Effects of spacer thickness on perpendicular anisotropy L10-FePt/TiN/L10-FePt pseudo spin valves

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Effects of spacer thickness on perpendicular anisotropy
$L_{10\text{-FePt}}$/TiN/$L_{10\text{-FePt}}$ pseudo spin valves

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Pseudo spin valves (PSVs) with the structure MgO substrate/$L_{10\text{-FePt}}$/TiN/$L_{10\text{-FePt}}$ were fabricated with varying TiN spacer thickness from 3 to 7 nm. The giant magnetoresistance (GMR) reached a maximum before diminishing with increasing TiN spacer thickness. The initial enhancement of the GMR was attributed to the reduction in interlayer coupling between the $L_{10\text{-FePt}}$ layers. However, a decline in GMR sets in when the current shunting effects negated the enhancement brought about by the improved decoupling. Magnetostatic coupling was the primary source of interlayer coupling in the PSVs. The dependence of interlayer coupling on the remanent state of the hard $L_{10\text{-FePt}}$ was also examined based on the magnitude and direction of shift in the center of the minor hysteresis loop. While magnetostatic coupling was present in fully saturated hard $L_{10\text{-FePt}}$, dipolar stray field coupling contributed more significantly to the interlayer coupling strength in partially saturated hard $L_{10\text{-FePt}}$. The stray field coupling strength depended on both the thickness of the spacer and the density of the reversed domains in the hard $L_{10\text{-FePt}}$. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.3700252]

I. INTRODUCTION

The discovery of the giant magnetoresistance (GMR) effect sparked a surge in interest for the integration of spintronics into high-impact technological devices such as the high density hard-disk recording read heads or the emerging magnetoresistive random access memories (MRAM).1,2 In particular, magnetic trilayers have garnered much scientific interest due to their widespread applications in the rich and growing field of spintronics. The magnetic trilayer system comes in the form of a spin valve, with a non-magnetic (NM) metal spacer sandwiched between two ferromagnets (FM). The GMR phenomenon is attributed to the spin dependent scattering, which occurs in the bulk of the FM, at the FM/NM interfaces, and/or at the surfaces. A difference in the resistance between the parallel and anti-parallel magnetic configuration of the FM constitutes the GMR. The independent switching of the FMs is crucial and this is ensured by the deliberate creation of larger anisotropy energy for the fixed FM or the pinning of the fixed FM using an anti-ferromagnetic layer.

Spin valves were originally developed with in-plane magnetization but systems with high perpendicular magneto-crystalline anisotropy ($K_u$) have become more attractive due to the demand for greater areal density improvements while maintaining thermal stability.3–6 $L_{10\text{-FePt}}$ is a suitable candidate for the FM because of its high $K_u$ of $7 \times 10^5$ erg/cc. However, the high deposition temperature required of $L_{10\text{-FePt}}$ ordering results in interlayer diffusion within the spin valve. Diffusion within the spin valve affects the interfacial, magnetic and spin transport properties, which in turn adversely impacts the magnetoresistance of the system.7,8 Hence, it is crucial to adopt spacers with good diffusion barrier properties and/or the ability to lower the deposition temperature of the adjacent $L_{10\text{-FePt}}$, while being able to sustain the differential scattering within the spin valve. Recently, $L_{10\text{-FePt}}$ based pseudo spin valves (PSVs) with a TiN spacer have been reported.9 TiN displays excellent diffusion barrier properties and desirable qualities of being chemically stable toward FePt.10,11 It is also a perpendicular anisotropy inducer, due to the large lattice mismatch of 9.5% between FePt and TiN, which imposes strain ordering on FePt.

The thickness of the spacer layer affects the exchange interactions, such as the magnetostatic interactions through pinholes, Ruderman-Kittel-Kasuya-Yosida (RKKY), Néel and dipolar coupling, between the FM.12–15 It also influences the extent of current shunting within the PSV. These factors are detrimental to the GMR. A detailed study of the influence of spacer layer thickness on the magnetization reversal and GMR is crucial for a deeper understanding of the $L_{10\text{-FePt}}$/TiN/$L_{10\text{-FePt}}$ PSV. In this work, we carried out a study on the effects of varying TiN spacer thickness on the crystallographic, magnetic, reversal, interlayer coupling, and magnetotransport properties of the $L_{10\text{-FePt}}$ PSV structures.

II. EXPERIMENT

Samples with the structure $L_{10\text{-Fe}}$/TiN ($20\text{nm}$)/$L_{10\text{-FePt}}$ ($20\text{nm}$) were fabricated on single crystal (001) MgO substrates, with $x$ varied between 3 to 7 nm. The nominal thickness was obtained by calibrating the sputtering parameters with the reference sample. These were prepared using the magnetron sputtering system with a base pressure better than $8 \times 10^{-7}$ Torr. In all of the samples, the bottom and top $L_{10\text{-FePt}}$ layers were deposited at 400 and 500°C, respectively. The TiN spacer was deposited at 350°C. Crystallographic studies were performed using X-ray diffraction.
selected area electron diffraction (SAED) pattern along a strong MgO reflection. Figure 2(a) shows the cross-sectional resulting in its negligible signal being overshadowed by the assessed a (002) Bragg angle that was close to that of MgO, XRD signal beyond the noise level. In addition, TiN pos-
sence of TiN (002) reflection in the XRD was attributed to I ratios
ing TiN spacer thickness (Fig. 1). Their integrated intensity and FePt (001) superlattice peaks in all of the PSVs of vary-
band structures were performed using the Vienna simulation package (VASP).18

III. RESULTS AND DISCUSSION

The XRD results show similar FePt (002) fundamental and FePt (001) superlattice peaks in all of the PSVs of varying TiN spacer thickness (Fig. 1). Their integrated intensity ratios \( I_{[001]} / I_{[002]} \) lie in the range of 0.68 to 0.79.19 The absence of TiN (002) reflection in the XRD was attributed to the thin TiN spacer that was unable to produce a significant XRD signal beyond the noise level. In addition, TiN possessed a (002) Bragg angle that was close to that of MgO, resulting in its negligible signal being overshadowed by the strong MgO reflection. Figure 2(a) shows the cross-sectional selected area electron diffraction (SAED) pattern along a (001) zone axis for the PSV with TiN spacer thickness of 5 nm. The (001) and (002) FePt spots were aligned with the strong (002) MgO spots. The cross-sectional HRTEM image in Fig. 2(b) shows a highly contrasted TiN spacer and FePt layers due to the large difference in their atomic numbers. The observation of lattice fringes in the FePt and TiN layers ascertainment the epitaxial growth of (001) textured FePt and (002) TiN crystalline films.

The magnetization hysteresis loop of the bottom \( L_{10-FePt} \) deposited at 400°C exhibits a coercivity of 1.8 kOe [Fig. 3(a)]. In all of the PSVs, the top \( L_{10-FePt} \) showed a larger coercivity \( (H_c) \) due to a higher \( K_p \), which arose from the higher deposition temperature condition [Figs. 3(b)–3(f)]. The bottom \( L_{10-FePt} \) behaved as the softer free layer while the top \( L_{10-FePt} \) the harder fixed layer of the \( L_{10-FePt}/T i N/ L_{10-FePt} \) PSVs. With increasing TiN spacer thickness, the PSVs became increasingly well-decoupled [Figs. 3(b)–3(f)], exhibiting a larger difference in the \( H_c \) between the top and bottom \( L_{10-FePt} \) (Table I). This was attributed to a reduction in interlayer coupling strength with a thicker spacer thickness. The interlayer coupling was largely contributed by the magnetostatic effects due to the magnetic dipoles setup within the \( L_{10-FePt} \) layers. Lee et al. reported earlier an exponential relationship between the magnetostatic coupling field \( (H_{\text{stat}}) \) and spacer thickness \( t \) (Ref. 20)

\[
H_{\text{stat}} = \frac{\pi^2 \gamma M_p}{\sqrt{2} \lambda F} \exp \left( -\frac{2\pi \sqrt{2}}{\lambda} \right),
\]

where \( \gamma \) is the peak-to-peak waviness amplitude of the film, \( \lambda \) is the in-plane wavelength of the surface variations, \( M_p \) is the magnetization of the fixed layer, and \( F \) is the thickness of the free layer. \( M_p \) did not vary significantly while \( F \) was kept constant across the PSVs with varying thickness. In addition, as seen in Table I, the root mean square roughness \( (R_{\text{rms}}) \) of the spacer did not vary significantly with thickness. With the same degree of roughness, a smaller TiN thickness resulted in a more significant contribution from the magnetostatic coupling, thus preventing the independent switching of the \( L_{10-FePt} \) layers. Another minor contribution could presumably arise from the direct coupling due to pinholes. Pinhole defects can be thought of as localized regions where the roughness was greater than the thickness of the spacer, hence resulting in physical gaps that promoted direct interactions between the FMs. Pinhole defects were likely to
be more prevalent in a thinner TiN spacer, thereby creating a stronger direct interlayer coupling. This is substantiated with the maximum roughness ($R_{\text{max}}$) values in Table I, in which these values generally increased with decreasing spacer thickness. In particular, for TiN spacer thickness of 3 and 4 nm, the maximum roughness was larger than the spacer thickness, thus suggesting the possible presence of pinhole defects. The oscillatory RKKY coupling favors ferromagnetic or anti-ferromagnetic coupling depending on the thickness of the spacer. The presence of this oscillatory coupling could not be determined in this range of TiN spacer thickness studied. The RKKY coupling is understood to have originated from the quantum interference of electrons confined within the non-magnetic spacer. Thus, its strength is typically dominant at spacer thickness of several monolayers. With increasing spacer thickness to a length scale of several nanometers (>3 nm), the RKKY coupling strength diminishes drastically. As such, contribution to the interlayer coupling by RKKY was assumed to be negligible in the PSVs in this work.

![Graphs showing out-of-plane magnetization and magnetoresistance curves](image)

**FIG. 3.** Out-of-plane magnetization (■) and magnetoresistance (x) curves measured at room temperature for (a) MgO/L10-FePt, MgO/L10-FePt/TiN/L10-FePt PSVs with TiN spacer thickness of (b) 3, (c) 4, (d) 5, (e) 6, and (f) 7 nm.

<table>
<thead>
<tr>
<th>TiN thickness (nm)</th>
<th>$H_{\text{c(soft)}}$ (kOe)</th>
<th>$H_{\text{c(hard)}}$ (kOe)</th>
<th>$R_{\text{KMS}}$ (nm)</th>
<th>$R_{\text{max}}$ (nm)</th>
<th>GMR (%)</th>
<th>Actual GMR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2.60</td>
<td>5.14</td>
<td>0.27</td>
<td>6.44</td>
<td>0.53</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>2.57</td>
<td>5.98</td>
<td>0.28</td>
<td>5.58</td>
<td>0.78</td>
<td>0.37</td>
</tr>
<tr>
<td>5</td>
<td>2.30</td>
<td>7.55</td>
<td>0.30</td>
<td>4.46</td>
<td>0.61</td>
<td>0.20</td>
</tr>
<tr>
<td>6</td>
<td>2.28</td>
<td>7.52</td>
<td>0.26</td>
<td>3.75</td>
<td>0.59</td>
<td>0.18</td>
</tr>
<tr>
<td>7</td>
<td>2.44</td>
<td>8.23</td>
<td>0.29</td>
<td>4.82</td>
<td>0.52</td>
<td>0.11</td>
</tr>
</tbody>
</table>
The reversal mechanism of both top and bottom $L_1$-$FePt$ layers in the PSV with TiN spacer thickness of 5 nm is shown in Fig. 4. The remanent magnetic configurations of both $L_1$-$FePt$ layers were studied at the intermediate stages of their reversal process. A $+20$ kOe field was first applied to fully saturate both $L_1$-$FePt$ layers in the same spin down direction. A field in the range of 0 to $-20$ kOe was then applied to attain different magnetization states of the hard top $L_1$-$FePt$. A minor loop below the switching field of the hard magnetic layer, between $+5$ to $-5$ kOe, was then cycled. The difference between the $H_c$ in the first and second quadrants of the minor loop was termed the interlayer coupling field $H_{int}$. At an applied field of 0 [Fig. 5(b)] and $-20$ kOe [Fig. 5(e)] where the hard top $L_1$-$FePt$ was fully saturated, the shift observed in the minor loop was an indication of the influence of interlayer coupling of the hard and soft $L_1$-$FePt$ layers due to the presence of magnetostatic coupling. At an applied field of 0 kOe, the hard top $L_1$-$FePt$ was fully saturated in the spin down configuration. When the minor loop had cycled from $+5$ to $-5$ kOe, the soft bottom $L_1$-$FePt$ had to overcome the interlayer interactions from the hard top $L_1$-$FePt$ to attain an anti-parallel configuration [inset of Fig. 5(b)]. This resulted in the shift in $H_{int}$ in the negative direction. Conversely, a positive $H_{int}$ was observed at an applied field of $-20$ kOe, where the soft bottom $L_1$-$FePt$ reversed more easily to the same parallel configuration as the hard top $L_1$-$FePt$ with the assistance of the interlayer interactions [inset of Fig. 5(e)].

There was a decrease followed by a peak in $H_{int}$ in the region of applied field of $-6$ to $-10$ kOe [Fig. 5(a)]. Figures 4(e)–4(g) discussed earlier show that partially reversed states of the hard top $L_1$-$FePt$ were present in this region. As such, apart from the magnetostatic effect, dipolar stray field due to the non-uniformly magnetized hard top $L_1$-$FePt$ film also played a major role in influencing the $H_{int}$. The direction

![MFM images showing the magnetization states of the $L_1$-$FePt$ layers in the PSVs with applied field of (a) 0, (b) $-2$, (c) $-3$, (d) $-4$, (e) $-6$, (f) $-8$, (g) $-10$, and (h) $-12$ kOe. Brighter regions are reversed domains with spin up configuration.](image-url)
and strength of the stray field depended on the density of reversed domains present in the hard top \(L1_0\)-FePt. At an applied field of \(-6\) kOe, reversed domains with spin up configuration began to nucleate but the density of unreversed domains with spin down configuration remained larger in the hard top \(L1_0\)-FePt \([\text{Fig. 4(e)}]\). This resulted in a larger extent of dipolar coupling stray field emanating from the walls of the unreversed domains, which impeded the propagation of the reversed domains in the adjacent soft bottom \(L1_0\)-FePt, when the minor loop was swept from \(+5\) to \(-5\) kOe \([\text{inset of Fig. 5(d)}]\). With increasing negative applied field, the increasingly saturated hard top \(L1_0\)-FePt generated fewer stray fields and the effects of dipolar coupling gradually diminished.

The \(H_{int}\) values obtained from the minor loops of the PSV with TiN thickness of 5 and 7 nm are shown in Fig. 5(a). The minor loops of the PSV with TiN thickness smaller than 5 nm were not compared here as fully saturated minor loops were unobtainable. A sufficiently large field range to saturate the minor loop could not be achieved in these poorly decoupled PSVs without capturing the magnetization loop of the hard top \(L1_0\)-FePt. With a thicker TiN spacer, the reduced interlayer coupling strength between the \(L1_0\)-FePt...
layers was reflected with $H_{\text{int}}$ values, which were closer to zero, indicating a greater extent of independent reversal of the soft bottom $L_{10}$-FePt.

A single layer of bottom $L_{10}$-FePt shows a linear behavior of resistivity with magnetic field, displaying a MR of 0.41% [Fig. 3(a)]. At finite temperatures, the directions of the localized $d$ electrons spins fluctuated and the $s$ electrons coupled to them scattered from their inhomogeneous exchange potential. This spin flip scattering contributed to the resistivity of the $L_{10}$-FePt film. The linear decrease in resistivity occurred with increasing applied field, which acted to suppress the spin disorder scattering. In addition, the spike followed by sharp drop in resistivity at the coercive field of the $L_{10}$-FePt film was contributed by magnon magnetoresistance (MMR). At an applied field slightly smaller than the coercive field, the applied field acted in an opposite direction from the magnetization direction. The destabilization of the magnetization direction led to a surge in magnon population, thus bringing about an upsurge in MMR. The magnon population decreased sharply when the applied field and magnetization direction acted in the same direction at the coercive field. Consequently, a reduction in MMR was observed.

Similar contributions by spin disorder and MMR were observed in the MR loops of the PSVs with different TiN thicknesses [Figs. 3(b)–3(f)]. However, the effects of MMR were not prominent at the coercivity of the hard top $L_{10}$-FePt, compared to the soft bottom $L_{10}$-FePt, due to its larger switching field distribution. At an applied field slightly smaller than the coercive field of the hard top $L_{10}$-FePt, a considerable number of spins had already reversed and the remaining spins that could contribute to the MMR effect was significantly reduced. The electron mean free path for TiN is in the range of 39 to 41 nm, which is large enough for the electrons to pass through all the layers successfully when the current flows in the plane of the layers. As such, in addition to the spin disorder and MMR contributions, resistivity due to the spin dependent scattering of the conduction electrons at the trilayer interfaces was also present. The actual GMR contributed by the spin dependent scattering at the interfaces of the $L_{10}$-FePt/TiN/$L_{10}$-FePt PSV was obtained by subtracting the slope of the background $L_{10}$-FePt layer contribution (Table I). With increasing TiN spacer thickness, the actual GMR reached a maximum and then decreased with further increase of TiN thickness (Fig. 6). The initial increase in GMR with an increase in TiN thickness was the result of a reduction in the short-range interlayer magnetostatic interaction. This permitted a difference in the coercivity between the top and bottom $L_{10}$-FePt as well as an increase in the effectively decoupled regions, increasing the sample area over which a high resistance anti-parallel configuration of the PSV may be realized. However, with a further increase in TiN thickness, the GMR gradually declined despite a more effectively decoupled PSV and a further reduction of the interlayer coupling strength. Further increasing the spacer thickness increased the probability of conduction electrons being channeled away from the $L_{10}$-FePt/TiN interface and confined within the TiN spacer. Due to this current shunting effect, the GMR eventually diminished at larger TiN spacer thickness.

The GMR observed with the TiN spacer was smaller than with the use of metallic spacers such as Ag (1.1%) in similar (001) textured $L_{10}$-FePt based PSVs. Based on the resistor model for CIP GMR illustrated in Eq. (2), the magnetoresistance ratio of a multilayer with spacer layer of finite resistance is given by

$$\Delta R = \frac{\rho_{\text{NM}}}{\rho_{\text{FM}}},$$

where $\rho$ is the resistivity defined by $\rho_{\text{NM}}/\rho_{\text{FM}}$, where $\rho_{\text{NM}}$ is the resistivity of the non-magnetic spacer, and $\rho_{\text{FM}}$ is the majority spin resistivity. It should be noted that this is a largely simplified resistor model that is only applicable for TiN thickness $d_{\text{NM}}$ smaller than its electron mean free path. Assuming that the PSVs with various spacer materials possessed the same structure with the same $d_{\text{NM}}$ and $d_{\text{FM}}$, the CIP GMR of the PSV would then be largely dependent on the scattering spin asymmetry and resistivity of the spacer. Thus, the smaller GMR in the $L_{10}$-FePt/TiN/$L_{10}$-FePt PSV was possibly due to the larger resistivity of TiN (15 $\mu\Omega$ cm) compared to Ag (1.6 $\mu\Omega$ cm) which led to a greater extent of spin independent scattering. Another possible reason is the smaller scattering spin asymmetry of TiN with FePt compared to Ag with FePt. Near the Fermi energy level of 0 eV, the energy band structures of TiN and Ag displayed better band structure matching with the FePt spin up electrons [Figs. 7(a) and 7(c)] compared to the FePt spin down electrons [Fig. 7(b) and 7(d)]. This indicates a higher transmission of the majority spin up electrons and a poorer transmission of minority spin down electrons at both the FePt/TiN and FePt/Ag interfaces. The scattering spin asymmetry is the difference in the conductivities ($\sigma$) of these two spin channels, where $\sigma = \sigma_1 - \sigma_2$. When the $L_{10}$-FePt layers were aligned, the majority spin up electrons passed through relatively easily, giving a low resistance state. A higher resistance state was produced when the $L_{10}$-FePt layers were anti-aligned and electrons in both channels were reflected at either one of the interfaces. As such, to attain a larger GMR, a larger spin scattering asymmetry would be desirable. The band structures of Ag with FePt spin up...
electrons [Fig. 7(c)] displayed better band compatibility, with larger regions of similar energy and slope, compared to that of TiN with FePt spin up electrons [Fig. 7(a)]. This suggests the presence of a larger density of states available for the majority spin up electrons at the FePt/Ag interface compared to that of FePt/TiN. The lower GMR observed in the L1₀-FePt PSV with TiN spacer could thus be a result of its smaller interfacial scattering spin asymmetry.

IV. SUMMARY

The GMR of the L1₀-FePt/TiN/L1₀-FePt PSV was strongly dependent on the TiN spacer thickness. The GMR increased to a peak before diminishing with increasing TiN spacer thickness. The initial enhancement of the GMR was attributed to the reduction in interlayer coupling between the L1₀-FePt layers. The interlayer coupling was contributed largely by the magnetostatic coupling. However, a decline in GMR set in when the current shunting effects offset the enhancement brought about by the improved decoupling with increasing TiN spacer thickness. The presence of dipolar stray field as well as magnetostatic coupling was also demonstrated through the study of the shift in the center of the minor loops. The reduction in the magnitude of the $H_{int}$ in the minor loops with a thicker TiN spacer reaffirmed the fact that the interlayer coupling strength reduced with increasing spacer thickness.

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