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We report the investigation of the static and dynamic magnetic properties of type-*A* MnAs/$Ga_{0.945}Mn_{0.055}As$ (001) bilayers. Static magnetization measurements show them to be ferromagnetically coupled with an exchange bias field of ~340 Oe. The magnetocrystalline anisotropy constants of the (Ga,Mn)As layer were determined by *X*-band ferromagnetic resonance (FMR) spectroscopy. The (Ga,Mn)As layers are magnetically inhomogeneous as evidenced by a strong broadening of the (Ga,Mn)As uniform mode linewidth. The MnAs FMR spectra reveal the presence of a small MnAs fraction with a different orientation. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3059391]

I. INTRODUCTION

The basic understanding of spin-dependent transport and exchange coupling in ferromagnetic semiconductor multilayers is of current interest within the context of semiconductor spintronics. The exchange biasing of the ferromagnetic semiconductor (Ga,Mn)As layer by interfacing it with an antiferromagnetic layer has been investigated recently by superconducting quantum interference device (SQUID) magnetometry and ferromagnetic resonance (FMR).[1,2] Exchange bias effect is detected from the shift H_{EB} of the magnetization loop $M(H)$ relative to the $H=0$ position. The unidirectional magnetic anisotropy H_{UD}, which characterizes the exchange biasing of the ferromagnetic (Ga,Mn)As layer by the antiferromagnetic top layer, can be investigated by FMR.[2]

Exchange coupled bilayers of hard and soft ferromagnetic thin films show many analogies to antiferromagnetic/ferromagnetic exchange biased heterostructures which have been studied in the past.[3] MnAs/(Ga,Mn)As bilayers are a good example of such composite ferromagnetic thin films. As the MnAs layer can be epitaxially grown on (Ga,Mn)As abrupt interfaces with low interface defect densities can be obtained. For two different uniaxial anisotropic films in close contact with each other ferromagnetic exchange coupling occurs between the spins in the neighborhood of the interface of the two ferromagnetic films.[4] A recent study[5] reported the observation of the current-perpendicular-to-the-plane spin valve effect in such "self-exchange biased" bilayers. In this letter we report the results of SQUID and FMR measurements on MnAs/(Ga,Mn)As bilayers with very thin (15 nm) MnAs layers.

The presence of the MnAs layer on top of the (Ga,Mn)As layer is also expected to modify the strain and thus its magnetic properties. It is one of the characteristics of FM (Ga,Mn)As thin layers grown on GaAs that the lattice mismatch induced strain leads to strong anisotropy fields which determine the easy axes of magnetization. Up to now no information is available on how the strain will be modified by the MnAs top layer. We have investigated this problem by FMR spectroscopy.

II. EXPERIMENTAL DETAILS AND RESULTS

A. Sample preparation and measurement techniques

Bilayers were grown by low temperature molecular beam epitaxy on a semi-insulating (001) GaAs substrate after the deposition of a 170-nm-thick high temperature GaAs buffer layer (grown at 580 °C). The 50-nm-thick $Ga_{1-x}Mn_xAs$ ($x\sim 0.055$) layer is grown at a substrate temperature of ~240 °C. After this growth, the substrate temperature is further lowered to 200 °C with the As shutter open. A few monolayers of MnAs are first deposited at 200 °C to form a template for "type-*A* MnAs." Then, the substrate temperature is raised to ~240 °C to deposit a 15-nm-thick MnAs layer. This protocol consistently produces high quality type-*A* MnAs. In this particular crystalline orientation, the [0001] axis of the MnAs layer lies in the plane of the (001) GaAs substrate and is parallel to the [1−10] (Ga,Mn)As axis. The GaMnAs layer has not been annealed purposely but the growth of the MnAs layer at 250 °C is expected to indirectly anneal it.

The FMR measurements were performed at 9.5 GHz (*X*-band) in the 4–110 K temperature range. The maximum available magnetic field *H* was 17.8 kOe. The angular dependence of the (Ga,Mn)As FMR spectra was measured in two planes, (001) and (1−10). These two sets of measurements enable us to determine the resonance position for the high symmetry orientations of (Ga,Mn)As film: $H\|[001]$, [110], [1−10], and [100] from which the anisotropy constants can be obtained.[6] In the SQUID measurements discussed here, the external magnetic field is applied parallel to the [110]

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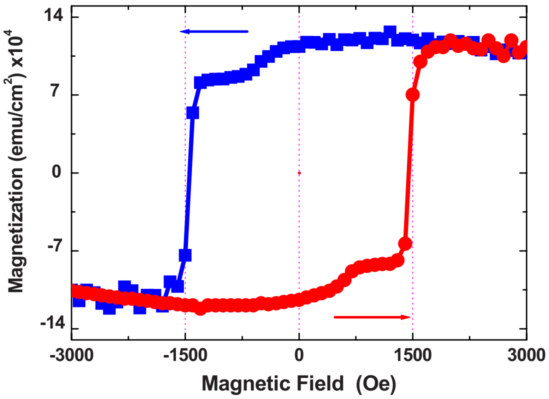

FIG. 1. (Color online) Major magnetization loop $M(H)$ at 4 K for a bilayer sample, showing two distinct coercive fields of the (Ga,Mn)As and MnAs layers.

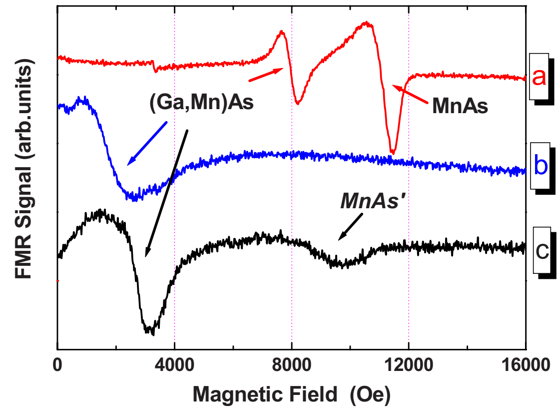

FIG. 3. (Color online) FMR spectra at $T=4$ K for $H\|[001]$ (a), $H\|[1-10]$ (b), and $H\|[110]$ (c) of the MnAs/(Ga,Mn)As bilayer. The low intensity MnAs spectrum in (c) results from a fraction of the MnAs layer with a different orientation as compared to the main A phase, characterized by an in-plane intermediate axis.

direction of the GaAs substrate which corresponds to the $[11-20]$ easy axis of magnetization of the MnAs layer.

B. Self-exchange bias and determination of the magnetocrystalline anisotropy constants

The temperature dependence of the remanent magnetization $M(T)$ measured by SQUID magnetometry clearly reveals the two different Curie temperatures for the (Ga,Mn)As ($T_C=110$ K) and MnAs ($T_C=320$ K) layers. The saturation magnetizations (M_S) were 28 and 666.6 emu/cm^3 for (Ga,Mn)As and MnAs, respectively (data not shown). Figure 1 shows the major magnetization hysteresis loop measured after first saturating the MnAs layer in a field of 20 kOe. We observe very different coercive fields for MnAs ($H_c=1.4$ kOe) and (Ga,Mn)As ($H_c=\sim 500$ Oe). Figure 2 shows the minor hysteresis loop measured over a field range of $-1 \leqslant H \leqslant 1$ kOe after first saturating the MnAs layer in a field of -20 kOe. The positive displacement of the center of the hysteresis loop from zero field $H_{EB}=\sim 340$ Oe indicates that the MnAs and (Ga,Mn)As layers are FM coupled. We have observed similar results after saturating the MnAs layer in the positive direction in which case the minor hysteresis loop is shifted in the negative direction.[5]

In Fig. 3, we show typical X-band FMR spectra of the bilayer for $H\|[001]$, $H\|[1-10]$, and $H\|[110]$ at $T=4$ K. For $H\|[001]$ [Fig. 3(a)], we observe both the uniform mode of

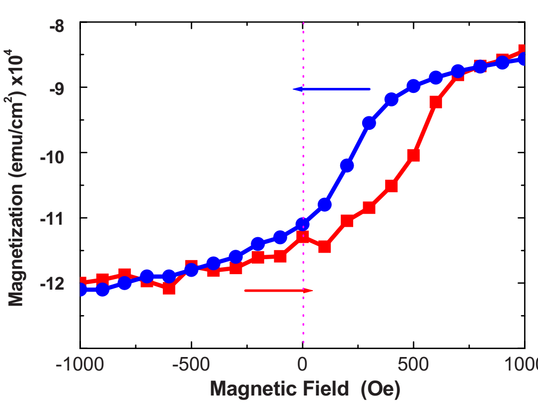

FIG. 2. (Color online) Minor magnetization loop of the (Ga,Mn)As layer measured at 4 K after saturating the MnAs layer in a field $H=-20$ kOe.

the (Ga,Mn)As and the MnAs layers. For $H\|[1-10]$ [Fig. 3(b)] parallel to the hard axis [0001] of MnAs only the (Ga,Mn)As spectrum can be observed in the available magnetic field range. For $H\|[110]$ [Fig. 3(c)] the easy axis of magnetization of the MnAs layer, the MnAs spectrum cannot be observed at X-band spectroscopy; its observation requires at least Q-band measurements. We observe nevertheless a weak spectrum at the resonance position close to the intermediate axis orientation, suggesting that a small fraction of the MnAs film has a different $\approx 90°$ rotated crystallographic orientation.

The linewidths of the (Ga,Mn)As spectra are highly increased, in particular, for the in-plane orientation; typical linewidths of comparable single layers of (Ga,Mn)As are in the 100–200 Oe range, whereas in the bilayer they increase up to 2000 Oe. An increase in the linewidth can be due to different mechanisms such as low carrier concentrations, increased Gilbert damping factors in bilayer systems, or magnetic inhomogeneities. The high critical temperature of 110 K indicates a hole concentration of $>10^{20}$ cm^{-3} which are to high to explain this increase in linewidth.[8] We think that magnetic inhomogeneities related to the imperfect thermal annealing of the GaMnAs layer capped by the MnAs layer and strain distributions are the dominant sources of line broadening.

The angular variation in the (Ga,Mn)As FMR spectra was measured at different temperatures between 4 and 110 K and the anisotropy constants have been determined by the standard procedure.[6–8] We observe the usual in-plane [100] easy axis and [001] hard axis orientation. However, the dominant uniaxial constant $K_{2\perp}$ is strongly reduced and the cubic constant $K_{4\perp}$ increased as compared to comparable standard layers (Fig. 4).[8] The growth of the MnAs layer on top of the (Ga,Mn)As layer seems to modify the strain dependent anisotropy constants from those of comparable uncapped layers.

In principle it is also possible to study the exchange coupling of two layers by FMR via the resonance field shifts of the (Ga,Mn)As layer if parallel and antiparallel magnetization orientations can be realized. However, this appears to

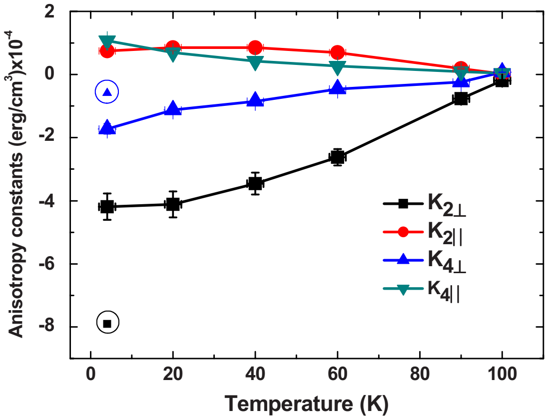

FIG. 4. (Color online) Variation in the four magnetocrystalline anisotropy constants $K_{2\perp}$(square), $K_{2\|}$(circle), $K_{4\perp}$(upper triangle), and $K_{4\|}$(lower triangle) (symbols) as a function of temperature for the MnAs capped (Ga,Mn) As/GaAs layer. The symbols are experimental results; lines are guides for the eyes. Circles show typical values observed in comparable (Ga,Mn)As monolayers.

be precluded in this case since the resonance field for $H\|[110]$ is comparable to the coercive field of MnAs. Indeed, the SQUID major loop measurements with $H\|[110]$ show that the MnAs layer is already fully magnetized for $H=1.4$ kOe whereas the FMR resonance field of the uniform mode in (Ga,Mn)As occurs at a higher field of 2.5 kOe. Thus, a field reversal will always lead to parallel oriented magnetizations in both layers and consequently no shift in the resonance fields will be observed. It would be interesting to further test this model by measuring the uncapped (Ga,Mn)As layer after etching off the MnAs top layer. Such measurements are planned in the future.

III. CONCLUSION

In summary, we have investigated the magnetic properties of MnAs/(001)(Ga,Mn)As bilayers with a 15 nm thin MnAs layer by SQUID and FMR spectroscopies. We have determined the exchange coupling and the anisotropy constants of the MnAs capped GaMnAs layer. The MnAs layer is not single phase but contains a fraction with an in-plane oriented intermediate axis.

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