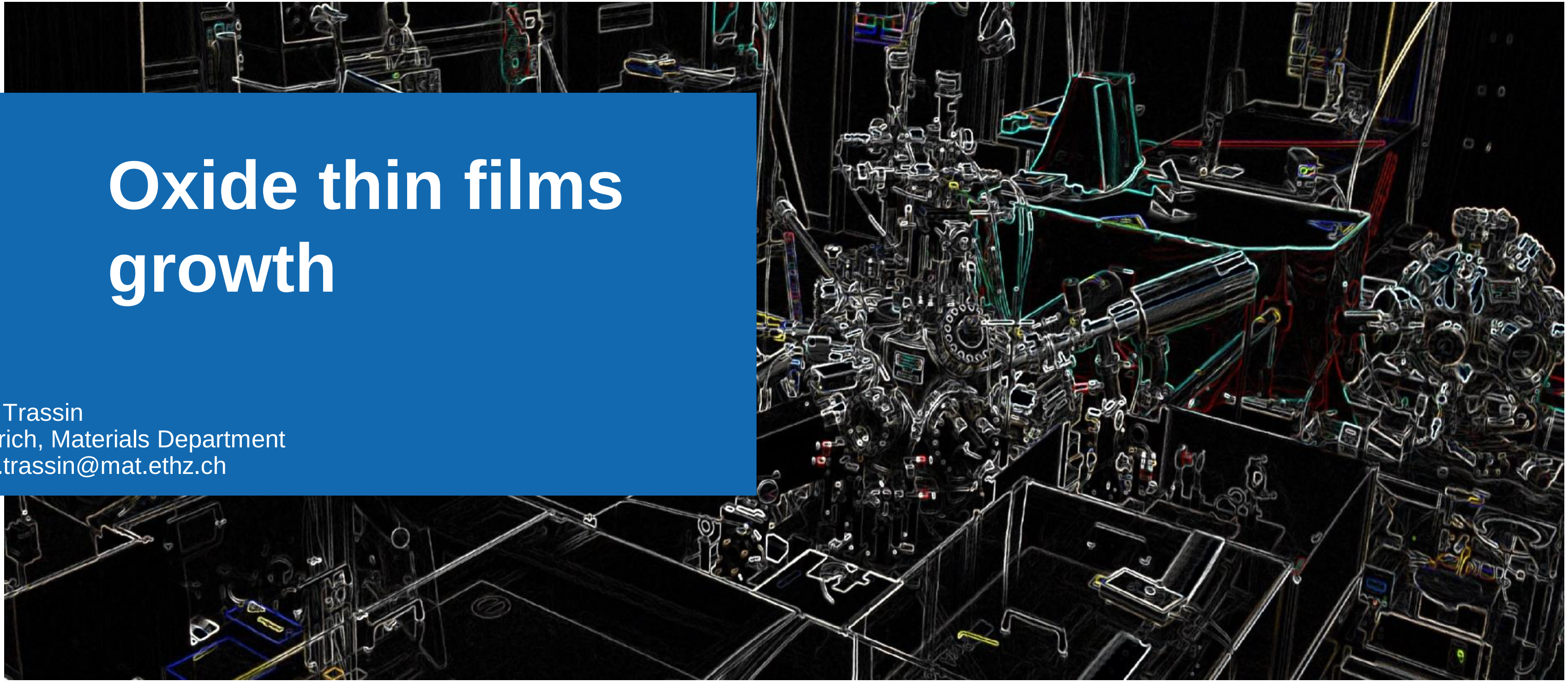


Oxide thin films growth

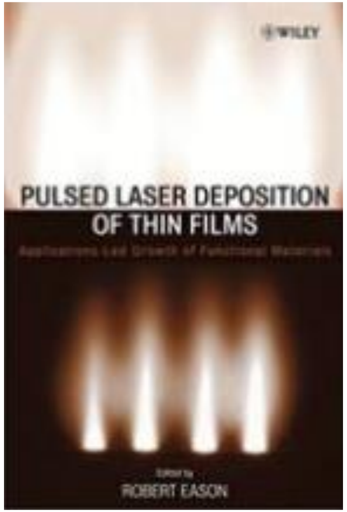
Morgan Trassin
ETH Zurich, Materials Department
morgan.trassin@mat.ethz.ch

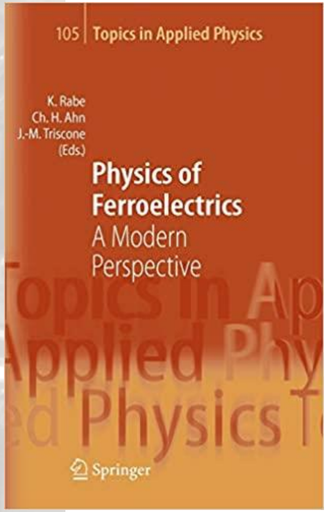
Thin films epitaxy

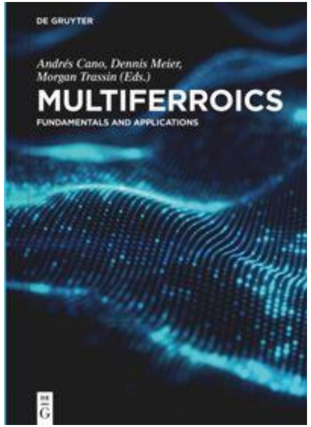
- Brief definitions
- Epitaxial strain as a control parameter
- Materials, substrates

Growth process
- Growth modes and growth mechanisms
- In situ monitoring of 2D growth
- Growth techniques
- Structural characterization

The case of ferroelectrics
- In-situ diagnostic tools
- Monitoring of ferroelectricity during the epitaxial growth
  interface contributions







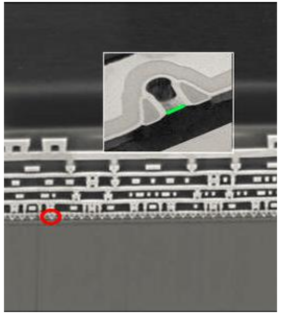
Thin films research and applications

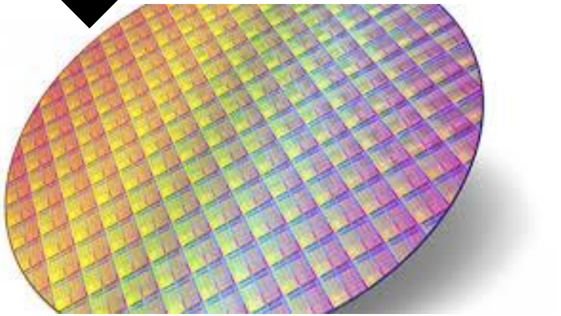
D MATL.

Why thin film form?

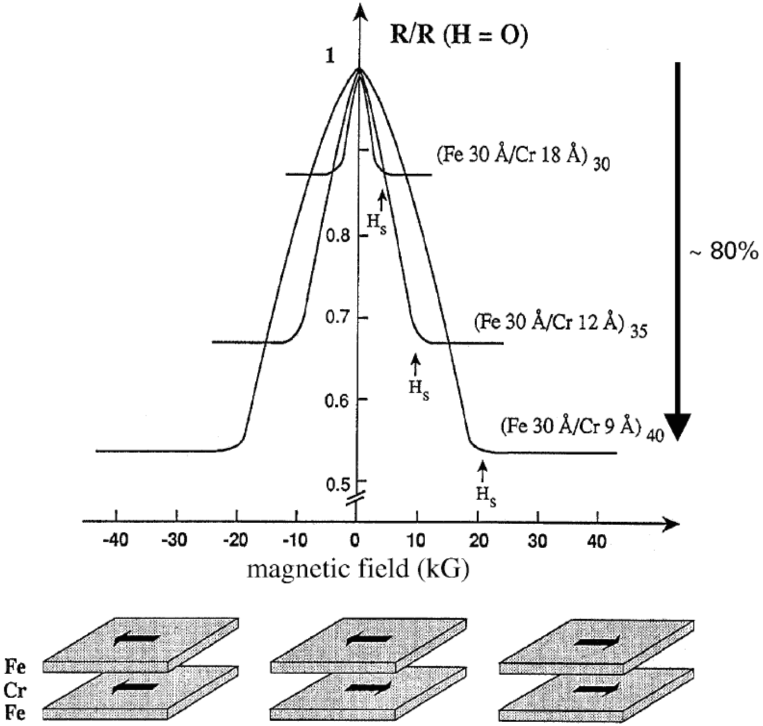
www.computerhistory.org

Thin film processing





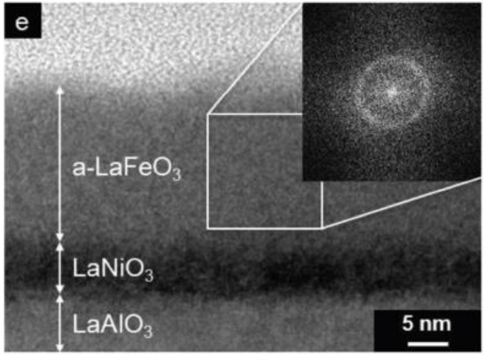
Reproduce bulk properties in reduced dimensions, technologically relevant design, etc…



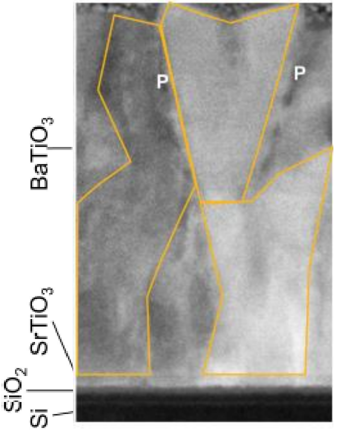
- **Tune** the physical properties of bulk (strain, confinement effects, etc…)
- **Create** new materials (stabilizing new states of matter), multilayers and new interfaces

Phys. Rev. Lett. 61 (1988) 2472.
Phys. Rev. B 39, (1989) 4828.

Thin films research and applications

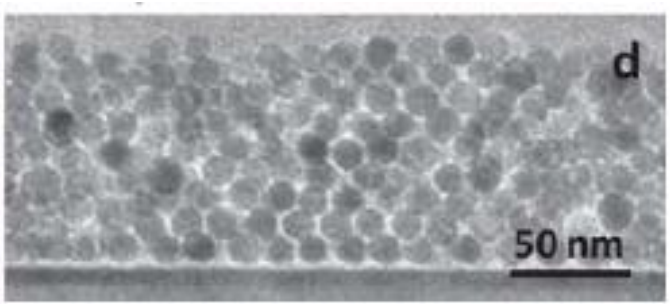


Adv. Funct. Mater. 2018, 1804782



A wide variety of textures, mophologies, applications…

Spray pyrolysis, sol-gel deposition, Langmuir-Blodgett, evaporation, molecular beam epitaxy, pulsed laser depostion, sputtering, chemical vapor depostion, etc…



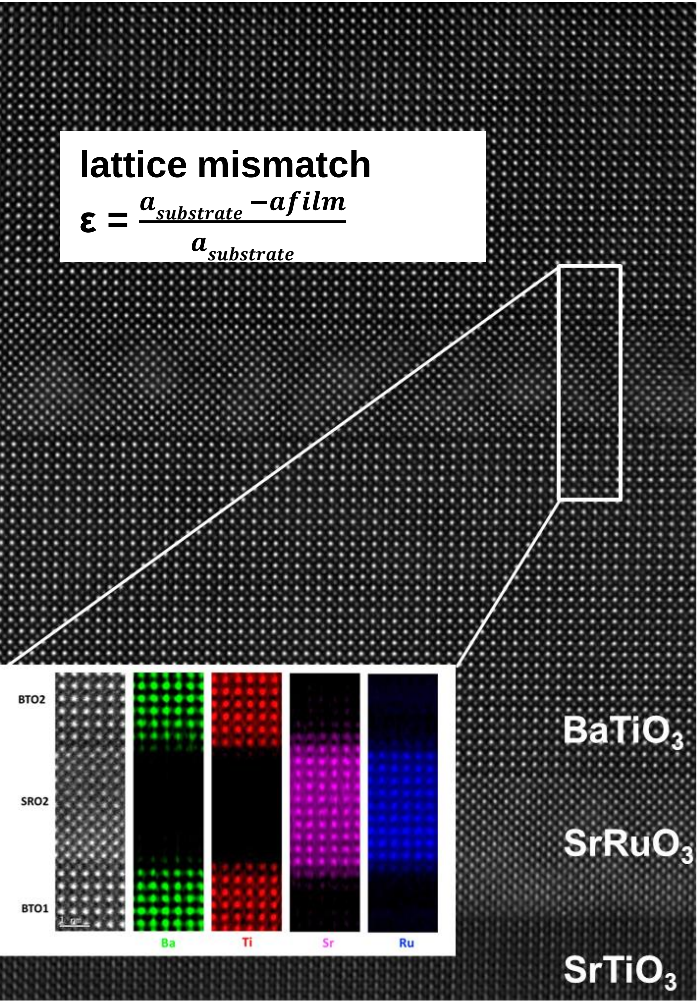
J. Mater. Chem., 2011,21, 16018-16027

Epitaxy

épi-táxis « on top» «order»

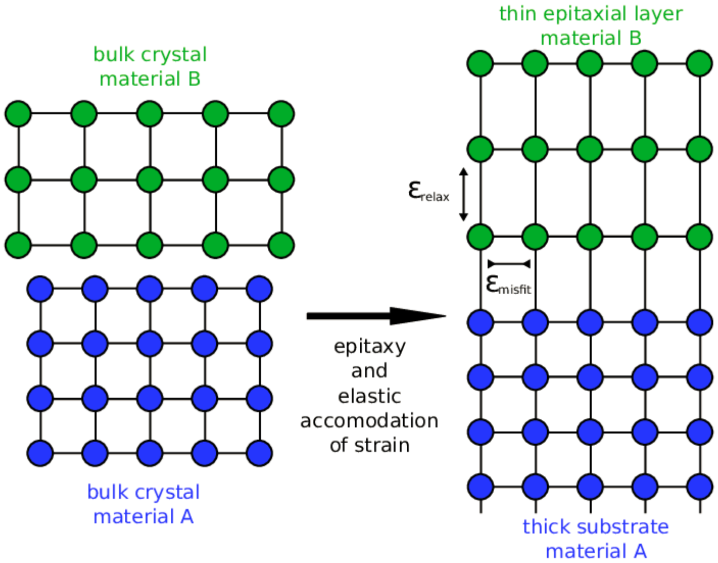
lattice mismatch

$$\varepsilon = \frac{a_{substrate} - afilm}{a_{substrate}}$$



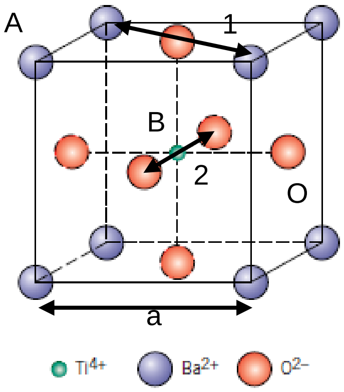
Ordered growth of single crystalline material using an oriented single crystal as a substrate

Control:
- crystallinity of the film
- orientation of the film
- strain state of the deposited lattice
(unit cell symmetry breaking, bond angle)



Phys. Rev. B 85, 035211 (2012)

Epitaxy

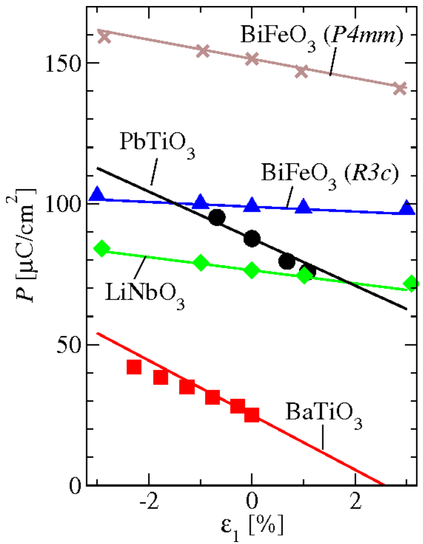


épi-táxis « on top» «order»

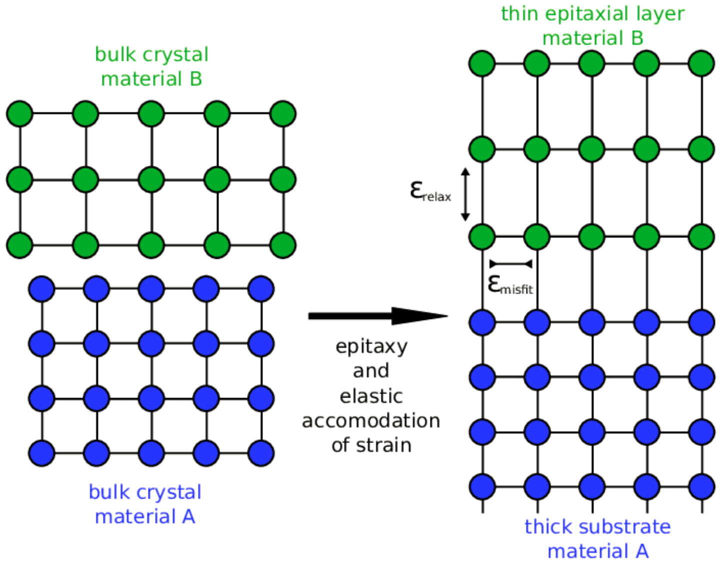
Ordered growth of single crystalline material using an oriented single crystal as a substrate

Control:
- crystallinity of the film
- orientation of the film
- strain state of the deposited lattice
(unit cell symmetry breaking, bond angle)

Oxide electronics: Ferroelectrics (B-driven)
Boost of polarization



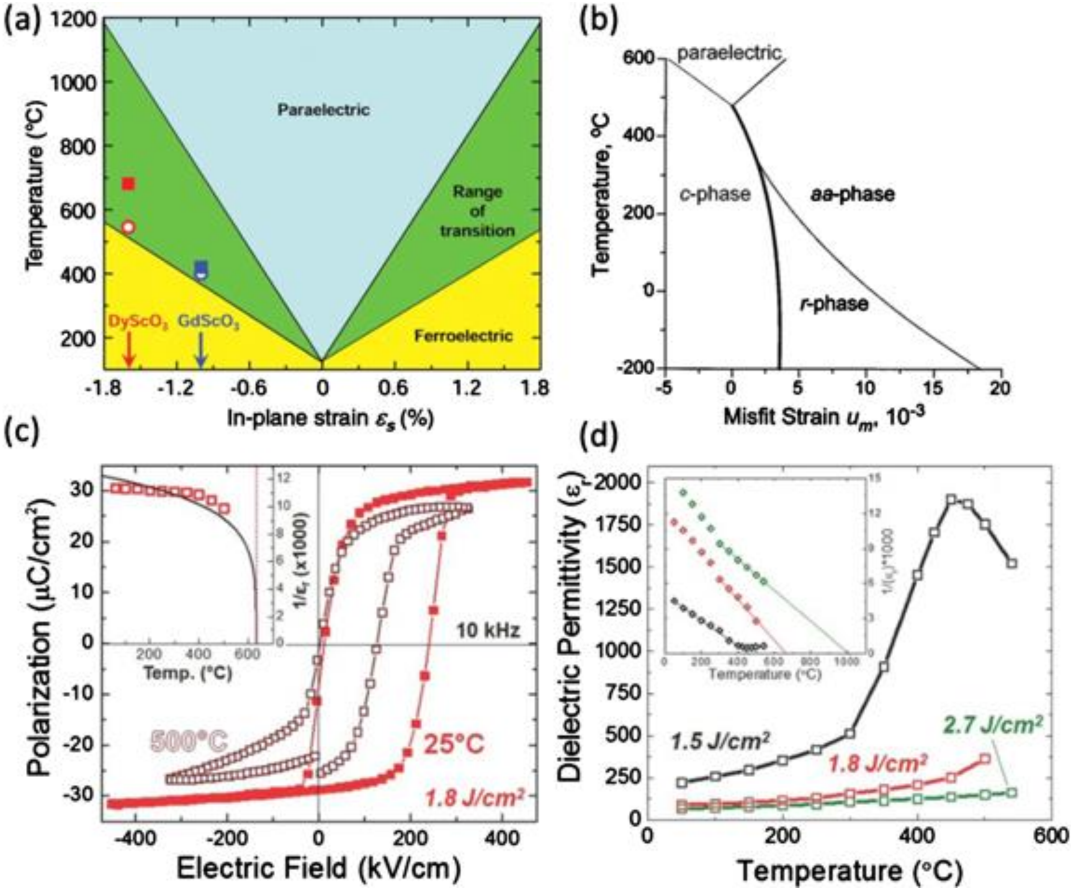
Phys. Rev. Lett. 95, 257601 (2005)



Phys. Rev. B 85, 035211 (2012)

Oxide electronics: Ferroelectrics (B-driven)

Boost of Transition temperature



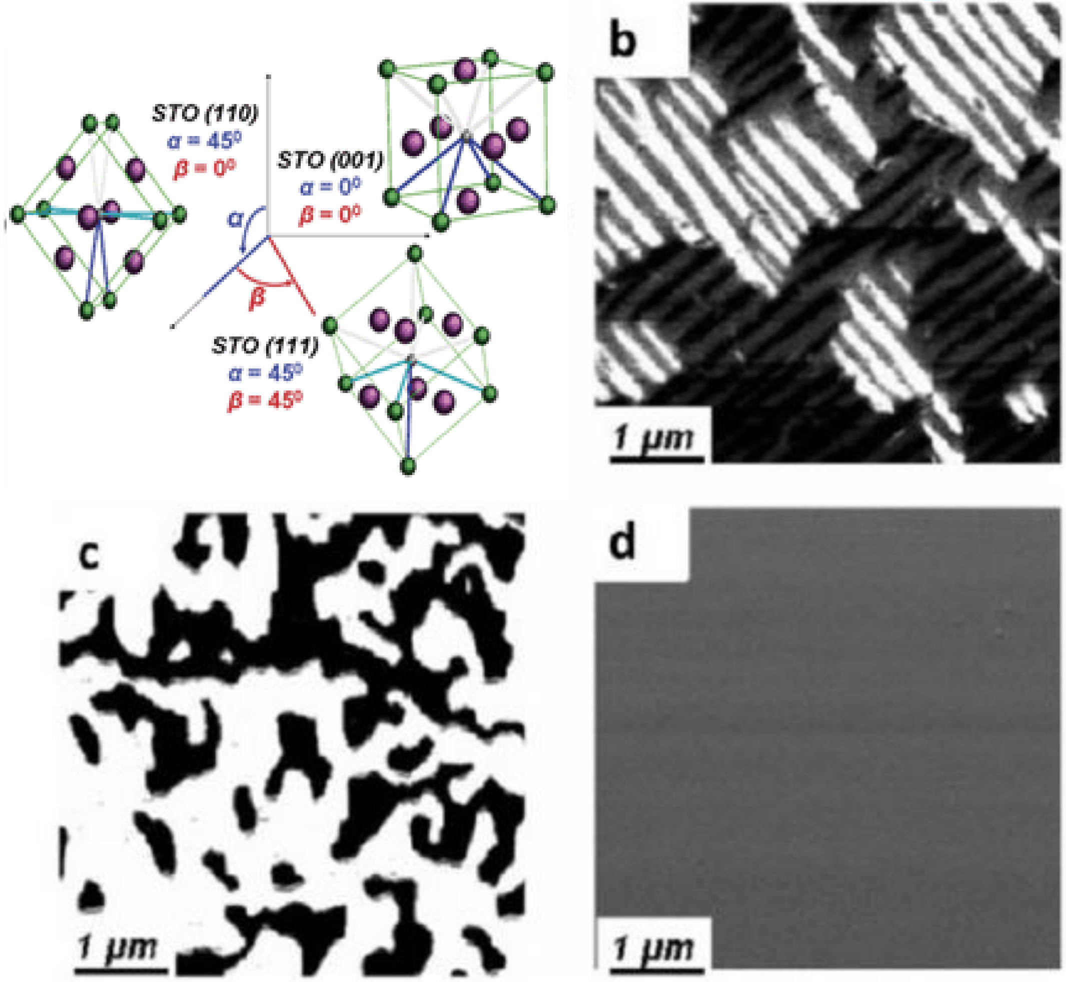
J. Phys.: Condens. Matter 33 293001 (2021)

Epitaxy

Oxide electronics: Ferroelectrics

Domain engineering, polarization orientation

Nano Lett, 8, 2, 405–410 (2008)
Nat. Commun. 5 4289 (2014)

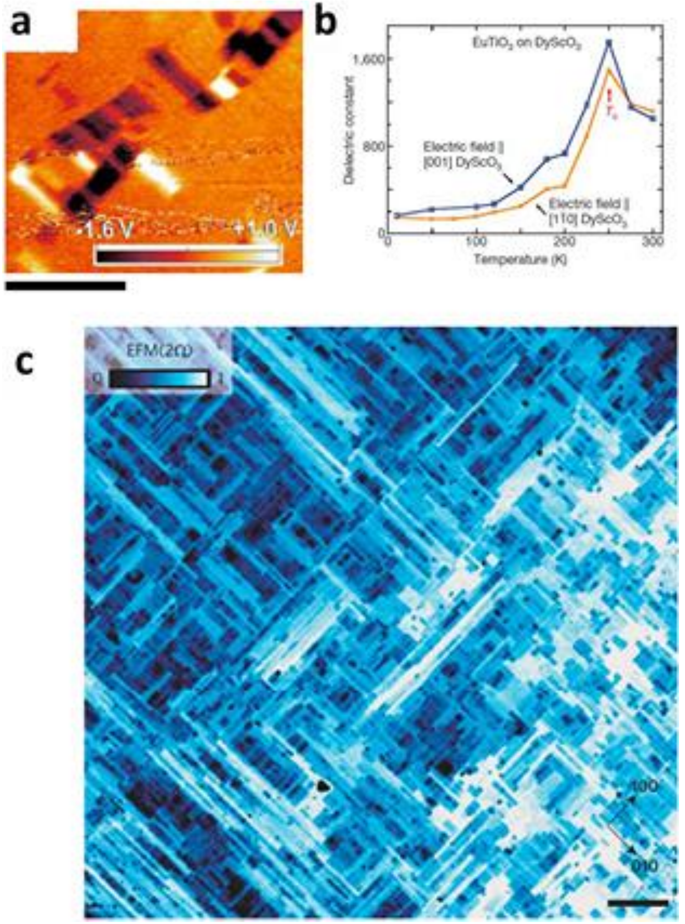


Adv. Mater. 19 2662 (2007)

Oxide electronics: Inducing a polarization

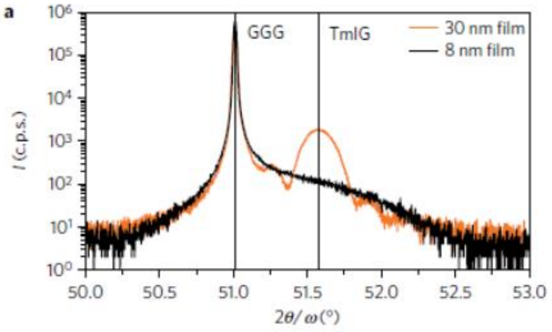
Designing new multiferroics

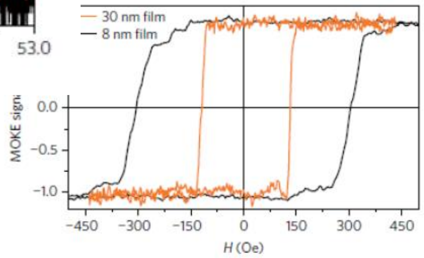
J. Phys.: Condens. Matter 28 033001 (2016)
Phys. Rev. Lett. 97 257602 (2006)
Nature 466 954 (2010)
Nat. Nanotechnology 10 661 (2015)



Oxide electronics: Ferromagnets

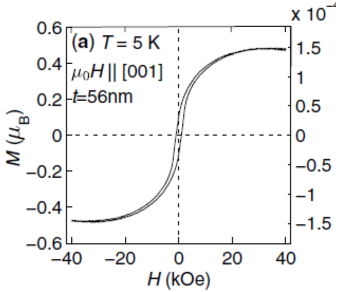
Magnetostriction in garnets for PMA





Nat. Mater.16, 309–314 (2017)
Nat. Commun.10, 4750 (2019

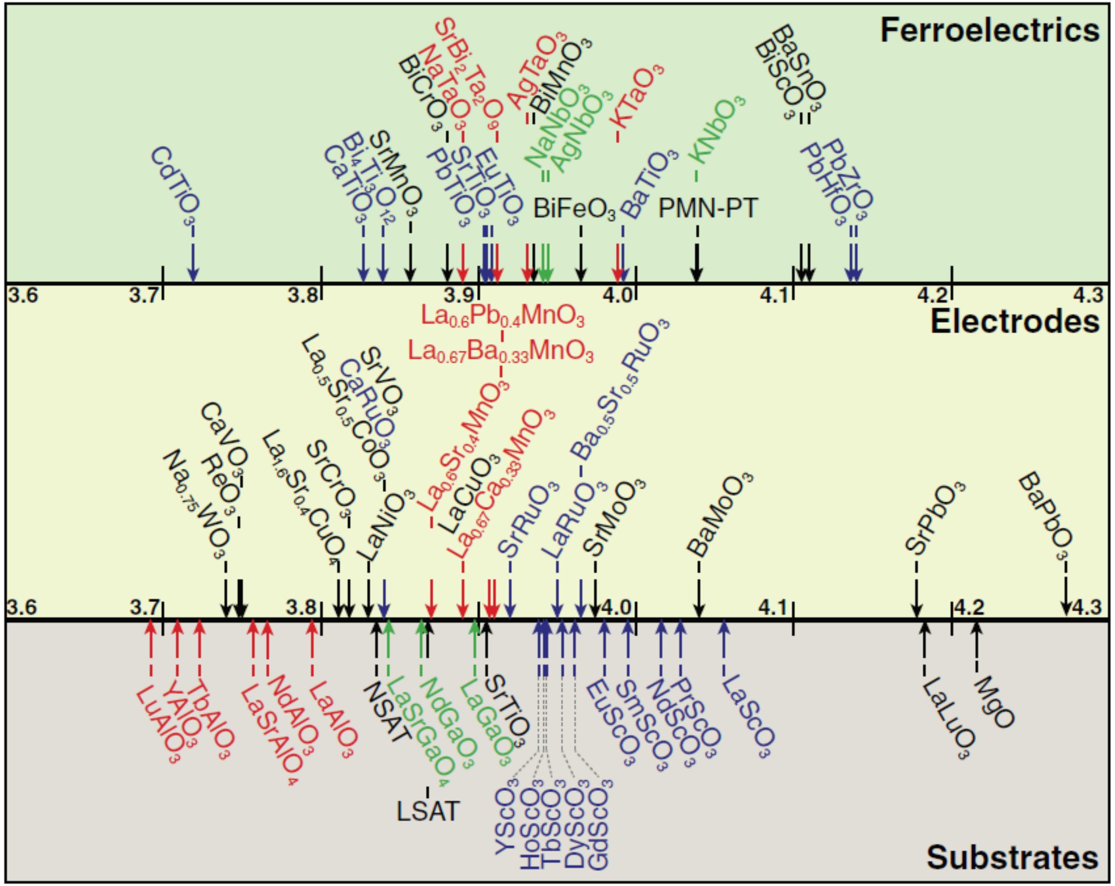
Strain induced ferromagnetism in antiferromagnet $LuMnO_3$



Phys Rev. Lett 111, 037201 (2013)

Epitaxy

Finding the right substrate



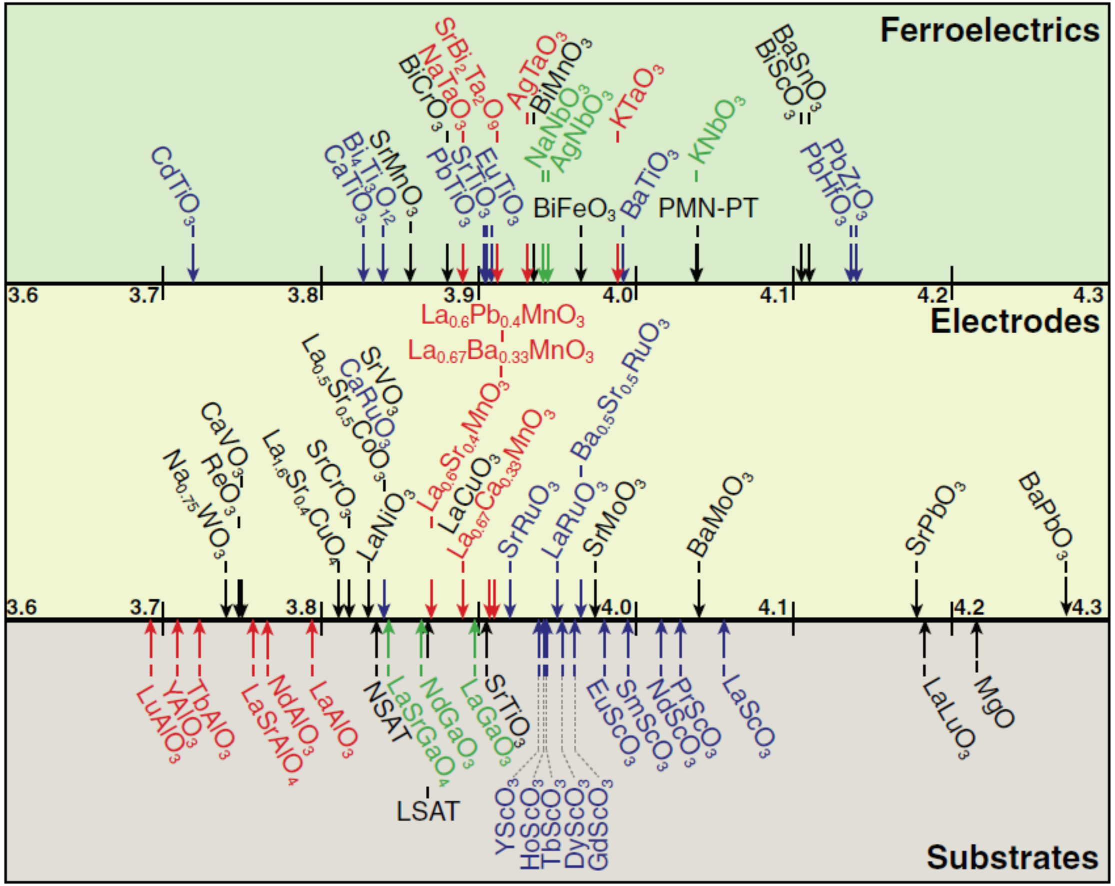
J. Phys.: Condens. Matter 28 263001 (2016)

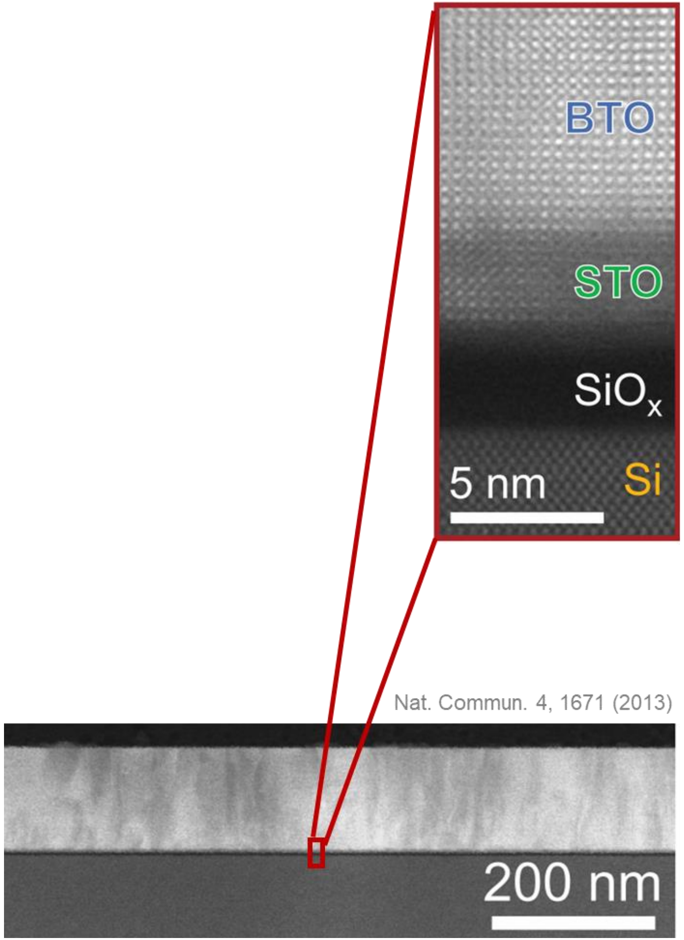
Pseudo cubic unit cells

Epitaxy

D MATL.

Finding the right substrate



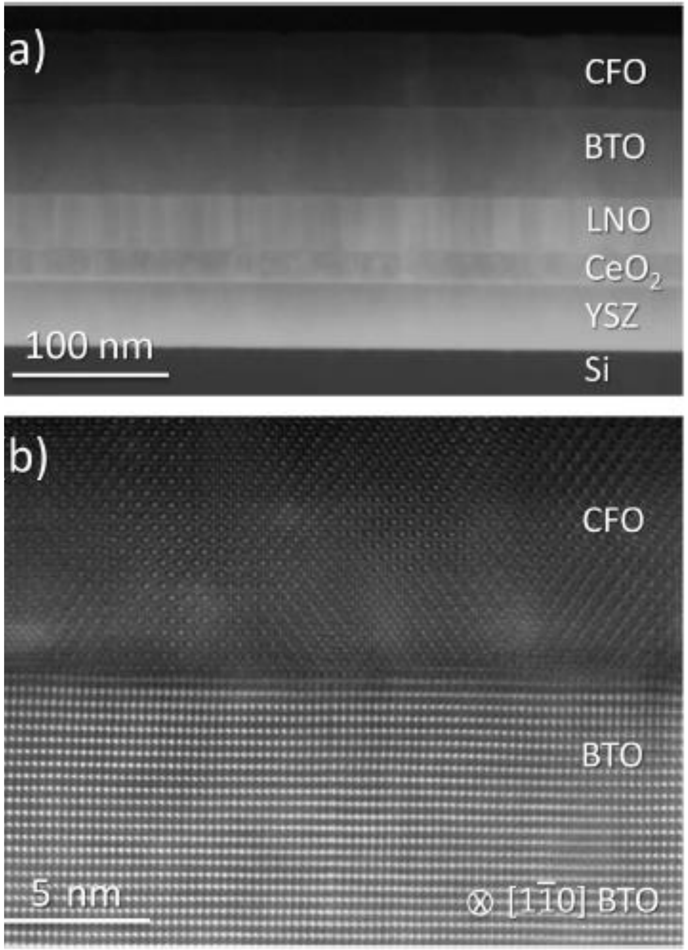


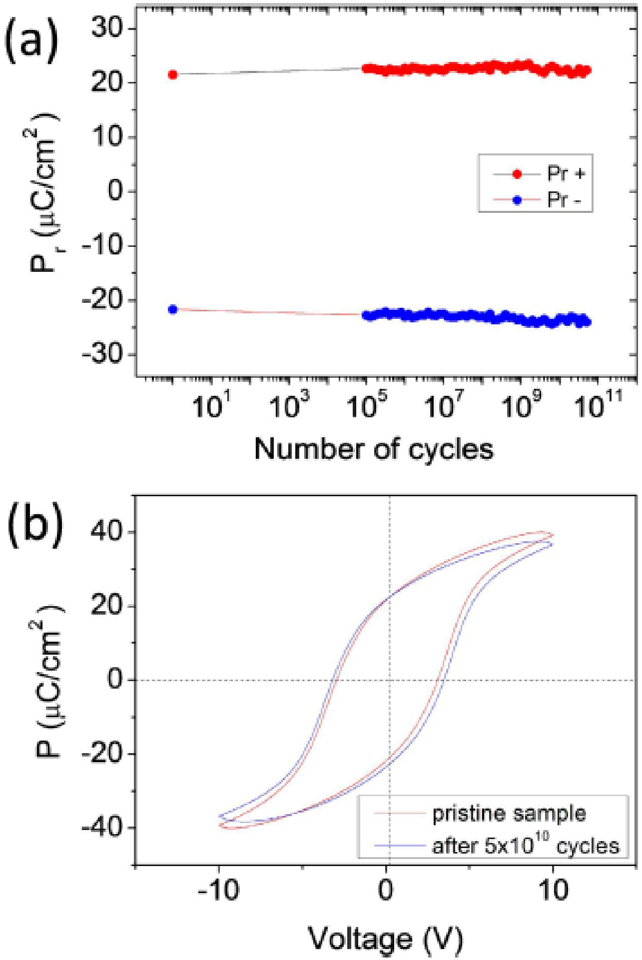
Nat. Commun. 4, 1671 (2013)

Epitaxy

D MATL.

Finding the right substrate and buffers…





Scientific Reports 6, 31870 (2016)

Epitaxy

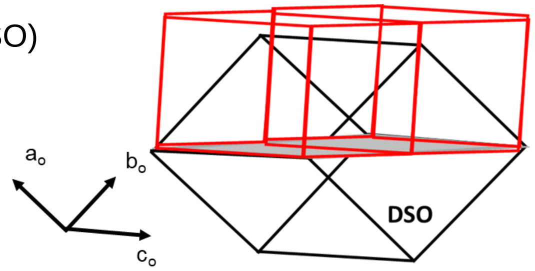
D MATL

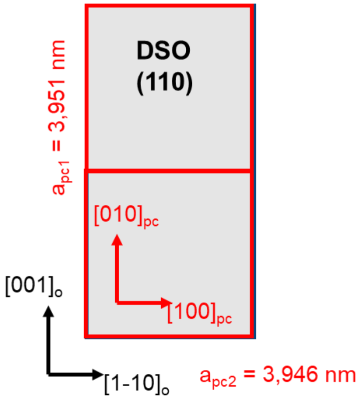
Oxide electronics: Ferroelectrics
Domain engineering with anisotropic in-plane strain

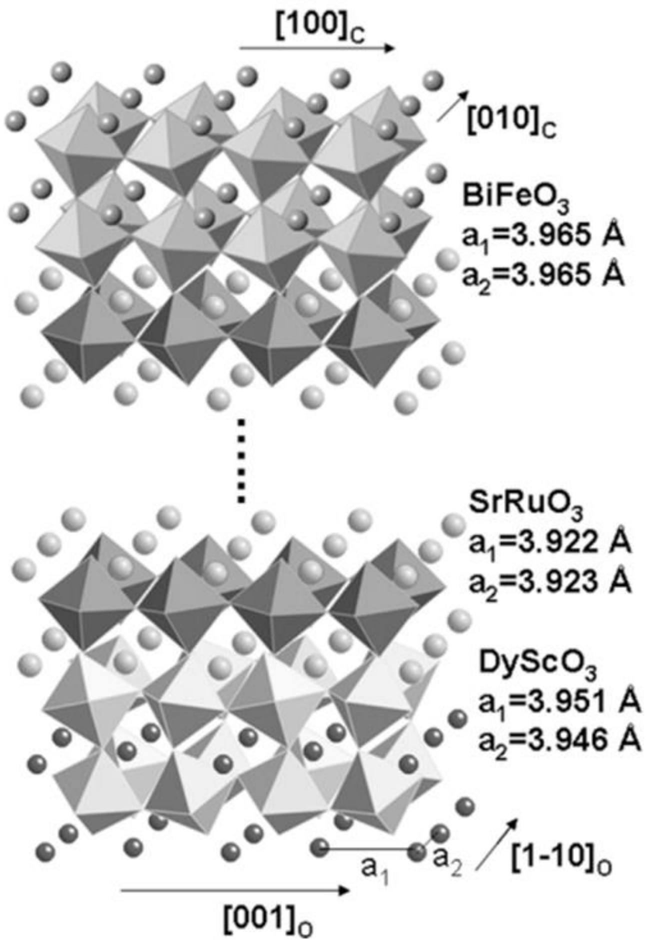
The scandates

The case of $DyScO_3$ (DSO)
Orthorhombic

a_o = 0,544 nm
b_o = 0,571 nm
c_o = 0,789 nm







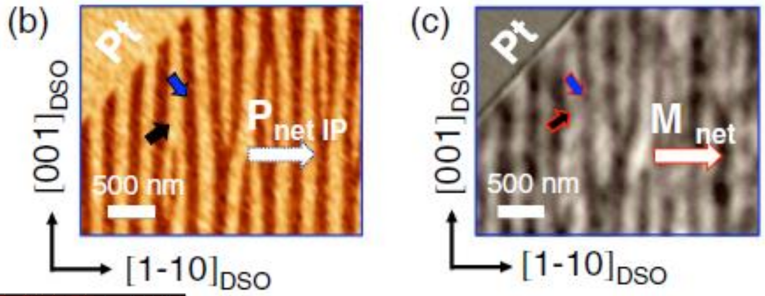
Adv. Mater. 2006, 18, 2307–2311

Epitaxy

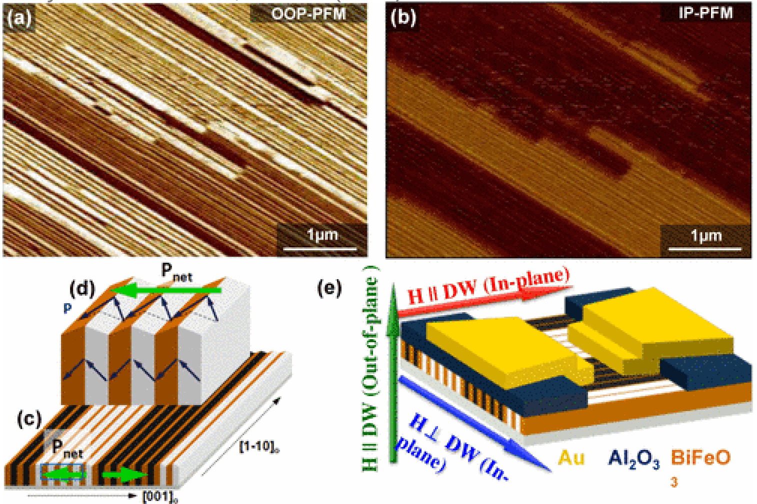
Oxide electronics: Ferroelectrics

Domain engineering with anisotropic in-plane strain

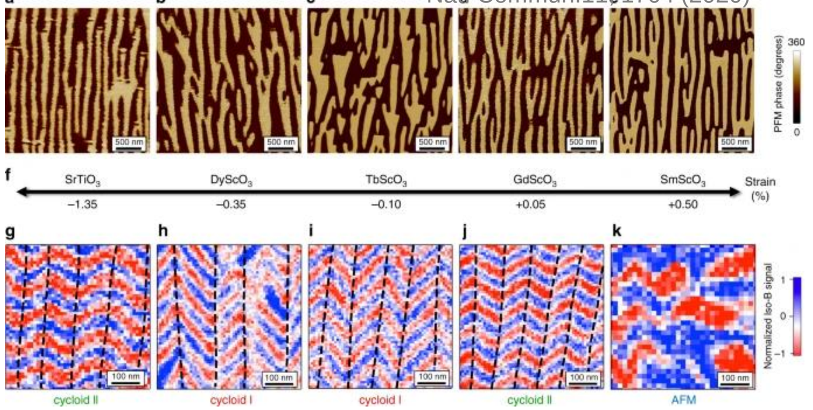
Phys. Rev. Lett. 107, 217202 (2011)



Phys. Rev. Lett. 108, 067203 (2012)



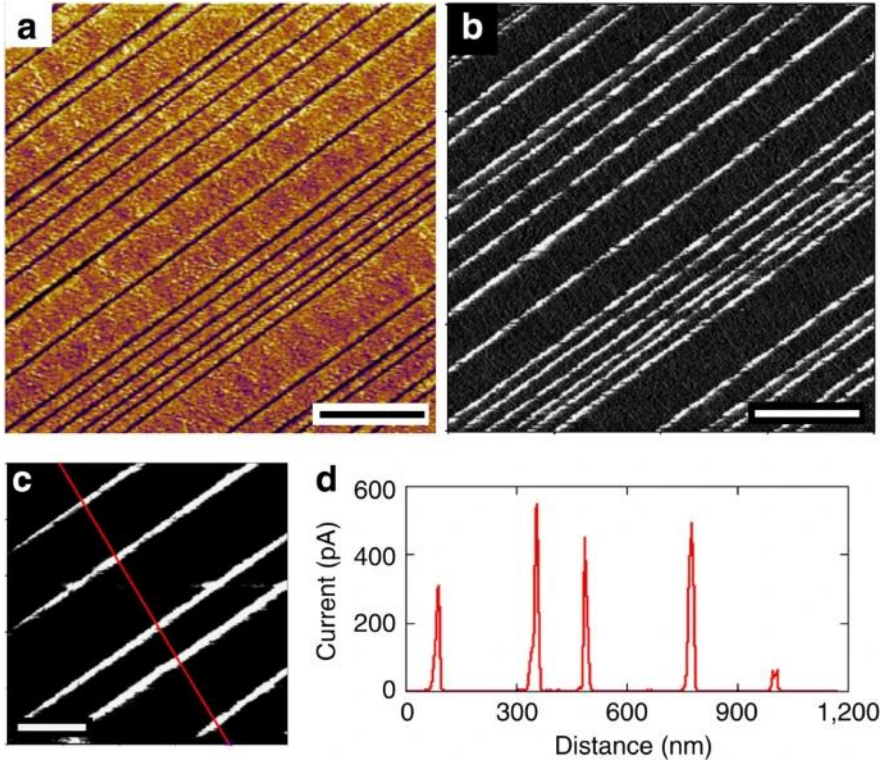
Nat. Commun.11, 1704 (2020)

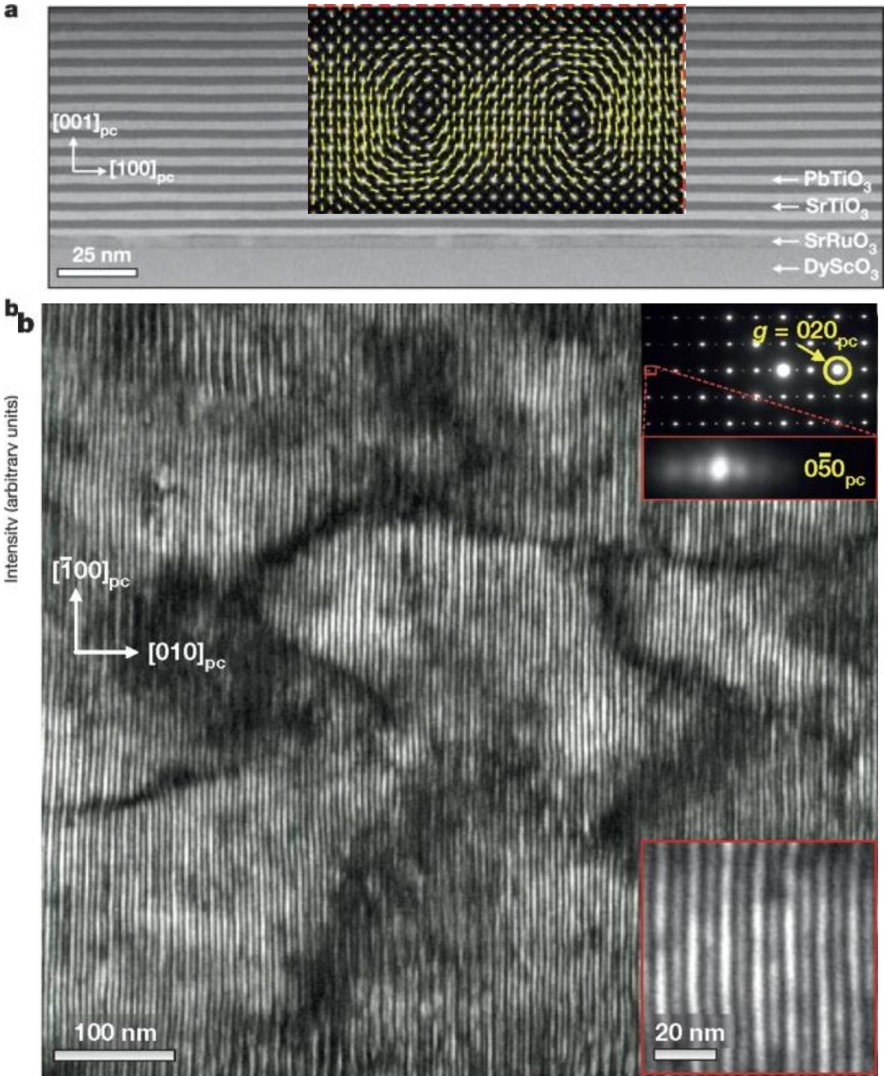


Epitaxy

Oxide electronics: Ferroelectrics

Domain engineering with anisotropic in-plane strain





Nature Communications 5, 4677 (2014)
Nature 530, 198–201 (2016)

Thin films epitaxy

- Brief definitions
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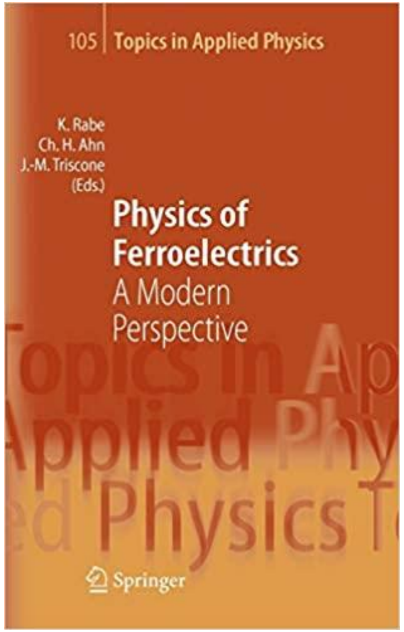
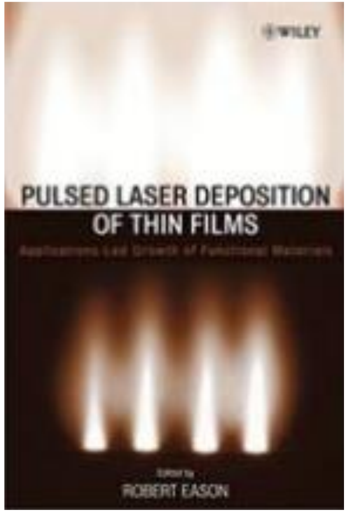
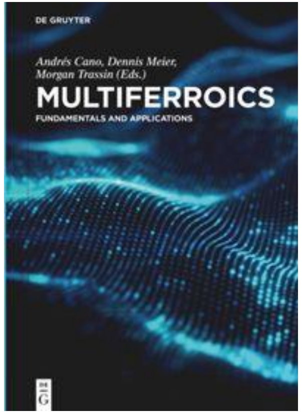
- Materials, substrates

Growth process
- Growth modes and growth mechanisms
- In situ monitoring of 2D growth
- Growth techniques
- Structural characterization

The case of ferroelectrics
- In-situ diagnostic tools
- Monitoring of ferroelectricity during the epitaxial growth interface contributions



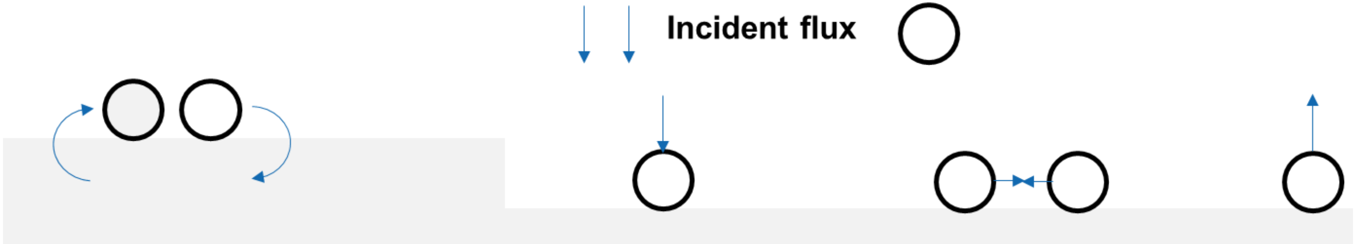




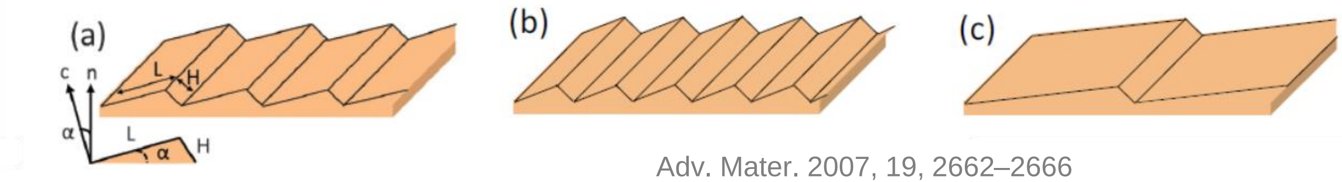
Growth processes and growth modes

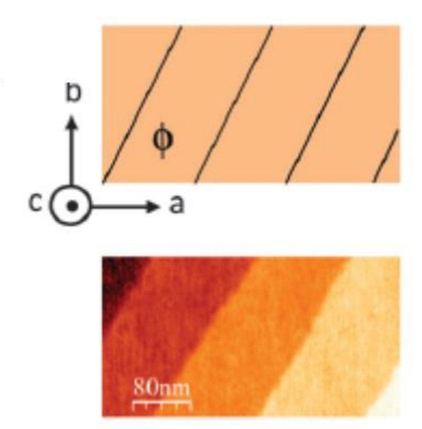
What do we need to get controlled two dimensional epitaxial growth

During deposition

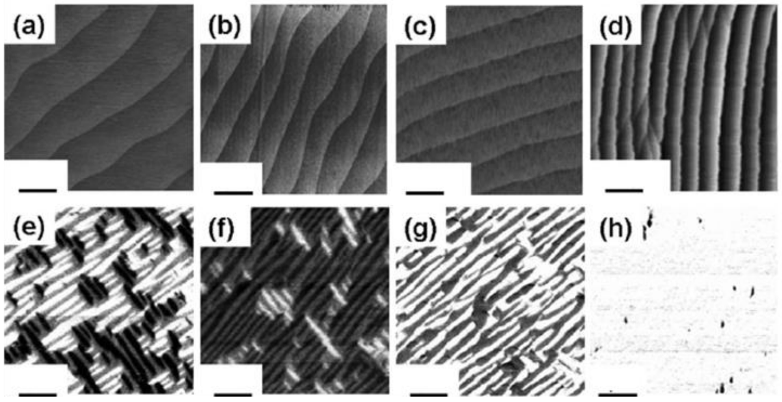


Rep. Prog. Phys., Vol 47, pp 399-459, 1984.





Adv. Mater. 2007, 19, 2662–2666



Growth processes and growth modes

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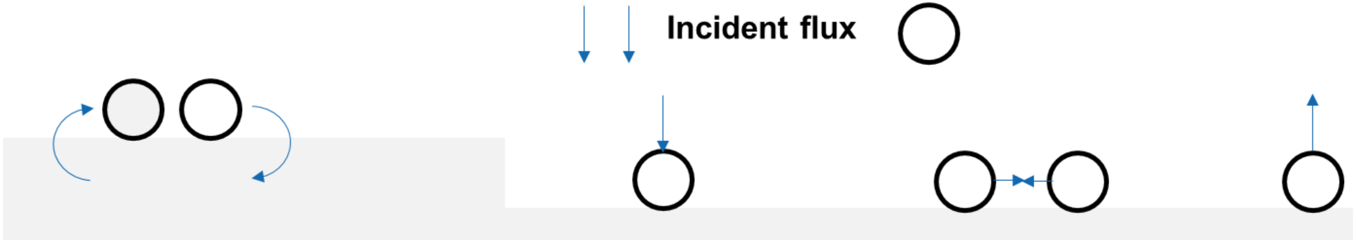
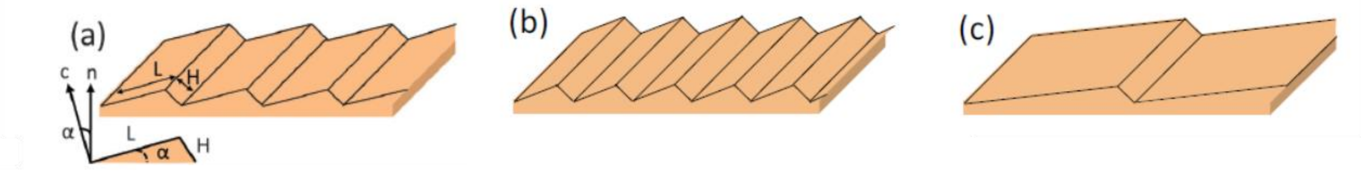
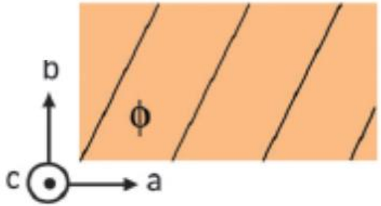
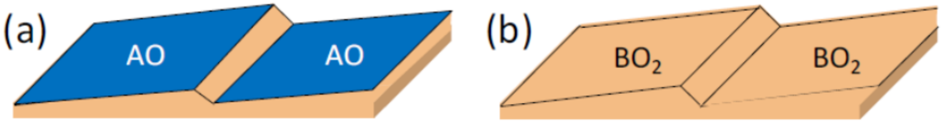


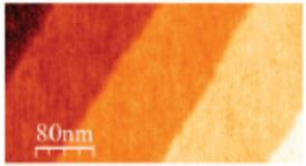
Rep. Prog. Phys., Vol 47, pp 399-459, 1984.







Chem. Soc. Rev., 2014, 43, 2272



SrO terminated $SrTiO_3$: 1300C in air

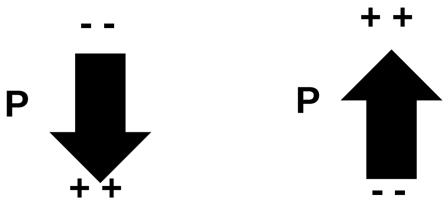
TiO_2 terminated $SrTiO_3$: water + etching solution + 950 C

Growth processes and growth modes

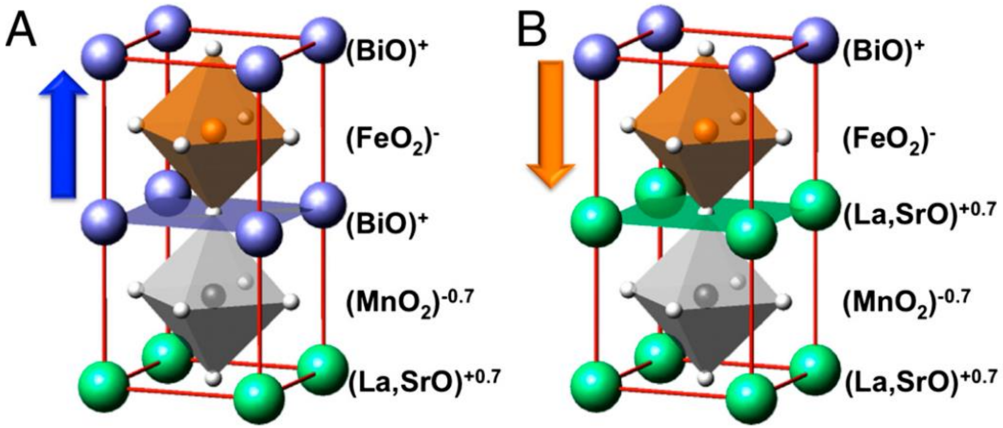
D MATL.

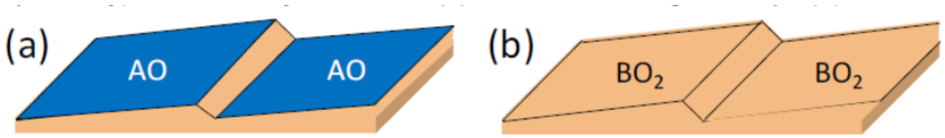
What do we need to get controlled two dimensional epitaxial growth

Screening charges at the surfaces
set the final direction of the polarization



Control from the **bottom** interface





Chem. Soc. Rev., 2014, 43, 2272

SrO terminated $SrTiO_3$: 1300C in air
TiO_2 terminated $SrTiO_3$: water + etching solution + 950 C

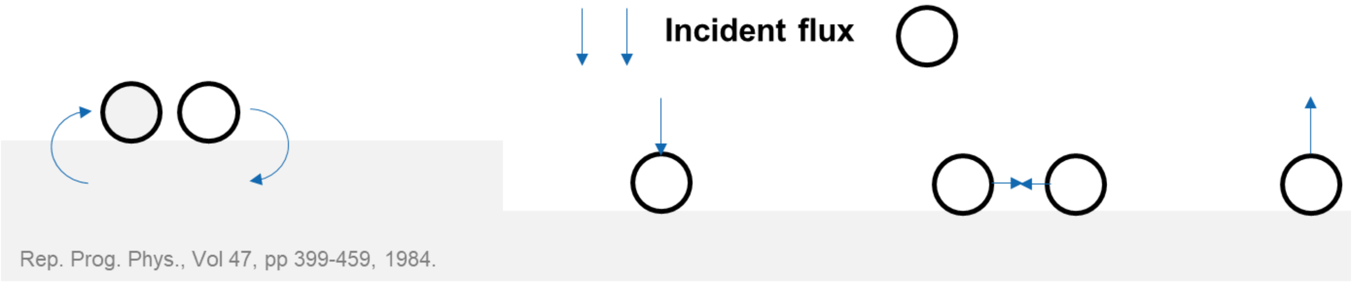
PNAS 109 9710 (2012)
Nat. Commun 8, 1419 (2017)
Nat. Commun. 11, 5815 (2020)
PNAS. 117, 28589 (2020)

ETH zürich

Growth processes and growth modes

What do we need to get controlled two dimensional epitaxial growth

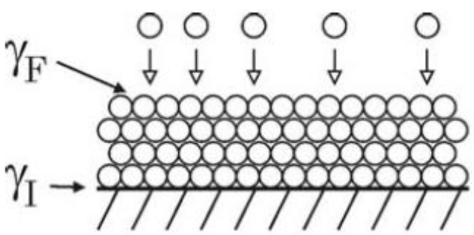
During deposition



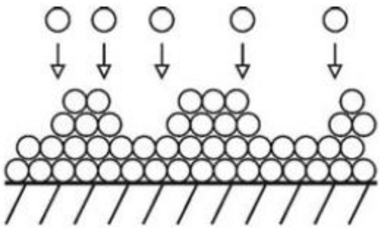
Thermodynamic approach: surface free energies of the films, substrates and interfaces determine the morphology of the film

$$\Delta\gamma = \gamma_{film} + \gamma_{interface} - \gamma_{substrate}$$

$\Delta\gamma < 0$

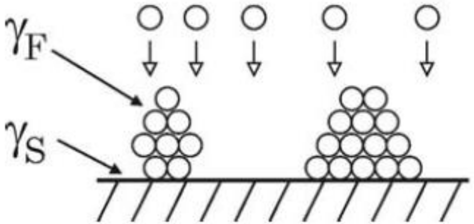


Van der Merve
Layer by layer



Stranski Krastanov
(SK)

$\Delta\gamma > 0$



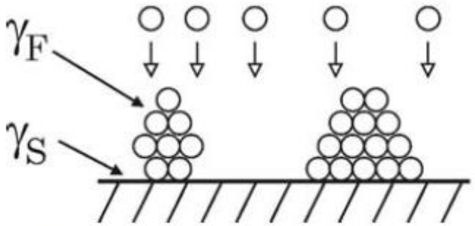
Volmer Weber
(3D)

Growth processes and growth modes

What do we need to get controlled two dimensional epitaxial growth

Volmer Weber (3D) $\Delta\gamma > 0$

Pt on Y doped Zirconia



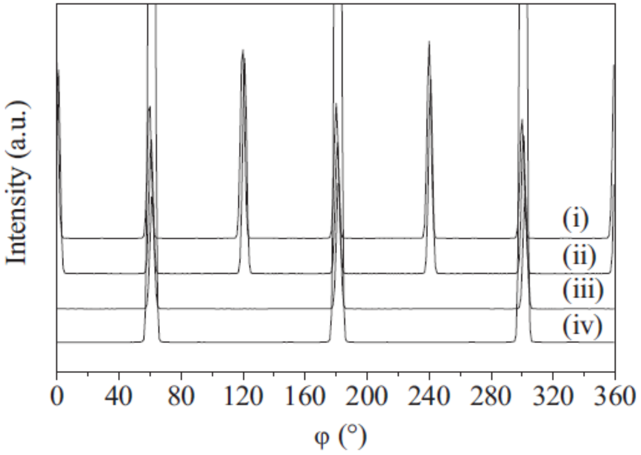
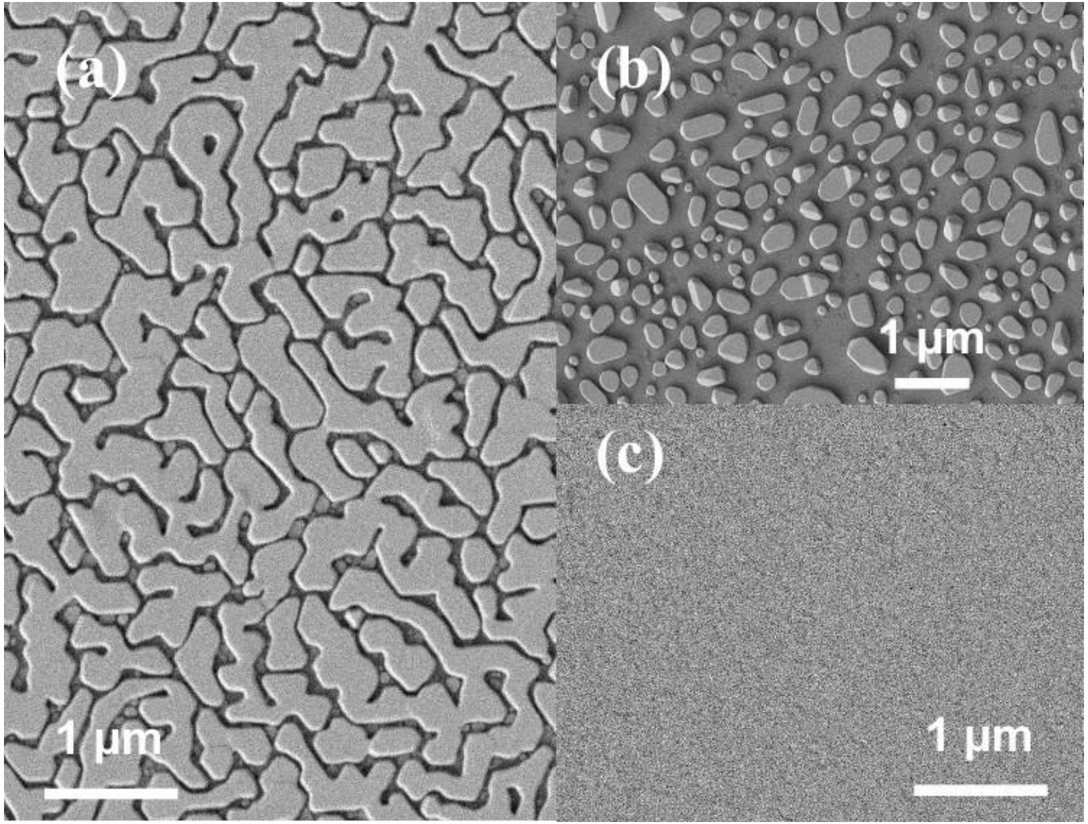


FIG. 3. φ-scans of the Pt {311} planes for the following three types of Pt films: (i) deposited directly on YSZ (111), (ii) with a further annealing at 800 °C for 48 h, and (iii) deposited using Ti adhesion layer. φ-scans of the substrate peak YSZ {422} are given in (iv).



J. Appl. Phys. 105, 106101 (2009)

Growth processes and growth modes

What do we need to get controlled two dimensional epitaxial growth

2D growth modes

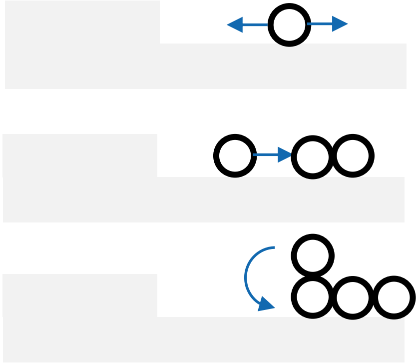
$\Delta\gamma < 0$ (during growth homoepitaxy)

The 2D growth behavior is determined by kinetic parameters

- the surface diffusion coefficient Ds of the ad-atoms

- the sticking coefficient of an atom at the edge of a terrace

- the energy barrier to descend the edge to a lower terrace
(Ehrlich–Schwoebel barrier Journal of Applied Physics 37, 3682–3686 (1966))



Ds determines the average distance an atom travels before being trapped

$$l_D = \sqrt{\tau . D_s}$$

and

$$D_s = \upsilon . a^2 e^{-Ea/K_B T}$$

τ residence time before evaporation,
υ attempt frequency,
a characteristic jump distance,
E_a activation energy for diffusion

Temperature controls the diffusivity

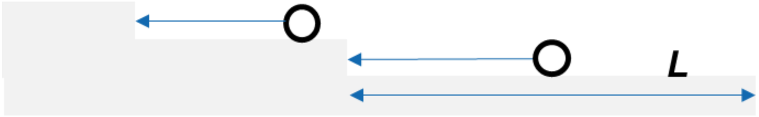
Growth processes and growth modes

What do we need to get controlled two dimensional epitaxial growth

2D growth modes

$\Delta\gamma < 0$ (during growth homoepitaxy)

Step flow growth



If the diffusion of the ad-atoms is too high, l_D >> average terrace width L

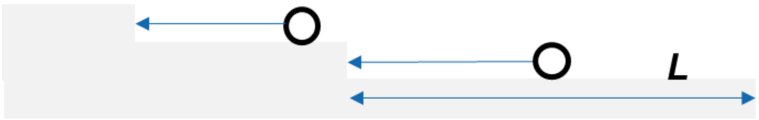
Growth processes and growth modes

What do we need to get controlled two dimensional epitaxial growth

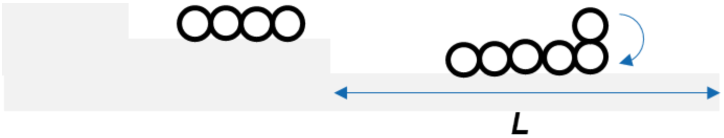
2D growth modes

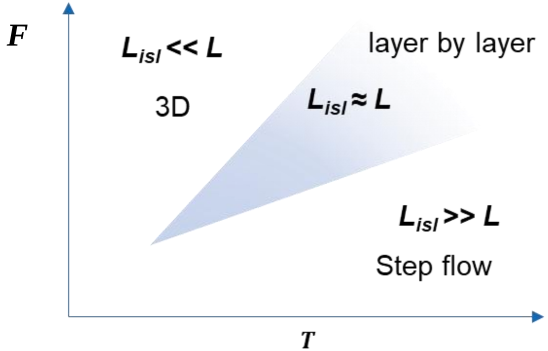
$\Delta\gamma < 0$ (during growth homoepitaxy)

Step flow growth



Lower diffusion of ad-atoms, the probability for atoms to bond to an existing island exceeds the probability to form a new one (high impact of the diffusion to a lower terrace).
Ideal case, layer by layer : Atoms first have to reach the island edge and diffuse to a lower terrace





Mean distance between islands $$L_{isl} \sim \left(\frac{D_s}{F}\right)^p$$

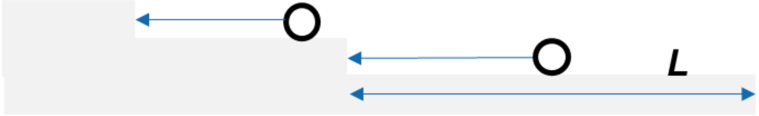
p < 1
p exponent linked to the number of atoms to form a stable island, F incident flux

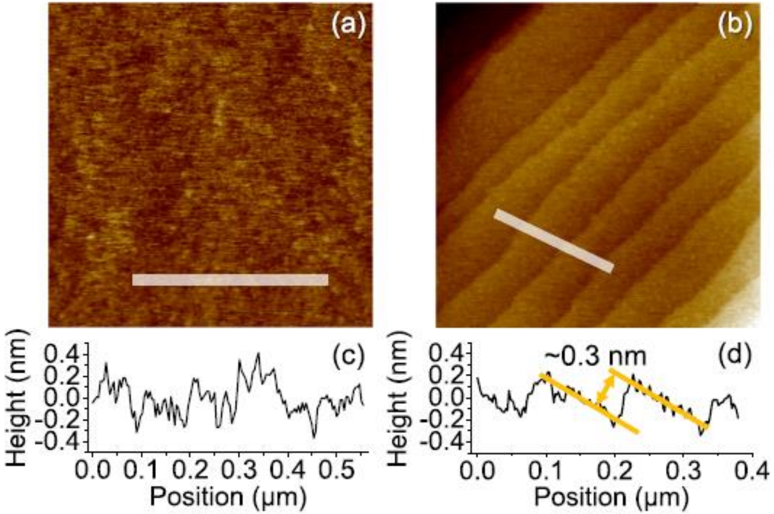
Growth processes and growth modes
What do we need to get controlled two dimensional epitaxial growth

2D growth modes

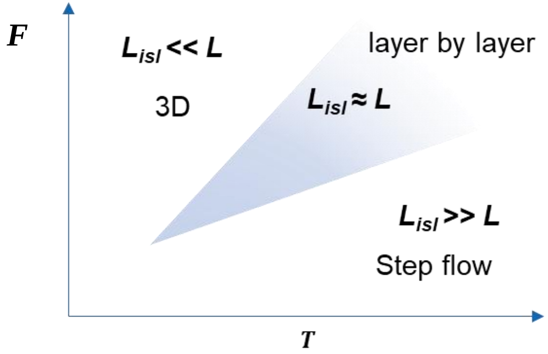
$\Delta\gamma < 0$ (during growth homoepitaxy)

Step flow growth





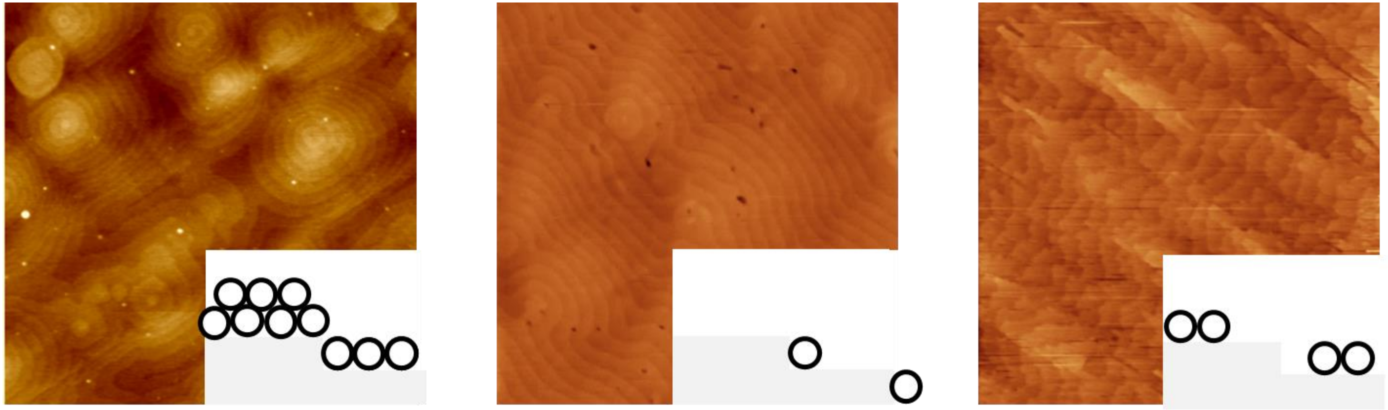
Phys. Rev Mater. 4, 124403 (2020)



Growth processes and growth modes

What do we need to get controlled two dimensional epitaxial growth

2D and 3D growth modes

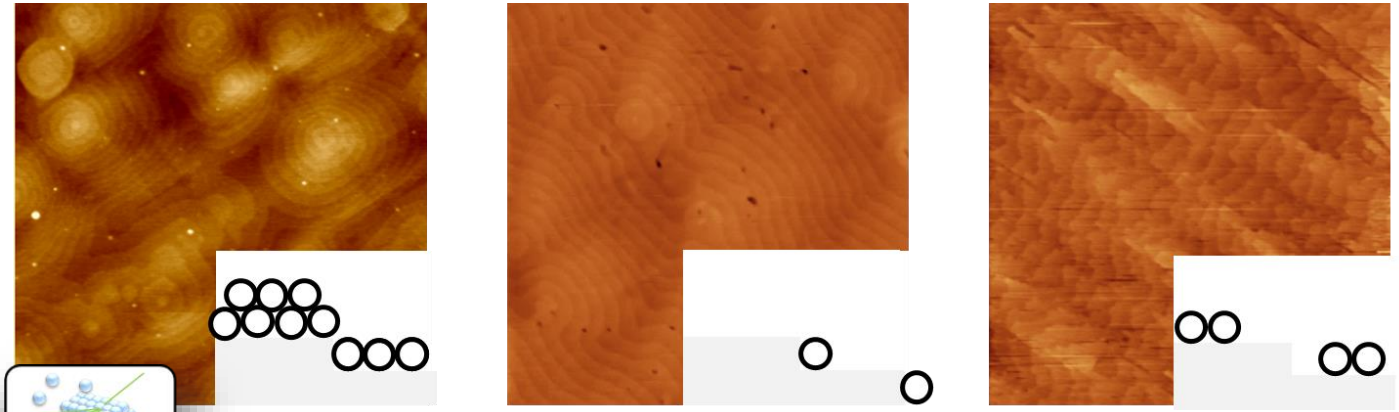


Why do we need layer by layer?

Growth processes and growth modes

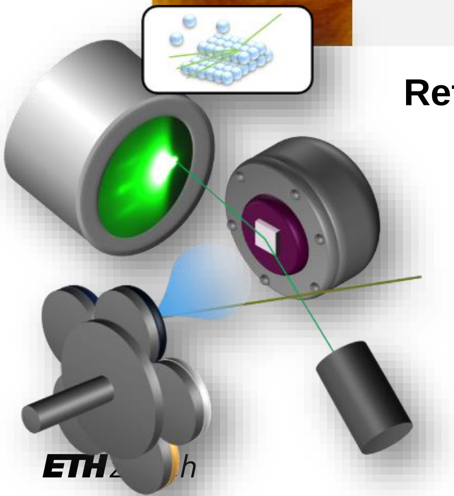
What do we need to get controlled two dimensional epitaxial growth

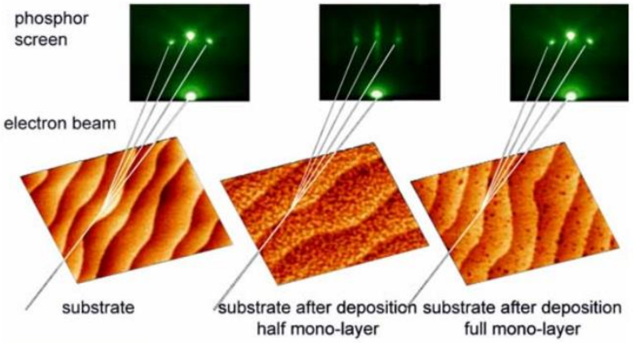
2D and 3D growth modes



Reflection High Energy Electron Diffraction (RHEED)

In-situ monitoring of surface structure and roughness





Growth processes and growth modes

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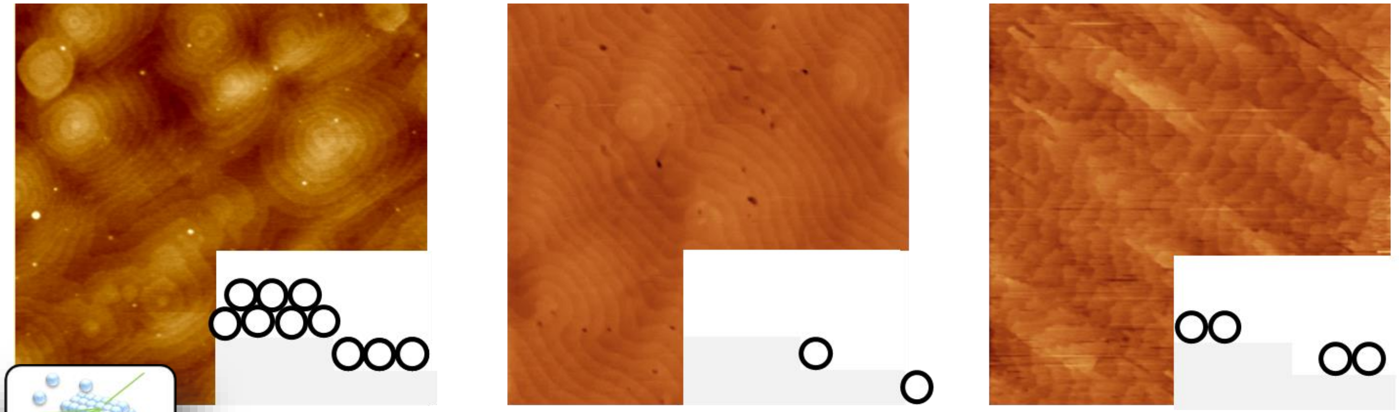
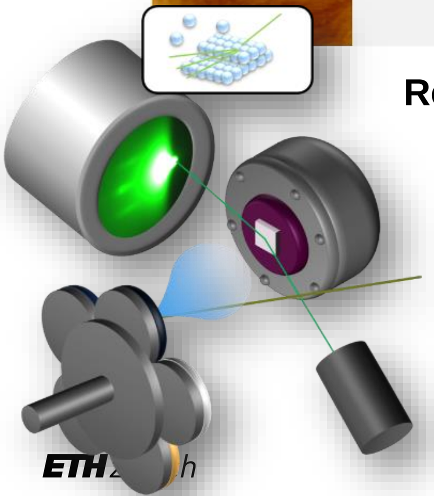
2D and 3D growth modes





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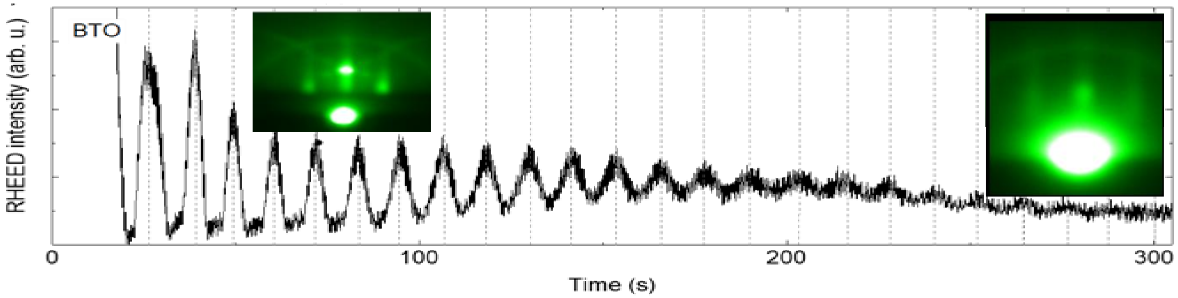
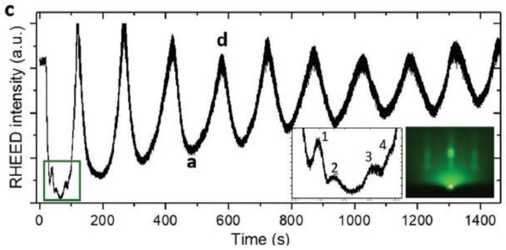
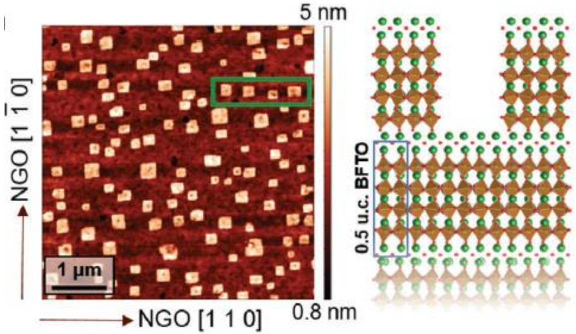


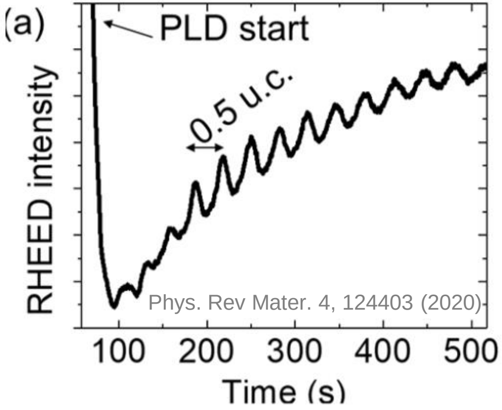
Growth processes and growth modes

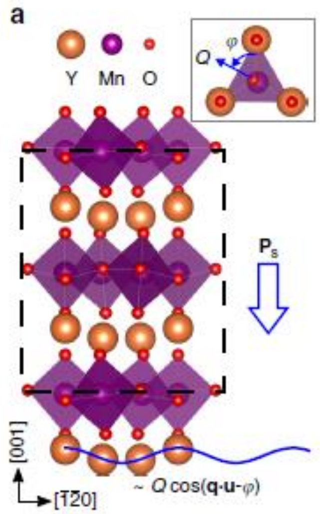
Unit cell and sub-unit cell thickness accuracy using RHEED

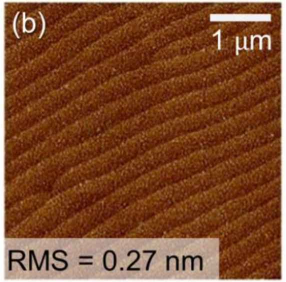


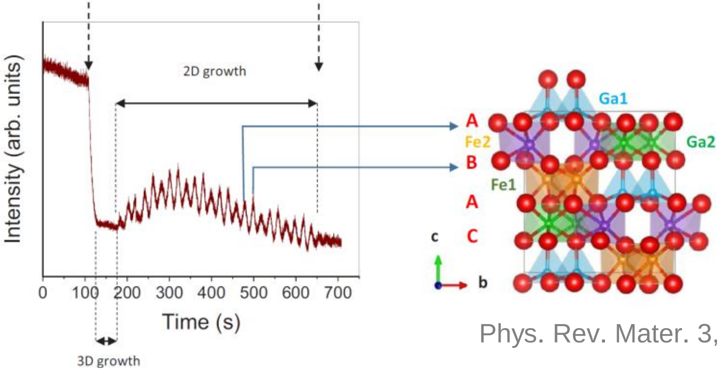


Adv. Mater Inter. 2000202 (2020)
ACS Appl. Electron. Mater. 1, 1019 (2019)







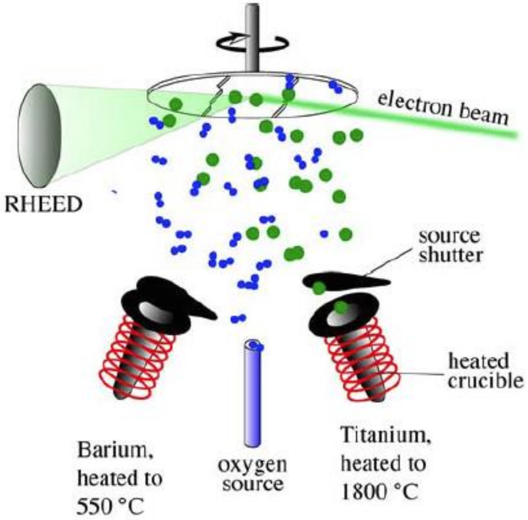


Phys. Rev. Mater. 3, 124416 (2020)

Growth techniques

We need an incident flux,
high temperature

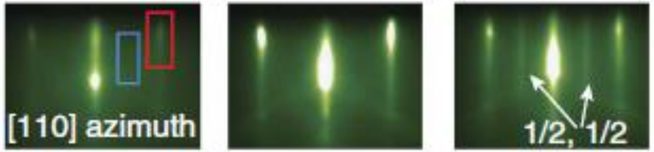
Oxide molecular beam epitaxy (OMBE)

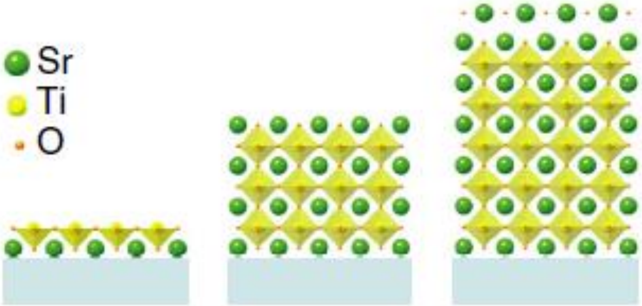


K. Rabe, C. H. Ahn, J.-M. Triscone (Eds.): Physics of Ferroelectrics: A Modern Perspective,
Topics Appl. Physics **105**, 219–304 (2007)

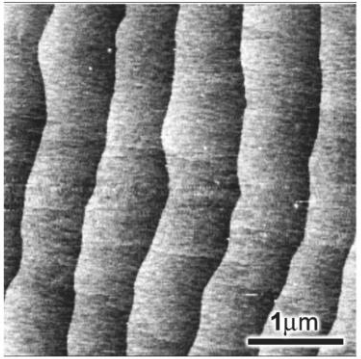
Atomically precise interfaces from non-stoichiometric deposition

Y.F. Nie[1,2,*], Y. Zhu[3,*], C.-H. Lee[1], L.F. Kourkoutis[3,4], J.A. Mundy[3], J. Junquera[5], Ph. Ghosez[6], D.J. Baek[7], S. Sung[3], X.X. Xi[8], K.M. Shen[2,4], D.A. Muller[3,4] & D.G. Schlom[1,4]





Nat. Commun 5, 4530 (2014)
J. Mater. Res. 23, 1417 (2008)



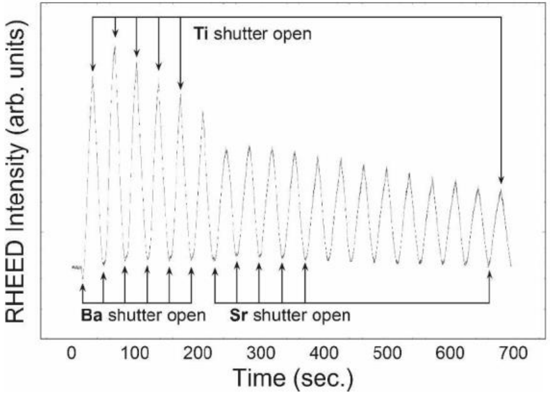
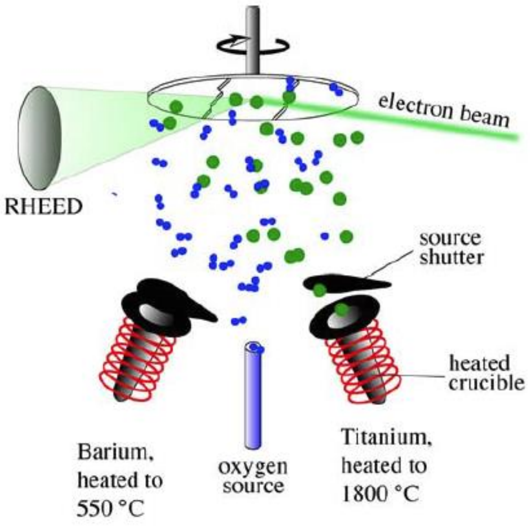


FIG. 6. Shuttered RHEED intensity oscillation observed from the beginning of the growth of a $[(BaTiO_3)_6/(SrTiO_3)_{13}]_{15}$ superlattice (sample no. 12) on a TiO_2-terminated (001) $SrTiO_3$ substrate. The intensity of the 01 RHEED streak along the [110] azimuth of the first superlattice period is shown.

Growth techniques

We need an incident flux,
high temperature

Oxide molecular beam epitaxy (OMBE)



K. Rabe, C. H. Ahn, J.-M. Triscone (Eds.): Physics of Ferroelectrics: A Modern Perspective, Topics Appl. Physics **105**, 219–304 (2007)
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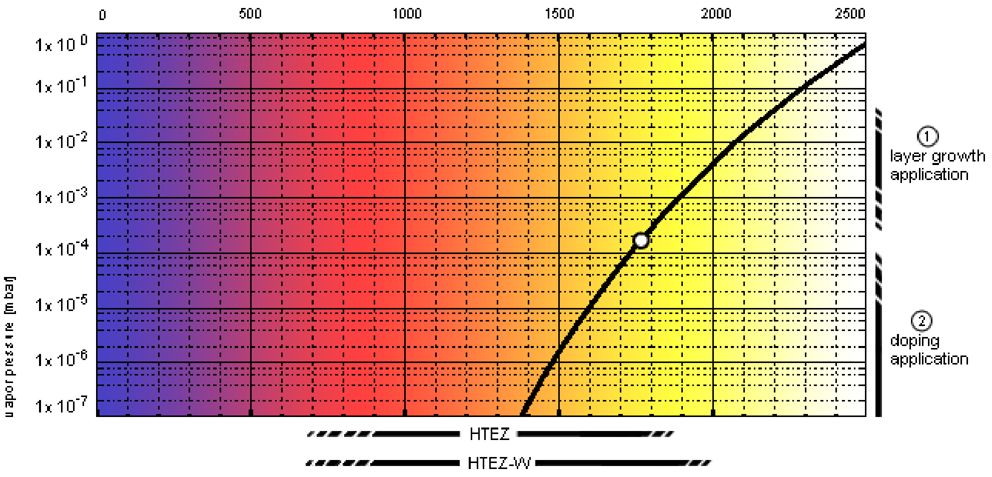

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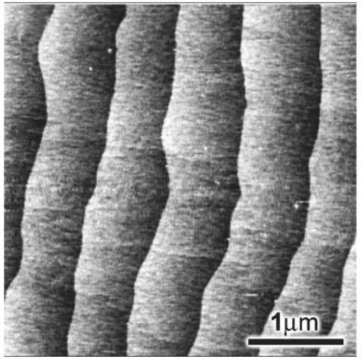

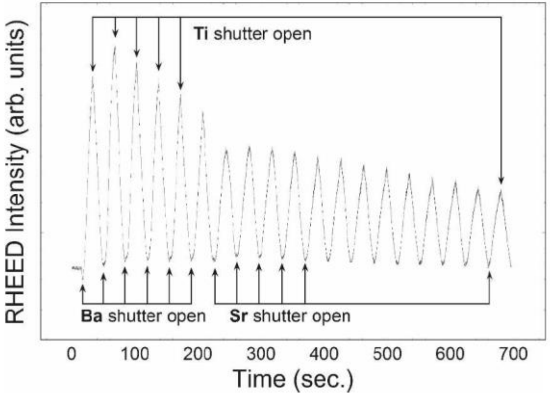

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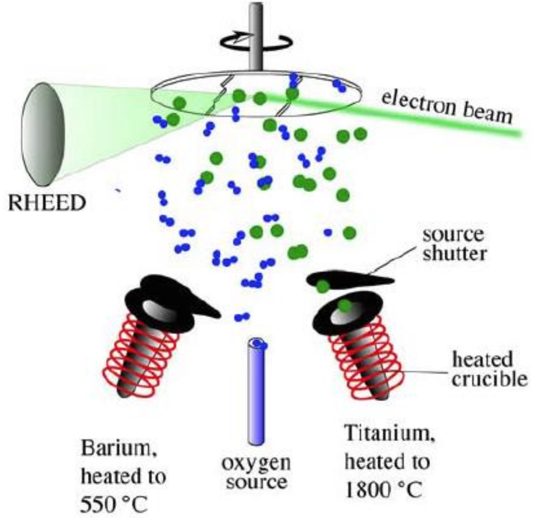
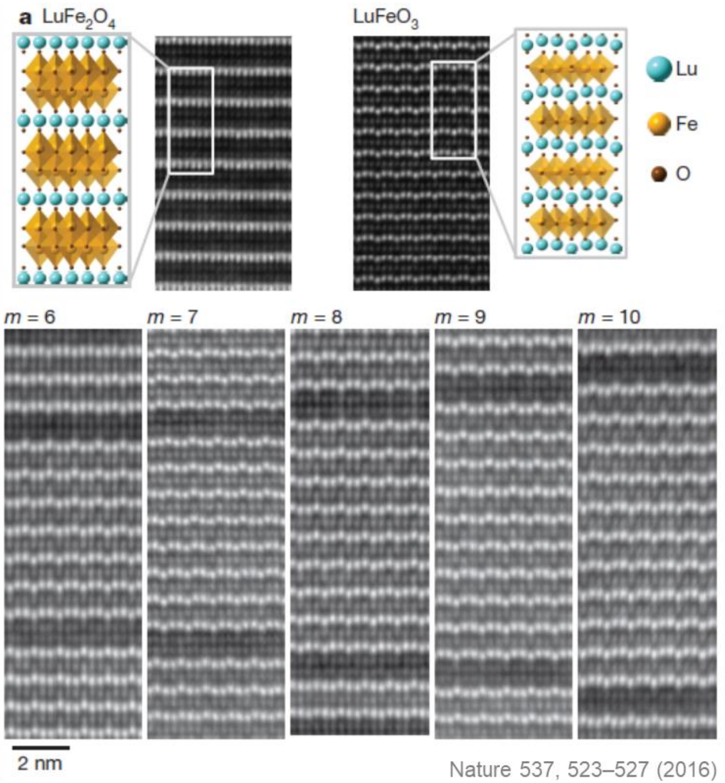
Growth techniques

We need an incident flux,
high temperature

Oxide molecular beam epitaxy (OMBE)





Nature 537, 523–527 (2016)

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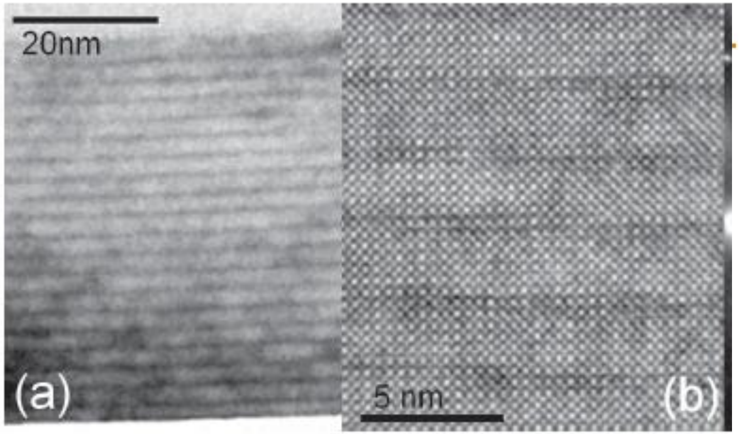
- **+ Fine control on the atomic plane level**
- **+ Large surface**
- **- Calibration (precise timing of shutters)**
- **- High temperatures get high flux, slow deposition**

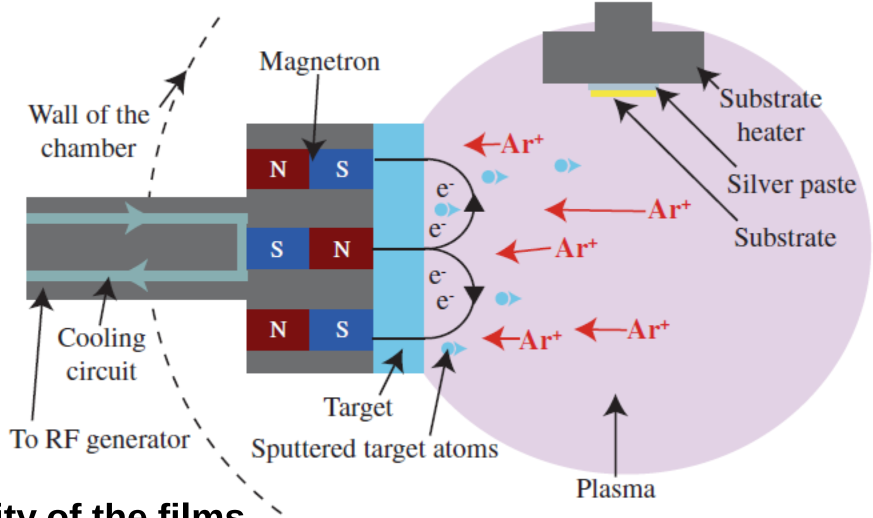
Growth techniques

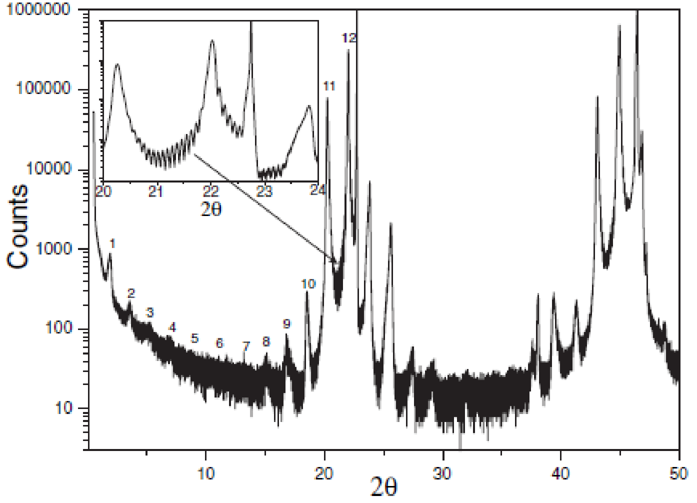
We need an incident flux,
high temperature



Phys. Rev. Lett. 95, 177601 (2005)

Radio Frequency Magnetron Sputtering





+ High quality of the films
+ Large surface
- Low deposition rate
- In-situ monitoring challenging

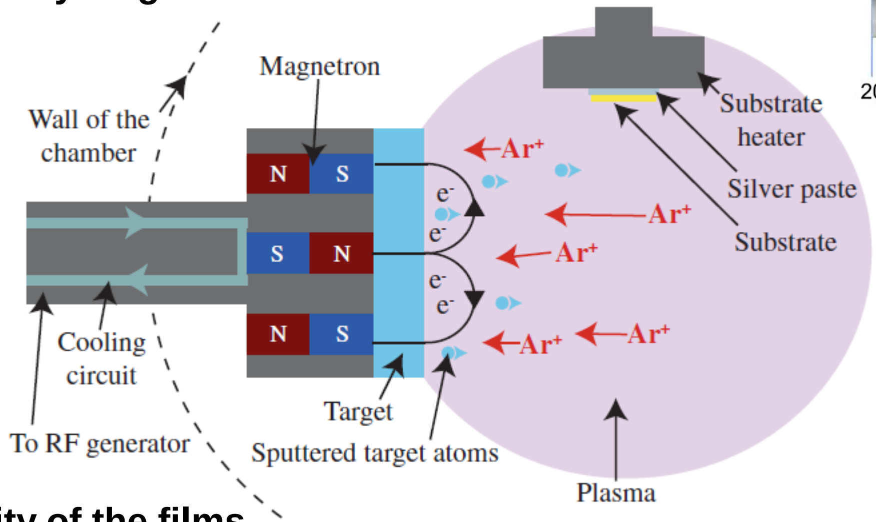
https://doi.org/10.1007/978-3-030-15238-3
Fowlie PhD thesis

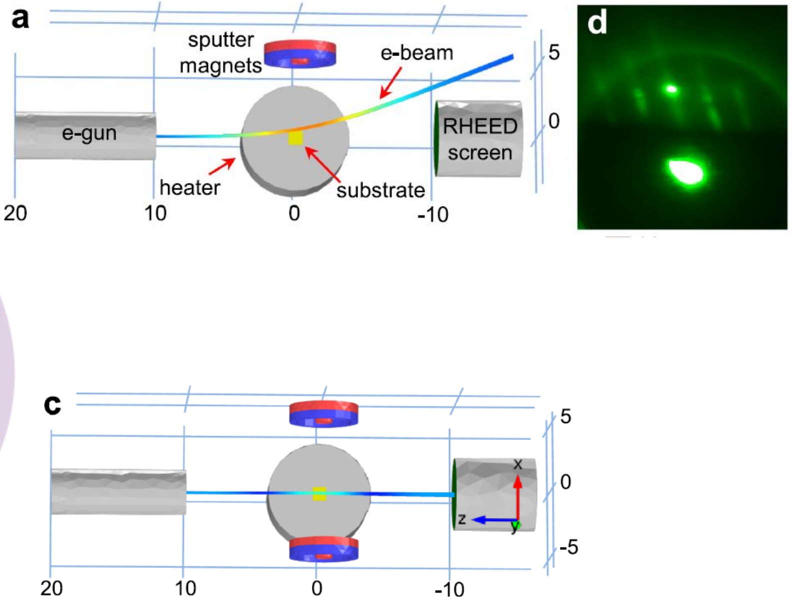
Growth techniques

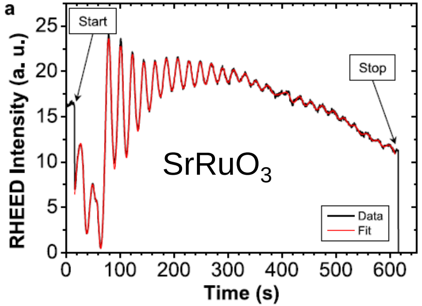
We need an incident flux,
high temperature

APL Mater 4, 086111 (2016)

Radio Frequency Magnetron Sputtering







+ High quality of the films
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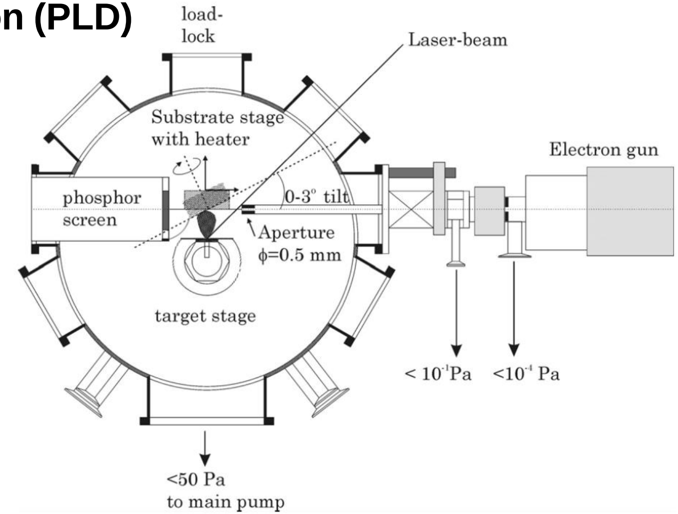
Fowlie PhD thesis

Growth techniques

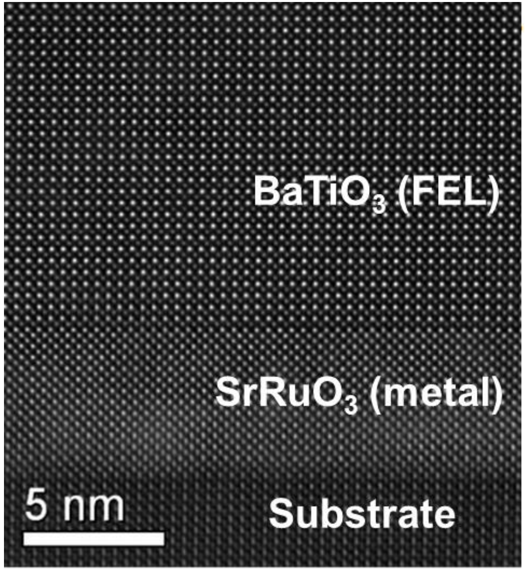
We need an incident flux,
high temperature

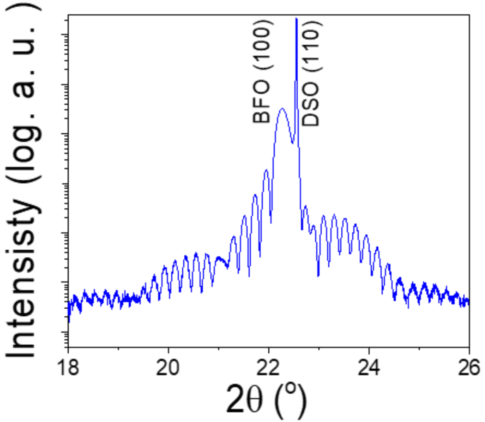
Pulsed laser deposition (PLD)



+ “Easy” to operate
+ Stoichiometric deposition (248 nm)
+ in situ monitoring
- Small area only

K. Rabe, C. H. Ahn, J.-M. Triscone (Eds.): Physics of Ferroelectrics: A Modern Perspective,
Topics Appl. Physics **105**, 219–304 (2007)





Growth techniques

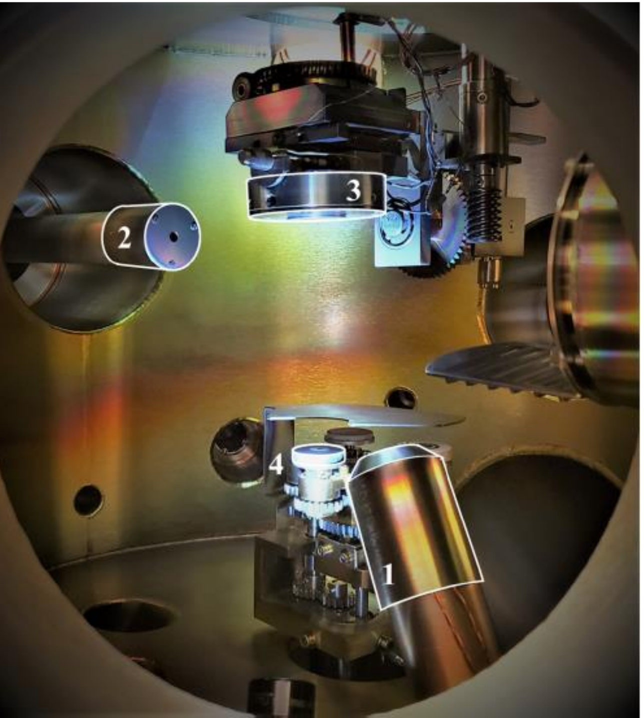
We need an incident flux,
high temperature

In plane lattice parameter determination

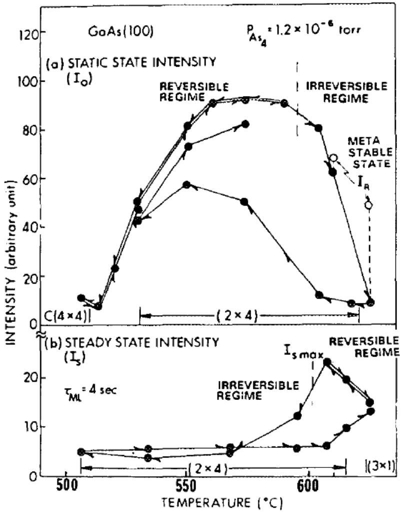
$$d = 2\lambda_e L / a_{\|}$$

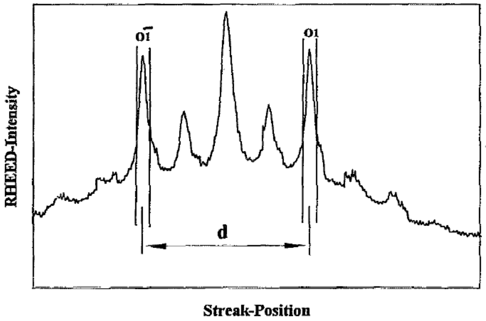
Pulsed laser deposition (PLD)

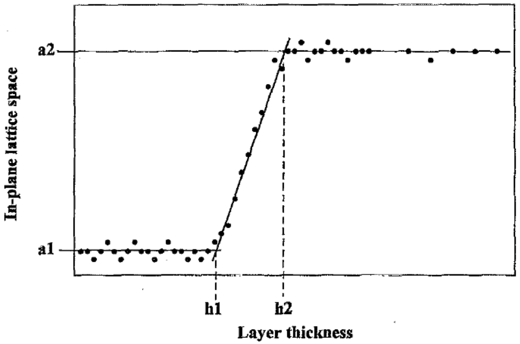
Differential pumping, beam enclosing, screen geometry
Now compatible with high pressure oxide thin films processes



Surface reconstruction and
absolute temperature measurement







Journal of Vacuum Science & Technology B: Microelectronics Processing and Phenomena 4, 890 (1986)

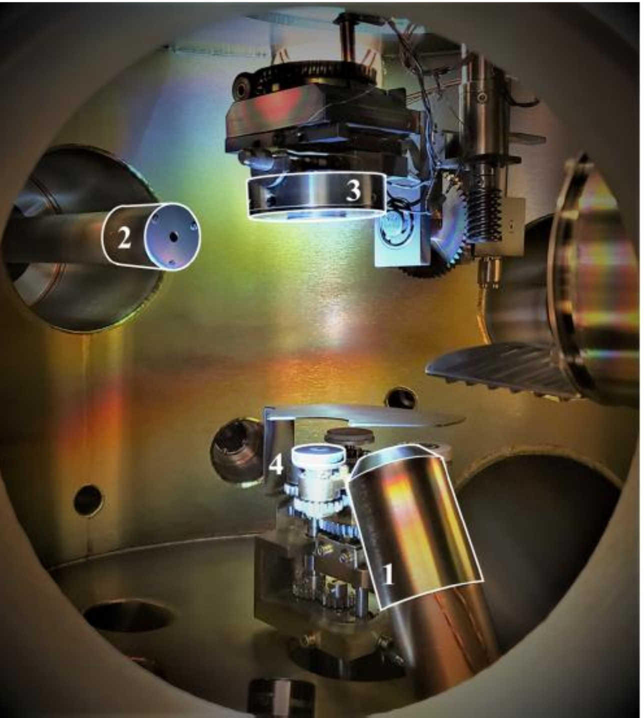
Appl. Phys. Lett. 65, 630 (1994)

Growth techniques

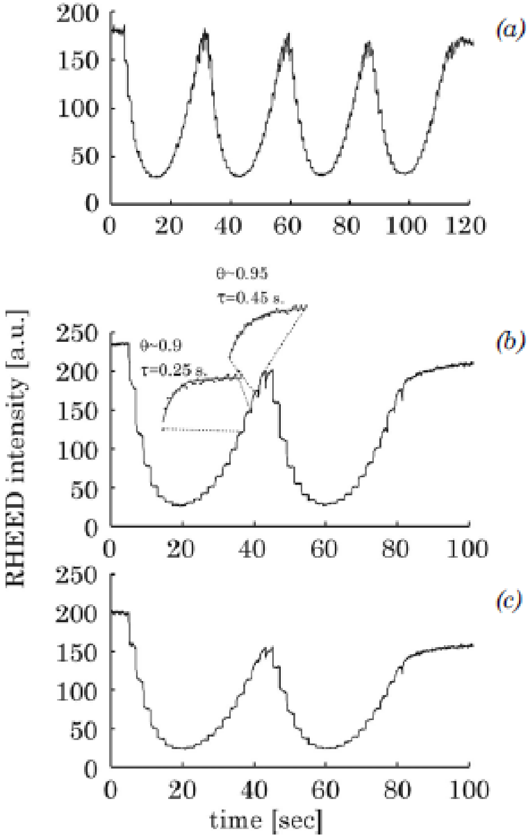
We need an incident flux,
high temperature

Pulsed laser deposition (PLD)

Differential pumping, beam enclosing, screen geometry
Now compatible with high pressure oxide thin films processes



Growth modes.
Surface diffusion probe



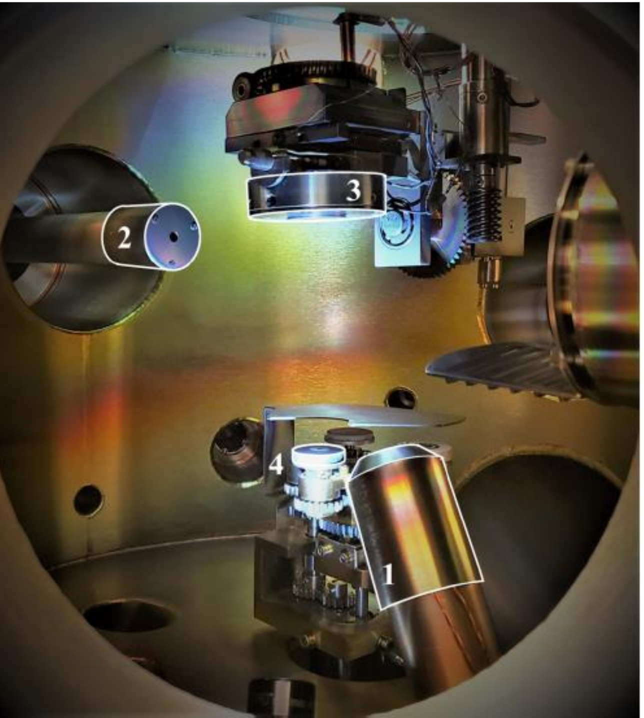
Thesis Rijinders (2001)

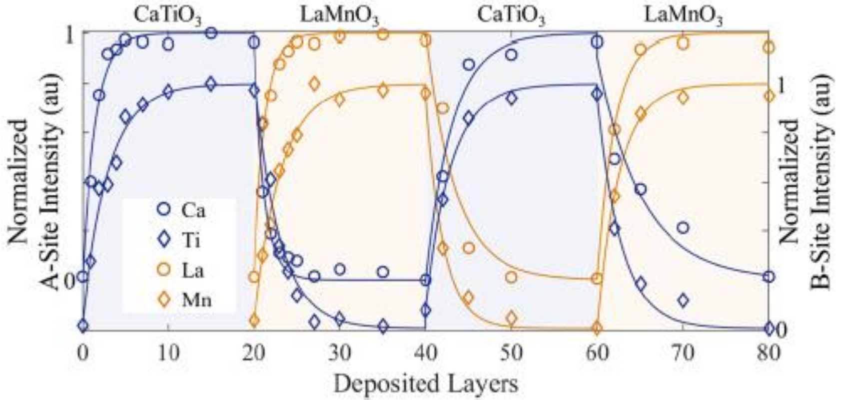
Growth techniques

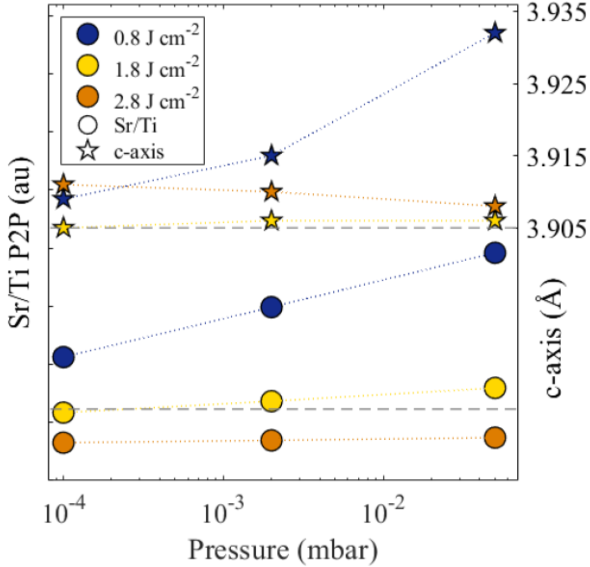
We need an incident flux,
high temperature

Pulsed laser deposition (PLD)

Electron beam irradiation, Auger electron emission,
characteristic of the atomic element.







Nano Lett. 21, 10, 4160 (2021)

Growth techniques

We need an incident flux,
high temperature, not just PVD

Solution based Chemistry (SBC)

Sol-Gel, Spin coating, Dip coating, Spray pyrolysis, Chemical bath deposition, …

Chemical Vapor Deposition (CVD)

Atmospheric pressure CVD, Low/Ultra-low pressure CVD, Metal organic CVD, Plasma assisted CVD, Atomic layer deposition (ALD), Vapor phase epitaxy

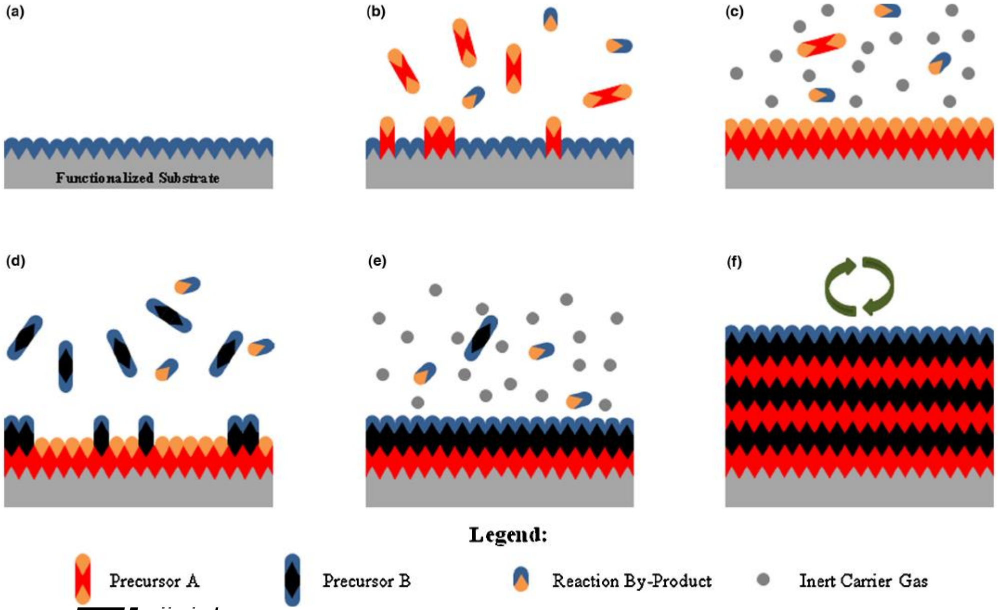
Physical Vapor Deposition (PVD)

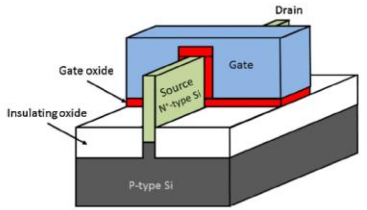
Thermal evaporation, Pulsed laser deposition, Molecular beam epitaxy, Sputtering (DC and RF)

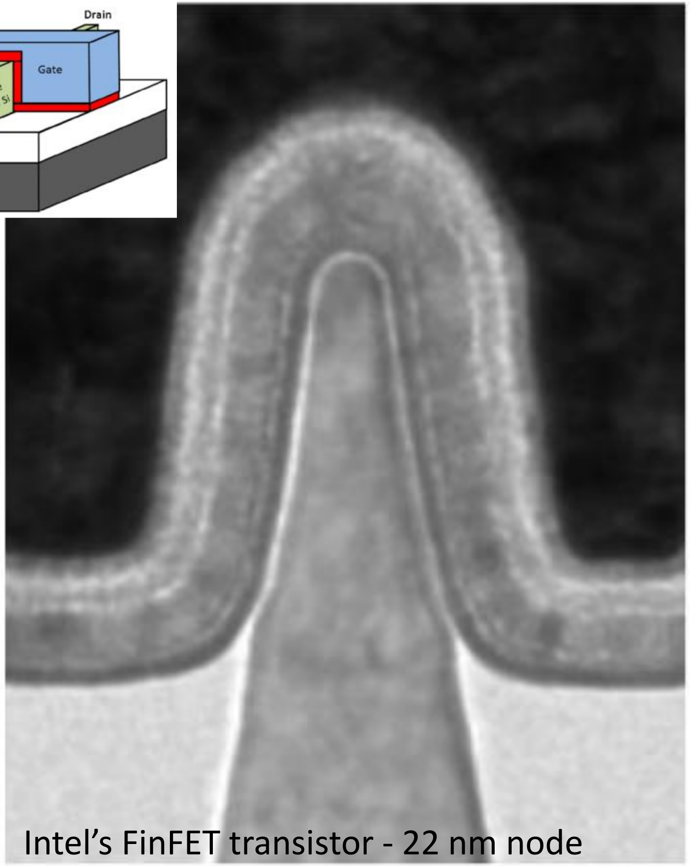
Growth techniques
the case of atomic layer deposition

For Ferroelectric HfO_2 based compounds, precursors: $Hf(diethylamino)_4$ and H_2O

ALD processes are conducted
at moderate temperatures (<350C).
compatible with backend of line for microelectronics







Intel's FinFET transistor - 22 nm node

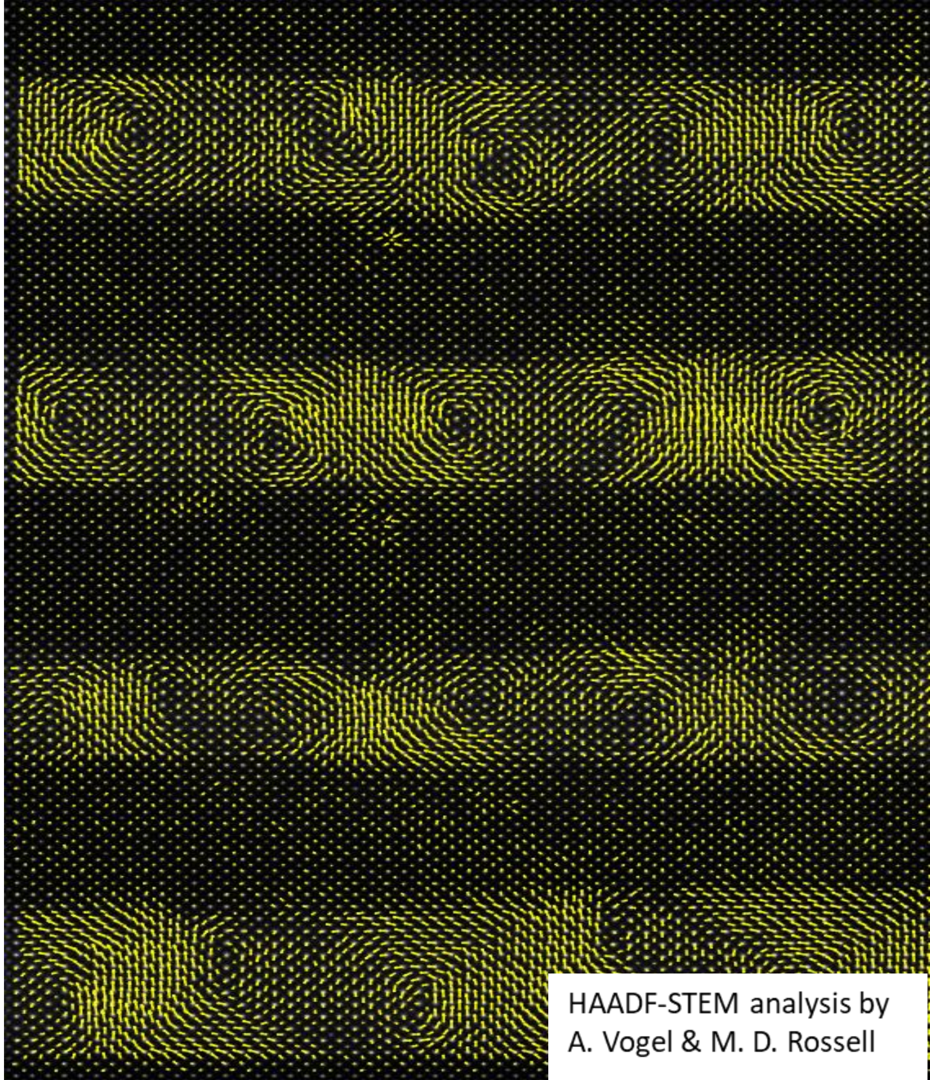
Growth techniques

We need an incident flux, high temperature

Substrate lattice and surface morphology is important

OMBE, RF sputtering and PLD bring the control parameter to achieve layer by layer growth

How do we characterize an epitaxial deposition?

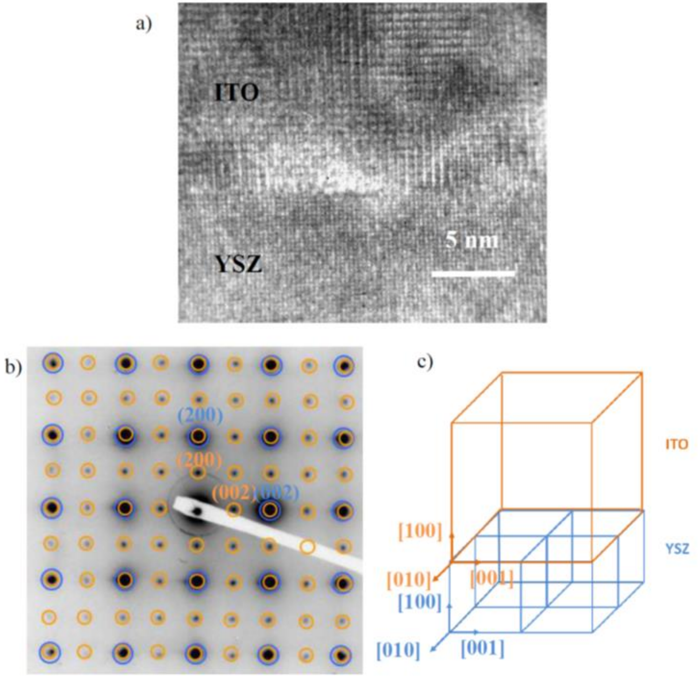


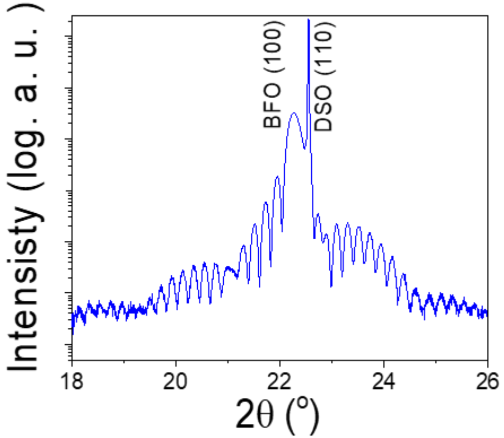
Growth techniques

Structural characterization

X-ray diffraction experiments
- Identification of the material, phase
- Strain state
- Epitaxial relationship

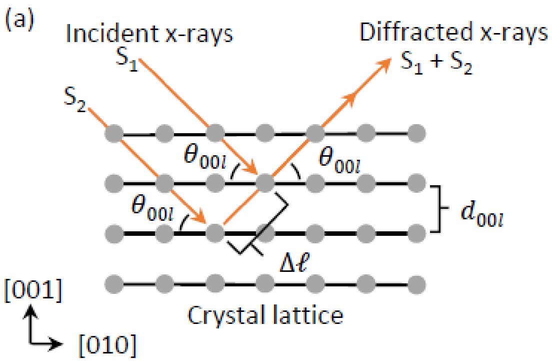
Investigation of the reciprocal space





Bragg's law

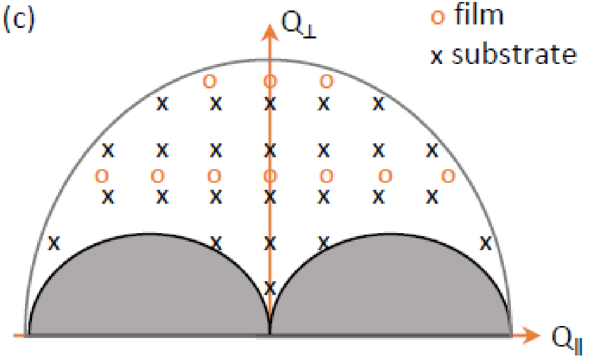
$$2d \sin\theta = n\lambda;\ n = 1, 2, 3...,$$



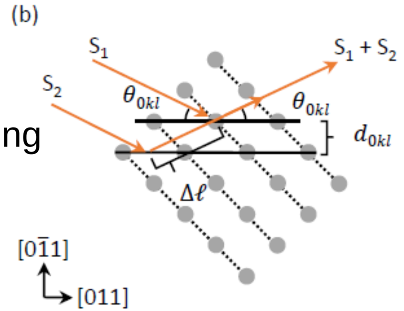
Thesis Nordlander doi.org/10.3929/ethz-b-000446702

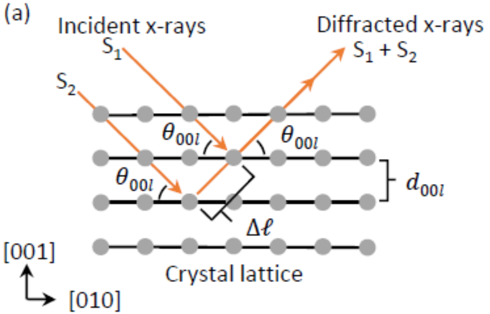
X-ray diffraction experiments

- Identification of the material, phase
- Strain state
- Epitaxial relationship



Reciprocal space mapping

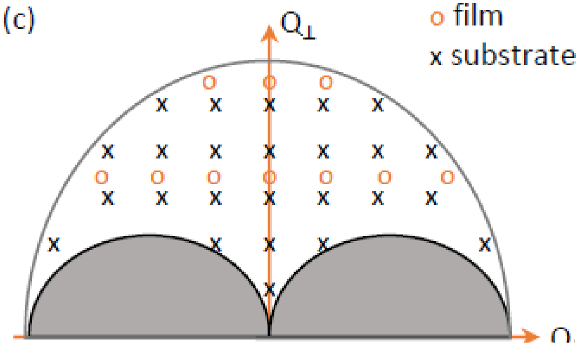


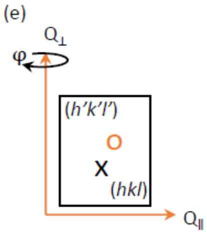


Thesis Nordlander doi.org/10.3929/ethz-b-000446702

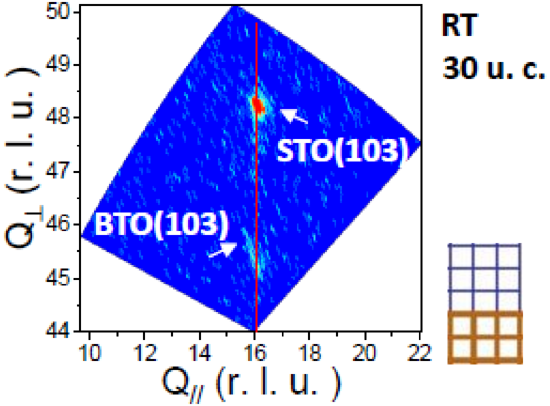
X-ray diffraction experiments

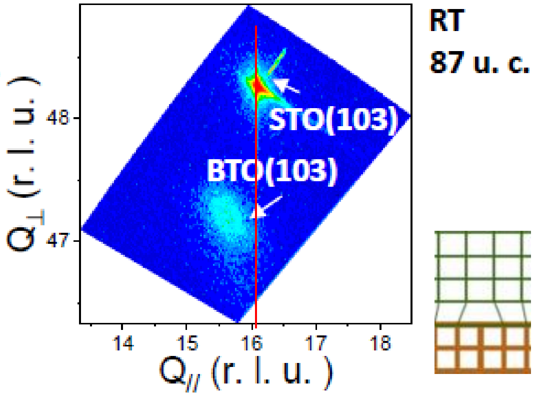
- Identification of the material, phase
- Strain state
- Epitaxial relationship





In-plane lattice parameter





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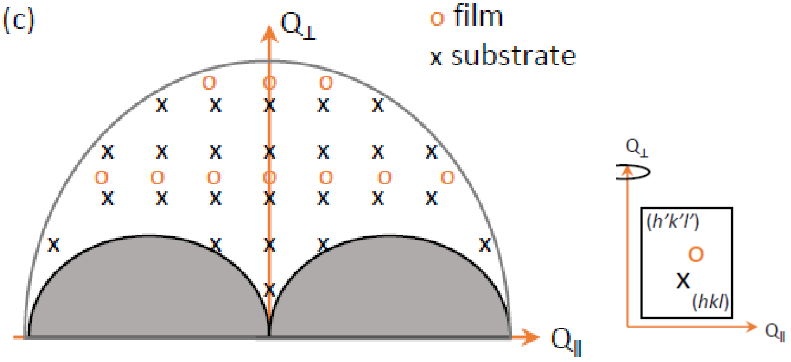
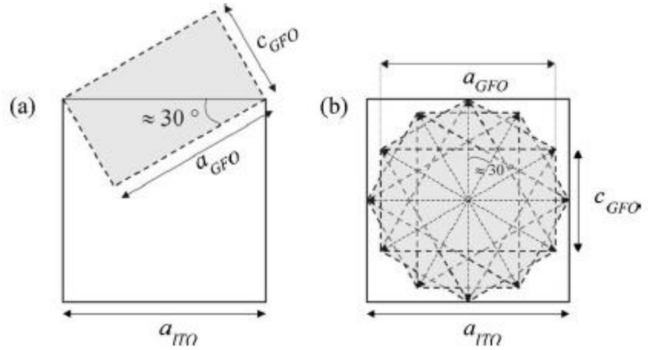
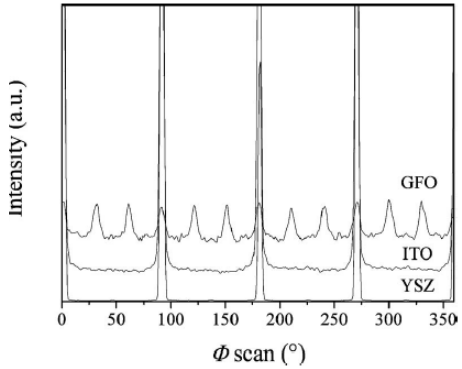
X-ray diffraction experiments
- Identification of the material, phase
- Strain state
- Epitaxial relationship





Appl. Phys. Lett. 91, 202504 2007



Advice to young scientists ;)

- Never start a conversation like this:

  "We are finishing a paper on [...] and would like to include a thickness dependence that supports our amazing interpretation. How can you help?"

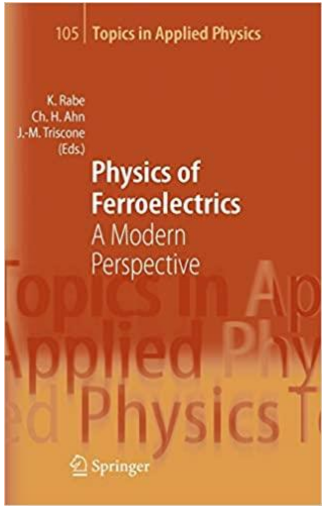
- When talking to a thin film grower
  - (Good growth) takes time
  - The results from growth may or may not agree with your theory or your interpretation of it. Be ready for that!
  - That's OK because (good) experiment (and its comparison with theory) will allow you to learn about your problem

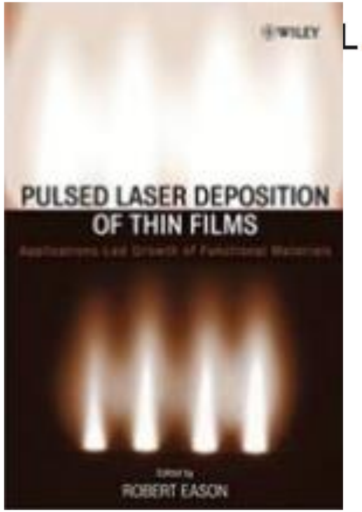
Thin films epitaxy

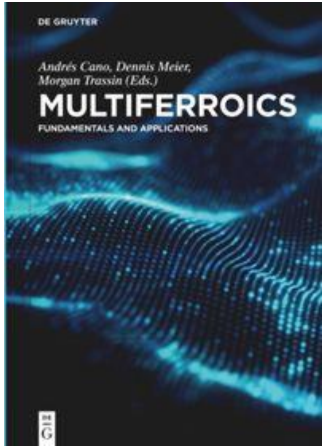
- Brief definitions
- Epitaxial strain as a control parameter
- Materials, substrates

Growth process
- Growth modes and growth mechanisms
- In situ monitoring of 2D growth
- Growth techniques
- Structural characterization

The case of ferroelectrics
- In-situ diagnostic tools
- Monitoring of ferroelectricity during the epitaxial growth
  interface contributions



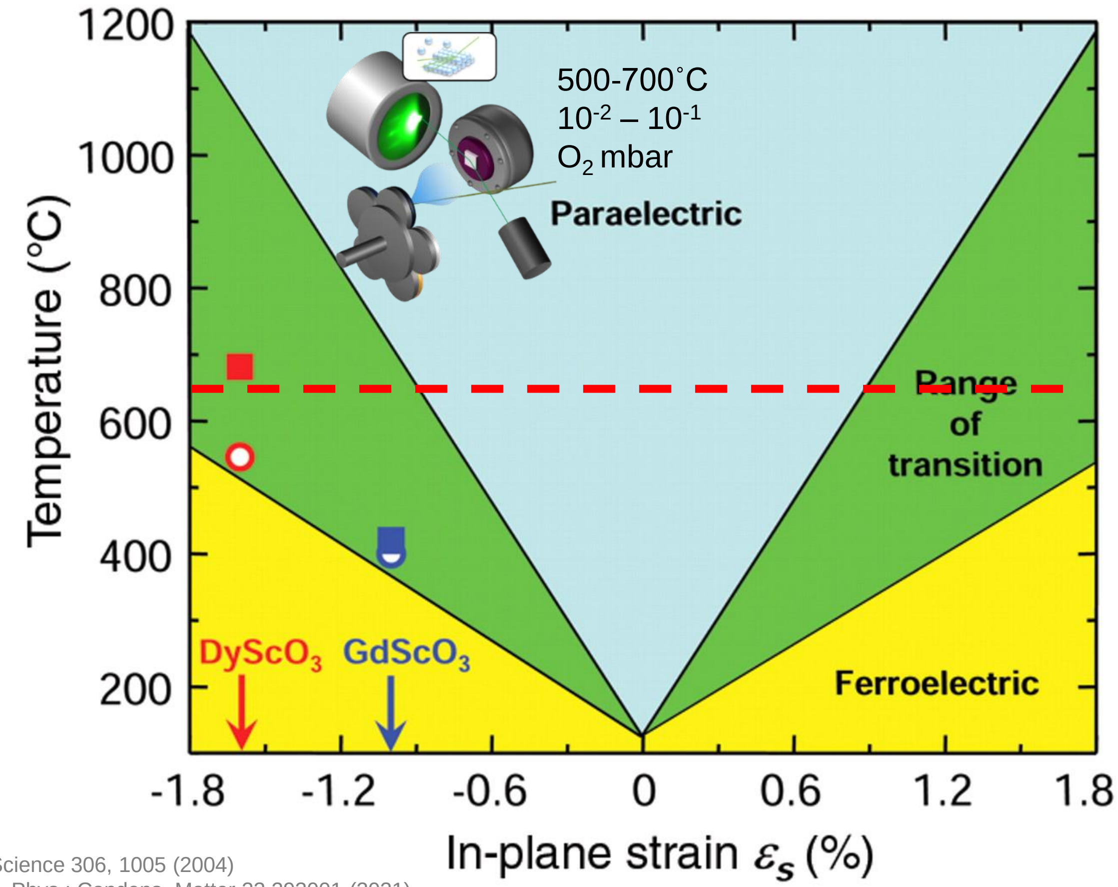




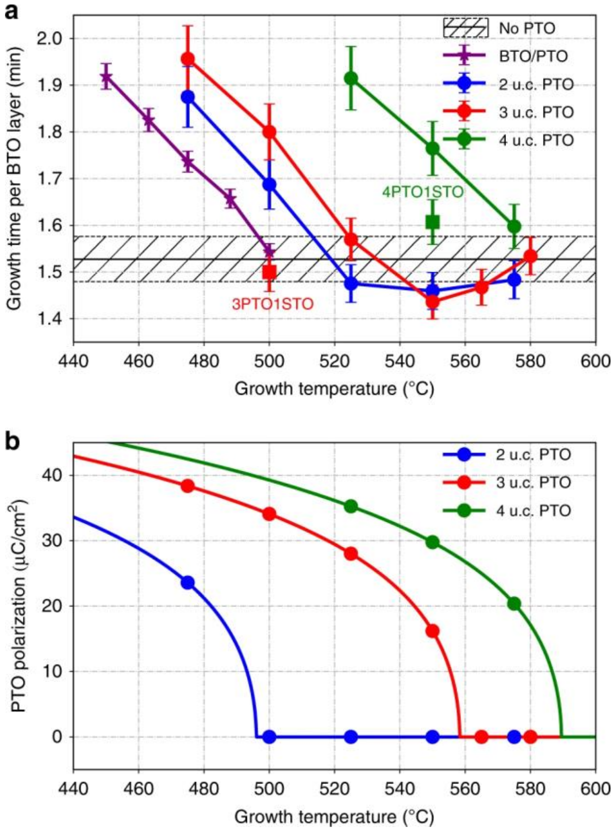
Growth techniques

Growth of ferroelectric in the polar phase

$BaTiO_3$



Process ⟷ Ferroelectricity



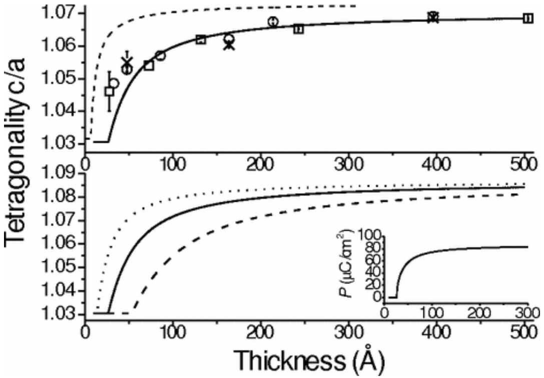
Science 306, 1005 (2004)
J. Phys.: Condens. Matter 33 293001 (2021)

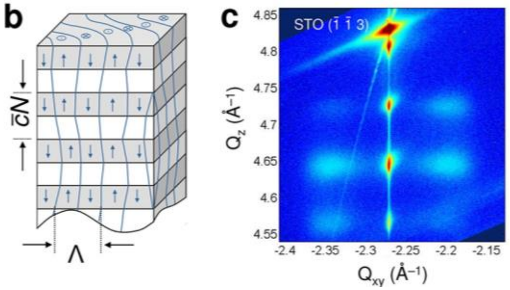
Nat. Commun. 11, 2630 (2020)

Epitaxy of ferroelectrics

In-situ monitoring techniques for ferroelectricity
X-ray diffraction
Probing the functionality noninvasively, the ferroelectricity

Phys. Rev. Lett. 94, 047603

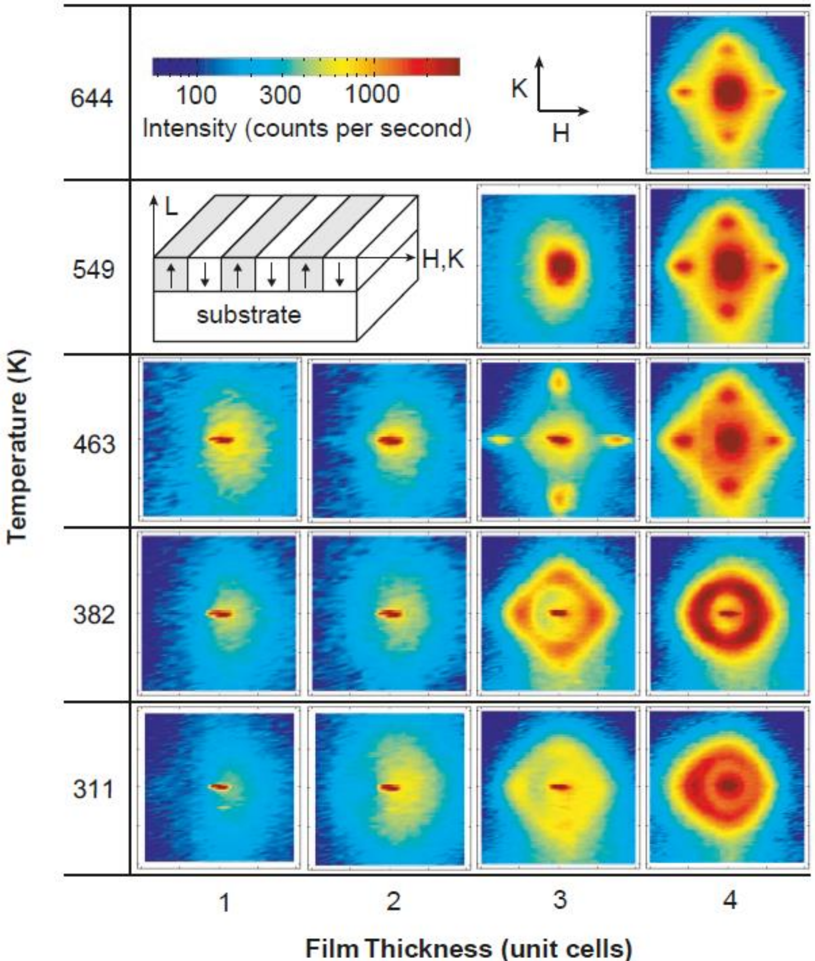




Domain ordering

Domain formation

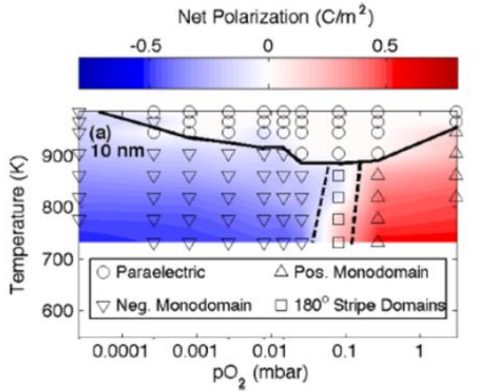
Science 304, 5677 (2004)

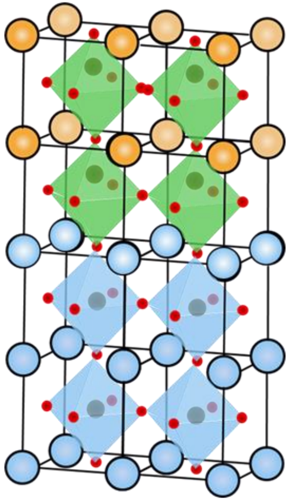


In-situ monitoring techniques for ferroelectricity

Probing the functionality noninvasively, the ferroelectricity

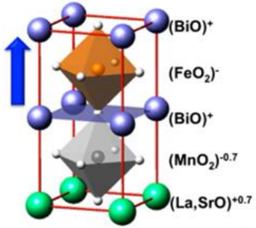
PRL. 107, 187602 (2011)
Nat Commun. 9, 3809 (2018)
Adv. Electron. Mater. 6, 2000852 (2020)
Adv. Funct. Mater. In press

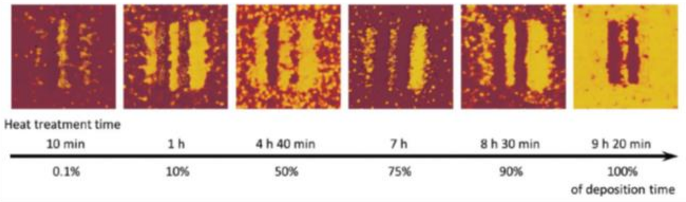




Final state

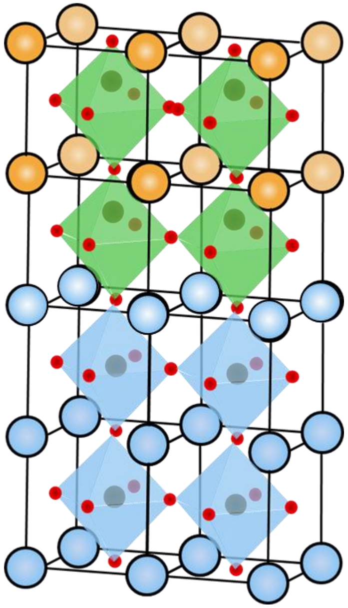
Nat. Commun 8, 1419 (2017)
PNAS 109 9710 (2012)
Nat. Commun. 11, 5815 (2020)
PNAS. 117, 28589 (2020)





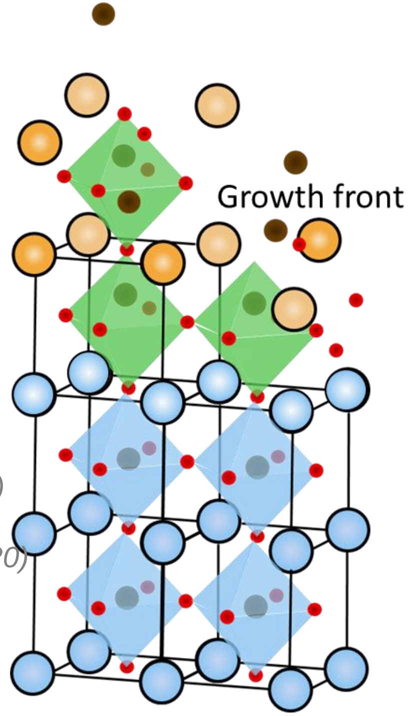
Epitaxy of ferroelectrics

In-situ monitoring techniques for ferroelectricity
Probing the functionality noninvasively, the ferroelectricity



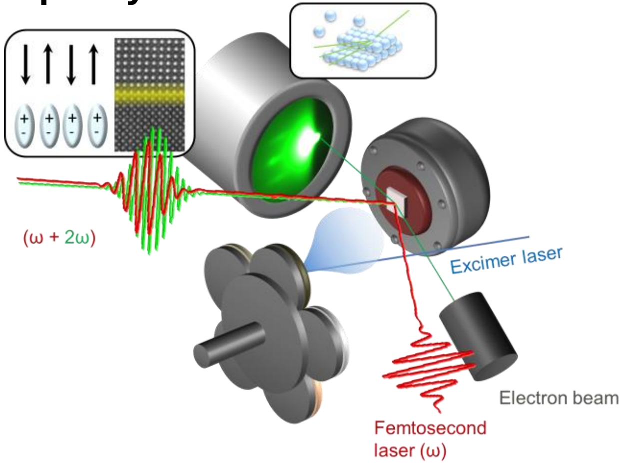
Final state

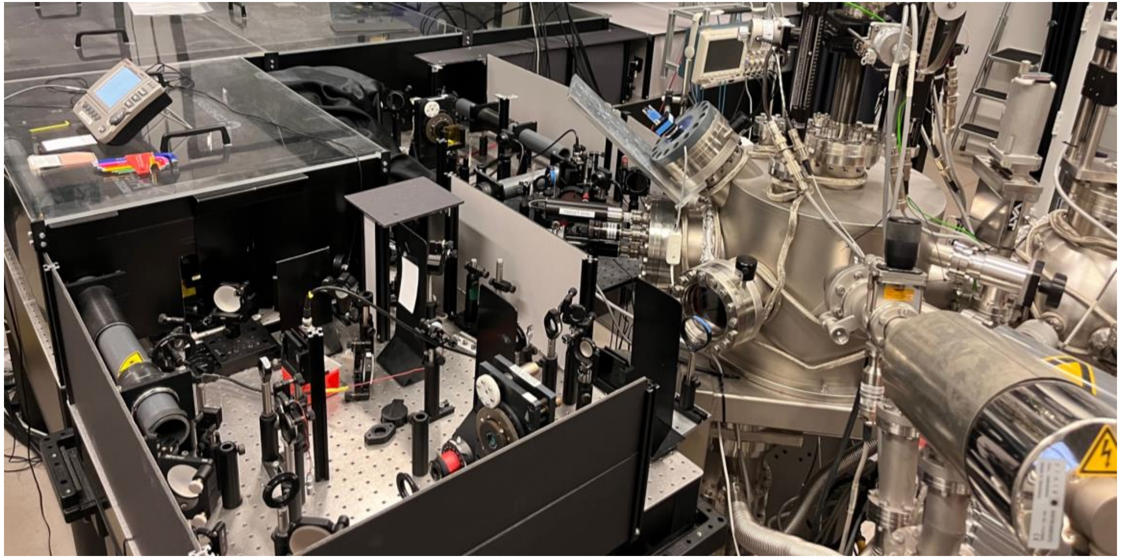
Nat. Commun 8, 1419 (2017)
PNAS 109 9710 (2012)
Nat. Commun. 11, 5815 (2020)
PNAS. 117, 28589 (2020)



During growth

Epitaxy of ferroelectrics

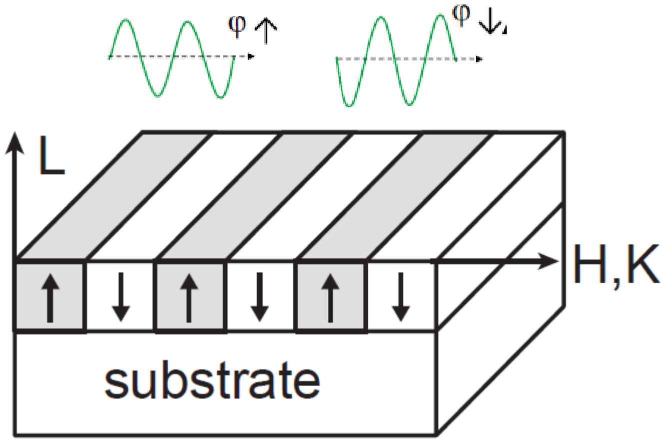




SHG checklist (courtesy of referee #2)

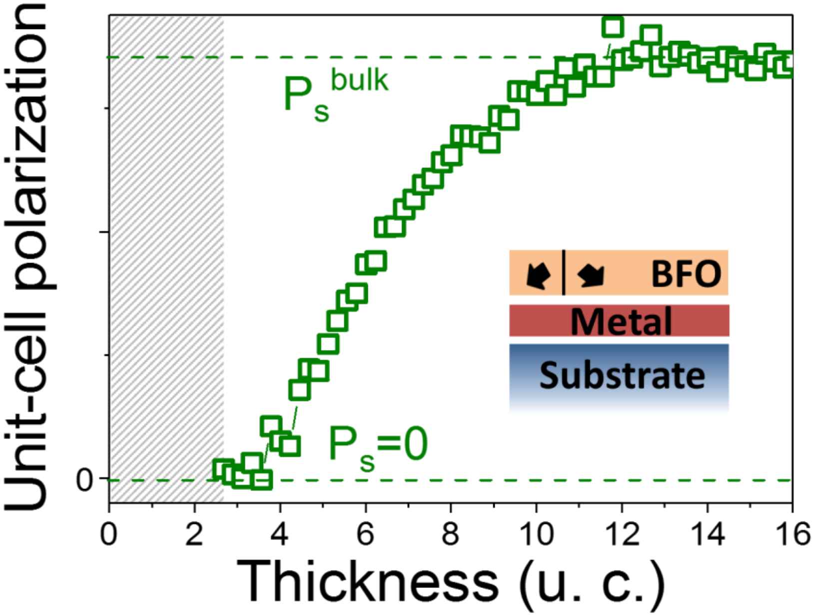
-data fitted considering point group symmetry
-temperature dependence (cooldown, heating up)
-sample orientation dependent
-substrate/ buffer / surface contribution?

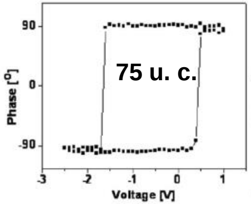
Adv. Mater. 27, 4871. (2015)
Nat. Commun 8, 1419 (2017)
Appl. Sci., 8, 570 (2018)
Materials, 12, 3108 (2019)

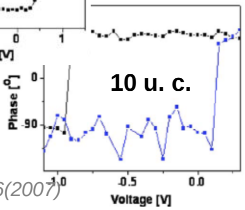


Epitaxy of ferroelectrics

Real time monitoring of polarization during the growth

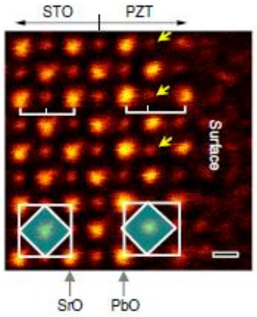


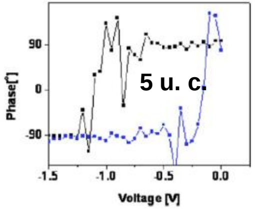


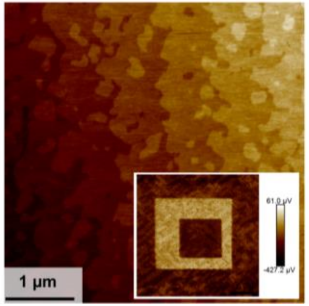


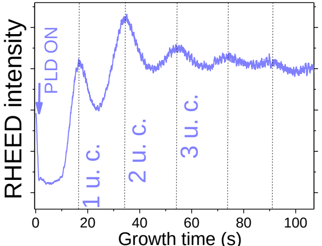
Chu, et al.,
APL 90, 252906(2007)

Gao, et al.,
Nat Comm. 8, 15549 (2017)









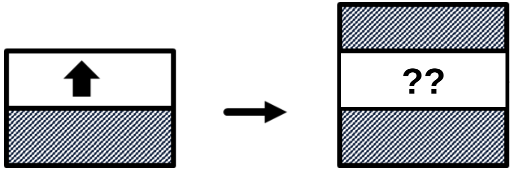
Direct access to

- the critical thickness
- the Tc (strain dependent)
- the polarization dynamics and domain formation

Adv. Mater. 27, 4871. (2015)
Nat. Commun 8, 1419 (2017)
Appl. Sci., 8, 570 (2018)

Epitaxy of ferroelectrics

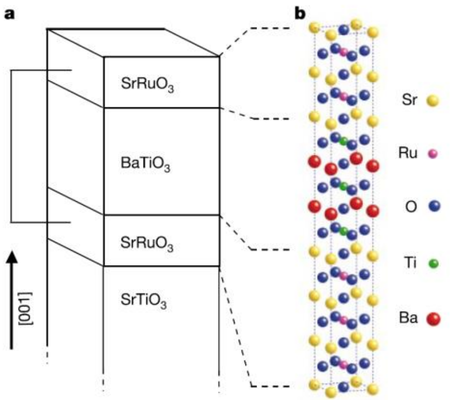
Real time monitoring of polarization during the growth

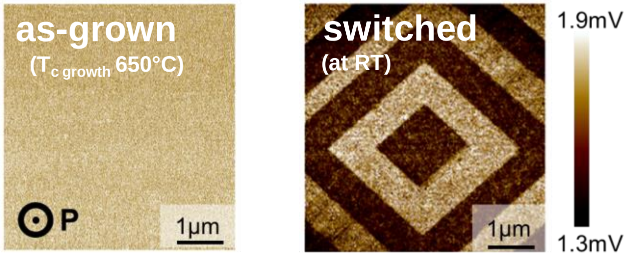


Critical thickness for ferroelectricity in perovskite ultrathin films

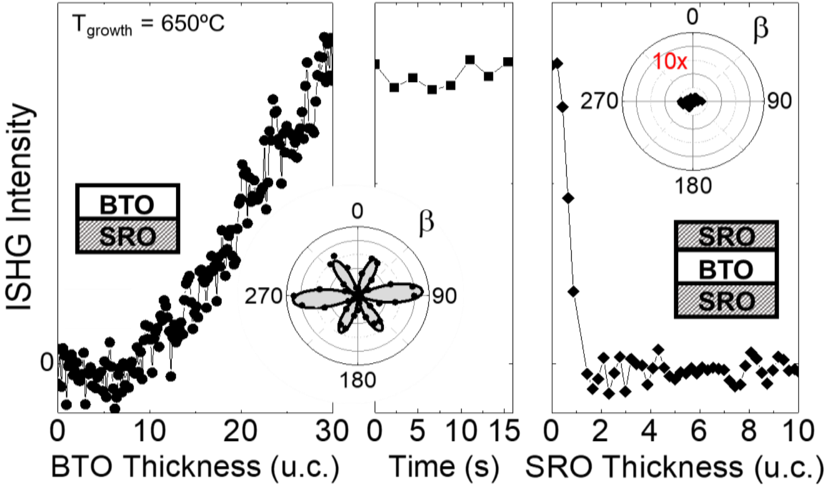
Javier Junquera & Philippe Ghosez

NATURE | VOL 422 | 3 APRIL 2003





PRL 123, 147601 (2019)



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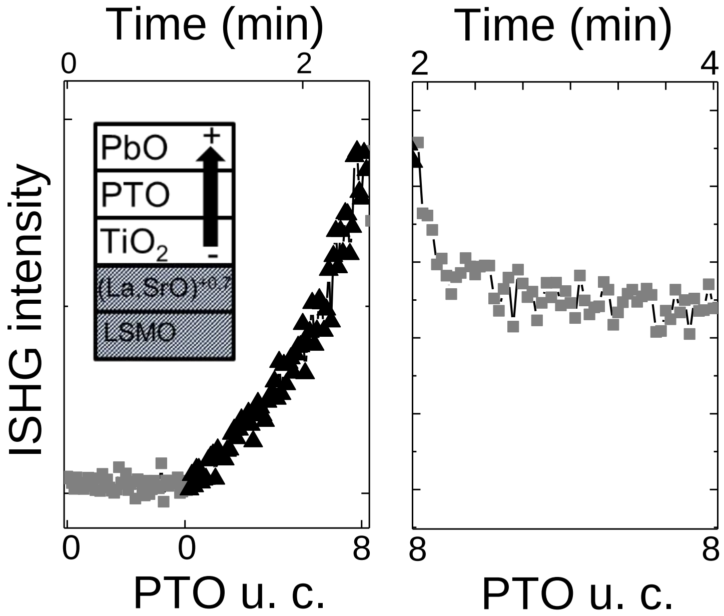
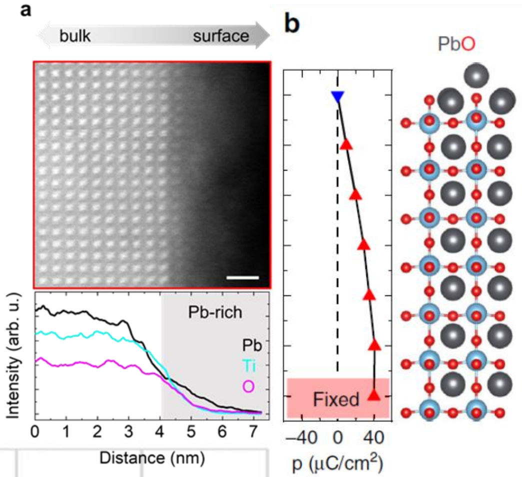
Epitaxy of ferroelectrics

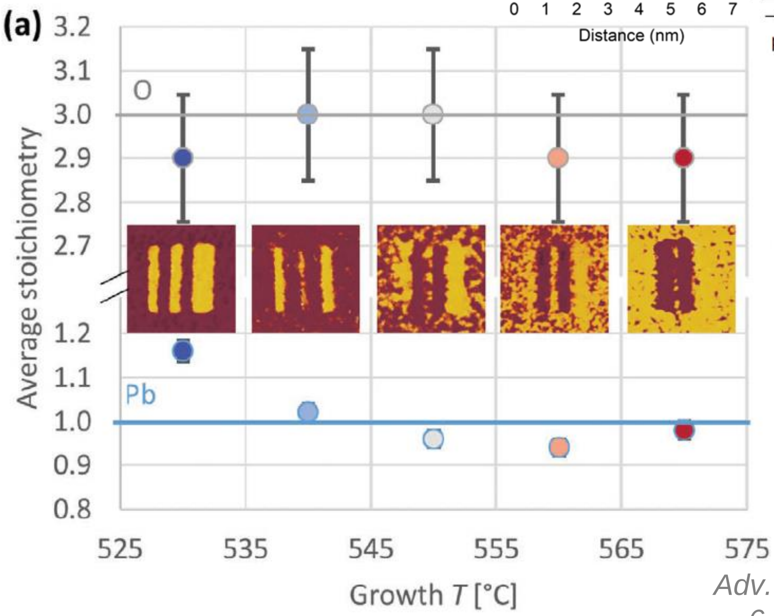
The growth of $PbTiO_3$

Defect gradient formation affect the net polarization state



Nat. Commun. 11, 5815 (2020)



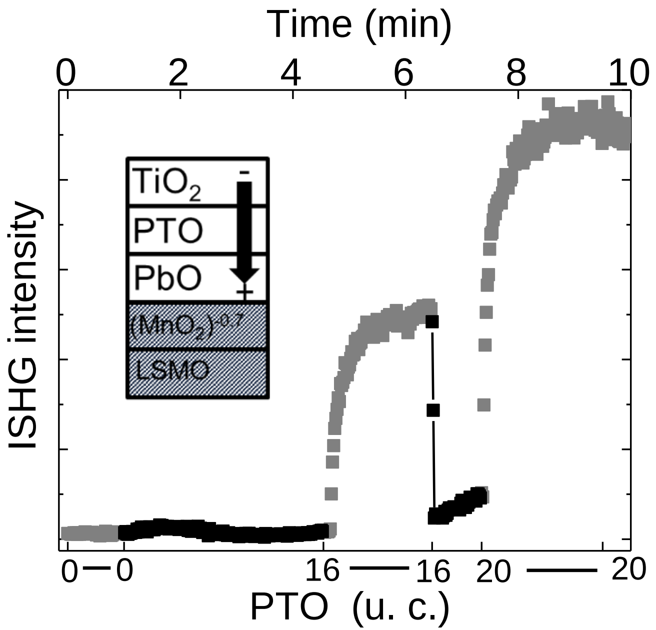


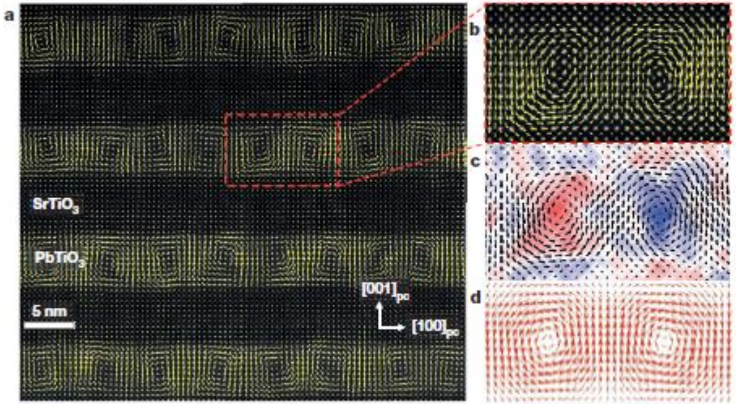
Adv. Electron. Mater. 6, 2000852 (2020)

Epitaxy of ferroelectrics

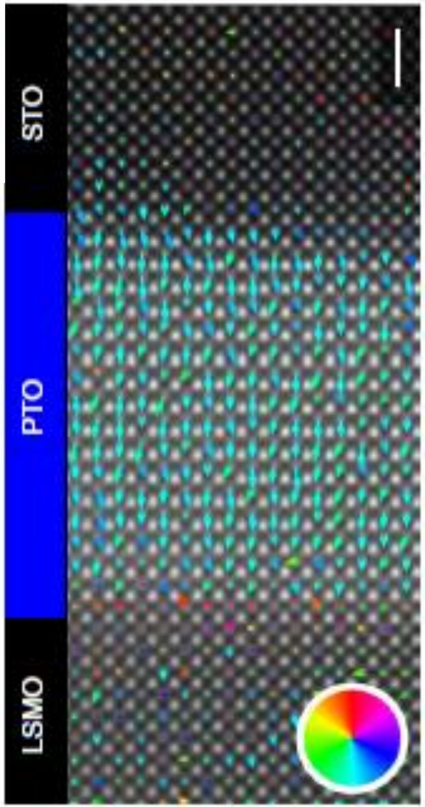
The growth of $PbTiO_3$

Polarization orientation dependent





Nature 530, 198–201 (2016)

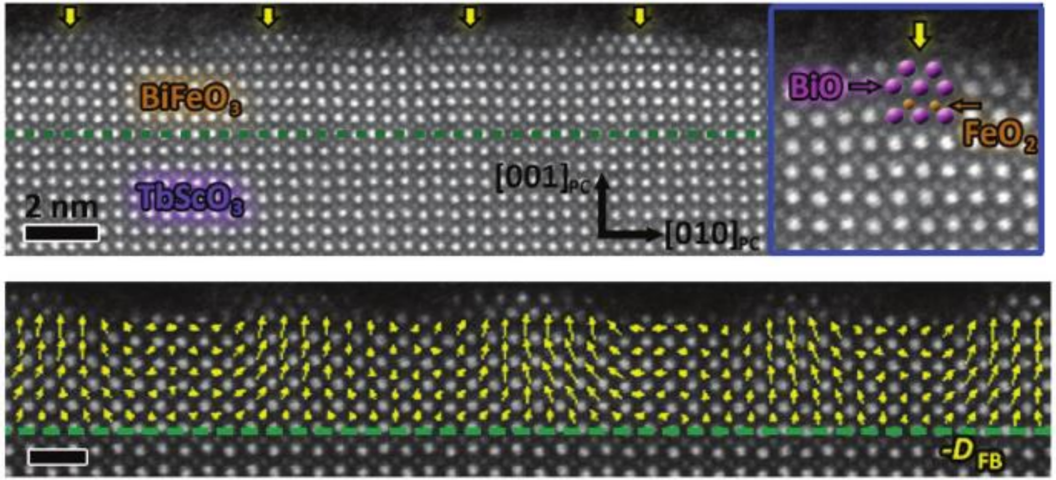


Nat. Commun. 11, 5815 (2020)

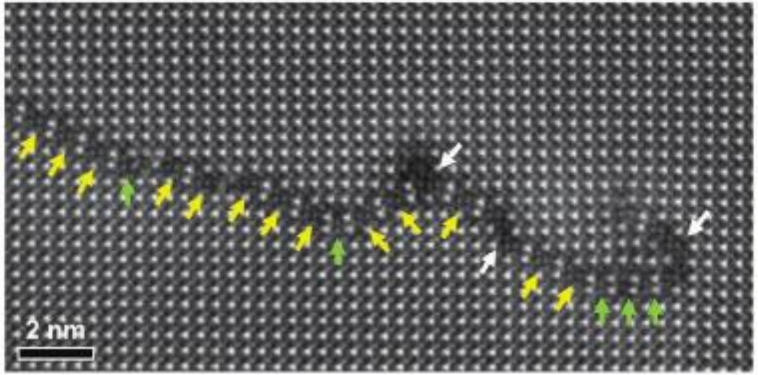
PNAS. 117, 28589 (2020)

Epitaxy of ferroelectrics

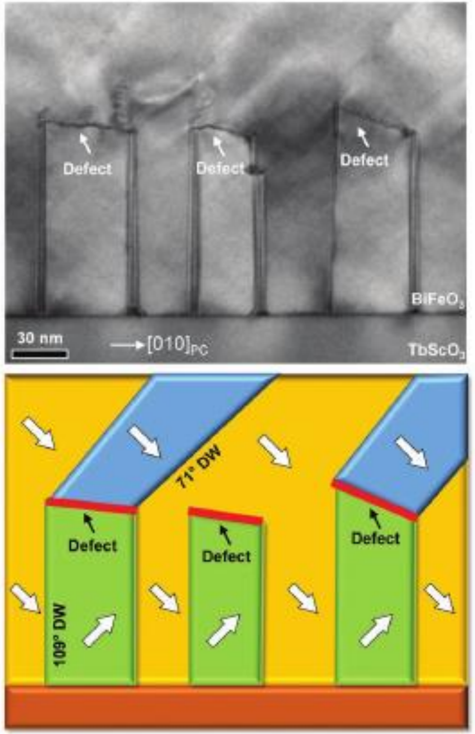
Spontaneous surface reconstruction



Adv. Mater. 29, 1701475 (2017)
Adv. Mater. 2018, 30, 1802737



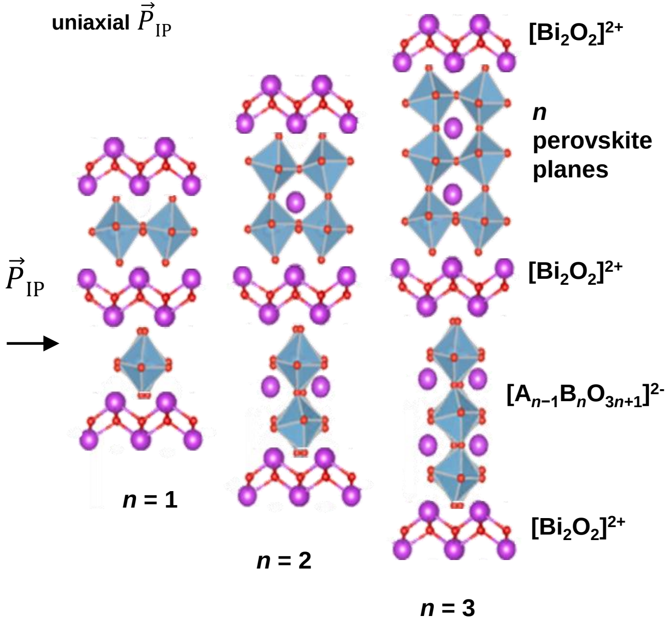
Induced surface reconstruction



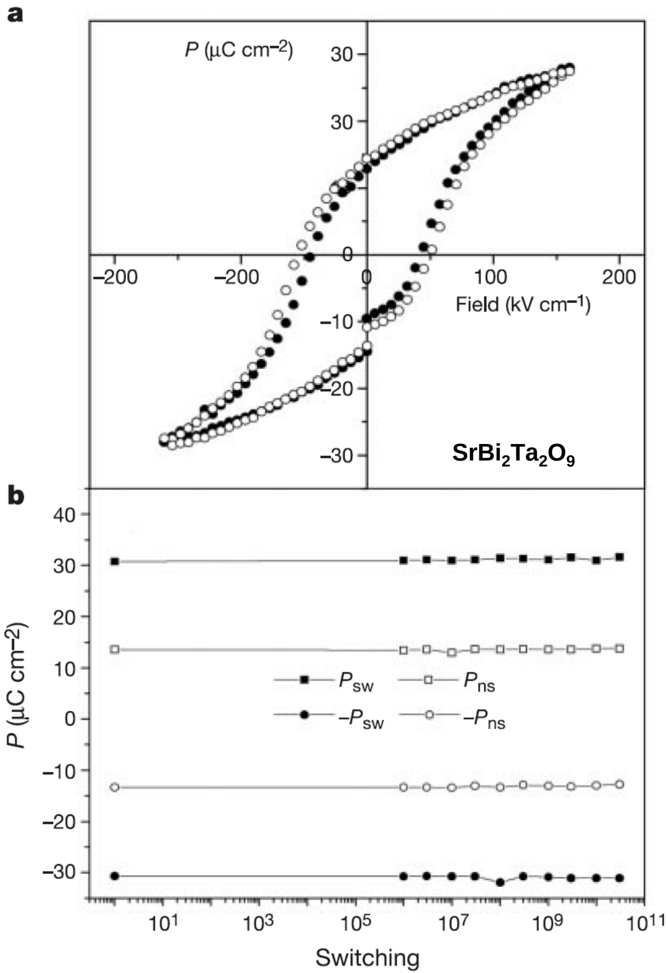
Layered ferroelectrics

Aurivillius thin films

Commonly uniaxial $\vec{P}_{\mathrm{IP}}$



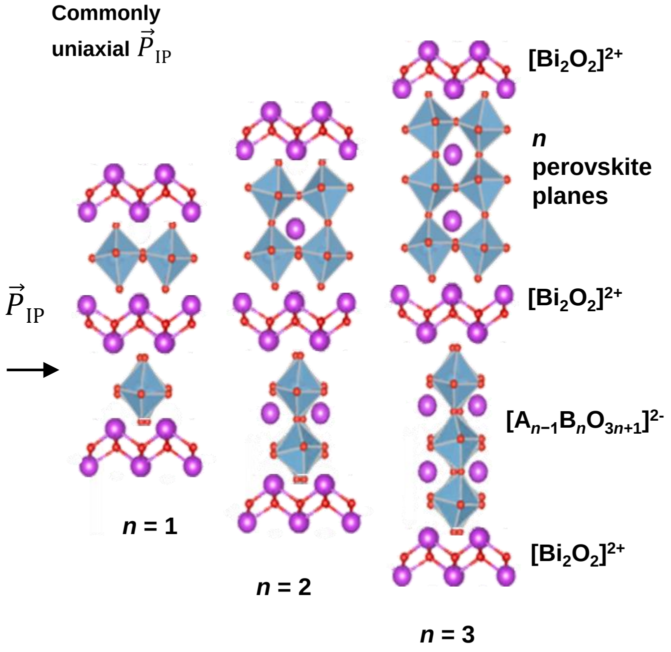
Ark. Kemi. 1, 463 (1949)

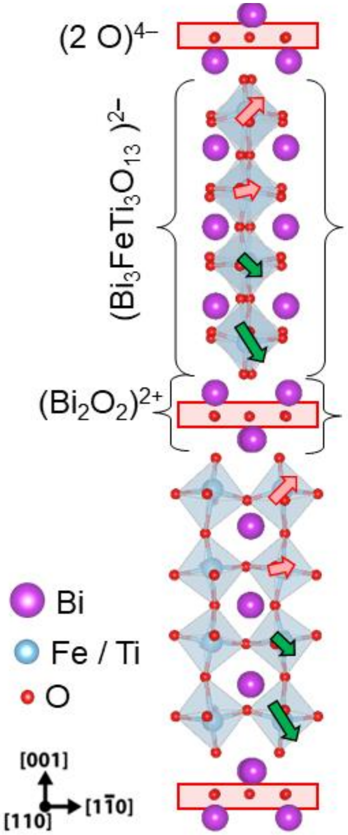


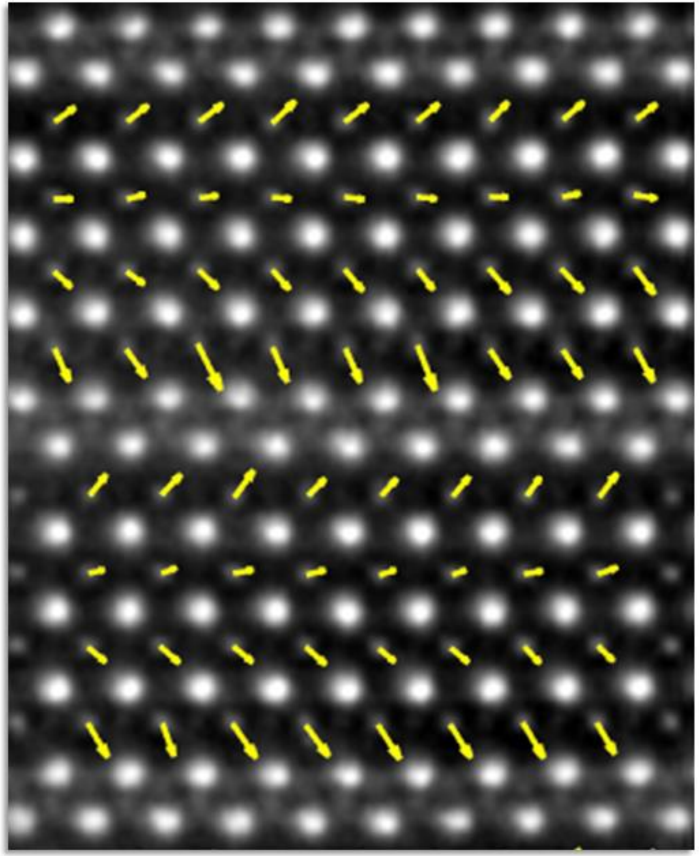
Nature 1995, 374, 627.
Appl. Phys. Lett. 2001, 78, 4175.
J. Mater. Res. 2007, 22, 1439.

Layered ferroelectrics

Aurivillius thin films







Ark. Kemi. 1, 463 (1949)

Adv. Mater. Inter. 7, *2000202 (2020).*

Chem. Mater. 2021, 33 (2021).

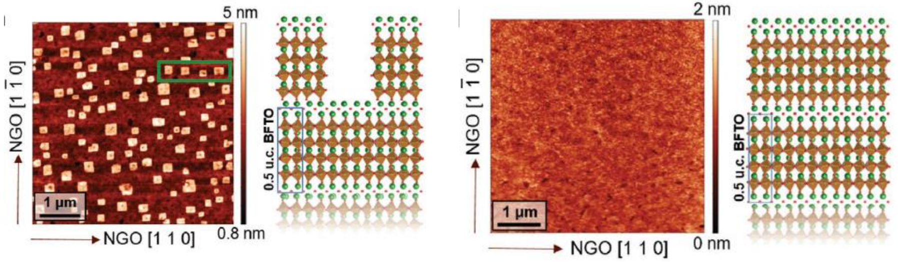
ACS Appl. Electron. Mater.1, 1019 (2019)

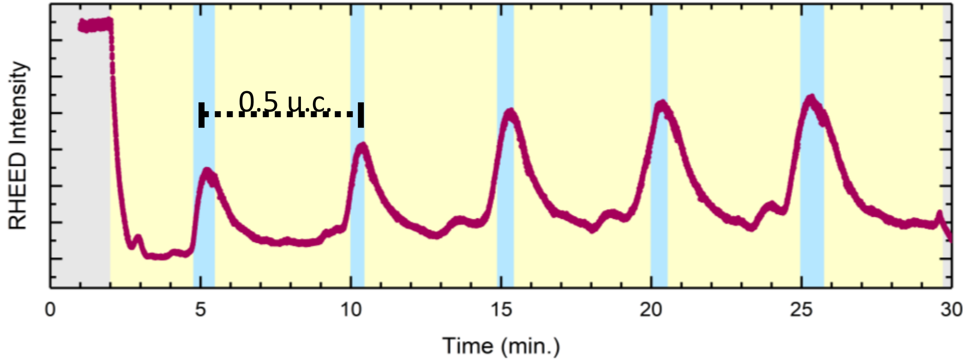
Epitaxy of ferroelectrics

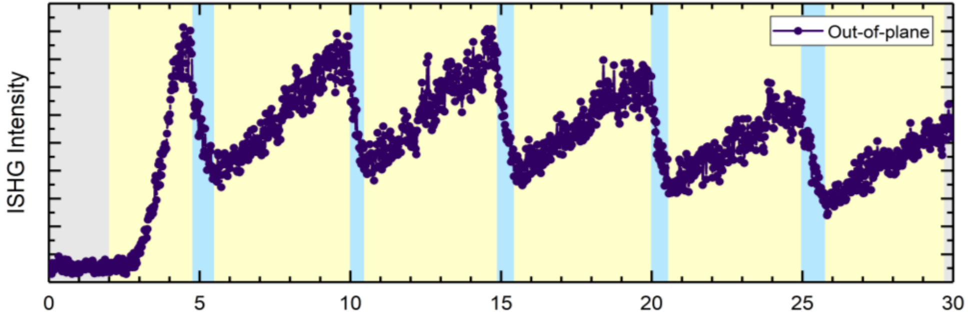
Layered ferroelectrics

Aurivillius thin films

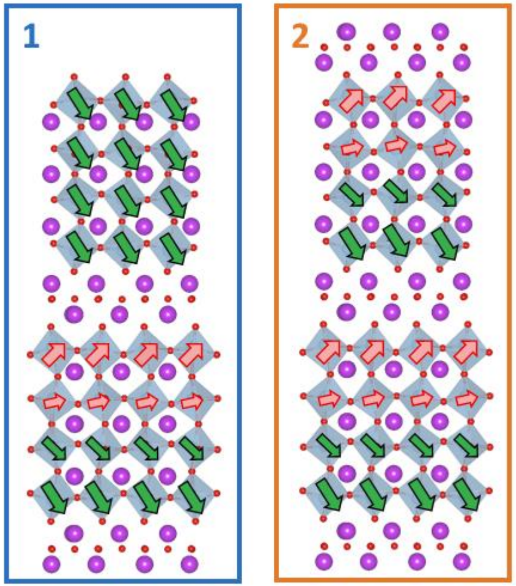
Combination of structural and functional properties monitoring in real time





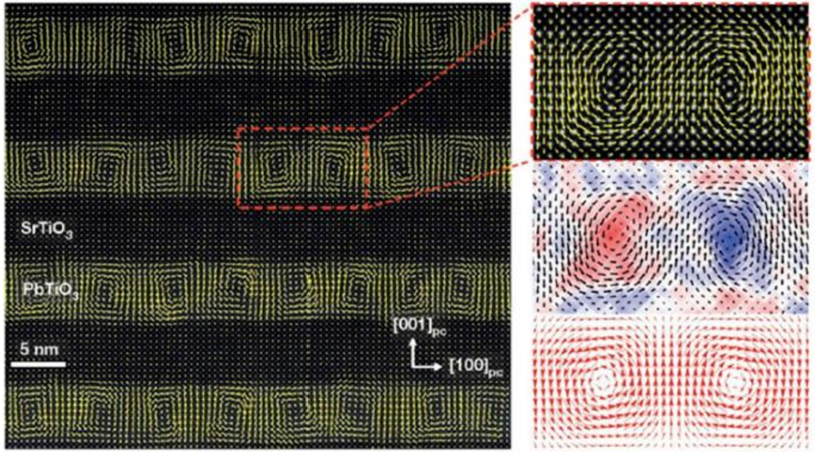


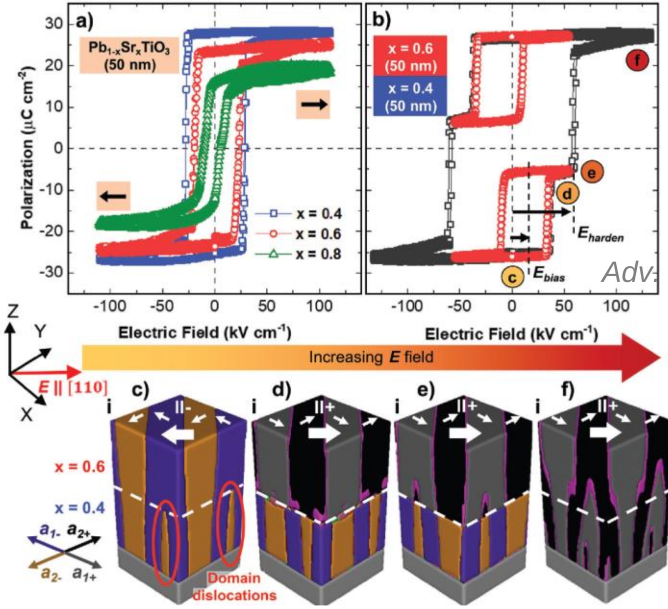
PhD work Ipek Efe



Epitaxy of ferroelectrics

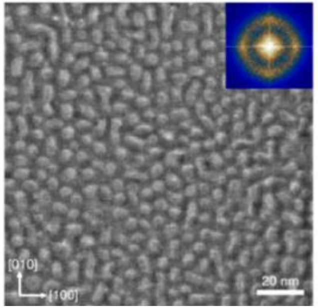
Strain and electrostatics in complex heterostructures





at ferroelectric-ferroelectric interfaces

Adv. Mater. 2023, 2301934



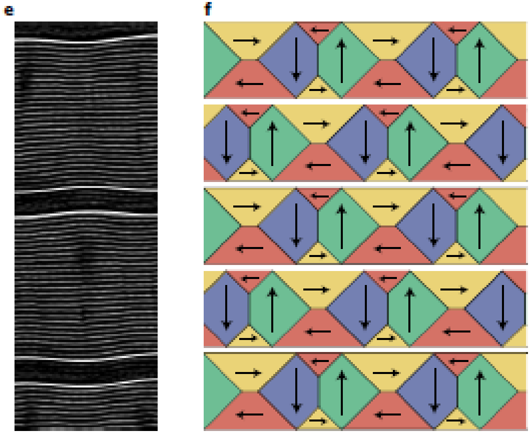
at ferroelectric-dielectric interfaces

Nature 2016, 530, 198–201.

Nature 2019, 568, 368–372

at ferroelectric-metal interfaces

Nature Materials 20, 495 (2021)



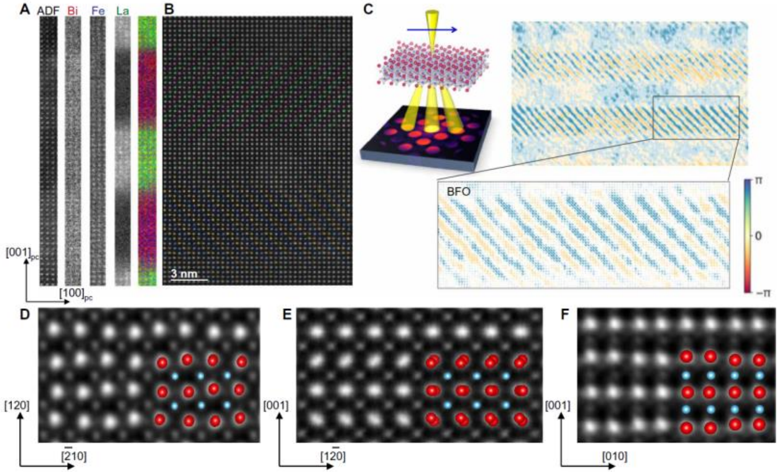
What's next?

Epitaxy with simultaneous, structural, chemical and symmetry monitoring

- identification of optimal growth processes
- reproducibility of the depositions
- identification of phase transition in situ
- design of antiferroic properties

Epitaxy on non-crystalline substrates, VdW epitaxy and freestanding membranes for beyond «classical epitaxial design» capacity

Sci. Adv. 8, eabg5860 (2022)



Nature Materials 22, 207 (2023)