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FAST TRACK COMMUNICATION

Epitaxial growth and characterization of MnAs on InP and $In_{0.53}Ga_{0.47}As$

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Abstract

The heteroepitaxial growth of type-B ferromagnetic MnAs on InP and lattice matched $In_{0.53}Ga_{0.47}As$ has been investigated for the first time. *In situ* reflection high energy electron diffraction during molecular beam epitaxy and atomic force microscopy are used to study the reconstruction and morphology, respectively, of the MnAs surface. The in-plane magnetic properties of the film are studied by magneto-optic Kerr effect measurements. The Curie temperature is estimated to be 315 K. The coercivity of 35 nm films measured at room temperature and 10 K are 860 Oe and 1410 Oe, respectively. The measured in-plane magnetocrystalline anisotropy constants K_{u1} and K_{u2} for the film are 2.747×10^6 and $7.086 \times 10^6\,\mathrm{erg\,cm^{-3}}$, respectively. The magnetization and hysteresis in the out-of-plane direction are characterized by a saturation magnetic field of 1.2 T and coercivity of 1600 Oe at 10 K.

(Some figures in this article are in colour only in the electronic version)

Epitaxial growth of ferromagnetic spin injectors on semiconductor substrates is key to the design and realization of spin based logic devices and large scale circuits [1, 2], which promise low power operation. The growth of MnAs as a ferromagnetic spin injector by heteroepitaxy on (0 0 1)GaAs substrates has been studied extensively [3, 4] and several spin based electronic and optoelectronic devices [5, 6] have been recently realized based on this technology. The optimization of growth conditions for single crystal growth of NiAs type hexagonal MnAs and Schottky tunnel barriers to ensure efficient spin injection in GaAs based semiconductor materials has provided numerous avenues for spintronic device research [7].

While such progress has been made in the study of GaAs based spin devices, spin injectors on InP and related ternary and quaternary lattice matched alloys have received less attention [8–10]. InP-based semiconductors are the materials of choice for optoelectronic devices for optical communication and high-frequency and low noise microwave devices. The ability to grow thin film ferromagnetic contacts on these materials will lead to the possibility of integrating spin based devices with electronic and optoelectronic devices on a InP platform. In this paper, we show for the first time that thin films of ferromagnetic NiAs type hexagonal MnAs which have their easy axis of magnetization parallel to $[\bar{1}\,1\,0]$ (type-B) can be grown reproducibly on (0 0 1)InP and on $In_{0.53}Ga_{0.47}As$ lattice matched to InP. The surface reconstruction of MnAs during molecular beam epitaxy (MBE) was observed by reflection high energy electron diffraction (RHEED), the surface morphology was characterized by atomic force microscopy (AFM) and the ferromagnetic properties of the films were characterized by the magneto-optic Kerr effect (MOKE) and superconductor quantum interference device (SQUID) measurements.

Epitaxial layers of MnAs were grown directly on Sn-doped InP(0 0 1) substrates and on Si-doped $In_{0.53}Ga_{0.47}As$ lattice matched to InP using solid source MBE. The lattice mismatch between the *a* axis of MnAs and InP is 36.5%. For growth on InP, the substrate temperature was first raised to 535 °C with an arsenic (As_4) beam equivalent pressure (BEP)

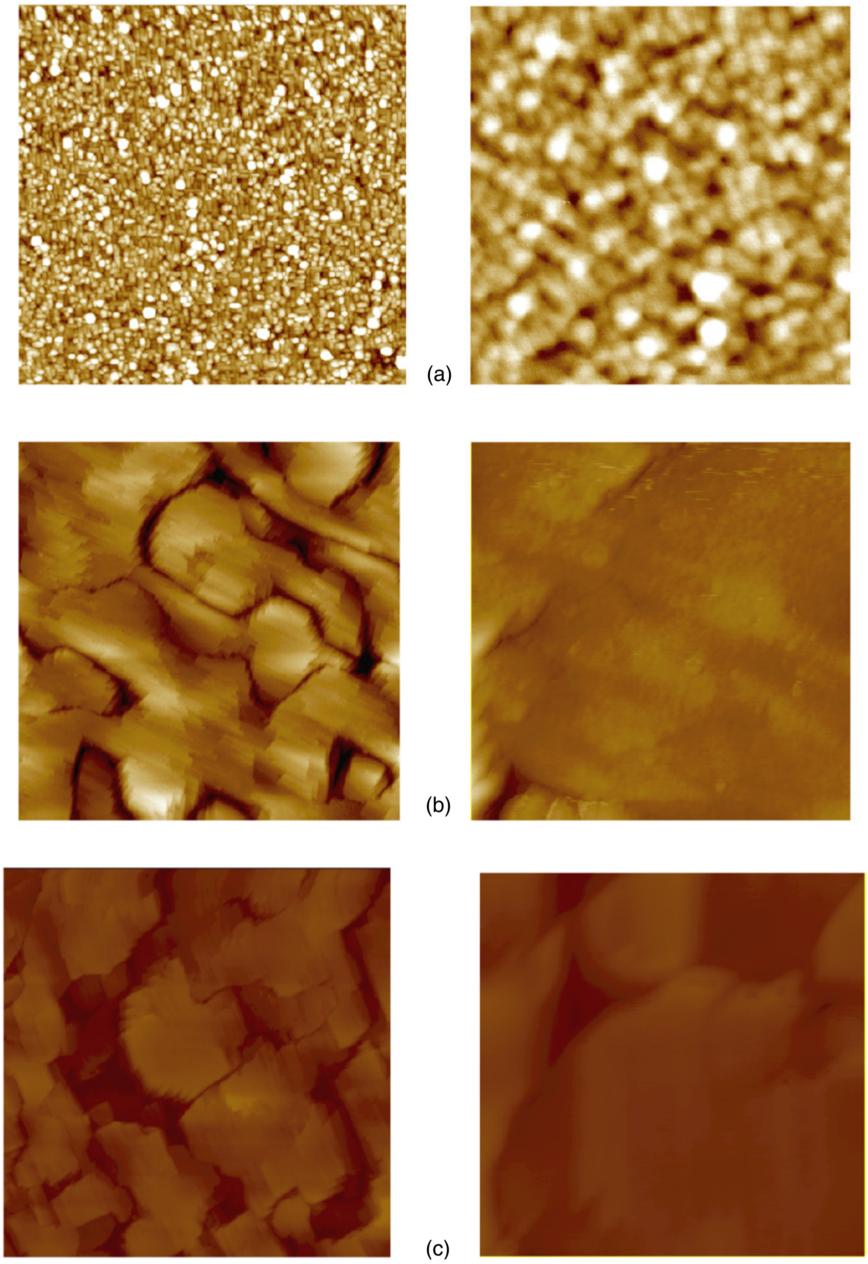

Figure 1. Roughness and surface morphology of MnAs film (2.5 μm × 2.5 μm) (left) and (500 nm × 500 nm) (right): (*a*) after 5 nm of growth on (0 0 1)InP; (*b*) after annealing a 35 nm film on (0 0 1)InP; (*c*) after annealing a 35 nm film on InGaAs lattice matched to (0 0 1)InP.

of 6.6×10^{-6} Torr to remove surface oxides. The temperature was then reduced to 200 °C. A few monolayers of MnAs were grown in the nucleation phase with a As/Mn BEP ratio of 90. The substrate temperature was then raised to 250 °C and the As/Mn flux ratio was reduced to 50 to ensure a higher growth rate. Conditions for the growth of MnAs on $In_{0.53}Ga_{0.47}As$ were identical. Finally, a post growth anneal was done at 360 °C for 2 min under an arsenic BEP of 7×10^{-6} Torr in both cases, to improve the surface morphology. *In situ* RHEED patterns were observed during epitaxy of the MnAs films. A (1 × 1) surface reconstruction was observed in the case of growth on (0 0 1)InP which abruptly changed to a (4 × 1) reconstruction, upon annealing under conditions mentioned above. The change in reconstruction was not reversible on lowering the anneal temperature. In contrast, the RHEED patterns in the case of MnAs grown on $In_{0.53}Ga_{0.47}As$ show a (1 × 1) reconstruction, with no observable change after annealing. The surface reconstruction of InP consists of mixed InP dimers while $In_{0.53}Ga_{0.47}As$ consists of dimers and missing dimers along the symmetry directions, resulting in a very different template for growth initiation. Hence there is a significant difference in the surface phase diagram of MnAs [11] grown on these different materials under the same conditions of growth. The surface morphology of these as-grown and annealed MnAs layers were then investigated by AFM. The results are depicted in figure 1 for 2.5 μm × 2.5 μm (left) and 500 nm × 500 nm (right) surface areas. The images from a 5 nm thick as-grown layer of MnAs on (0 0 1) InP (figure 1(*a*)) indicate that growth is in the form of 3D islands (Volmer–Weber or Stranski–Krastanov growth modes). As the layer thickness increases these islands coalesce. The root mean square (rms) value of the surface roughness of a 35 nm MnAs epitaxial layer on InP was found to be 19 Å over a lateral distance of 2.5 μm. The surface morphology of this layer improved considerably after annealing, as shown in figure 1(*b*). The small and separated islands coalesce and form larger ones with an rms value of surface roughness of 7 Å over a lateral distance of 0.5 μm. This occurs in spite of the fact that the annealing step creates a layer with a (4×1) reconstruction. The surface roughness increases with increasing layer thickness and is 31 Å for a 200 nm film grown on (0 0 1)InP. AFM measurements were also done on as-grown and annealed MnAs layers on $\mathrm{In_{0.53}Ga_{0.47}As}$ lattice matched to InP and the rms value of the surface roughness was found to be 22 Å for a 35 nm thick layer (figure 1(*c*)). The surface morphology of the film was not much different from that of MnAs grown on InP.

The in-plane magnetic properties of 35 nm MnAs epitaxial layers grown on InP and lattice matched $\mathrm{In_{0.53}Ga_{0.47}As}$ were studied by longitudinal MOKE measurements. Results indicate that in both cases the $[\bar{1}\,\bar{1}\,2\,0]$ MnAs orientation, which is the easy axis of magnetization, is parallel to $[\bar{1}\,1\,0]$ InP. This direction of magnetization is the same as in type-B MnAs [12]. The Kerr rotation θ_k is 6.2 mdeg (millidegrees) at 10 K (figure 2(*a*)) but decreases to 2 mdeg at 290 K. The lack of squareness of the Kerr rotation versus applied magnetic field curves at the point where the direction of magnetization switches can be attributed to the coexistence of two planes, $(\bar{1}\,1\,0\,2)$ and $(\bar{1}\,1\,0\,1)$, for epitaxially grown type-B MnAs [12]. The coercivity (H_C) of the film decreases with temperature as shown in figure 2(*b*). The change in the value of H_C over the temperature range 10–300 K is 39%. Magnetic hysteresis is not observed in the InP[1 1 0] direction, which indicates that the MnAs layer has in-plane uniaxial magnetic anisotropy. The inset to figure 2(*b*) shows the temperature dependence of the differential Kerr rotation, $\Delta\theta_\mathrm{k}$. Here $\Delta\theta_\mathrm{k} = \theta_\mathrm{k,max} - \theta_\mathrm{k,min}$ and $\theta_\mathrm{k,max}$ and $\theta_\mathrm{k,min}$ are respectively, the maximum and minimum Kerr rotation angles measured at a particular temperature. The Curie temperature of the MnAs layer, estimated from the Kerr rotation data and the Curie–Wiess law, is 315 K which is comparable to that measured for films grown on (0 0 1)GaAs [13]. The Kerr rotation characteristics and Curie temperature of MnAs grown on lattice matched $\mathrm{In_{0.53}Ga_{0.47}As}$ were identical to the ones grown on (0 0 1)InP.

At equilibrium, in the presence of an external magnetic field H, the orientation of film magnetization M, is such that the sum of external field energy, demagnetizing energy and anisotropy energy is minimized. The uniaxial magnetocrystalline anisotropy constants K_u1 and K_u2 [14, 15] associated with the anisotropy energy are calculated from this energy minimization criteria for different orientations of M. Figure 3(*a*) shows the variation of the Kerr magneto-optic signal with increasing H applied along the in-plane hard axis of magnetization for a 35 nm MnAs film on (0 0 1)InP. Here the normalized Kerr rotation $\theta_\mathrm{k}/\theta_\mathrm{k,max}$ is a direct measure of the orientation of M. The values of K_u1 and K_u2 calculated at room temperature are 2.747×10^6 erg cm^{-3} and 7.086×10^6 erg cm^{-3}, respectively. Similar values were also obtained for MnAs on lattice matched $\mathrm{In_{0.53}Ga_{0.47}As}$. It is seen that the anisotropy constants are lower than that for bulk MnAs [16]. The magneto crystalline anisotropy arises due to spin orbit coupling with contributions from the heterointerface and the crystalline structure of the thin film. The presence of dangling bonds and stress at the semiconductor–ferromagnet interface results in reduced orbital symmetries which may contribute to the lower values of the anisotropy constants [17] compared with bulk. Figure 3(*b*) shows the out-of-plane magnetization characteristics for a 35 nm MnAs film grown on InP, measured using a SQUID magnetometer and recorded at 10 K. The saturation magnetic field (M_S) was measured to be at 1.2 T. The inset to figure 3(*b*) shows that the sample has a small remanence ($0.11 \times M_\mathrm{S}$) with a coercivity of 1600 Oe. Similar out-of-plane remanence was also observed for epitaxially grown MnAs films on $\mathrm{In_{0.53}Ga_{0.47}As}$ and GaAs [18].

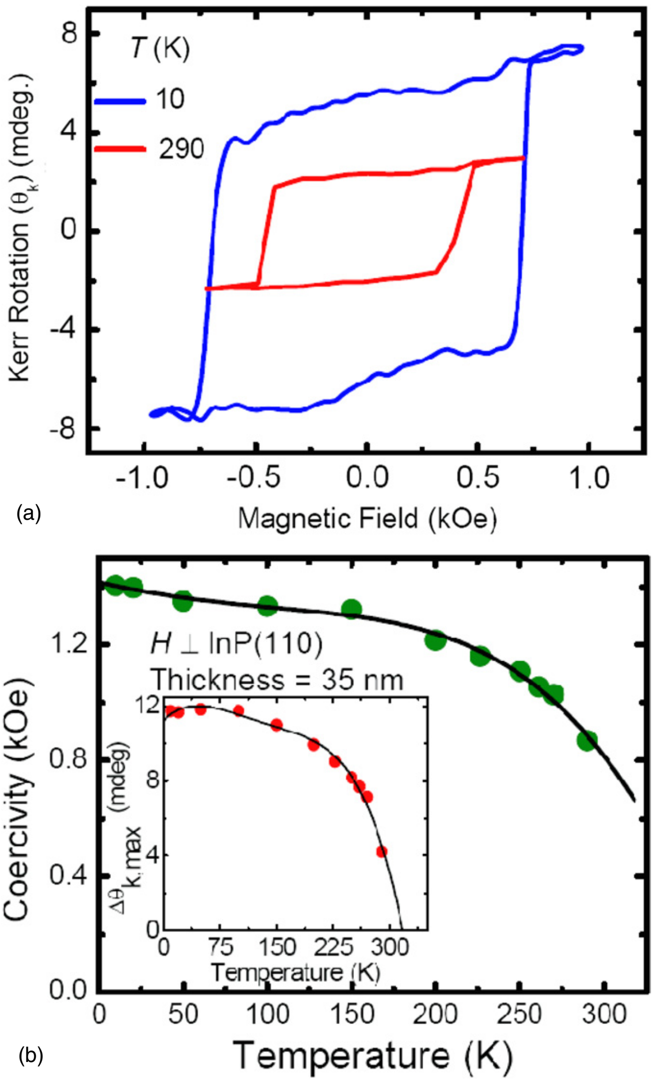

Figure 2. (*a*) Kerr rotation of epitaxially grown and annealed type-B MnAs on InP(0 0 1) measured at 10 and 290 K with applied magnetic field in the $[\bar{1}\,1\,0]$ direction; (*b*) coercivity measured at different temperatures for 35 nm epitaxially grown layer. Inset shows the variation in $\Delta\theta_\mathrm{K}$ as a function of temperature. The solid lines are drawn as a guide for the eye.

In summary, type-B MnAs epitaxial layers have been grown on (0 0 1)InP substrate and on lattice matched

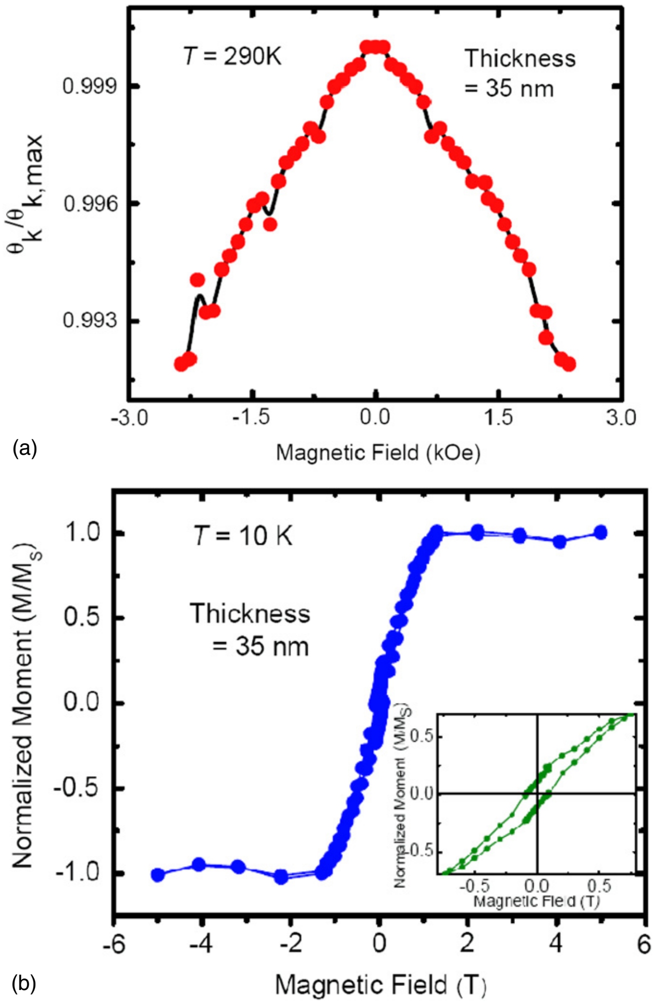

Figure 3. (*a*) Normalized values of the longitudinal Kerr magneto-optic effect versus in-plane applied field H for the MnAs sample at room temperature; (*b*) magnetic hysteresis measured for a 35 nm MnAs/InP(0 0 1) layer recorded at 10 K in the out-of-plane direction using a SQUID magnetometer. Inset shows variation of the normalized moment at low applied fields, indicating small remanence and coercivity.

$In_{0.53}Ga_{0.47}As$/InP. The RHEED surface reconstructions were distinctly different even under the same growth conditions, indicating that the surface phase diagrams for these heterostructure systems are different. The peak Kerr rotation measured for the type-B MnAs film decreases with increasing temperature and provides an estimate of the Curie temperature (315 K) along the in-plane easy axis. The coercivity of the film was found to decrease by 39% over the temperature range 10–290 K. The magnetocrystalline anisotropy constants in the MnAs layer determined from MOKE measurements were found to be lower than those in bulk MnAs or epitaxially grown type-A MnAs layers on GaAs. The out-of-plane saturation magnetization measured by a SQUID magnetometer at 10 K was found to be at 1.2 T with a coercivity of 1600 Oe for a 35 nm MnAs layer. These results indicate that type-B MnAs epitaxial layers can be used as ferromagnetic spin injectors for InP and InP-based semiconductor.

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