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Magnetic Domain Characterizations of MnAs Nanoclusters on Si (111) Substrate

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Abstract

We report on the magnetic domain characterizations of MnAs/AlGaAs nanoclusters selectively-grown on Si (111) wafers. Thickness of MnAs nanoclusters on AlGaAs buffer layers is estimated to be approximately 30 nm from the acceleration voltage dependence of backscattered electron images. Magnetic force microscopy shows spontaneous magnetizations from a marked single magnetic domain in nanoclusters with a relatively small diameter. Applied magnetic field dependence of magnetic domains reveals that single magnetic domains are formed even in nanoclusters with a larger diameter. The results show that magnetic domains are controllable by the size of nanoclusters.

1. Introduction

The heterostructures of ferromagnetic and III-V compound semiconducting layers (FM III-V hybrids) have attracted considerable attention because huge magnetoresistance (MR) effects were reported in granular FM III-V hybrids, in which ferromagnetic nanoclusters (NCs) are embedded in semiconducting layers. [1] FM III-V hybrids have been fabricated by conventional top-down-type fabrication methods after the heteroepitaxy of thin film layers. We have, on the other hand, developed a novel bottom-up-type fabrication method based on selective-area metal-organic vapor phase epitaxy (SA-MOVPE), which enable us to adjust the position, number, spatial arrangement, size, and shape of ferromagnetic MnAs NCs, [2] and demonstrated MR effects in ordered planar arrangements of coupled NCs on semiconducting GaAs (111)B substrates. [3] However, it is difficult to grow such ferromagnetic MnAs NCs directly on Si (111) substrates by SA-MOVPE without an interlayer owing to unintentional MnSi alloy formation near the Si surface under standard SA-MOVPE conditions for MnAs NCs. We reported on one of the solutions to the problem above, in which we used crystallized Al_2O_3 interlayers before the MnAs/AlGaAs NC growth to prevent unintentional Mn diffusion into the Si substrates. [4] In addition, we have investigated the designs for the initial mask opening patterns and thin film mask materials themselves, i.e., SiO_2 and SiON, deposited on Si (111) substrates for SA-MOVPE to offer other solutions to the problem above. [5] In this paper, therefore, we reports mainly on the magnetic domain characterization results of MnAs/AlGaAs NCs selectively-grown on Si (111) wafers with such patterning designs and materials of thin film masks.

2. Experimental procedure

We characterized some of the samples which we fabricated in our previous studies. [5] (I) The mask pattern of one type was the one that the SiON films outside the 100 x 100 μm^2 square regions with periodical circular mask openings were removed, and (II) that of another type was the one that the SiO_2 films were removed only for the periodical circular mask openings. These pre-patterned masks enable us to grow MnAs/AlGaAs NCs selectively on Si (111) substrate. The sample preparation procedures were reported elsewhere. [5] Growth temperature was 800 °C for both MnAs NCs and AlGaAs buffer layers. To roughly estimate layer thickness in NCs, backscattered electron (BSE) images were observed by scanning electron microscopy. We observed magnetic domains in MnAs NCs by magnetic force microscopy (MFM) at room temperature under zero-field condition after the applications of external magnetic fields, $\boldsymbol{B}$, as well as spontaneous magnetizations in the NCs before applying $\boldsymbol{B}$.

3. Results and discussion

Figure 1 shows typical top view of BSE images. We observed dark and bright contrasts in the areas where MnAs/AlGaAs NCs were formed, as shown in Fig. 1(a). BSE emission increases with the mean atomic number of materials. [6] In this study, the mean atomic number of AlGaAs is larger than that of MnAs. Therefore, the BSE images from the AlGaAs buffer layers should be brighter than those from the MnAs layers in the NCs. Therefore, it was highly possible that the dark regions of, e.g., NC-A and NC-B in Fig. 1(a), are attributed to MnAs layers in the NCs, and that the bright regions under the dark ones are due to the AlGaAs buffer layers. Next, we changed the acceleration voltage of electrons from 0.5 to 3.0 kV for BSE observations. Figure 1(b) shows a BSE image obtained at 2.0 kV, for example, which indicates no difference in the brightness of NCs. The penetration length of electrons depends on the acceleration voltage of electrons. It was calculated to be 27 nm at 1.5 kV and 44 nm at 2.0 kV using the equation given in Ref. [7]. Therefore, the thickness of MnAs layers in NCs was estimated to be approximately 30 to 40 nm in this study. This result is consistent with the cross-sectional observation results by transmission electron microscopy in our previous study. [5] We also observed other regions with a different brightness near the NCs, as indicated by a thin white arrow in Fig. 1(c). Judging from the observed brightness in the image and energy dispersive X-ray spectroscopy in our previous study, [5] it was possible that MnSi alloys were formed near the Si substrate surface owing to unintentional Mn diffusion into the substrates in the design and material of thin film mask pattern (I) in this study.

Figure 2 shows spontaneous magnetizations from the NCs, i.e., NC-A and NC-C in the images, with different diameters. NC-A is the same as the one observed by BSE microscopy in Fig. 1. NC-C was formed using another design and material of thin film mask pattern (II). The dependence of MFM images on the magnetization directions of MFM tips, $\boldsymbol{M_t}$, used here ensured that we obtained magnetic responses from the NCs. Therefore, as shown in Fig. 2, the MFM images clearly indicated that NC-A with a relatively large diameter tended to show multiple magnetic domains, whereas relatively-small NC-C had a marked single magnetic domain. Figure 3 shows the dependence of magnetic domains in NC-A on the strengths of applied external magnetic fields, $\boldsymbol{B}$. We observed multiple magnetic domains in NC-A up to $\boldsymbol{B}$ = 1000 Gauss (G) in Fig. 3(a). However, as shown in the case of $\boldsymbol{B}$ = 1500 G in Fig. 3(b), we markedly obtained a single magnetic domain even in NC-A with a relatively large diameter. The results in this study show that magnetic domains are controllable by the NC size.

4. Conclusions

Thickness of MnAs NCs on AlGaAs buffer layers selectively-grown on Si (111) substrates was estimated to be 30 to 40 nm from the acceleration voltage dependence of BSE images. MFM showed spontaneous magnetizations from a single magnetic domain in NCs with a relatively small diameter. In addition, the $\boldsymbol{B}$-dependence of magnetic domains revealed that single magnetic domains were formed even in NCs with a larger diameter. The results showed that magnetic domains were controlled by the NC size.

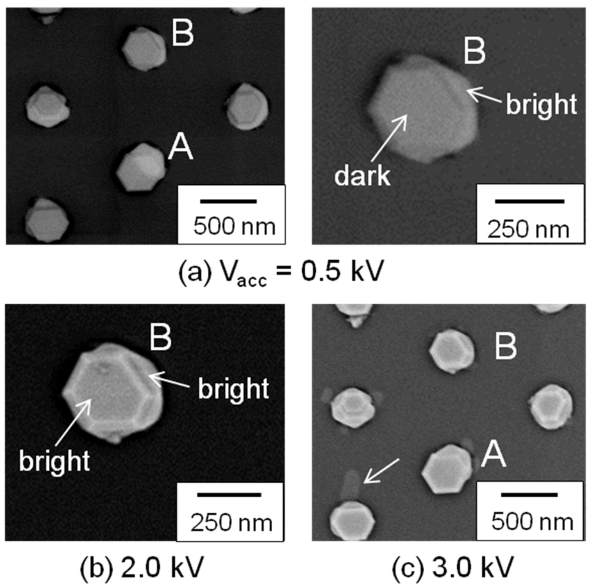

Figure 1 Acceleration voltage dependence of BSE images of MnAs/AlGaAs NCs, A and B. Dark and bright contrasts in the images, (a) and (b), are attributable to MnAs and AlGaAs under MnAs, respectively. (c) Judging from the brightness observed in the image and energy dispersive X-ray spectroscopy in our previous study, [5] MnSi alloys are formed near Si wafer surface.

References

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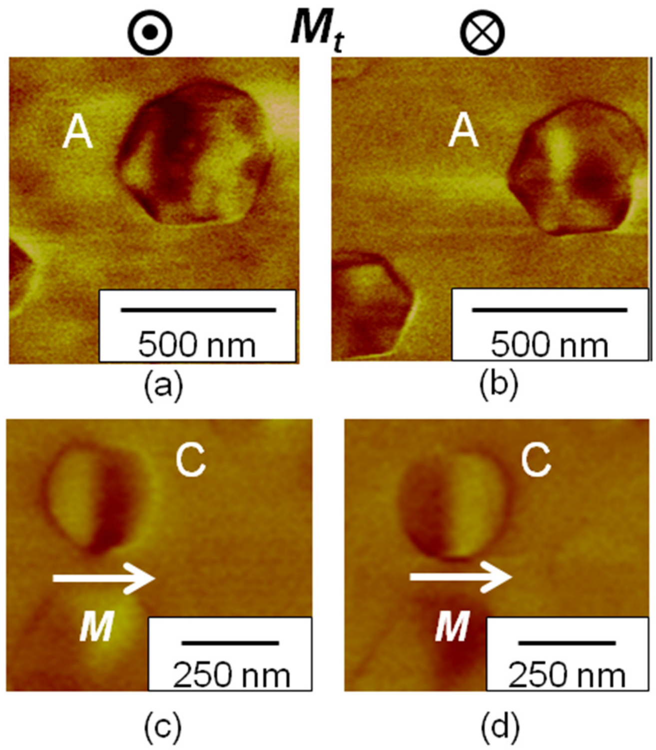

Figure 2 Magnetic responses, spontaneous magnetizations, from MnAs/AlGaAs NCs with different diameters and their dependence on magnetization directions of the MFM tips, $\boldsymbol{M_t}$: (a, b) NC-A and (c, d) NC-C. (a, c) the same $\boldsymbol{M_t}$ directions and (b, d) the $\boldsymbol{M_t}$ directions opposite to those for (a, c). NC-A is the same as the one observed by BSE microscopy in Fig. 1. The NCs with a smaller diameter, such as NC-C, tend to have a single magnetic domain.

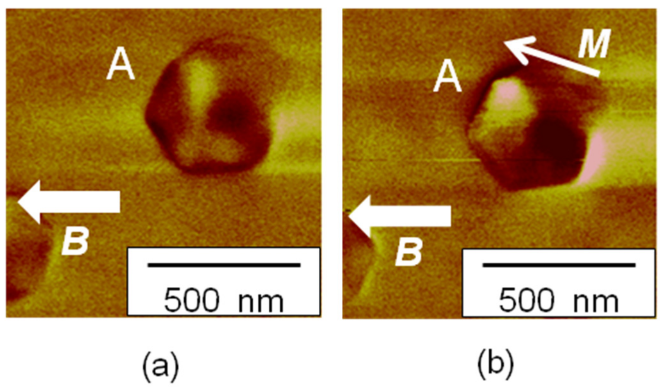

Figure 3 MFM images of NC-A: (a) Multiple magnetic domains are observed after applying the external magnetic fields, $\boldsymbol{B}$, of 1000 G. However, (b) a single magnetic domain, in which a thin white arrow indicates the magnetization direction, $\boldsymbol{M}$, is observed at $\boldsymbol{B}$ = 1500 G. Thick white arrows in the images indicate the applied $\boldsymbol{B}$ directions.