Strain Tuning the Emergent Properties in Pyrochlore Thin Films

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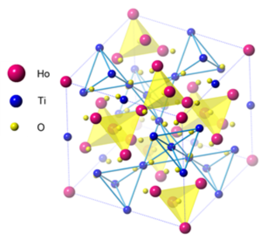
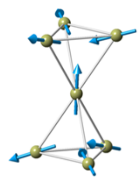
Introduction

Geometrical frustration occurs in systems that are unable to minimize their energy due to competing magnetic interactions leading to ground state degeneracy. Pyrochlore titanates, with the $A_2B_2O_7$ structure are examples of highly frustrated materials which display finite entropy at 0 K. Attempts to minimize the 0 K entropy lead to exotic magnetic properties.





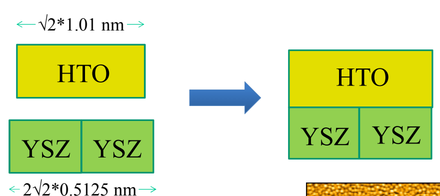
Magnetic interactions

$$H_{ex} = -\sum_{i,j} J_{ij} S_i \cdot S_j$$

$$H_D = \frac{1}{2}(g\mu_B)^2 \sum_{i,j} \left\{ \frac{S_i \cdot S_j}{r_{ij}^3} - 3\frac{(S_i \cdot r_{ij})(S_j \cdot r_{ij})}{r_{ij}^5} \right\}$$

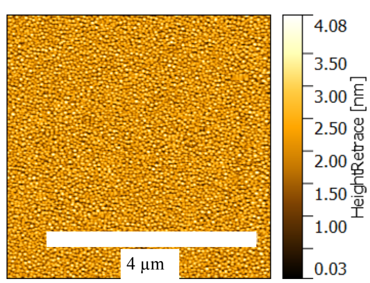
In $Ho_2Ti_2O_7$ (HTO) the magnetic Ho^{+3} ions occupy a lattice of corner sharing tetrahedra. The competition between antiferromagnetic coupling (J) and dipole-dipole interactions (D) of the Ho^{+3} leads to the geometrical frustration. As a result HTO shows a spin ice (two-in/two-out) ground state, equivalent to the proton disorder observed in water ice, below a spin freezing temperature of T ~ 0.7 K [1]. We use epitaxial strain to change the distance between neighboring Ho^{+3} spins and the relative strengths of the J and D interactions. Our goal is to tune the degree of frustration and the ground state (i.e., force the material to adopt a long range antiferromagnetically ordered ground state). This research will contribute to a better understanding of frustrated magnetism, the spin ice state and other emergent phenomena predicted and observed in pyrochlores.

Pulsed Laser Deposition of HTO on YSZ(111)

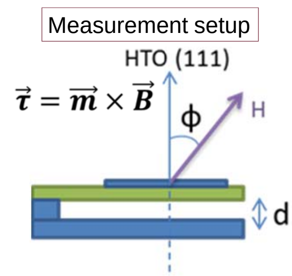


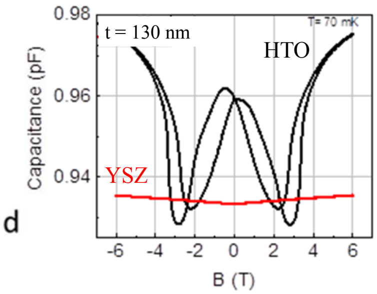
Lattice Mismatch:
-1.46% => Tensile strain

Atomic force microscopy image of a 56 nm thick HTO film (scan size: 5 x 5 μm) grown on YSZ (111). The rms roughness ~ 0.4 nm is comparable to observations made by others [2].



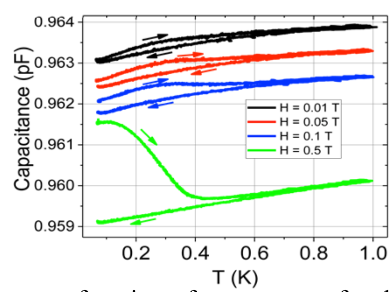
Capacitive Torque Magnetometry





Capacitance as function of applied field of a 130 nm HTO thin film grown on YSZ (black) and of a bare YSZ substrate (red), measured at T = 70 mK with H//(111), normal to the film plane, ϕ=0°. The film shows a strong hysteretic signal as function of applied field.

Magnetic Phase-Transition: Spin Ice State?



Capacitance as function of temperature for the 130 nm thick HTO film. The sample was zero field cooled and subsequently measured in a varying applied measurement field while warming and cooling the sample. The curves were translated vertically for clarity. Clear hysteretic behavior is observed below 0.6 K indicating that a magnetic phase transition occurs at that temperature.

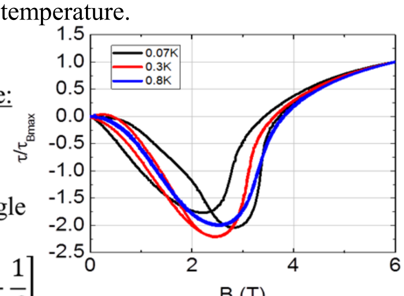
Relationship Between Torque and Capacitance:

Zero Field Capacitance

$$C_0 = \frac{\varepsilon A}{d_0}$$

For small deflection angle θ of the capacitor plate,

$$\tau \propto \theta \approx \frac{\delta d}{L} \propto \left[\frac{1}{C_0} - \frac{1}{C}\right]$$



Normalized torque as function of applied magnetic field for the 130 nm sample measured at various temperatures. The hysteresis diminishes with increasing temperature and seems to disappear around the magnetic phase transition.

Conclusions and Future Work

- We have grown high quality epitaxial thin films of HTO on YSZ(111) using pulsed laser deposition.
- We observed a magnetic phase transition at T ~0.6 K, which is near the spin ice freezing temperature reported in bulk.
- We use neutron scattering studies to determine the underlying spin configuration, which provides insight into the effect of tensile strain on the frustration in pyrochlore thin films.
- We will study the influence of film thickness on the magnetic properties.
- We will investigate the effects of strain by growing HTO on different substrates (i.e., different lattice mismatch).

References

[1] C. R. Wiebe and A. M. Hallas, APL Mater. **3**, 041519 (2015)

[2] D. Leusink, et al., APL Mater. **2**, 032101 (2014)

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