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Spintronics

Switching with ions

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Solid-state hydrogen gating of a ferrimagnetic metal enables independent reversal of Néel and magnetization vectors by electric field.

The use of spin-based phenomena is of great appeal for reliable information storage and computing as it enables non-volatile memory with high endurance, embedded memory, i.e., memory-in-logic, as well as neuromorphic and quantum computing strategies. Traditionally, spin-based devices employ ferromagnets that have a single magnetic lattice and a macroscopic magnetization. Recently, systems with two magnetic sublattices oriented opposite to one another such as antiferromagnets or ferrimagnets have become of interest due to their robustness to magnetic field and speed of operation [[1]]. Yet, the manipulation of their magnetic order is challenging. In this issue of *Nature Nanotechnology*, Mantao Huang et al. employ solid-state hydrogen gating to show deterministic reversal of Néel and magnetization vectors in the ferrimagnet GdCo under ambient conditions.

The order parameter determines the state of a magnetic device: the macroscopic magnetization vector M characterizes ferromagnets and the Néel vector $N=M_{sublattice1}-M_{sublattice2}$ antiferromagnets, which possess two oppositely oriented magnetic sublattices. Ferrimagnets hold a third type of magnetic ordering. The two magnetic sublattices $M_{sublattice1}$ and $M_{sublattice2}$ do not fully compensate each other such that the material possesses both a magnetization and a Néel vector (Fig. 1). Interestingly, the two magnetic sublattices can have differing sublattice exchange energies and ordering temperatures. The control of one of the sublattices' magnetization direction and magnitude holds the key to an alternative type of magnetization reversal. Seminal time-resolved studies in the prototypical ferrimagnetic GdFeCo alloys revealed timescale differences in magnetization dynamics of individual sublattices upon ultrafast demagnetization triggered by optical pulses [2]. From this difference, a transient ferromagnetic order emerges and determines the direction of the dominating magnetic sublattice as the system cools down, leading to an all-optical control of magnetization.

Huang et al. now establish a new mechanism to realize this deterministic reversal of magnetization, and more, in a ferrimagnetic system (GdCo) under ambient conditions. Instead of using dynamical differences in Gd or Co magnetization sublattices, they employ electrochemistry and solid-state hydrogen gating to modify the magnetic exchange interaction. Thereby, the researchers control the magnitude of the Gd moments. The explored heterostructure consists of a Au gate electrode, a GdO_x layer acting as proton injector, and a perpendicularly magnetized amorphous GdCo ferrimagnetic layer. The layers are grown by magnetron sputtering on various substrates, demonstrating scalable processing and integration with the silicon oxide platform. The application of a gate voltage can reversibly tune the Gd moments from being larger to being smaller than the Co moments, the total magnetization from Gd dominated to Co dominated in the ferrimagnetic layer.

Solid state ionic gating, i.e., the induction of ionic migration in a solid under the application of an electric field, is an exciting tool to manipulate magnetic order. It can control the oxidation state at an interface, or in a ferromagnetic layer, and the associated electric field can manipulate the magnetic anisotropy [3,4]. The researchers now expand the applications to purely electric-field-induced reversal of magnetization for maximum ON/OFF contrast in spintronic devices. They observe that the Gd and Co moments respond differently upon hydrogen loading in GdCo. Element specific X-ray circular magnetic dichroism (XCMD) unveils that hydrogenation barely affects the Co moments while the Gd moments show a pronounced decrease. Remarkably, the process is fully reversible and allows for a selection of the dominant magnetic sublattice and an independent inversion of Néel and magnetization vectors. Hydrogen gating in an external magnetic field, or in the stray field from an underlying magnetic layer ─ both can pin the direction of magnetization ─ toggles between the dominant magnetic sublattice, Gd or Co, and inverts the Néel vector, as sketched in Fig 1b. Alternatively, the coupling to an adjacent antiferromagnetic layer, such as NiO, fixes the orientation of the sublattices and hydrogen gating then inverts the relative sizes of the Gd and Co moments leading to a reversal of the magnetization vector, see Fig. 1c.

Prior to this study, deterministic voltage induced local reversal of magnetic order in absence of an external magnetic field has relied on multistage switching processes [5], on precisely timed voltage pulses [6], or on materials which possess concomitant breaking of time reversal and of inversion symmetries, so called multiferroics, with a specific intrinsic coupling between electric polarization and magnetic ordering [7]. In the latter, the coupling between the applied electric field and the material's magnetic order is weak or relegated to low temperatures and most often occurs in antiferromagnetic insulators. In contrast, the observations made by Huang et al. demonstrate robust magnetization and Néel vector switching in a metal at room temperature. A single gate voltage suffices for control and the synthesis and integration of the material system are relatively simple. Strikingly, the independent control of the orientation of the two vectors brings new possibilities for disparate, reconfigurable, and multimodal magnetoelectronics.

With the advent of topological and quantum materials, the area of voltage-controlled magnetism sees significant efforts in the creation of magnetic textures with complex topologies using electric fields. Such magnetic textures present opportunities to alter the paradigm of computing. For instance, there are proposals to employ magnetic textures with non-trivial topologies, such as skyrmions for quantum computing [8,9]. Nanoscale skyrmions can be created at will, are stable, and can be efficiently propagated. For technological implementation, however, the ability to write these textures locally only by means of a gate voltage is of importance. In the present work, the authors make this leap to quantum with the integration of the magnetoionic write element developed earlier in the study into a magnetic racetrack-like structure. They demonstrate the creation and propagation of domain walls and skyrmion bubbles in a ferrimagnet. While many questions remain, the present work sets the stage for hybridized magnetoionic quantum devices.

In principle, the gate voltage and time dependence of hydrogenation can provide plasticity - the continuous change of a remanent property in response to an external stimulus - of the magnetic response. Plasticity is a key ingredient for neuromorphic computing type applications.

This work demonstrates the analog, i.e., continuous tunability brought by magneotionics with the gating pulse profile, but important aspects such as the identification of the available magnetic states beyond the binary frame, state retention, temperature dependent parasitic diffusion, and possible size limitations are not yet explored. Furthermore, while the present study focuses on amorphous GdCo layers, one may wonder if crystallinity in the magnetic component could add an extra degrees of freedom. For instance, single crystalline ferrimagnetic insulators are promising materials for spintronics with low damping and exceptional magneto-dynamics [[10]] and the anisotropic ionic conduction in crystalline lattices could offer additional functionalities from solid state ionic gating.

Conflict of interests

The authors declare no competing interests.

Figure caption

Reversal of a net magnetization and Néel vector in a ferrimagnet using solid state ionic gating. a, Schematic illustration of the Gd and Co magnetic sublattices in ferrimagnetic GdCo. The net magnetization M is given by $M_{Co} + M_{Gd}$. The Neel vector N is defined as M_{Co}-M_{Gd}. Gating the system triggers the hydrogenation of the GdCo layer. b, In presence of an external magnetic field, or in the stray field from an underlying magnetic layer, the gate voltage leads to the inversion of N. c, In contrast, pinning the sublattice configuration (N fixed) using an adjacent anitferromatically ordered layer during gating allows for a reversal of the net magnetization M.

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