Direct observation of tensile-strain-induced magnetic hardening in a ferromagnet

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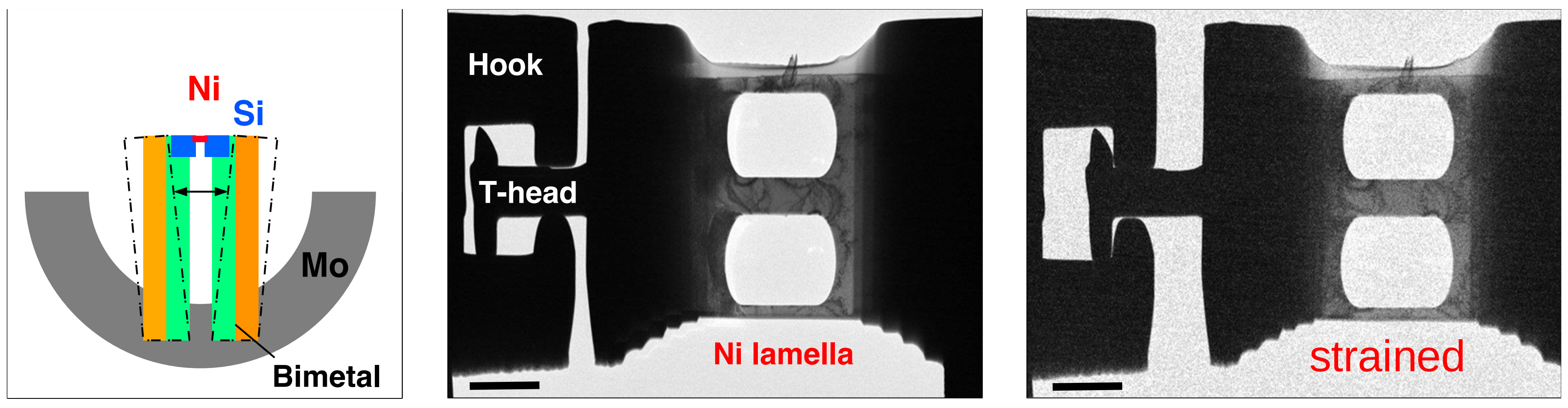
Introduction

Magnetoelasticity is the bond between magnetism and mechanics, but the intricate mechanisms via which magnetic states change due to mechanical strain remain poorly understood. Here, we provide direct nanoscale observations of how tensile strain modifies magnetic domains in a ferromagnetic Ni thin plate using in situ Fresnel defocus imaging, off-axis electron holography and a bimetallic deformation device [1]. We present quantitative measurements of magnetic domain wall structure and its transformations as a function of strain. We observe the formation and dissociation of strain-induced periodic 180° magnetic domain walls perpendicular to the strain axis. The magnetization transformation exhibits stress-determined directional sensitivity and is reversible and tunable through the size of the nanostructure. In this work, we provide direct evidence for expressive and deterministic magnetic hardening in ferromagnetic nanostructures, while our experimental approach allows quantifiable local measurements of strain-induced changes in the magnetic states of nanomaterials.

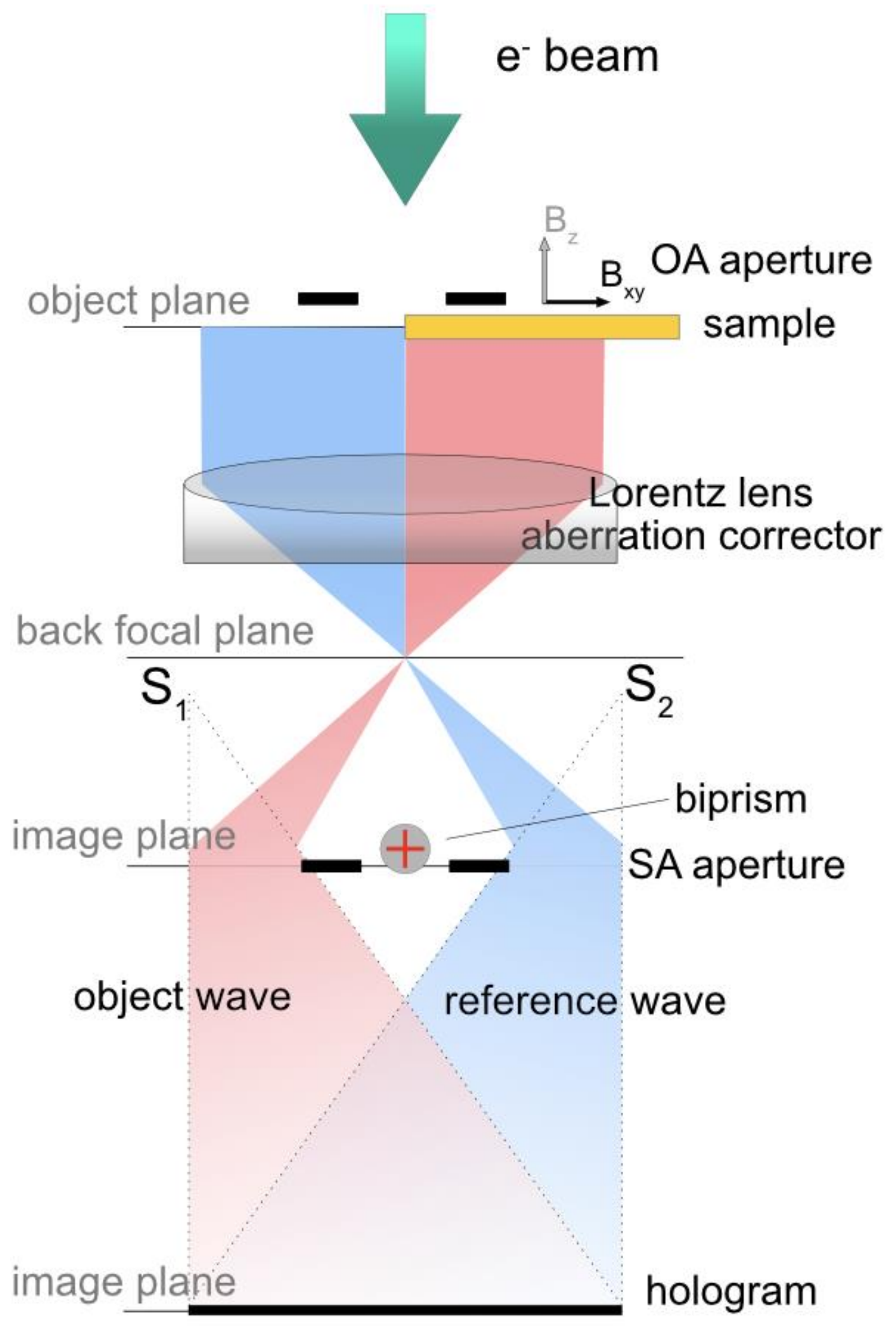
[1] D. Kong et al., Nature Communications **14**, 3963 (2023)

In situ tensile straining in the TEM



The FIB prepared specimen was mounted between two bimetal stripes, which deforms upon a moderate heating applying a tensile strain on the specimen.

Off-axis electron holography



Raypath of the electron wave for off-axis electron holography.

It measures the phase shift of the electron wave that interacts with the electromagnetic field of the sample. The phase shift contains electrostatic and magnetic contributions that needs to be separated to measure the magnetic induction quantitatively.

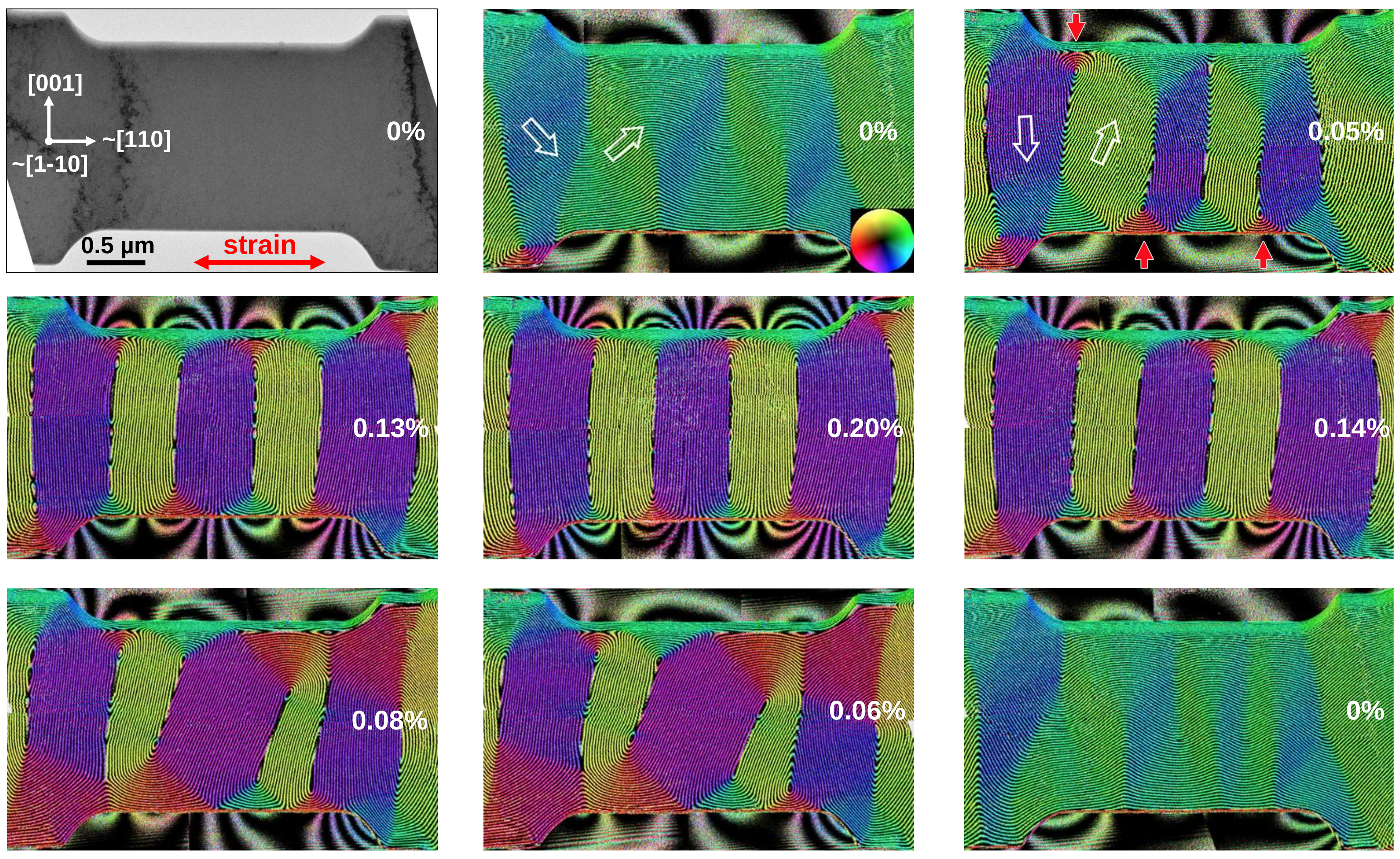
$$\phi(x) = \phi_E + \phi_M = C_E \int V(x,z)dz - \frac{2\pi e}{h}\int A_z(x,z)dz$$

The magnetic induction lines can be visualised by adding contours and colors.

Furthermore the magnetic phase can be used to recover the projected in-plane magnetisation (M) using a model-based reconstruction algorithm.

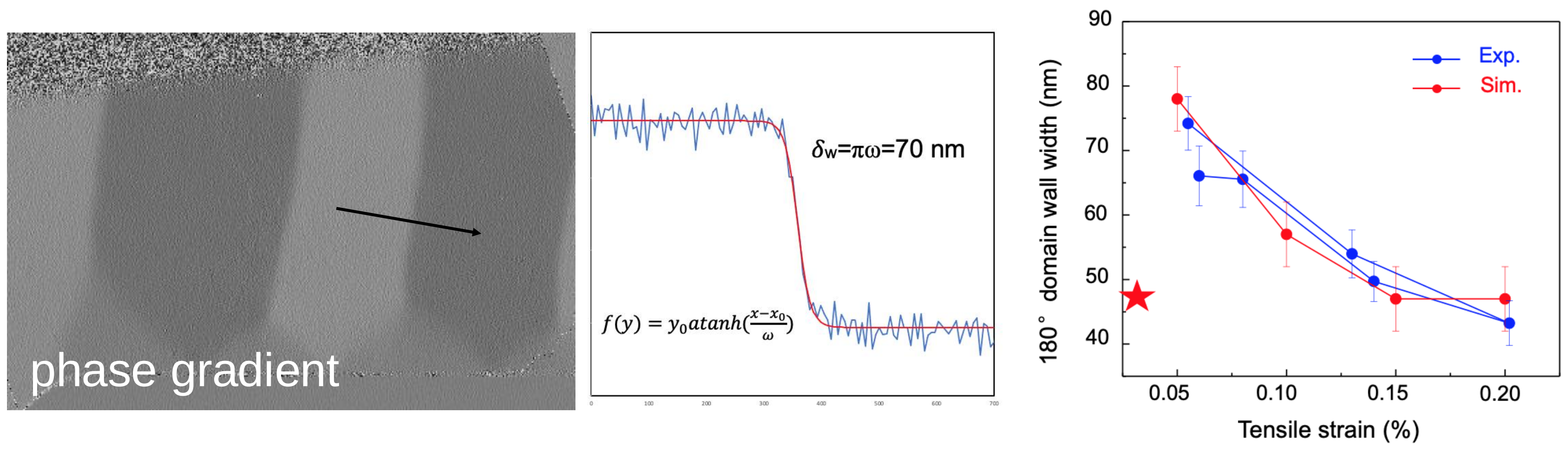
[1] A. Kovács, R.E. Dunin-Borkowski, Handbook of Magnetic Materials, vol 27. (2018) 59

Methods and Results



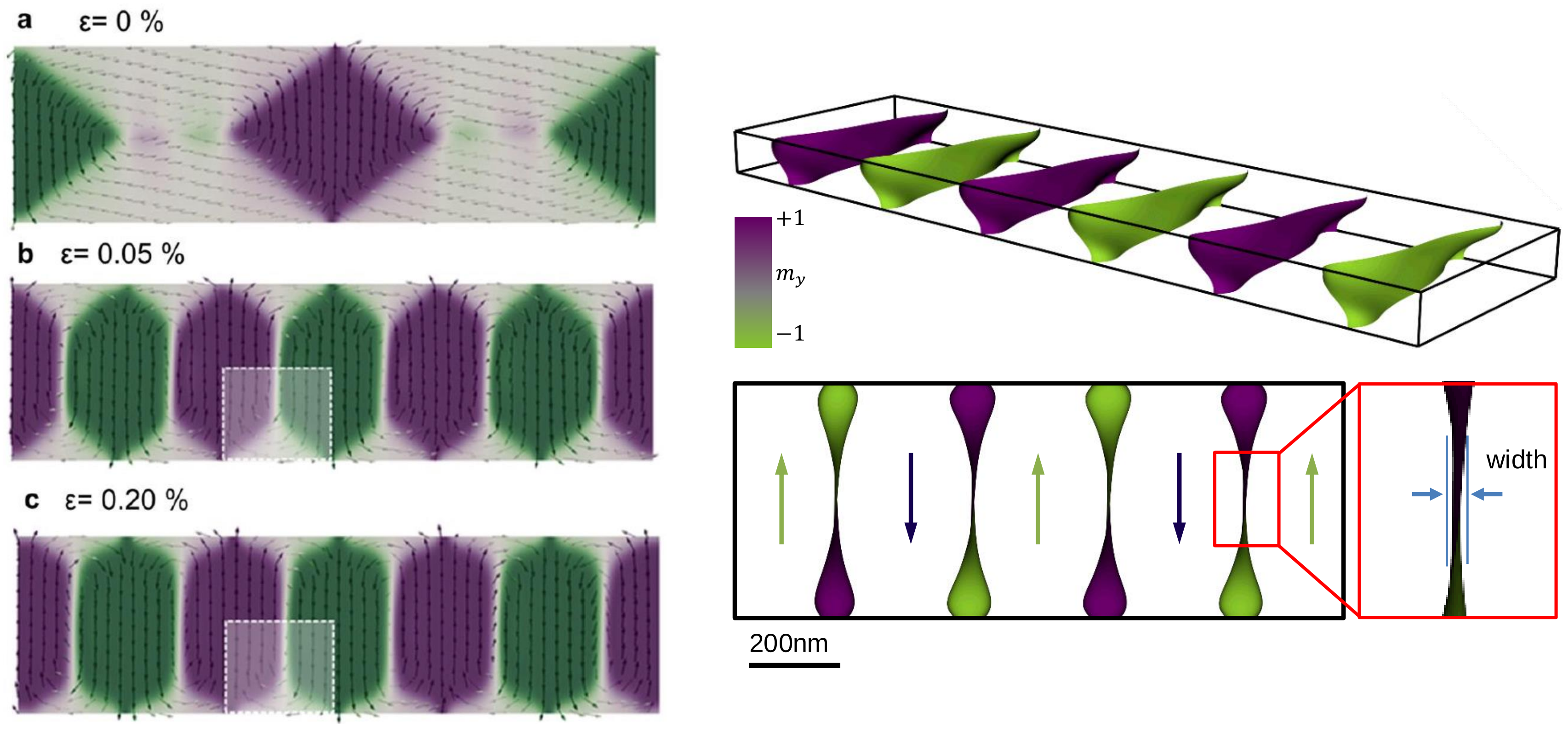
Magnetic induction maps as a function of in-plane tensile strain showing the reorientation of the domains perpendicular to the strain direction (negative magnetostriction) and formation of 180º domain walls. The contour spacing is 2π/3 rad.

Domain wall width measurement



Width ≈$\sqrt{A/K_{eff}}$, thus it gives information of the effective anisotropy changes. The larger than nominal width is due to the twisted shape of the walls inside the specimen.

Micromagnetic simulations



Simulations and domain wall iso-surfaces showing the 3-dimensional shapes, which are twisted from edge to edge.

Our results demonstrate directly that a change in interatomic spacing associated with strain induces a substantial anisotropy that can lead to a transformative change in the magnetic state and magnetic hardening of a nanoscale sample.

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