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Analysis of Bending Mechanism in MnAs/InAs Heterojunction Nanowires

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Abstract

We report on analysis of bending mechanism in MnAs/InAs heterojunction nanowires by endotaxy of MnAs nanoclusters in combination with selective-area metal-organic vapor phase epitaxy of InAs nanowires. To investigate in which orientations the nanowires were bent, angle distributions of the bending nanowires were analyzed from the top view of scanning electron microscopy images. The analysis reveals that a large number of MnAs/InAs heterojunction nanowires was mostly bent in one of the directions of six ridges of host hexagonal InAs nanowires, in particular, at the case that MnAs nanoclusters were grown at 580 °C. After the cross-sectional transmission electron microscopy observations, it was possible that the heterojunction nanowires were bent owing to the insufficient interface formation and lattice mismatch between MnAs nanoclusters and InAs nanowires.

1. Introduction

Vertical free-standing semiconducting nanowires (NWs) have attracted considerable attention for potential applications to next-generation electronics, photonics, sensing, and even spintronics devices. We have demonstrated the catalyst-free formation of vertical heterojunction NWs between ferromagnetic MnAs nanoclusters (NCs) and semiconducting InAs NWs by selective-area metal-organic vapor phase epitaxy (SA-MOVPE), which has enabled us to control the size, aspect ratio, position, and density of NWs, in combination with the endotaxy of MnAs NCs. [1-3] We successfully fabricated that vertical heterojunctions between ferromagnetic MnAs NCs and semiconducting InAs NWs with atomically abrupt heterointerfaces. We believe that these abrupt heterointerfaces offer a possibility for overcoming major obstacles, namely, conductance mismatch and poor controllability in the formation of heterointerfaces in current nanospintronic devices and creating a novel vertical spin-NW-transistor.

To realize such novel nanospintronic devices, a high degree of controllability in the MnAs NC formation is required in the host semiconducting NWs. In this paper, therefore, we discuss a possible mechanism of the bending structure formation, which was occasionally observed, in the heterojunction NWs after the analysis how the MnAs NCs were formed in and on the sidewalls of host InAs NWs in combination with the experimental results in our previous studies. [1-3]

2. Experimental procedure

First, we prepared the initial circuit openings, which were arranged and defined in SiO_2 thin films deposited on GaAs (111)B substrates by electron beam lithography for SA-MOVPE of host InAs NW templates at 580 °C for 30 min. The sample preparation procedures were reported elsewhere in detail. [1] For the MnAs NC growth after the InAs NW formation, we utilized the phenomenon of "endotaxy". During the endotaxy, we only supplied the organometallic source of $(CH_3C_5H_4)_2Mn$ diluted in H_2. For the MnAs NC formation, the growth temperatures were 490 and 580 °C, and the growth time was 1 min. The estimated partial pressure of $(CH_3C_5H_4)_2Mn$ was 3.0×10^{-6} atm. For the structural characterizations of bending structures in MnAs/InAs heterojunction NWs, we mainly analyzed the top views of scanning electron microscopy (SEM) images. Transmission electron microscopy (TEM) was also used for the cross-sectional observations of lattice images of the heterojunction NWs.

3. Results and discussion

Figure 1 shows typical bird's-eye views of SEM images of MnAs/InAs heterojunction NWs, and the MnAs NCs were grown at (a) 580 and (b) 490 °C, respectively. Most of the heterojunction NWs were grown in the vertical direction, i.e., <111>B direction, of the substrate. However, we occasionally observed bending heterojunction NWs mostly after the NC formation, as shown in NWs marked by white circles in Figs. 1(a) and 1(b). When the growth temperature of NCs was a relatively low, i.e., 490 °C, a larger number of NCs formed on the sidewalls in the middle part of host InAs NWs was observed, [1] and the number of bending heterojunction NWs tended to increase, as indicated in Fig. 1(b).

To investigate the bending heterojunction NWs, next, we measured in which directions the NWs were bent from the top view of SEM images. Figure 2(a) shows a typical top view of SEM image of heterojunction NWs, and the inset shows a relationship between crystal orientations and a hexagon of a host InAs NW. For the analysis of angle distributions, we set the <-211> direction of host InAs NWs as $\theta = 0°$, as shown in Fig. 2(a). Figure 2(b) shows the angle distribution of bending heterojunction NWs for the sample in which MnAs NCs were grown at 580 °C. We observed that a large number of heterojunction NWs was bent in one of the six ridge directions, which were between two {0-11} crystal facets of sidewalls of host InAs NWs. Figure 2(c), next, shows the angle distribution of bending heterojunction NWs for the sample with the MnAs NCs grown at 490 °C. A similar tendency, which a larger number of NWs was bent in one of the six ridge directions, was observed in Fig. 2(c). In addition, the NWs bent in one of the <0-11> directions, i.e., the directions of six sidewall crystal facets of hexagonal InAs NWs, was markedly increased, although the number of the NWs bent in the six ridge directions was large, similarly in the case of Fig. 2(b). Figure 3 shows cross-sectional TEM images of a bending MnAs/InAs heterojunction NW, in which MnAs NCs were grown at 490 °C. We observed that the NW was bent in the middle part, where a MnAs NC was partly grown into a NW from one of the sidewall surfaces of the NW, as shown in Fig. 3(a). The highly-magnified lattice image in Fig. 3(b) reveals that the <111>B direction of InAs NW was tilted against the <111>B direction of the NW under the MnAs NC at around the part where a MnAs NC was formed, and that the heterojunction NW was bent toward the part where the MnAs NC started to grow from the sidewall surface of the NW. Lattice constant of InAs is larger than that of MnAs. It is possible, therefore, that the bending of heterojunction NWs occurs owing to insufficient interface formation and lattice mismatch between InAs and MnAs.

These results indicate that the nucleation on MnAs NCs possibly tends to start from one of the six ridges, at which a larger number of atomic steps was formed. This is consistent with our previous study, in which we showed that MnAs NCs were formed at one of the six ridges of hexagonal GaAs NWs. [4] When the diameter of GaAs NW became relatively large, MnAs NCs grew both at the six ridges and on the {0-11} planes of six sidewall facets of GaAs NWs. [4] A possible reason why NCs were formed on the {0-11} planes of NWs was that the surface migration length of Mn adatoms on the NW surfaces was smaller than the sidewall width of NWs. In the case of InAs NWs in the current work, the surface migration length of Mn adatoms at 490 °C was approximately 120 nm at most. [1] It was much larger than the observed width of one of the sidewall facets of InAs NWs was estimated to be approximately 50 nm. Therefore, it seemed to be hard in this case that the nucleation of MnAs NCs occurred on one of the six sidewall facets of InAs NWs because Mn adatoms easily reached one of the six ridges at which there are a larger number of atomic steps. In addition, as shown in our previous study, [1] the depth of endotaxial MnAs nanoclustering decreased with decreasing the growth temperature of MnAs NCs because the diffusion coefficient of Mn adatoms was smaller at 490 °C than at 580 °C. The Mn adatoms were easily incorporated into the sites where the NCs started to be formed first. These results led to the shallower depth of MnAs growth into NWs, and the NC formation from the ridges spread to {0-11} planes near the surface, although the nucleation possibility of NCs on {0-11} planes is not excluded in this study.

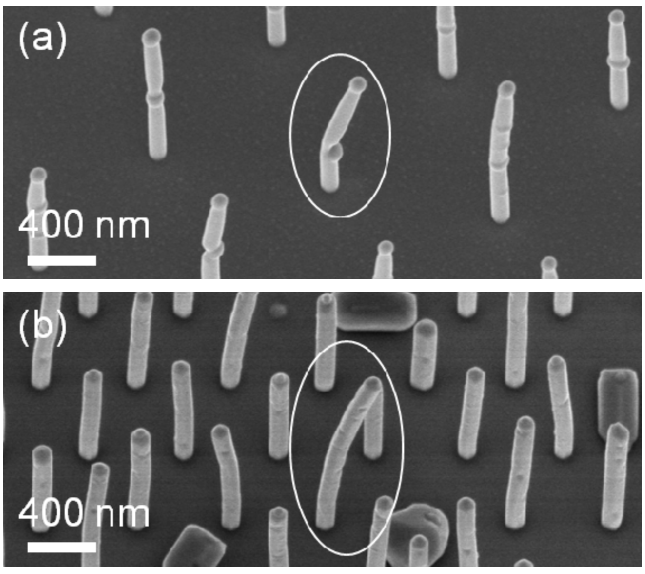

Figure 1 Bird's-eye views of SEM images of typical MnAs/InAs heterojunction NWs. Growth temperatures for the NC formation are (a) 580 and (b) 490 °C, respectively.

4. Conclusions

The analysis of angle distributions in the bending NWs revealed that a large number of heterojunction NWs was mostly bent in one of the directions of six ridges of host hexagonal InAs NWs, in particular, at the case that MnAs NCs were grown at 580 °C. After the cross-sectional TEM observations, it was possible that the heterojunction NWs were bent owing to the insufficient interface formation and lattice mismatch between MnAs NCs and InAs NWs.

References

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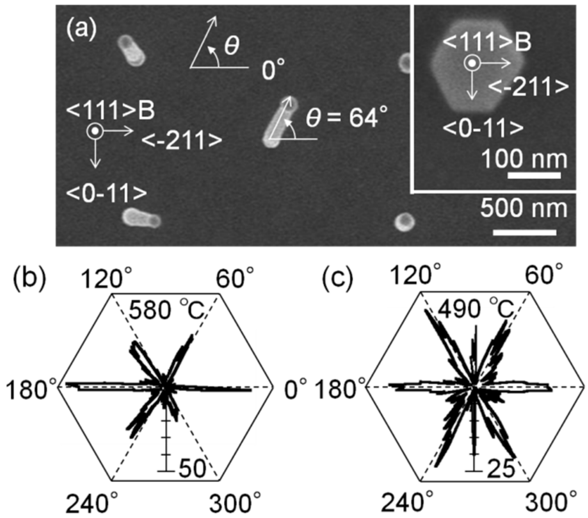

Figure 2 (a) Top views of SEM images of MnAs/InAs heterojunction NWs, in which MnAs NCs were grown at 580 °C. The inset of (a) is a top view showing crystal facets typically formed in host hexagonal InAs NWs. The angle distribution charts of the observed bending structures in the heterojunction NWs, in which MnAs NCs were grown at (b) 580 and (c) 490 °C, respectively. The definition of the angle, θ, is shown in (a). The number of data obtained in units of 2° is more than 1,400 for both (b) and (c).

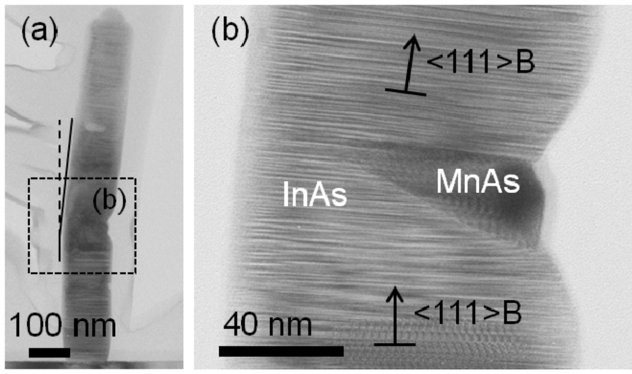

Figure 3 (a) Cross-sectional TEM image of a MnAs/InAs heterojunction NW. (b) Highly-magnified lattice image around the middle part of the NW shown in (a).