Micromagnetic simulations of coupled out-of-plane spin-torque oscillators

G. Csaba*, M. Pufall**, W. Porod*
*Center for Nano Science and Technology, University of Notre Dame, Notre Dame IN 46556 USA
**National Institute of Standards and Technology, Boulder, Colorado 80305, USA
e-mail: gcsaba@nd.edu

INTRODUCTION

Spin-torque oscillators (STOs) are nanometer-scale devices, capable of generating self-sustaining magnetization and current oscillations in the microwave range [1]. They became a hot research topic of magnetoelectronics, since (1) they are an experimental platform study highly nonlinear nanoscale dynamics (2) arrays of interacting STOs may act as microwave power sources [2] (3) synchronization phenomena in STO arrays may enable practical realization or oscillatory neural networks [3]. In this paper, we present micromagnetic models of STOs. Our goal is to develop compact models for the study of complex systems of interacting STOs.

MACROSPIN SIMULATIONS

We study STOs exhibiting out-of-plane anisotropy, such as CoNi [4]. Simulations were performed by a C++ ODE solver, integrating the standard Landau-Lifshitz-Slonczewski equation [1,4]. Current through an in-plane magnetized polarizer layer induces precession (Fig 1) and pushes the magnetization vector toward the plane (Fig 2). The oscillation have a characteristic threshold, and the cut-off value and its frequency decreases with current (Fig 3). Higher harmonics appear already at lower driving currents.

FULL MICROMAGNETIC SIMULATIONS

Our micromagnetic simulation takes into account the nonuniform states induced by strong currents. If the STO is part of magnetic film, spin waves are emitted from the oscillator (Fig 4, Fig 5). We found that the macrospin and OOMMF [5] simulations agree well (Fig 6) if the Landau-Lifshitz damping constant is treated as a fitting parameter and a higher (α=0.03) value used in the macrospin simulation instead of the more realistic (α=0.008) value of OOMMF model.

COUPLING BETWEEN STOS

Micromagnetic simulations show that the spin-wave interaction between nearby STOs (Fig 7) is sufficiently strong that they interact and phase lock to each other (Fig 8), as it was demonstrated earlier experimentally [6]. Work is in progress to develop a coupling model in the macrospin approximation.

ACKNOWLEDGEMENT

The authors are grateful to George Bourianoff (Intel Corp.) for initiating their work on this topic and to the Intel grant "Ulta-Low Power Non Boolean systems."

REFERENCES

[1.] S. E. Russek, W. H. Rippard, T. Cecil, R. Heindl: *Spin Transfer Nano Oscillators* in: Handbook of Nanophysics: Functional Nanomaterials, ed: K. D. Sattler, CRC press 2010
[2.] A. Slavin, "*Microwave sources: Spin-torque oscillators get in phase*" Nature Nanotechnology, vol. 4, no. 8, pp. 479–480, Aug. 2009.
[3.] F. Macia, A. D. Kent, F. C. Hoppensteadt: *Spin-wave interference patterns created by spin-torque nano-oscillators for memory and computation* Nanotechnology 22 (2011) 095301
[4.] W. H. Rippard, A. M. Deac, M. R. Pufall, J. M. Shaw, M. W. Keller, S. E. Russek: *Spin-transfer dynamics in spin valves with out-of-plane magnetized CoNi free layers* Phys. Rev. B 81 014426 (2010)
[5.] http://math.nist.gov/oommf/
[6.] S. Kaka, M. R. Pufall, W. H. Rippard, T. J. Silva, S. E. Russek, J A. Katine: *Mutual phase-locking of microwave spin torque nano-oscillators* Nature 437 (2005)

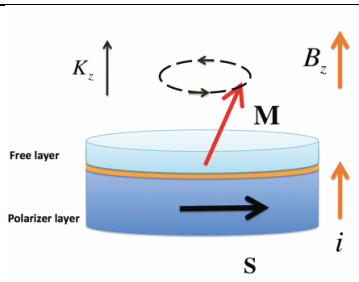

Fig 1. Schematics of an out of plane magnetized STO. The free layer is a 5 nm thick, 50 nm diameter CoNi disk with parameters $M_s = 8.6 \cdot 10^5\ A/m$, $B_z = 0.5$ T, $K = 5 \cdot 10^5$ J/m^3 $\alpha = 0.03$ ·

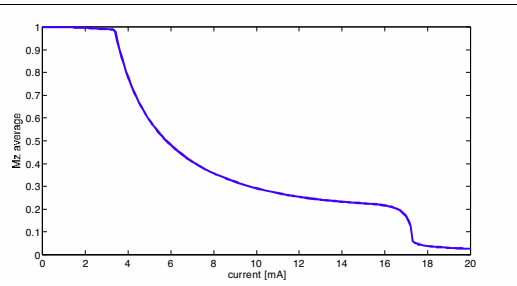

Fig 2. Dependence of the M_z (out of plane) magnetization component on the current. As the current increases, the magnetization oscillates in larger angles to the surface normal.

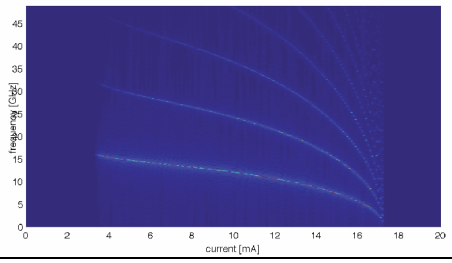

Fig 3. Fourier transform of the magnetization at different currents, calculated from the macrospin model. Oscillations start at *i*=4 mA, and at 15 GHz frequency.

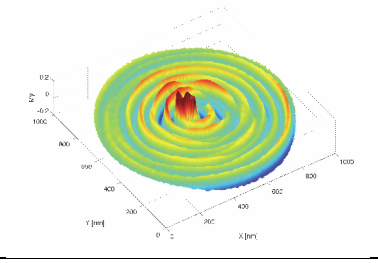

Fig 4. Micromagnetic simulation of spin waves radiating from an STO.

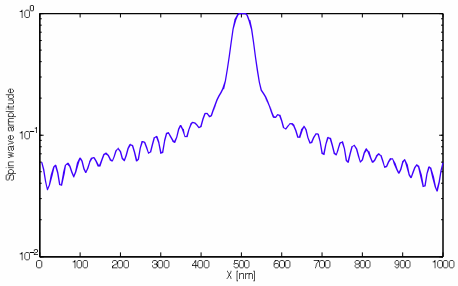

Fig 5. Damping of spin waves. The STO is in the center. Spin waves show an exponential decay (linear on the above log scale).

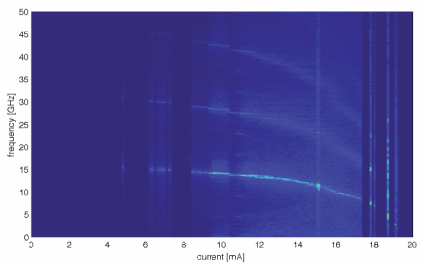

Fig 6. Full micromagnetic simulation of the STO using α=0.008, which fits well to the macrospin calculations.

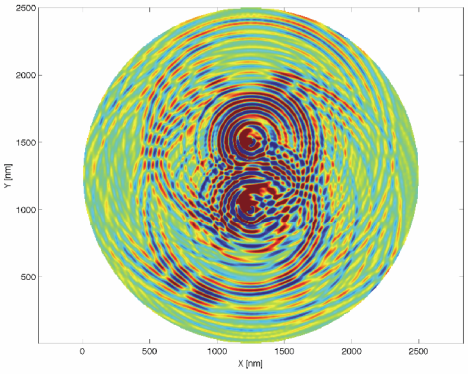

Fig 7. Spin waves created by two STOs, placed 500 nm apart.

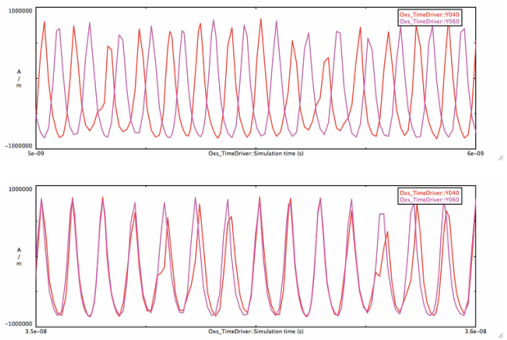

Fig 8. Synchonization in double STOs. The phase of magnetic oscillations from the two STOs locks to each other after a 30 ns time period.