Substrate bias effect on AlO$_x$ based magnetic tunnel junctions

Ajeesh M Sahadevan$^{1,4}$, Jae S Son$^2$, Hyunsoo Yang$^1$, Aaron J Danner$^2$, and Charanjit S Bhatia$^{1,3}$

$^1$Information Storage Materials Laboratory, Department of Electrical and Computer Engineering, NUS, Singapore

$^2$Centre for Optoelectronics, Department of Electrical and Computer Engineering, NUS, Singapore

$^3$Institute of Materials Research and Engineering, 3 Research Link, Singapore

E-mail: g0800464@nus.edu.sg

Abstract. The effect of substrate bias during deposition on the properties of magnetron sputtered aluminium oxide-based magnetic tunnel junctions (MTJ) is investigated. Ge buffer layers have been used for MTJs for the first time. Transmission electron microscope (TEM) images clearly indicate that application of substrate bias during the deposition of MTJ layers [IrMn/Co/AlO$_x$/NiFe/Cu] provides extremely smooth layers and flat interfaces (without annealing) in comparison to the layers deposited without bias. But hysteresis loops (magnetization v/s magnetic field M-H) obtained from alternating gradient force magnetometer (AGFM) make it clear that IrMn deposited with a substrate bias is not effective in providing exchange bias. The reason is the change in composition of IrMn with bias as shown by Rutherford backscattering (RBS) experiments. RBS for AlO$_x$ shows a clear Ar peak with the application of substrate bias.

1. Introduction

Magnetic Tunnel Junctions (MTJs) will play a key role in the future of storage devices such as the read heads of hard disc drives (HDD) and memory elements in magnetic random access memory (MRAM) [1, 2]. Though MTJs have been commercialized, the mechanisms involved as well as the exact structural conditions required for a high tunnel magnetoresistance (TMR) value are not completely clear. Recently TMR close to 1000% has been reported using MgO tunnel barriers [3]. Crystalline barriers like MgO enable huge TMR through coherent tunneling of electrons even using conventional ferromagnetic (FM) elements and alloys. Interface properties such as stoichiometry as well as the crystallinity play a very important role and can be tuned to change the TMR significantly [4]. A recent paper shows the effect of substrate bias during MgO deposition on CoFeB/MgO based MTJs [5]. They show an increase in TMR and a reduction in resistance area (RA) product with the application of bias to the substrate and explain the reason to be the enhanced MgO (001) growth, required for high TMR. Here we study the effect of substrate bias during the deposition on the properties of Aluminium oxide-based MTJs by magnetron sputtering.

$^4$To whom any correspondence should be addressed.
2. Experiments

The films are deposited in an ultra-high vacuum (10^{-9} Torr) sputter chamber. Atomic force microscopy is used to study the effect of substrate bias on film roughness and deposition rate. Germanium is deposited in a high vacuum (10^{-7} Torr) electron beam evaporator on Si/SiO\(_2\) (thermally oxidized) substrates. Two sets of the same structure are then deposited [Ge (40nm)/IrMn (25nm)/Co (3.5nm)/AlO\(_x\) (3nm)/Co (0.5 nm)/NiFe (5nm)/Cu (2nm)/Ge (5nm)] - one with a 20W RF bias to the substrate during deposition for all the layers and no bias for any of the layers in the other. The aim of this study is simply to see the effect of bias deposition on the properties of an MTJ (mainly the structure) and 20W RF is the maximum bias power possible. A 200kV Transmission electron microscope (TEM) is used to get the cross-sectional images of the two structures. The switching characteristics are obtained form an atomic force gradient magnetometer (AGFM). The effect of substrate bias on the composition of the antiferromagnetic IrMn and its crystal orientation is studied using Rutherford Backscattering (RBS) and X-ray diffraction (XRD) experiments, respectively. RBS is used to study the AlO\(_x\) composition as well.

3. Results and discussions

As an initial study the roughness and deposition rates for all the relevant layers in the structure are obtained. For most of the materials, both the parameters are reduced with the application of bias during deposition. E-beam evaporated Ge on Si/SiO\(_2\) substrate is found to be extremely smooth. The root-mean-square value (RMS) roughness is measured to be less than 3 Å. Cross-sectional TEM images for the two structures (without and with bias) are shown in figure 1a) and b).

![Figure 1 a)](image1a) Cross-sectional TEM image for MTJ [Ge (buffer) /IrMn/Co/AlO\(_x\)/Co/NiFe/Cu/Ge] without substrate bias

![Figure 1 b)](image1b) Cross-sectional TEM image for MTJ with substrate bias

The effect of bias to improve the uniformity of the layers and sharpness of the interfaces is clear. But alternating gradient force magnetometer (AGFM) measurements for hysteresis loops (magnetization v/s magnetic field M-H) show no switching for the layers deposited with a substrate bias of 20W, while the layers deposited without any bias show clear switching between the two magnetic layers. The M-H loops have been shown in figure 2a) and b). It is clear from these loops that in layers deposited with a bias there is no significant coercivity (H\(_c\)) difference between the FM layers to observe independent switching.
The reason for above observation is found to be the change in composition of the IrMn antiferromagnet layer. The compositional variation of a sputtered alloy with substrate bias has been studied elsewhere using both experiments and modelling [6]. Substrate bias as such has minimal effect on coercivity of a Co free layer. A 5nm Co layer has a coercivity of about 10 Oe, both with and without substrate bias during deposition. No unidirectional anisotropy is observed in figure 2a) since the deposition was done without an in-situ magnetic field.

Although substrate bias improves the surface RMS roughness of IrMn by over 100% (from 9Å to 4Å) as observed from the AFM data, it turns out that its composition no longer makes it an antiferromagnet to exchange bias the fixed layer in the MTJ. RBS experiments indicate that IrMn composition changes from 34:66 to about 82:18 with substrate bias indicating a preferential re-sputtering of Mn from the substrate (due to its lower atomic mass). The results are shown in figure 3. XRD also shows a shift in the (111) peak of IrMn from 40.92° to 40.73°, closer to the elemental Ir peak (40.044°). At the same time the IrMn (111) peak, which is critical to get a good exchange bias, is broadened with substrate bias as shown in figure 4. A 5 nm film of Co, deposited (with an in-situ field) over IrMn without substrate bias shows an exchange bias of about 150 Oe whereas Co on IrMn with substrate bias, shows
no exchange bias as shown in figure 5a) and b). In order to observe the exchange bias effect, the composition of the IrMn is very critical [7]. The M-H loop for a structure with an applied bias for all layers except IrMn shows switching as shown in figure 2 c).

Antiferromagnetic materials like FeMn might be used with substrate bias without any significant changes in the composition as Fe and Mn masses are similar, unlike Ir and Mn in IrMn.

The RBS signal for AlO$_x$ did not show any significant differences in the Al:O ratio (being 2:3) except a relatively higher Ar concentration with bias as shown in figures 6 a) and b). Even without a substrate bias presence of Ar is possible and substrate bias provides an efficient way of tuning it. The presence of Ar and its role in ultrathin barrier layers in MTJ structures will be of special interest.
4. Conclusion

The importance of process parameters on the physical structure of thin films and interfaces is demonstrated. Applying a substrate bias during deposition of multilayers is a very effective way to get smooth layers and flat interfaces even without annealing. Post deposition annealing may further improve the uniformity and crystallinity of the layers. But unwanted consequences with substrate bias deposition like change in composition and deterioration of crystallinity need to be taken care of. A Ge buffer layer also provides a smooth surface for the layers to be grown on. Studying the effect of substrate bias on crystallinity and composition of layers other than IrMn and barrier in the MTJ structure is also very important along with studying the effect on the transport properties. Such a study will help to develop a better understanding of MTJs.

5. Acknowledgments

The present work is supported by the Singapore Ministry of Education Academic Research Fund Tier 2 (MOE2008-T2-1-105). The author acknowledges experimental support from Dr. Kalon Gopinadhan, Mallikarjuna Rao Motapothula, Dr. Zhang Jixuan and Kwon Jae Hyun.

References

1. Yuasa, S. and D.D. Djayaprawira, Giant tunnel magnetoresistance in magnetic tunnel junctions with a crystalline MgO(001) barrier. Journal of Physics D-Applied Physics, 2007. 40(21): p. R337-R354.
2. Parkin, S., et al., Magnetically engineered spintronic sensors and memory. Proceedings of the IEEE, 2003. 91(5): p. 661-680.
3. Ikeda, S., et al., Tunnel magnetoresistance of 604% at 300 K by suppression of Ta diffusion in CoFeB/MgO/CoFeB pseudo-spin-valves annealed at high temperature. Applied Physics Letters, 2008. 93(8).
4. Velev, J.P., et al., Interface effects in spin-polarized metal/insulator layered structures. Surface Science Reports, 2008. 63(9): p. 400-425.
5. Choi, G.M., et al., Substrate Biasing Effect during MgO Deposition in CoFeB/MgO/CoFeB MTJs. IEEE Transactions on Magnetics, 2009. 45(6): p. 2371-2373.
6. Sinder, M., G. Sade, and J. Pelleg. Modeling of substrate bias effect on the compositional variations in sputter-deposited TiB2+x diffusion barrier thin films. in Computational and Mathematical Models of Microstructural Evolution. Symposium, 13-17 April 1998. 1998. Warrendale, PA, USA: Mater. Res. Soc.
7. Devasahayam, A.J., P.J. Sides, and M.H. Kryder, Magnetic, temperature, and corrosion properties of the NiFe/IrMn exchange couple. Journal of Applied Physics, 1998. 83(11): p. 7216-7218.