Magnetization switching by ultrashort acoustic pulses

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Abstract

The knowledge of the fundamental limits of information transfer and data recording rates are crucial for the development of new ultrafast data recording technologies. However, there is a need to develop even faster data recording schemas operating in the terabit per second (Tbit/s) based on new physical principles. Here we study the possibility of ultrafast magnetization switching using THz acoustic pulses which have potential applications in future telecommunication and data recording technologies.

So far the magnetization switching has been demonstrated by applying pulses of magnetic field and spin-polarized current, and, in the most spectacular way, by single circularly polarized femtosecond laser pulses [1]. Trying to take advantage of the recently reported generation of giant ultrashort acoustic pulses in hybrid metal-ferromagnet structures [2,3] here we present a new concept for the magneto-acoustic switching in Terfenol-D [4].

This rear-earth-based compound is well suited for magneto-acoustic investigations due to the large value of magneto-elastic (magnetostrictive) coupling [5]. The realistic design of a hybrid magneto-acoustic multilayer sample is presented in Fig.1a. An opto-acoustic cobalt transducer excited through the substrate launches through the buffer layer of gold a giant ultrashort acoustic pulse, which is injected in a thin (110) layer of Terfenol-D. If the investigated Terfenol-D film is sufficiently thin and is covered by an acoustically matched dielectric layer, the action of the acoustic pulse can be adequately described by applying an ultrafast but spatially homogeneous time-dependent strain.

The dynamics of magnetization induced by an ultrashort acoustic strain pulse $\eta(t)$ can be described by the Landau-Lifshitz-Gilbert (LLG) equation

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{eff} - \frac{\alpha\gamma}{M_s}\left[\vec{M} \times \left(\vec{M} \times \vec{H}_{eff}\right)\right], \quad (1)$$

which describes the precession of the magnetization vector $\vec{M}$ around the effective magnetic field $\vec{H}_{eff} = -\frac{1}{\mu_0}\frac{dF}{d\vec{M}} + \vec{H}_{ext}$. In the absence of the external magnetic field $\vec{H}_{ext} = 0$ it is determined by the gradient $\frac{\mathrm{dF}}{\mathrm{d\vec{M}}}$ of free on free energy density F with respect to magnetization direction. The second term in Eq. (1) describes the damping of magnetization direction with Gilbert constant $\alpha = 0.1$. The phenomenological expression $F = F_k + F_{MEL} + F_d + F_Z$ for free energy density of Terfenol-D [5] is dominated by the competition of the magnetocrystalline anisotropy

$$F_k = K_1\left(\alpha_x{}^2\alpha_y{}^2 + \alpha_x{}^2\alpha_z{}^2 + \alpha_y{}^2\alpha_z{}^2\right) + K_2(\alpha_x{}^2\alpha_y{}^2\alpha_z{}^2) \quad (2)$$

and the magnetoelastic energy density

$$F_{MEL} = b_1\left(\alpha_x{}^2\varepsilon_{xx} + \alpha_y{}^2\varepsilon_{yy} + \alpha_z{}^2\varepsilon_{zz}\right) + b_2(\alpha_x\alpha_y\varepsilon_{xx} + \alpha_x\alpha_z\varepsilon_{xz} + \alpha_z\alpha_y\varepsilon_{zx}) \quad (3)$$

The explicit dependence of the magnetoelastic term on the components ε_{ij} of the strain tensor and the directional cosines α_i of the magnetization vector $\vec{M} = M_s(\alpha_x, \alpha_y, \alpha_z)$ suggests that the application of a time-dependent strain will modify the total free energy density and induce magnetization precession. Whereas for arbitrary acoustic pulses only numerical solutions can be obtained, an ultrashort acoustic pulse $\eta(t)$ with a duration significantly shorter than the precession period (about 25 ps in Terfenol-D) results in the 'out-of-plane kick' of the magnetization vector by an angle [4]

$$\Delta\theta_{ac} \cong \gamma\frac{(b_2 + 2b_1)}{2M_s}\alpha'_y\alpha'_z\int \eta\,(t)dt\,. \quad (4)$$

This kick angle appears to be proportional to the acoustic pulse area resembling similar phenomena in coherent optics. Numerical simulations show that sufficiently strong acoustic pulses can switch the magnetization vector back and force between two different metastable states 1 and 2 (Fig. 1b). The magneto-elastic phase diagram in Fig. 1c shows that depending on the acoustic pulse duration amplitude, switching is possible between all four metastable magnetization directions. Whereas at short pulse durations below 10 ps the switching strain is inversely proportional to pulse duration, for longer pulses it saturates and reaches the value of 0.3%. Therefore, according to our simulations the conditions for ultrafast magneto-elastic switching in Terfeno-D are experimentally accessible.

References

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Figures

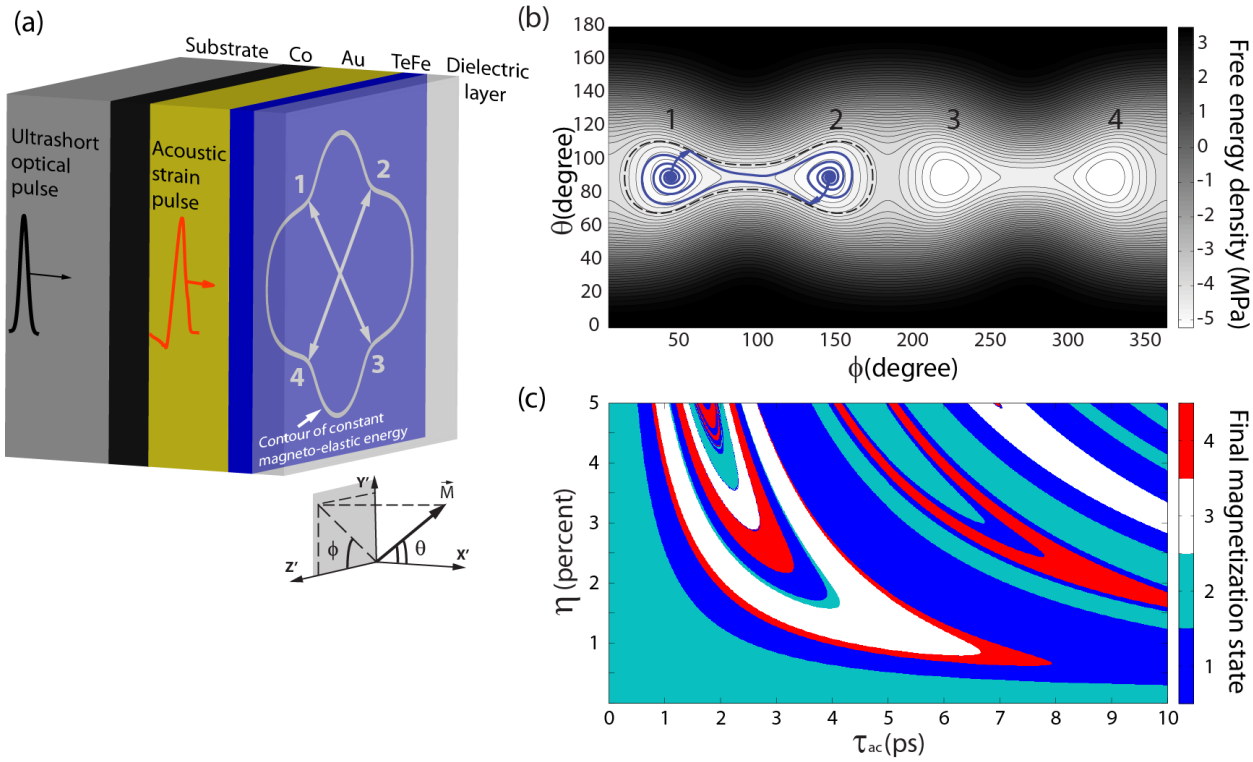

Fig.1: (a) Design of a multilayer structure for the acoustic magnetization switching. An opto-acoustic cobalt transducer is excited by an ultrashort optical pulse and generates a giant acoustic pulse with 1% amplitude and 4 ps duration (see Ref. [3] for details). An acoustic pulse propagates through the gold buffer layer and interacts with magnetization in Terfenol. (b) The magnetization vector in a thin (110) Terfenol film possesses four metastable in-plane magnetization directions: 1,2,3 and 4. An ultrashort tensile strain pulse with an amplitude of 0.9% and 3 ps duration 'kicks' the magnetization vector out of the sample plane, resulting into its precession and decay into another minimum (magnetization switching between energy minima 1 and 2 occurs). (c) Depending on the duration τ_{ac} and amplitude η of rectangular acoustic pulses, the magnetization can be switched between its all four metastable states. The initial magnetization state is 2.