Electrical switching of antiferromagnetic CoO across the Néel temperature

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One of the most important challenges in antiferromagnetic spintronics is the read-out of the Néel vector state. High current densities up to $10^8 \text{ A cm}^{-2}$ used in the electrical switching experiments cause notorious difficulty in distinguishing between magnetic and thermal origins of the electrical signals. To overcome this problem, we present a temperature dependence study of the transverse resistance changes in the switching experiment with CoO | Pt devices. We demonstrate the possibility to extract a pattern of spin Hall magnetoresistance for current pulses density of $5 \times 10^7 \text{ A cm}^{-2}$ that is present only below the Néel temperature and does not follow a trend expected for thermal effects. This is the compelling evidence for the magnetic origin of the signal, which is observed using purely electrical techniques. We confirm these findings by complementary experiments in an external magnetic field. Such an approach can allow determining the optimal conditions for switching antiferromagnets and be very valuable when no imaging techniques can be applied to verify the origin of the electrical signal.

Intensive interest in electrical manipulation of antiferromagnetism is caused by their potential appealing applications such as efficient and magnetic-field-robust data storage or long-range spin transport. The electrical current can be used to control the spin axis of antiferromagnets. Numerous physical mechanisms can be responsible for that process. Experimental studies of antiferromagnetic oxides demonstrate the dominating role of the thermomagnetoelastic effect, in which magnetic reorientation is driven by thermally induced strain. In principle, the reorientation of the Néel vector (n) can be probed by either anisotropic magnetoresistance (AMR) or spin Hall magnetoresistance (SMR), the effects relying on resistivity dependence on the angle between n and current density or spin accumulation, respectively. However, a notorious difficulty in electrical probing is the presence of non-magnetic thermal effects such as inhomogeneous heating or electromigration that can contribute to the measured resistance changes. It creates the need to use imaging techniques to provide an unambiguous proof of magnetic reorientation and show the correspondence between the electrical signals and the domains reorientation. Unfortunately, magnetic imaging techniques often exhibit complexity and surface sensitivity which limits their practical application in antiferromagnetic devices.

However, any electrical signal pattern of magnetic origin, that is resulting from the reorientation of antiferromagnetic spins, should be present only in magnetically ordered antiferromagnetic phase unlike non-magnetic thermal effects, that

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To realize the experimental goal, 8 arm cross devices (Fig. 1) were prepared by e-beam lithography and ion milling from CoO thin-films of 5 nm thickness. They were grown by reactive DC magnetron sputtering at 430 °C on MgO (001) single crystals with Pt top layer of 5 nm thickness that has been deposited at room temperature. The LEED pattern proves a good crystalline quality and XPS shows a spectrum typical for CoO. We adopt the value of $T_N = 272 \pm 5$ K that was determined by the point in which the spin-flop transition disappears in the temperature-dependent spin Hall magnetoresistance studies of analogous CoO | Pt samples. Therefore, an experiment performed in the temperature range $T \in [240 \text{K}, 305 \text{K}]$ will cover both interesting regimes: below and
above the $T_N$ as well as in the vicinity of the critical point.

The electrical switching experiment consists of two parts. During the pulsing, a sequence of high-density current pulses $J$ is applied. Each pulse has a length of 3 ms. At $T = 240 \, \text{K}$, each sequence consists of 5 pulses of 3 ms, separated by 5 seconds; at higher temperatures each sequence consists of a single pulse. The pulses are expected to cause a reorientation of the Néel vector $n$. The pulses are applied along two orthogonal axes, [110] or [1T0] (Fig. 1), which are the magnetic easy directions that are preferred by spins. During the probing, transverse resistance is measured with a small current magnitude (0.25 mA, corresponding to current density of $0.6 \, \text{MAcm}^{-2}$) 1 second after each pulsing sequence using a lock-in amplifier. The reorientation of the Néel vector should be reflected in transverse resistance variations due to SMR. The experiment is performed for different magnitudes of current pulses $J$ and at different temperatures. The results are presented in the form of relative transverse resistivity changes $\Delta R_{xy}/R$ as a function of pulse number where $\Delta R_{xy}$ is the change of the transverse resistance upon reorientation of the pulsing direction and $R$ is mean longitudinal resistance which is $21.6 \, \Omega$ at $T = 240 \, \text{K}$. The direction of the current pulse is changed between the two perpendicular easy axes after every 5 pulses whereas probing is always performed in the same configuration. The values of $J$ describing different experimental data sets are calculated by dividing the current that is stabilized during the pulsing by the narrow cross-section.

The experimental results for the largest current density in the range of $J_1 \in [89, 92] \, \text{MAcm}^{-2}$ yield saw-tooth like patterns of transverse resistivity typical for thermal non-magnetic effects (Fig. 2). This can be concluded from its presence above $T_N$ as shown by the data set collected at $T = 305 \, \text{K}$ (orange). Moreover, this type of signal exhibits a magnitude that increases with ambient temperature and exceeds $10^{-4}$. This magnitude is larger above $T_N$ than for the antiferromagnetic phase. No saturation of the signal with the increasing number of pulses of the same type was observed. Such behavior is caused by non-homogeneous current distribution within the device. The pulsing procedure creates non-equivalent current density points in the corners of the device. It results in different local heating and non-zero transverse voltage during the probing. Apart from such temperature gradient also Seebeck effects and structural changes like electromigration or recrystallization may play an important role in contributing to the electrical probing signal. For the smallest current magnitudes of pulsing (below 40 MAcm$^{-2}$) no significant variations of $\Delta R_{xy}/R$ is recorded at any temperature.

The most interesting results are obtained for intermediate values of the current pulse magnitude. Close to $J_m \in [47, 56] \, \text{MAcm}^{-2}$ a pattern of $\Delta R_{xy}/R$ appears, which is present only below $T_N$ (Fig. 3). The pattern collected for this range of current magnitudes is reproducible after days of performing multiple experiments with higher currents and at higher temperatures. Its presence below $T_N$ and absence above it can be a strong indication of its magnetic origin in contrast to the data recorded for the highest current densities (Fig. 2).

To highlight that distinct physical mechanisms are responsible for the appearance of the signal in different current density regimes, the temperature dependence of the transverse resistance patterns in the electrical switching experiment are summarized in Fig. 4. It shows that the thermal effects, crucial in the highest current densities ($J_1$), result in the increasing magnitude of the signal with temperature. This is not the case for the moderate current densities ($J_m$), where the signal is clearly decreasing between $T \in [240 \, \text{K}, 260 \, \text{K}]$ and it is practically undetectable above $T_N$. These tendencies are reproducible among different devices (Fig. 4). They allow suspecting the resistance variations detected for $J_m$ are caused by the spin reorientation in AF CoO. This is finally verified in the...
FIG. 3. Transverse resistance pattern recorded for 52 MA cm$^{-2}$. A switching pattern is only present below $T_N$ (blue squares). The pattern is reproducible (white-blue circles) after several days of other switching experiments performed at higher $T$ and with larger $J$. The pattern is absent above $T_N$ (red). The lines on the plot are guides for the eye.

FIG. 4. Relative transverse resistance changes $\Delta R_{xy}/R$ in electrical switching experiment as a function of temperature recorded for $J_m$ (pink) and $J_t$ (black) and two different devices A and B (squares and circles, respectively). The lines are guides for the eye.

FIG. 5. The magnetic field dependence of the mean transverse resistance changes $\Delta R_{xy}$ in the switching experiment recorded for 50 MA cm$^{-2}$ (violet) and 90 MA cm$^{-2}$ (black) for the magnetic field parallel to the (a) [100] hard magnetic direction and (b) [110] easy magnetic direction. The experiment was conducted at $T = 240$ K. Lines on the plot are guides for the eye.

Electrical switching of antiferromagnetic CoO across the Néel temperature

Unambiguous proof of the magnetic origin of the electrical signal for $J_m$ is provided by the switching experiment in the external magnetic field. The reorientation of spins in an antiferromagnet can be suppressed by a strong magnetic field that sets the AF in the spin flop state. It can occur for $B$ strong enough to overcome the anisotropy. For a thin-films of CoO at $T = 240$ K the spin flop field state can be reached at 7T when $B \parallel [110]$. Even if electrical current switches the spin axis of the antiferromagnet it should immediately come back to the initial state due to the spin flop induced by the magnetic field once the current pulse is turned off. Meanwhile, thermal effects, in principle, are not dependent on the magnetic field. Therefore, by studying the magnetic field dependence of the electrical switching patterns it is possible to identify the magnetic component of the signal. Similar approaches to use a magnetic field to validate the origin of the electrical signal have been used in hematite and CoO.

The in-field experiment shows that the electrical switching pattern for $J_m$ disappears upon increasing magnetic field (Fig. 5b), whereas the thermal pattern remains nearly unchanged as expected. The resistance changes for $J_m$ at 5T are diminished and above this value they become undetectable. Moreover, the response of the system to the magnetic field is anisotropic - such dependence is not observed for $B \parallel [100]$ (Fig. 5a). It is in agreement with the anisotropy of thin films of CoO, in which [100] is a magnetic hard direction and the magnetic field of 10T does not cause perpendicular alignment $n \perp B$ in this geometrical configuration.

Therefore, the signal obtained for $J_m$ can be interpreted as spin Hall magnetoresistance (SMR). The sign of the resistance variations corresponds to setting $n \parallel J$. This is different from another study of CoO electrical switching and may suggest that an antidamping torque mechanism is responsible for the antiferromagnetic reorientation. However, it has to be noted that even the same thermomagnetoelastic mechanism can result in different end states of $n$ depending on device design and experimental geometry.

Finally, we estimate the temperature increase of the CoO layer in the device region due to the electrical pulses by a 3D finite element method model. It reveals that the $T_N$ is not exceeded during the pulsing at $T = 240$ K presented in Fig. 3 and the temperature rise for 50 MA cm$^{-2}$ is around 7 K. It means that the device remains in the antiferromagnetic state during the whole experiment. It is also true even for such high cur-
rent densities as 92 MA cm$^{-2}$ at $T = 240$ K. Most of the heat is dissipated in the first few milliseconds after the pulsed current is turned off. Still, a slight temperature increase is present even for long timescales typical for probing. Together with the symmetry of the device design, this can produce patterns of the electrical signal visible at elevated current densities and at high temperatures as shown in Fig. 2.

In summary, we demonstrate that it is possible to determine whether a signal in an electrical switching experiment of an antiferromagnet is of magnetic origin, using purely electrical techniques. The method relies on comparing the signal at temperatures above and below the Néel temperature. Finally, we validated the study by performing the experiment in a strong external magnetic field. Such an approach can allow determining the optimal experimental conditions for switching antiferromagnets and be very valuable when no imaging techniques can be applied.

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23. Supplementary Information.