Micromagnetic Simulation of Hard Bias Field Effects on Submicron Spin Valve Heads Susumu HARATANI, Tsutomu AOYAMA and Isamu SATO

Advanced Products Development Center, TDK Corporation
2-15-7, Higashi-Ohwada, Ichikawa-shi, Chiba 272, Japan

Abstract --- The three-dimensional micromagnetic simulations of submicron spin valve (SV) heads are presented. At such sensor widths, the amplitude of SV head output is reduced. An effective way to improve this reduction is to weaken the longitudinal bias field from permanent magnets. Results of simulations reveal that the magnetizations of the pinned layer near the air bearing surface rotate irregularly below a critical permanent magnet strength at a positive external medium field. This irregular rotation causes hysteresis of transfer curve. The critical permanent magnet strength decreases linearly with an increase in the reciprocal of the square of the sensor width. At the optimum permanent magnet strength, the amplitude of the sensor with $0.3\ \mu\text{m}$ wide is almost the same as that of the sensor with $1.0\ \mu\text{m}$ wide. It is important to evaluate the domain stability of the pinned layer when designing a SV head with submicron sensor widths.

Key words: high density recording, magnetic head, computer simulation, micromagnetics, spin valve, magnetoresistance effect

I. Introduction

The sensor width of the spin valve (SV) heads appropriate for high density recording more than $10\ \text{Gb/in}^2$ should be less than $1.0\ \mu\text{m}$. At such sensor widths, complications may appear in designing submicron spin valve heads. Micromagnetic simulation is a very effective tool for designing spin valve heads, and several micromagnetic simulations for SV heads have been presented[1][2].

In this paper, we use micromagnetic simulations to study performance characteristics of the submicron SV head. This work will focus on the effect of the strength of the permanent magnet which acts to prevent the formation of multidomain states in the free layer of the SV head.

II. Model for simulation

Figure 1 shows a schematic illustration for the modeled spin valve (SV) head. In the model, the free layer and pinned layer are discretized into two individual 2-dimensional rectangular arrays of cubic element. The size of the 2-dimensional rectangle is $5\ \text{nm} \times 5\ \text{nm}$. The number of cubic elements range from 7,200 to 80,000. Our calculations were performed on a supercomputer. The Landau-Lifshitz-Gilbert gyromagnetic equation of motion is used to calculate the magnetization configurations in both layers[3][4]. The magnetoresistance of a SV head is proportional to the cosine of the relative angle $\Delta\theta$ between the magnetization vectors of the free and pinned layers. In our simulation, SV output is defined as $\langle \cos\Delta\theta \rangle$. Ideal permanent magnets (PM) are assumed. The shield effects are included for both PM field and demagnetizing field[5]. The exchange field arising from the antiferromagnetic layer

Fig. 1 Schematic illustration of a spin valve head.

are applied to the pinned layer as an unidirectional field along the direction perpendicular to the air bearing surface (ABS).

In our calculations, the saturation magnetizations of the free and pinned layer are $800\ \text{emu/cc}$ and $1430\ \text{emu/cc}$. Anisotropic fields of $2.5\ \text{Oe}$ are assumed for both the free and pinned layers. The anisotropic easy axis of the free layer is assumed to be parallel to the ABS in the film plane. The anisotropic easy axis of the pinned layer is assumed to be perpendicular to the ABS in the film plane. The direction of the sensing current of density $3 \times 10^7\ \text{A/cm}^2$ is set such that the field generated on the free layer counterbalances the demagnetizing field arising from the pinned layer. An interlayer ferromagnetic exchange coupling of $10\ \text{Oe}$ between the free and pinned layers is assumed. The film thicknesses of the free layer, conductor layer, and pinned layer are $6\ \text{nm}$, $3\ \text{nm}$, and $2\ \text{nm}$, respectively. The sensor height is equal to the sensor width. The shield to shield separation is $0.2165\ \mu\text{m}$.

The medium field from the recorded medium is calculated with the presence of the semi infinite soft magnetic shields. It is defined that the medium field is positive when the y component of the medium field passes through the SV head from the ABS. A flying height of $50\ \text{nm}$ is assumed. The transfer curves are created by computing the SV output from the SV head while the transitions are cycled from zero, to positive, to negative, and back to zero again.

III. Results and discussion

A. Signal output for submicron track widths.

Figure 2 shows the calculated dynamic range as a function of the SV sensor width. Here, the calculated dynamic range is defined as an amplitude of the SV output

Fig. 2 Calculated dynamic range as a function of the SV sensor width.

between the positive and the negative transitions with the medium area moment thickness of 0.8 memu/cm^2 . The calculated dynamic range decreases with a decrease in sensor widths.

Figure 3 shows the change in the x components of the stray fields from PM films for the sensor widths of both $1.0 \mu\text{m}$ and $0.3 \mu\text{m}$ along the x axis between the PM films with the remanent magnetization of 800 emu/cc . We call the

Fig. 3 Change in the x component of the stray field along the x axis between the permanent magnetic films with the remanent magnetization of 800 emu/cc at the center of the film height. Distances between two permanent magnets are (a) $1 \mu\text{m}$ and (b) $0.3 \mu\text{m}$.

remanent magnetization of the PM "PM strength". In this figure, the position between the PM films is normalized. In both sensor widths, the x components of the stray fields at the track center are much smaller than the x components of the stray fields at the track edge. But, the x component of the stray field for the sensor width of $0.3 \mu\text{m}$ is larger than that for the sensor width of $1.0 \mu\text{m}$. This phenomena causes a decrease in the calculated dynamic range at the submicron track widths, since the stray field acts to prevent the magnetizations of the free layer from rotating with an increase in the medium field[6].

Then, the calculated dynamic range dependence on the PM strength is simulated. Figure 4 shows the relationship

Fig. 4 Relationship between the permanent magnet strength and the calculated dynamic range.

between the PM strength and the calculated dynamic range for the sensor width of $0.3 \mu\text{m}$. The calculated dynamic range increases with a decrease in the PM strength. For a PM strength of 500 emu/cc and a sensor width of $0.3 \mu\text{m}$, the calculated dynamic range is almost the same as that for a PM strength of 800 emu/cc and a sensor width of $1.0 \mu\text{m}$. Therefore, an effective way to increase the calculated dynamic range is to reduce the PM strength.

However the reduction of the PM strength causes some problems. Figure 5 shows transfer curves for the PM strength of $500, 450$ and 400 emu/cc at a sensor width of $0.3 \mu\text{m}$. For a PM strength of 450 emu/cc , a small hysteresis is observed on the transfer curve at the positive transition of 0.96 memu/cm^2 . For a PM strength of 400 emu/cc , the transfer curve is bent at the positive transition of 0.32

Fig. 5 Calculated transfer curve for various permanent magnet strength.

memu/cm^2 . Such a irregular transfer curve may cause a noise on the playback waveform from the SV head. The origin of the hysteresis will be discussed in the next section.

B. Analysis of the hysteresis

Figure 6 shows the change in the averaged rotation angle of the free layer and the pinned layer, where the PM strength is 450 emu/cc and the sensor width is $0.3 \mu\text{m}$. The rotation angle of the free layer changes smoothly in this

Fig. 6 Averaged rotation angle of the free layer and the pinned layer.

rotation angle of the free layer changes smoothly in this case. But the rotation angle of the pinned layer has a hysteresis at the positive transition of 0.96 memu/cm². To understand the source of the hysteresis on the pinned layer, the magnetization configurations of the pinned layer are considered.

Figures 7(a) and (b) show the two magnetization orientation configurations of the pinned layer for a positive transition of 0.96 memu/cm², where (a) is the state before experiencing a maximum positive medium field and (b) is the state after experiencing a maximum positive medium field. It is observed that the magnetization configuration in

Fig. 7 Magnetization configurations of the pinned layer. One arrow represents four discretized cubic elements.

the region delineated by the dashed box in Fig. 7(b) is different from the magnetization configuration in Fig. 7(a). We call this region "Local domain", because there exist 90° domain wall in the left side of the region. For a PM strength of 400 emu/cc, such a local domain appears beyond the positive transition of 0.32 memu/cm².

The change in the magnetization configuration of the pinned layer for a positive medium field is investigated. The

Table I Magnetic energy of pinned layer with a medium field.

Unit: pico-erg

	Before experience	After experience
Total	-27.1	-26.87
magnetostatic	25.52	25.36
Exchange	1.687	1.722
Anisotropic	0.02413	0.02283
External	-54.33	-53.97

local domain appears on the state for the positive transition of 1.12 memu/cm² before experiencing a maximum positive medium field. Then, the local domain continues existing on the states after experiencing a maximum positive medium field. Finally, the local domain disappears on the state for the positive transition of 0.80 memu/cm² after experiencing a maximum positive medium field. Thus, it is indicated that the state in Fig. 7(b) is affected by the former magnetization configuration.

Table I shows energy in the pinned layer for the two states in Figs. 7(a) and (b). Total energy in Fig. 7(a) is smaller than that in Fig. 7(b). But, magnetostatic energy in Fig. 7(a) is larger than that in Fig. 7(b). To remove the local domain, it is necessary to increase magnetostatic energy. This is the reason why the local domain remains in Fig. 7(b).

C. SV transfer curve for various Hua

The exchange field pinning the pinned layer is important parameter in the spin valve head. Fig. 8 shows that transfer curves at various pinning fields with the sensor width of 0.3 μm where the PM strength is 450 emu/cc. In

Fig. 8 Calculated transfer curve for various Hua strength.

the pinning field $H_{ua} = 150, 300, 450$ Oe, the hysteresis is observed. The strength of the positive medium field at which hysteresis is observed decreases with an increase in the pinning field. The local domain appears beyond the strength of the positive medium field at which hysteresis is observed. However, in the case of a pinning field $H_{ua} = 600$ Oe, the hysteresis is not observed. The transfer curve is bent at the positive transition of 0.64 memu/cm². The local domain appear beyond the positive transition of 0.64 memu/cm². Therefore, the strength of the positive medium field at which the local domain appears decreases with an increase in the pinning field. To understand this phenomena, the change in the magnetization configuration of the pinned layer is investigated.

In the quiescent state, the magnetization near the ABS edge of the pinned layer rotates to be parallel to the ABS edge in order to minimize the magnetic charge density at the surface of the ABS edge. We call the region "Tilted region". The direction of magnetization near the ABS is affected by the PM field. When a vertical magnetic field such as the y component of a positive medium field and a pinning field increases, it is observed that the magnetization in the tilted region near the center of the pinned layer rotates to be vertical to the ABS edge. And the area of the tilted region decreases, simultaneously. When a vertical magnetic field becomes large enough, the magnetization on the right part near the ABS edge rotates to be vertical to the ABS edge. However, this situation is not stable, since the magnetic charge density at the surface of the ABS edge becomes larger than the quiescent state. Therefore, to minimize the magnetic charge density at the surface of the ABS edge, the local domain appears. In summary, both a pinning field and a positive medium field can reduce the area of the tilted region. This is the reason why the strength of the positive medium field at which the local domain appears decreases with an increase in the pinning field.

D. Critical permanent magnet strength

As discussed previously, the tilted region decreases with a decrease of the PM strength, since the area of the

Fig. 9 Relationship between the critical permanent magnet strength and the sensor width.

region is affected by the PM field. Hence, the local domain may appear at a weak PM strength. As shown before, the local domain appears at a PM strength of 450 emu/cc for the sensor width of $0.3 \mu\text{m}$, but the local domain does not appear at a PM strength of 500 emu/cc for the sensor width of $0.3 \mu\text{m}$. Thus, there exist a critical permanent magnet strength. The critical PM strength is the minimum PM strength at which the local domain does not appear while experiencing a positive medium field.

Finally, the critical PM strength is investigated for various sensor widths. Figure 9 shows the relationship between the critical PM strength and the reciprocal of the square of the sensor width. The critical PM strength decreases linearly with an increase in the reciprocal of the square of the sensor width.

IV. Conclusion

The micromagnetic simulations of submicron spin valve heads are presented. At the sensor widths less than $1 \mu\text{m}$, the calculated dynamic range is almost the same as that for the sensor width of $1 \mu\text{m}$, when a permanent magnet strength is optimized. It is found that there exist a critical permanent magnet strength. Below the critical permanent magnet strength, a local domain appears in the pinned layer, and the strength of the positive medium field at which the local domain appears decreases with an increase in the pinning field. The critical permanent magnet strength decreases linearly with an increase in the reciprocal of the square of the sensor width. These results show that the stability of the pinned layer is very important factor to consider when designing a submicron spin valve head.

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