Temperature Increase in MRAM at Writing: A Finite Element Approach

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***Abstract* – Elevated temperatures facilitate the data writing in spin-transfer torque magnetoresitive random access memories (STT-MRAM). We demonstrate a fully three-dimensional (3D) finite element simulation approach to numerically solve the heat transport equation coupled to the electron transport and magnetization dynamics in an STT-MRAM cell at switching. As a particular result, the average temperature in the free layer can be obtained from a one-dimensional (1D) model based on an averaged current density and an averaged potential drop across the tunnel barrier. However, to evaluate the large local temperature variations, a 3D model is required.**

Keywords - MRAM, magnetic tunnel junction, current-induced heating, heating asymmetry, temperature variations

I. INTRODUCTION

The intrinsically nonvolatile magnetoresitive random access memory (MRAM) is a promising emerging candidate to tackle the increased stand-by power consumption in modern circuits. MRAM is complementary metal-oxide semiconductor (CMOS) compatible and can be integrated into logic circuits.

In spin-transfer torque MRAM (STT-MRAM), relatively high current densities pass through the cell to switch the magnetization of the free layer (FL) in the magnetic tunnel junction (MTJ). This results in an increased temperature of the structure, which can mediate the switching of the FL magnetization [1]. On the other hand, the increased temperature should be rapidly relaxed as it can cause a random magnetization flip in the FL and thus an information loss.

Therefore, to model the temperature in MRAM, the heat equation must be coupled to the current and magnetizations dynamics.

II. METHOD

The evolution of the temperature T in the structure at time t and position $\boldsymbol{r}$ is governed by the heat equation.

$$c_v \rho \frac{\partial T(\boldsymbol{r},t)}{\partial t} - \boldsymbol{\nabla} \cdot [\kappa \cdot \boldsymbol{\nabla} T(r,t)] = q(r,t) \qquad (1)$$

c_v, ρ, and κ stand for the thermal capacity, mass density, and heat conductivity of the material, respectively, $q(r,t)$ is the source term. The first of the two main heat sources in MTJs, the Joule heating, can be written as: $q_r(\boldsymbol{r}) = \boldsymbol{j}^2(\boldsymbol{r})\rho_{\mathrm{E}}$, where ρ_{E} is the material resistivity and $\boldsymbol{j}$ is the current density. The second heat source is associated with hot electrons/holes tunneling through the barrier [1, 2]. When an electron tunnels from the source side, it arrives as a hot electron at the receiver side where its energy is dissipated. Similarly, the hole left in the source after the tunneling electron is filled by an electron from a higher energy level, the energy of which is therefore released. With the x-axis being the axis along the structure, the hot electron/hole heat source is described by

$$q_t(\boldsymbol{r}) = \left(1 \pm \alpha(\Delta U)\right) \frac{j_x(y,z)\Delta U(y,z)}{2\lambda} \exp\left(-\frac{|x - x_{F/P}|}{\lambda}\right), \qquad (2)$$

where $\Delta U(y,z)$ and j_x stand for the potential drop and the x-component of the current density at position (y,z) across the barrier, and λ is a characteristic length at which hot electrons/holes lose their energy due to various inelastic scattering processes. The x-coordinate of the position of the free/pinned layer is denoted $x_{F/P}$. $\alpha(\Delta U)$ is an asymmetry coefficient characterizing the imbalance between receiver and source side heat production. In this work this coefficient is set to zero in order to investigate the details of inhomogeneous temperature development due to current density inhomogeneity.

To describe the magnetization dynamics, the Landau-Lifshitz-Gilbert equation is used. The demagnetization field contributing to the magnetization dynamics is determined by an optimized hybrid FEM-BEM approach [3]. To determine the STT, the spin accumulation in the structure is computed [4]. The currents and potentials are determined by solving the Poisson equation. The described approach has been implemented in 3D with the use of the finite element method.

III. RESULTS

In Fig. 1 the simulated structure is shown. The MTJ consisting of CoFeB(1 nm)/MgO(1 nm)/CoFeB(1.2 nm) is connected to non-magnetic metal (NM) contacts (30 nm). The diameter of the structure is 40 nm. Both ends of the contacts are kept at constant temperature while a 2 V potential difference is applied across the structure.

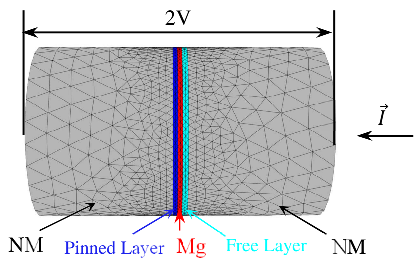

Figure 1. The *simulated structure consisting of a CoFeB (1nm)/MgO(1nm)/CoFeB(1.2nm) MTJ connected to non-magnetic metal (NM) contacts (30nm). The diameter of the structure is 40 nm. Both contact ends are kept at a constant temperature. 2V are applied across the structure.*

When the potential difference is applied, the electrical current flows through the structure and the STT starts to act on the free layer magnetization, which eventually leads to a magnetization flip as displayed in Fig. 2. At the beginning, the magnetization oscillates in the y-z plane. After about 0.5 ns these oscillations stop and the m_x component begins to change faster. At approximately 1.1 ns, the change of m_x slows down, and the oscillations of the y- and z-components appear again.

Fig. 3. shows the temperature dependencies at the FL. The average temperature T_{avg} of the FL is shown in green (coincides with the dashed orange). The maximum and minimum temperatures, T_{max} (in black) and T_{min} (in gray) are also shown. The difference in the maximum and minimum temperature is caused by inhomogeneous current densities. The average temperature T_{avg-1D} calculated with an average current density and the potential drop across the barrier is shown in dashed orange and coincides with the 3D calculation of T_{avg}.

The temperature profile of the FL at $t = 0.74$ ns is shown in Fig. 4. The figure indicates a maximum temperature difference of about 12 K. In Fig. 5, the ratio of the maximum temperature difference at the FL to T_{avg} is displayed. At the beginning, when the magnetization oscillations are present, this ratio is small, but considerably increases during the rapid m_x magnetization change to above 30 % of T_{avg}. Consequently, when the oscillations of the magnetization appear again in the y-z plane, this ratio drops significantly.

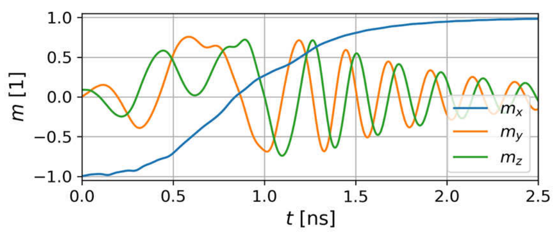

Figure 2. Averages of the x, y and z components of the normalized free-layer magnetization during switching from anti-parallel to parallel state. The initial magnetisation was tilted by 5° in the z-direction from the x-direction to accelerate the incubation phase.

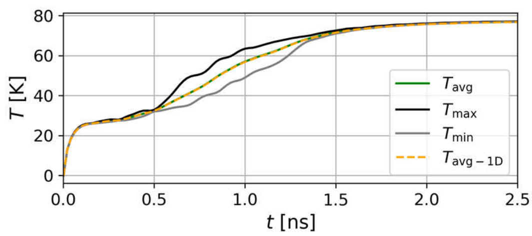

Figure 3. Temperature at the free layer. An average temperature T_{avg} of the free layer (green, coinsides with dashed orange), maximum temperature (black), minimum temperature (grey), and T_{avg-1D} calculated using averages of current densities and potential drop across the barrier (dashed orange).

IV. Conclusion

We have developed a fully three-dimensional finite element simulation approach to numerically solve the system of heat, charge, and spin transport equations coupled to the magnetization dynamics of the free layer in STT-MRAM cells. It was demonstrated that the temperature profile of the free layer is highly inhomogeneous during switching. It is caused by the inhomogeneous current density distribution through the MTJ due to noncollinear magnetizations at switching. The ratio of the maximum temperature difference to the average temperature is above 30% at the free layer. While the average temperature at the free layer can be well approximated by a 1D heat simulation when and an average current density and an average potential drop across the barrier are used, the accurate modeling of the temperature profile requires a 3D simulation setup.

References

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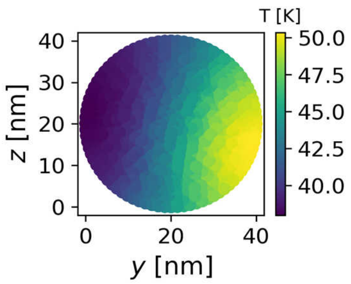

Figure 4. Temperature profile of the free layer at t = 0.74 ns. The maximum temperature difference is around 12 K.

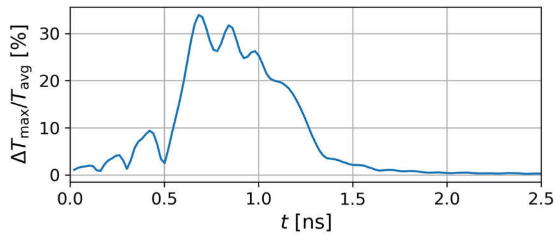

Figure 5. Ratio of the maximum temperature difference ΔT_{max} at the free layer to the average temperature T_{avg} at the same layer. ΔT_{max} reaches 30% of the average temperature, when m_y and m_z stop to oscillate between 0.5 ns and 1.1 ns (see Fig. 2.).