Biaxial exchange anisotropy in PtMn/Ni$_{80}$Fe$_{20}$(110) bicrystal films

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By using molecular beam epitaxy PtMn/Ni$_{80}$Fe$_{20}$ bilayers were prepared on Mo(100) seeding layer on MgO(100) substrate. X-ray diffraction showed that the PtMn/Ni$_{80}$Fe$_{20}$ bilayers were mainly grown as (110) bicrystal films with 90° twin domains. The exchange anisotropy was studied by angular dependent magneto-optical Kerr effect. The results indicate that the PtMn/Ni$_{80}$Fe$_{20}$(110) bicrystal films possess biaxial exchange anisotropy with exchange field up to 130 Oe. © 2000 American Institute of Physics.

I. INTRODUCTION

The exchange bias effect caused by magnetic coupling across an antiferromagnetic–ferromagnetic interface has attracted much attention as it plays a key role in spin valve sensors. Various Mn based antiferromagnetic (AF) alloys, such as FeMn, NiMn, and PtMn, have been used as exchange biasing layers in spin-valve structures. PtMn and NiMn exhibit higher blocking temperatures and are more corrosion resistant than FeMn. Since the AF phase of PtMn is the chemically ordered L1$_0$-type structure similar to NiMn, the exchange coupling of PtMn/Ni$_{80}$Fe$_{20}$ is expected to be sensitive to the crystal structure. In this article the exchange anisotropy of the as-deposited PtMn/Ni$_{80}$Fe$_{20}$(110) bicrystal films is studied. Biaxial exchange anisotropy across the PtMn/Ni$_{80}$Fe$_{20}$ interface was found. The result is explained by the existence of bicrystal structure in the PtMn/Ni$_{80}$Fe$_{20}$(110) films.

II. SAMPLE PREPARATION

The samples studied here were prepared by a molecular beam epitaxy system (Vacuum Product made MBE-930). The PtMn/Ni$_{80}$Fe$_{20}$ films were grown at 200 °C on epitaxial-grade MgO(100) substrates. Before initial deposition of the PtMn(100–500 Å)/Ni$_{80}$Fe$_{20}$(100 Å) bilayers, about 100-Å-thick Mo(100) layer was established as a seeding layer. The deposition rates of the Ni$_{80}$Fe$_{20}$ and PtMn were controlled at about 0.1 and 0.3 Å/s, respectively. During deposition of the PtMn and Ni$_{80}$Fe$_{20}$ layer, the growth pressure was controlled below 2 × 10$^{-8}$ Torr.

The crystal structure was studied by x-ray diffraction (XRD) and reflection high-energy electron diffraction (RHEED). The correlation between magnetic and crystal structure was investigated by magneto-optical Kerr effect (MOKE). Because the penetration of the MOKE (He–Ne) laser light is quite limited, only samples with thin (less than 150 Å) PtMn layer can be probed by MOKE.

III. RESULTS AND DISCUSSIONS

On MgO(100) substrate the Mo seeding layer was grown as bcc (100), and the subsequent Ni$_{80}$Fe$_{20}$ and PtMn layers were mainly grown as (110) structure with, however, relatively weaker PtMn(001) and (002) peaks, as evidenced by XRD shown, for example, in Fig. 1. The main out-of-plane epitaxial relations are PtMn(110)∥Ni$_{80}$Fe$_{20}$(110)∥Mo(100)∥MgO(100). Note that the PtMn/Ni$_{80}$Fe$_{20}$(110) films were not single crystal, but were grown as a bicrystal structure, with two equal abundance domains 90° apart. The bicrystal structure was verified by detailed in-plane x-ray diffraction. The main in-plane epitaxial relations of the epilayers and substrate were thus determined as the following:

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\begin{align*}
\text{PtMn}[001] & \parallel \text{Ni$_{80}$Fe$_{20}$}[001] \parallel \text{Mo}[010] \parallel \text{MgO}[010], \\
\text{PtMn}[1-10] & \parallel \text{Ni$_{80}$Fe$_{20}$}[1-10] \parallel \text{Mo}[001] \parallel \text{MgO}[001], \\
or \\
\text{PtMn}[1-10] & \parallel \text{Ni$_{80}$Fe$_{20}$}[1-10] \parallel \text{Mo}[010] \parallel \text{MgO}[010], \\
\text{PtMn}[001] & \parallel \text{Ni$_{80}$Fe$_{20}$}[001] \parallel \text{Mo}[001] \parallel \text{MgO}[001].
\end{align*}
\]

![FIG. 1. X-ray diffraction scanned from PtMn(500 Å)/Ni$_{80}$Fe$_{20}$(100 Å)/Mo(100 Å) films grown on MgO(100) substrate.](image-url)
The mismatch of crystal symmetry between the Mo structure, which is shown in Fig. 2, leads to anisotropy being observed as depicted in Figs. 3. This bidirectional layers was measured by angular dependent MOKE technique. The two-dimensional unit cells of Mo(100) (solid lines) and PtMn/Ni$_{80}$Fe$_{20}$(110) (dashed lines) planes and epitaxial relations are schematically illustrated in (g).

Typical RHEED images of the Mo, Ni$_{80}$Fe$_{20}$ and PtMn layers are provided in Figs. 2(a)–2(f). The Ni$_{80}$Fe$_{20}$(110) and PtMn(110) surfaces were rougher and more disordered than that of the Mo(100). This is likely due to the formation of twins in the PtMn/Ni$_{80}$Fe$_{20}$ bilayers and high surface energy of the (110) surface. The splitting of the RHEED streaks in Figs. 2(d) and 2(f) together with the fourfold symmetry also indicate the existence of twinned structure (bicrystal) in the PtMn/Ni$_{80}$Fe$_{20}$(110) films. Note that the growth of 90° twin structure (bicrystal) in PtMn/Ni$_{80}$Fe$_{20}$(110) bilayer is due to the mismatch of crystal symmetry between the Mo(100) (fourfold) and PtMn/Ni$_{80}$Fe$_{20}$(110) (twofold) plane, as schematically illustrated in Fig. 2(g). X-ray diffraction studies further suggest that the PtMn layer was grown as a partially ordered, tetragonal structure with lattice parameters $a = 3.97$ Å and $c = 3.66$ Å.

The exchange anisotropy of the PtMn/Ni$_{80}$Fe$_{20}$(110) bilayers was measured by angular dependent MOKE technique (magnetic field fixed and sample rotated). For MOKE laser light focused on small sample area, bidirectional exchange anisotropy was observed as shown in Figs. 3(a)–3(h). For magnetic field $H$ directed parallel to the underlying as-defined Mo[010] or Mo[001] azimuth ($\theta = 0°, 90°$), the exchange fields were of about $-130$ Oe, while for $H$ along the Mo[0-10] or Mo[00-1] azimuth ($\theta = 180°, 270°$), the exchange fields were of about $+130$ Oe. For these four principal azimuths ($\theta = 0°, 90°, 180°, 270°$), the MOKE hysteresis loops were somewhat asymmetric (with respect to the loops’ center) because they contain both magnetic easy and hard components. The easy component (shifted to left or right from $H = 0$) is likely due to the magneto-crystalline anisotropy and exchange coupling effect, while the hard component (symmetric to $H = 0$) is caused by the easy axis in the perpendicular direction. For magnetic field directed between Mo[010] and [001] azimuths ($\theta = 0°$ to $90°$), the MOKE hysteresis loops [see, for example, Fig. 3(b) for $\theta = 45°$] were somewhat similar to those of Figs. 3(a) and 3(c), where the $M$-$H$ loops of these azimuths shifted to the negative field. A similar trend was found for magnetic field directed between Mo[0-10] and [00-1] azimuths ($\theta = 180°$ to $270°$). In these cases the $M$-$H$ loops shifted to the positive field (see, for example, Fig. 3(f) for $\theta = 240°$).

For field directed between Mo[001] and [0-10] azimuths ($\theta = 90°$ to $180°$), on the other hand, the MOKE hysteresis loops were more symmetric like (with respect to $H = 0$) without any significant exchange field (see, for example, Fig. 3(d) for $\theta = 135°$ or Fig. 3(b) for $\theta = 315°$). The same situation was found for field directed between Mo[001] and [0-10] directions ($\theta = 270°$ to $360°$).

As mentioned above, the bidirectional exchange anisotropy was found if the laser beam is well focused. For MOKE laser beam shined on a large sample area, biaxial exchange anisotropy, namely dual exchange bias loops, can be observed for field along any one of the principal easy axes ($\theta = 0°, 90°, 180°, 270°$). The results suggest that there is an equivalent amount of 0°, 90° and 180° and 270° antiferromagnetic domains in the PtMn/Ni$_{80}$Fe$_{20}$(110) bicrystal films. In addition, these antiferromagnetic domains are rather small compared to the unidirectional exchange bias sample.

Obviously, the bidirectional or biaxial magnetic exchange anisotropy reported here is directly related to the bi-
crystal structure in the PtMn/Ni$_{80}$Fe$_{20}$ (110) film. For comparison we have indeed prepared PtMn/Ni$_{80}$Fe$_{20}$ (111) single crystal films [on Mo(110) plane on sapphire (11–20) substrate]. In this (111) case, a relatively weak, unidirectional or uniaxial exchange anisotropy was observed.\textsuperscript{10}

Finally we point out that the PtMn/Ni$_{80}$Fe$_{20}$ (110) bicrystal films could be somewhat similar to the PtMn/Ni$_{80}$Fe$_{20}$ (100) (uncompensated plane for spin alignment) in terms of crystal symmetry and magnetic behavior. The fact that the exchange field is relatively small in the PtMn/Ni$_{80}$Fe$_{20}$ (111) films compared to that of the (110) bicrystal samples implies that uncompensated plane [(100) like] may be beneficial to exchange coupling effect in this system. Note that the orientation dependent results for PtMn/Ni$_{80}$Fe$_{20}$ are very different from those of PtMn/Ni$_{80}$Fe$_{20}$ and CoMn/Ni$_{80}$Fe$_{20}$ cases, where for the latter two cases the (111) oriented films show the best exchange coupling effect and the uncompensated plane seems not to result in better exchange coupling effect.\textsuperscript{11}

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