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Asymmetric Magnetization Reversal in the Exchange-Biased MnO/(Ga,Mn)As Heterostructure Studied by Ferromagnetic Resonance

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We report ferromagnetic resonance study of the magnetization reversal in the exchange-coupled MnO/(Ga,Mn)As system. The low-field parts of ferromagnetic resonance spectra measured along $[1\bar{1}0]$ and [100] directions of (Ga,Mn)As were combined into hysteresis loops, which under field-cooling conditions similarly to SQUID loops are shifted toward negative magnetic fields. The magnetization reversal process revealed by the loops occurred remarkably asymmetric for both sample configurations.

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1. Introduction

Since a prediction of room-temperature ferromagnetism, (III,Mn)V compounds stay under intense scientific investigation, as they are regarded as prospect candidates for applications in spintronic/magnetoelectronic devices [1]. The epitaxial gallium arsenide doped with manganese, with tuned critical temperature of ferromagnetic/paramagnetic transition reaching 173 K [2], is nowadays the most interesting representative of (III,Mn)V alloys, thus many experimental and theoretical studies were devoted in order of tailoring its electronic, magnetic and optical properties for the purposes of technological feasibility [3, 4].

One of the phenomena already used in magnetoelectronics is the interfacial coupling in antiferromagnet/ferromagnet (AFM/FM) heterostructure [5]. The exchange interaction is induced by field-cooling (FC) down below the Curie temperature (T_C) of FM and the Néel temperature (T_N) of AFM, and leads to broadening

and horizontal shift of SQUID hysteresis loop of a ferromagnet [6]. This phenomenon is called exchange bias and an enhancement of coercive field related to it is employed for pinning the magnetization in spin valve devices.

Recently, the successful attempt of exchange biasing of ferromagnetic (Ga,Mn)As ($T_C \approx 55 \div 70$ K) with antiferromagnetic MnO ($T_N \approx 120$ K) was reported [7]. SQUID magnetometry revealed significant shift of the hysteresis loop, $H_{EB} \approx 200$ Oe, with no reduction of H_{EB} in a series of measurements carried out in succession (no training effect) [7, 8]. Similar absence of training effect was observed for the exchange-induced unidirectional anisotropy of FM (i.e., the breaking of the 180°-symmetry). In that study performed with the use of ferromagnetic resonance (FMR) technique the interfacial coupling occurred surprisingly robust with respect to temperature and changing magnetic field [8].

2. Experimental

In this paper we report magnetization reversal study in the exchange-coupled MnO/(Ga,Mn)As system grown in molecular beam epitaxy (MBE) setup. On a semi-insulating (001) GaAs substrate the high- and low-temperature buffers of GaAs were deposited with thicknesses of 160 and 4 nm, respectively. Subsequently $Ga_{0.94}Mn_{0.06}As$ layer was grown, with a thickness d_{FM} estimated by monitoring reflection high-energy electron diffraction (RHEED) to be about 15 nm. Then the sample was capped with a thin film of Mn, whose crystalline ordering was clearly evidenced by the RHEED pattern. After electron and X-ray diffraction studies performed on Mn/GaAs(001) by Jin et al. [9], we adopt the following orientation of manganese film with respect to (Ga,Mn)As:

$$[001]_{Mn} \parallel [001]_{(Ga,Mn)As},$$

$$[100]_{Mn} \parallel [110]_{(Ga,Mn)As},$$

$$[010]_{Mn} \parallel [1\bar{1}0]_{(Ga,Mn)As},$$

assuming also these relations to hold true after oxidation of Mn to MnO. The thickness d_{AFM} of manganese oxide layer was determined by X-ray reflection to be about 15 nm.

The ferromagnetic resonance (FMR) experiments were performed with standard X-band electron spin resonance (ESR) spectrometer equipped with a helium cryostat. In a microwave cavity the sample was mounted with [110] or [001] crystal directions as an axis of rotation. The former (vertical) configuration provides high signal-to-noise ratio and enables a change of the direction of dc magnetic field between $[1\bar{1}0]$ and $[\bar{1}10]$. The latter (horizontal) mounting is less convenient due to poor magnitude of the recorded FMR signal, this way however one can alternate the direction of dc field between [100] and $[\bar{1}00]$. It should be noted here that in both configurations the magnetic fields referred below as negative were obtained with rotation of a sample by 180°.

3. Results and discussion

The upper right part of Fig. 1 shows the FMR spectra obtained after cooling down to 4 K in the presence of dc magnetic field $H_{\mathrm{FC}} = 1$ kOe applied along $[1\bar{1}0]$ crystal axis. The broad line around 3 kOe corresponds to the uniform mode of ferromagnetic resonance in (Ga,Mn)As (the Curie temperature of FM layer was determined by SQUID to be about 60 K). While dc magnetic field $\boldsymbol{H}$ is reversed from $[1\bar{1}0]$ to $[\bar{1}10]$ direction and the sign of the magnetization in the FM layer is changed, the antiferromagnet stays unaffected. Then the atomic layers of MnO being in the proximity of (Ga,Mn)As are the source of gain or loss of the magnetic energy of (Ga,Mn)As, leading to a distinct shift of the resonance line by about 180 Oe [8]. This occurrence of different resonance fields H_{RES} for two *opposite* directions of $\boldsymbol{H}$ is called unidirectional anisotropy and expressed quantitatively by the anisotropy field H_{UD} equal to half the difference between resonance fields H_{RES} for $\boldsymbol{H} \parallel [1\bar{1}0]$ and $\boldsymbol{H} \parallel [\bar{1}10]$. One can easily notice that under zero-field--cooling (ZFC) conditions the spectra recorded for $\boldsymbol{H} \parallel [1\bar{1}0]$ and $\boldsymbol{H} \parallel [\bar{1}10]$ are virtually the same and no unidirectional anisotropy is observed in the upper left part of Fig. 1.

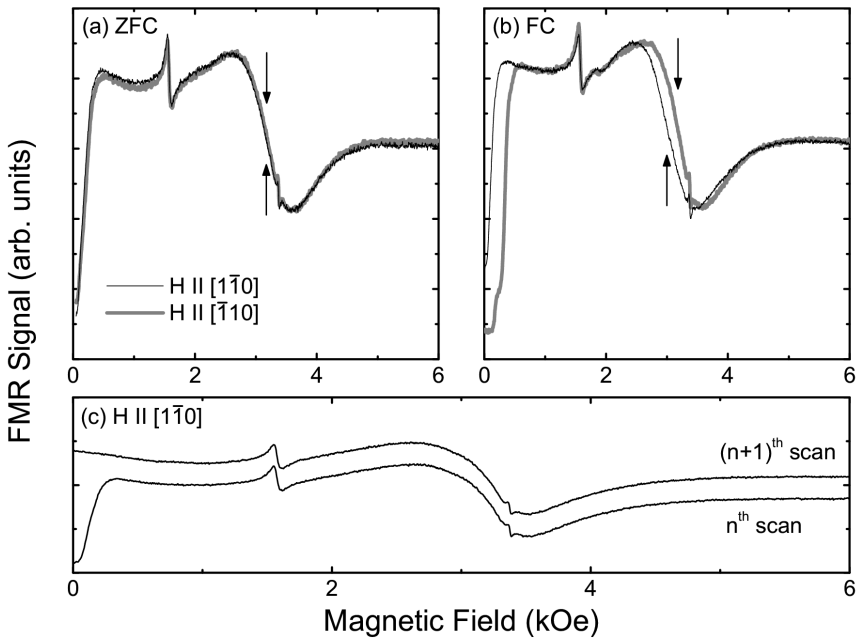

Fig. 1. FMR spectra recorded at 4 K in (a) zero-field-cooled and (b) field-cooled experiments, for two opposite orientations of dc magnetic field. The arrows mark resonance fields. (c) FMR spectra — separated vertically for clarity — recorded consecutively with the same orientation of dc magnetic field.

In the low-field range of ZFC and FC spectra one sees the slope-like features manifesting the magnetization reversal process. If the consecutive scans of dc magnetic field are performed for alternated directions, then mentioned slopes are present in each recorded spectrum, which is the case of spectra depicted in the upper parts of Fig. 1. On the other hand, when successive FMR measurements are done for the same direction of magnetic field, then no slope feature is observed in the second spectrum as shown in the lower part of Fig. 1. These two spectra may be combined with similar pair obtained for opposite magnetic field into a kind of "hysteresis loop". One should however remember that FMR is a modulation technique providing as an output a field derivative $\mathrm{d}P/\mathrm{d}H$ of the absorbed microwave power. When a sample is rotated we change its position with relation to the direction of *both* static (dc) and modulation (rf) magnetic fields. Thus the spectra regarded as collected for negative magnetic fields should be reversed upside-down in order to keep a proper sign of derivative in the entire range of magnetic field.

Figure 2 presents hysteresis loops combined from the low-field slopes of FMR spectra recorded for $\boldsymbol{H}$ and $\boldsymbol{H}_{\mathrm{FC}}$ magnetic fields oriented along $[1\bar{1}0]$ crystal axis, where positive/negative fields are defined as parallel/antiparallel to the direction of cooling field. Under FC conditions the loop is shifted horizontally with respect to the origin of coordinate system by about 100 Oe, which is close to the value of unidirectional anisotropy field $H_{\mathrm{UD}} \approx 90$ Oe. Aside the expected shift, the loop is remarkably asymmetric with a distinct step on its negative side, clearly showing

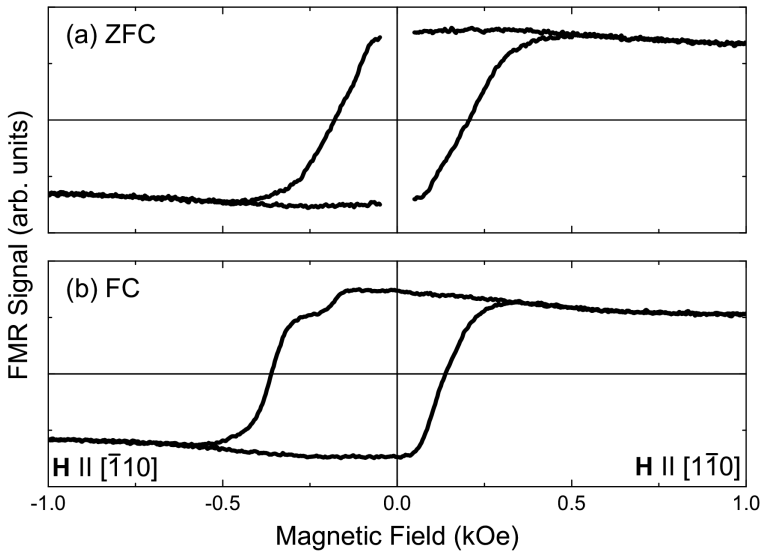

Fig. 2. FMR hysteresis loops obtained at 4 K under (a) zero-field-cooling and (b) field--cooling conditions. The dc magnetic field and cooling field (if applied) were along $[1\bar{1}0]$ direction.

different character of the magnetization reversal process, depending on whether the magnetic field is swept downward or upward. In the case of horizontal mounting configuration, with $\boldsymbol{H}$ and $\boldsymbol{H}_{\mathrm{FC}}$ fields applied along [100] axis of (Ga,Mn)As, one obtains a noisy hysteresis loop resulting from typical of this configuration weak FMR signal (see Fig. 3). Nevertheless, one may easily distinguish the steps on both sides of the hysteresis loop, from which the one on the negative-field side occurred wider than its positive-field counterpart. By making separate measurements performed with *cooling* fields oriented in opposite directions (i.e. $[1\bar{1}0]$ and $[\bar{1}10]$, [100] and $[\bar{1}00]$), we confirmed the asymmetry of hysteresis loops obtained in both configurations to be not related to the crystal structure: for $\boldsymbol{H}_{\mathrm{FC}}$ along $[1\bar{1}0]$ the step always appears on the negative side, for $\boldsymbol{H}_{\mathrm{FC}}$ along [100] the step on the negative-field side is systematically wider.

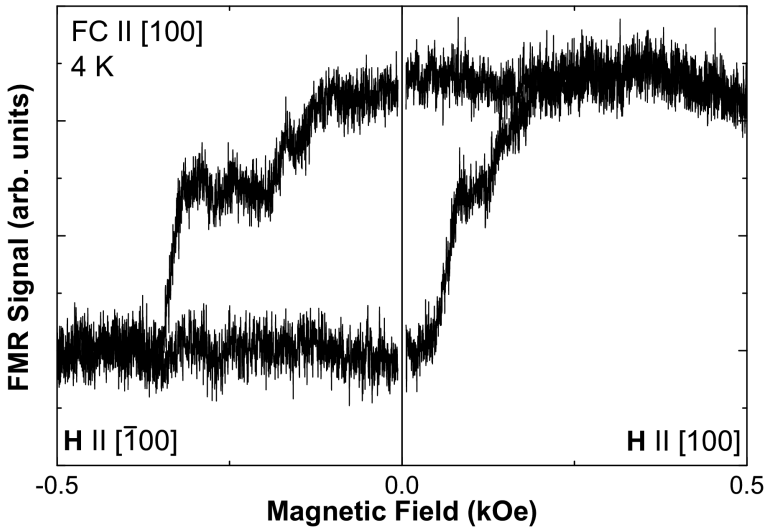

Fig. 3. The hysteresis loop for the cooling field applied along [100] crystal axis of (Ga,Mn)As.

According to our best knowledge this is the first FMR observation of asymmetric magnetization reversal. Nevertheless, several magnetometric studies were already devoted to this phenomenon and explained by means of different nature of the reversal processes occurring on negative- and positive-field side of the hysteresis loop: a coherent Stoner–Wohlfarth rotation and a nucleation of domain walls, respectively [10, 11]. Since our preliminary results should be related to detailed FMR and SQUID measurements of the anisotropy and coercivity fields, at the present stage of this study we refrain from providing a microscopic explanation of the asymmetric magnetization reversal in MnO/(Ga,Mn)As system and settling conclusively whether this process undergoes in the Stoner–Wohlfarth or domain nucleation mode.

4. Conclusions

In summary, we presented an alternative approach in the investigation of magnetization reversal in ferromagnetic layers, for which purpose the low-field FMR spectra were employed. With the use of this method applied for the exchange-biased MnO/(Ga,Mn)As system, the unusual asymmetry of FMR hysteresis loop was revealed for the case of cooling field parallel to $[1\bar{1}0]$ and [100] directions of (Ga,Mn)As.

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