A novel approach towards manipulation of vortex matter in a superconductor with micromagnetic structures

Experimental Physics of Nanostructured Materials

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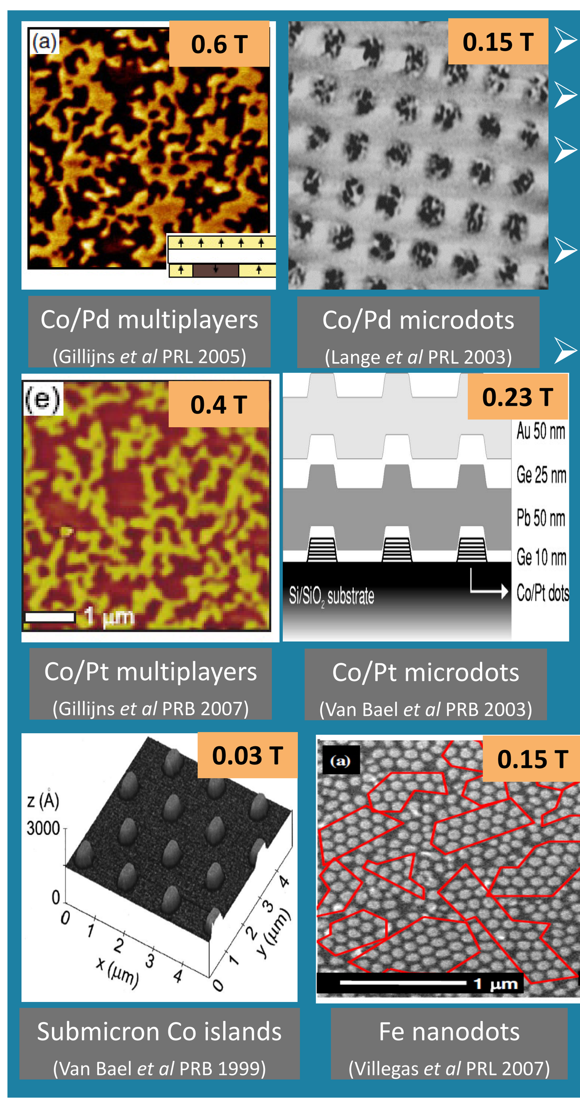
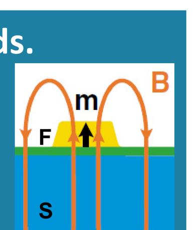
Permanent micromagnet structures prepared using thermomagnetic patterning (TMP) present an interesting and so far unexplored option for controlled vortex pinning in a superconductor. We have investigated the vortex matter in superconductor/TMP micromagnet heterostructures (Nb/NdFeB) using quantitative Magneto-Optical Imaging (MOI). Comprehensive protocols have been developed for calibrating and converting Faraday rotation data acquired by MOI to magnetic field maps. These protocols reveal the comparatively weaker magnetic response of the superconductor from the background of larger fields associated with the magnetic layer in its vicinity. Further, TMP micromagnet structures have been imprinted in a Permalloy (Py) layer to obtain flexible magnetic landscapes for flux guidance in a Nb layer below it.

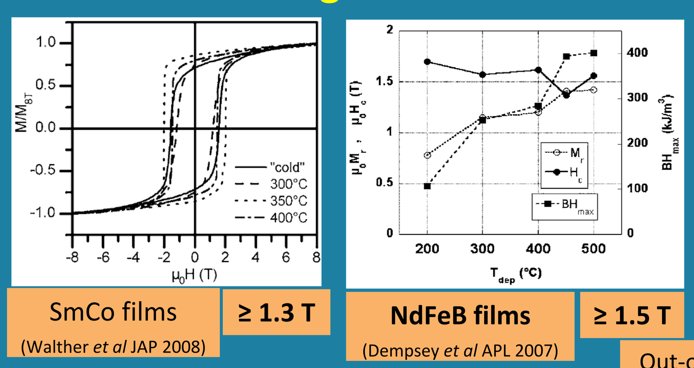
Permanent magnets to manipulate vortex matter



- Superconductor/Ferromagnet (S/F) hybrids.
- Our interest: 'Hard ferromagnets'.
- Ferromagnet M determined only by magnetic history.
- Unaffected by H_{ext} or screening currents in the S-layer.
- Large coercive field $H_c >> H_{c2}$ of S-layer.



Pushing the limits

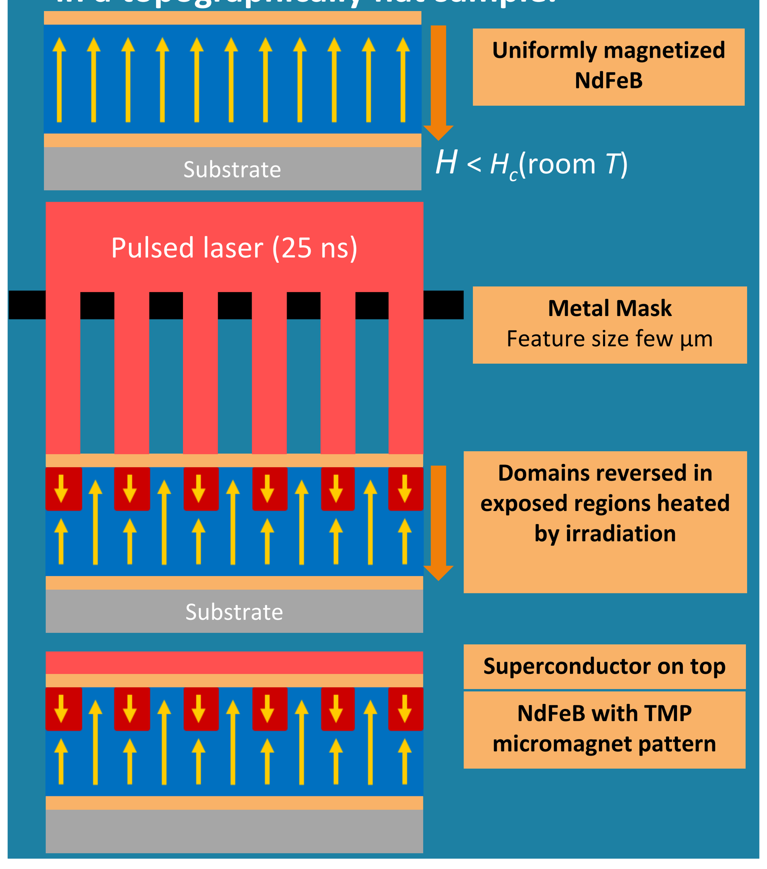


Why these materials?

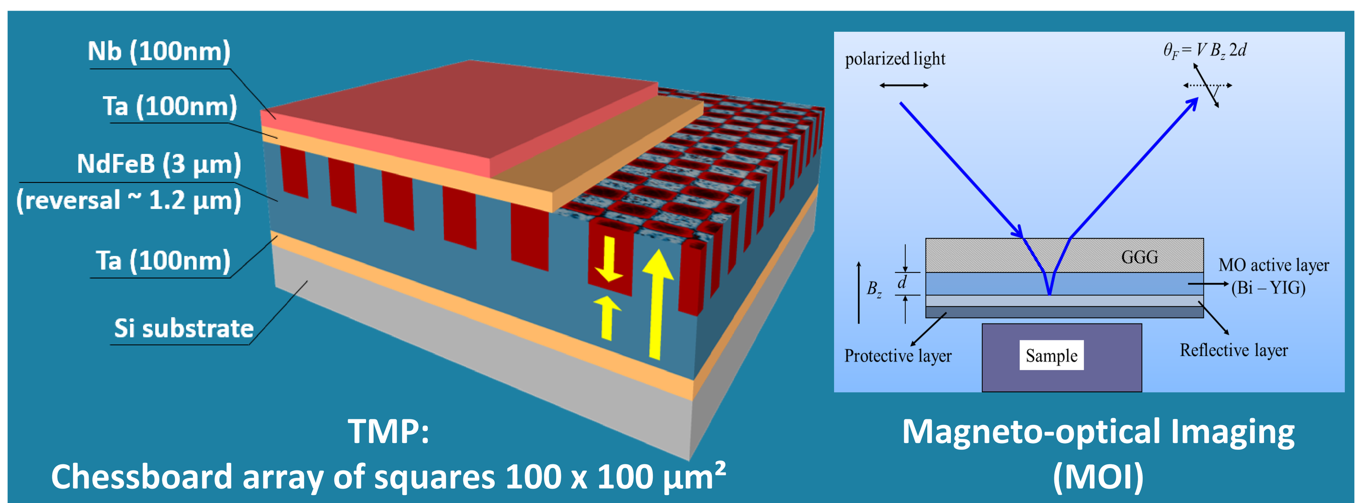
- High $\mu_0 H_c$ and $\mu_0 M_r$ (~$\mu_0 H_c$)
- Greater field stability
- Much larger magnetic field amplitudes of interest in technological applications

TMP: A new approach

- **Thermomagnetic patterning (TMP)**[1] to prepare *Micromagnets*: micro flux sources.
- Controlled pinning by spatial modulation of magnetic field at mesoscopic length scales in a topographically flat sample.



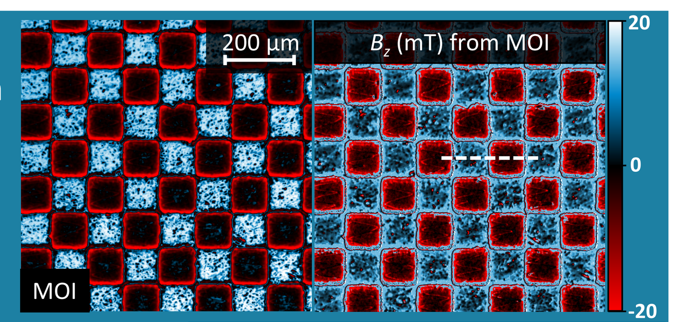
Sample and experiment



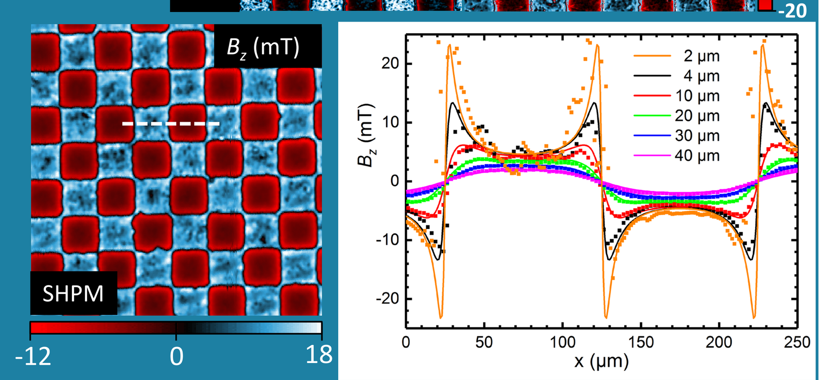
- **Quantitative MOI**[3] to Convert MO intensities to local B values.
- Pixel-by-pixel calibration of intensities.
- Removal of artifacts like inhomogeneous illumination.
- Information on sources of constant magnetic field (such as the ferromagnetic layer).
- Superconductor response. Reveal magnetic response of the superconductor.

Characteristics of the TMP layer

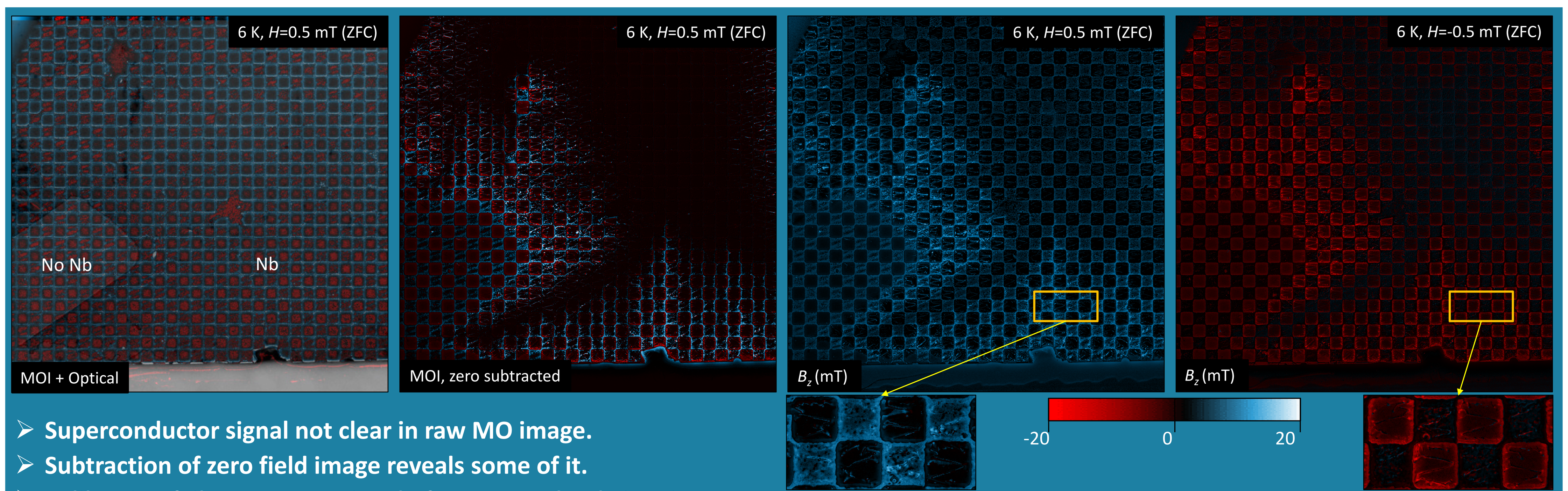
- MO Calibration works except at domain boundaries with large gradients.
- In good agreement with SHPM measurements at room T.



- Experimental profiles compared to calculated profiles for parallelepiped domains with out-of-plane magnetization.
- Effective height of the MO imaging plane from the sample surface ~ 2 µm.



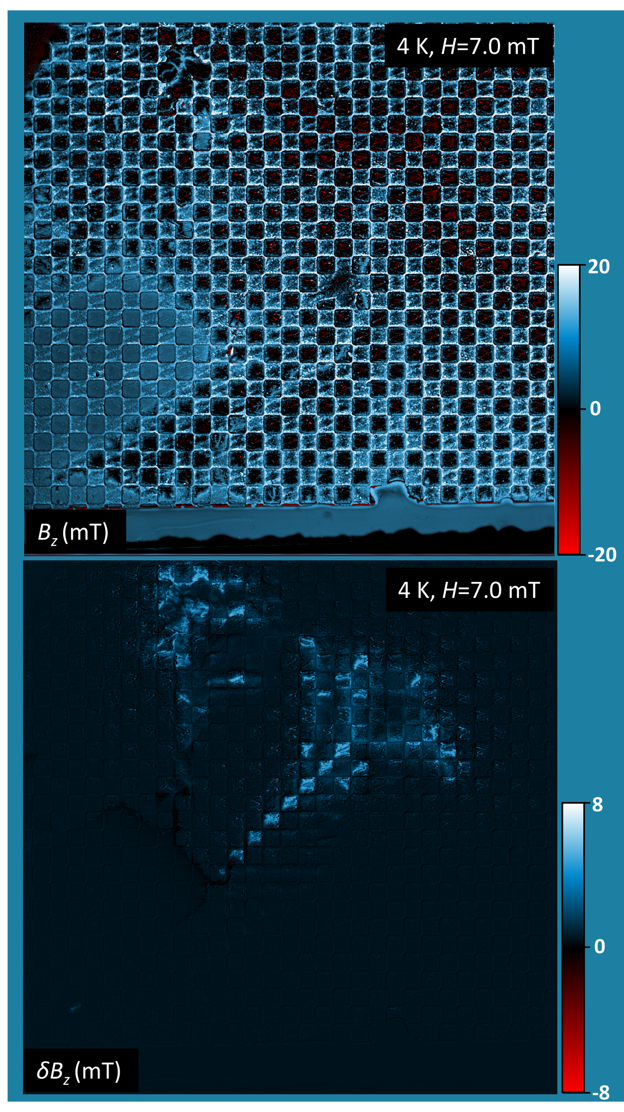
Smooth flux penetration in Nb



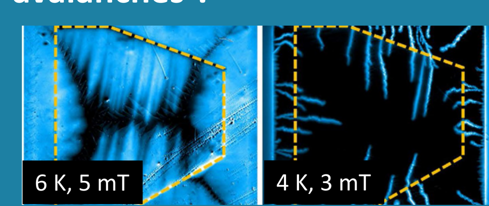
- Superconductor signal not clear in raw MO image.
- Subtraction of zero field image reveals some of it.
- Calibration fails to remove signal of TMP completely in B image.
- Interesting feature revealed in the B image.
- Strong flux accumulation in one set of squares.
- Indicates flux guidance by the TMP pattern.
- Flux accumulation in other set of squares upon reversing H.

- Spontaneous vortices induced by the magnetic pattern.
- Incoming 'positive' vortices annihilated by antivortices in 'negative' squares. Unimpeded entry into 'positive' squares.
- Strong magnetic pinning of positive vortices in positive squares.
- More accumulation near square edges.

Flux jumps guided by the magnetic pattern

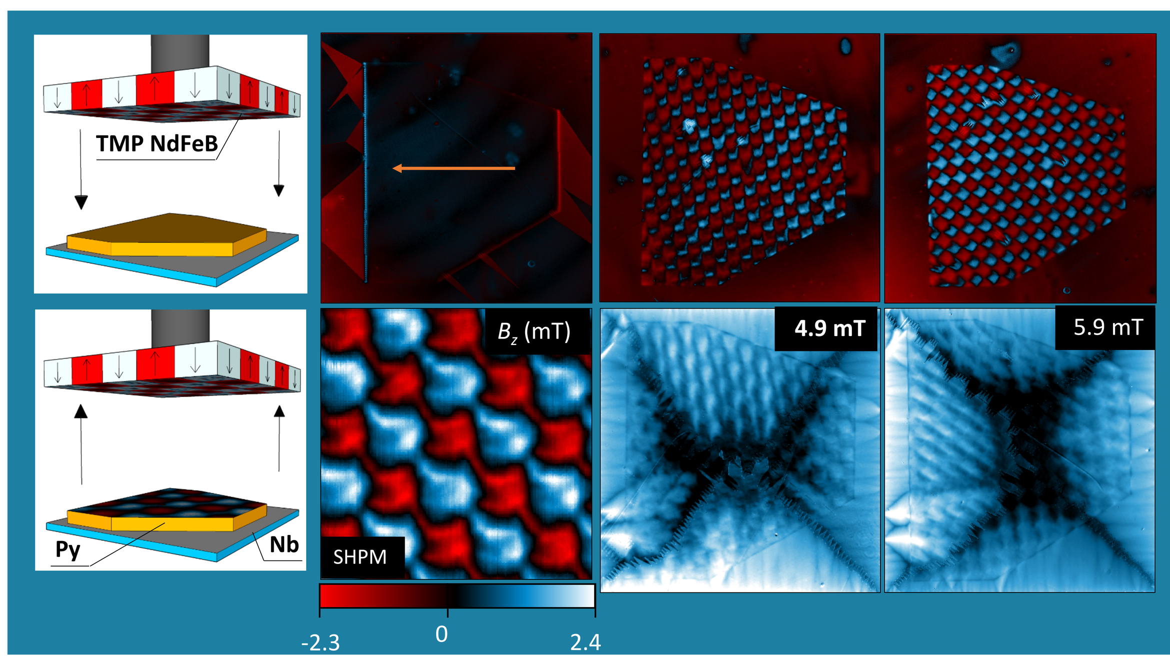


- At lower T, smooth flux penetration interspersed with avalanche-like flux jumps.
- Distinct from usually observed avalanches[2].



- Flux jumps strongly influenced by the magnetic landscape.
- Rapid build-up of flux at the borders of squares with increasing H.
- Resulting steep gradients trigger large flux jumps across squares.
- Smooth flux flow with increasing H as gradients ease out.
- Till gradients become steep enough to trigger flux jumps again.
- Occurs in different regions at different H.

Flux propagation in Nb guided by pattern in Py



- TMP pattern imprinted the in Permalloy in a Py/Nb sample.
- Erasable and tailored magnetic landscape.
- Staircase-like paths of flux flow in Nb,
- Clearly guided by the chessboard pattern in Py.
- Revealing superconductor signal much easier than in Nb/NdFeB due to weaker fields and gradients in Py.

Acknowledgements

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References

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3. G. Shaw et al, unpublished.

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