

Magnetization switching without charge or spin currents

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We propose schemes of reversing the magnetization of a ferromagnet by electric fields alone, without charge or spin currents or external magnetic fields. The switching is triggered by picosecond manipulation of the atomic positions or subpicosecond distortion of the valence charge distribution, which through spin-orbit coupling modifies the magnetic anisotropy. We discuss how such time-even anisotropies can be used to switch the time-odd magnetization for in-plane and out-of-plane magnetization directions. In all cases the switching process is completely determined by the appropriately chosen orientation, magnitude, and temporal length of the electric field created by a voltage or photon pulse. © 2009 American Institute of Physics. [DOI: 10.1063/1.3081421]

Conventional switching of the magnetization of a ferromagnet (FM) between two opposite directions is initiated by the torque due to an applied magnetic field generated by current flow through wires. More recently, it has been demonstrated that in nanoscale magnetic cells the switching torque may also be generated by spin polarized currents.^{1,2} In the pursuit of smaller and faster switching devices, Ohmic heating has become a technological obstacle, and the demonstration of currentless reversal of the magnetization by an electric field \vec{E} has emerged as a challenge. Besides constituting an interesting scientific topic, \vec{E} -field induced switching may avoid energy dissipation by current flow and overcome impedance induced speed limitations in triggering the switching process. It may therefore extend switching speeds into the femtosecond regime. While it has been demonstrated that electric fields can influence the direction of magnetization,³⁻⁵ magnetization reversal has so far proven elusive. E -field effects may also play a role in “all-optical switching,”¹ where electromagnetic fields have been employed to reverse the magnetization.⁶

Similar to anisotropic ligand fields, which may create a preferred magnetic anisotropy axis in single crystal FMs, in principle, applied electric fields can also create a magnetic anisotropy axis. Once a dominant new anisotropy axis is created, the magnetization \vec{M} will move into the direction determined by its projection along the new axis by precession and damping. Such manipulation of the magnetization in response to an E -field modified anisotropy has been observed in $\text{Co}_{0.9}\text{Fe}_{0.1}$ exchange coupled to the AFM axis in multiferroic BiFeO_3 .⁴ Others observed some electric field modification of \vec{M} in a ferromagnetic semiconductor⁵ or at an electrolytic interface.³ In all cases the \vec{E} -field controlled rotation of \vec{M} was however limited to $\leq 90^\circ$ and does not correspond to the desired “switching” or magnetization reversal, i.e., a 180° rotation of \vec{M} . The key distinction between $\leq 90^\circ$ rotation and switching arises from the intrinsically incompatible symmetry properties of linear electric fields, which are

parity-odd and time-even, and the parity-even and time-odd properties of magnetic fields and angular momenta, the key vectors in magnetism.¹ Since the switched magnetic state corresponds to the time reversed original state, time-even \vec{E} -fields alone cannot create a switched state.

Here we propose a way out of this dilemma. Our concept is based on the use of an E -field pulse that in conjunction with the spin-orbit coupling and exchange interaction creates a transient new magnetic anisotropy axis and associated time-odd anisotropy field that triggers the switching process. In practice, the key time of the switching process is the “writing time” during which the magnetization is put into an excited state from which it deterministically decays into the reversed state. The writing time can be much shorter than the “switching time,” allowing the parallel processing of bits. Here we discuss the reversal of either the in-plane or out-of-plane magnetization and propose two schemes based on either picosecond voltage pulses or femtosecond photon pulses. In both cases the switching process is initiated and predetermined by the orientation, magnitude, and temporal length of the E -field writing pulse.

In principle, the application of an oriented and strong \vec{E} field can induce a charge anisotropy in a suitably chosen material. In a FM or AFM a charge anisotropy is felt by the atomic moments through the spin-orbit coupling, which turns the charge anisotropy into a magnetic anisotropy.¹ Because \vec{E} and the spin-orbit coupling (dot product of two time-odd vectors) are time-even, they can only define a magnetic axis, not direction. By symmetry, the \vec{E} -field induced magnetic easy axis can only be parallel or perpendicular to \vec{E} and does not depend on the sign of \vec{E} . In the following we shall assume for convenience that the anisotropy axis is induced parallel to \vec{E} . If a sufficiently strong magnetic anisotropy axis has been created, \vec{M} will align itself along the axis through precession and damping. The alignment direction is determined by the direction of the magnetic anisotropy field \vec{H}_E , which like a real magnetic field determines the motion of \vec{M} . The direction of the time-odd vector \vec{H}_E along the anisotropy axis depends on that of \vec{M} and changes sign when \vec{M} changes

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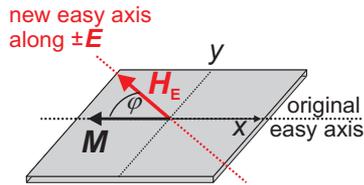


FIG. 1. (Color) Illustration of the concept of an \vec{E} -field induced anisotropy field \vec{H}_E for a uniaxial FM with an in-plane easy axis, as discussed in the text. Note that $\vec{H}_E=0$ for $\varphi=90^\circ$.

sign. It may be expressed by the general expression $\vec{H}_E = H_E^0(\hat{e} \cdot \hat{m})\hat{e}$, where \hat{e} and \hat{m} are unit vectors along \vec{E} and \vec{M} , respectively, and the maximum anisotropy field H_E^0 is related to the anisotropy energy density K_E by $H_E^0 = 2K_E/M$.

In Fig. 1, we illustrate the case of an uniaxial FM with magnetization \vec{M} , assuming an in-plane easy axis and an induced magnetic anisotropy axis parallel to \vec{E} .

Since $H_E = H_E^0 \cos \varphi$, the magnitude of \vec{H}_E decreases to zero as the angle φ between \vec{H}_E and \vec{M} is increased to 90° and per definition φ cannot exceed 90° . Therefore the relaxation of \vec{M} into the \vec{E} -field created anisotropy field can never switch the magnetization.

Instead, one may utilize “precessional” or “ballistic” switching of \vec{M} about \vec{H}_E , as with magnetic field pulses, which is the most economical method of magnetization reversal.¹ Conceptually, the simplest case of \vec{E} -field induced precessional switching is for a FM with a perpendicular out-of-plane easy axis and no in-plane anisotropy, as illustrated in Fig. 2. If we create a sufficiently strong anisotropy field \vec{H}_E at an angle θ from the out-of-plane easy axis and damping is weak, the torque $\vec{H}_E \times \vec{M} = H_E^0 M \cos \theta \sin \theta$ will cause \vec{M} to precess about \vec{H}_E . The torque is largest for $\theta=45^\circ$, and for $\theta > 45^\circ$, \vec{M} can cross the hard plane of the sample, as indicated by a red line. If the field pulse is then terminated, \vec{M} will spiral into the opposite easy direction as indicated by a green line in Fig. 2. In practice, this scheme requires delicate control of the length of the field pulse.

A more favorable case is that of a FM with an in-plane easy axis. This case, illustrated in Fig. 3, also utilizes precessional switching of \vec{M} about \vec{H}_E . The \vec{H}_E -field induced torque

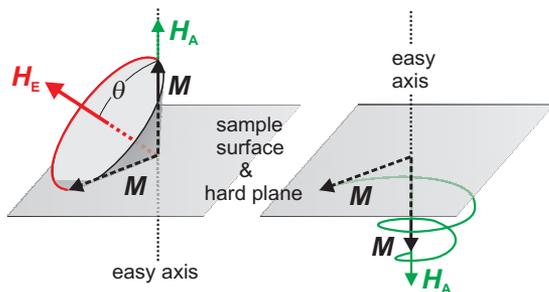


FIG. 2. (Color) Illustration of \vec{E} -field induced precessional switching of \vec{M} about \vec{H}_E (red path) for an uniaxial FM with out-of-plane easy axis and original orientation along \vec{H}_A , as shown. For $\theta > 45^\circ$, \vec{M} can precess below the hard plane and then switch by precessing and damping (green path) into the new anisotropy field \vec{H}_A . Note that for large angles $\theta \rightarrow 90^\circ$, the anisotropy field $H_E = H_E^0 \cos \theta \rightarrow 0$.

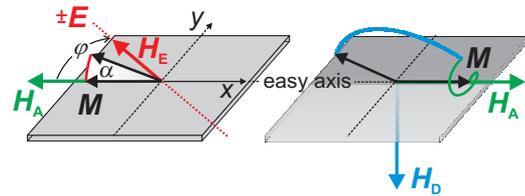


FIG. 3. (Color) Precessional switching process of \vec{M} induced by an electric field \vec{E} pulse. We have again assumed a uniaxial FM with an in-plane easy axis. The E -field induces a new anisotropy axis parallel to \vec{E} but independent of the sign of \vec{E} . The new anisotropy field \vec{H}_E lies along this axis with its direction defined by the projection of \vec{M} . The field \vec{H}_E exerts a torque on \vec{M} , rotating it out of the plane of the sample by an angle α . The torque is maximum for $\varphi=45^\circ$ and zero for $\varphi=90^\circ$ since $H_E=0$. Switching occurs when α exceeds a threshold given by Eq. (1).

$\vec{H}_E \times \vec{M} = H_E^0 M \cos \varphi \sin \varphi$ causes a motion of \vec{M} out of the plane by an angle α . The out-of-plane precession angle is obtained by use of the Larmor frequency ω as $\alpha = \omega \tau = (ge\mu_0/2m_e)H_E^0 \cos \varphi \sin \varphi \tau$, and the torque is largest for $\varphi=45^\circ$. The actual switching process, however, takes place after the field pulse and the induced anisotropy field H_E^0 have stopped, by precession of \vec{M} about the out-of-plane demagnetizing field of magnitude $H_D = -M \sin \alpha / \mu_0$. After \vec{M} has precessed about \vec{H}_D across the hard plane, which is perpendicular to x , the switching process concludes by damping into the new anisotropy field direction \vec{H}_A , as shown. The reverse switching process simply proceeds by a second identical field pulse.

In principle, the switching process in Fig. 3 is triggered and entirely predetermined by properly choosing the \vec{E} -field direction, magnitude, and pulse length, which is assumed to determine the transient anisotropy field \vec{H}_E . If we denote the ground state in-plane anisotropy energy density by $K_A = M H_A/2$ and the out-of-plane anisotropy energy density arising from the demagnetizing field by $K_D = M^2/2\mu_0$, the threshold condition for a switch is given by

$$(K_D + K_A) \sin^2 \alpha \geq K_A. \quad (1)$$

The energy density deposited during the field pulse, creating the out-of-plane motion of \vec{M} by α , has to overcome the in-plane uniaxial anisotropy energy density. For small α , $\varphi = 45^\circ$, and $g=2$, we obtain the switching condition

$$\mu_0 H_E^0 \tau \geq \frac{2m_e}{e} \sqrt{\frac{K_A}{K_D + K_A}} = \frac{2m_e}{e} \sqrt{\frac{\mu_0 H_A}{M + \mu_0 H_A}}. \quad (2)$$

For a practical in-plane anisotropy field of $\mu_0 H_A = 10$ mT ($H_A = 100$ Oe) and a magnetization of $M = 2$ T for CoFe alloys, the switching threshold corresponds to $\alpha \geq 4^\circ$ and $\mu_0 H_E^0 \tau \geq 0.80$ T ps so that switching would proceed, for example, if a ≈ 50 ps E -field pulse induces an anisotropy field $\mu_0 H_E^0 \approx 20$ mT. The created demagnetizing field $\mu_0 H_D = M \sin \alpha = 0.14$ T then rotates the magnetization across the hard plane in 129 ps before it spirals in a damped motion into the new anisotropy field direction \vec{H}_A , as shown in Fig. 3.

The question arises whether, in practice, electric fields can induce anisotropy fields H_E^0 in FMs that are large and fast enough to satisfy the switching condition (2). In conventional FMs and AFMs it is difficult to significantly change

the magnetic anisotropy by application of an E -field because of the small size of magnetoelastic effects. This has led to the exploration of multiferroics, which may exhibit a coupled electric and magnetic response.⁷⁻⁹ In general, such studies utilize an E -field to modify atomic positions in an electrically polarizable material, which is either also magnetic or is coupled to a magnetic material. For example, in multiferroic BiFeO₃, which is both ferroelectric and antiferromagnetic, the orientation of the AFM axis can be rotated by directional application of an \vec{E} -field.¹⁰ The magnetization in an exchange coupled FM then follows the rotation of the AFM axis.⁴ However, for BiFeO₃ the orthogonal and nontransient nature of the AFM axes prevented true magnetization reversal.

Overcoming this limitation requires the use of a multiferroic with two nonorthogonal AFM axes or a suitably engineered multicomponent system that is coupled to a FM and use of a bipolar field pulse. For example, in the ground state, the FM magnetization would be unidirectionally aligned by AFM-FM exchange coupling, arising from uncompensated interfacial spins¹ or biquadratic exchange¹¹ into a direction \vec{H}_A , as illustrated on the left side of Fig. 3. The first half cycle of the E -field pulse then creates the new AFM axis, which is rotated by $20^\circ \leq \varphi \leq 70^\circ$ from the original axis. This reorientation creates a transient new anisotropy axis and field \vec{H}_E in the FM, and \vec{M} responds by out-of-plane precession as in Fig. 3. If the pulse is too long, the magnetization will equilibrate into the new anisotropy field \vec{H}_E . This is avoided by use of a bipolar pulse, where in the second half cycle the AFM axis is reversed to the original direction. Thus during the $>90^\circ$ precession of \vec{M} about \vec{H}_D , the old anisotropy axis is re-established and the magnetization will damp into the opposite \vec{H}_A , as shown in Fig. 3. The pulse length needs to be several picoseconds, long enough that the lattice and spin-orbit anisotropies can establish themselves, yet shorter than the hundreds of picoseconds damping time of the magnetization into the field \vec{H}_E .

Another possible mechanism consists of the ultrafast electronic distortion of the valence charge in the atomic volume by a sufficiently strong E -field. Charge deformation can proceed on the femtosecond timescale of valence electron motion before the heavier nuclei and the attached core electrons respond. By application of a subpicosecond \vec{E} -field pulse with field strengths of order 1 V/nm, the charge distribution within the atomic volume due to the ligand fields may be modified since for such field strengths the second order Stark effect becomes comparable to or exceeds the first order Stark effect.¹² Since in high fields the valence charge distortion scales with E^2 , switching can be triggered by use of photon pulses. Suitable photon pulses have pulse lengths of <1 ps, frequencies of >1 THz,^{13,14} and power densities of $>10^{15}$ W/m². In full or multiple cycle pulses the \vec{H} -field

dependence averages to zero and switching proceeds entirely by the second order E -field. The optimum frequency in the far-infrared to visible range will depend on the material because one needs to avoid photon absorption that creates heat. The suggested mechanism also provides a novel all-optical switching mechanism using linearly rather than circularly polarized photons.⁶

Finally, we briefly comment on the energetics of \vec{H} -field and \vec{E} -field induced switching. To switch the magnetization, the minimum energy needed is given by the magnetic anisotropy energy density K_A . In practice, the intrinsic energy densities stored in the switching fields \vec{H} and \vec{E} , $\mu_0 H^2/2$ and $\epsilon_0 E^2/2$, need to exceed K_A because they have to compensate for losses resulting in undesired heating. H -field related losses in conventional switching are dominated by Ohmic heating in the coils during H -field generation. In E -field switching, losses arise mainly from photon absorption when using electromagnetic wave excitation and from dielectric displacement currents when applying voltage pulses across insulators. The quantitative comparison of losses is complicated by the fact that they depend on the material, geometry, excitation method, and pulse length. The important question of energy dissipation can only be answered after experimental demonstration of E -field induced switching.

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