Magnetism of $Co_{1-x}Fe_x$-NOL in Specular Spin-Valves

Masaaki Doi, Masato Izumi, Hiromi Niu Fuke, Hitoshi Iwasaki, and Masashi Sahashi

***Abstract*—We investigated the magnetic properties of the $Co_{1-x}Fe_x$-natural oxidized nano-oxide layer (NOL) in the specular spin-valve system by precise measurement of magnetization at 77 K and M-T curves after field cooling at ±5 kOe. The result suggests the antiferromagnetic component behavior of the NOL and its Néel temperature (T_N) shifts to the higher temperature with increasing Fe composition. Below the T_N, the antiparallel spin configuration at the pinned layers is stabilized by the exchange bias field induced from antiferromagnetic component of NOL by the field cooling in negative field direction.**

***Index Terms*—Exchange coupling, giant magnetoresistance, nano-oxide layer (NOL), specular reflection, spin-valves.**

I. Introduction

TO CONTINUE to apply the giant magnetoresistive (GMR) spin valves sensor as an element of reading heads for the advanced recording densities in hard-disk drive, the increment of head sensitivity is required. To realize high sensitivity in CIP (current into the plane) configuration, the specular GMR spin-valve (SPSV) multilayer is attractive [1]. It is now well known that the introduction of a nano-oxide layer (NOL) in a SPSV multilayer is fairly effective to enhance the MR ratio [2]–[4]. However, the structural and magnetic properties of the NOL itself are still not clear because of its very thin thickness. Recently, $Co_{90}Fe_{10}$-NOL was reported as antiferromagnetic and the Néel temperature (T_N) is around 175 K [5], [6]. Understanding the NOL in an SPSV multilayer is of great interesting from the view point of the specularity of the electron and the magnetic exchange coupling in the spin-valve type multilayers. Beside the enhancement of the MR ratio, strong pinning field is also required for the application. Fig. 1 shows the typical structure of our synthetic SPSV with NOL. In order to keep the superior pinning effect (J_{ex}) from the antiferromagnetic (AFM) PtMn layer to CoFe (m_{p4}) layer, the NOL (m_{p3}) layer should provide strong ferromagnetic coupling between ferromagnetic m_{p4} and m_{p2} layers. It is necessary to clarify the magnetic properties of NOL to realize strong ferromagnetic coupling through NOL.

In this paper, we focus on investigating the magnetic properties of the NOL ($Co_{1-x}Fe_x$-natural oxidation) in the SPSV system by precise measurement of magnetization from 77 to 293 K (R.T.).

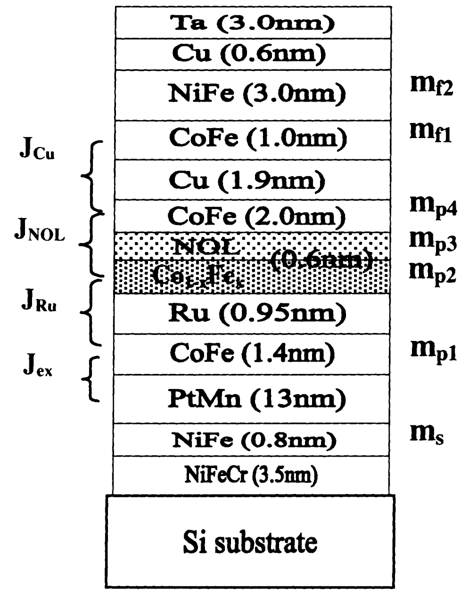

Fig. 1. Schematic diagram of a synthetic spin valve with specular NOL structure.

II. Experimental Procedure

The sequential sputtering method was used for the sample preparation. The typical design of the synthetic SPSV sample was underlayer (NiFeCr/NiFe)/PtMn/CoFe /Ru /$Co_{1-x}Fe_x(x = 0.08, 0.17, 0.26)$ /Cr /natural oxidation /CoFe /Cu /CoFe /NiFe /Cu /Ta on Si substrate (Fig. 1). The conventional natural oxidation process was carried out in an extra chamber [7]. The thickness of $Co_{1-x}Fe_x$ was 0.6 nm. All of the film were annealed at 270 °C for 1 h under a magnetic field of 7 kOe. Details of the sample preparation were given in [3] and [7]. It should be mentioned that the 0.08 nm of Cr layer was deposited on the surface of $Co_{1-x}Fe_x(m_{p2})$ for the improvement of the stability of NOL layer [8] while the without oxidation sample was prepared without Cr. The MR ratio and the flat area with high resistance of the R-H curve (H^{flat}) estimated from the extrapolated cross point of the flat line and decreasing slope line of R-H curve for each sample are listed in Table I. The flat area of the R-H curve corresponse to the antipallalell configration of the magnetization for the free layer (m_{f1}) and m_{p4}, which is stabilized by the total exchange coupling of J_{ex}, J_{Ru}, J_{NOL}, and J_{Cu}. MR ratio of the without NOL sample was 13%. In comparison, NOL inserted samples show constant

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TABLE I
MR RATIO AND THE H^{flat} ESTIMATED FROM R-H CURVE FOR WITHOUT NOL SV AND $Co_{1-x}Fe_x$-NOL SPSV SAMPLE

$Co_{1-x}Fe_x$	MR ratio(%)	H^{flat} (Oe)
X=0.08 Without NOL	13.0	<600
0.08	14.3	410
0.17	14.1	390
0.26	14.4	280

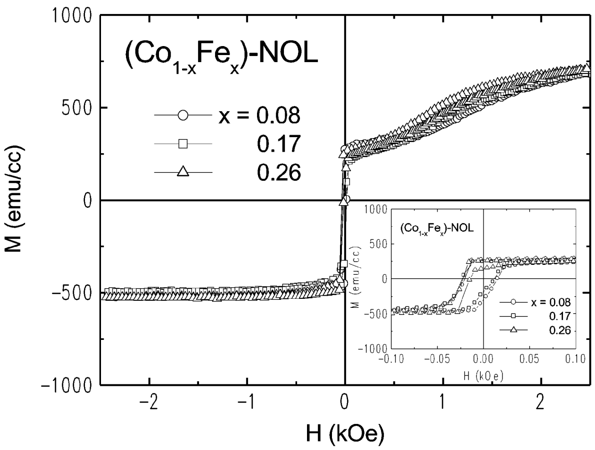

Fig. 2. Magnetization curve of SPSV with $Co_{1-x}Fe_x$-NOL at R.T. within the magnetic field of 2.5 kOe. Inset shows an enlargement at the low magnetic field.

value around 14%. Increment of MR ratio is caused by the specular effect of the NOL. However, the H^{flat} decreases with increasing of Fe composition. Taking into account that the variation of J_{Cu}, J_{Ru}, and J_{ex} with increasing Fe composition are negligible, the decrease of H^{flat} suggests the ferromagnetic coupling between ferromagnetic m_{p4} and m_{p2} layers through NOL (m_{p3}) layer is weakened for Fe-rich-NOL. Accordingly, magnetization process through J_{NOL} should be discussed within relatively low magnetic field. The magnetization was measured by conventional vibrating sample magnetometer (VSM) within the sample size of 10×10 mm. The temperature dependence of magnetization was measured in the magnetic field at 3 kOe and 300 Oe with heating rate of 1.2 C°/min. The field cooling effect (FC:$H = \pm 5$ kOe) was measured from room temperature to 77 K.

III. RESULT AND DISCUSSION

Fig. 2 shows the magnetization curve of SPSV with $Co_{1-x}Fe_x$-NOL $(x = 0.08, 0.17, 0.26)$ at R.T. within the magnetic field of 2.5 kOe. The value of the magnetization in this figure is described per volume of the magnetic layer (m). The decrease of the coercive force and the increase of the exchange coupling through Cu (J_{Cu}) in the negative sign were observed by the increment of Fe composition (see inset of Fig. 2). These results suggest that the roughness of CoFe(m_{f1})/Cu/CoFe(m_{p4}) interfaces are improved by the Fe-rich NOL. This result gives no explanation of the decreasing of H^{flat} with the increase of Fe composition. Further, the magnetization was measured at 77 K after the field cooling (FC) for the characterization of the magnetic properties of NOL and J_{NOL}. We defined the positive field direction parallel to the pinned field direction of AFM PtMn layer. Fig. 3 shows magnetization curves at 77 K for the $Co_{1-x}Fe_x$-NOL SPSV sample and the sample without oxidation after FC at $H = \pm 5$ kOe. No difference of the magnetization curve is observed for the sample without oxidation (Fig. 3). In contrast, the magnetization for the NOL introduced samples show a difference between field cooled at $+5$ kOe and -5 kOe in the positive applied field area. The smaller values of the magnetization are observed for the FC at -5 kOe in the positive applied field, compared to FC at $+5$ kOe. These results suggest that the m_{p2}, m_{p3}, and m_{p4} layers are stabilized in the negative direction by the negative FC process. This result can be explained as follows. If we assume NOL as antiferromagnetic, the high negative field cooling through T_N of the NOL should induce exchange bias effect in negative field direction. This effect leads to higher exchange coupling between m_{p2} and m_{p4} in negative field direction, which stabilizes antiparallel spin configuration at the pinned layers. In contrast, the positive field cooling induces exchange bias in the positive direction, which leads to unfavored parallel spin configuration of pinned layer. To confirm the AFM behavior of the NOL, FC M-T curves were measured (Fig. 4). The branch of the M-T curves is observed for Co_{1-x} Fe_x-NOL with $x = 0.08$ and 0.17, compare to the well agreement for the sample without NOL. It is considered that the branch point (shown by an arrow in the figure) corresponds to the

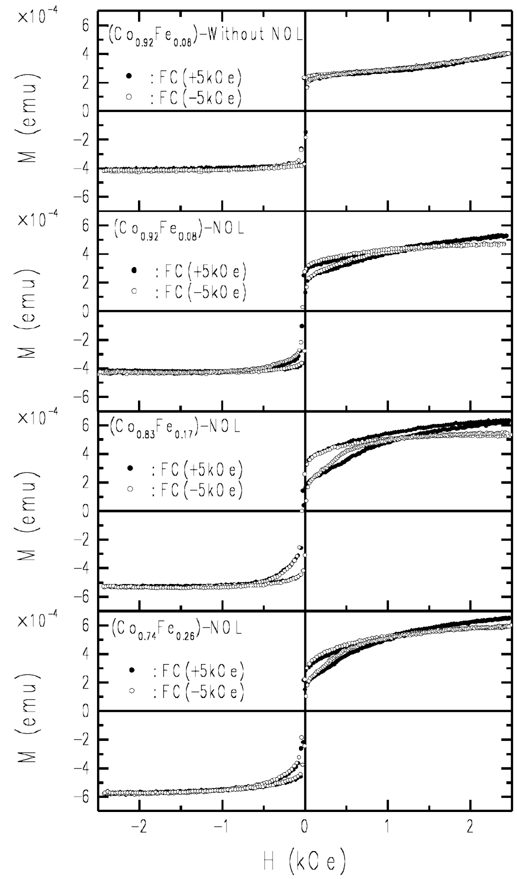

Fig. 3. Magnetization curves at 77 K for the $Co_{1-x}Fe_x$-NOL and without NOL SPSV sample after FC at $H = \pm 5$ kOe.

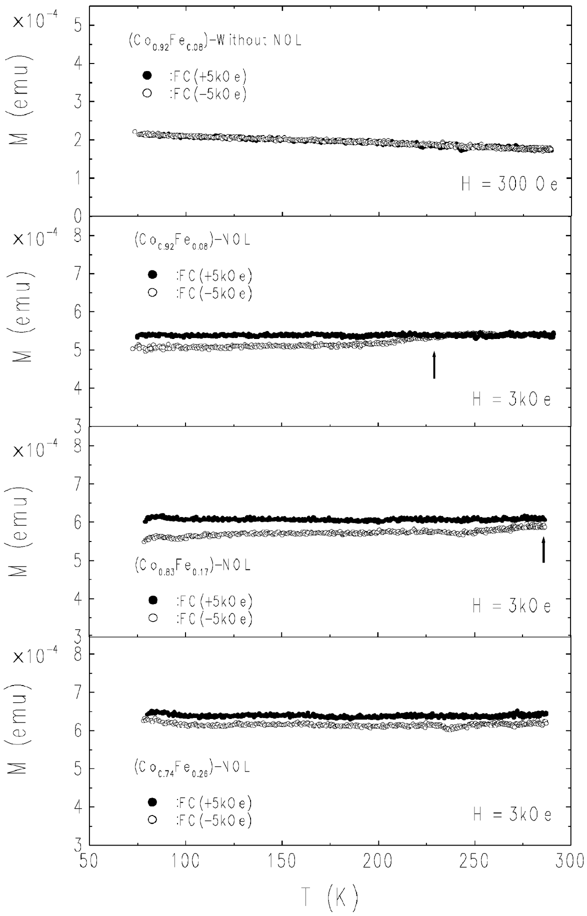

Fig. 4. M-T curves for the without NOL and $Co_{1-x}Fe_x$-NOL SPSV sample after FC at $\mathrm{H} = \pm 5$ kOe.

T_N of the AFM NOL because of the appearance of induced exchange bias field below T_N. It is clear that the T_N shifts to the higher temperature with increasing Fe composition. T_N of $x = 0.26$ sample is suggested to be above R.T. The reason of the increment of T_N with increasing Fe composition is not clear from this experiment. T_N might vary with the thickness of NOL or by the composition of Fe, Co, Cr, and O in the oxide compound. The composition of the oxide compound is likely a CrO_x, CoO, or Fe_2O_3, which may be a disordered phase or a phase substituted with other elements present in the film structure. In addition to the oxide compound, nonoxidized metallic area is partially observed by using our relatively soft oxidation process, which is confirmed by TEM observation [8]. The remained metallic ferromagnetic component maintains ferromagnetic coupling through J_{NOL}. On the contrary, the paramagnetic component above T_N weakens J_{NOL} which leads the decrease of the stability of antipallalell configration of the magetization between m_{f1} and m_{p4} layer. The existence of the AFM component at R.T. might be one possibility for the explanation of the rapid decrease of H^{flat} for Fe-rich sample. Further systematic measurements which include Mössbauer spectroscopy are now in progress to confirm more details of the structural and magnetic properties of the $Co_{1-x}Fe_x$-NOL.

IV. Summary

The magnetic properties of the $Co_{1-x}Fe_x$-natural oxidized NOL in the specular spin-valve (SPSV) system was investigated by precise measurement of magnetization at 77 K and M-T curves after field cooling at ± 5 kOe. The field cooling effect is observed. This result suggests that the antiferromagnetic component exists in the NOL and its Néel temperature (T_N) shifts to the higher temperature with increasing Fe composition. To realize both high specularity and stable ferromagnetic coupling through J_{NOL} in the synthetic SPSV, the NOL should be uniformly ferromagnetic without paramagnetic or antiferromagnetic component.

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