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Revolutionizing Silicon: The Synergy of Complex Oxides in Chip Technology

Complex oxide integration with Silicon

Guus Rijnders

MESA+ Institute for Nanotechnology

University of Twente, The Netherlands

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Nicolas Gauquelin
(Antwerp)

Jean Fompeyrine
(IBM, Lumiphase)

ect SIOX, Dutch NWO DESCO, ESTEEM

esteem 3
european network for electron microscopy

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UNIVERSITEIT TWENTE.

- Technical and social sciences
- 12000 students / 3000 staff
- 5 Faculties, 3 Research Institutes
  - Nanotechnology MESA$^+$ (550 researchers/staf.)
  - TechMed Research Center
  - Digital innovation institute






University of Twente / MESA$^+$ Institute for Nanotechnology

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VISIT THE NANOLAB SITE

MESA+ INSTITUTE

REALISING **GRAND SOLUTIONS** WITH THE **EXTREMELY SMALL**

At MESA+, we believe in realising grand solutions with the extremely small. We contribute to solving current and future societal challenges. We do this by using our fascination with the extremely small. We bring societal challenges inside and use our fascination to work on innovative and sustainable solutions. We focus on societal challenges in four application areas: Health, AgriFood & Water, Security, and Energy & Sustainability.

With our research, we contribute to a fair, sustainable and digital society.

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An extremely small number:

0.000 000 000 000 000 01 (=10^{-17})

≈ energy cost per switch event for a modern transistor, in Joules

(= 0.000 000 01 nJ)

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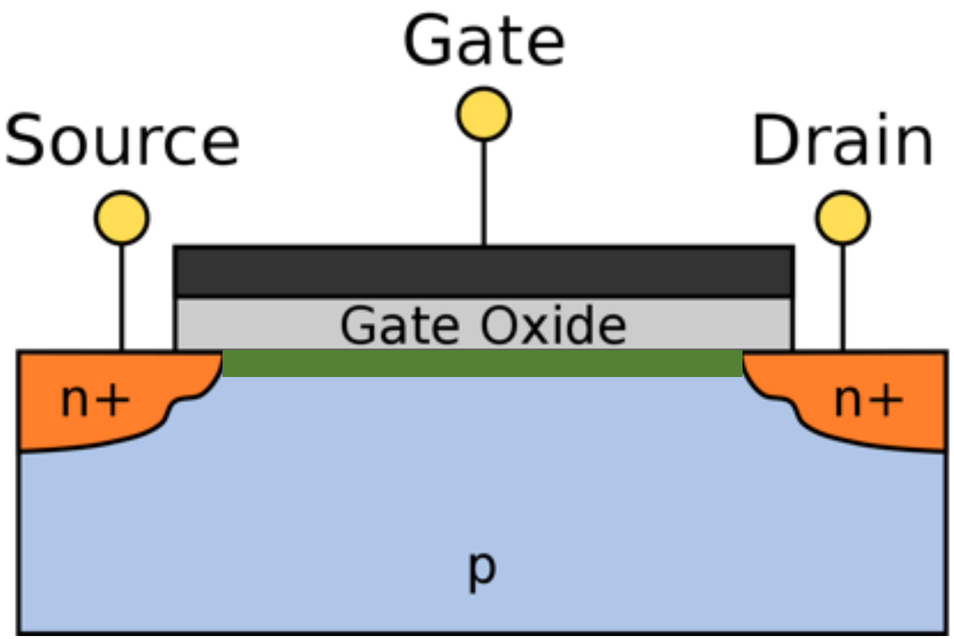
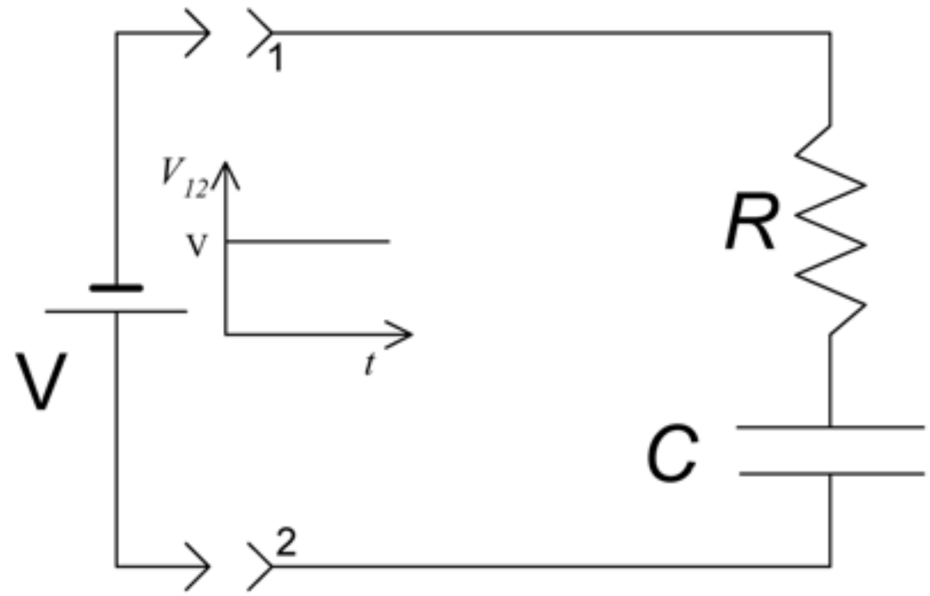
Transistor (MOS-FET)





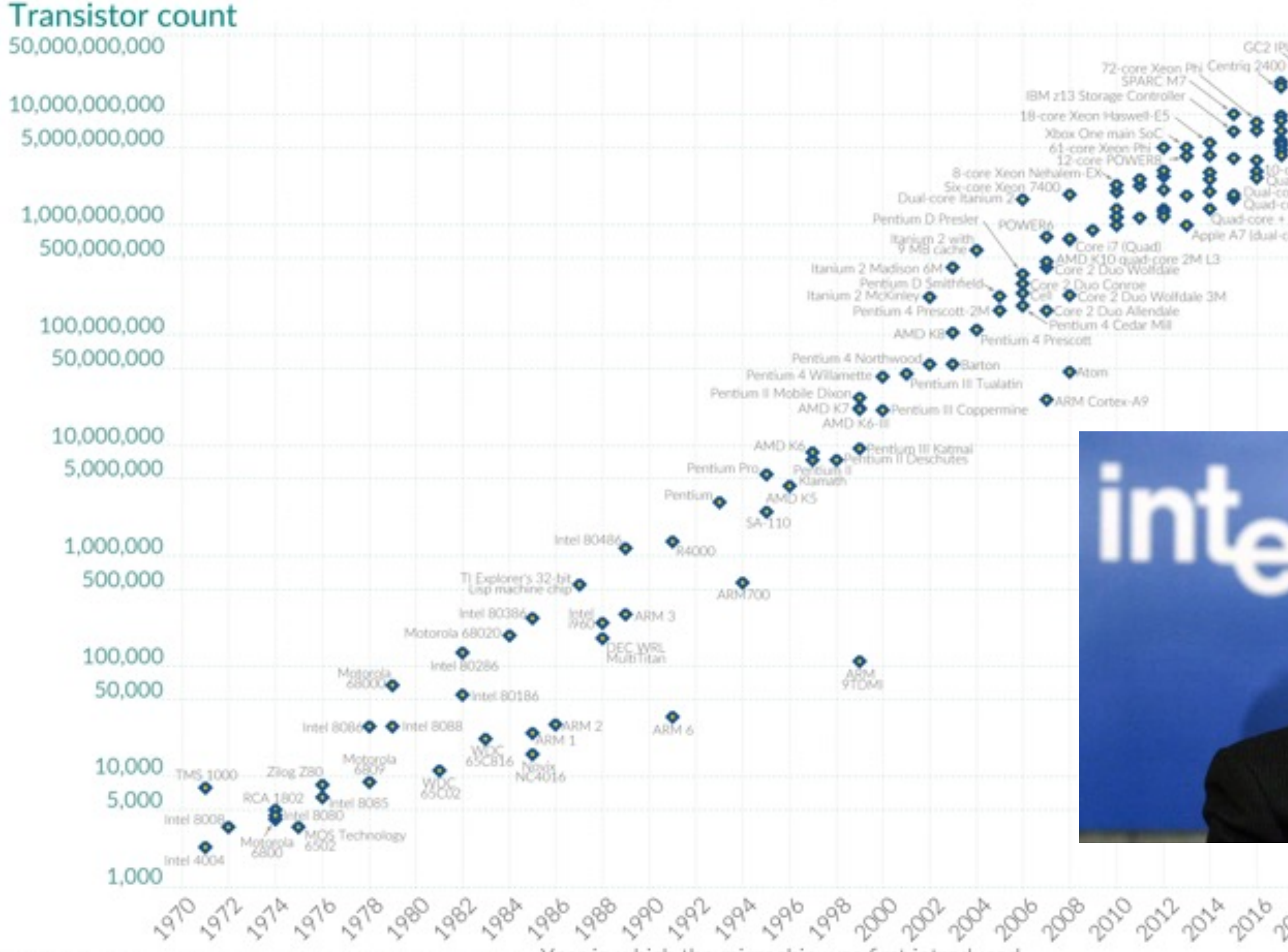
$$E = ½\, CV^2$$

Characteristic charging time is *RC*

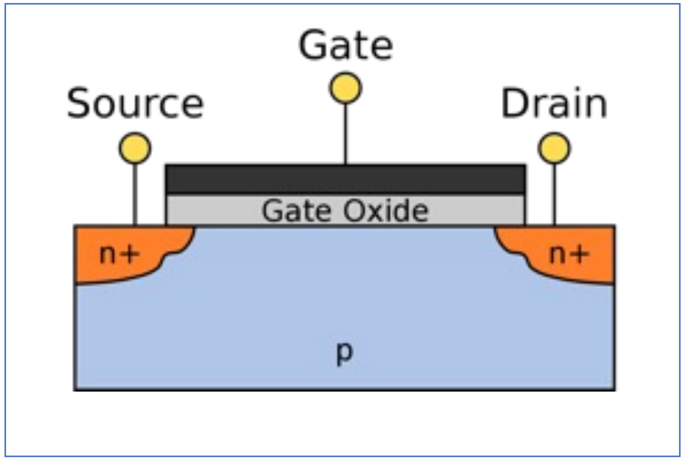
Moore's Law: The number of transistors on microchips doubles every two years

Our World in Data

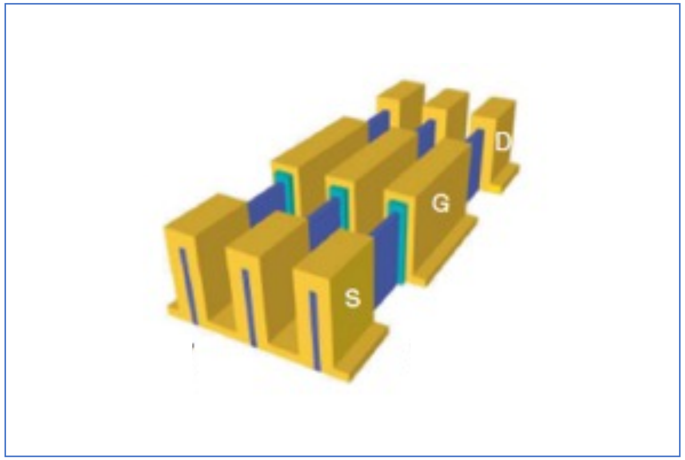
Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years.
This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.



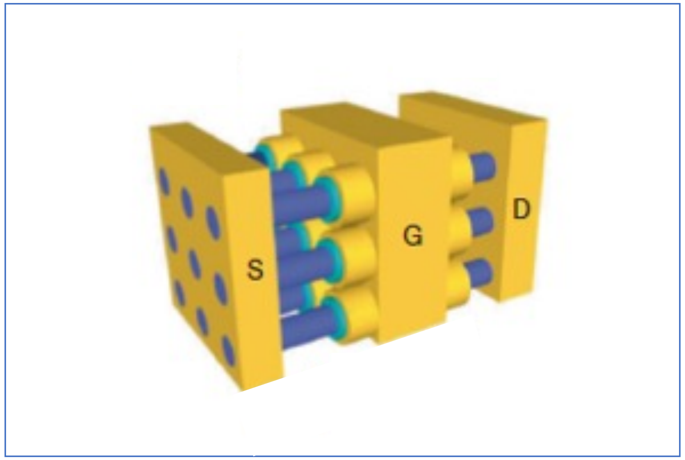
Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)
OurWorldinData.org – Research and data to make progress against the world's largest problems.



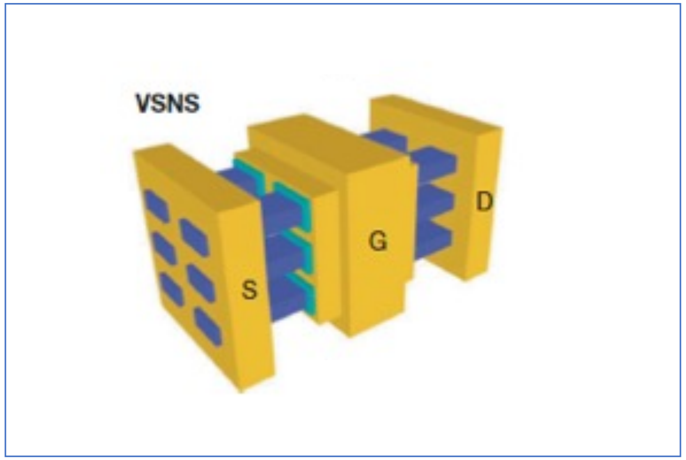
planar MOS-FET



Fin-FET

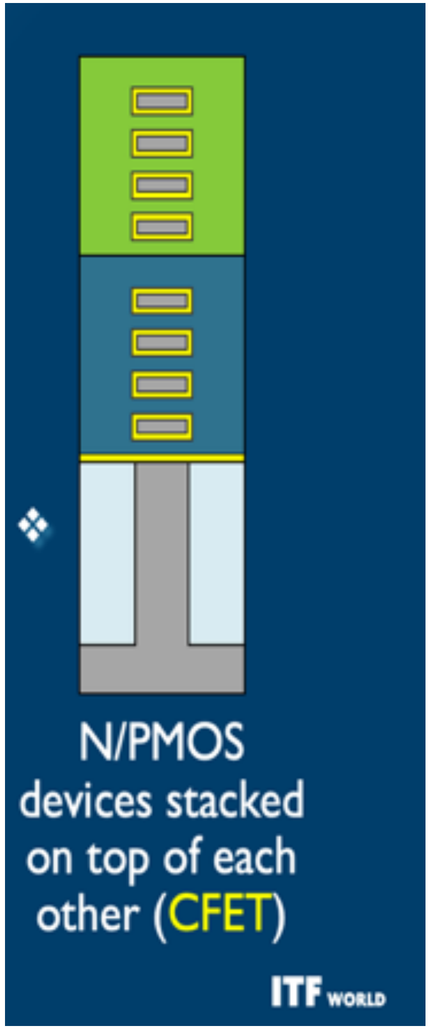


Gate all around-FET

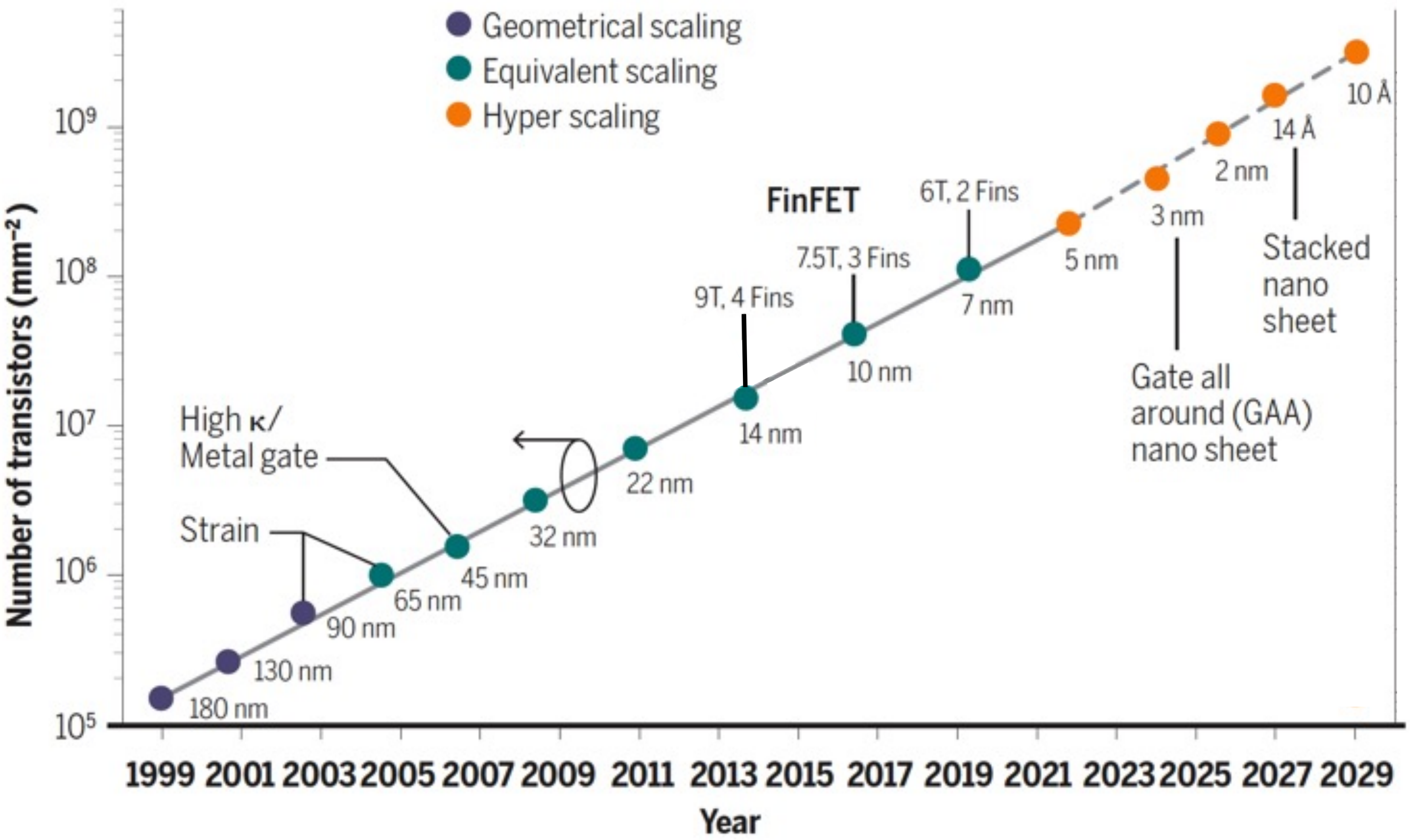


Vertically stacked nanosheets-FET

W. Cao *et al.*, *Nature* 620, 501 (2023)



IMEC (ITF World Forum, 2023)



Datta *et al.*, *Science* 378, 733 (2022)

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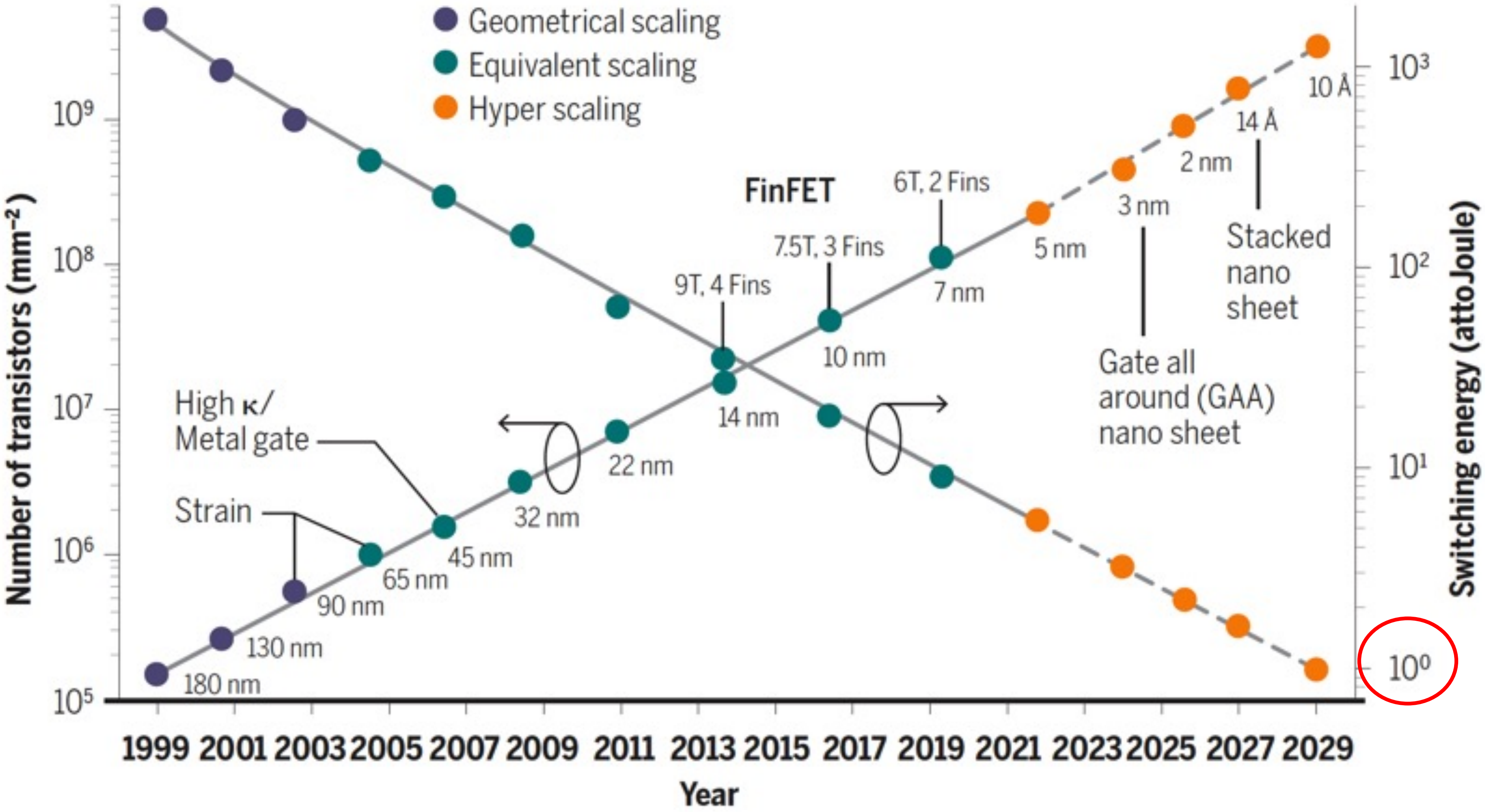


Datta *et al.*, *Science* 378, 733 (2022)

Opportunities for complex oxide research in the context of ‘more Moore’:

Concepts and materials for next generations CMOS:
2D materials (properties and synthesis), CMOS configurations (tunnel FETS etc), novel dielectrics, ferroelectrics, high-mobility / low scattering materials, low contact resistances, etc.

Materials transferring concepts (e.g., using nano-sheets)

Merging functions like sensing, imaging and information processing ’at the edge’;
(a.k.a.: ’More than Moore’)
Many possibilities for e.g.: CMOS-based chip design, (’chiplet’-)integration with photonics, biochemical devices, NEMS, local energy harvesting/storage devices, etc.

Thermal management (fluidics/gas/foams, thermal diodes, thermoelectrics)

Let’s also look outside of the Moore box

An extremely big number:

1 000 000 000 000 000 000 000 000 000 000 000 000 000

= estimated number of transistor switch events per year worldwide (10^{36})

SIA/SRC Decadal Plan for Semiconductors (2021)

A big number times a small number can still be a big number ...

$$1000000000000000000000000000000000000 \quad (10^{36})$$

$$\times$$

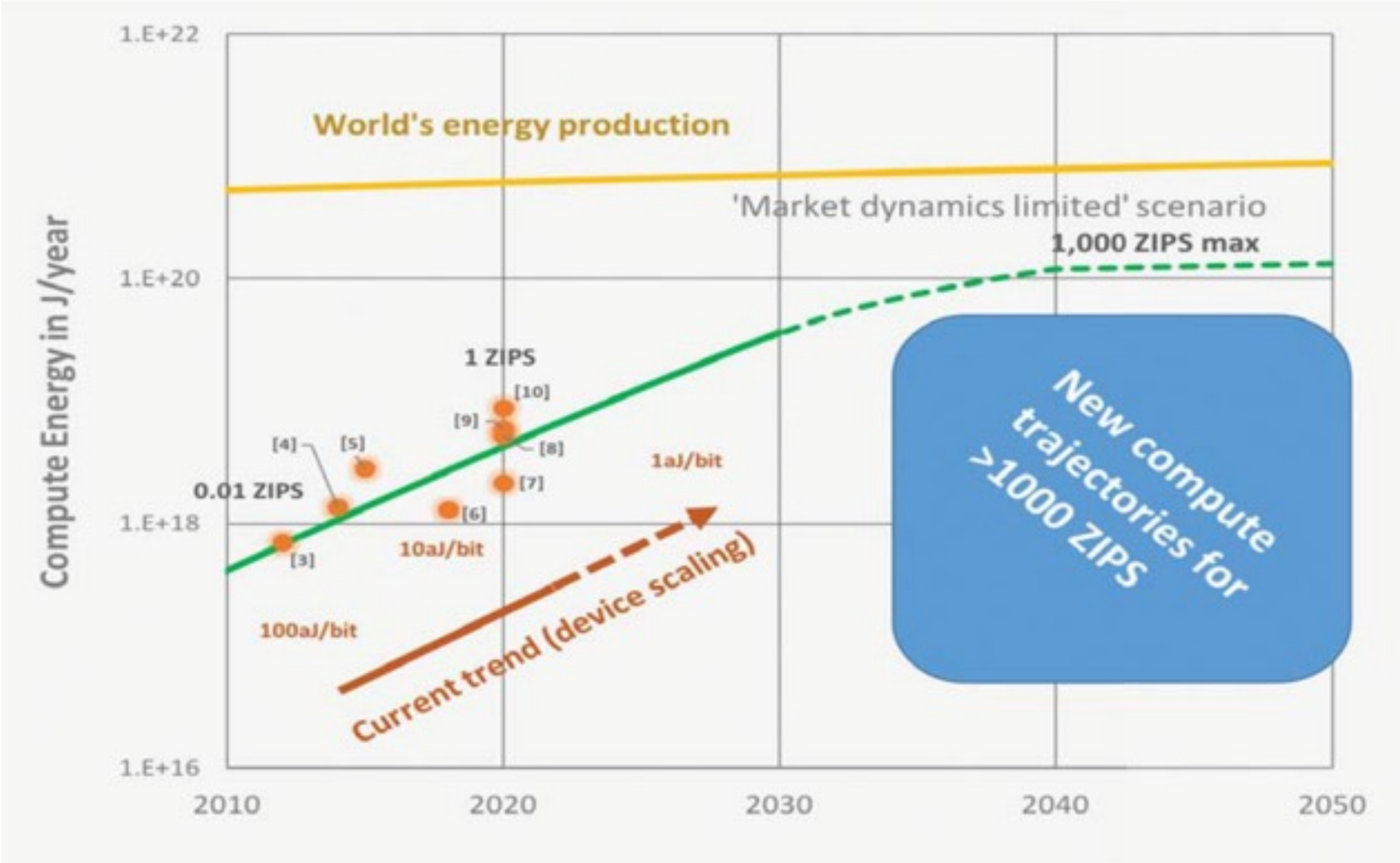
$$0.00000000000000001 \quad (10^{-17})$$

$$=$$

$$10\ 000\ 000\ 000\ 000\ 000\ 000 \quad (10^{19})$$

≈ Energy consumption transistor switching worldwide per year in Joules

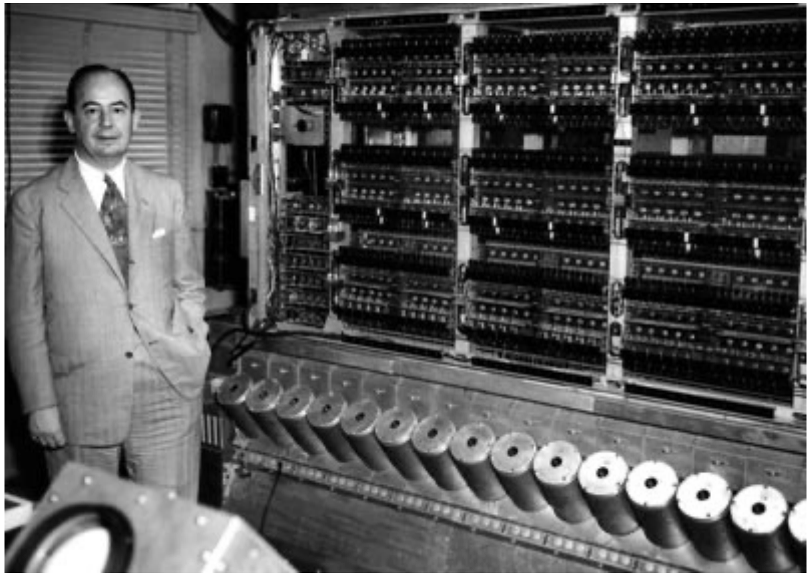
Problem: Energy consumption of computing is large and increasing



SIA/SRC Decadal Plan for Semiconductors (2021)

Currently: approx. 10^{36} transistor switches / year
Moving towards $> 10^{42}$ transistor switches / year in 2050

In addition: Von Neumann computing involves separation of processing and memory



Data-transport and read/write operations:

On chip (SRAM):	fJ/bit
Off chip nearby: DRAM/USB/Harddisk:	pJ/bit – nJ/bit
External (e.g. data centers)	nJ/bit – □J/bit

John von Neumann
(1903 – 1957)

Why do we need new computing technologies?

1 training: 9,200 GPUs 2 weeks: 1,287MWh
enough for 120 households for 1 year
CO_2 emissions equal to 1300 cars in 1 year.

~ 250 TWh per year
4.5 billion searches per day, more than
1.4 million kilograms of CO_2 per day

Growth of energy use is not sustainable

1: Brown, T. et al. Language models are few-shot learners. Adv. Neural Inf. Process. Syst. 33,1877.
1.D. Patterson, et.al, The Carbon Footprint of Machine Learning Training Will Plateau, Then Shrink, arxiv (2022)
2.L.F.W. Anthony, et.al, "tracking and predicting the carbon footprint of training deep learning models", arxiv 03051 (2020).
3.N. Jones, "How to stop data centres from gobbling up the world's electricity. Nature, (12 September 2018).

NOS Nieuws · Sport · Live · Programma's

NOS Nieuws • Woensdag 30 september 2020, 17:05

Opening grootste windpark van Nederland; meeste stroom naar datacenter Microsoft

Heleen Ekker
redacteur Klimaat en Energie

In de Wieringermeer is het grootste windpark op land van Nederland geopend. Voor de eigenaar van het park, het bedrijf Vattenfall, betekent het een feestje, voor een aantal omwonenden een bittere pil. Zij voelen zich onvoldoende serieus genomen in hun bezwaren tegen het park.

Een van de dingen die ze stoort, is dat veel groene stroom naar een datacentrum van Microsoft gaat. De molens kunnen stroom opwekken voor 370.000 huishoudens, maar het grootste deel van de elektriciteit gaat naar dat datacentrum, in het nabijgelegen Middenmeer.

fd. Mijn nieuws · Net binnen · Beurs · Krant · Podcasts

Analyse • 9 aug 12:19

Waterslurpende datacenters verergeren de gevolgen van hete zomers

Clara Hernanz Lizarraga, Olivia Solon

Wereldwijde watertekorten leiden tot conflicten tussen AI-bedrijven die steeds meer koelwater nodig hebben en de bewoners van gebieden waar die centers zijn gevestigd. De enorme rekenkracht nodig voor AI doet de vraag explosief stijgen.

De plek waar het nieuwe datacenter van Meta Platforms gebouwd moet worden op de droge vlakte even buiten Talavera de la Reina in Spanje. Geschat koelwaterverbruik: piekverbruik tot 195 liter per seconde, 665 miljoen liter water per jaar. Foto: Paul Hanna/Bloomberg

Urgent interest in alternative energy-efficient concepts

blending in with ongoing developments in CMOS according to Moore’s law.

From ’Beyond Moore’ to ’Besides Moore’

-> Role for academic research to explore new concepts

’Besides Moore’, possible directions:

Approximate/probability computing

Heterogenous integration of electronics / photonics / spintronics / ’any-other-onics’
(combining the best of different domains, requires good interfaces)

Analog/digital combinations

Cryo-CMOS and other low temperature concepts

Quantum Computing

Neuromorphic computing

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$$256 \times 11 = ?$$

$$256 \times 11 = 2816$$

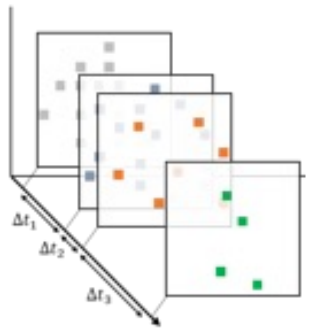
Application: Neuromorphic computing

ULPEC

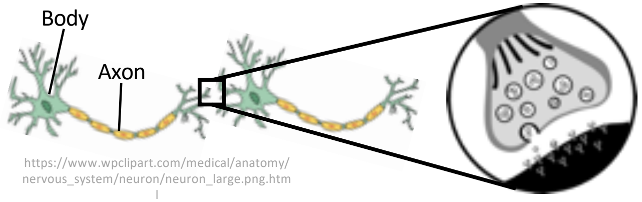
Brain-inspired processing unit

http://www.stevefloyd.me/neuromorphic-computing-race-brain-chips/

Dynamic vision sensor



Synaptic plasticity



https://www.wpclipart.com/medical/anatomy/nervous_system/neuron/neuron_large.png.htm

http://www.clker.com/clipart-26784.html

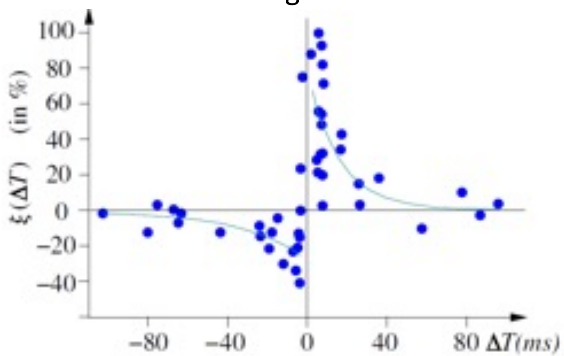
Spike time-dependent plasticity

$\Delta t = t_1 - t_2 > 0 \rightarrow$ synaptic strength is increased

$\Delta t = t_1 - t_2 < 0 \rightarrow$ synaptic strength is decreased

$\Delta t > \pm 80\ ms \rightarrow$ no change

"Learning function"

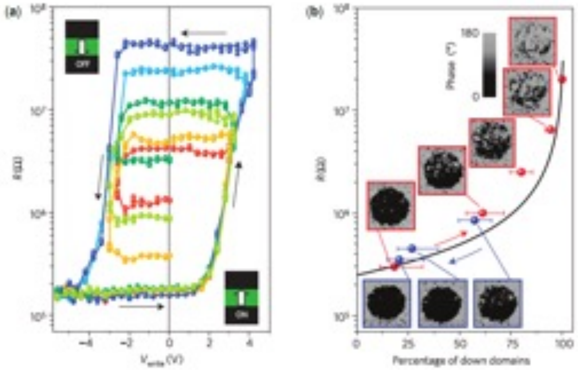


Saighi, S., *Frontiers in Neuroscience*, *9*, 1–16.

Si-STO(4nm)//$SrTiO_3$(40nm) buffer

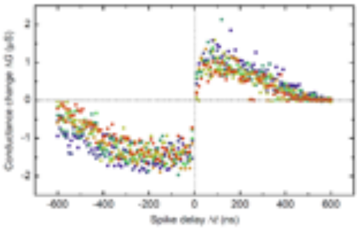
Memristive FTJs

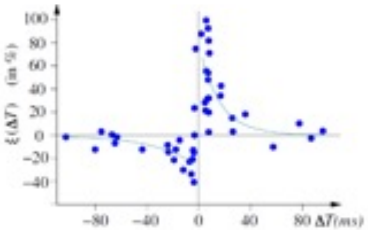
Stack: NGO(001)//LSMO(30nm)/BTO(2nm)/Co(10nm)/Au(10nm)



Chanthbouala, (2012). *Nat Mater*

“Learning function”

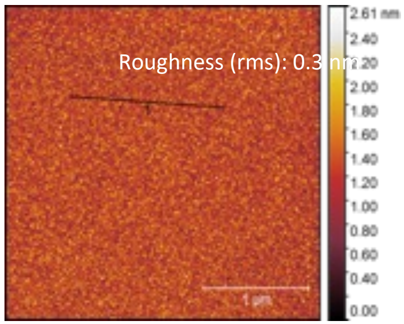


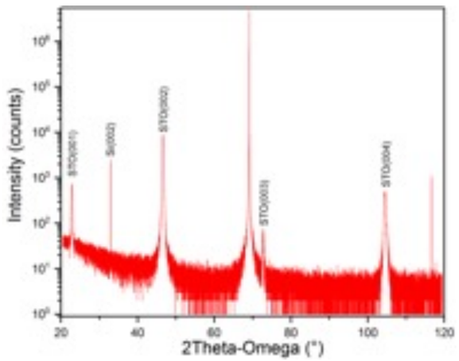


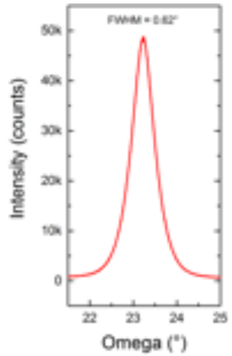
Saighi, S., *Frontiers in Neuroscience*, *9*, 1–16.

Heterostructure: $SrRuO_3$/2nm $BaTiO_3$

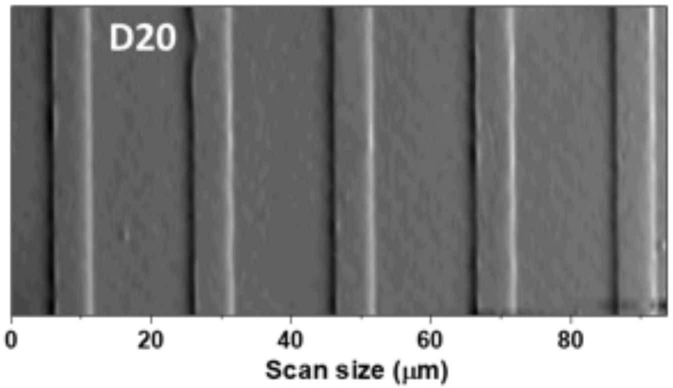
0.001 mbar O2	600 °C	2 Hz	1.3 J/cm²

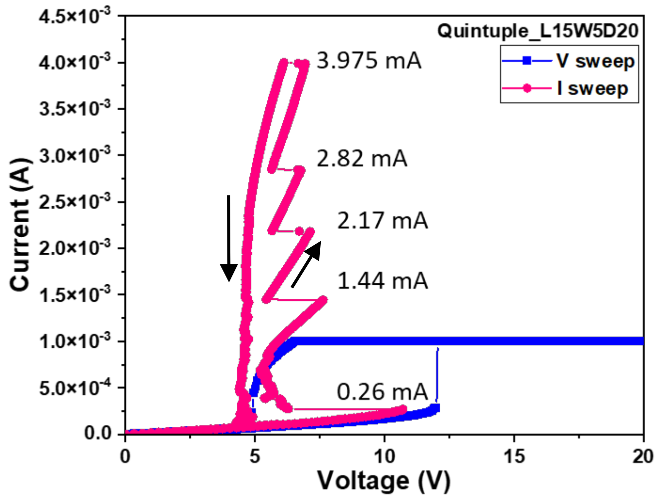


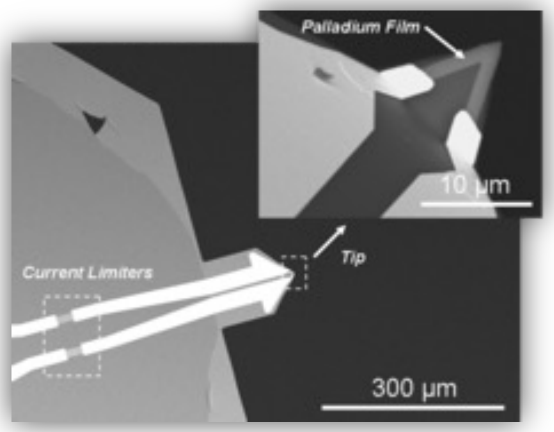


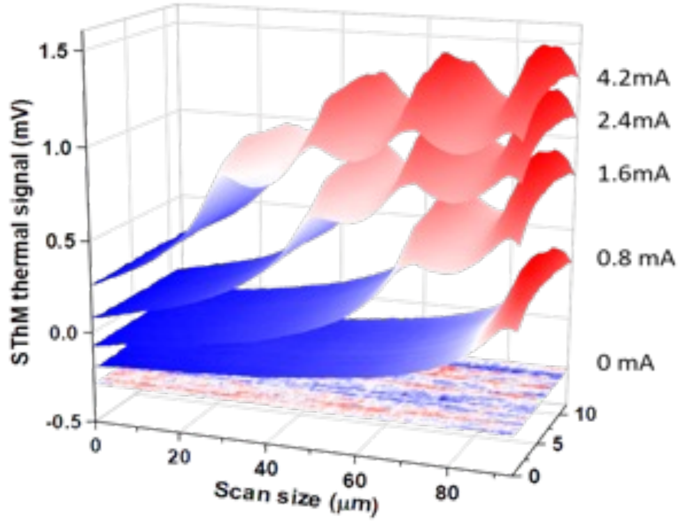


Multiple VO_2 bridges in parallel









Scanning Thermal Microscopy

X. Gao, T. Roskamp, T. Swoboda, C.M.M. Rosário,
S. Smink, M. Muñoz Rojo, H. Hilgenkamp, *Adv. Electr. Mater.* (Sept. 2023)

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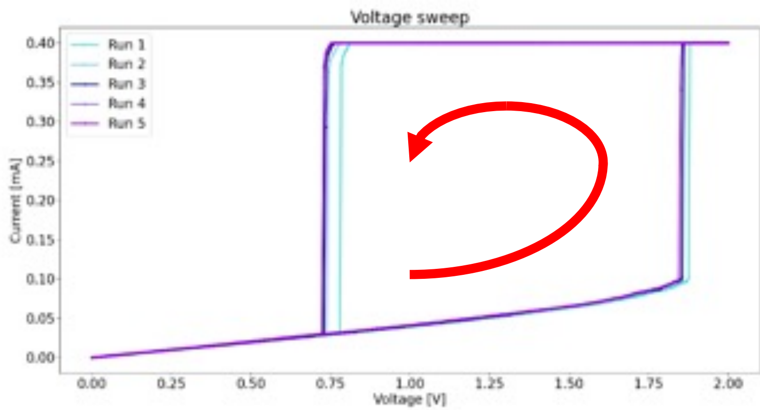
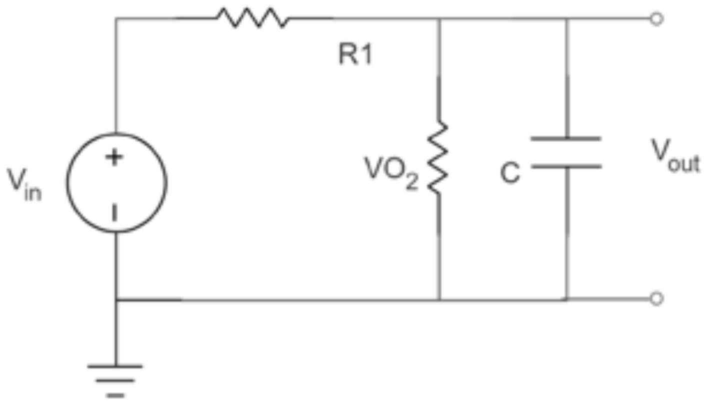
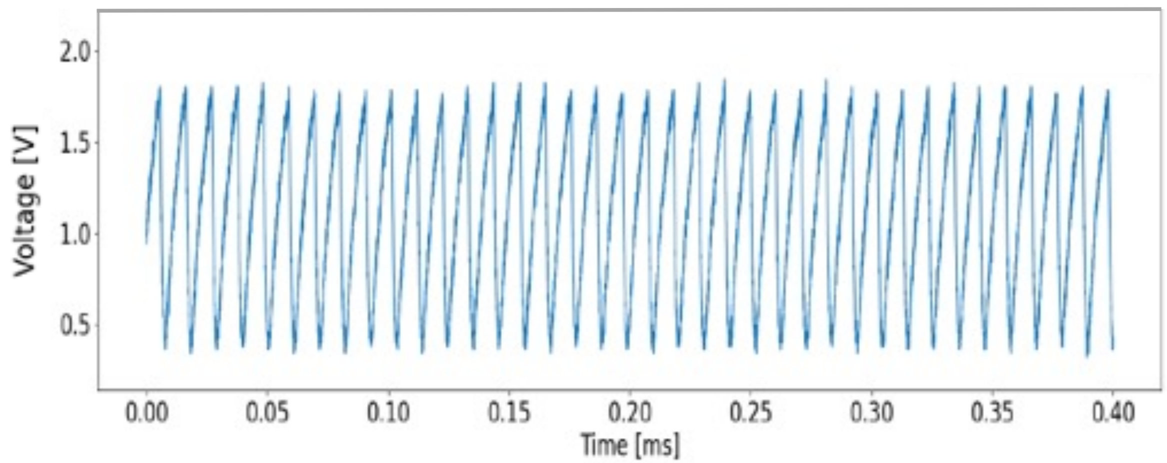
Artificial Neurons in VO_2







Renske van Poppelen,
Bachelor thesis (2023).

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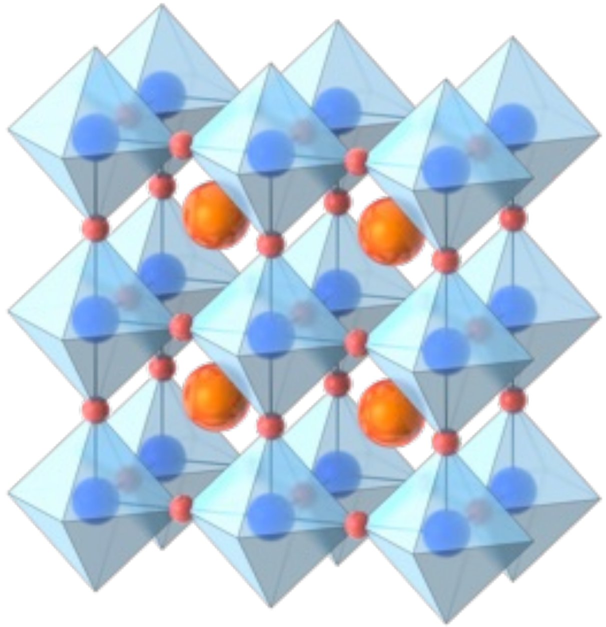
Transition metal oxides exhibit a wide range of functionalities due to the unique electronic and structural properties of transition metals. Here are some key functionalities :

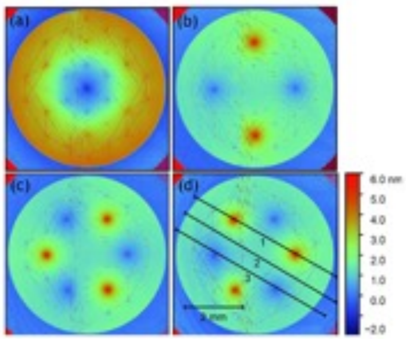
1. **(Photo)-Catalysis**
2. **Magnetic Properties**
3. **Electrical Conductivity**
4. **Superconductivity**
5. **Optical Properties**
6. **Ion Storage and Batteries**
7. **Gas Sensing**
8. **Ferroelectricity and Piezoelectricity**



ABO_3 perovskite

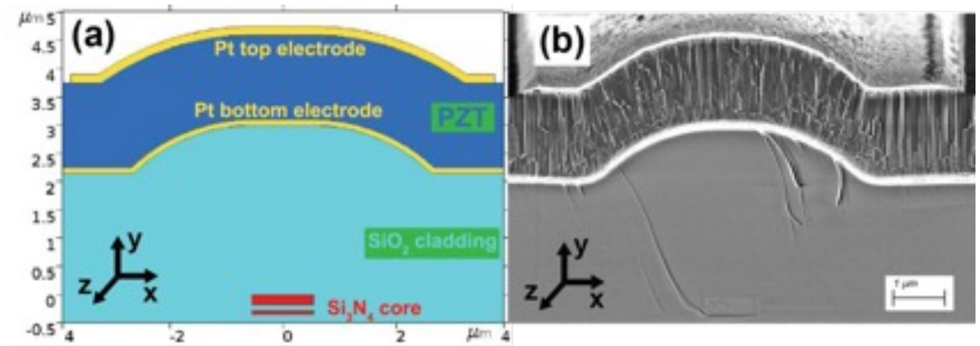
These functionalities arise from the diverse electronic configurations and bonding characteristics of transition metal oxides, making them versatile materials in various scientific and industrial fields.

Large area oxide thin film growth (100 mm and above) for Ferroelectric/Piezoelectric applications



Adaptive optics for XUV lithography

Optics Letters Vol. 44, Issue 20,
pp. 5104-5107 (2019)

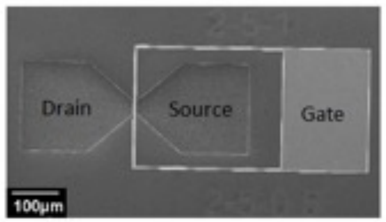


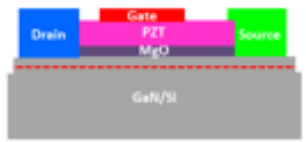
Ultra-low power stress based phase actuation in SiN (quantum) photonic circuits

doi: 10.1117/12.2609405

PiezoMEMS sensors and actuators

Adv. Energy Mater. 2022, 12, 2200517
ACS Appl. Mater. Interfaces 2016, 8, 45, 31120–31127
J. Phys.: Conf. Ser. 922 012022



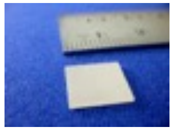


High Power GaN field effect transistors

Journal of Crystal Growth, 538, 15 May 2020, 125620

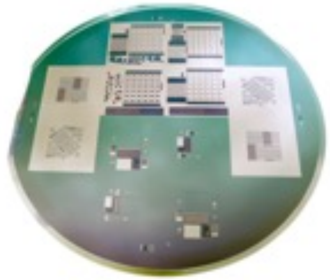
- Large area deposition; PLD, sputter depostion, MBE, ….
- Epitaxial growth on non oxide/crystalline substrates; Si, Glass, ….
- How to deal with inhomogeneous deposition; growth rate, composition

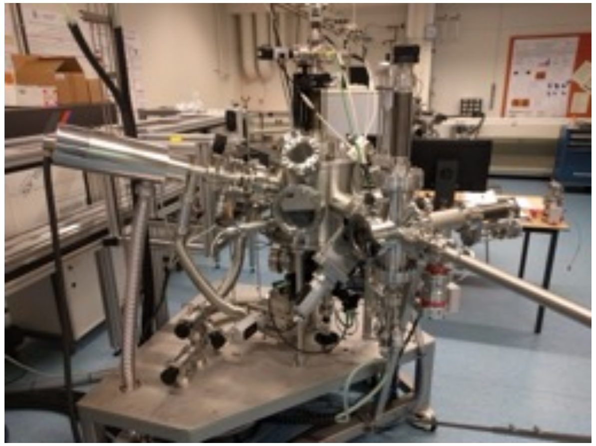
Pulsed Laser Deposition:
From Lab-scale to Industrial-scale



Up to 100 mm

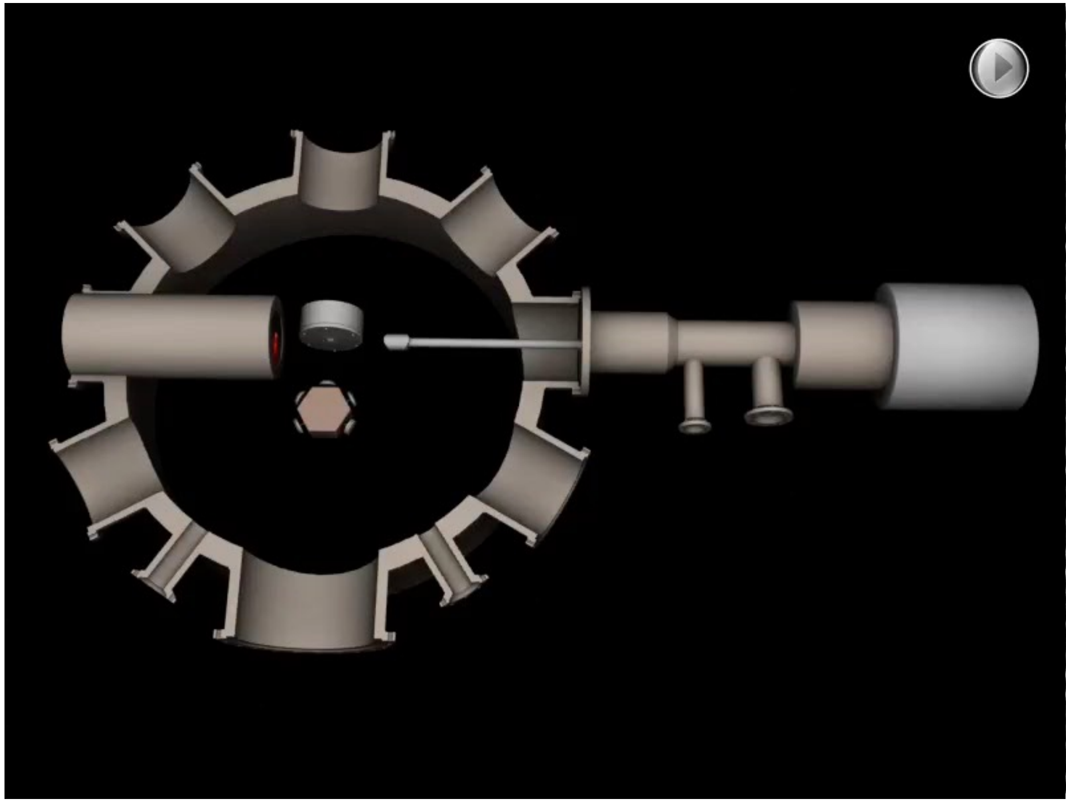
Up to 300 mm

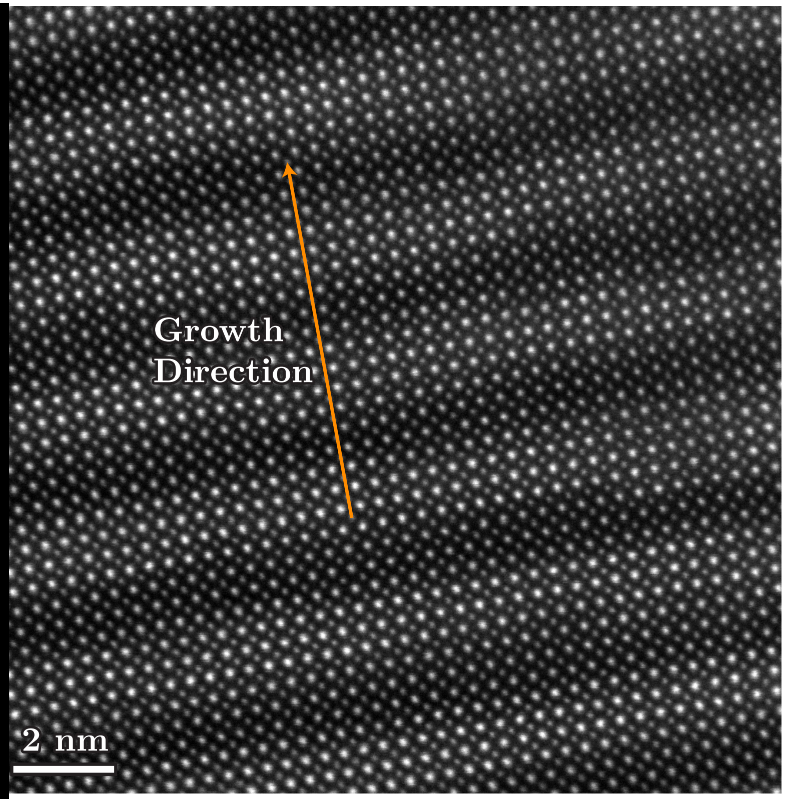




DEMCON | TSST

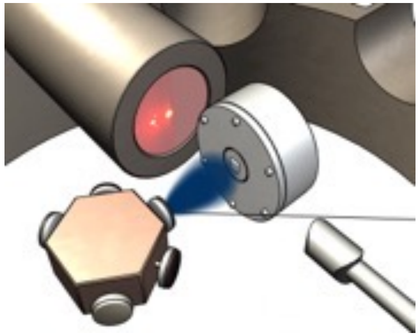
SOLMATES
THIN FILM EQUIPMENT
A Lam Research Company



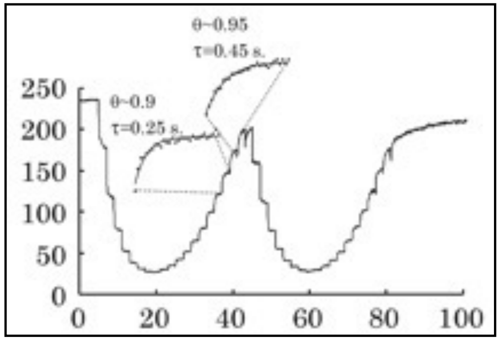

Growth
Direction
2 nm

Atomic controlled epitaxial growth by PLD
Lessons learned

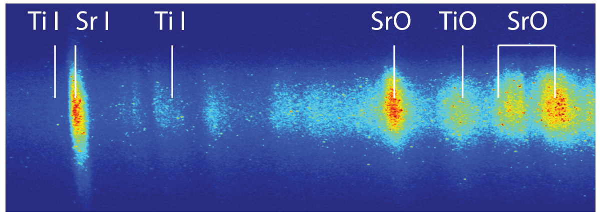
Single termination of perovskite substrates



In-situ growth control



Understanding growth mechanism, nucleation and growth



Understanding role of chemistry/physics of deposited particles

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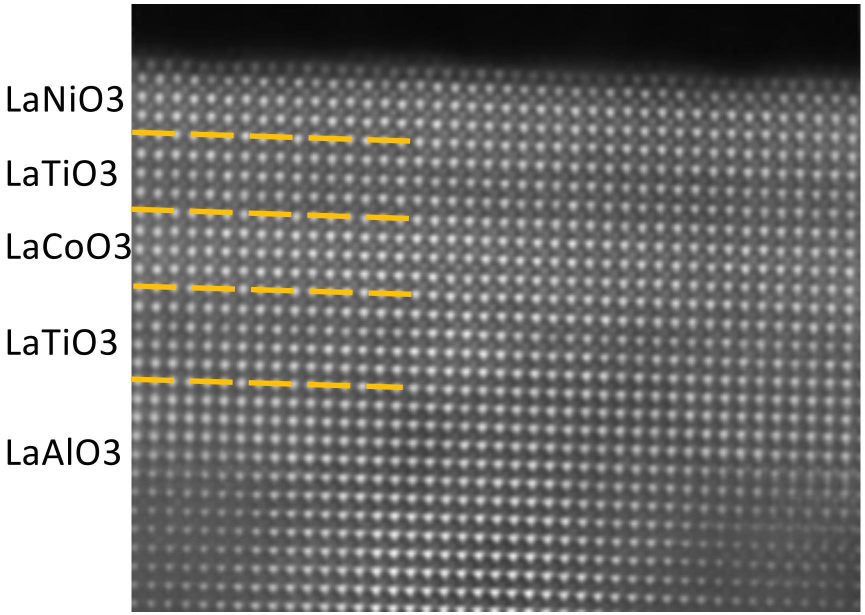
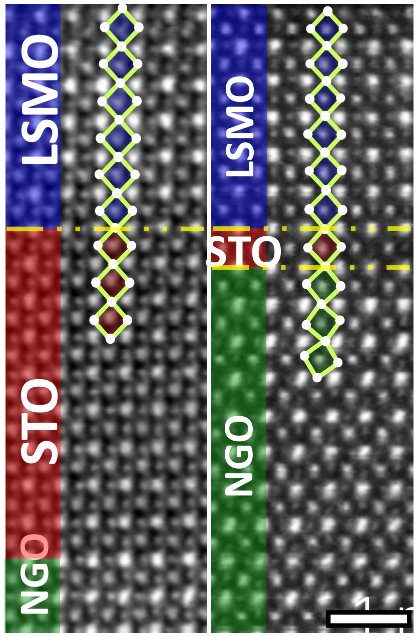
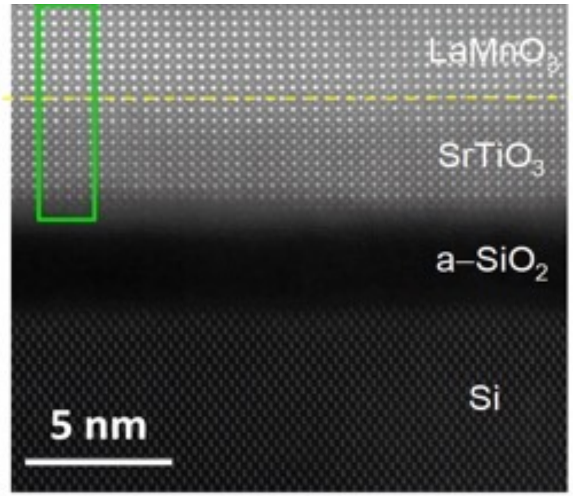
Epitaxial heterostructures



Charge transfer at interface of
$LaCoO_3$-$LaTiO_3$
J. Geessinck, GR, et al,
https://doi.org/10.1103/PhysRevMaterials.4.026001

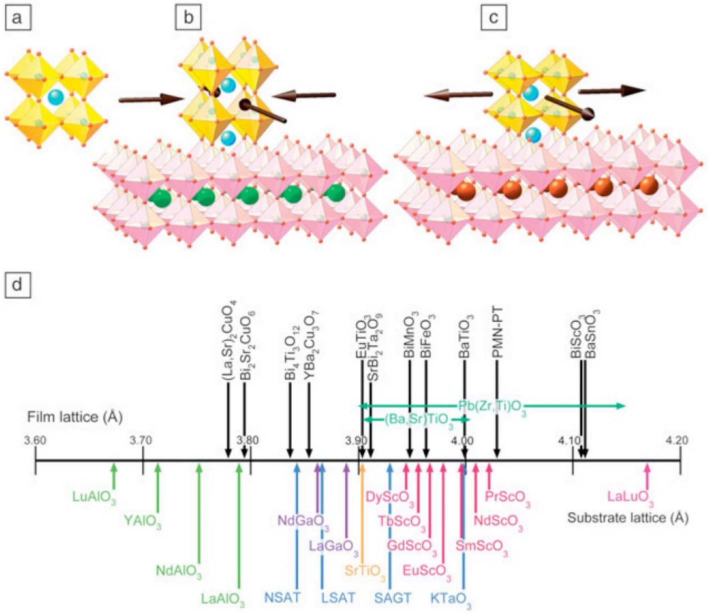


Symmetry transfer
Manipulate magnetic anisotropy
In (La,Sr)MnO_3
Z. Liao, GR, et al, Nature Materials volume 15, pages 425–431 (2016)



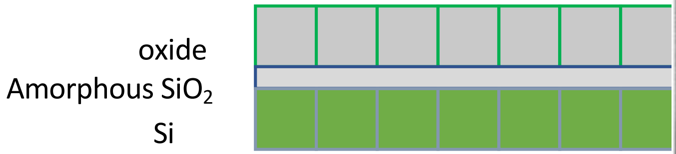
Complex oxide epitaxy on
Silicon.
Darrell Schlom, Cornell
Jean Fompeyrine, IBM, Lumiphase

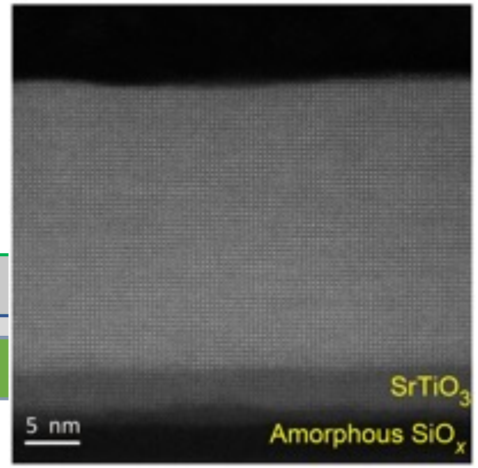
Prominent features of oxide-Si integration: **buffer layer** and **thermal tensile strain**



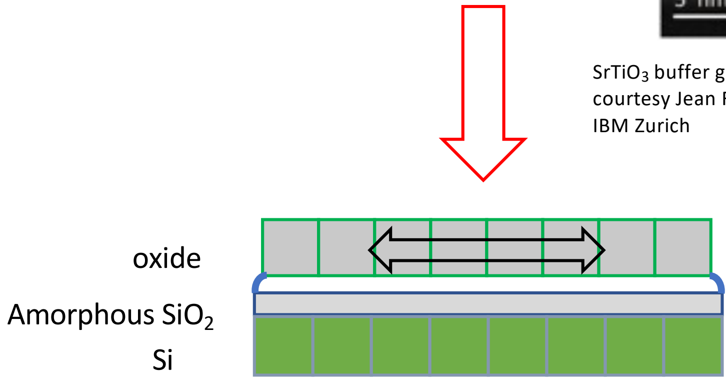
Epitaxial strain induced by lattice mismatch

Epitaxially strained or relaxed at high temperature





$SrTiO_3$ buffer grown by MBE, courtesy Jean Fompeyrine, IBM Zurich

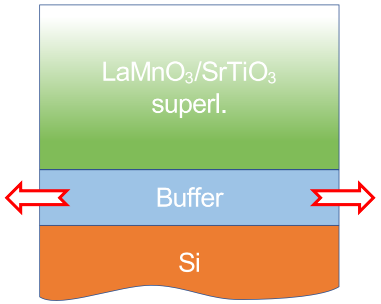


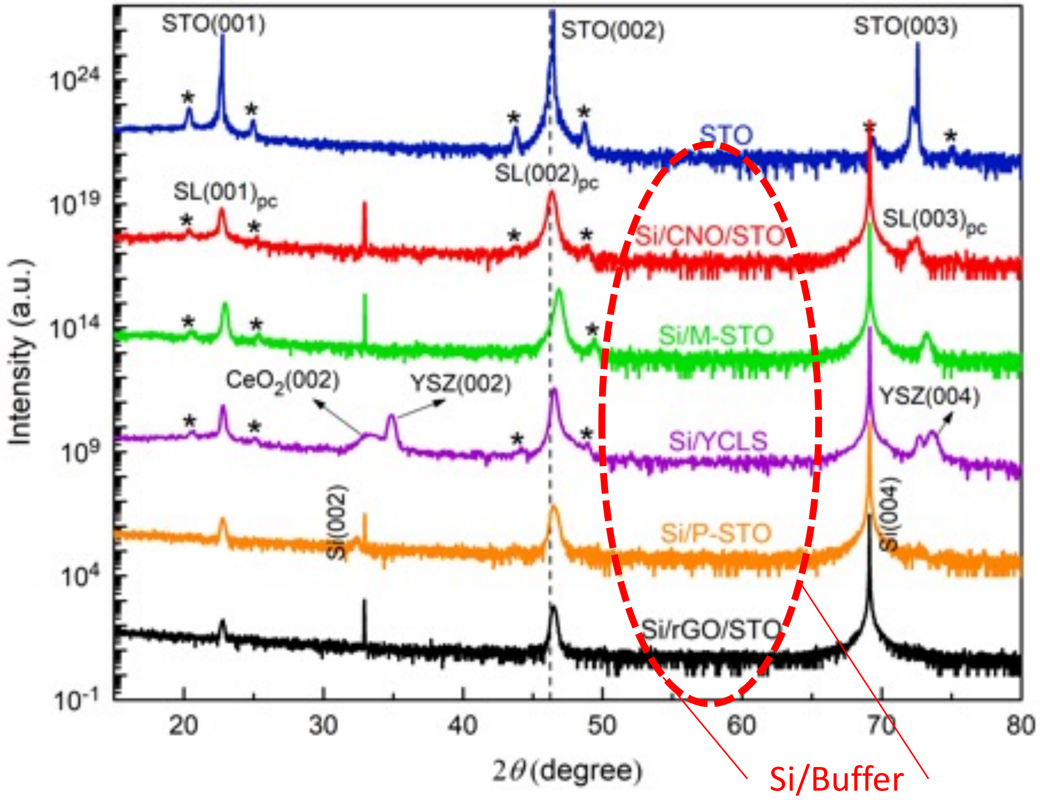
Tensile strained after cooling down

Thermal expansion coefficient α: $\alpha_{oxide} >> \alpha_{Si}$

Thermal strain scales with the temperature difference between growth and final operating temperature.

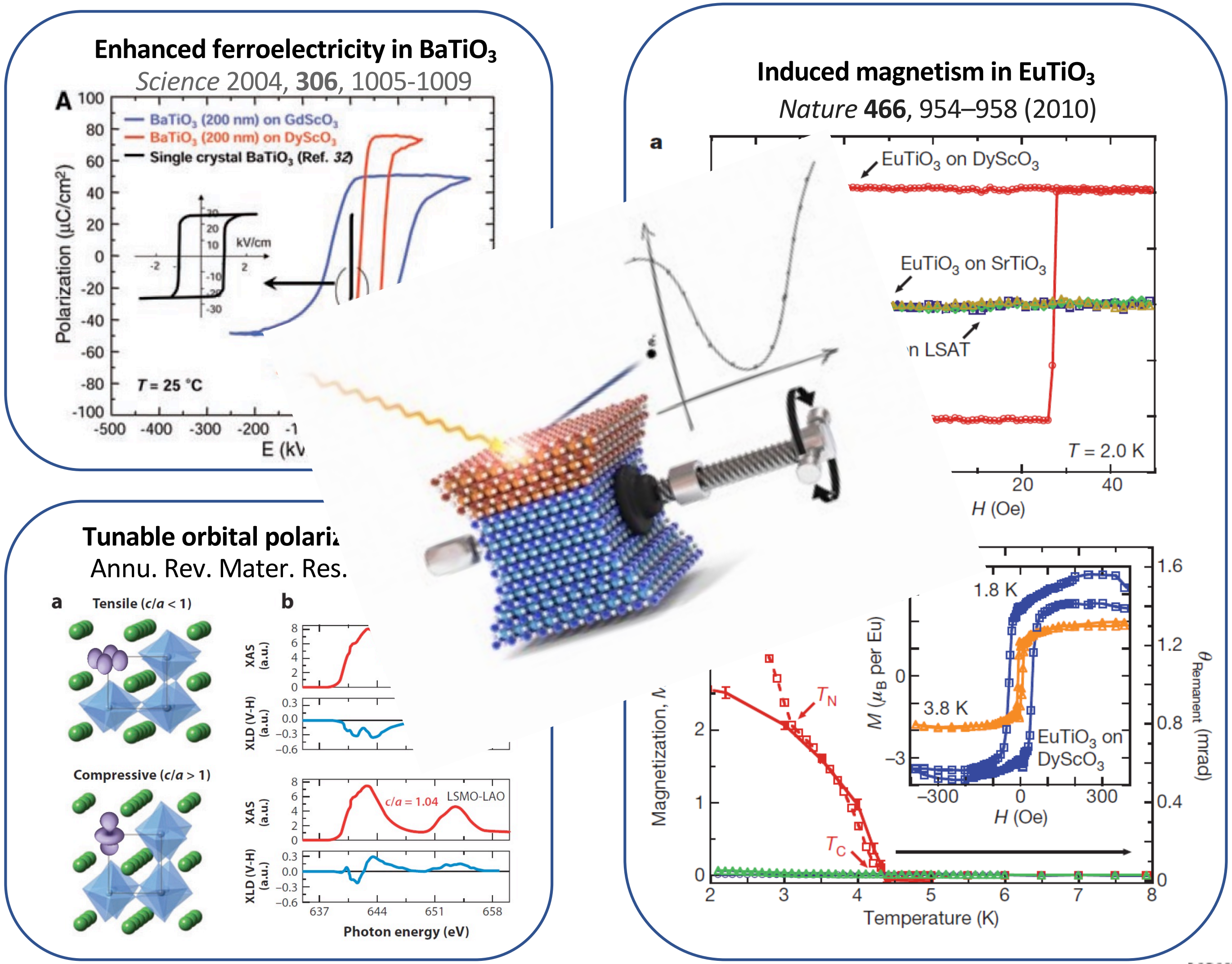
Integrating $LaMnO_3/SrTiO_3$ superlattices on silicon using various template techniques:



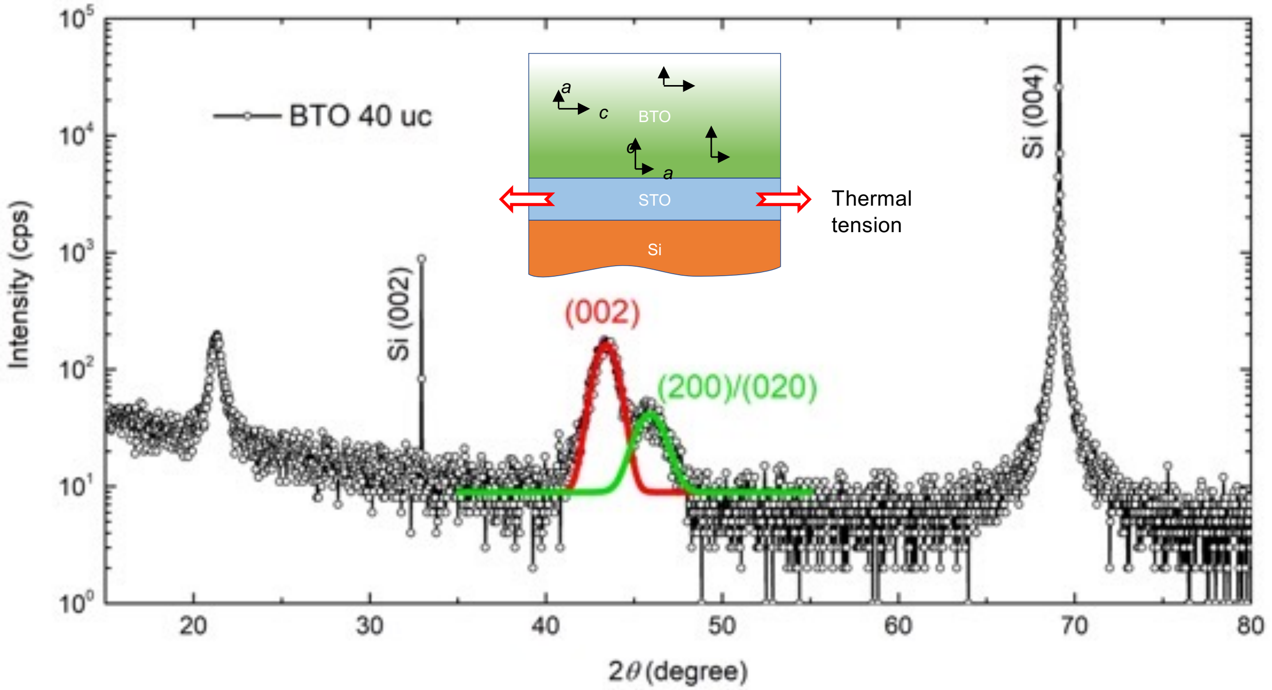


Chen, GR et al, ACS Appl. Mat.&Int.

Strain and oxide functionalities: charge, spin, orbital

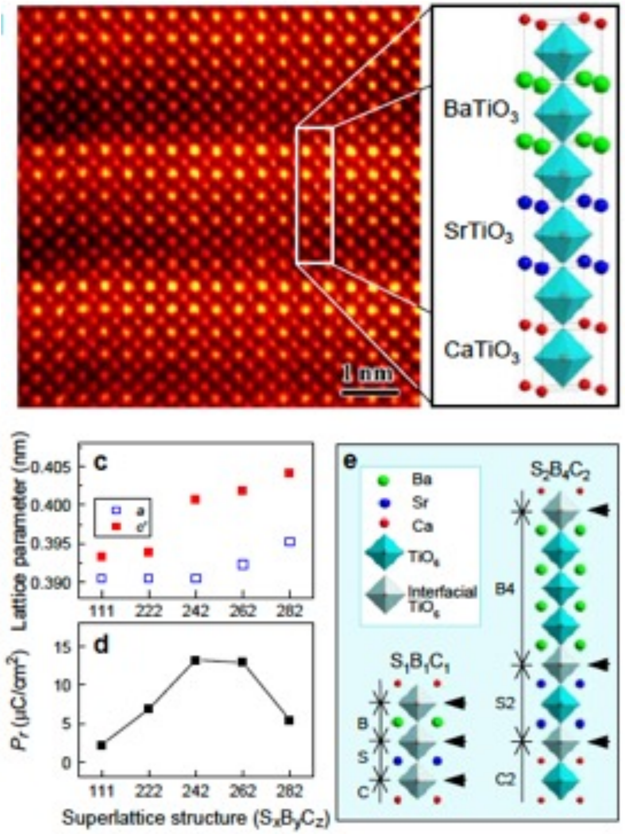


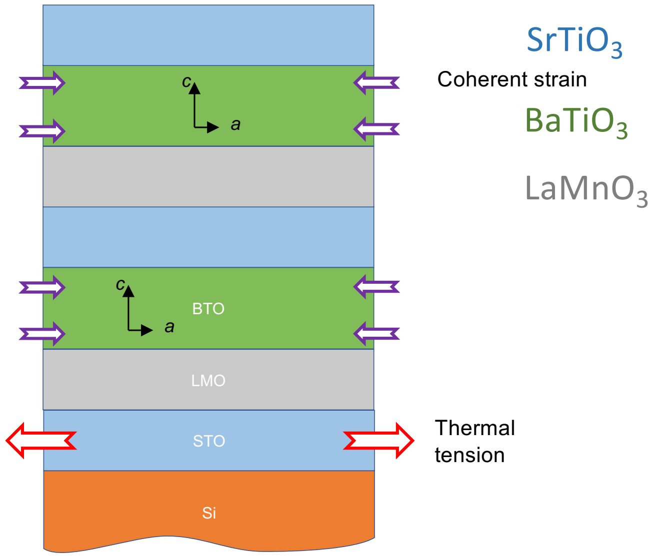
Multi-domain states in $BaTiO_3$ single films grown on Si/$SrTiO_3$:



X-ray diffraction of a 40-uc thick BTO film grown on Si/STO. The double-peak feature clearly shows the coexistence of *a*- and *c*- domains, consistent with previous reports (Nature Nanotechnology **8**, 748 (2013); Nature Communications **4**, 1671 (2013); Nanotechnology **24**, 285701 (2013)).

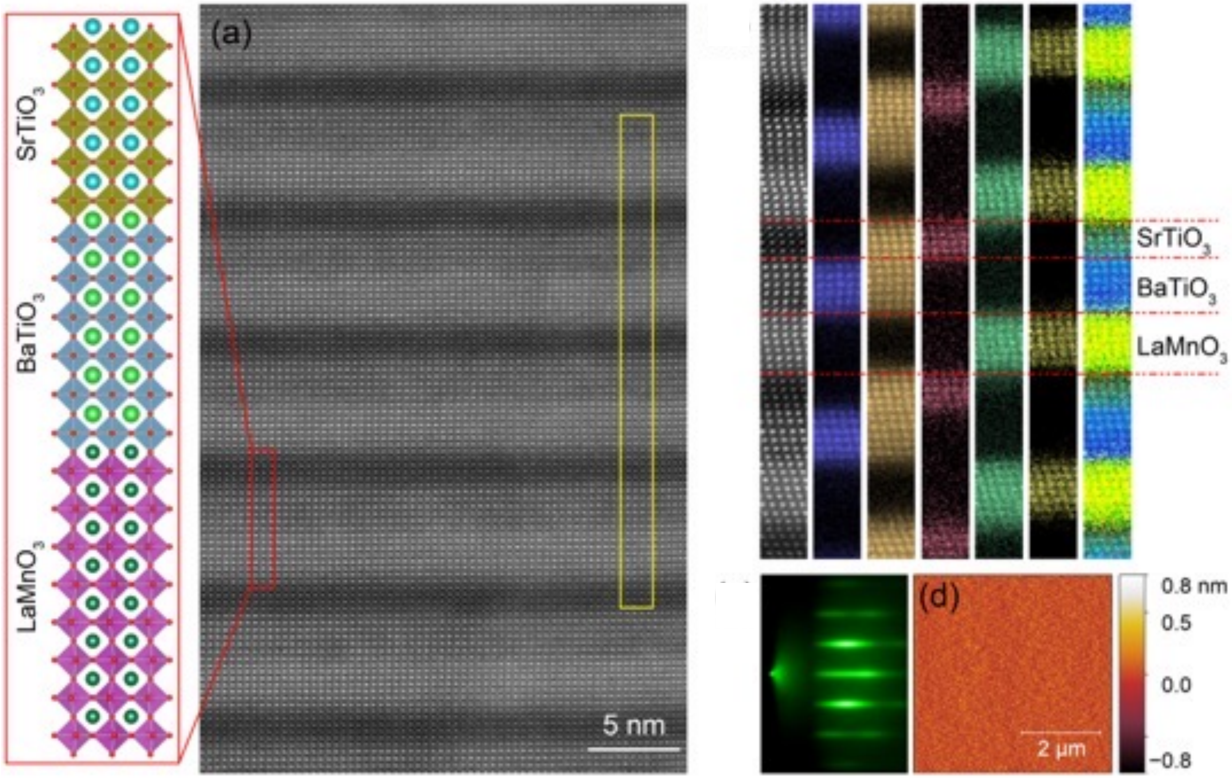
$BaTiO_3$ in three component ferroelectric superlattices





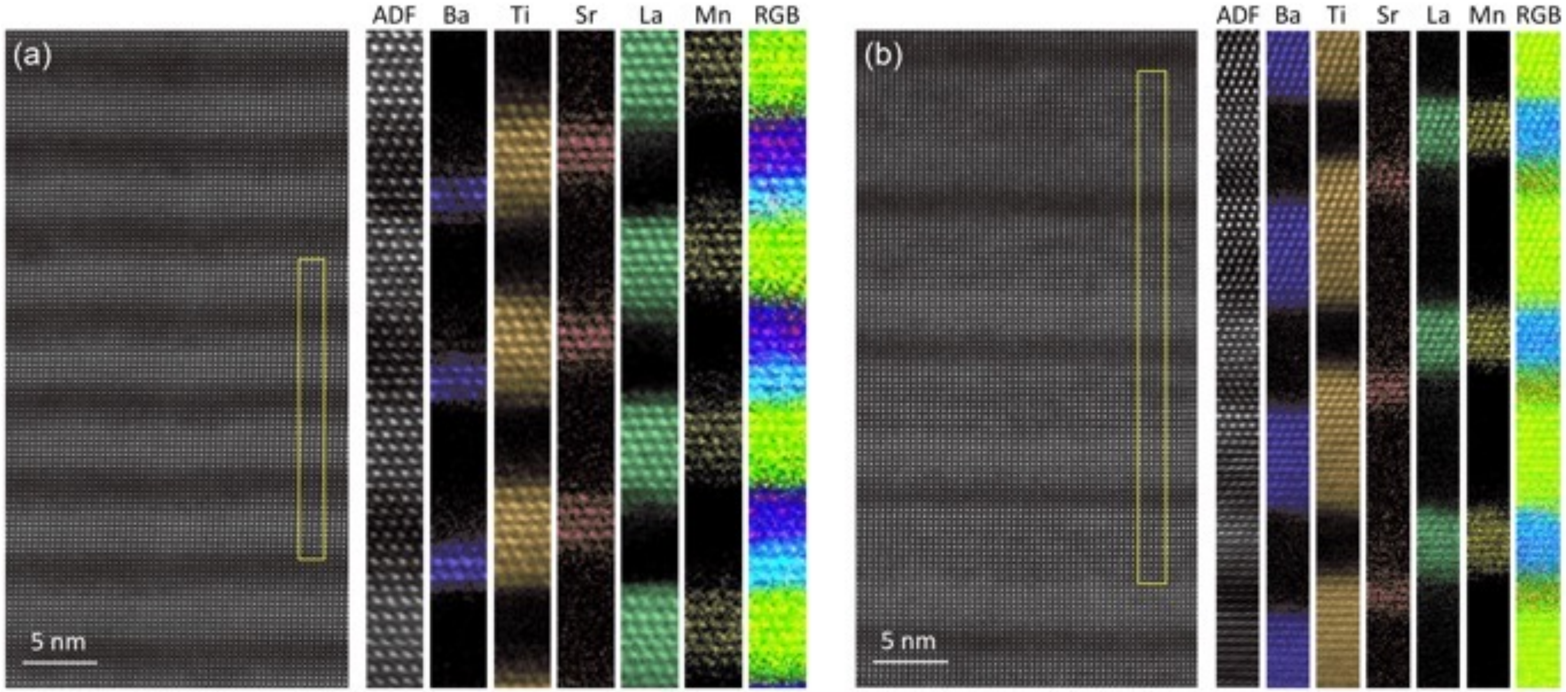
Strong polarization enhancement in asymmetric three component ferroelectric superlattices
Ho Nyung Lee, Nature 433, 395-399 (2005)

Structural characterization

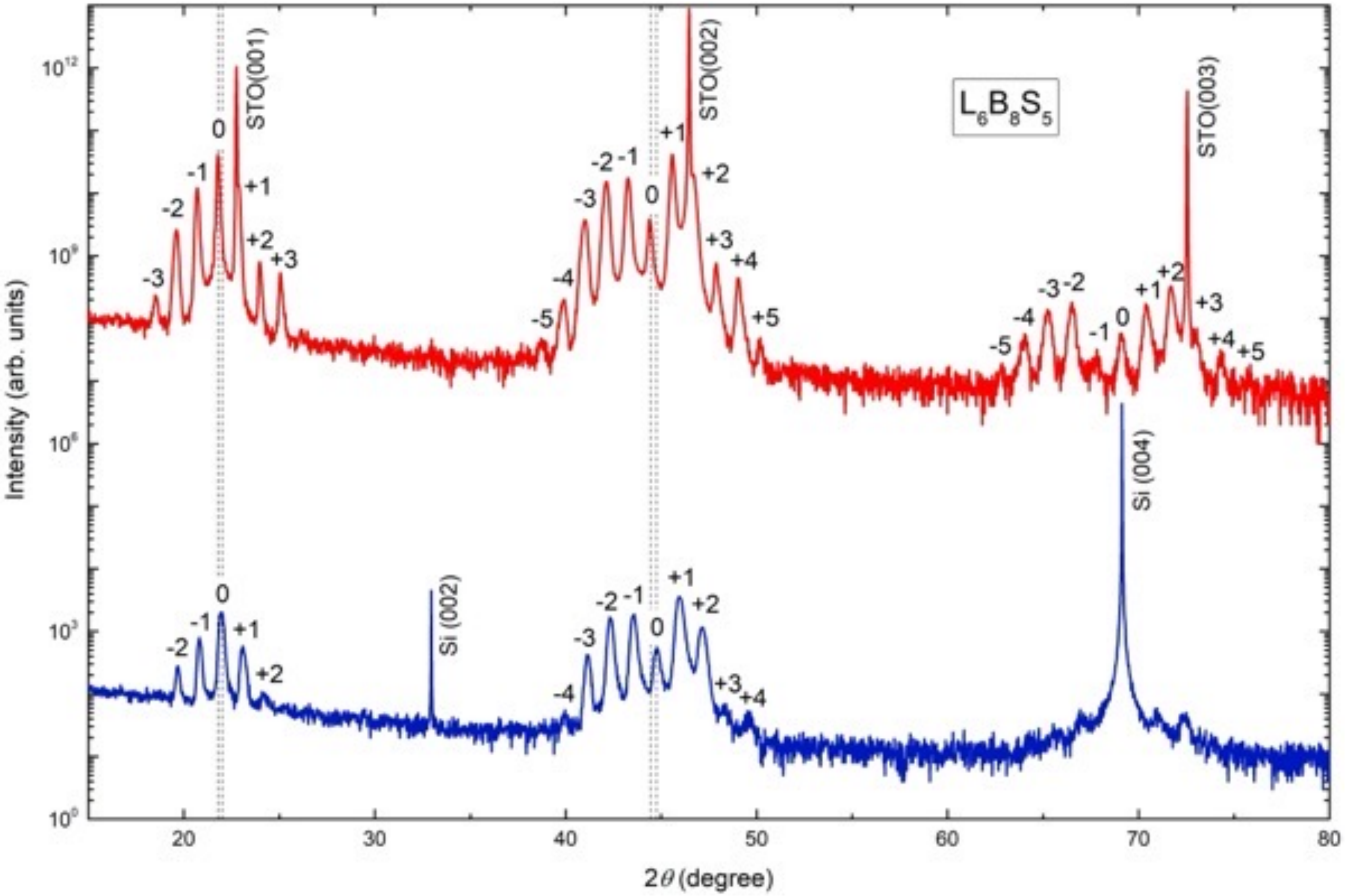


STEM-EELS measurements courtesy Nicolas Gauquelin, UAntwerpen

(a) STEM image of $L_8B_6S_5$ superlattice grown on Si/STO. The sketch on the left shows the atomic structure in one period. The EELS elemental maps taken from the yellow rectangular area are shown in (b). (c) and (d) show the RHEED image taken along the Si[110] azimuth and AFM image.

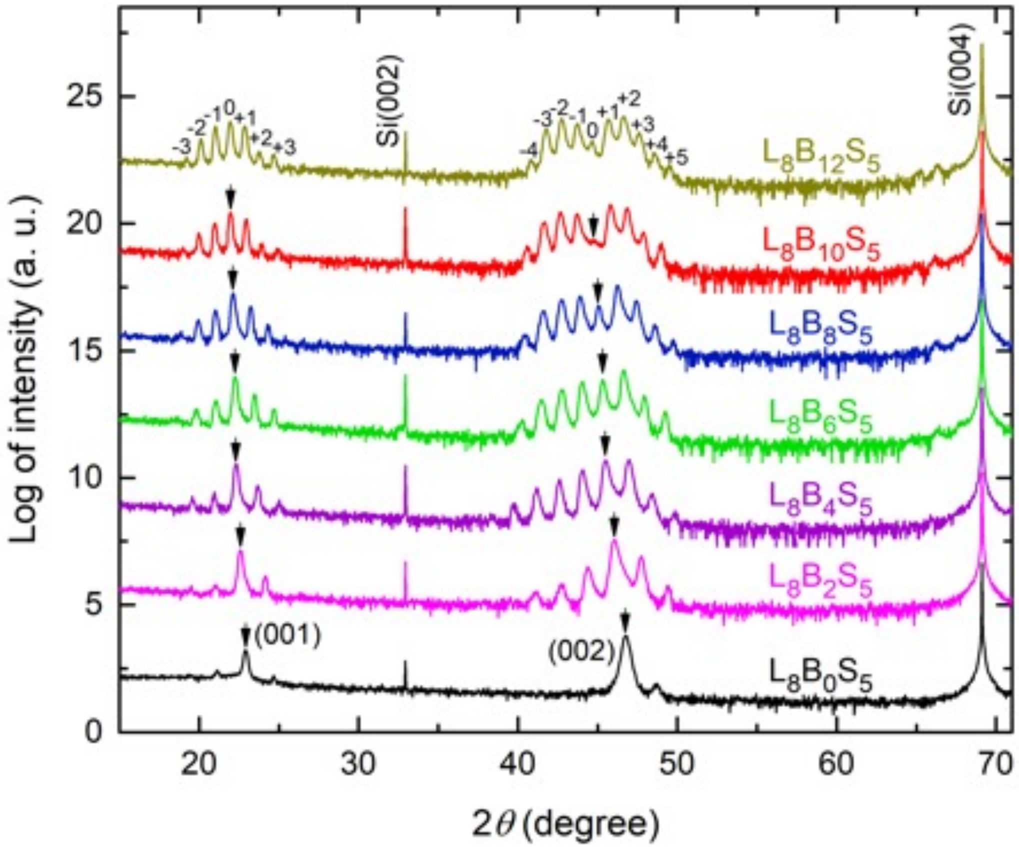


STEM images and EELS elemental maps of $L_8B_2S_5$ (a) and $L_8B_{12}S_5$ (b) superlattice grown on Si/STO.



XRD θ-2θ scans of two $L_6B_8S_5$ SLs grown on STO single crystal (red) and Si/STO (blue) substrates. The main peaks, as indicated by dotted lines, shift to higher angles for the SL grown on Si/STO because of the in-plane thermal tension.

$LaMnO_3/BaTiO_3/SrTiO_3$ superlattices with varied BTO thickness:



XRD linear scans of LMO/BTO/STO superlattices with various layer thickness of BTO grown on Si/STO. The arrows indicate the (001) and (002) main peaks.

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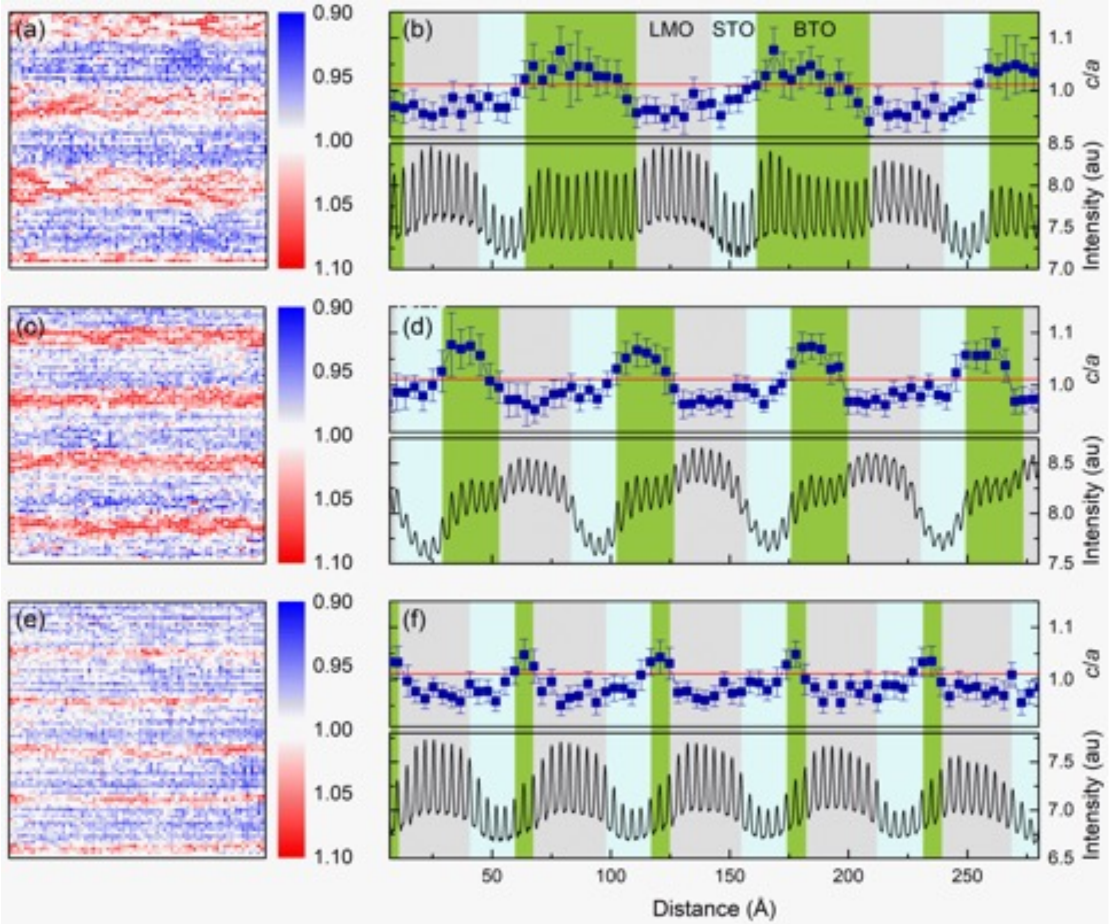
Mapping tetragonal distortions:



Two-dimensional mapping of tetragonality (*c*/*a*) for $L_8B_{12}S_5$ (a), $L_8B_6S_5$ (c) and $L_8B_2S_5$ (e). The corresponding *c*/*a* averaged within each atomic layer is plotted in (b), (d) and (f), respectively. In (b), (d) and (f), the red line in upper panels indicates the *c*/*a* value of BTO single crystal, and the bottom panels show the HAADF intensity for identifying each layers.

For comparison:

Bulk BTO : *c*/*a* = 1.01

$PbTiO_3$: *c*/*a* = 1.06

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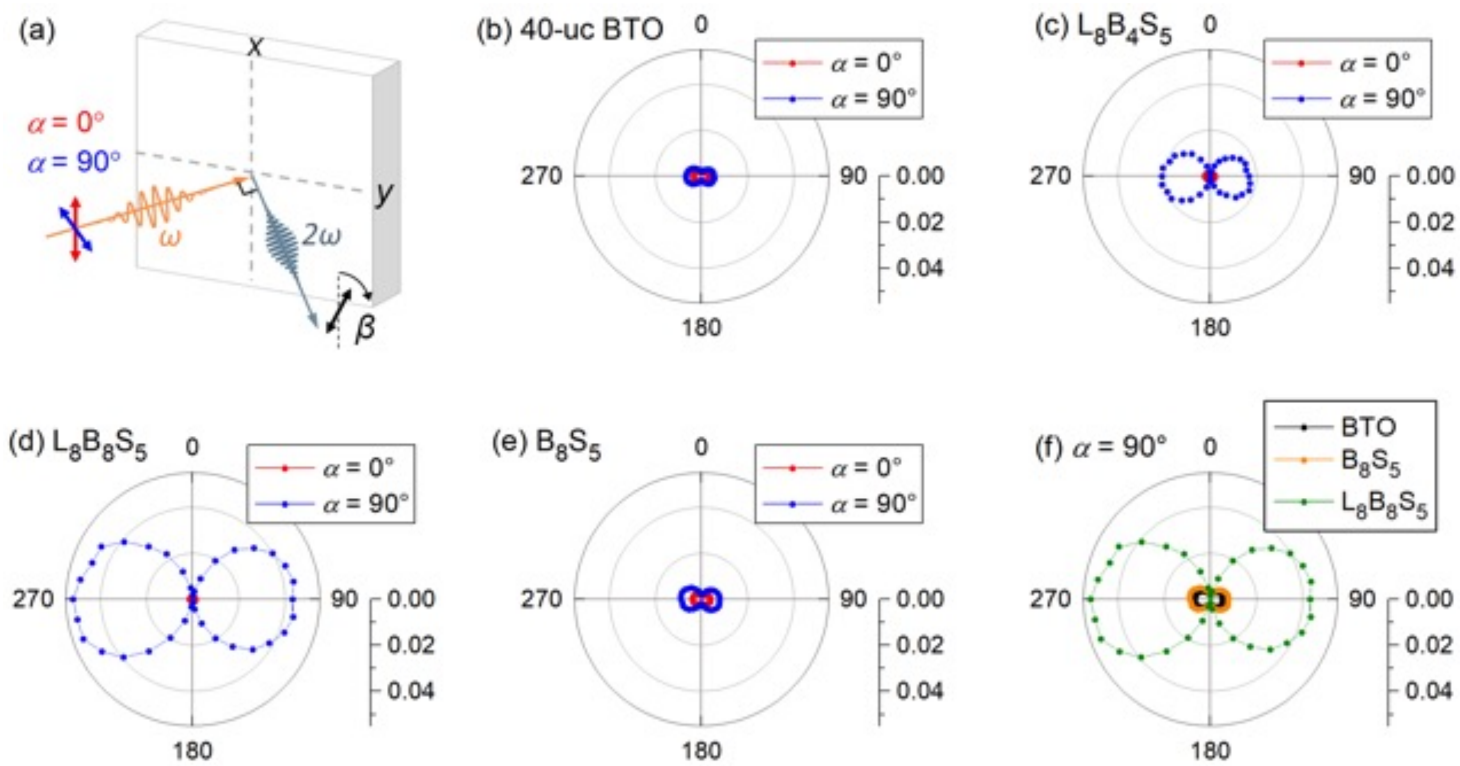
polarization

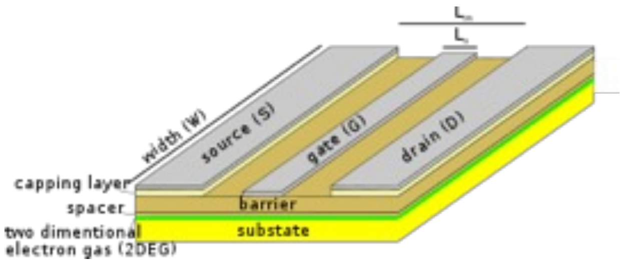


SHG measurements done in collaboration with Nives Strkalj, Martin Sarott, Manfred Fiebig, Morgan Trassin, (ETH Zurich)

Chen, GK, GR et al, Nature communications, 2021

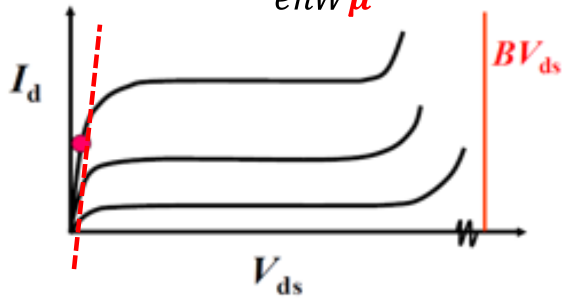
Epitaxial PZT films on GaN

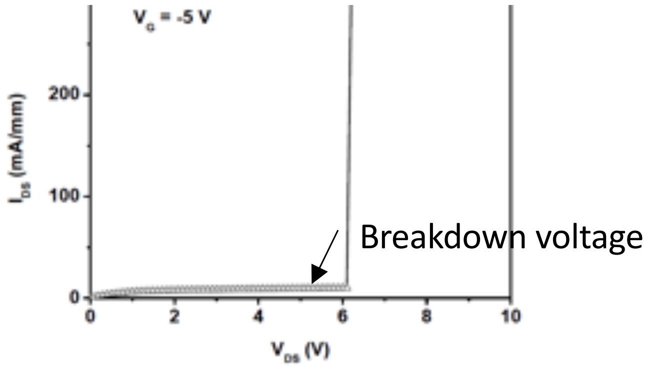
Ideal high power FET: Low R_{on} and high breakdown voltage V_{br}



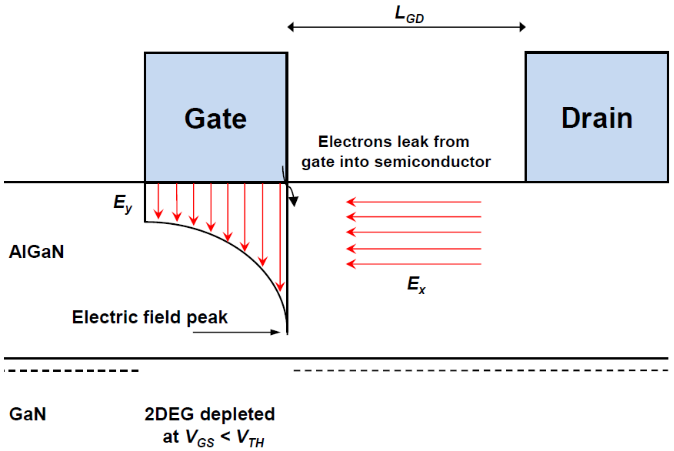
High power field effect transistor

$$R_{on} = \frac{L}{enW\mu}$$

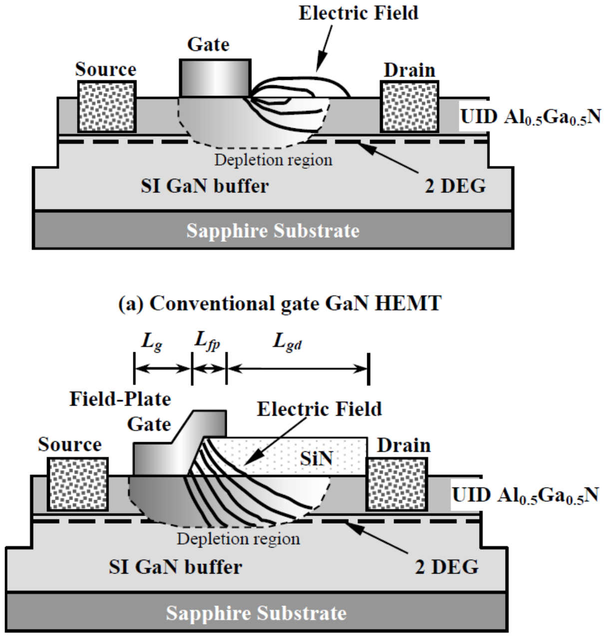




Non-uniform electric field distribution induced low breakdown voltage



Peak electric field at gate edge lower the breakdown voltage



(b) Field-plate GaN HEMT

R. Zhou, GR, *et al.*, "Polarization effects in ferroelectric gate AlGaN/GaN High Electron Mobility Transistors," *2020*, doi: 10.1109/ISPSD46842.2020.9170173.

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High Dielectric Materials

Dielectric Material	Dielectric Constant
Silicon dioxide (SiO_2)	3.9
Silicon nitride (Si_3N_5)	7-8
Aluminum Oxide (Al_2O_3)	8-10
Zirconium oxide (ZrO_2)	~14-28
Titanium oxide (TiO_2)	~30-80
Tantalum pentoxide (Ta_2O_5)	~25-50
Barium-strontium-titanate (BST/BSTO)	~100-800
Strontium-titanate-oxide (STO)	~230+
Lead-zirconium-titanate (PZT)	~400-1500

R. Zhou, GR, *et al*., "Polarization effects in ferroelectric gate AlGaN/GaN High Electron Mobility Transistors," *2020*, doi: 10.1109/ISPSD46842.2020.9170173.

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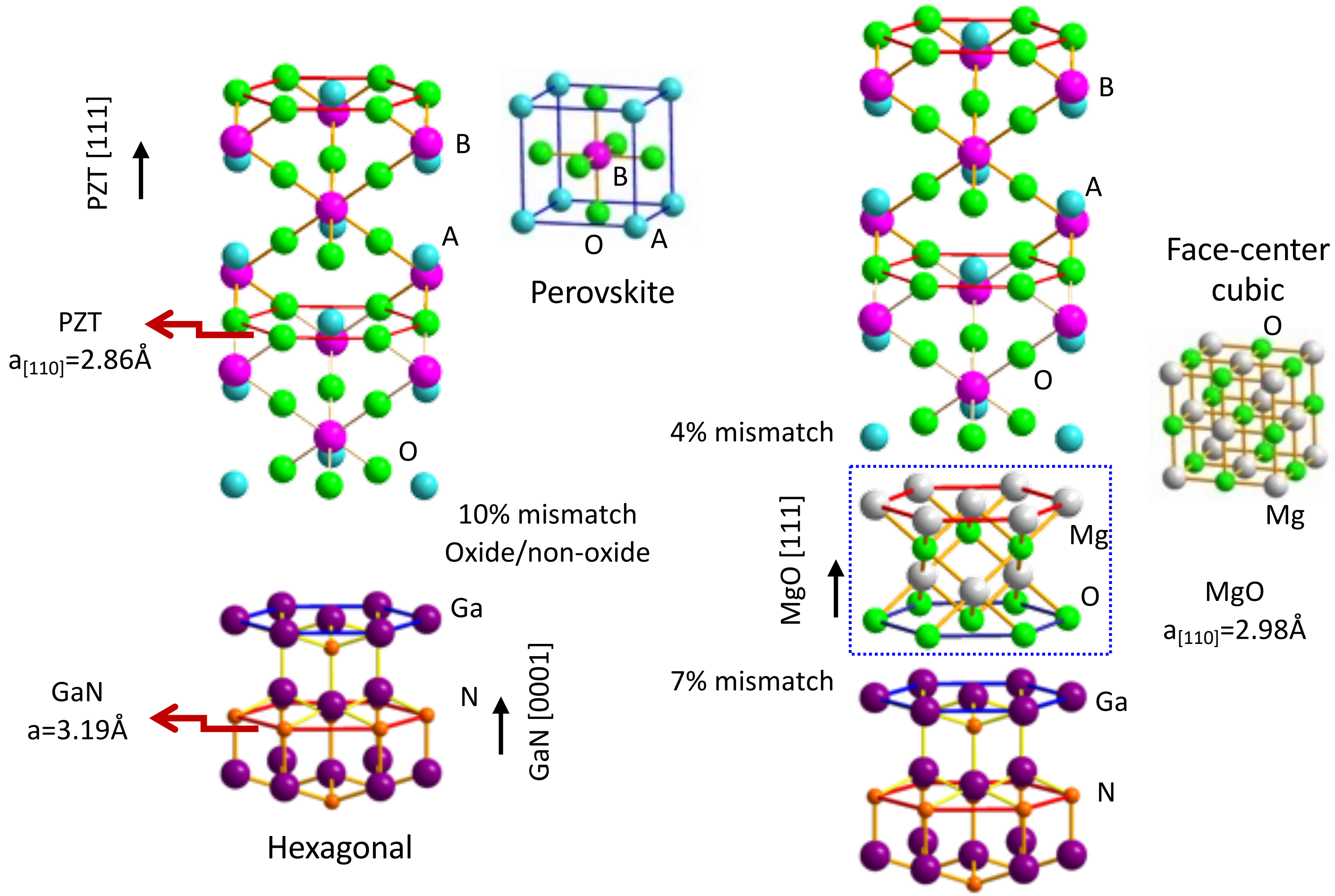
Growth of PZT on GaN



Usually, a buffer layer to reduce lattice mismatch is required to get high quality PZT.

H. Craft, J. Ihlefeld, M. Losego, R. Collazo, Z. Sitar, J-P. Maria, “MgO epitaxy on GaN (0002) surfaces by molecular beam epitaxy.” Appl. Phys. Lett. 88 212906 (2006).

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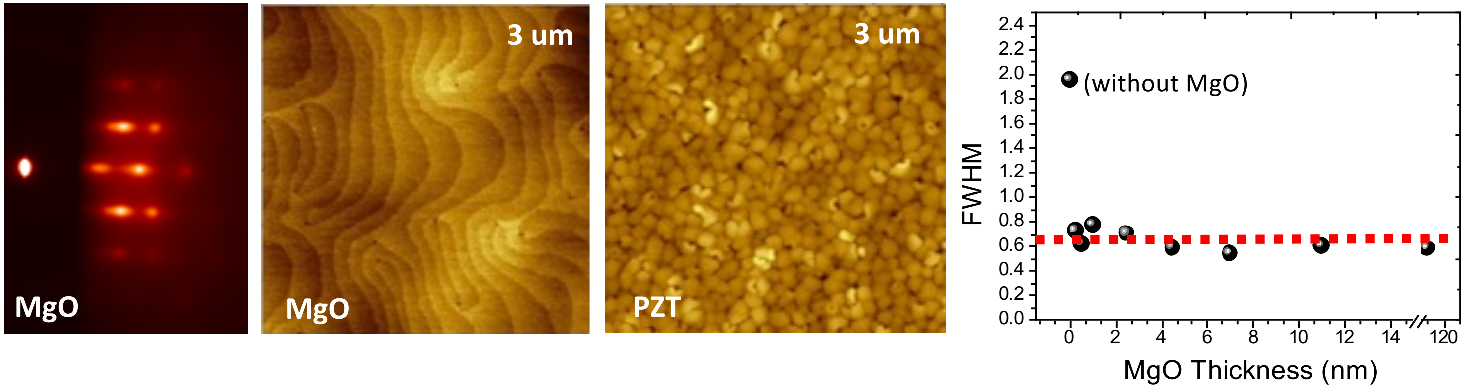
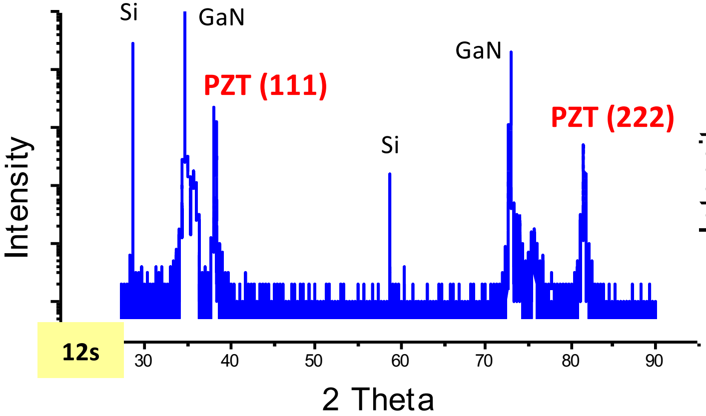
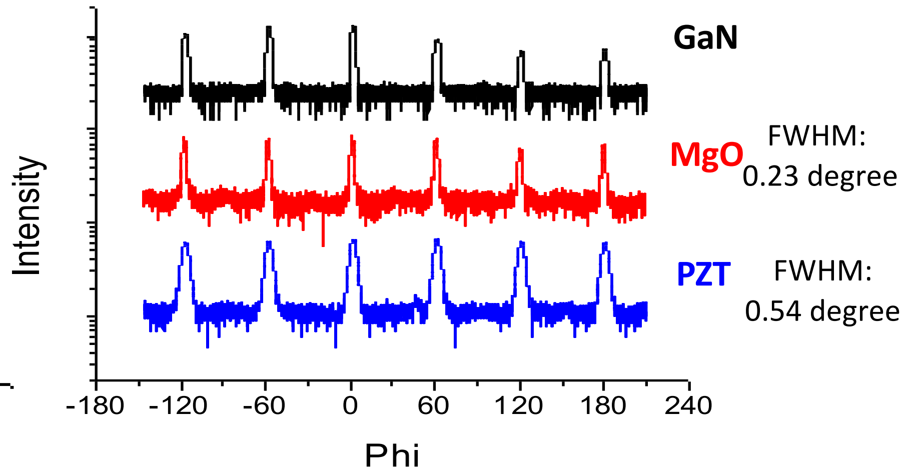
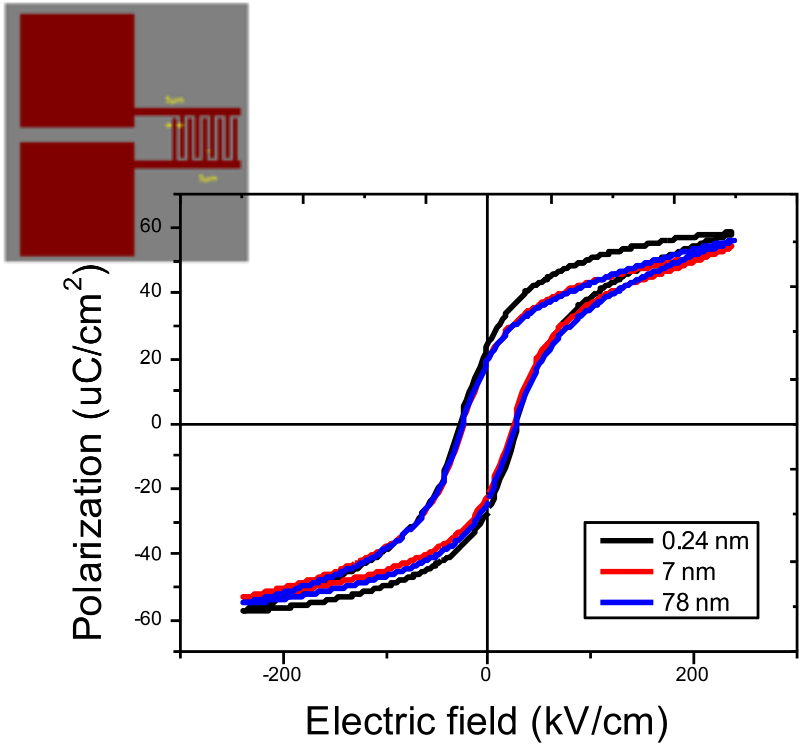
Epitaxial growth of PZT on GaN

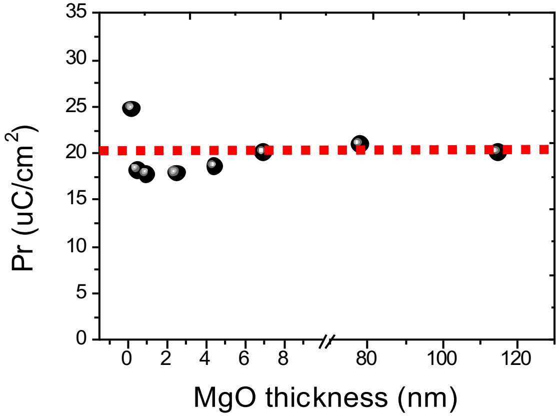


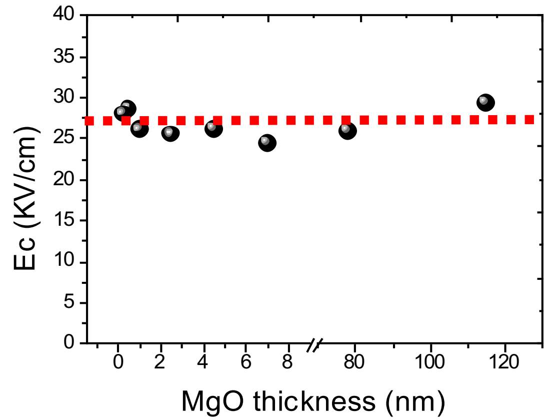




Ferroelectric property of PZT with different thickess of MgO buffer layer

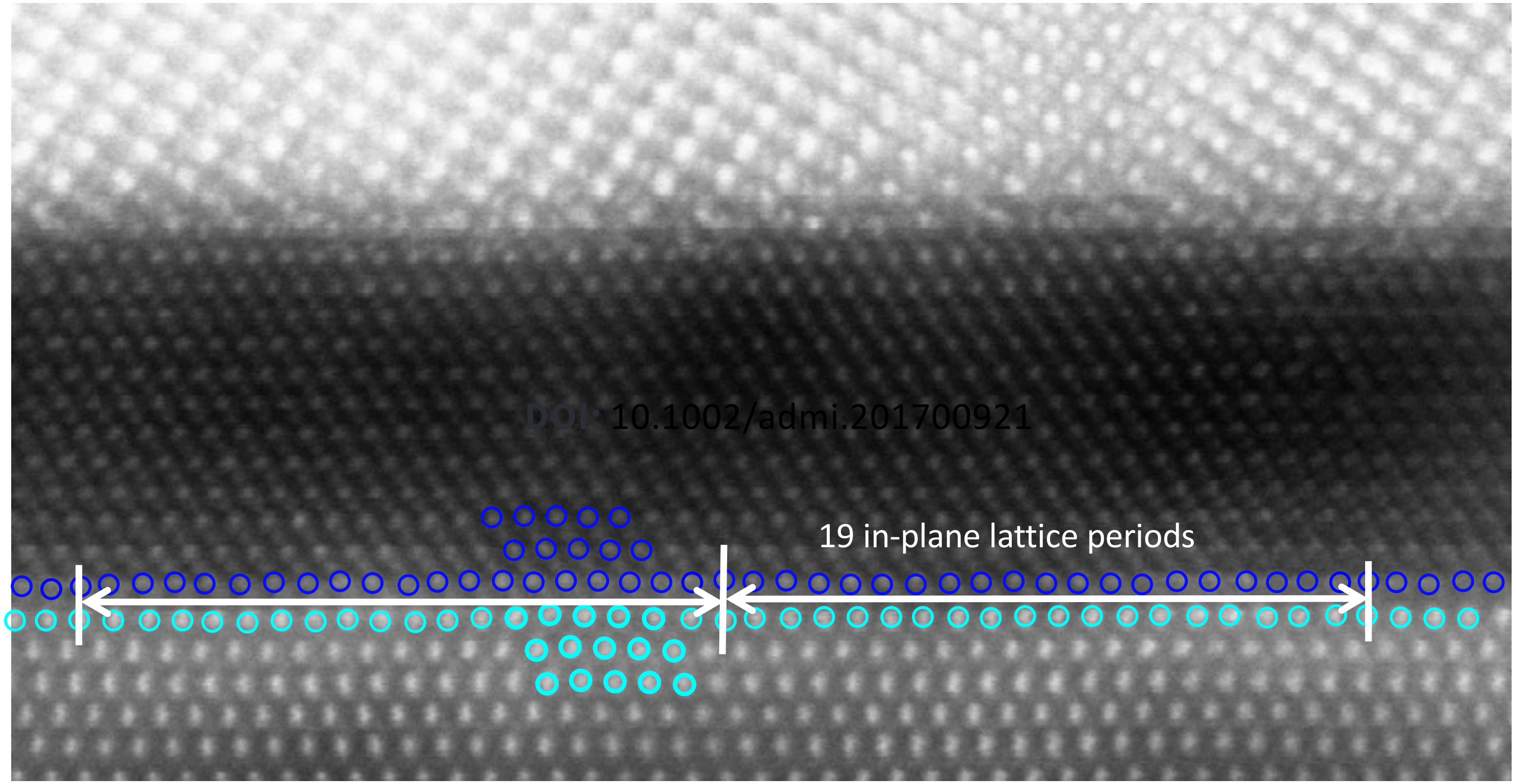






Ferroelectric property of PZT can be maintained with ultrathin MgO.

Epitaxial PZT films on GaN



Why epitaxy with lattice mismatch:
long range in-plane lattice relaxation to accommodation the strain

Lin Li, GR, et all. ADVANCED MATERIALS INTERFACES, DOI: 10.1002/admi.201700921

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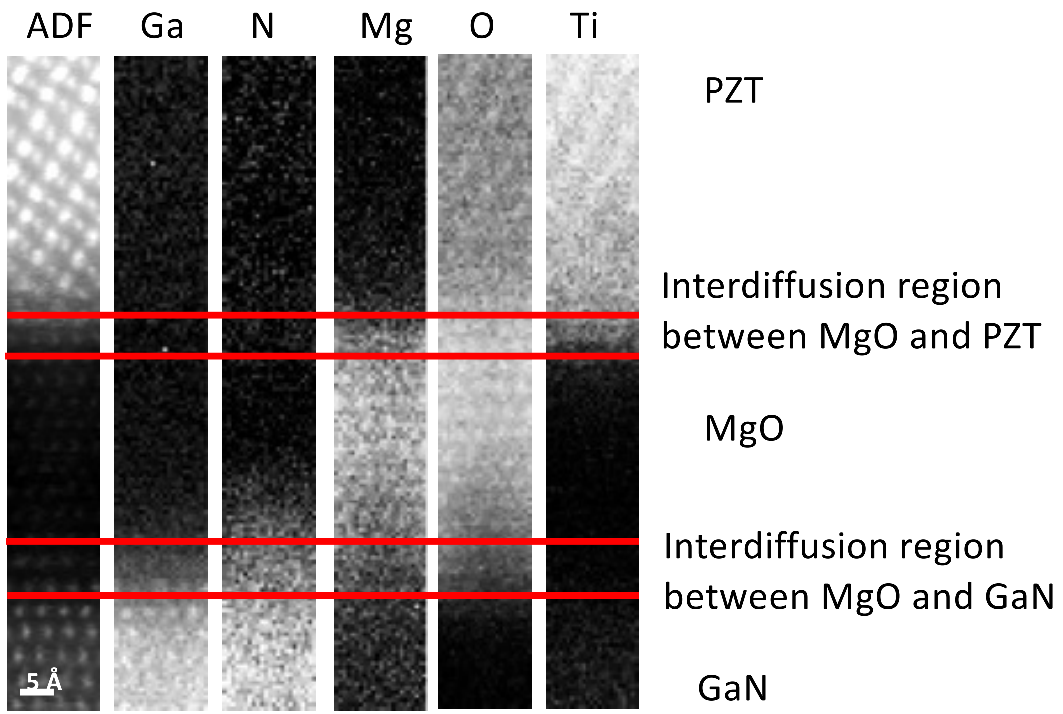
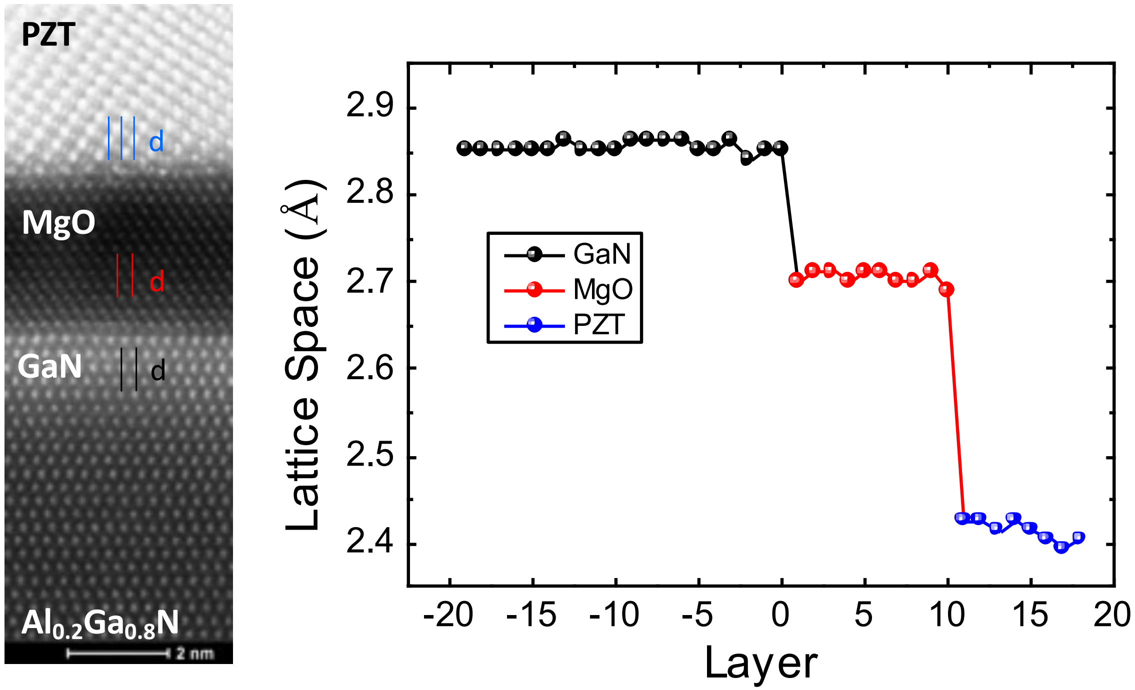
EELS mapping



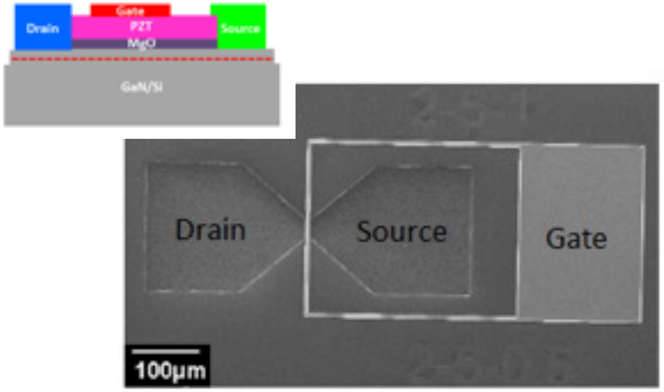
Interdiffusion region is very thin.

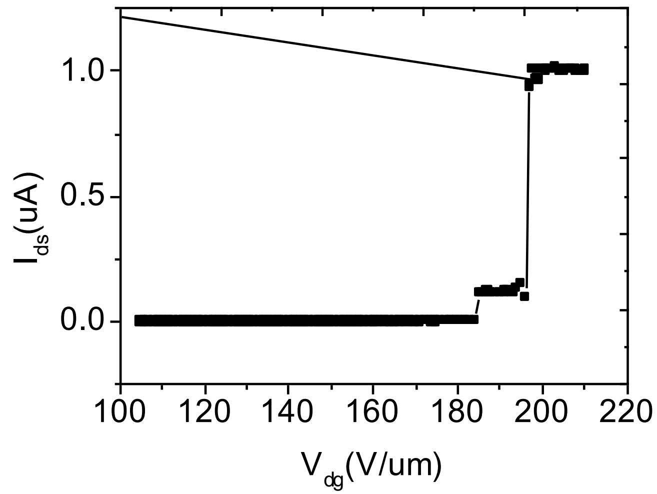
In-plane lattice constant profile along out-of-plane direction

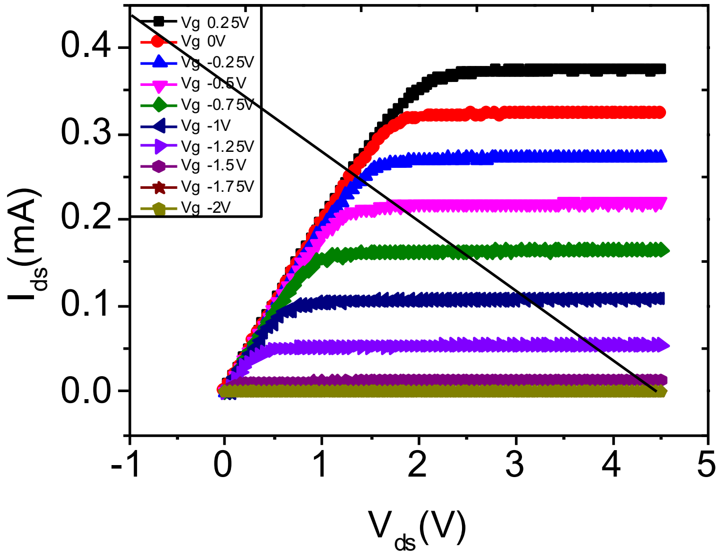


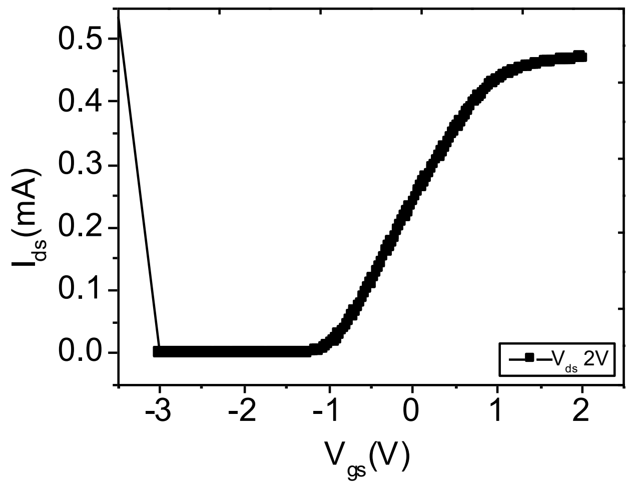
Step-transition of lattice constant without gradual relaxation can explain why thickness of MgO is not crucial to the growth of PZT.

Performance of PZT-GaN FET device



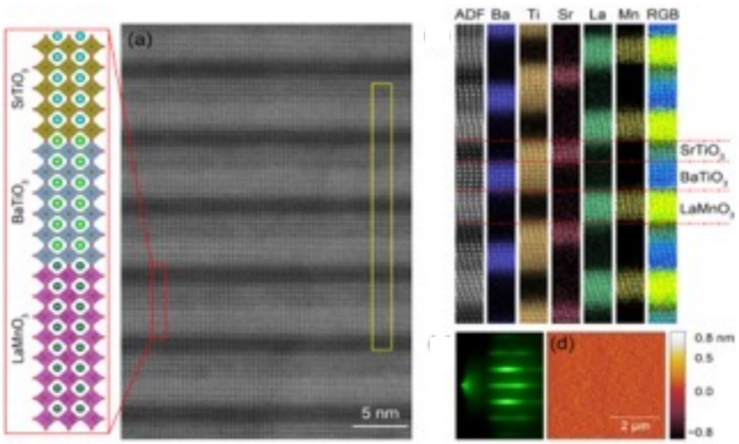


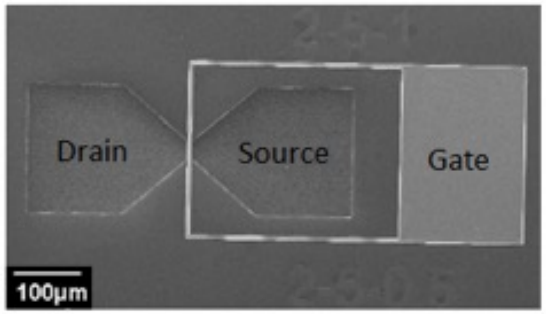




Conclusions

- High quality oxide heterostructures on buffered Si
- Oxide layers typically tensely strained
- New functionalities possible on Si and III-V, by integration of complex oxides.
- Lots of opportunities for complex oxides






Thank you