Recent Developments in ST-MRAM, Including Scaling

E. J. O'Sullivan, M. J. Gajek, J. J. Nowak, S. L. Brown, M. C. Gaidis, G. Hu, J. Z. Sun, P. L. Trouilloud, D. W. Abraham, R. P. Robertazzi, W. J. Gallagher and D. C. Worledge
IBM Research Division, T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, NY 10598, USA

Spin-torque [1] Magnetoresistive Random Access Memory (ST-MRAM) is the subject of intense investigation since it extends MRAM technology to densities well beyond those achieved with the earlier "Toggle" switching approach, and its scalability has made it a potential successor to high-density DRAM.

An ST-MRAM memory cell, which consists of an MTJ and a transistor, has the attractive property that if the critical current density for spin-torque switching (Jc) remains constant, then the critical current for magnetic tunnel junction (MTJ) switching (Ic) will scale as λ^2, where λ is MTJ area. Thus, scaling is highly desirable for ST-MRAM. At small device size limits, constant current rather than constant current density scaling should apply; however, down to 20nm, our MTJ structures appear to exhibit constant current density scaling behavior.

Scaling is not without challenges, however, and the ST-MTJ arrays must exhibit sufficient statistical margins between reading and writing operations, and must satisfy other key design properties including, a) sufficient tunneling magnetoresistance (TMR) for the read signal, b) compatibility of the MTJ operating point with CMOS transistor capability, and c) a high enough energy barrier for up to 10 years of data retention. A critical requirement for a practical ST-MRAM is achieving a critical voltage distribution (Vc) that is well separated from the tunnel barrier voltage breakdown (Vb) and read out voltage (Vr) distributions.

Early demonstrations of ST-MRAM involved magnetic layers with magnetization lying in the film plane (in-plane) [2]. This is the low energy configuration for most thin-film magnetic materials patterned into dots whose lateral size is significantly larger than the film thickness. However, this in-plane configuration results in inefficient spin torque switching, causing an order of magnitude increase in the switching current for the same activation energy, when compared to devices fabricated from perpendicularly magnetized materials [3]. Perpendicular magnetization is therefore required for dense ST-MRAM in order to achieve acceptably low switching currents, e.g., 30 uA. Thus, a significant research effort has recently been devoted to developing MTJs with perpendicular magnetic anisotropy (PMA) materials [4].

The Ta | CoFeB | MgO system has attracted particular interest since its interface anisotropy in allows the use of thin magnetic free layers, which enable fast switching, with additional benefits of being able to be grown at room temperature . Measurements on PMA devices in the diameter range 80 – 140 nm confirmed that the switching currents were lower than for in-plane magnetized junctions of the same activation energy [5]. The high tunneling magnetoresistance and PMA of the Ta | CoFeB | MgO system has enabled a basic write functionality demonstration in fully integrated ST-MRAM arrays [6].

To improve the spin torque efficiency, it is necessary to fabricate devices smaller than 50 nm. Smaller MTJ devices were patterned [7] using an ion beam etch (IBE) trim to reduce the size of the junction after reactive ion etch (RIE). Transmission electron microscopy (TEM) confirmed fabrication of devices down to 20 nm diameter; Fig. 1 shows an example of a 25 nm device.

A switching current (Ic0) of 29 uA and magnetic thermal activation energy (Eb) of 29.4 kT were measured for a 20 nm diameter MTJ [7]. Using Eb/Ic0 as a measure spin torque switching efficiency, efficiencies of up to 1.0 kBT/uA were obtained, which were the highest reported , and close to the expected single domain model value. This is extremely encouraging from a device point of view, although significant fabrication challenges will likely need to be overcome to realize such scaled MTJs in dense ST-MRAM memory.

[1] J. C. Slonczewski, *J. Magn. Magn. Mater.*, 159, L1 (1996).
[2] For example, M. Hosomi et al., *IEDM Tech. Dig.* 459 (2005); R. Beach, et al., *IEDM Tech. Dig.,* 305 (2008).
[3] J. Z. Sun, *Phys. Rev. B* 62, 570 (2000); J.Z. Sun and D.C. Ralph, *J. Magn. Magn. Mater*., 320, 1227 (2008).
[4] For ex., D. C. Worledge et al., *IEDM Tech. Dig.,* 296 (2010); S. Ikeda et al., *Nature Mater.,* **9**, 721 (2010).
[5] D. C. Worledge et al., *Appl. Phys. Lett.,* **98**, 02250 (2011).
[6] J.J. Nowak et al., *IEEE Magn. Lett.* 2, 3000204 (2011).
[7] M. Gajek et al., *Appl. Phys. Lett.,* **100**, 132408 (2012)

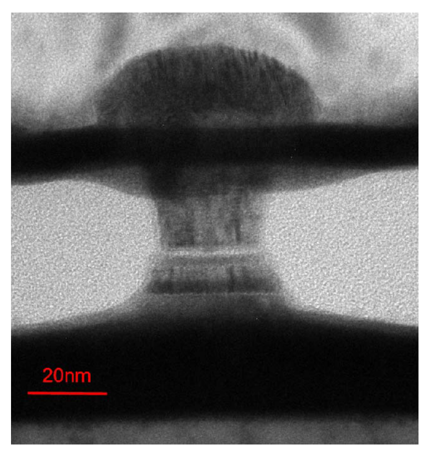

Fig. 1. TEM cross-section of a 25 nm diameter MTJ device.

Acknowledgements

We wish to thank E. Galligan, C. Jessen, and D. Milletics for technical support, and Y. Zhu for the TEM picture in Fig. 1. The authors gratefully acknowledge the efforts of the staff of the Microelectronics Research Laboratory (MRL) at the IBM T. J. Watson Research Center, where the magnetic device layers were fabricated. The scaling part of this work was partially supported by DMEA through the University of California at Riverside's Center of Nanomaterials and Nanodevices (CNN) under award no. H94003-09-2-0904.