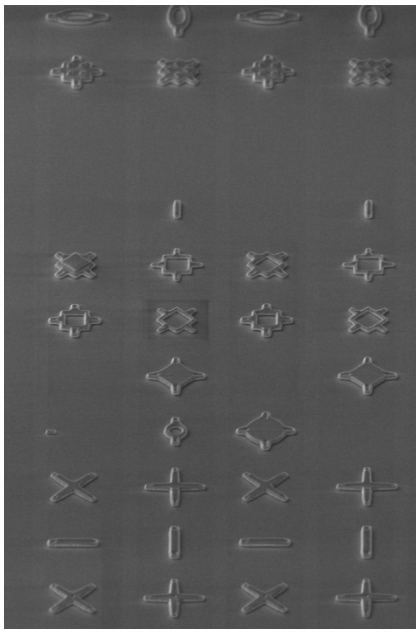
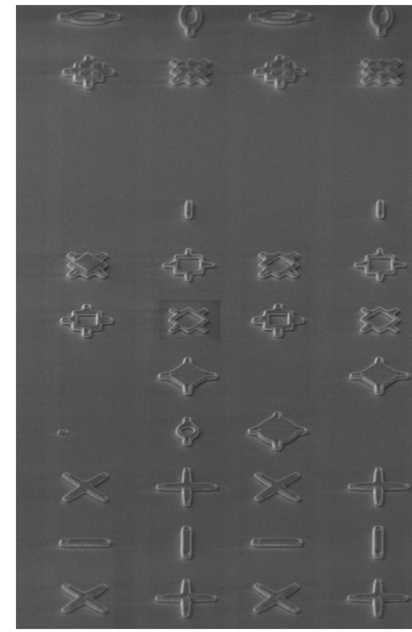
Making high quality freestanding magnon nanoresonators





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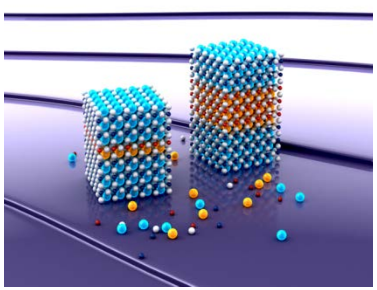
Financial support

EC funding: IP-IFOX

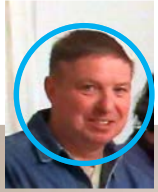
DFG: SFB 762

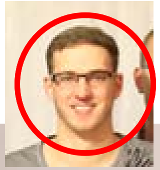


Funktionalität Oxidischer Grenzflächen

SFB 762

Contributors/Collaborators





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Overview

Why YIG nanoresonators?

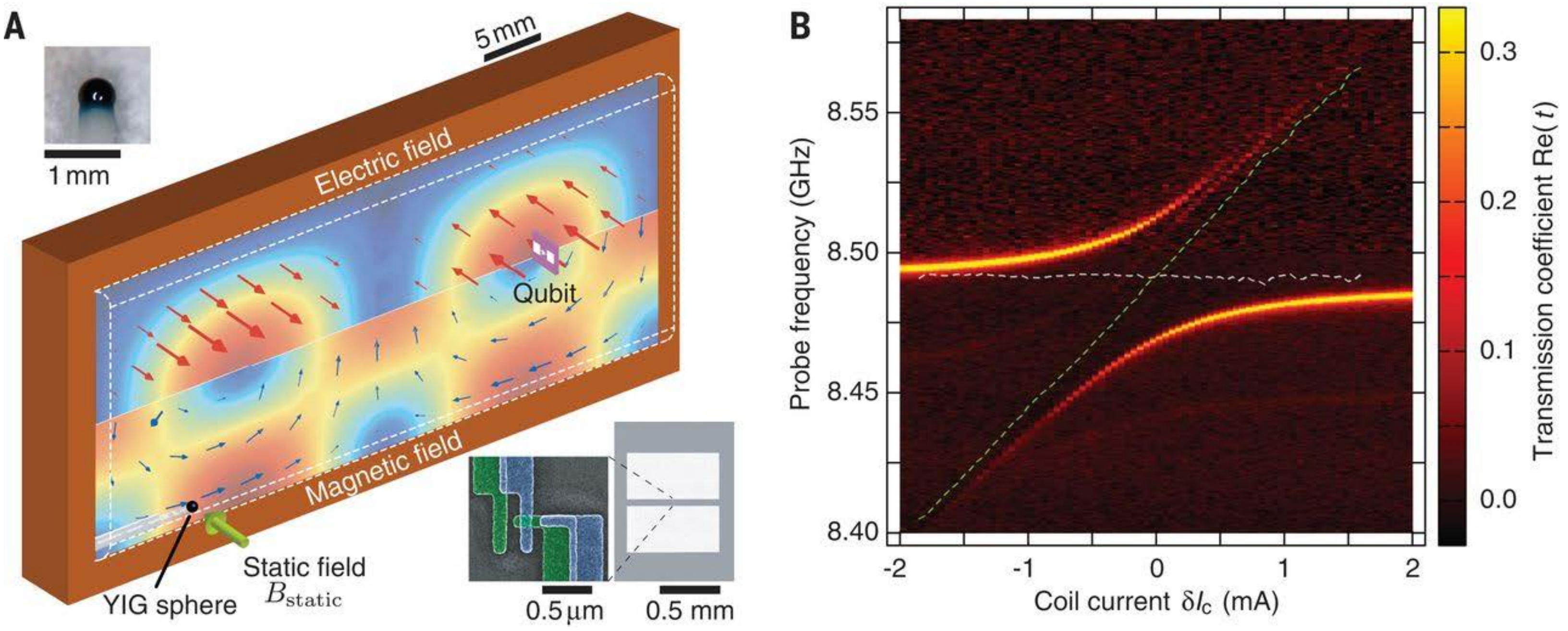
How to make them?

Structural properties

Magnonic properties

Quantum information processing

- Coupling of qubits to magnons successfully demonstrated
- Also promising: coupling of qubits to mechanical oscillators (by electric fields: Chu et al. Science **358**, 199 (2017))
- Why not use magnons and magnetoelastic coupling?

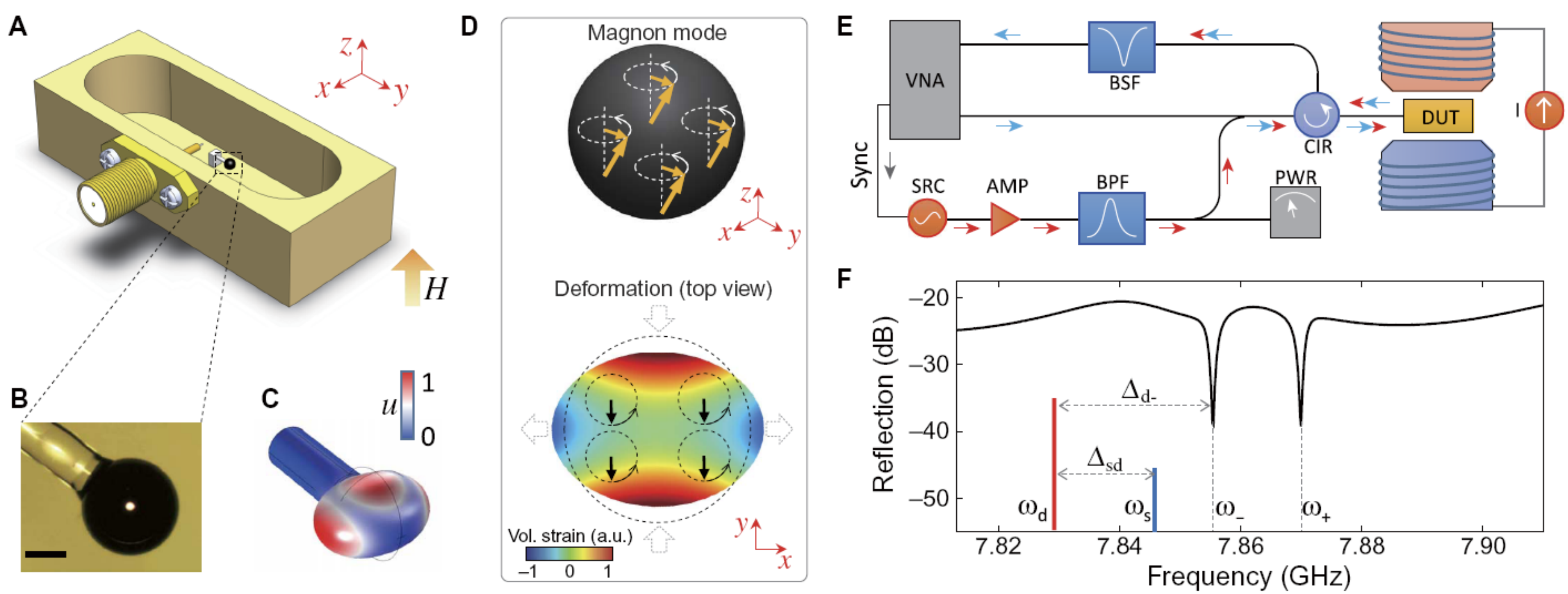


(Tabuchi et al. Science **349**, 405 (2015))

Magnonmechanics

Magnons and Phonons

- Coupling of magnons and phonons recently demonstrated
- Drawback: YIG resonators are macroscopic spheres (250 μm) not suitable for integration



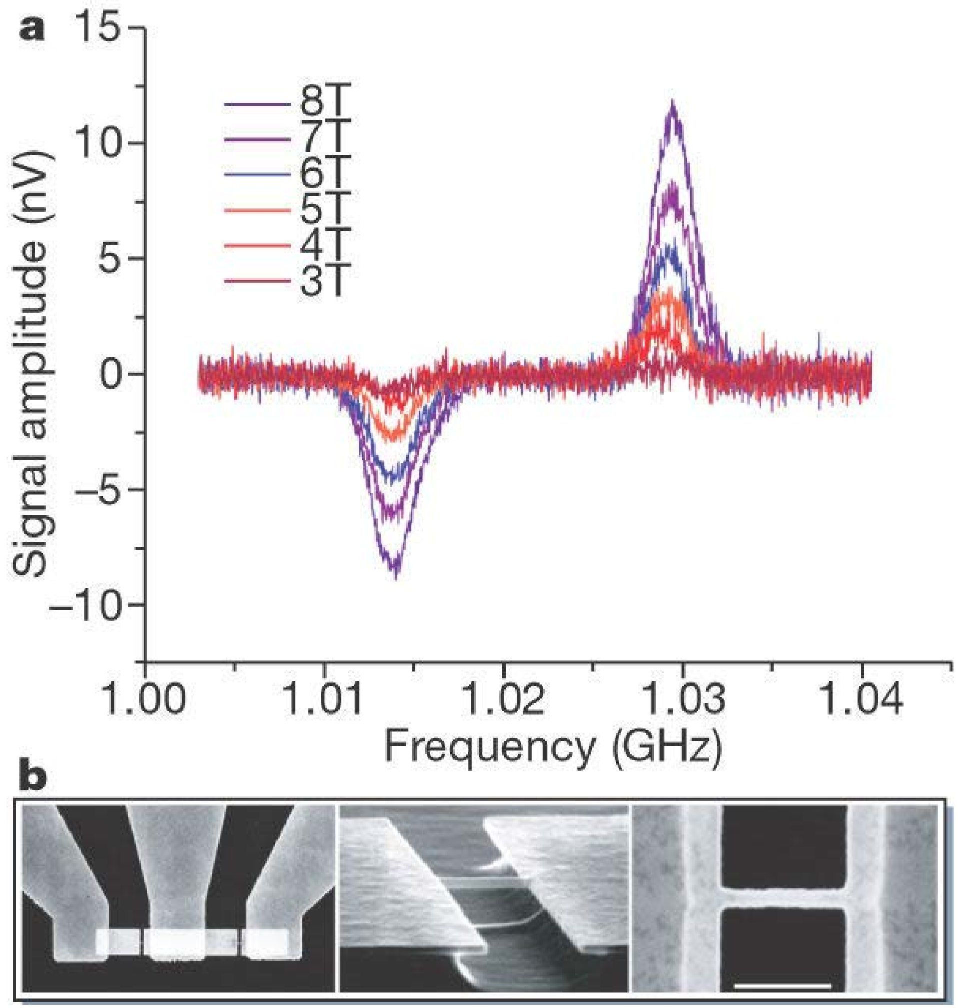
Zhang et al. Sci. Adv. 2016; 2 : e1501286

Overview

Nanostructured
Materials

Can frequencies match?

- Demonstrated in 2003:
  Mechanical nanoresonator with resonance frequency above 1 GHz
- Approaching range of useful magnon frequencies
- Example for YIG:
  1 μm length, 150 nm thickness
  f ~ 1 GHz
- Typical shape:
  cantilever (1 anchor point)
  bridge (2 anchor points)
- How to make them?



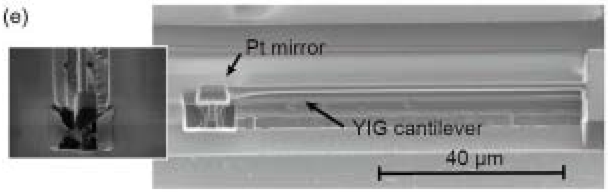
Huang et al. Nature **421**, 496 (2003)

Making cantilevers and bridges

Nanostructured Materials

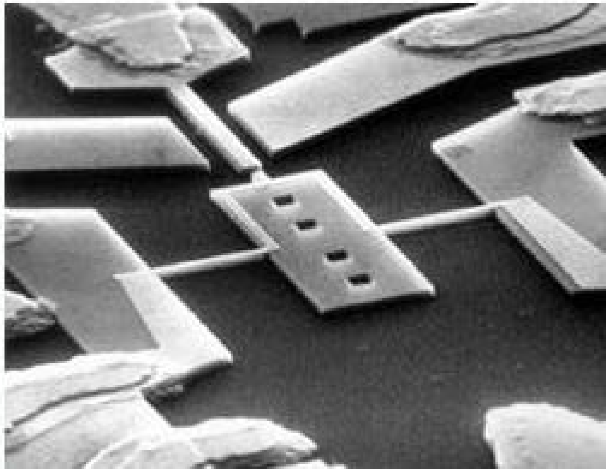
Crystalline materials

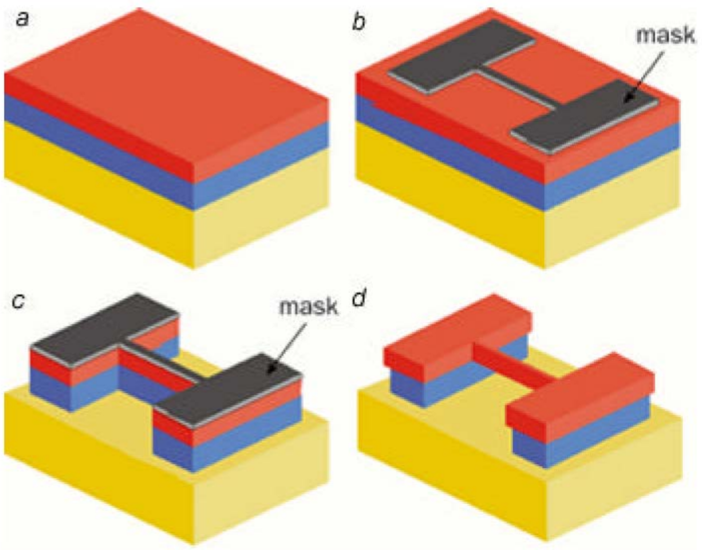
- Epitaxial growth at high temperatures
  - No patterning by resist and lift-off possible
- Use of sacrificial layers and wet etching
- Limited use of focused ion beam techniques



Seo et al. APL **110** (2017)

M.L. Roukes Physics World (2001)

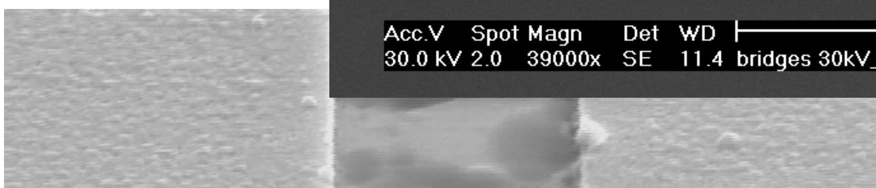


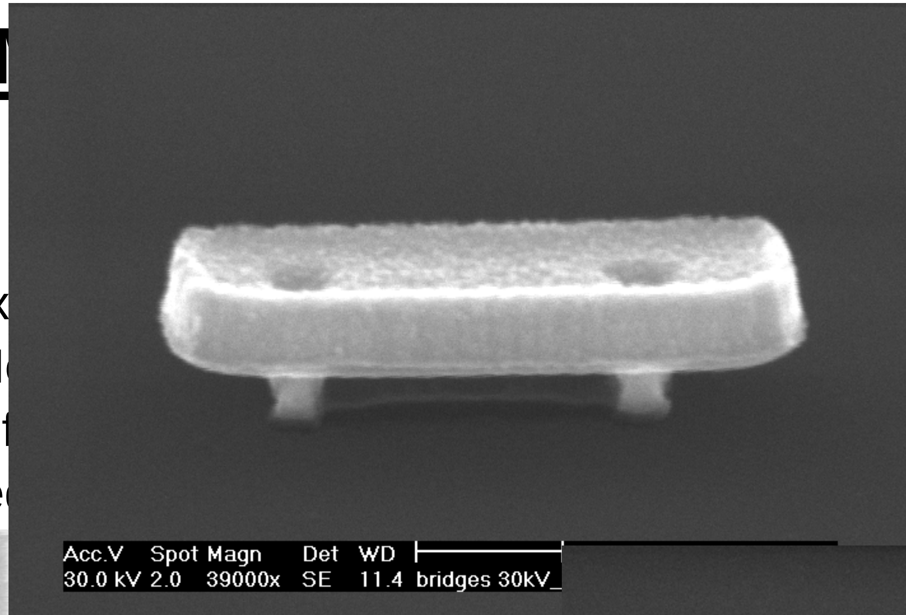


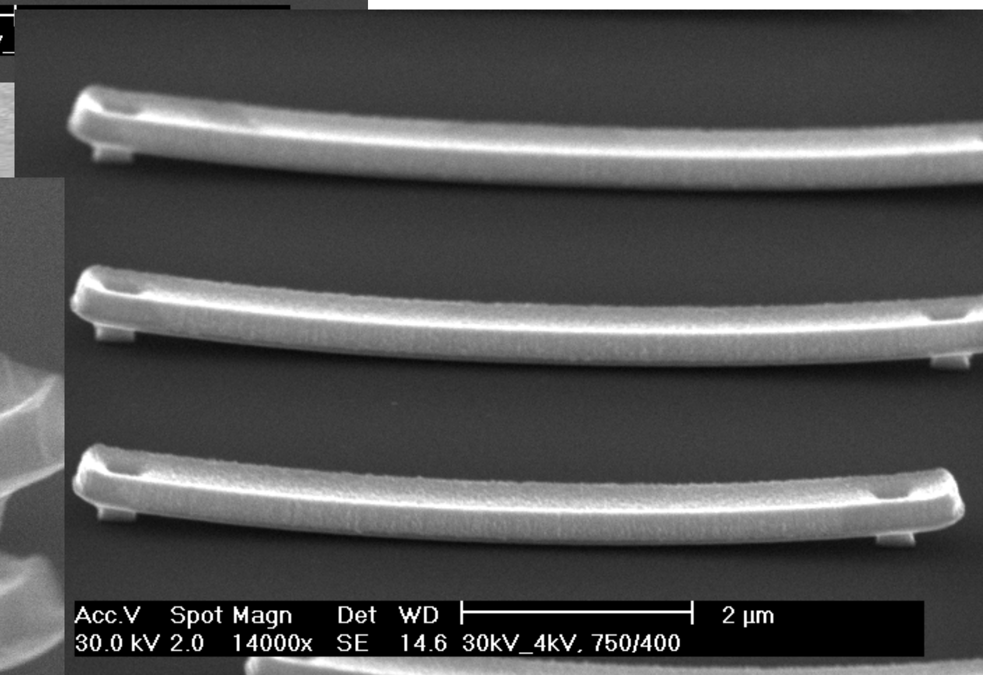
N bridges

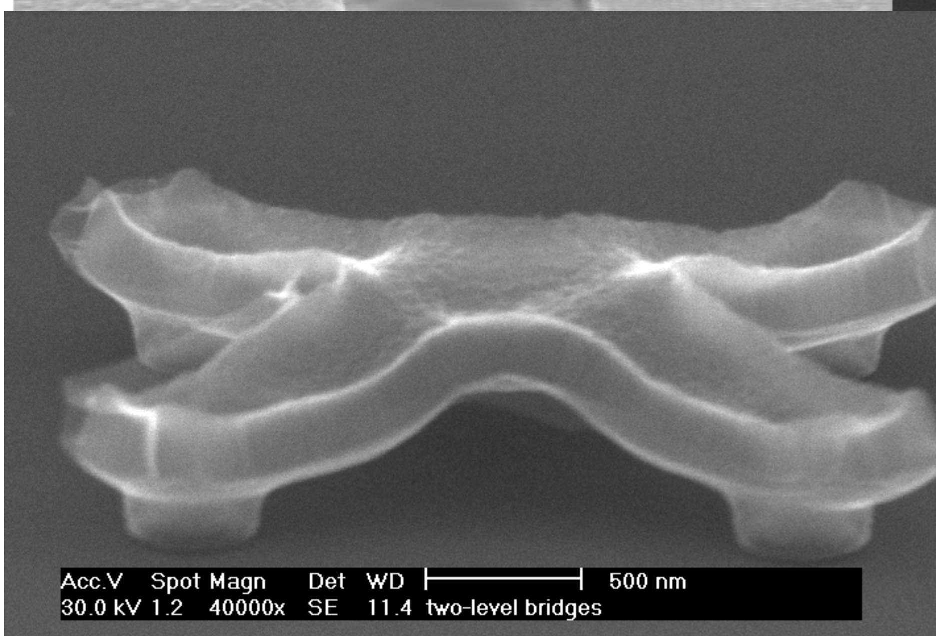
Nanostructured Materials

- Epitax
  - N
- Use of
- Limite









Making cantilevers and bridges

Crystalline materials

– Epitaxial growth at high temperatures
  - No patterning by resist and lift-off possible
– Use of sacrificial layers and wet etching
– Limited use of focused ion beam techniques

Amorphous/polycristalline

– Patterning by lift off
  - Use multilayer resists with different sensitivity
  - Use different acceleration voltages

No sacrificial layers for YIG/GGG!!!

Deposition by LPE or PLD at high temperatures forbids resist-based lift-off!!!

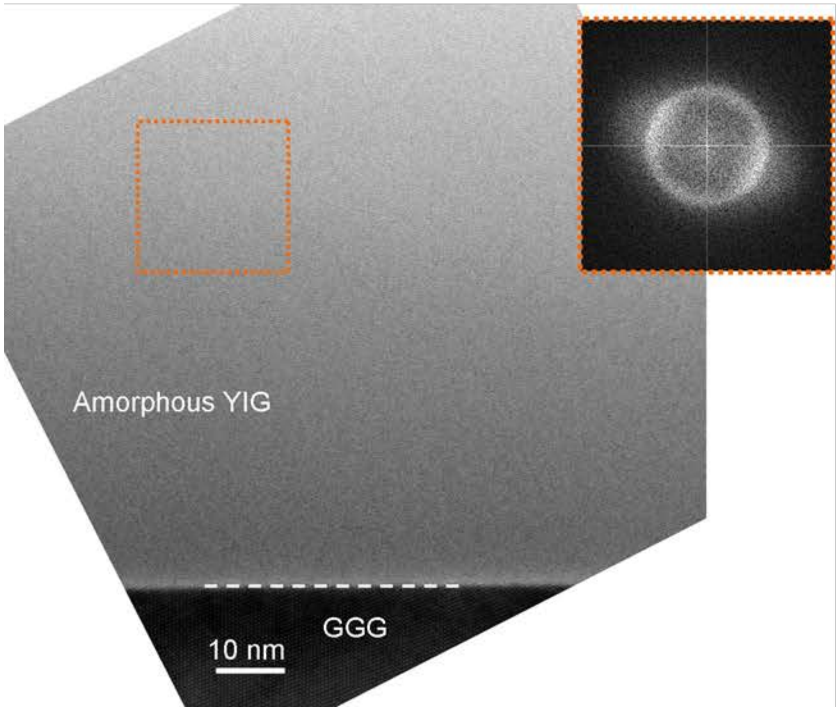
How to combine Lift-Off with crystalline YIG???

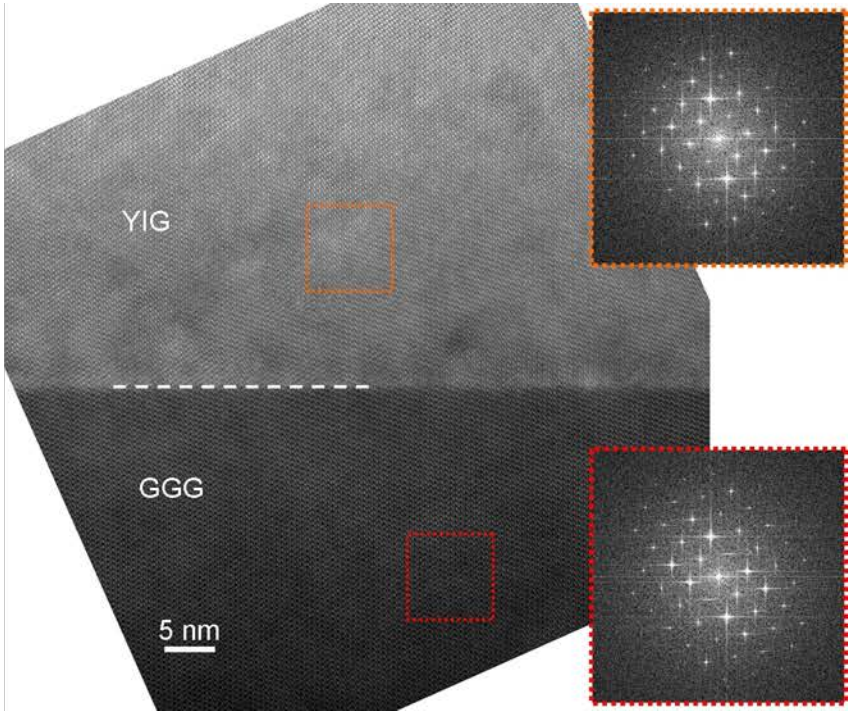
Breakthrough

Nanostructured Materials

YIG deposition by PLD at RT

- Amorphous YIG deposited at RT
- Annealing leads to high quality material
- Perfect crystallization over at least 100 nm
- Substrate acts as seed.





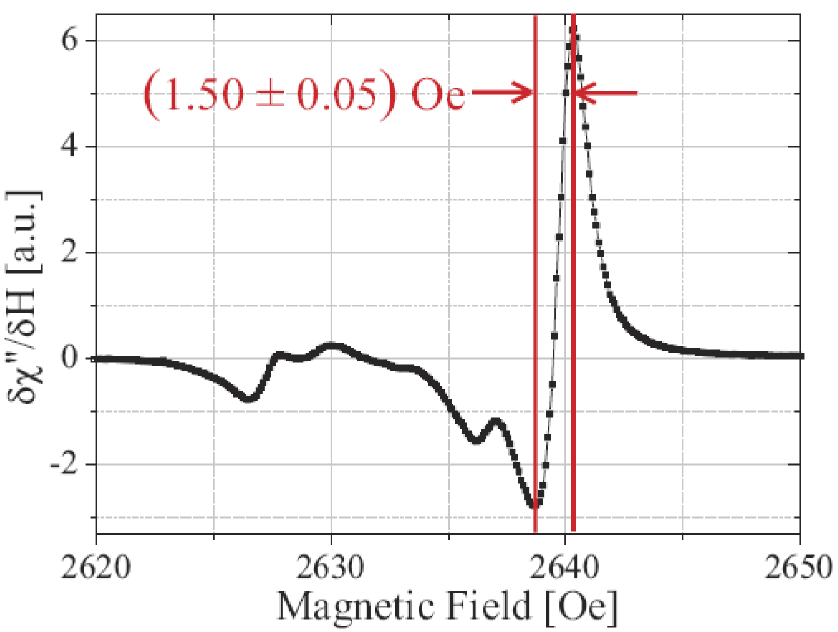
(C. Hauser, GS et al. Scientific Reports **6**, 20827 (2016))

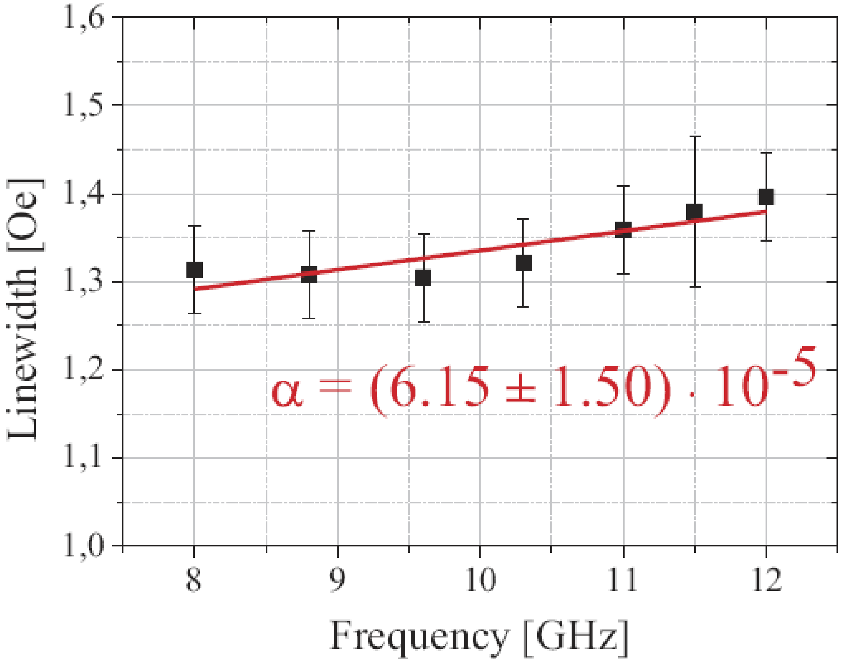
Breakthrough

Nanostructured Materials

YIG deposition by PLD at RT

- Annealed material has very low damping
- For a 56 nm thick layer:
  - Linewidth of 0.13 mT @ 9.6 GHz
  - Damping α=6.15x10^{-5}

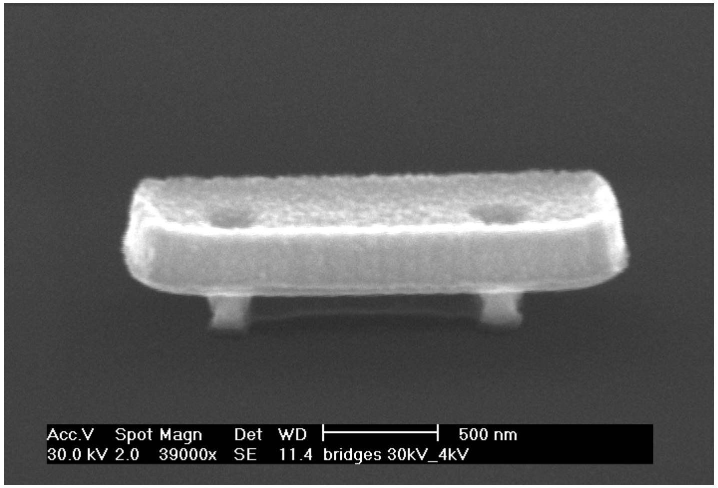




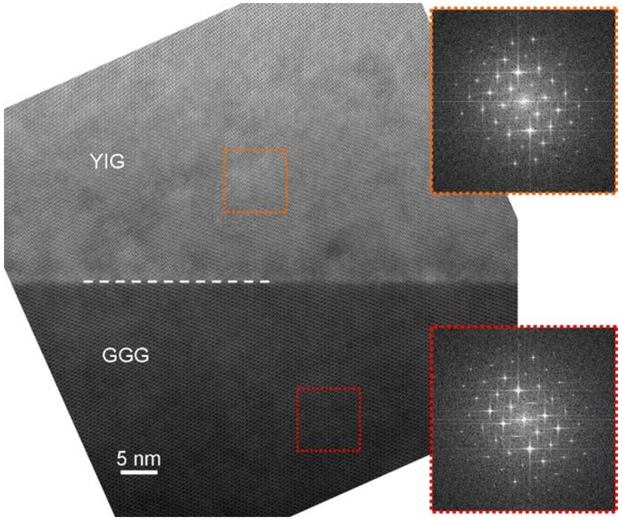
Breakthrough

Nanostructured Materials

Combine the two



+



- Big questions:

Are PLD and 3D lift-off compatible?

Can the crystallization propagate from the substrate through the resonator?

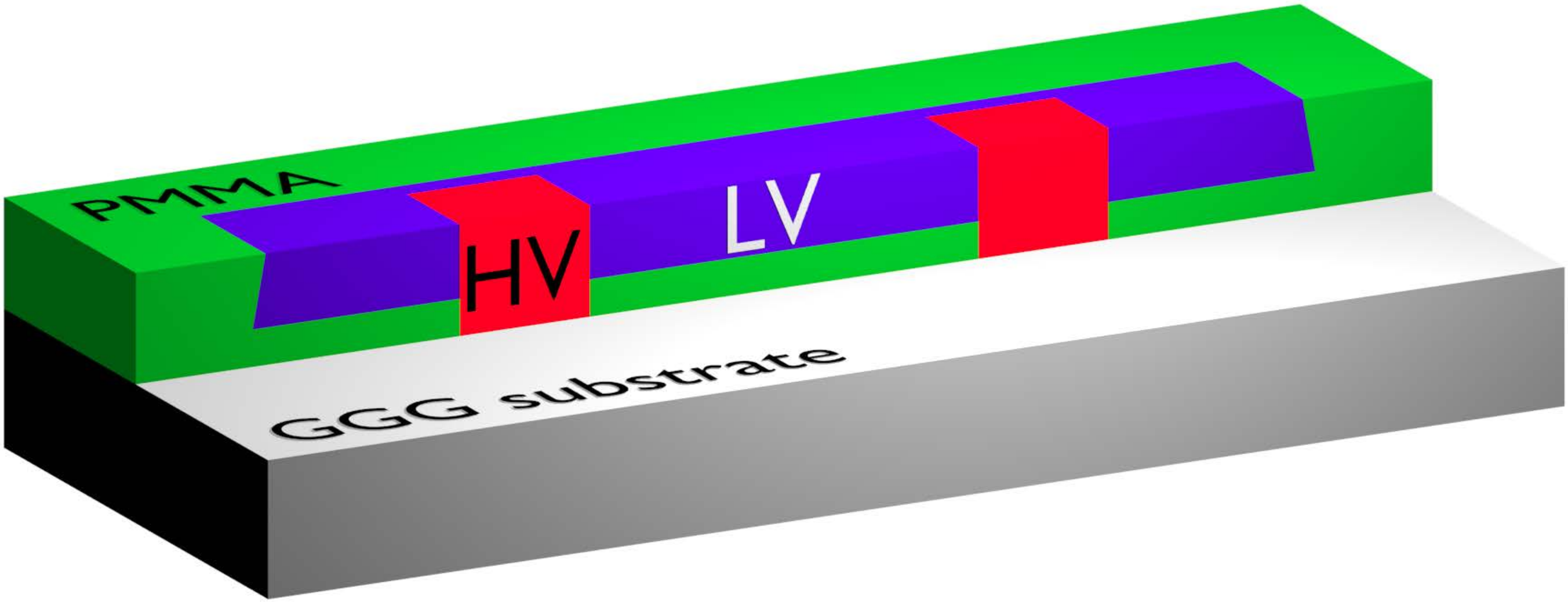
Is the magnonic quality still good?

Process

Nanostructured
Materials

Multi-voltage electron beam exposure

- Exposure with different penetration depth defines profile: HV for posts, LV for span



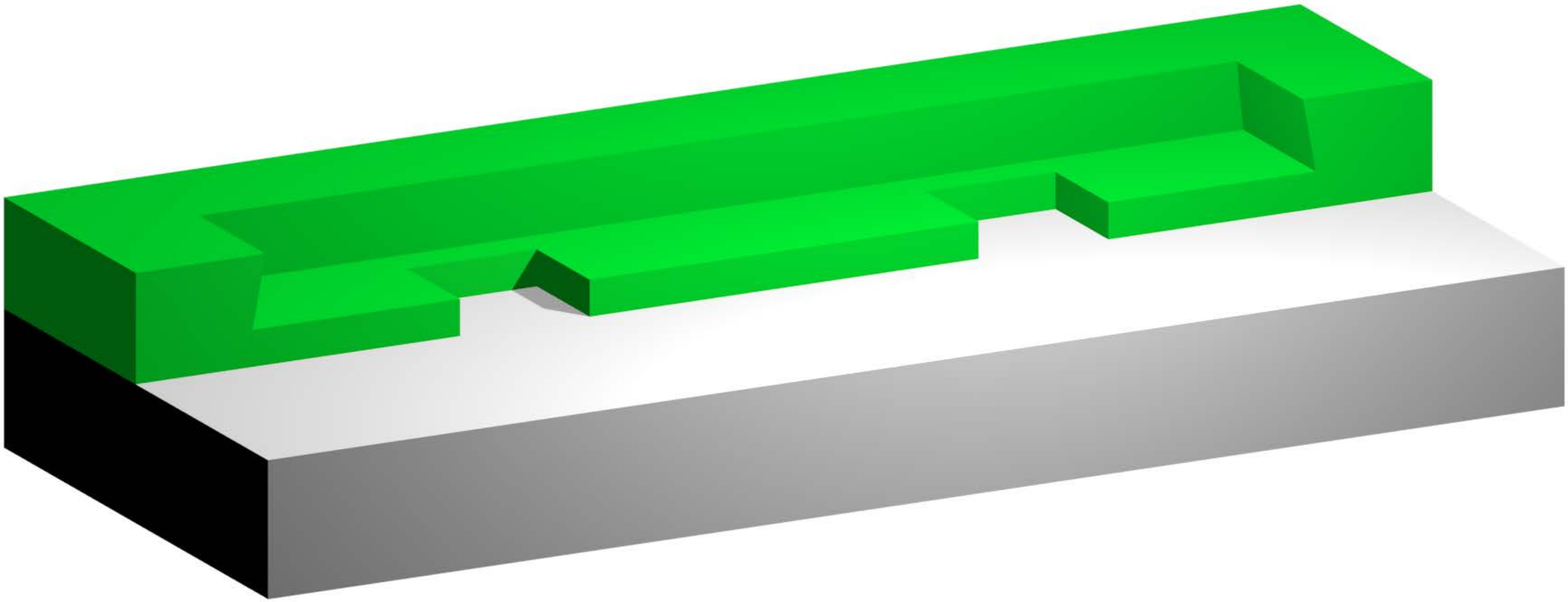
(F. Heyroth, GS et al. cond-mat.1802.03176)

Process

Nanostructured Materials

Development

– Results in slight undercut suitable for lift-off

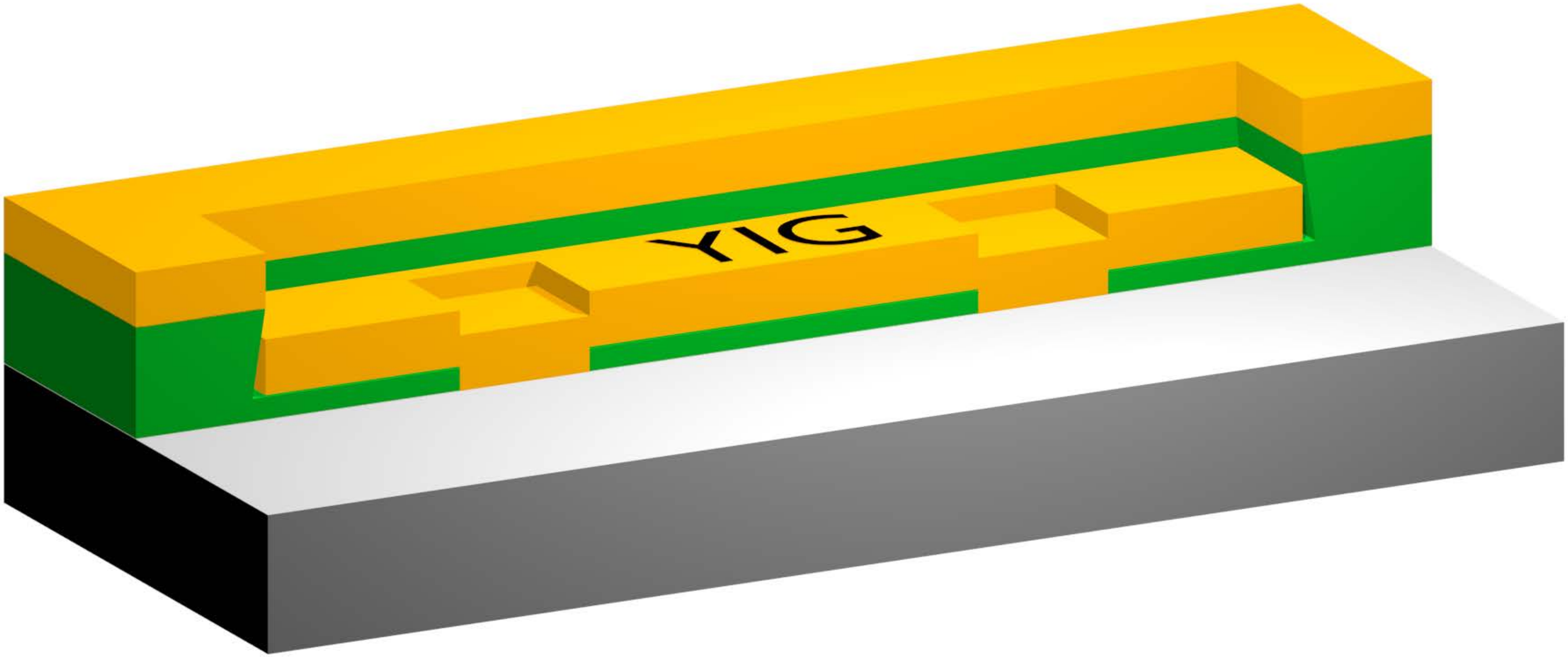


(F. Heyroth, GS et al. cond-mat.1802.03176)

Process

Pulsed laser deposition

– Directed deposition (beam-like) separates top layer from bridge (more critical than for 2D structures)

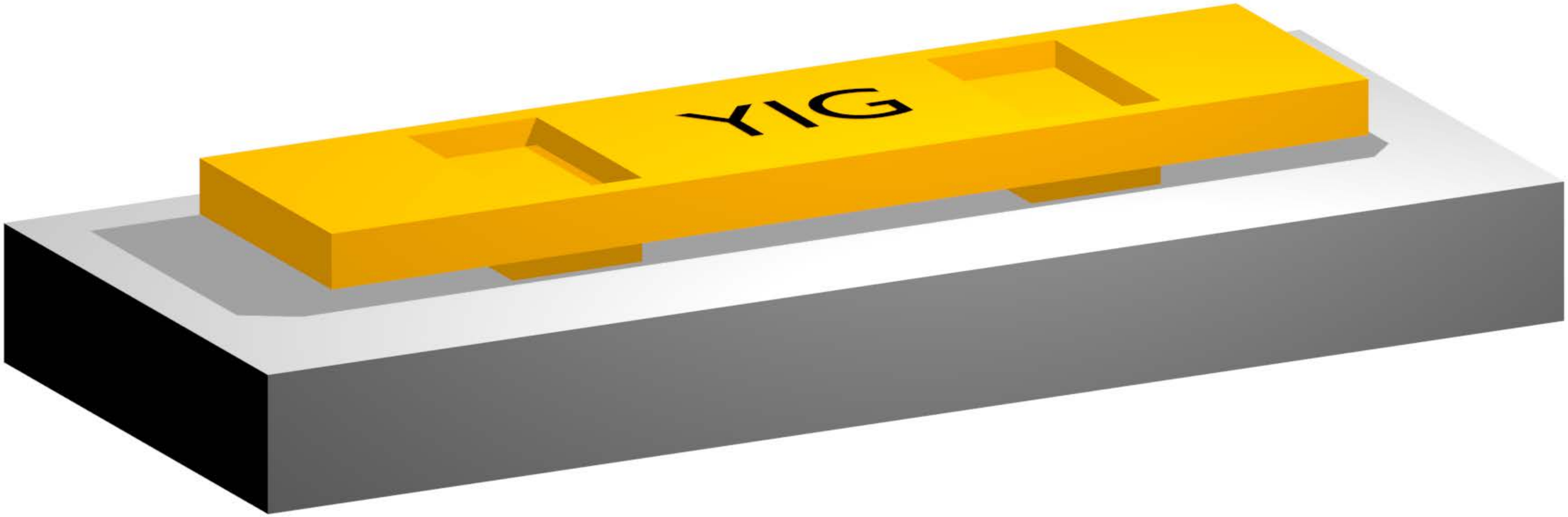


(F. Heyroth, GS et al. cond-mat.1802.03176)

Process

Lift-off

– Top layer is removed, bridge remains (ideally)

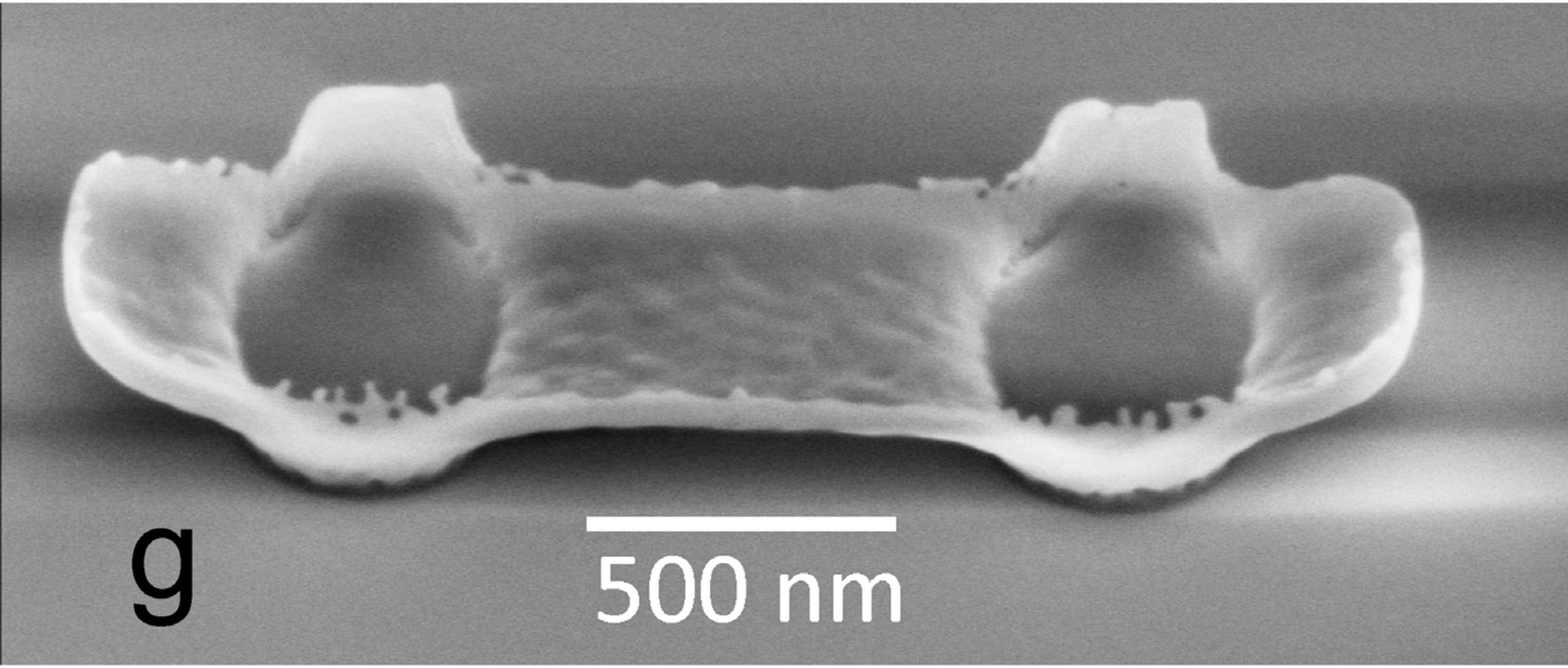


(F. Heyroth, GS et al. cond-mat.1802.03176)

Results

Nanostructured Materials

Yeah! Bridges!

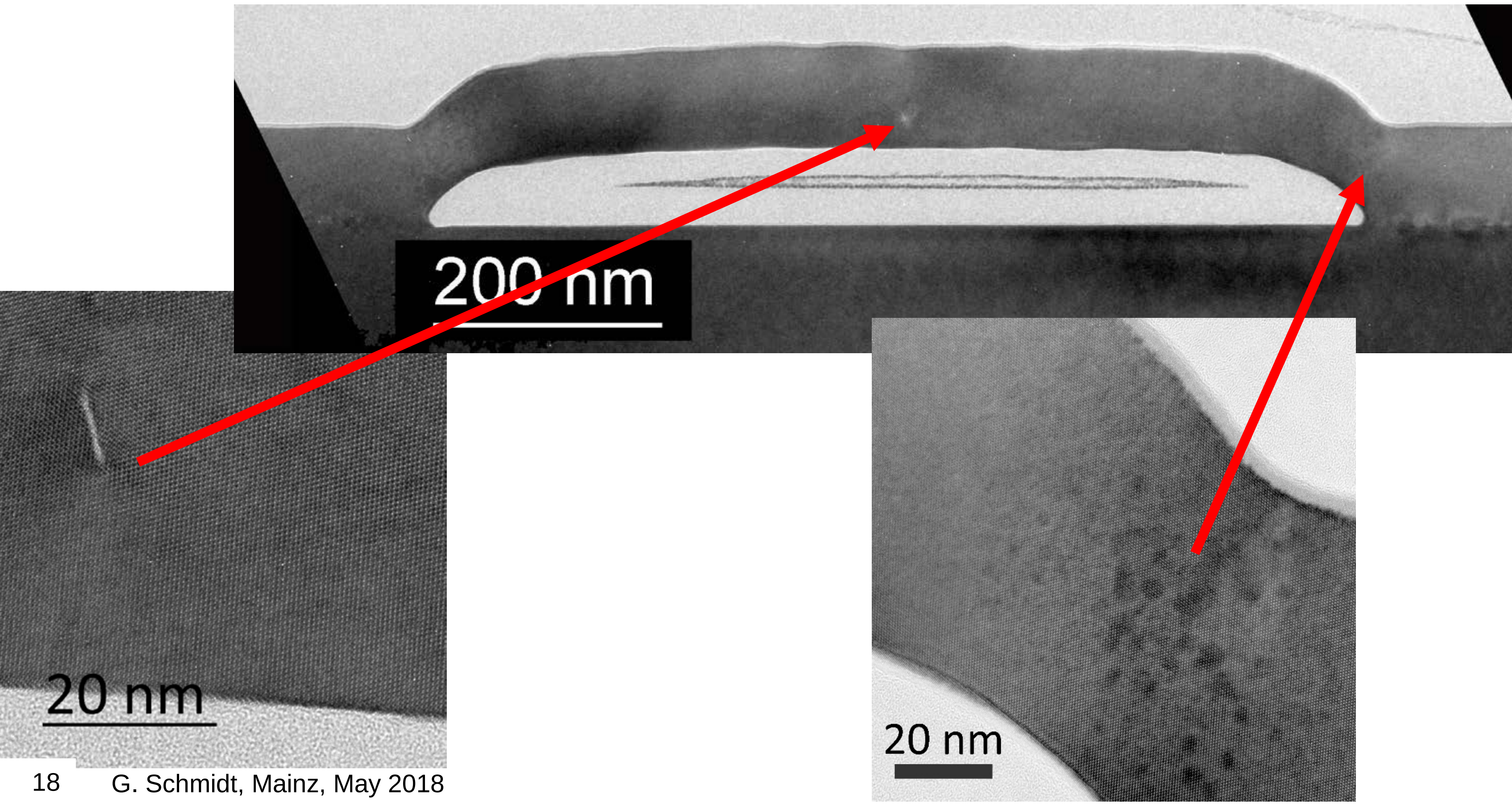


(F. Heyroth, GS et al. cond-mat.1802.03176)

Transmission electron microscopy

Monocristalline span (almost)

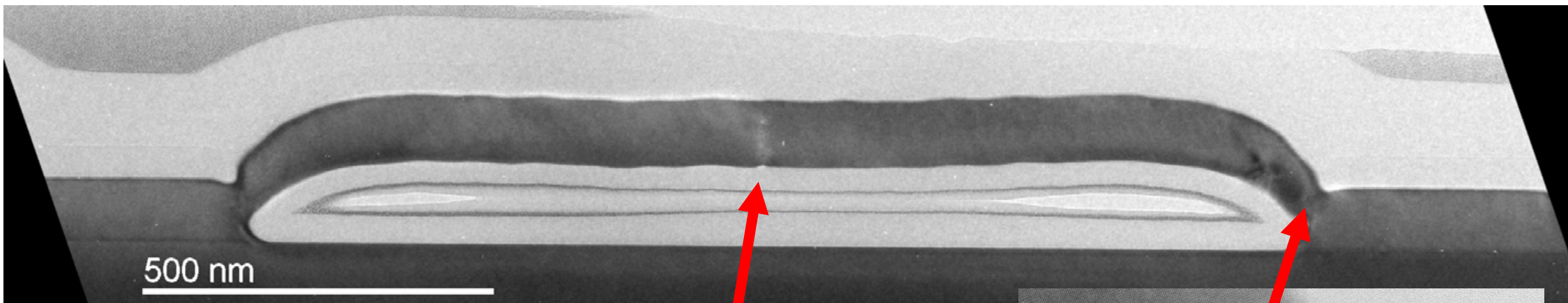
– Crystallization frots propagate from the substrate, single defect at center of span
– Transition from post to span shows accumulation of defects

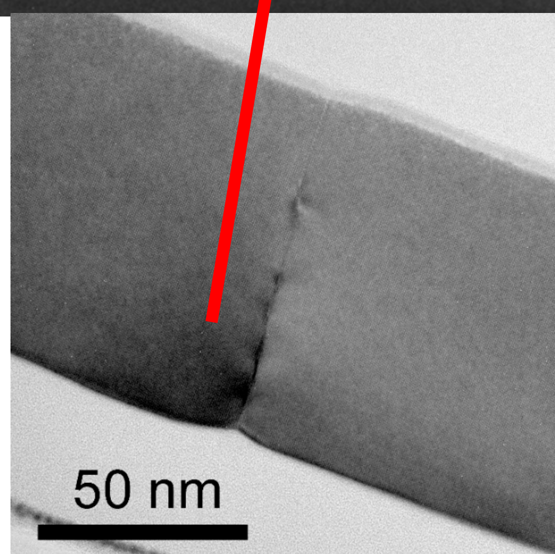


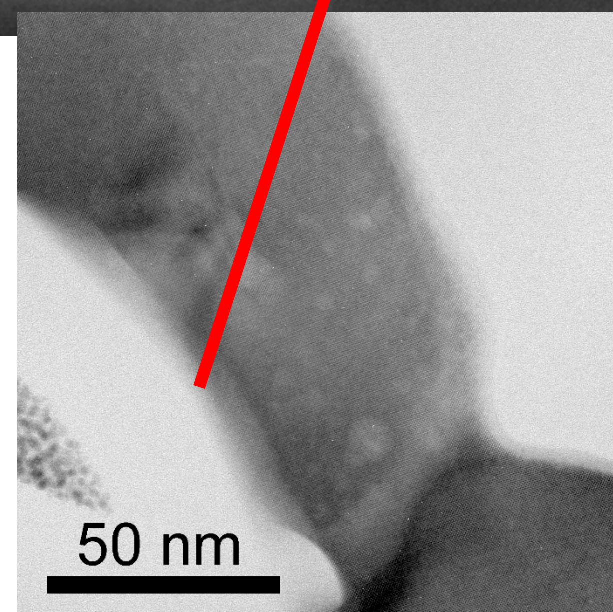
Transmission electron microscopy

Higher bridges

- 200 nm high bridge shows increased strain
- Larger defect at center
- More defects at post





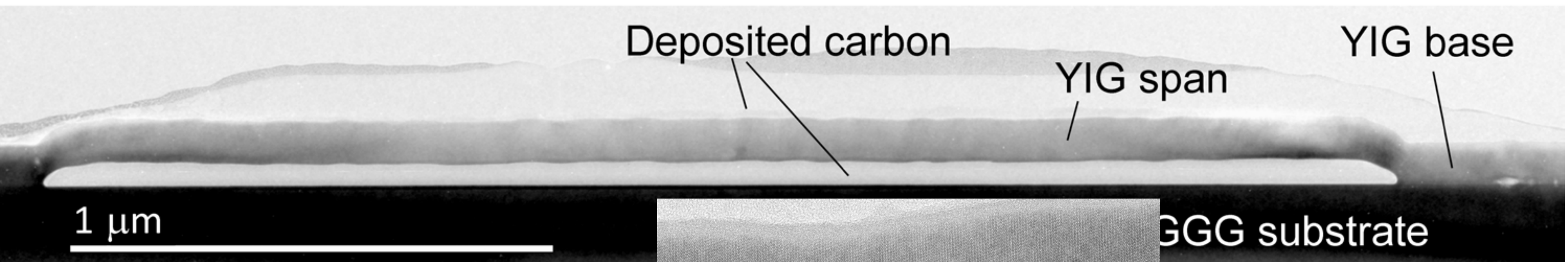


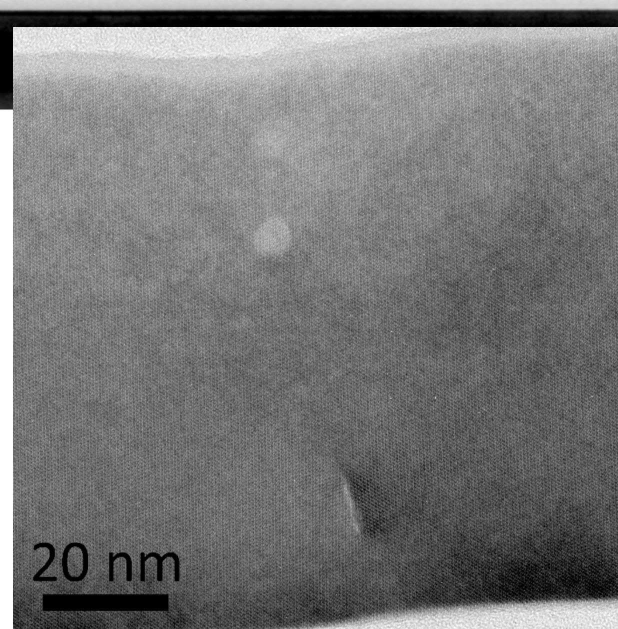
(F. Heyroth, GS et al.
cond-mat.1802.03176)

Transmission electron microscopy

Longer bridges

– Bridges of several micron length are possible
– Still defect in span only at center
– No visible bending due to strain (all images after annealing)



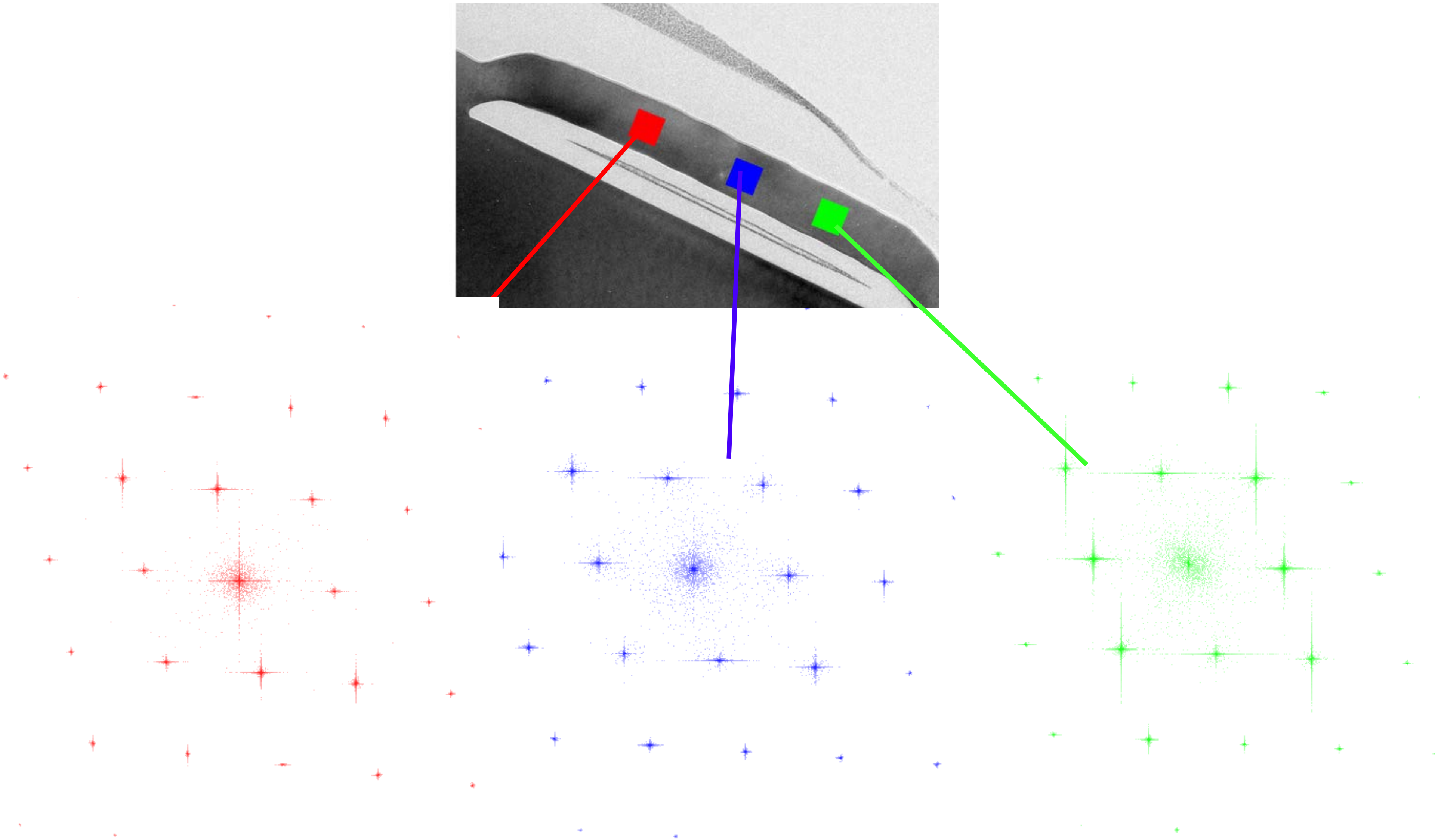


(F. Heyroth, GS et al.
cond-mat.1802.03176)

Lattice tilt?

FFT

- Image different areas on the bridge
- Make FFT of lattice

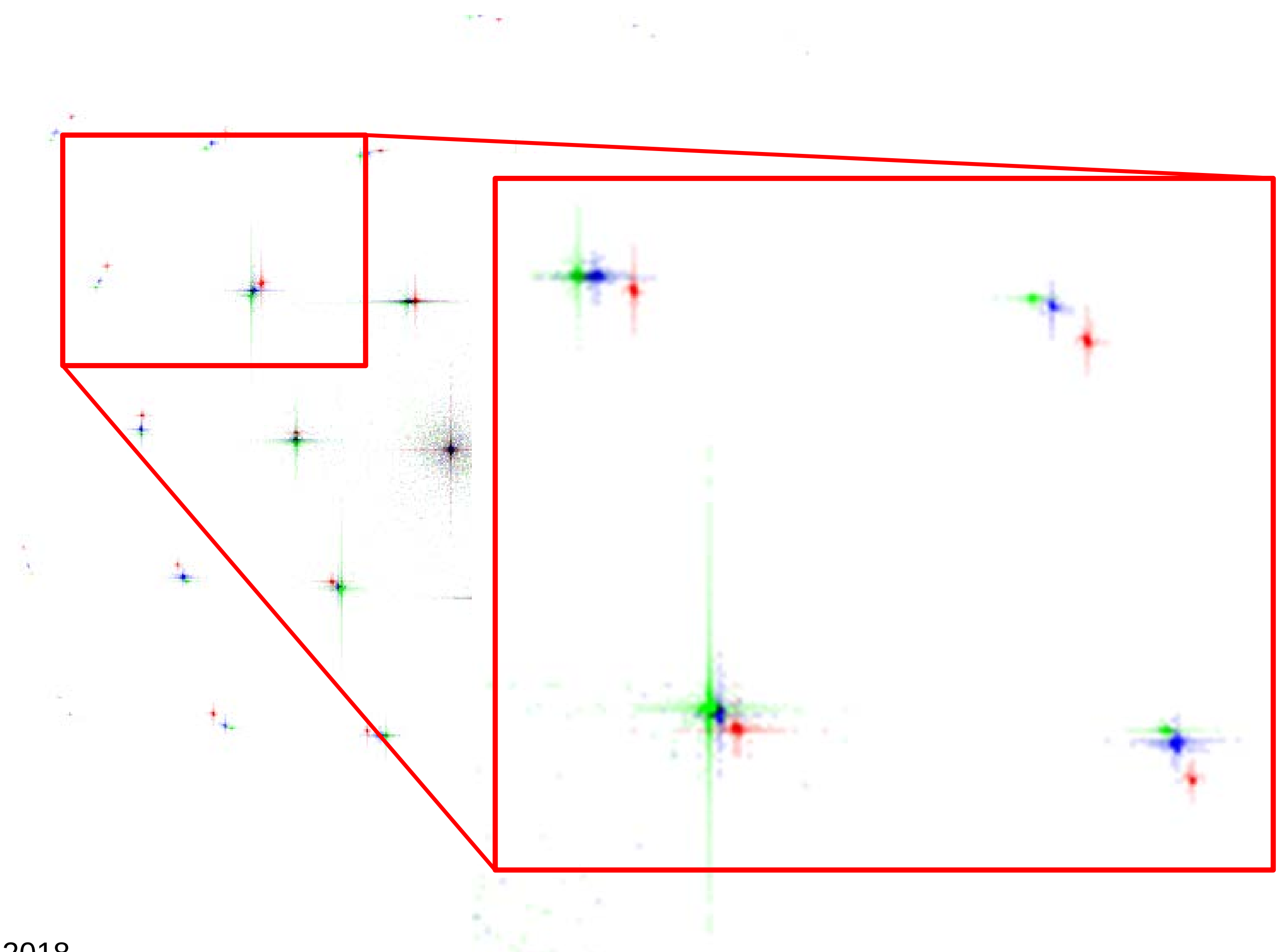


Lattice tilt?

Nanostructured
Materials

Superposition

- Superposition shows small rotation (between 0.5 and 3°)
- Rotation between left and right side of the bridge (obviously also between side of the span and substrate



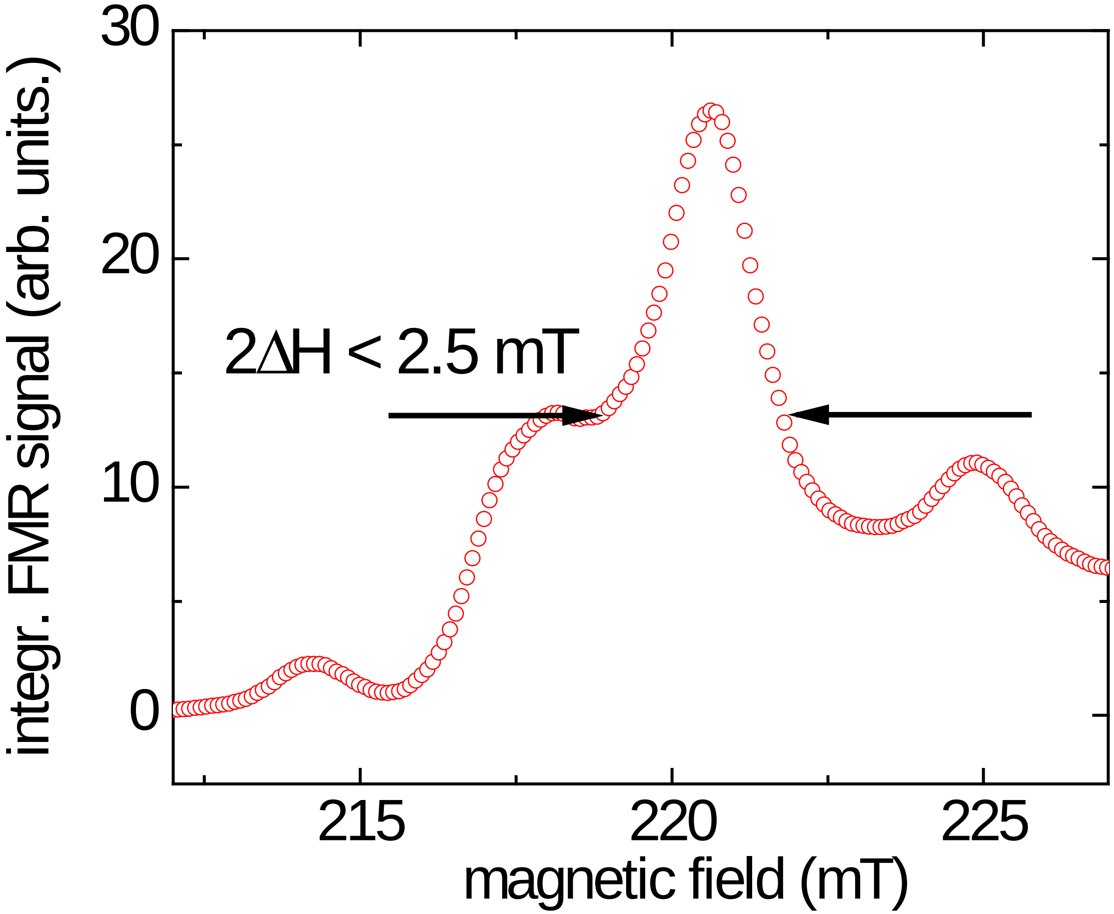
(F. Heyroth, GS et al. cond-mat.1802.03176)

Ferromagnetic resonance

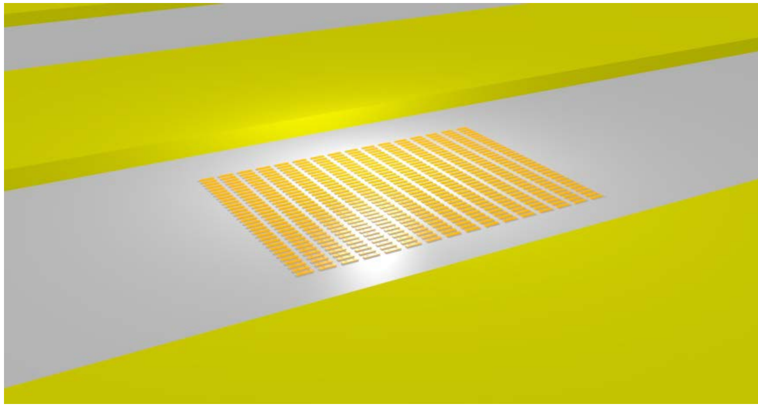
Nanostructured Materials

Array of bridges

- Measurement on 8000 (nominally) identical bridges (3000x500 nm)
- Linewidth of main resonance ΔH=1.25 mT@8 GHz
- Either very similar bridges or very narrow lines



(F. Heyroth, GS et al. cond-mat.1802.03176)

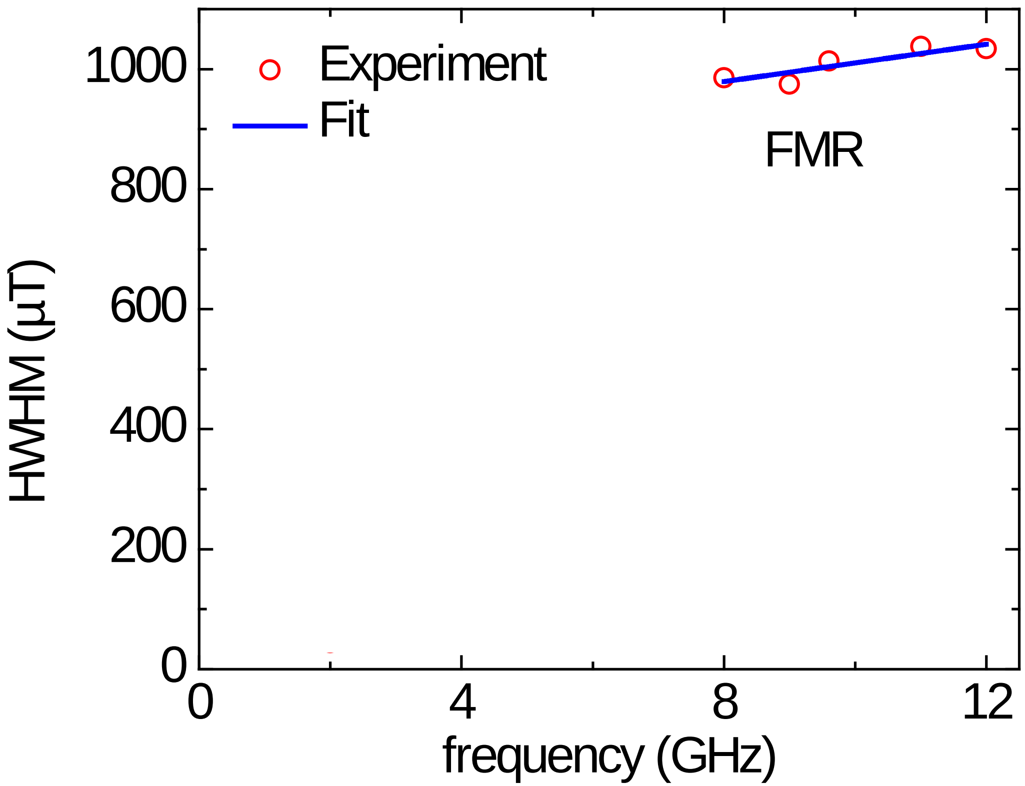


Ferromagnetic resonance

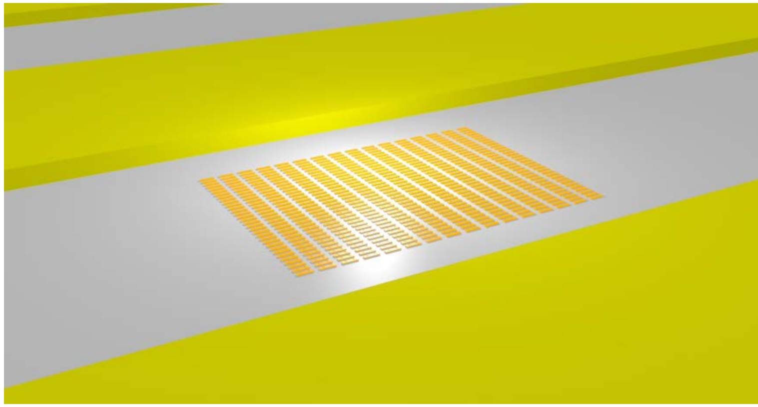
Nanostructured
Materials

Damping

- Measurements at various frequencies
- At low frequencies lines cannot be resolved
- Measurements between 8 and 12 GHz indicate Damping $\alpha \leq 4.1 \times 10^{-4}$



(F. Heyroth, GS et al. cond-mat.1802.03176)

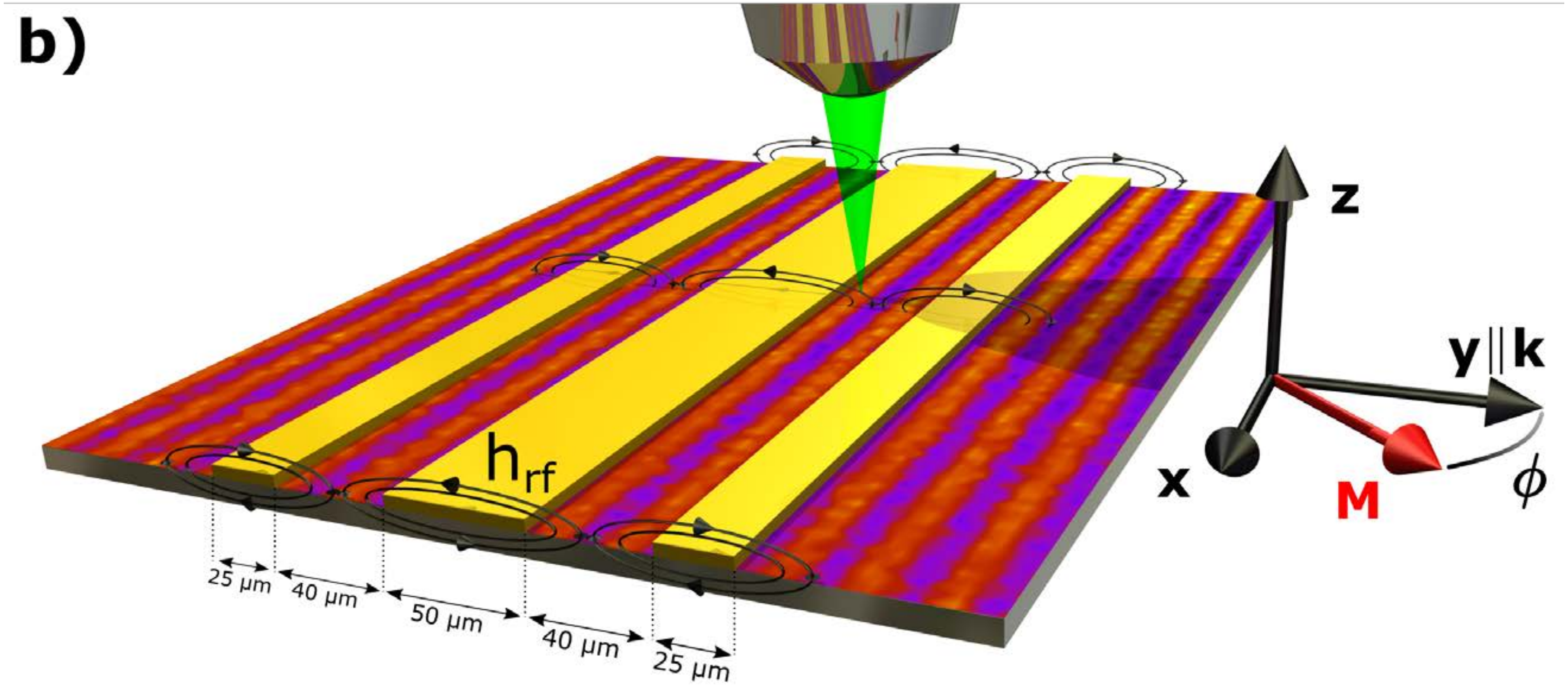


TR-MOKE

Nanostructured Materials

Time resolved scanning Kerr microscopy

- Allows to locally visualize time development of x or y-component of magnetization vector
- Resolution: ~300 nm
- Time resolution ~1 ps

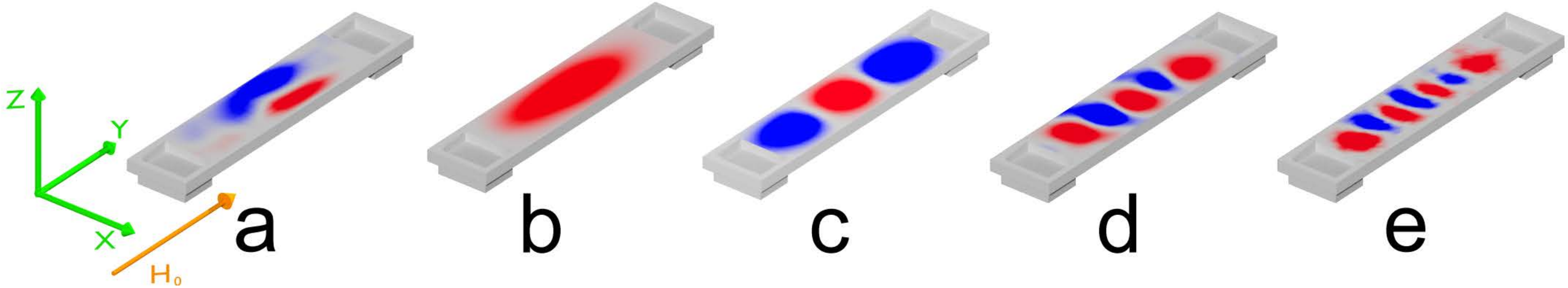


TR-MOKE

Nanostructured Materials

Standing spin waves

- Homogeneous mode (zero nodes)
- Damon Eshbach mode at lower fields (as expected)
- Backward volume modes at higher fields (up to 6 nodes)



11.9 mT 2 GHz	21.9 mT 2 GHz	25.6 mT 2 GHz	89.7 mT 4 GHz	92.5 mT 4 GHz

(F. Heyroth, GS et al. cond-mat.1802.03176)

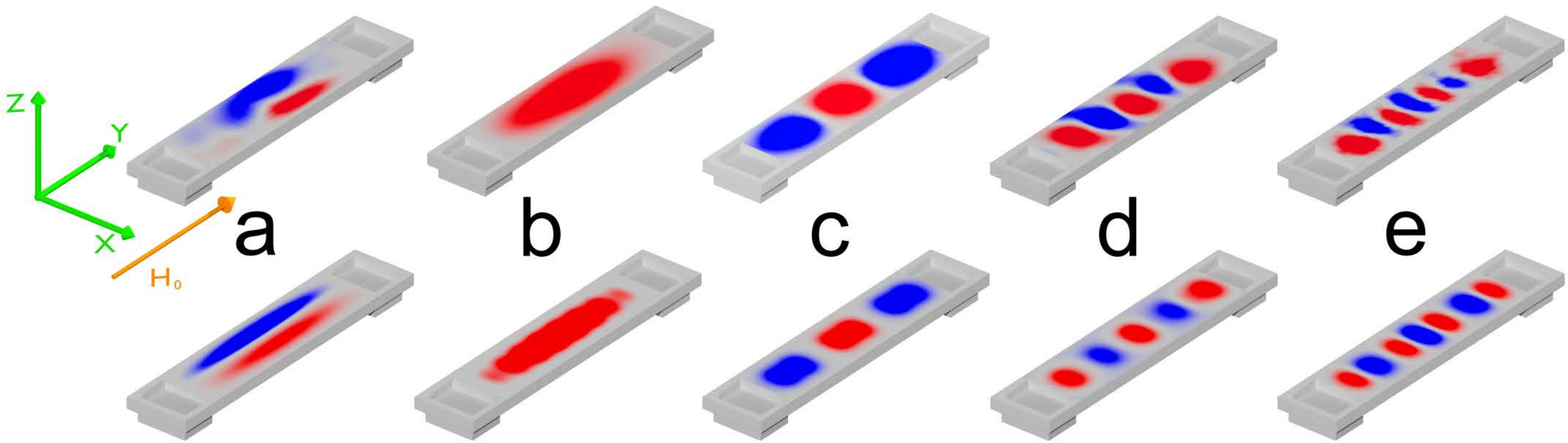
Simulation

Spin dynamics simulation using mumax 3*

- Single step excitation
- FFT for each point of the bridge
- Select frequency
- Reconstruct image from amplitude and phase

*"The design and verification of mumax3", AIP Advances 4, 107133 (2014).

Nanostructured Materials



19.4 mT	19.4 mT	19.4 mT	83.8 mT	83.8 mT
2.32 GHz	2 GHz	1.85 GHz	3.73 GHz	3.66 GHz

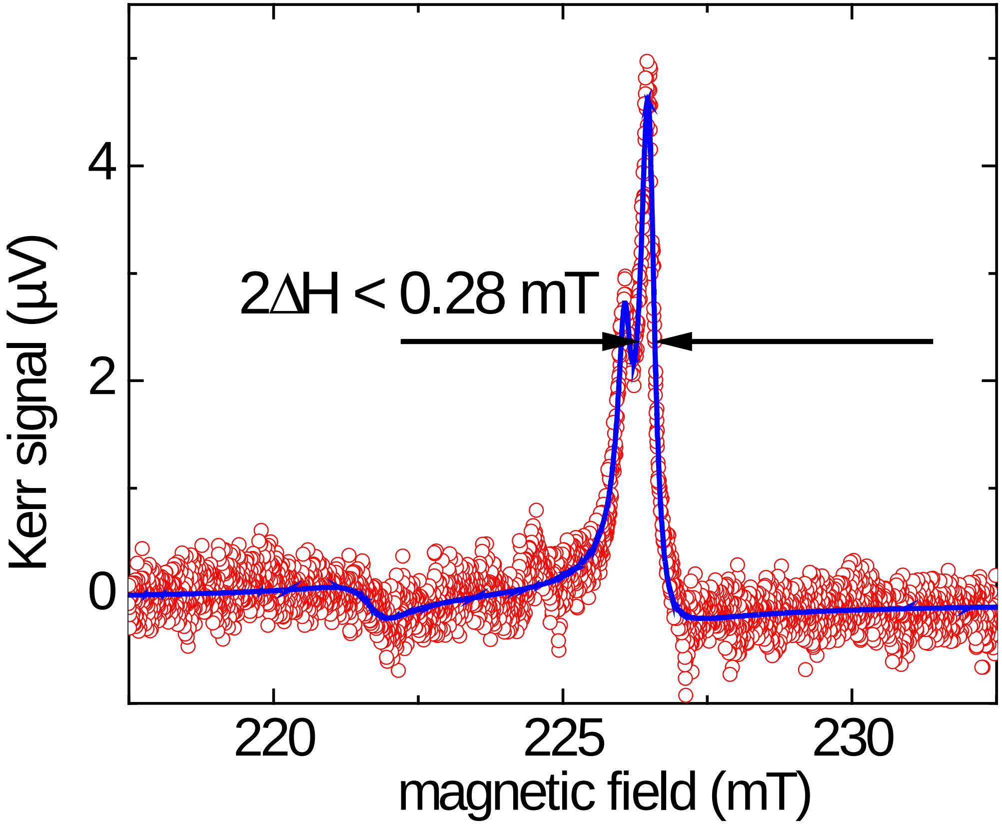
(F. Heyroth, GS et al. cond-mat.1802.03176)

Scanning TR MOKE

Nanostructured Materials

Ferromagnetic resonance

- FMR on single spot on single bridge
- Linewidth of main resonance $\Delta H=140\ \mu T@8GHz$
- Corresponds to high quality thin film material
- Much more narrow than for array: Possible reasons?



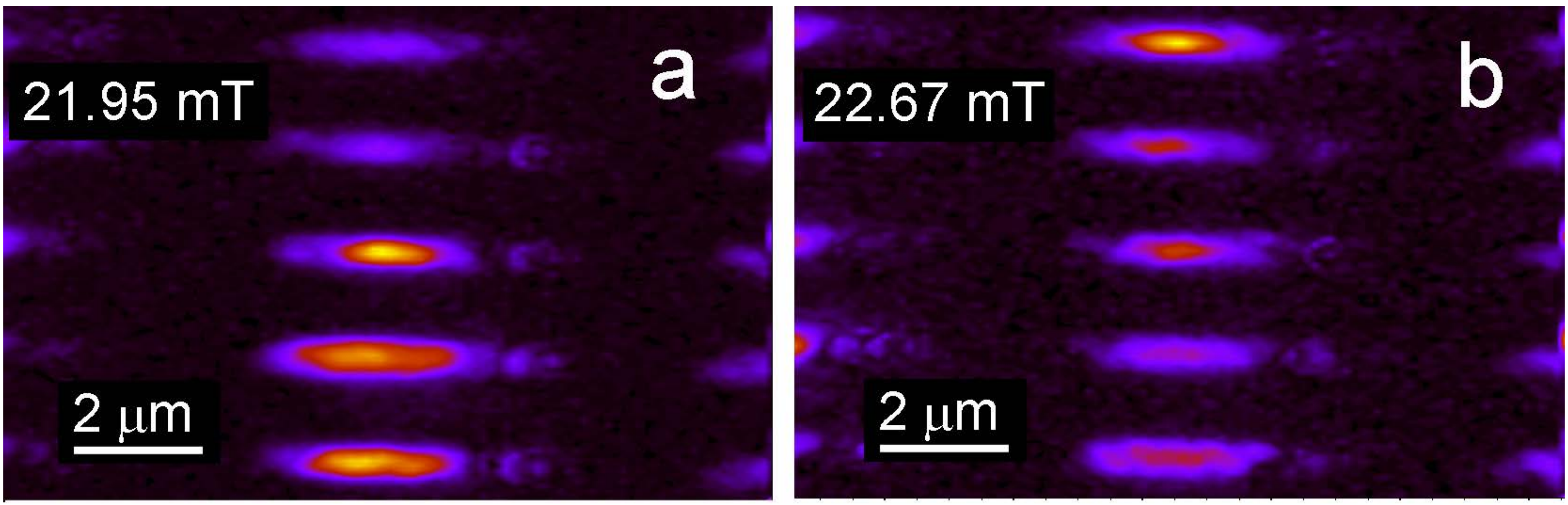
(F. Heyroth, GS et al. cond-mat.1802.03176)

Scanning TR MOKE

Nanostructured
Materials

Different bridges?

- Main resonance on different bridges may at leat vary by 0.7 mT @ 2 GHz
- May explain the broadening in the array at 8 GHz (1.4 mT)



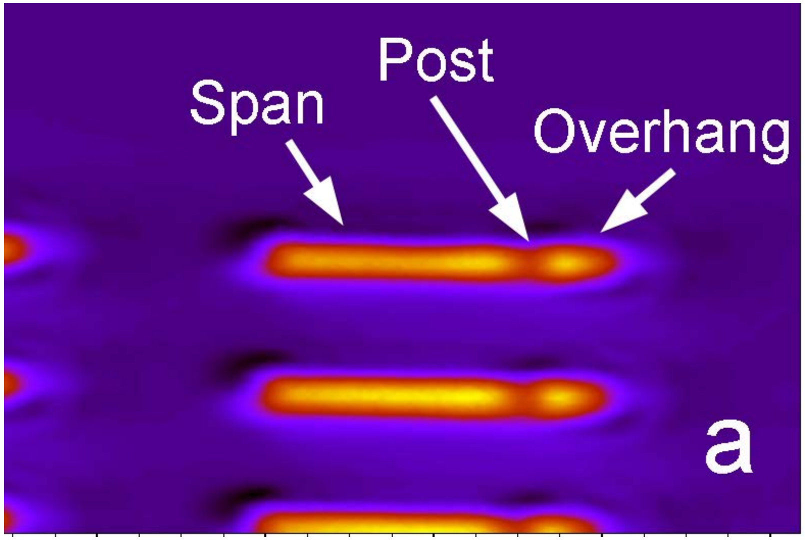
(F. Heyroth, GS et al. cond-mat.1802.03176)

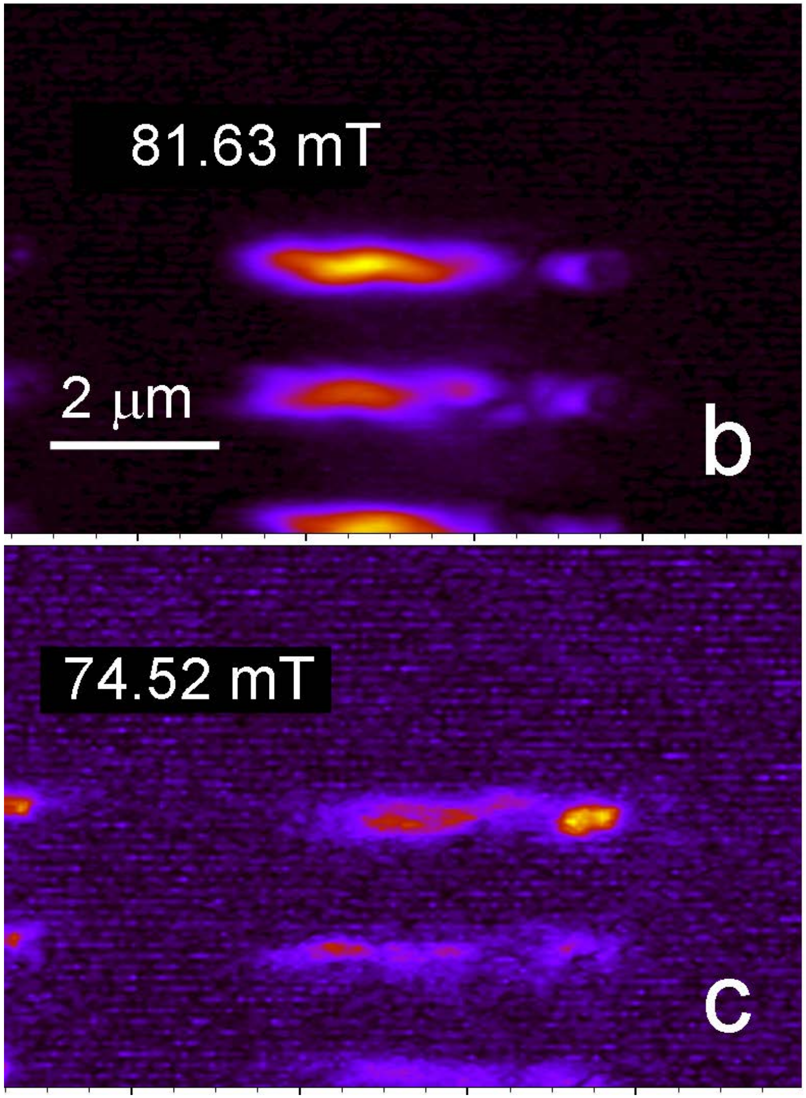
Scanning TR MOKE

Nanostructured Materials

Different parts (span/post)?

- Resonance of span and overhang differ by 7 mT
- Much more than broadening of array
- Leads to additional peak





(F. Heyroth, GS et al. cond-mat.1802.03176)

Ferromagnetic resonance

Array of bridges

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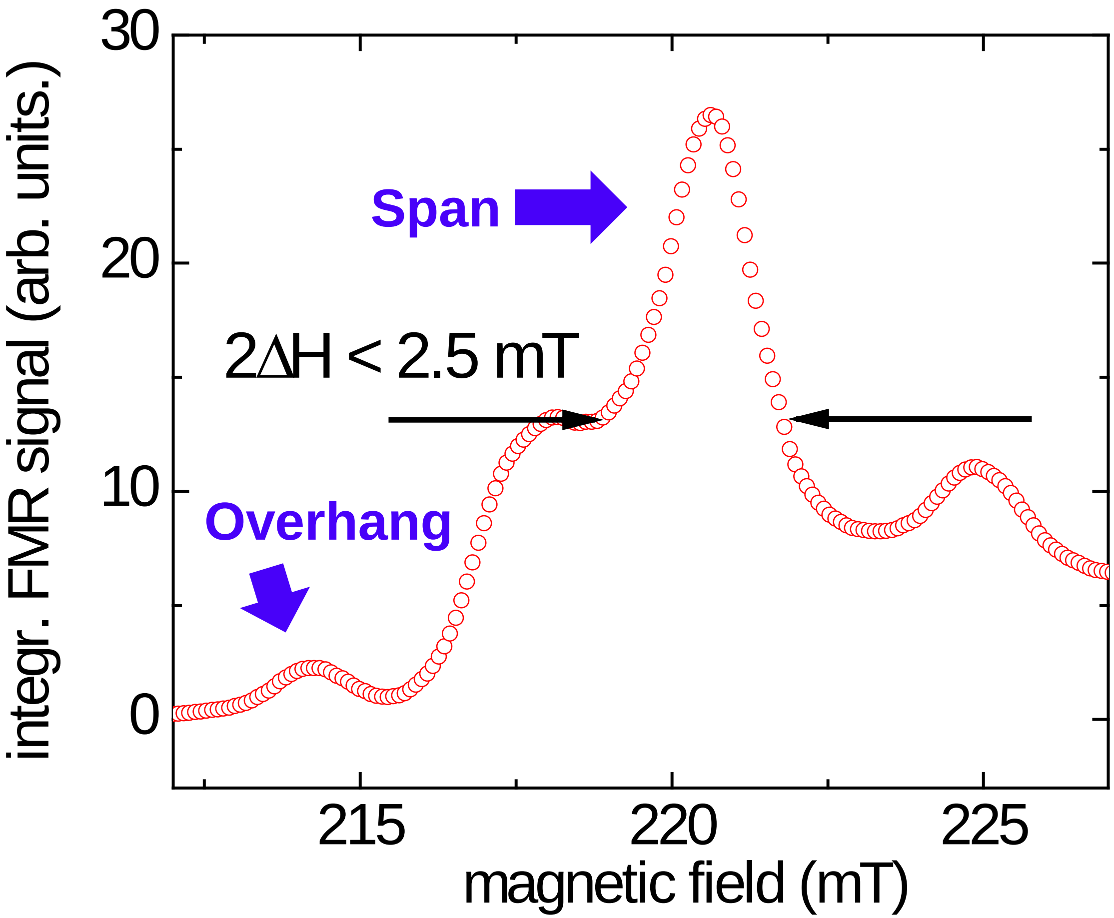
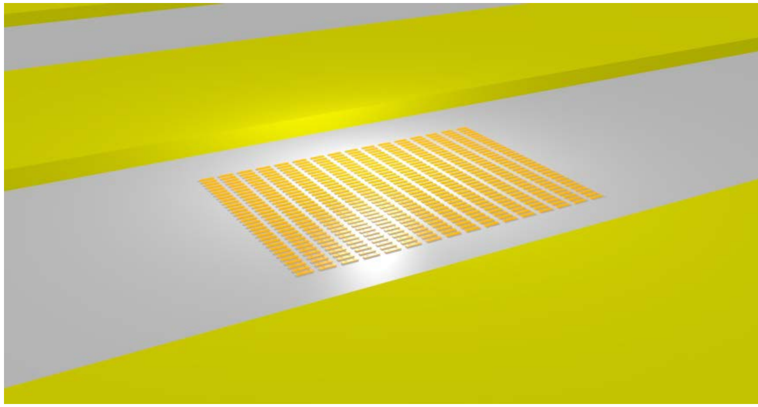
Nanostructured
Materials



(F. Heyroth, GS et al. cond-mat.1802.03176)

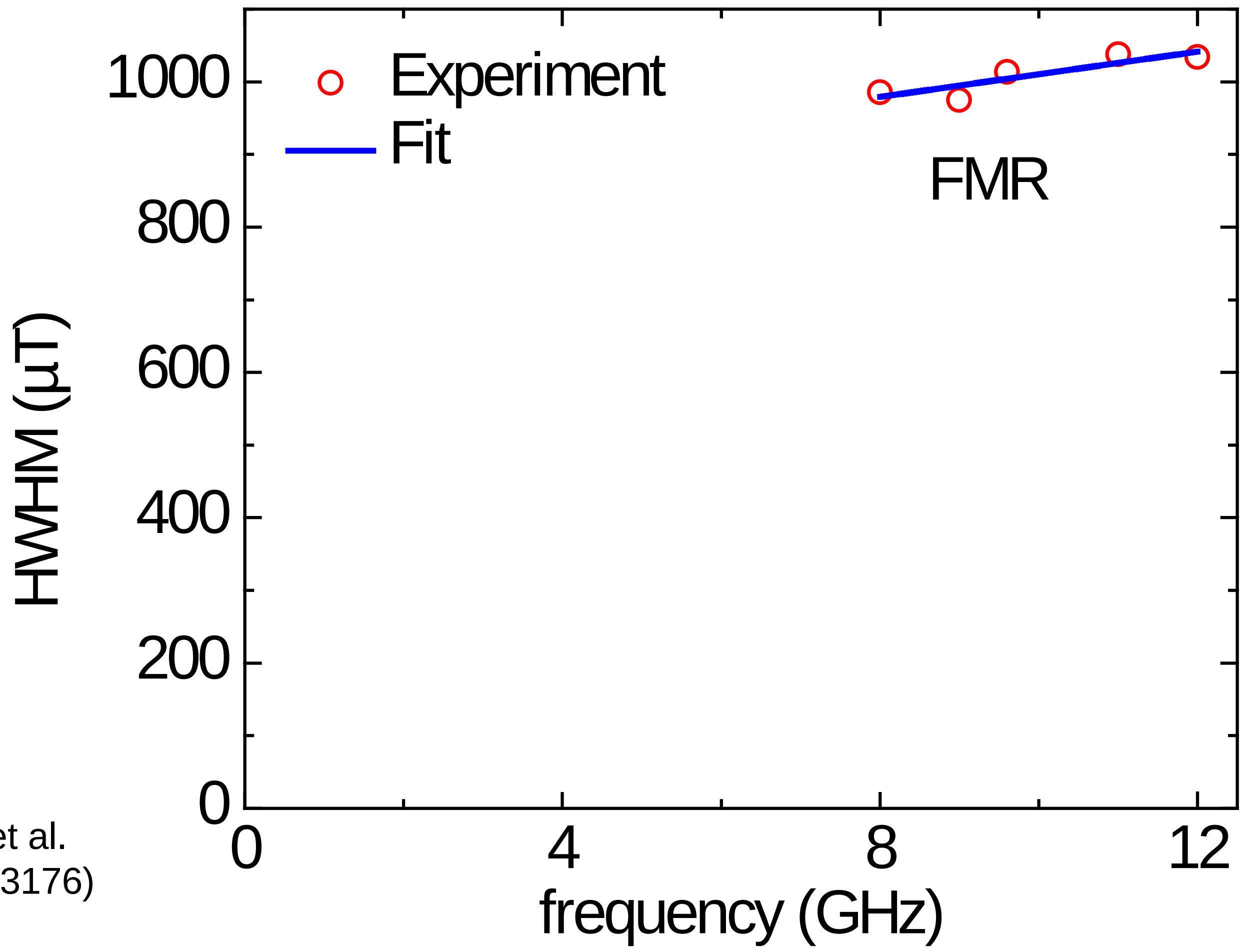


Scanning TR MOKE

Damping

Nanostructured Materials

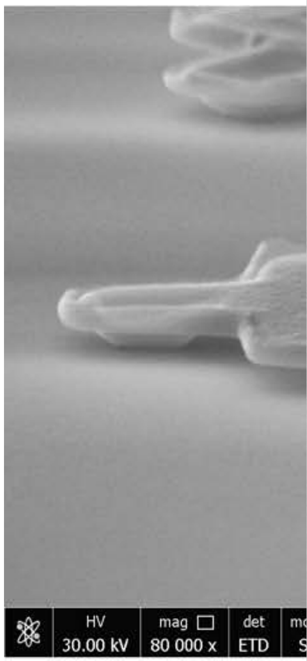
- For single spot Gilbert damping $\alpha \leq 2.4 \times 10^{-4}$
- Intrinsic linewidth at zero field: ΔH=75 μT
- Really high quality thin film YIG

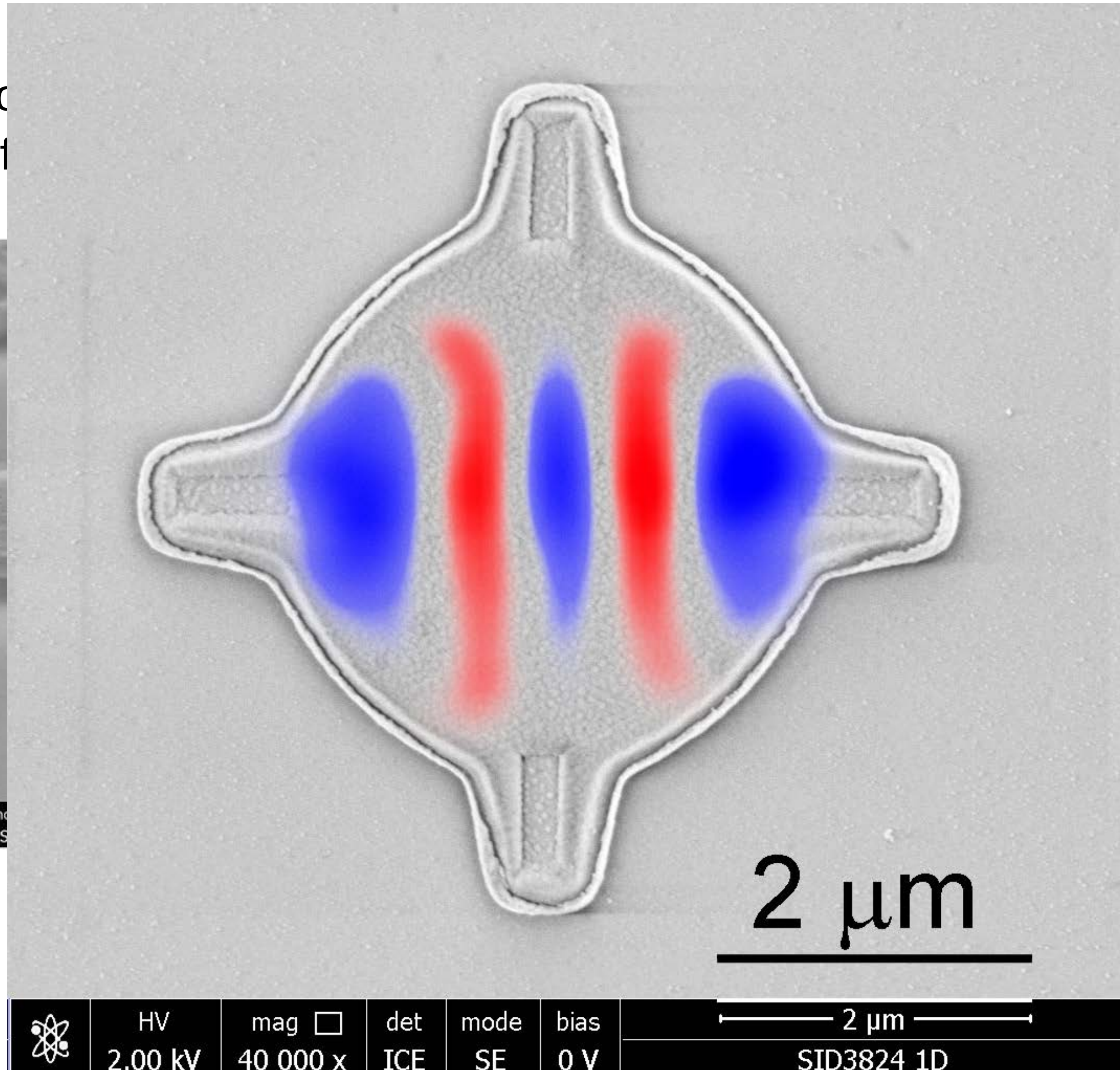


(F. Heyroth, GS et al. cond-mat.1802.03176)

Different shapes

- Allo
- Diff sible

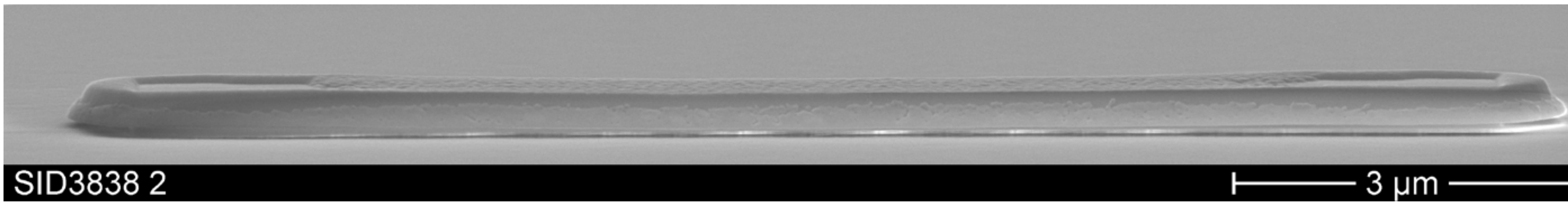


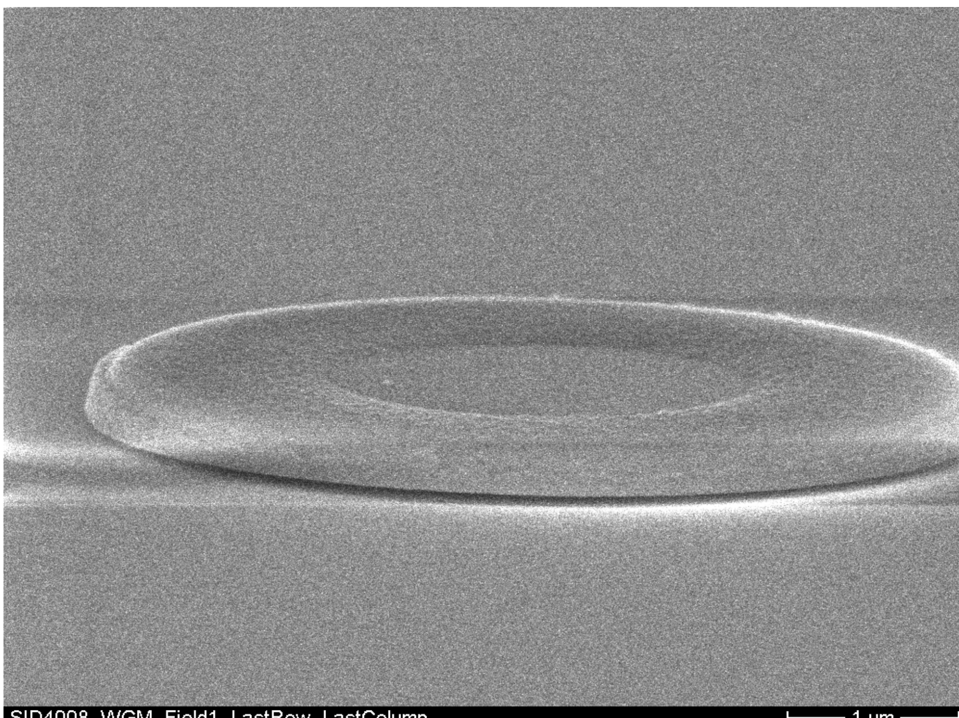


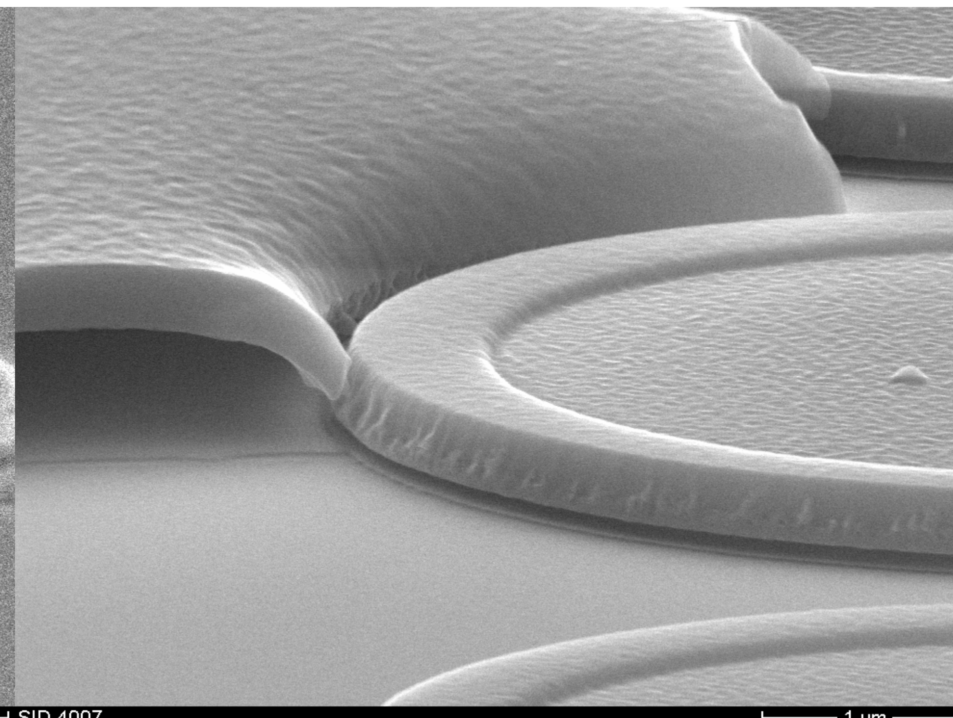
A few more

Nanostructured Materials

Optimized process





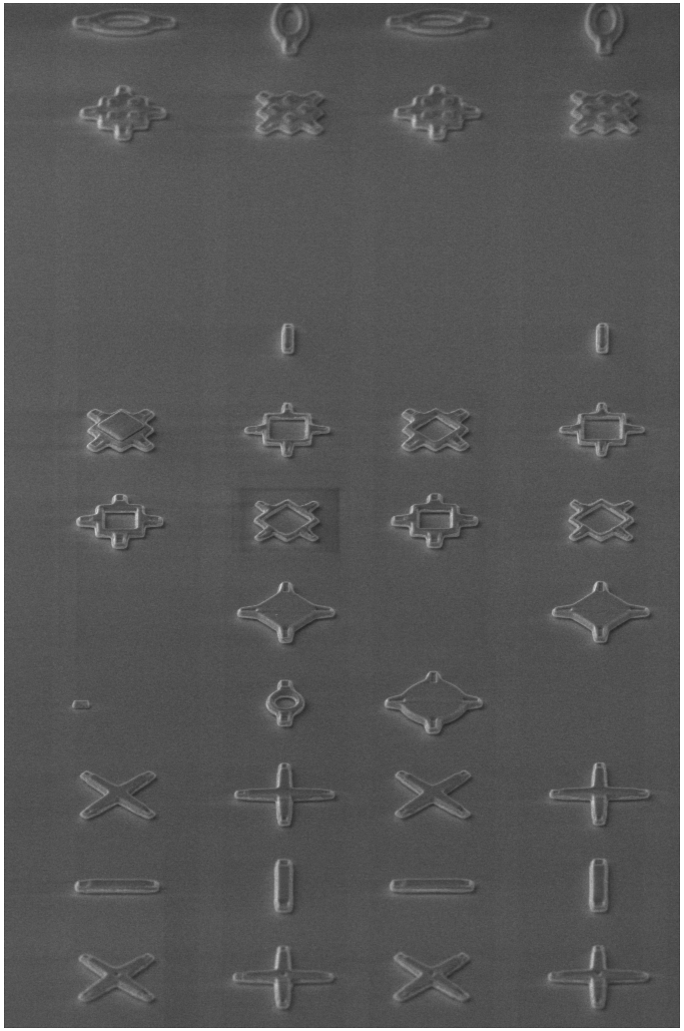


Conclusion

Nanostructured
Materials

Results

- New process allows the fabrication of nano-sized free standing YIG resonators
- Span is monocrystalline with single defect
- Crystal structure adopted from substrate
- Resonators can accomodate magnons with **low damping and narrow linewidth**
- Additive process compatible with post processing and addition of more microelectronics (waveguides, magnets, etc.)



Outlook

- Coupling to mechanical vibrations must be investigated
- Ultimately coupling to qubits / integration of multiple devices
- Collaborations welcome!

Jobs

Nanostructured
Materials

PhD positions

- Ultrafast spintronics:
  - Electrical detection of GMR in the 100 GHz regime
  - Electrical detection of ultrafast demagnetization (sub 10 ps)

- YIG Spin Hall nano-oscillators
  - Fabrication and nanopatterning
  - Characterization in the GHz regime