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Magnetic moment in Diluted Magnetic Semiconductor GaGdAs measured by Magnetic Circular Dichroism

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1. Introduction

Materials for spintronics devices, such as diluted magnetic semiconductor(DMS), which have both magnetism and a semiconductor property, have been drawing great attention and studied prosperously. In most of III-V based DMS, it has reported that ferromagnetism is caused by carriers which intermediates the spin between ferromagnetic elements. In our previous report, we found ferromagnetic coupling in the rare earth elements Gd doped GaAs DMS, abbreviated as GaGdAs, which was grown by molecular beam epitaxy(MBE). On the other hand, GaGdAs is easy to have distortions or dislocations, because the atomic size of Gd is large compared to GaAs matrix, and also there is lattice mismatch between GaGdAs layer and substrate. Superlattice(SL) structure of GaGdAs/GaAs, in which GaGdAs layers are interleaved with a few mono-layer(ML) thick GaAs layer, is expected to have a good crystallinity. We fabricated magnetic semiconductor GaGdAs/GaAs SL samples and GaGdAs ML samples by MBE and analyzed them, using Alternating Gradient Magnetometer (AGM) for macroscopic magnetization and, Magnetic circular dichroism (MCD) and X-ray absorption fine structure (XAS) for basic electronic states. MCD and XAS spectrum were obtained using synchrotron radiation at BL39XU, SPring-8

2. Experiments

GaGdAs DMS samples with various Gd composition were grown by MBE after stacking buffer layer on GaAs (001) substrate, changing Gd cell temperature, 1300-1450 ^{o}C. We made GaGdAs/GaAs SL and ML samples by controlling shutter sequence of Gd K-cell. Design structures of SL samples and monolayer sample are:

(i) $[GaGdAs_{10nm} / GaAs_{40nm}]_{x120}$ (Gd cell 1350 ^{o}C),
(ii) $[GaGdAs_{10nm} / GaAs_{40nm}]_{x40}$ (Gd cell 1330 ^{o}C),
(iii) $GaGdAs_{1000nm}$ (Gd cell 1300 ^{o}C),
(iv) $GaGdAs_{1000nm}$ (Gd cell 1450 ^{o}C),

as shown in Fig. 1.

Concentration of Gd in sample (iv), which was grown at Gd cell temperature of 1450 ^{o}C, is expected to be much higher than that of the other samples. Crystalline state was checked by RHEED *in situ* observation during growth. We measured AGM for all samples at room temperature and analyzed the magnetic properties. Cross-sectional TEM observations and Higher Angle Annular Dark-Field Scanning TEM (HAADF-STEM) observation were done to obtain direct information of local nano-structures.

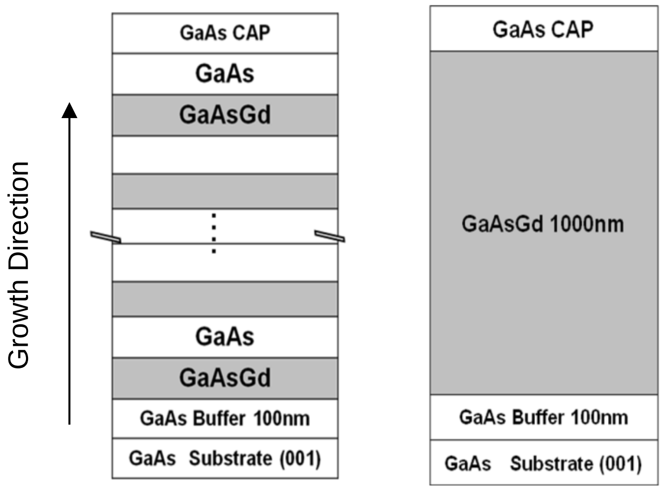

Fig.1 Simplified schematic layer structures of GaGdAs/GaAs SL and GaGdAs monolayer.

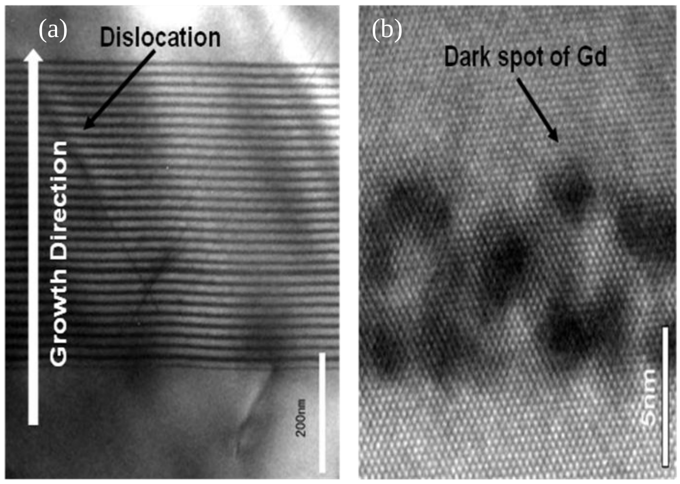

Fig.2 Cross-sectional TEM image of Sample(ii). (a) Whole SL structure. (b) GaGdAs grains.

3. Results and Discussion

Fig. 2 shows a cross-sectional TEM image of the sample (ii). It is clear from Fig.2 that we succeeded to grow the GaGdAs/GaAs SL structure which has flat interfaces in whole SL structure. In Fig.2 (a), there are a few dislocations along to <111>, which is typical to GaAs, and this supports the fact that the SL was epitaxial grown with zinc blend structure. High resolution image of the same sample is shown in Fig.2 (b) where a dark part of the contrast forms nanosize particles. These particles seem to be GaGdAs grains, *i.e.* the domain which includes a lot of Gd atoms in zinc blend matrix. Diameter of the grains is approximately 2-3 nm.

XAS profiles at Gd L_3-edge measured by synchrotron radiation are shown in Fig.3. Where a profile of Gd metal layer is also plotted measured for comparison. Samples (i) ~ (iii) have substantially a same shape of spectrum, while sample only (iv) has a different shape, which is rather similar to that of Gd metal layer.

Fig. 4 shows the normalized MCDs at Gd L_2-edge, where the MCD signals were normalized by edge jumps of XAS. The magnitudes of MCD signals shown in Fig.4, which reflects the magnetization of Gd ion, are not the same between samples. Especially, sample (iv) has no MCD signal in our measurement SN ratio, which might be inconsistent to the high Gd concentration expected in sample (iv).

Results of macroscopic magnetization measurements obtained by AGM are shown in Fig.5. The SL sample (i) is the largest saturation magnetization among samples, and the smallest for ML sample (iii). Comparing Fig.5 to Fig.6, we can say that the Gd magnetic moment in GaGdAs can be decided by not only Gd concentration but also the other growth condition, such as substrate temperature or grown rate of matrix GaAs. There is a trend of larger Gd magnetization for SL samples than for ML samples.

4. Conclusion

We made magnetic semiconductor samples of GaGdAs/GaAs SL and GaGdAs ML by MBE. In TEM images of SL sample, Gd grains of 2-3 nm diameter were observed, which is thought to have no significant effect to sample magnetization. MCD measurements revealed that the magnetization depends on not only Gd concentration but also other growth conditions. Compared to ML structure, SL structure has an advantage for sample crys-talinity, leading to large magnetization.

References

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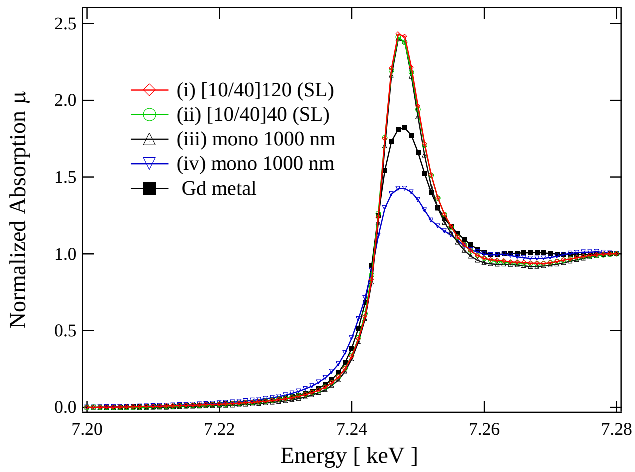

Fig.3 XAS of low temperature (30K). sample (i) and (ii) is SL. Sample (iii) and (iv) is ML.

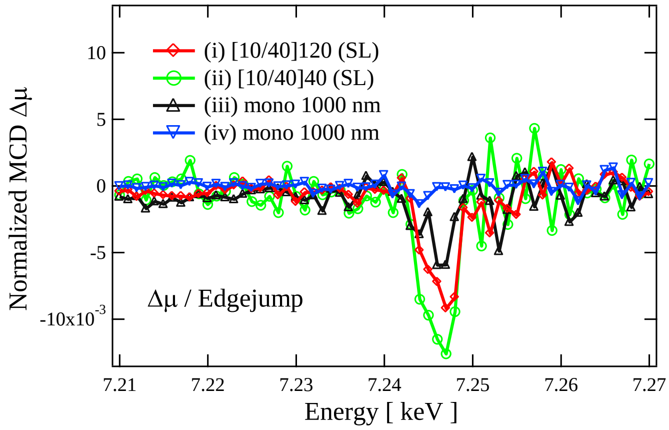

Fig.4 MCD of low temperature (30K). sample (i) and (ii) is SL. Sample (iii) and (iv) is ML.

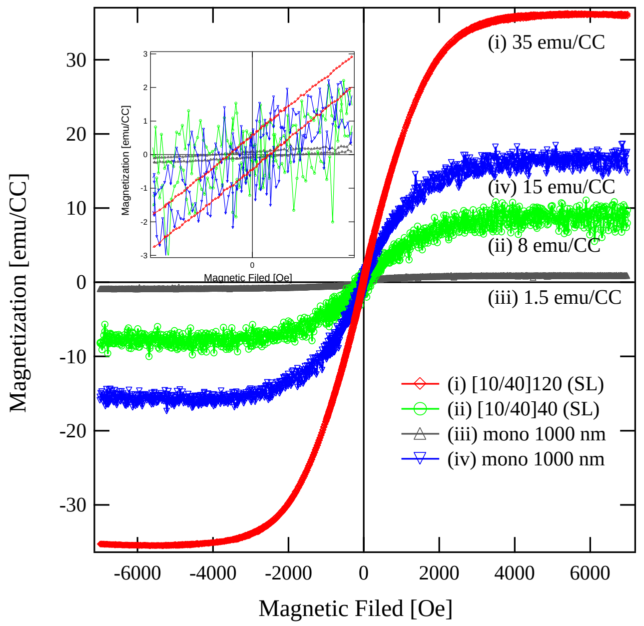

Fig.5 Magnetization of sample (i) - (iv). Inset shows the close-up around origin.