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著者	角田　匡清
journal or publication title	Applied Physics Letters
volume	85
number	17
page range	3812-3814
year	2004
URL	http://hdl.handle.net/10097/35035

doi: 10.1063/1.1812597

APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 17 25 OCTOBER 2004

Giant exchange anisotropy observed in Mn–Ir/Co–Fe bilayers containing ordered Mn_3Ir phase

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(Received 4 June 2004; accepted 1 September 2004)

Exchange anisotropy of $Mn_{73}Ir_{27}/Co_{70}Fe_{30}$ bilayers fabricated on a 50-nm-thick Cu under layer by changing the substrate temperature (T_{sub}) during the deposition of Mn–Ir layer was investigated, correlating with the crystallographic structure of Mn–Ir layer. The unidirectional anisotropy constant (J_K) of the bilayers remarkably varied as a function of T_{sub}. After the thermal annealing of bilayers at 320 °C in a magnetic field of 1 kOe, J_K steeply increased from 0.3 to 1.3 erg/cm^2, as T_{sub} was raised from room temperature to 170 °C. The blocking temperature was enhanced from 270 to 360 °C, simultaneously. The J_K of 1.3 erg/cm^2 is nearly ten times larger than the values reported in Mn–Ir/Co–Fe bilayers early in the research of them. The x-ray diffraction profiles showed that the ordered Mn_3Ir phase was formed in the antiferromagnetic layer with increasing T_{sub}. From the coincidence of enhancing J_K and increasing peak intensity of superlattice diffraction lines, the Mn_3Ir phase was suggested to be an origin of the giant J_K and the high blocking temperature. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1812597]

The nature of the exchange anisotropy observed in ferromagnetic (FM)/antiferromagnetic (AFM) bilayers has attracted a great deal of attention in recent years due to the intriguing physics and its central role in spin-valve-type magnetoresistance devices that are applied in magnetic recording and magnetoresistive random access memories (MRAMs). Although the discovery of the exchange anisotropy occurred nearly fifty years ago, it is still a challenge to both theorists and experimentalists to understand quantitatively the strength of the exchange anisotropy, the so-called unidirectional anisotropy constant, J_K, in terms of the spin structure in atomic scale. The first phenomenological model for the exchange anisotropy was established by Meiklejohn and Bean (MB) in the 1950s, and it dealt with the origin of J_K as the exchange interaction at the interface.[1] However, the expected value of J_K at the perfect uncompensated interface is too large by orders of magnitude, compared to the experimentally obtained values. In order to explain this factor-of-100 discrepancy, two individual theoretical works were proposed by Mauri *et al.*[2] and by Malozemoff[3] in the 1980s. They considered the formation of domain walls in the AFM layer and succeeded in explaining the exchange anisotropy strength of the bilayer systems. However, recent experimental progress for the exchange-coupled bilayers, such as material research for both the AFM layer[4–6] and the FM layer,[7–9] the stacking structure modification of bilayers,[10–12] and fabrication process controls of bilayers,[12–14] continue to enhance the J_K and reduce the discrepancy in magnitude between the MB model and the experimental values. The present authors also enlarged J_K of Mn–Ir/Co–Fe bilayers to 0.87 erg/cm^2 by applying long-time field annealing.[15] Furthermore, in this letter, the authors report quite large J_K at room temperature in excess of 1 erg/cm^2. It is ten times larger than the values of the bilayers in 1980–1990s and thus requires further theoretical works for the quantitative understanding of exchange anisotropy. From the application point of view, the large J_K allows us to reduce the dimensions of spin-valve-type magnetoresistance devices, since it means the enhanced stability of the pinned magnetization in submicron patterned devices against its own demagnetization field. Within this sense, the present result is a promising technology to achieve ultrahigh density magnetic recording and high capacity MRAMs.

Bilayers in the form of substrate/$Ni_{27}Fe_7Cr_{66}$ 5 nm/Cu 50 nm/$Mn_{73}Ir_{27}$ 10 nm/$Co_{70}Fe_{30}$ 4 nm/Cu 1 nm/$Ni_{24}Fe_{10}Cr_{66}$ 2 nm were prepared on thermally oxidized silicon wafers with magnetron sputtering method. The ultimate pressure of the sputtering chamber was 3×10^{-11} Torr. The highly purified (9N) Ar was used for the processing gas. During the deposition, except for the Mn–Ir layer, the substrates were held at room temperature (RT). A dc magnetic field of 30 Oe was always applied in the film plane. In order to obtain a template layer with flat surface for the epitaxial growth of fcc Mn–Ir, the 50-nm-thick Cu underlayer was heated at 250 °C for 10 min after its deposition on the Ni–Fe–Cr layer without breaking vacuum by using infrared lamp heater. The crystallographic orientation of the Cu layer obtained was well-defined out-of-plane <111>-fiber texture, and its surface roughness, R_a, determined from atomic force microscopy, was 0.38 nm. The Mn–Ir layer was deposited on it at the respective substrate temperature, T_{sub}. The Co–Fe layer and the remaining capping layers were further deposited on the Mn–Ir layer, after cooling down the substrate to RT. In order to induce exchange bias to the Co–Fe layer, specimens were annealed in a vacuum furnace, whose pressure was less than 5×10^{-6} Torr, at T_a=250–400 °C for 1h

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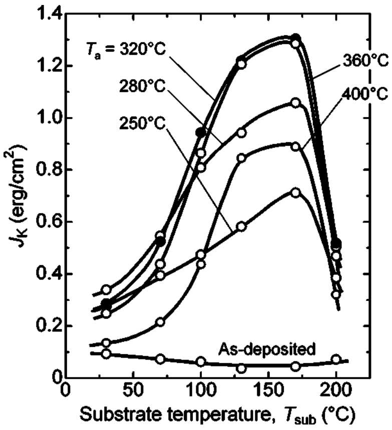

FIG. 1. Unidirectional anisotropy constant, J_K, of Mn–Ir/Co–Fe bilayers annealed at various temperature, T_a, in the in-plane magnetic field of 1 kOe. The horizontal axis corresponds to the substrate temperature, T_{sub}, during the deposition of the Mn–Ir layer.

by applying a magnetic field of 1 kOe along the same direction to the field during the deposition. The field annealing was performed successively on the same specimens. The microstructure of the films was examined by x-ray diffraction (XRD) and grazing incident x-ray diffraction (GID) with a Cu $K\alpha$ radiation source. M–H loops were measured with a vibrating sample magnetometer. Magnetic torque curves were measured with a null method torque magnetometer having a sensitivity of about 1×10^{-3} dyn cm. All the measurements were performed at RT. Unidirectional anisotropy constant, J_K, was calculated with the equation of $J_K = M_s d_F H_{ex}$, where $M_s d_F$ is the areal saturation magnetization of Co–Fe layer, and H_{ex} is the exchange biasing field determined as a shift of the center of M–H loops along the field axis.

Figure 1 shows the changes of J_K of the bilayers annealed at various temperatures, T_a, as a function of the substrate temperature during the deposition of the Mn–Ir layer, T_{sub}. One can clearly see the enhancing J_K with increasing T_{sub} up to 170 °C, regardless of T_a. As T_{sub} further increases, the J_K steeply drops. The maximum J_K value achieved in the present study is 1.3 erg/cm^2 under the conditions of T_{sub} = 170 °C and T_a = 320 °C. It is nearly ten times larger than the values reported in Mn-Ir/Co-Fe bilayers early in the research of them.[16,17] Figure 2 shows the in-plane (a) M–N loops and (b) magnetic torque curve of the bilayer showing J_K = 1.3 erg/cm^2. The vertical axis of both figures is normalized by the film area. The well-defined shifted loop along negative direction of the field of thermal annealing and the hard to saturate S-figure shaped loop along the transverse direction are observed in Fig. 2(a). Corresponding with these loops, the magnetic torque curve behaves well defined $-\sin\theta$ shape with the amplitude of 1.3 dyn cm/cm^2, with finite rotational hysteresis loss.

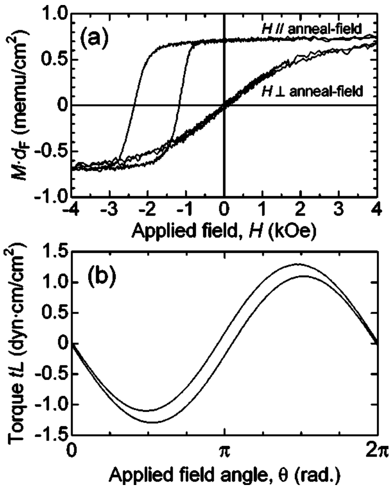

FIG. 2. In-plane (a) magnetization curves and (b) magnetic torque curve of the Mn–Ir/Co–Fe bilayer fabricated with the condition of T_{sub} = 170 °C and T_a = 320 °C. The strength of magnetic field applied for the torque measurement is 15 kOe.

In order to know the origin of the giant J_K in the present bilayers, structural analysis was performed. The conventional XRD profiles showed the well-defined out-of-plane fiber texture of the bilayers, as <111> texture for the fcc structured Cu and Mn–Ir layers and <110> texture for the bcc structured Co–Fe layer. Figure 3 shows the GID profiles of the bilayers annealed at T_a = 320 °C. The T_{sub} for the Mn–Ir layer deposition was varied from RT to 200 °C. In order to emphasize the diffraction lines from the Mn–Ir layer, separately observed GID profiles of the 20-nm-thick Mn–Ir films, fabricated on the same Cu template layers and capped with a 2-nm-thick Ta layer, are shown as small portions on the respective profiles. The calculated powder diffraction pattern of Mn_3Ir, having $L1_2$ ordered structure, was also attached at the top of the figure. The Lorentz factor of $1/\sin 2\theta$ was used for the calculation, since the GID profiles were measured for the specimens having strong out-of-plane fiber texture. Because of the respective texture of the fcc and the bcc layers, we can clearly see the fundamental diffraction lines from (220) planes of both the Mn–Ir and the Cu layers around $2\theta_\chi$ = 70°–75°, and those from (110) and (200) planes of the Co–Fe layer around $2\theta_\chi$ = 45° and 66°. The remarkable feature that should be noticed here is the appearance of the superlattice diffraction lines from (110) and (211) planes of Mn_3Ir for the bilayers with $T_{sub} \geqslant 100$ °C, while only the fundamental lines are observed for the bilayers with $T_{sub} \leqslant 70$ °C. The change of the diffraction intensities of these superlattice lines fairly corresponds to the change of J_K shown in Fig. 1 as a function of T_{sub}. Namely, the diffraction intensities increase with increasing T_{sub} up to 170 °C and

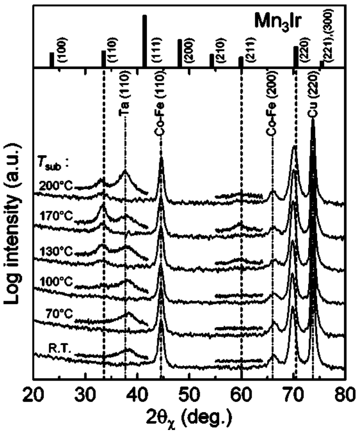

FIG. 3. Grazing incident x-ray diffraction profiles of Mn–Ir 10 nm/Co–Fe 4 nm bilayers fabricated on Ni–Fe–Cr 5 nm/Cu 50 nm underlayer and capped with Cu 1 nm/Ni–Fe–Cr 2 nm layer. Small portions of diffraction profiles on the respective profiles are those of the 20-nm-thick Mn–Ir films fabricated on the same underlayer and capped with a 2-nm-thick Ta layer. The incident x-ray angle to the film plane was 0.5°.

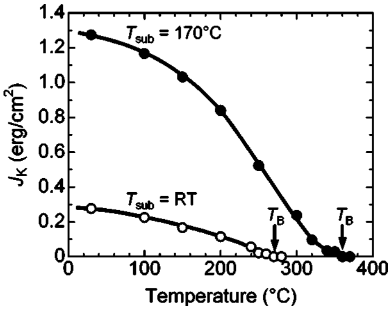

FIG. 4. Temperature dependencies of J_K of the bilayers fabricated with $T_{sub}=170$ °C and room temperature (RT). The field annealing temperature, T_a, was 320 °C for both the bilayers.

then decrease. This fact implies that the giant J_K in the present bilayers is closely related with the Mn_3Ir phase in the AFM layer. The ordering parameter, S, of the Mn_3Ir phase, determined from the integral intensity ratio of Mn_3Ir (110) peak to that of (220) peak, was 0.45 for the bilayer with $T_{sub}=170$ °C. We therefore may expect further strong exchange anisotropy, when the S could be 1.0, the perfect ordering.

Figure 4 shows the changes of J_K as a function of measuring temperature for the bilayers with $T_{sub}=170$ °C and RT, annealed at $T_a=320$ °C. For both the bilayers, J_K monotonously decreases as measuring temperature increases and comes to be zero at the respective blocking temperature, T_B. While the $T_B=270$ °C, observed for the bilayer with T_{sub} $=$RT is comparable to the values in the previous reports,[9] $T_B=360$ °C for the bilayer showing the giant J_K is fairly higher than them. The mechanism of this enhancing T_B is not clear. However, taking into account the fact that atomic ordering raises the Néel temperature by 200 °C in 25 at % Ir–Mn alloy,[18,19] we may say that the Mn_3Ir phase in the AFM layer is not only the cause of the giant J_K but also the cause of the raised T_B of the bilayer with $T_{sub}=170$ °C.

In summary, a giant unidirectional anisotropy constant in excess of 1 erg/cm^2 at room temperature and its high blocking temperature of 360 °C in Mn–Ir/Co–Fe bilayers were induced by elevating the substrate temperature during the deposition of Mn–Ir layer. We believe that the giant J_K and high T_B originate from the Mn_3Ir phase, which is partially formed in the antiferromagnetic layer.

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