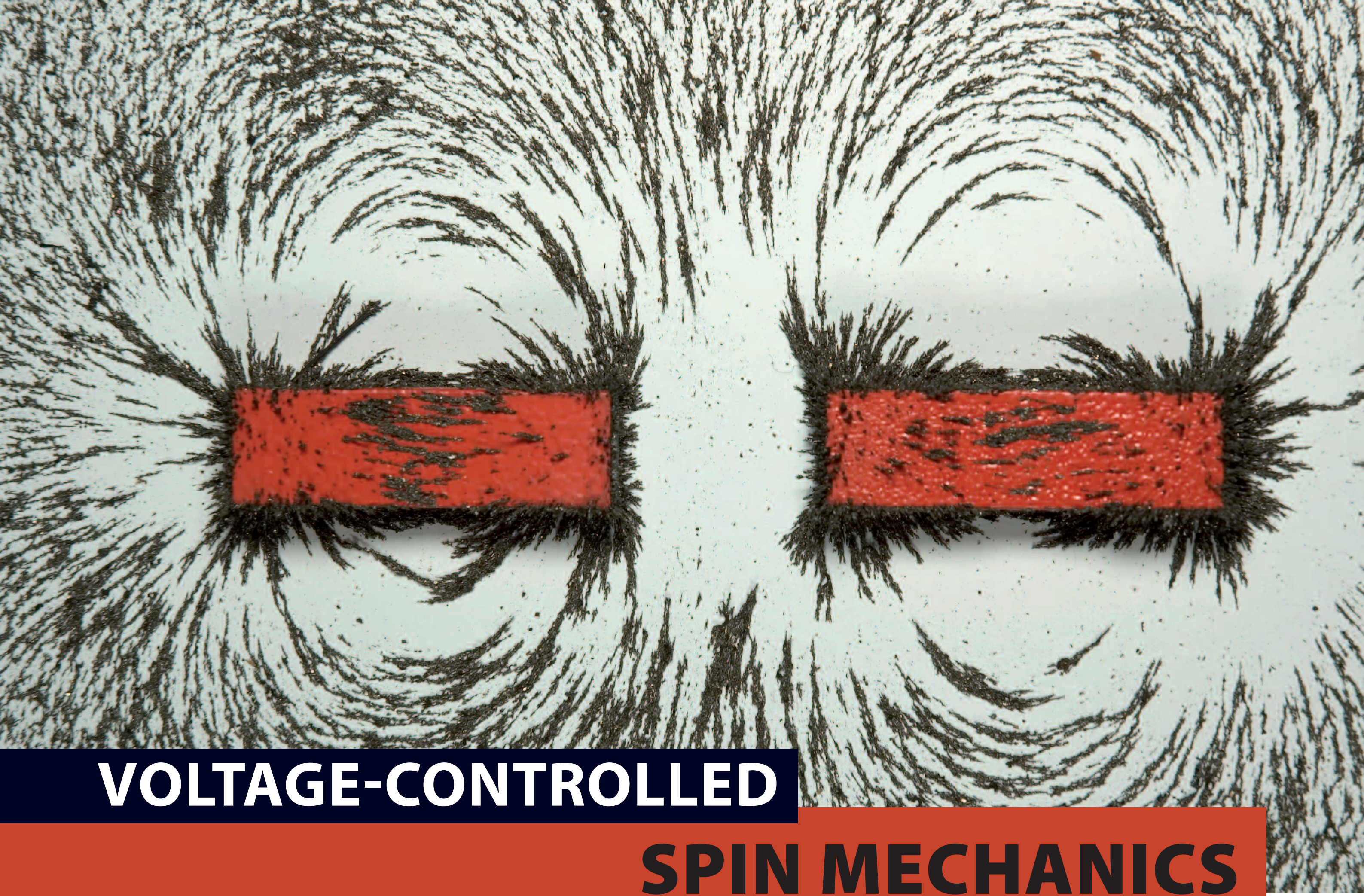

VOLTAGE-CONTROLLED SPIN MECHANICS

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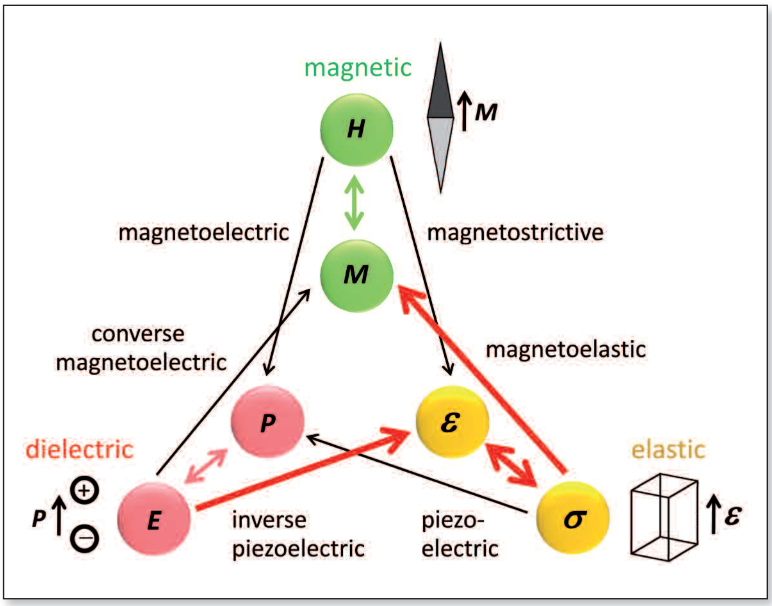
The magnetization of a ferromagnet is usually controlled by means of a magnetic field. In contrast, an electric-field control of magnetization becomes possible in multifunctional ferromagnetic-ferroelectric hybrid structures. The "spin mechanics" scheme discussed here takes advantage of the elastic channel to establish a continuous, reversible, electric-field control of magnetization orientation by up to 90°.

▲ Magnetic field demonstration with iron filings. © iStockPhoto

Ferromagnetic materials and devices are exploited in a variety of application fields today, *e.g.*, in magnetic bearings, magnetic actuators, magnetic sensors, or in magnetic data storage devices. Many of these applications require a control of the magnetic properties *in situ*. Since the orientation of the magnetization vector **M** often plays a key role, schemes enabling a *control of the magnetization orientation* are of particular relevance [1]. For example, in computer hard disk drives, the information is stored in magnetic bits – *i.e.*, in regions on the magnetic disk with a well defined **M** orientation. Thus, writing information onto the hard disk is tantamount to (locally) changing **M** in a controlled fashion.

Magnetization Orientation Control Schemes

Several qualitatively different magnetization orientation control schemes are established today. The most natural scheme relies on the magnetic field **H** as the control parameter. Indeed, **M** and **H** are conjugate variables in thermodynamics [2], and the ubiquitous magnetization hysteresis loop **M**(**H**) (see Fig. 3(b)) directly shows that the magnetization orientation can be inverted using an appropriate magnetic field. A very elegant magnetization orientation control scheme relies on the so-called spin torque effect, in which a spin-polarized electric current is exploited to change **M** [3]. This mechanism is particularly efficient in magnetic nanostructures, while in larger devices the Oersted magnetic field produced by the current flow dominates. Last but not least, novel magnetization control schemes are enabled in multifunctional materials [4]. The functionality hereby arises from the combined action of several, distinctively different material properties, as illustrated in Fig. 1 [5]. For example, an electric-field control of magnetization orientation, **M**(**E**), becomes possible if a finite magnetoelectric effect couples the magnetic and the dielectric properties of a given device.



▲ **FIG. 1: The interaction between magnetic, dielectric and elastic degrees of freedom yields novel functionalities. An example is an electric-field (E) control of the magnetization orientation (M) [5]. This can either be achieved by exploiting the converse magnetoelectric effect (lower left black arrow), or by a combination of the inverse piezoelectric and the magnetoelastic effect (red arrows). The symbols H and M are magnetic field and magnetization, respectively; E and P are electric field and polarization; and σ and ε are applied stress and elongation or strain.**

A substantial such magnetoelectric coupling can be expected in materials which are simultaneously ferromagnetic and ferroelectric, *i.e.* in magnetoelectric multiferroics [5]. In spite of vivid research activities, however, single phase magnetoelectric multiferroics still are scarce. An attractive and powerful alternative platform are composite materials, in which an electric-field control of magnetic properties indeed is possible [6,7,8,9,10,11]. Such composites are composed of a ferromagnetic constituent, which shares at least one interface with a ferroelectric (or piezoelectric) material. As the composites are multi-phase by design, they do not qualify as multiferroics in the strict sense. In the following, we therefore rather use the term ferromagnetic-ferroelectric hybrids for such artificial, multifunctional heterostructures.

Ferromagnetic-Ferroelectric Hybrids

In ferromagnetic-ferroelectric hybrids, a direct control of magnetic properties via electric fields has been demonstrated [9]. However, this approach is limited by the electric screening length in ferromagnetic metals, which restricts the interaction to a narrow region (a few nanometers at best) at the ferromagnetic-ferroelectric interface. In comparison, the elasto-mechanical interaction between the ferromagnetic and ferroelectric constituents is of much longer range. Such an *electrically controlled spin mechanics scheme* exploits the inverse piezoelectric effect in combination with magnetoelastic coupling (inverse magnetostriction), as indicated by the red arrows in Fig. 1 [6,11]. In the following, we highlight the fundamental properties and the opportunities of the spin mechanics concept.

The Spin Mechanics Scheme

Figure 2 schematically shows a ferromagnetic-ferroelectric hybrid sample for electrically controlled spin mechanics. The ferromagnetic constituent (green ellipse) is mechanically connected to the ferroelectric constituent (orange square). In the hybrid sample concept, this connection can be realized via various techniques, *e.g.*, by growing an epitaxial ferromagnetic film onto the ferroelectric [6,7], by evaporating the ferromagnet onto the ferroelectric [11], or by cementing the two constituents together [10]. The only fabrication requirement is to achieve an efficient strain transfer from the ferroelectric into the ferromagnetic constituent.

The basic idea behind the spin mechanics scheme is the following: Upon the application of a voltage V_p, the ferroelectric will deform because of the inverse piezoelectric effect. The corresponding elastic strain is not restricted to the ferroelectric, but spreads across the hybrid sample. In other words, in an appropriate ferromagnetic-ferroelectric hybrid, the inverse piezoelectric effect in the ferro*electric* allows to establish a voltage-controllable elastic strain in the ferro*magnet*. This strain then influences the magnetization orientation because of the magnetoelastic effect. Taken together, the spin mechanics scheme thus enables a control of the magnetization orientation via the application of an electrical voltage. It is important to emphasize that the (uniaxial) strain in the ferromagnet can be continuously tuned *in situ*, from tensile to compressive, solely by changing the magnitude and the sign of V_p. This process is schematically illustrated Figs. in 2(a) and (b). A positive voltage V_p results in an elongation of the ferroelectric along the vertical (y) direction, which deforms the ferromagnet's initial circular shape into an prolate ellipsoid. In contrast, negative V_p yields an oblate ellipsoid, with a corresponding reorientation of the magnetization vector due to magnetoelastic coupling.

To quantify the impact of the elastic strain onto the magnetic properties, we use the concept of the magnetic free enthalpy *F*, *i.e.* the appropriate thermodynamic potential [2]. According to the principle of energy minimization, the magnetization vector will point along a direction corresponding to a (local) minimum of *F*. Thus, in a Stoner-Wohlfarth type of approach, it is possible to calculate the evolution of the magnetization orientation as a function of a given control parameter, by tracking the evolution of the minima of *F*. Figure 2(c) shows how the free enthalpy changes as a function of the magnitude and the sign of V_p. The $F(\Theta, V_p)$ curves were calculated with the free enthalpy parameters experimentally determined in a Ni thin film-piezoelectric actuator hybrid sample [11], see Fig. 3(a). Because the thickness of the ferromagnetic film is several orders of magnitude smaller than its lateral dimensions, strong demagnetizing fields constrain **M** to the film plane. The angle Θ between **M** and the **y** direction thus suffices to quantify the magnetization orientation in the film plane. As evident from Fig. 2(c), for large, negative voltages V_p, the global minimum of F is at $\Theta = 0°$. **M** thus points along **y**, as schematically indicated by the red arrow in Fig. 2(b). Upon increasing V_p the free enthalpy minimum gradually shifts towards larger Θ values, and approaches $\Theta = 90°$ for large, positive V_p. The magnetization thus rotates to the right (see Fig. 2(a)). In summary, the magnetic free enthalpy picture thus suggests that a continuous, fully reversible, electric voltage control of the magnetization orientation by up to 90° should be possible within the spin mechanics scheme.

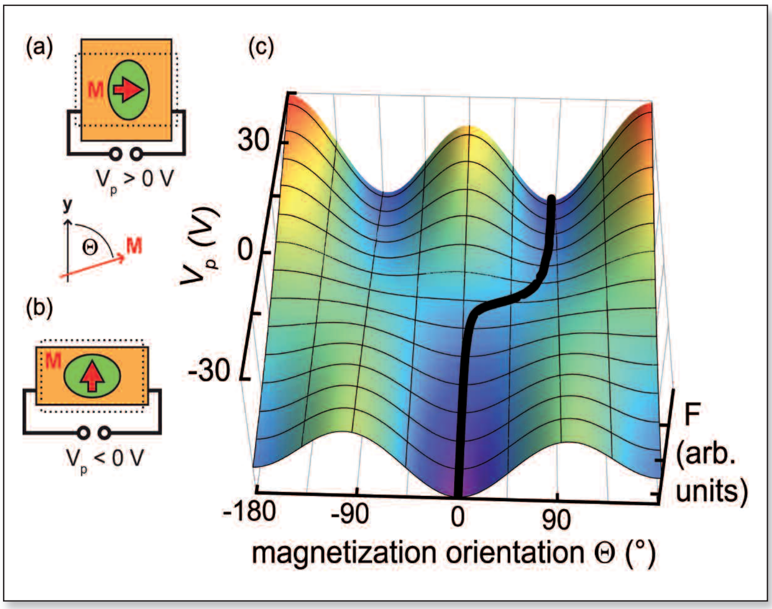
Voltage Control of Magnetization Orientation

Figure 3 demonstrates the voltage control of magnetization orientation in a real spin mechanics hybrid. The ferromagnetic-ferroelectric hybrid sample used in these experiments consists of a 70 nm thick ferromagnetic nickel disk, evaporated onto a commercially available piezoelectric actuator (Fig. 3(a)) [11]. The piezoelectric actuator in fact is made of a fine grained ferroelectric ceramic, which exhibits a strong inverse piezoelectric response, and thus yields reproducible, voltage-controllable elastic strains. Figure 3(b) shows a conventional $M(H)$ magnetization hysteresis loop (full grey line) of the hybrid sample, recorded at room temperature with $V_p = -30$ V applied to the actuator. For the spin mechanics experiments, the Ni film first is magnetized into a single domain state by applying a large positive magnetic field. Then, the magnetic field strength is reduced to zero (point A in Fig. 3(b)), and kept constant throughout the following, voltage dependent measurements. As evident from Fig. 3(c), a substantial voltage control of magnetization is possible. Starting from the large positive magnetization value at point A, M decreases and nearly vanishes with increasingly positive V_p (point B). Upon decreasing V_p back to negative values, M recovers to its initial large value (*cf.* point A). The hysteresis in $M(V_p)$ can be quantitatively traced back to the hysteretic expansion and contraction of the actuator. Note also that the experimental data shown in Figure 3(c) correspond to several, consecutive voltage cycles. The $M(V_p)$ evolution thus is reversible and fully reproducible. For comparison, the $M(V_p)$ loop calculated from the free enthalpy landscape (see Fig. 2(c)) is also included as a full line in Fig. 3(c). Considering that the entire 2 mm diameter nickel disk is treated as one single magnetic domain in the Stoner-Wohlfarth calculation, the agreement between experiment and simulation is fully satisfactory.

Taken together, the magnetometry data presented in Fig. 3 exemplarily demonstrate that in ferromagnetic-ferroelectric hybrids, the magnetization orientation can be continuously rotated back and forth within a range of approximately 90°, simply by applying an appropriate electric voltage V_p. Indeed, one can show that the *reversible* voltage control of magnetization orientation is limited to a range of ≤90° in the spin mechanics scheme, given that the external magnetic field strength is kept constant (zero) [10,11]. Furthermore, if the magnetization is prepared into a metastable initial state (a local minimum of F) via a dedicated magnetic field sweep, a one-shot, voltage-controlled, 180° magnetization reversal is possible. Voltage controlled spin mechanics thus is a viable pathway for the electric field control of magnetization orientation. The scheme is fully operational at room temperature, and in technologically relevant ferromagnets.

The **spin mechanics scheme** enables a **control** of the **magnetization orientation** via the application of an **electrical voltage**

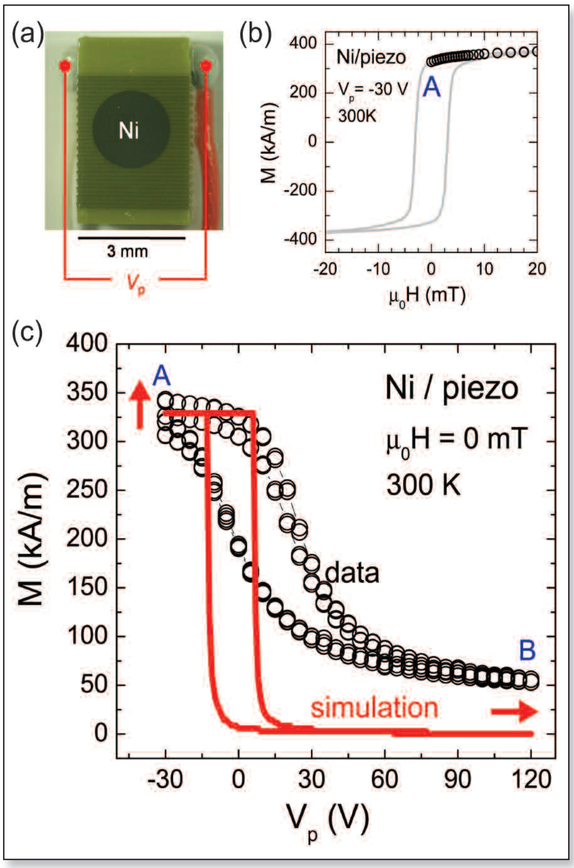
▼ **FIG. 2: (a), (b) Sketch of the ferromagnetic-ferroelectric hybrid samples for spin mechanics. Depending on the polarity of the voltage V_p applied, the ferroelectric (orange) expands (panel (a)) or contracts (panel (b)) along the y direction. This induces an elastic strain in the ferromagnet (green) affixed to the ferroelectric, and thus enables a voltage control of magnetization orientation. The red arrows show the magnetization vector M for the two strain states. The elastic deformations are greatly exaggerated for clarity. (c) The magnetic free enthalpy F of a nickel thin film-piezoelectric actuator hybrid [11] changes as a function of the voltage V_p. The full black line traces the global minimum of F; Θ is the orientation of M in the ferromagnetic film plane with respect to y. Note also that for the sake of simplicity, the free enthalpy was calculated for a constant, small magnetic field $\mu_0 H = 1$ mT, oriented at 10° to y within the magnetic film plane. This ensures a single, unambiguous, global minimum in F for any given V_p.**



Requirements for Voltage-Controlled Spin Mechanics

To achieve a large-angle voltage control of magnetization in spin mechanics devices, several requirements must be met. (i) Voltage-controllable elastic strains of sufficient magnitude must be generated in the ferromagnetic film. This implies that the ferroelectric "stressor" layer dominates the elastic properties of the hybrid. One possibility to fulfill this requirement is to integrate a ferromagnetic film with a ferroelectric which is at least one order of magnitude thicker (cf. Fig. 3). A promising alternative are micro-electro-mechanical systems (MEMS) incorporating a ferromagnet. (ii) Only ferromagnets with finite (large) magnetostriction qualify for the use in spin mechanics hybrids. (iii) The magnetoelastic contribution to the free enthalpy must be dominant in a given plane of interest – an important constraint in particular for spin mechanics hybrids made from single crystalline ferromagnets [10].

▼FIG. 3: (a) Micrograph of a Ni thin film-piezoelectric actuator hybrid sample [11]. (b) Conventional *M*(*H*) loop of the hybrid sample. After the application of a large positive magnetic field, the Ni film is in a well defined magnetic state at $\mu_0H = 0$ mT (point A). (c) The magnetization of the spin mechanics hybrid substantially changes as a function of the electrical voltage applied (open symbols). The *M*(V_p) evolution is reversible and reproducible. The full red line depicts *M*(V_p) calculated from the magnetic free enthalpy in a Stoner-Wohlfarth approach. The red arrows schematically show the magnetization vector at points A and B, respectively.



Outlook

With the concept of voltage controlled spin mechanics established, many questions related to both basic research and to applications still remain to be answered. One important research direction deals with the electrical generation and/or control of magnetic texture, *e.g.* using an array of micro- or nanopatterned electrodes to generate position-dependent elastic strain, which then in turn yields a position-dependent magnetization orientation. The properties and the control of ferro*electric* domain patterns and their impact on the *magnetic* texture in epitaxial ferromagnetic-ferroelectric hybrid structures is one important challenge in this regard. Another important step is to transfer the spin mechanics concept from DC to high frequencies. Using magnetic MEMs or acoustic waves to generate high frequency elastic strain fields, magnetoelastically driven spin dynamics up to GHz frequencies can be investigated. This enables the study of ferromagnetic resonance phenomea, such as the interaction between spin wave modes and high-frequency elastic modes. ■

About the Author

Sebastian T.B. Goennenwein is working on multifunctional materials, (hybrid) magnetic nanostructures, and spin dynamics. After a PhD from Technische Universität München (D) and a post-doc at the Kavli Institute of NanoScience in Delft (NL), he now is a research scientist at the Bavarian Academy of Sciences (D).

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