Optimization of Perpendicular Anisotropy of Ta-Inserted Double CoFeB/MgO Interface MTJ's for STT-MRAM

Billy D. Clark¹, Soumalya Paul², Samuel C. Schwarm³, Amritpal Singh², Anusha Natarajathinam^{1*}, Subhadra Gupta^{3**},

1. Department of Electrical Engineering Computer Engineering Engineering, University of Alabama, Tuscaloosa, Alabama

2. Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama

3. Department of Metallurgical and Materials Engineering, University of Alabama, Tuscaloosa, Alabama

Abstract— Ta inserts in double magnetic tunnel junctions have been shown to induce perpendicular magnetic anisotropy. We fabricated the central layers of a CoFeB / MgO based double magnetic tunnel junction with a Ta insertion layer between the free layers of the magnetic tunnel junctions. The thickness of the Ta insert and CoFeB layer were varied from 0.5 to 1.1 nm and 0.9 to 1.7 nm respectively, to find which minimum thickness of Ta will induce perpendicular anisotropy in the MTJ. FMR studies were performed to measure the interfacial anisotropy K_u . We demonstrated that the most effective stack minimized the CoFeB thickness while maximizing the Ta thickness. This was balanced with the need to keep both CoFeB layers from decoupling or becoming magnetically dead.

Keywords: Perpendicular Magnetic Anisotropy, Perpendicular Magnetic Tunnel Junctions, STT-MRAM, Ta Insertion Layer

1. Introduction

Spin-Transfer Torque Magnetic Random Access Memory (STT-MRAM), is a rapidly growing field of study as it represents a potential nonvolatile random access memory. The key component to making STT-MRAM a reality is improving current Magnetic Tunnel Junctions (MTJs). [1] Perpendicular MTJs (p-MTJs) have drawn interest due to their favorable thermal stability [2], fast switching speed [3] and low write error rate. [2] Recently, there have been several reports on p-MTJs based on CoFeB/MgO interfacial anisotropy. [1,4-8] There is also evidence that using the ferromagnetic electrodes with double CoFeB/MgO interface-based MTJ layers can increase the thermal stability. [5] It has been reported that in double interface MTJs, the thermal stability is increased by a factor of 1.9 as compared to single interface CoFeB/MgO based MTJs 70 nm in diameter. [5]

In this paper we have explored an interesting way of making a perpendicular MTJ, and we have investigated the

interfacial perpendicular magnetic anisotropy (IPMA) as a function of Ta and CoFeB thickness in MgO/CoFeB/Ta/CoFeB/MgO double interface structures. IPMA is critical to understand as it measures how perpendicular a sample is. This method entails placing a Ta insert in the central CoFeB layer of Double Magnetic Tunnel Junctions, henceforth referred to as DMTJ's. The experimental results demonstrate the strong correlation between layer thickness and its effect on perpendicular anisotropy. [4,9,10]

To achieve the above goal, we focused on the effects of the coupled CoFeB layers from two single magnetic tunnel junctions (SMTJ's) separated by a thin Ta insert. The CoFeB / Ta interface is known to contribute to perpendicular anisotropy,[9] and the CoFeB / MgO interface causes interfacial perpendicular anisotropy. [11] These effects, when combined, can be leveraged to make a perpendicular MTJ free from a complex multilayer structure.

2. Experimental procedure

To properly explore the double interface MTJ structure it was necessary to first create a simple test stack. We selected Si/Ta 5/Co₂₀Fe₆₀B₂₀ 0.6/MgO 2.0/Co₂₀Fe₆₀B₂₀ Y/ Ta X /Co₂₀Fe₆₀B₂₀ Y/MgO 2.0/Ta 5 (nm), where X varied from 0.5 to 0.9 (nm) and Y varied from 0.9 to 1.3 (nm). [5, 9] The variation in thickness was designed to explore the behavior of the stack by varying the CoFeB (Y) from near its dead layer thickness to a thickness great enough that the stack is no longer perpendicular. The Ta (X) layer was varied from its minimum thickness - small enough to ensure a continuous layer - to its maximum thickness with a still measurable signal. Increasing the Ta thickness decreased M_s , since Ta produced a dead layer in the adjacent ferromagnetic layer. While this stack did not represent a full DMTJ, it did simulate the central layer of a DMTJ and allowed it to be observed more clearly. [5]

All samples were deposited on Si wafers with a native SiO₂ surface layer. The purpose of the first Ta layer was to

* Currently at Seagate Technology, Minneapolis, MN Digital

** Corresponding author: Dr. Subhadra Gupta (e-mail: sgupta@eng.ua.edu).

prevent silicide formation and help control the crystalline structure of the CoFeB layer grown on it. The CoFeB layer was set at 0.6 nm to ensure that it was magnetically dead. The dead layer thickness was determined experimentally using independently sputtered films and is between 5 to 6 Angstroms. This method allowed the thicker CoFeB layers to be studied independently while still properly crystallizing the seed MgO layer, which was 2 nm thick to obtain the desired resistance. The first MgO layer was positioned to help pull the CoFeB [11] layer above it magnetically perpendicular to the layer plane. This CoFeB layer was also being pulled perpendicular by the Ta layer above it. [5] This strategy was mirrored by the second CoFeB and MgO layers. The last layer of 5 nm of Ta was a capping layer designed to help protect the stack during testing and prevent any oxidation of the ferromagnetic layer. Removal of the top CoFeB layer from the DMTJ helped to reduce complexity, enabling easier examination of the central layer.

All layers were deposited using an SFI Shamrock planetary sputtering system. The system was maintained at a base vacuum of 5×10^{-8} Torr. All metallic layers were deposited using DC magnetron sputtering, while MgO was deposited via RF magnetron sputtering from a MgO target. In order to verify the layer thicknesses, metallic layers were checked with both x-ray reflectivity (XRR) with Bragg's law [12] and four-point probe resistivity measurements, coupled with profilometry. The MgO rate was checked with a spectrophotometer and an ellipsometer. In order to crystallize these samples they were rapid thermally annealed (RTA) in the Shamrock sputtering system at 400°C for 8 minutes under high vacuum using radiant heat lamps. The optimized time and temperature were derived from our previous work. [10] RTA was selected as it has a much faster processing time when compared to oven annealing and allows for processing under high vacuum, 1×10^{-7} Torr.

To examine the magnetic properties of these samples and explore the variations in the stacks, they were measured on a Princeton alternating gradient magnetometer (AGM) and custom-built ferromagnetic resonance (FMR) system. FMR is a versatile measurement technique that simultaneously employs ac and dc magnetic fields to precisely quantify quasi-static and dynamic magnetic properties such as damping parameter (α), gyro-magnetic ratio (γ) and magnetic anisotropy. In this case the FMR set up was a fully automated broadband FMR system using a coplanar waveguide with frequency range of 4-36 GHz. the magnetic field was applied perpendicular to the plane of the sample. M_{eff} was determined by fitting frequency vs. resonance field.

3. Results and Discussion

The M-H loops, shown in Figure 1, illustrate the effects of varying layer thickness on the magnetic behavior. As is shown below, increasing Ta thickness corresponded to a decrease in M_s . It was also observed that the loops indicated increasing perpendicular anisotropy as the Ta thickness was increased. Furthermore, annealing the sample helped to increase the

perpendicular anisotropy of the samples, as seen in Table 2.

FIG 1 HERE

As seen from the out-of-plane M-H loops in Figure 1, two distinct regions may be observed. A region of partial perpendicular anisotropy. (with 100% perpendicular anisotropy at Ta = 1.1 and CoFeB = 0.9) In this section Ta ranged from 0.7 to 1.1 nm and CoFeB from 0.9 to 1.1 nm, excluding Ta = 0.7 nm and CoFeB = 1.1 nm. The other area shows in-plane behavior. This in-plane behavior arose because, as the CoFeB thickness increased, the MgO/CoFeB interfacial anisotropy became insufficient to pull the remaining CoFeB perpendicular.

FIG. 2 HERE

Figure 2 shows that H_{sat} decreased as the Ta insertion layer thickness increased. The saturation field, H_{sat} , was approximated by finding the applied field strength (H) where the demagnetization field equaled the magnetization field, correlating to the knee in the raw M-H loops from the AGM. This AGM is known to have a read error around 2% or less when measuring both the applied field and sample magnetization. Thus lower values of H_{sat} show more perpendicular behavior while higher values represent more in-plane behavior.

$$4\pi M_{eff} = 4\pi M_s + \frac{2K_{u,i}}{M_{st}} \quad (1)$$

FMR experiments were performed on a smaller subset of the full data set, where Ta ranged from 0.5 to 0.9 nm and CoFeB ranged from 0.9 to 1.3 nm. These samples were tested both as-deposited and after rapid thermal annealing at 400 °C for 8 minutes. (1) Shows the relationship between the effective magnetization (M_{eff}), saturation magnetization (M_s), interfacial anisotropy constant ($K_{u,i}$), and the saturation magnetization times the film thickness (M_{st}). Normally this equation is expressed in terms of the total anisotropy, K_u but as we are dealing with a thickness of a few nanometers, the bulk anisotropy is presumed to be negligible. We derived $K_{u,i}$ by holding the Ta thickness constant and plotting $4\pi M_{eff}$ vs. the reciprocal of the CoFeB thickness. The slope of this line gives us two times $K_{u,i}$ divided by M_{st} . We then used the M_s value from the M-H loops to find $K_{u,i}$. Assuming that the perpendicular anisotropy is of interfacial origin. [5] Note that equation (1) is normally given in reference to the in-plane behavior; in this case we are using the out of plane form of the equation.

In Tables 1 & 2, we have listed the effective magnetization, M_{eff} , derived from the FMR analysis, the saturation magnetization, M_s , derived from the AGM analysis, and lastly the Interfacial Perpendicular Magnetic Anisotropy [14], IPMA, that is defined in (2), and gives an indication of the interfacial (or partial) perpendicular anisotropy in these samples. Negative values of M_{eff} indicate fully perpendicular anisotropy. IPMA is a useful tool for distinguishing how perpendicular a sample is as it allows us to directly measure the perpendicularity and see to what degree the sample is out of plane. Figure 3 and 4 represent IPMA from the as-deposited samples as a function of CoFeB and Ta

thickness for unannealed samples and rapid thermally annealed samples respectively. The changes in M_s reflect the changing size of the dead layer created by Ta/CoFeB interface.

$$IPMA = \left(\frac{4\pi M_s - 4\pi M_{eff}}{4\pi M_s} \right) \times 100\% \quad (2)$$

TABLE 1 HERE

FIG 3 HERE

TABLE 2 HERE

FIG 4 HERE

$K_{u,i}$, which is derived from 0.9 to 1.3 nm of CoFeB, of the unannealed, or as-deposited, samples is approximately constant, taking into account our measurement error. For the annealed samples we see that a Ta thickness of 0.5 nm results in a much less negative, less perpendicular, value for $K_{u,i}$ while 0.7 nm and 0.9 nm are more negative, more perpendicular. The results from the two tables, shown above, agree with Figure 5, showing that annealing positively affects the perpendicular anisotropy.

FIG 5 HERE

4. Conclusion

We have explored the behavior of the double magnetic tunnel junction partial stack Si/Ta 5/CoFeB 0.6/MgO 2.0/CoFeB Y/ Ta X /CoFeB Y/MgO 2.0/Ta 5 (nm) as a function of a range of thicknesses of Ta and CoFeB. As the Ta thickness increased, the sample achieved greater partial perpendicular anisotropy, becoming fully perpendicular at Ta = 1.1 nm and CoFeB = 0.9 nm. It would be interesting to keep increasing Ta thickness and observe the increase in anisotropy energy, K_u , but unfortunately, a thicker Ta layer decreased M_s and the sample became difficult to measure compared to background noise. A thinner CoFeB layer led to a higher degree of perpendicular anisotropy as the interfacial anisotropy became more dominant. The samples with the highest perpendicular anisotropy in the above format maximized the Ta thickness, X, and minimized the CoFeB thickness, Y, achieving a balance within the limits to have a sufficiently large M_s to maintain measurable magnetization levels. Lastly we have shown that the interfacial anisotropy was not changing, but we had simply decreased the amount of material to be pulled perpendicular. This work shows a promising outlook for STT-MRAM, as we see that perpendicular behavior is possible over a range of thicknesses. There are many directions in which to extend this work further. These include varying the annealing conditions, the thickness of the MgO layer, and investigating other insertion materials than Ta.

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Figures

Figure 1. Plots of magnetization out of plane vs. applied field for thickness ranges of CoFeB 0.7 to 1.7 nm and Ta 0.5 to 1.1 nm (unannealed)

Figure 2. Hsat (Oe) vs. CoFeB and Ta (nm) thickness plotted using Minitab® Statistical Software. [13]

Table 1. As Deposited Samples.

CoFeB (nm)	Ta (nm)	M_{eff} (emu/cc)	M_s (emu/cc)	IPMA
0.9	0.5	141.1	764	82%
0.9	0.7	35.8	717	95 %
0.9	0.9	17.28	733	98 %
1.1	0.5	211.73	829	74%
1.1	0.7	137.46	876	84%
1.1	0.9	84.91	561	85%
1.3	0.5	307.04	886	65%
1.3	0.7	245.03	789	69%
1.3	0.9	323.1	795	59%

Figure 3. Plot of IPMA vs CoFeB (nm) and Ta (nm) for unannealed samples, plotted using Minitab® Statistical Software. [13]

Table 2. Rapid Thermally Annealed Samples at 400 °C for 8 minutes.

CoFeB (nm)	Ta (nm)	M_{eff} (emu/cc)	M_s (emu/cc)	IPMA
0.9	0.5	90.96	1008	91%
0.9	0.7	-54.83	1004	100%
0.9	0.9	-77.91	673	100%
1.1	0.5	100.8	1263	92%
1.1	0.7	27.33	903	97%
1.1	0.9	77.54	1001	92%
1.3	0.5	223.37	1046	79%
1.3	0.7	147.05	938	84%
1.3	0.9	232.59	958	76%

Figure 4. Plot of IPMA vs CoFeB (nm) and Ta (nm) for Rapid Thermally Annealed Samples at 400 °C for 8 minutes, plotted using Minitab® Statistical Software. [13]

Figure 5. FMR results for $K_{u,i}$