Supercooling effect in arrays of FeRh meso- and nanostructures

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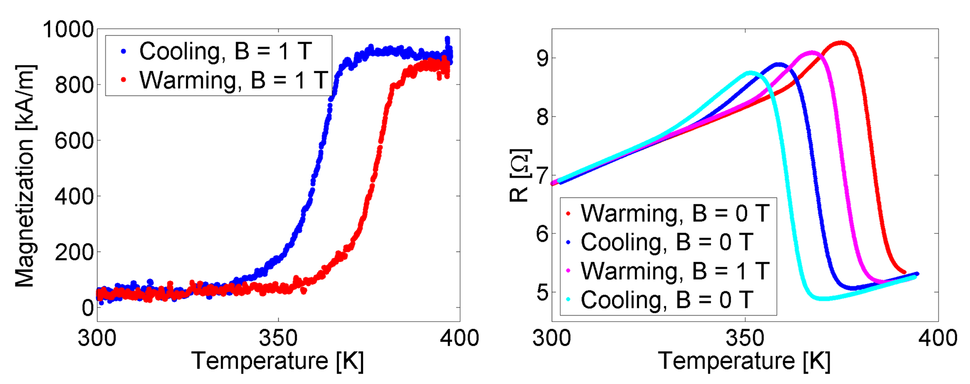
Our focus

We performed MFM measurements of arrays of submicron FeRh discs to get the statistical aspects of the recently observed asymmetric phase transition in confined FeRh structures [1], [2].

1 Introduction – FeRh

- FeRh undergoes a first-order metamagnetic phase transition from antiferromagnetic (AF) to ferromagnetic (FM) order at 360 K (with a thermal hysteresis of 10 K) [3].
- The transition is accompanied by a volume increase and a reduction in resistivity, thus possessing interconnected structural, magnetic and electronic order parameters [3].



Changes in magnetization and resistivity of a 35-nm FeRh thin film on MgO.

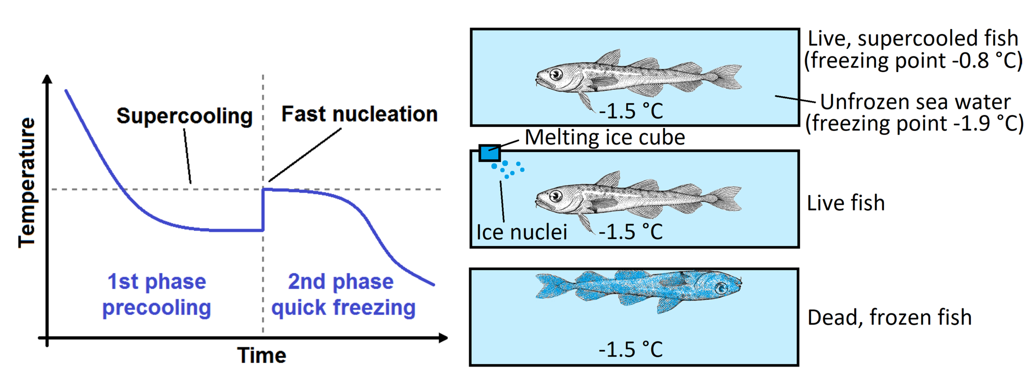
- The phase transition in FeRh can be controlled via different external stimuli (temperature, magnetic field, strain, electrical current or optical pulses).

2 Supercooling effect

- Thermodynamically unstable state in which matter remains in the 1st phase after it is cooled down below the temperature needed for phase transition to the 2nd phase.
- Creation of nucleation centres in the supercooled matter causes a sudden phase transition.

In case of water:

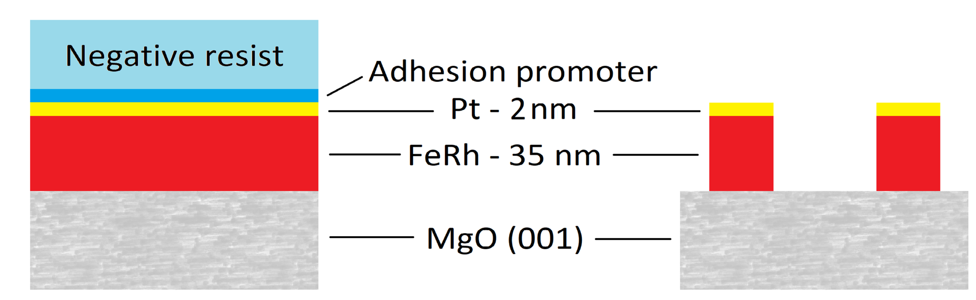
- Water under standard conditions frozen at $T = 0\,^\circ$C.
- High purity water can remain liquid below $0\,^\circ$C (maximum $-50\,^\circ$C [4]) under special conditions.
- Supercooling effect is very important for animals and plants or food industry and biological applications.
- Mpemba effect – warmer water freezes faster [5].



Cooling curve showing the supercooling effect (left). Fish e.g. Boreogadus saida (right) survives thanks to the supercooling effect in cold fjord water. Its fluids stay liquid below the freezing point in case of lack of ice nuclei in the environment [6].

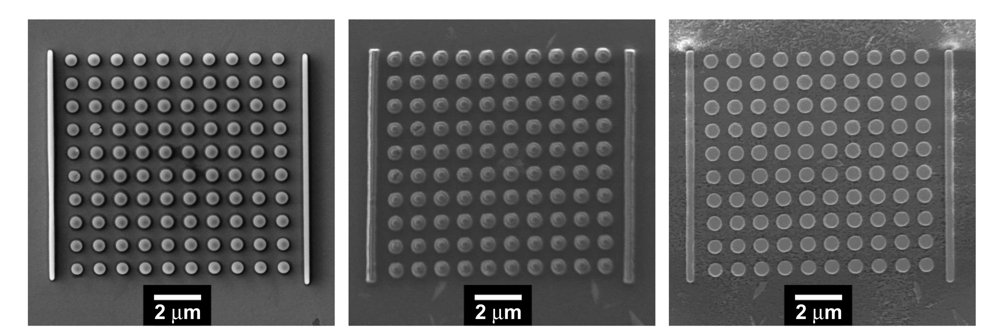
3 Sample preparation

- Epitaxial FeRh thin films were deposited on a single-crystal MgO (001) substrate by magnetron sputtering.



Schema of preparation of FeRh nanostructures.

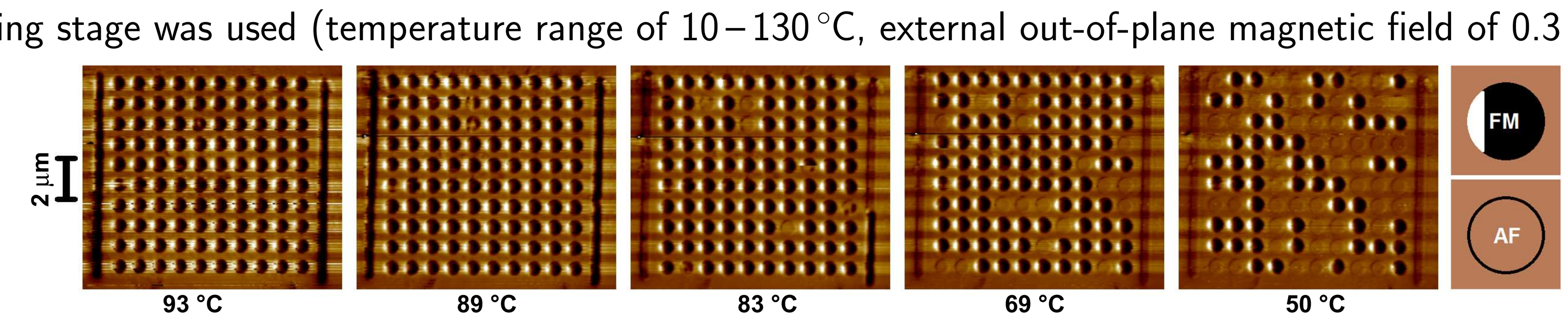
- The source FeRh film was patterned into 10×10 arrays of submicron nanodiscs using electron beam lithography (EBL), ion beam etching (IBE) and BOE etching (Buffered Oxide Etch).



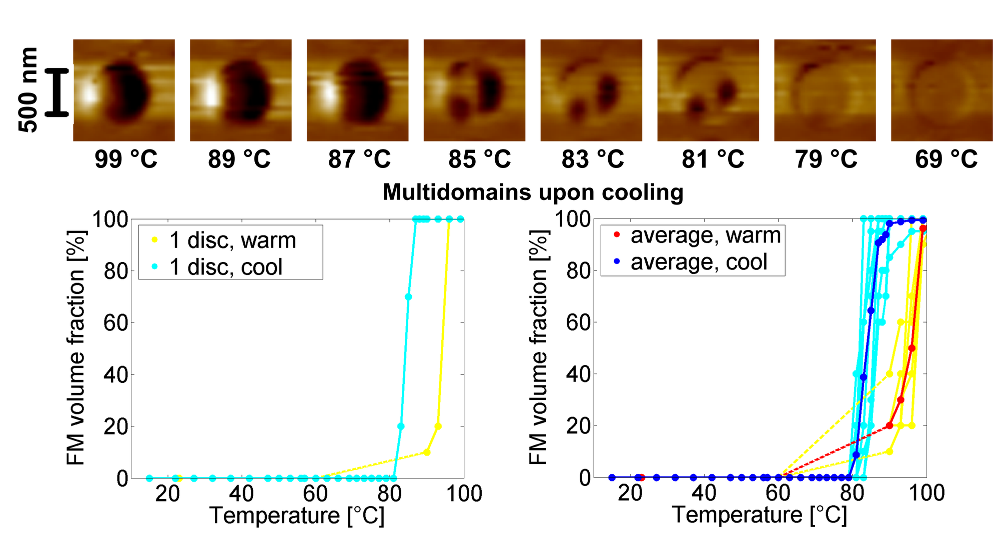
Array of 10×10 discs with 500-nm diameter after EBL and negative resist development (left), after IBE (centre) and after BOE etching (right).

4 MFM measurements of arrays of FeRh discs

- Magnetic force microscopy (MFM) measurements with Co-Cr tips were performed to image the magnetic domains.
- Special heating stage was used (temperature range of 10 – 130 °C, external out-of-plane magnetic field of 0.3 T).

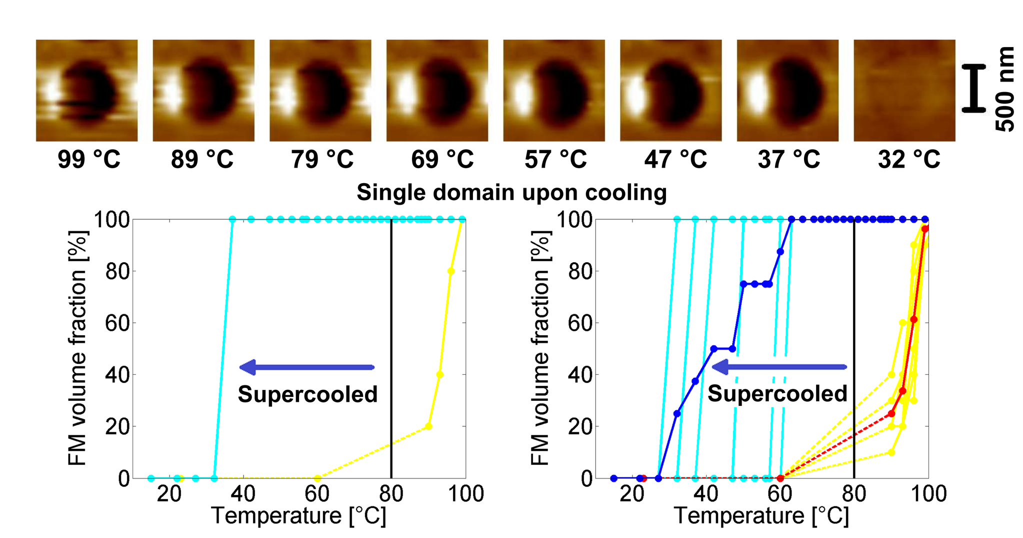


Magnetic signal from MFM – array of 10×10 discs with $d = 500\,$nm – cooling part (phase transition FM → AF).



Magnetic signal corresponding to 1 disc.

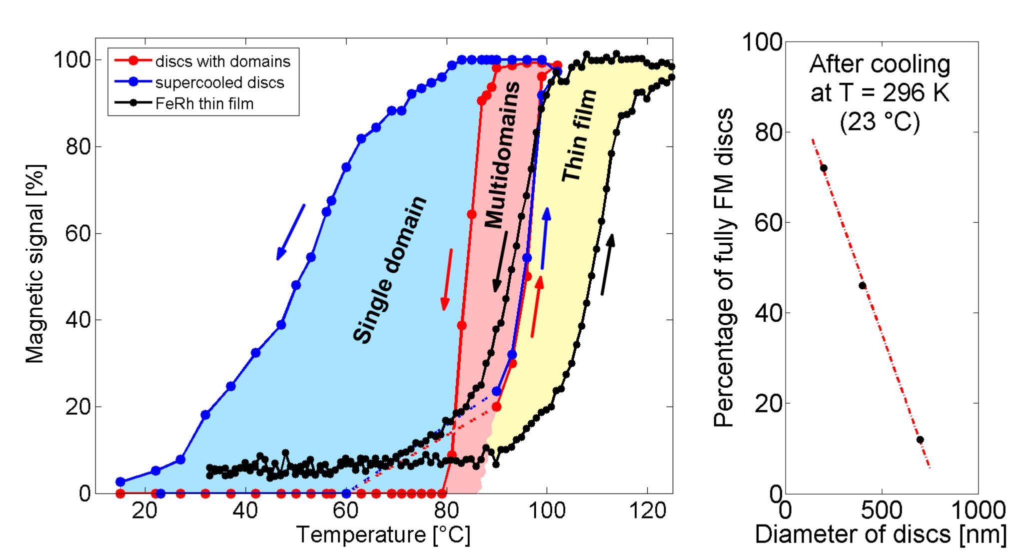
Magnetic signal averaged for 8 discs.



Magnetic signal corresponding to 1 disc.

Magnetic signal averaged for 8 discs.

5 Statistics



Comparison of averaged magnetic signal (discs, the source thin film, left). Decreasing disc size improving chance to survive supercooled (right).

- Upon heating, the phase transition proceeded through nucleation of FM domains in each 500nm disc (15 K shift to lower temperature in contrast to the source thin film due to strain relaxation [2]).

6 Summary

- FeRh meso- and nanostructures were prepared and their metamagnetic phase transition was studied via MFM.
- Upon cooling, small percentage of discs underwent phase transition via disintegration of FM domains. Most of the discs stayed in a fully FM supercooled state at temperatures below the phase transition temperature of the thin film.
- Upon further cooling, supercooled discs showed the transition in form of abrupt change (one by one). The individual transition temperatures of the discs span over more than 50 K, i.e. discs survived in FM even below T_{room}.
- High reproducibility of the supercooled state in each disc.
- Smaller discs showed higher probability to be supercooled.

References

1. V. Uhlíř, J. A. Arregi, and E. E. Fullerton, *Nat. Commun.* **7**, 13113 (2016).
2. J. A. Arregi et al., *J. Phys. D: Appl. Phys.* **51**, 105001 (2018).
3. L. H. Lewis, C. H. Marrows, and S. Langridge, *J. Phys. D: Appl. Phys.* **49**, 323002 (2016).
4. E. B. Moore, and V. Molinero, *Nature* **479**, 10586 (2011).
5. E. Mpemba, and D. Osborne, *Phys. Educ.* **4**, 172 (1969).
6. J. Davenport, Animal Life at Low Temperature, *Springer Science & Business Media* (1992).

Acknowledgements

We acknowledge the Grant Agency of the Czech Republic (grant no. 16-23940Y). This research was carried out under the project CEITEC 2020 (LQ1601) with financial support from the Ministry of Education, Youth and Sports of the Czech Republic under the National Sustainability Programme II. This work was carried out with the support of CEITEC Nano Research Infrastructure (ID LM2015041, MEYS CR, 20162019), CEITEC Brno University of Technology. This work has received funding from the European Union's Horizon 2020 research and innovation programme under the Maria Sklodowska-Curie and is co-financed by the South Moravian Region under grant agreement No. 665860. This material reflects only the author's view and the EU is not responsible for any possible use of the information contained herein.