Influence of epitaxial strain on the magnetic order in antiferromagnetic thin films

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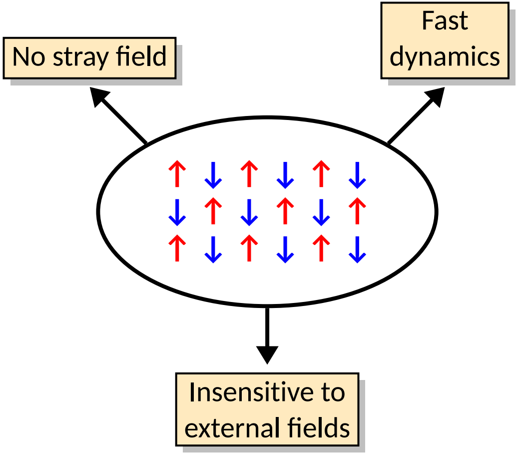
SPEC, CEA, CNRS, Université Paris-Saclay, Gif-sur-Yvette, France

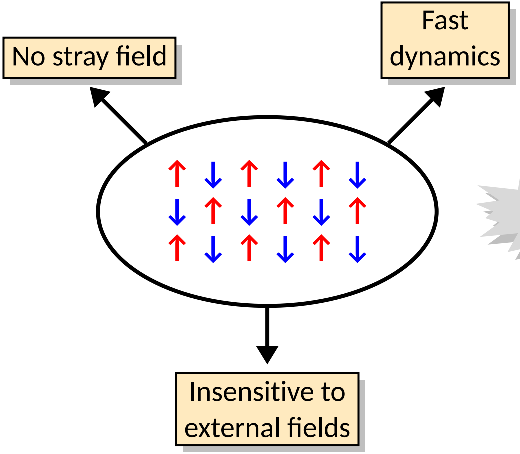
Slides available at https://magimag.eu

Antiferromagnets



T. Jungwirth *et al.* *Nat. Nano.* 11 (2016), 231–241

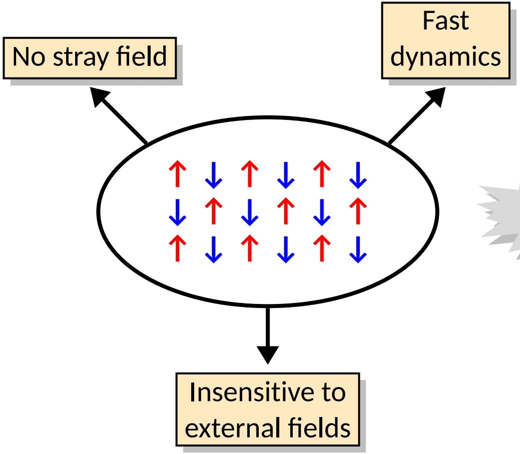
Antiferromagnets



Need for efficient and reliable control and manipulation

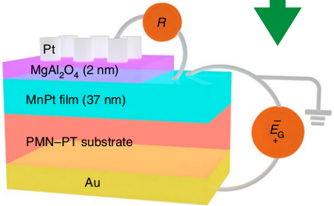
T. Jungwirth *et al.* *Nat. Nano.* 11 (2016), 231–241

Antiferromagnets



T. Jungwirth *et al.* Nat. Nano. 11 (2016), 231–241

Need for efficient and reliable control and manipulation



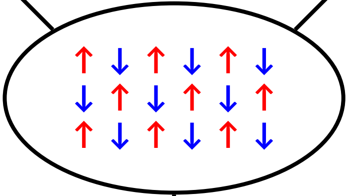
Control by strain!

H. Yan *et al.* Nat. Nano. 14 (2019), 131–136

Antiferromagnets

No stray field

Fast dynamics

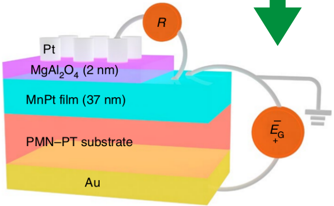


Insensitive to external fields

T. Jungwirth *et al.* Nat. Nano. 11 (2016), 231–241

Magnetoelectric coupling

Need for efficient and reliable control and manipulation



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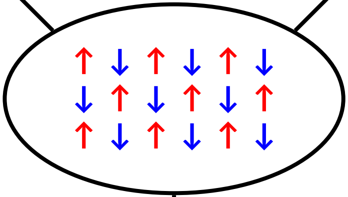


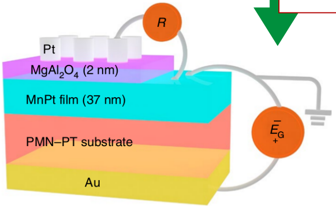
Insensitive to external fields

T. Jungwirth *et al.* *Nat. Nano.* 11 (2016), 231–241

Need for efficien
control and ma

Magnetoelectric coupling

Exploration of the strain-dependent phase diagram of the multiferroic $BiFeO_3$

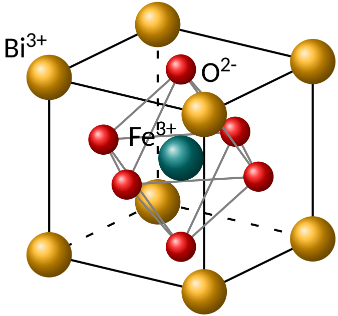


Control by strain!

H. Yan *et al.* *Nat. Nano.* 14 (2019), 131–136

$BiFeO_3$, a room temperature multiferroic

Electric polarization

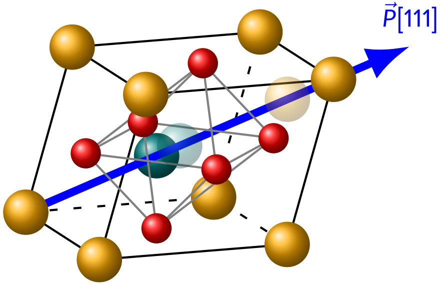


Paraelectric phase (T>1100 K)

G. Catalan *et al.* *Advanced Materials* 21 (2009), 2463–2485

$BiFeO_3$, a room temperature multiferroic

Electric polarization

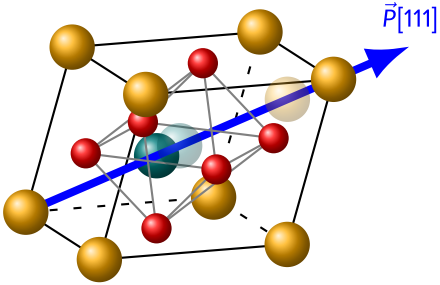


Ferroelectric phase (T<1100 K)

G. Catalan *et al.* *Advanced Materials* 21 (2009), 2463–2485

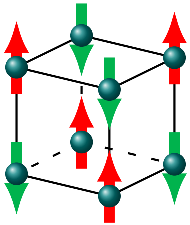
$BiFeO_3$, a room temperature multiferroic

Electric polarization



Ferroelectric phase (T<1100 K)

Magnetism

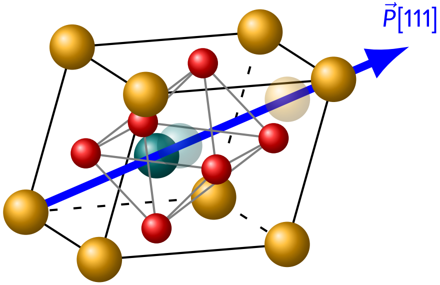


G-type
antiferromagnet

G. Catalan *et al.* *Advanced Materials* 21 (2009), 2463–2485

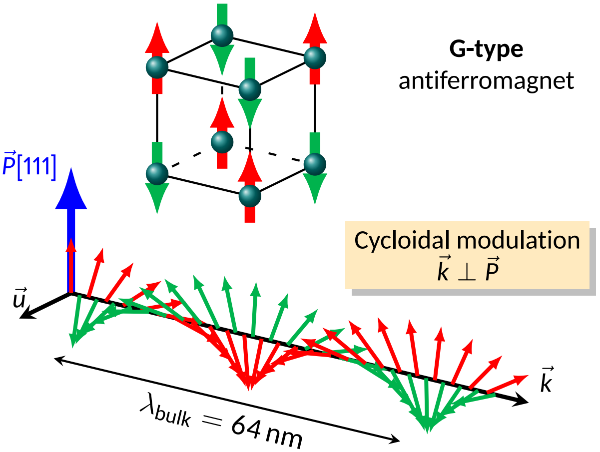
$BiFeO_3$, a room temperature multiferroic

Electric polarization



Ferroelectric phase (T<1100 K)

Magnetism

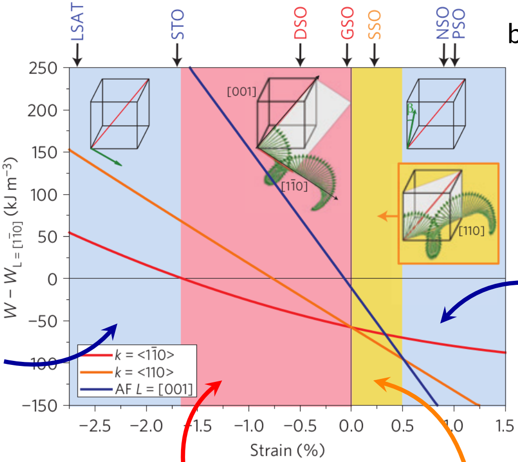


G. Catalan *et al.* *Advanced Materials* 21 (2009), 2463–2485

Known effect of epitaxial strain on the cycloid

Phase diagram obtained from spectroscopic measurements

Epitaxial strain tuned by changing the substrate



Large tensile strain antiferromagnetic order

Large compressive strain antiferromagnetic order

Small compressive strain cycloid type I

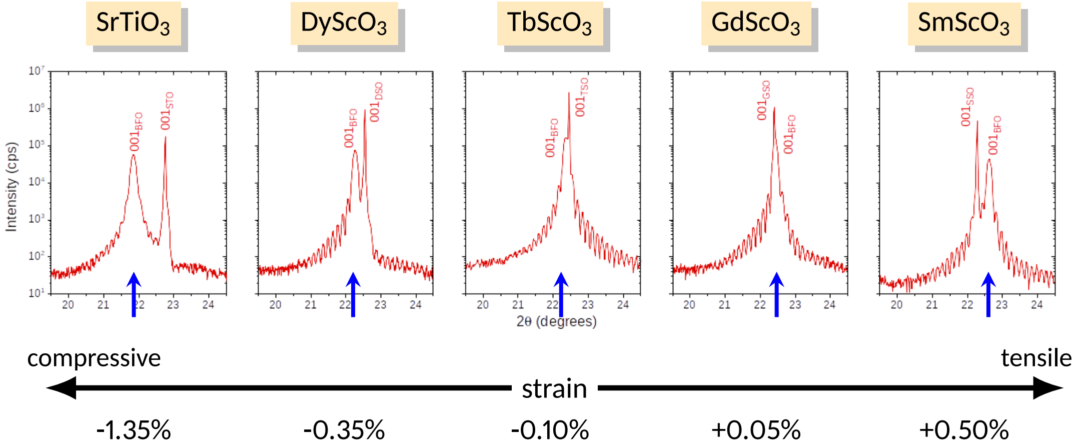
Small tensile strain cycloid type II

D. Sando *et al.* *Nature Materials* 12 (2013), 641–646

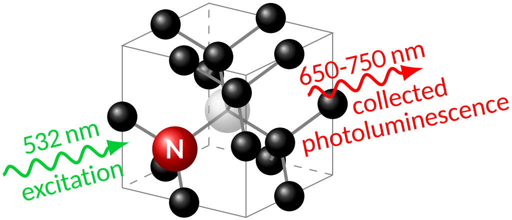
Tuning of epitaxial strain

$BiFeO_3$ thin film samples grown on various substrates

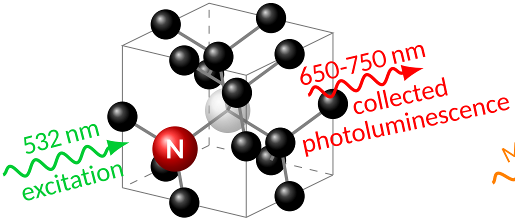
Samples from UM CNRS/Thales
J. Fischer, V. Garcia, S. Fusil

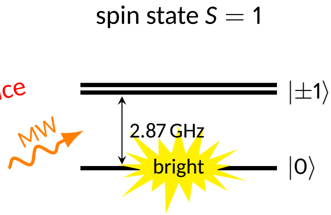


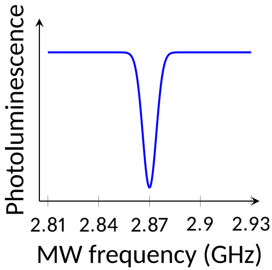
NV center magnetometry



NV center magnetometry







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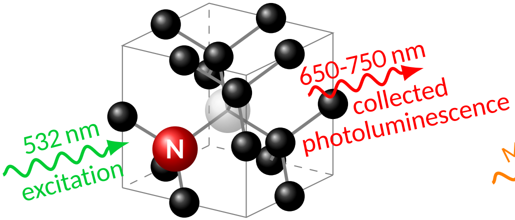
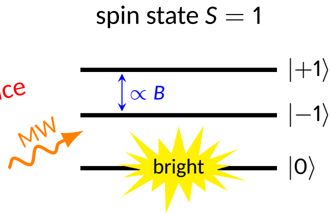
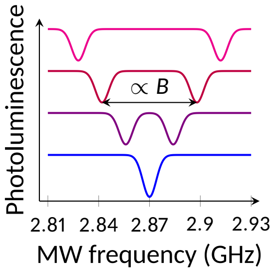
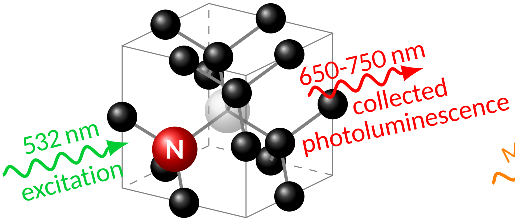
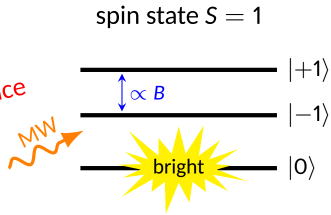


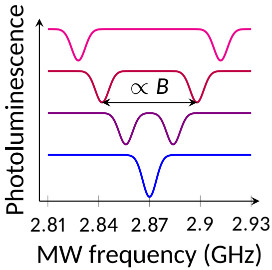


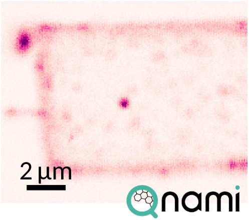


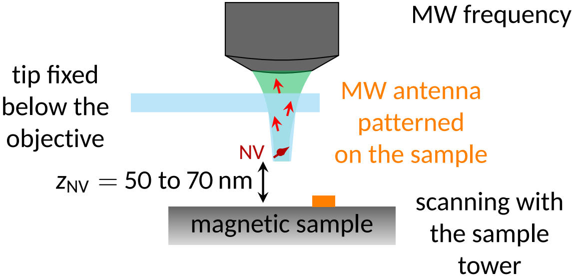
NV center magnetometry







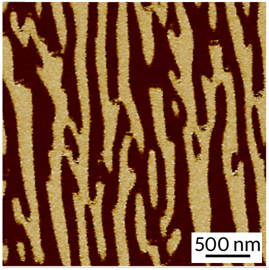




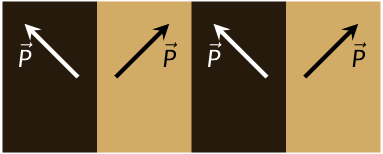
More about NV magnetometry:
tomorrow 11:15, S8:2, Florentin Fabre

NV imaging of the cycloid, iso-B mode

$DyScO_3$, strain -0.35%



PFM image
ferroelectric domains



I. Gross *et al.* *Nature* 549 (2017), 252–256

NV imaging of the cycloid, iso-B mode

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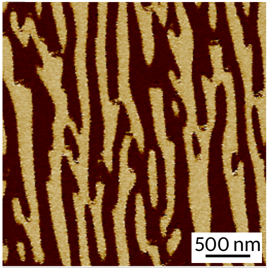

PFM image
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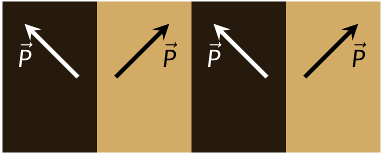
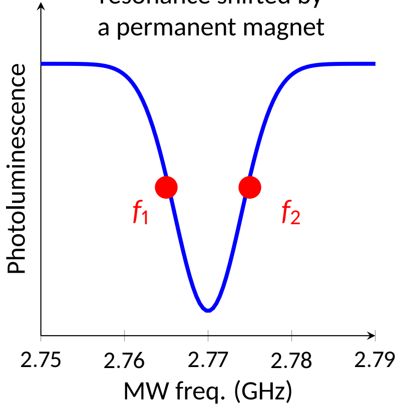


Reference spectrum
resonance shifted by
a permanent magnet

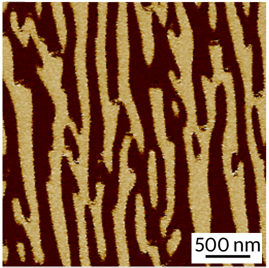


$$\Delta PL = PL(f_2) - PL(f_1)$$

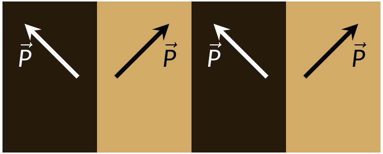
I. Gross *et al.* *Nature* 549 (2017), 252–256

NV imaging of the cycloid, iso-B mode

$DyScO_3$, strain -0.35%

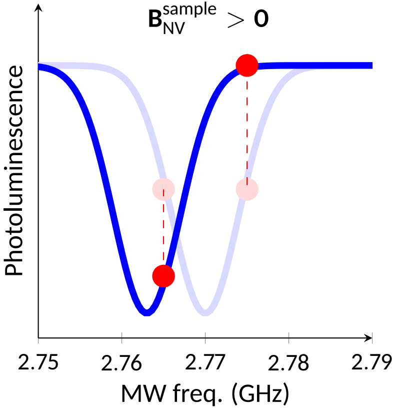


PFM image
ferroelectric domains



Spectrum for

$\mathbf{B}_{NV}^{sample} > 0$



$$\Delta PL = PL(f_2) - PL(f_1)$$

$$\Delta PL > 0$$

I. Gross *et al.* *Nature* 549 (2017), 252–256

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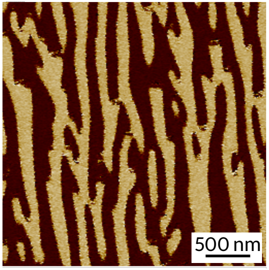
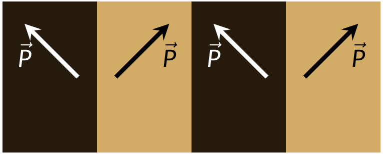
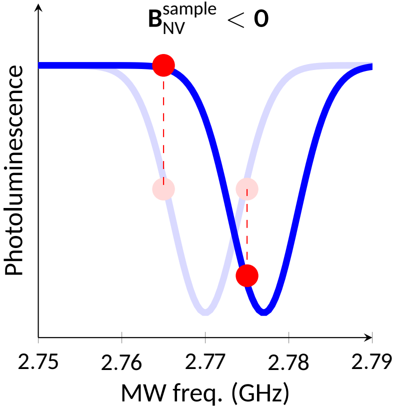


PFM image
ferroelectric domains



Spectrum for

$\mathbf{B}_{NV}^{sample} < 0$



$$\Delta PL = PL(f_2) - PL(f_1)$$

$$\Delta PL < 0$$

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NV imaging of the cycloid, iso-B mode

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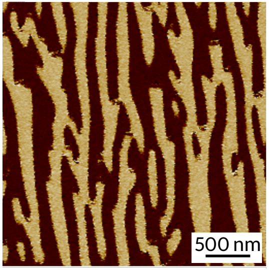

PFM image
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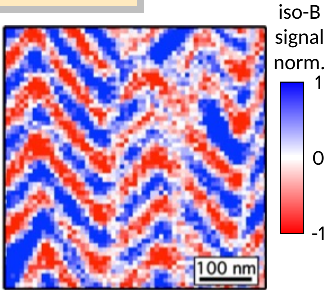
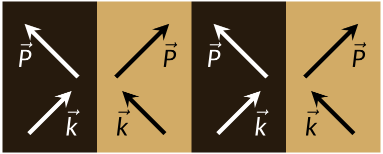
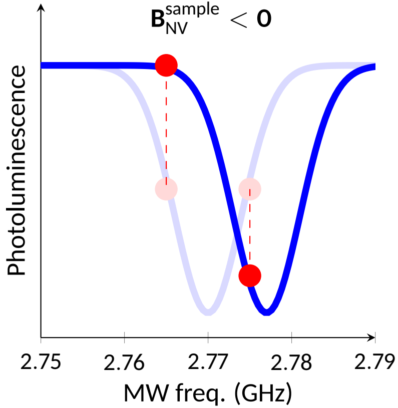


NV image
cycloid



Spectrum for



$$\Delta PL = PL(f_2) - PL(f_1)$$

$$\Delta PL < 0$$

I. Gross *et al.* *Nature* 549 (2017), 252–256

NV imaging of the cycloid, iso-B mode

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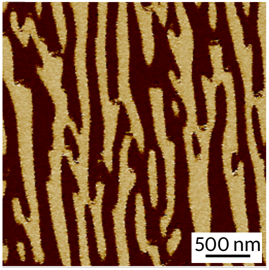
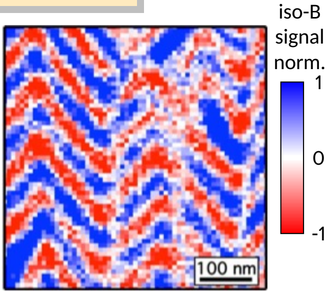
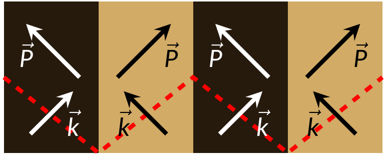


PFM image
ferroelectric domains

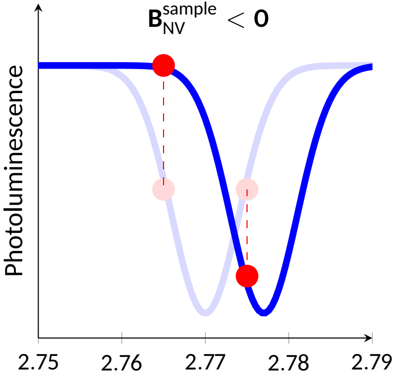


NV image
cycloid



Spectrum for

$\mathbf{B_{NV}^{sample} < 0}$

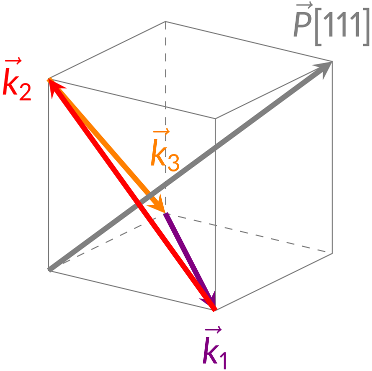


$$\Delta PL = PL(f_2) - PL(f_1)$$

$$\Delta PL < 0$$

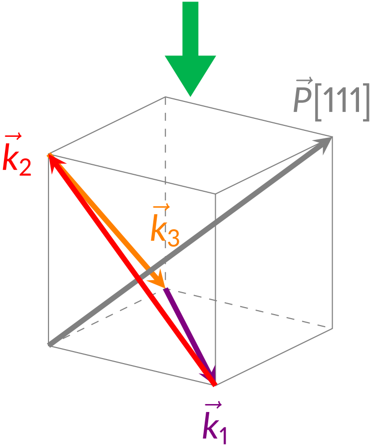
I. Gross *et al.* *Nature* 549 (2017), 252–256

The type I cycloid



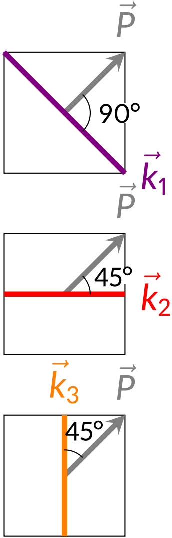
$\vec{k}_1 \parallel [1\bar{1}0]$
$\vec{k}_2 \parallel [\bar{1}01]$
$\vec{k}_3 \parallel [01\bar{1}]$

The type I cycloid



$\vec{k}_1 \parallel [1\bar{1}0]$
$\vec{k}_2 \parallel [\bar{1}01]$
$\vec{k}_3 \parallel [01\bar{1}]$

Top view



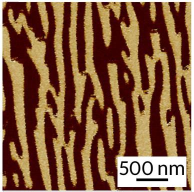
$\lambda_{\text{IP}} = \lambda_{\text{bulk}}$
64 nm

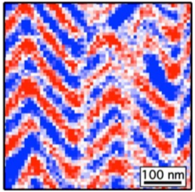
$\lambda_{\text{IP}} = \sqrt{2}\lambda_{\text{bulk}}$
90 nm

$\lambda_{\text{IP}} = \sqrt{2}\lambda_{\text{bulk}}$
90 nm

Stripy ferroelectric domains

$DyScO_3$





-0.35%

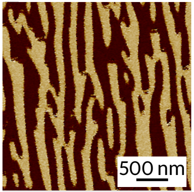
compressive — strain — tensile

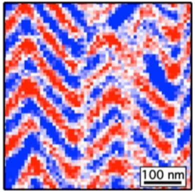
type I cycloid

$\vec{k}_1$

Stripy ferroelectric domains

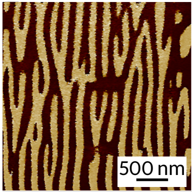
$DyScO_3$

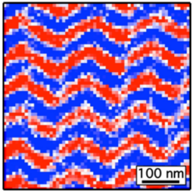




-0.35%

$GdScO_3$





+0.05%

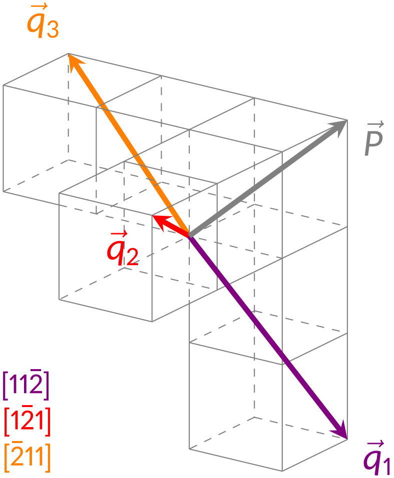
compressive ← strain → tensile

type I cycloid

$\vec{k}_1$

type II cycloid?

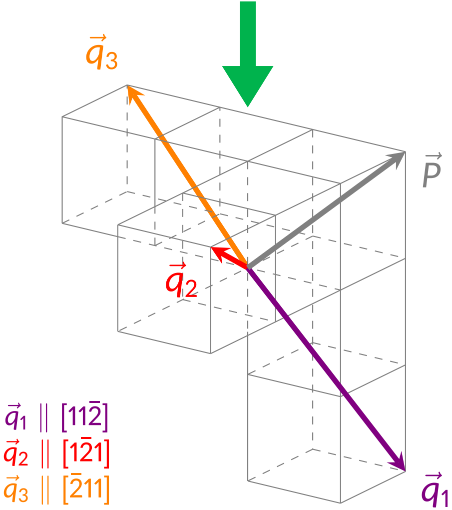
The type II cycloid

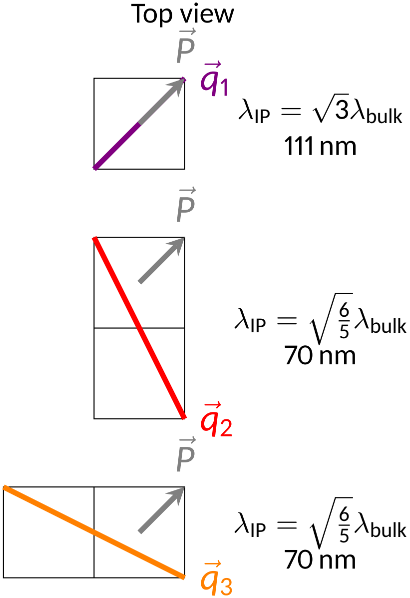


$\vec{q}_1 \parallel [11\bar{2}]$
$\vec{q}_2 \parallel [1\bar{2}1]$
$\vec{q}_3 \parallel [\bar{2}11]$

D. Sando *et al.* *Nature Materials* 12 (2013), 641–646

The type II cycloid





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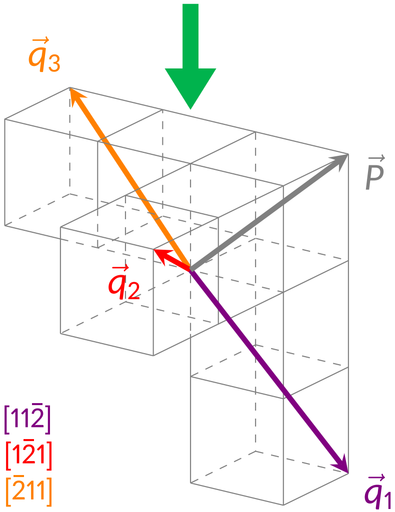
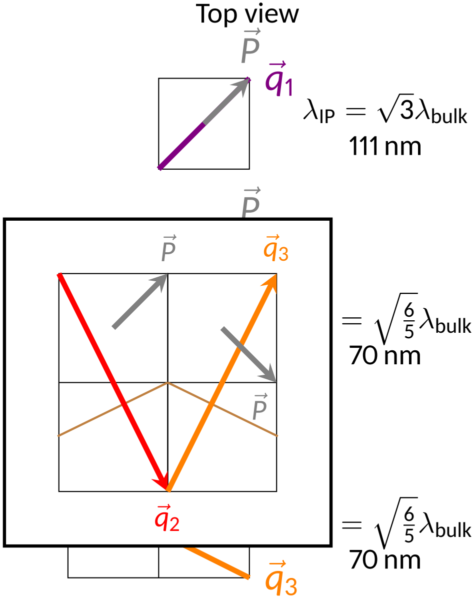
The type II cycloid



$\vec{q}_1 \parallel [11\bar{2}]$
$\vec{q}_2 \parallel [1\bar{2}1]$
$\vec{q}_3 \parallel [\bar{2}11]$



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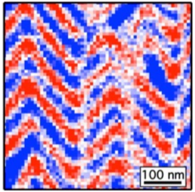
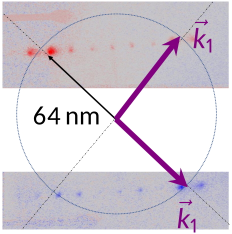
X-ray diffraction

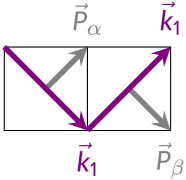
N. Jaouen, J.-Y. Chauleau, M. Viret

$DyScO_3$

type I cycloid
$\vec{k}_1$







$\lambda_{\text{IP}} = \lambda_{\text{bulk}}$
64 nm

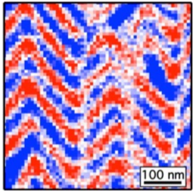
X-ray diffraction

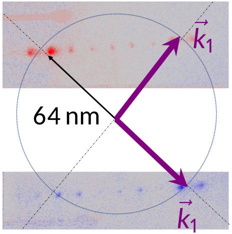
N. Jaouen, J.-Y. Chauleau, M. Viret

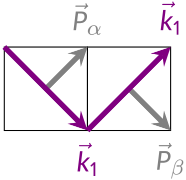
$DyScO_3$

type I cycloid

$\vec{k}_1$







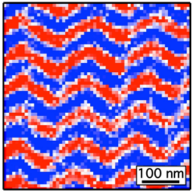
$\lambda_{IP} = \lambda_{bulk}$

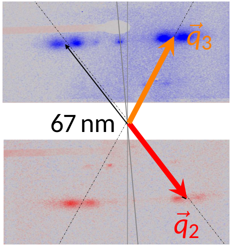
64 nm

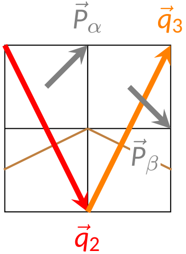
$GdScO_3$

type II cycloid

$\vec{q}_2, \vec{q}_3$





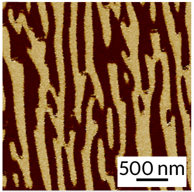


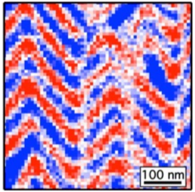
$\lambda_{IP} = \sqrt{\frac{6}{5}}\lambda_{bulk}$

70 nm

Stripy ferroelectric domains

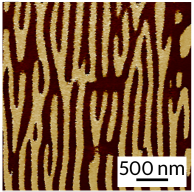
$DyScO_3$

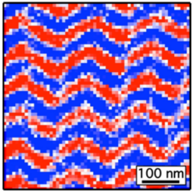




-0.35%

$GdScO_3$





+0.05%

compressive ← strain → tensile

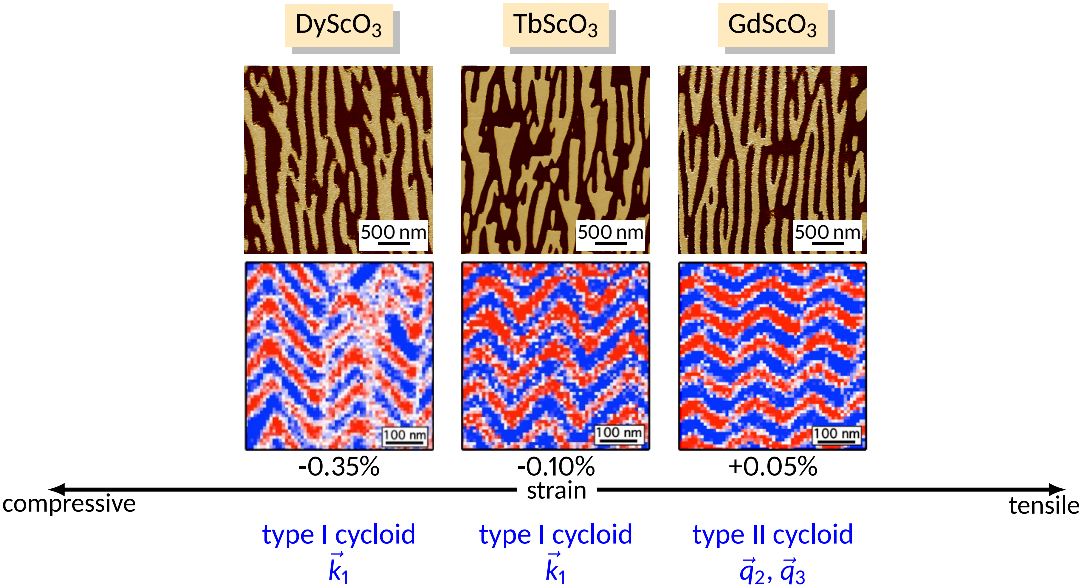
type I cycloid

$\vec{k}_1$

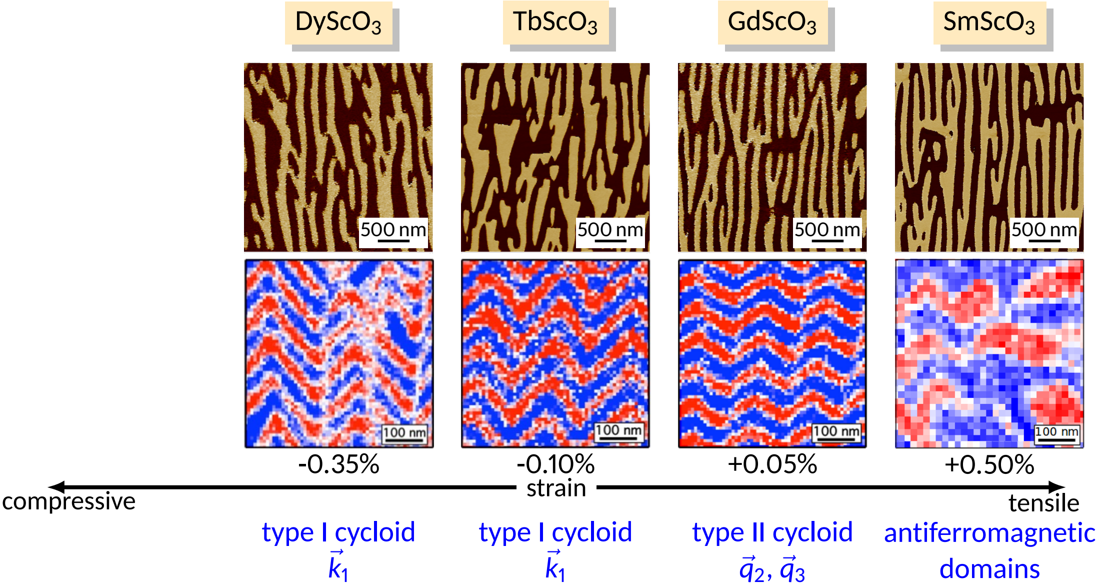
type II cycloid

$\vec{q}_2, \vec{q}_3$

Stripy ferroelectric domains

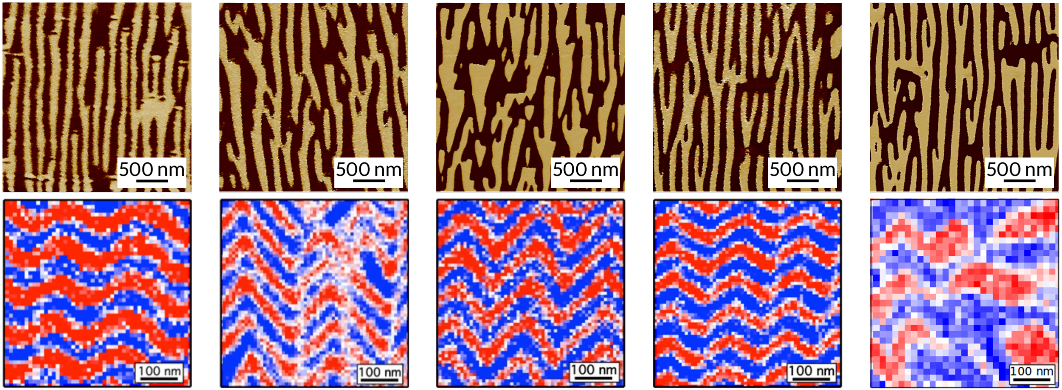


Stripy ferroelectric domains



Stripy ferroelectric domains

$SrTiO_3$ $DyScO_3$ $TbScO_3$ $GdScO_3$ $SmScO_3$

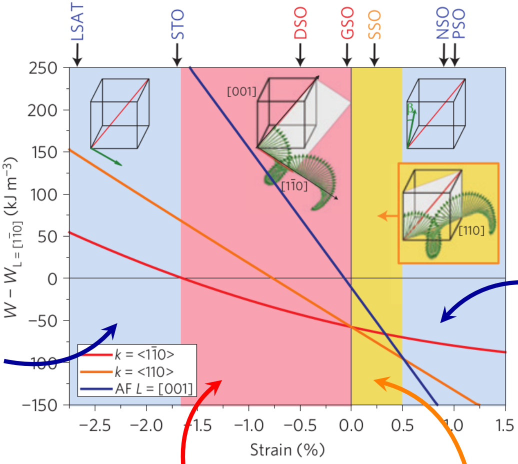


-1.35% -0.35% -0.10% +0.05% +0.50%

compressive ← strain → tensile

$SrTiO_3$	$DyScO_3$	$TbScO_3$	$GdScO_3$	$SmScO_3$
-1.35%	-0.35%	-0.10%	+0.05%	+0.50%
type II cycloid	type I cycloid	type I cycloid	type II cycloid	antiferromagnetic domains
$\vec{q}_2, \vec{q}_3$	$\vec{k}_1$	$\vec{k}_1$	$\vec{q}_2, \vec{q}_3$	

Known effect of epitaxial strain on the cycloid



Large tensile strain antiferromagnetic order

Large compressive strain antiferromagnetic order

Small compressive strain cycloid type I

Small tensile strain cycloid type II

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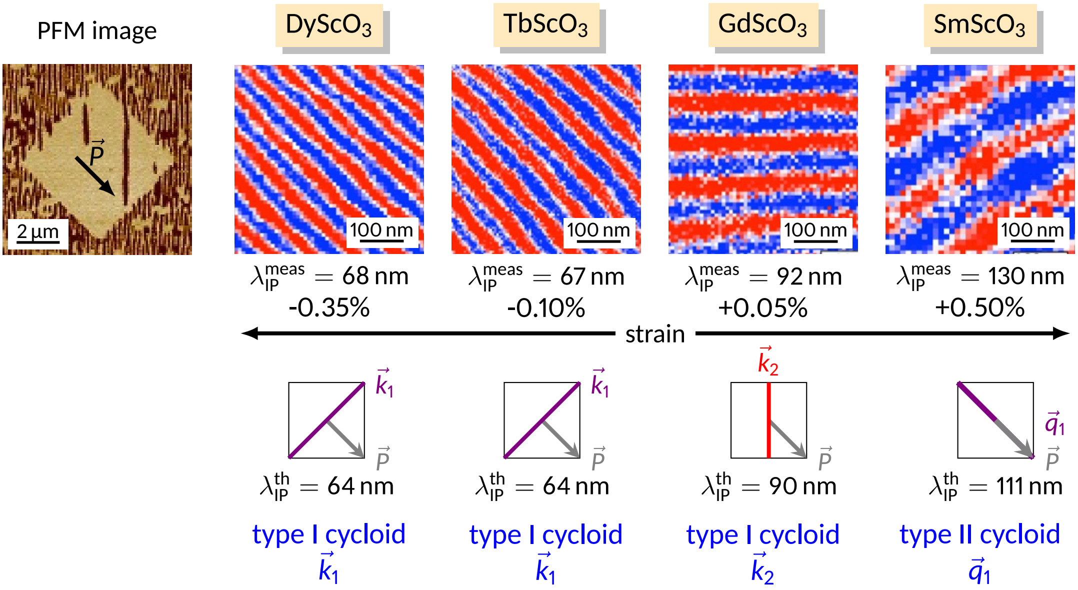
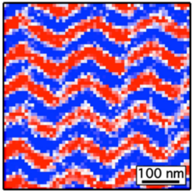
Manipulation via magnetoelectric coupling

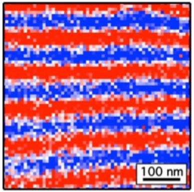


Summary

- New exploration of the phase diagram of $BiFeO_3$ thin films using **real-space imaging**



- Demonstration of the ability to manipulate **electrically** the magnetic cycloid



- Next step: use a piezoelectric substrate to vary the strain inside the NV magnetometer