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Relation between exchange coupling and enhanced coercivity in the free layer of a patterned magnetic tunnel junction

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A magneto-optical Kerr effect system with a spatial resolution of 2 μm was used to measure the local M-H loops for the free layer of a magnetic tunnel junction with a structure of Ta/Cu/Ta/NiFe/Cu/$Mn_{75}Ir_{25}$/$Co_{70}Fe_{30}$/Al_2O_3/$Co_{70}Fe_{30}$/Ta to investigate the exchange bias field H_E and the coercivity H_C for the free layer. The H_E and H_C measured along the direction of the free layer varied symmetrically with respect to the junction center. The measurements indicate that the enhanced H_C correlated with H_E, and H_E could be reasonably explained by using an “orange-peel-type” coupling based on variations in the thickness of the pinned layer along the direction of the free layer. The variation in H_E along the pinned-layer’s direction could be ascribed to that of the free-layer’s thickness, and the increase in H_E at the junction edge along the pinned layer was due to a decrease in the thickness of the free layer near the edge. However, the nearly constant H_C along the pinned layer indicates that the thickness of the free layer can be excluded from the mechanism for enhancing H_C, which is a unique difference in the parameters involved in H_E and H_C, and in the mechanism for enhancing H_C. *© 2004 American Institute of Physics*. [DOI: 10.1063/1.1811776]

I. INTRODUCTION

Ever since the discovery of the spin-valve structure consisting of a ferromagnetic (FM) free-FM/spacer metal or insulator/ferromagnetic pinned-FM/antiferromagnetic (AF) multilayer,[1] there has been renewed interest in investigating exchange coupling due to its role in the response of the magnetoresistance to an external field. Exchange coupling induces both an exchange bias field H_E, representing a shift of the hysteresis loop, and an enhancement of the coercivity H_C, which was observed by Meiklejohn and Bean in the granular Co/CoO system.[2] In the spin-valve structure, an interplay between two kinds of couplings, interfacial coupling between the pinned-FM and pinned-AF layers and interlayer coupling between the free FM and the pinned-FM layers, is observed.[3]

The investigation of interlayer coupling between the free- and the pinned-FM layers through a nonmagnetic spacer has mostly focused on the exchange field rather than on the enhanced coercive force of the free layer. In the literature, several mechanisms have been proposed for interlayer coupling: RKKY-like coupling through an indirect exchange mediated by itinerant electrons,[4,5] Neel’s orange-peel coupling which is due to the magnetic dipole interaction and is related to interfacial morphological corrugations,[6–8] the dipole interaction through stray fields induced by domain walls[9,10] or ripple domains,[11,12] and pinhole coupling.[13] When an insulating layer prevents electron itinerancy as in a magnetic tunnel junction, reducing the possibility of RKKY-like coupling, orange-peel coupling may be responsible for exchange coupling.[14,15]

Only recently have there been a few reports on the mechanism of the enhanced coercivity originating from the interlayer coupling between the free- and the pinned-FM layers.[7,11] An available model is based on the magnetostatic interaction of stray fields. That is, the stray field induced by domain walls[7,11,16] or magnetization ripple[12,17] in the pinned-FM layer couples magnetostatically through the nonmagnetic spacer with the stray field of the free-FM layer to enhance the coercivity.

In this work, we measured the local distributions of H_E and H_C on the free layer of a patterned junction prepared using a dc sputtering deposition method. We also discuss the mechanism of enhanced coercivity in terms of an orange-peel-type exchange coupling.

II. EXPERIMENTAL DETAILS

Tunnel junctions with a Ta (50 Å)/Cu (100 Å)/Ta (50 Å)/Ni Fe (20 Å)/Cu (50 Å)/$Mn_{75}Ir_{25}$ (100 Å)/$Co_{70}Fe_{30}$ (25 Å)/Al_2O_3 (15 Å)/$Co_{70}Fe_{30}$ (25 Å)/Ta (50Å) structure were prepared on thermally oxidized Si wafers by using dc magnetron sputtering, with ultraclean Ar(9N) as the process gas, in a chamber with a base pressure of 3×10^{-9} Torr. For barrier formation, metallic Al with a thickness of 15 Å was deposited and subsequently oxidized in an oxidation chamber with a radial slot antenna for 2.45 GHz microwaves.[18] Kr was used as the inert gas and was mixed

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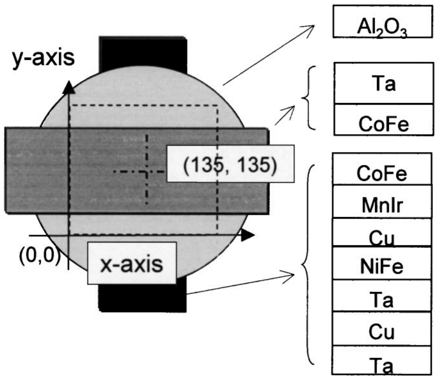

FIG. 1. Schematic view of the sample geometry.

with O_2 molecular gas for plasma oxidation. *In situ* patterned junctions were prepared using a $100 \times 100\ \mu m^2$ shadow mask during deposition, but the junction size was measured to be $180 \times 180\ \mu m^2$ due to the edge effect of the spatial distribution of sputtered atoms.[19]

The junction samples were annealed at 200 °C for 1 h under a magnetic field of 1 kOe, followed by field cooling. The stacks of Ta/NiFe/Cu below $Mn_{75}Ir_{25}$ improved the crystalline orientation of the fcc-(111) MnIr plane,[20] causing the exchange coupling to be enhanced.[21] The magneto-optical Kerr effect (MOKE) method was used to obtain the local *M-H* loops under a 50 Hz driving magnetic field with a 100 Oe amplitude. The penetration depth of the He–Ne laser light was about 20 nm, which was enough to affect the entire thickness of the free layer. The laser beam size was about $2\mu m$ in diameter, which corresponds to the spatial resolution of the micro-MOKE system. The light beam was moved along the free layer (across the pinned layer) and the pinned-layer directions, denoted by the *x* axis and the *y* axis in Fig. 1, respectively, crossing the junction center. The origin was regarded as being 50 μm from the junction edge. The surface roughness was determined by using atomic force microscopy (AFM) at different points across the junction.

III. RESULTS AND DISCUSSION

Figures 2(a) and 2(b) show the measured *M-H* loops at several positions along the free layer (*x* axis) and the pinned-layer (*y* axis) directions, respectively, where the *M-H* loops were measured under a cyclic field along the pinned-layer direction, that is, the annealing field direction. Here, the zero field of each loop is shifted by 50 Oe. The loop at the outside edge of the junction, $x=45\ \mu m$ is not shifted, as shown in Fig. 2(a). The shift representing the exchange coupling (bias) field H_E increases as the measurement point is moved toward the junction center $x=60$, 75, and 135 μm but then decreases as the point is moved away from the center. We can also see a similar variation in the coercivity H_C.

When the measurement point is at the outside edge of the junction along the pinned layer $y=60\ \mu m$ the loop is negligible, as shown in Fig. 2(b). A large shift of the loop is seen for $y=75\ \mu m$, and the variation is not significant for $y=90$ and 135 μm. The magnetization, however, increases as the measurement point is moved toward the junction center, i.e., toward $y=135\ \mu m$. The exchange bias field and the coercivity of the pinned layer are measured to be 1470 Oe and 810 Oe, respectively. As a result, the magnetization of the pinned layer is not affected by magnetic fields of about 100 Oe.

The magnetization evaluated by using the MOKE signal is reflected in the thickness of the free layer because the optical parameters, the extinction ratio of the polarizer, the optical reflectivity, and the analyzer angle are fixed during the measurement. Thus, we know that a gradual variation in the thickness exists from the edge along the pinned layer, but the thickness variation along the free layer is relatively small. In fact, the gradual variation near the junction edge is the outside of the shadow mask and may arise from edge effects during deposition using a mask.[19] As the inset of Fig. 3 shows, the variation along the *y* axis could be fitted with the following quadratic equation:

$$-33.7 + 1.08x - 1.07 \times 10^{-2}x^2 + 4.70 \times 10^{-5}x^3 - 7.79 \times 10^{-8}x^4 (x \text{ is distance in units of } \mu m).$$

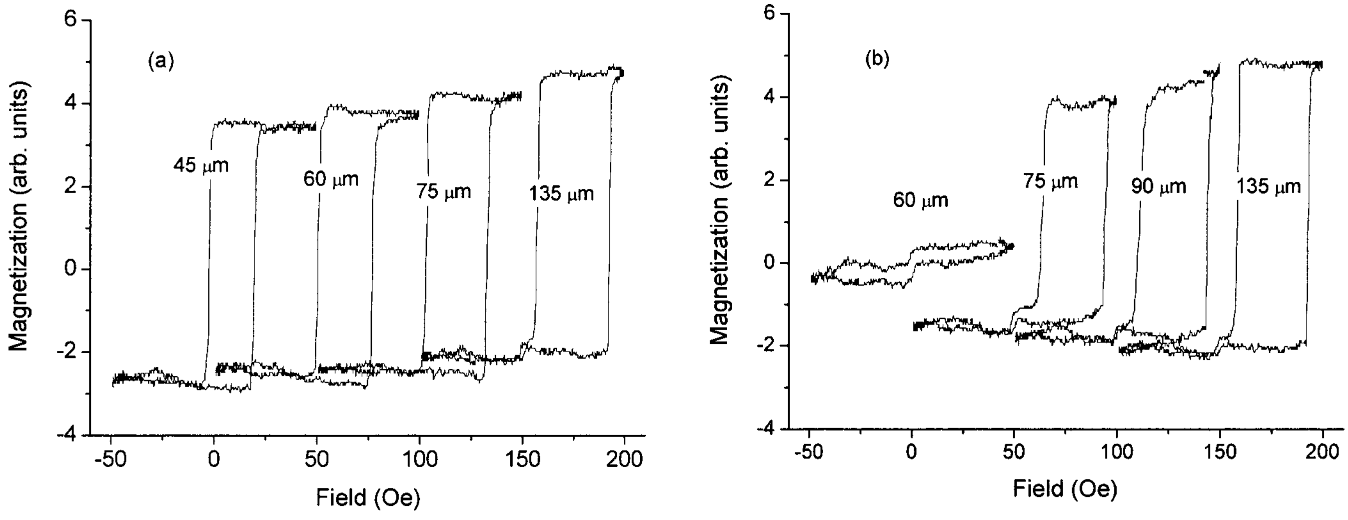

FIG. 2. *M-H* loops for different measuring points along (a) the *x* axis and (b) the *y* axis. The *x* and the *y* axes are the directions of the free layer and the pinned layer, respectively.

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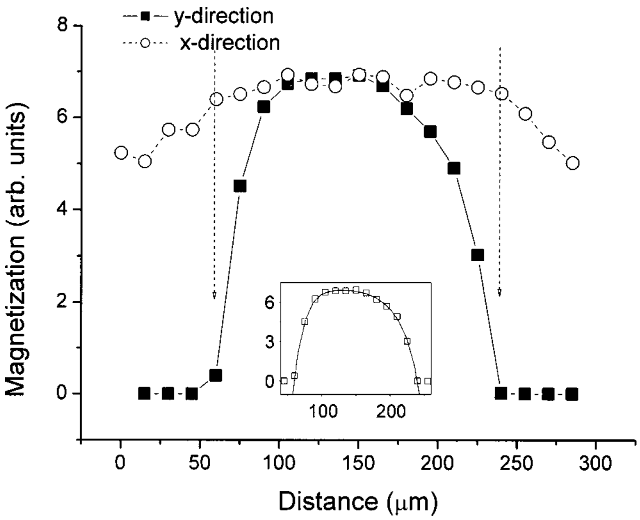

FIG. 3. Variation of the magnetization along the x- and the y-axis directions. The thickness of the free layer, fitted by a quadratic equation, is given by $-3.37\times10+1.08x-1.07\times10^{-2}x^2+4.70\times10^{-5}x^3-7.79\times10^{-8}x^4$ (x is distance in units of μm).

Figure 4 shows the change in the thickness profile of the total stack along the x axis (crossing the pinned layer), as measured by using an α-step thickness profilometer (TENCOR 500 model). The gradual variation of the profile near the edge spans a distance of up to 100 μm from the edge, irrespective of the junction size.[22,23] Even though the profile is affected by the relative bluntness of the tip of the profilometer, we can still determine the gradual variation of thickness from edge, as schematically depicted in the inset of Fig. 4. This thickness variation could be fitted with the quadratic equation

$$-7.46\times10^2+3.15\times10x-3.33\times10^{-1}x^2+1.66\times10^{-3}x^3-3.25\times10^{-6}x^4 (x \text{ is distance in units of } \mu m).$$

The variations of H_C and H_E along the x axis and the y axis are shown in Figs. 5(a) and 5(b), respectively. In Fig. 5(a), the zero value of H_E gradually increases to 25 Oe at the junction center. The value of H_C outside the junction is 7.5 Oe, which corresponds to the intrinsic coercivity of CoFe. H_C along the x axis increases to 15 Oe at the junction center, indicating an enhancement of H_C by 7.5 Oe. In Fig. 5(b), H_E exhibits a ridge-type variation along the y axis, but H_C is nearly constant.

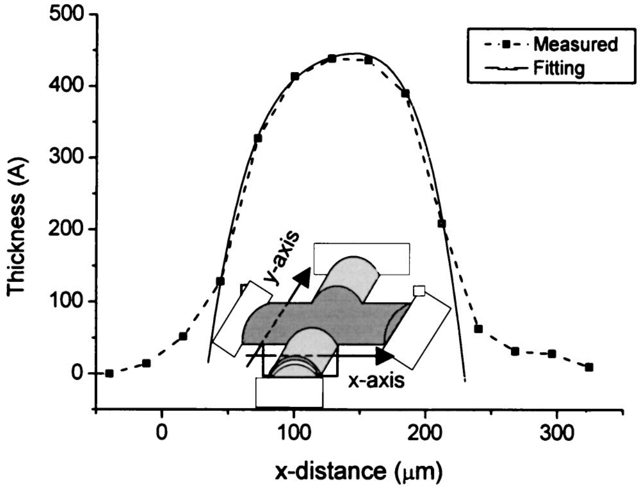

FIG. 4. Variation of the total film thickness, as checked by using an α-step profilometer, fitted to the following quadratic equation: $-7.46\times10^2+3.15\times10x-3.33\times10^{-1}x^2+1.66\times10^{-3}x^3-3.25\times10^{-6}x^4$ (x is distance in units of μm). The variation in the thickness of the pinned layer is evaluated by normalizing the total thickness of the stack.

The exchange coupling on the FM layer invokes interlayer coupling of an orange-peel type between the pinned-FM and the free-FM layers, and H_E can be represented as a function of the surface roughness and the film thickness as follows:[24]

$$H_E = M_p f(r) g(t_s,t_P) h(t_F),$$

$$f(r) = \frac{\pi^2 r^2}{\sqrt{2}\lambda},$$

$$g(t_s,t_P) = \exp(-2\pi\sqrt{2}t_s/\lambda)[1-\exp(-2\pi\sqrt{2}t_P/\lambda)],$$

$$h(t_F) = \frac{[1-\exp(-2\pi\sqrt{2}t_F/\lambda)]}{t_F}, \qquad (1)$$

where r and λ are the height and the wavelength of the sinusoidal roughness, respectively, t_F, t_P, and t_S are the thicknesses of the free, the pinned, and the insulating layers, respectively, and M_p is the saturation magnetization of the pinned layer. Here, the function is written as a multiple of individual functions $f(r)$, $g(t_P,t_S)$, and $h(t_F)$, which depend on the parameters r, t_P, t_S, and t_F.

The roughness seems to have a symmetric variation in range from 2.5 Å to 5.8Å with respect to the center of the pinned layer's axis.[25,26] However, because of difficulty positioning the AFM tip accurately, expressing that variation in terms of an appropriate equation was not attempted, so we used a constant value of 5.6 Å for the surface roughness in the calculation.

The insulating layer's thickness t_S is assumed to be a constant 15 Å because its area is much larger than the junction area, as shown in Fig. 1. If t_P is varied according to the quadratic function in Fig. 4, the values of H_E can be calculated along the x axis by using $f(r=5.6\text{ Å})\times g(t_P,t_S=15\text{ Å})\times h(t_F=25\text{ Å})$ and are compared with the measured values in Fig. 5(a). Here, the wavelength of the roughness profile corresponds to the grain size of polycrystalline IrMn$_3$, whose value has been measured to be 100 Å.[27] The calculated value at the center nearly equals the measured H_E if M_p is given the nominal value of 1300 emu/cc for CoFe as the fitting value. On the whole, the calculated H_E along the x axis gives reasonable agreement with the measured H_E, but some deviation of the calculated values from the measured values is observed near the edges and might be due to the surface roughness having a smaller value near the edge than it does at the center. The measured H_C variation is similar to the measured H_E variation, indicating that the H_C enhancement mechanism has some commonality with that of H_E in the dipole interaction of the "orange-peel" model.

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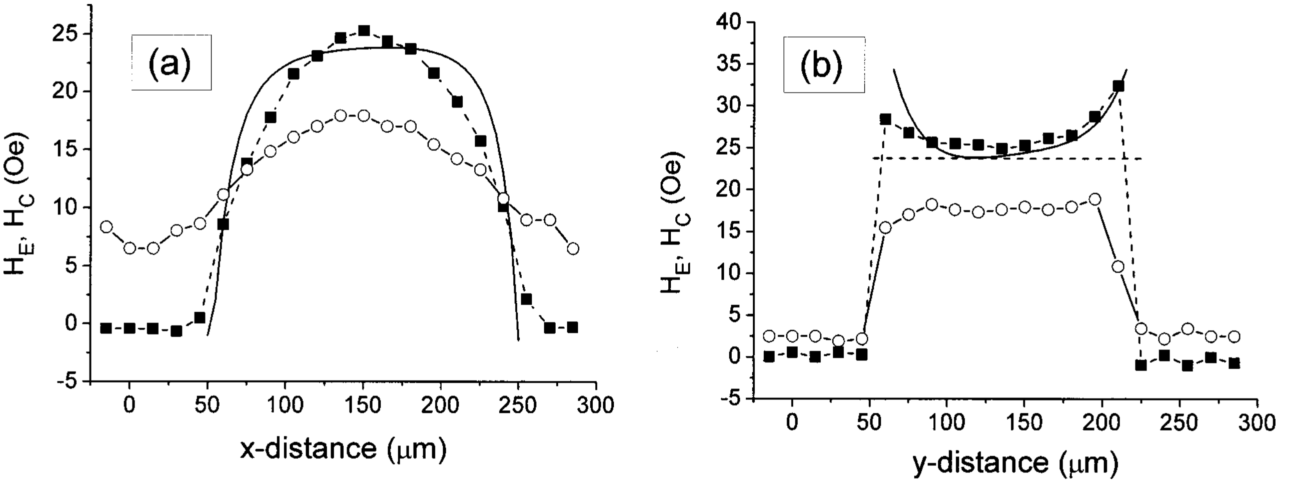

FIG. 5. Comparison of the measured H_E (■) and H_C (○) and the calculated H_E (a) along the free layer [solid line: $f(r=5.6\ \text{Å})\times g(t_P,t_S=15\ \text{Å})\times h(t_F=25\ \text{Å})$] and (b) along the pinned layer [solid line: $f(r=5.6\ \text{Å})\times g(t_P=25\ \text{Å},t_S=15\ \text{Å})\times h(t_F)$, dotted line: $f(r=5.6\ \text{Å})\times g(t_P=25\ \text{Å},t_S=15\ \text{Å})\times h(t_F=25\ \text{Å})$]

The free layer's thickness t_F influences the variation of H_E along the y axis. When t_F is varied according to the quadratic equation in Fig. 3, the calculation gives a ridge-type curve with peaks at the junction edges, as shown in Fig. 5(b). However, if the thickness of the free layer t_F is assumed to be constant (25 Å) along the y axis, the calculated value of H_E is constant. Thus, H_C measured along the y axis, which reflects the t_F dependence, is nearly constant, which indicates that free layer's thickness is not involved in the mechanism for enhancing H_C and that the enhancement mechanisms for H_C and H_E are different.

IV. CONCLUSION

The local variations of the enhanced coercivity H_C and of H_E along the direction of the free layer follow similar trends, and H_E can be reasonably described by using orange-peel coupling with a gradual variation in the thickness of the pinned layer. The increase in H_E at the edge along the pinned layer is due to a gradual decrease in the free layer's thickness near the edge. However, the nearly constant value of H_C along the pinned layer indicates that the free layer's thickness is not involved in the mechanism for enhancing H_C. From these analyses, H_C enhancement could be due to a magnetostatic coupling of domain walls in the free layer with stray fields from the pinned-FM layer; these fields may originate from the orange-peel dipole of domain walls in the pinned-FM layer. However, a more elaboratate calculation is required to fully understanding the H_C enhancement mechanism.

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