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Computer simulation of magnetization flop in magnetic tunnel junctions exchange-biased by synthetic antiferromagnets

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Abstract

Computer simulation in a single domain multilayer model is used to investigate magnetization flop in magnetic tunnel junctions, exchange-biased by pinned synthetic antiferromagnets with the multilayer structure NiFe/AlO_x/Co/Ru/Co/FeMn. The resistance to magnetization flop increases with decreasing cell size due to increased shape anisotropy and hence increased coercivity of the Co layers in the synthetic antiferromagnet. However, when the synthetic antiferromagnet is not or weakly pinned, the magnetization directions of the two layers sandwiching AlO_x, which mainly determine the magnetoresistance, are aligned antiparallel due to a strong magnetostatic interaction, resulting in an abnormal MR change from the high MR state to zero, irrespective of the direction of the free layer switching. This emphasizes an importance of a strong pinning of the synthetic antiferromagnet at small cell dimensions. The threshold field for magnetization flop is found to increase linearly with increasing antiferromagnetic exchange coupling between the two Co layers in the synthetic antiferromagnet. The restoring force from magnetization flop to the normal synthetic antiferromagnetic structure is roughly proportional to the resistance to magnetization flop. Irrespective of the magnetic parameters and cell sizes, the state of magnetization flop does not exist near $H_a = 0$, indicating that magnetization flop is driven by the Zeeman energy.

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Keywords: Magnetic tunnel junctions; Magnetization flop; Synthetic antiferromagnets; Size effects; Computer simulation

1. Introduction

Magnetic tunnel junctions (MTJs) with a large room temperature magnetoresistance (MR) are considered to be suitable for magnetic random access memory (MRAM) devices. It is well understood that a high memory density is one of the most important factors to the successful realization of commercially viable MRAM [1]. In a practical density level, the cell dimensions are expected to be in the submicron size range, where the switching of a magnetic layer is dominated by magnetostatic interactions. Switching fields are related to two characteristic magnetic fields: the bias (or offset) field and the coercivity. This indicates that switching characteristics can be understood through detailed knowledge of these two magnetic parameters. Two separate field components, the self-demagnetizing field and

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the interlayer magnetostatic interaction field, can be identified from the magnetostatic interactions, and it was shown previously in a single domain multilayer model that the coercivity and the bias field, respectively, are completely explained by the self-demagnetizing field and the interlayer magnetostatic interaction field [2]. The self-demagnetizing field is determined by two factors, the self-demagnetizing coefficient and saturation magnetization, the former being only a function of the geometry (dimensions including the aspect ratio) of a magnetic layer. This indicates that the self-demagnetizing field (and hence the coercivity) of a magnetic layer is dependent on the related properties of the magnetic layer itself under consideration, but is independent of the multilayer structure (or design). On the other hand, the interlayer magnetostatic interaction field, which is caused by the stray fields from neighboring layers, is dependent on the structure of a multilayer [3].

In conventional MTJs where the pinned layer is exchange-biased by a single layer of antiferromagnet (AF) (FeMn, for example), the stray field from the pinned layer plays a role of biasing the free layer causing the hysteresis loop asymmetry. The switching asymmetry is actually very large at submicron cell dimensions [2,3]. This problem can be relieved, if not solved, by substituting a synthetic antiferromagnet (SyAF) for a single AF layer. Currently, popular SyAFs are Co/Ru/Co [4] and Co/Ru/Co/AF (called a pinned SyAF) [5,6]. In this structure, the magnetic flux closure is formed within the SyAF; specifically, a large portion of the stray field radiating from one Co layer is absorbed by the other Co layer. As a result of this, the stray field reaching the free layer can be significantly reduced. Additionally, the use of a SyAF has other important advantages of a large unidirectional pinning field and a good thermal stability over a single layered AF [4].

In spite of many merits of a SyAF, a potentially serious problem may result from the magnetization-flop phenomenon [6–9]. In the simple Stoner–Wohlfarth model, where the total energy consists of the Zeeman energy and the exchange coupling between the two Co layers, it was shown in a SyAF that the reduction of the Zeeman energy is always greater than the increase of the interlayer antiferromagnetic exchange coupling as long as the deviation from the antiparallel alignment of the Co layers is small [7]. This indicates that, whenever a magnetic field is applied to a SyAF, the magnetization direction of the Co layers is not completely antiparallel, but is deviated toward the applied field direction. Furthermore, the Zeeman energy reduction is greatest when the magnetization directions of the Co layers are orthogonal to the applied field in the film plane. This essentially gives a SyAF, an effective uniaxial anisotropy with easy axis perpendicular to the applied field, and provides a driving force for magnetization flop. Obviously, the occurrence of magnetization flop is very harmful to MRAM devices, because MTJs are no longer in a bi-stable state with different resistance that is necessary to store the digital information. In the case of a complete magnetization flop where the magnetization directions of the two Co layers are orthogonal to that of the free layer, no change in resistance occurs accompanying the free layer switching.

Only a few articles have been published dealing with magnetization flop since the first theoretical prediction by Zhu and Zheng [7], and all the previous work was confined to spin-valve multilayers. Zhu and Zheng [7] examined the effects of the aspect ratio and the unidirectional pinning strength by an AF on the rigidity of a SyAF in a full micromagnetic model by using the LLG equation. They observed, in a $0.5\,\mu m \times 0.5\,\mu m$ cell, a very small threshold field of 40 Oe for magnetization flop, which is even smaller than the switching field of the free layer. The rigidity of a SyAF, however, was found to improve with increasing aspect ratio, and also the introduction of unidirectional pinning field by an AF. The first experimental observation of magnetization flop was reported by Tong et al. [6] in spin-valves exchange-biased by pinned SyAFs (CoFe/Ru/CoFe/IrMn). Magnetization flop was observed from post-field-annealing experiments by changing the magnitude and the direction of applied magnetic field. Magnetization flop was also observed by Marrows et al. [8] during sputtering under applied magnetic field (200 Oe) by simply changing the relative thickness of the two Co layers in a SyAF.

In this work, computer simulation in a single domain multilayer model is used to investigate magnetization-flop behavior in MTJs exchange-biased by a pinned SyAF. The main objective is to examine how the rigidity of SyAFs is affected by various magnetic parameters and the cell size. A particular emphasis is given to the cell size effects due to their importance in high density MRAM devices.

2. Models and computation

In the model, each magnetic layer consisted of a single domain, indicating that the magnetization is uniform within a layer. The structure of MTJs modeled in this work was NiFe(I) (7.5 nm)/AlO_x (0.7 nm)/Co(I) (3.5 nm)/Ru (0.7 nm)/Co(II) (3.5 nm)/FeMn (10 nm) (see Fig. 1 for a schematic illustration). A similar structure was previously investigated by Parkin et al. [5]. In order to examine the size effects, the multilayers with varying dimensions were investigated; namely, 0.8×0.4, 1.2×0.6, 2.8×1.4, 4×2, 6×3, 8×4, 11.2×5.6 and 16×8 (all dimensions in μm). Note that the aspect ratio (defined by the ratio of the length to the width) of all the MTJs was fixed at 2.0. The uniaxial induced anisotropy in the free layer (H_{Py}) was 5 Oe and that in the Co layers (H_{Co}) was 20 Oe [3,5]. The ferromagnetic exchange coupling (more specifically, the Néel orange-peel coupling, the origin of which is magnetostatic interactions in nature) between the free layer and the Co(I) layer (next to the AlO_x layer) (H_{bias}) was 26 Oe [3,5]. The magnitude of the antiferromagnetic coupling field between the two Co layers separated by a thin Ru layer (H_{anti}) was varied from -600 to -1200 Oe (the negative sign indicates the antiferromagnetic coupling), although it is estimated to be approximately -1200 Oe at the present interlayer separation [10]. The widely varied values of H_{anti} may reflect the variation in surface properties and/or Ru thickness in real experiments. The exchange coupling between the FeMn and Co(II) layers (H_{pin}) was also varied widely from 0 to 800 Oe. All the uniaxial and unidirectional anisotropies were formed in the length (x) direction. The magnetization direction of Co(II) was set to be in the $+x$ direction. This determines the magnetization direction of the Co(I) layer through the antiferromagnetic exchange coupling and that of the free layer through the orange-peel coupling at the conditions of no magnetostatic interactions (namely, very large cell dimensions) and zero applied field. Specifically, the magnetization directions of both the Co(I) and free layers point in the $-x$ direction. The magnetization directions of all the magnetic layers are shown in Fig. 1. In this magnetic configuration, the orange-peel coupling biases the free layer to the positive direction, since the coupling gives the free layer a torque in the negative direction. It is noted that the bias field direction of a magnetic layer is opposite to the unidirectional torque applied to the layer. A good example is the exchange bias in AF/F (ferromagnet) bilayers. Exchange coupling between the two layers is usually set, by first annealing the bilayers well above the Néel temperature of the AF and subsequently cooling them with the applied field on. In this case, the shift in loop is in the opposite direction to the setting field. The

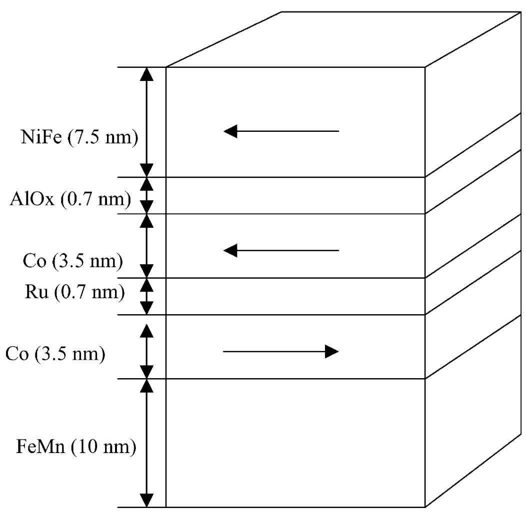

Fig. 1. The MTJ structure modeled in this work. The magnetization direction indicated in the ferromagnetic layers is at conditions of no magnetostatic interactions and zero applied field.

magnetization of the NiFe (more specifically $Ni_{60}Fe_{40}$) layer was taken as $1055\,emu/cm^3$ and that of Co as $1400\,emu/cm^3$ [11]. The applied magnetic field (H_a) pointed in the length direction (the same as all the anisotropy fields). The maximum applied field during the field cycle was suitably varied in accordance with magnetic parameters of the multilayers.

3. Results and discussion

From a simple energy consideration, magnetization flop should occur on applying a magnetic field to a SyAF. However, magnetization flop only occurs at magnetic fields greater than a threshold field (H_{th}) due to the energy barrier to the flop. This is illustrated in Figs. 2 and 3, where the results for M–H and MR–H curves for two field cycles with different maximum applied fields are: 300 Oe which is below H_{th} (Figs. 2a and b), and 2000 Oe which is above H_{th} (Figs. 3a and b). The results are obtained for $H_{bias} = 26\,Oe$, $H_{Py} = 5\,Oe$, $H_{anti} = -1000\,Oe$, $H_{Co} = 20\,Oe$ and $H_{pin} = 0$. The largest cell of $16\,\mu m \times 8\,\mu m$ is used to minimize the shape anisotropy, which cannot be avoided in the present rectangular cell geometry. When the maximum applied field is smaller than H_{th}, only the free layer switches during the field cycle while the rest of the magnetic layers remain fixed. The bias field (or offset field) of the free layer, which is defined to be the center of the hysteresis loop, is obtained to be 26 Oe. Note that the bias field is the vector sum of the orange-peel coupling field (+26 Oe) and the interlayer magnetostatic interaction field (−0.02 Oe for the present results shown in Figs. 2 and 3) [3]. During the cycle, the magnetization directions of all the layers are completely parallel or antiparallel, resulting in very simple M–H and MR–H hysteresis loops, and also a maximum MR change accompanying free layer switching. This situation is ideal for MRAM applications.

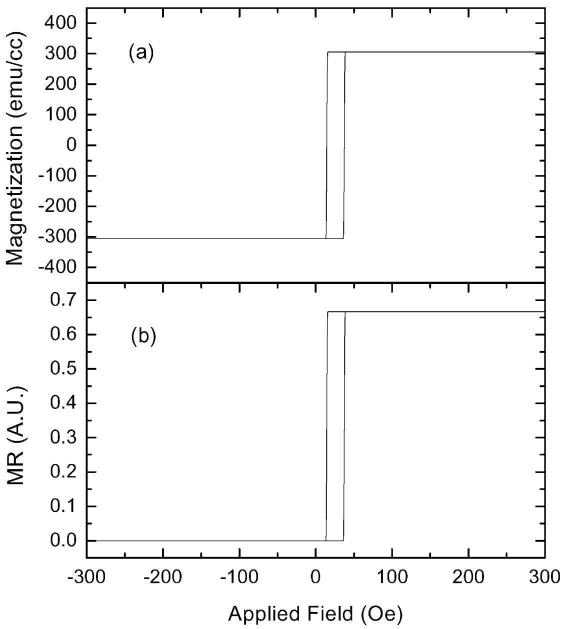

Fig. 2. (a) M–H and (b) MR–H hysteresis loops for a cell size of $16\,\mu m \times 8\,\mu m$ at a maximum applied field of 300 Oe which is below the threshold field for magnetization flop. The results are obtained for $H_{bias} = 26\,Oe$, $H_{Py} = 5\,Oe$, $H_{anti} = -1000\,Oe$, $H_{Co} = 20\,Oe$ and $H_{pin} = 0$.

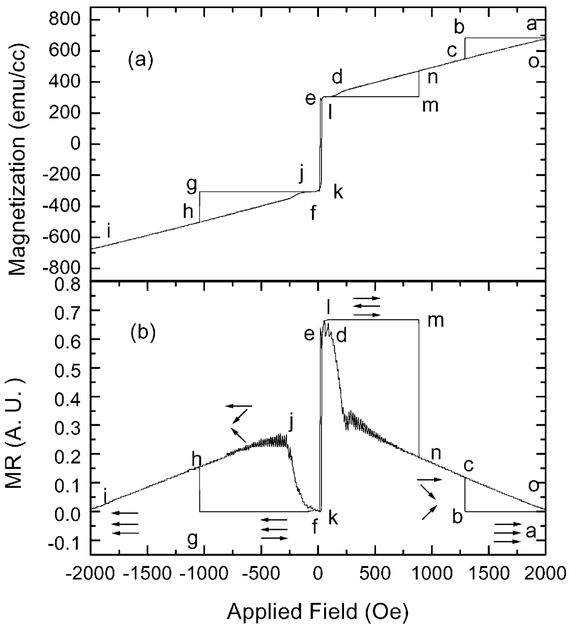

Fig. 3. (a) M–H and (b) MR–H hysteresis loops for a cell size of $16\,\mu m \times 8\,\mu m$ at a maximum applied field of 2000 Oe, which is above the threshold field for magnetization flop. The results are obtained for $H_{bias} = 26\,Oe$, $H_{Py} = 5\,Oe$, $H_{anti} = -1000\,Oe$, $H_{Co} = 20\,Oe$ and $H_{pin} = 0$. The magnetic configuration at some important points during the field cycle is also illustrated.

When magnetization flop occurs, magnetic configuration becomes complicated, causing complicated M–H and MR–H loops. Two main factors are responsible for the complicated M–H and MR–H loops. One is, of course, magnetization flop. The other is related to the fact that the magnetization of the two Co layers in SyAF scissors toward the axis of the applied field. The latter factor is responsible for the linear change of magnetization and MR as a function of applied field. Eventually, the magnetization directions of the two Co layers are expected to be parallel at saturation field where MR is lowest (zero), which corresponds to the points a and i in Figs. 3(a) and (b). In order to better understand the magnetic configuration during the field cycle, it is also illustrated in Figs. 3(a) and (b). The parallel alignment is maintained until b, below which magnetization flop occurs (point c). This change occurs abruptly, so does the change in M and MR. An important change at this point is that the two Co layers in the SyAF are aligned antiparallel due to H_{anti}. The antiparallel alignment, however, is far from complete at point c, but it improves with decreasing H_a. As the magnitude of H_a decreases from c to e, M continuously decreases nearly linearly due to the improvement of antiparallel alignment, but this is not the case for the MR–H curves where a large fluctuation is observed (at around d) and an abrupt change in MR occurs as H_a varies from d to e. In the present model, the change in MR is solely dependent on the angle between the free and Co(I) layers. With a small coercivity of the free layer, magnetization always points in the $+x$ direction in this H_a range, so MR is dependent on the magnetization direction of Co(I). Even in the magnetization-flop state, the magnetization direction of Co(I) is not orthogonal to H_a but is directed toward the H_a direction in case H_a is large. As H_a decreases from c to d, the angle between Co(I) and H_a approaches to 90° and hence MR increases. The large fluctuation in MR observed at d (and also j) is related with the orthogonal relationship between the magnetization directions in the SyAF and H_a where a small rotation of the SyAF causes a large MR change. The sudden jump in MR from d to e is due to the disappearance of magnetization flop. This clearly demonstrates that magnetization flop is driven by H_a (the Zeeman energy). So, the change in M and MR near $H_a = 0$ is similar to the case of no magnetization flop where the change is dominated by the free layer switching. The conventional SyAF structure is stable (more precisely, metastable) as H_a increases in the $-x$ direction from f to g where magnetization flop occurs again. With the further increase of H_a in the $-x$ direction, the magnetization of the two Co layers in the SyAF scissors toward the $-x$ direction, and subsequent change in M and MR can accordingly be explained. The sudden decrease of MR from j to k is also due to the disappearance of magnetization flop as H_a approaches to zero, similarly to the path from d to e. The change in M and MR along the path $l \rightarrow m \rightarrow n \rightarrow o$ can be explained similarly to the path of $f \rightarrow g \rightarrow h \rightarrow i$.

Let us now examine the effects of the magnetic parameters and cell size on the rigidity of the SyAF. In Fig. 4 are shown the results for H_{th} as a function of H_{anti} for all the cell sizes investigated in

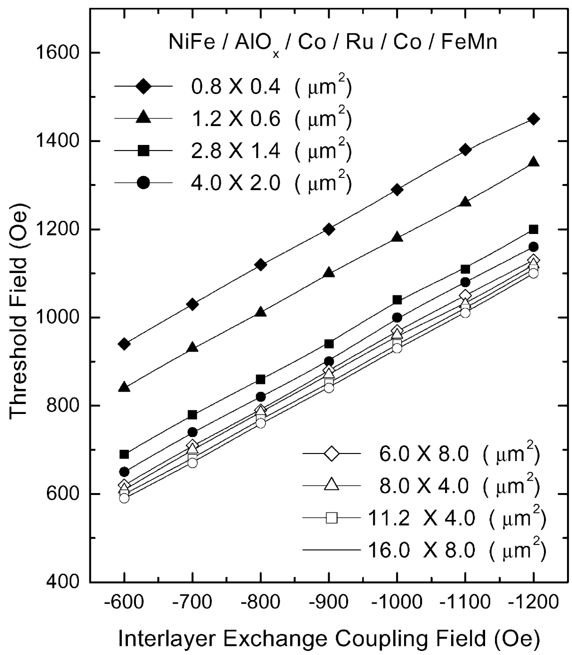

Fig. 4. The threshold field as a function of the antiferromagnetic exchange coupling strength at various cell sizes. The results are obtained for $H_{bias} = 26$ Oe, $H_{Py} = 5$ Oe, $H_{Co} = 20$ Oe and $H_{pin} = 400$ Oe.

this work. The results are obtained for $H_{bias} = 26$ Oe, $H_{Py} = 5$ Oe, $H_{Co} = 20$ Oe and $H_{pin} = 400$ Oe. The magnitude of H_{th}, above which magnetization flop occurs during the field cycle, was determined by scanning the maximum applied field at a step of 10 Oe. For all the cell sizes, the value of H_{th} increases linearly with increasing H_{anti}. This indicates that H_{anti} plays an effective role in resisting magnetization flop. If the magnetization of the two Co layers in the SyAF is *completely* antiparallel, torques on the two Co layers are identical but opposite. This makes magnetization flop hard to occur, since the torque (or rotation) of one Co layer is *exactly* counteracted by that of the other. The present results for the effects of H_{anti} on the rigidity of the SyAF, shown in Fig. 4, can be explained by the change of the strength of antiparallel alignment as a function of H_{anti}. At a smaller value of H_{anti}, the deviation from the complete antiparallel alignment is greater and hence smaller rigidity. It is worth noting that the slope of H_{th} vs. H_{anti} curves is identical for all the cell sizes. The slope is obtained to be 0.85 in the present model, indicating that the increase of H_{th} is 85% of that of H_{anti}.

For a fixed H_{anti}, the value of H_{th} increases with decreasing cell size. In order to see the cell size dependence of H_{th} more clearly, the results shown in Fig. 4 are re-plotted and are shown in Fig. 5 where the change in H_{th} is given as a function of the cell size (more specifically, cell width) at fixed values of H_{anti}. The increase of H_{th} with the decrease of the cell size is small in the large cell size range, but the increase becomes very steep in the submicron size range. This increase of the rigidity of the SyAF is considered to be due to the increase of the coercivity of the Co layers with the decrease of the cell size. The coercivity of a magnetic layer is the sum of the induced anisotropy (20 Oe in the present case) and the shape anisotropy, which is related with the self-demagnetizing field [2]. The shape anisotropy (coercivity) increases from 4 (24) to 78 (98) Oe as the cell size decreases from $16\,\mu m \times 8\,\mu m$ to $0.8\,\mu m \times 0.4\,\mu m$. The increase of H_{th}, however, is much greater than that of the coercivity; at the same cell size change and at a fixed H_{anti} of -1000 Oe, the value of H_{th} is increased by 360 Oe (from 930 to 1290 Oe) while

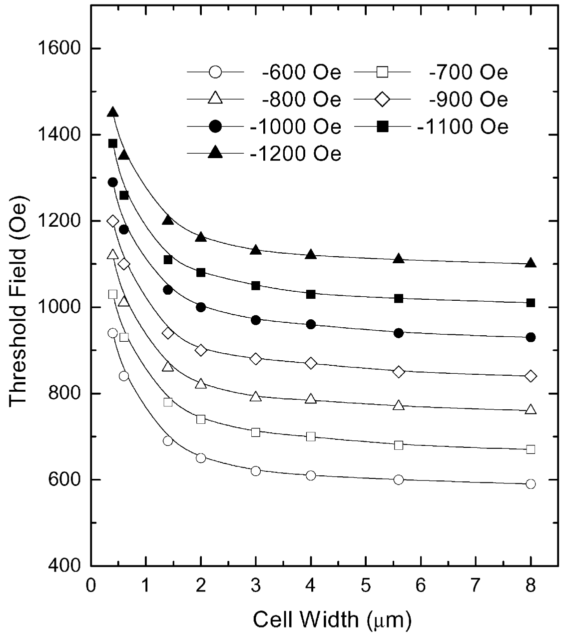

Fig. 5. The threshold field as a function of the cell size at various antiferromagnetic exchange coupling strengths. The cell size is indicated by the cell width. The results are obtained for $H_{bias} = 26$ Oe, $H_{Py} = 5$ Oe, $H_{Co} = 20$ Oe and $H_{pin} = 400$ Oe.

the coercivity increase is only 74 Oe. This indicates that the resistance to magnetization flop by the coercivity of the Co layers in the SyAF is very strong. The role played by the coercivity of the Co layers in the SyAF in resisting magnetization flop is much greater than that by the antiferromagnetic exchange coupling between the two Co layers. It is reminded that the increase of H_{th} is 85% of that of H_{anti}). The resistance to magnetization flop depending on the cell size is shown in more detail in Figs. 6(a) and (b) where MR–H hysteresis loops are presented for the two extreme cell sizes of $16\,\mu m \times 8\,\mu m$ and $0.8\,\mu m \times 0.4\,\mu m$, respectively. The comparison of the two loops clearly shows a significant increase in the coercivity of the free layer at the small cell size, which can also be explained by the increase of the shape anisotropy with the decrease of the cell size. Another important feature is that the H_a range in which the conventional SyAF structure is stable (in other words, no magnetization flop occurs) is large at the small cell size; specifically, the H_a range is -1388

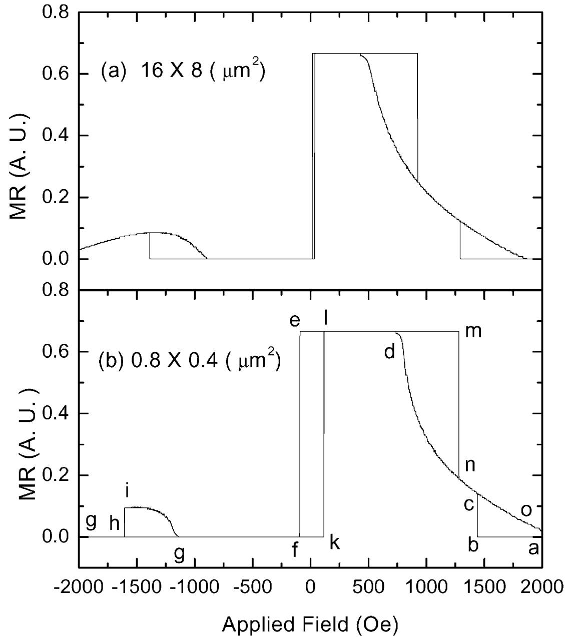

Fig. 6. MR–H hysteresis loops for the two extreme cell sizes of (a) $16\,\mu m \times 8\,\mu m$ and (b) $0.8\,\mu m \times 0.4\,\mu m$. The results are obtained for $H_{bias} = 26$ Oe, $H_{Py} = 5$ Oe, $H_{anti} = -1000$ Oe, $H_{Co} = 20$ Oe and $H_{pin} = 400$ Oe.

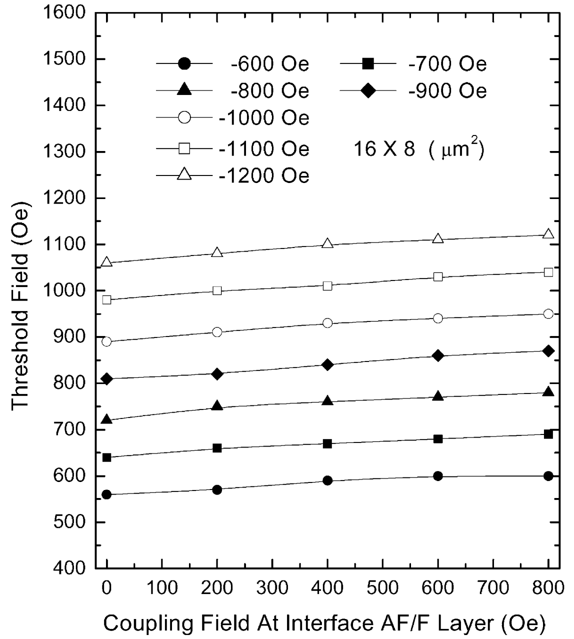

Fig. 7. The threshold field as a function of the exchange coupling field between SyAF and AF at various antiferromagnetic exchange coupling strengths for a cell size of $16\,\mu m \times 8\,\mu m$. The results are obtained for $H_{bias} = 26$ Oe, $H_{Py} = 5$ Oe and $H_{Co} = 20$ Oe.

to 926 Oe in the $16\,\mu m \times 8\,\mu m$ cell while it is -1607 to 1281 Oe in the $0.8\,\mu m \times 0.4\,\mu m$ cell. Note that the magnetization flop occurs at significantly higher values of H_a in the $-x$ direction. This is because the Co(II) layer is pinned in the $+x$ direction at a strength of 400 Oe by the AF layer.

In Fig. 7 are shown the results for H_{th} as a function of H_{pin} at several fixed values of H_{anti}. It is rather surprising to see that the value of H_{th} is slightly affected by H_{pin}. For example, at a fixed H_{anti} of –1000 Oe, the increase of H_{th} is only 60 Oe as H_{pin} increases from 0 to 800 Oe. However, a rather substantial change occurs in hysteresis loops depending on H_{pin}, as can be seen from the results shown in Figs. 8(a) and (b) for the two extreme cell sizes of $16\,\mu m \times 8\,\mu m$ and $0.8\,\mu m \times 0.4\,\mu m$, respectively. The magnetic parameters used are identical to those for Figs. 6(a) and (b), except for $H_{pin} = 0$ in this case ($H_{pin} = 400$ Oe for the results shown in Figs. 6(a) and (b)). So, by comparing the results shown in Figs. 6(a) and (b) with those in Figs. 8(a) and (b), one is able to see the difference in MR–H behavior depending on H_{pin}. The comparison of the MR–H loop shown in Fig. 8(a) with that in Fig. 6(a) for the large cell size indicates that the stability region for the conventional SyAF structure is narrowed in the absence of H_{pin}. In particular, the reduction in the negative direction is substantial, and this can be understood from the direction of H_{pin}, already mentioned in the previous paragraph. More prominent difference, however, is the significant reduction of the stability region for the SyAF structure, *once magnetization flop occurs*. This can be seen from the magnitude of H_a at which magnetization flop transforms into the conventional SyAF structure. In the case of $H_{pin} = 0$, once magnetization flop occurs, this state prevails since the transformation from magnetization flop into the conventional SyAF structure only occurs near $H_a = 0$. However, the state of magnetization flop returns to the normal SyAF structure at high H_a values in the presence of H_{pin}.

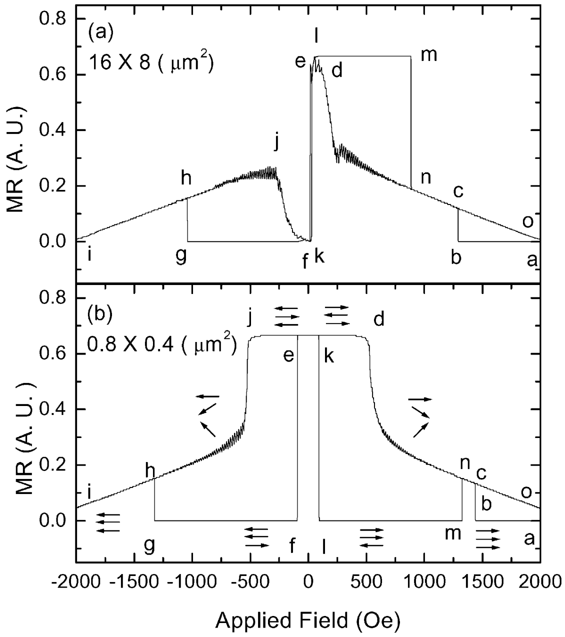

Fig. 8. MR–H hysteresis loops for the two extreme cell sizes of (a) 16 μm × 8 μm and (b) 0.8 μm × 0.4 μm. The results are obtained for $H_{bias} = 26$ Oe, $H_{Py} = 5$ Oe, $H_{anti} = -1000$ Oe, $H_{Co} = 20$ Oe and $H_{pin} = 0$ Oe. The magnetic configuration at some important points during the field cycle is also illustrated in Fig. 8(b).

At $H_{pin} = 400$ Oe, for example, the values of H_a at which the magnetic configuration transforms from magnetization flop into the SyAF structure are −895 and 430 Oe.

Much more striking difference is observed at small cell sizes and $H_{pin} = 0$. At these conditions, totally different MR–H hysteresis loop is observed as can be seen in Fig. 8(b). The loop is now nearly symmetrical with respect to $H_a \approx 0$. The cell sizes of 2.4 μm × 1.2 μm and below exhibit this type of hysteresis loop. The main difference is that the MR change accompanying the free layer switching is identical (from the high MR state to zero) irrespective of the direction of the free layer switching. In conventional SyAF-type MTJs, however, the MR change is opposite when the direction of the free layer switching is opposite. The reason for this strange hysteresis loop is a large contribution of the magnetostatic energy to the total energy at small cell dimensions, in particular, a large interlayer magnetostatic interaction field from the free layer, which determines the magnetization direction of Co(I), the nearest neighbor magnetic layer, (and hence Co(II) through strong antiferromagnetic coupling) in a way to minimize the dominant magnetostatic energy. Specifically, when the state of magnetization flop transforms into the normal SyAF structure (points d and j in Fig. 8(b)), the magnetization direction of Co(I) is aligned antiparallel to that of the free layer, which is parallel to H_a due to a small coercivity. This always results in the high MR state before the free layer switching. A similar behavior is expected to occur at small values of H_{pin}. The magnetization directions of all the magnetic layers are indicated at some important points in Fig. 8(b). After the free layer switching, the magnetization direction of the free layer is parallel to that of Co(I) which significantly increases magnetostatic energy. However, this state is maintained up to high H_a values, due to a large shape anisotropy (and hence coercivity) of the Co layers which provides a large resistance to magnetization flop, as was discussed earlier.

The magnetic configuration of the present MTJs is relevant to MRAM applications. The size of an MRAM cell should be in the submicron range in order for MRAM to compete favorably with other memory devices [12]. In this size range, magnetization flop is expected to be not a serious problem, if a strongly SyAF is used. Actually, in this case, the dominant magnetostatic interactions increase the resistance to magnetization flop. However, it is worth mentioning that, in a real MRAM device, the magnitude of H_{th} will not be that great, compared with that observed in this model. This is because a real MTJ even with a submicron size may have a complicated spin structure, not a simple single domain structure, in a way to reduce the dominant magnetostatic interactions. One example of the complicated spin structure is the magnetization curling formed at the edge of the layers [13,14]. With the presence of a multidomain structure, the rigidity of a SyAF will be reduced. In this sense, the values of H_{th} are considered to provide the upper limit.

4. Conclusions

Computer simulation in a single domain multilayer model has been carried out in this work to investigate magnetization flop in MTJs exchange-biased by pinned SyAFs for MRAM applications. As the cell size decreases, the resistance to magnetization flop increases due to increased shape anisotropy and hence increased coercivity of the Co layers in the SyAF. In the case of no or weak pinning of the SyAF, MTJs with small cell dimensions are not suitable for MRAM applications, since the MR change accompanying the free layer switching is always from the high MR state to zero, irrespective of the direction of the free layer switching. A large interlayer magnetostatic interaction field from the free layer is responsible for this behavior. This emphasizes an importance of a strong pinning of a SyAF at small cell dimensions. The resistance to magnetization flop increases linearly with increasing antiferromagnetic exchange coupling between the two Co layers in the SyAF. This is because, for a given applied field, the deviation from the complete antiparallel alignment is higher at a smaller exchange coupling. The transition from magnetization flop to the normal SyAF structure, which is the opposite direction of magnetization flop, occurs at high (low) H_a values when the resistance to magnetization flop is high (low). Irrespective of the magnetic parameters and cell sizes, the state of magnetization flop does not exist near $H_a = 0$, indicating that magnetization flop is driven by the Zeeman energy.

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