Non-Equilibrium Investigations of Canted Antiferromagnet Under Flowing Electrical Current

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Abstract:

Strontium iridium oxide (Sr_2IrO_4) is an antiferromagnetic Mott insulator, driven by strong spin-orbit coupling and Coulomb repulsion. The spin-orbit interaction locks the IrO_6 octahedra rotation and Ir magnetic moment canting. Recently, the current-induced metal-insulator transition in bulk single crystals of Sr_2IrO_4 was reported [1]. According to the study, the coupling of flowing electrical current and canting angle leads to an a-axis lattice expansion of up to 1%; this nonlinear change in lattice and magnetic structure drives a unique resistive switching behavior. For the 2018 PARADIM REU Program, we tested the electrical control of Sr_2IrO_4 in a thin film platform and clarified the physical mechanisms behind the current-induced metal-insulator transition of Sr_2IrO_4.

Summary of Research:

Epitaxial Sr_2IrO_4 thin films, grown by molecular-beam epitaxy on LSAT <001>, NGO <001>, and STO <001> substrates, were tested at the probe station equipped with Keithley 4200A-SCS Parameter Analyzer and 4225-PMU Ultra-Fast I-V Module (for pulsed-IV). For low temperature measurements, the probe station was cooled down to T = 80 K by liquid nitrogen.

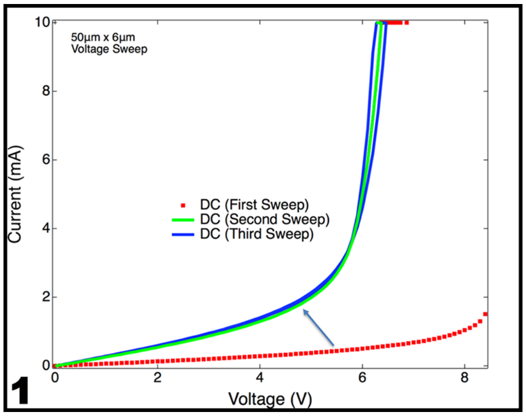
The current-induced electrical control implies that the current density required for metal-insulator transition should be comparable across Sr_2IrO_4 samples with different sizes. Comparison with the reported single crystal data [1], along with simple calculations of the ratio of cross-sectional area of current flow, gave a rough estimation on the amount of current required for switching in Sr_2IrO_4 thin film (~ 1 µA). However, no nonlinear behavior was observed with Sr_2IrO_4 thin films within the compliance limit (10 mA) imposed by the probe station electronics. It was clear that the mechanism of switching in epitaxial thin films is different from bulk single crystals, because of the huge disparity of current density required for resistive switching.

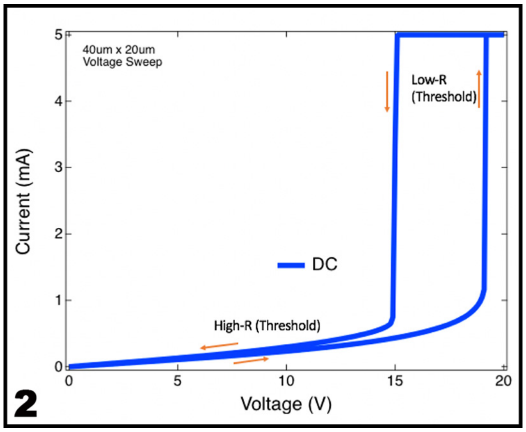
Subsequent experiments were done with smaller film devices fabricated and patterned by platinum electrodes on each side. The devices' dimension was in the order of 10 µm × 10 µm. Film devices with smaller cross-sectional area of current flow enabled larger current density input, and we were able to induce the nonlinear resistive switching both at T = 300 K and T = 80 K.

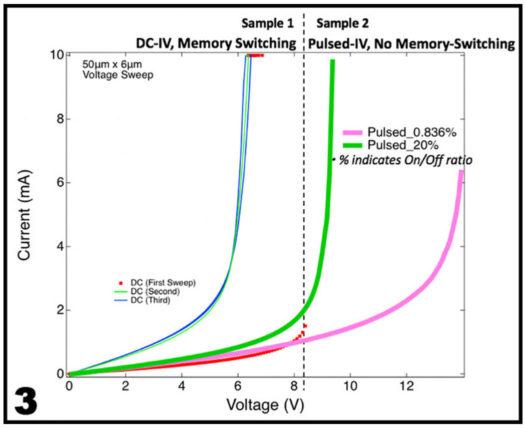
Results and Conclusions:

Switching behaviors and Joule heating effect observed at room temperature can be explained by the oxygen vacancy migration-driven resistive switching of oxide thin films. Under a large electric field, oxygen vacancies migrate, cluster, and form conducting filaments in oxide films [2]. If the filaments are stable after an initial voltage sweep, the film enters into a non-volatile low-resistance state—memory switching (Figure 1). On the other hand, if the filaments cannot be maintained during the voltage sweep, the low-resistance state is volatile and only maintained at the large voltage bias, returning to the original high-resistance state below a certain voltage threshold—threshold switching (Figure 2).

The migration of oxygen vacancies can be modeled as a 'hopping' process in a periodic potential. The hopping rate is very slow under E-field alone. Joule heating accelerates the hopping rate by creating a large thermal







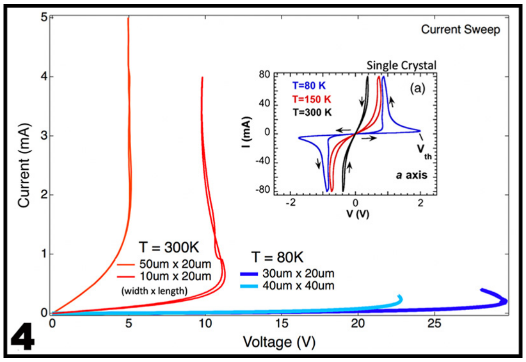


Figure 1, top: *Memory resistive switching observed in* Sr_2IrO_4 *thin film (film dimension: width × length).* ***Figure 2, upper middle:*** *Threshold resistive switching observed in* Sr_2IrO_4 *thin film.* ***Figure 3, lower middle:*** *Nonlinear resistive switching: Comparison of DC- and pulsed-mode.* ***Figure 4, bottom:*** *DC current-induced resistive switching observed in* Sr_2IrO_4 *thin film at T = 300 K and T = 80 K. Inset: I-V characteristic of DC current applied along the a-axis of* Sr_2IrO_4 *single crystal reported by G. Cao, et al. [1].*

gradient near the conducting filaments [2]. Figure 3 shows that the reduction of Joule heating under the pulsed I-V mode subdues the memory resistive switching originally found on the other film device of the same geometry.

Comparison of DC and pulsed I-V characteristic of multiple devices further showed that the nonlinear behavior originally found under DC mode disappeared under pulsed mode. The necessity of Joule heating in the resistive switching supports our hypothesis that the switching behavior of Sr_2IrO_4 at room temperature is an indication of the formation of conducting filaments consisting of oxygen vacancies.

The nonlinear I-V characteristic at T = 80 K, cut off at the onset of the switching behavior, exhibits a similar pattern of negative differential resistance found with the bulk single crystal [1] (Figure 4). It gives an inconclusive hint of what can potentially be the metal-insulator transition driven by the coupling of electrical current and Ir magnetic moment canting.

Further increase in current bias destroyed the film devices under testing, the reason why a comprehensive study on Sr_2IrO_4's metallic state could not be done.

Future Work:

Further exploration of the nonlinear switching behavior below room temperature is required. More experiments with pulsed I-V should be done at low temperature to root out the possibilities of oxide film's typical oxygen vacancy migration- or joule heating-driven resistive switching.

The film devices cracked most likely due to structural changes. Sr_2IrO_4 in a thin film is more prone to cracking under structural changes than in a bulk single crystal, because of the hard substrate clamping the film grown above. This unfortunately means that it is hard to investigate deep into the metallic state, because current-induced metal-insulator transition is accompanied by large structural change—in particular, the expansion of a-axis lattice as a result of IrO_6 octahedral rotation.

If the device breakdown can be circumvented, the electronic structure of Sr_2IrO_4 in the current-induced metallic state will be studied by angle-resolved photoemission spectroscopy (ARPES). If the metallic state cannot be achieved in the thin film platform, we plan to perform the ARPES study with a bulk single crystal Sr_2IrO_4.

Acknowledgements:

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