

Fabrication and Structural Characterization of Vertical Free-Standing InAs Nanowires Hybridized with Ferromagnetic MnAs Nanoclusters

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1. Introduction

Semiconductor nanowires (NWs) have recently attracted extensive attention in electronic industries as well as in the fields of bio-chemical engineering, because of the expected versatility in potential applications to the electronic, photonic, and sensing devices in next generation. We have fabricated III-V compound semiconductor NWs by using selective-area metal-organic vapor phase epitaxy (SA-MOVPE) [1], which is a bottom-up type fabrication method with high controllability of the position and size of nanostructures. Using our method, we have demonstrated bottom-up fabrication of ferromagnetic nanostructures for nanospintronic device applications. We reported on the formation of ordered arrays of chain structures comprising elongated MnAs nanoclusters (NCs), and the strong influence on magneto-resistance (MR) effects of the applied currents [2]. Such MnAs NC chain arrays showed strong angle-dependent MR effects originated from the influence of the MnAs NCs' magnetization on the transport properties. In order to enhance the angle-dependent MR effects further, we fabricated vertical free-standing GaAs NWs hybridized with ferromagnetic MnAs NCs [3]. We have recently introduced such a hybridization technique to InAs NW systems because of high electron mobility in InAs and Fermi-level pinning at the surface of InAs. Therefore, in order to realize the nanospintronic devices with hybrid NWs of semiconductor and ferromagnetic materials, in this paper, we report on the structural characterization and the fundamental MOVPE growth condition dependences of the formation of MnAs NCs embedded in InAs NW arrays.

2. Experimental Procedure

The SA-MOVPE process for the template of the typical InAs NW arrays on GaAs (111)B substrates is summarized as follows. On the substrate, we deposited 20 nm-thick SiO₂ films which have periodic circular openings. The diameter of the openings and the distance between them, a , were from 50 to 200 nm and from 0.5 to 3.0 μm , respectively. For the MnAs NC growth using the InAs NW arrays, we utilized the phenomenon of the "endotaxy". This is the key technique to form MnAs NCs "into" semiconductor NWs in the current work. Under the gas supply conditions of (CH₃C₅H₄)₂Mn and H₂ (no AsH₃

supply), the growth temperature, T_g , was changed from 400 to 580°C, the growth time is 1 min to form MnAs NCs. The estimated partial pressure of (CH₃C₅H₄)₂Mn was 1.16×10^{-6} atm.

For observing surface morphologies, we used scanning electron microscopy (SEM). We characterized crystal structures and solid compositions of NWs and NCs by electron-beam diffraction (ED) measurements and transmission electron microscopy (TEM).

3. Results and Discussion

Figure 1(a) shows the SEM image of the typical template of InAs NW arrays, which was grown as vertical free-standing hexagonal columns toward to $\langle 111 \rangle_B$. After the growth of the InAs NW templates, we supplied only Mn source materials in H₂ atmosphere. We observed NCs formed on the top surfaces and the side walls of InAs NWs, as shown in Fig. 1(b). From the cross-sectional TEM images of the typical InAs NWs with the NCs in Fig. 2, we found that the NCs were mostly embedded in the InAs NWs. ED patterns from the NCs in Fig. 3 revealed that the NCs have hexagonal NiAs-type crystal structures. The results show that the MnAs NCs were formed in and on the InAs NWs as a result of endotaxial nanoclustering. Cross-sectional lattice image, Fig. 4(a), shows that c-axis of the NCs grown on the top surfaces of NWs was parallel to InAs $\langle 111 \rangle_B$. On the other hand, the c-axis of the NCs grown from the side

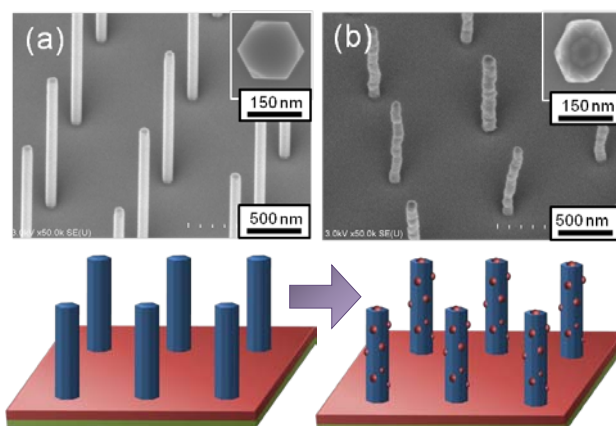


Fig. 1 Bird's-eye views taken by SEM and schematic illustrations of (a) the template structures of InAs NW arrays and (b) the sample after supplying Mn source materials on the InAs NW template in hydrogen atmosphere. The insets in the SEM images are the typical top views of the samples.

walls of NWs was perpendicular to InAs $\langle 111 \rangle$ B, as shown in Fig. 4(b).

Next, we investigated the dependences of the MnAs endotaxial nanoclustering on the periodical distances between the InAs NWs, a , and the growth temperature, T_g . SEM images in Fig. 5 show the dependence of MnAs NC formation on the T_g . We found that the density of the MnAs NCs on the InAs NWs tended to be increased with decreasing T_g , while decreased with decreasing a (not shown here).

Comparing to our previous work on the formation of MnAs NCs on GaAs NWs, the height of GaAs NWs has not changed even after Mn source materials were supplied, and MnAs NCs were formed only from the side walls of GaAs NWs. In the case of InAs NWs, on the other hand, the height of NWs decreased after supplying Mn source materials, and MnAs NCs were formed from the side walls and on the top surfaces of InAs NWs. In addition, the height uniformity of InAs NWs after the MnAs NC growth became poorer than that of InAs NW templates before the NC growth. This is possibly because InAs is thermally less stable than GaAs. Therefore, it is likely that the desorption rate of As atoms from InAs

compounds is much enhanced comparing to that from GaAs compounds, since there is no AsH_3 supply during the MnAs NC growth.

4. Summary

We realized the MnAs/InAs hybrid NWs by combining the SA-MOVPE of InAs NWs and the endotaxy of MnAs NCs. MnAs NCs on the top and embedded in the side of InAs NWs were observed.

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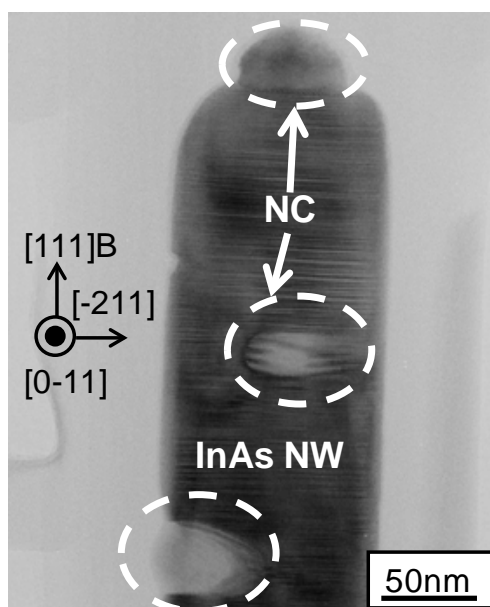


Fig. 2 Cross-sectional TEM image of MnAs NCs grown on and in InAs NW.

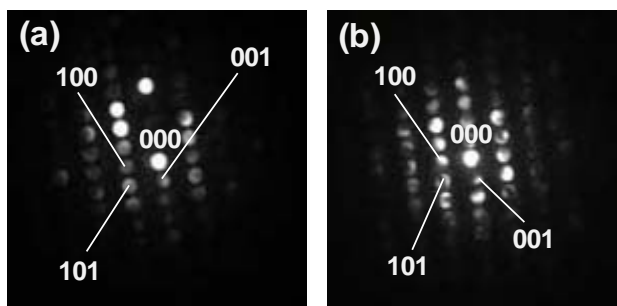


Fig. 3 ED patterns for MnAs NC grown (a) on the top surfaces of InAs NW and (b) from the side walls of InAs NW.

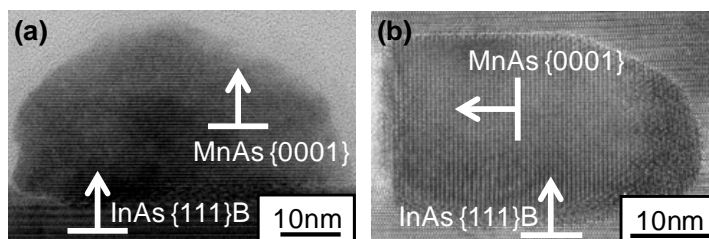


Fig. 4 Cross-sectional lattice images of MnAs NC grown (a) on the top surfaces of InAs NW and (b) from the side walls of InAs NW.

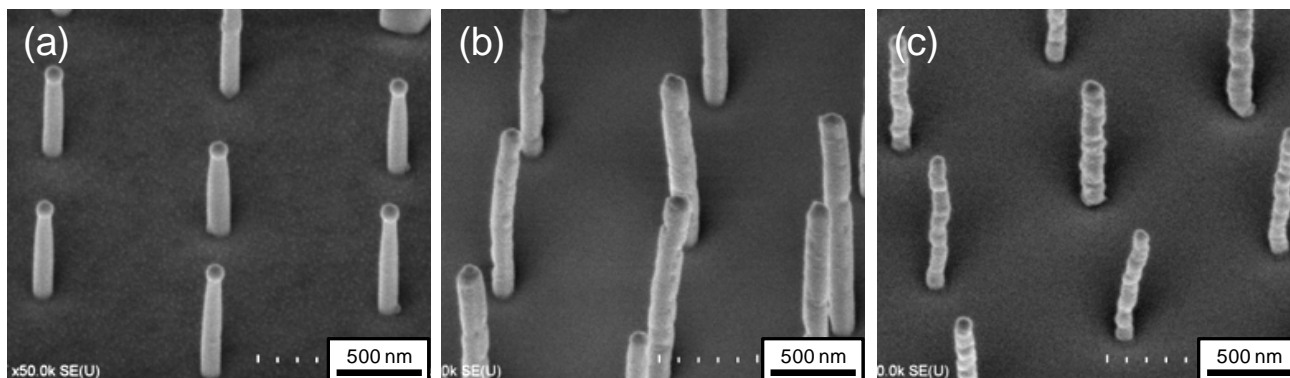


Fig. 5 Dependence of MnAs/InAs hybrid NW formation on the growth temperatures, T_g , of MnAs NCs on InAs NWs: T_g at (a) 580, (b) 490, and (c) 400°C.