Spin Seebeck Imaging of Spin-Torque Switching in Antiferromagnetic Pt/NiO Heterostructures

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Abstract:

As electrical control of Néel order opens the door to reliable antiferromagnetic (AF) spintronic devices, understanding the microscopic mechanisms of AF switching is crucial. Spatially-resolved studies are necessary to distinguish multiple nonuniform switching mechanisms; however, progress has been hindered by the lack of tabletop techniques to image the Néel order. We demonstrate spin Seebeck microscopy as a sensitive table-top method for imaging antiferromagnetic order in thin films and apply this technique to study spin-torque switching in NiO/Pt and Pt/NiO/Pt heterostructures. We establish the interfacial antiferromagnetic spin Seebeck effect in NiO as a probe of surface Néel order. By imaging before and after applying current-induced spin torque, we resolve spin domain rotation and domain wall motion, acting simultaneously.

Summary of Research:

Antiferromagnets (AFs) are attractive candidates for spintronic devices due to their lack of stray fields, their terahertz switching speeds, and their stability to magnetic field [1]. They are also notoriously difficult to read and write [2]. Recent demonstrations of electrical switching of Néel order [3-6] may provide a path to overcome this difficulty and potentially construct practical devices. However, AF switching is nonuniform and multiple switching mechanisms contribute simultaneously, making device-level readout difficult to interpret. Systematic imaging studies of AF switching are necessary to understand the microscopic mechanisms. The best-established technique for imaging Néel order — XMLD-PEEM7 — requires synchrotron facilities that are generally only available in 24-48-hour runs, therefore tabletop imaging techniques are necessary to better understand and optimize AF switching.

In this work [8] we demonstrate spin Seebeck microscopy as a sensitive tabletop probe of the Néel order and image current-induced spin-torque switching in antiferromagnetic Pt/NiO and Pt/NiO/Pt heterostructures.

Our technique is based on the interfacial antiferromagnetic longitudinal spin Seebeck effect (AF-LSSE) [9] in so-called *uncompensated* antiferromagnets such as the insulator NiO<111>, in which the spins in the interfacial layer are aligned parallel as shown schematically in Figure 1(a). A local thermal gradient at this interface generates a spin current that reports the Néel orientation of the interfacial spins. We generate local thermal gradients by focusing a pulsed laser to 650 nm spot size and detect the resulting spin current by transducing it into a charge current through the inverse spin Hall effect in the adjacent Pt layer. We therefore measure the in-plane component of the surface Néel orientation. Figure 1(b) shows an example AF LSSE image of a 20 µm-wide Hall bar of 165 nm NiO<111>/ Pt on $MgAl_2O_4$. Blue and red $V_{AF\ LSSE}$ contrast represents spins pointing towards the right and left, respectively.

In contrast to an uncompensated AF, Figure 1(c) diagrams a *compensated* AF, in which the spins in the interfacial layer are anti-aligned. The spin current from this interface should cancel out to zero over the laser spot area. To test this prediction, in Figure 1(d) we image

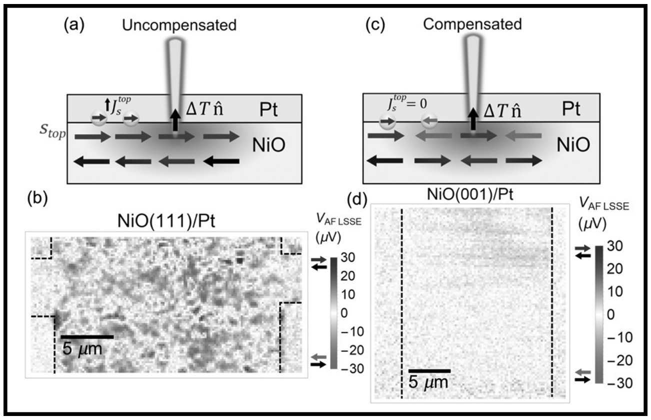

Figure 1: Demonstrating interfacial antiferromagnetic longitudinal spin Seebeck effect (AF LSSE). (a) Diagram of uncompensated NiO<111>/Pt, in which the spins on the top interface are aligned. A thermal gradient across this interface generates a spin current that reports the surface Néel orientation. (b) AF LSSE image of a 165 nm NiO<111>/Pt sample, showing AF domains. (c) Diagram of compensated NiO<001>/Pt, in which the spins on the top interface are anti-aligned and produce no net spin current. (d) AF LSSE image of a 136 nm NiO<001>/Pt sample, showing no measurable contrast. (Find full color on pages xiv-xv.)

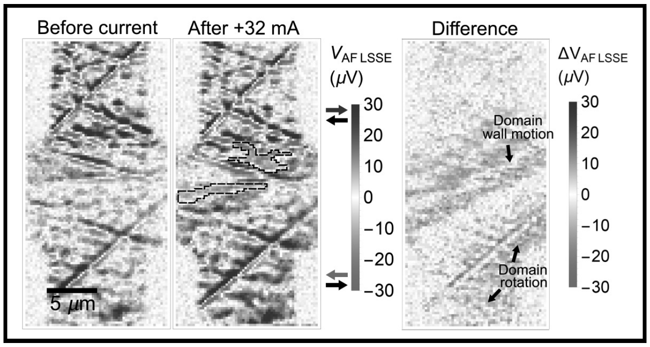

Figure 2: AF LSSE images of Pt/6 nm NiO<111> before and after applying 7 × 10^7A/cm^2 DC current. Prominent regions of switching are highlighted. The difference image shows switching both by rotation of AF domains and by domain wall motion. (Find full color on pages xiv-xv.)

another 20 µm-wide Hall bar of 136 nm NiO<001>/Pt on MgO<001>, similar to the NiO<111>/Pt sample except that NiO<001> has a compensated interface. We obtain no measurable contrast from NiO<001> compared with NiO<111>, which confirms that the uncompensated interface is necessary and indicates that we indeed measure surface Néel order.

We then image spin-torque switching in a 10 µm-wide device of Pt/6 nm NiO<111> in Figure 2. We image before and after applying 7 × 10^7A/cm^2 current density along the device and take the difference to show the changes in domain structure. Prominent regions of switching are highlighted in black dashed line. The lower portion of the difference image shows nearly uniform contrast, meaning different AF domains rotate by the same angle. The middle of the channel shows adjacent regions of blue and red, which indicate domain wall motion in response to current. Our findings are consistent with recently-developed models of spin-torque switching in NiO/Pt[6].

In conclusion, we demonstrate spin Seebeck microscopy as a powerful tabletop technique for imaging surface Néel order in an antiferromagnetic insulator and apply this technique to image spin-torque switching in NiO/Pt heterostructures. We find that switching occurs by domain rotation and domain wall motion acting simultaneously. Our results provide critical insight into the complex processes in electrical control of antiferromagnetism and we expect our technique to generalize to a variety of antiferromagnetic insulators.

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