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Temperature-induced transition of magnetic anisotropy between in-plane and out-of-plane directions in GaMnAs film

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ABSTRACT

We used the Hall effect and magnetization measurements to investigate the temperature dependence of the magnetic anisotropy of a ferromagnetic semiconductor GaMnAs film grown on a (001) GaAs substrate. The Hall effect was systematically measured by applying an external magnetic field within and normal to the film plane. The switching behavior of the magnetization during the reversal process revealed the coexistence of in-plane and out-of-plane magnetic anisotropies in the film. However, these two types of magnetic anisotropies strongly depended on the temperature. Specifically, the out-of-plane anisotropy was dominant in the low-temperature region (i.e., 3–10 K), whereas the in-plane anisotropy became dominant in the temperature region higher than 15 K. This temperature dependent change in the magnetic anisotropy was further confirmed using direct magnetization measurements.

1. Introduction

The magnetic anisotropic properties of GaMnAs ferromagnetic films have received much attention because of their potential applications in practical spin memory devices [1]. It is known from earlier studies that the magnetic anisotropy of a GaMnAs film depends on many material parameters, including the strain, alloy composition, and carrier concentration [2–6]. In particular, the magnetic anisotropy (either in-plane or out-of-plane) of a GaMnAs film strongly depends on the strain within the film [7–9]. For example, although the in-plane magnetic anisotropy is dominant in a GaMnAs film under a compressive strain, the out-of-plane anisotropy is dominant when it is under a tensile strain.

Because of the easy growth of a GaMnAs film on a GaAs substrate, in which the film is under a compressive strain, the in-plane magnetic anisotropy has primarily been investigated. Numerous experimental studies have revealed the complex nature of the magnetic anisotropies of a GaMnAs film within the film plane. For example, cubic anisotropy in the ⟨100⟩ directions, uniaxial anisotropy in the ⟨110 ⟩ directions, and another uniaxial anisotropy in the [100] direction have been detected in a GaMnAs film [10–16]. These anisotropies show dependence not only on the material parameters, as previously mentioned, but also on the temperature [17,18]. Many investigations have shown that the dominant magnetic anisotropy changes from cubic to uniaxial with increasing temperature [10,19].

Although the investigations of the magnetic anisotropy within the (100) plane have been intense, not much attention has been given to the out-of-plane magnetic anisotropy of a GaMnAs film. Furthermore, the temperature-induced transition of the magnetic anisotropy between the in-plane and out-of-plane directions has never been reported for a GaMnAs film. In this study, we investigated the temperature dependent change in the magnetic anisotropy between the in-plane and out-of-plane directions in a GaMnAs film. For this purpose, we adopted direct magnetization measurements and Hall effect measurements, which are very sensitive to the direction of the magnetization in a magnetic film and thus provided a straightforward method for obtaining information about the magnetic anisotropy of the GaMnAs film.

2. Experiments

A ferromagnetic GaMnAs film was grown on a (001) GaAs substrate using a low substrate temperature of 250 °C in a RIBER R&D 32 molecular beam epitaxy system equipped with Ga, As, and Mn as elemental sources. A 10-nm GaAs layer was first grown on the substrate at a low temperature, followed by the deposition of a 75-nm $Ga_{1-x}Mn_xAs$ film (with $x=0.02$). The growth of the

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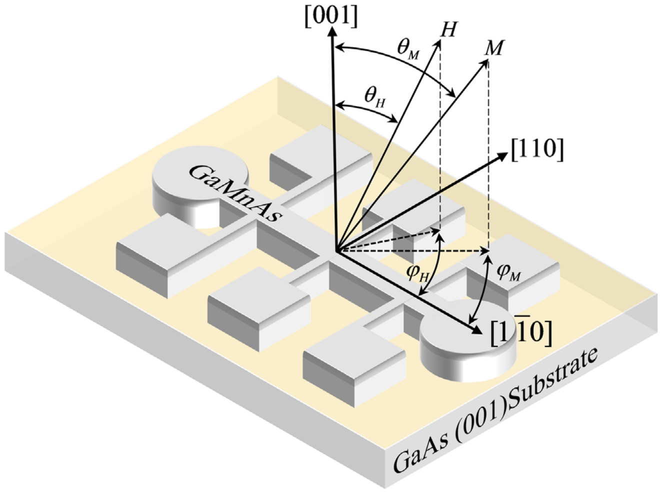

Fig. 1. Schematic diagram of Hall device patterned on GaMnAs film. The directions of the external field and magnetization are shown with arrows. The measurement schemes for the angles defining the field and magnetization directions are also shown, together with crystallographic directions.

GaMnAs film was monitored using reflection high-energy electron diffraction (RHEED). The RHEED pattern was streaky throughout the film deposition, indicating smooth two-dimensional growth. A 5×5 mm^2 square piece was then cleaved from the wafer for the fabrication of the Hall device. A 300×1500 μm^2 rectangular Hall device with a long dimension in the $[1\bar{1}0]$ direction was finally patterned on the cleaved piece using photolithography and chemical wet etching.

Transport measurements were performed using a direct current of 20 μA along the $[1\bar{1}0]$ direction, which was used as a sensing current for detecting the Hall resistance. The Curie temperature T_C of the film was estimated from the magnetization measurements, which showed an increase in magnetization near 25 K. The angular dependence of the Hall effect was measured by mounting the sample on a special holder designed to allow the applied magnetic field to be rotated within and out of the film plane. In discussing the configuration of the experiment, we use the θ_H and φ_H angles to define the direction of the external field, and θ_M and φ_M to indicate the direction of the magnetization in the film, as shown in Fig. 1. The φ_H and θ_M angles were measured from the [001] direction (i.e., the normal to the film plane); θ_H and φ_M were measured counterclockwise from the $[1\bar{1}0]$ direction in the (001) plane.

3. Results and discussion

The Hall effect measurement is known to be especially useful for studying the magnetic anisotropic properties of ferromagnetic materials because of its sensitive dependence on the direction of the magnetization, as given by the following [20]:

$$R_H = \frac{R_0}{t} H \cos\theta_H + \frac{R_S}{t} M \cos\theta_M + \frac{k}{t} M^2 \sin^2\theta_M \sin 2\varphi_M \tag{1}$$

where the first, second, and third terms represent the normal, anomalous, and planar Hall resistances, respectively. In the case of a ferromagnetic material, the normal Hall resistance (NHR) is negligible compared to the anomalous Hall resistance (AHR) and planar Hall resistance (PHR). Therefore, in this work, only the AHR and PHR will be considered in discussing the Hall effect data measured on the ferromagnetic GaMnAs film. In Eq. (1), R_0 and R_S are the normal and anomalous Hall coefficients, respectively, and k is a constant related to the anisotropic magnetoresistance. Finally, M and t are the magnetization and thickness of the film, respectively.

As seen in Eq. (1), the value of the Hall resistance is a function of the direction of magnetization θ_M and φ_M. In the case of a ferromagnetic film with in-plane easy axes, the anomalous Hall effect becomes zero (i.e., $\theta_M = 90°$) when the external field is applied in the film plane, and the changes in the magnetization within the film plane are then reflected only in the planar Hall effect (i.e., in the third term of Eq. (1)). Therefore, planar Hall effect (PHE) measurements can be used to monitor the direction of the magnetization within the film plane during the magnetization reversal and to study the details of the in-plane magnetic anisotropy [21–23]. Specifically, the angular dependence of the PHR can be used to determine the directions of the magnetic easy and hard axes of the film.

We first started the Hall measurements at 3 K to identify the magnetic anisotropic properties of the GaMnAs film. The PHR (i.e., with an in-plane applied field) was measured by rotating the direction of the field while keeping its strength constant. The observed dependences of the PHR on the field angle at field strengths between 250 and 3000 Oe are plotted in Fig. 2. The PHR data obtained with a magnetic field larger than 1000 Oe vary periodically between +75 Ω and −75 Ω, with a rather abrupt transition near $\varphi_H = 0°$, $\varphi_H = 90°$, and $\varphi_H = 180°$. This is a typical angle-dependent behavior of the PHR for a GaMnAs film with in-plane magnetic anisotropy, indicating the presence of two nearly orthogonal magnetic easy axes along the ⟨100⟩ directions and two hard axes along the ⟨110⟩ directions in the film plane.

However, the amplitude of the PHR decreases dramatically as the field strength is reduced to 500 Oe and below. This is due to the presence of areas with strong out-of-plane anisotropy and pinning field distributions even within the in-plane magnetic domains [18,21,24]. When a strong external field is applied along the film plane, total magnetization of the sample will align with the field and follow the direction of the field when it rotates. However, when a small field strength is used, the magnetization in the areas with a vertical easy axis will remain in the vertical direction rather than follow the rotation of the field. Furthermore,

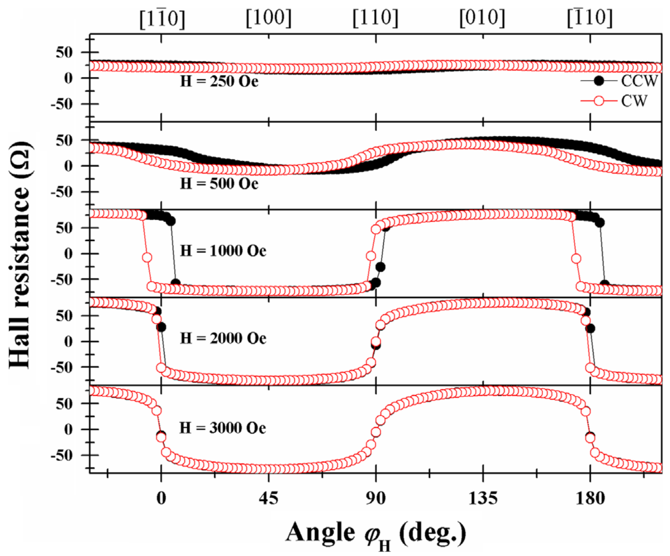

Fig. 2. (Color online) Angular dependence of planar Hall resistance (PHR) obtained for several different magnetic fields. The open (red) and solid (black) circles show data obtained by CW and CCW rotations of the field, respectively. The PHR shows abrupt transitions between the two PHR values near the ⟨110⟩ direction, indicating the presence of in-plane magnetic anisotropy with four-fold symmetry in the GaMnAs film.