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ABSTRACT

Electrical control of magnetic order in antiferromagnetic insulators (AFIs) using a Pt overlayer as a spin current source has been recently reported, but detecting and understanding the nature of current-induced switching in AFIs remain a challenge. Here, we examine the origin of spin Hall magnetoresistance-like signals measured in a standard Hall bar geometry, which have recently been taken as evidence of current-induced switching of the antiferromagnetic order in Pt/AFI bilayers. We show that transverse voltage signals consistent with both the partial switching and toggle switching of the Néel vector in epitaxial Pt/NiO bilayers on Al2O3 are also present in Pt/Al2O3 in which the AFI is absent. We show that these signals have a thermal origin and arise from (i) transient changes in the current distribution due to non-uniform Joule heating and (ii) irreversible changes due to electromigration at elevated current densities, accompanied by long-term creep. These results suggest that more sophisticated techniques that directly probe the magnetic order are required to reliably exclude transport artifacts and thus infer information about the antiferromagnetic order in such systems.

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Antiferromagnetic (AF) materials have historically played only a passive role as biasing layers in spintronic applications due to the challenges in manipulating and detecting the magnetic order. However, substituting ferromagnets by antiferromagnets as active switching elements in spintronic devices offers the potential for ultrahigh speed dynamics (terahertz), stability against external magnetic fields, and higher bit packing density due to the lack of stray fields, as well as qualitatively new physical phenomena. These advantages have motivated intensive research, most recently in current-induced magnetization switching in both metallic and insulating AFs. In metallic AFs (CuMnAs or Mn2Au), a current-induced staggered spin polarization can rotate the magnetic sublattices and AF spin axis via the Néel spin–orbit torque (NSOT). In antiferromagnetic insulators (AFIs), the Néel order can be switched by the antidamping spin–orbit torque (SOT) generated by the spin accumulation from the spin Hall effect (SHE) in an adjacent heavy metal (HM) layer without the need for an external field. Switching by antidamping SOT does not require that the spin sublattices form inversion partners as in NSOT switching, and hence, it is a more general approach that may enable all-electrical control over a wider variety of AFs. In AF/heavy-metal (HM) heterostructures, the spin Hall magnetoresistance (SMR) can be used for the electrical detection of sublattice switching and Néel vector orientation, where longitudinal ($R_{xx}$) and transverse ($R_{xy}$) resistances vary by the relative angle between the Néel vector in the AF and the orientation of the spin polarization created by the SHE in an adjacent HM layer.

Recently published studies of AFI/HM bilayers provided the first steps toward the electrical control and detection of the Néel order. Two types of transverse Hall signal signatures after current pulse injection have been attributed to AF phenomena, but their origins are contested. Reference reported a saw-tooth-shaped change in $R_{xy}$ while injecting a series of switching current pulses in epitaxial, biaxially strained NiO(001). The results were interpreted as arising from partial SOT switching of a multidomain state, where the Néel order rotated in the direction of the writing current along one of the easy axes. In epitaxial Pt/NiO(111)/Pt trilayers in Ref. 11, the Néel order was believed...
to rotate orthogonal to the writing current due to additive SOTs from the Pt layers. The steplike $R_{xy}$ shape was attributed to toggle-switching between two distinct magnetic states\textsuperscript{11} and in Ref. 12 to the spin-transport across the NiO(001)/Pt interface.\textsuperscript{12} Very recent works found evidence for nonmagnetic contributions to $R_{xy}$ in the Pt layer used for SOT switching and suggested that the saw-tooth-like signal is a parasitic effect, whereas the steplike signal is of magnetic origin.\textsuperscript{12,14,15}

In this Letter, we show that all transport features previously identified as SOT from an AF layer are also present in isolated Pt layers on a nonmagnetic substrate and can be attributed to two mechanisms: read current path deviations in the device following localized Joule heating and Pt electromigration (EM) following large current pulses that ultimately causes irreversible device degradation. We show that simple interpretations of transport measurements cannot be reliably used to infer information about the magnetic state of AFs.

Epitaxial NiO films of thicknesses 5, 25, and 50 nm were grown on Al$_2$O$_3$(0001) substrates at 600 °C by off-axis radio frequency magnetron sputtering\textsuperscript{28,29} from a NiO target (off-axis angle, 45°) at 5 mTorr (2.5 sccm of O$_2$, 47.5 sccm Ar). The epitaxial growth and strain state of NiO films were confirmed with a high-resolution x-ray diffraction 2\theta/ω coupled scan of the (111) reflection and reciprocal space maps (see the supplementary material). On top of NiO and bare Al$_2$O$_3$ substrates, we grew Pt(5 nm) by magnetron sputtering. The continuous layers were patterned into four-arm Hall cross devices with 10 × 40 μm arm dimensions using optical photolithography.

Figure 1(a) shows the Hall cross geometry and current configurations used to attempt current-induced switching of the Néel vector by 90° and SMR detection. Write current pulses, $I_w$, with 1 ms width were injected such that the current in the center flowed approximately along +45° (Write 1) and −45° (Write 2) relative to the read current direction. The read current, $I_r$, probes the transverse Hall resistance $R_{xy}$. In the case where $R_{xy}$ is purely of SMR origin, $R_{xy} = 10 \sin \phi$, where $\phi$ is the angle between the Néel vector and the current direction and $\Delta R_{xy}^{ \text{SMR}}$ is the SMR coefficient.\textsuperscript{24} Complete SOT switching of the AF order should orient the Néel vector at ±45° current pulse configurations, which should switch $R_{xy}$ between $\pm \Delta R_{xy}^{ \text{SMR}}$. However, in our work and others,\textsuperscript{12,14,15} the SMR signal in NiO/Pt is masked by parasitic contributions to $R_{xy}$.

To show this, we injected write current pulse sequences with a fixed amplitude and recorded $R_{xy}$ 10 s after each write pulse (to minimize transient thermal effects\textsuperscript{12}) with a small read current ($I_r$ = 1 mA and current density $j_r = 2 \times 10^{11}$ A/m$^2$). Figures 1(b) and 1(c) show a periodic change in $R_{xy}$ in NiO(50 nm)/Pt(5 nm) bilayers while applying current pulse sequences of five Write 1 followed by five Write 2 pulses (see the full current range in the supplementary material). A saw-tooth $R_{xy}$ signal is observed for the first five cycles for both low ($j_w = 5.6 \times 10^{11}$ A/m$^2$) in Fig. 1(b) and high ($j_w = 7.2 \times 10^{11}$ A/m$^2$) current densities in Fig. 1(c) but relaxes to a more steplike shape at high $j_w$, as seen after 16 cycles following the axis break. We define the peak-to-peak magnitude of $R_{xy}$ for a single cycle of Write 1-Write 2 pulses as $\Delta R_{xy}^{\text{pp}}$, illustrated in Fig. 1(b), When NiO was omitted, a persistent saw-tooth signal was also observed for low $j_w$ in Pt in Fig. 1(d). At high $j_w$, continuous device cycling reveals a relaxation to a steplike signal, which persists after 18 cycles (Fig. 1(e)). We show that both types of $R_{xy}$ signal shapes can originate from the bare Pt layer and cannot be used to confirm the $R_{xy}$ origin.

In both NiO/Pt and Pt, $\Delta R_{xy}$ declines in magnitude considerably after a series of cycles at high $j_w$, suggesting irreversible device damage at these densities. At $j_w = 7.2 \times 10^{11}$ A/m$^2$, we observe an irreversible decline in the maximum $\Delta R_{xy}$, which is thought to originate from device breakdown or irreversible switching occurring at the highly heated corners of the device.\textsuperscript{20} When current pulses of lower amplitude were again applied to the same device, $\Delta R_{xy}$ did not return to its original magnitude. Thus, it is necessary to study the mechanisms that lead to device breakdown, as they may affect the detected resistance before any visible damage occurs.

To examine the behavior of $R_{xy}$ caused by Joule heating from current pulses, we plot the maximum $\Delta R_{xy}$ reached for each $j_w$ as a function of increasing $j_w$ in Pt and NiO/Pt bilayers with NiO thicknesses of 5, 25, and 50 nm in Fig. 2(a) (see the source in the supplementary material). While the behavior is exponential for lower current values, $\Delta R_{xy}$ saturates at higher current densities. Although no NiO thickness dependence of threshold $j_w$ has previously been reported,\textsuperscript{10,11,12} we found that the current threshold is significantly smaller for Pt devices on NiO(50 nm). As the thermal conductivity of NiO is smaller than that of Al$_2$O$_3$, the rate of heat dissipation is lower in the NiO(50 nm)/Pt bilayer. This suggests that the mechanism behind the $R_{xy}$ signal from the Pt layer is thermally driven. Meanwhile, the Joule heating for this range of $j_w$ is estimated to contribute to a temperature rise $\Delta T$ between 70 K (at the first detectable signal measured) and 260 K (at the point of irreversible degradation) during the duration of the pulse (see the supplementary material).

To confirm the role of heating, we recorded $R_{xy}$ during a sequence of write pulses with $j_w = 5.6 \times 10^{11}$ A/m$^2$ at temperatures $T = 25$, 45, and 65 °C, while the samples were in good thermal contact with the heating stage. Figures 2(b) and 2(c) show the $T$-dependent $R_{xy}$ in fresh NiO(50 nm)/Pt(5 nm) and Pt(5 nm) films, respectively.
after 100 pulses when the signal equilibrated. $\Delta R_{xy}$ increases with increasing substrate $T$ in both materials, mirroring the increase in $D R_{xy}$ as a function of $j_w$. A thermally generated and/or activated mechanism is thus likely responsible for the signal change in both cases.

To consider the symmetry of the parasitic $R_{xy}$ in Pt, we averaged four “read” measurements of read configurations each rotated by 90°, after each write pulse [Fig. 3(a)]. This approach has been previously used to eliminate parasitic $R_{xx}$ contributions due to geometric effects in a similar device.30 In Fig. 3(a), a single read current configuration produces a saw-tooth signal, while an average of four read configurations eliminates the signal entirely, eliminating the possibility of any out-of-plane contribution to the $R_{xy}$ signal.

We propose a mechanism that contributes to an in-plane symmetry breaking in Pt. When $I_w$ is applied to the Hall cross, $j_w$ and thus the Joule heating are the highest around the two constricting corners [red spots in Fig. 3(b)]. Consequently, the resistivity of these “hot spots” increases, leading to a significant asymmetry in the $I_r$ paths. This generates a $R_{xx}$ contribution to $R_{xy}$, which depends on the previous $I_w$, resulting in a positive (negative) resistance for Write 1 (Write 2), and the “saw-tooth” shape. Thus, increasing $T$ (via substrate heating or Joule heating) increases the resistance of the devices and the contribution from the thermoresistive effect to $\Delta R_{xy}$. When these localized hot spots reach certain $T$ thresholds, the device becomes irreversibly damaged.

Finally, to directly confirm these irreversible changes to the Pt layer after current pulse injection, we used scanning electron microscopy (SEM) to image corners of four different devices. Figure 4(a) shows a fresh device. The device in Fig. 4(b) has undergone 6 write cycles with a saw-tooth $R_{xy}$ signal ($I_w = 6.7 \times 10^{14}$ A/m$^2$) and shows formation of small hillocks. In Fig. 4(c), void formation is observed in a device that has been pulsed with 6 write cycles with larger current.
densities ($j_w = 9.8 \times 10^{11} \text{ A/m}^2$), with $R_{xy}$ having equilibrated to a steplike signal. In Fig. 4(d), hemispherical electrically separated islands are observed after device breakdown ($j_w = 1.0 \times 10^{12} \text{ A/m}^2$). This is a characteristic manifestation of electromigration that eventually leads to migration-induced breakdown beginning at the corners. The Pt grain boundaries acting as sources and sinks for point defects are responsible for the long-term relaxation of $R_{xy}$ due to point defect diffusion following read measurements. We suggest that systematic studies of activation energies for thermal migration may additionally yield understanding of the long-term structural changes to the Pt layer, which manifest in the transverse resistance signal. Our results imply that more sophisticated methods that do not rely solely on the electrical signal from the metal overlayer are required to detect the AF order. Furthermore, our findings open venues for further studies on the role of the heavy-metal overlayer structural integrity and quality on such parasitic heating effects and emphasize the general importance of more careful consideration of all possible contributions to a thermally induced signal (e.g., choice of substrate and current pulse characteristics).

See the supplementary material for complete structural characterization and current-dependent switching measurements.

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