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Effect of interlayer coupling on the reversal process of differential dual spin valves

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Differential dual spin valve (DDSV) is a potential read sensor for ultrahigh density magnetic recording. Recently, it has been found that self-biased DDSVs in which the two free layers (FLs) align in flux closure configuration could potentially remove permanent hard bias. In the present work, we have carried out a systematic study of the effect of the interlayer coupling through gap layer on the reversal process of a self-biased DDSV. From the uniform field response of the DDSV, it was found that the competition among magnetostatic coupling, interlayer coupling and the shape anisotropy of the FLs gives rise to distinctive reversal behaviors, and the magnetostatic coupling could not be perfectly compensated by the interlayer exchange coupling. The down track response of the DDSV reveals that interlayer coupling could play a dominant role on the performance of the DDSV. © *2012 American Institute of Physics*. [doi:10.1063/1.3679764]

To survive in the competition with other data storage technologies, the hard disk (HDD) has to reach an areal density of 10 Tb/in^2 by 2015. This high density requires the bit length (BL) of the media to shrink down to 4–8 nm. In a conventional spin-valve (SV) type of reader, the overall thickness of the multilayer will hit a wall at 20 nm, which limits the detectable BL to be more than 10 nm.[1] It is thus crucial to develop new sensor designs. Differential dual spin valves (DDSV) were proposed as potential read sensors for 10 Tb/in^2 and beyond.[2,3] Recently, it has been found that self-biased DDSVs in which the two free layers (FLs) align in flux closure configuration could potentially remove permanent hard bias which is a common feature in conventional SV read sensors. Here, we have investigated the effect of interlayer coupling on reversal process of the self-biased DDSV.

In this study, we have considered the active potion of a DDSV consisting of two identical FLs separated by a gap layer (GL) as shown in Fig. 1(a). For FLs, a rectangular geometry has been considered with stripe height (SH) = 10 nm and reader width (RW) = 12 nm with thickness = 2 nm. FLs are separated by a GL of 1 nm thickness. The Object Oriented Micromagnetic Framework code[7] was used to simulate the quasi-static reversal process of the structure. The material parameters used in the simulation were saturation magnetisation (M_s) = 800 $\times 10^3$ A/m, exchange stiffness constant (A_{ex}) = 30×10^{-12} J/m. Gilbert damping constant (α) which is fixed to 0.5 with a stopping criterion of dm/dt < 0.001. The mesh size for all simulations was set to be $1 \times 1 \times 1$ nm^3. The reversal process is characterized by the GMR effect using cosine dependence for the respective SV. For simplicity, the resistance of individual SV in quiescent state is assumed to be 0.5 Ω, and an MR% of 40% is defined as $(R_{max} - R_{min})/R_{min}$. The total MR response of the DDSV is simply the arithmetic sum of the two GMR responses. The initial magnetization of the FLs is fixed as anti-parallel to each other to form flux closure configuration. The interlayer coupling is introduced through an exchange coupling constant between two FLs due to the Ruderman-Kittel-Kasuya-Yosida (RKKY) effect.[4–6] In this paper, only the bilinear exchange constant (σ) is considered, as its contribution is prominent in common ferromagnetic-metal-ferromagnetic sandwich structures. The exchange coupling energy as a function of bilinear coupling constant (σ) can be expressed as

$$E_{ex} = -\sigma\cos(\Delta\theta), \tag{1}$$

where $\Delta\theta$ is the angle between the magnetization of the two FLs. A negative σ promotes an anti-parallel magnetization configuration.

Shown in Fig. 1(b) is the uniform field MR response of a DDSV where the external field is applied along the SH with no interlayer coupling being considered. The DDSV scissors the magnetic moments in the FLs with almost identical spin rotation resulting in a constant net-response due to the cancellation of GMR effect in the respective SV. For this reversal process, the Zeeman energy due to the external magnetic field needs to conquer both the demagnetization energy of the individual SV and the magnetostatic coupling between them, which prefers an anti-parallel magnetization state along the RW direction. As we vary the bilinear coupling constant from -0.1 to 0.1 erg/cm^2, the symmetry and linearity of the MR response in the respective SV remain the same as the case with no interlayer exchange coupling interaction. However, the sensitivity of the SV, which is signified by the saturation field in the respective SV, is increased almost linearly as σ

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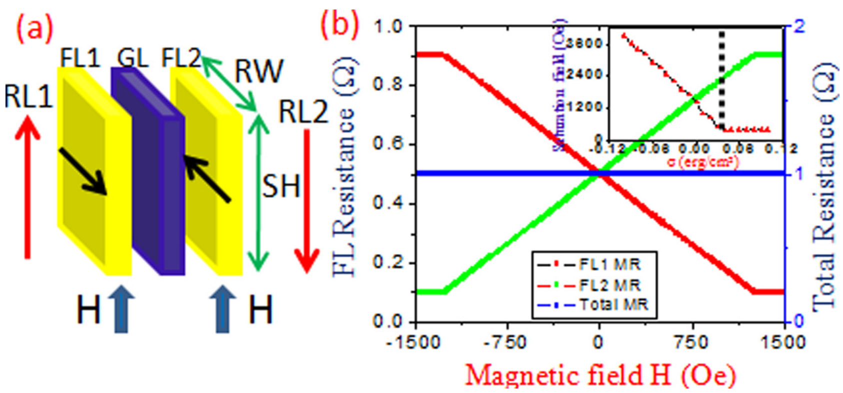

FIG. 1. (Color online) (a) Pictorial representation of the active of portion of the DDSV consisting of two identical FLs separated by a gap layer (b) The normalized MR response of the DDSV with zero interlayer coupling in the uniform field test. Shown in the inset is the variation of the saturation magnetic field as a function of the interlayer coupling (σ).

becomes more negative, as shown in inset of the Fig. 1(b). The increase can be attributed to the fact that the negative exchange coupling promotes the anti-parallel alignment between the two FLs reinforces the magnetostatic coupling, heightening the energy barrier between anti-parallel alignment along the RW direction and the final parallel alignment along the SH direction. Interestingly a different behavior can be seen when the two FLs coupled via ferromagnetic coupling. When σ is in between 0 to 0.04 erg/cm^2, the saturation magnetic field decreases linearly and saturates at 400 Oe beyond that. When $0 < \sigma < 0.04$ erg/cm^2, the ferromagnetic coupling introduced by the interlayer coupling counteracts the magnetostatic coupling, and the anti-parallel aligned state is less stable with higher σ. As σ further increases, the ferromagnetic exchange coupling dominates, and it was observed that the magnetic moments of the two FLs acting as a single giant spin respond in unison during the reversal process. For σ in this range, the energy cost of varying the magnetization state of a-single-giant-spin-like DDSV as a whole is invariant, leading to the observed constant saturation field. This results in the same reversal response observed for a uniform field, and hence a constant saturation field.

It is interesting to note that the interlayer coupling cannot perfectly compensate the effect of magnetostatic coupling, so that the DDSV behaves as two independently operating SVs. This can be seen from the saturation field as a function of σ terminates at 400 Oe, in contrast with the saturation of a single free layer or decoupled FLs which has a saturation field of 300 Oe (not shown here). This is attributed to the fact that the interlayer coupling energy is only dependent on the angle between the two ferromagnetic layers ($\Delta\theta$), not the absolute orientation of the individual ferromagnetic layer. In another word, once $\Delta\theta$ is fixed, the interlayer coupling energy is isotropic regardless of the magnetization orientation. The magnetostatic coupling energy, though commonly understood to favor anti-parallel magnetization state, is anisotropic in an elongated DDSV, as it can be seen from the energy profile for a perfectly anti-parallel aligned DDSV as a function of the free layer magnetization orientation in Fig. 2. From the figure, we can see that, the magnetostatic coupling energy is highest along the RW direction and lowest when the magnetization along the SH direction, while the exchange energy is constant. This anisotropy will gradually disappear as the geometry of the DDSV becomes more circular. The elongated DDSV is however necessary for the reader application, as the FLs need shape anisotropy to bias the sensor at the most sensitive operating point (90° apart from the reference layer).

The dependence of the reading performance of a DDSV on the interlayer coupling is evaluated in the down track response. We have modeled the reader response from the bit transition in a 1-D perpendicular recording media with a thickness of 20 nm.[8] The saturation magnetization of media is taken to be 200×10^3 A/m and the magnetic spacing is considered to be 5 nm above the media. Shown in Fig. 3 is the MR response of an ideal DDSV (the two FLs are not coupled) for comparison study and the magnetic field profile is superimposed at the background. The signal of the DDSV output is higher when the DDSV is at the center of the transition, with an opposite field of the same magnitude sensed by the two FLs. When DDSV is at point A, both the SVs experience a magnetic field higher than 300 Oe from the media which drives the spins to saturate along the SH direction so that the GMR response of the two SVs is same. The overall response of the DDSV is low at this point due to the cancellation of the individual GMR effect of the respective SV. When DDSV is at point B, SV1 experiences higher field as compared to SV2. The GMR response is higher for SV1 as compared to SV2 which results in an increase in the overall response as compared with point A. When DDSV is at point C, the two SVs experience the same and opposite fields from

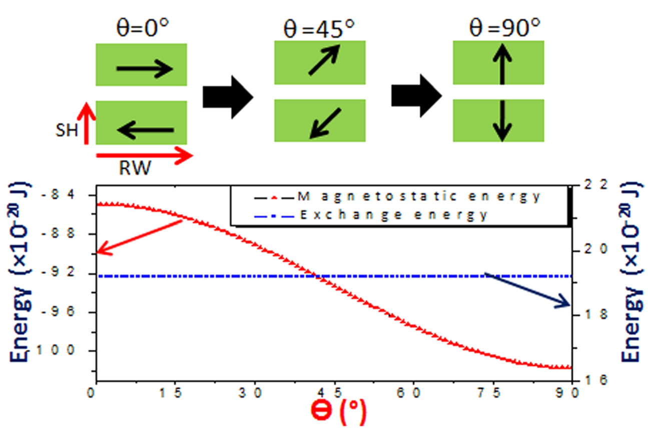

FIG. 2. (Color online) The profile of the interlayer exchange energy and the magnetostatic coupling energy during the rotation of the spins of the two FLs from RW direction to SH direction in flux closure configuration. θ is the angle between the magnetization of RL and FL.

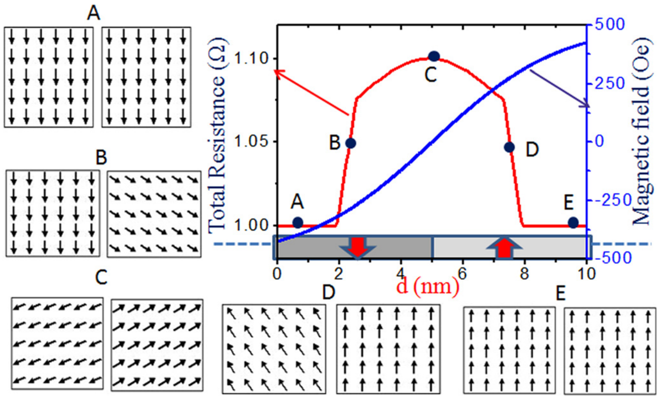

FIG. 3. (Color online) The down track response of the ideal DDSV (The two FLs are independent of each other) and the magnetic field profile along with the snapshots of the magnetization states of the FLs at various positions on the down track.

the media. The response is highest due to the large differential field. The response of the DDSV at D and E points can be explained by the same and opposite effects at B and A respectively. When the two FLs are coupled by anti-ferromagnetic coupling, the sensitivity of the DDSV is improved as signified by the higher dynamic range as shown in Fig. 4(a). The sensitivity however is nearly σ-independent, as shown by the largely overlapped curves for different σ. If we look into the detailed magnetization state, a distinctive mode of operation as compared to ideal DDSV can be identified near the bit transition when the sensed fields have the same polarity, e.g., at point B and D. At point B, The FL of SV2 of the anti-ferromagnetically coupled DDSV, which senses smaller negative field, instead of following the media field pointing downwards, rotates its magnetization away from media trying to respond to the antiferromagnetic coupling due to the FL of SV1, as shown in the magnetization state B in Fig. 4(a). In this sensing mode, only one of the two FLs experiencing higher magnitude is driven by the media field and the anti-ferromagnetic coupling spontaneously drives the other.

When the two FLs are coupled via ferromagnetic coupling for $\sigma \geq 0.04\,\mathrm{erg/cm^2}$, the sensitivity of the DDSV is deteriorated with the increase in the strength of the coupling as shown in Fig. 4(b). When DDSV is at point A and E, the field from the media is above the saturation field of the two SVs resulting the overall output to be minimum. At point B and D, the magnetization states of the two FLs respond swiftly to the uniform field as can be seen from the tilting of the magnetization states compared with anti-ferromagnetic coupled DDSV in Fig. 4(a). However, due to the net effect of the SVs being compensated, the net output from the DDSV is low for ferromagnetic coupling. When the differential field with the same polarity emerges, the magnetization of the two FLs prefers to stay aligned due to the ferromagnetic coupling energy. It is expected that higher the strength of the ferromagnetic coupling, smaller is the angle between the FLs for the same differential field. The similar argument is valid at the bit transition (C), where the magnetization

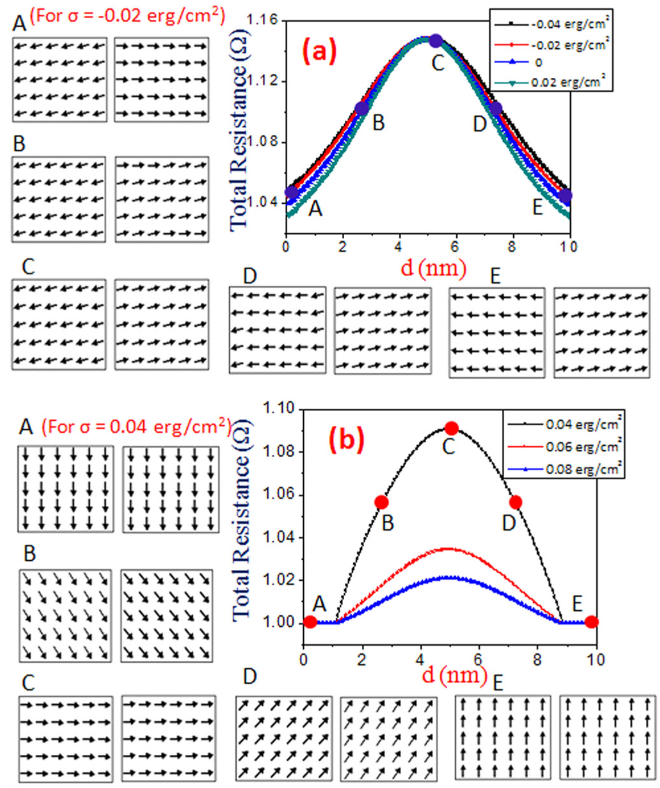

FIG. 4. (Color online) (a) The down track response of the DDSV when the two FLs are coupled via anti-ferromagnetic coupling along with the magnetization states of the FLs at various positions on the down track. (b) The down track response of the DDSV when the two FLs are under the ferromagnetic coupling. Below are the snapshots of the magnetization states of the FLs at various positions on the down track.

symmetrically aligned close to the RW direction. Therefore, a drop in DDSV sensitivity is expected with σ. It clearly suggests that DDSV needs to operate in the anti-ferromagnetic coupled region to ensure a good performance in sensitivity.

In summary, the effect of the interlayer coupling on the reversal process of the DDSV has been systematically studied. DDSV shows different reversal mechanism depending on the sign and the magnitude of the interlayer coupling due to the gap layer. It is observed that interlayer coupling along with the magnetostatic coupling and the shape anisotropy strongly influence the overall response of the DDSV. The one dimensional down track response reveals that the sensitivity of the DDSV is improved when the two FLs are coupled anti-ferromagnetically as compared to the decoupled DDSV. The results shown here suggest that interlayer coupling can be employed as a vital parameter to tune the performance of the DDSV reader.

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