Advanced Modeling of Emerging Nonvolatile Magnetoresistive Devices

J. Ender[1], S. Fiorentini[1], R. Orio[2], S. Selberherr[2], W. Goes[3], and V. Sverdlov[1]

[1] *Christian Doppler Laboratory for Nonvolatile Magnetoresistive Memory and Logic at the*
[2] *Institute for Microelectronics, TU Wien, Gußhausstraße 27–29, A-1040 Wien, Austria*
[3] *Silvaco Europe, Cambridge, United Kingdom*
sverdlov@iue.tuwien.ac.at

As scaling of CMOS transistors shows signs of saturation, considerable research is focusing on exploring new computing paradigms for energy efficient scalable devices based on novel physical principles. Emerging nonvolatile magnetoresistive memories are CMOS-compatible and electrically addressable. They possess a simple structure and require only a few additional masks for fabrication while offering high endurance and a speed superior to that of flash memory. Fast operation of magnetoresistive memories makes them suitable for SRAM applications [1], while their broad temperature operation range is attractive for flash replacement in, e.g., automotive applications [2]. Nonvolatile magnetoresistive devices integrated with CMOS can not only efficiently store, but also help to process the information, opening perspectives for conceptually new low power and high-performance computing paradigms. As spin-transfer torque (STT) magnetoresistive random access memory (MRAM) is entering mass production, TCAD tools and performance optimization tools facilitating the design for specific applications are urgently needed.

We pursue a fully three-dimensional finite element method (FEM) based modeling and simulation approach (Fig.1) incorporating all essential physical phenomena responsible for proper MRAM operation, sufficient stability, and reliability. To solve the Landau-Lifshitz-Gilbert equation describing the magnetization dynamics in an MRAM cell, the effective field and current-induced torques must be computed. To efficiently compute the contribution of the demagnetizing field, a hybrid approach with the FEM coupled to the boundary element method (hybrid FEM-BEM) [3] is employed in order to restrict the computational effort to the magnetic domain (Fig.2). By modeling the tunnel barrier of a magnetic tunnel junction (MTJ) as a poor conductor with a magnetization-dependent conductivity, we extend the spin transport approach (Fig.3) commonly applied in metallic valves to compute the spin accumulation in an MTJ (Fig.4). By adjusting the diffusion coefficient in the barrier, a free parameter of the model, the spin accumulation continuity is preserved allowing to evaluate the torques (Fig.5). A unique framework to evaluate torques and magnetization dynamics in spin valves and MTJs allows to efficiently describe the behavior of emerging STT-MRAM.

[1] S.H. Han et al., Proc. IEDM, 215 (2020).

[2] V.B. Naik et al., Proc. IEDM, 219 (2020); Y.-C. Shith et al., Proc. IEDM, 223 (2020).

[3] D.R. Fredkin et al., IEEE T-Magnetics, **26**, 415 (1990); J. Ender et al., Proc. SISPAD, 213 (2020).

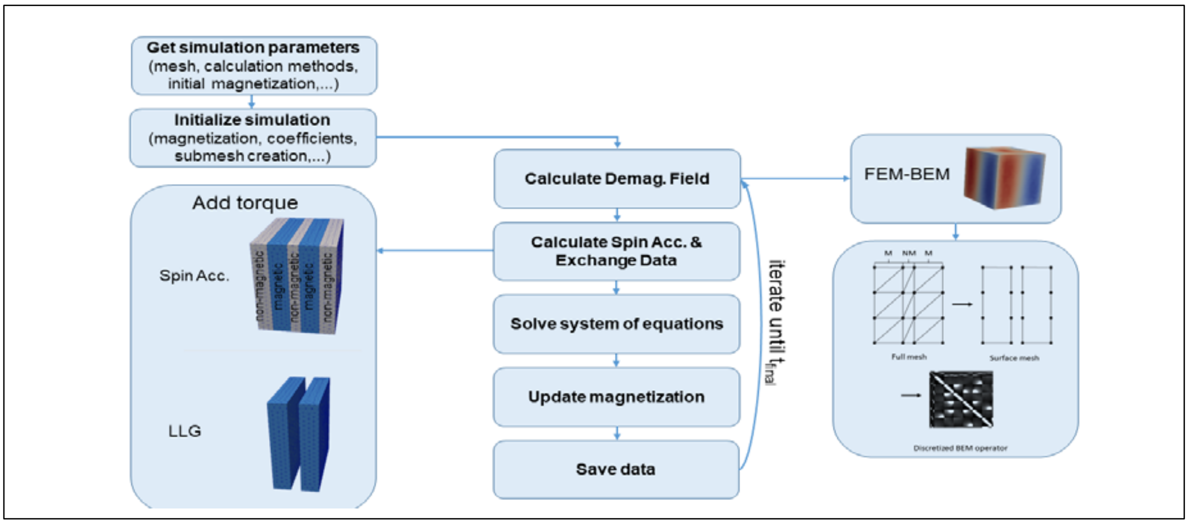

Fig.1: Structure of FEM-based simulator of magnetization dynamics.

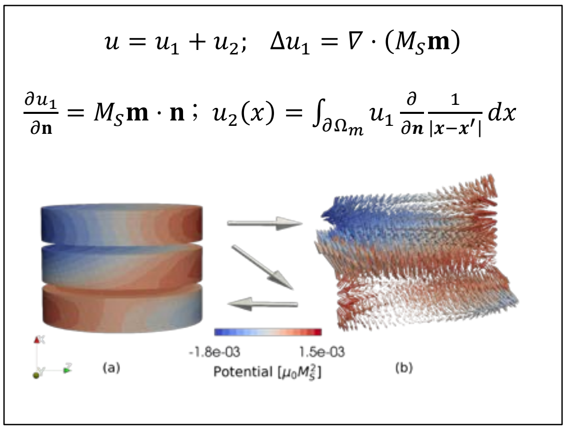

Fig.2: Magnetic potential (left) and demagnetization field /right) in a three-layer structure with noncolinear magnetizations (middle).

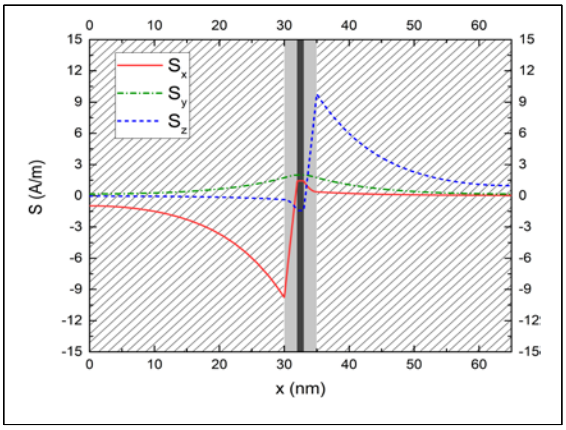

*Fig.4: Spin accumulation **S** in an MTJ (gray) with a barrier (black) connected to normal contacts (shaded) created by the current.*

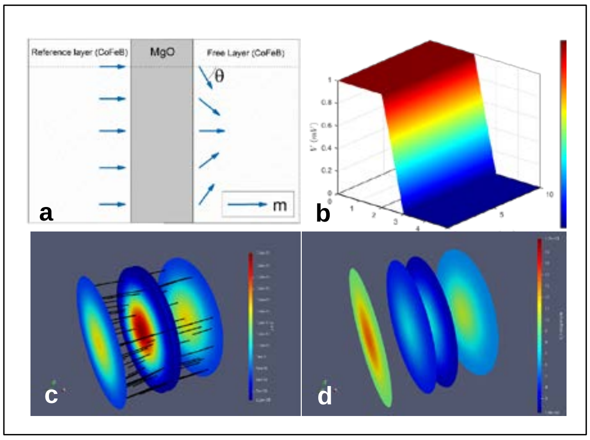

Fig.3: An. MTJ with nonuniform relative magnetization; b. Potential drop across an MTJ; c. Current density distribution; d. Spin accumulation created by the current.

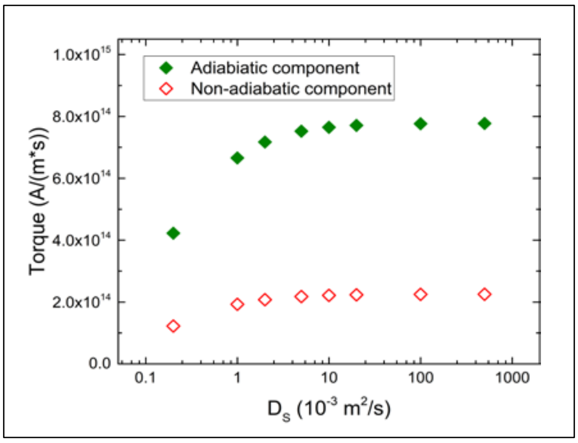

Fig.5: Torque dependence on the diffusion coefficient in the barrier modeled as a poor conductor with the resistivity depending on the relative magnetization orientation across the barrier.