Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 68-69

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Structure and Magnetic Properties of Gd-doped Gallium Arsenide Grown by MBE

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1. Introduction

Diluted-magnetic semiconductors (DMSs) grown epitaxially on conventional non-magnetic semiconductors have attracted great attention in recent years due to the potentiality for next-generation spintronics devices and also have much interests in basic physics. It is necessary to make DMSs with a higher Curie temperature and a large magnetization. Recently it was reported that Gd doped GaN has a colossal magnetic moment and a ferromagnetic coupling above the room temperature [1-3]. In this report, we investigate DMSs of Gd doped GaAs (GaAs:Gd) with Gd concentration ranging from 2.4 % to 4.7 %, which were grown on GaAs(001) substrate by means of molecular beam epitaxy. Crystal structures of the samples were studied from the cross-sectional TEM observation and magnetic properties were characterized by macroscopic magnetization measurements.

2. Experimental

GaAs:Gd DMSs were grown on GaAs(001) substrate by means of solid-source molecular beam epitaxy (MBE) method. Substrate temperature was set at 580 ºC and Ga cell and As cell were set at 950 ºC and 220 ºC, respectively. A base pressure in the chamber is about 1×10^{-9} torr. Samples with different Gd concentration were obtained by changing the Gd vapor flux rate, which was controlled with the temperature of Gd evaporation cell from 1350 ºC to 1420 ºC. *In-situ* RHEED pattern during MBE growth showed clearly streak-like spots for all samples and this means GaAs:Gd has been grown epitaxially on GaAs buffer. Crystal structures of samples were studied by XRD using Cu Kα (Shimadzu XRD-6100) and by cross-sectional TEM observation (JEOL JEM-3010) with 300 kV high voltages. Magnetizations of samples were measured using vibration sample magnetometer (Toei VSM-5) at room temperature.

3. Results and Discussions

Figure 1 shows Gd concentrations in GaAs:Gd DMSs grown at different temperatures of Gd evaporation cell. This temperature dependence were estimated from the ratio of EDS peak intensities of Gd Lα(6.06keV) to a sum of Ga Kα(9.25keV) and As Kα(10.54keV), which were measured at TEM observation. These ratios of EDS peaks, $I_{Gd}/(I_{Ga}+I_{As})$, is thought to be proportional to Gd concentrations and were normalized using the value, 4.4 atom%, at Gd cell temperature of 1400 ºC shown as a open circle in Figure 1. This value was derived from GaAs growth rate and Gd vapor flux, where the latter was measured at a

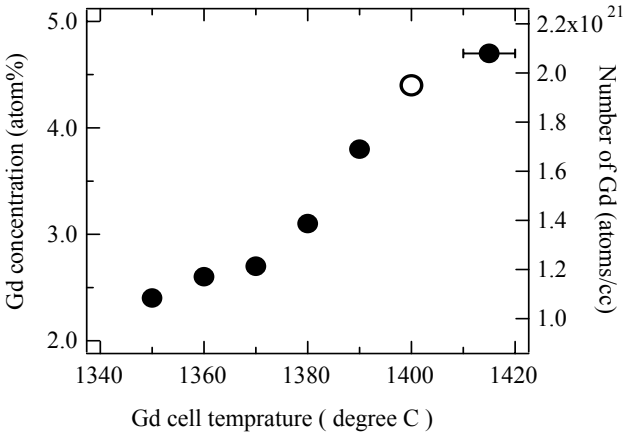

Fig. 1 Dependence of Gd concentration in GaAsGd DMSs as a function of temperature of Gd evaporation cell.

growth of pure-metallic Gd using the same Gd evaporation cell [4]. Figure 1 indicates that Gd concentration increases monotonically with increased cell temperature and that one can control Gd concentration in wide range by changing cell temperature around from 1300 to 1500 ºC.

Figure 2 shows XRD profile of GaAs:Gd sample grown at Gd cell of 1400 ºC (a upper line) and also shows GaAs bulk substrate (a lower line). As compared to GaAs bulk, a broad peak exists at little lower 2θ than GaAs substrate (0 0 6) peak in a profile of GaAs:Gd sample. This means that the

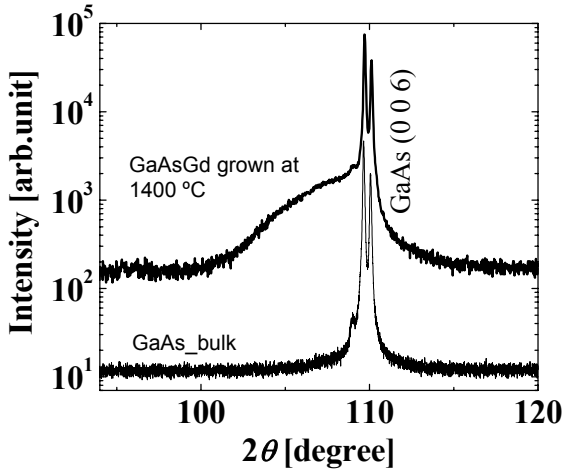

Fig. 2 XRD profiles of GaAsGd DMS grown at Gd cell of 1400 ºC (a upper line), and GaAs bulk substrate (a lower line).

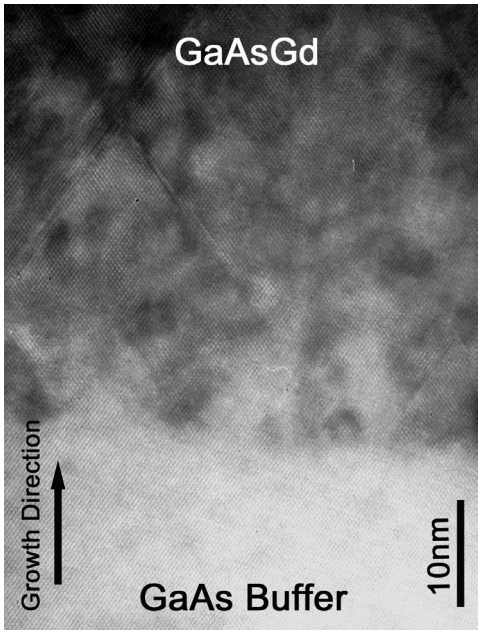

Fig. 3 Hetero-structural interface between GaAs buffer and GaAsGd layer in Cross-sectional TEM image of GaAsGd grown at Gd cell 1400 ºC.

lattice constant around a Gd atom seems to be larger than GaAs one, and Gd atoms are positioned randomly in the matrix.

Cross-sectional TEM image of GaAs:Gd grown at Gd cell of 1400 ºC is shown in figure 3. From figure 3, it is confirmed that GaAs:Gd layer was grown successfully with good lattice matching to GaAs buffer. However, there is a little flatness at the interface, which is thought to be due to the diffusion of Gd atoms.

Figure 4 shows high-resolution TEM image in GaAs:Gd layer. There exits a lot of dislocations at a certain angle,

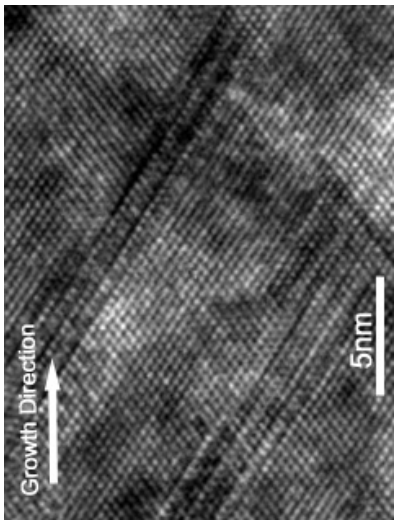

Fig. 4 High-resolution TEM image of GaAsGd grown at Gd cell 1400 ºC. Dislocation along (1 1 1) plane exists.

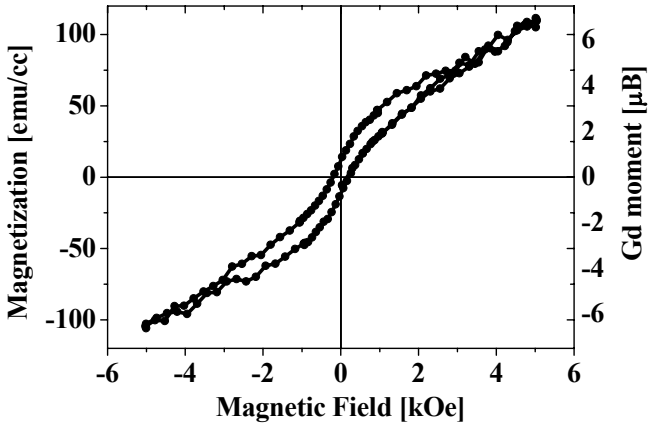

Fig. 5 Magnetization hysteresis curves of GaAsGd DMSs grown at 1400 C measured at room temperature.

35.3°, with the growth direction in GaAs:Gd layer, and these dislocations are interpreted to be along {1 1 1} plane.

Magnetization curves versus magnetic field of GaAs:Gd grown at Gd cell 1400 °C is shown in figure 5, where magnetic field is applied in the sample plane. From figure 5, the GaAs:Gd is found to be ferromagnetic at the room temperature and the magnetic moment of Gd is evaluated as more than 7 Borh mangetons (μ_B) per atom. This value is smaller than previous reports [1][2], and is equivalent to a free atomic magnetic moment of Gd, 7.94 μ_B. As compared to Gd doped GaN having 'colossal magnetic moment' reported by S. Dhar, our samples includes more rich Gd atoms as shown in figure 1, and Gd-Gd distance in our samples, estimated as 8 ~ 10 Å, is too short to have influence on surrounding non-magnetic atoms. We predict that, when Gd concentration in GaAs:Gd becomes lower than $1x10^{19}$ cm^{-3}, a number of spin-polarized Ga or As increases relatively and the magnetic moment per Gd atom may become colossal.

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