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Size and Aspect Ratio Effects on the Magnetic Properties of a Spin-Valve Multilayer by Computer Simulation

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The change in the magnetic properties of a spin-valve multilayer with the structure IrMn (9 nm)/CoFe (4 nm)/Cu (2.6 nm)/CoFe (2 nm)/NiFe (6 nm) is investigated as a function of the size and the aspect ratio. At a fixed aspect ratio (the length/width ratio) of 2, the magnetostatic interactions begin to affect the magnetic properties substantially at a spin-valve length of 5 μm, and, at a length of 1 μm, they become even more dominant. In the case of a fixed multilayer size (2.4 μm) which is indicated by the sum of the length and the width, magnetization change occurs by continuous spin-reversal and M-H loops are characterized by no or very small hysteresis at aspect ratios smaller than unity. At aspect ratios greater than unity, magnetization change occurs by spin-flip resulting in squared hysteresis loops. A very large changes in the coercivity and the bias field is observed, and these results are explained by two separate contributions to the total magnetostatic interactions: the coercivity by the self-demagnetizing field and the bias field by the interlayer magnetostatic interaction field.

1. Introduction

A large, sometimes dominant role played by magnetostatic interactions in determining the magnetic properties of a spin-valve multilayer is well-recognized through numerous studies in the past. A spin-valve multilayer possessing giant magnetoresistance is being widely used as read head in a computer hard disc drive. Recently, great interest arose to apply the spin-valve multilayer to magnetic random access memory (MRAM) devices [1]. In these applications, the technology push towards the miniaturization is increasing immensely to the point that magnetostatic interactions play an even more dominant role in determining magnetic properties (including magnetoresistance). This emphasizes the importance of clearly understanding the role of magnetostatic interactions in a small-sized multilayer device. Russek *et al.* [2] examined magnetoresistance response of spin-valves for MRAM applications in a multilayer single-domain model. The same model was used by Oti *et al.* [3] to investigate spin-valves for magnetic recording applications. A particular emphasis was placed on the deviation of the pinned layer spin direction from the exchange bias field (or pinning field) and the resultant output of GMR signals. Micromagnetic computer simulation utilizing the Landau-Lifshitz equation was also used to investigate the role of the magnetostatic interactions in patterned spin-valves by Zheng and Zhu [4], Oti and Russek [5], and Mao *et al.* [6]. It was shown from these previous researches that a significant change in the magnetic and magnetoresistance properties occurs as the spin-valve size varies, demonstrating the importance of the magnetostatic interactions in the small size range. Despite of many previous research efforts, it seems that there is no clear and quantitative explanation on this important issue. For example, Russek *et al.* [7] investigated, both experimentally and theoretically, switching characteristics in MRAM-type spin valves. They observed a large increase in both positive and negative switching fields, and also a large switching field asymmetry when the size becomes small. However, they were unable to offer a quantitative explanation on their results. In the case of switching field asymmetry, for example, they did mention that magnetostatic interactions between the free and pinned layers were responsible for the asymmetry, but no detailed analysis was given. In an effort to rectify this situation, a systematic investigation is carried out in this work on the change in the magnetic properties of a spin-valve multiplayer as a function of the size and the aspect ratio over a wide range, and a quantitative explanation is offered to explain the magnetic properties in order to better understand the overall picture on the size and aspect ratio dependence of the magnetostatic interactions and hence magnetic properties of spin-valve multilayers.

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2. Model and Computation

In the model, each magnetic layer consists of a single domain, indicating that the magnetization is uniform within a layer. The spin-valve modeled in this work is IrMn (9 nm)/CoFe (4 nm)/Cu (2.6 nm)/CoFe (2 nm)/NiFe (6 nm). In order to examine the size effects, the multilayer dimensions are varied widely from 20 mm × 10 mm to 0.5 μm × 0.25 μm. It is noted that the aspect ratio is fixed at 2.0 in this case. The aspect ratio effects were investigated at a fixed multilayer size (2.4 μm), which is indicated by the sum of the length and the width, but at varying aspect ratios of 0.5 to 3.0. Specifically, the multilayer dimensions investigated here range from 0.8 μm × 1.6 μm to 1.8 μm × 0.6 μm. The unidirectional pinning field (H_{pin}) acting on the pinned layer is 280 Oe. The magnitude of the uniaxial induced anisotropy is 46 Oe in the pinned layer ($H_{A,p}$) and is 5 Oe in the two free layers ($H_{A,f}$). The direction of H_{pin}, $H_{A,p}$ and $H_{A,f}$ is parallel to the length direction. Magnetic layers are coupled through the magnetostatic and interlayer exchange interactions. The ferromagnetic exchange coupling (H_{exch}) (more specifically, the Neel orange coupling the origin of which is magnetostatic interactions in nature) exists between the pinned and free layers and its magnitude is 12 Oe. The magnetization of the CoFe layers is taken as 1300 emu/cm^3 and that of NiFe as 800 emu/cm^3. In the actual calculation, the two free layers (CoFe (2 nm) and NiFe (6 nm)) are treated as a single layer, for calculational simplicity, with an average magnetization of 925 emu/cm^3. This indicates that one of the free layers exactly follows the other, which is in agreement with experimental observations for this type of spin-valves. This assumption is expected to affect detailed magnetostatic interactions, but will not influence the main conclusion of this work. Neither the magnetic field from sensing currents nor the hard-biased field (which is used to stabilize the domain of the free layer) is considered in this model. The change in magnetoresistance is calculated by using the expression $\Delta R = 1 - \cos\theta$, where θ is the angle between the magnetization directions of the pinned and free layers. The magnetic field is applied in the length direction and is cycled between +500 and −500 Oe (a higher field is also applied in some cases). The present multilayers are relevant to an MRAM cell, rather than a spin-valve read head used in magnetic recording, the applied field (H_a) being parallel to the pinning field and the anisotropy field.

3. Results and Discussion

3.1 The size effects

The change in the magnetic properties was investigated mainly by measuring M-H hysteresis loops, and some of the results are shown in Figs. 1(a)-(d) for several spin-valves, 20 mm × 10 mm, 20 μm × 10 μm, 5 μm × 2.5 μm and 1 μm × 0.5 μm, respectively. The M-H loops obtained from the smallest spin-valve of 1 μm × 0.5 μm are also shown in Fig. 1(a) together with the largest spin-valve of 20 mm × 10 mm, in order to emphasize the difference of the loops. It is seen from the figures that, indeed, a significant difference is observed to exist in the M-H loops. A prominent phenomenon common to all is that the magnetization changes abruptly by spin-flip. This is expected, since the direction of H_a is parallel to all the unidirectional and uniaxial anisotropy fields.

Several characteristic fields can be identified from the loops; the coercivities of the pinned and free layers ($H_{c,p}$ and $H_{c,f}$, respectively) and the bias fields of the pinned and free layers ($H_{bias,p}$ and $H_{bias,f}$, respectively). In the case of the largest spin-valve of 20 mm × 10 mm, the values of the characteristic fields are identical to those expected from the values of $H_{A,p}$, $H_{A,f}$, H_{pin} and H_{exch}. Specifically, the values of the coercivity are equal to the uniaxial anisotropy fields in the respective layers ($H_{c,p} = H_{A,p} = 46$ Oe; $H_{c,f} = H_{A,f} = 5$ Oe), and the bias fields are identical to the unidirectional exchange fields ($H_{bias,p} = H_{pin} = 280$ Oe; $H_{bias,f} = H_{exch} = 12$ Oe). However, as the multilayer size decreases, these characteristic fields change significantly. In order to see the size dependence of these characteristic fields more clearly, the magnetic fields at which spin-flip occurs in the M-H loops are plotted as a function of the size, and these results are shown in Fig. 2. The spin-flip positions of a-d in Fig. 2 are indicated in the M-H loops in Fig. 1(c). In Fig. 2, the spin-valve size (the x-axis) is indicated only by the length (the long dimension of the device). The following relationships exist between the spin-flip fields and the characteristic fields; $H_{c,p} = (d-a)/2$, $H_{c,f} = (c-b)/2$, $H_{bias,p} = (a+d)/2$, and $H_{bias,f} = (b+c)/2$.

From Figs. 1 and 2, it is seen that the spin-flip positions of a and c vary slightly with the size, but, the other positions of b and d vary significantly with the dimension. The small size dependence of the spin-flip fields of a and c, compared with that of b and d, is considered to be related with the spin configuration. The spin-flip positions of a and c correspond to magnetization change from parallel spin configuration to antiparallel one. The situation is opposite at the spin-flip positions of b and d. Spin-flip from antiparallel to parallel spin configuration is considered to be more difficult than the opposite direction, since the interlayer magnetostatic interaction field (H_{ms}) favors the antiparallel spin configuration. At the spin-flip position b, for example, the free layer spin rotates towards the −x direction, the same direction of the pinned spin. The spin rotation will occur at $H_a = +7$ Oe provided no magnetostatic interactions exist. This rotation of the free layer, however, will occurs at a large H_a value, since H_{ms} from the pinned layer acts on the free layer in the +x direction, making it difficult for the free layer spin to be rotated.

Over the whole size range investigated in this work, the variation of the spin-flip field with the size is as follows: a = 234~298 Oe; b = 7~256 Oe; c = 16~40 Oe; d = 325~606

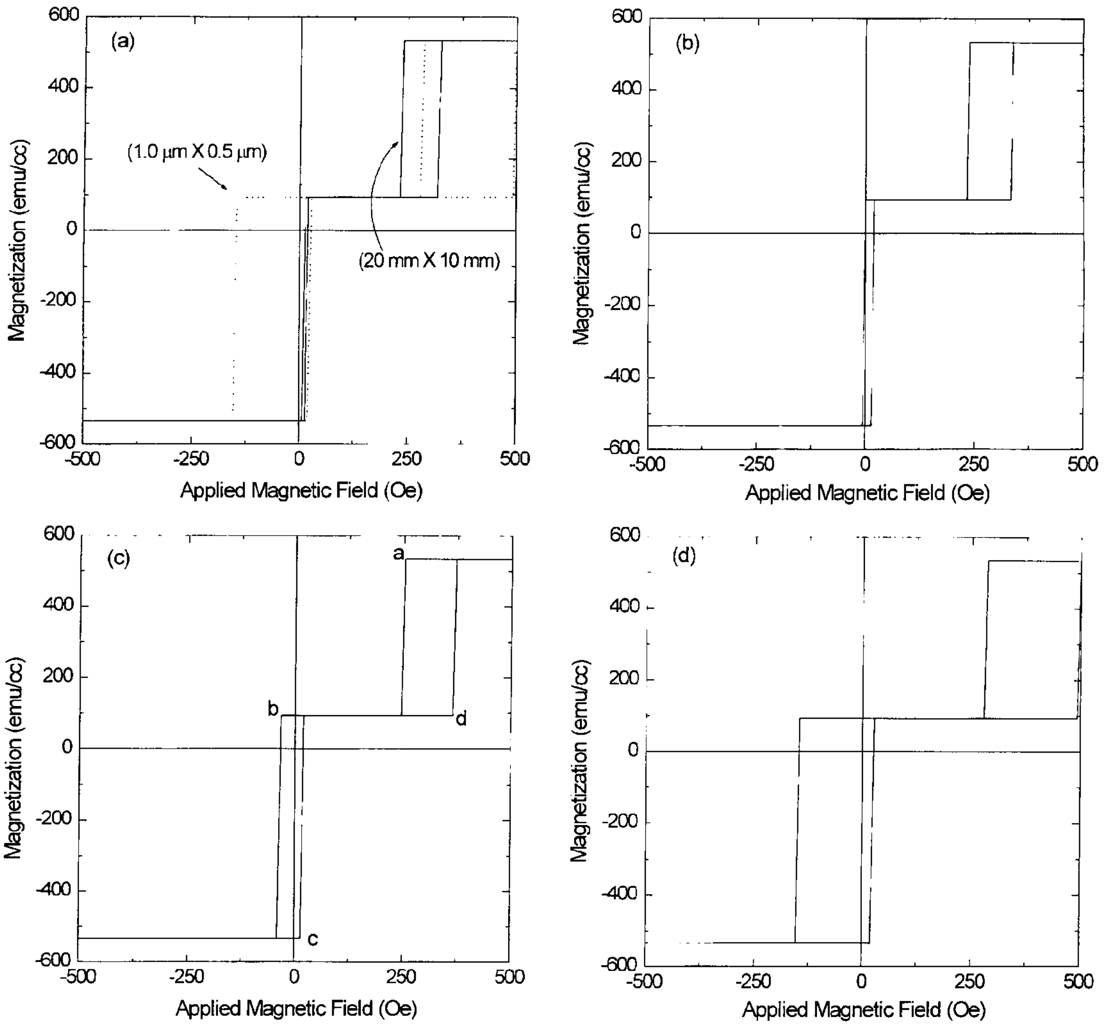

Fig. 1. M-H hysteresis loops for several spin-valve dimensions. (a) 20 mm × 10 mm, (b) 20 μm × 10 μm, (c) 5 μm × 2.5 μm, and (d) 1 μm × 0.5 μm. The M-H loops obtained for the smallest spin-valve of 1 μm × 0.5 μm are also shown in (a) for comparison.

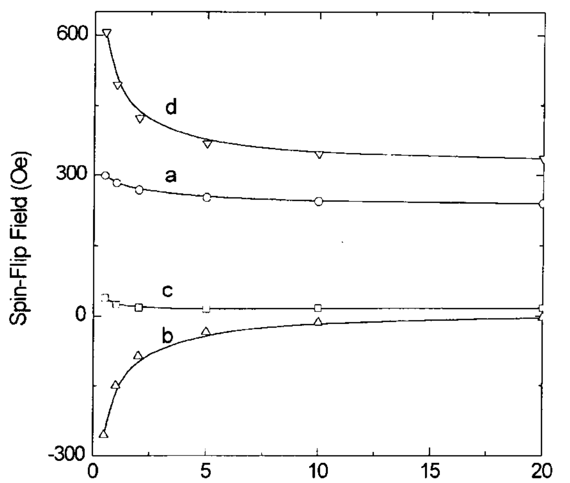

Fig. 2. The applied magnetic fields at which spin-flip occurs as a function of the spin-valve length. The spin-flip positions of a-d are indicated in the M-H loops of Fig. 1(c).

Oe. It is interesting to see that the change of the characteristic fields related to the free layer (b and c) is slightly smaller than that related to the pinned layer (a and d). In the case of the spin-flip positions of b and d where a large size dependence is observed, the change of the spin-flip fields is actually not very significant as the spin-valve length changes from 20 mm to 5 μm. Below this dimension, however, a significant change is observed, the variation being even greater as the length becomes smaller than 1 μm. This size dependence of M-H hysteresis loops (or in other words, the spin-flip fields) is obviously related with the magnetostatic interaction fields which can be divided into the self-demagnetizing field (H_{demag}) and H_{ms} already mentioned in the previous paragraph.

The increase of the coercivity with the decrease of the spin-valve size, which can be easily obtained from the results shown in Fig. 2 for the size dependence of the spin-flip fields, can be explained by the change of the uniaxial shape anisotropy. Although, in this work, the aspect ratio (the length/width ratio) is fixed at 2 for all the samples, the value of H_{demag} in the length direction is different from that in the width direction, and, furthermore, the difference in the values of H_{demag} in the two directions increases with

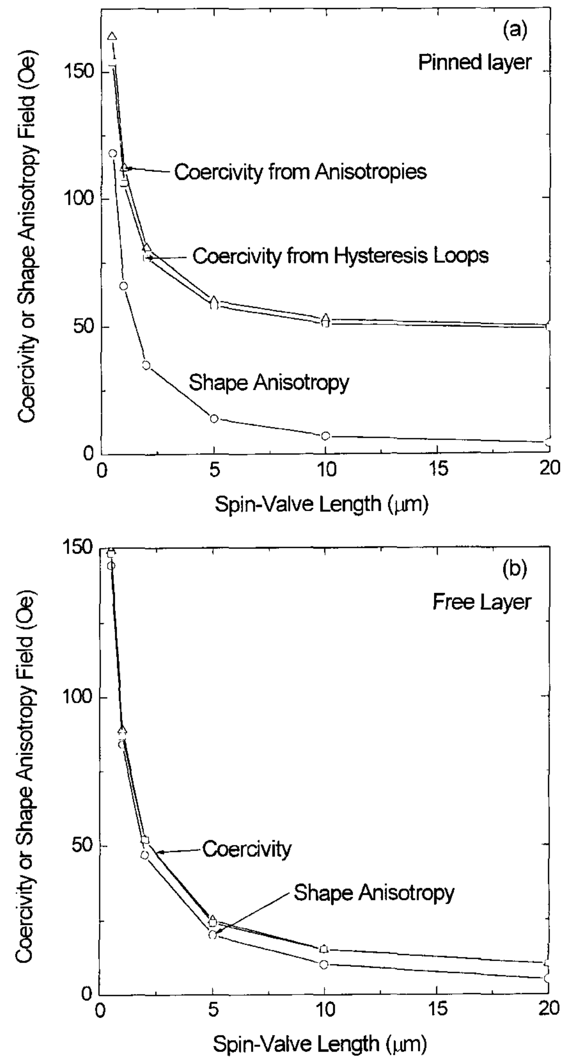

Fig. 3. The shape anisotropy (circles), and the two sets of the coercivities, one obtained from the hysteresis loops (squares) and the other from the shape anisotropy (triangles), as a function of the spin-valve length for (a) the pinned layer, and (b) the free layer.

decreasing size. The difference in the values of H_{demag} in the two principal directions corresponds to the shape anisotropy, which is uniaxial in nature. In Figs. 3(a) and (b) are shown the results for the shape anisotropy in the pinned and free layers, respectively. The magnitude of the coercivity in each layer is then expected to be the sum of the (uniaxial) induced anisotropy and this shape anisotropy. The coercivity obtained in this way is also shown in the figures, together with those obtained from the hysteresis loops.

From Figs. 3(a) and (b) it is seen that a very large size dependence on the shape anisotropy and the coercivity is observed, in a way similar to the results shown in Fig. 2 for the spin-flip field. The magnitude of the shape anisotropy is nearly zero at the largest spin-valve of 20 mm × 10 mm, but it increases exponentially with the decrease of the size. The magnitude of the shape anisotropy is greater in the free layer than that in the pinned layer, in spite of a smaller saturation magnetization of the free layer. This is because the free layer is thicker than the pinned layer and hence the difference of the demagnetization coefficients in the length and the width direction is greater in the case of the free layer. In the case of the free layer, the value of $H_{c,f}$ obtained from the results shown in Figs. 1 and 2 for the hysteresis loop is in excellent agreement with that from the shape anisotropy (the sum of the shape anisotropy and 5 Oe for the induced anisotropy). In the case of the pinned layer, however, the magnitude of $H_{c,p}$ from the hysteresis loop is lower than that estimated from the shape anisotropy (the sum of the anisotropy and 46 Oe for the induced anisotropy). The discrepancy between the two increases with decreasing size. The reason for this discrepancy is not clearly understood at this moment. Considering that the coercivity is equal to the total (uniaxial) anisotropy only for the condition that magnetization change occurs by a complete spin-flip, the spin-flip behavior in the pinned layer may deviate from this ideal flip and the ideality increases with decreasing size. In this sense, the value of the coercivity obtained from the sum of all the uniaxial anisotropies is considered to be the upper limit of this magnetic parameter.

Let us now consider the bias (or offset) fields of the pinned and free layers. In the absence of the magnetostatic interactions such as the case for the 20 mm × 10 mm spin-valve, the bias fields of the pinned and free layers are, respectively, +280 and +12 Oe. However, these bias fields change in the presence of magnetostatic interactions. It is observed that, over the whole size range, the change of the bias field is completely explained by the change of H_{ms}, the results for which are shown in Figs. 4(a) and (b) in the pinned and free layers, respectively. Also shown in the figures are the values of H_{bias} obtained from the hysteresis loops and H_{ms}. Again, the size dependence of H_{ms} is similar to those observed for spin-flip field and the shape anisotropy. The value of $H_{bias,p}$ can be obtained by adding H_{pin} (280 Oe) to H_{ms} acting on the pinned layer, resulting in a very large positive $H_{bias,p}$ value; for example, +452 Oe in the smallest spin-valve of 0.5 μm × 0.25 μm. The bias field obtained in this way is in perfect agreement with that obtained from the results shown in Figs. 1 and 2 for the hysteresis loop. In the case of the free layer, the bias field can be obtained by adding H_{ms} to H_{exch} (12 Oe). Since the value of H_{ms} at small sizes is large negative, $H_{bias,f}$ in this case, therefore, is large negative; −108 Oe in the smallest spin-valve of 0.5 μm × 0.25 μm. Again, the magnitude of H_{bias} obtained from H_{ms} is in excellent agreement with that obtained from the hysteresis loops. This relationship between H_{bias} and H_{ms} can be understood, since H_{ms} is unidirectional in nature, like the pinning field and the exchange field. It is worth noting that the value of H_{ms} acting on the pinned layer is greater than that acting on the free layer. This can be understood, since the product of the thickness and saturation magnetization of the free layer, to which the value of H_{ms} acting on the pinned layer is proportional, is

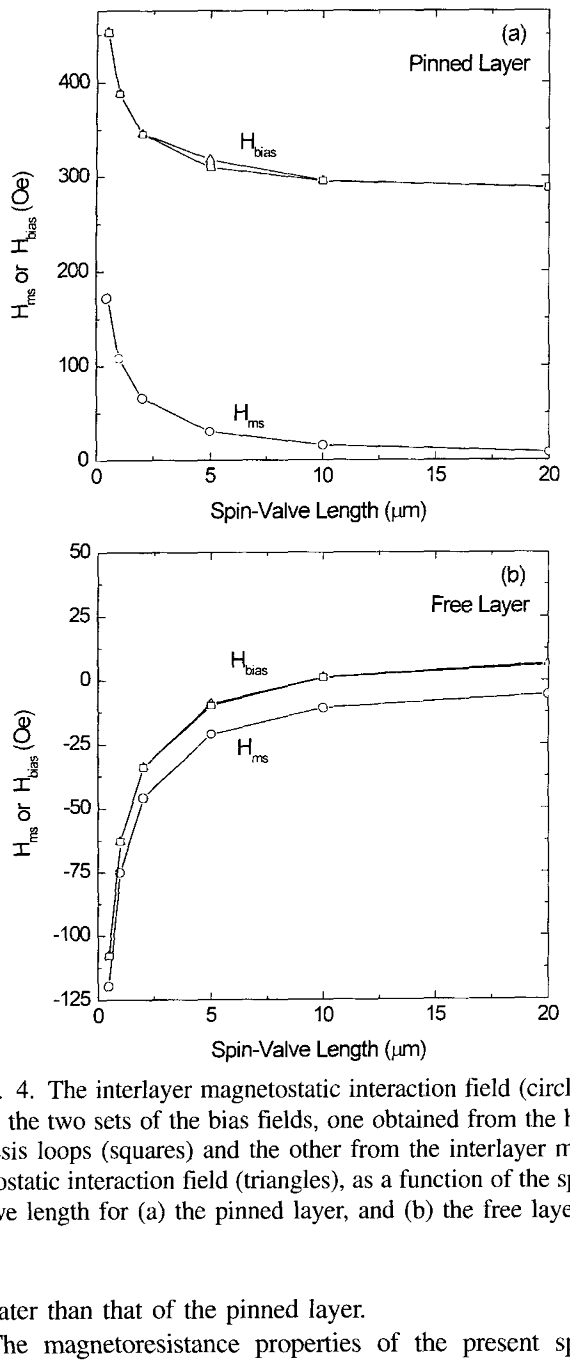

Fig. 4. The interlayer magnetostatic interaction field (circles), and the two sets of the bias fields, one obtained from the hysteresis loops (squares) and the other from the interlayer magnetostatic interaction field (triangles), as a function of the spin-valve length for (a) the pinned layer, and (b) the free layer.

greater than that of the pinned layer.

The magnetoresistance properties of the present spin-valves can easily be estimated from the M-H loops since the magnetization occurs only by spin-flip. In the case of the spin-valve shown in Fig. 1(c), for example, as H_a decreases from 500 Oe to a, the spins in the pinned and free layers are parallel to each other and hence the magnetoresistance is minimum. The magnetoresistance becomes maximum in the H_a range from a to b where the spins are antiparallel. At H_a values lower than b, the magnetoresistance is minimum again.

3.2 Effects of the aspect ratio

Calculation was performed over a wide aspect ratio of 0.5 to 3.0 to systematically investigate aspect ratio effects, and some of the results are shown in Figs. 5(a)-(d) for several aspect ratios of 0.5 and 0.85 (a), 1.0 (b), 1.4 (c) and 3.0 (d). Similarly to the previous results for the multilayers with varying sizes but at a fixed aspect ratio, the characteristics fields of small-sized samples such as those shown in Figs. 5(a)-(d) differ significantly from the *ideal* values, due to a large contribution of magnetostatic interactions to the total energy. At a small aspect ratio of 0.5 (Fig. 5(a)), essentially no hysteresis is observed in the M-H loops. This indicates that magnetization change occurs by continuous spin-rotation, not by abrupt spin-flip, which would be expected in this kind of multilayer spin-valves where the uniaxial anisotropy fields in both the pinned and free layers are parallel to the applied field direction. This behavior is due to the uniaxial shape anisotropy. The calculated values of the shape anisotropy from H_{demag} for the pinned and free layers are shown in Figs. 6(a) and (b), respectively. Note that the values of H_{demag} and also the shape anisotropy are only dependent on the geometry and the saturation magnetization. In the figures, a positive (negative) value indicates that the easy axis of the shape anisotropy is in the length (width) direction. It is seen from Figs. 6(a) and (b) that the shape anisotropy of the free layer is again greater than that of the pinned layer. At the smallest aspect ratio, the shape anisotropy is large negative (indicating a strong shape anisotropy in the width direction) in both layers. Specifically, in the case of the pinned layer, the shape anisotropy is slightly smaller than the induced anisotropy by 2.5 Oe resulting in a net uniaxial anisotropy in the length direction, but the shape anisotropy is dominant in the case of the free layer, indicating a very large uniaxial anisotropy in the width direction in this case. The continuous spin-rotation in the free layer can thus be well expected, since the direction of H_a is perpendicular to that of the net uniaxial anisotropy. It appears, however, not easy to understand the continuous spin-reversal in the case of the pinned layer, since the direction of H_a is parallel to that of the net uniaxial anisotropy. In order to understand this behavior, the spin configuration of the multilayer is examined during the whole field cycle. From this investigation it is found that, during the magnetization reversal of the pinned layer, the free layer spin direction is away from the length direction and this provides, through interlayer magnetostatic interactions, an additional field to the pinned layer in the width direction. The deviation of the free layer spin direction from the length direction can be well expected due to a large (uniaxial) anisotropy in the width direction *and* the interlayer magnetostatic interactions acting on the free layer from the pinned layer. Note that the pinned layer is undergoing magnetization reversal and hence it is away from the length direction. A similar magnetization reversal behavior is also observed at an aspect ratio of 0.71 (1.0 μm × 1.4 μm) (results are not shown here), even though, in this case, the total uniaxial anisotropy in the length direction is fairly strong, the shape anisotropy being smaller than the induced anisotropy by 26 Oe. This again emphasizes a large role of the interlayer magnetostatic interactions. As the aspect ratio

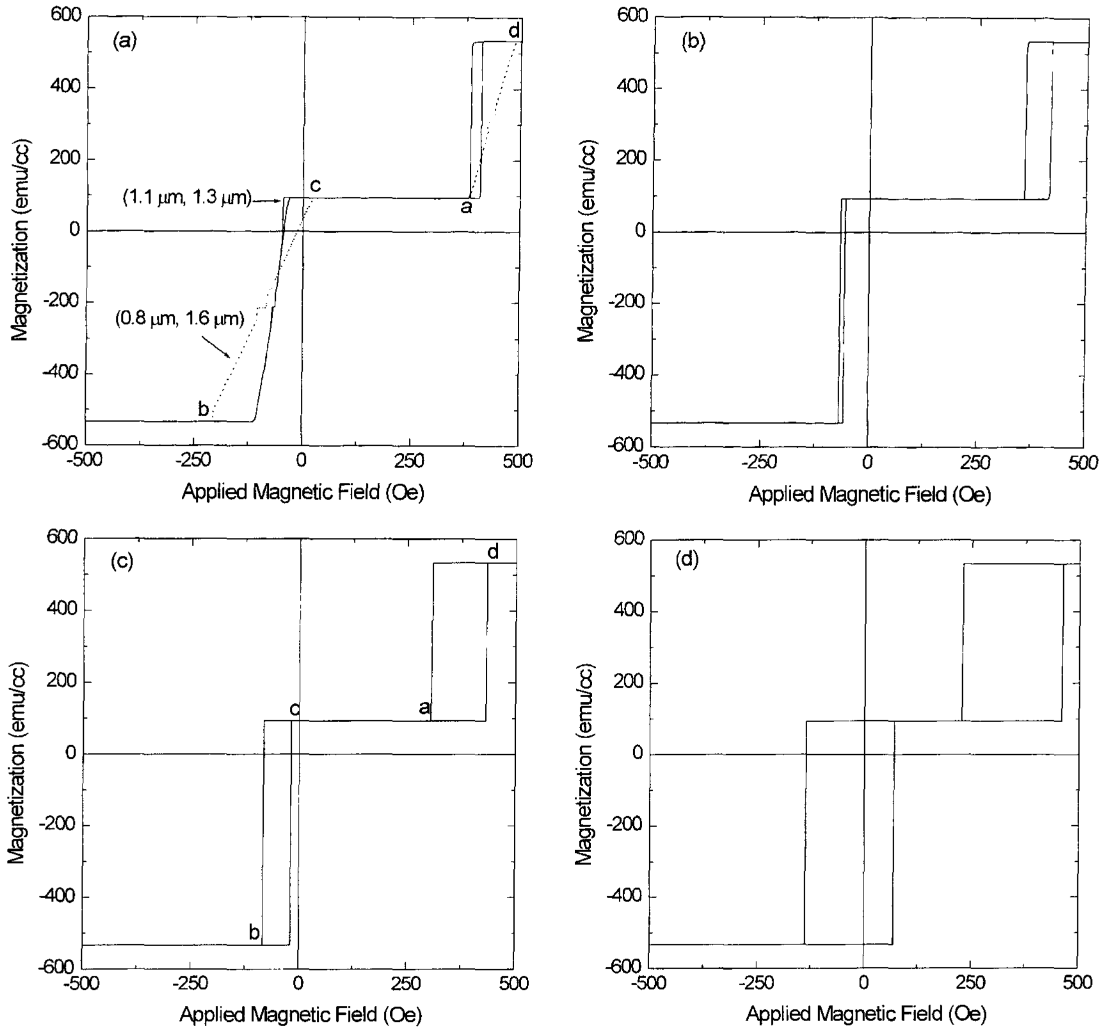

Fig. 5. M-H hysteresis loops for several spin-valves with various aspect ratios. (a) 0.8 μm × 1.6 μm and 1.1 μm × 1.3 μm, (b) 1.2 μm × 1.2 μm, (c) 1.4 μm × 1.0 μm, and (d) 1.8 μm × 0.6 μm.

increases to 0.85 (1.1 μm × 1.3 μm) (Fig. 5(a)), a spin-flip like behavior is finally observed in the pinned layer resulting in non zero coercivity, but the free layer spin still rotates continuously. This is because the net uniaxial anisotropy is still negative at this aspect ratio. Even in this case (1.1 μm × 1.3 μm) where the net uniaxial anisotropy of the pinned layer is fairly strong (36 Oe) in the length direction, the M-H loop of the pinned layer is not completely squared but slightly round (particularly at the onset of the magnetization change), indicating an existence of continuous spin-reversal.

Two additional points can be noted from the results for the spin-valves with the aspect ratio smaller than unity. Firstly, the range of H_a over which magnetization reversal occurs is greater in the free layer than that in the pinned one, and it decreases with increasing aspect ratio. This can be seen more clearly from Fig. 7 where four different positions (a-d) in hysteresis loops at which magnetization reversal process is *completed* are plotted as a function of the aspect ratio. The four spin-reversal positions are indicated in some of the M-H loops (Figs. 5(a) and (c)). The range of H_a over which magnetization reversal occurs in the pinned layer corresponds to the difference (d-a) in Fig. 7, and that in the free layer is given by the difference (c-b). The results shown in Fig. 7 can also be used to see the dependence of the characteristic magnetic fields on the aspect ratio, since the relationships exist between the characteristic fields and the spin-reversal positions as was already mentioned in Sec. 3.1. The results for the magnetization reversal range can be explained by the fact that the net uniaxial anisotropy of the free layer in the width direction is larger than that of the pinned layer, and it decreases with increasing aspect ratio in both layers. Secondly, during the magnetization reversal by continuous spin-rotation, a plateau occurs in the M-H curves where the magnetization does not vary with H_a. This plateau, which is observed in both the pinned and free layers, is related with the stabilization of the spin by the shape anisotropy. Specifically, in the case of the magnetization reversal of the pinned (free) layer, the plateau occurs when the pinned (free) layer points in the width direction. Since the shape anisotropy of the free layer is greater than that of the pinned layer, the plateau length is larger in the case of the free layer, indicating a stronger spin stabilization of this

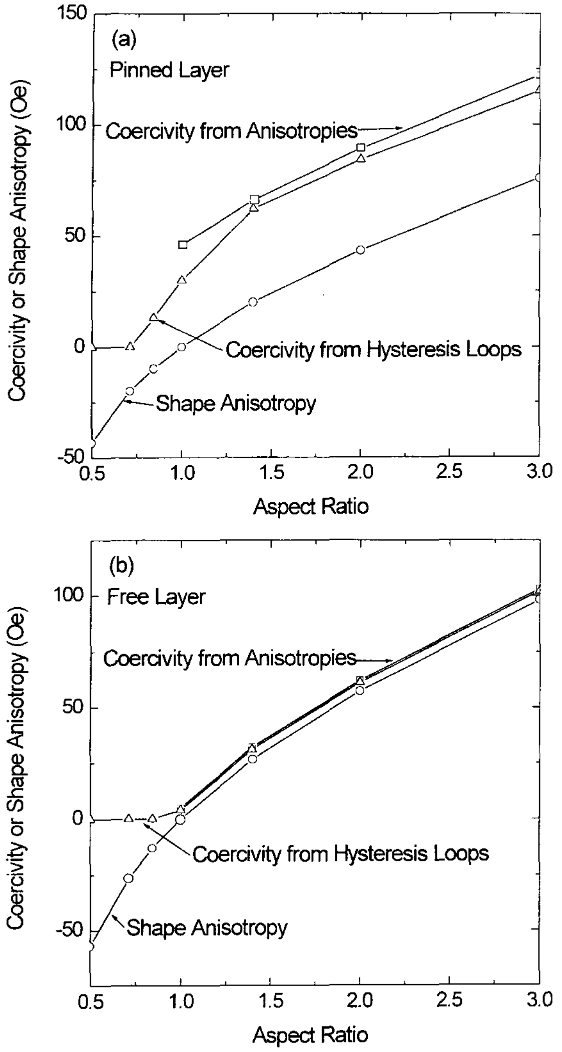

Fig. 6. The shape anisotropy (circles), and the two sets of the coercivities, one obtained from the hysteresis loops (squares) and the other from the shape anisotropy (triangles), as a function of the aspect ratio for (a) the pinned layer, and (b) the free layer.

layer. The fact that the plateau length decreases with increasing aspect ratio can also be explained similarly; namely, the shape anisotropy in the width direction decreases with increasing aspect ratio.

When the aspect ratio is greater than unity, M-H hysteresis loops are squared, indicating that the magnetization reversal occurs by spin-flip. This means that the direction of the spins in the pinned and free layers points, all the time, in the length direction, the same direction of H_a. This can be understood from the fact that all the anisotropies including the shape anisotropy are aligned in the length direction. The most prominent change in the loops with the increase of the aspect ratio is the increase of the coercivity. At the highest aspect ratio investigated in this work, for example, the coercivity is really enormous; $H_{c,p}$ = 115 Oe and $H_{c,f}$ = 102 Oe. The results for the coercivity as a function of the aspect ratio are shown in Figs. 6(a) and (b) for the pinned and free layers, respectively. Similarly, the increase of the

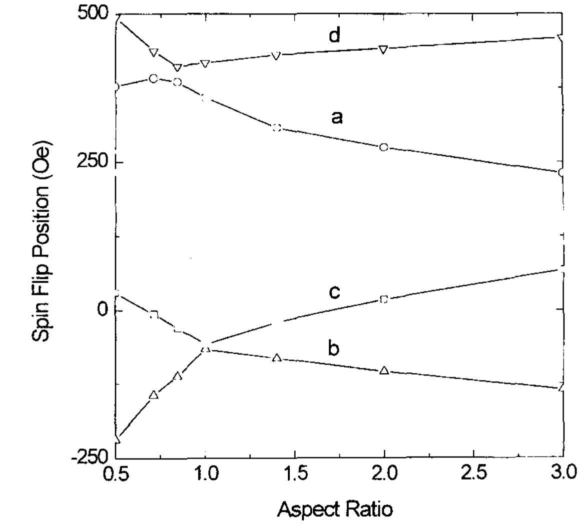

Fig. 7. The applied magnetic fields at which spin-reversal is completed as a function of the aspect ratio. The spin reversal positions of a-d are indicated in some M-H loops (Figs. 5(a) and (c)).

coercivity can be explained by the shape anisotropy. The coercivity obtained from the sum of the (uniaxial) induced anisotropy and the shape anisotropy is also shown in Figs. 6(a) and (b), together with those obtained from the hysteresis loops. It is noted that the coercivity from the shape anisotropy cannot be obtained for the spin-valves with the aspect ratio smaller than unity, where magnetization reversal does not occur by spin-flip.

In the case of the free layer, the values of $H_{c,f}$ obtained from the hysteresis loops are in excellent agreement with those estimated from the shape anisotropy (the sum of the shape anisotropy and 5 Oe for the induced anisotropy) as can be seen from Fig. 6(b). In the case of the pinned layer, however, the magnitude of $H_{c,p}$ from the hysteresis loop is lower than that estimated from the shape anisotropy (the sum of the anisotropy and 46 Oe for the induced anisotropy) (see Fig. 6(a)). The discrepancy is largest at an aspect ratio of 1.0. It is noted here that the shape anisotropy for the multilayer with an aspect ratio of 1.0 is calculated to be zero (isotropic) in the present work, but actually it is not zero, the easy axis being in the diagonal direction. This may be partly responsible for the discrepancy, but a clear reason for this discrepancy is not understood at this moment.

The aspect ratio dependence of the bias field is again completely explained by that of H_{ms}, the results for which being shown in Figs. 8(a) and (b) in the pinned and free layers, respectively. Also shown in the figures are the values of H_{bias} obtained from the hysteresis loops, and H_{ms} (namely, the sum of H_{ms} and the exchange field (H_{pin} or H_{exch})). It is seen from Figs. 8(a) and (b) that, in both pinned and free layers, the magnitude of H_{bias} obtained from H_{ms} is in excellent agreement with that obtained from the hysteresis loops over the whole aspect ratio range. Two

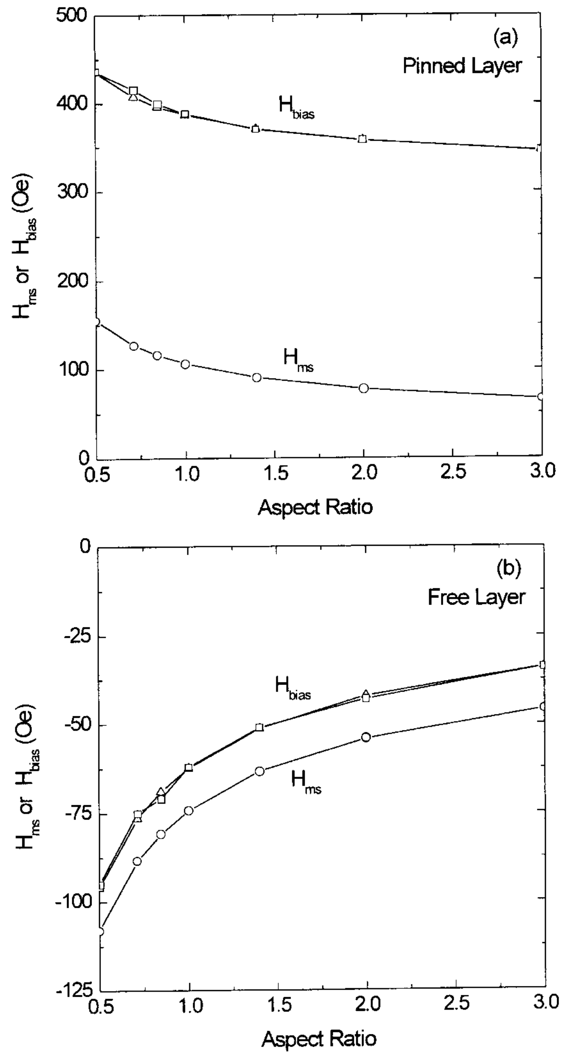

Fig. 8. The interlayer magnetostatic interaction field (circles), and the two sets of the bias fields, one obtained from the hysteresis loops (squares) and the other from the interlayer magnetostatic interaction field (triangles), as a function of the aspect ratio for (a) the pinned layer, and (b) the free layer.

points can be noted from the H_{ms} results. Firstly, for a given aspect ratio, the value of H_{ms} acting on the pinned layer is greater than that acting on the free layer. This is because the product of the cross section (width × thickness) and saturation magnetization is greater in the free layer than in pinned one, causing more free poles to be formed in the free layer. Note that the value of H_{ms} acting on the pinned (free) layer is proportional to the free poles in the free (pinned) layer. Secondly, the absolute magnitude of H_{ms} (and hence H_{bias}) decreases with increasing aspect ratio in both the pinned and free layers. This can also be explained similarly; namely, as the aspect ratio increases, the width and hence the cross section decreases, causing less free poles and hence smaller H_{ms}.

3.3 Overall discussion

As was already pointed out, the magnetic configuration of the present spin-valve is relevant to an MRAM cell. Since the size of an MRAM cell is expected to be in the submicron range [8], it is expected from the present results that the magnetic properties of a spin-valve in an MRAM device are affected significantly by the magnetostatic interactions, one typical example being a very large coercivity. However, it is important to note at this stage that, in a real MRAM device, the change of the characteristic fields will not be that great, compared with that observed in this model. This is because a real spin-valve even with a submicron size may have a complicated spin structure, not a simple single domain structure, in a way to reduce the magnetostatic interactions. One example of the complicated spin structure is the magnetization curling formed at the edge of the layers [4, 5]. With the presence of the complicated spin structure, the magnetization change will not occur abruptly by spin-flip, causing to decrease the coercivity, among many others. In this sense, the present results for the characteristic fields are considered to provide the upper limit; in other words, the values of the coercivity and bias field obtained at a given spin-valve size are always greater than those observed in real devices. It is ironic to see that this complicated spin-structure obtained in a more realistic model provides an obstacle to a clear understanding of an overall picture on the size dependence of the magnetic properties. Due to small magnetostatic interactions at large sizes, the difference in the values between the model calculations and experiments is expected to be small in this size range. As the size of a magnetic material becomes very small, a single-domain state is favored. In this size range, this difference will be also small, indicating that the present single-domain model works well.

4. Conclusions

Computer simulation has been carried out in this work to examine the size and aspect ratio dependence of the magnetic properties of a spin-valve multilayer. The size effects are examined at a fixed aspect ratio of 2.0, but the spin-valve size is varied widely from 20 mm × 10 mm to 0.5 μm × 0.25 μm. The aspect ratio effects are investigated at a fixed multilayer size (2.4 μm) which is indicated by the sum of the length and the width, but at varying aspect ratios of 0.5 to 3.0. The spin-valve modeled in this work is IrMn (9 nm)/CoFe (4 nm)/Cu (2.6 nm)/CoFe (2 nm)/NiFe (6 nm). M-H hysteresis loops of various sized spin-valves indicate that, at small lengths below 5 μm, characteristic magnetic fields such as the coercivity and the bias field vary significantly with the spin-valve size in both the pinned and free layers, and the variation is even greater at lengths below 1 μm. Characteristic magnetic fields also vary greatly with the aspect. At aspect ratios smaller than unity where the shape anisotropy is formed in the width direction, the uniaxial anisotropy is perpendicular to the applied field, resulting in magnetization reversal by continuous spin rotation and no or very small hysteresis. At aspect ratios greater than unity, however, magnetization change occurs by spin-flip, resulting in squared hysteresis loops, and the coercivity increases significantly with the increase of the aspect ratio. A significant change occurs in the bias field, and its absolute magnitude decreases with increasing aspect ratio. This size and aspect ratio dependence of the magnetic properties is due to the magnetostatic interactions. Two separate field components, the self-demagnetizing field and the interlayer magnetostatic interaction field, can be identified from the magnetostatic interactions, and it has been shown that the change of the coercivity and the bias field can be explained, respectively, by the self-demagnetizing field and the interlayer magnetostatic interaction field. The coercivities in both the pinned and free layers obtained from the hysteresis loops are in good agreement with those estimated from the uniaxial shape anisotropy which is defined as the difference of the self-demagnetizing fields in the width and the length directions. Also, the bias fields in the two magnetic layers are in excellent agreement with those estimated from the unidirectional interlayer magnetostatic interaction field.

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