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Magnetic oscillation of the transverse domain wall in a penta-layer MgO-MTJ

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Abstract. The switching probability of In-Plane penta-layer MTJs for different switching current densities and pulse durations is investigated by means of extensive micromagnetic simulations. We reveal a non-negligible probability of the formation of a vortex state/transverse domain wall during switching. Based on the current-induced transverse domain wall periodic motion a new type of magnetic nano-oscillator is proposed.

Introduction

Nowadays, new types of spintronics devices using spin-torque switching, such as spin-torque transfer RAM (magnetic random access memory using spin-torque switching for data writing) and spin-torque oscillators, have been intensely developed based on the large magneto-resistance ratio in MgO-MTJs (magnetic tunnel junctions using a MgO tunnel barrier) [1–3]. At the same time the research on new materials and architectures for MTJ structures has recently gained momentum.

1. Model description

The simulations of a penta-layer MTJ are based on the magnetization dynamics described by the Landau–Lifschitz–Gilbert (LLG) equation with additional spin torque terms [4]:

$$\frac{dm}{dt} = -\frac{\gamma}{1+\alpha^2}\ ((m \times h_{\mathrm{eff}}) + \alpha\ [m \times (m \times h_{\mathrm{eff}})]$$
$$+\frac{g\mu_{\mathrm{B}} j}{e\gamma M_s d}\ (g_1(\Theta_1)\ (\alpha\,(m \times p_1) - [m \times (m \times p_1)])$$
$$-\ g_2(\Theta_2)\ (\alpha\,(m \times p_2) - [m \times (m \times p_2)])))\ .$$

Here, $\gamma = 2.3245 \times 10^5$ m/(A s) is the gyromagnetic ratio, α is the Gilbert damping parameter, μ_{B} is Bohr's magneton, j is the current density, e is the electron charge, d is the thickness of the free layer, $m = M/M_s$ is the position dependent normalized vector of the magnetization in the free layer, $p_1 = M_{p1}/M_{sp1}$ and $p_2 = M_{p2}/M_{sp2}$ are the normalized magnetizations in the first and second pinned layers, respectively. M_s, M_{sp1}, and M_{sp2} are the saturation magnetizations of the free layer, the first pinned layer, and the second pinned layer, correspondingly. We use Slonczewski's expression for g in the MTJ with a dielectric layer [5]:

$$g(\Theta) = 0.5\,\eta\left[1 + \eta^2\ \cos(\Theta)\right]^{-1}\ .$$

The local effective field is calculated as:

$$h_{\mathrm{eff}} = h_{\mathrm{ext}} + h_{\mathrm{ani}} + h_{\mathrm{exch}} + h_{\mathrm{demag}} + h_{\mathrm{th}} + h_{\mathrm{amp}} + h_{\mathrm{ms}}\ .$$

Here, h_{ext} is the external field, h_{ani} is the magnetic anisotropy field, h_{exch} is the exchange field, h_{demag} is the demagnetizing field, h_{th} is the thermal field, h_{amp} is the Ampere field, and h_{ms} is the magnetostatic coupling between the pinned layers and the free layer. The model parameters are: $T = 300$ K, $M_s = M_{sp} = 8.9 \times 10^5$ A/m, the exchange constant $A = 1 \times 10^{-11}$ J/m, the crystalline anisotropy constant $K = 2 \times 10^3$ J/m^3, the Gilbert damping parameter $\alpha = 0.005$, and the spin polarization factor $\eta = 0.63$ [6].

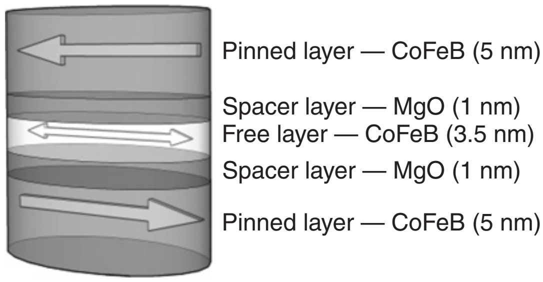

Fig. 1. Schematic illustration of a penta-layer MTJ.

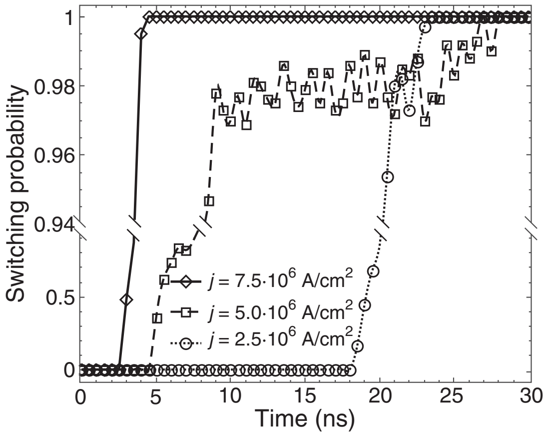

Fig. 2. Switching probability as a function of the pulse duration for three current densities. For switching probability estimation, 1000 simulations of switching were performed on each pulse width.

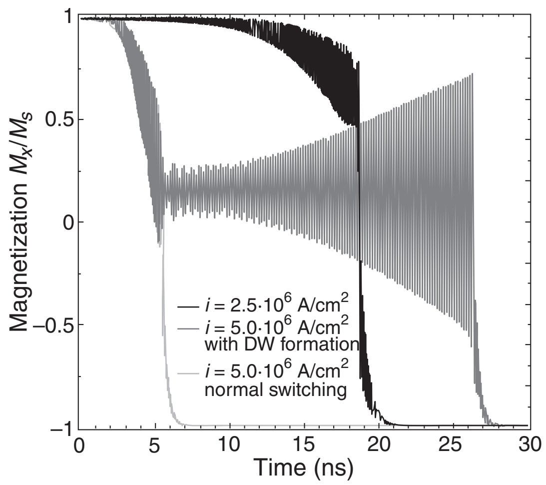

Fig. 3. Averaged magnetization component along the direction of the long axis as function of time.

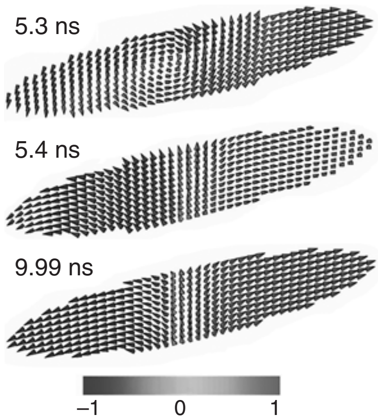

Fig. 4. Snapshots of the switching process for a penta-layer MTJ with transverse domain wall formation. The direction of the magnetization is shown by unit vectors, the color indicates the value of the component in direction of the long axis.

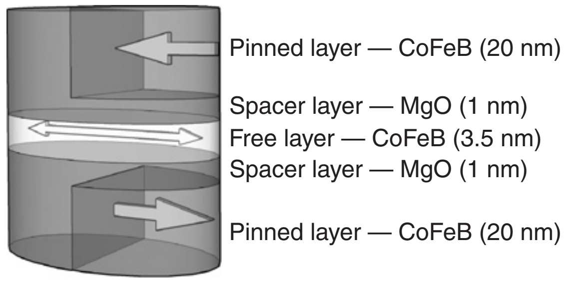

Fig. 5. Schematic illustration of a penta-layer MTJ with half-ellipsis pinned layers.

2. Results and discussion

First simulations were performed for a penta-layer nanopillar with an elliptical cross section 52.5×15 nm^2 (Fig. 1). We have investigated the dependence of the switching statistics on the current density and pulse duration (Fig. 2). For that purpose we have simulated 100 switching cycles under the current densities 2.5×10^6, 5×10^6, and 7.5×10^6 A/cm^2 and a time pulse 30 ns. We took the state of the system at the time intervals multiple of 0.5 ns, and for each of these states we computed 10 relaxation processes under the influence of temperature. This gave us 1000 simulation realizations of the switching process for each pulse duration (multiple of 0.5 ns) and for each of the three values of the current density for switching probability evaluation.

We found that the switching probability for the current density 5×10^6 A/cm^2 is equal to one if the pulse is longer than 26.5 ns. This pulse duration is longer than the respective value of 23 ns needed to achieve the ultimate switching at the current density 2.5×10^6 A/cm^2. Interestingly, for the current density 5×10^6 A/cm^2 and a pulse duration between 8 and 26.5 ns the switching probability is less than one and fluctuates. This is in striking contrast to earlier results, where an increasing pulse duration and current density always led to a switching probability increase [7]. To determine the reason for this discrepancy, we have considered the switching process in details (Figs. 3 and 4). We found that during some of the switching realizations at the current density 5×10^6 A/cm^2 a vortex is created (Fig. 4, 5.3 ns). The formation of the vortex state in films thicker than 3.2 nm is fully consistent with the results obtained previously for three-layer structures with a synthetic free layer [8]. The vortex transforms later into a transverse domain wall (Fig. 4, 5.4 ns). Thereafter the transverse wall starts oscillating around the center of the free layer with an increasing amplitude (Fig. 3), which leads to the increase of the switching time. We note that at a lower current density the domain wall is not formed and the switching proceeds normally.

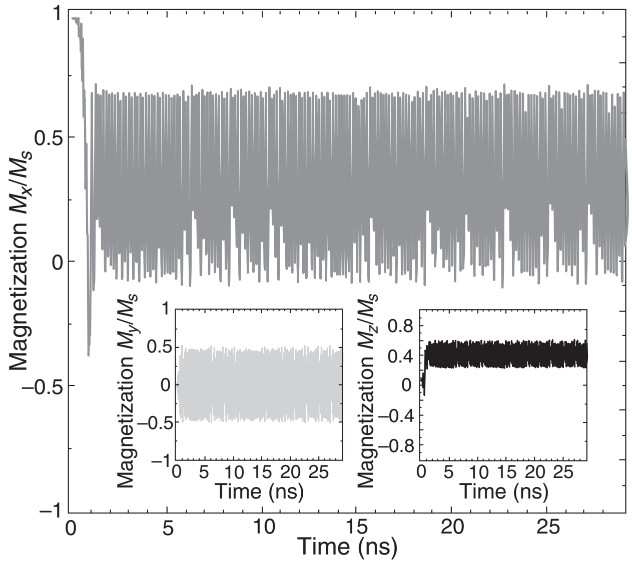

Fig. 6. Averaged magnetization along the long axis, along the short axis (inset left), and perpendicular to the free layer (inset right) as function of time.

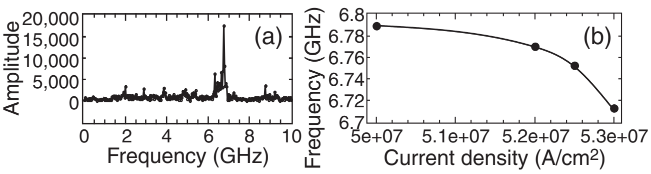

Fig. 7. Signal's Fourier transform for current density $j = 5 \times 10^6$ A/cm^2 (a). Frequency as function of current density (b).

We investigated a penta-layer MTJ structure with only half-ellipsis pinned layers (Fig. 5). Fig. 6 shows the switching process in such a structure in details. We found that the structure with half-ellipsis pinned layers, in contrast to the standard structure with the elliptic pinned layers, showed stable oscillations with nearly constant amplitude provided the domain wall was formed. The Fourier transform of the signal is sharply peaked around the frequency ∼6.785 GHz (Fig. 7). We note that the frequency of the oscillation only slightly depends on the current value frequency for current densities 5×10^6, 5.2×10^6, 5.25×10^6, and 5.3×10^6 A/cm^2, as shown in Fig. 7.

The proposed structure can be used to fabricate nano-oscillators based on oscillations of the transverse domain wall.

Acknowledgements

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