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High Exchange Coupling Field and Thermal Stability of Antiferromagnetic Alloy NiMn Spin Valve Films

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NiMn-pinned spin valve films consisting of a layered glass/NiFe/Co/Cu/Co/NiFe/NiMn/Ta stack were made by dc magnetron sputtering. After deposition, the structure was annealed in a series of cycles each including three hours at 220 °C, 2×10^{-6} Torr, in a field of 350 Oe, to create an ordered antiferromagnetic structure in the NiMn layer and produce a strong unidirectional pinning field in the pinned magnetic layer. Optimum spin valve properties were obtained after seven annealing cycles, or 21 hours at 220 °C, and were : MR ratio 1%, exchange coupling field 620 Oe, and coercivity of pinned layer 250 Oe. The exchange coupling field remained constant up to an operating temperature of 175 °C, and the blocking temperature was about 380 °C.

1. Introduction

There has been considerable interest in spin valve (SV) films, since they have been shown to be candidates for high density read heads in hard disk drives because of their high sensitivity, and because their relatively simple structure should be suitable for mass production [1]. In general, an SV has a sandwich structure consisting of two magnetic layers separated by a non-magnetic layer (Cu) [2]. One of the magnetic layers is called the pinned layer, since it has high coercivity and maintains a fixed direction of magnetization through exchange coupling with an adjacent antiferromagnetic (AFM) layer, called the pinning layer. The other magnetic layer, separated from the first by a non-magnetic layer, is called the free layer, since its direction of magnetization rotates in response to an external magnetic field. In the SV structure, a giant magnetoresistance (GMR) effect, which depends on the angle between the magnetization in the two layers, becomes the sensor output.

An exchange coupling field, or pinning field, greater than ~300 Oe is required to keep the magnetization direction of the pinned layer unchanged during the operation of the GMR spin valve sensor [3]. Various AFM materials, such as FeMn and NiO, have been used as pinning layers. [4, 5]. However, some limitations are found: some materials have an exchange coupling field H_{ex} greater than 300 Oe at room temperature, but none retain this value at 120 °C, which is the anticipated operating temperature of a practical head [6]. Moreover, due to the temperature rise caused by electrostatic discharge and Joule heating by the sensor current, magnetization reversal of the pinned layer may occur around 250 °C, if the blocking temperature B_T of the AFM layer is low [7, 8]. It is therefore desirable to have an AFM material with a blocking temperature above 300 °C.

The alloy NiMn is a strong candidate for the AFM pinning layer, having the advantages of high exchange coupling field, high B_T, good corrosion resistance, and low cost. However, it requires a high temperature annealing step to develop the AFM structure, and this annealing process destroys the GMR effect in a typical SV.

In December 1996, S. Mao *et al.* of Seagate Technology fabricated by ion beam sputtering an SV having the structure: substrate/Ta/NiFe/Co/Cu/Co/NiFe/NiMn/Ta. They used a 42 at% Ni NiMn alloy for the pinning layer, annealed at 240 to 280 °C for 45 hours at a base pressure of 2×10^{-8} Torr. They reported an MR ratio of 4%, H_{ex} of 660 Oe, and B_T of 380 °C [9]. In 1997, Xavier Portier *et al.* of Oxford University produced a similar SV by dc magnetron sputtering at 220 °C, which had MR ratio 6%, H_{ex} of 420 Oe, and a free layer coercivity of 8.6 Oe [10].

In this paper, differing somewhat from the experiment of Mao *et al.*, we report the fabrication of an SV by dc magnetron sputtering, with the following structure : glass/NiFe (70)/Co(10)/Cu(35)/Co(15)/NiFe(35)/NiMn(250)/Ta(50), with 25 at% Ni NiMn alloy as the pinning layer. We have investigated the effect of cyclic annealing treatments on the magnetic, magnetoresistive, and structural properties of the device.

2. Experiment

An SV structure as described above was made by multi-target dc magnetron sputtering under a pressure of 1.5×10^{-6} Torr with Ar partial pressure of 5 mTorr. The layers were sequentially deposited at a rate of 1.5 to 2 Å/sec. During the deposition, a field of 80 Oe was applied in the film plane. The pinning film was deposited from a 25 at% Ni NiMn alloy target on Corning 7059 glass. After the sample was prepared by sputtering, it was subjected to a series of annealing cycles in order to create antiferromagnetic ordering in the NiMn layer and thus develop exchange coupling between the NiMn pinning layer and the NiFe pinned layer. Each annealing cycle consisted of the following steps, controlled by a programmable temperature controller: heat in one hour to 220 °C; hold at 220 °C for three hours; cool to room temperature in five hours. The pressure during the annealing cycle was 5×10^{-6} Torr, and a field of 350 Oe was applied in the film plane. Magnetic, magnetoresistive, and structural properties could be measured at room temperature after each cycle. The MR curve was drawn using a four-probe method. X-ray diffraction (Bruker D8 Advance Type) was used to determine crystal structure, and scanning probe microscopy (Park Scientific Autoprobe CP Type) was used to measure surface roughness.

3. Results and Discussion

3.1. Crystal Structure and Surface Morphology

Figure 1 shows the CuAu-I ($L1_0$) ordered tetragonal structure, consisting of alternating planes of Mn and Ni atoms, and the ordered NiMn phase spin arrangement. Strong exchange anisotropy can be expected from the growth of the NiMn (100) plane parallel to the film plane, since the spins in the (100) plane are aligned in a single direction. Here Ni atoms have no spin configurations by nonmagnetic site role in antiferromagnetic phase. It is reported that the Néel temperature of the ordered NiMn is around 800 °C, so in the SV using a NiMn pinning layer we expect high B_T and high H_{ex} after an annealing treatment to produce antiferromagnetic ordering in the NiMn layer.

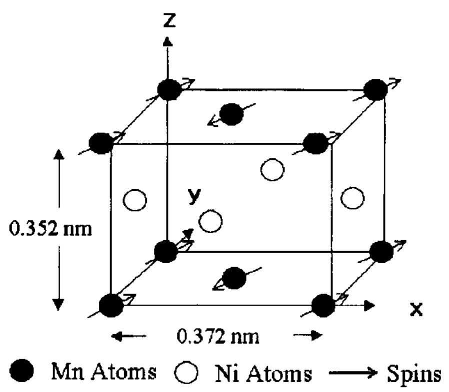

Fig. 1. Crystal structure of NiMn ordered unit cell. Because the alloy target used in the pinned layer is 25 at% Ni, the real antiferromagnetic layer is a difference in the ideal CuAu-I (110) ordered NiMn crystal structure.

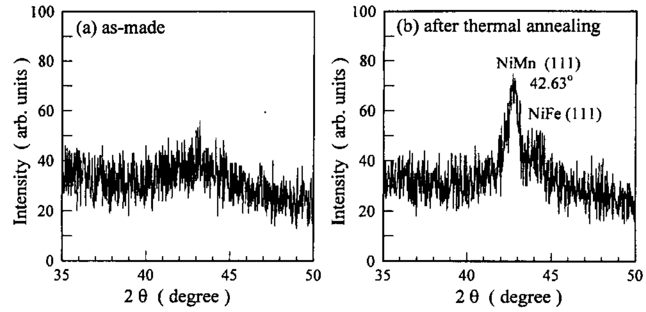

Fig. 2. X-ray diffraction scan patterns for the NiMn-pinned spin valve film of (a) as-made and (b) after 7th annealing.

Figures 2(a) and (b) show the X-ray diffraction patterns of the as-prepared and annealed (seven cycles) samples. The pattern in Fig. 2(a) appears to be amorphous (non-crystalline), while in Fig. 2(b) we see the (111) peak of the fct ordered NiMn plus a weaker peak attributed to the (111) of NiFe, plus possible contributions from the (111) of Cu and Co. This confirms the production of AFM NiMn by annealing the as-deposited structure and the possibility of exchange coupling between the NiMn and NiFe layers [11, 12].

Figures 3(a) and (b) show the surface roughness of the SV structure, measured by a scanning probe microscope, before and after annealing. The as-prepared surface is rough, due to the low atomic mobility resulting from deposition at room temperature, but after vacuum annealing for a total of 21 hours, the surface roughness is greatly reduced.

3.2. Magnetic and magnetoresistive properties

Magnetic hysteresis loops measured parallel to the easy axis of the SV structures are shown before and after annealing in Figs. 4(a) and (b), and major and minor MR curves are shown after annealing (seven cycles) in Fig. 4(c). In Fig. 4(a) there is no exchange coupling between the NiMn pinning layer and the NiFe pinned layer. However, in Fig. 4(b), there is an obvious shift in the upper half of the hysteresis loop. The values of H_{ex} and H_c of the pinned layer are found to be 600 Oe and 280 Oe, respectively. A corresponding result is obtained from the major MR curve of Fig. 4(c).

Fig. 5 shows the major and minor MR curves after five annealing cycles, or a total of 15 hours at 220 °C. Here, H_{ex} and H_c of the pinned layer are 560 Oe and 280 Oe, respectively. From this, it is found that the interlayer coupling field between the free layer and the pinned layer is about 30 Oe, and the coercive field of the free layer is 15 Oe. In addition, we note that the pinned layer, which is critical for the operation of an SV head, shows very stable MR properties. There is no change in behavior caused by applied fields up to about 600 Oe.

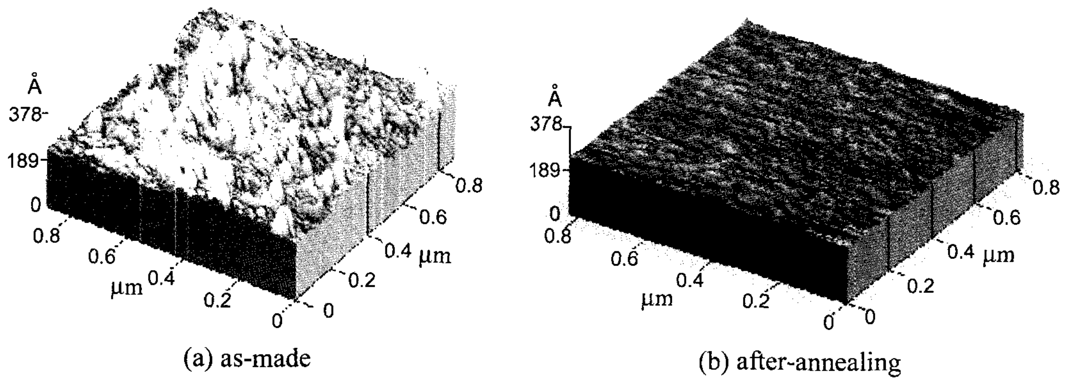

Fig. 3. SPM Topography of the NiMn-pinned spin valve film for (a) as-made and (b) after 7th annnealing.

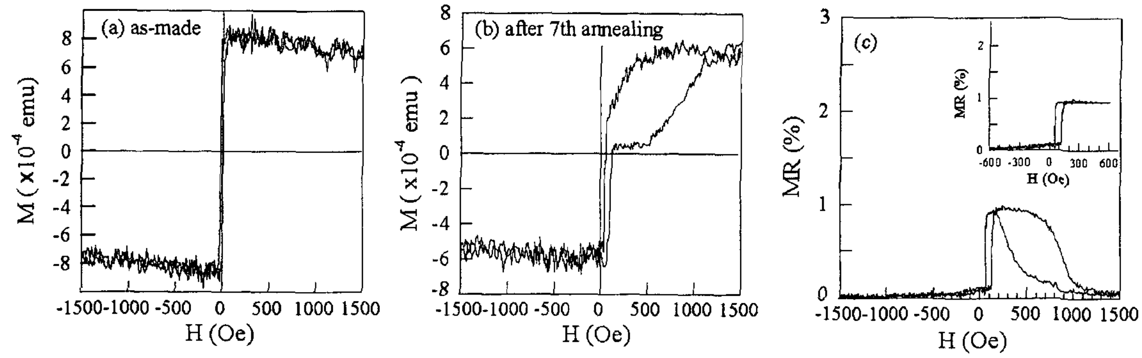

Fig. 4. Magnetization curves of (a) as-made, and (b) after 7th thermal annealing for the NiMn-pinned spin valve film. (c) is major and minor MR curves of the spin valve after 7th annealing.

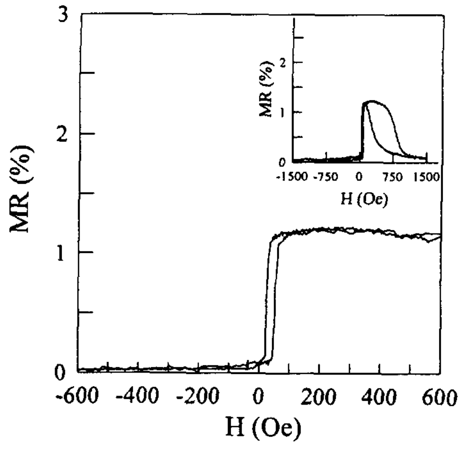

Fig. 5. Major and minor MR curve of the NiMn-pinned spin valve film after 5th thermal annealing.

3.3. Varying the Number of Annealing Cycles

Figure 6 shows the MR curves of the SV as-prepared, and after increasing numbers of annealing cycles. The as-prepared sample shows no exchange coupling. After one annealing cycle, exchange coupling appears, and the MR ratio is about 2.5%. After the third annealing cycle, the MR ratio decreases slightly, and the curves become relatively stable with H_{ex} and H_c values of 420 Oe and 350 Oe, respectively. After seven cycles, the MR ratio is about 1%, H_{ex} has its maximum value of 620 Oe, and H_c is 250 Oe.

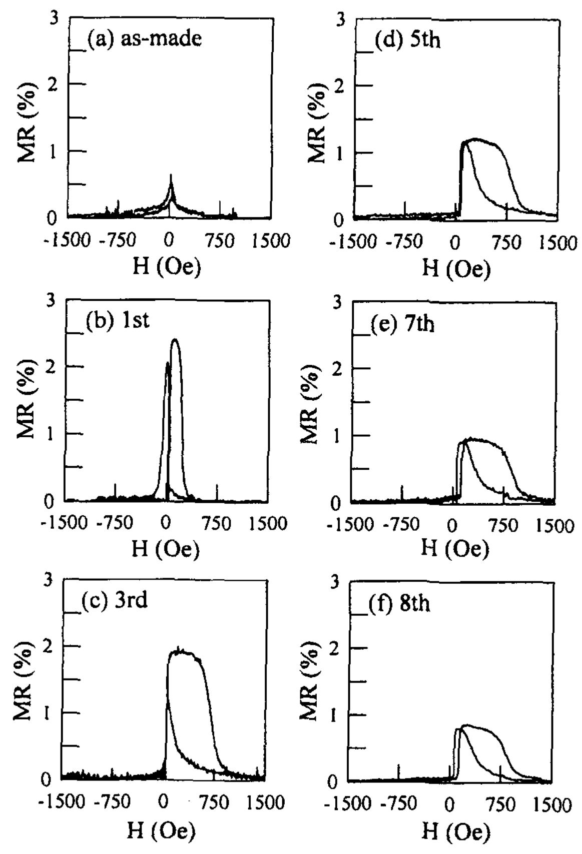

Fig. 6. MR curves of the spin valve film with annealing cycles.

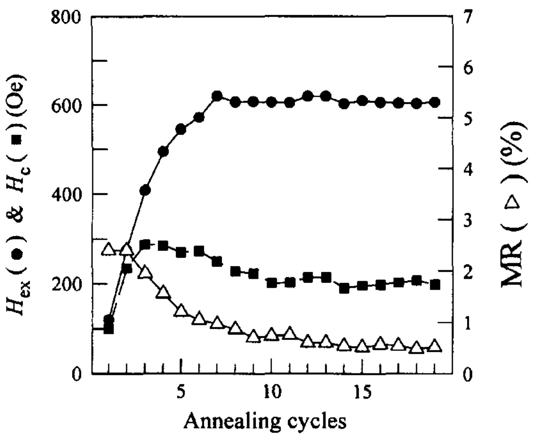

Fig. 7. Annealing cycles dependence of H_{ex}, H_c and MR ratio for the NiMn-pinned spin valve film.

After further cycles, H_{ex} and H_c remain about the same, but the MR ratio decreases. The decrease in MR ratio may be due to interdiffusion of the layers, increasing the shunting current in the NiMn layer causing loss of spin information.

Figure 7 shows the dependence of H_{ex}, H_c, and MR ratio on the number of annealing cycles. It is seen that H_{ex} first increases linearly and reaches a maximum value of 620 Oe after seven cycles, after which it remains constant. The value of H_c reaches 280 Oe after three cycles, and remains above 250 Oe even after almost 60 hours at 220 °C. The blocking temperature must be much higher than 220 °C.

3.4. Blocking temperature

For use in an SV read head, the exchange coupling field should be greater than 300 Oe, and H_{ex}, H_c, and MR ratio should not be affected by temperatures of 200 °C during device production, or temperatures of 200 to 250 °C produced by electrostatic discharge or sensing current during device operation [7, 8]. Consequently, the temperature dependence of the pinning field and of the coercivity of the pinned layer are important. Figure 8 shows the blocking temperature of our SV, and the temperature dependence of H_{ex} and H_c, in an SV film previously subjected to seven annealing cycles. The pinning field remains constant at 620 Oe up to 175 °C, and then falls to zero at 380 °C. The value

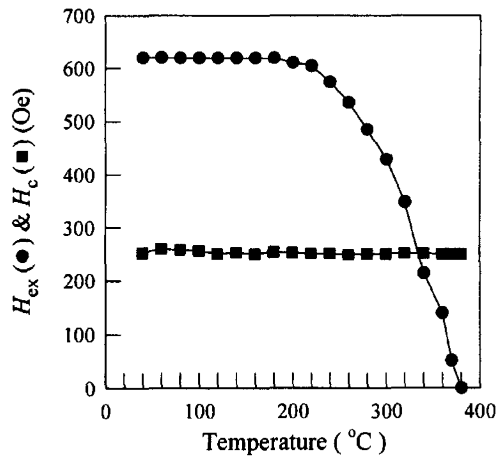

Fig. 8. Temperature dependence of H_{ex} and H_c for the pinned layer.

of H_c remains constant at 250 Oe, independent of temperature up to the highest temperature measured.

Table 1 compares the results of this work with those of Mao *et al.* and of Portier *et al.* on similar SV structures. Our total annealing time is shorter than that of Mao *et al.*, but our maximum H_{ex} of 620 Oe is slightly lower than their 650 Oe. Our MR ratio is inferior to Portier *et al.*'s value of 6.3%, but our value of H_{ex} is much higher than their 420 Oe. Our SV structure shows high thermal stability, indicating its suitability for use as a read head.

4. Conclusions

We have fabricated an SV structure by dc magnetron sputtering using 25 at% Ni NiMn as the pinning layer, and examined its magnetic, magnetoresistive, and structural properties after various numbers of annealing cycles at 220 °C.

1. An SV film structure consisting of: glass/NiFe(70)/Co(10)/Cu(35)/Co(15)/NiFe(35)/NiMn(250)/Ta(50), with 25 at% Ni NiMn alloy as the pinning layer, annealed a total of 21 hours at 220 °C in a field of 350 Oe, shows MR ratio about 1%, H_{ex} of 620 Oe, and H_c of 250 Oe.

2. This SV structure withstands thermal treatments up to

Table 1. Magnetic and MR properties of NiMn-Pinned Spin-Valves

Structure thickness (Å)	at.% Ni in NiMn	Sputter. Method	Depos. Field (Oe)	Base Pres. (Torr)	Anneal. Field (Oe)	Anneal. Temp. (°C)	Anneal. Time (hr)	H_{ex} (Oe)	H_c (Oe)	MR (%)	B_T (°C)	H_{cf} (Oe)	Remarks
sub/Ta_{25}/$NiFe_{55}$/Co_{15}/ Cu_{30}/Co_{15}/$NiFe_{25}$/ $NiMn_{200}$/Ta_{80}	42	Ion Beam	–	2×10^{-8}	-	240 ~280	45	~650	350	4.0	380	7	S. Mao *et al.* [9]
sub/$NiFe_{65}$/Co_{15}/ Cu_{30}/Co_{20}/$NiFe_{30}$/ $NiMn_{250}$/Ta_{50}	–	dc magnetron	70	–	1000	220	–	420	–	6.3	–	8.6	Xavier Portier *et al.* [10]
sub/$NiFe_{70}$/Co_{10}/ Cu_{35}/Co_{15}/$NiFe_{35}$/ $NiMn_{250}$/Ta_{50}	25	dc magnetron	80	1×10^{-6}	350	220	21	620	280	2.5	370	15	present work

220 °C or higher.

3. The pinning field of the SV stays constant up to 175 °C and then decreases to zero at the blocking temperature of 380 °C. The coercivity of the pinned layer remains constant at 250 Oe up to 380 °C.

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