**Spintronics**

**Electrical switching of an antiferromagnet**

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Antiferromagnets are hard to control by external magnetic fields because of the alternating directions of magnetic moments on individual atoms and the resulting zero net magnetization. However, relativistic quantum mechanics allows for generating current-induced internal fields whose sign alternates with the periodicity of the antiferromagnetic lattice. Using these fields, which couple strongly to the antiferromagnetic order, we demonstrate room-temperature electrical switching between stable configurations in antiferromagnetic CuMnAs thin-film devices by applied current with magnitudes of order $10^6$ ampere per square centimeter.

Electrical writing is combined in our solid-state memory with electrical readout and the stored magnetic state is insensitive to and produces no external magnetic field perturbations, which illustrates the unique merits of antiferromagnets for spintronics.

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**Fig. 1. Theory of the staggered current-induced field in CuMnAs.** (A) Schematic of the inverse spin-galvanic effect in a model inversion asymmetric Rashba spin texture (red arrows). $k_{xy}$ are the in-plane momentum components. The nonequilibrium redistribution of carriers from the left side to the right side of the Fermi surface results in a net in-plane spin polarization (thick red arrow) along $+z \times J$ direction, where $J$ is the applied current (black arrow). (B) Same as (A) for opposite sense of the inversion asymmetry, resulting in a net in-plane spin polarization (thick purple arrow) along $-z \times J$ direction. (C) CuMnAs crystal structure and AFM ordering. The two Mn spin-sublattices A and B (red and purple) are inversion partners. This and panels A and B imply opposite sign of the respective local current–induced spin polarizations, $\rho_A = -\rho_B$, at spin sublattices A and B. The full CuMnAs crystal is centrosymmetric around the interstitial position highlighted by the green ball. (D) Microscopic calculations of the components of the spin-orbit field transverse to the magnetic moments per current density $10^7$ A cm$^{-2}$ at spin sublattices A and B as a function of the magnetic moment angle $\phi$ measured from the x axis ([100] crystal direction). The electrical current is applied along the x and y axes.

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from a fixed FM polarizer by out-of-plane electrical current driven in a FM-AFM stack. However, relativistic spin-orbit coupling may offer staggered current-induced fields, which do not require external polarizers and which act in bare AFM crystals (19). The effect occurs in AFMs with specific crystal and magnetic structures for which the spin sublattices form space-inversion partners. Among these materials is a high-\(N\)éel temperature AFM, tetragonal-phase CuMnAs, which was recently synthesized in the form of single-crystal epi-layers on III-V semiconductor substrates (20).

Relativistic current-induced fields observed previously in broken inversion-symmetry FM crystals (21–29) can originate from the inverse spin-galvanic effect (30–34) (Fig. 1, A and B). The full lattice of the CuMnAs crystal (Fig. 1C) has an inversion symmetry with the center of inversion at an interstitial position (green ball in the figure). This implies that the mechanism described in Fig. 1, A and B, will not generate a net current-induced spin density when integrated over the entire crystal. However, Mn atoms form two sublattices (depicted in Fig. 1C in red and purple) whose local environment has broken inversion symmetry, and the two Mn sublattices form inversion partners. The inverse spin-galvanic mechanisms of Fig. 1, A and B, will generate locally nonequilibrium spin polarizations of opposite signs on the inversion-partner Mn sublattices. For these staggered fields to couple strongly to the AFM order, it is essential that the inversion-partner Mn sublattices coincide with the two spin sublattices A and B of the AFM ground state (19). The resulting spin-orbit torques have the form \(d\mathbf{M}_{A,B}/dt \sim \mathbf{M}_{A,B} \times \mathbf{P}_{A,B}\), where the effective field proportional to \(p_A = -p_B\) acting on the spin-sublattice magnetizations \(\mathbf{M}_{A,B}\) alternates in sign between the two sublattices. The CuMnAs crystal and magnetic structures (Fig. 1C) fulfill these symmetry requirements (20).

To quantitatively estimate the strength of the staggered current-induced field, we performed microscopic calculations based on the Kubo linear response formalism (35) (see supplementary text for details). The calculations (Fig. 1D) confirm the desired opposite sign of the current-induced field on the two spin sublattices and highlight the expected dependence on the magnetic moment angle, which implies that the AFM moments will tend to align perpendicular to the applied current. For reversible electrical switching between two stable states and the subsequent electrical detection by the AMR, the setting current pulses can therefore be applied along two orthogonal in-plane cubic axes of CuMnAs. The magnitude of the effect seen in Fig. 1D is comparable to that of typical current-induced fields applied in FMs, suggesting that CuMnAs is a favorable material for observing current-induced switching in an AFM.

Our experiments were conducted on epitaxial films of the tetragonal phase of CuMnAs, which is a member of a broad family of high-temperature I-Mn-V AFM compounds (6, 7, 20). We have observed the electrical switching and readout

**Fig. 2. Electrical switching of the AFM CuMnAs.** (A) Scanning transmission electron microscopy image of CuMnAs/GaP in the [100]–[001] plane. (B) Magnetization versus applied field of an unpatterned piece of the CuMnAs/GaP wafer measured by SQUID magnetometer. (C) XMLD-PEEM image of the CuMnAs film with x-rays at the Mn L3 absorption edge incident at 16° from the surface along the [001] axis. (D) Optical microscopy image of the device and schematic of the measurement geometry. (E) Change in the transverse resistance after applying three successive 50-\(\)ms writing pulses of amplitude \(J_{\text{write}} = 4 \times 10^{6}\) \(\text{A} \cdot \text{cm}^{-2}\) alternately along the [100] crystal direction of CuMnAs (black arrow in panel D and black points in panel E) and along the [010] axis (red arrow in panel D and red points in panel E). The reading current \(J_{\text{read}}\) is applied along the [\(\text{T}10\)] axis, and transverse resistance signals \(R_{\perp}\) are recorded 10 s after each writing pulse. A constant offset is subtracted from \(R_{\perp}\). Measurements were done at a sample temperature of 273 K.

**Fig. 3. Dependence of the switching on the writing pulse length and amplitude.** Transverse resistance after successive writing pulses along the [100] axis (black points) and [010] axis (red points) for different current amplitudes (A) or pulse lengths (B). \(R_{\perp}\) is recorded 10 s after each writing pulse. \(R_{\parallel}\) is the average of the longitudinal resistance \(R\). Measurements were done at sample temperature of 273 K. A constant offset is subtracted from \(R_{\perp}\).
effects described below in more than 20 devices fabricated from five different CuMnAs films, with thicknesses ranging from 40 to 80 nm, grown on either GaP or GaAs substrates. The electrical data shown in Figs. 2 to 4 were obtained on a 46-nm epilayer on lattice-matched GaP(001), whose transmission electron microscopy image (Fig. 2A) demonstrates excellent structural and chemical order (20). Consistent with the AFM order of the CuMnAs film, superconducting quantum interference device (SQUID) magnetometry measurements (Fig. 2B) show only the diamagnetic background of the sample substrate. X-ray magnetic linear dichroism–photoelectron emission microscopy (XMLD-PEEM) measurements (Fig. 2C) were used to reverse magnetization in a Pt/Co bilayer (29).

In Fig. 3, A and B, we explore in more detail the domain reconfiguration by applying a series of 50 \( J_{\text{write}} \) pulses of varying length and amplitude along the [010] direction (red points) and [100] direction (black points) at 273 K. The data, which again show highly reproducible switching patterns, illustrate that the imbalance in the domain populations increases with the length and amplitude of the writing pulses and tends to saturate with the increasing number of pulses. Because in these measurements, heating of the central region of the device can reach tens of degrees during the writing pulses, we did not explore the switching behavior further beyond the pulse lengths and amplitudes shown in Fig. 3, A and B. More intense pulses in our device design can lead to irreproducible characteristics or device failure due to structural changes. Apart from the absolute \( R_j \) values, we also indicate in Fig. 3, A and B, relative values \( R_j / R \) of the signal, where \( R \) is the longitudinal resistance \( R \) averaged over the different states set by the writing pulses along the [100]/[010] directions. Below we will associate \( R_j / R \), reaching 0.2%, with the transverse AFM AMR. Further confirmation of the picture of the current-induced domain reconfiguration by the applied writing pulses is given by XMLD-PEEM measurements and XMLD spectroscopy (see figs. S1 and S2 and supplementary text.)

We now analyze the symmetry of the measured resistances for different probe current directions. Figure 4 shows switching data for both the transverse resistance signal and the longitudinal signal, \( \Delta R / R \), where \( \Delta R = R - \overline{R} \), obtained at the sample temperature of 150 K. In these lower-temperature experiments, we applied five successive 275-ms pulses of amplitude \( J_{\text{write}} = 4.5 \times 10^8 \text{ A cm}^{-2} \) along the [100] or [010] axis to obtain signals comparable to the higher-temperature measurements. Each row in Fig. 4 corresponds to a different axis along which we probe the current \( J_{\text{read}} \). From top to bottom, the reading current is applied along the crystal axis [1\( \overline{1} \)0], [110], [100], and [010].

Consistent with the AMR symmetry, the transverse signals (also known as the planar Hall effect) are detected for the AFM spin axes angle set toward \( \pm 45^\circ \) from the probe current, and the transverse signal flips sign when the probe current is rotated by 90\(^\circ\). The corresponding longitudinal signals vanish in this geometry. For AFM spin axes set toward \( \pm 90^\circ \) from the probe current, the transverse signal vanishes and the longitudinal signal is detected, which is again consistent with the AMR symmetries. The AMR nature of the electrical signals is further confirmed by the comparative amplitudes of the transverse and longitudinal signals. We note that apart from the stable AMR signals, the longitudinal resistances show an additional time dependence, which is due to the cooling of the sample after the writing
ICE SHEETS

Holocene deceleration of the Greenland Ice Sheet

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Recent peripheral thinning of the Greenland Ice Sheet is partly offset by interior thickening and is overprinted on its poorly constrained Holocene evolution. On the basis of the ice sheet’s radiostratigraphy, ice flow in its interior is slower now than the average speed over the past nine millennia. Generally higher Holocene accumulation rates relative to modern estimates can only partially explain this millennial-scale deceleration. The ice sheet’s dynamic response to the decreasing proportion of softer ice from the last glacial period and the deglacial collapse of the ice bridge across Nares Strait also contributed to this pattern. Thus, recent interior thickening of the Greenland Ice Sheet is partly an ongoing dynamic response to the last deglaciation that is large enough to affect interpretation of its mass balance from altimetry.

The dynamics of the Greenland Ice Sheet (GrIS) are coupled intimately with the surrounding ocean (1), overlying atmosphere (2), and underlying lithosphere (3). The large range of time scales spanned by these interactions and the GrIS’s own internal dynamics (4) challenge our ability to predict GrIS evolution within the context of ongoing Holocene climate change (5, 6).

Despite a rapidly warming climate (6), recent dramatic changes in ocean-terminating outlet glaciers along the margin of the GrIS (7–9), its vulnerability to further oceanic erosion (10), and a sustained negative total mass balance (11–13), more than half of the GrIS interior is presently thickening (8, 14–16), and a portion of its southwestern margin is decelerating (17). Climate histories reconstructed from ice cores show that the GrIS persisted even when atmospheric temperatures were higher by several degrees Celsius (18) and insolation forcing was larger than at present (19). Reconciling these observations is critical to

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