VSM show features common to bulk Fe single crystal. The in-plane magnetic anisotropy was investigated by Q-band FMR spectroscopy. The angle dependence of the resonance fields shows four-fold in-plane magnetic anisotropy. The uniaxial component observed in MBE-grown Fe thin films was not detected in our sputter-deposited samples.

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