phys. stat. sol. (c) **1**, No. 12, 3440–3442 (2004) / **DOI** 10.1002/pssc.200405476

# Local measurements of magnetization reversal in thin films of $SrRuO_3$

**Isaschar Genish**[*, 1], **Yevgeny Kats**[1], **Lior Klein**[1], **James W. Reiner**[**, 2], and **M. R. Beasley**[2]

[1] Department of Physics, Bar-Ilan University, Ramat-Gan 52900, Israel
[2] T. H. Geballe Laboratory for Advanced Materials, Stanford University, Stanford, California 94305, USA

Received 27 June 2004, accepted 14 October 2004
Published online 20 December 2004

**PACS** 75.60.Ej, 75.70.-i

$SrRuO_3$ is a 4d itinerant ferromagnet. Thin films of $SrRuO_3$ on $SrTiO_3$ substrate have Curie temperature of ~150 K and are characterized by extremely large uniaxial anisotropy ($H_{anis}$ ~ 10 T) with the easy axis at 45° relative to the film normal. We explore local magnetization reversal events in this system by measuring the extraordinary Hall effect in micron-size patterns. With this technique we follow distinct magnetization events and can detect flipping of less than 1% of the probed area which for our samples amounts to ~$2 \times 10^7$ spins.



Magnetization reversal in magnetic films has been the focus of intensive research for several decades for its theoretical and practical importance. Here we study this phenomenon in thin films of the 4d itinerant ferromagnet $SrRuO_3$. These films have $T_c$ of ~150 K and large uniaxial anisotropy (~10 T) with the easy axis at 45° relative to the film normal. When cooled below $T_c$ at zero field, the films exhibit stripe domain structure [1] with domain width of ~200 nm and the calculated width of the Bloch walls is ~3 nm [2]. Theoretical calculations and preliminary measurements indicate that the extraordinary magnetic properties of $SrRuO_3$ make it an ideal system for identifying macroscopic quantum tunneling either in nucleation processes [3] or in domain wall propagation [4]; therefore, it is important to understand and characterize the magnetization reversal process in this compound.

We study thin films of $SrRuO_3$ grown on miscut (2°) $SrTiO_3$ substrates using reactive electron beam epitaxy. The films have orthorhombic structure ($a$ = 5.53 Å, $b$ = 5.57 Å, $c$ = 7.85 Å) which is slightly strained due to the substrate, and they grow uniformly (without twinning) with the $c$ axis in the film plane and the $a$ and $b$ axes at 45° out of the plane [1, 5]. The magnetocrystalline anisotropy is uniaxial with the easy axis along the $b$ axis. The sample whose measurements are presented here is 30 nm thick with $T_c$ ~ 147 K and resistivity ratio of ~13.

To follow particular nucleation and propagation events, we measure the extraordinary Hall effect (EHE) [6, 7] which is proportional to the perpendicular component of the internal magnetization $\boldsymbol{M}$. The measurements presented here are of a cross-shape pattern with probed area of 4 $\mu m^2$.

To characterize the process of magnetization reversal we perform two types of measurements: field sweeps and temperature sweeps. To ensure that we start our magnetization reversal with a uniformly magnetized film we cooled the sample from above $T_c$ in a field of –2 T. This is necessary since due to the extremely high magnetocrystalline anisotropy it is difficult to obtain completely full magnetization by field sweeps at low temperatures. For the field sweeps, we cooled the sample to the measuring temperature and then the field was slowly swept to +2 T. For the temperature sweeps we cooled it to 10 K where

* Corresponding author: e-mail: ph174@mail.biu.ac.il, Tel: 972-3-5317629, Fax: 972-3-5353298
** Present address: Department of Applied Physics, Yale University, New Haven, Connecticut 06520-8284

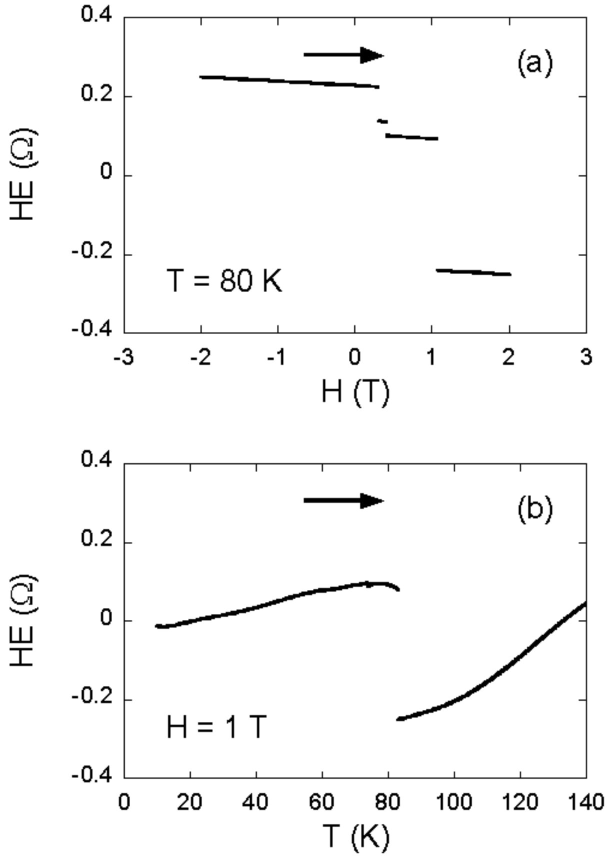


**Fig. 1** (a) Hall effect vs $H$ at 80 K after cooling in a field –2 T from above $T_c$. (b) Hall effect vs temperature after cooling in a field of –2 T from above $T_c$ down to 10 K and setting the field to 1 T at that temperature.

a positive field was applied and the sample was swept in temperature up to above $T_c$. The latter method is less common; however, we found that in some cases it is more sensitive to small changes of magnetization reversal. Particularly, when we measure magnetization reversal via temperature sweeps we can detect magnetization reversal of less than 1% of the probed area volume. For our sample it amounts to ~$2 \times 10^7$ spins; however, with decreased pattern size and film thickness this number could be reduced by more than an order of magnitude.

Figure 1 shows a typical field sweep measurement at $T = 80$ K. We see that the process is characterized by 3 discrete jumps. Similarly, discrete jumps are observed in temperature sweeps.

Figure 2 presents a summary of all magnetization jumps for a particular pattern in field and temperature sweeps. (Qualitatively similar data are obtained for other patterns; however there are significant quantitative differences). We note that the various jumps seem to fall on three distinct curves, suggesting three specific magnetization events. This assumption is supported by the observation (based on the magnitude of the jumps) that points falling on a particular curve reflect magnetization reversal of almost the same volume at all temperatures. The temperature dependence of the curves varies between the jumps. Thus, for instance, while the first jump is almost temperature independent below 120 K, the third jump more than triples.

The magnetization events presented in Fig. 2 are stochastic in nature and the points represent only a typical ($T$, $H$) value. Thus, for following distinct events, the width of the statistical distribution should be smaller than the distance between the mean values of different events. This requirement is clearly met for our sample; however, as the probed area increases the jumps become smaller and denser; thus, the distinction becomes harder.

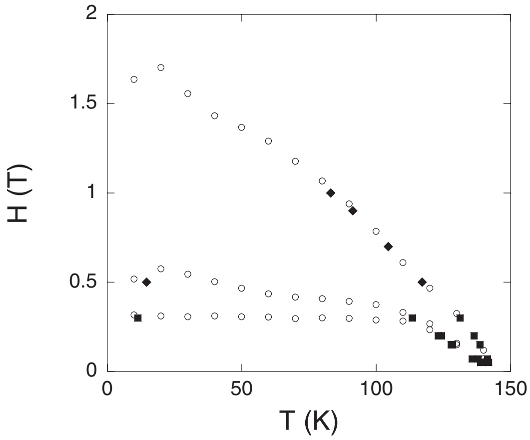


**Fig. 2** Fields at which magnetization jumps were observed at different temperatures in field sweeps (circles) and temperature sweeps (squares). Diamonds represent jumps in temperature sweeps that yielded magnetization jumps already during the field sweep at 10 K.

The nature of the three magnetization events is unclear. It could either be a nucleation event followed by propagation, or domain wall depinning followed by propagation. Either way, the possibility of following distinct events and particularly the third jump, which is biggest in size and very far in parameter space from the two other jumps, opens the door for detailed analysis of the relevant potential barrier. We hope that by comprehensive understanding of the thermal activation process that enables the jump at high temperatures, we will be able to identify a crossover to macroscopic quantum tunneling at low enough temperatures.

**Acknowledgements** L. K. acknowledges support by the Israel Science Foundation founded by the Israel Academy of Sciences and Humanities.

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