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Molecular-beam epitaxy of MnAs on patterned GaAs substrates

Y.Morishita, Y.Sugawara, M.Kato, and K.Sato
Faculty of Technology, Tokyo University of Agriculture and Technology, Koganei, Tokyo 184-8588, Japan

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MnAs were grown on (001) GaAs substrates with mesa-grooves along the [$\bar{1}$10] and [110] directions having outward sloping sidewalls and inward sloping sidewalls, respectively, by molecular-beam epitaxy with/without the supply of hydrogen radicals (H·). The epilayer shapes have been investigated using secondary electron microscope observations after growth. The vertical film thickness on the (001) surface is irrespective of the rotation of substrates during growth. On the other hand, the lateral film thickness on the sidewall decreased as the Mn flux was decreased. The shapes of MnAs layers were independent on the supply of H·, although the irradiation of H· improves the surface smoothness. These results indicate that the surface-diffusion length of Mn adatoms is small. Consequently, by adjustment of the direction of Mn flux, MnAs layers can be selectively grown on the one side of the sidewalls of patterned substrates.

Key words: molecular-beam epitaxy, MnAs, surface diffusion, lateral epitaxy, quantum wires

1. Introduction

Ferromagnet/semiconductor heterostructures are attracting much attention because of their potential application in fabricating new devices integrating magnetic, electronic and optical properties[1]. Recent progress in the molecular-beam epitaxy (MBE) technique has demonstrated that CuAu-type ferromagnetic compounds such as MnGa and MnAl[2), 3)], as well as NiAs-type ferromagnetic compounds such as MnSb and MnAs[4-10)] can be grown on III-V substrates such as GaAs and InAs. We have also elucidated the effect of hydrogen radicals on the structure and magnetic properties of MnAs epilayers grown by MBE[10)].

Epitaxial growth on patterned substrates is useful for achieving advanced structures of magneto-optoelectronic devices[11-14)]. For these devices, it is important to control the shapes of the epitaxial layers, especially in the active region of the device. It is well known that crystal planes with different indices affect the growth behavior on neighboring surface and that facets are formed near edges with different indices from that of the sidewall in MBE[14)] and metalorganic chemical vapor deposition (MOCVD) on patterned substrates[15)]. In this paper, we report on the MBE growth of MnAs on mesa-etched (001) GaAs surfaces.

2. Experimental

MnAs MBE growth was carried out on (001) substrates with mesa-grooves along the [$\bar{1}$10] and [110] GaAs directions having outward sloping sidewalls and inward sloping sidewalls, respectively. Mesa-grooves were formed by conventional chemical etching. After growing a 100 nm thick undoped GaAs buffer layer on the substrates at 600 °C, the substrate temperature (T_s) was lowered to 250 °C. During the cooling process, the As_4 shutter was closed at T_s of about 480 °C. A c(4×4) reconstruction was observed from the GaAs surface after closing the As shutter.

MnAs layers were grown under following conditions: A Mn beam equivalent pressure (BEP) was fixed at about 8×10^{-8} Torr on a beam-flux monitor, and the As_4/Mn BEP ratio was kept constant at about 50. MnAs layers with thickness of about 150 nm were grown on the patterned substrates with a growth rate of about 0.4 Å/s, while T_s was kept constant at about 250 °C, as measured by an infrared pyrometer.

The growth direction and the crystal structure of MnAs epitaxial layers were studied by reflection high-energy electron diffraction (RHEED) and x-ray diffraction (XRD). The epilayer shapes have been investigated using secondary electron microscope (SEM) observations after growth.

3. Results and discussion

Fig. 1 shows XRD patterns for MnAs epilayers grown on (001) substrates with mesa-grooves along the [$\bar{1}$10] and [110] GaAs directions. In all cases, besides a GaAs (002) peak at 31.6 ° and a huge GaAs (004) peak at 66.0 °, two peaks were observed at 27.7 and 91.7 ° in the epilayer grown on both patterned substrates, corresponding to ($\bar{1}$100), ($\bar{3}$300) reflection of hexagonal MnAs, respectively. These results indicate that the growth plane of MnAs epilayers on (001) GaAs surfaces is the ($\bar{1}$100) plane, independent of the direction of mesa-grooves.

In the present epilayers, the orthorhombic paramagnetic βMnAs coexisted with hexagonal ferromagnetic αMnAs at

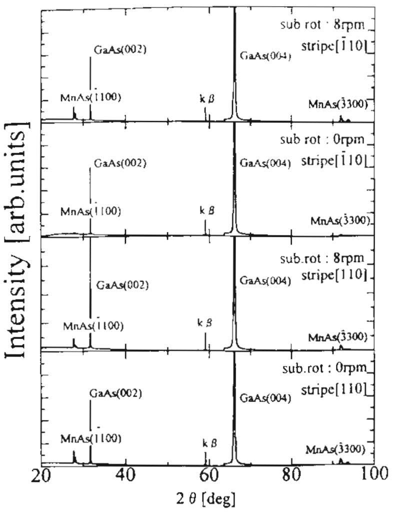

Fig. 1 XRD patterns for MnAs epitaxial layers grown on (001) substrates with mesa-grooves along the [$\bar{1}$10] and [110] GaAs directions.

room temperature, although the dominant phase was αMnAs. The difference in the structures between the MnAs epilayer and GaAs substrate is considered to cause the existence of the βMnAs below the Curie temperature (40 °C). However, it is not possible to clarify how the βMnAs is formed at present.

Fig. 2 shows a set of RHEED patterns of the epilayers grown on the substrates with mesa-grooves along the [$\bar{1}$10] direction together with those just before the growth of MnAs. By measuring the interval between the integral-order streaks, the lattice constant in the layer plane of MnAs epilayers was estimated. The estimated atomic distances along the various directions were in good agreement with those of bulk hexagonal MnAs. It was also found that the in-plane relationship between the ($\bar{1}$100) MnAs epilayer and the GaAs substrate is MnAs [$\bar{1}\bar{1}$20] // GaAs [110] and MnAs [0001] // GaAs [$\bar{1}$10], agreeing with that reported for the MBE growth of MnAs on (001) GaAs at T_s of about 250 °C[6]. Much the same tendency was observed regarding the RHEED patterns for the epilayers grown on GaAs substrates with mesa-grooves along the [110] GaAs direction.

Fig. 3 shows ($\bar{1}$10) cross-sectional SEM photographs of MnAs epilayers after growth. Besides the initial (001) surface and (111)A sidewall, a (114)A facet was formed at the upper sidewall after the growth of GaAs buffer layer, independent of the rotation of substrates during growth. Moreover, since the growth rate on the (001) surface near the edge of the mesa-groove varied exponentially as a function of the distance from the edge during MBE of GaAs due to the flow of Ga adatoms from the (111)A sidewall to the (001) surface of the mesa pattern, bump-like shapes were formed on epilayers grown on convex surfaces. The average thickness of MnAs epilayers

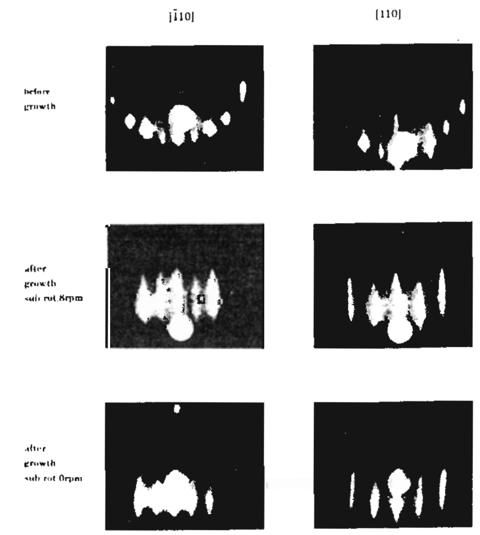

Fig. 2 RHEED patterns of the epilayers grown on the substrates with mesa-grooves along the [$\bar{1}$10] direction together with those just before the growth of MnAs.

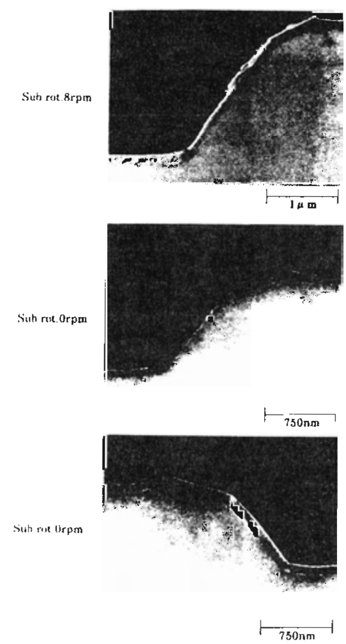

Fig. 3 ($\bar{1}$10) cross-sectional SEM photographs of MnAs epilayers grown on the substrates with mesa-grooves along the [$\bar{1}$10] direction.

normal to the (001) surface was about 150 nm for all samples, showing that the vertical growth rate is irrespective of the rotation of substrates during growth. On the other hand, the lateral film thickness strongly depended on the direction of Mn flux. The film thickness on the (111)A sidewall decreased as the Mn flux was decreased; growth was hardly observed on the sidewall which was not faced to the direction of Mn flux. The results indicate that the surface-diffusion length of Mn adatoms is small and by adjustment of the directions of Mn flux, MnAs layers can be selectively grown on the one side of the sidewalls of patterned substrates.

Fig. 4 shows (110) cross-sectional SEM photographs of MnAs epilayers after growth. Similarly, as described regarding the ($\bar{1}$10) case, the vertical film thickness is irrespective of the rotation of substrates during growth. On the other hand, the lateral film thickness on the (111)B sidewall decreased as the Mn flux was decreased.

In order to investigate the effects of hydrogen radicals (H·) on the shape of MnAs layers, MnAs were also grown on patterned (001) GaAs substrates by MBE in the presence of H· which were generated by flowing H_2 through a tungsten filament cell heated at about 1600 °C. Although the irradiation of H· improves the surface smoothness, the shapes of MnAs layers were independent of the supply of H·.

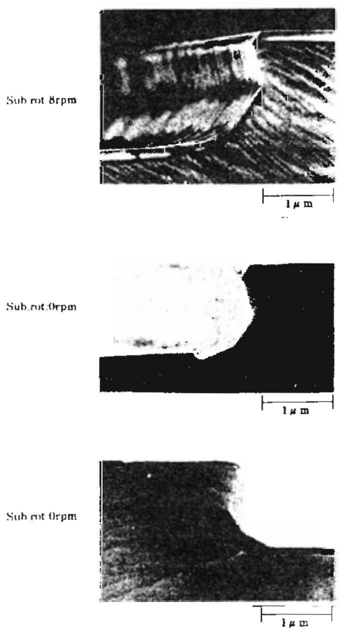

Fig. 4 (110) cross-sectional SEM photographs of MnAs epilayers grown on the substrates with mesa-grooves along the [110] direction.

4. Summary

MnAs layers were grown on (001) GaAs substrates with mesa-grooves along the [$\bar{1}$10] and [110] directions by MBE with/without the supply of H·. The epilayer shapes have been investigated using SEM observations after growth. The vertical growth rate on the (001) surface is irrespective of the rotation of substrates during growth. On the other hand, the lateral growth rate on the sidewall strongly depended on the direction of Mn flux. The film thicknesses on the (111)A and (111)B sidewalls decreased as the Mn flux was decreased; growth was hardly observed on the sidewalls which were not faced to the direction of Mn flux. Although the irradiation of H· improves the surface smoothness, the shapes of MnAs layers were independent on the supply of H·. The results indicate that the surface-diffusion length of Mn adatoms is small and by adjustment of the directions of Mn flux, MnAs layers can be selectively grown on the one side of the sidewalls of patterned substrates.

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