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Distribution of Mn in ferromagnetic (In,Mn)Sb films grown on (0 0 1) GaAs using MBE

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ABSTRACT

We characterize structural and magnetic properties of the dilute magnetic semiconductor (In,Mn)Sb grown on GaAs (0 0 1) by molecular beam epitaxy. The films have surface features consisting of dense orthogonally oriented strain-driven hillocks. In addition, triangularly shaped hillocks, presumed to be MnSb clusters, are observed with diameters in the range of 200 nm. The density and size of these triangular hillocks depend strongly on the Mn content. X-ray scattering shows that the presence of Mn in the InSb films decreases the average lattice constant as well as the degree of relaxation of the (In,Mn)Sb films. The distribution of Mn is also investigated by cross-sectional transmission electron microscopy. Two regions are observed: a (In,Mn)Sb film with small defect density and MnSb clusters on the surface. Magnetization measurements indicate that both the (In,Mn)Sb alloy as well as the MnSb inclusions are ferromagnetic.

1. Introduction

Diluted magnetic semiconductors (DMS) are characterized by the random substitution of a fraction of original atoms by magnetic atoms. Therefore, magnetic properties with semiconducting properties are combined. The III–V DMS have been extensively studied, particularly those alloys with the smallest lattice constants and largest energy gaps such as (Ga,Mn)As and (Ga,Mn)N, respectively, which are expected to possess the highest Curie temperatures T_c. It is also very important to explore the opposite extreme of the family, (In,Mn)Sb, because it opens opportunities for applications in spin-photonics in the far infrared and, due to its high carrier mobility, in devices based on spin-dependent transport. However, there is still not much studied about bulk (In,Mn)Sb DMS crystals [1,2]. Recently, Ganesan and Bhat [3] reported studies on bulk Mn-doped InSb materials grown by the horizontal Bridgman technique. They found that one ferromagnetic phase below 10 K arises from the (In,Mn)Sb alloy, while other ferromagnetic phase results from MnSb clusters in the crystals. In this paper, we describe the distribution of Mn atoms in (In,Mn)Sb films grown on GaAs (0 0 1) by molecular beam epitaxy (MBE). Our results also show the presence of two magnetic phases in the system, due to the (In,Mn)Sb alloy and clusters of MnSb. The presence of such ferromagnetic clusters in these hybrid systems may be important for semiconductor-based spin-photonics applications and devices with a higher Curie temperature.

2. Experimental procedure

The (In,Mn)Sb films were grown on semi-insulating epi-ready (0 0 1) GaAs substrates using a Riber Compact 21T MBE system equipped with reflection high energy electron diffraction (RHEED). A VEECO valved cracker cell was used as the Sb source. Before initiating the Mn flux, 0.4 μm thick InSb buffer layer was grown at a manipulator temperature of 350 °C at a growth rate of 2 Å/s and Sb/In flux ratio of about 5. Based on an absolute temperature calibration that was done for significantly higher temperatures, we estimate the actual surface temperature to be about 310 °C. This temperature was earlier determined to be optimum in our MBE system for InSb/GaAs growth [11]. A (2×4) reconstruction of the RHEED pattern was observed during the growth of the InSb. The (In,Mn)Sb layer was deposited under the same conditions as those of the InSb layer, generally with a thickness of 0.4 μm. Samples were used in this study with various Mn concentrations corresponding to different temperatures of the Mn effusion cell. The Mn concentrations were estimated from the Mn/In flux ratio and confirmed by using a dynamical simulation of rocking curve analysis to be about 0.7%, 0.4%, and 0.2% for the samples grown with Mn effusion cell temperatures of $T_{\rm Mn}$=670, 600, and 560 °C, respectively. The structural properties were characterized by transmission electron microscopy (TEM), atomic force microscopy (AFM), and X-ray diffraction. The Hall measurements were carried

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out on photo-lithographically patterned Hall bars with a width of 2 mm and a length of 8 mm using a 7 T superconducting magnet with a variable temperature insert in the range 1.5300 K and a He cryostat. Magnetization measurements were performed using a commercial superconducting quantum interference device (SQUID) in the temperature range 2–400 K and a 7 T superconducting magnet control system.

3. Results and discussion

Both θ–2θ symmetric (0 0 4) and asymmetric (1 1 5) reflection rocking curves were used together with simulated curves to estimate the average Mn content in the samples. The samples are p-type with mobilities and carrier concentrations at 300 K of 192 cm^2/V s with 7.4e19 cm^{-3}, 255 cm^2/V s with 1.8e19 cm^{-3}, and 340 cm^2/V s with 5.4e18 cm^{-3} for the samples with 0.7% Mn, 0.4% Mn, and 0.2% Mn, respectively. At 77 K, the corresponding mobilities increase to be 275, 431, and 455 cm^2/V s; at 15 K, the corresponding carrier concentrations decrease to 4e19, 1.2e19, and 4.6e18 cm^{-3}.

The AFM topographs of the four films, which are 5 μm by 5 μm scans, are shown in Fig. 1. The samples have well-interconnected surface features with average height of 30 nm; these features are basically independent of Mn content, as seen in Fig. 1, and are apparently due to the metamorphic growth of InSb on GaAs [4]. According to our RHEED data and preliminary TEM results, the features appear only on the surface. In addition, the AFM images reveal small triangular hillocks (as indicated with arrows) with base dimensions in the range of about 200 nm and average height of 120 nm. As the Mn content decreases, the density and size of these triangular hillocks decrease. In the sample with Mn content of 0.7%, the areal density of the triangular hillocks is found to be 4/μm^2, decreasing to 1/μm^2 in the sample with 0.2% Mn. One can note that the triangular hillocks are observed only in the samples with Mn; in the bulk InSb sample, no triangular hillocks are found. The presence of Mn in InSb can result in MnSb clusters [3–6] and we believe that the triangular hillocks are, in fact, such clusters representing a second magnetic phase in the samples.

The θ–2θ rocking curves obtained using high resolution X-ray diffractions (XRD) for both symmetric (0 0 4) and asymmetric (1 1 5) reflections show that the presence of Mn decreases the lattice constant as well as the degree of relaxation of (In,Mn)Sb films. The values of perpendicular lattice constant $a_\perp$, in-plane lattice constant $a_{||}$, relaxed lattice constant a_{relax}, and the degree of strain m for three samples determined from the XRD data are

Table 1
Results for the perpendicular lattice constant $a_\perp$, the in-plane lattice constant $a_{||}$, the relaxed lattice constant arelax a_{relax}, and the degree of strain m of samples with different Mn contents.

Sample (%Mn)	$a_\perp$ (Å)	$a_{||}$ (Å)	a_{relax} (Å)	m
0.7	6.48978	6.46778	6.47348	0.14509
0.4	6.49580	6.46834	6.47546	0.14544
0.2	6.50002	6.47054	6.47818	0.14592
0.0	6.50162	6.47262	6.48014	0.14627

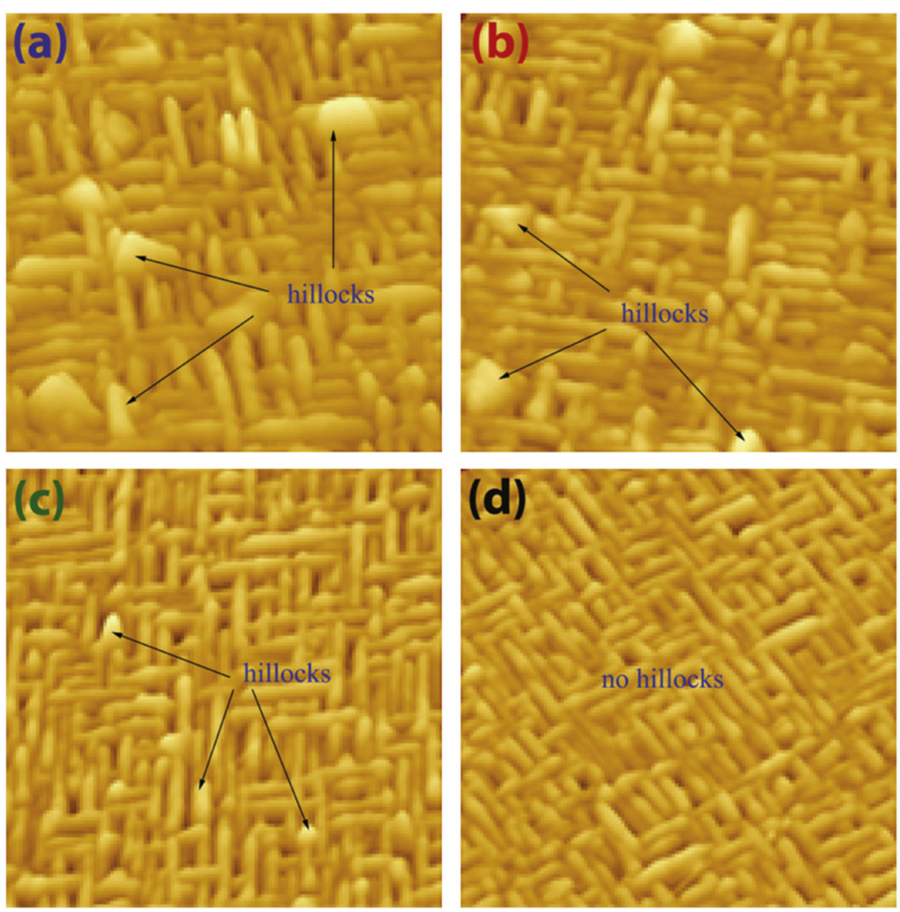

Fig. 1. 5 μm by 5 μm AFM scans of the (In,Mn)Sb films with different Mn contents: (a) 0.7%, (b) 0.4%, (c) 0.2%, and (d) 0.0%.