Hexagonal ferromagnetic MnAs nanocluster formation on GaInAs/InP (111)B layers by metal-organic vapor phase epitaxy

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The authors report the self-assembly of hexagonal MnAs nanoclusters on GaInAs (111)B surfaces by metal-organic vapor phase epitaxy. The ferromagnetic behavior of the nanoclusters dominates the magnetic response of the samples when magnetic fields are applied in a direction parallel to the wafer plane. For the magnetic fields applied in a direction perpendicular to the plane, diamagnetic characteristics are dominant. The results indicate that the c axis of the nanoclusters is perpendicular to the plane, and that their a axis is in plane. They are consistent with the results of crystallographic analysis, where the nanoclusters’ c axis is shown to be along a GaInAs [−1 1 −1] direction. © 2006 American Institute of Physics. [DOI: 10.1063/1.2349309]

Ferromagnetic materials hybridized in III-V compound semiconductors (FM III-V hybrids) and III-V compound-based diluted magnetic semiconductors (III-V DMSs) are promising for the realization of nanospintronic devices using not only the charge but the spin of carriers. In MnAs/GaAs, GaMnAs, and InMnAs materials systems where extensive research efforts have been carried out, magnetic thin films have been grown on GaAs layers by molecular beam epitaxy at an extremely low growth temperature (LT-MBE).\(^1\)\(^2\) Implantaion of magnetic ions into semiconductors,\(^3\)\(^4\) and metal-organic vapor phase epitaxy (MOVPE).\(^5\)\(^6\) We have pursued FM III-V hybrids, in particular, using MnAs nanoclusters (NCs) embedded in GaInAs/InP (001) layers grown by MOVPE.\(^7\)\(^8\) InP-related materials are more suitable for the fabrication of key devices in optical communication systems for 1.3 and 1.55 μm wavelength bands. Recently, LT-MBE of III-V DMS, e.g., GaMnAs, on InP (001) wafers has been reported,\(^9\)\(^10\) and waveguide-type optical isolators using the magnetooptical effects of MnAs NCs have been proposed.\(^11\) Ferromagnetic MnAs thin films, in addition, serve as an electrical spin injection source into semiconductors.\(^12\)

For the growth of hexagonal NiAs-type MnAs layers, \{111\} orientations of zinc-blende (ZB)-type materials are promising because of the similarity of crystallographic structures. MnAs “thin films” have been grown not only on GaAs (111)B (Refs. 13–18) but on Si (111) (Ref. 19) surfaces by LT-MBE. Another potential advantage using the \{111\} orientations is the catalyst-free formation of one-dimensional (1D) semiconductor nanowires (NWs) using selective-area MOVPE as promising building blocks for future nanophotonics and electronics.\(^20\)\(^21\) The hybridization of ferromagnetic NCs into 1D semiconductor NWs possibly leads to the understanding of physical properties in 1D spin-polarized electronic systems and the realization of 1D nanospintronic devices in the next generation. We believe that the MOVPE techniques in the present work are one of the most powerful methods to meet this future goal. In this letter, we demonstrate the self-assembly of ferromagnetic MnAs NCs on planar GaInAs (111)B surfaces by MOVPE. This letter describes the results of fundamental crystallographic and magnetic characterizations for the NCs.

\((\text{CH}_3)_2\text{Ga}, (\text{CH}_3)_2\text{In}, \text{t-C}_6\text{H}_{14}\text{PH}_2,\) and 20%-AsH\(_3\) diluted in H\(_2\) were used as group III and V source materials. (\text{CH}_3\text{C}_5\text{H}_2)_2\text{Mn} was chosen as a Mn organometallic precursor.\(^8\) After the growth of GaInAs layers on InP buffer layers, \((\text{CH}_3\text{C}_5\text{H}_2)_2\text{Mn}\) was introduced to the MOVPE reactor with AsH\(_3\). All the layers were grown on diamagnetic InP (111)B wafers, and, as a reference, InP (001) substrates were used at the same growth runs. The growth temperature \(T_g\) and the V/Mn ratio were 600 °C and 375, respectively. Here, the supply gas ratio between the partial pressures of a group V source, \(p[\text{AsH}_3]\), and a manganese precursor, \(p[(\text{CH}_3\text{C}_5\text{H}_2)_2\text{Mn}]\), is defined as V/Mn = \(p[\text{AsH}_3]/p[(\text{CH}_3\text{C}_5\text{H}_2)_2\text{Mn}]\) and is referred to as a “V/Mn ratio.” Surface morphologies of the samples were observed by atomic force microscopy (AFM). Cross-sectional lattice images and electron beam diffraction (ED) patterns were observed to investigate the crystallographic structures of NCs by transmission electron microscopy (TEM), and energy dispersive x-ray (EDX) spectroscopy was carried out for the compositional analysis. Vibrating sample magnetometer was used to characterize magnetic properties of NCs.

Initially, we revealed by AFM that GaInAs layers grown on InP buffer layers had no NCs on the surfaces. A flat GaInAs surface with steps and large terraces was formed. We find that NCs are formed on GaInAs (111)B and (001) surfaces after the MnAs growth. As shown in Fig. 1, hexagonal NCs with well-defined sidewall crystal facets were formed on the \(111\)B surfaces. Such facets are attributable to some low and high index crystal planes of a hexagonal structure. Typical hexagonal NCs measured about 330 nm in diameter and 6–20 nm in height. The lateral size of the NCs was increased with increasing \(p[(\text{CH}_3\text{C}_5\text{H}_2)_2\text{Mn}]\), whereas almost no change was observed with respect to the NC heights. The observed hexagonal NCs on the \(111\)B surfaces were mostly elongated toward a [−1−11] direction. On the (001) surfaces, on the other hand, rectangular NCs elongated toward a [110] direction were formed (not shown). Figure 2(a)
FIG. 1. (Color online) Surface morphology of hexagonal MnAs NCs grown on GaInAs (111)B surfaces.

shows a cross-sectional TEM image of the MnAs NC grown on GaInAs/InP (111)B layers. The observed NC measured about 250 nm wide and 23 nm high. The solid compositions of the hexagonal NCs examined by EDX spectroscopy are summarized in Table I. The analyzed regions are represented by the open circles 1 and 2 in Fig. 2. The analyzed regions are represented by the open circles 1 and 2 in Fig. 2 summarized in Table I. The analyzed regions are represented by the open circles 1 and 2 in Fig. 2 summarized in Table I. The analyzed regions are represented by the open circles 1 and 2 in Fig. 2 summarized in Table I. The analyzed regions are represented by the open circles 1 and 2 in Fig. 2 summarized in Table I. The analyzed regions are represented by the open circles 1 and 2 in Fig. 2 summarized in Table I. The analyzed regions are represented by the open circles 1 and 2 in Fig. 2 summarized in Table I. 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Figure 3. (Color online) Magnetization dependences on the directions of applied \( H \) to the MnAs NCs on GaAs (111)B surfaces: (a) in-plane and (b) out-of-plane rotations of the sample. \( M \)-\( H \) curves observed at (c) \( \theta=0^\circ \) in (a) and (d) \( \theta=90^\circ \) in (b).

Figure 4. (Color online) (a) Surface morphology of MnAs NC arrays self-assembled on GaInAs (111)B surfaces after optimizing MOVPE conditions and (b) highly magnified AFM image of the hexagonal NCs.

Detailed experimental results on growth condition dependence of the NC formation will be reported elsewhere. We believe that the hybridization of ferromagnetic MnAs NCs into 1D semiconductor NWs on (111)B layers is realized by the MOVPE techniques in the present work.

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