wildfire

APPLICATION NOTE

DENS solutions

Quantitative TEM imaging of the magnetic transition in FeRh thin films and current-driven domain wall motion

Experimental Setup:

TEM & Objective lens

JEOL ARM200CF Probe corrected

In Situ System

Lightning D9+ (Heating & Biasing) system

MEMS device

4 contact Wildfire D6, 8 contact Lightning D9+

Sample

FIB lamella: FeRh films on MgO substrate / NiAl buffer layer on GaAs substrate

Sample Preparation Technique

- Cross-sectional / planar TEM samples were prepared in a FEI Dual-Beam FIB-SEM
- Thinning and polishing procedure was performed on the MEMS Nano-Chip

In Situ Environmental Parameters

Temperature: 20 °C – 430 °C
Applied magnetic fields: 0 mT – 50 mT using magnetic field of the objective lens
Applied current pulses: 100 mV – 1000 mV

Analysis Techniques

HAADF-STEM, EDS, EELS, DPC

Keywords

In situ heating, Transmission Electron Mycroscopy (TEM), FeRh magnetic thin films, Differential phase contrast imaging, Magnetostructural phase transition, Focused Ion beam, MEMS Nano-Chips

Fields

Magnetic data storage, spintronics

Abstract

Equi-atomic FeRh is a very interesting material as it undergoes a magnetostructural transition from an antiferromagnetic (AF) to a ferromagnetic (FM) phase between 75–105 °C. Its ability to present phase co-existence separated by domain walls (DWs) above room temperature provides immense potential for exploitation of their DW motion in spintronic devices. The scanning transmission electron microscopy (STEM) technique of differential phase contrast (DPC) imaging permits ~ 1 nm spatial resolution imaging of magnetic induction within nanostructured thin films as a function of applied electric and magnetic fields, as well as temperature, as demonstrated in Figure 1.

Purpose

- Motivation: Improve the area bit density in magnetic data storage materials and provide effective control over DW movement for the reading / writing of information
- Fully understand the localised dynamic evolution of the domain nucleation, growth stages and DW movement associated with the magnetostructural transition in FeRh

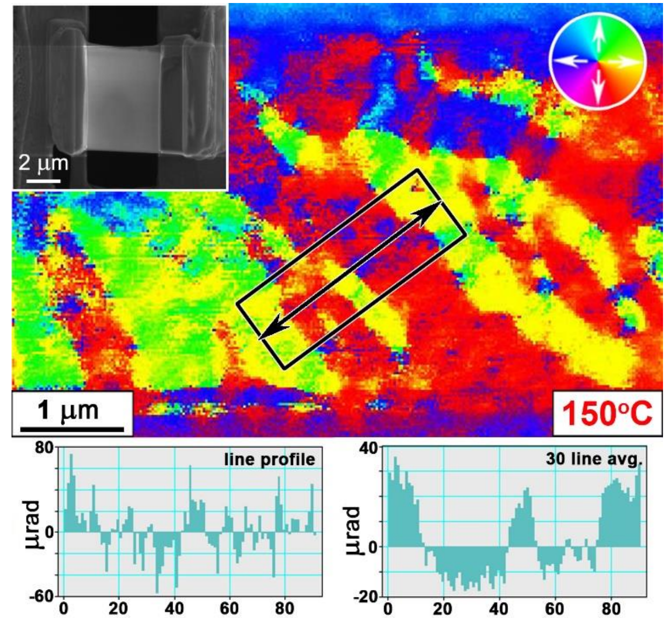

Figure 1. DPC image of a planar FeRh thin film heated in situ to 150 °C with the direction of magnetisation depicted in the colour wheel (inset). Measurements of magnetic deflection are taken across the line and average profile along the arrows and boxed region (black). The SEM image (inset) shows the FeRh FIB lamella positioned on a Wildfire D6 chip.

Challenges

- Prepare planar FeRh thin films on a MEMS chip using FIB
    - Transfer and final thinning on the MEMS chip without exposing the FeRh film to the Ga^+ beam
    - Good lamella quality with uniform thickness across the whole of the planar thin film
    - Good electrical contact with biasing lines
- DPC imaging of magnetic domains without diffraction contrast
- Applying current pulses whilst heating and imaging DW motion

Results

1. Sample preparation

In the current work, a series of planar FeRh thin film samples grown on a MgO substrate or NiAl buffer layer on GaAs substrate have been mechanically back-polished from ~ 500 μm until ~ 50 μm thick. The samples were then subsequently ion-milled within the FIB until ~ 1 μm thick and transferred onto the MEMS Nano-Chip using a micro manipulator. The final thinning on the Nano-Chip was performed using progressively lower ion-beam currents and the final polishing was completed using low energy ions at 5 kV.

The detailed description of the sample preparation is available in the associated manuscript:

Almeida, T. P. *et al.* Preparation of high-quality planar FeRh thin films for *in situ* TEM investigations. *Journal of Physics: Conference Series*, **903**, 012022 (2017).

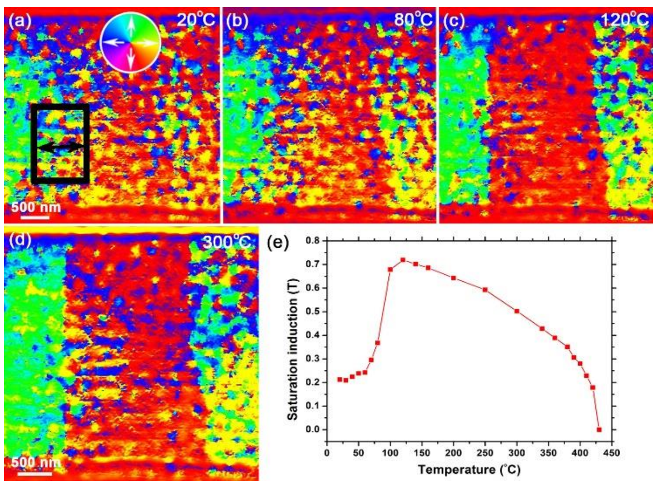

Figure 2. DPC images of DWs at (a) 20 °C; and during in situ heating to (b) 80 °C; (c) 120 °C; and (d) 300 °C. (e) Saturation induction measured from DWs as a function of temperature.

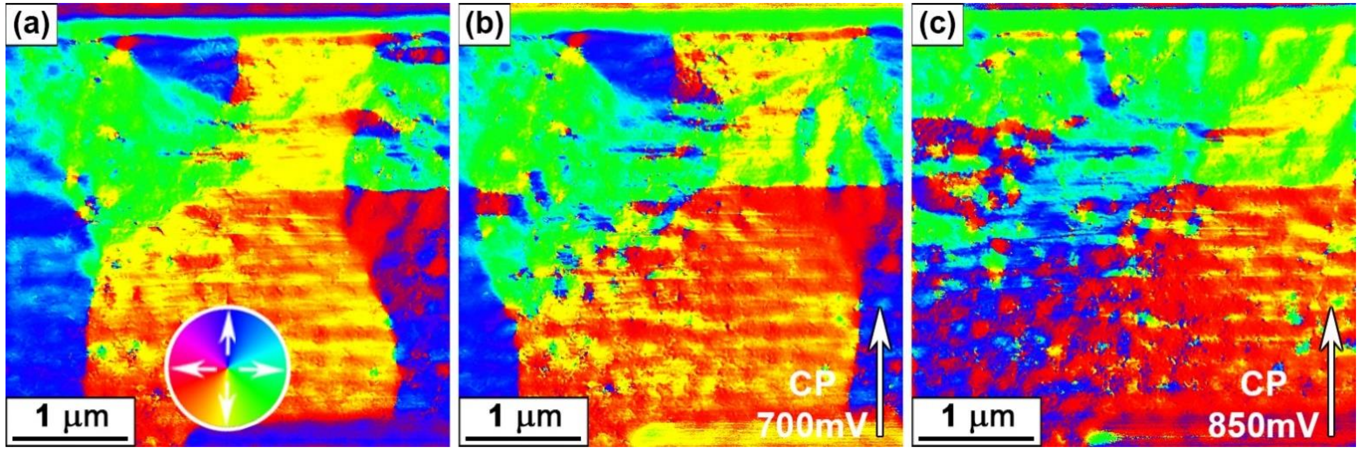

Figure 3. (a-c) DPC imaging of DWs in a planar FeRh thin film transferred onto a Lightning D9$^+$ TEM Nano-Chip heated to (a) 150°C, after application of 500μs current pulses (CPs) of (b) 950 mV and and (c) 1020mV in the arrowed direction. The direction of magnetization in (a-c) is depicted in the colour wheel in (a) (inset).

2. *In situ* heating and quantitative measurements from DWs

Using the Wildfire system, the FeRh planar thin films were heated *in situ* within the TEM, providing thermal energy to induce the magnetostructural transition from the AF to FM phase. The authors were then able to drive the DWs into a configuration of parallel DWs using sample tilting and the magnetic field of the objective lens (Figure 2). Direct measurements of magnetic deflection from the DWs (Fig. 2a, black boxed region) as a function of temperature (Fig. 2a-d) allowed for calculation of the saturation induction and quantitative charting of magnetic transition (Fig. 2e).

3. *In situ* biasing and current-induced DW movement

Combining the Lightning D9$^+$ system and Source Measure Unit from Keithley allowed synergistic *in situ* heating of the FeRh thin film (Fig. 3a) and application of current pulses (Fig. 3 b&c). The magnetostructural transition into the FM phase through *in situ* heating induced the formation of magnetic domains, which is demonstrated by an intricate system of DWs (Fig. 3a). The subsequent application of current pulses (Fig. 3b&c) promoted DW movement into a magnetic state of DWs lying normal to the direction of the application of current pulses.

4. Key Message

- These findings provide fundamental insight into the intricate details of magnetostructural transition from the AF to FM phase in equi-atomic FeRh thin film systems.
- Direct measurements from DWs allowed quantitative charting of the magnetic transition during *in situ* heating on a very localised scale and high level of detail.
- The ability to perform biasing &/or heating *in situ* within the TEM, together with visualising the magnetism using DPC imaging, allows for direct comparison with how the materials would behave on the nanoscale in functional devices.

Almeida T. P. et al. Quantitative TEM imaging of the magnetostructural and phase transitions in FeRh thin film systems. Scientific Reports, **7,** 17835 (2017).

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