SWISS CONTRIBUTION

NANOSPIN

Structure of artificial SPIN ICE

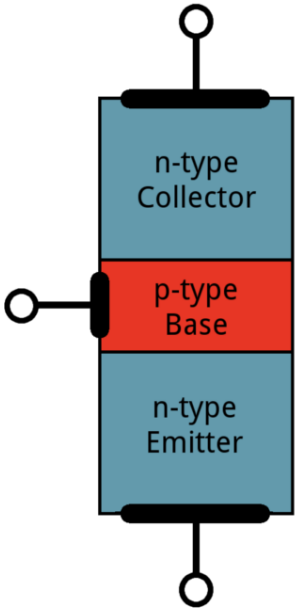
Łukasz Frąckowiak

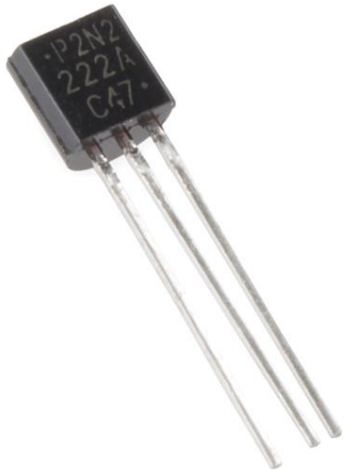
Plan of presentation

- (Spin) Ice
- Kagome lattice
- Dirac String and Magnetic Monopole
- Structuring – electron beam lithography
- Experimental results
- Summary

Motivation

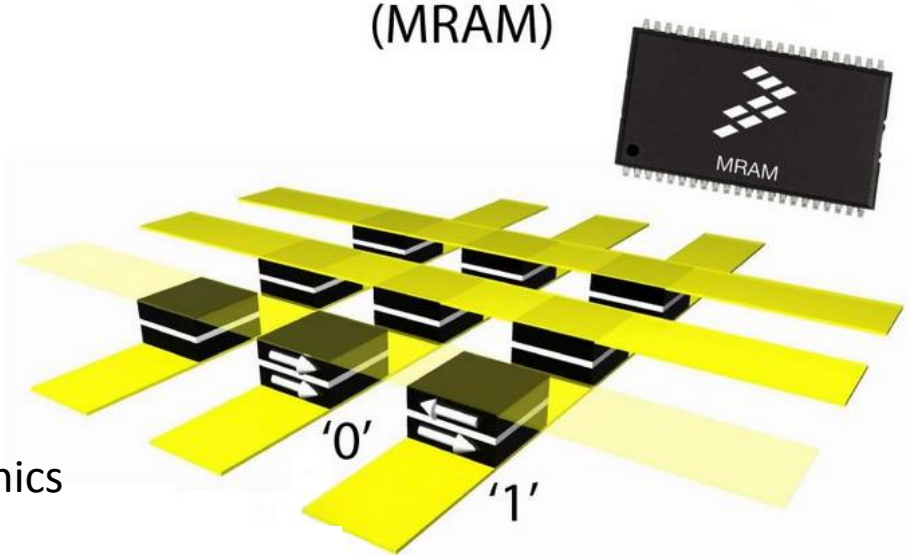
Electronics





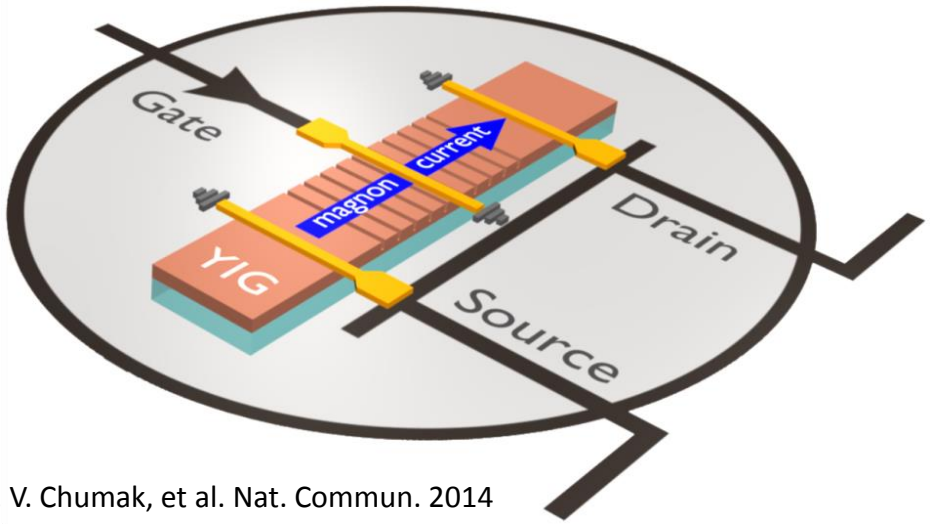
Spintronics

Magnetic Random Access Memory
(MRAM)



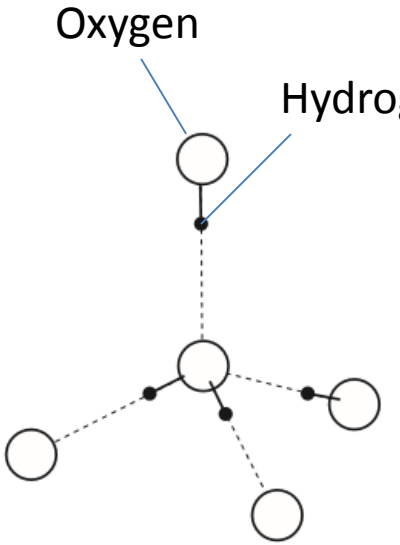
C.D. Stanciu

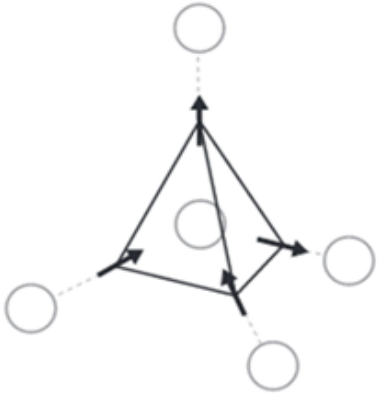
Magnonics



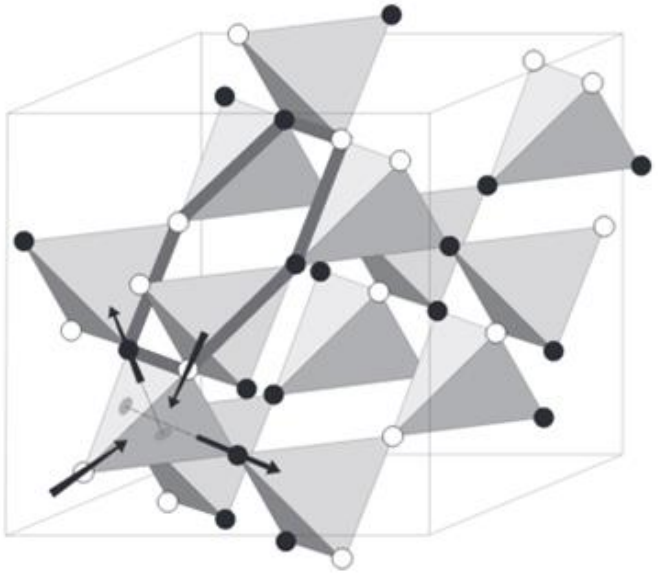
A. V. Chumak, et al. Nat. Commun. 2014

(Spin) Ice



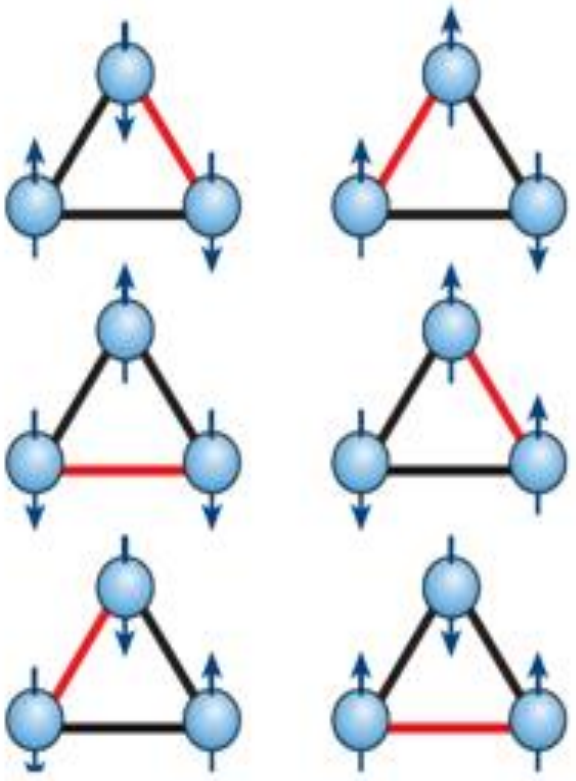


Ice



Spin Ice - pyrochlore lattice,
Example: $Dy_2Ti_2O_7$

Frustration



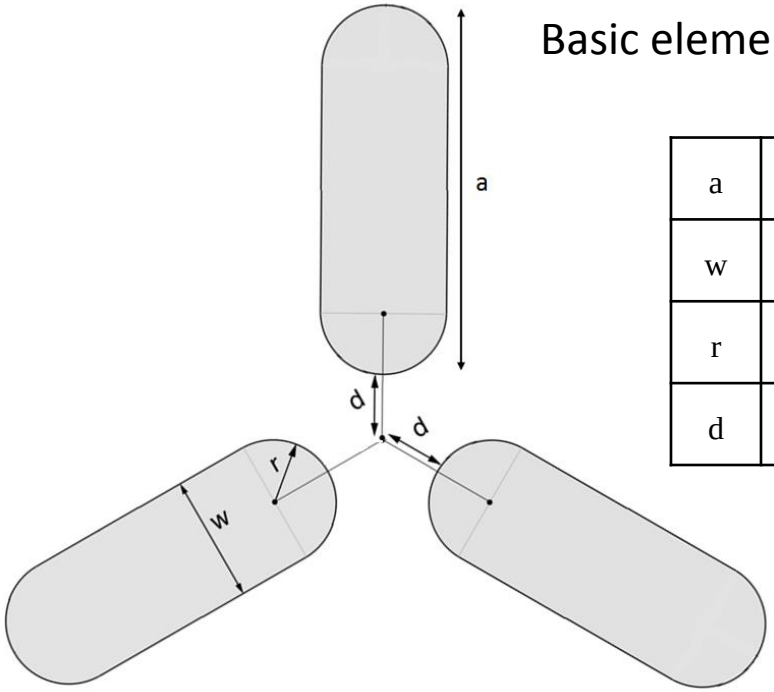
L. Balents, Nature, 7286, 199-208 (2010)

S. T. Bramwell et al., Science 7286, 199-208 (2001)

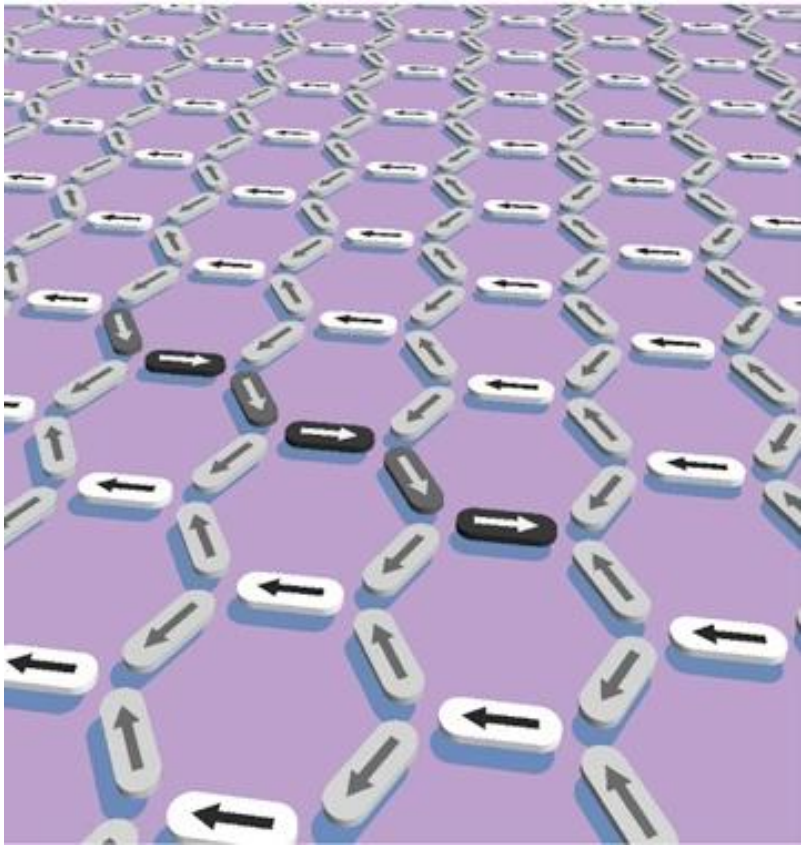
Artificial Spin Ice– kagome lattice

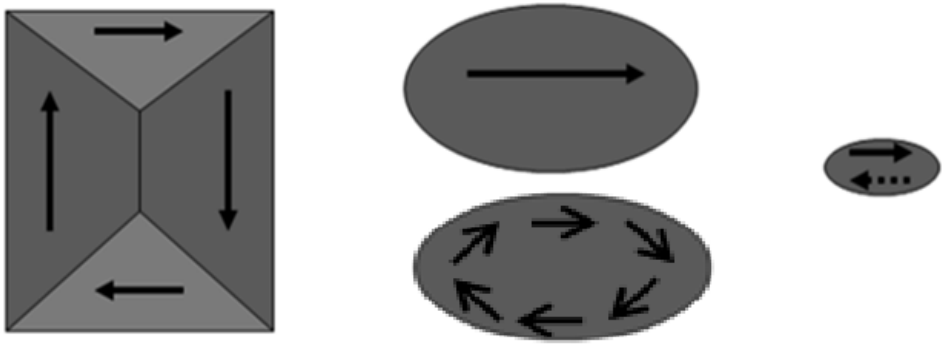
kagome - jap. 籠目 – a wicker

Basic element of kagome lattice



a	370 nm
w	170 nm
r	85 nm
d	100 nm



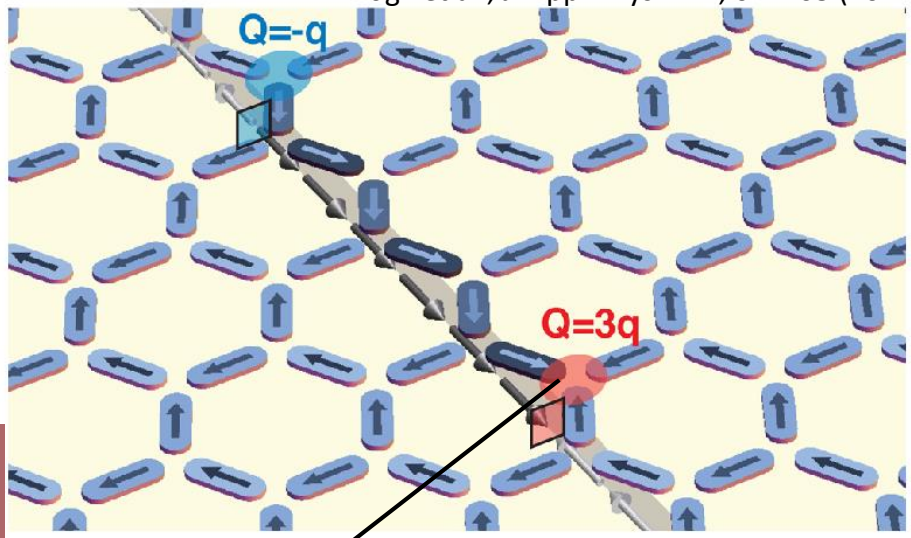


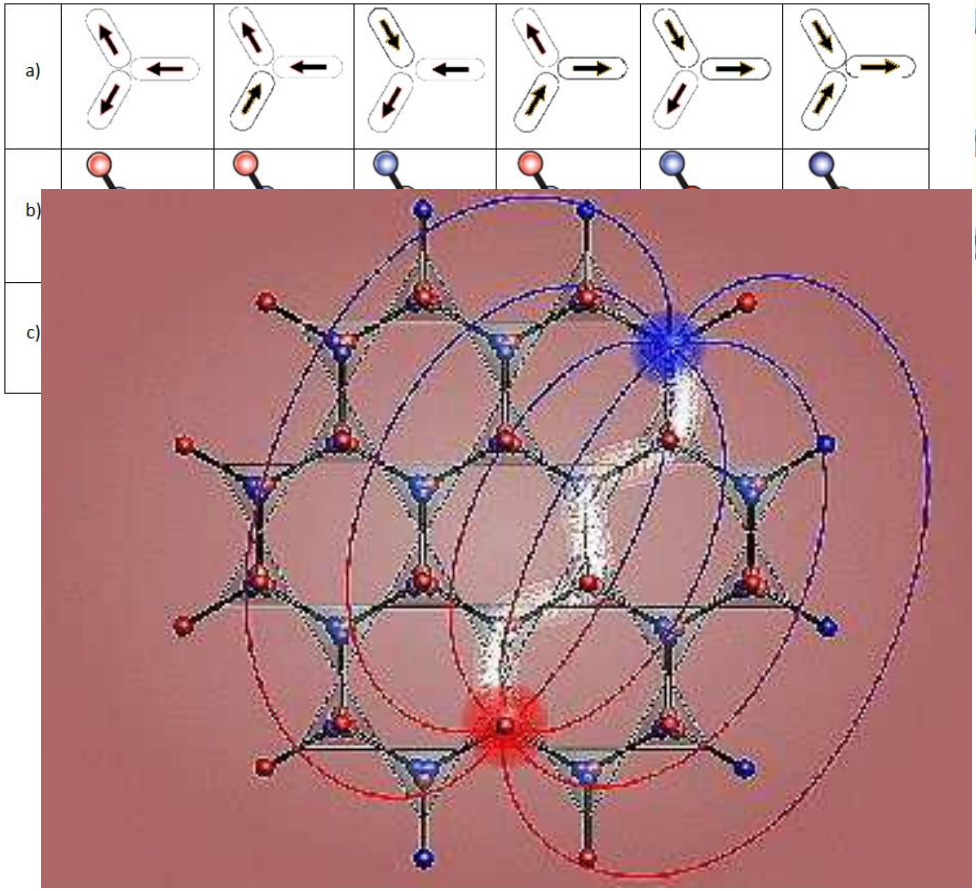
Scheme of magnetization in kagome lattice

E. Mengotti et al., Nat. Phys., 1, 68-74 (2011)

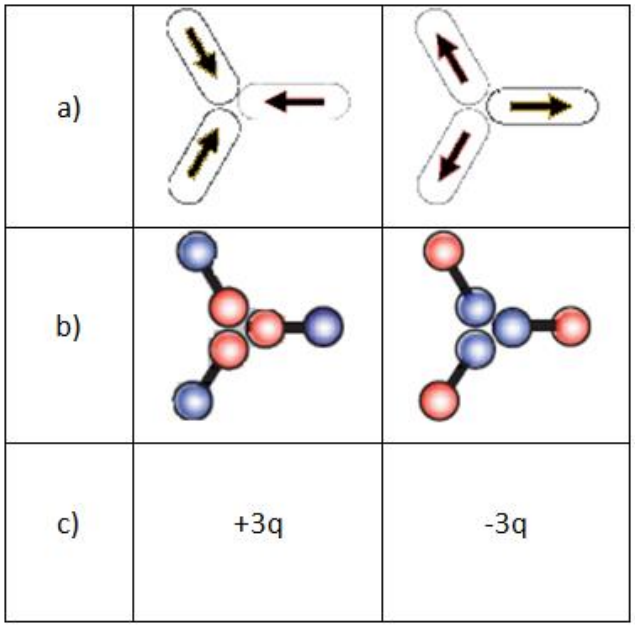
Dirac String and magnetic monopole

R. V. Hügli et al., J. App. Phys. 111, 07E103 (2012)





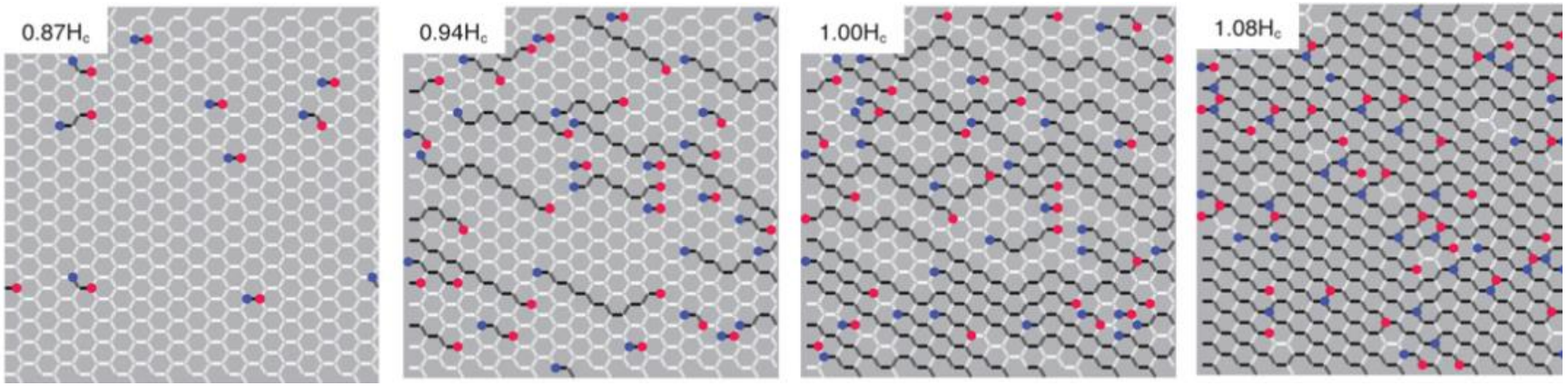
C. Castelnovo, et al. Nature 451, 42-45 (2008)



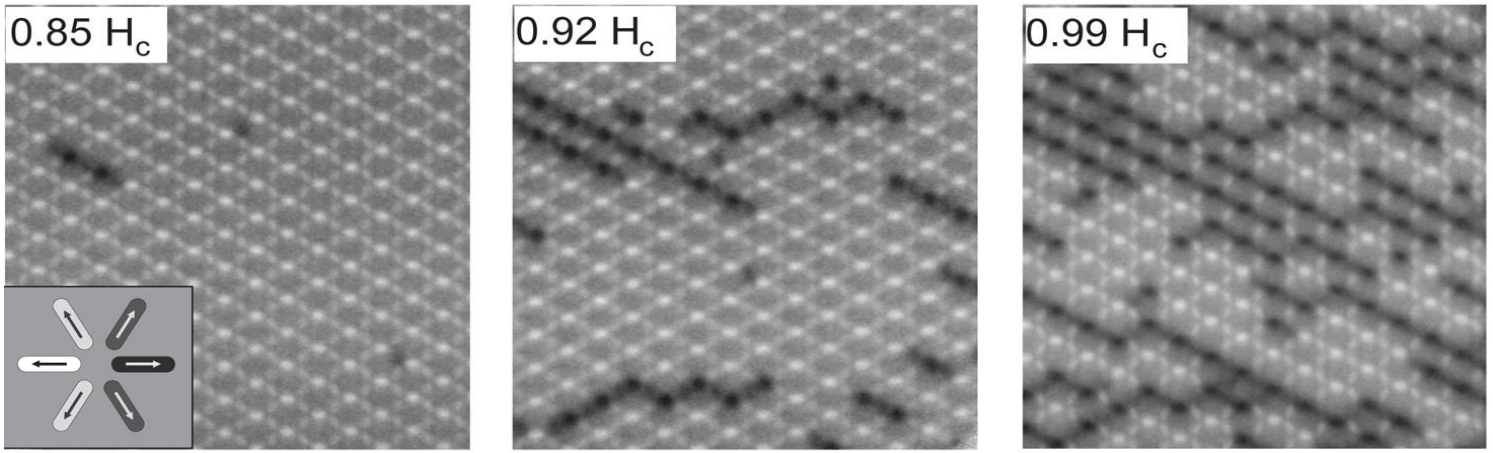
E. Mengotti et al., Nat. Phys., 1, 68-74 (2011)

Dirac String and magnetic monopole

Monte Carlo Simulation

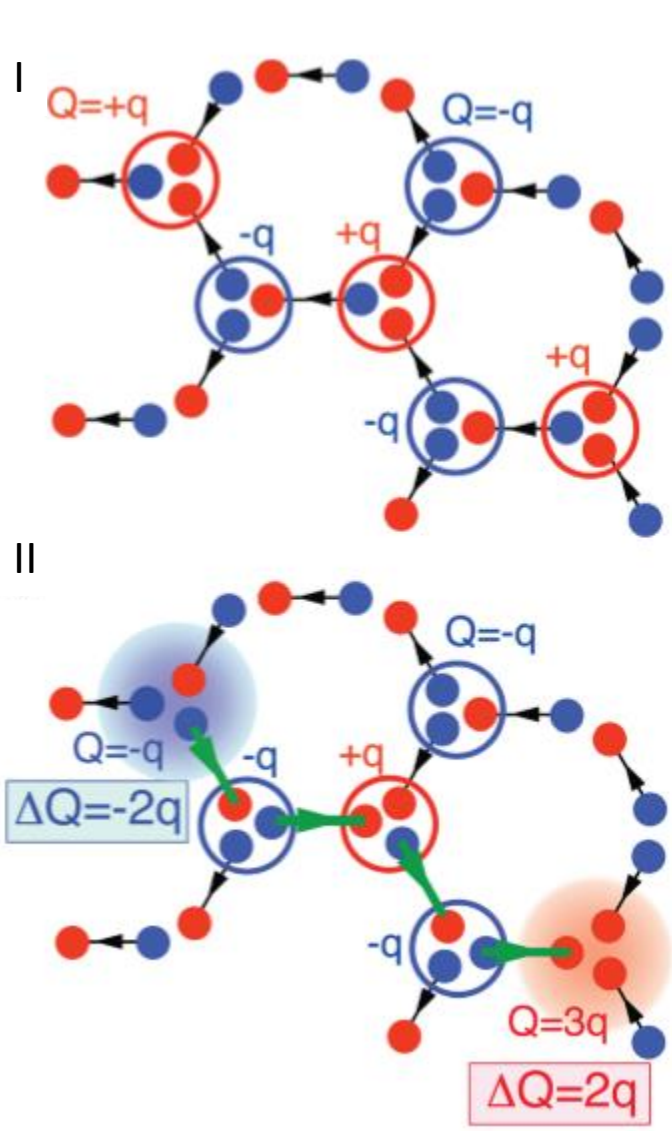


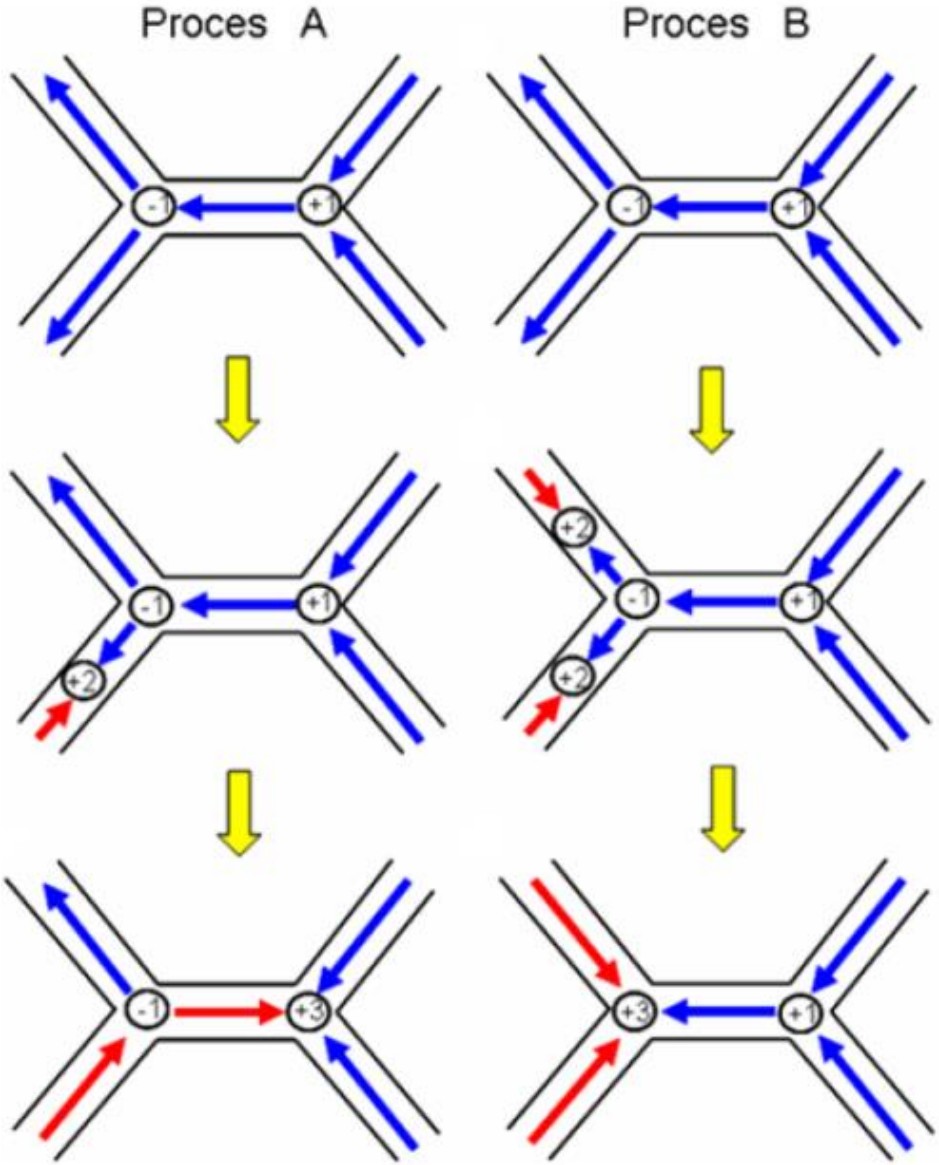
XMCD Measurement



R. V. Hügli et al., J. App. Phys. 111, 07E103 (2012)

Creation of magnetic monopoles

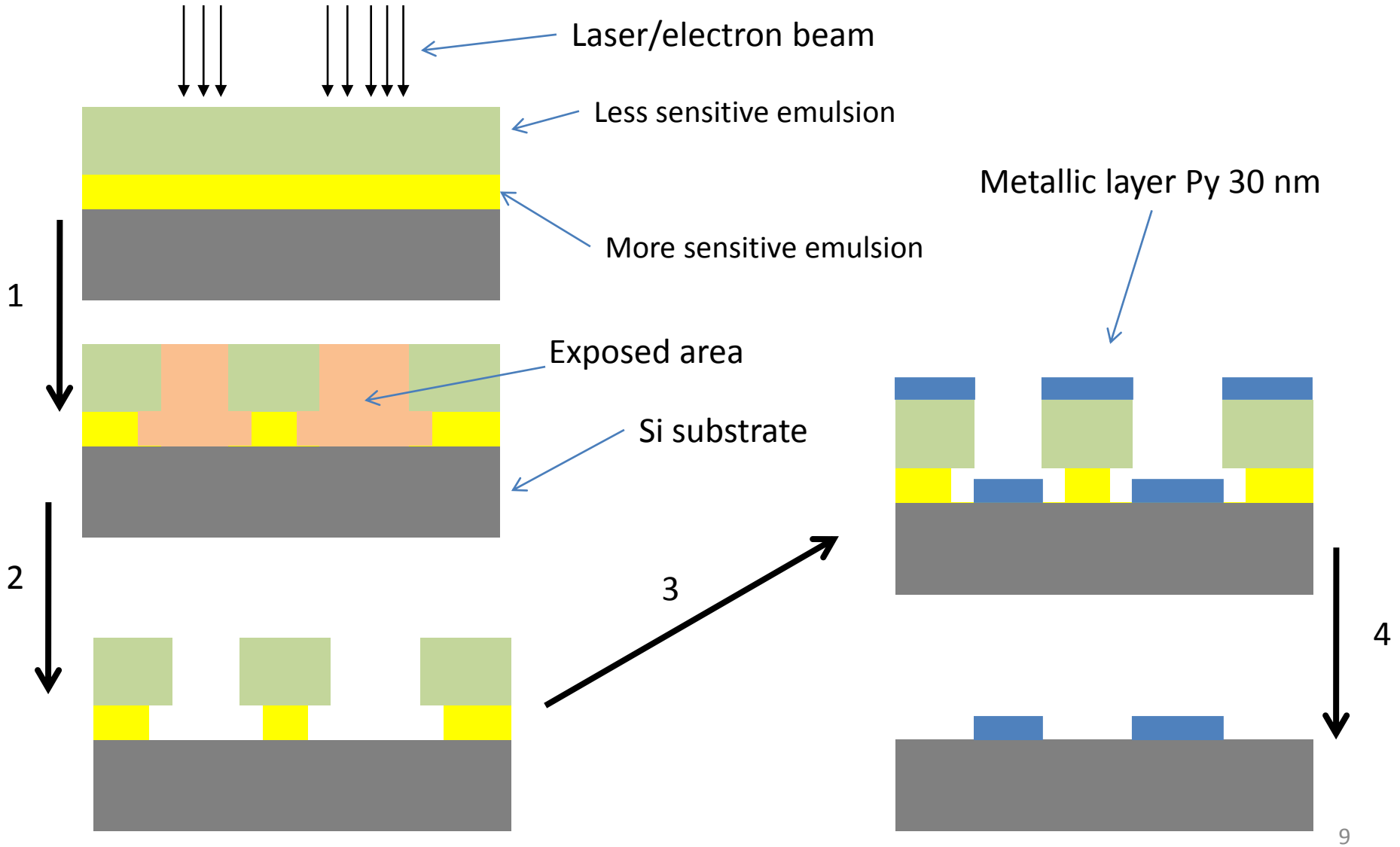


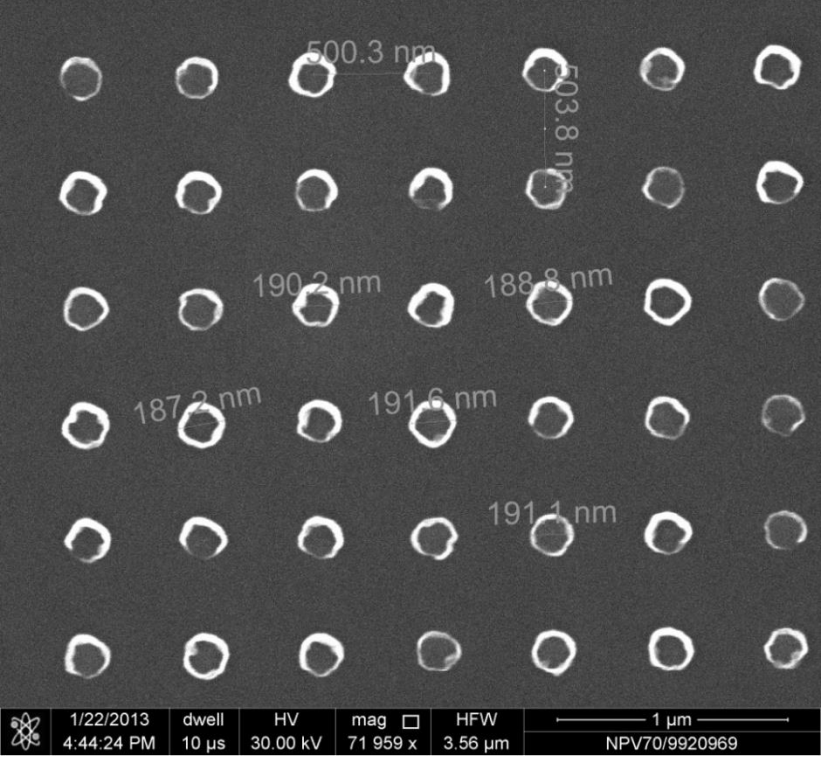


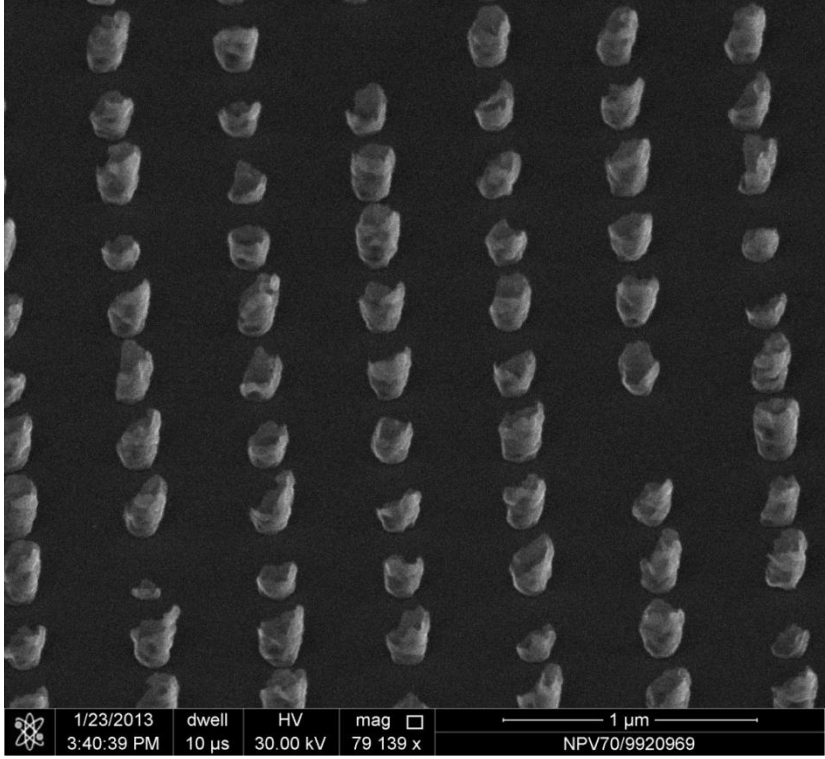
R. V. Hügli et al., J. App. Phys. 111, 07E103 (2012)

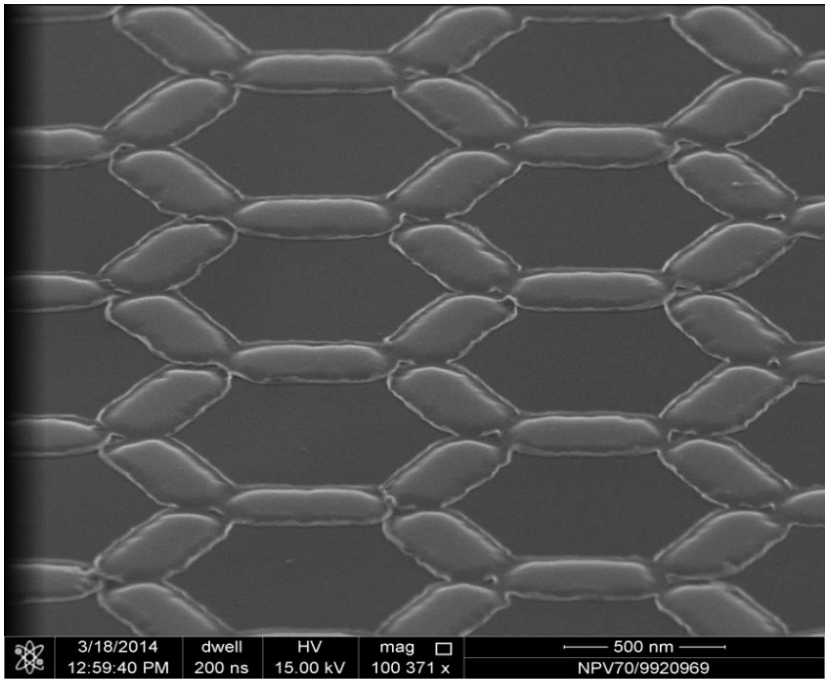
S. Ladak et al., New J. Phys., 13, 063032 (2011)

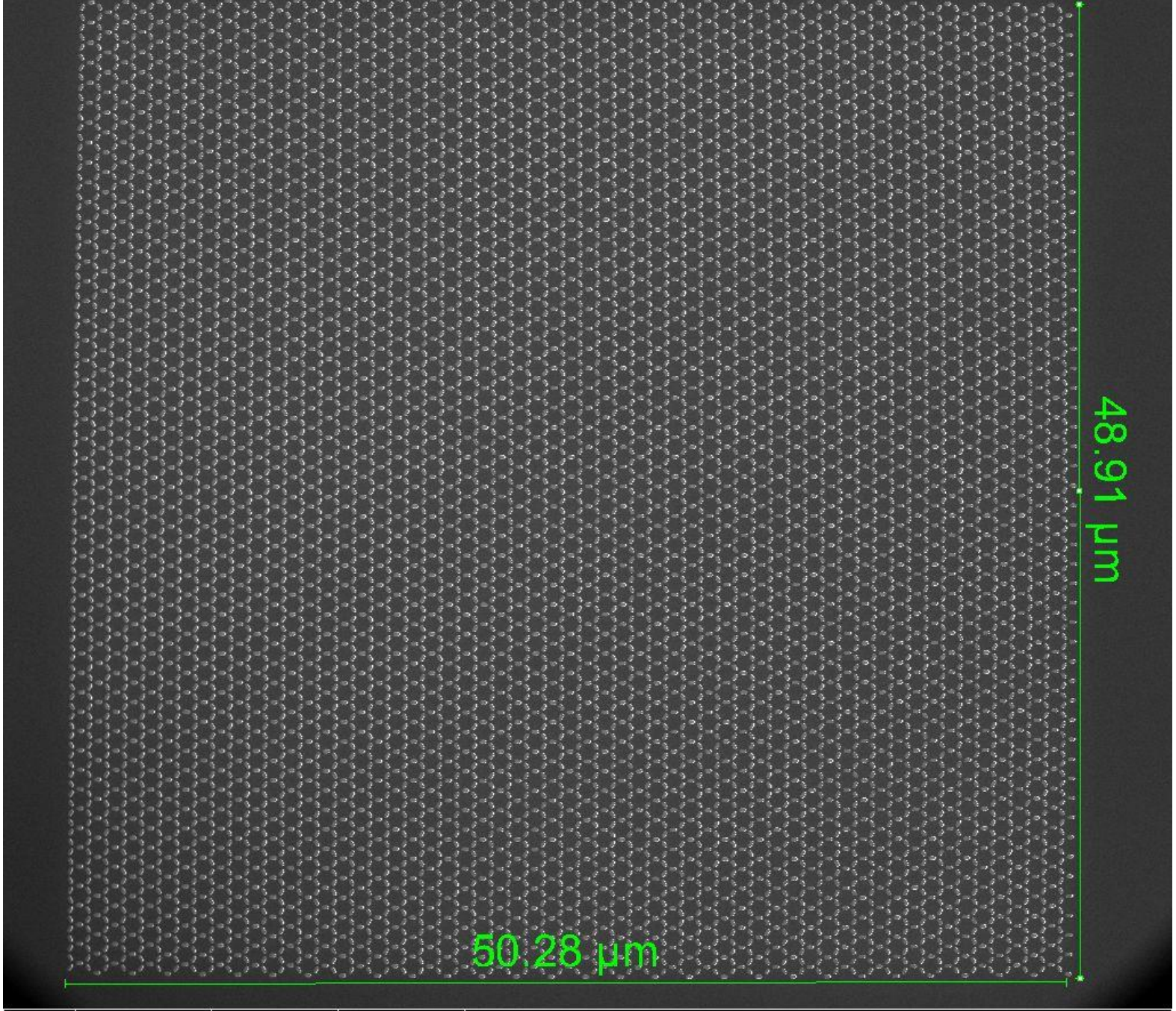
Structuring – electron beam lithography / maskless photolithography




500.3 nm
503.8 nm
190.2 nm
188.8 nm
187.2 nm
191.6 nm
191.1 nm
1/22/2013
4:44:24 PM
dwell
10 µs
HV
30.00 kV
mag
71 959 x
HFW
3.56 µm
1 µm
NPV70/9920969


1/23/2013
3:40:39 PM
dwell
10 µs
HV
30.00 kV
mag
79 139 x
1 µm
NPV70/9920969

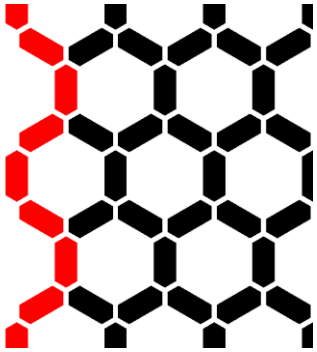

3/18/2014
12:59:40 PM
dwell
200 ns
HV
15.00 kV
mag
100 371 x
500 nm
NPV70/9920969



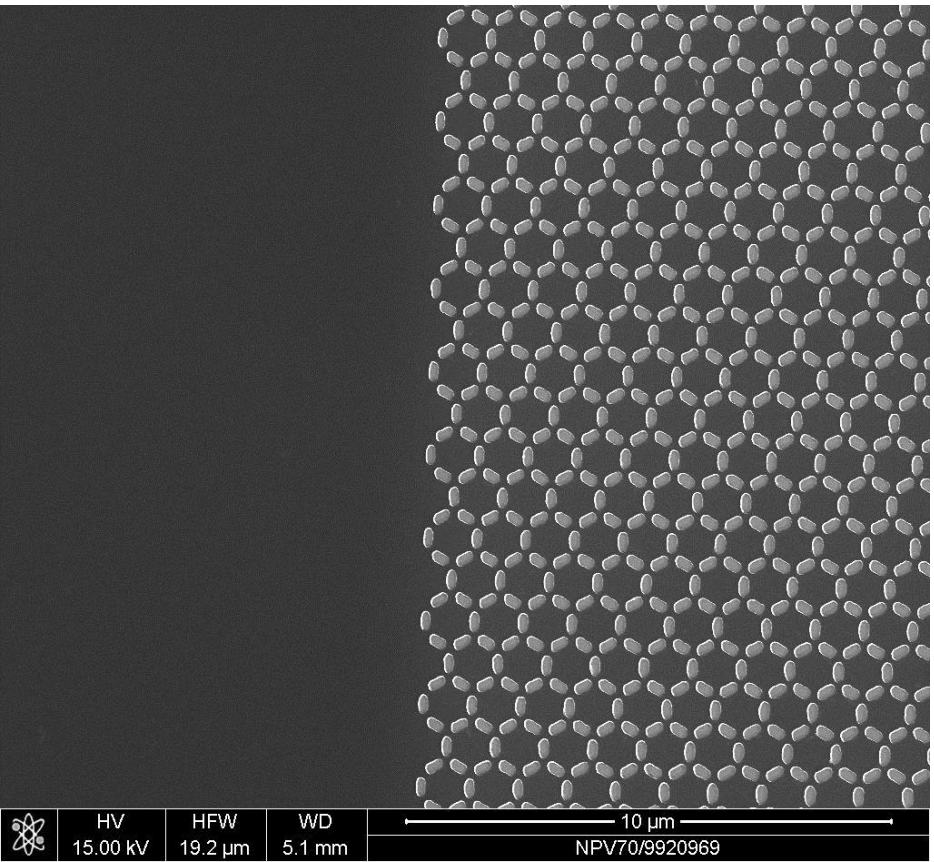
	HV	HFW	WD	30 µm
	15.00 kV	58.7 µm	5.1 mm	NPV70/9920969

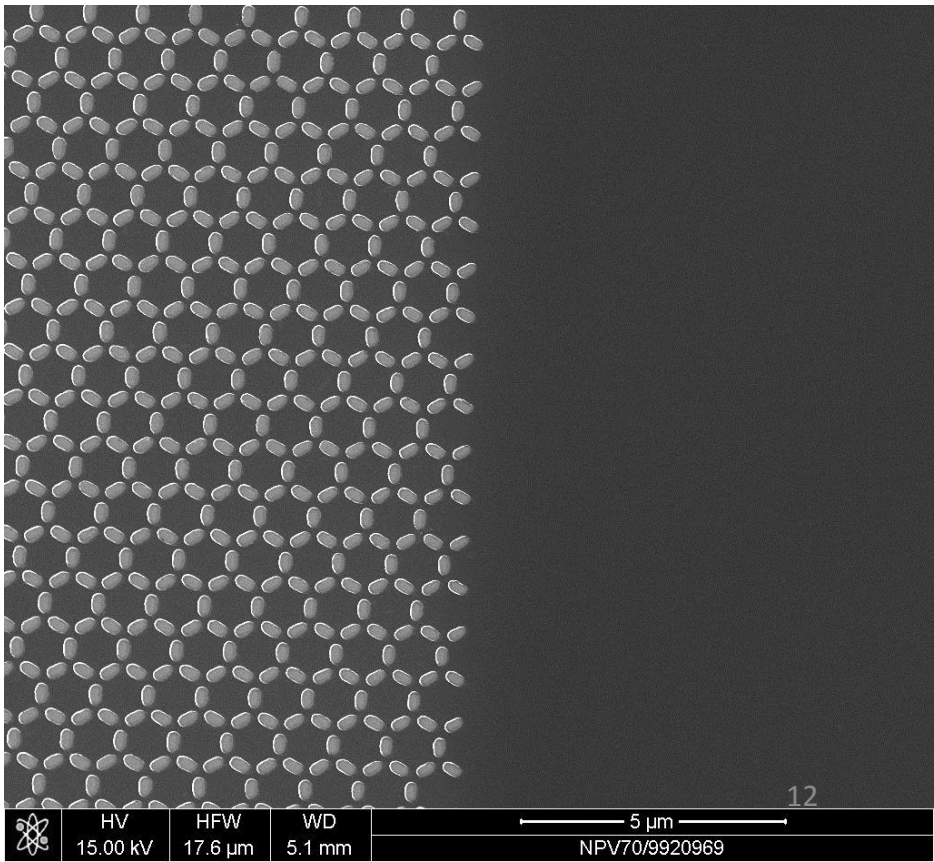
ARMCHAIR type of structure edge

armchair closed



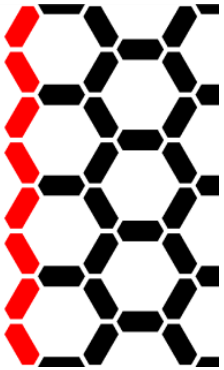
armchair open

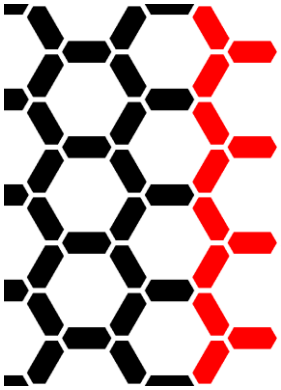




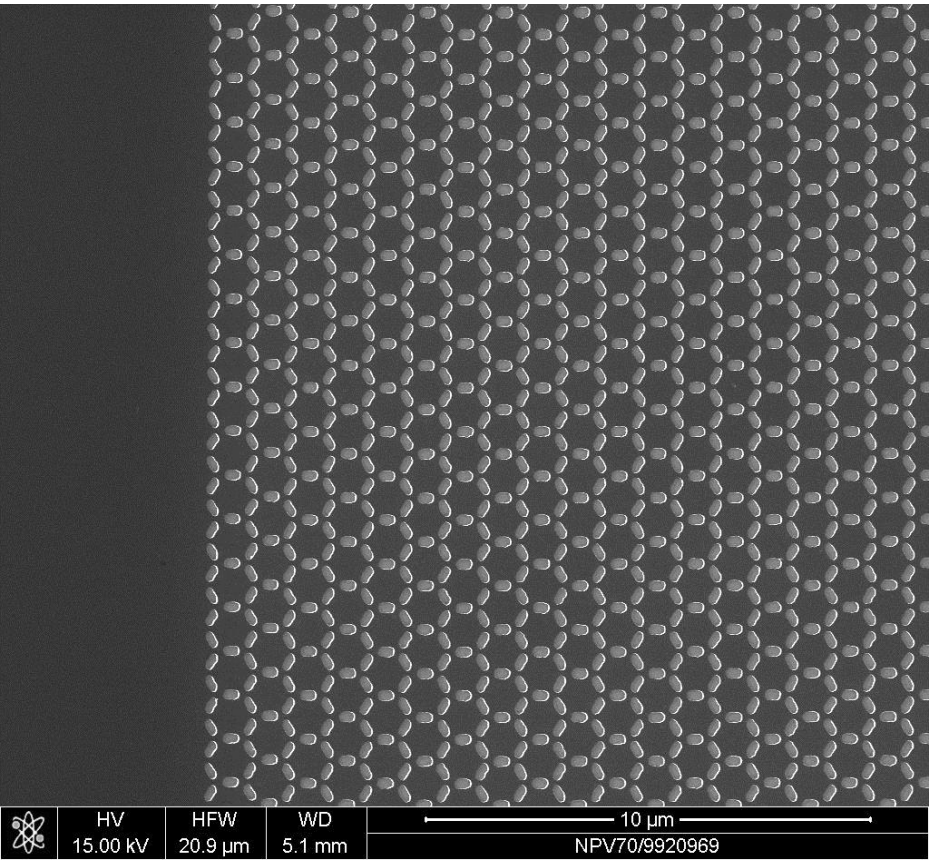
ZIGZAG type of structure edge

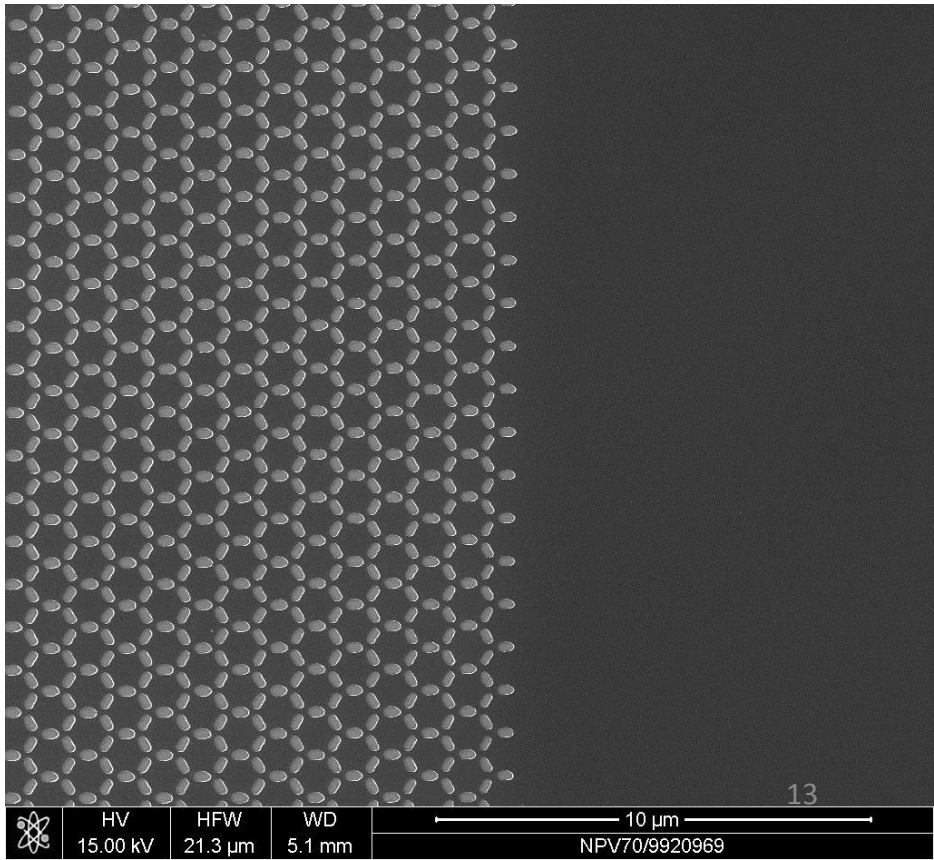
zigzag closed



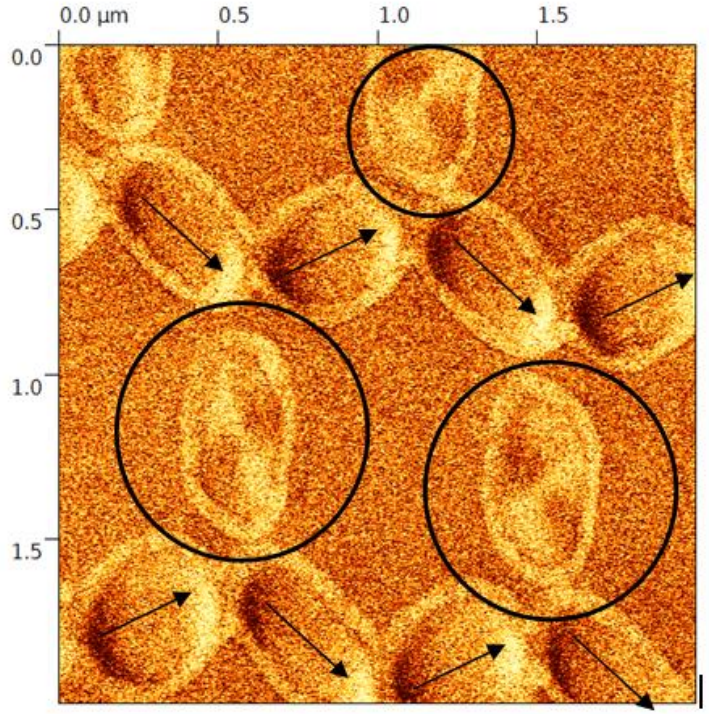


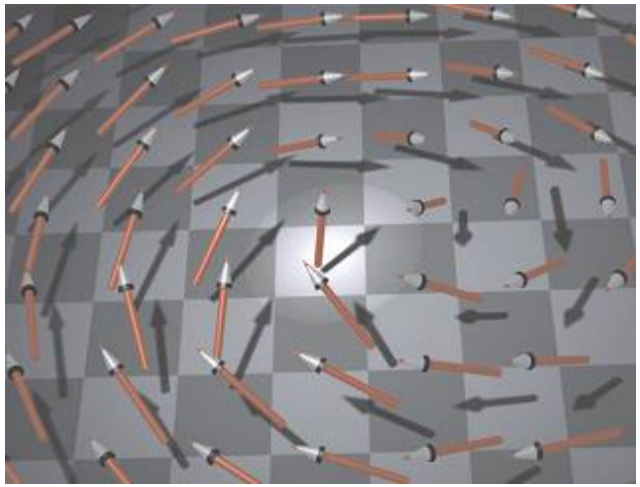
zigzag open

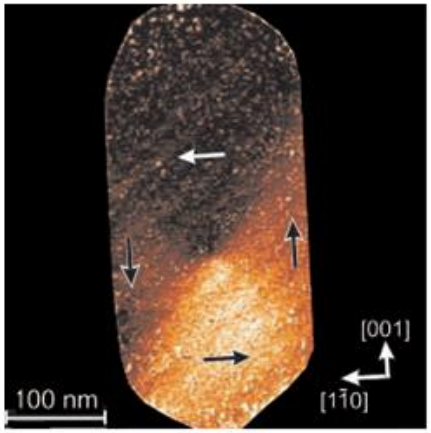




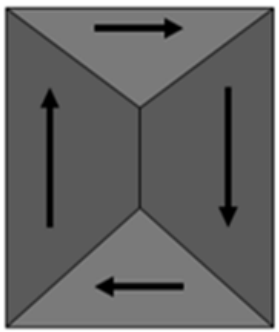
MFM measuremets – vortex structures

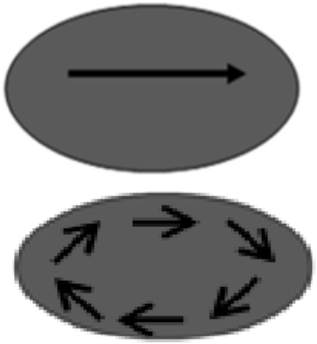






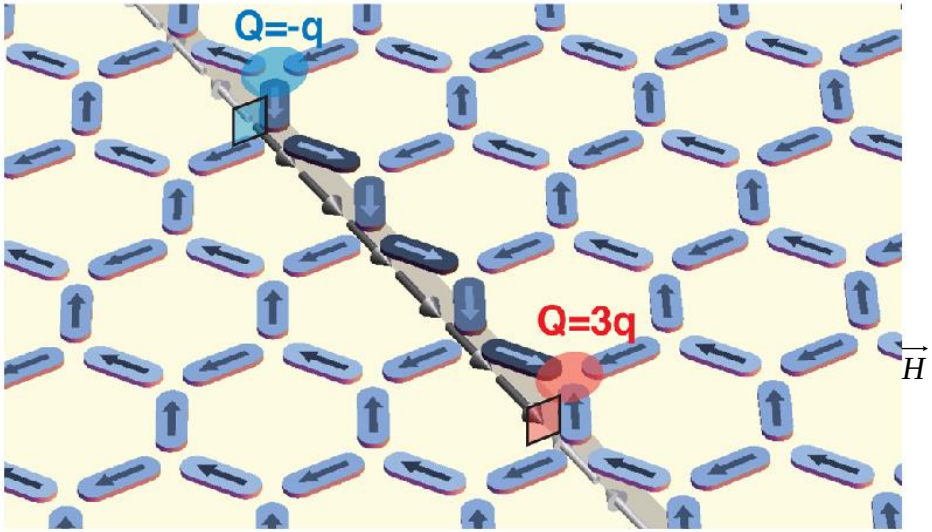
Vortex structure for Fe island



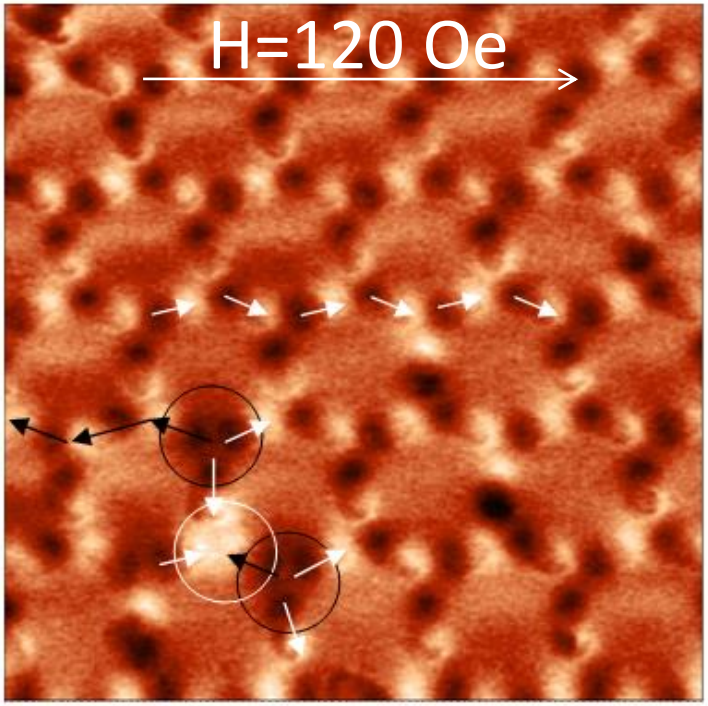


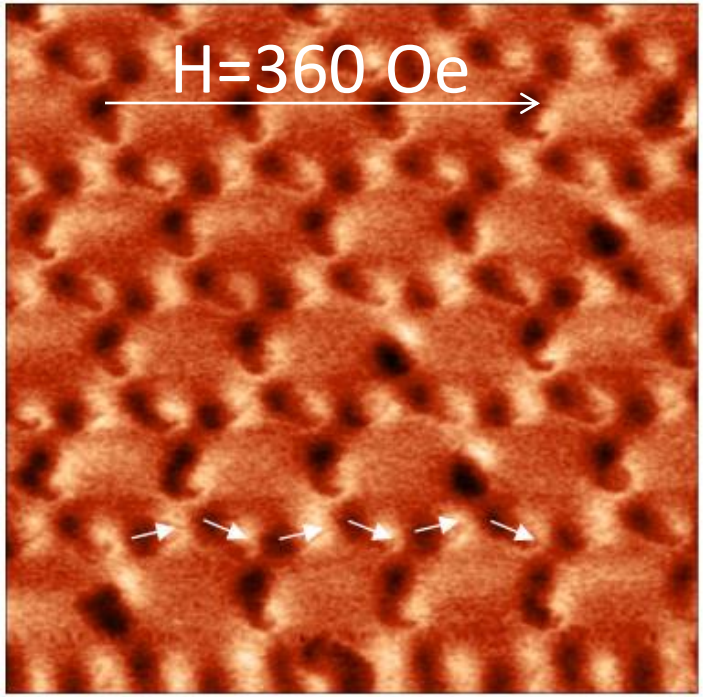
A. Wachowiak et al., Science, 5593, 577-580 (2002)

Magnetic monopoles



R. V. Hügli et al., J. App. Phys. 111, 07E103 (2012)



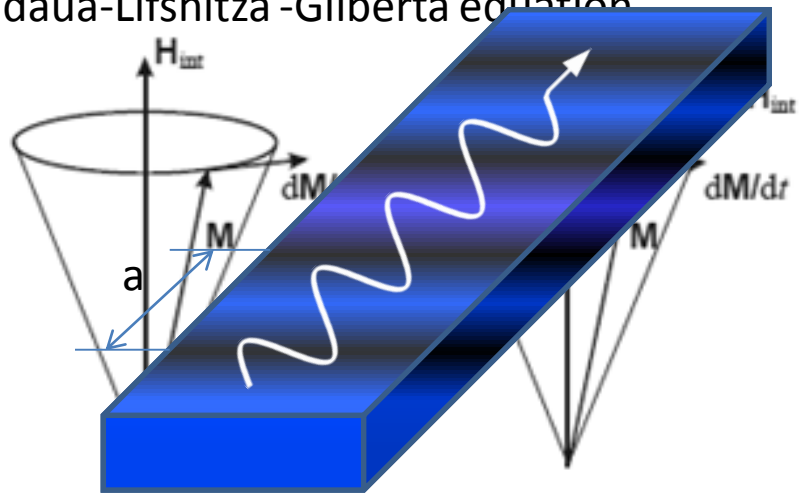


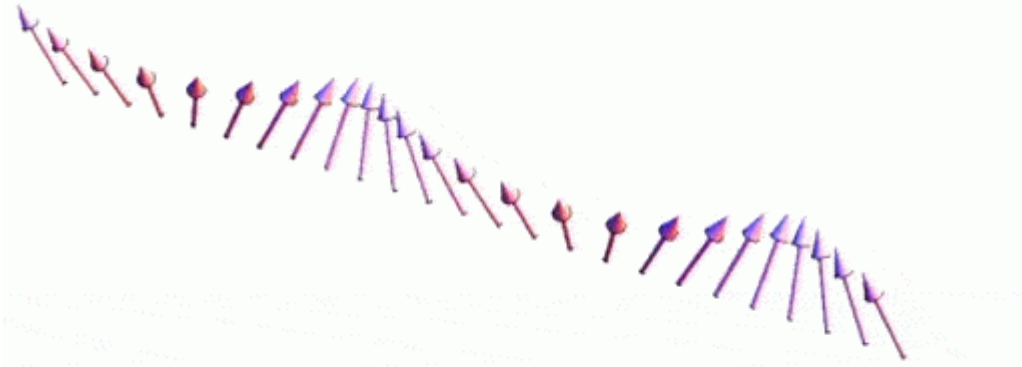
Measured at University of Białystok

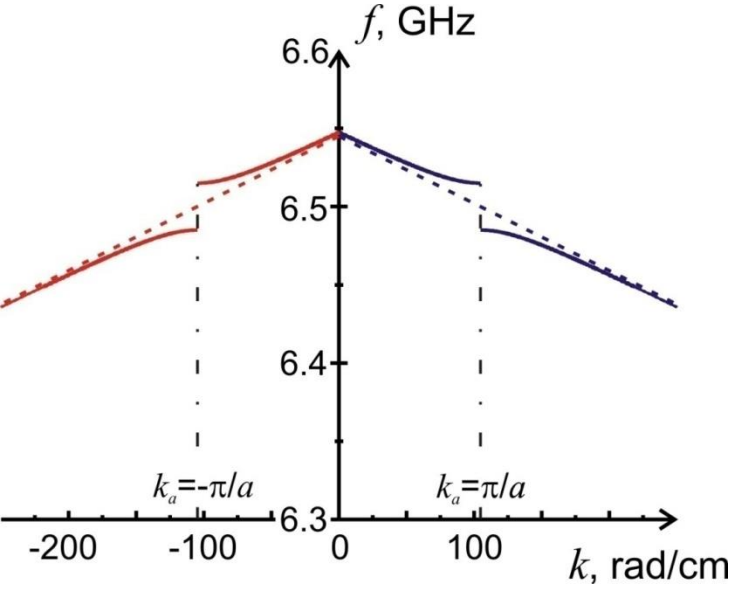
Spin wave

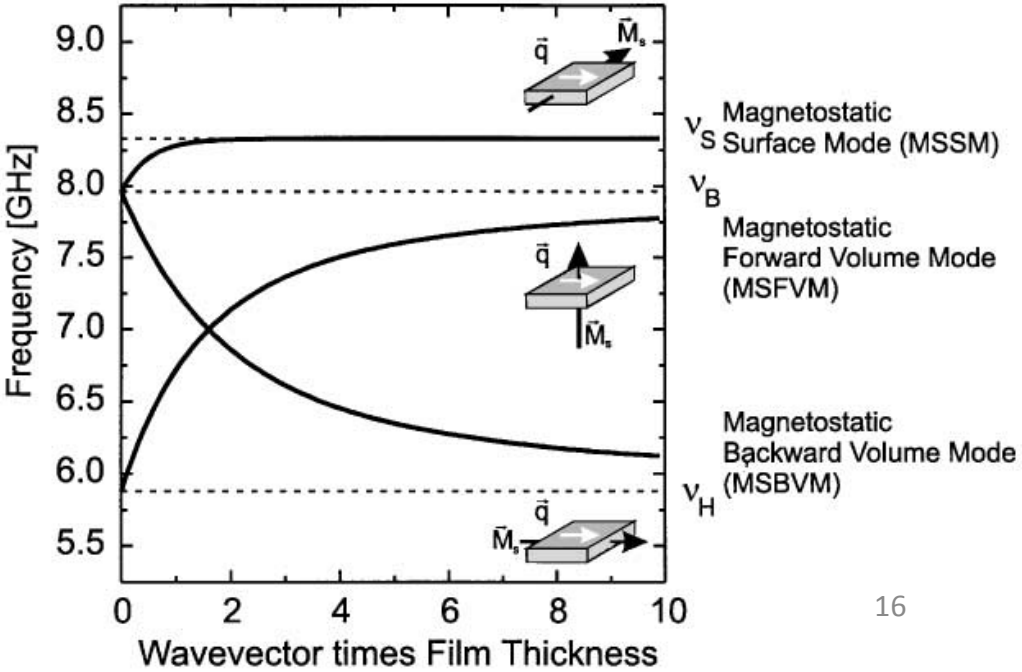
The dynamics of spin precession explain Landaua-Lifshitza -Gilberta equation

$$-\frac{1}{\gamma}\frac{d\vec{M}}{dt} = \vec{M}\times\vec{H}_{int} - \frac{\alpha}{|M|}\left(\vec{M}\times\frac{d\vec{M}}{dt}\right)$$

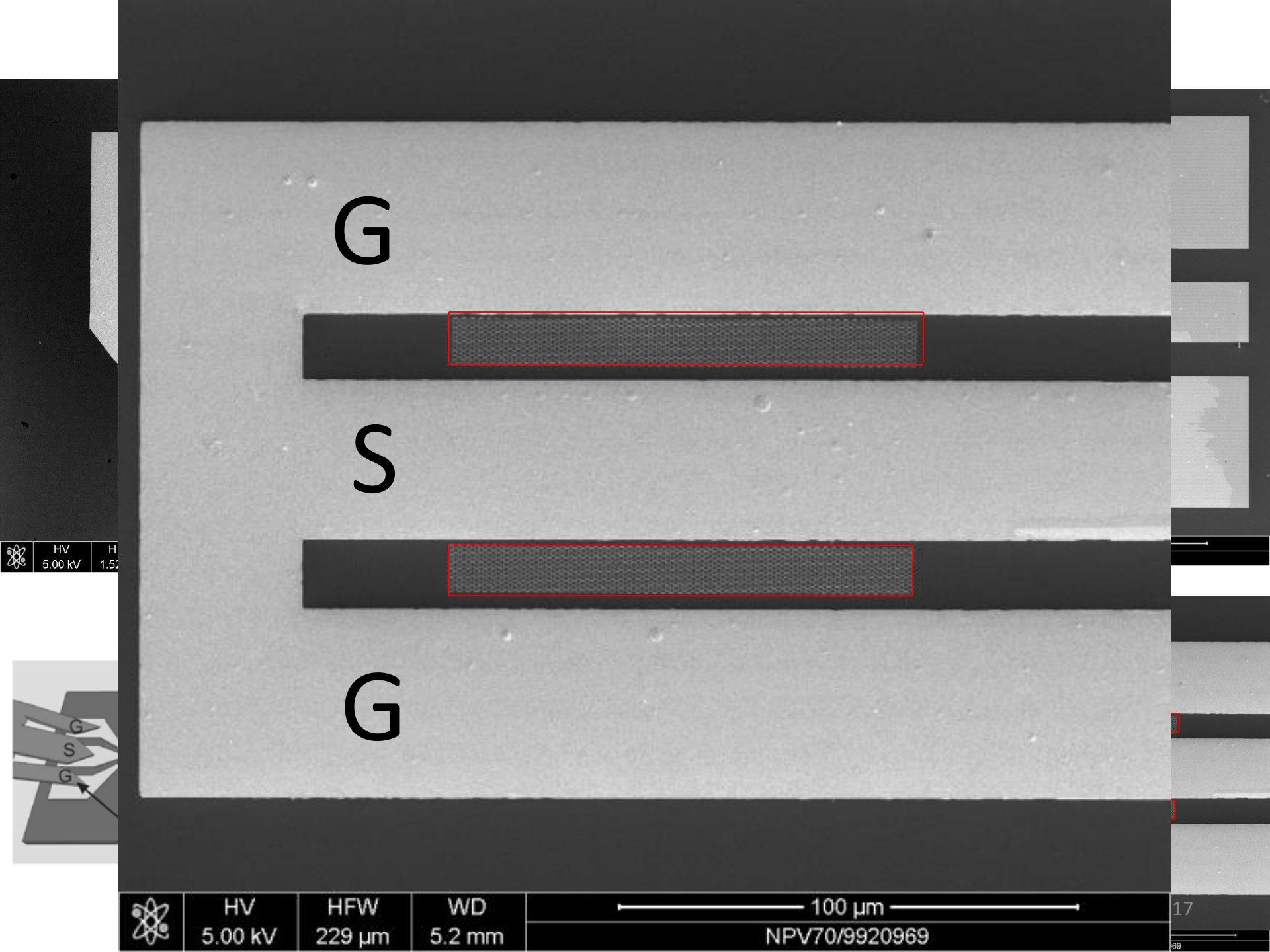




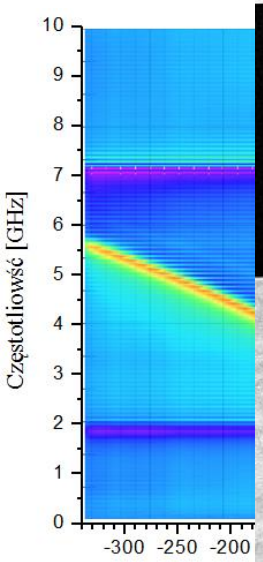




A. Chumak, TU Kaiserslautern


G
S
G
HV
5.00 kV
HFW
229 µm
WD
5.2 mm
100 µm
NPV70/9920969

Re

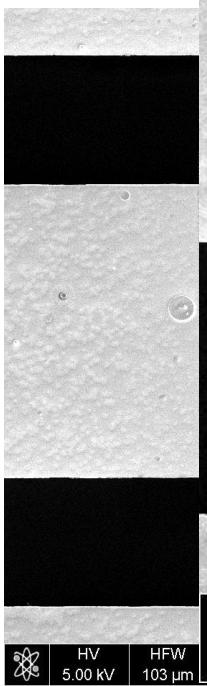


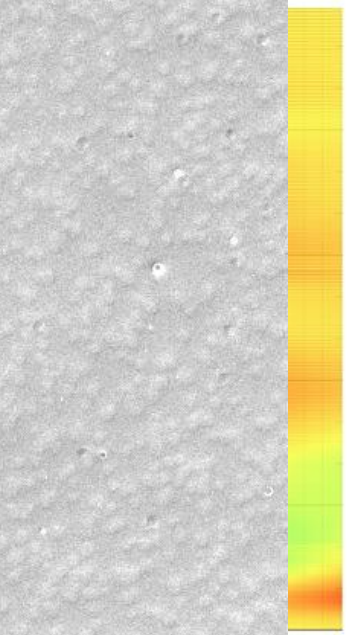
S

4.947 µm

40.89 µm

4.039 µm

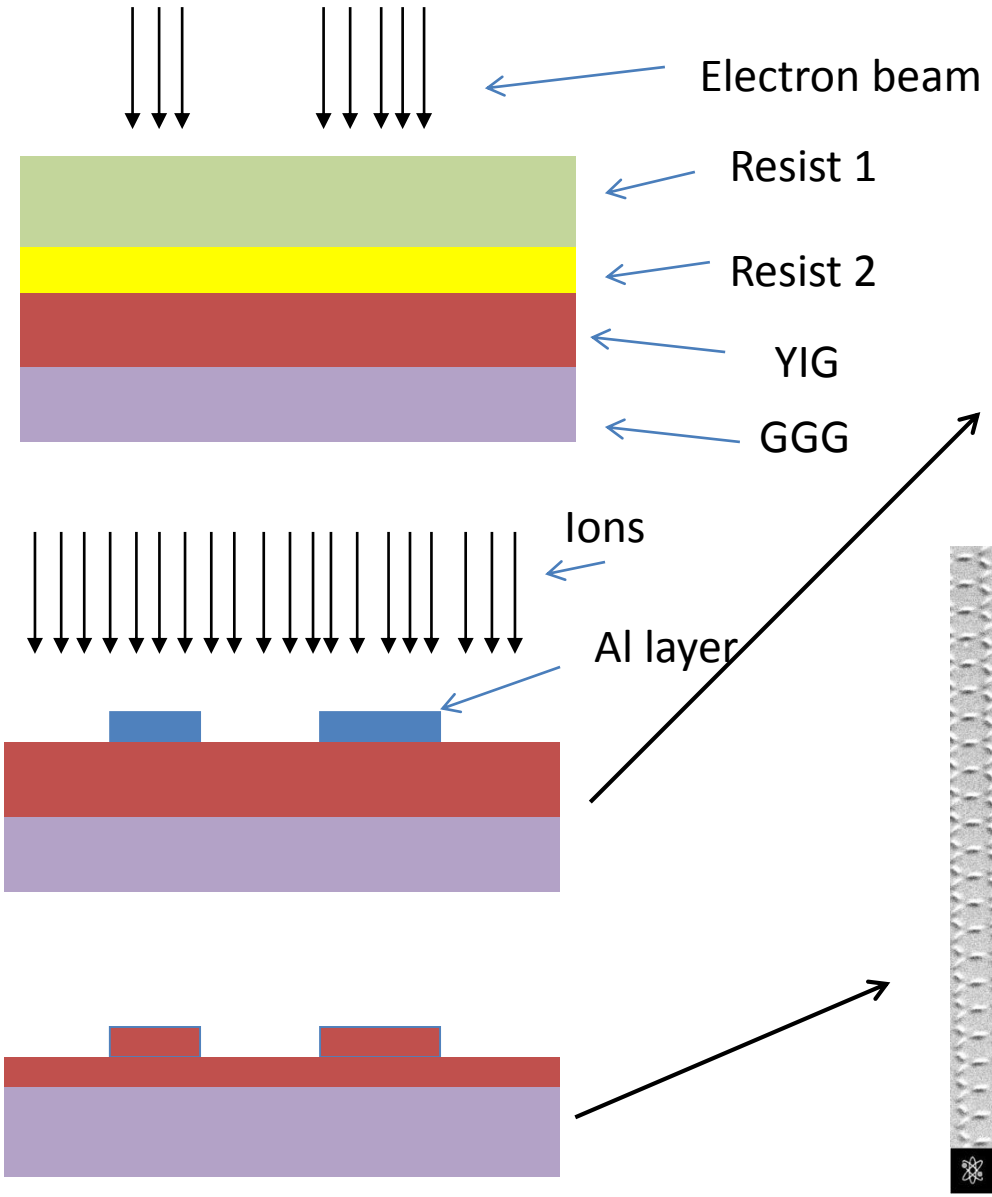


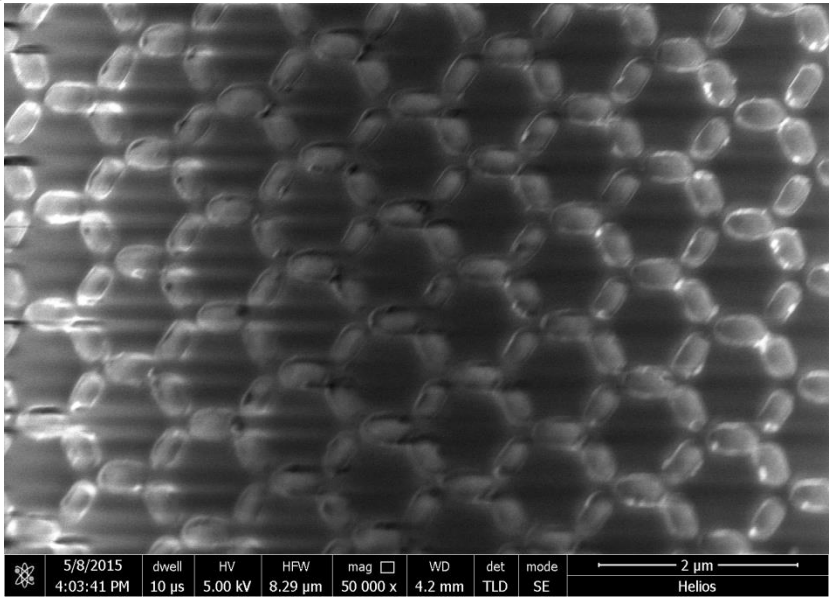


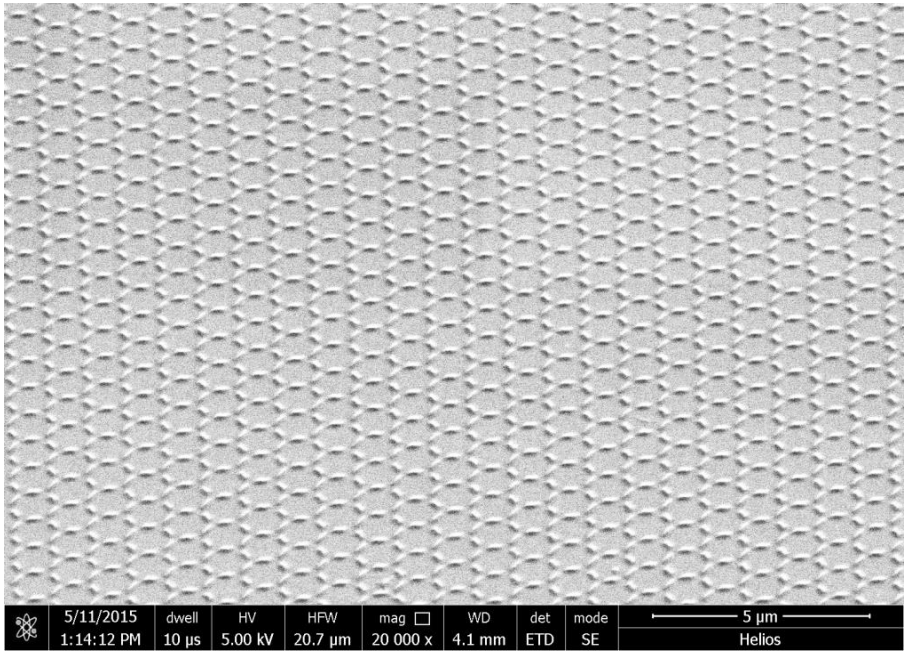
HV	HFW	WD	
5.00 kV	103 µm	5.2 mm	50 µm
			NPV70/9920969

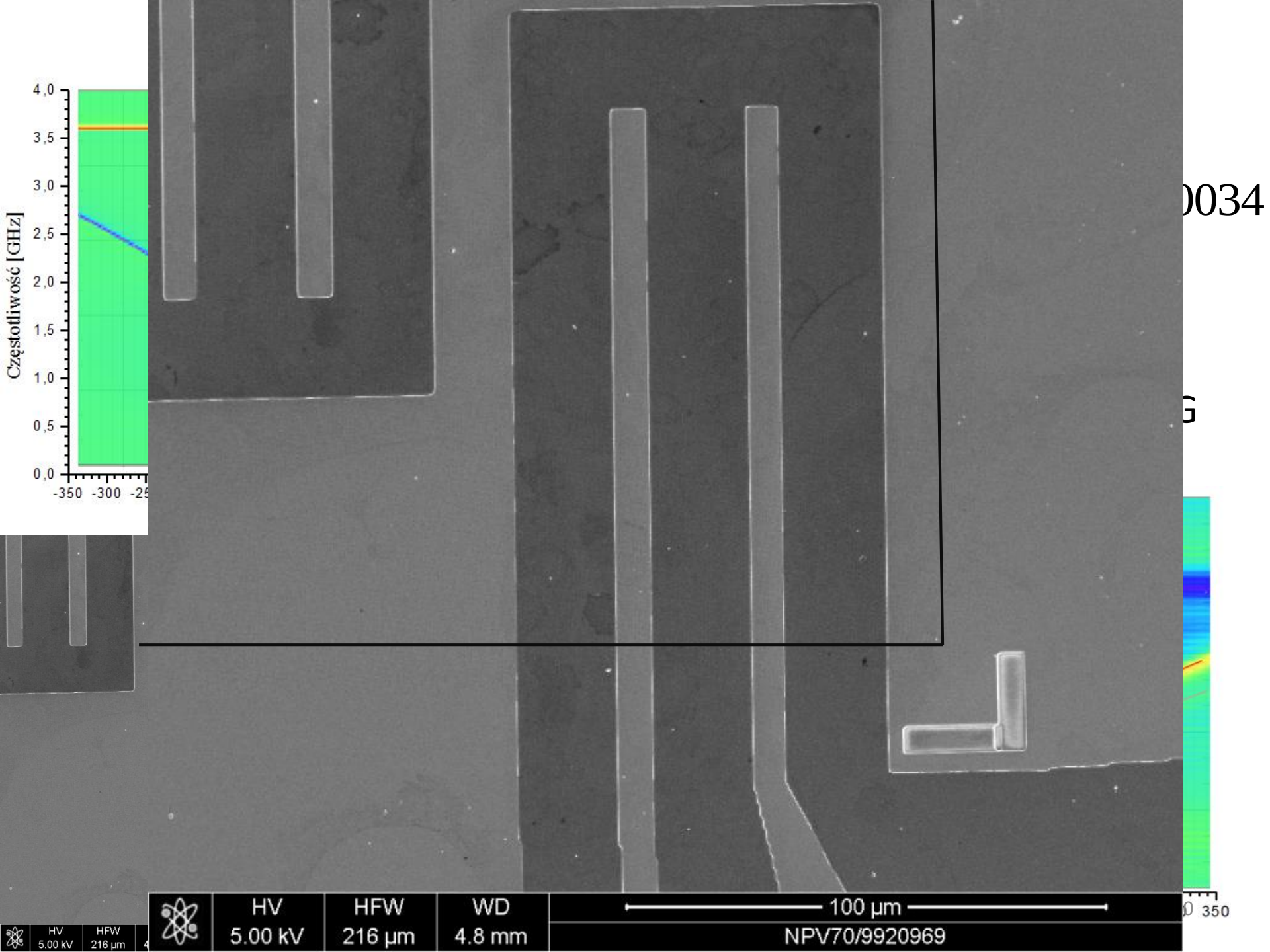
HV 5.00 kV HFW 103 µm

YIG structuring – Ion etching



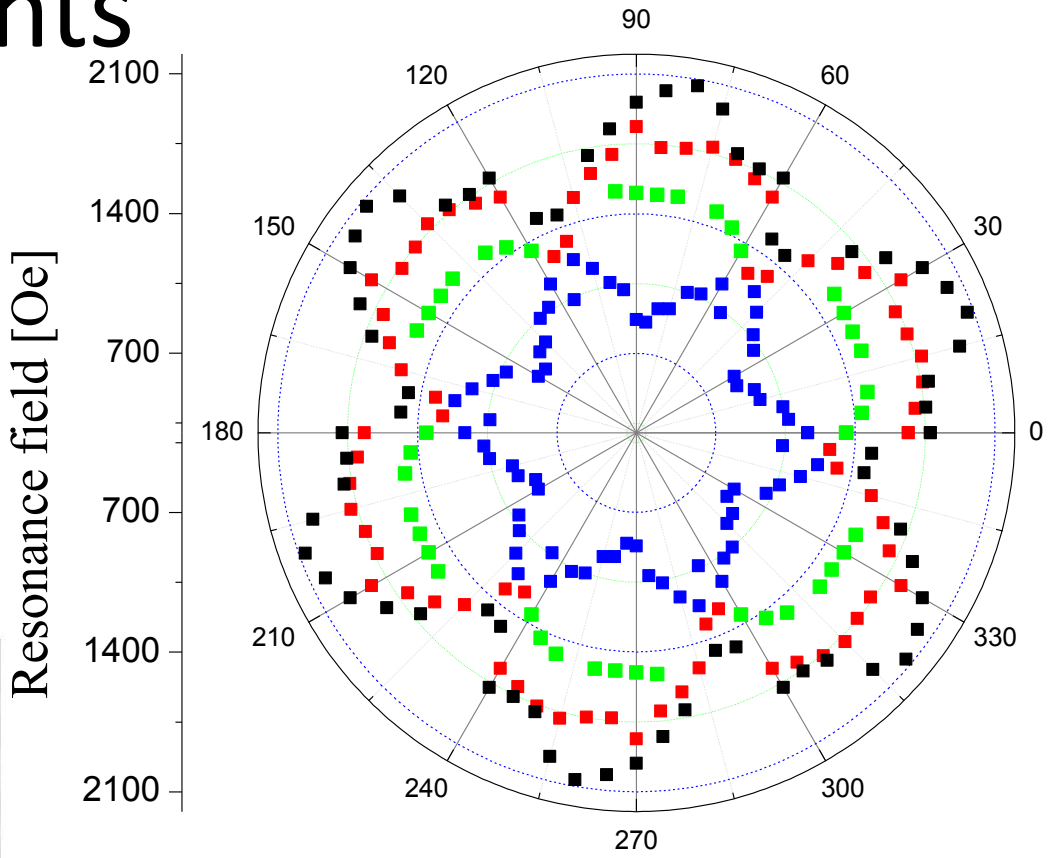


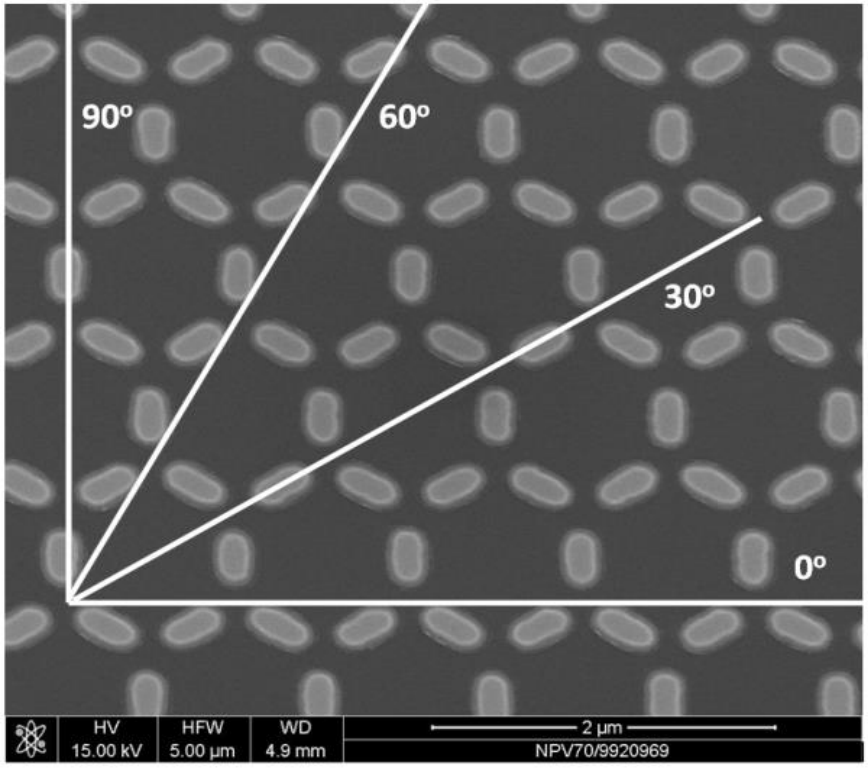



Częstotliwość [GHz]
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
-350
-300
HV
5.00 kV
HFW
216 µm
WD
4.8 mm
100 µm
NPV70/9920969
350

FMR measurements

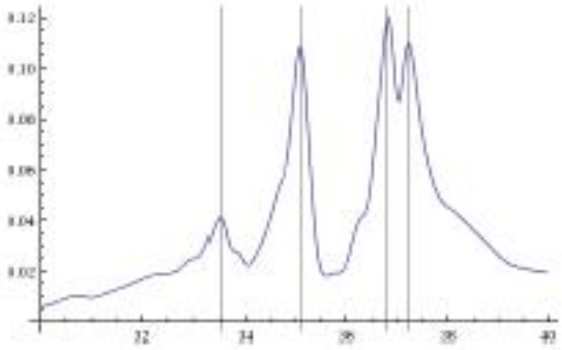
$$f_{rez} = \frac{\gamma \mu_0}{2\pi} \sqrt{H_{zew}\left(H_{zew} + M_{sat}\right)}$$



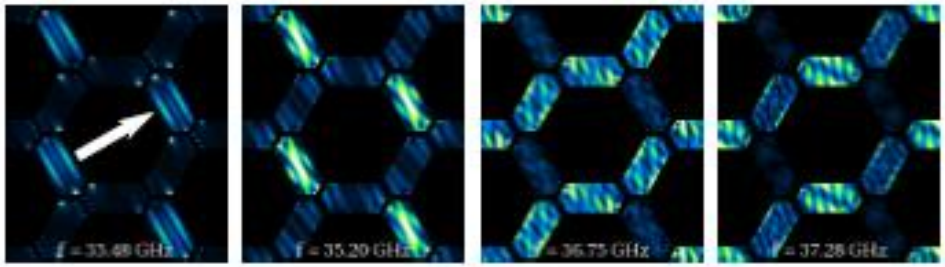


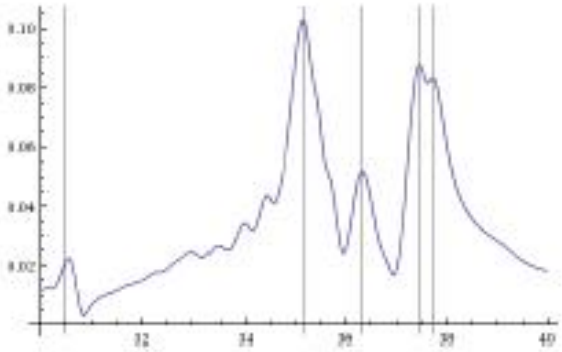
Measured at Department of Solid State Radiospectroscopy IMP PAS

Spin ice - spatial dependences of resonant frequency - results of OOMMF simulations

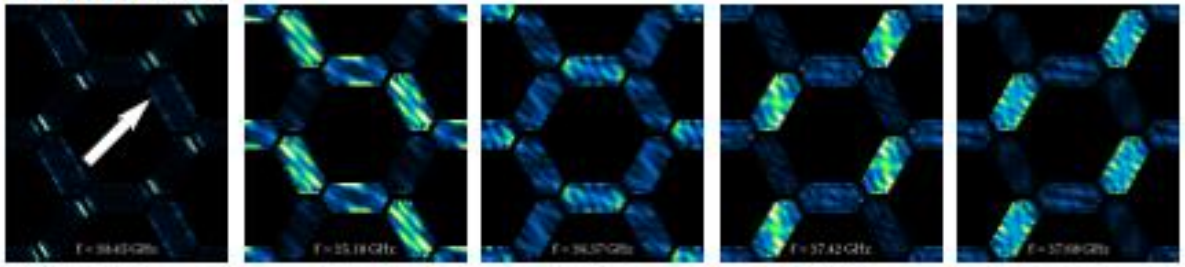


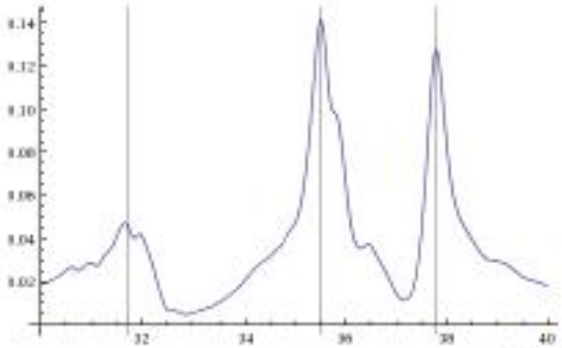
H = 900 mT @ 30°



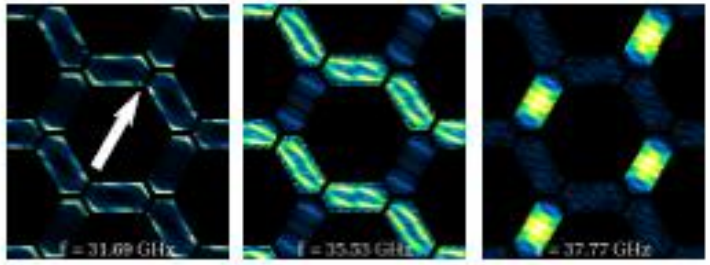


H = 900 mT @ 45°





H = 900 mT @ 60°



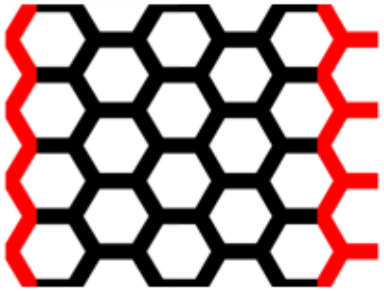
Summary

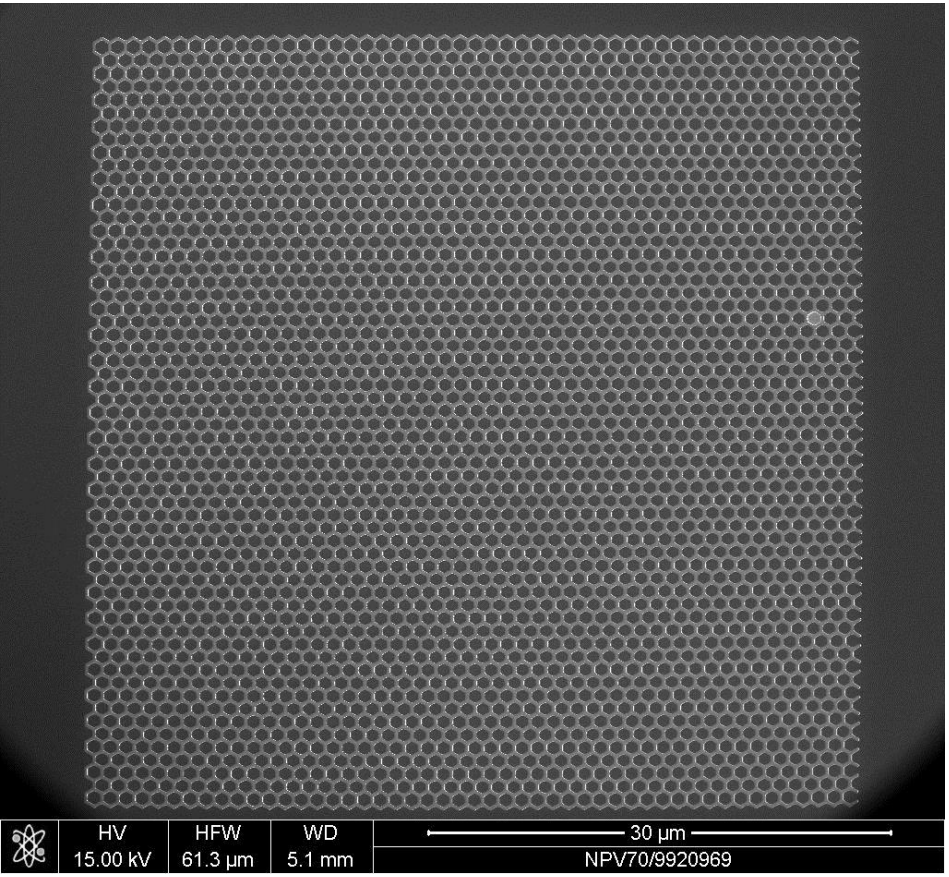
- At kagome lattice a magnetic monopole and Dirac string was observed by MFM technique

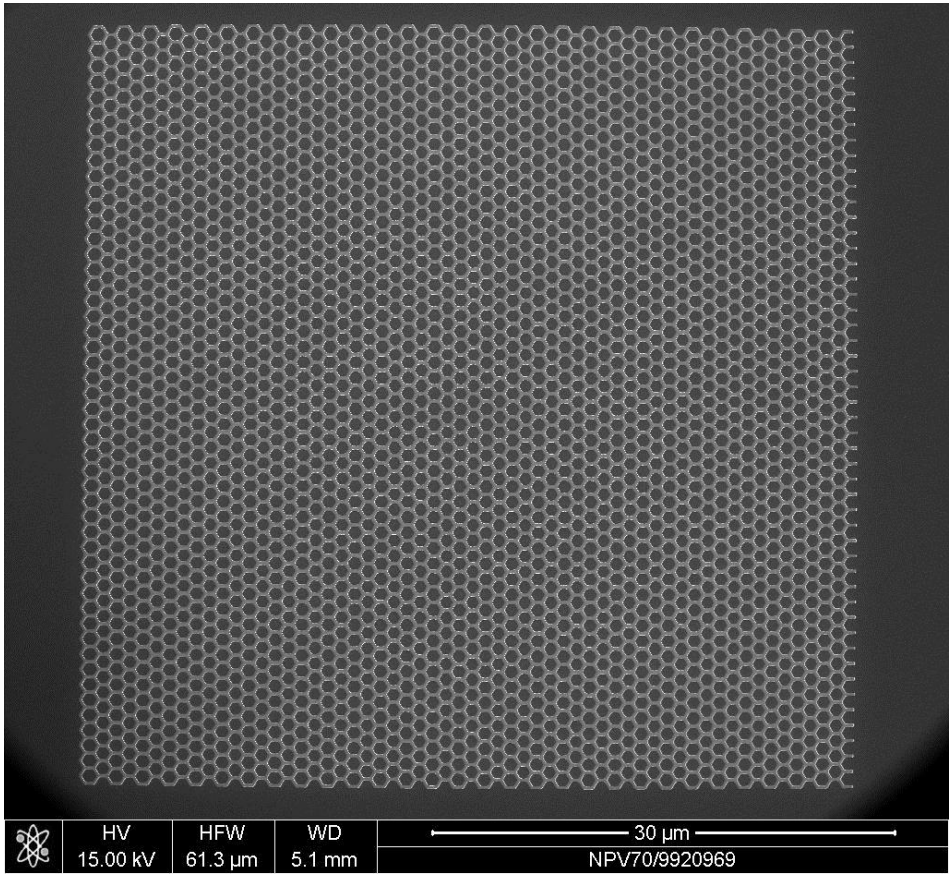
- Spin wave excitation in Py/YIG kagome was observed

Thank you for attention

Brzeg struktur dla sieci połączonych

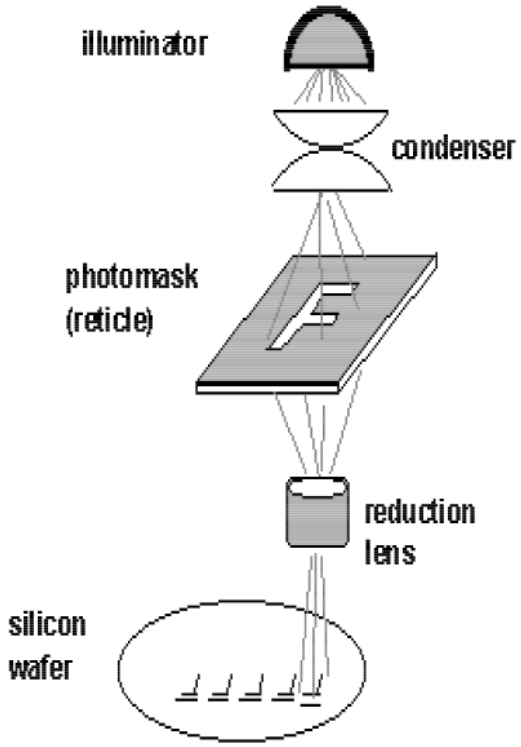




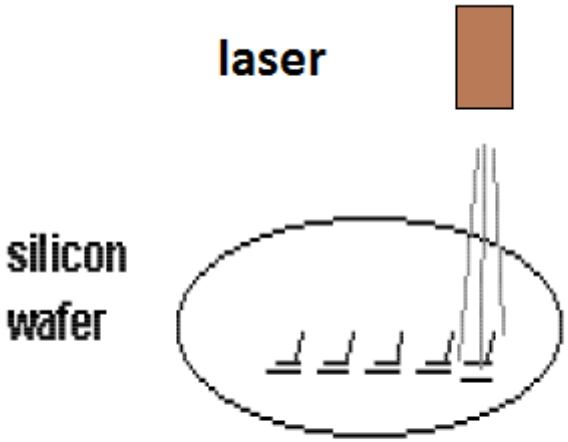


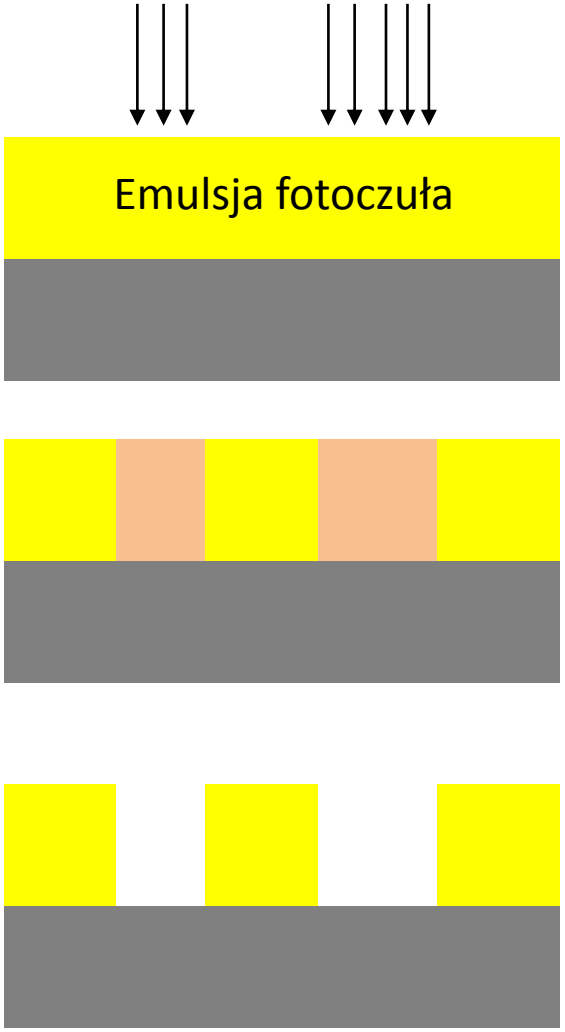
Fotolitografia bezmaskowa

Przy użyciu maski



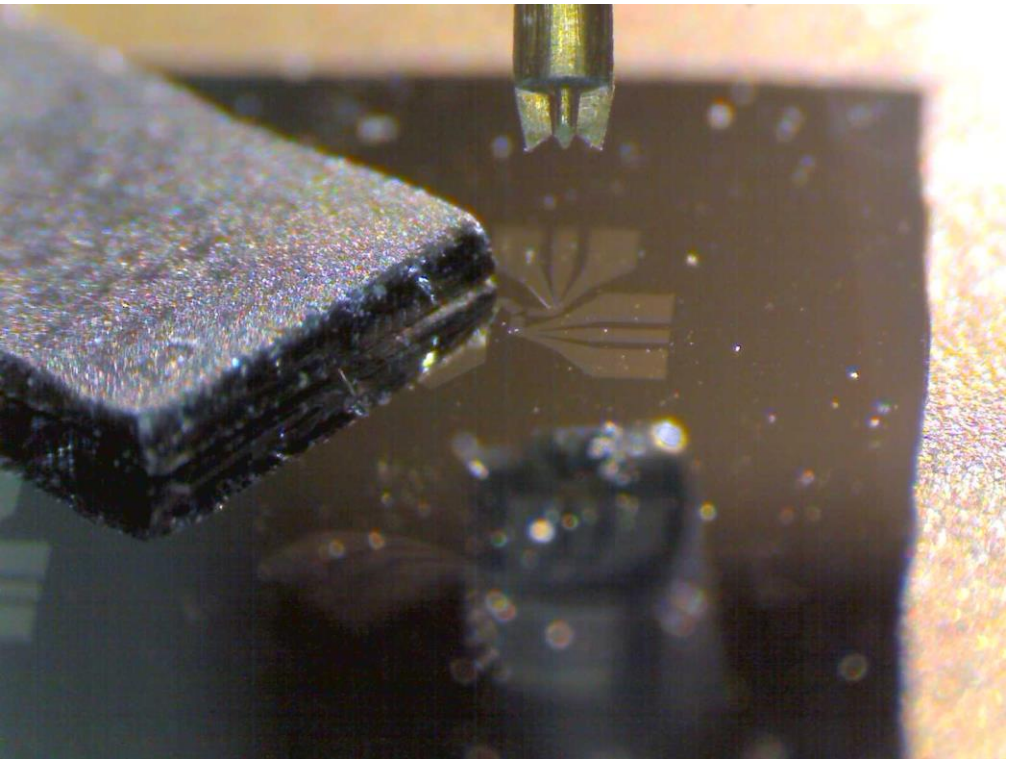
Bez użycia maski

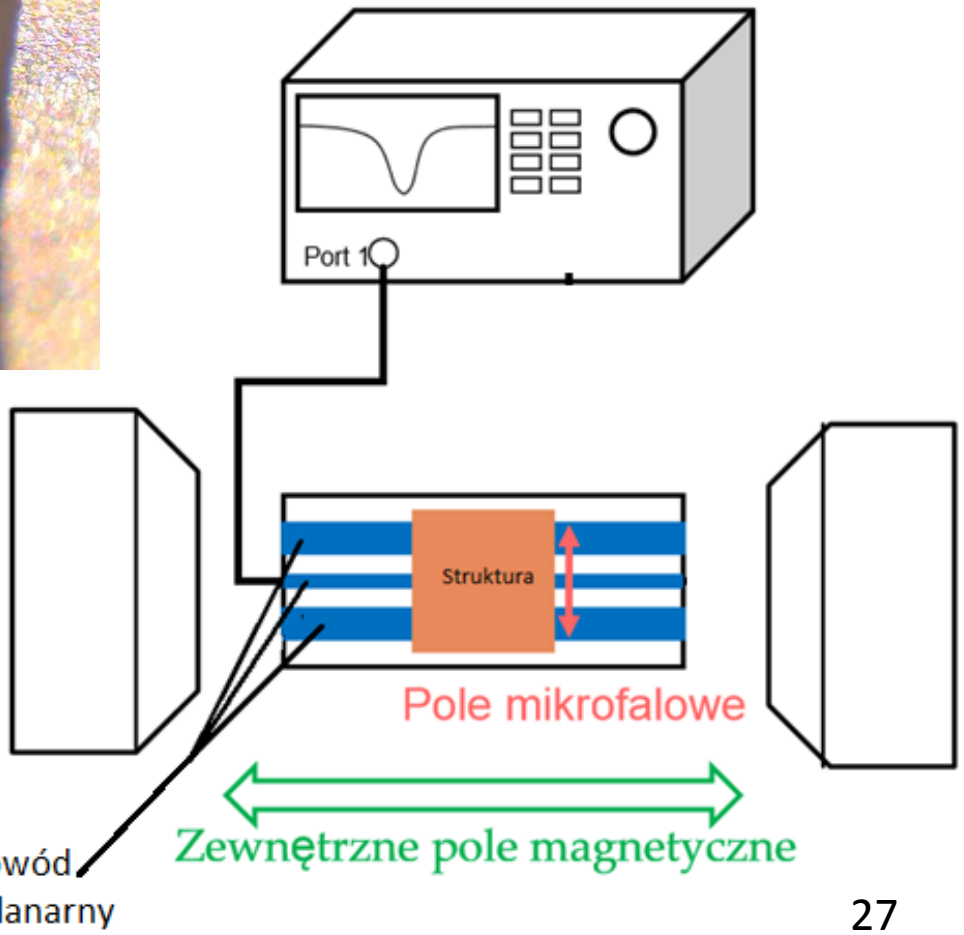




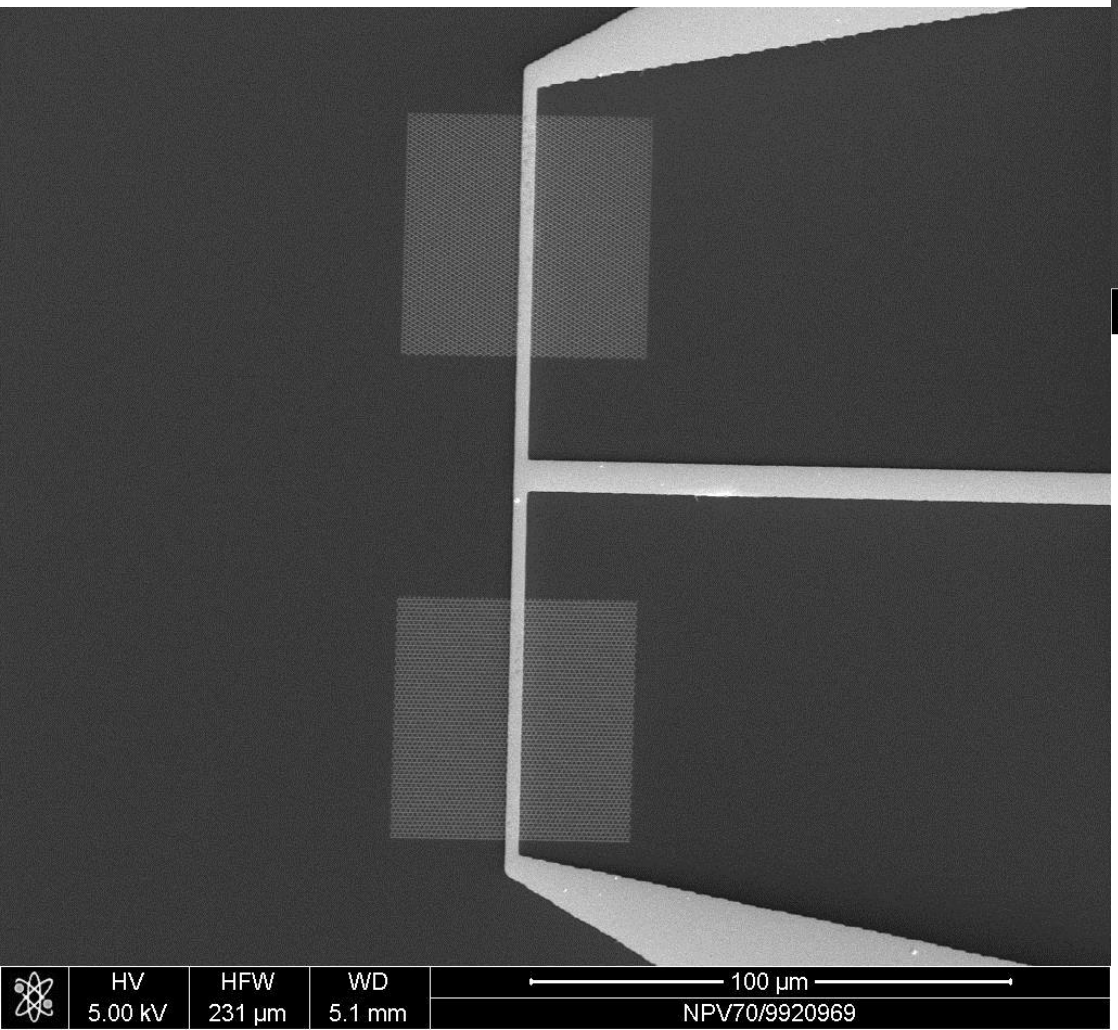
Źródło: http://www.mif.pg.gda.pl/homepages/maria/pdf/INM_07_8.pdf

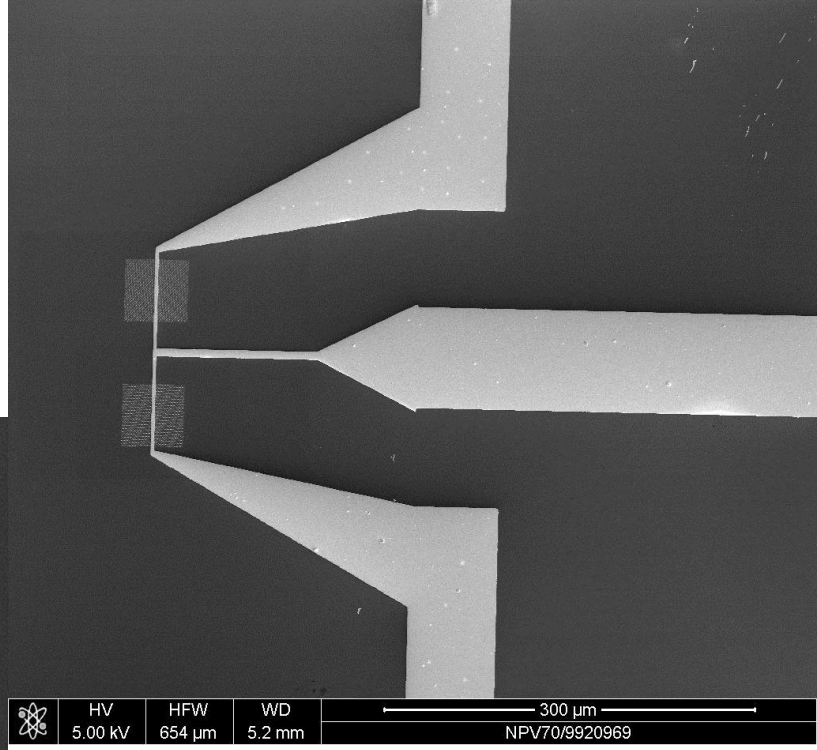
Schemat układu VNA-FMR

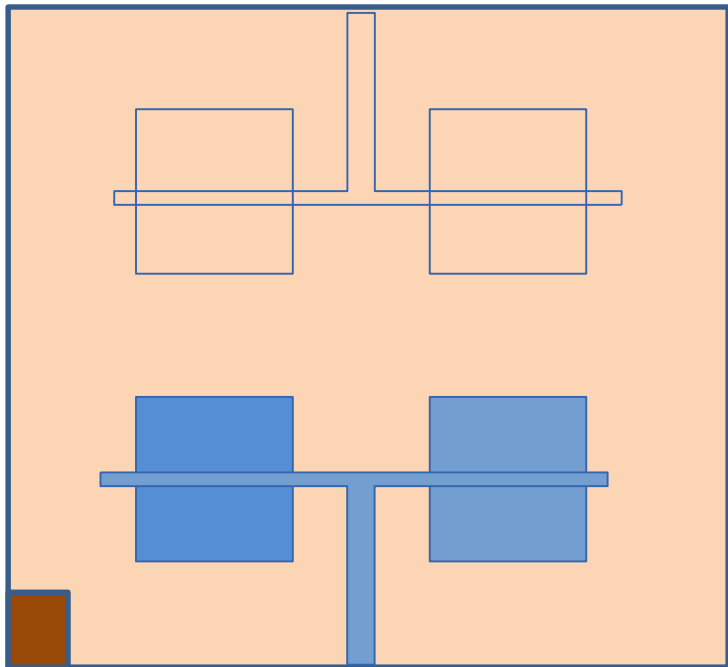




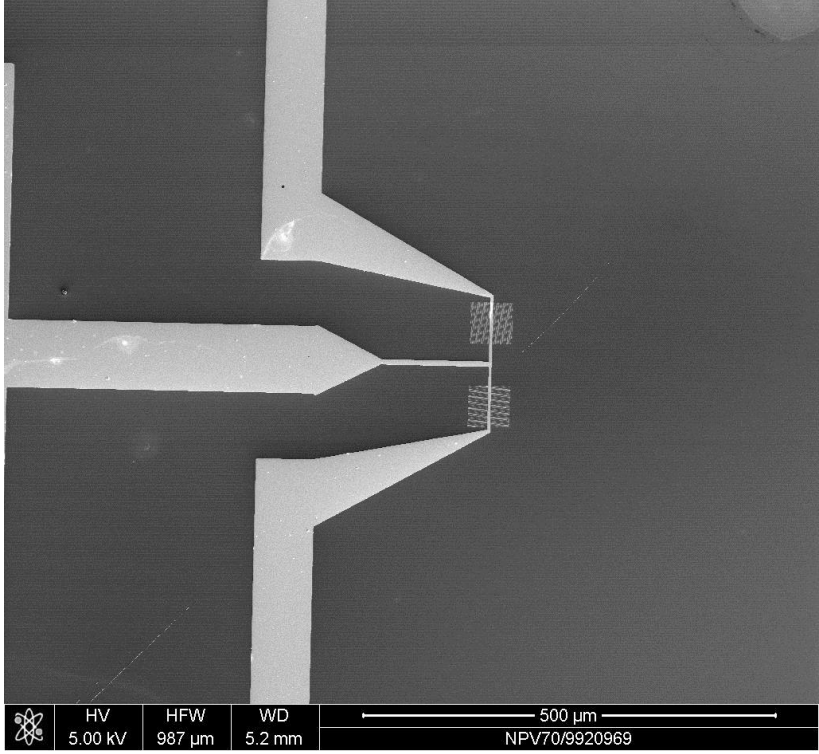
Antena dla isolated bars

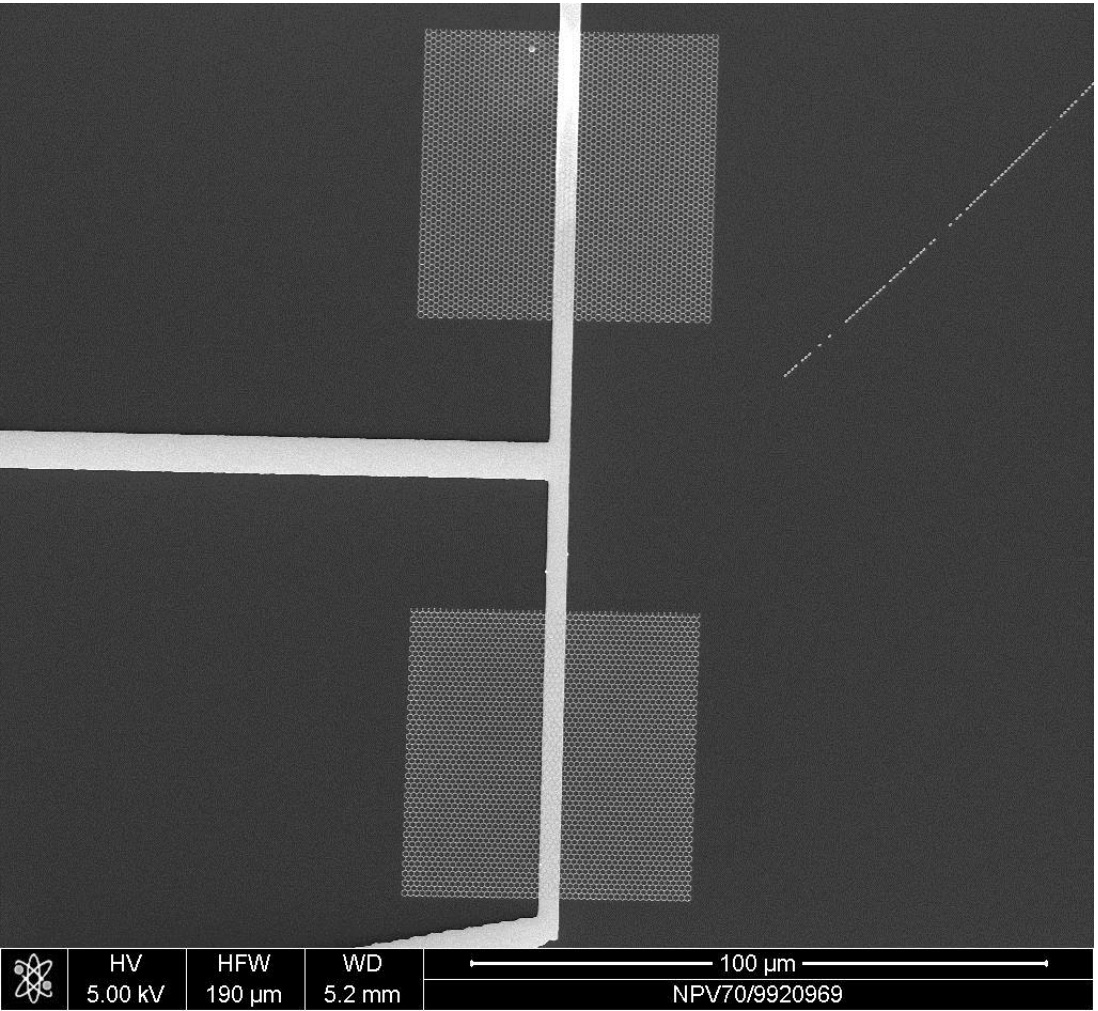


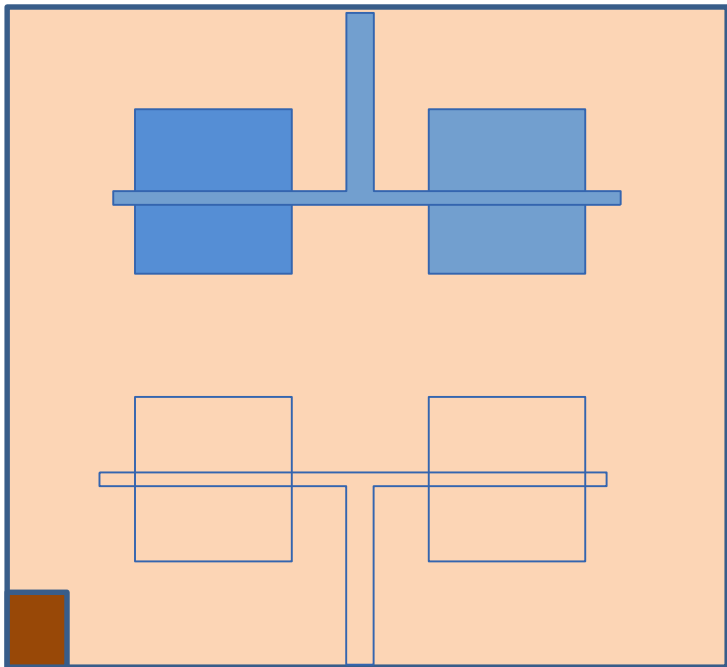


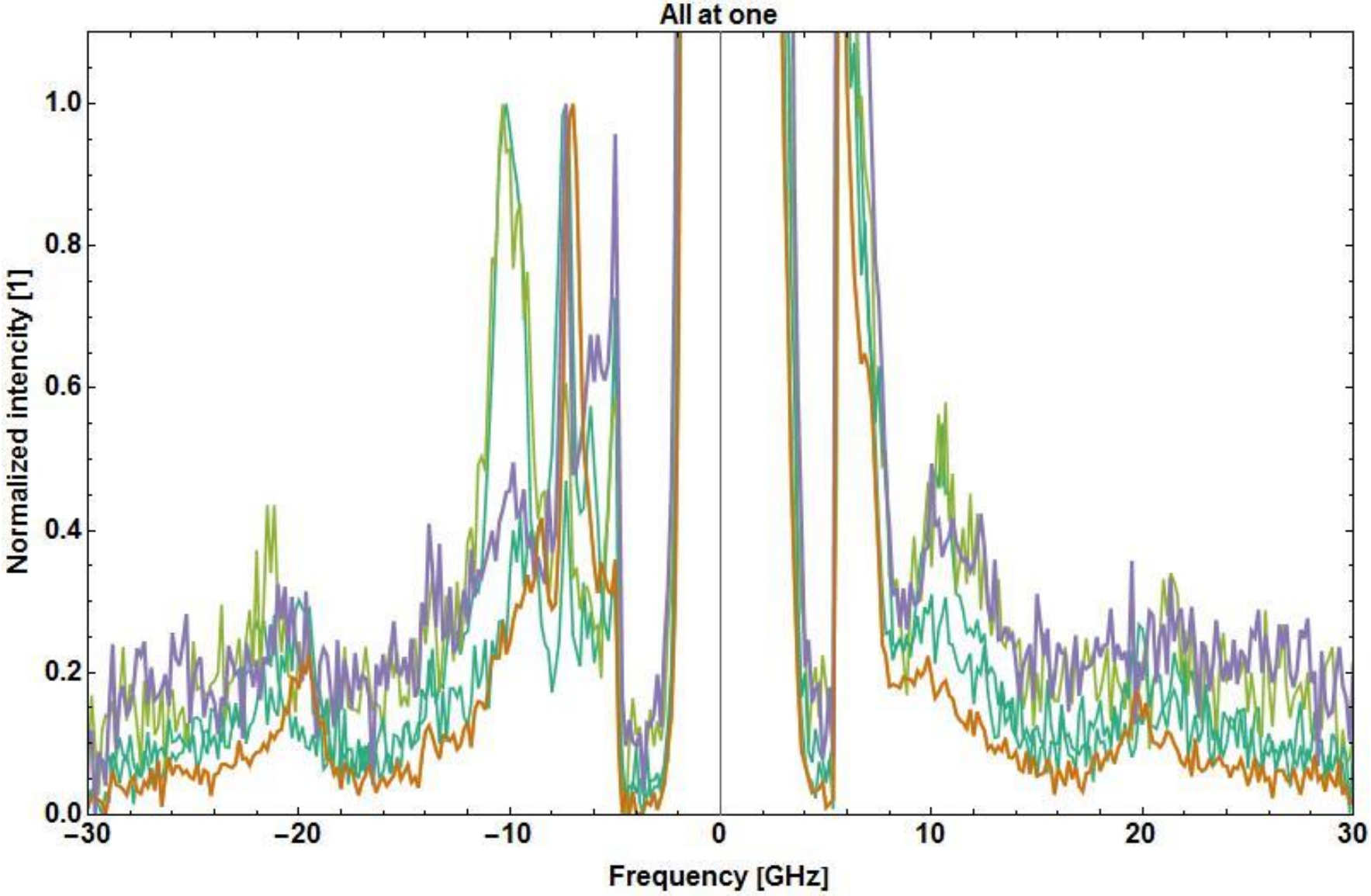


Antena dla connected bars





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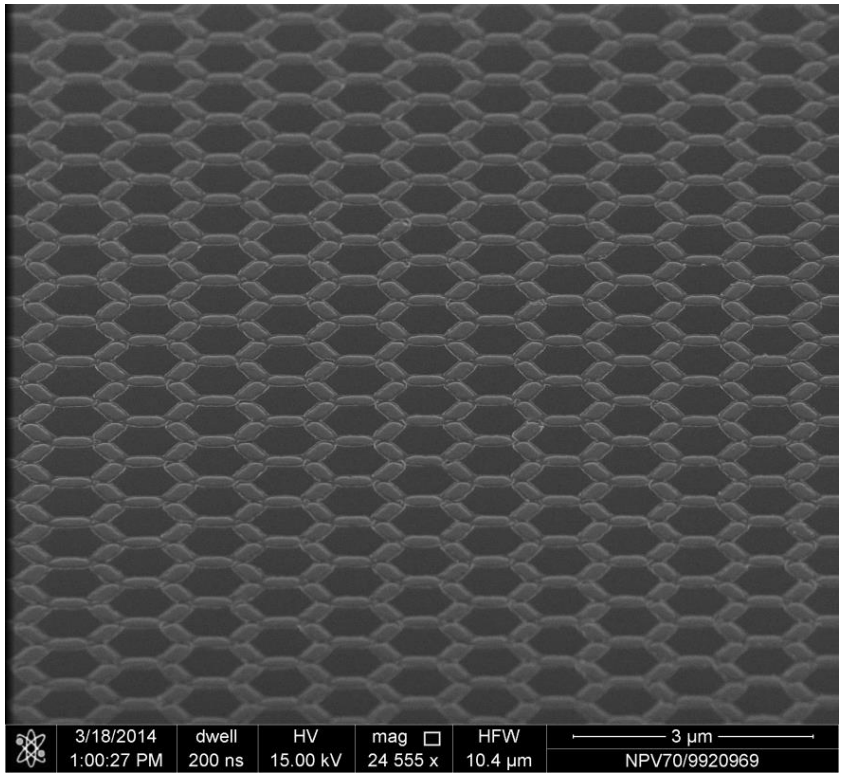
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The work was founding by FNP from project **TEAM „Statics and dynamics of magnonic and magnetophotonic crystals - SYMPHONY”** carried out by University of Białystok under the leadership prof. A. Maziewskiego