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Effects of the Hard-Biased Field on the Magnetic and Magnetoresistive Properties of a Crossed Spin-Valve Head by Computer Simulation

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The effects of a hard-biased field on the magnetic and magnetoresistive properties of a crossed spin-valve head are investigated by computer simulation with particular emphasis on the asymmetry of the output signal. The spin-valve considered in this work is NiMn (25 nm)/NiFe (2.5 nm)/Cu (3 nm)/NiFe (5.5 nm), with a length of 1500 nm and a width of 600 nm. A simple model is used where each magnetic layer consists of a single domain, and the magnetoresistance is a function of the angle between the magnetization directions of the two magnetic layers. The ideal crossed spin-valve structure is not realized with the present model and magnetic parameters, but the deviation from ideality is decreased by the hard-biased field. This results in the improvement of the linearity of the output signal with the use of the bias field. The magnetoresistance ratio and magnetoresistive sensitivity, however, are reduced. The magnetic properties including the magnetoresistance are found to be strongly affected by magnetostatic interactions, particularly the inter-layer magnetostatic field.

1. Introduction

Good linear response of a spin-valve head, which is widely used as a reading element in magnetic recording, is an important factor for achiving high density recording [1]. In a crossed spin-valve, good linear response may be achieved when the magnetization directions of the pinned and free layers are aligned in the width and length directions, respectively. This magnetic configuration is usually obtained using an exchange-biased field (often called the pinning field) acting on the pinned layer from an adjacent antiferromagnetic pinning layer. It is noted here that, from a geometrical consideration, the magnetization direction of the pinned layer is the hard axis. Although the magnitude of the exchange-biased field is relatively strong, of the order of hundreds of oersteds, canting of the magnetization direction often occurs causing asymmetry of the output signal [1, 2]. This problem becomes more prominent when the size of the sensor element is smaller, since the contribution of the magnetostatic interactions to the total energy increases with decrease of the sensor size [3, 4].

There are many other parameters, apart from the sensor size, that determine the magnetic configuration. These parameters may include the exchange-biased field, the hard-biased field for stabilizing the domain of the free layer, the uniaxial anisotropy, the exchange field between the two magnetic layers, and the sensing current. Systematic work is necessary to sort out the role of these parameters, and, as a first attempt, effects of the hard-biased field are investigated in this study of the magnetic and magnetoresistive properties of a crossed spin-valve head, with emphasis on the asymmetry of the output signal.

2. Model and Computation

In the model, each magnetic layer consists of a single domain, so that the magnetization is uniform within the layer. Magnetic layers are coupled through the magnetostatic and interlayer exchange interactions. The spin-valve modeled in this work is NiMn (25 nm)/NiFe (2.5 nm)/Cu (3 nm)/NiFe (5.5 nm). The sensor is 600 nm wide and 1500 nm long. The modeled spin-valve structure is shown in Fig. 1, together with the definition of the axes. The layer is in the xy plane, and the x and y axes are respectively parallel to the length and width directions. The antiferromagnetic layer is assumed to be pinned very strongly in the width direction, so its magnetization is essentially fixed. The unidirectional exchange-biased field (H_{e-b}) is 150 Oe and points in the +y direction. In the pinned and free layers, a

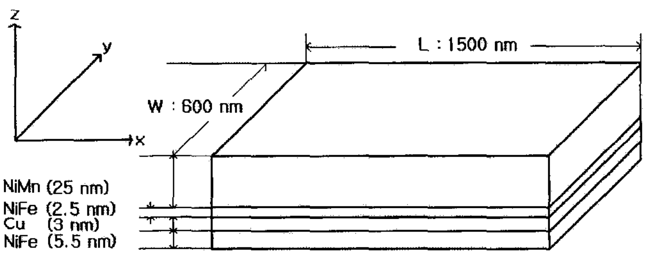

Fig. 1. The spin-valve structure modeled in this work, together with the definition of the axes.

uniaxial induced anisotropy with a strength of 5 Oe is assumed to lie in the x direction. The hard-biased field ($H_{h\text{-}b}$), which is used to stabilize the domain of the free layer, is applied to both the pinned and free layers in the +x direction and its magnitude is varied in this work from 0 to 100 Oe. Note that $H_{h\text{-}b}$ is unidirectional. No magnetic field from sensing currents is considered. The magnetization of the NiFe layers is taken as 800 emu/cm^3. The change in magnetoresistance is calculated using the expression $\Delta R = 1-\cos\theta$, where θ is the angle between the magnetization directions of the two magnetic layers. The magnetic field is applied in the width direction (y axis) and is cycled between +300 and −300 Oe, in order to observe how the magnetic and magnetoresistive properties vary with the applied field (H_a).

3. Results and Discussion

In Fig. 2 are shown the results for the magnetization directions of the pinned and free layers as a function of $H_{h\text{-}b}$ before applying magnetic field (at H_a=0) to see the initial magnetization configuration of the spin-valve. With the present magnetic parameters, the magnetization is always confined to the xy plane. This is expected because of the very large demagnetization factor in the thickness (z) direction. So the magnetization direction can be specified by an angle in the xy plane, and the angle used in this work is defined to be the angle between the magnetization direction and the +x axis. The symbols θ_p and θ_f are used to denote the magnetization angles of the pinned and free layers, respectively. At $H_{h\text{-}b}$=0, the magnetization directions of the pinned and free layers are away from the pinning (+y) and the easy (x) directions, respectively, the angles being 108° (the pinned layer) and −25° (the free layer). The canting of

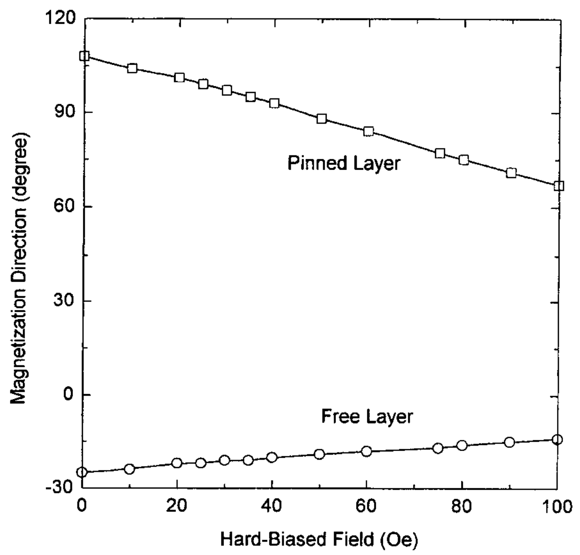

Fig. 2. Initial magnetization directions of the pinned and free layers measured at zero applied field as a function of the hard-biased field. The spins reside in the xy plane and the angle is between the magnetization direction and the +x axis.

the pinned layer, in spite of a rather strong pinning field (150 Oe), is mainly due to the magnetostatic field, particularly the self-demagnetization field which acts to rotate the spin toward the length direction. The self-demagnetization field is dependent on the layer geometry, and is related to the shape anisotropy, the magnitude of which is equal to the difference of the self-demagnetization fields in the x and y directions (note that the spins reside only in the xy plane in this work). The values of the shape anisotropy are 27 and 55 Oe, respectively, for the pinned and free layers. In the case of the free layer, the demagnetization field, together with the uniaxial anisotropy field, acts to align the spin in the length direction. However, the inter-layer magnetostatic field (due to the stray field) acts to rotate the magnetization away from the easy axis. Since the magnetization directions of the two magnetic layers deviate substantially from the ideal crossed spin-valve structure, the output signal is expected to be quite asymmetrical. The deviation from ideality decreases as $H_{h\text{-}b}$ increases, as can be seen from Fig. 2, as the magnetization directions of the two layers, expectedly, move towards the +x direction. Remember that $H_{h\text{-}b}$ is applied in the +x direction. The ideal crossed spin-valve configuration, however, cannot be achieved with the parameters used here. The magnetization of the pinned layer is nearly aligned in the +y direction at $H_{h\text{-}b}$ =50 Oe. At this $H_{h\text{-}b}$, however, the magnetization of the free layer is far from the +x direction. This is obviously due to a large inter-layer magnetostatic field from the pinned layer, which tries to rotate the free layer spin to the −y direction.

Although the ideal spin structure is not obtained in this work, the magnetic field is cycled between +300 and −300 Oe in the width direction in order to see the dependence of the magnetic and magnetoresistive properties on H_a. In Figs. 3(a) and (b) are shown the results for the magnetization directions of both the pinned and free layers as a function of H_a during the whole cycle at fixed $H_{h\text{-}b}$ values of 0, 25, 50, and 75 Oe. The H_a dependence of the magnetization direction at $H_{h\text{-}b}$=0 is very different from that in the presence of $H_{h\text{-}b}$, so the results at $H_{h\text{-}b}$=0 are shown separately in Fig. 3(a) and the rest are shown in Fig. 3(b).

In the case of $H_{h\text{-}b}$=0, the magnetization of both the pinned and free layers is aligned in the +y direction in the high H_a range 180 Oe $\leq H_a \leq$ 300 Oe, indicating that the Zeeman energy prevails in this region. As H_a decreases below 180 Oe, however, the magnetization direction rotates away from the +y direction, principally due to the shape anisotropy. The rotation of the free layer is larger than that of the pinned layer and this can be understood from the existence of the pinning field in the pinned layer. This rotation of the free layer, in turn, acts to rotate the pinned layer to an angle greater than 90°, through inter-layer magnetostatic interactions. As θ_f reaches 0°, a plateau occurs where both θ_p and θ_f do not vary with H_a. This plateau, which occurs in the H_a range 44 Oe $\leq H_a \leq$ 64 Oe, can be explained by the stabilization of the free layer by the self-

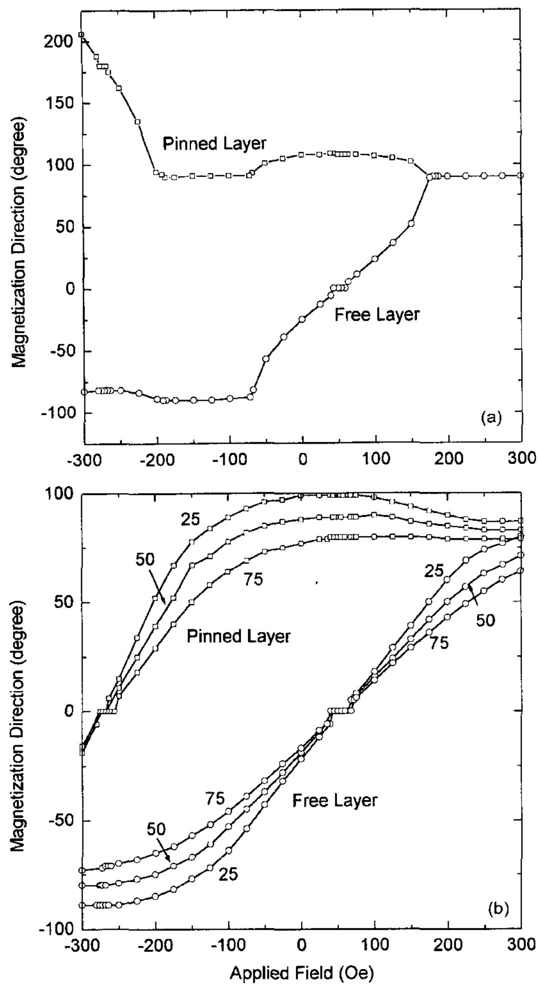

Fig. 3. Magnetization directions of the pinned and free layers during the whole cycle of applied field at various hard-biased fields of (a) 0 Oe and (b) 25, 50, and 75 Oe. The spins reside in the xy plane and the angle is between the magnetization direction and the +x axis. In Fig. 3(b), the numbers at the curves denote the values of the hard-biased field.

demagnetization field and the uniaxial field, combined with a large interlayer magnetostatic interaction field which fixes the pinned layer. Similar plateaus are also observed when both θ_p=90° and θ_f=−90° (−190 Oe $\leq H_a \leq$ −100 Oe), and θ_p=180° (−276 Oe $\leq H_a \leq$ −268 Oe). In all these cases, either the magnetization of the pinned or the free layer is stabilized by the self-demagnetization field and the uniaxial field (in the case of $\theta_p=\theta_f$=0 or 180°) and the pinning field (θ_p=90°). In the case of the plateau at θ_p=90° and θ_f=−90°, the spin stabilization is considered to be very strong, as indicated by a large plateau length of 90 Oe. This is because the spin configuration is additionally stabilized by the interlayer magnetostatic field, the spin directions being antiparallel to each other. Specifically, the magnitude of the interlayer-magnetostatic field on the pinned layer by the free layer is as high as 120 Oe in the +y direction, and the value of the field acting on the free layer by the pinned layer is −55 Oe in the −y direction. As H_a is negative (−y direction) and its absolute magnitude increases, θ_f approaches to −90° following the Zeeman torque, but it is of interest to observe that θ_p rotates back to 90° (+y direction) again, due to the dominant role played by the inter-layer magnetostatic coupling. As H_a further increases in the −y direction, θ_p varies so as to reduce the Zeeman energy; specifically, θ_p increases, goes through 180°, and then finally rotates towards the H_a direction (−y axis). Accompaning this variation of θ_p with H_a, θ_f is slightly away from −90° due to the interlayer magnetostatic interactions.

The H_a dependence of θ_p and θ_f in the presence of $H_{h\text{-}b}$ is substantially different from that in the case of $H_{h\text{-}b}$=0. This is mainly because, with $H_{h\text{-}b}$ in the +x direction, θ_p and θ_f mostly reside in the +x hemisphere. No parallel spin alignment in the +y direction occurs even at H_a=+300 Oe due to the torque of $H_{h\text{-}b}$ in the +x direction. As readily expected, θ_f decreases with decreasing H_a. This, in turn, increases θ_p through the interlayer magnetostatic interactions, the increase being greater at smaller $H_{h\text{-}b}$. Note that θ_p becomes as large as 100° (deviating by 10° from the direction of H_a) even at a relatively high H_a of +100 Oe. With the consideration of $H_{h\text{-}b}$ in the +x direction, the increase of θ_p above 90° (indicating the magnetization direction opposite to $H_{h\text{-}b}$) results from the high strength of the interlayer magnetostatic field. As θ_f reaches 0°, a plateau occurs, similar to the case $H_{h\text{-}b}$=0. Unlike the case of $H_{h\text{-}b}$=0, the magnetization of the free layer is further stabilized by $H_{h\text{-}b}$, together with the self-demagnetization field and the uniaxial field. This enhances the strength of the stabilization of the free layer, and the strength increases with increasing $H_{h\text{-}b}$, as can be seen from the increase of the plateau length with increasing $H_{h\text{-}b}$. Another plateau is observed when θ_p=0° at $H_a \approx$ 270 Oe. The factors affecting the stabilization in this case are the same as for θ_f=0°, but the strength of the stabilization is weaker than that for the case θ_f=0° due to the destabilization effect of $H_{e\text{-}b}$ which points in the +y direction. In this case again, the strength of the stabilization increases with increasing $H_{h\text{-}b}$. The long plateau observed for the case of $H_{h\text{-}b}$=0 in the magnetization directions θ_p=90° and θ_f=−90° cannot be seen in the case of $H_{h\text{-}b} \neq 0$, because $H_{h\text{-}b}$ prevents this magnetization configuration.

The H_a dependence of magnetization and magnetoresistance can easily be evaluated from that of θ_p and θ_f discussed so far, and the results for these properties are shown in Figs. 4 (magnetization) and 5 (magnetoresistance). No hysteresis is observed in the curves except for the case of $H_{h\text{-}b}$=0 where a very small hysteresis is observed. This indicates that the magnetization occurs mainly by a continuous rotation of magnetization, not by a sudden spin flip. This can be expected in a crossed spin-valve structure, although the ideal crossed structure is not realized in this work. Two points can be noted from the magnetoresistance results. First, for a given H_a cycle, the difference of the magnetoresistance ratio is highest at $H_{h\text{-}b}$=0. This is because both the parallel and anti-parallel spin alignments are realized during the H_a cycle in the absence of $H_{h\text{-}b}$, but the co-linear spin

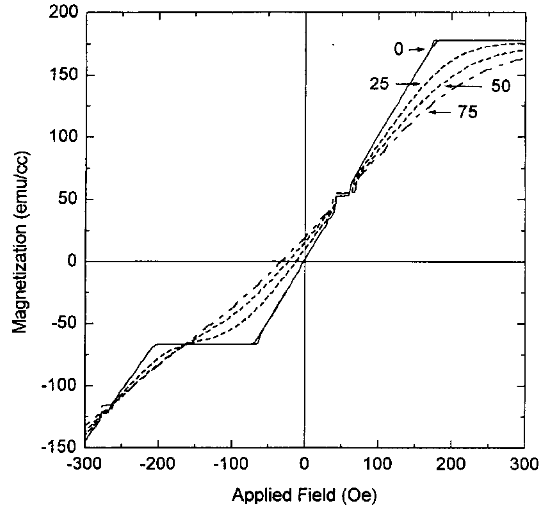

Fig. 4. M-H hysteresis loops at various hard-biased fields of 0, 25, 50, and 75 Oe. The numbers at the curves denote the values of the hard-biased field.

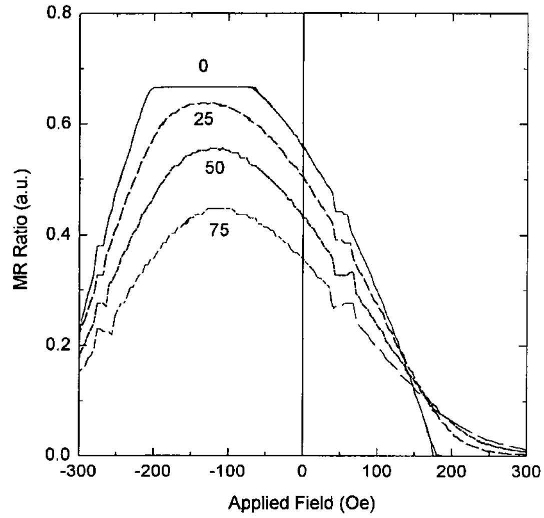

Fig. 5. Giant magnetoresistance curves at various hard-biased fields of 0, 25, 50, and 75 Oe. The numbers at the curves denote the values of the hard-biased field.

alignments are not realized at $H_{h\text{-}b} \neq 0$. The second point is that, at $H_a \approx 0$, the magnetoresistive sensitivity is highest, but the linearity is poorest in the case of $H_{h\text{-}b}$=0. The linearity tends to be improved with increasing $H_{h\text{-}b}$ in the present $H_{h\text{-}b}$ range. The linearity achieved in the present work, however, is considered to be rather poor, as can be expected from the rather large deviation from the ideal crossed spin-valve structure with the use of the present magnetic parameters. Since the realization of the ideal crossed spin-valve is usually hampered by strong magnetostatic interactions, particularly the inter-layer magnetostatic ones [3, 4], this problem can be relieved, if not solved, by devising a way of reducing the field from the magnetostatic interactions. One obvious way is to use a material with small magnetization through a suitable alloy selection. Another method might be to use a layer which can "absorb" the magnetostatic field. An example of this is the use of a compensation layer [1, 2] or synthetic pinning layers [5, 6]. Sensing currents are expected to reduce the linearity problem, since the current can produce a magnetic field in the +y direction in the pinned layer, so that θ_p can be pinned more effectively. Work considering these factors is planned in the future.

4. Conclusions

In an effort to improve the linearity of the output signal of a crossed spin-valve, which is important to achieve high density magnetic recording, we have investigated the effects of the hard-biased field on the magnetic and magnetoresistive properties by computer simulation. The spin-valve considered in this work is NiMn (25 nm)/NiFe (2.5 nm)/Cu (3 nm)/NiFe (5.5 nm), with a length of 1500 nm and a width of 600 nm. We used a simple model where each magnetic layer consists of a single domain, and the magnetoresistance is a function of the angle between the magnetization directions of the two magnetic layers. The deviation from the ideal crossed spin-valve structure is found to decrease with increasing hard-biased field, although it was not possible to achieve the ideal structure with the present model and magnetic parameters, mainly due to very strong magnetostatic interactions, particularly the interlayer interactions. The improvement of the ideal crossed spin-valve structure by the hard-biased field results in an increase of the linearity of the output signal. However, the magnetoresistance ratio and magnetoresistive sensitivity are decreased in the presence of the hard-biased field.

Acknowledgments

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