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Magnetotransport Properties of MnAs Film on GaAs(001) Substrate

Asawin Sinsarp*, Takashi Manago, and Hiroyuki Akinaga

Research Consortium for Synthetic Nano-Function Materials Project (SYNAF), Nanotechnology Research Institute (NRI), National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

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The magnetotransport properties at room temperature of the 250-nm-thick MnAs(-1100) film grown on GaAs(001) substrate by molecular beam epitaxy was investigated. The results measured with various magnetic field directions were reported. They show the negative magnetoresistive effect for all field directions. The difference in the magnetoresistance curves for different field directions is in agreement with the magnetic anisotropy of the film.

Key words : manganese arsenide, MnAs, gallium arsenide, GaAs, molecular beam epitaxy, MBE, magnetotransport, magnetoresistance

1. Introduction

Recently the hybrid ferromagnetic-metal/semiconductor heterostructures have been expected as effective structures for application in spintronics [1]. Among many materials, MnAs films on GaAs substrates are of active interest since they can be grown epitaxially by a conventional molecular beam epitaxy (MBE) system and have ferromagnetic properties at room temperature [2].

The physical properties of the epitaxial layers differ significantly from those of bulk samples. For instance, the MnAs films grown on the GaAs(001) substrate exhibit strain-stabilized co-existing phases of hexagonal ferromagnetic α-MnAs and orthorhombic paramagnetic β-MnAs at room temperature [3]. For the MnAs(-1100)/GaAs(001) films, the periodic α-MaAs/β-MnAs stripes are formed along the MnAs[0001]//GaAs[-110] direction [4]. The width and periodicity of the strips depend on the film thickness [5]. The magnetic easy axis is parallel to the MnAs[-1-120]//GaAs[110] direction [2]. Combination of this structures and magnetic anisotropy causes various magnetic domain structures [5]. Especially in the MnAs film with the thickness of around 250 nm, characteristic domain structure called 'ladder type structure' appears and it includes a lot of domain walls along MnAs[-1-120]. Therefore it is expected that the magnetotransport properties reflect the domain structures and the magnetoresistance strongly depends on the magnetization directions.

In this paper we report the magnetotransport properties measured at room temperature of the MnAs(-1100) film on GaAs(001) substrate grown by molecular beam epitaxy. The current flowed parallel to the direction of in-plane magnetic easy axis, MnAs[-1-120]//GaAs[110]. The anisotropic magnetoresistance under various magnetic field directions is discussed.

2. Experimentals

The MnAs film in this study was grown with the thickness of 250 nm by molecular beam epitaxy (MBE) on a non-doped GaAs(001) substrate. After thermal oxide removal under As exposure, a buffer layer was grown to prepare a flat surface. Decreasing the substrate temperature, the GaAs(001) surface exhibits the c(4×4) structure. The MnAs film was grown at As_4/Mn flux ratio of about 100 with the substrate temperature of 210°C. The growth direction is MnAs[-1100] and the epitaxial relationships between the MnAs film and the GaAs substrate are MnAs[0001]//GaAs[-110] and MnAs[-1-120]//GaAs[110] [2]. The fabrication details have been described in our previous report [5].

The magnetization properties were measured by a superconducting quantum interference device (SQUID). For the magnetotransport property measurement, the sample

*Corresponding author: Tel: +81-29-861-5080 (ext. 55535), Fax: +82-29-861-3211, e-mail: asawin.sinsarp@aist.go.jp

was patterned into Hall bars using conventional photolithography and Ar-ion-milling dry-etching. The Hall bars were patterned such that the direction of the current is parallel to the in-plane magnetic easy axis, the MnAs[-1-120]//GaAs[110] direction. Electrical contacts were made using gold wire leads. The in-plane magnetoresistances were measured in various directions of a magnetic field.

3. Results and Discussions

Figure 1 shows the magnetization curves of the MnAs film measured by the SQUID. Different magnetic properties are observed in three magnetic field directions: MnAs[-1-120]//GaAs[110], MnAs[0001]//GaAs[-110] and MnAs[-1100] normal to the plane. The film has the uniaxial magnetic anisotropy with the magnetic easy axis in the direction of MnAs[-1-120]. The magnetic reversal occurs within the magnetic field of 5 mT in the direction and shows good squareness. On the other hand, along MnAs[0001] direction which is the magnetic hard axis, the magnetization increases linearly with the magnetic field and finally saturates at about 2 T. The magnetization curve along the direction normal to the plane is between them, which is easier than that along the in-plane hard axis. The saturation field is around 0.8 T. It indicates that the film also has the weak perpendicular magnetic anisotropy.

The in-plane magnetoresistances (MR) of the film are shown in Figure 2 for various magnetic field (***H***) directions: (a) ***H***//MnAs[0001]//GaAs[-110] (hard axis), (b) ***H***//MnAs[-1100] (normal to the plane) and (c) ***H***// MnAs[-1-120]//GaAs[110] (easy axis). The values are expressed in MR ratio defined as ratio of the difference in resistance (R) under the magnetic field from the zero-field resistance (R_0) and the R_0, MR ratio = $(R-R_0)/R_0$. For all magnetic field directions, the results show negative magnetoresistive effect. The electrical resistances decrease in the present of the magnetic field, as expected for the case of ferromagnetic materials [6].

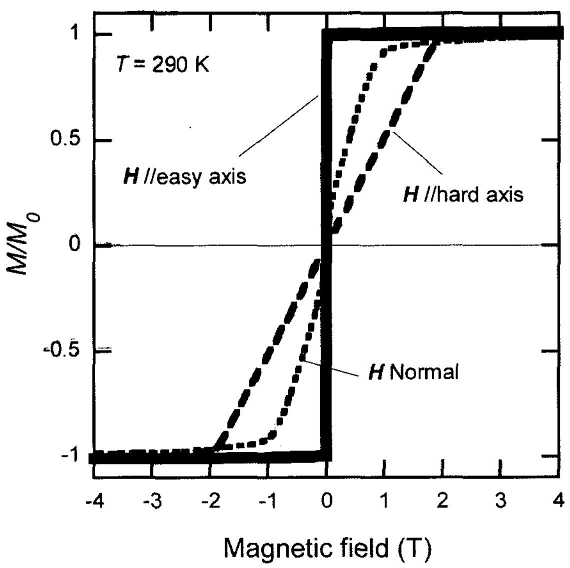

Fig. 1. The magnetization curves of the 250-nm-thick MnAs film at 290 K. The applied magnetic filed directions are along MnAs[0001]//GaAs[-110] (in-plane magnetic hard axis), MnAs[-1100] (normal to the plane) and MnAs[-1-120]// GaAs[110] (in-plane magnetic easy axis).

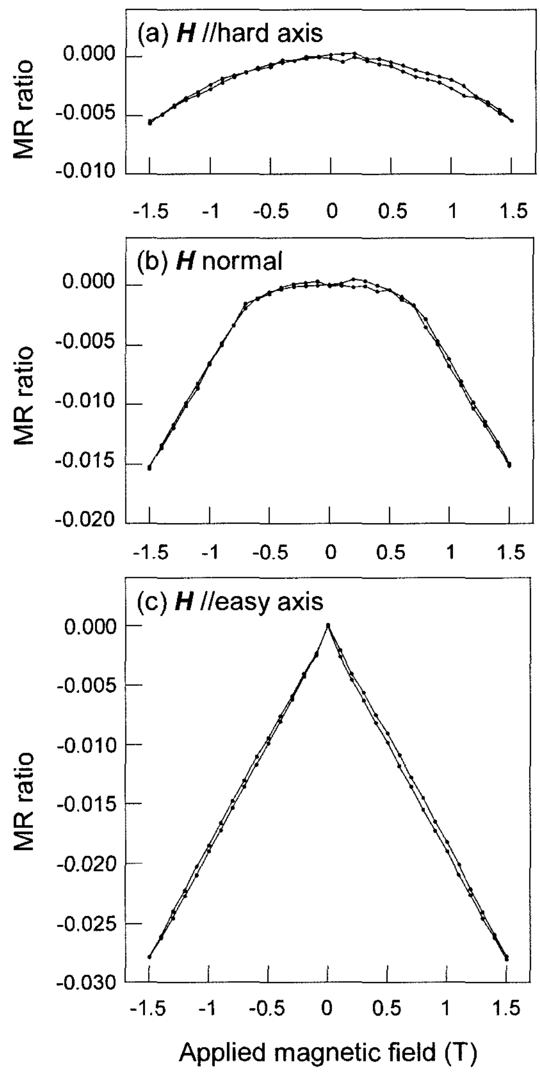

Fig. 2. The relationships between magnetoresistance ratio and the strength of magnetic field of the 250-nm-thick MnAs film at room temperature (290 K) for the current along MnAs[-1-120]//GaAs[110] (in-plane magnetic easy axis). The applied magnetic filed directions are along (a) MnAs[0001]//GaAs[-110] (in-plane magnetic hard axis), (b) MnAs[-1100] (normal to the plane) and (c) MnAs[-1-120]//GaAs[110] (in-plane magnetic easy axis).

It is clear for the case of the magnetic field normal to the plane, Figure 2(b), that the relation between the resistance and the magnetic field is divided into two regions: non-linear relation around the zero-field and linear relation at the higher field. These two regions are in agreement with the magnetization curves shown in Figure 1. The non-linear region of the MR is corresponding to the region where the magnetization is linearly increasing, whereas the linear region is corresponding to the region of the saturated magnetization. This characteristic is also consistent with the other two cases with different magnetic field directions. In the case of ***H*** // MnAs[0001]// GaAs[-110] (hard axis) shown in Figure 2(a), the saturation field deduced from Figure 1 is about 2 T, which is far beyond the limitation of our MR measurement apparatus. The abrupt change in the magnetization for the case of ***H***//MnAs[-1-120]//GaAs[110] (easy axis) results in only the linear relation region of the MR in Figure 2(c).

The non-linear region is generally attributed to an orientation effect which depends on the direction on the magnetization and the conduction electron scattering from the domain walls. The linear part of the curve in the region of the saturated magnetization has its origin related to the scattering of the conduction *s* electrons into the magnetic *d* band (*s*-*d* scattering) [7]. It is noted that the slopes of the linear relation are same, ~ −0.02/T, for both the cases of the magnetic fields normal to the plane (Figure 2(b)) and parallel to the easy axis (Figure 2(c)). It indicates that the origins of the linear decreases are same as expected in the forced effect. This MR variation is quite larger than that of conventional ferromagnetic metals. For example, it is −0.001/T for Ni at room temperature [6]. The Curie temperature of Ni is 627 K, whereas that of MnAs is 318 K [8], which is close to room temperature. Since the forced effect depends on temperature and takes a maximum value at the Curie temperature, the large MR variation of MnAs was observed.

4. Conclusions

We have studied the magnetotransport properties at room temperature of the MnAs(-1100) film grown on GaAs(001) substrate by molecular beam epitaxy. The thickness of the film in this study was 250 nm. The magnetoresistance effect with the current parallel to the magnetic easy axis has been studied for three directions of magnetic filed – parallel to the in-plane magnetic easy axis, parallel to the in-plane hard axis and normal to the plane. For all field directions, the resistances reduce as increasing the magnetic field strength. The magnetoresitance curve is divided into two regions – non-linear region corresponding to the region with magnetization increasing and linear region corresponding to the region with the magnetization is saturated.

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