# Asymmetry of Current-Induced Heating in Magnetic Tunnel Junctions

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Magnetoresistive random access memories (MRAM) are promising for automotive applications due to their broad temperature range of operation [1]. Additional heat is generated during the writing process due to the current running through a magnetic tunnel junction (MTJ). The increase in temperature facilitates the free layer switching but also lowers the cell thermal stability. Therefore, for long retention, the temperature must relax fast after the writing process is finished. To account for temperature in TCAD optimization of MRAM is therefore urgently needed.

We consider a CoFeB/MgO/CoFeB MTJ connected to normal metal (NM) electrodes (Fig.1). The current density $j(\mathbf{r})$ at a position $\boldsymbol{r}$ in the metal contact and the ferromagnetic layers produces a power density $q(\boldsymbol{r}) = j^{2}(\boldsymbol{r})\rho$ [2], where $\rho$ is the resistivity of the material. The power generated by hot electrons tunneling through the barrier in positive $x$ direction can be written as

$$Q(\boldsymbol{r}) = (1 \pm \alpha(\Delta U))\frac{j\Delta U}{2\lambda}\exp\left(-\frac{|x-x_{\mathrm{F/P}}|}{\lambda}\right). \quad (1)$$

Here $j$ and $\Delta U$ are the current dennsity and the potential drop across the barrier at a point $(y,z)$ and $x_{\mathrm{F/P}}$ is the $x$ position of the interface between the barrier and the free/pinned layer. The upper/lower sign corresponds to the heat generation in the free/pinned layer. The signs are inverted for the reverse current direction. The energy of a tunneling electron is relaxed down to the Fermi energy in the receiving electrode within a distance $\lambda$=1nm. The tunneling electron leaves an empty spot in the energy distribution within the emitting electrode, which is occupied by an electron relaxing from the Fermi-energy. Since electrons with a higher energy tunnel easier through the barrier, more heat is generated in the receiving electrode. This asymmetry is described by $\alpha(\Delta U)$ in (1). Because the asymmetry appears only at a finite voltage, $\alpha(\Delta U) = \alpha_1 \Delta U$ is a linear function of $\Delta U$ in the first approximation [3].

The temperature increase simulated with the parameters from Table 1 after the current pulse is turned on is shown in Fig.2. The increase saturates after 200ps. Fig.3 shows the temperature relaxation after the pulse is turned off. Again, the temperature of the environment is reached after 200ps. Fig.4 shows the temperature behaviour for a 0.4ns current pulse with consequent cooling, for several voltages. The curves for different voltages divided by the total voltage square are shown in Fig.5. Fig.5 demonstrates that the maximum saturation temperature $T_{SAT}$ increases faster than the pulse power by $\Delta T_{SAT}$ which scales linearly with voltage (Fig.5, Inset) due to the linear dependence of $\alpha$ on $\Delta U$.

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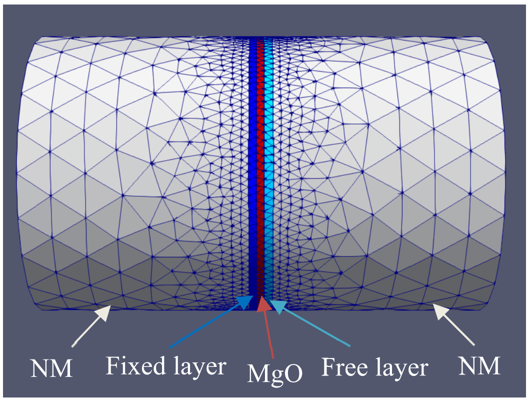


*Fig.1: Simulated cylindrical structure of 40nm diameter. The MTJ consisting of a fixed CoFeB layer (1nm), MgO layer (1nm) and CoFeB free layer (1.2nm) is connected to metal contacts (NM) (30nm). Both ends are kept at a constant temperature.*

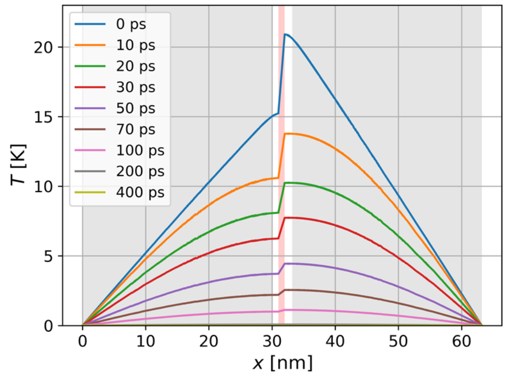


*Fig.3: Fig.4: Temperature decrease of the structure after the voltage driven current pulse is switched off. The temperature relaxes after 200ps.*

| | MgO | FeCoB | NM |
|---|---|---|---|
| Density [kgm$^{-3}$] | 340 | 7200 | 8000 |
| $c_v$ [ J K$^{-1}$kg$^{-1}$] | 796 | 500 | 500 |
| $\kappa$ [ W K$^{-1}$m$^{-1}$] | 0.38 | 43 | 43 |
| $\rho_e$ [Ω m] | - | 2x10$^{-5}$ | 2x10$^{-5}$ |

*Table 1: Parameters used in simulation: Density, thermal capacitance $c_v$, thermal conductivity $\kappa$ and electric resistivity $\rho_e$.*

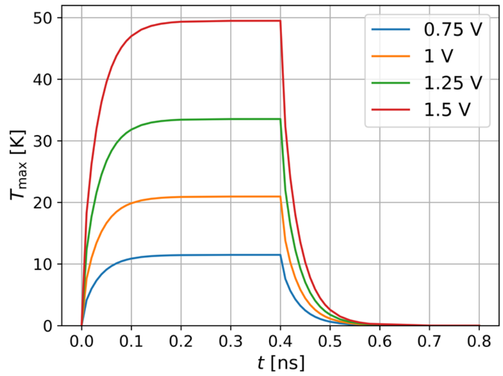


*Fig.4: Maximum temperature $T_{max}$ for different voltages U across the structure. Saturation of $T_{max}$ is observed at 200ps. At 400ps the voltage is turned off and cooling is observed.*

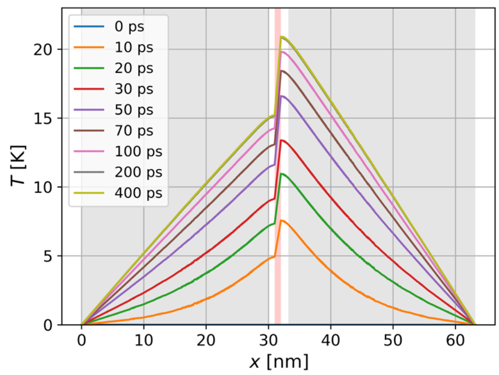


*Fig.2: Temperature increase in the structure due to a current from right to left. The asymmetry in hot-electron heating causes an asymmetry in the temperature profile. The temperature saturates after 200ps. The voltage across the structure is 1V.*

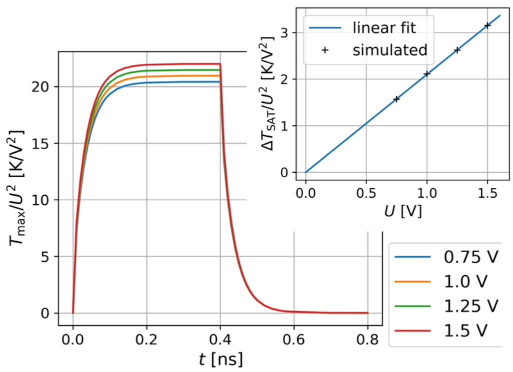


*Fig.5: Heating-cooling cycle for different voltages from Fig.4 normalized to $U^2$. Inset: $\Delta T_{SAT}$ as a function to the voltage U.*

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