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Magnetoresistive and Pinning Direction Behaviors of Synthetic Spin Valves with Different Pinning Layer Thickness

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The pinning direction, the spin flop behaviors and the magnetoresistive properties in top synthetic spin valve structure [NiFe/CoFe/Cu/CoFe (t_{P2})/Ru/CoFe (t_{P1})/IrMn] were investigated. The magnetoresistive and pinning characteristics of synthetic spin valves strongly depended on the differences in the two pinning layer thickness, Δt (=t_{P2}-t_{P1}). In contrast to the conventional spin valves, the pinning direction (P1) was canted off with respect to the growth field axis with Δt. We found that the canting angle Φ had different values according to the annealing field direction and Δt. When the samples were annealed at above the blocking temperature of IrMn with zero fields, the canted pinned layer could be set along the growth field axis. Because the easy axis which was induced by the growth field during deposition is still active in all ferromagnetic layers except the IrMn at 250 °C, the pinning direction could be aligned along the growth field axis, even in 0 field annealing.

Key words : synthetic spin valve, canting, field annealing, magnetoresistive properties

1. Introduction

Synthetic antiferromagnet or ferrimagnet (SAF) based spin-valves (SV) have many advantages over the conventional spin-vales: higher effective exchange bias field, much smaller magnetostatic field effect of pinned layer, sharper distribution of blocking temperature, and etc. However, the canting of the pinned layer magnetization with respect to the growth field axis usually occur in SAF SVs in the as-deposited state because they have strong exchange coupling and spin flop occurs due to the applied growth field during deposition [1, 2].

The pinning direction of SAF SV varies in accordance with the pinned layer thickness difference and the growth order of the layers [1]. During deposition of the layers, the magnetization direction of the thicker ferromagnetic layer of the two ferromagnetic layers will be parallel to the growth field. The thinner ferromagnetic layer will then rotate opposite to the growth field direction in order to make its magnetization antiparallel due to the strong antiferromagnetic exchange coupling. This results in canting of the magnetization direction of the pinned layer. The canted magnetization direction of the pinned layer reduces the MR ratio and also affects the pinning field strength. Consequently, the precise determination and control of the pinning direction are important to obtain optimal properties and sensing characteristics of the sensors.

Although several studies have been carried out to clarify the pinning direction [1] and the spin flop [1, 2] of the SAF SVs, little attention has been paid to the pinning behaviors of SAF SVs with various pinning layer thickness differences, Δt (=t_{P2}-t_{P1}).

In this report, we studied the magnetoresistive properties and pinned layer canting behavior of SAF SVs with various thickness differences, Δt (=t_{P2}-t_{P1}). In particular, we established the annealing conditions for controlling the canting angle of the pinned layer.

2. Experiment

Synthetic top SV films consisting of Si/Al_2O_3/Ta 5/$Ni_{81}Fe_{19}$ 3.2/$Co_{90}Fe_{10}$ 1.7/Cu 2.8/CoFe (t_{P2})/Ru 1/CoFe (t_{P1})/$Ir_{21}Mn_{79}$ 11/Ta 5 (thickness unit in nm) were prepared by a dc magnetron sputtering with base pressure below 8×10^{-9} Torr. Thickness of the P1 layer (t_{P1}) was fixed at 2 nm and thickness of the P2 layer (t_{P2}) changed from 1 to 3 nm. In other words, Δt (=t_{p2}-t_{p1}) were varied from −1 nm to +1 nm. Each layer was deposited with rates of 0.6~1.7 Å/s under 2~5 mTorr Ar pressure. During deposi-

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tion of the ferromagnetic layers, a growth field of 150 Oe was applied to the film in plane and the direction of the growth field for free and pinned layers was orthogonal. Some of the samples were annealed at 200 °C and 250 °C for 1 hr under pressure below 5×10^{-6} Torr under the annealing field (0~2 kOe) parallel and opposite to the growth field direction.

The magnetoresistive properties and magnetization of samples were measured by a dc-four point probe method and a vibrating sample magnetometer (VSM) at room temperature, respectively. At the same time, in order to study the pinning direction and flop behaviors of samples with various Δt, the MR curves were measured by rotating the samples clockwise with respect to growth field direction.

3. Results and Discussion

Fig. 1 shows MR curves of the SAF SVs with different Δt (=0, +0.5, +1). As the Δt increased, MR ratio increased, but the effective exchange field, H_{eex} decreased. In addition, it was observed that the tail (indicated by the circle) was present in a zero field for samples with Δt=0 nm and disappeared with increasing Δt. The tail indicated that the pinning direction of the P1 layer was not perfectly aligned to the growth field axis, that is, the pinning direction (P1) was canted with respect to the growth field direction. To measure the exact canting angle, MR curves were measured by rotating the samples clockwise with respect to the growth field axis.

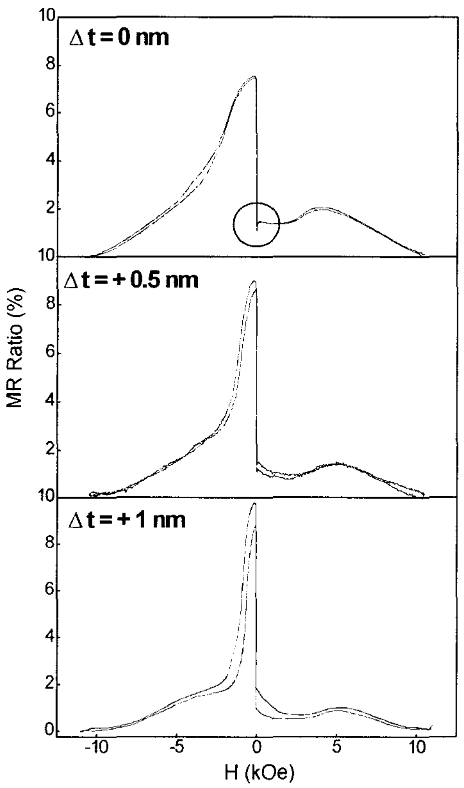

Fig. 1. MR curves of as-deposited synthetic ferrimagnet SVs with various Δt (=t_{P2}-t_{P1}). (Δt = 0, +0.5, +1 nm).

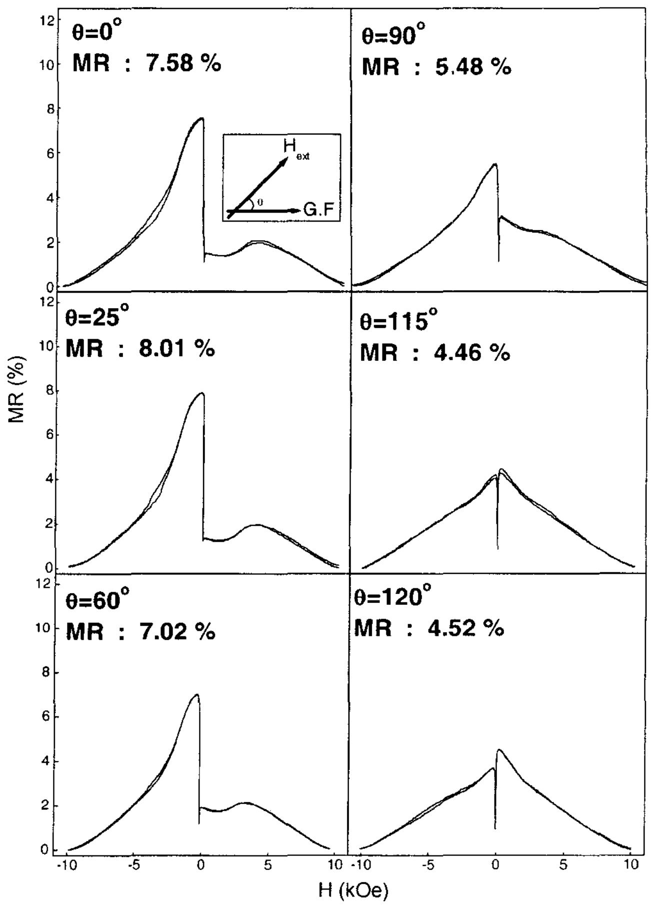

Fig. 2. Angular dependence of MR curves in as-deposited synthetic SV for Δt = 0 nm. θ is the angle between the external field and the growth field.

Fig. 2 shows MR curves of samples with Δt=0 nm as a function of the angle θ. The θ was the angle between the external field and the growth field direction. Since the pinning direction was unidirectional, the MR curves of the SAF SVs didn't appear symmetric when the external field was applied to the pinning axis. If the external field was applied orthogonal to the pinned direction, we should obtain a symmetric MR curve. But for samples with Δt=0 nm, we obtained a symmetric MR curve at about θ=115° as shown in Fig. 2. This means that the pinning direction was canted about 25° off from the growth field axis. Therefore, the maximum MR ratio of 8.01% was obtained at θ=25°. The angle θ where the maximum MR ratio appears represents the exact pinning direction with respect to the growth field axis.

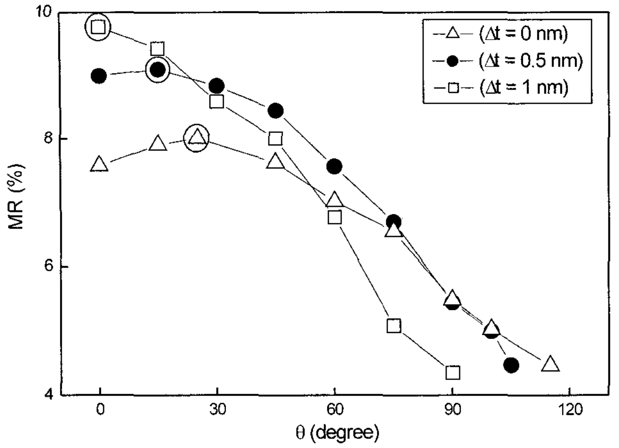

Fig. 3. MR ratio variation as a function of θ (angle between the external field and the growth field) for t = 0, +0.5 and +1 nm for as-deposited synthetic ferrimagnet SVs.

MR ratio variations as a function of the θ in accordance with Δt are summarized in Fig. 3. The angle θ where the maximum MR ratio appeared were 25°, 15° and 0° for SVs with Δt=0, 0.5 and 1 nm, respectively. The canting angles of the pinning direction with respect to the growth field axis depended largely on the Δt [1]. The angle θ becomes larger as the Δt approaches to 0 in the as-deposited state because the spin flop by the applied growth field during deposition occurs in order to minimize the Zeeman energy [1, 2]. As Δt increases, the P2 layer becomes more stable in the growth field direction so that the angle θ gets smaller. The canting of pinned layer P1 was diminished when $\Delta t \geq +1$ nm.

Fig. 4 shows the canting angle Φ variation with respect to growth field direction as a function of Δt. The samples were annealed at 200 °C and 250 °C for 1 hr with a 2 kOe field applied either parallel or antiparallel to the growth field direction. The canting angle Φ was defined as the angle between P1 layer and the growth field direction. The canting angle 180° means that P1 layer aligned in the growth field axis but antiparallel to the growth field direction. Thus, canting angles Φ of the as-deposited samples with Δt=0, +0.5 and +1 nm were 155°, 165° and 180°, respectively. The canting angle Φ approached near orthogonal direction with respect to the growth field axis if the samples with Δt=0 were annealed at 250 °C. This is because the spins in SAF with Δt=0 would flop when an proper external field was applied to the growth field axis above the blocking temperature of antiferromagnet, IrMn. The spin flop behavior of the SAF under a magnetic field has been theoretically predicted by Zhu *et al.* [3, 4]. The magnetization directions in SAF with Δt=0 are aligned orthogonal to the applied field to minimize the total energy consisting of interlayer coupling energy, the Zeeman energy, and uniaxial anisotropy energy [5-7]. When an annealing field was applied parallel to the growth field direction, the canting decreased with increasing Δt. This is because an annealing field exerted a torque on a net magnetization (M_{p2}-M_{p1}), so that the P2 layer rotated more parallel to the growth field direction. On the other hand, when an annealing field was applied opposite to the growth field direction, the P2 layer rotated opposite to the growth field direction. The variation of the canting angle Φ with Δt annealed at 200 °C is similar to that annealed at 250 °C, but the amount of change is small because the exchange coupling between IrMn and the pinned CoFe layer (P1) still exists up to that temperature.

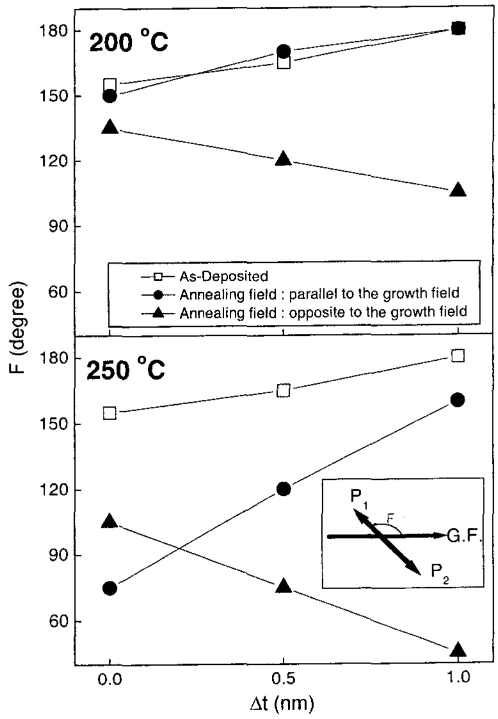

Fig. 4. Pinning direction (P1) variation of as-deposited and annealed samples as a function of Δt. Φ is the angle between the pinning direction (P1) and the growth field. a) Annealing with external field of 2 kOe at 200 °C for 1 hr. b) Annealing with external field of 2 kOe at 250 °C for 1 hr.

Fig. 5. shows the canting angle Φ variation as functions of an annealing field and Δt. The samples were annealed at 250 °C for 1 hr and the fields were applied the growth field direction. As the annealing field reduced, the canting angles approached 180°. When the samples were annealed under no magnetic field, the canted layer set along the growth field axis. Fig. 6 shows the canting angle Φ variation with respect to growth field direction when the samples were annealed at 200 °C and 250 °C for 1 hr without an annealing field. As the annealing temperature increases, the canting angle Φ approaches 180°. This indi-

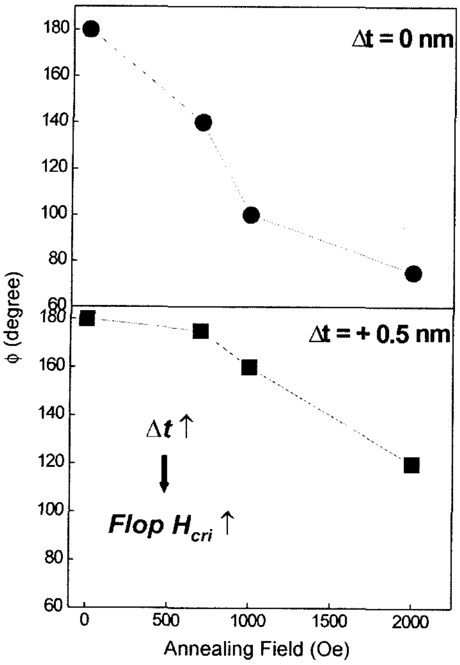

Fig. 5. Canting angle variation of annealed samples as a function of annealing field for $\Delta t = 0$ and 0.5 nm. Annealed at 250 °C for 1 hr.

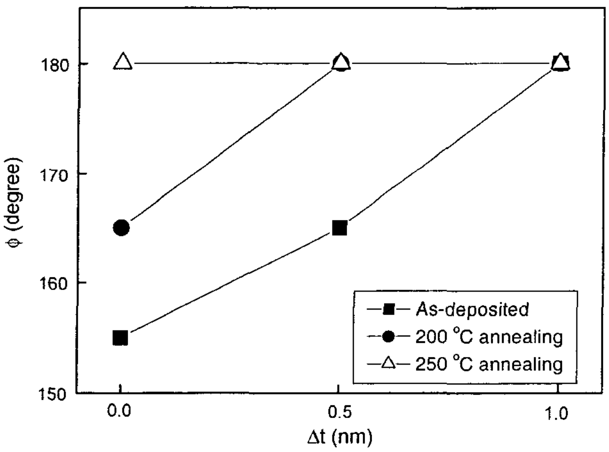

Fig. 6. Pinning direction (P1) variation as a function of Δt. Annealed at 200 °C and 250 °C for 1 hr without an external field.

cated that the pinning direction of the P1 layer was aligned to the growth field axis because the spin flop did not occur due to zero field annealing. The easy axis anisotropy, which was induced by the growth field during deposition, is still active in all ferromagnetic layer except the IrMn at 250 °C. Thus the pinning direction could be aligned along the growth field axis even in zero field annealing.

4. Conclusions

We investigated the dependence of magnetoresistive and pinning direction behaviors on different pinned layer thickness ratios of [NiFe/CoFe/Cu/CoFe (t_{P2})/Ru/CoFe (t_{P1})/IrMn]. The pinning angles of the P1 layer are 155°, 165°, and 180° off with respect to growth field direction for the samples with $\Delta t = 0$, +0.5 and +1 nm, respectively, in the as-deposited state. The pinning direction of the P1 layer were aligned almost orthogonal to the growth field direction to minimize the total energy when the samples with $\Delta t = 0$ was annealed at 250 °C. As t increases, torque is exerted on the net magnetization (thicker layer, P2) so that the direction of the net magnetization rotates toward the annealing field direction. However, in the case of samples with $\Delta t < 1$, it is difficult to align the pinned layer to the growth field axis when the samples are annealed with magnetic field. The pinning direction could be controlled and aligned to the growth field axis if the samples were annealed without magnetic field at above the blocking temperature.

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