Growth and Characterization of MnAs Nanoclusters Embedded in GaAs Nanowires by Metal-Organic Vapor Phase Epitaxy

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1. Introduction

As an emerging technology in future, free-standing semiconductor nanowires (NWs) attract much attention because they show the potential applications to electronic and photonic devices in a new generation. We have demonstrated the formation of semiconductor NW arrays on GaAs (111)B, Si (111), InP (111)A wafers, and so on, by selective-area metal-organic vapor phase epitaxy (SA-MOVPE) [1]. In order to realize magneto-electronic devices using NWs, in this paper, we report the hybrid NWs of semiconducting and magnetic materials. Our SA-MOVPE has made it possible to form ferromagnetic MnAs nanoclusters (NCs) on GaAs (111)B substrates [2]. Ordered arrays of the chain structures comprising of elongated MnAs NCs, in addition, strongly affected magneto-resistance (MR) effects of the applied currents [3], and showed the angle-dependent MR. These results in our previous study have showed the possibility to apply the hybrid NWs for magneto-nanoelectronic devices, such as a magnetic sensor device using NWs. Therefore, in order to realize the hybrid NWs, this paper describes the MOVPE growth condition dependence of the formation and the structural characterization of the MnAs NCs embedded in GaAs NW arrays.

2. Experimental Procedures

The SA-MOVPE process for the template of the typical GaAs NW arrays on GaAs (111)B substrates has been given in detail elsewhere [1]. The circular openings of SiO2 mask have the diameter of 100 nm, and the distance between them was from 0.5 to 3.0 µm. For the MnAs NC growth in the GaAs NWs, we utilized the phenomenon of the “endotaxy” of MnAs in GaAs. In our previous study [4], we have observed the single crystal MnAs NCs formed in GaInAs (111)A substrates [2]. Ordered arrays of the chain structures comprising of elongated MnAs NCs, in addition, strongly affected magneto-resistance (MR) effects of the applied currents [3], and showed the angle-dependent MR. These results in our previous study have showed the possibility to apply the hybrid NWs for magneto-nanoelectronic devices, such as a magnetic sensor device using NWs. Therefore, in order to realize the hybrid NWs, this paper describes the MOVPE growth condition dependence of the formation and the structural characterization of the MnAs NCs embedded in GaAs NW arrays.

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3. Results and Discussion

SEM image, in Fig. 1(a), shows a typical template of GaAs NWs. Highly-magnified SEM images in Figs. 1(b) and (c) clearly shows that, introducing only the Mn source in H2 at Tg of 600°C after the growth of GaAs NWs with the estimated diameter of 130 nm, NCs are formed on the six ridges of hexagonal GaAs NWs from the top to the bottom, while the height of the NWs has not been changed. Figure 2 shows cross-sectional TEM images for the NCs and the ridges of GaAs NWs, and ED patterns of the NCs. We observed that the NCs with a triangular cross-section were embedded in the ridges of the NW, and estimated that the average width, depth in the NW and distance between the NCs were about 10, 8, and 40 nm, respectively. Lattice image and ED pattern, in Fig. 2(c), showed that the NCs had hexagonal NiAs-type crystal structure, while GaAs NWs had zinc-blende-type one (not shown). Combining EDX analysis for the line across the NWs and NCs, in Fig. 3, we confirmed that the MnAs NCs were formed in the GaAs NWs by “endotaxy”. The results are consistent with the endotaxial nanoclustering of MnAs in the planar GaInAs (111)A [4], GaAs (111)A and GaAs (111)B layer surfaces (not shown). The solid compositions (atomic %) of Mn, As, and Ga in the NCs were estimated to be 43.7, 49.9, and 6.4%, respectively, in the current work, as shown in Fig. 3.

Next, under various Tg conditions, we investigated the dependences of the MnAs endotaxial nanoclustering behavior on the periodical distances between the GaAs NWs, a. As shown in Fig. 4, the estimated diameter and density of the MnAs NCs have the tendency to be increased with increasing a. In the case of a = 3 µm, it appeared that the adjacent NCs were merged together presumably because of the increase in their size. That resulted in the decrease, or the saturation, in the NC density. In addition, as depicted by “a” in Fig.4, the NC size was increased by introducing AsH3 and H2 after the growth during decreasing Tg. Typical SEM images in Fig. 5 clearly show the possibility to control the size and the density of the NCs by optimizing the conditions.

4. Summary

We realized the MnAs/GaAs hybrid NWs by combining the SA-MOVPE of GaAs NWs and the “endotaxy” of MnAs NCs. The MnAs NCs embedded in and along the six ridges of the hexagonal GaAs NWs were observed.

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References

Fig. 1 Bird’s-eye view for (a) the template of GaAs NW arrays, in which distance between NWs, \(a\), was 1.0 \(\mu\)m. Highly-magnified bird’s-eye and top (insets) views for (b) hexagonal GaAs NW (\(a = 3.0 \mu\)m) and (c) NCs grown on the six ridges of the NW.

Fig. 2 (a) Schematic illustrations for cross-sectional TEM observations of NW. (b) Cross-sectional TEM image of MnAs NCs grown in the ridges of GaAs NW. (c) Cross-sectional lattice image of MnAs NC and GaAs NW, and ED pattern (inset) for MnAs NC.

Fig. 3 EDX line profile of NW and NCs.

Fig. 4 Dependences of NC (a) diameter and (b) density on distance between NWs, \(a\). Mn source and \(\text{H}_2\) were supplied for the growth, but, after the growth during decreasing \(T_g\), the gases in round brackets in the inset were supplied.

Fig. 5 Bird’s-eye views by SEM for typical NWs (\(a = 1.0 \mu\)m) grown at \(T_g\) of (a) 600\(^\circ\)C (Decreasing \(T_g\) only with \(\text{H}_2\) supply), (b) 600\(^\circ\)C (Decreasing \(T_g\) with \(\text{AsH}_3\) and \(\text{H}_2\) supply), and (c) 500\(^\circ\)C (The same gas supply as (a), i.e., only \(\text{H}_2\) decreasing \(T_g\)).