Ferroelectric materials: from actuators to neuromorphic devices

Beatriz Noheda

Zernike Institute for Advanced Materials

Groningen Cognitive Systems and Materials center (CogniGron)

university of groningen / faculty of science and engineering / zernike institute for advanced materials

Nanostructures of functional oxides

university of groningen

faculty of science and engineering

zernike institute for advanced materials

Ferroelectric thin films

Fundamental **Materials** research that aims to drive the applications future

Piezoelectrics

Ferroelastics

Nano-domains

Domain walls

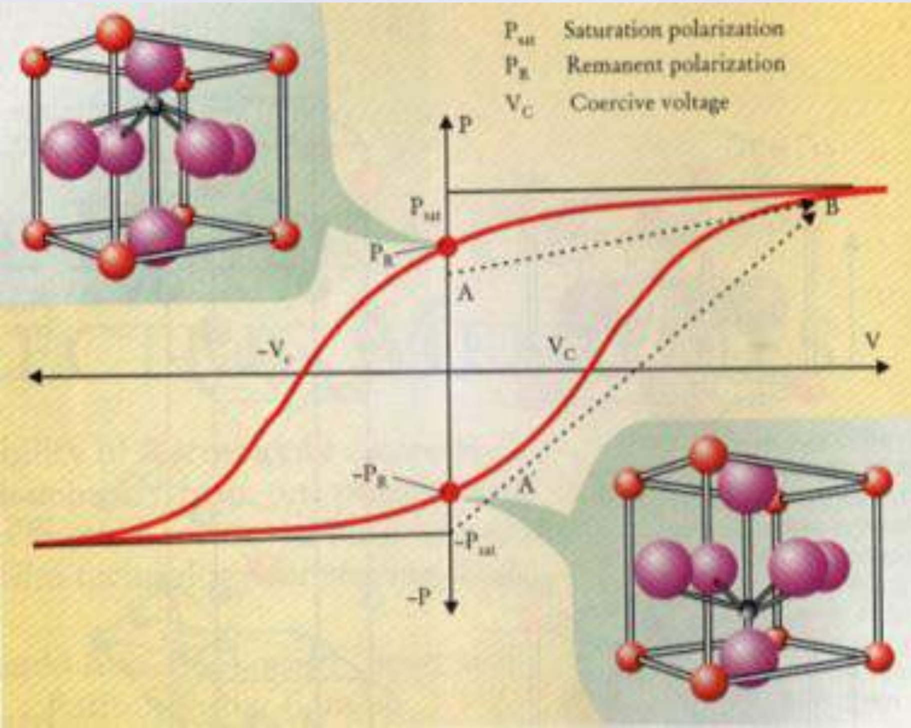
Energy harvesting sensors

Non-volatile FeRAM

Adaptable electronics

Ferroelectrics

$$\vec{P}_j(E) = \varepsilon_{ij}(E)\vec{E}_i$$



$\pm P_R$ at E=0

Non-volatile FeRAM

Challenge: 1Tbit/in^2 → 1bit/(25 x 25)nm^2

Piezos in the car

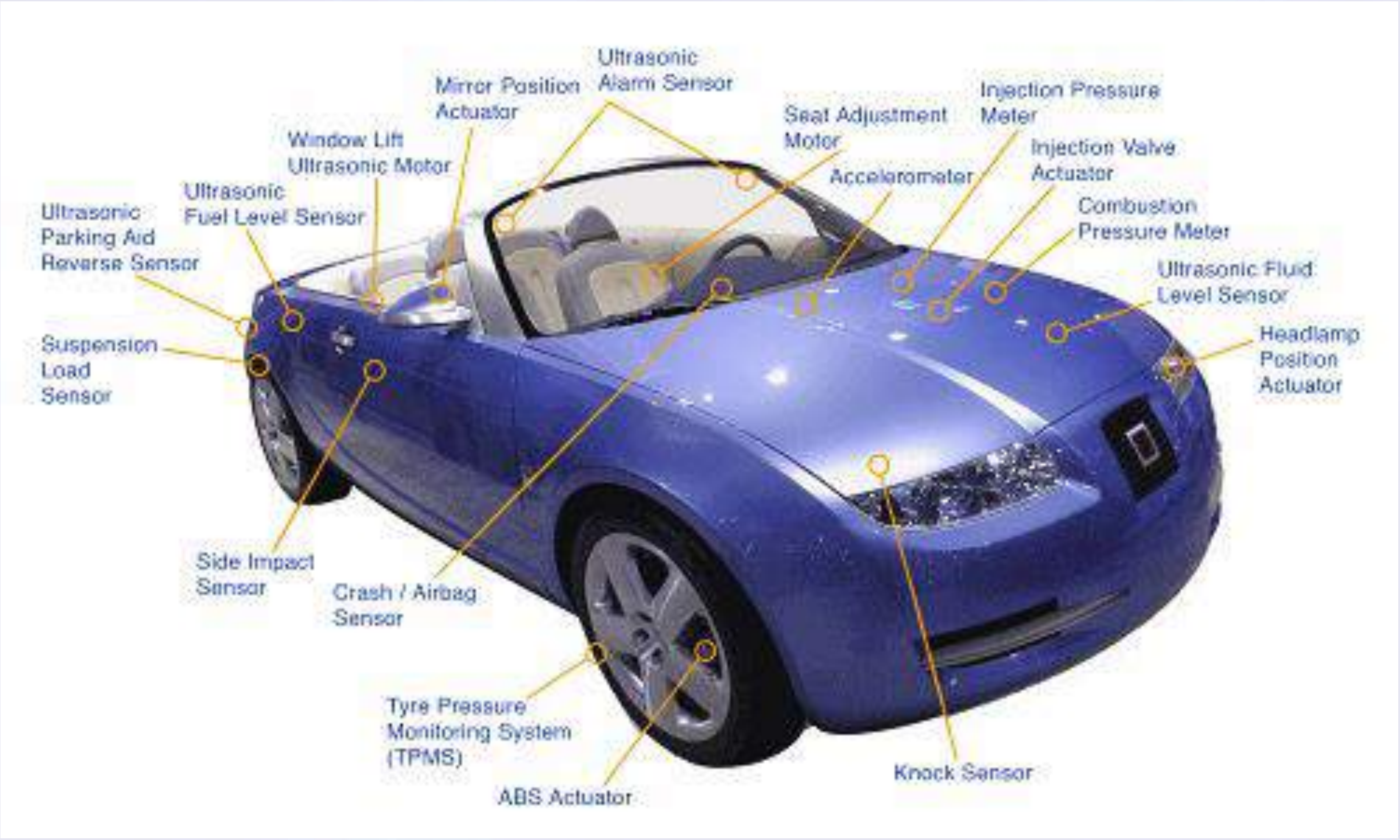
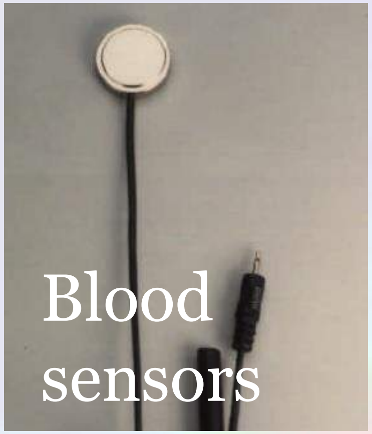
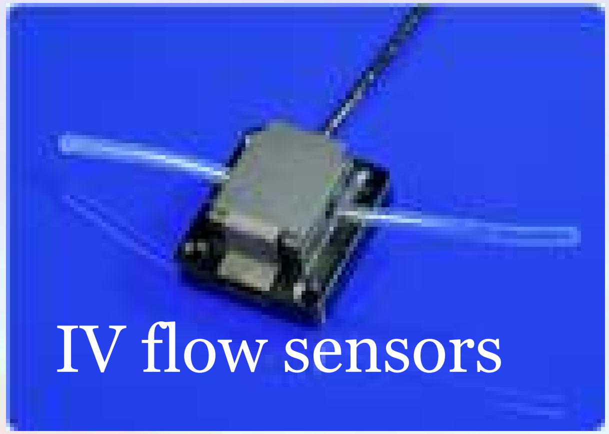
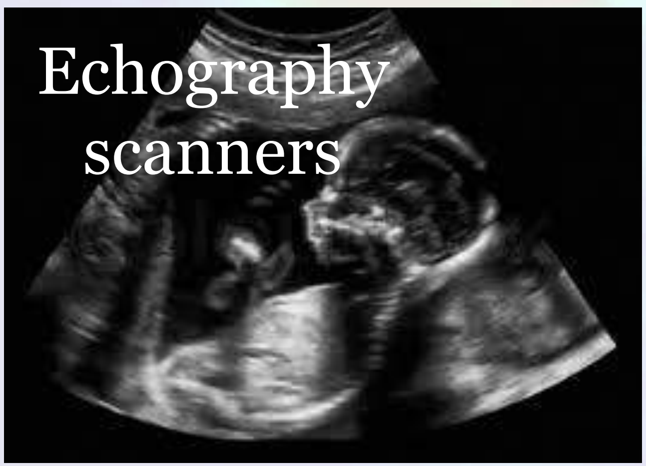


Image from Morgan Technical Ceramics

Piezos in the hospital

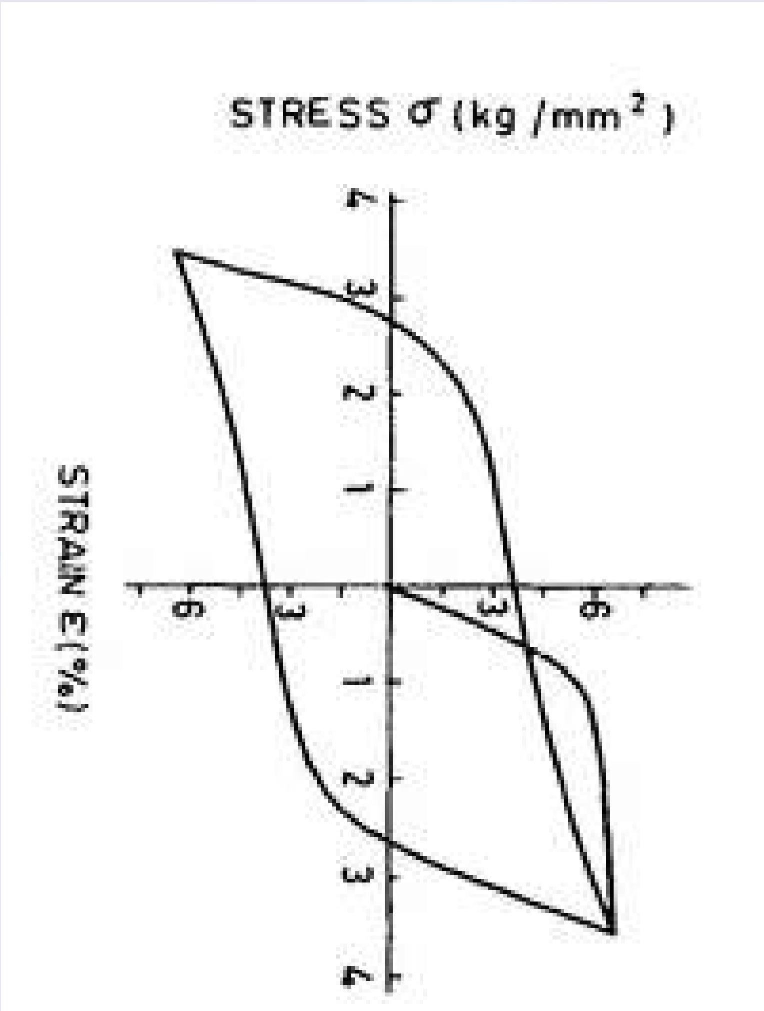






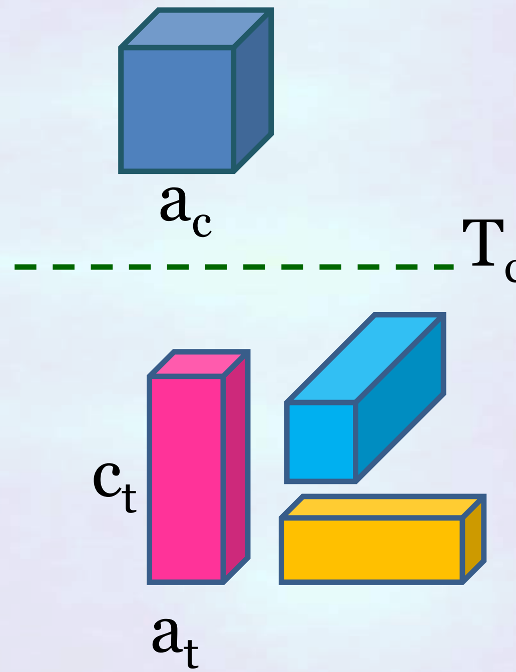
Lead-containing materials (PZT)

Ferroelastic materials



- Non-linear
- Hysteresis (bi-valued)

Domains



High symmetry

Low symmetry

Ferroelastic phase

Spontaneous strains

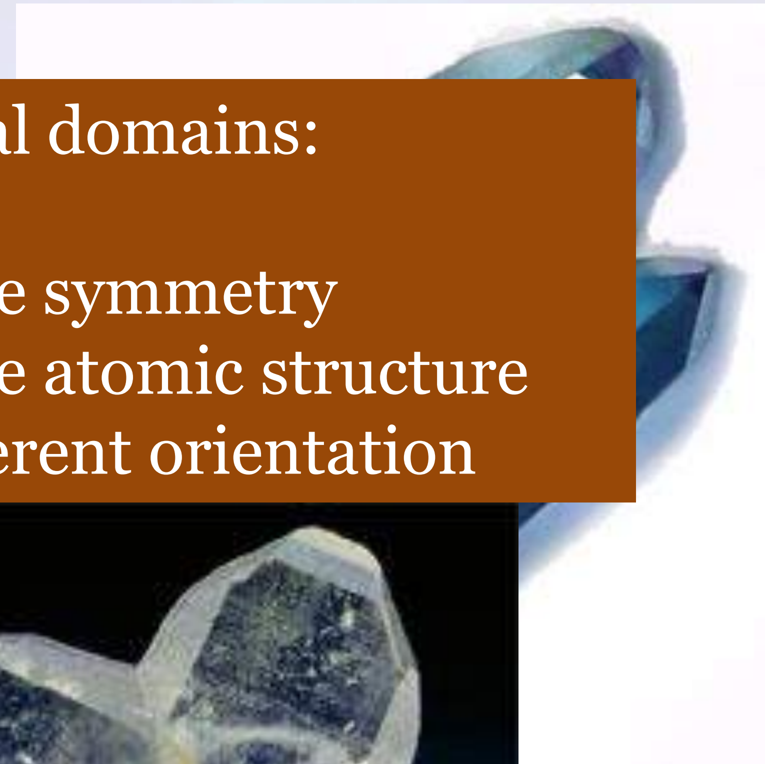
$\varepsilon_1=(a_t-a_c)/a_c=\varepsilon_2$

$\varepsilon_3=(c_t-a_c)/a_c$

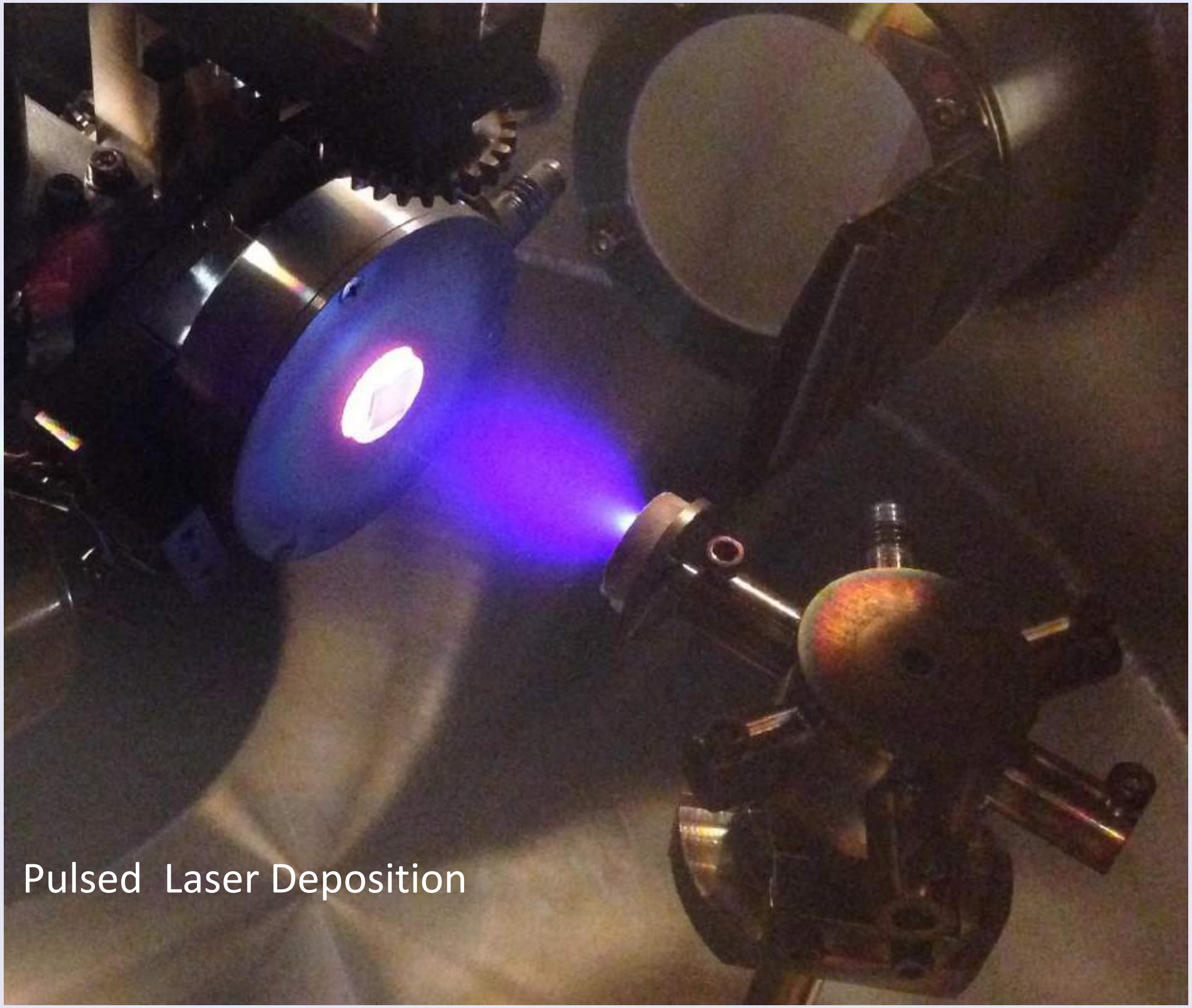
Twins

Crystal domains:

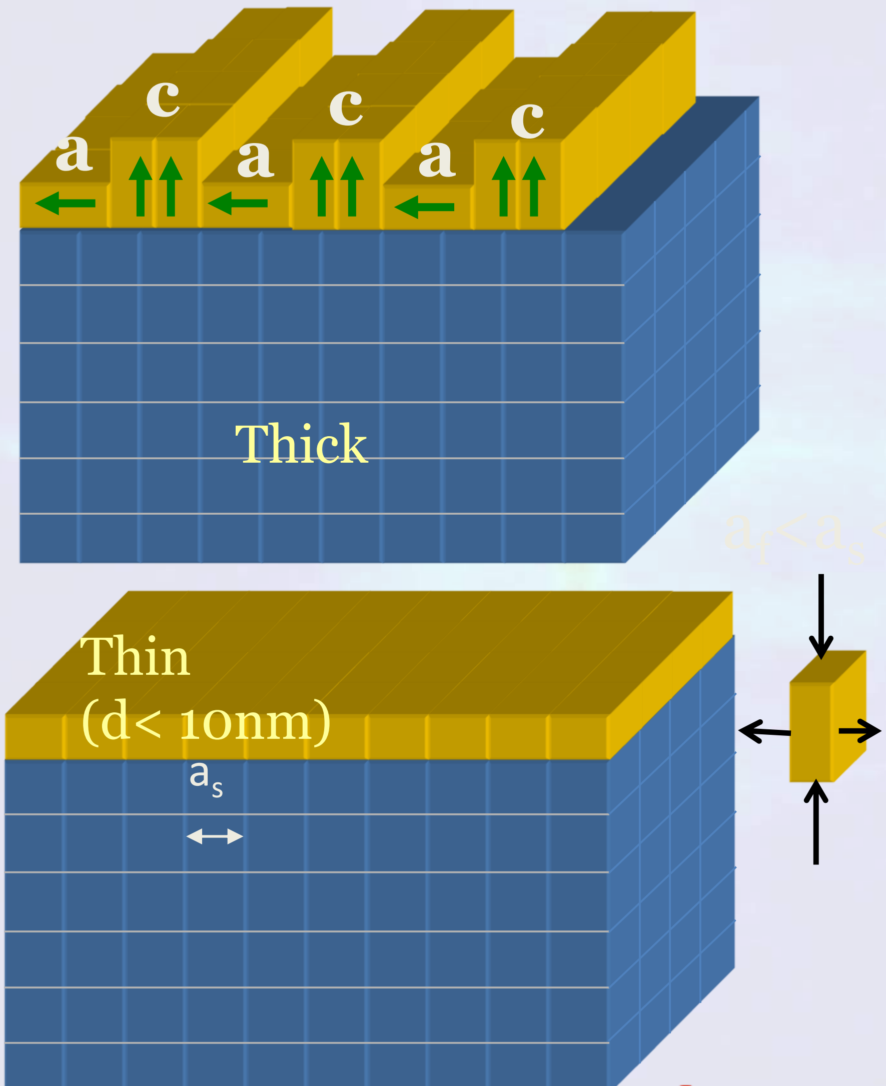
- Same symmetry
- Same atomic structure
- Different orientation

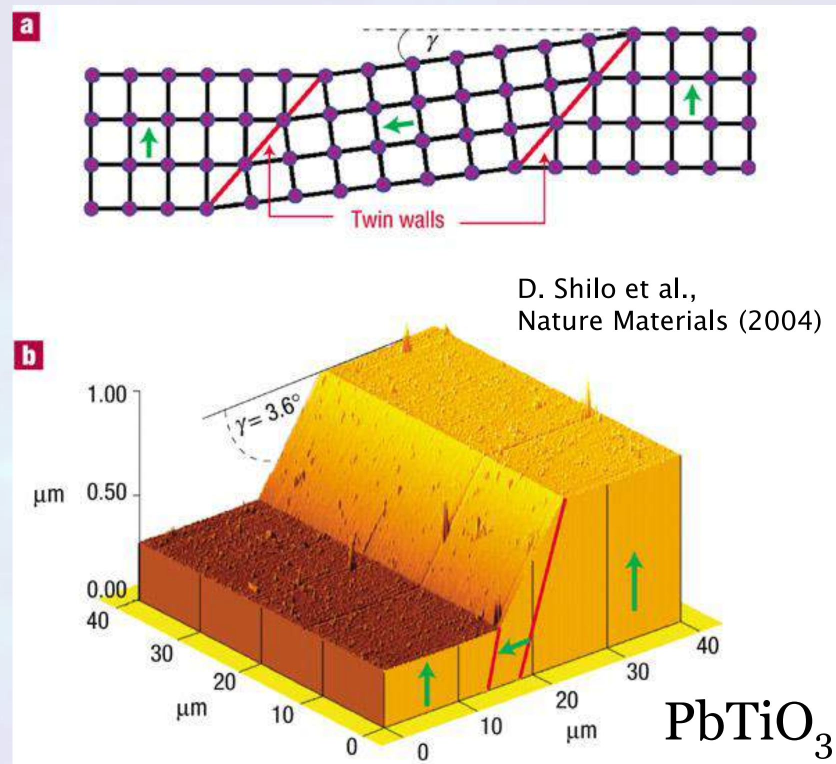


Epitaxial growth of oxides



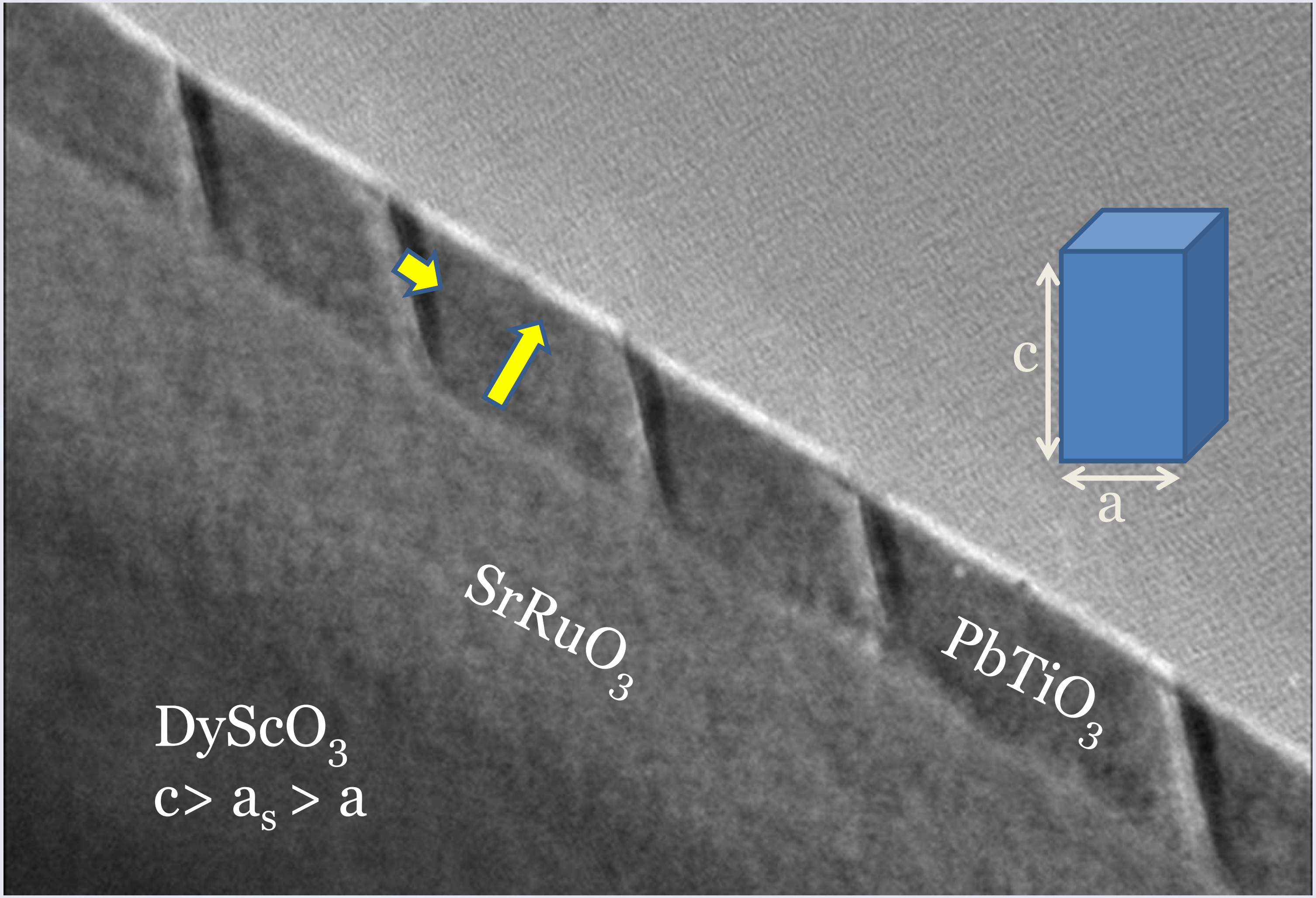
Epitaxial strain and domain formation





Periodic **a/c** (twinned) domains
Domain walls relieve strain

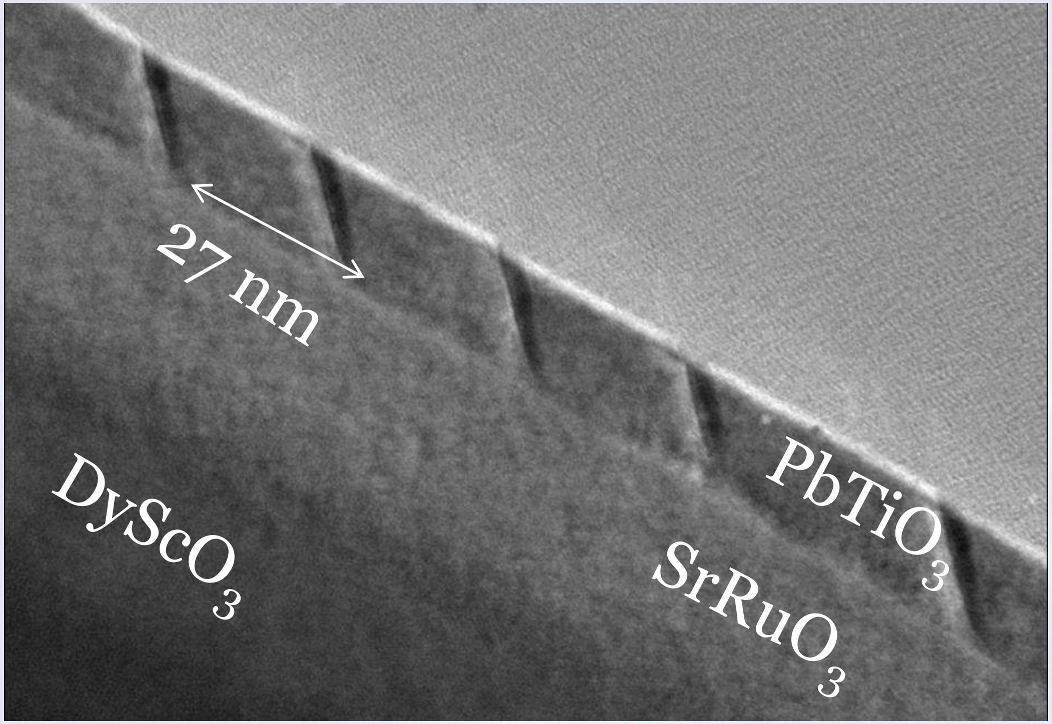
Pompe & Speck, JAP(1995)



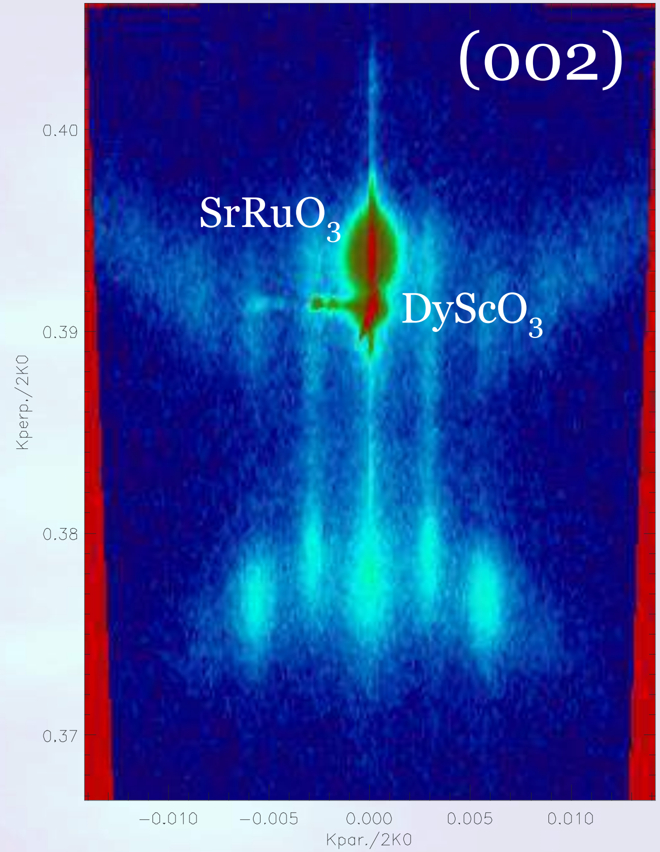
TEM image by S. Venkatesan & B.J. Kooi

Engineering nanodomains

Twin domains



TEM



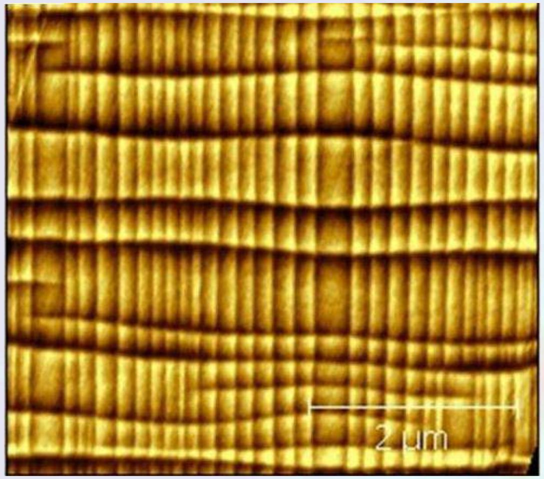
XRD

Avoiding defects ($T>T_c$) → highly periodic domain arrays ($T<Tc$)

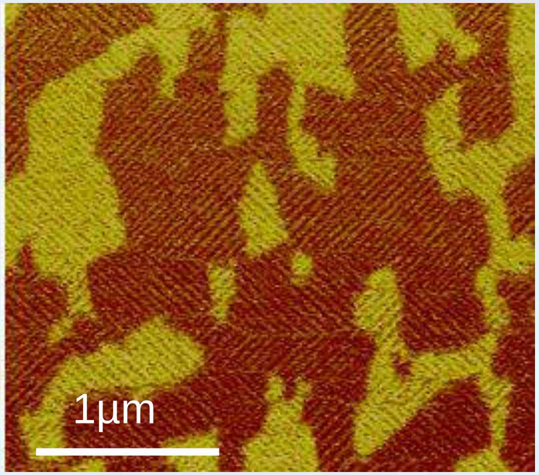
G. Catalan, BN et al., *Nature Mat.* (2011)

Domain formation in ferroic materials

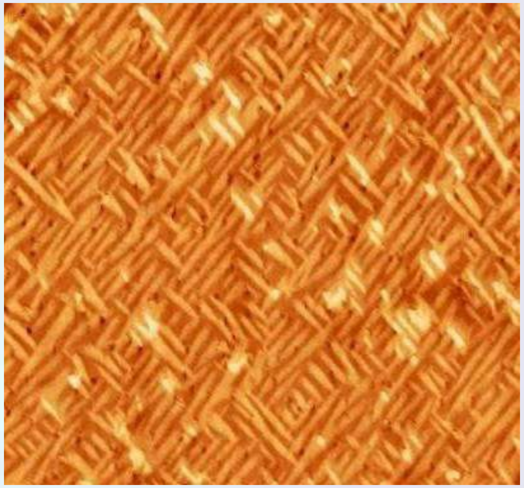
$PbTiO_3$

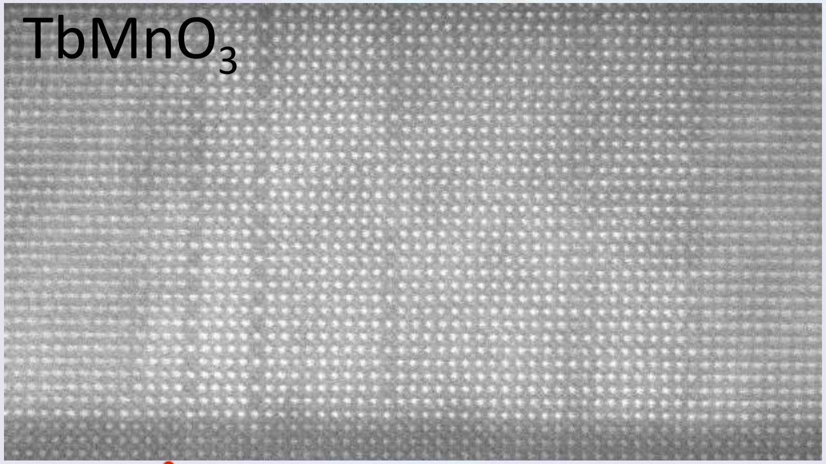


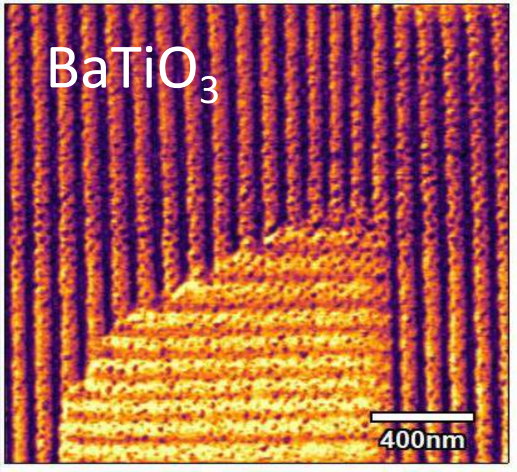
$(Pb,Sr)TiO_3$



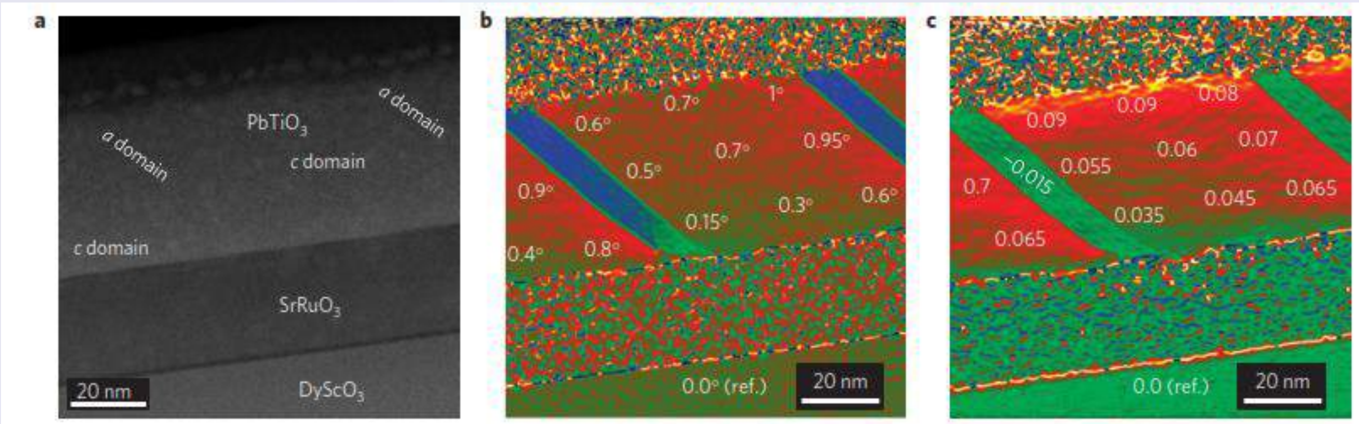
$BiFeO_3$

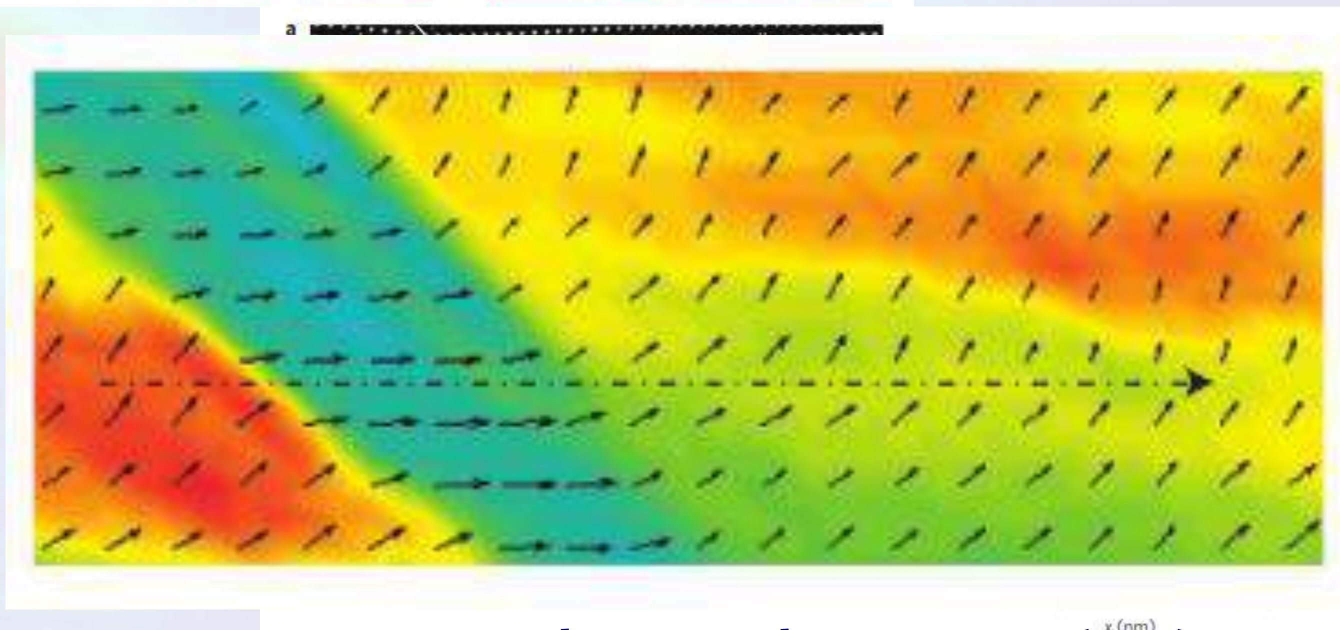






Engineering strain gradients

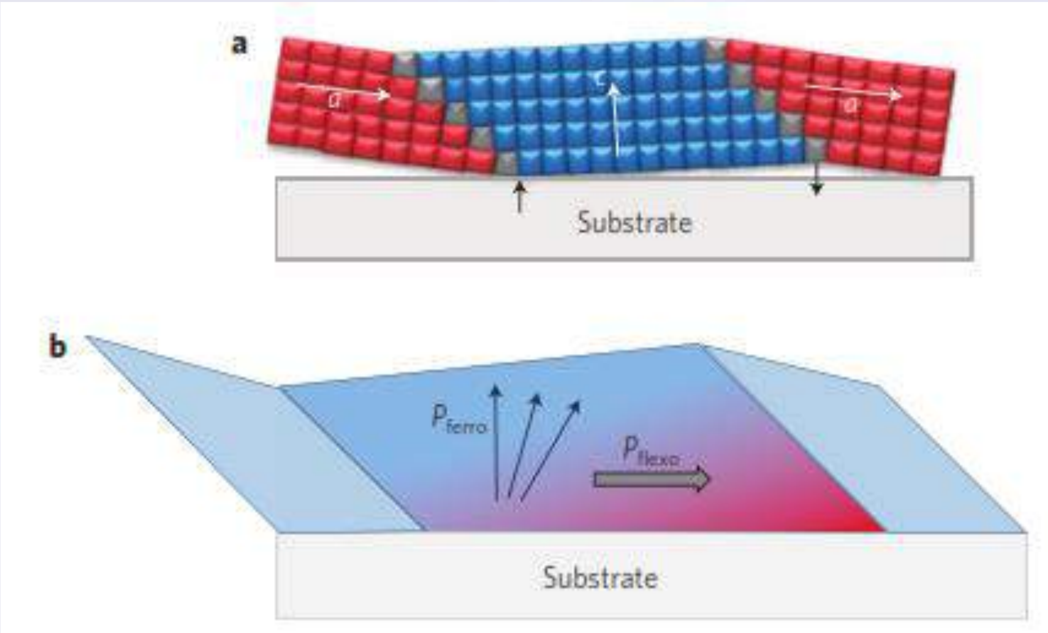


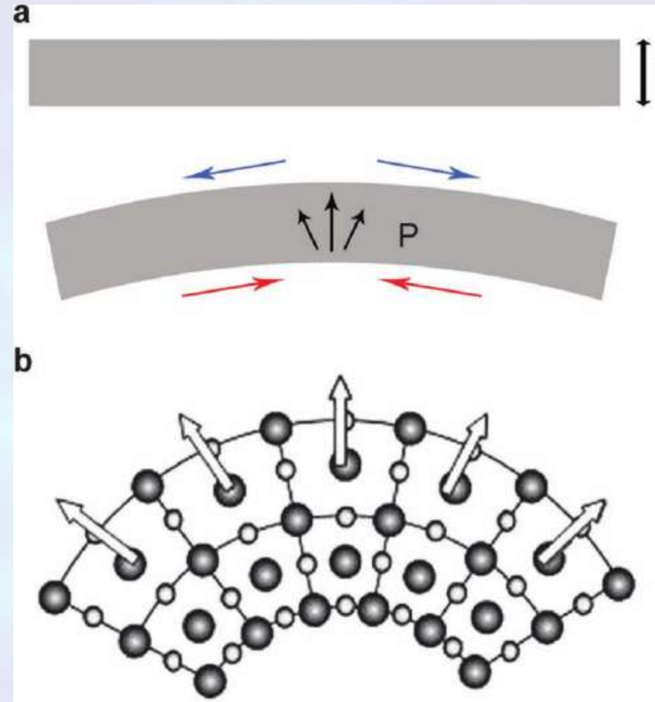


G. Catalan, BN et al., *Nature Mat.* (2011)

Engineering strain gradients

Induced Flexoelectric Polarization

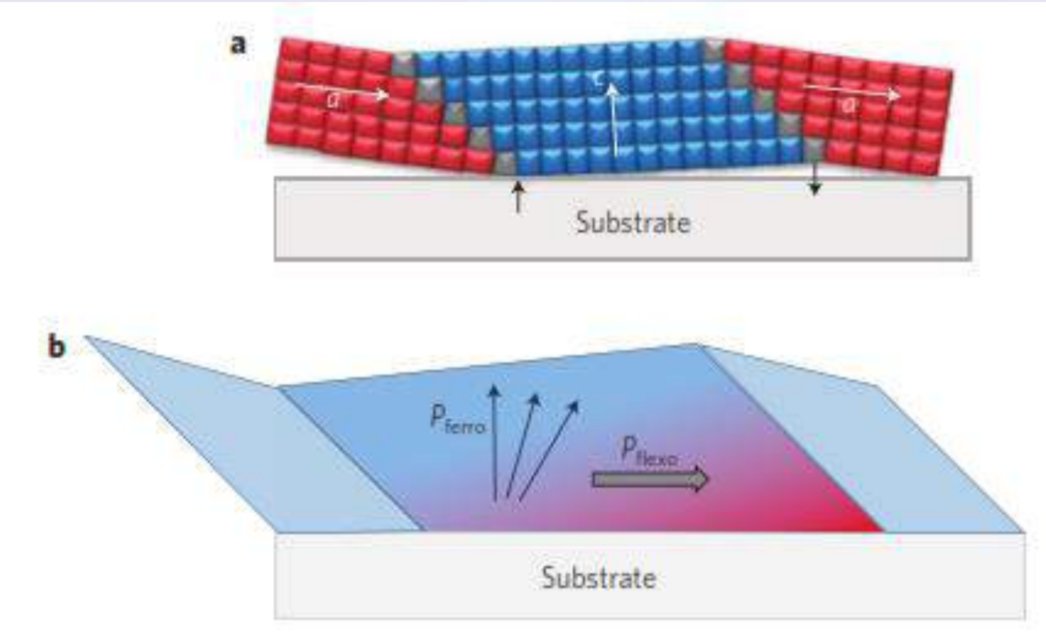




$$P_i = d_{ijk}\sigma_{jk} + \mu_{ijkl}\frac{\partial \varepsilon_{jk}}{\partial x_l}$$

G. Catalan, BN et al., *Nature Mat.* (2011)

Engineering strain gradients



Flexoelectric Polarization

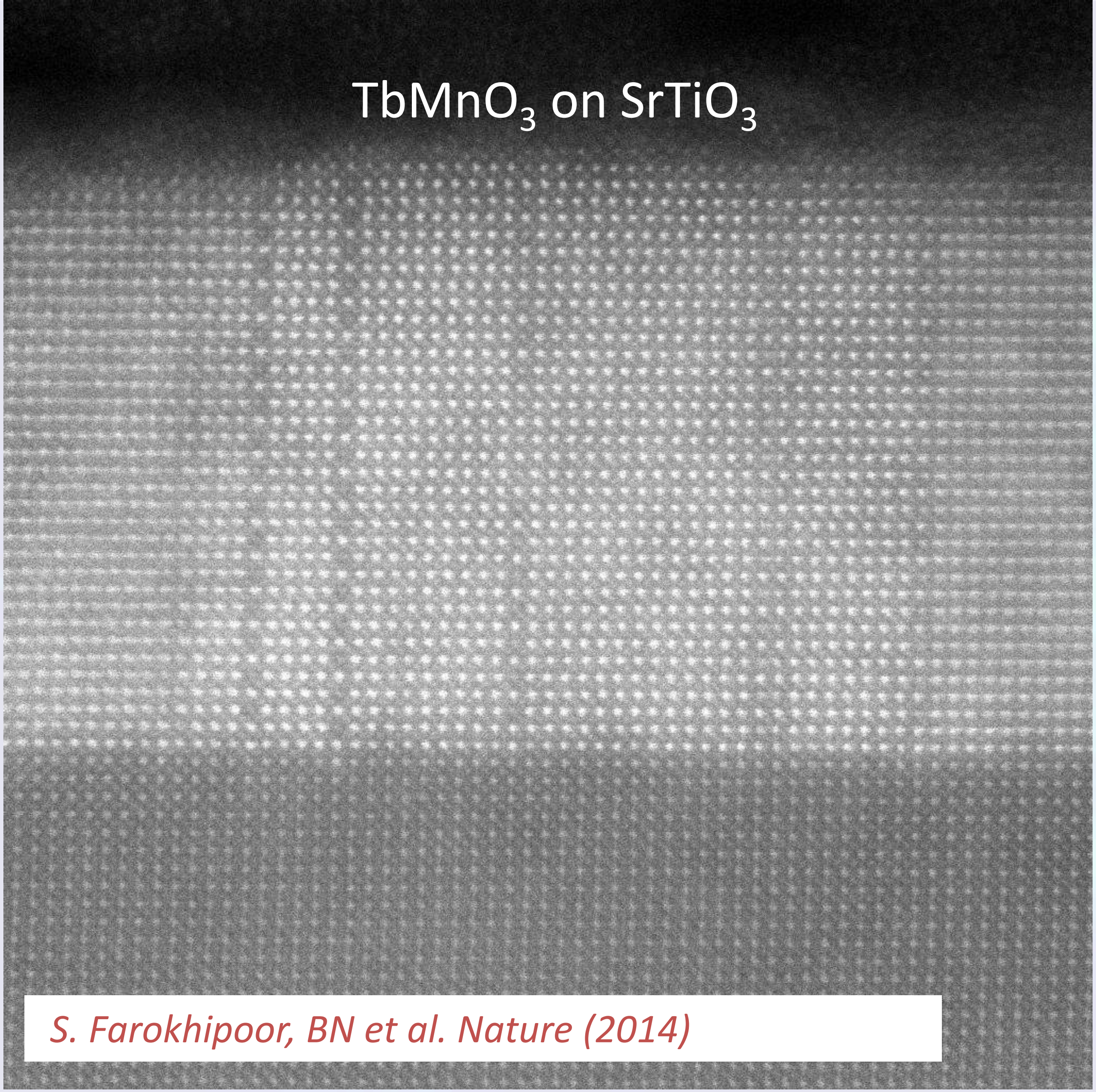
→ Polar rotation

→ Symmetry breaking

→ Enhanced piezo-response

Lesser role of chemistry (more sustainable piezoelectrics)
Intrinsic nanoscale response

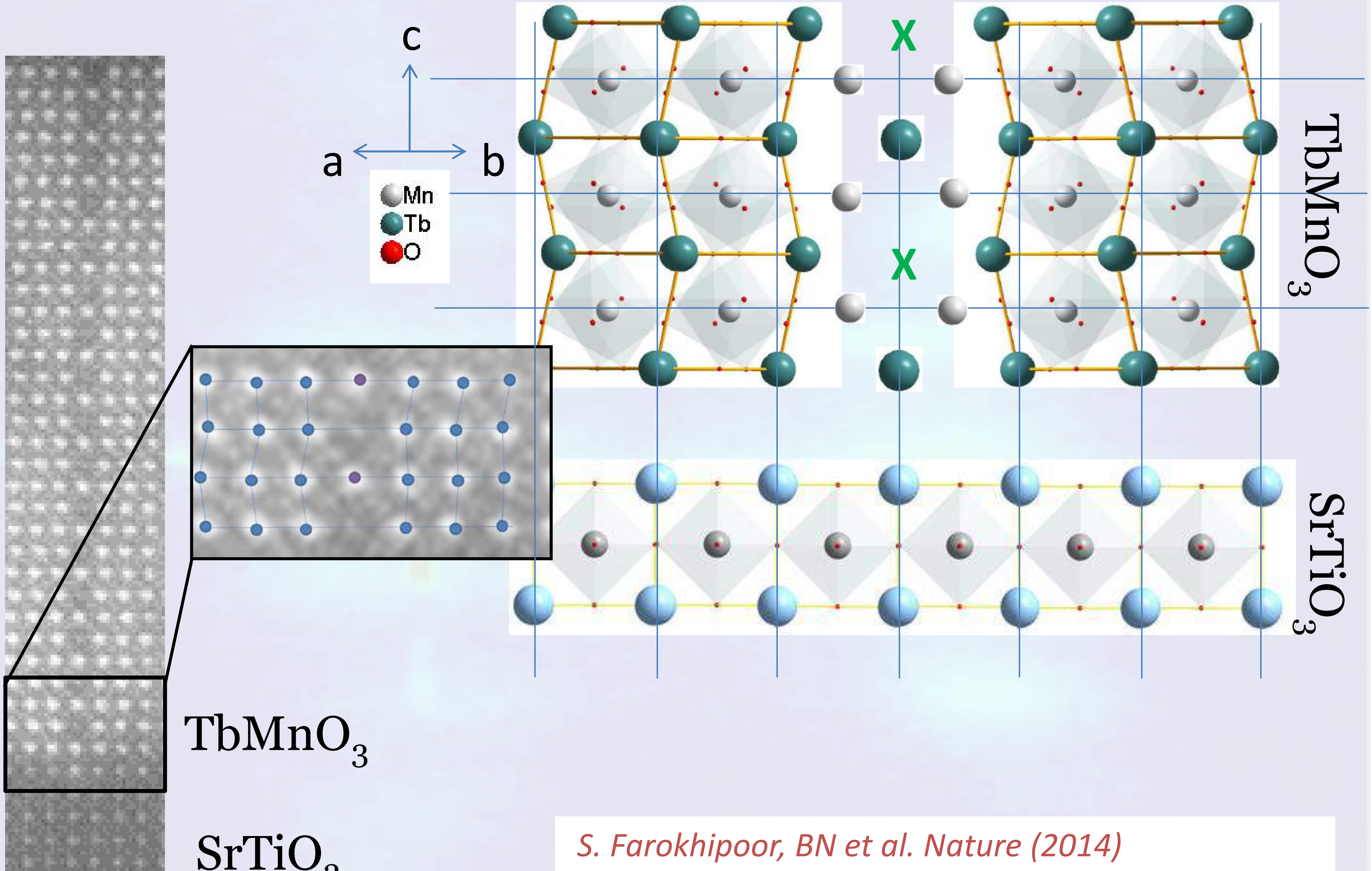
G. Catalan, BN et al., *Nature Mat.* (2011)



S. Farokhipoor, BN et al. Nature (2014)

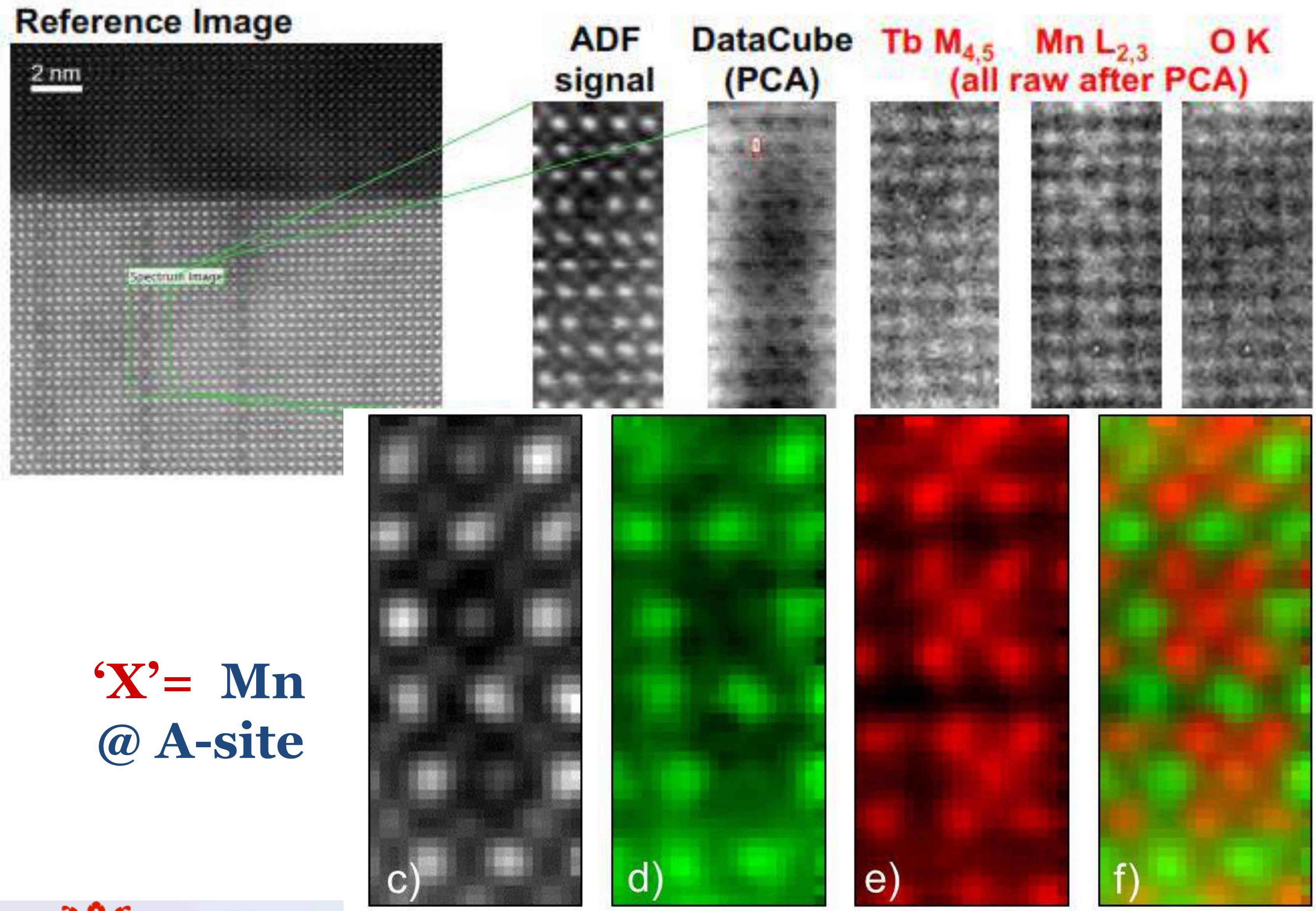
Chemical contrast at domain walls

Alternating Tb-X-Tb-X columns



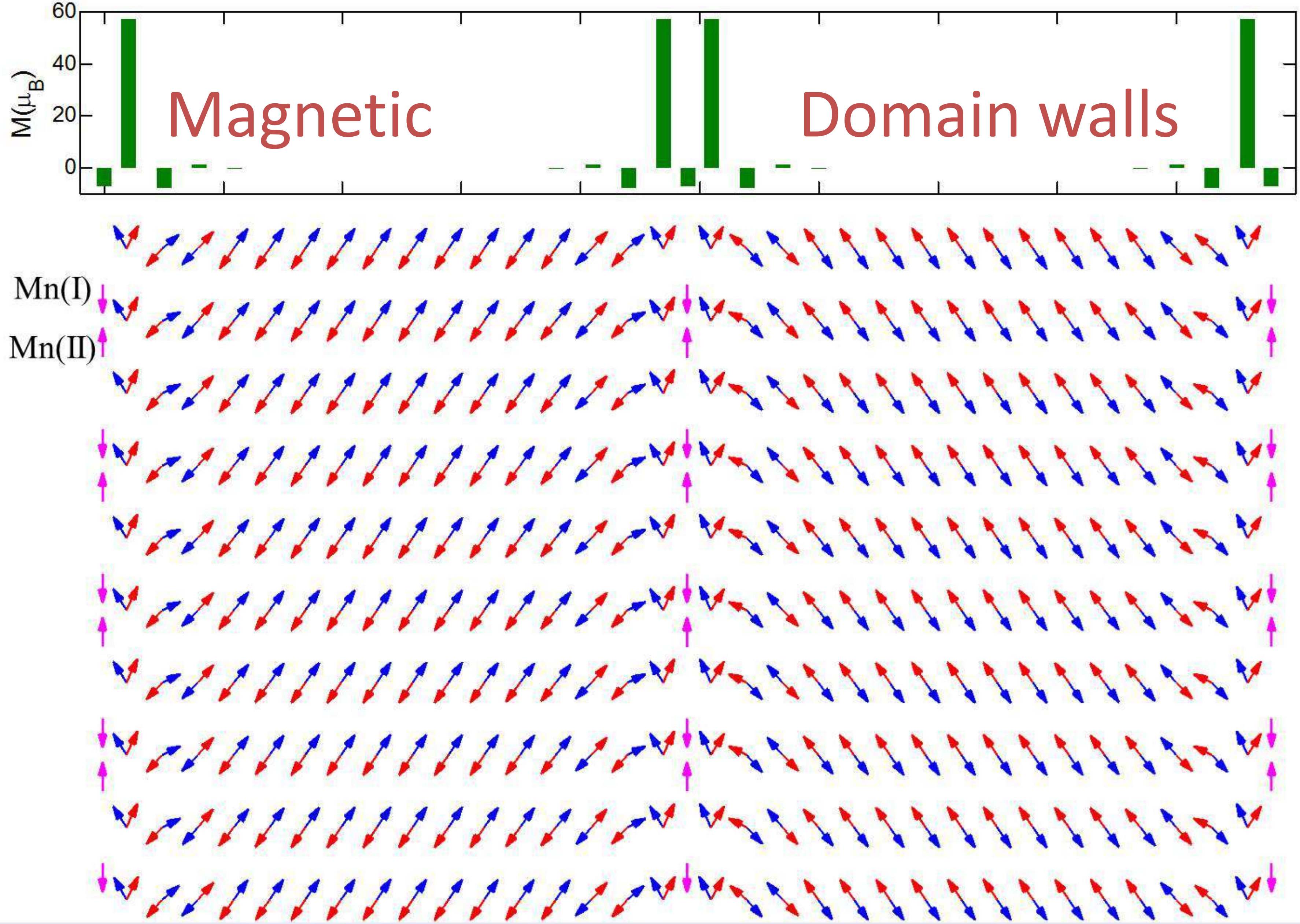
S. Farokhipoor, BN et al. Nature (2014)

STEM-EELS Spectrum Imaging

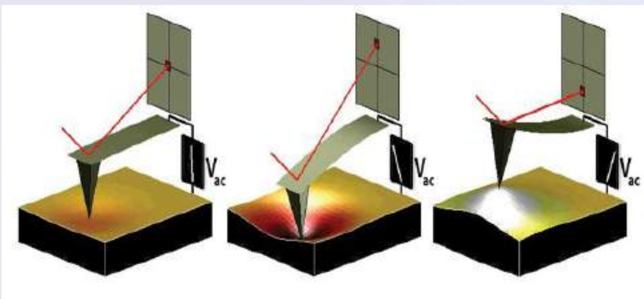


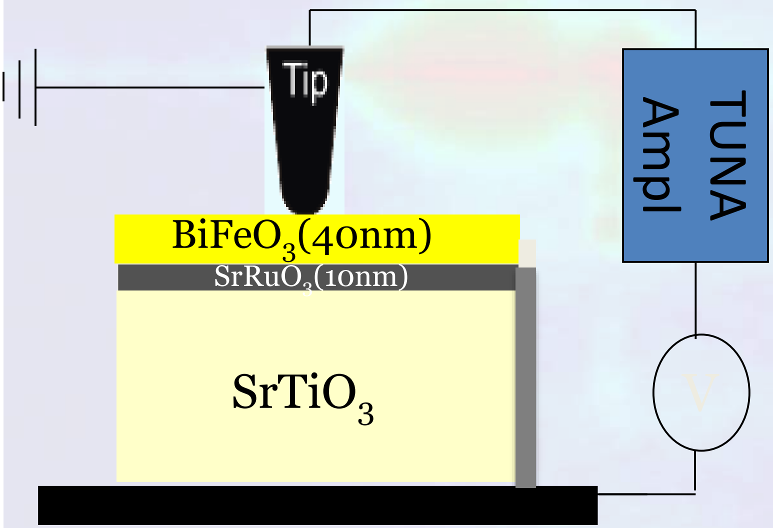
‘X’= Mn @ A-site

Magnetic Domain walls

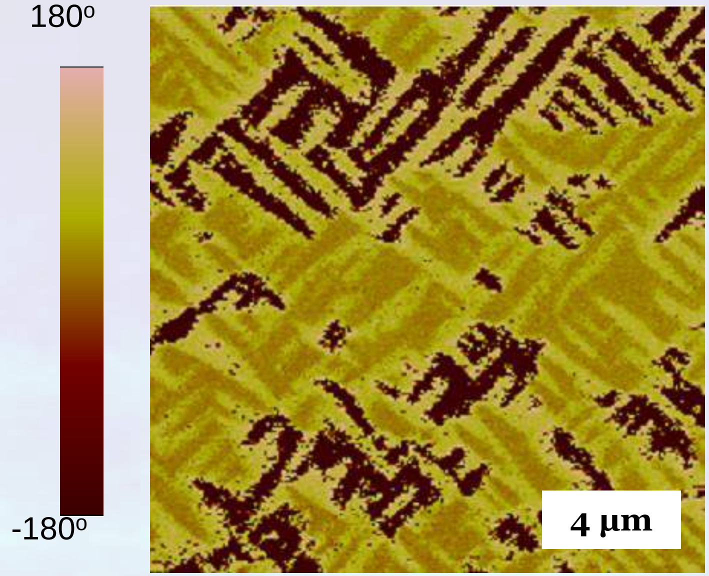


Conductivity at ferroelastic/ferroelectric DWs



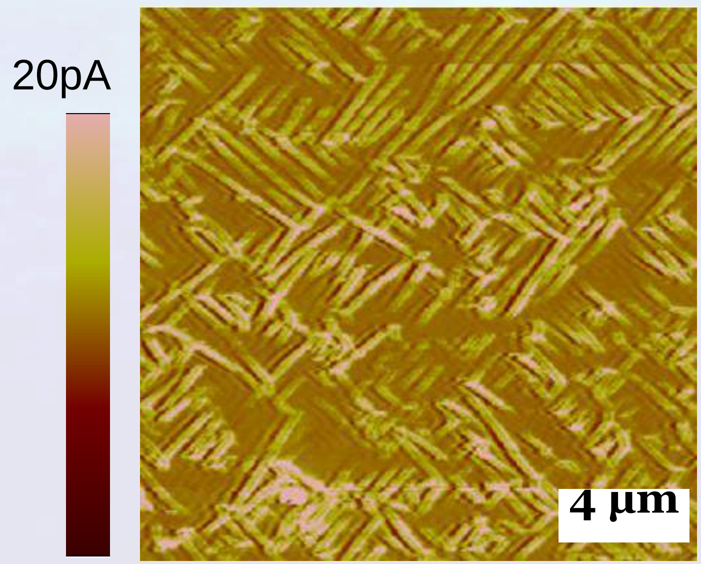


S. Farokhipoor and BN, PRL 2011



In-plane Piezo-FM (IP-PFM)

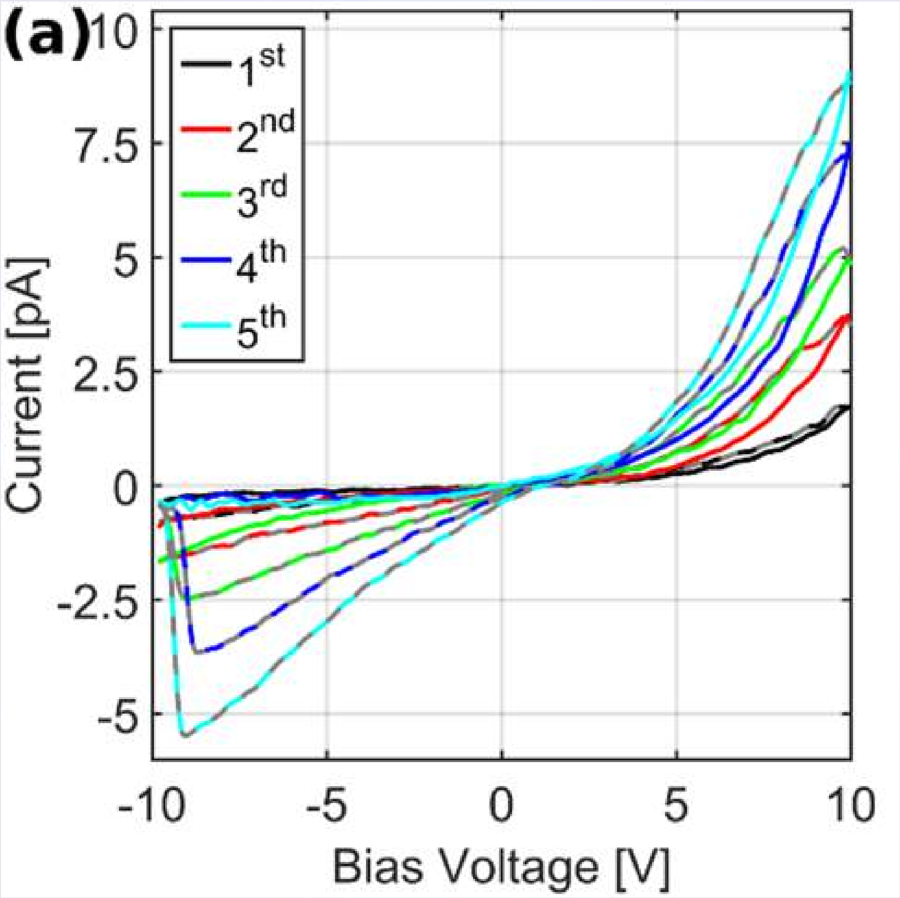
Ferroelectric/ piezoelectric Domains visible

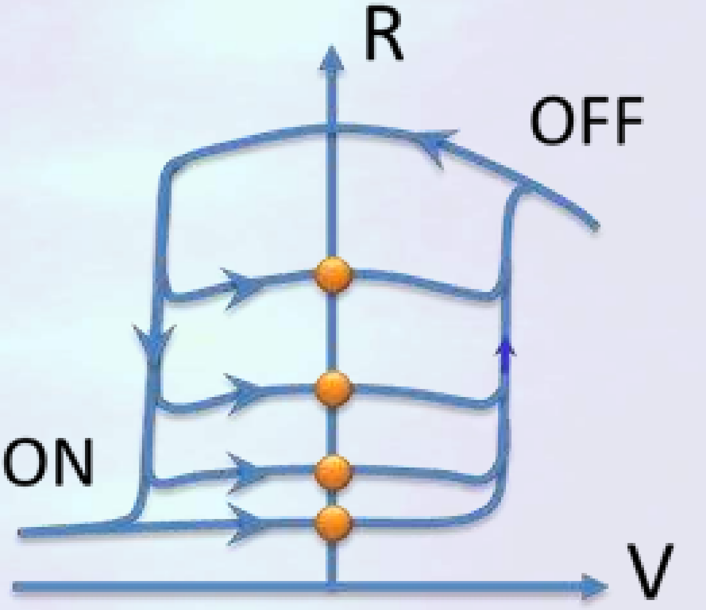


Conductive -AFM

fA - μA sensitivity

Memristive domain walls in ferroic oxides





Adaptable electronics

G. Lindgren & C. Canalias,

*APL Materials **5**, 076108 (2017)*

Why Adaptable electronics?

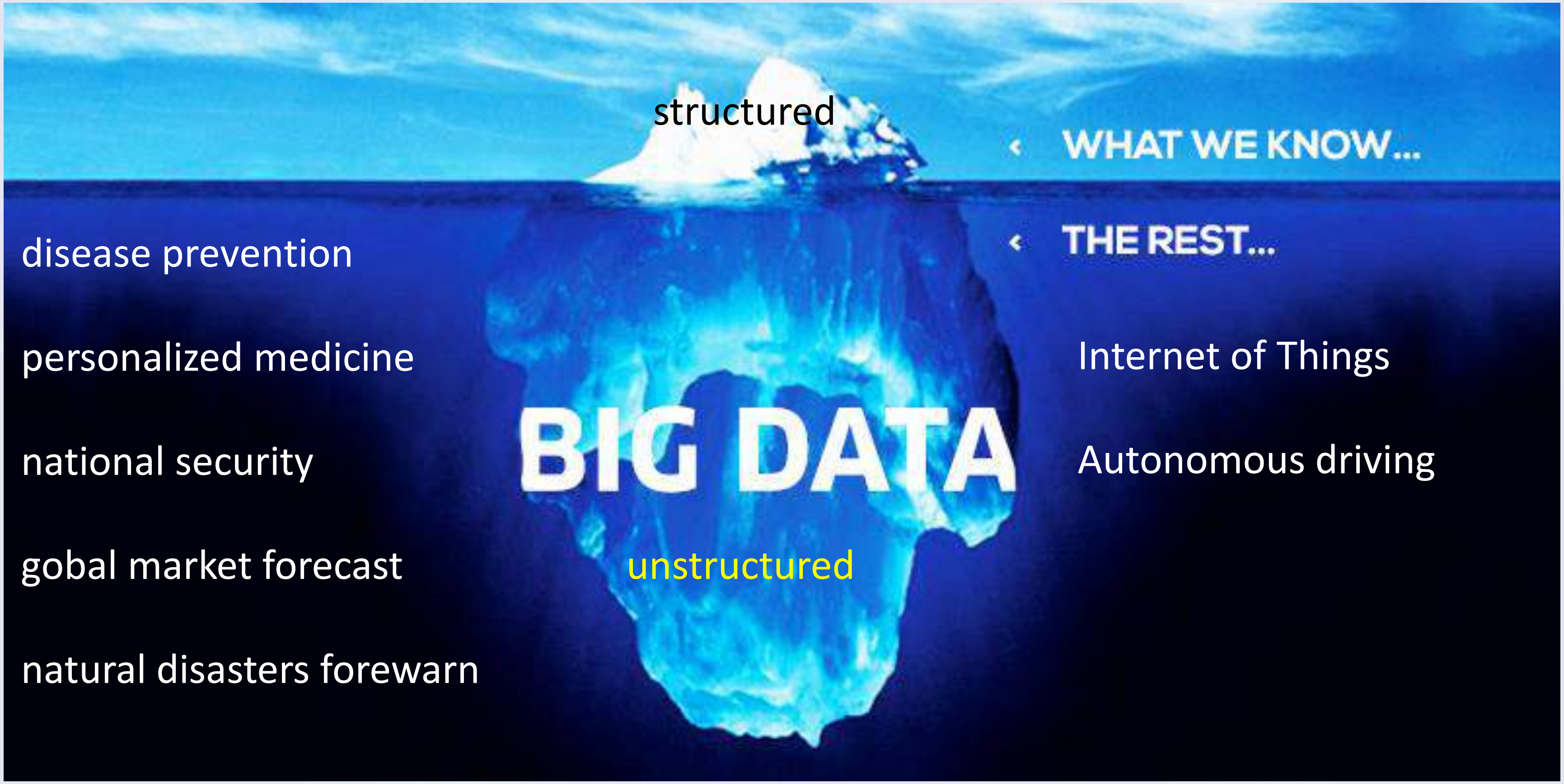


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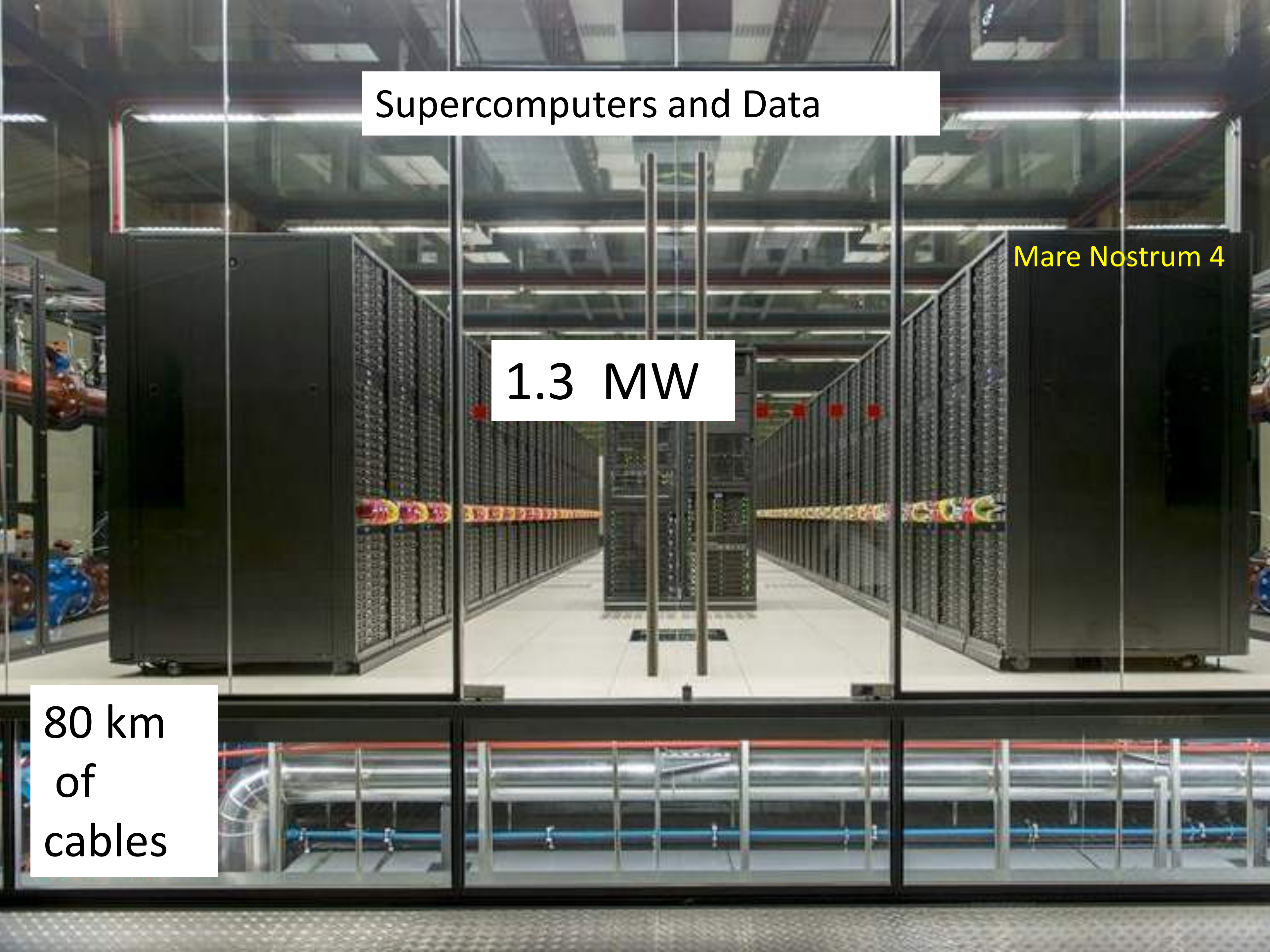
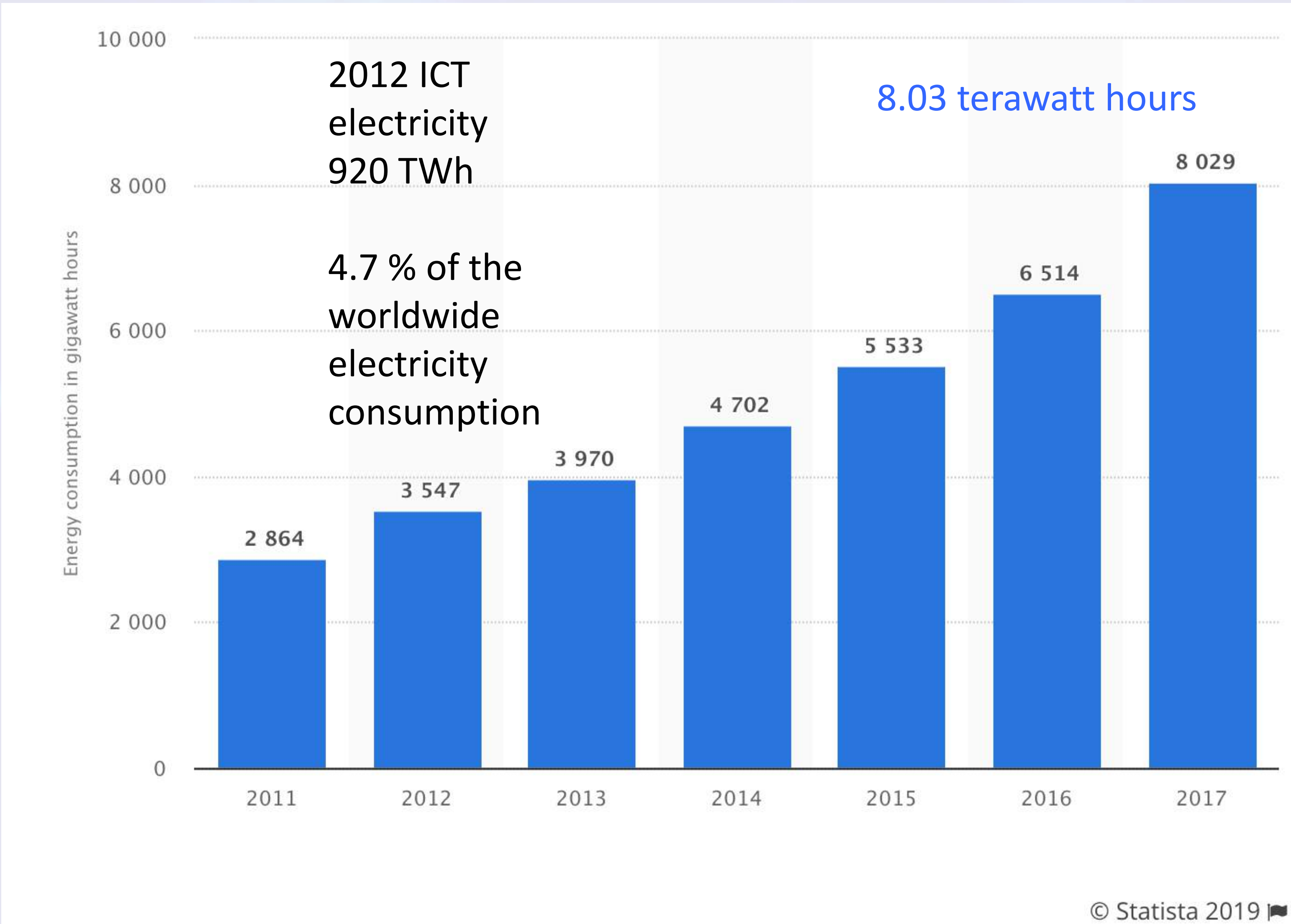
Image from http://wpmu.mah.se/nmict171group6/tag/big-data/

university of groningen / faculty of science and engineering / zernike institute for advanced materials

Supercomputers and Data

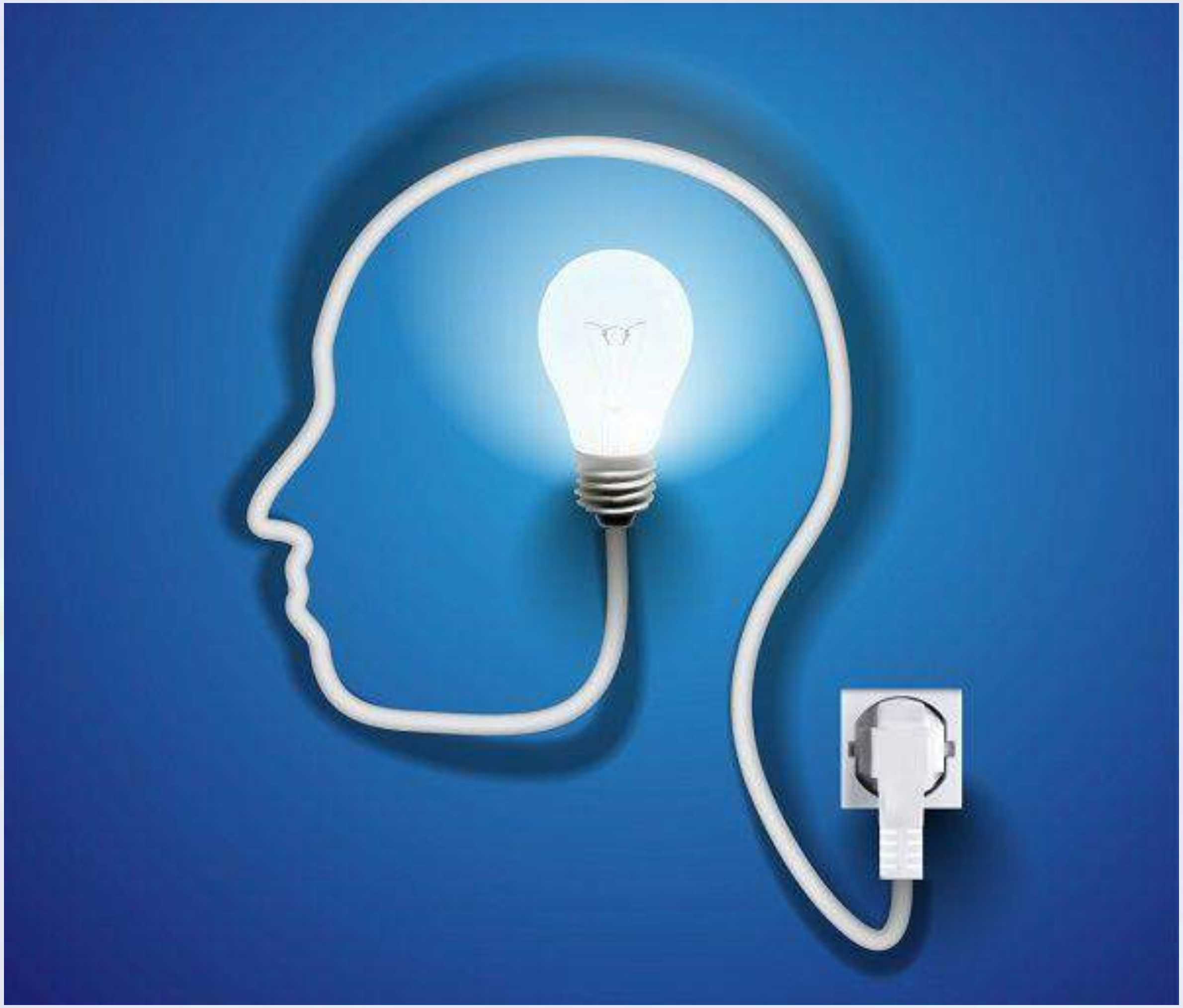


Energy consumption Google (2011-2017)



Cat or dog?

Effortless pattern recognition



Our brain needs ~20 watt

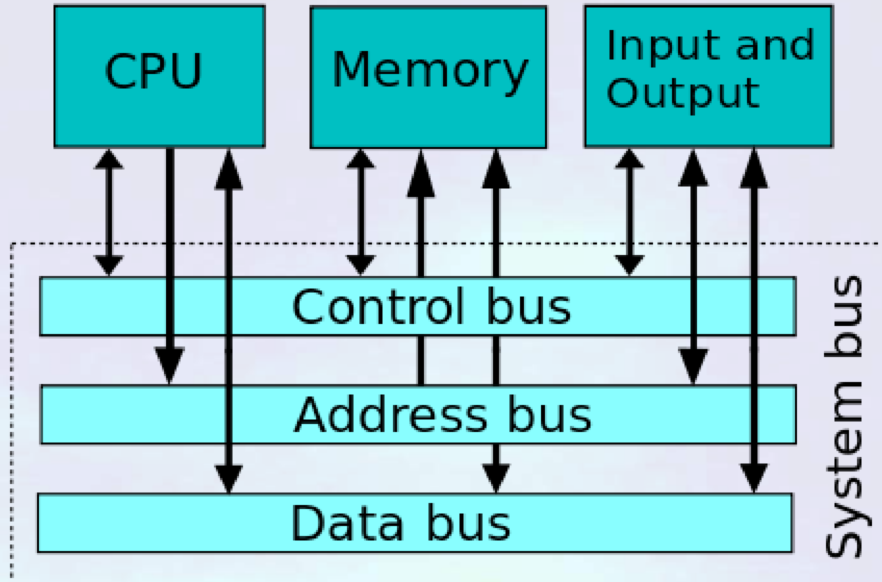
Our computers 200.000 watt

Our brain:

- Neurons host both storage and processing
- Neurons are intertwined
- Large connectivity

1 neuron→10^3-10^4 synapses

- Parallel processing
- 10^{11} neurons (redundancy)
- Plasticity→ learning



Von Neumann computers;

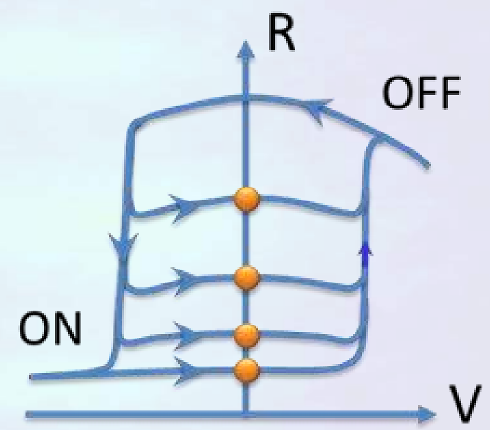
- Memory and processor are separated
- The bus uses most of the energy
- Information is handled sequentially

From learning software to ***learning hardware***

→ Architectures based on adaptable electronics

→ Elements with intrinsic plasticity

Memristive devices:



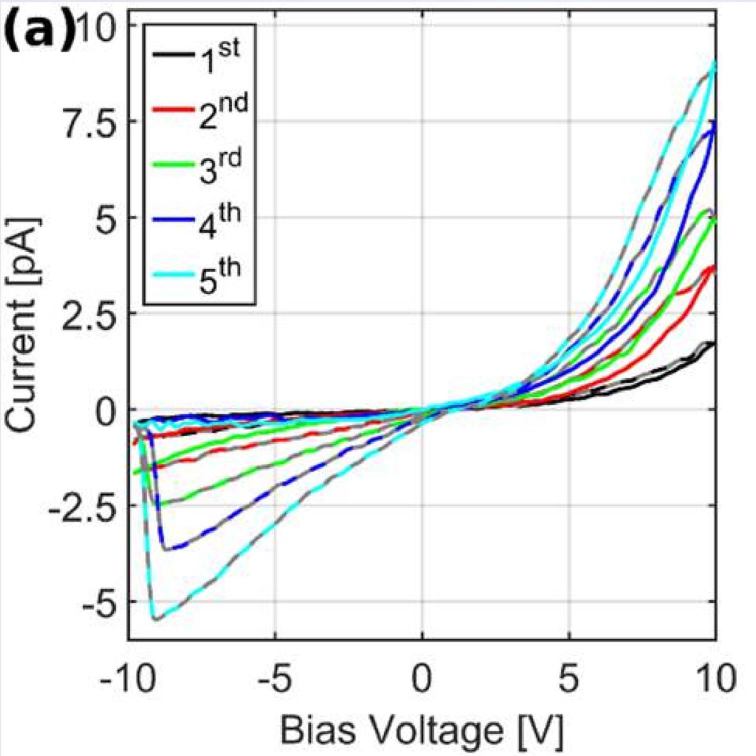
→ Large interconnected network
(nanoscience + statistics)

→ Robustness against nanoscale failure (redundancy)

→ Re-routing/Parallel processing

Materials: Self-assembled nanoscale networks

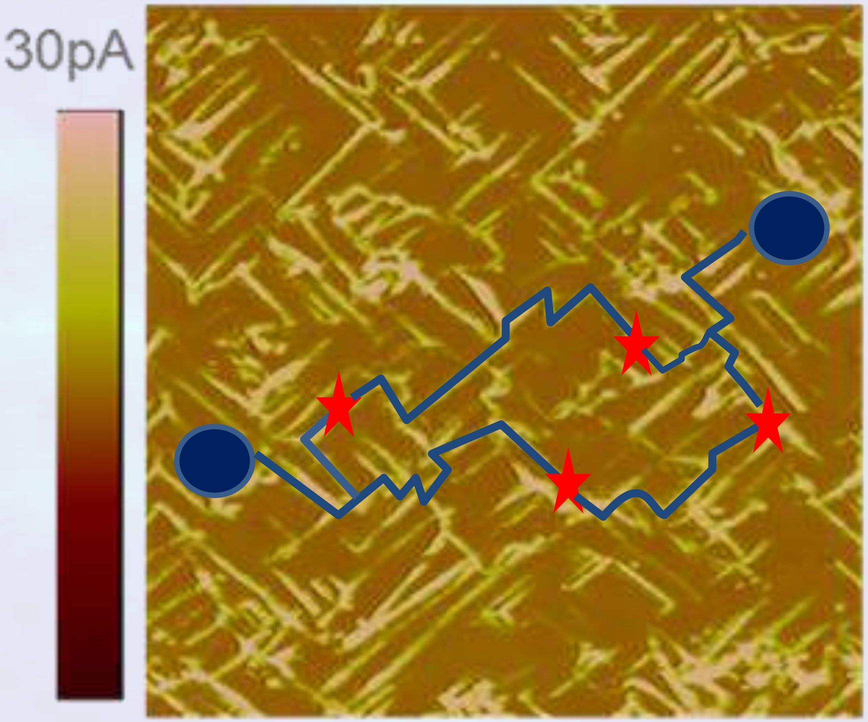
Memristive domain walls in ferroic oxides



G. Lindgren & C. Canalias,

*APL Materials **5**, 076108 (2017)*

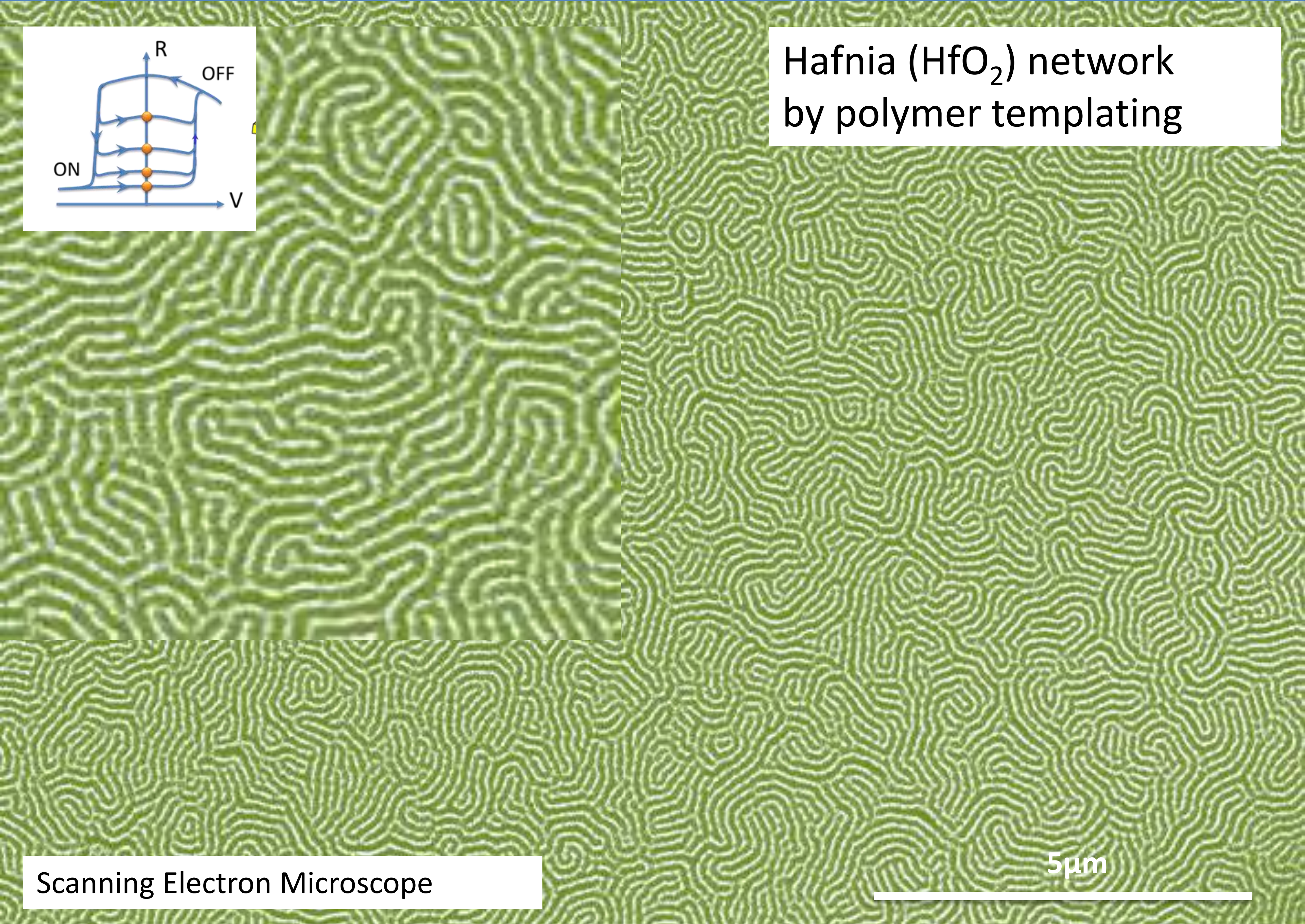
Conduction AFM-map



2 µm x 2 µm

Ferroelectric $BiFeO_3$ thin films

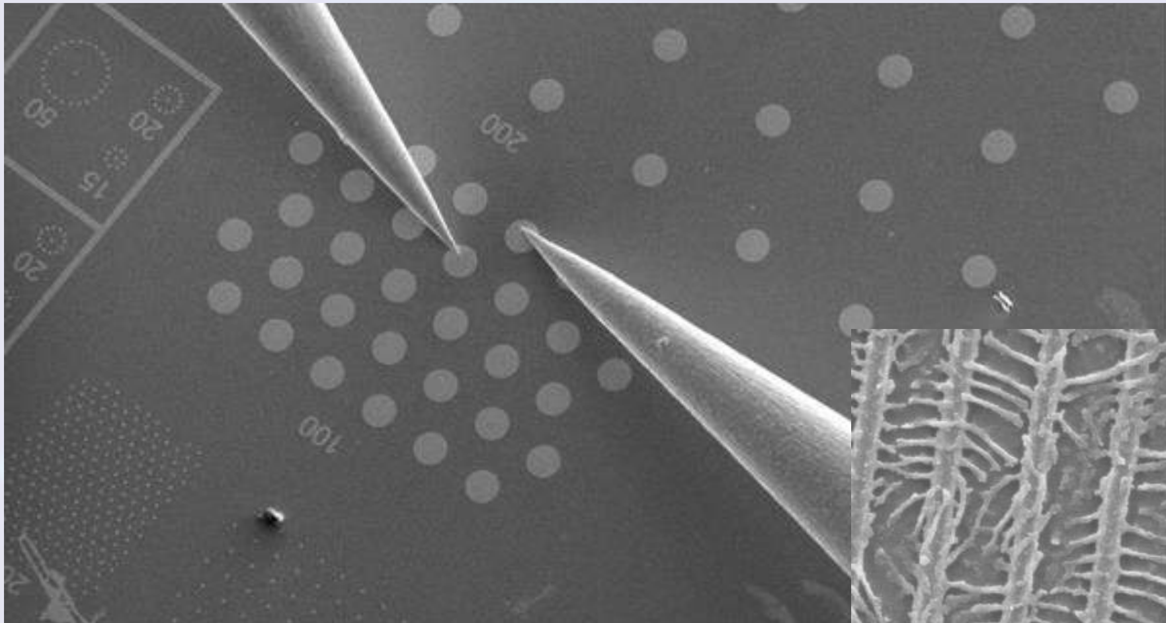
Hafnia (HfO_2) network by polymer templating

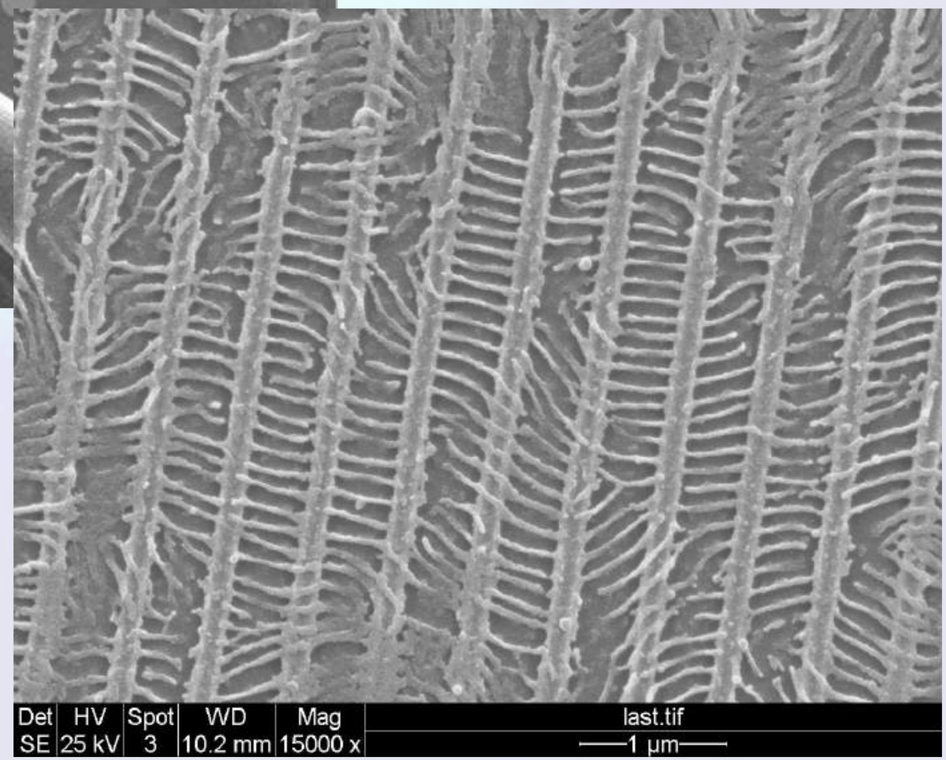


Sanne Berg & Beatriz Noheda

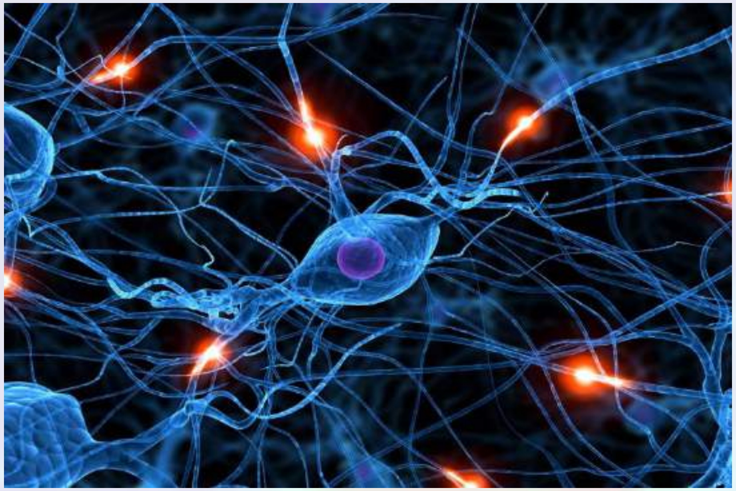
In collaboration with Jin Xu & Katja Loos

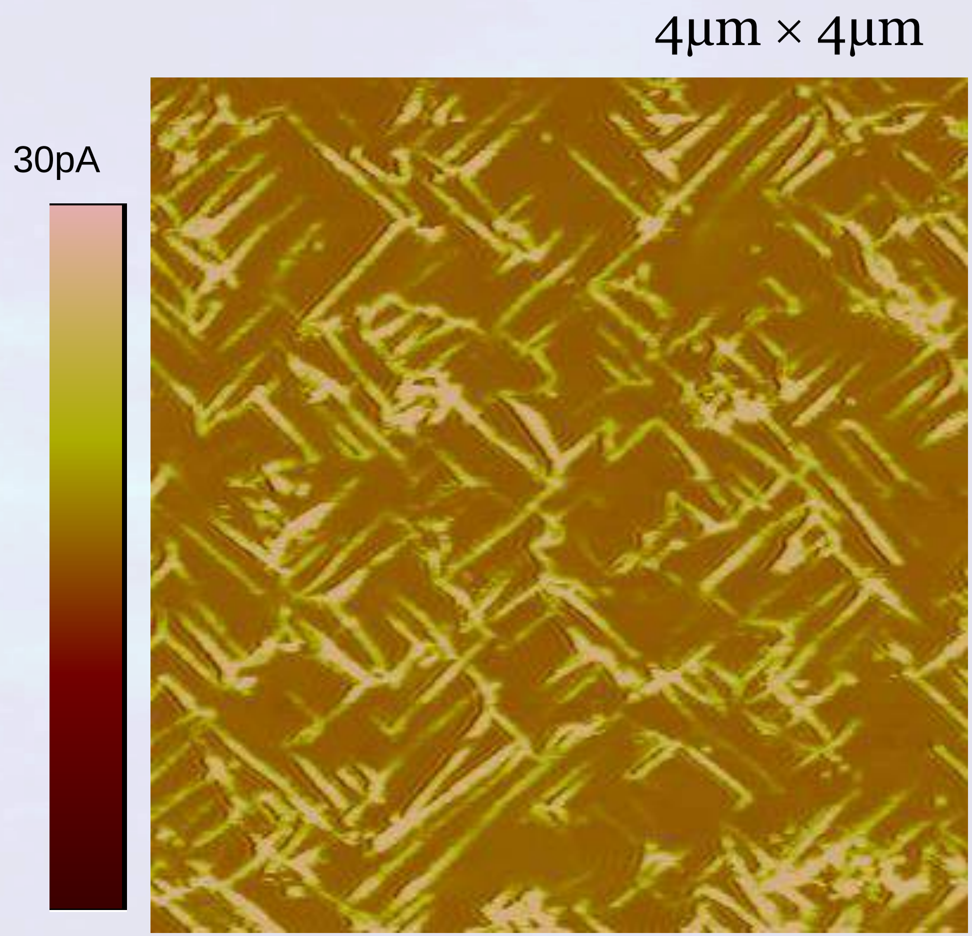
Self-assembled nanoscale networks





Novel materials for neuromorphic computing





DWs can provide conducting networks that mimic synaptic connections

university of groningen

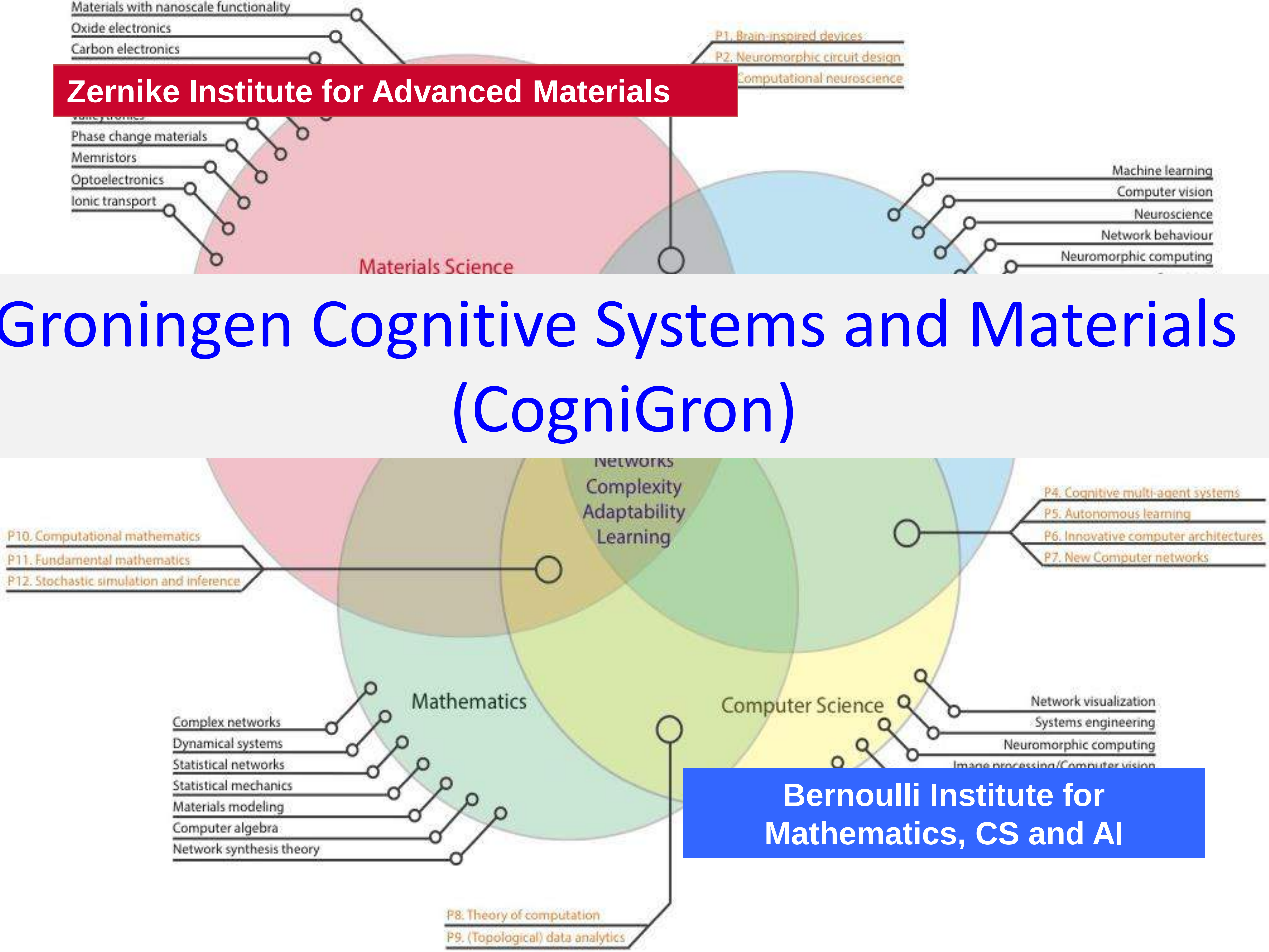
faculty of science and engineering

zernike institute for advanced materials

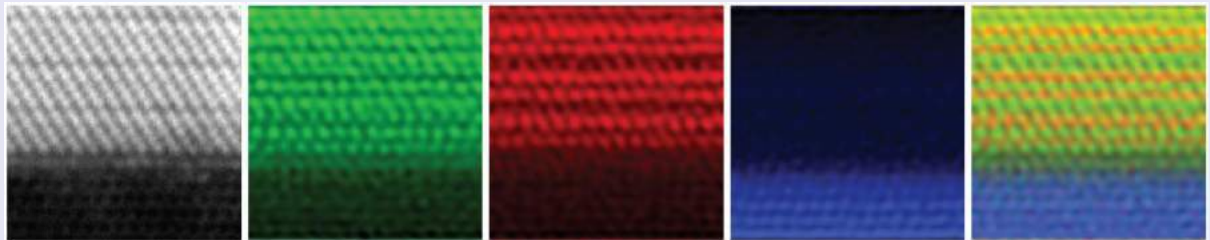
Zernike Institute for Advanced Materials

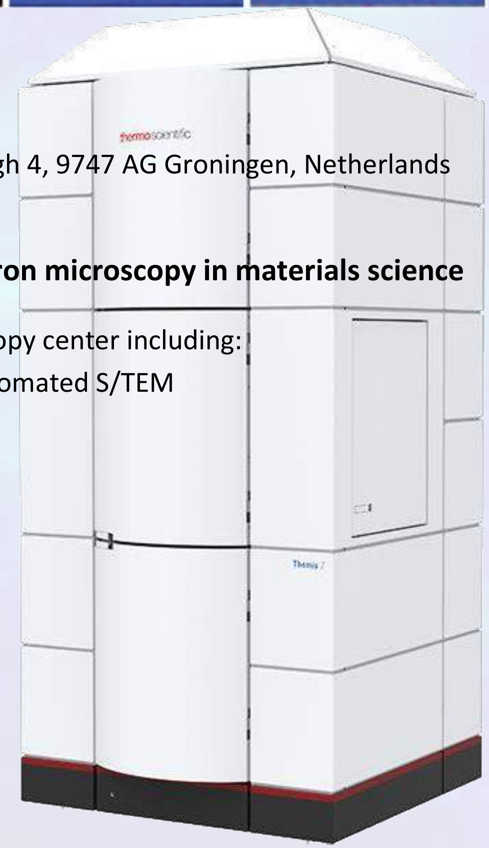
Groningen Cognitive Systems and Materials (CogniGron)

Bernoulli Institute for Mathematics, CS and AI



Groningen Microscopy Center





Save the date:

Sept. 19th, 2019.

Where?: Zernike Institute for Advanced Materials, Nijenborgh 4, 9747 AG Groningen, Netherlands

Why?: Workshop
The power of aberration corrected transmission electron microscopy in materials science

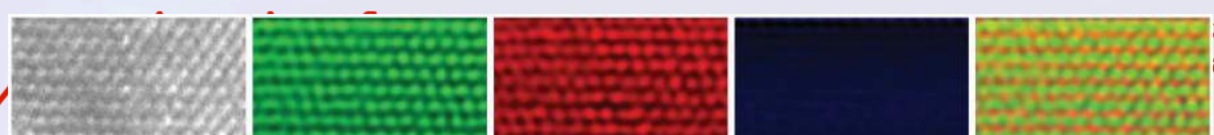
To celebrate the inauguration of our ZIAM electron microscopy center including:

- Themis Z double aberration corrected and monochromated S/TEM
- Helios G4 dual beam (FIB-SEM) system
- Nova NanoSEM

Confirmed invited speakers:
Prof. Rafal Dunin-Borkowski (Jülich)
Prof. Gertjan Koster (Twente)
Prof. Beatriz Noheda (Groningen)
Dr. Marcel Verheijen (Eindhoven)
Dr. Marijn van Huis (Utrecht)

Host: Prof. Bart J. Kooi (Groningen)

A detailed program and registration options will follow soon.



itute for
aterials

Conclusions

- Thin film epitaxy allows control of domain walls densities: miniaturization of FE and improved piezo
- Local stresses at domain walls can lead to novel 2D materials: chemical environments that cannot be synthesized in bulk.
- In $BiFeO_3$, domain walls provide networks of conducting channels
- Combined resistive switching + ferroelectricity + magnetism: adaptable electronics for ‘neuromorphic/cognitive devices’
- Domain wall in ferroelectrics conform self-assembled memristor networks

THANK YOU

Center for Cognitive Systems and Materials

Our mission is to develop materials-centred systems paradigms for cognitive computing based on modelling and learning at all levels: from materials that can learn to devices, circuits and algorithms.

About us

Our goals

Our approach

Computers and Data

- Image/text recognition
- Search
- Classification
- Advice
- Play games

Learning algorithms
for
pattern recognition

(software-based)

Artificial Neural Networks