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Structure and Magnetic Properties of Diluted Magnetic Semiconductor Superlattice GaGdAs/GaAs Grown by MBE

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1. Introduction

In the development of spintronics technology, materials which has both magnetism and a semiconductor property, such as diluted magnetic semiconductor(DMS), 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 ML thick GaAs layer, is considered to have a good crystallinity. We fabricate magnetic semiconductor superlattice GaGdAs/GaAs and mono layer GaGdAs by MBE and analyze the crystal structure by means of Transmission Electron Microscopy (TEM) and measured the macroscopic magnetic properties by Alternating Gradient Magnetometer (AGM).

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, 1350-1400 ^{o}C and growth rate, 0.15–0.3 Å/sec. We made GaGdAs/GaAs SL samples and GaGdAs mono layer sample by controlling shutter sequence of Gd K-cell. Design structures of SL samples and monolayer sample are:

(i) $[GaGdAs_{10nm} / GaAs_{40nm}]_{x40}$,
(ii) $[GaGdAs_{5nm} / GaAs_{35nm}]_{x30}$,
(iii) $GaGdAs_{1000nm}$,

as shown in Fig. 1. K-cell temperatures of Ga, As, and Gd, are 950 ^{o}C, 260 ^{o}C, and 1350^{o}C-1400^{o}C, respectively. 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. We evaluated the Gd concentrations for sample (i), (ii), and (iii) as 2.8%, 1.3%, and 5.2%, respectively, from flux rate of each atoms. These flux rate were obtained from cross-sectional TEM observations of Gd metal layer and GaAs layer which were grown separately.

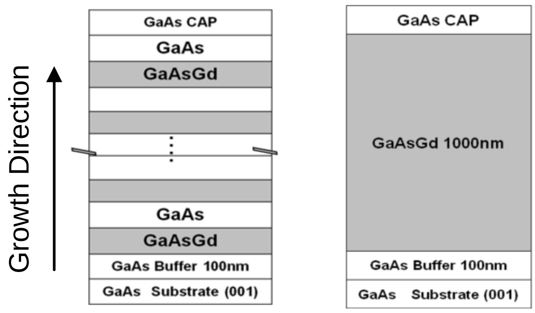

Fig.1 Simplified schematic layer structures of GaGdAs/GaAs SL and GaGdAs monolayer.

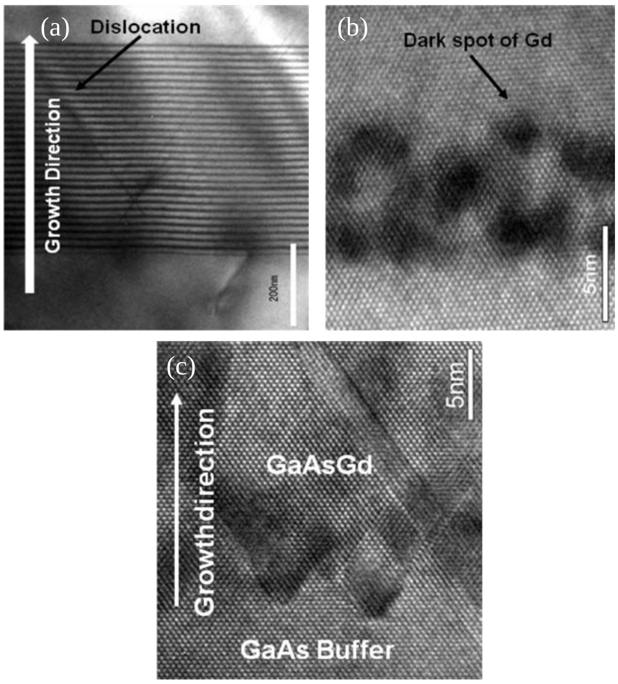

Fig.2 Cross-sectional TEM image of Sample(ii). (a) Whole SL structure. (b) GaGdAs grains (c) Interface between GaGdAs layer and substrate.

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. In order to verify the unevenness of Gd concentration in these GaGdAs grains, We performed HAADF observations using STEM mode. HAADF image and bright field image are shown in Fig.3(a),(b). In GaGdAs layers in HAADF image of Fig.3(a), and more clearly in Fig.3(c), which is close up of HAADF image, there are several white contrasted grains. These white grains means that the higher angle reflection has occurred due to segregated heavy Gd atoms. It is noteworthy that in TEM images of sample (iii), we did not observed such GaGdAs grains.

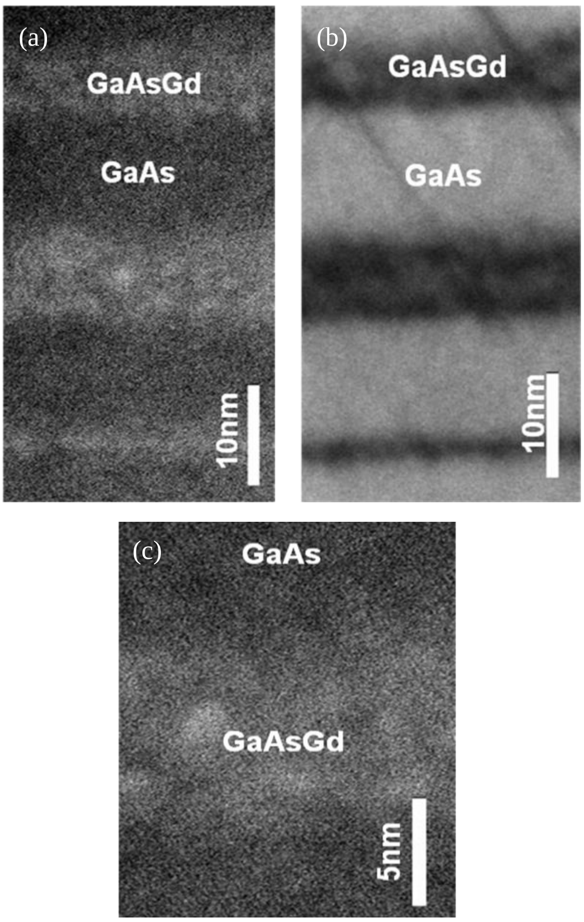

Fig.3 Scanning TEM images of Sample(ii). (a) HAADF image (b) Bright field image (c) Close-up of HAADF

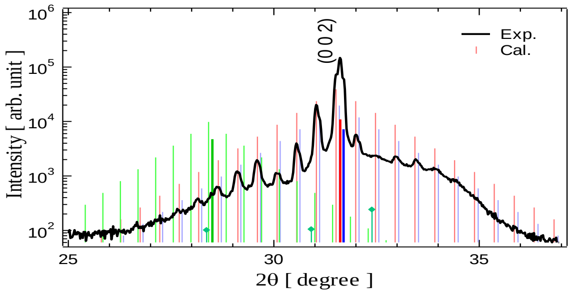

Fig.4 XRD profile near (0 0 2) reflection of sample(ii)

As shown in Fig.4, in XRD profile around (0 0 2) of sample (ii), clear satellite peaks originated from SL structures are clearly observed. We estimated lattice constants and period length of SL. Satellite peak intensity is stronger in lower angle side against substrate (0 0 2) peak than higher side, which is due to (0 0 2) peak positioning of SL.

Results of AGM measurement are shown in Fig.5. Magnetizations in Fig.5 were normalized by volume of magnetic layers in samples. After the normalization, there is still clear difference in magnification of saturated magnetization between samples. From several measurements of other SL samples and monolayer samples, we can say it is likely that SL structures have larger saturated magnetization than that of monolayers. It is possible that the GaGdAs grains, which are observed only in SL structures, has main contribution to generate ferromagnetism. Coercive field of SL samples are around 50 Oe, while that of monolayer is a little larger.

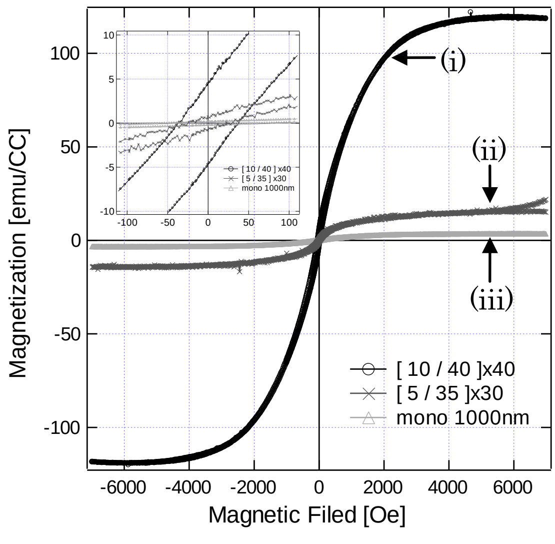

Fig.5 Magnetization of sample (i),(ii), and (iii). Inset shows the close-up around origin.

4. Conclusion

We made magnetic semiconductor SL of GaGdAs/GaAs by MBE. TEM images show GaGdAs grains in SL structures,which possibly contribute to ferromagnetism in room temperature.

References

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