Controllable Exchange Bias Effect in (Ga, Mn)As/(Ga, Mn)(As, P) Bilayers With Non-Collinear Magnetic Anisotropy

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We have investigated the exchange bias (EB) effect occurring in (Ga, Mn)As/(Ga, Mn)(As, P) bilayers, in which tJ1e (Ga, Mn)As layer has an in-plane (IP) magnetic anisotropy, and the magnetic anisotropy of the (Ga, Mn)(As, P) layer is out-of-plane (OP). Planar HaU resistance (**PHR**) measured during magnetization reversal in tJiis system showed a clear shift of the hysteresis loops, indicating the p1·esence of EB in the (Ga, Mn)As layer. The EB significantly depends on the direction of the field used in the field-cooling process. The observed EB occurring in a bilayer in which the constituent layers have orthogonal magnetic anisotropies can be understood in terms of the formation of magnetic closure domains in the (Ga, Mn)(As, P) layer during field cooling. We show that such EB can be effectively controlled by the process of field cooling, suggesting the possibility of' memory device applications based on bilayer systems with ortJ1ogonal magnetic anisotropy.

Index Terms-Exchange bias (EB) effect, magnetic anisotropy, planar Hall effect **(PHE).**

1. INTRODUCTION

EXCHANGE bias (EB), i.e., the shift of the hysteresis loop during magnetization reversal depending on the cooling field in a magnetic multilayer structure, is a phenomenon that originates from spin interactions between two magnetic layers **[l]**. A magnetic structure showing EB effect normally involves ferromagnetic (FM) and anti-FM (AFM) layers that are interfaced with each other. The rigid spin configuration of the AFM layer provides the bias field that acts on the FM layer via exchange coupling (EC) at the interface between the two layers. Such EB can be controlled by cooling or annealing the **AFM/FM** system in the presence of external magnetic field along a specific crystalline direction and has been used in various magnetic device applications [2]-[4]. Most investigations involving such EB have so far been carried out on metallic FM/AFM multilayers.

FM semiconductors, such as (Ga, Mn)As and (Ga, Mn)(As, P), have been widely studied because of their promise of magnetic device applications, since their magnetic properties can be easily controlled by changing the alloy composition and/or the carrier concentration in these materials [5]-[8]. A highly promising property of FM semiconductor films in this context is their magnetic anisotropy, which can be either in-plane (IP) or out-of-plane (OP), depending on strain conditions [9], [10]. For example, when these materials are grown on GaAs substrate, the (Ga, Mn)As film has IP magnetic anisotropy due to the compressive strain of the film, while (Ga, **Mn)(As,** P) film has OP magnetic anisotropy due to tensile strain [5], [6], [11]. To date, however, most investigations of FM semiconductors have been done on (Ga, Mn)As films which, as noted, bas IP magnetic anisotropy. Studies of the EB effect have so far also been limited to the (Ga, Mn)As layers with IP magnetic anisotropy by interfacing them with MnO AFM layers [12]-[16].

In this article, we present our study of EB effect in (Ga, Mn)As/(Ga, Mn)(As, P) bilayers grown on a GaAs substrate. Owing to the different strain conditions in the (Ga, Mn)As and (Ga, Mn)(As, P) layers, the system realizes orthogonal magnetic configurations in the two layers, that is, the magnetic easy axes are IP and OP in the (Ga, Mn)As and (Ga, Mn)(As, P) layers, respectively. The investigation of EB in this magnetic system can then provide us with an understanding of interlayer coupling in magnetic bilayers with orthogonal magnetic configurations. In this study, we have used magnetotransport measurements, and especially planar Hall resistance (PHR), which is particularly sensitive to bow the magnetization is oriented, thus providing valuable information on the EB effect in our (Ga, Mn)As/(Ga, Mn)(As, P) bilayer with orthogonal magnetic easy axes. Interestingly, we found that the EB effect in this system can be controlled by changing the direction of the cooling field.

II. EXPERIMENTS

An FM Ga1-xMnxAs(l2 nm)/Ga1-xMnxAs1-yPy(21 nm) bilayer with Mn concentration x :::::: 0.06 and P concentration y :::::: 0.2 was grown by molecular beam epitaxy (MBE) on a (001) GaAs substrate. Schematic of the bilayer is shown in Fig. !(a). The MBE-grown (Ga, Mn)As/(Ga, Mn)(As, P) bilayer was then used to fabricate Hall bars for magnetotransport measurements in the form of a 100 μm x 1500 μm rectangle, with the long dimension (i.e., current channel) along

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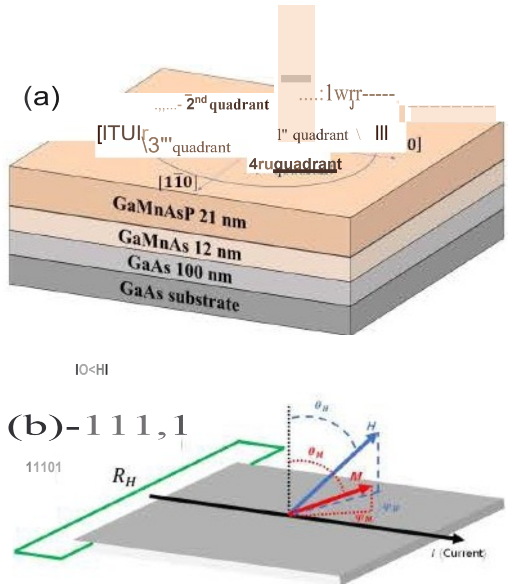

Fig. 1. (a) Schematic of the (Ga, Mn)As/(Ga, Mn)(As, P) bilayer structure. The four quadrants used later in our discussion are marked on the (001) plane of the sample. (b) Hall measurement scheme.

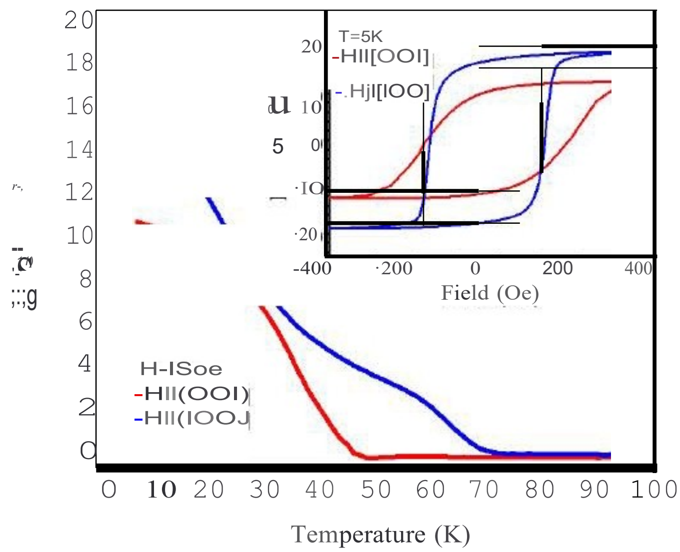

Fig. 2. Magnetization of the (Ga, Mn)As/(Ga, Mn)(As, P) bilayer measured with IP (blue line) and OP (red line) magnetic fields. The values of T_C of the (Ga, Mn)As and (Ga, Mn)(As, P) layers are estimated from these data as 70 and 45 K, respectively. Inset shows hysteresis obtained at 5 K.

the [110] crystallographic direction of GaAs substrate. The Hall device was fabricated by using photolithography and chemical etching in a solution of HCl, HNO_3, and H_2O with a ratio of 1:1:30, for 2 min.

For transport measurements, we placed the sample in a closed cycle cryostat, whose temperature could be varied from 3 to 300 K. The cryostat was located in an electromagnet mounted on a turntable, arranged so as to allow the magnetic field to be applied along arbitrary directions of the sample. The electromagnet allowed us to apply magnetic fields up to 7000 Oe. The Hall resistance (HR) was measured using a current of 100 μA along the current channel. The measurement scheme is shown in Fig. 1(b), where θ stands for the polar angle measured from the [001] direction; and φ is the azimuthal angle measured counterclockwise (CCW) from the [110] direction. The subscripts H and M of θ and φ refer to external magnetic field and magnetization, respectively.

III. RESULTS AND DISCUSSION

We first investigated magnetic properties of our bilayer system by measuring magnetization using a superconducting quantum interference device (SQUID). Fig. 2 shows the temperature dependence of magnetization measured in a weak field of 15 G. The hysteresis obtained at 5 K is shown in the inset. The data plotted with blue and red lines are IP (i.e., along the [100]) and OP (i.e., along the [001]) magnetizations of the bilayer, respectively. Note that the IP magnetization is larger than the OP magnetization. This is unexpected from our (Ga, Mn)As/(Ga, Mn)(As, P) bilayers, because the (Ga, Mn)(As, P) layer, in which the easy axis is OP, is thicker than the (Ga, Mn)As layer whose easy axis is IP. The observation of a larger IP magnetization in the (Ga, Mn)As/(Ga, Mn)(As, P) bilayer suggests that a part of the (Ga, Mn)(As, P) layer has an IP magnetic easy axis, a feature that has also been revealed by polarized neutron reflection experiment [17].

From the observed temperature dependence of magnetization, the Curie temperatures T_C of the IP and OP magnetizations are identified as 70 and 45 K, respectively.

Electrical transport in FM film strongly depends on the magnitude of magnetization and its direction. Specifically, the HR of an FM film is given by [18]

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

where M is the magnetization of the film, t is its thickness, R_0 and R_S are the normal and the anomalous Hall coefficients, respectively, and k is the anisotropic magnetoresistance coefficient θ and φ are polar and azimuthal angles measured as shown in Fig. 1(b), respectively. The first term of (1) comes from the normal Hall effect (NHE), which in FM materials is negligible because of magnetization of the sample. The second term is the anomalous HR (AHR) originating from the OP component of magnetization. Finally, the third term is the PHR arising from the IP component of magnetizatio.

Reversal of magnetization in the bilayer system can be achieved by rotating the external field direction. We set the external field strength at 300 G and rotate the field either CCW or clockwise (CW) in the plane of the film. Angular scans of PHR measured in this way at 3 K are plotted in Fig. 3, in which transitions of magnetization are observed as abrupt changes of the PHR value. In the case of CCW rotation, the field direction is rotated from $\varphi_H = -60°$, which is in the fourth quadrant, as shown in Fig. 1(a). As the field is rotated CCW, the magnetization experiences a sequence of transitions over magnetic easy axes in the four quadrants, that is, from the fourth to first to second to third and back to the fourth quadrant. In Fig. 3, we marked these four transitions as $T1$, $T2$, $T3$, and $T4$, following the transition order. The reverse sequence of transitions (i.e., the fourth to third to second to

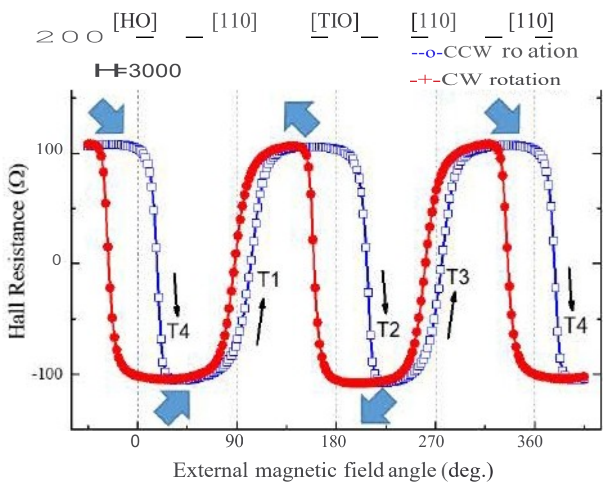

Fig. 3. Angular scan of PHR observed on the bilayer in a field of 300 G. Blue open squares and red solid circles represent data obtained with CCW rotation and CW rotation of the applied field.

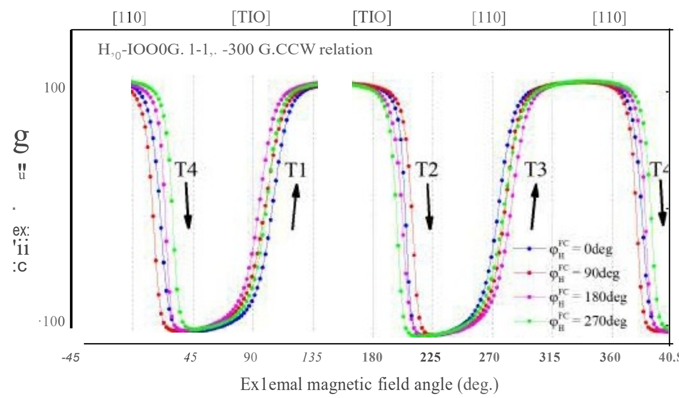

Fig. 4. Angular CCW scans of the PHR data obtained after using different directions of cooling fields. The angles corresponding to the Tl, *T2*, T3, and *T4* transitions systematically vary with the cooling field direction.

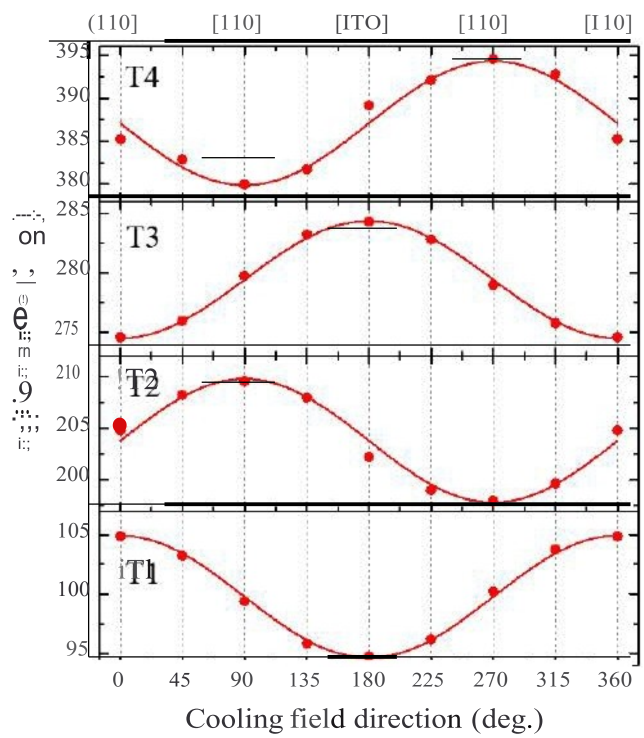

Fig. 5. Transition field angles of Tl, T2, T3, and *T*4 as a function of the cooling field direction. Lines are sinusoidal functions. All data show a sinusoidal-like behavior.

first to the fourth quadrant) is achieved when the rotation of the field is CW.

The PHR data plotted in Fig. 3 exhibit a feature that is normally not observed in single layers of (Ga, Mn)As film. Note that the centers of hystereses observed in the angular scan of PHR show small shifts from the quadrant boundaries at 0°, 90°, 180°, 270°, and 360°. Such asymmetry is not expected in magnetization reversal in the (Ga, Mn)As layers, where magnetic anisotropy is known to be symmetric with respect to the (100} and (llO} crystallographic directions. The observed asymmetry in the **PHR**, thus, signals the presence of an additional field in our bilayer sample, such as an EB field.

To obtain further understanding of the effects of EB in our structure, we have performed systematic field cooling experiments. In these experiments, the strength of the cooling field was fixed at HFc = 1000. The film was then first cooled to 3 K in the presence of the cooling field, and the angular scans of PHR were carried out by rotating a fixed field of 300 G in the CCW direction. This was then repeated by systematically varying the direction of the cooling field from 0° to 360°, with intervals of 45° for each successive experiment. Representative angular scans of PHR obtained at 3 **K** after four different cooling field directions are shown in Fig. 4. Note that the four PHR data are each slightly shifted, even though the measurement process was exactly the same in all four measurements except for the cooling field direction. This indicates that the cooling field initiates the observed differences in the angular dependence of the PHR data.

It appears that the transitions marked as *TI, T2, T3,* and *T*4 in Fig. 4 systematically shift depending on the cooling field direction. We plot the transition field angles as a function of the cooling field direction for all four transitions in Fig. 5. The orientation of the applied field at each transition follows a sinusoidal behavior on the cooling field direction. In order to understand this behavior, we first consider transition *Tl,* at which magnetization rotates from the first quadrant to the second quadrant. The change of magnetization direction after tbe *Tl* transition is given by $(M_1 - M;)$, which points along the 180° direction (i.e., along [HO]). This transition will, thus, be assisted when the exchange field is along the 180° direction, while it will be hindered by the oppositely directed exchange field (that is, when it is oriented along 0°, i.e., along the [110] direction). The observed transition angles of *T* 1 are plotted as a function of the cooling field angles in the fourth panel of Fig. 5. It is clear that the Tl transition occurs at the smallest angle when the cooling field is at the 180° direction, while it occurs at the highest angle for the cooling field along 0° (or 360°). This indicates that the cooling field sets the direction of EB in our bilayer system.

For the other cooling field directions, the component of the cooling field along 180° will determine the magnitude of **EB** and, thus, of the transition angle. Such dependence is clearly seen in the experimental data, which indeed follows a cosine-like behavior, as plotted in the fourth panel of Fig. 5. The dependence of transition angles on the cooling field directions for the other transitions (i.e., *T2,* T3, and T4) can also be explained by EB fields along the respective cooling field directions. That is, transition angles are smallest whenever the direction of the cooling field is the same as that of *(M_1 - M;)* for the respective transition, which leads to observed sinusoidal-like behavior shown in the other panels of Fig. 5.

The observed EB effect in our bilayer with orthogonal magnetizations in the two layers can be understood based on a magnetic closure domain model [19], [20]. This model describes how magnetic closure domains form in a magnetic layer with an OP anisotropy in the bilayer system with orthogonal magnetizations as the bilayer is cooled. If the external magnetic field is absent during the cooling process, the magnetic layer having the IP anisotropy magnetizes along the easy axes in the film plane [21]. However, when a bilayer such as our (Ga, Mn)As/(Ga, Mn)(As, **P**) system is cooled in an IP cooling field, the magnetization of the (Ga, Mn)As layer will preferentially aljgn along the direction of that field, and this will affect the IP component of magnetization of the closure domain in the (Ga, Mn)(As, **P**) layer via EC [22]. The asymmetry between the IP components of magnetization in the closure domains of the (Ga, Mn)(As, P) layer then act as an EB effect on the (Ga, Mn)As layer, as is observed in this study.

IV. CONCLUSION

In summary, we have studjed the process of magnetization reversal of a (Ga, Mn)As/(Ga, Mn)(As, **P**) bilayer structure using PHR measurements. We observe clear IP and OP magnetic anisotropies in the (Ga, Mn)As and the (Ga, Mn)(As, P) layers, respectively, which results in orthogonal orientation of magnetizations in the bilayer. The angular dependences of PHR measured on the bilayer show an asymmetry in the IP magnetization transitions during magnetization reversal, indicating the presence of EB acting on the GaMnAs layer in the bilayer system. Systematic investigation of the angular dependences of PHR has revealed that the EB strongly depends on the cooling field direction. It turns out that the effect of th.is EB is proportional to the magnitude of the cooling field projection to the direction of the change of magnetization at each of the IP transitions in the (Ga, Mn)As layer. Such relation between the EB and the cooling field can be understood in terms of closure domains formed in the magnetic layer with the OP anisotropy (in our case, the (Ga, Mn)(As, **P**) layer), in which the IP components of magnetization become asymmetric in the presence of the IP cooling field. This investigation, thus, shows the possibility of engineering EB by utilizing bilayer structures with orthogonal configurations of magnetization.

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