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Magnetization manipulation using ultra-short laser pulses in ferromagnetic cells for spintronics applications

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Introduction & Aim

- Magnetization reversal processes and magnetization dynamics in general are of utmost importance for many spintronics applications, e.g. bit patterned media [1]
- Such ultrafast dynamics can be measured by pump-probe experiments with pulsed lasers: a strong pump laser excites a sudden change of the magnetization vector leading to magnetization precession, measured by the weak probe laser
- To simulate this process, a model has been developed based on the micromagnetic simulator MagPar-LLB
- Using simulated ultra-short laser pulses, we investigated a matrix of separate ferromagnetic cylindrical cells to prototype possible memory applications
- FePt cells immersed in an MgO layer for adequate thermal conditions, heat-transport was solved by the two-temperature model
- Simulations were performed using the micromagnetic Landau-Lifshitz-Bloch (LLB) equation and the finite element method (FEM)
- Calculations were carried out for different distances between cells and a variety of laser pulse durations and intensities
- The results inform about stability conditions for magnetization states and the possible spatial density of such memory devices

Simulation

1. Stochastic LLB equation [2]:

$$\frac{1}{\gamma}\frac{d\vec{M}}{dt} = [\vec{M} \times \vec{H}_{eff}] + \frac{\alpha_1}{|\vec{M}|^2}(\vec{M} \cdot \vec{H}_{eff})\vec{M} - \frac{\alpha_2}{|\vec{M}|^2}[\vec{M} \times [\vec{M} \times (\vec{H}_{eff} + \vec{R})]] + \vec{R_t}$$

$\vec{M}$ magnetization, $\vec{H}_{eff}$ effective field, α_1, α_2 damping factors, γ gyromagnetic factor

$$\vec{R} = \sqrt{\frac{2k_B T_e(\alpha_1 - \alpha_2)}{\gamma \Delta t M_{s_0} V_s {\alpha_1}^2}}\vec{r}; \vec{r} = [r_x, r_y, r_z]; \vec{R_t} = \sqrt{\frac{2k_B T_e \alpha_2 M_{s_0}}{\gamma \Delta t V_s}}\vec{r_t}; \vec{r_t} = [r_x, r_y, r_z];$$

$$r_{x,y,z} = \sqrt{-2\log(x_1)}\sin(2\pi x_2);\ x_{1,2} \in rand(0,1)$$

k_B Boltzmann constant, $T_e = T_e(x,y,z,t)$ electron gas temp., M_{s_0} saturation magn., V_s stochastic vol., Δt integration step

2. Equilibrium magnetization M_{eq} equation [3]:

$$M_{eq}(\vec{r}, T) = n_{mb} g J \mu_B n B_J(x) = M_{s_0} B_J(x)$$

$$B_J(x) = \frac{2J+1}{2J} ctgh(\frac{2J+1}{2J}x) - \frac{1}{2J} ctgh(\frac{x}{2J})$$

$$\frac{dx}{dt} = -\left(\frac{3JT_c}{J+1}\right)\frac{dT_e}{dt}B_J(x)/(T_e^2 - \left(\frac{3JT_eT_c}{J+1}\right)\frac{dB_J(x)}{dx})$$

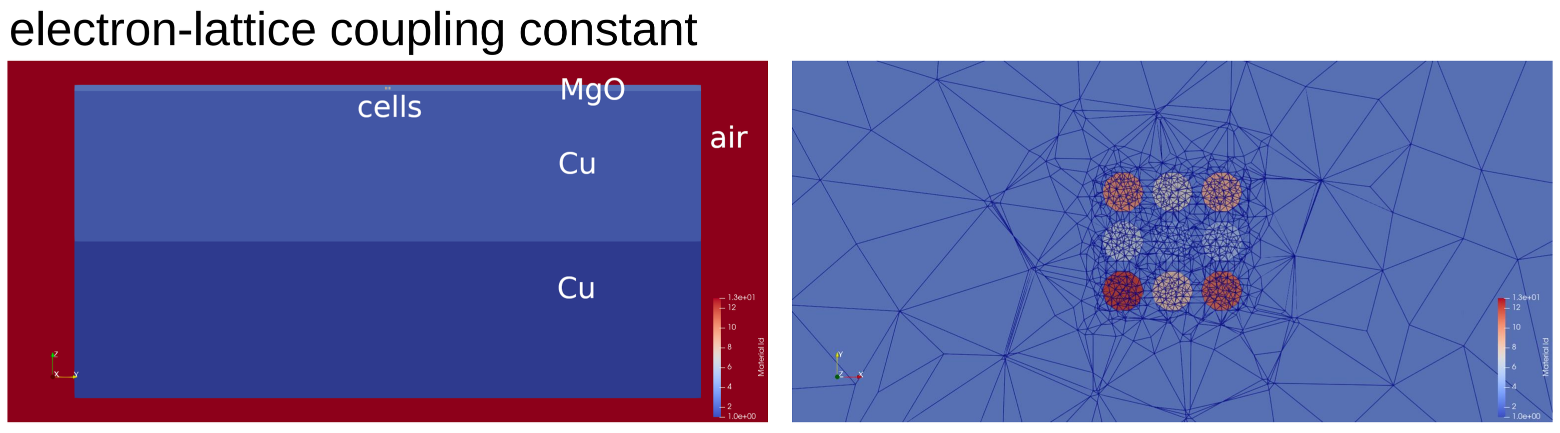
n_{mb} Bohr magneton number, g-factor, J quantum number, μ_B Bohr magneton, n particle concentration, B_J Brillouin function

3. Two temperature model [3]:

$$c_e \rho \frac{\partial T_e}{\partial t} = \lambda[\frac{\partial^2 T_e}{\partial x^2} + \frac{\partial^2 T_e}{\partial y^2} + \frac{\partial^2 T_e}{\partial z^2}] - G_e(T_e - T_l) + Q(x,y,z,t)$$

$$c_l \rho \frac{\partial T_l}{\partial t} = G_e(T_e - T_l)$$

$T_l = T_l(x,y,z,t)$ lattice temperature, Q heat density, c_e, c_l specific heat of electron gas and lattice, ρ material density, λ thermal conductivity, G_e electron-lattice coupling constant



Material parameters for FePt, air, Cu and MgO from the literature. Cells: 10 nm height, 2.5 nm radius, center distance 6 nm, temperature 300 K

Literature

[1] J.-G. Zhu, Y. Yan, Incoherent Magnetic Switching of $L1_0$ FePt Grains, IEEE Transactions on Magnetics 57, 3200809 (2021)

[2] R. F. L. Evans, D. Hinzke,U. Atxitia, U. Nowak,R. W. Chantrell, O. Chubykalo-Fesenko, Stochastic form of the Landau-Lifshitz-Bloch equation, Physical Review B 85, 014433 (2012)

[3] A.H. Morrish, The physical principles of magnetism (1965)

Results

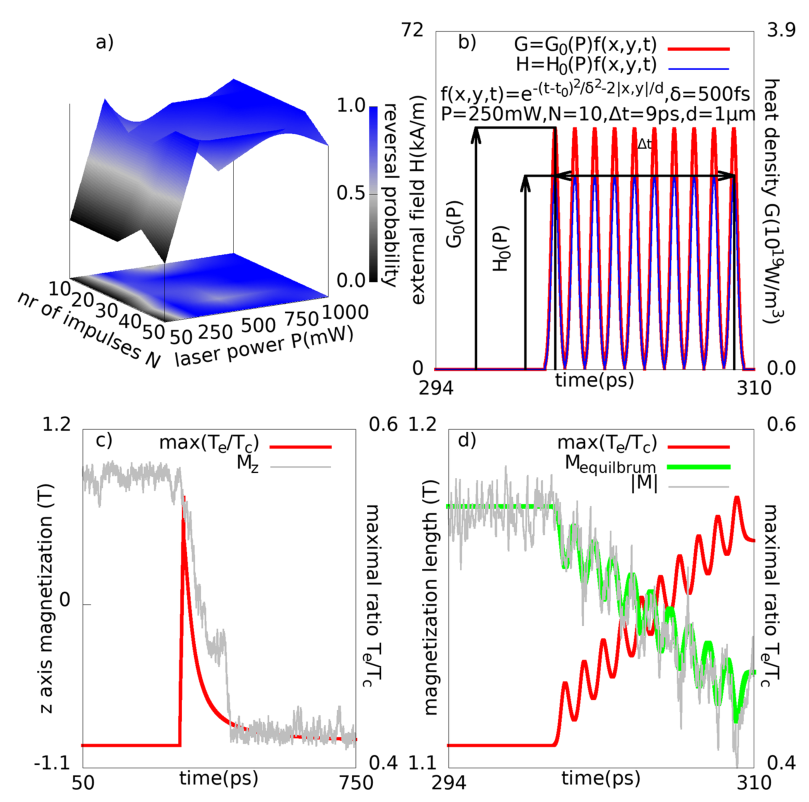


Fig. 1: (a) single cell reversal probability map, (b) laser impulse time-shape for P = 250 mW total power and N = 10 impulses; magnetization response (c) for the stimuli shown in (b) with magnetization reversal and (d) for N = 10 impulses (T_e/T_c is the ratio of electron gas temperature to Curie temperature)

→ Reversal – indicated blue (Fig. 1a) – is obtained for laser powers of around 250 mW and 10-50 pulses

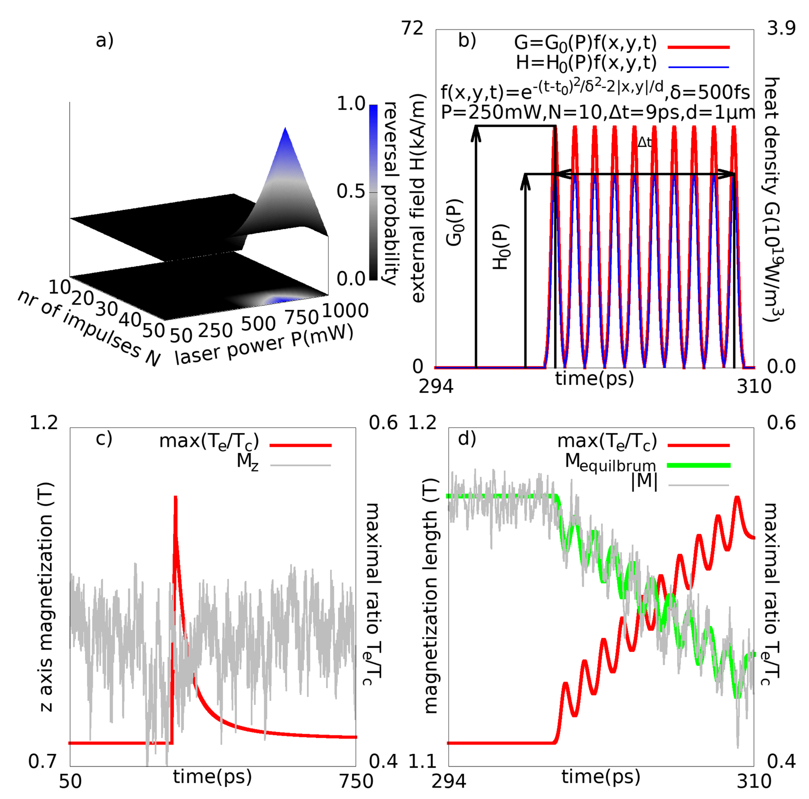


Fig. 2: (a) system of 9 cells reversal probability map, (b) laser impulse time-shape for P = 250 mW and N = 10 impulses; magnetization response (c) for the stimuli shown in (b) without reversal and (d) N = 10 impulses

→ Reversal (blue area in Fig. 2a) is only obtained for high enough laser powers and large enough numbers of impulses (here ~ 50 impulses, 750 mW laser power)

Conclusion

- Single separate short time laser impulse stimuli have no significant impact on single cell memory system
- A group of short time laser impulse stimuli may lead to reversal for nearly all examined laser impulse power cases
- For N = 10 impulses and a laser power P ≥ 0.2 W, it is possible to obtain proper reversal with high probability close to 1 (blue color in Fig. 1a), while more pulses and higher power are required for 9-cell system center cell (Fig. 2a)

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