Heating Asymmetry in Magnetoresistive Random Access Memories

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ABSTRACT

Time-dependent current induced heating in a magnetic tunnel junction-based memory cell is investigated by numerically solving the heat transport equation with finite element methods. The Joule heat sources and the sources due to electron tunneling are considered. It is shown that a CoFeB|MgO|CoFeB cell connected to 20 nm long metal electrodes reaches a stationary temperature in 100 ps after a constant current pulse is applied. A similar time is required to cool the cell to the ambient temperature after the current is turned off. The saturation temperature increases with the current pulse power. Due to an asymmetry of the heat generated by tunneling electrons, the temperature profile is not symmetric. The asymmetry of heat generation increases linearly with the voltage up to 1 V and slowly starts to saturate at higher voltages. Because of the increasing asymmetry, the maximum saturation temperature rises faster and is not linear with respect to the pulse power.

Keywords:, non-volatile magnetoresistive memory, magnetic tunnel junction, current-induced heating, heating asymmetry

1. INTRODUCTION

For decades, the increase in performance and energy efficiency of complementary metal-oxide semiconductor (CMOS) devices has been facilitated by continuous miniaturization. However, a decreasing transistor size also leads to increasing leakage currents which result in higher standby power consumption and worse data retention of the classical charge-based memories. In order to reduce the power consumption and reliability, new technologies are needed.

An appealing solution can be found in the field of spin electronics (spintronics). Therein, spin, an inherent electron property responsible for magnetic properties of materials, is utilized instead of the electron charge. Magnetoresistive random access memories (MRAM) have gained a lot of attention for applications in the automotive industry [1,2] and they are already commercially available [3-5]. The strong interest stems from their nonvolatility, high operation frequencies, broad temperature operation range [1-3], and CMOS compatibility [6-8].

The basic element of the MRAM cell is a 3-layer magnetic tunnel junction (MTJ) consisting of a thin oxide clammed between a free and a pinned magnetic layer. The information is retained in the orientation of the magnetic layers and can be read using a tunnel magnetoresistance principle [9,10]. If a current is passed through the structure, the resistance is low/high for a parallel/anti-parallel arrangement of the magnets.

For information writing, several methods have been developed in the past [11-15]. The most used switching method utilizes spin transfer torque (STT). During the writing process, a high current density passes through the structure and the STT acting on the free layer leads to its magnetization flip. Due to the high current density an excess heat is produced, which results in a temperature increase in the memory cell. This facilitates the free layer switching [11,12,16], however, the increased temperature reduces the thermal stability of the memory. Therefore, fast cooling, after the writing current pulse is switched off, is required for the information to survive the writing process. In order to properly model the switching processes, the introduction of temperature and heat transport into the already coupled charge, spin and magnetization dynamics is required.

In previously conducted numerical studies of heat transport in MTJs all the heat power caused by the tunneling electrons was attributed just to the hot electrons receiver side [17,18]. This appears to be in contradiction with the real tunneling experiments

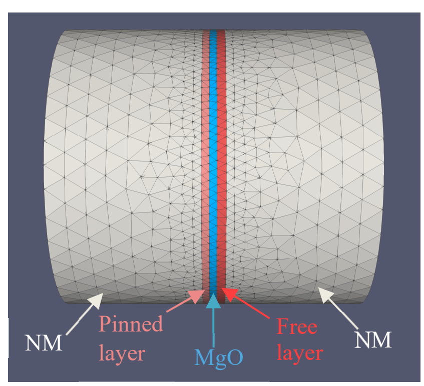

Fig 1: Simulated cylindrical structure. The MTJ consists of a fixed CoFeB layer (1 nm), a MgO layer (1 nm), and a CoFeB free layer (1.2 nm) connected to normal metal contacts (20 nm). The diameter of the structure is 40 nm.

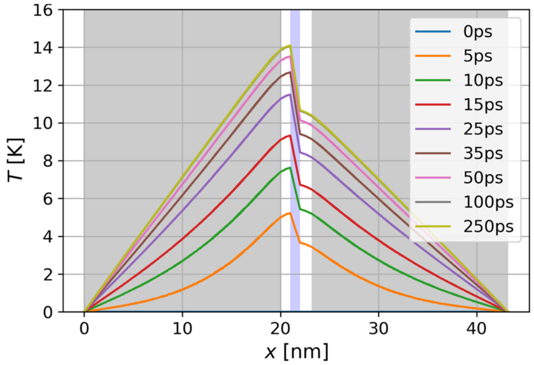

Fig. 2: Temperature increase and asymmetry development in the temperature profile of the structure after a voltage driven current pulse is applied. For the current in the positive x-direction, tunneling electrons cause the pinned layer, left to barrier, to reach higher temperatures. The structure temperature saturates after 100 ps. The voltage across the structure and the asymmetry parameter α were set to 1V and 0.2, respectively. Both ends are kept at constant temperature.

[19,20], where the heating due to tunneling electrons was also discovered in the source electrode. As the effective thermal conductivity of the thin MgO layer in the MTJ is by an order of magnitude smaller in comparison to the thin film conductivity [21, 22] significant temperature differences can be expected between the free and the pinned layers, which in turn can critically impact magnetization dynamics and hence the switching times. The main objective of this work is to investigate how an asymmetry of the hot electron heating on both sides of an MTJ affects the temperature profile in an MRAM cell.

In Section 2 the theoretical framework and solution methods are described. Section 3 presents results of the simulations. The summary of the work is given in Section 4.

2. METHODS

The development of temperature T over time t at position $\boldsymbol{r}$ of a material with a thermal capacity c_v, material density ρ, and heat conductivity $\boldsymbol{\kappa}$ is governed by the heat equation.

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

$q(\boldsymbol{r},t)$ stands for the heat source power density. In an MRAM cell, two main heat sources can be identified [12]. The first one is attributed to Joule heating in the ferromagnetic materials (FM) of the MTJ and the attached normal metal (NM) contacts with an electric resistivity ρ_{E}. The current density $j(\boldsymbol{r})$ produces a power density $q_r(\boldsymbol{r}) = j^2(\boldsymbol{r})\rho_{\mathrm{E}}$. The second heat source is attributed to electrons tunneling through the thin oxide barrier. In the ballistic tunneling model, the tunneling electrons arrive at the receiver side of the barrier as hot electrons and their energy must relax to the Fermi level through scattering processes inside the receiving FM and NM layers within a distance λ. Similarly, the hole left behind the tunneling electron at the source side relaxes to the Fermi level of the source FM and NM layers. Considering the x-axis being the axis along the MRAM layer stack, the heating power density due to the tunneling electrons/holes can be written as

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

where ΔU accounts for the potential drop across the barrier, j_{x} is the current density at the supply-barrier interface and x_F, and x_P are the coordinates of the free and pinned layer-barrier interfaces, respectively. Due to a higher tunneling probability of the electrons with higher energies, more heat is generated on the receiver side [17,19,20]. As shown in [17], this heating asymmetry can lead to about 10 % more heating of the free layer in an MTJ for reversed current direction even at current densities below the critical value required for STT switching. This heating asymmetry increases with increasing potential bias across the structure [19,20]. To model the heating asymmetry, the heat asymmetry parameter $\alpha(\Delta U)$ was introduced in (2). The + and – signs in front of $\alpha(\Delta U)$ represent the hot electron receiver and source sides, respectively. The total heat production due to the hot electrons is equal to $I\Delta U$, where I is the current through the structure.

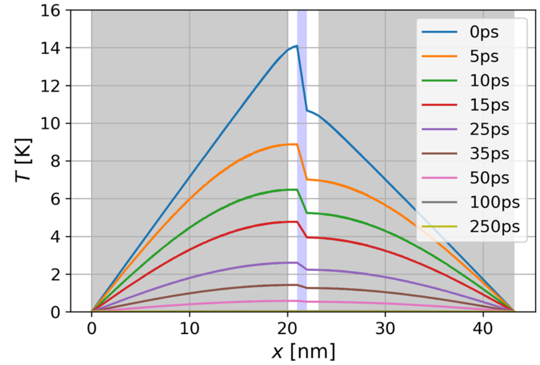

Fig. 3: Temperature relaxation after the voltage driven current pulse it turned off. The structure reaches the ambient temperature in 100 ps. Both ends are kept at constant temperature.

We investigate the asymmetry parameter voltage dependence for the chosen structure by developing a quantum mechanical model. The ferromagnetic layers are modeled as a three-dimensional free electron gas reservoir [19]. The tunneling probability is calculated by numerically solving the Schrödinger equation for a trapezoidal barrier accounting for the potential drop across the barrier. The MgO|CoFeB barrier height was set to 4.8 V corresponding to a work function of CoFeB [23].

The heat transport equation (1) including both types of heat sources has been numerically solved using the finite element method (FEM) implemented into ViennaMRAM[1] based on an open source MFEM library [24]. The FEM approach is chosen for facilitating compatibility with more complex magnetic structures we plan to simulate in the future. To determine the current densities and the potential, the electron transport equation [25] is solved. For convenience, we consider below the parallel magnetization orientation. Our approach is based on a well-

Table 1: Material density ρ, heat capacity c_v, heat conductivity κ, and electric resistivity ρ_e of the materials used in the simulations.

	MgO	CoFeB	NM
ρ [$\mathrm{kgm^{-3}}$]	340	7200	8000
c_v [$\mathrm{J\,K^{-1}kg^{-1}}$]	796	500	500
κ [$\mathrm{W\,K^{-1}m^{-1}}$]	0.38	43	43
ρ_e [Ω m]	-	2×10^{-5}	2×10^{-5}

[1] In-house developed software at the Christian Doppler Laboratory for Nonvolatile Memory and Logic: https://www.iue.tuwien.ac.at/novomemlog/

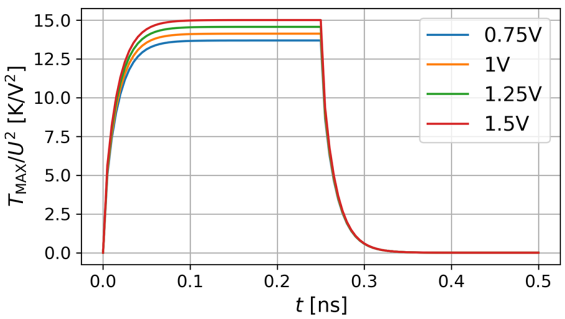

Fig. 4: Time development of the maximum temperature T_{MAX} of the structure (pinned layer) for different applied voltages U scaled to U^2. Due to the increasing asymmetry for higher voltages ($\alpha = 0.2\Delta U$), T_{MAX}/U^2 increases for higher voltages.

established set of equations for heat, charge, and spin transport coupled to magnetization dynamics. It is complemented with $\alpha(\Delta U)$ not considered in [17,18], which, however, according to [19,20] must be included. The implicit Euler method is utilized for the time integration.

3. RESULTS

For the analysis of the heat asymmetry, we choose an MTJ consisting of a pinned CoFeB layer (1 nm), a MgO (1 nm), and a free CoFeB layer (1 nm) connected to 20 nm non-magnetic metal (NM) contacts (Fig. 1). The structure has a cylindrical shape with a diameter of 40 nm. The resistance-area product RA of the oxide layer was set to $1.4 \times 10^3 \Omega \mathrm{m}^2$. Material properties relevant to the simulation are listed in Table 1.

We first approximate the asymmetry parameter by a linear function $\alpha(\Delta U) = \alpha_1 \Delta U + \alpha_0$ of the potential drop ΔU across the barrier. In order to investigate the effects of the asymmetry parameter on the structure temperature, three different setups are considered: Constant asymmetry $\alpha = 0.1$, asymmetry linearly varying with the potential drop $\alpha = 0.2\Delta U$, and a combination of both $\alpha = 0.2\Delta U + 0.1$. The actual values of the asymmetry parameter are consistent with the experimental values [18].

The temperature increase of the structure after a current pulse is applied is shown in Fig. 2. Both ends are kept at a constant temperature and the current direction is from the left to the right. The bias of the left contact is higher than that of the right contact forcing electrons to tunnel from the right to the left in the opposite direction to the current direction. The tunneling electrons cause an asymmetry in the heat generation with respect to the current direction. As the heat conductivity of the middle MgO layer is two orders of magnitude lower than in the FM and NM layers, the asymmetry of the heat generation results in an asymmetrical profile of the temperature: The temperature becomes higher in the contact at a positive bias, in agreement with [17,19,20]. The reduced heat conductivity of the barrier plays an important role as the previous numerical simulations could not fully explain the experimental values. In [17] the experimental results show 10% more efficient heating of the free layer for a reversed current. In the same work, numerical simulations of the temperature asymmetry show only a 1% difference even though a single-sided heating is considered. In contrast to the bulk MgO heat conductivity value 37 $Wm^{-1}K^{-1}$ used in [17] we employ a more appropriate value of 0.38 $Wm^{-1}K^{-1}$ [22]. In our simulations, the temperature difference is around 13% for 0.75 V applied across the structure and α=0.15 which better matches the experimental values [17]. Fig. 2 shows that the temperature of

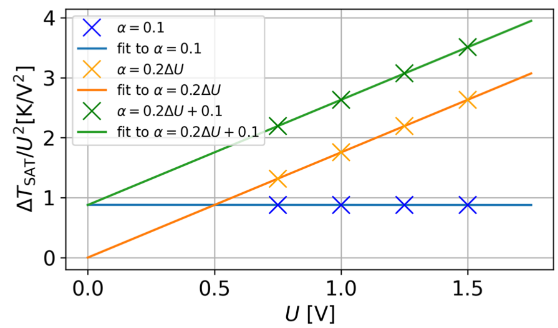

Fig. 5: Simulated (x) and fitted (-) T_{MAX}/U^2 for different asymmetry dependences on the potential drop. The data reveal a perfect linear scaling of T_{MAX}/U^2 with the asymmetry parameter α.

structure reaches saturation after approximately 100 ps after the current pulse is turned on. The stationary regime is achieved, when the heat caused by the voltage pulse is balanced by the heat flow into the heat sinks at the outer contact interfaces.

Fig. 3 demonstrates the temperature relaxation after the current is turned off. Despite the fast temperature relaxation to the ambient temperature in about 100 ps, the asymmetry of the temperature profile remains pronounced during the relaxation. This is because the heat conductivity of the ferromagnetic and contact metal layers is significantly higher than the one of the middle dielectric layer, preventing the heat exchange between the free and pinned layers in the MTJ.

In order to investigate the saturation temperature dependence on the current pulse parameter, we consider the temperature behavior for a 0.25 ns current pulse with consequent cooling, for several voltages U applied to the structure. The maximal temperature as a function of time divided by the total voltage square is shown in Fig. 4. If all curves in Fig. 4 were collapsed on a single universal curve, the maximal temperature would be proportional to the total pulse power $P = UI = U^2/R$, where I is the current and R is the structure resistance. Fig. 4 demonstrates that the maximum saturation temperature increases faster than the pulse power, if the asymmetry parameter $\alpha = 0.2\Delta U$ depends on the voltage. The additional increase of the temperature ΔT_{SAT} is linear with the voltage as shown in Fig. 5. In order to demonstrate that the increase of the saturation temperature ΔT_{SAT} is precisely due to the voltage dependence of the asymmetry parameter, the corresponding dependences for $\alpha = 0.1$ and $\alpha = 0.2\Delta U + 0.1$ are also shown in Fig. 5. As one observes from Fig. 5, the functional dependence of ΔT_{SAT} on the voltage coincides with the dependence of the asymmetry parameter. Therefore, we can conclude that the voltage

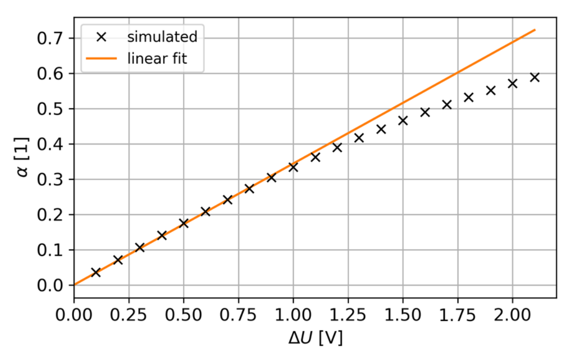

Fig. 6: Calculated asymmetry for different potential drops across the barrier for a barrier hight of 4.8 eV and thickness 1 nm.

dependence of the asymmetry parameter causes an increase of the saturation temperature beyond proportionality to the pulse power.

Fig. 6 shows the calculated asymmetry parameter. Its voltage dependence is similar to the one observed experimentally [19,20]. For voltages below 1 V the curve can be well fitted with a linear dependence, while at higher voltages a linear fit with an offset is more appropriate. This justifies our choice for the studied voltage dependences of the asymmetry parameter.

4. CONCLUSION

Current induced heating in a model for magnetic tunnel junction-based memory cells is studied by investigating numerically the heat transport coupled to the charge and spin transport. The heat sources due to Joule heating and hot tunneling electrons are included. It is demonstrated that a stationary regime is achieved in 100 ps after the current pulse is turned on in a structure with 20 nm long metal contacts. The elevated temperature relaxes to the ambient temperature in about 100 ps after the pulse is turned off. The temperature profile at saturation is not symmetric, with the temperature being higher on an MTJ side connected to the contact at positive voltage. The difference is caused by the energy relaxation of tunneling hot electrons. A quantum mechanical model for the asymmetry coefficient dependence on the applied voltage is developed, which is consistent with the experimental findings. It is shown that the saturation temperature is almost proportional to the current pulse power, with a deviation increase caused by the voltage dependence of the asymmetry parameter.

5. ACKNOWLEDGEMENT

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