Special issue on voltage control of nanomagnetism

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~~Preface on a~~ Special issue on Voltage Control of Nanomagnetism

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Electric field is easier to localize than magnetic field and is non-power-dissipating in contrast to electric current. Therefore, using an electric voltage to control magnetism enables developing low-power, on-chip magnetic devices for a wide variety of potential applications such as data storage, non-von Neumann computing, and cell manipulation. Voltage control of magnetism has commonly been demonstrated in ~~a~~ magnetoelectric heterostructures that ~~integrates~~ comprise a magnetic thin film and ~~or nanostructure with~~ a dielectric layer. Depending on the functional responses of the dielectric to applied voltage, voltage control of magnetism can be achieved through a number of routes, mediated by strain, charge, exchange bias, or redox reaction. This special issue covers the latest computational and experimental developments in the field of voltage control of magnetism, with a strong focus on the nanoscale phenomena. These works ~~outline~~ evidence ~~at least~~ four ~~opportunities~~ key research objectives which show great promise both ~~for continued discovery~~ for novel ~~of~~ fundamental science and ~~creation of~~ new technology concepts.

Precise control of ferroelectric domain switching. Strain-mediated voltage control of magnetism is achieved in heterostructures where the dielectric layer is a ferroelectric material that transmits sizeable strains (produced by ferroelectric domain switching) to an overlying magnetic film~~First, opportunities can arise from a precise control of ferroelectric domain switching (when the dielectric layer is also ferroelectric) and thereby the magnetization switching in the overlaying magnet~~. Ferroelectrics can display complex polarization domain patterns and kinetic switching paths as voltage is applied. This ~~complexity can induce~~can result in complex strain distributions which in turn complicate the magnetic switching. In this special issue, Pati and Taniyama [1] reported the coexistence of hysteresis-like and butterfly-like behaviors in the magnetization vs. voltage curves measured using Kerr microscopy in a $(La,Sr)MnO_3$ film on a ferroelectric lead magnesium niobate-lead titanate (PMN-PT) single crystal. This mixed feature is attributed to the coexisting 71°, 109°, and 180° ferroelectric domain switching in the rhombohedral PMN-PT. A thorough understanding of how local polarization switching influences local magnetization switching requires *in situ* imaging of both ferroelectric and magnetic domains in 3D and even 4D (time) ~~under zero magnetic field~~, which is ~~still~~ under active research.

Voltage control of topologically non-trivial spin textures (vortices and skyrmions). ~~Second, opportunities can arise from voltage control of spin texture.~~ Compared to voltage-controlled switching of average magnetization, voltage control of spin textures, including both topologically

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Commentato [MG1]: I think it would look better with a reference for each of these items…or if not possible we should make it clear they are possibilities..

Commentato [JH2R1]: I checked the earlier published prefaces in JPhysD. I found that they only cite papers published on JPhysD, not from other journals. For example,

https://doi.org/10.1088/1361-6463/aaf9d5
https://doi.org/10.1088/1361-6463/aa8d41

Commentato [MG3]: Is this really a "or"? The next sentence only discusses one case-"dielectric", making the reader think that this "or" should be an "and", implying that to achieve VCM we always need a magnetic film and some sort of dielectruc. Do I understand correctly?

Commentato [MG4]: Here as well we could cite a key paper for each.

Commentato [JH5R4]: Shall we check with the JPhysD whether citing papers in the prefaces are ok?

I think citing only 1 paper for each mechanism is likely not enough, but citing too many papers here won't look good for a preface article either?

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Commentato [MG6]: I think it is a good idea to group papers along 4 key points. However, the strcture as it is is perhaps not very readable as the paragraphs are long, and usually the use of "First" etc, works well on short paragraphs. How about writing the titles for each section.

Commentato [MG7]: The title reflects the papers discussed.

Commentato [JH8R7]: The section titles look great!

ha formattato: Tipo di carattere: Corsivo trivial (e.g., domain walls) and nontrivial (e.g., vortices, skyrmions) ones, is less explored. In this special issue, Ghidini *et al*. [2] used photoemission electron microscopy to simultaneously image the ferroelectric domains at the surface of a $BaTiO_3$ single crystal and the magnetic vortices in micrometer-sized Ni disks as DC voltage is applied to $BaTiO_3$. By varying the in-plane sample orientation, they were able to construct high-spatial-resolution vector maps of local magnetization at zero magnetic field under different voltages. The vector maps show the displacement of magnetic vortex cores driven by the voltage. The translation of vortex core is attributed to the change in the asymmetric strain distribution caused by the motion of 90° ferroelectric domain walls at the $BaTiO_3$ surface. This interpretation is corroborated by the authors' own micromagnetic simulations, and consistent with the micromagnetic modeling by Azaceta *et al*.[3] investigating the effect of strain gradient symmetry on vortex core translation.

Magnetic skyrmions, which typically have a topological charge number Q of ±1 (c.f., $Q=\pm0.5$ for vortices), have been intensively studied since the late 2000s. However, research into voltage control of magnetic skyrmions has not appeared until recently. Using micromagnetic simulations, Mehmood *et al*. [4] investigated strain-induced transition between magnetic skyrmion and other topological spin textures in the Pt/Co/Ir trilayer nanodisk through the modification of magnetoelastic anisotropy. Strain may also modify the strength of the interfacial Dzyaloshinskii-Moriya interaction (DMI) which is critical for stabilizing Néel-type skyrmions. The effects of strain-induced change in DMI on the thermodynamic stability and switching kinetics of the skyrmion deserve further study. Moreover, Rushforth *et al*. [5] propose a promising method to drive the motion of different types of topological spin textures including skyrmions. Combining micromagnetic and finite-element modeling, they predicted that sequential strain pulses from a piezoelectric layer can drive a deterministic motion of domain wall in an overlaying magnetic nanowire. Another promising method to drive the motion of skyrmions is to apply surface acoustic waves (SAWs). Notably, when the SAWs frequency is near the ferromagnetic resonance (FMR) frequency of the magnet, the resonant magnon-phonon coupling may facilitate the skyrmion manipulation. The physical principles of SAWs-driven excitation of FMR are reviewed by Puebla *et al*. [6]. Strain is, of course, not the only means for controlling skyrmions. In this special issue, Gu *et al*. [7] experimentally demonstrated a charge-mediated voltage control of the topological Hall effect (a fingerprint of DMI) in ultrathin $SrRuO_3$ films grown on (001)$SrTiO_3$ substrate. The authors' first-principle calculations reveal the presence of DMI at the $SrRuO_3/SrTiO_3$ interface where the titled RuO_6 octahedra breaks the inversion symmetry. This work suggests opportunities for realizing voltage control of DMI and hence the skyrmions in all-oxide heterostructures.

Voltage control of phase transitions and chemical reactions in a magnetic film. FeRh alloys display competing ground states of ferromagnetic (FM) and antiferromagnetic (AFM) structural phases. Upon cooling, AFM phase nucleates and grows from the parent FM phase, and the volume fractions of both phases vary continuously. Since such a phase transition is extremely sensitive to strain, it is possible to exploit voltage-induced strains from a piezoelectric substrate for *in situ* tuning the microstructure of a FeRh thin film and the associated magnetic properties. Fina and Fontcuberta [8] reviewed the achievements along this direction. In parallel, Nichterwitz *et al*. [9] demonstrated the possibility to control the direction of the redox reaction between a paramagnetic FeOOH and ferromagnetic Fe through the voltage-modulation of OH^- concentration in alkaline aqueous electrolytes. Such ON/OFF switching of magnetization by liquid electrolyte gating offers new opportunities for the applications of magneto-electronic devices.

Exploiting dipolar interactions for voltage control of nanomagnetism. Zhou *et al*.[10] considered two coupled CoFeB nanoislands grown on a (001) PMN-PT ferroelectric substrate. Using phase-field simulations, they demonstrated that the dipolar interaction assists a voltage-induced full 180° switching in each nanoisland, an event which is fundamentally challenging to achieve because voltage does not break the time-reversal symmetry. Nomura *et al*.[11] considered an array of single-domain nanomagnets coupled via dipolar interactions. Using micromagnetic simulations, they demonstrated that the array can be exploited for realizing reservoir computing: the magnetization of each nanomagnet represents a node state of the reservoir, which can be updated through voltage-induced magnetization switching. Finally, Chen *et al*. [12] explored a different downstream task of voltage-induced magnetization switching in nanomagnets, by modeling how the associated change in magnetic stray field drives the motion of an adjacent magnetic nano-bead. This scheme is potentially useful for biological applications such as cell manipulation.

Commentato [MG9]: Do we mean virtually impossible for fundamental reasons?

Commentato [JH10R9]: I made some changes.

Looking ahead, we expect the field of voltage control of magnetism will continue to grow and that the research objectives outlined in this special issue will attract considerable interest. Moreover, we expect exciting science from the intertwining of voltage control of magnetism with the latest developments in other fields, such as two-dimensional ferroic materials, neuromorphic spintronics, nano-bio interfaces, and beyond.

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