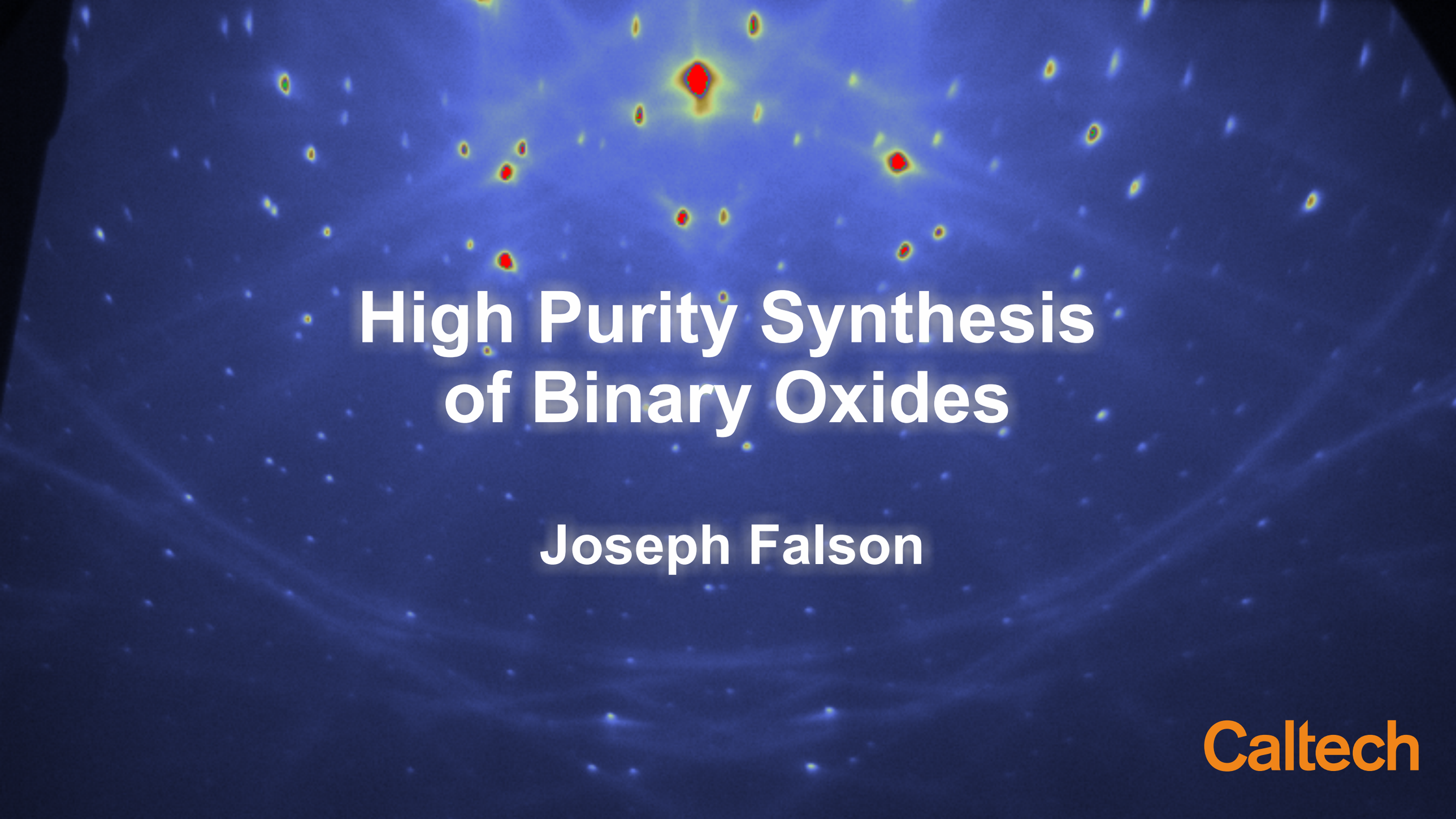


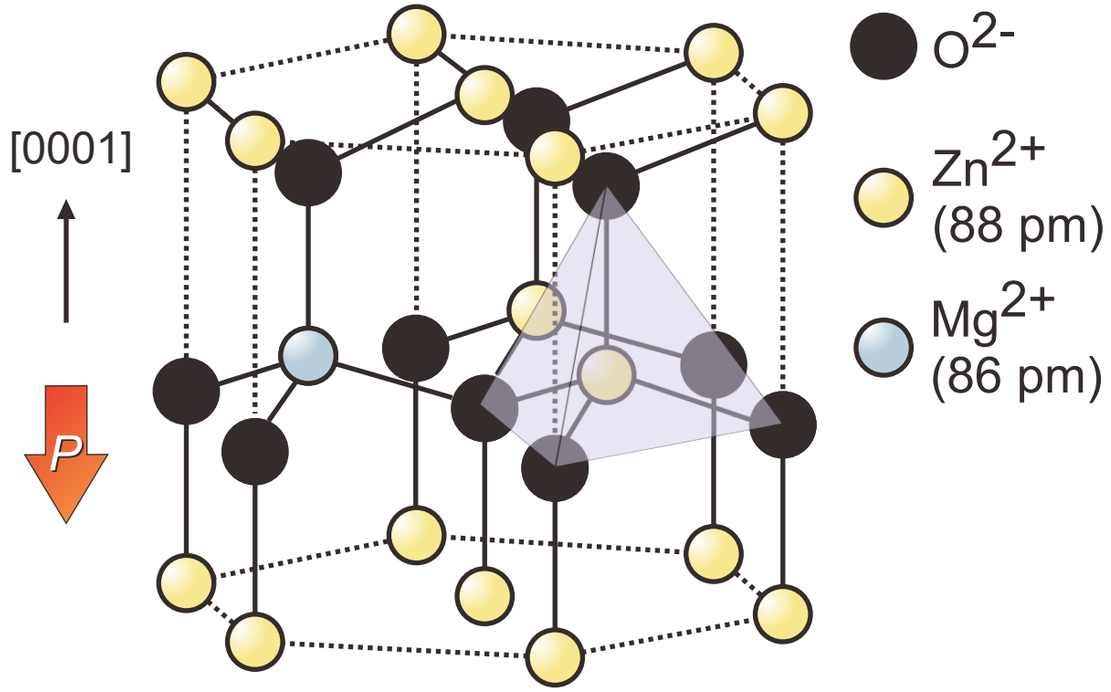
High Purity Synthesis of Binary Oxides

Joseph Falson

Caltech

Talk outline

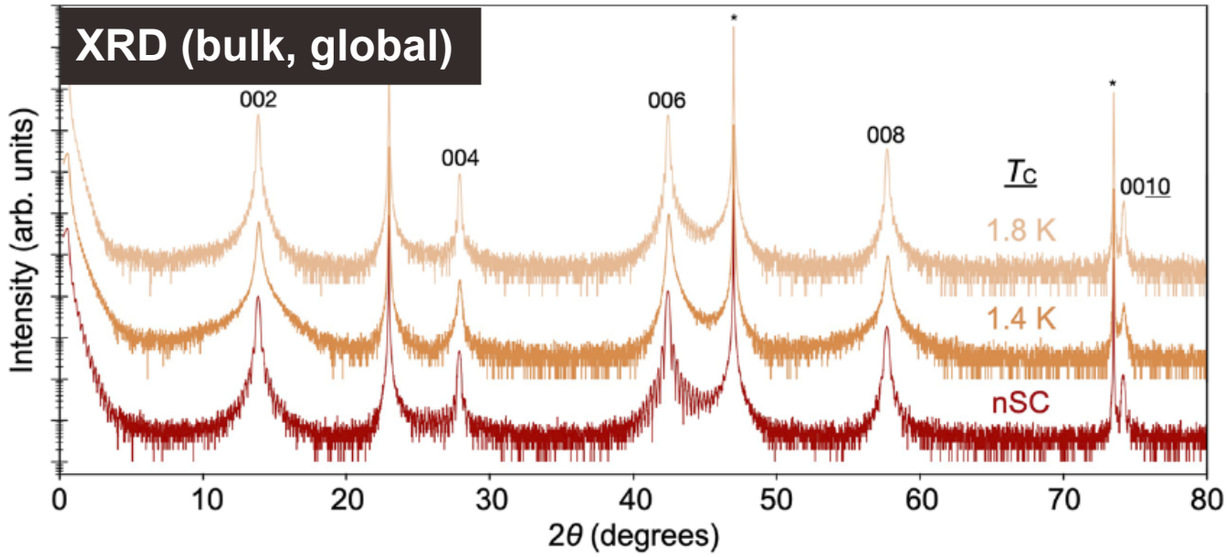
- What defines high purity?
- Motivation and background
- MBE introduction
- Substrate preparation
- Band gap engineering
- Growth Parameters
- Interfacial conductivity
- Impurity sources
- Future perspectives

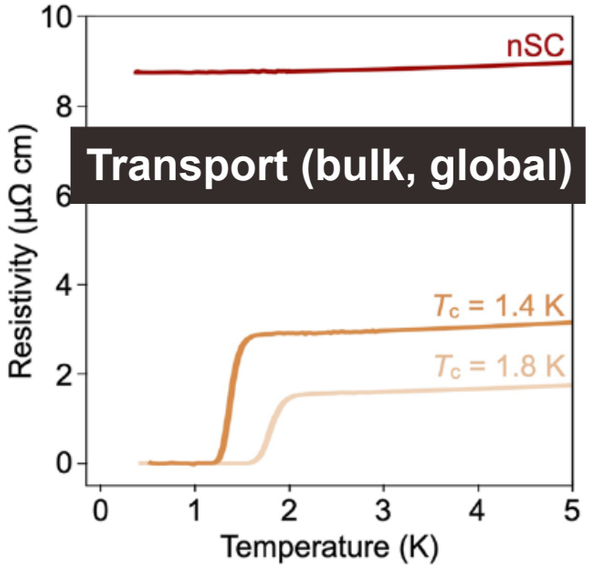


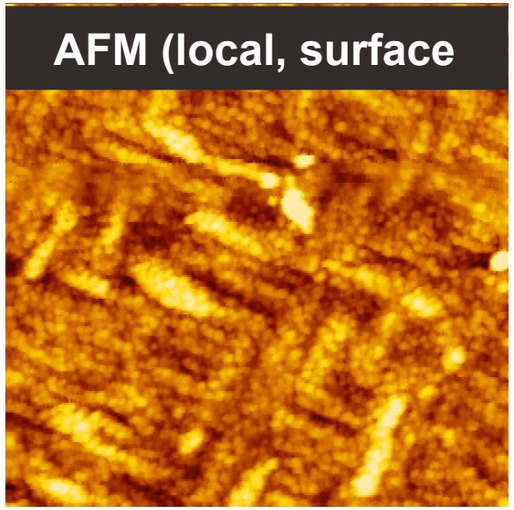
What defines high purity?

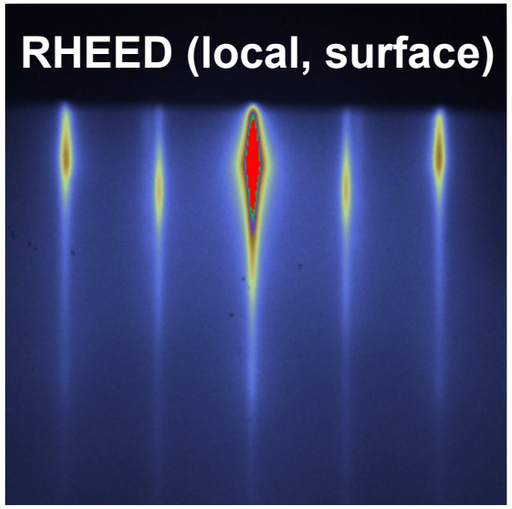
Sr_2RuO_4/(110)$NdGaO_3$

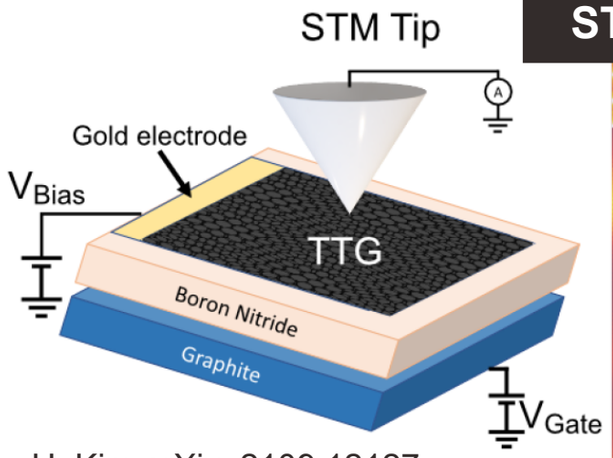
B. Goodge, ... D.G Schlom, *APL Mater.* **10**, 041114 (2022)



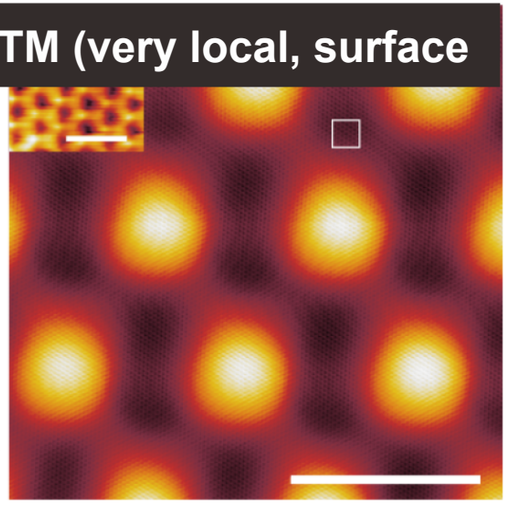




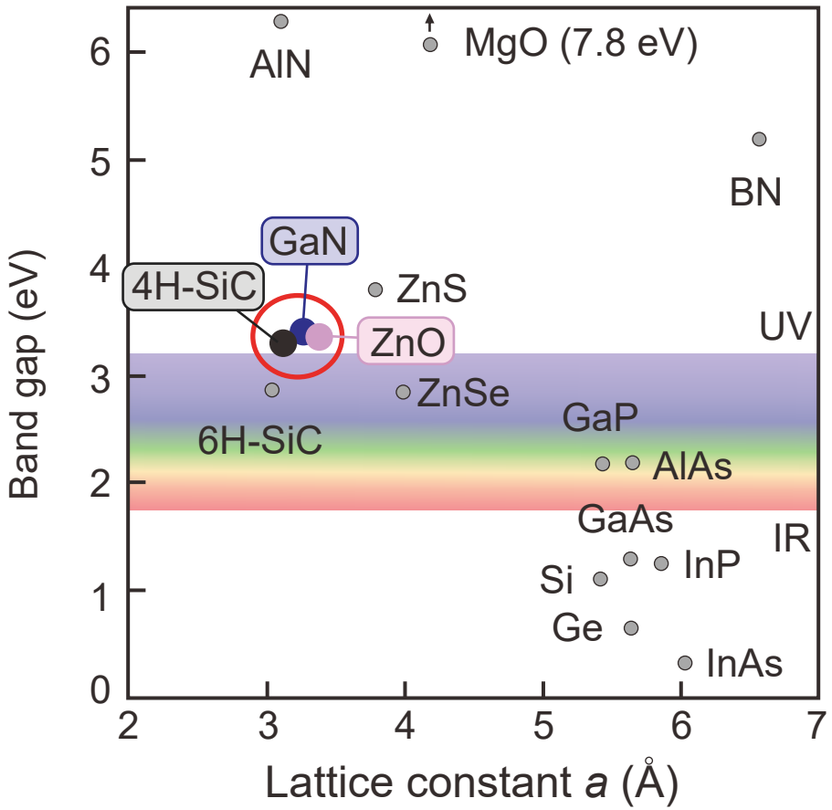




H. Kim arXiv: 2109.12127

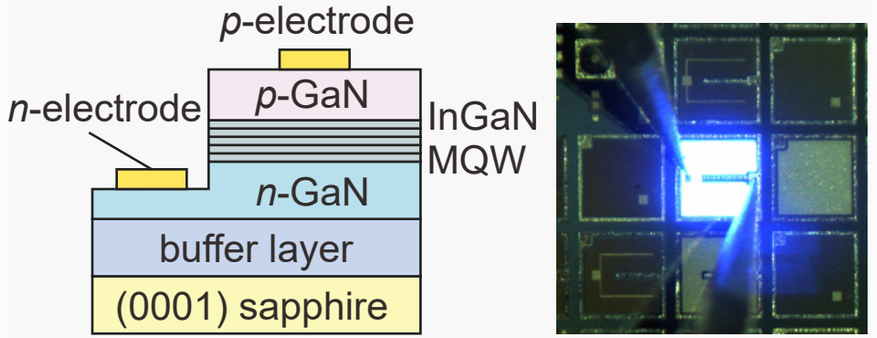


Wide band gap materials

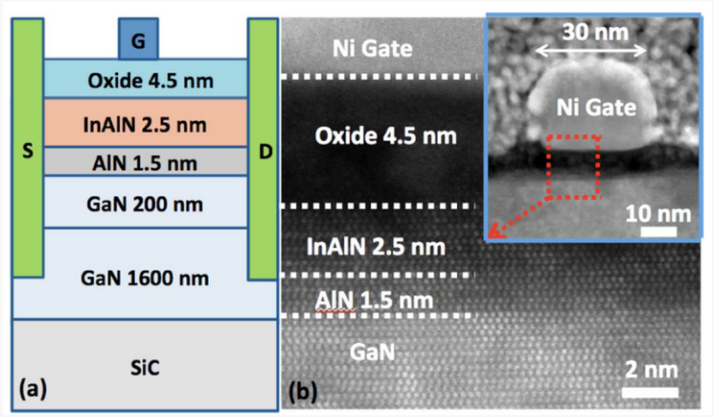


	Breakdown field	Saturation drift velocity
Si:	0.3×10^6 V/cm	1×10^7 cm/s
4H-SiC:	3.0×10^6 V/cm	2×10^7 cm/s
GaN:	3.5×10^6 V/cm	2.5×10^7 cm/s

Short wavelength LED

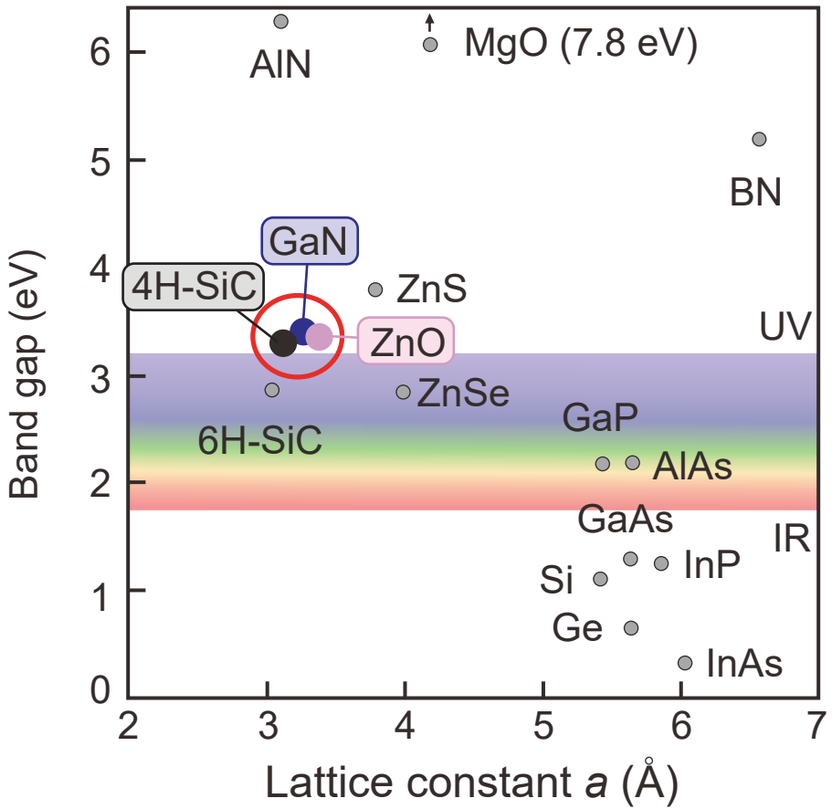


High performance electronics



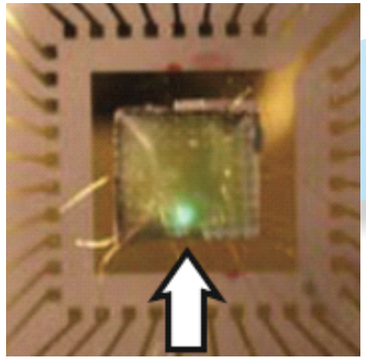
Y. Yue, *et al.*, *IEEE Electron Device Letters* **33**, 988 (2012)

A brief history of ZnO



2010 MBE
UV LED &
Green phosphor

Applied Physics Letters,
97, 013501 (2010).

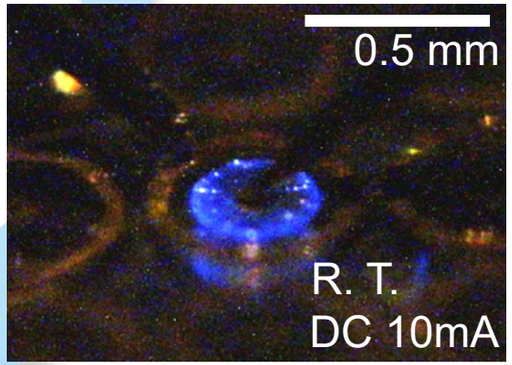


Stimulated excitonic emission

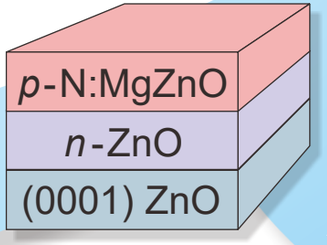
Solid State Communications,
103, 459 (1997).

2005
Blue LED

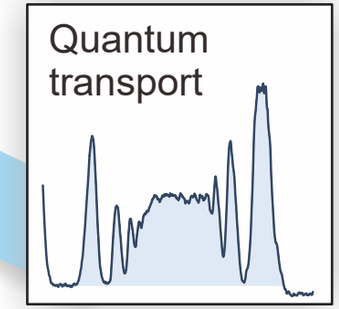
Nature Materials,
4, 42 (2005).



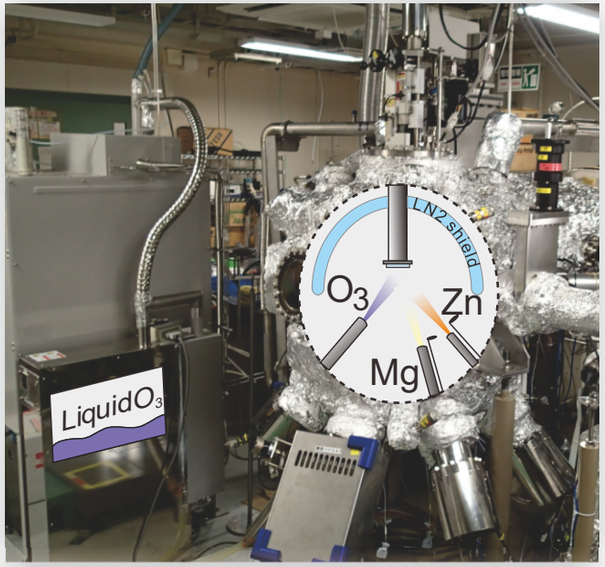
Optics

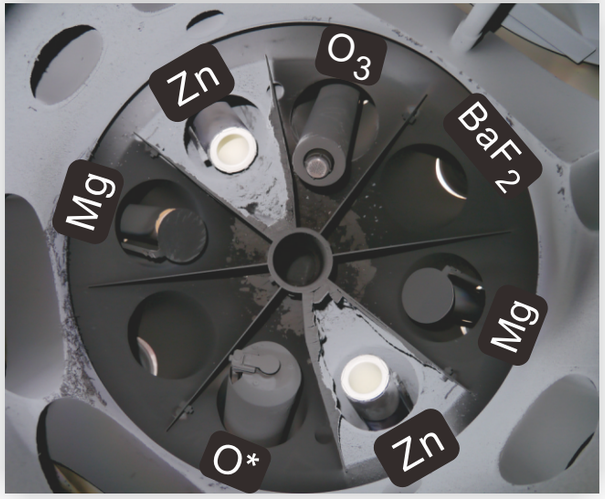


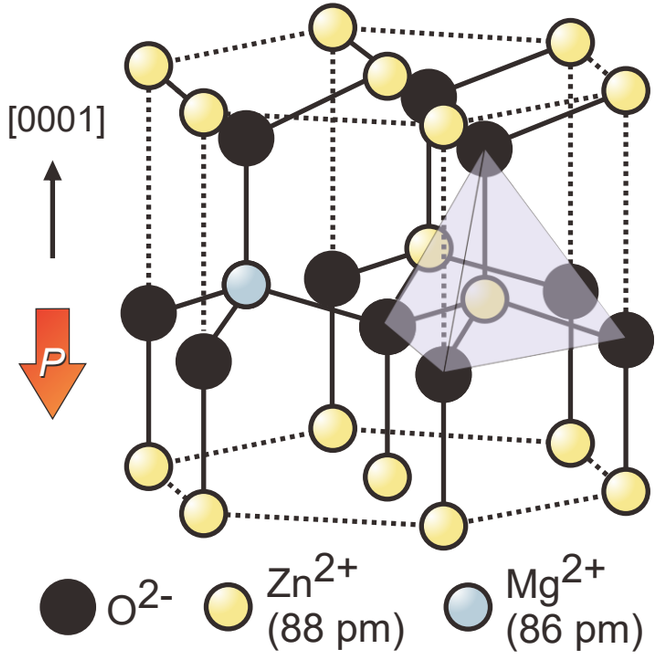
2DES

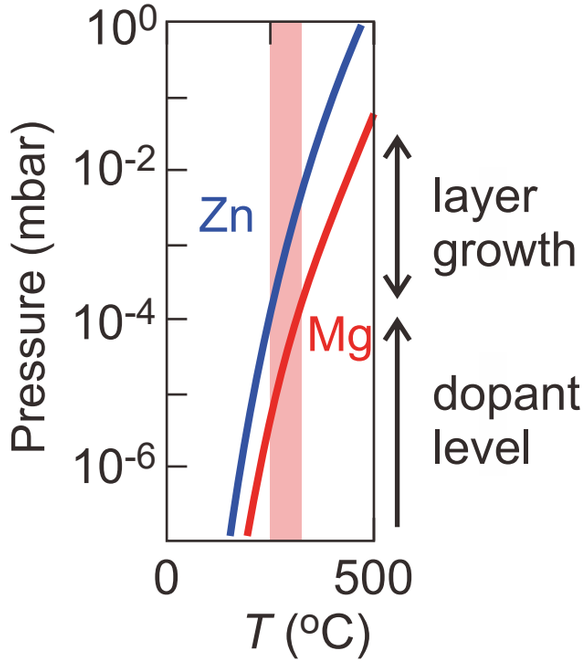


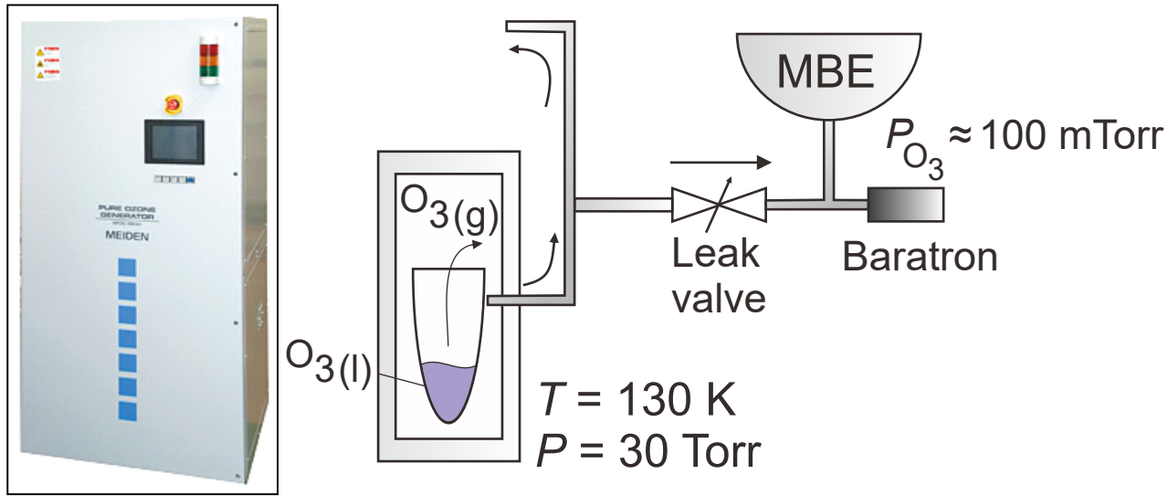
Outline of ZnO MBE



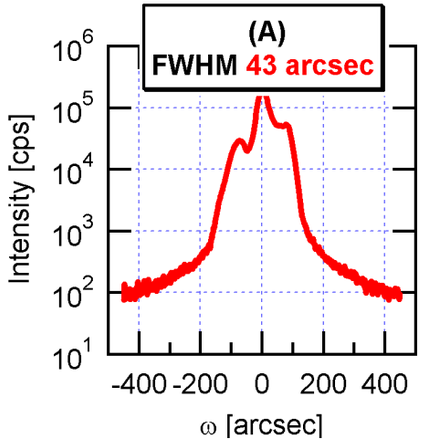


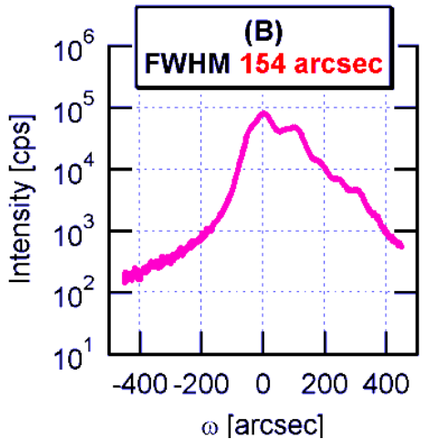


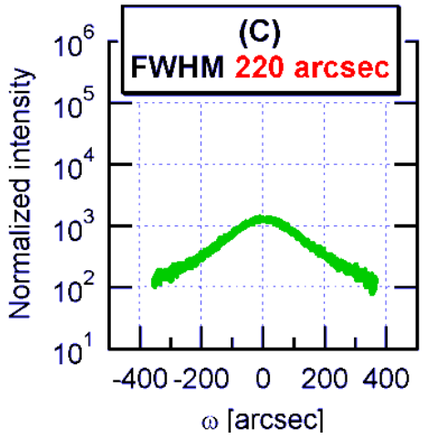


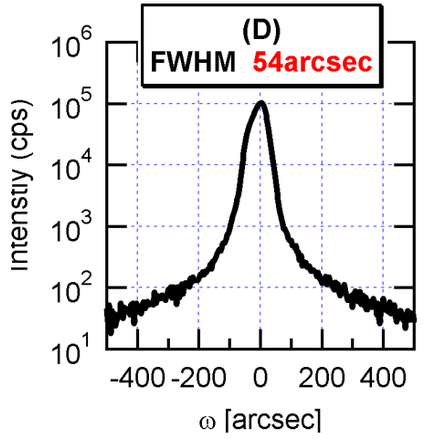


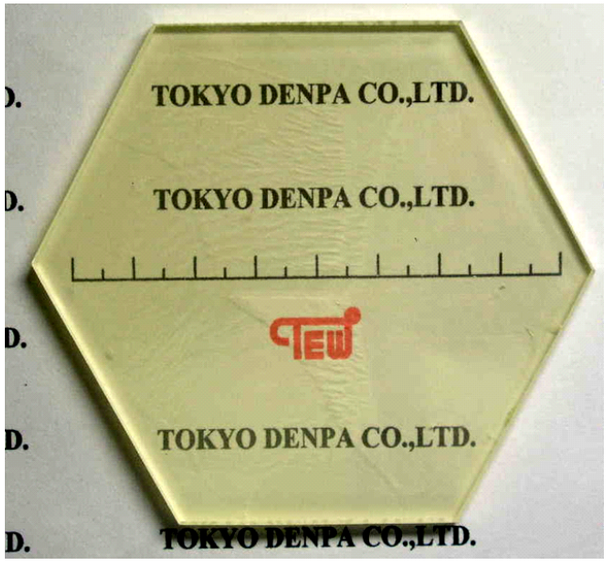
Substrate crystallinity



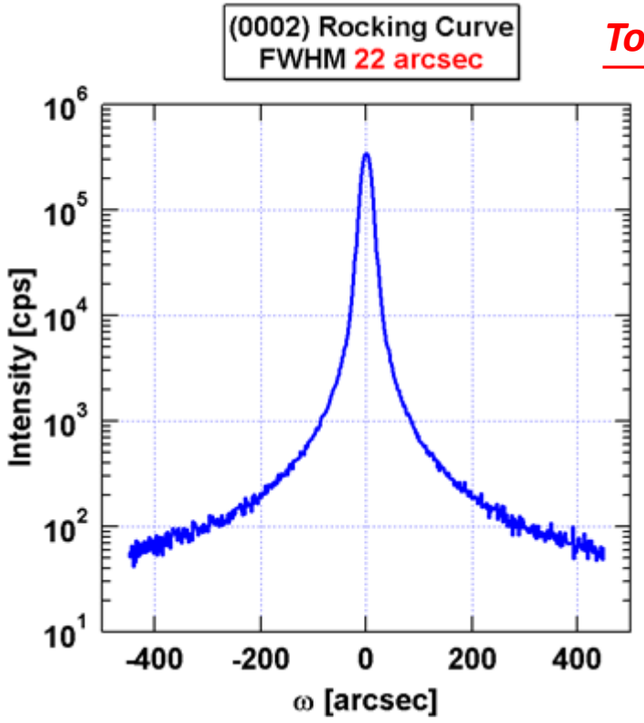


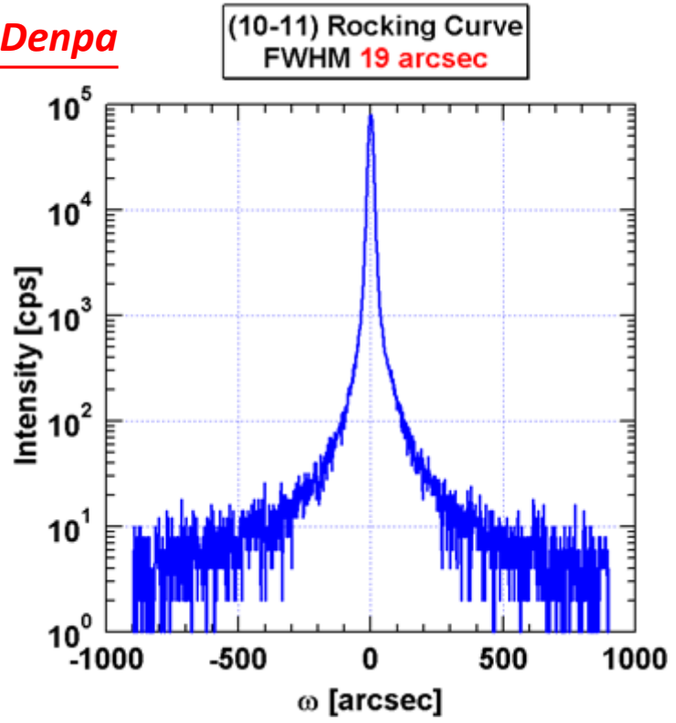






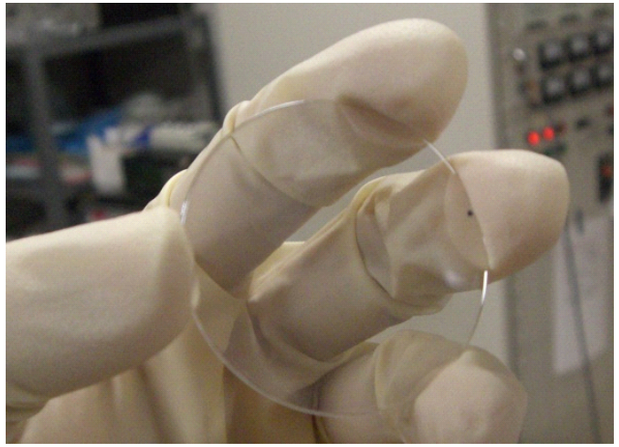
Tokyo Denpa

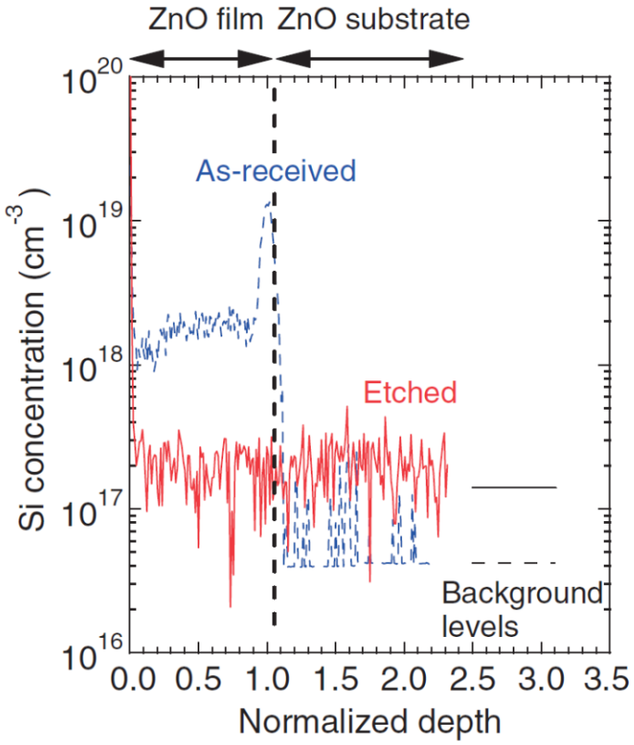


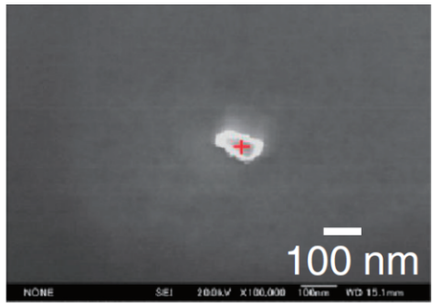


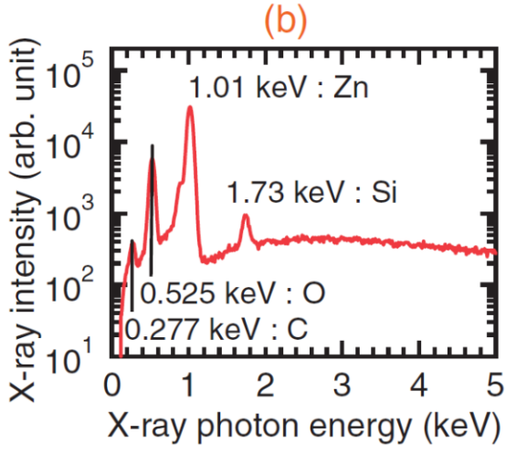
ZnO substrate preparation

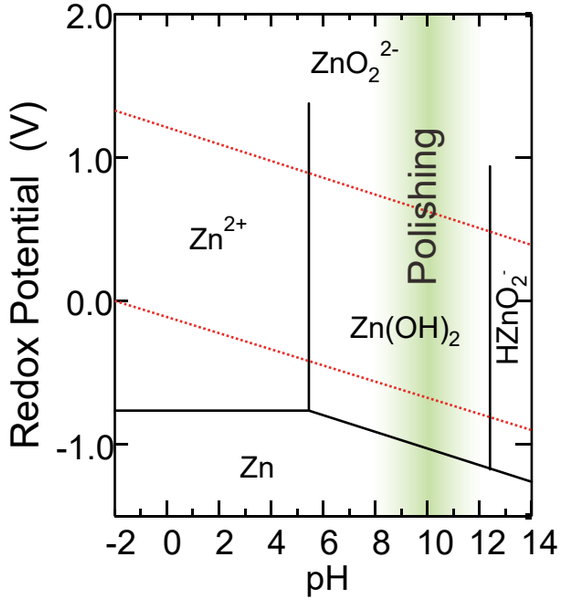
S. Akasaka, *et al.*,
Applied Physics Express **4**, 035701 (2011)

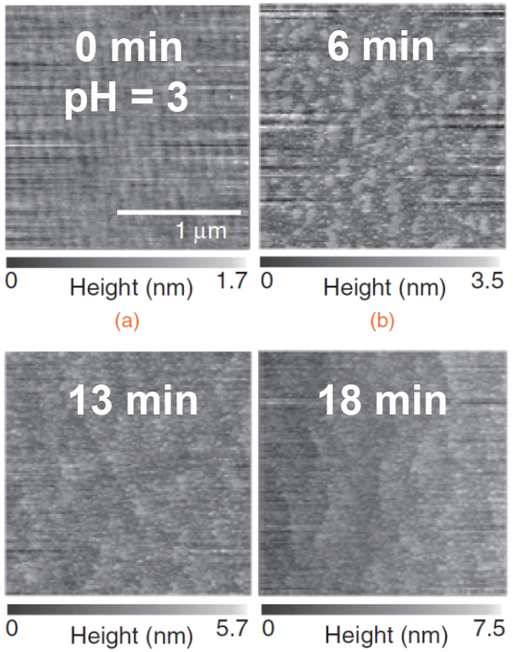




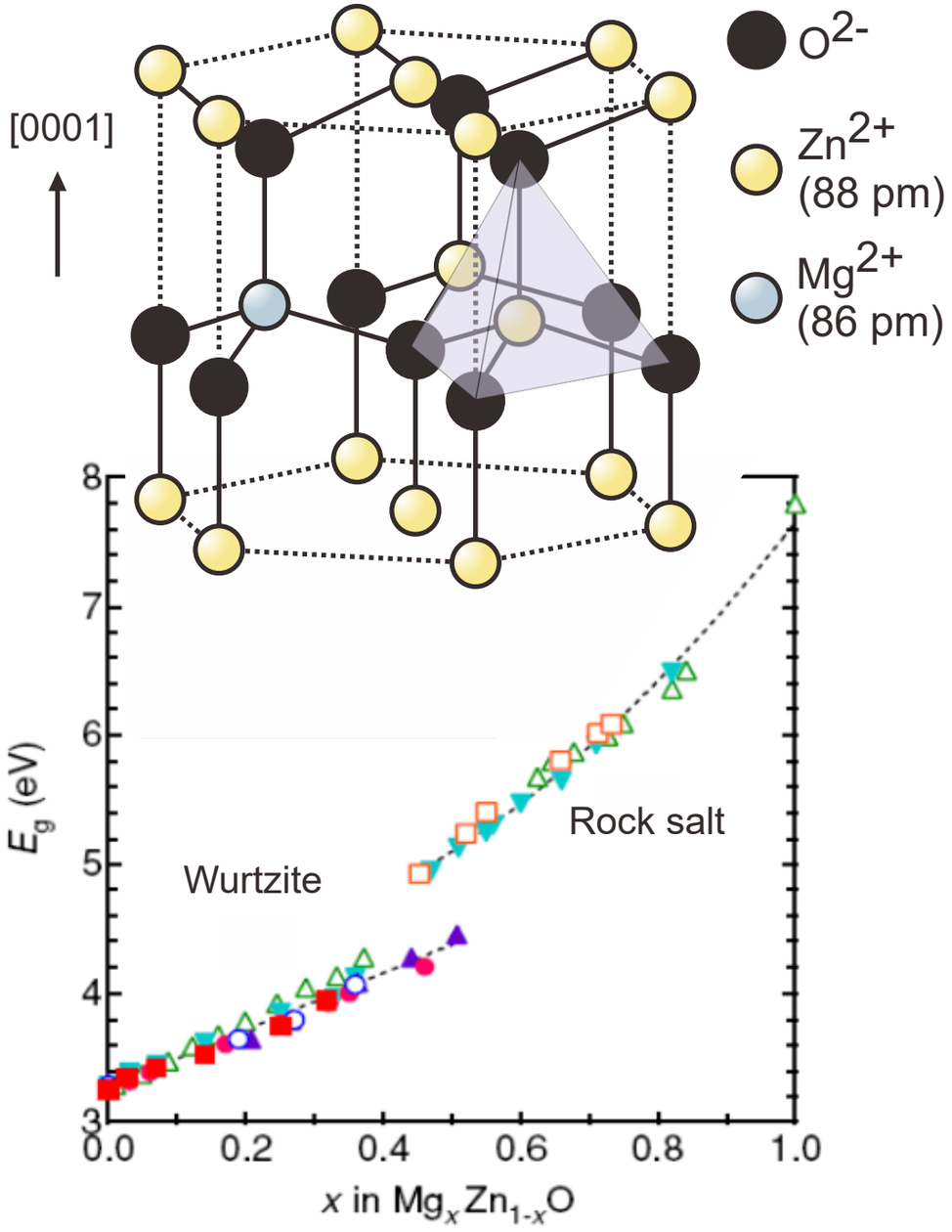






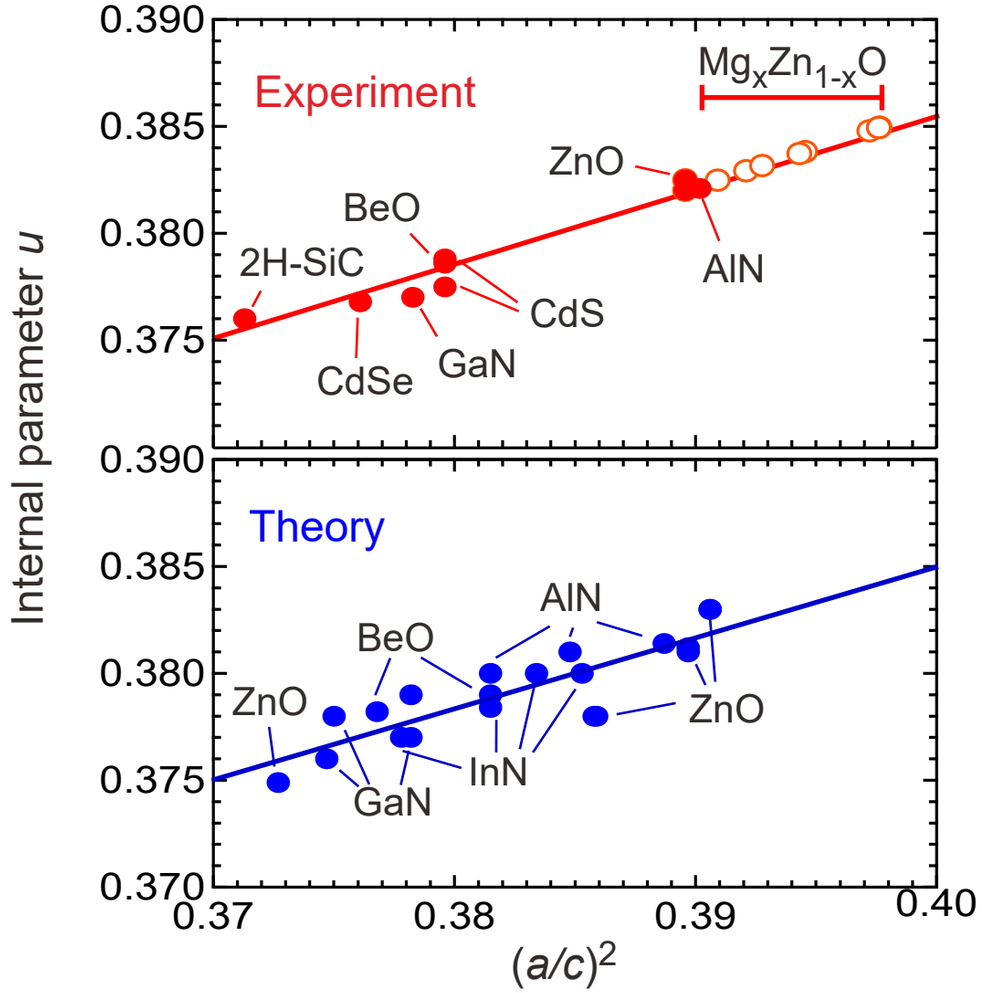


Band and structure engineering



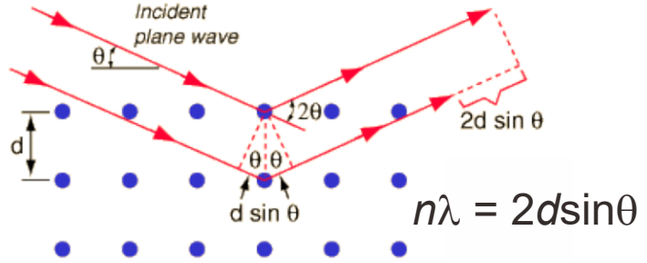
$$u = \frac{a^2}{3c^2} + \frac{1}{4}$$

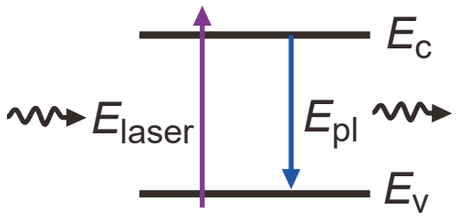
H. Schulz *et al*, *Solid State Commun.* **32**, 783 (1979).

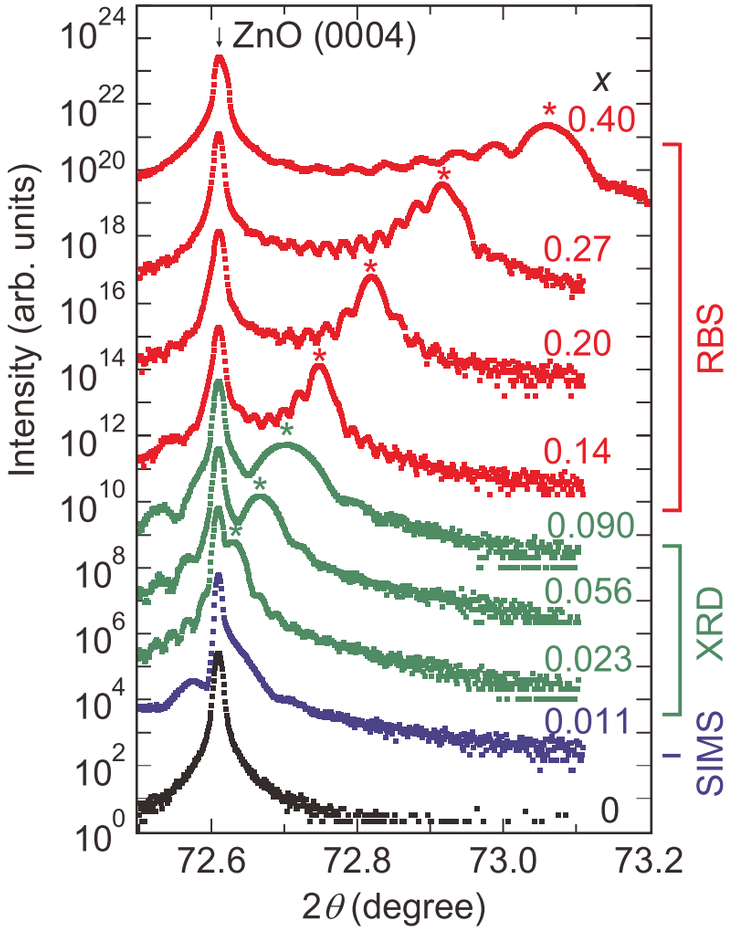


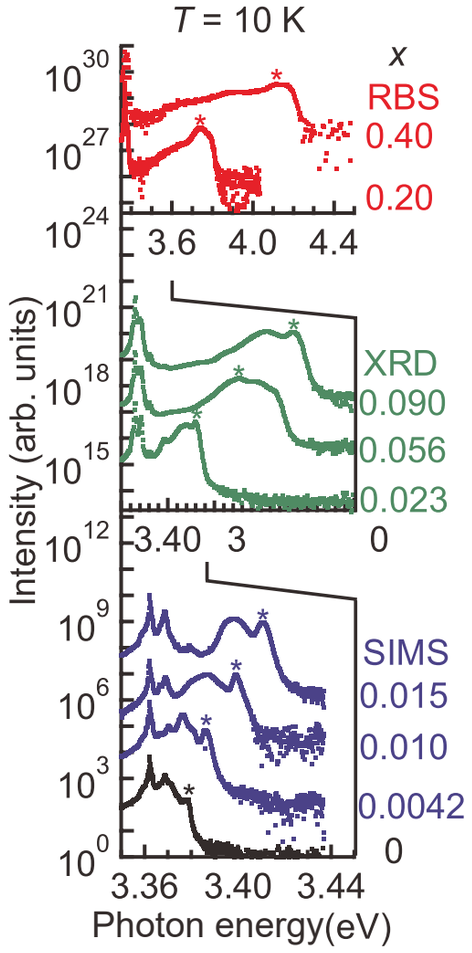
Epitaxial Mg alloying

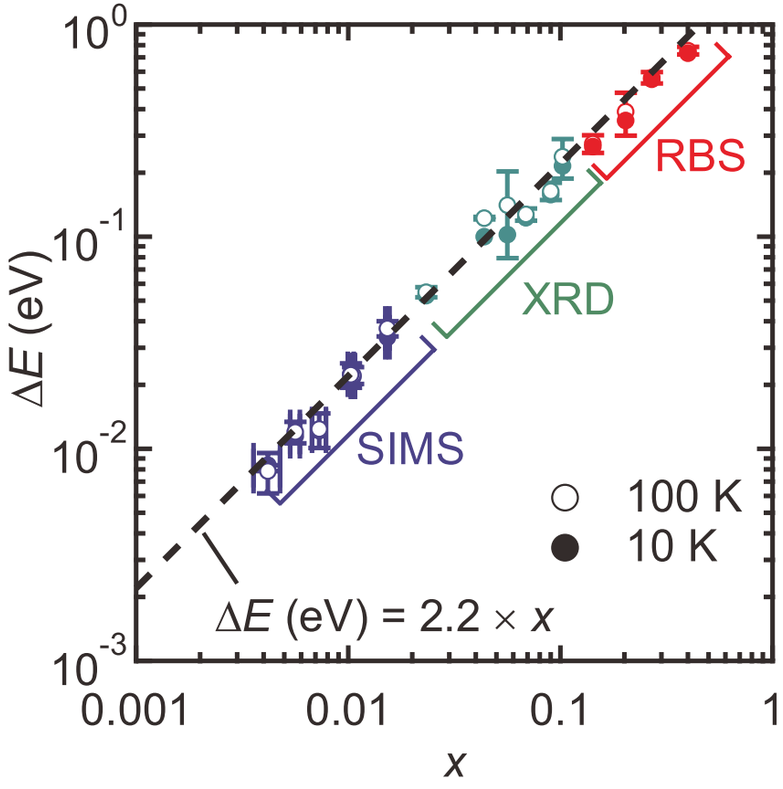
Y. Kozuka, *et al.*,
Journal of Applied Physics **112**, 043515 (2012).





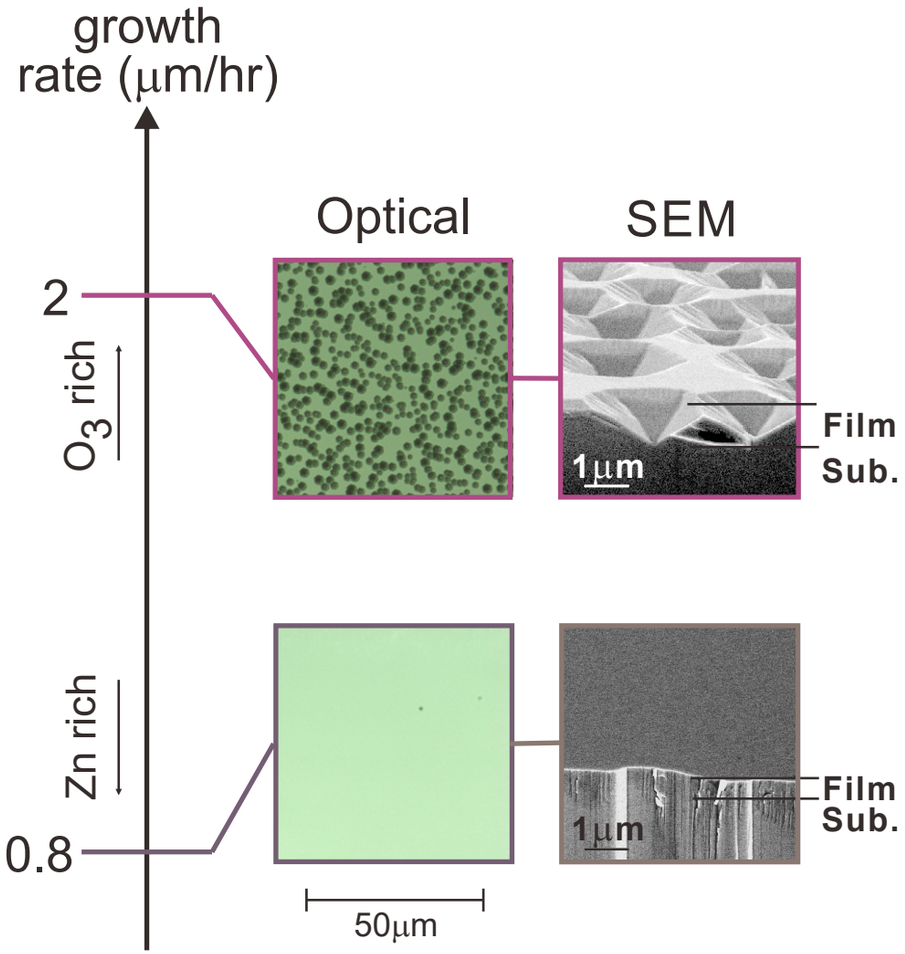


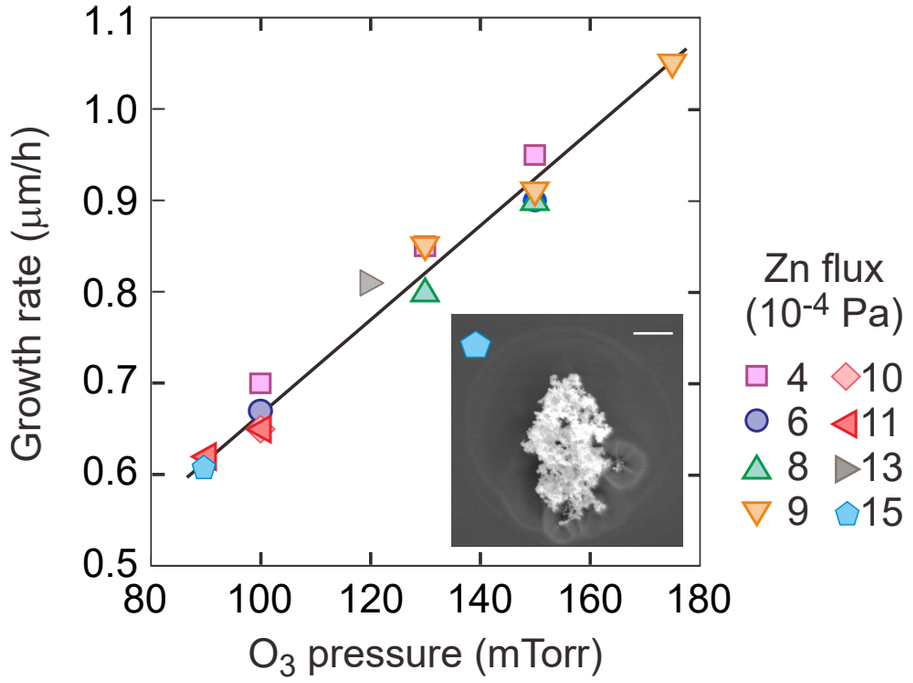




Flux ratios: surface morphology

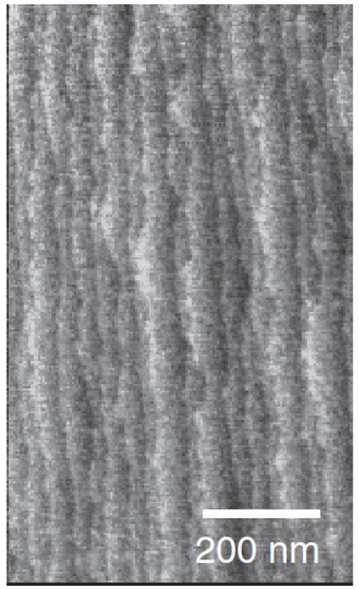
Falson, *et al.*,
Scientific reports **6**, 26598 (2016).

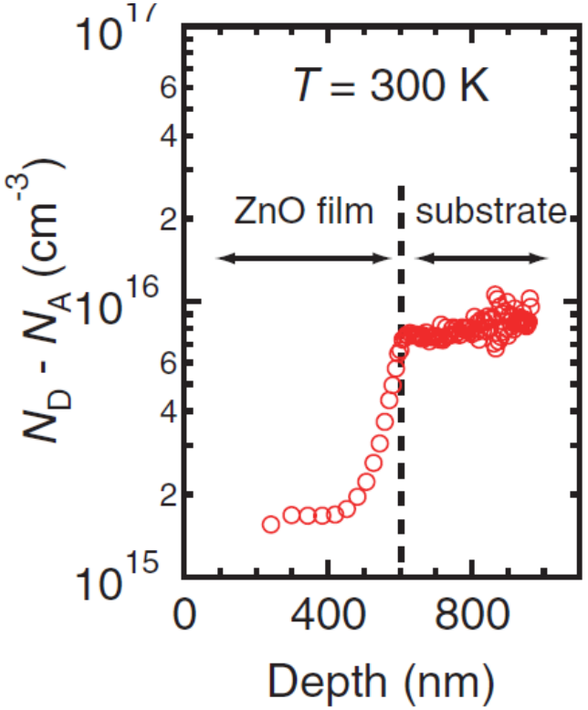


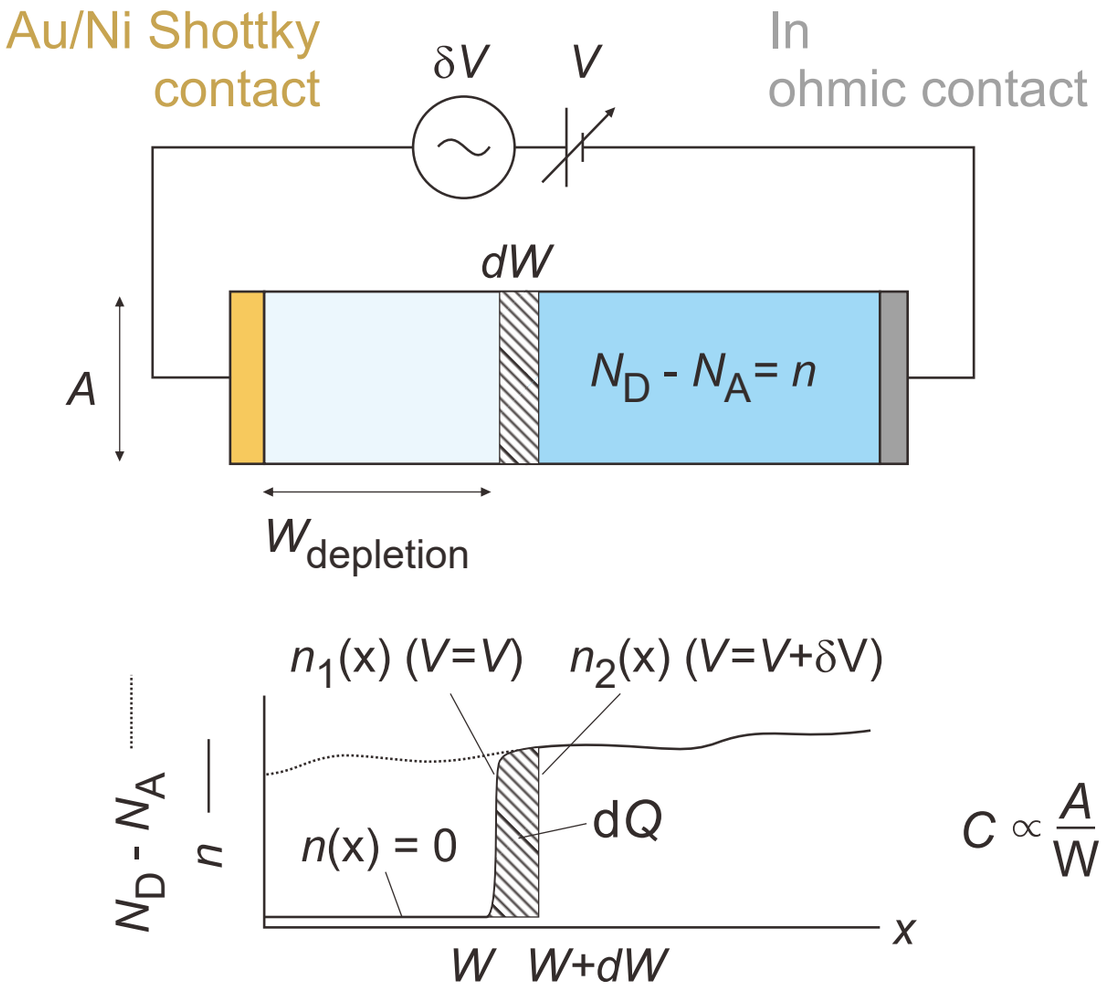


Residual carrier density

S. Akasaka, *et al.*,
Applied Physics Express **4** 035701 (2011).







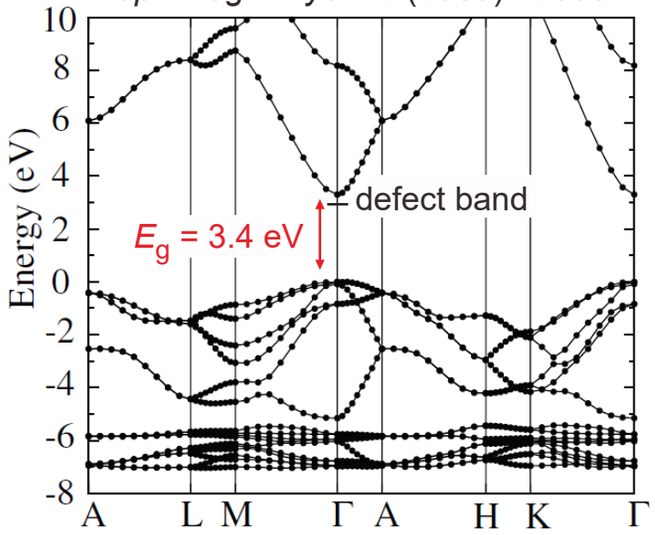
See:
D. Schroder, Semiconductor Material and Device Characterization (2005)

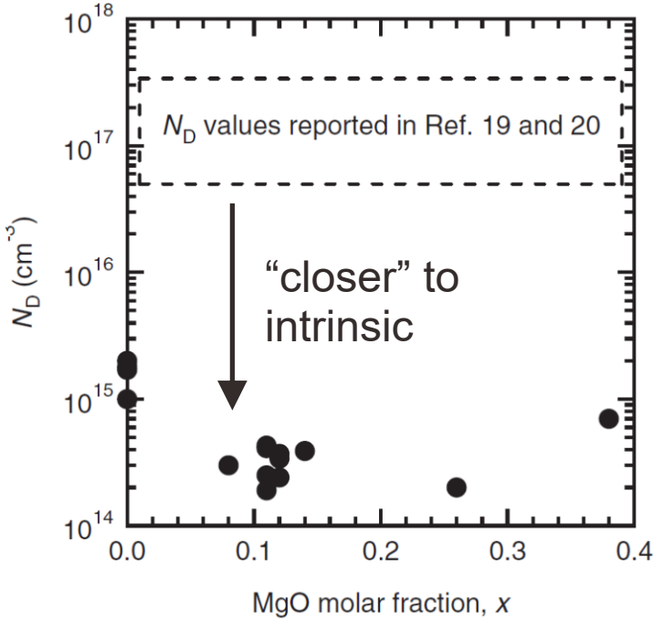
p-n junctions

S. Akasaka, *et al.*, *Appl. Phys. Express* **3**, 071101 (2010).

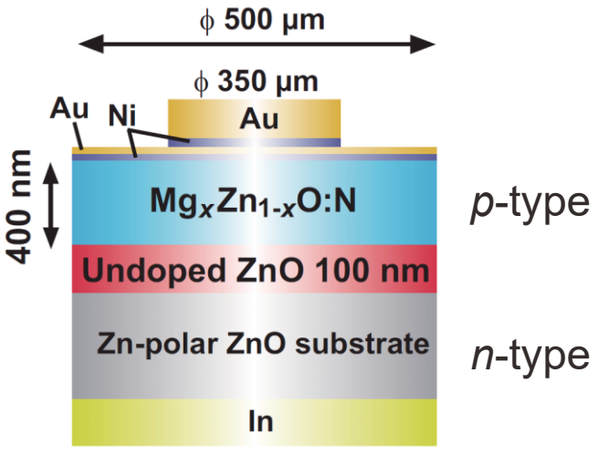
Nakahara, *et al.*, *Appl. Phys. Lett.* **97**, 013501 (2010)

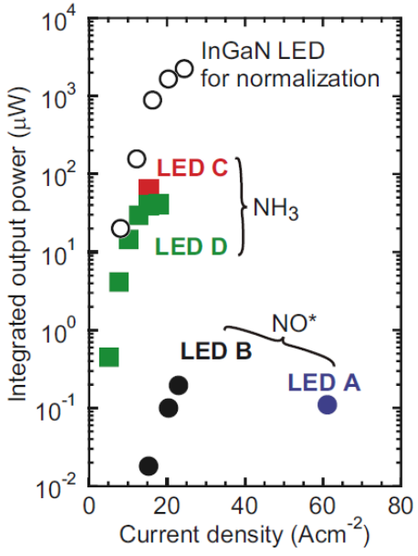
Janotti and van de Walle, *Rep. Prog. Phys.* **72** (2009) 126501.

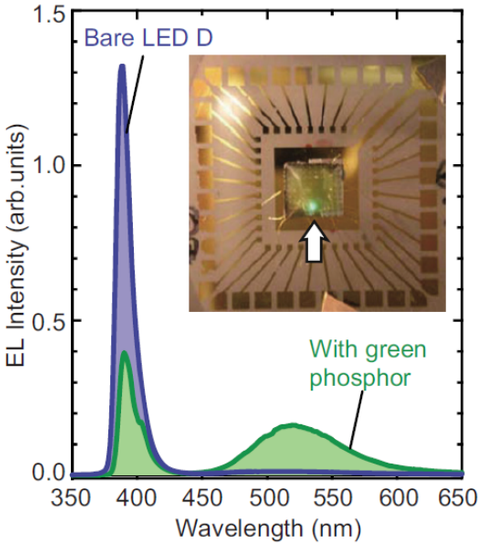




N, Mg co-doping

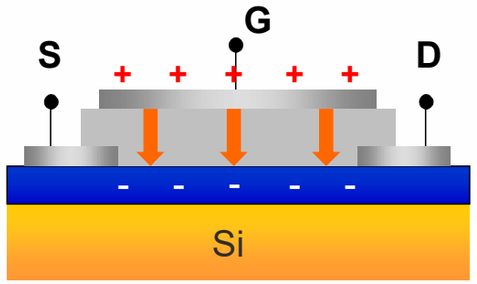


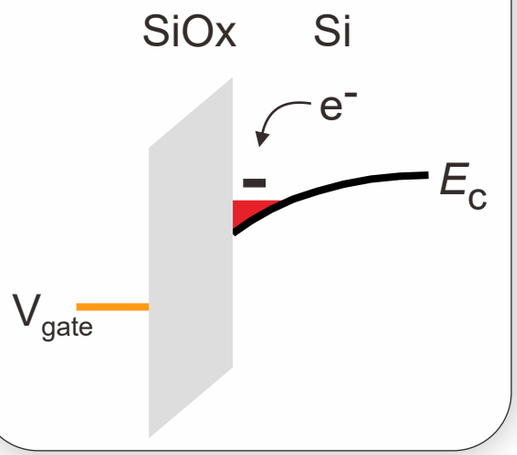




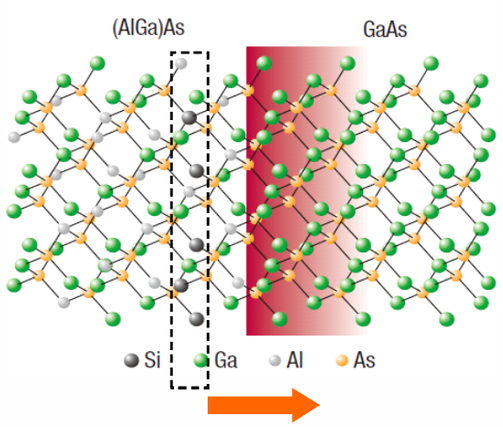
Electrons in a two-dimensional world

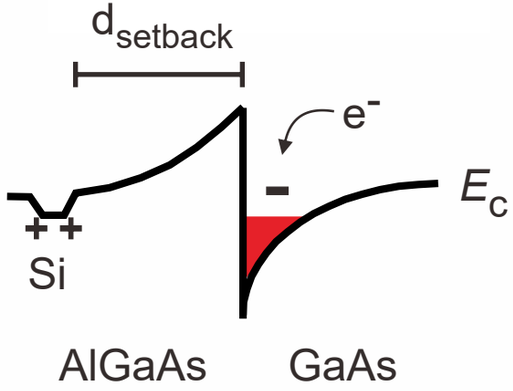
Field effect induced



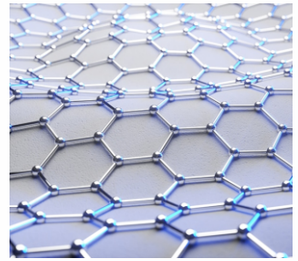


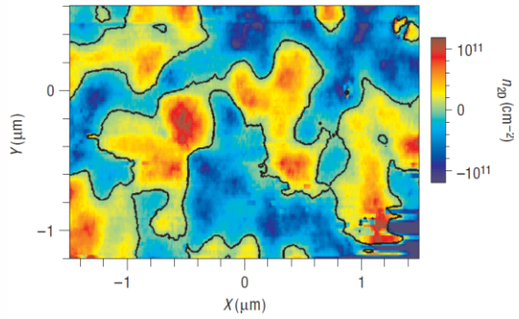
Modulation Doping

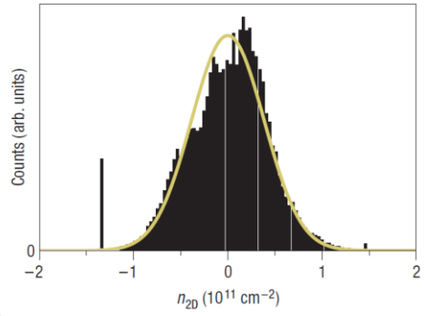




Exfoliated



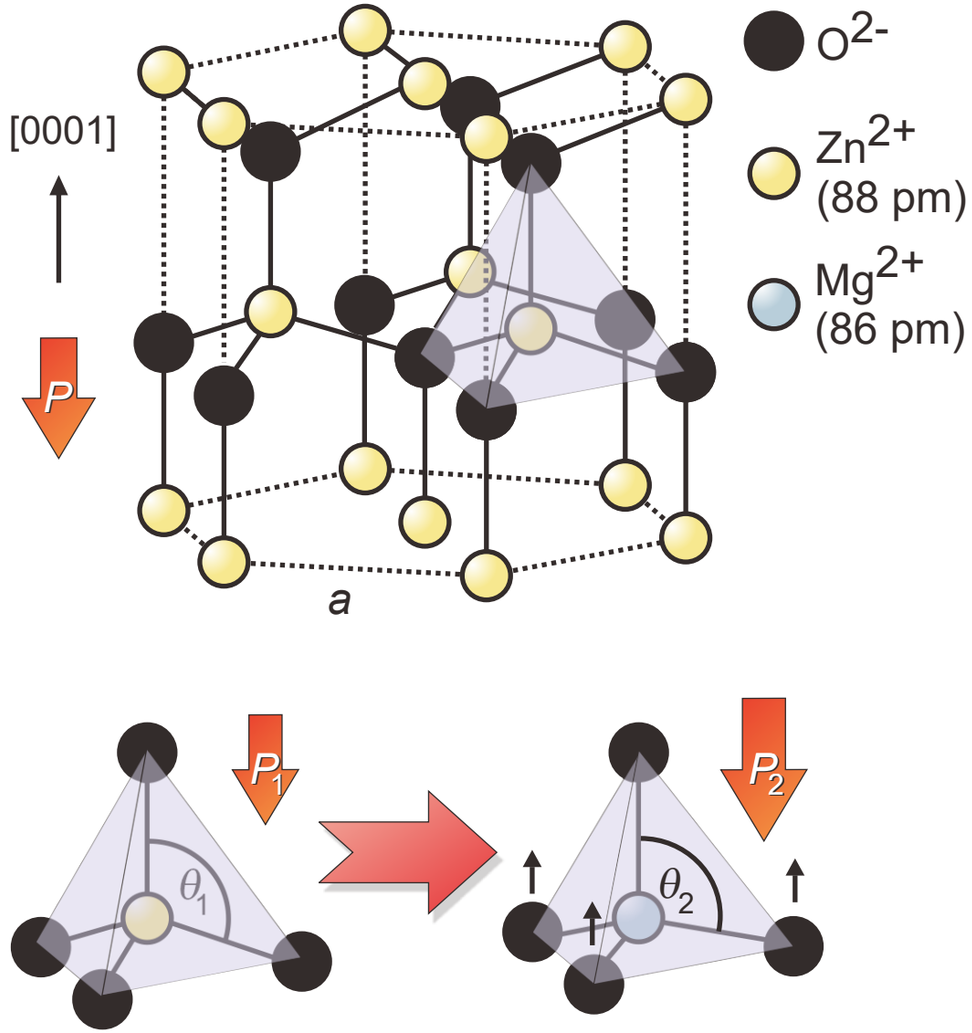


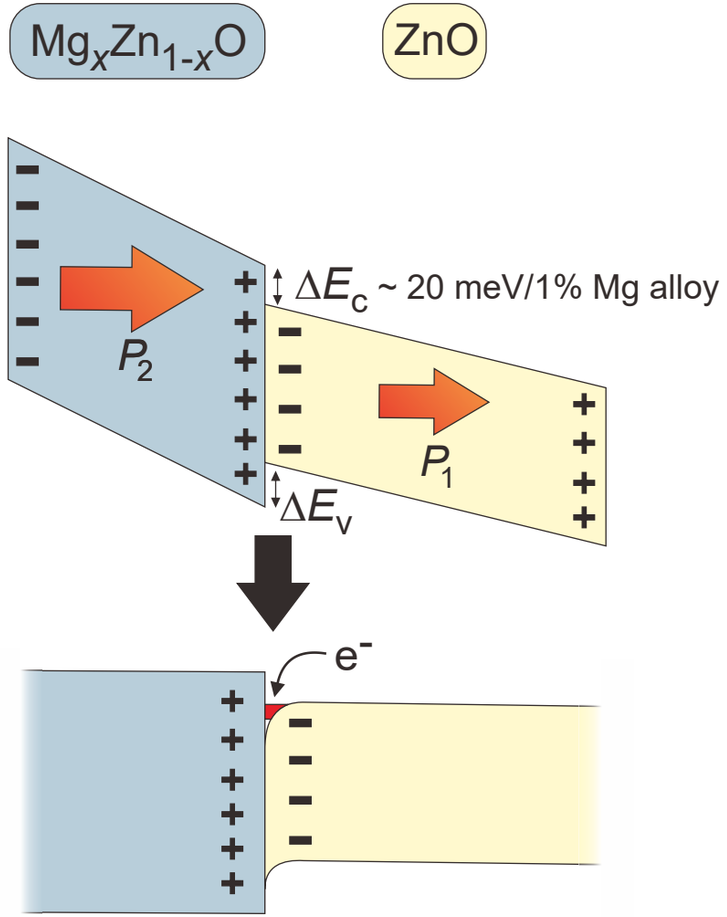


J. Martin, *et al.*, *Nature Physics* **4**, 144 (2008).

The king: Modulation doped GaAs

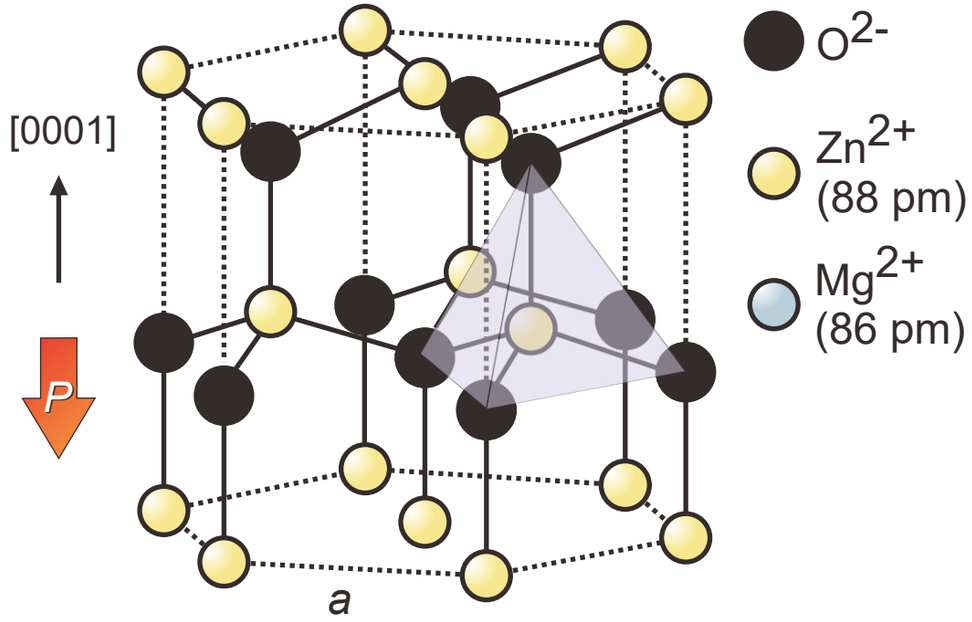
ZnO two-dimensional electron system

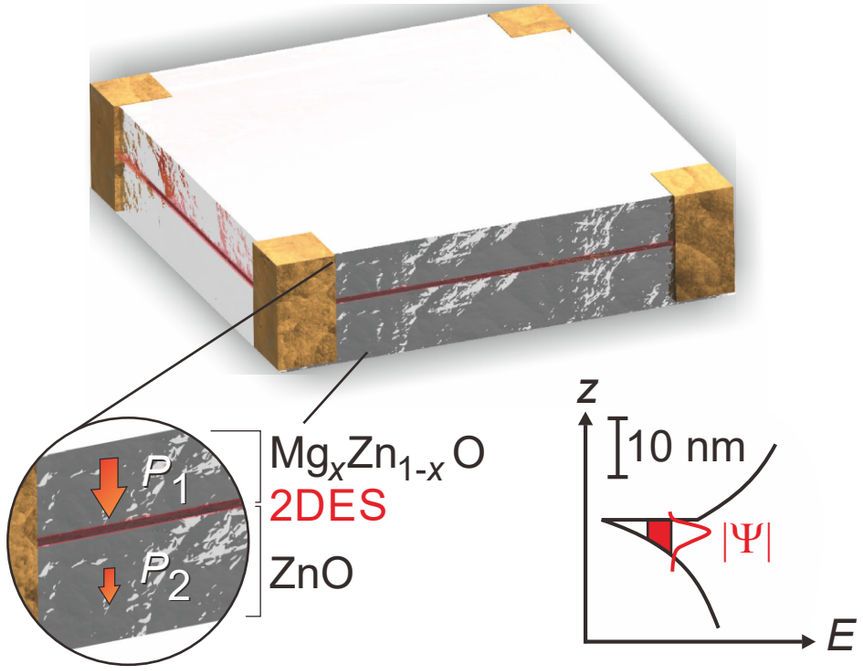


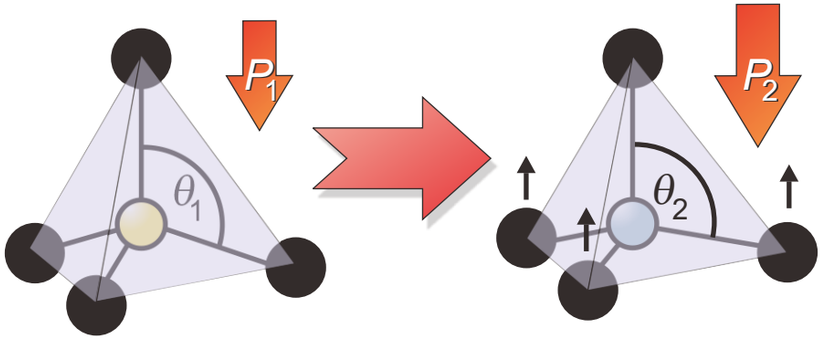


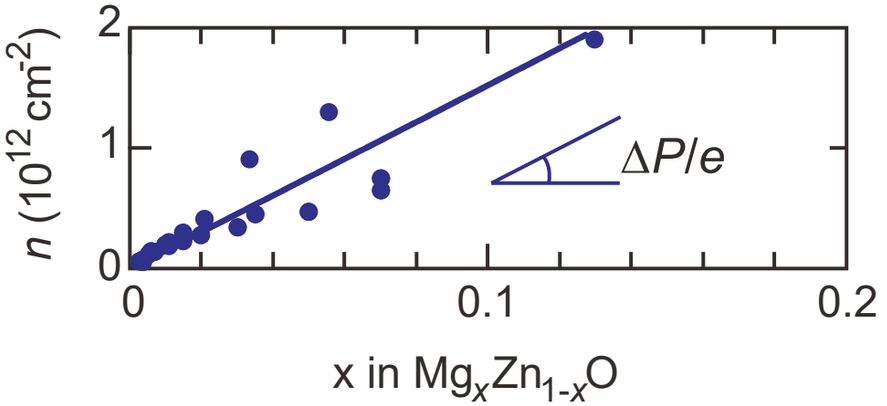
JF and M. Kawasaki., *Rep. Prog. Phys.* **81**, 056501 (2018).

ZnO two-dimensional electron system







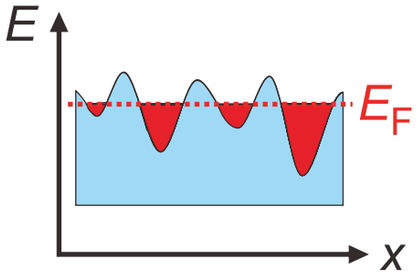


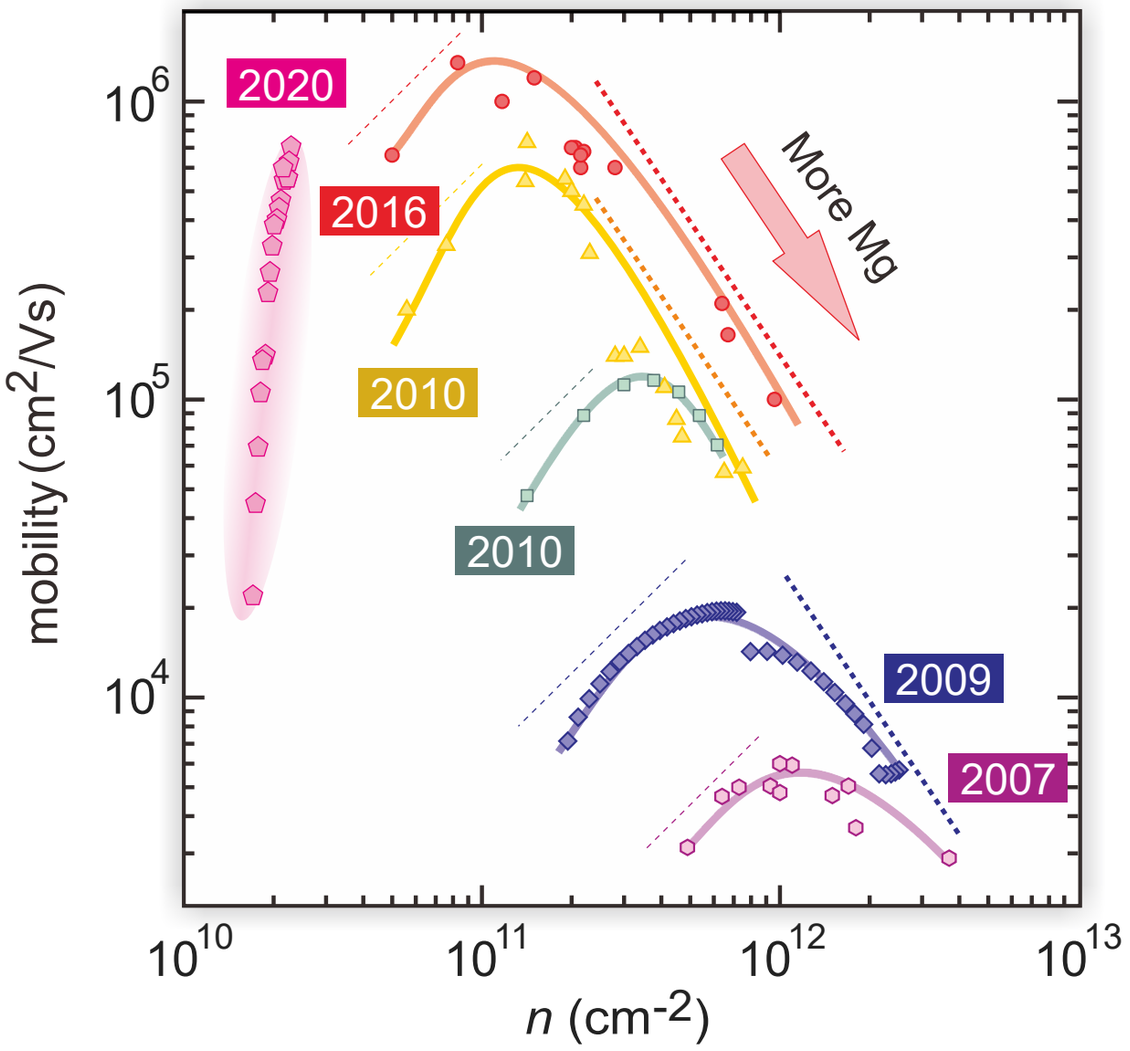
JF and M. Kawasaki., *Rep. Prog. Phys.* **81**, 056501 (2018).

Record electron mobility

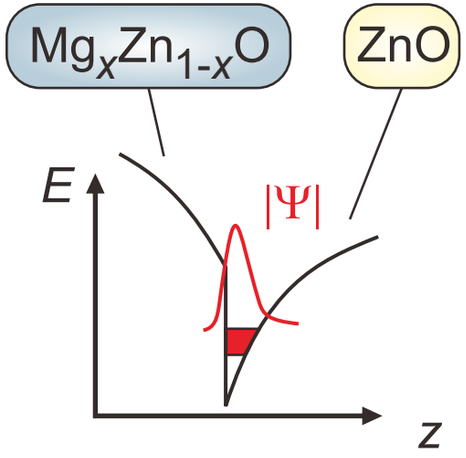
JF, et al., Scientific Reports **6**, 26598 (2016)
JF and M. Kawasaki., Rep. Prog. Phys **81**, 056501 (2018).

- Screening enhanced as E_F (=n) is increased





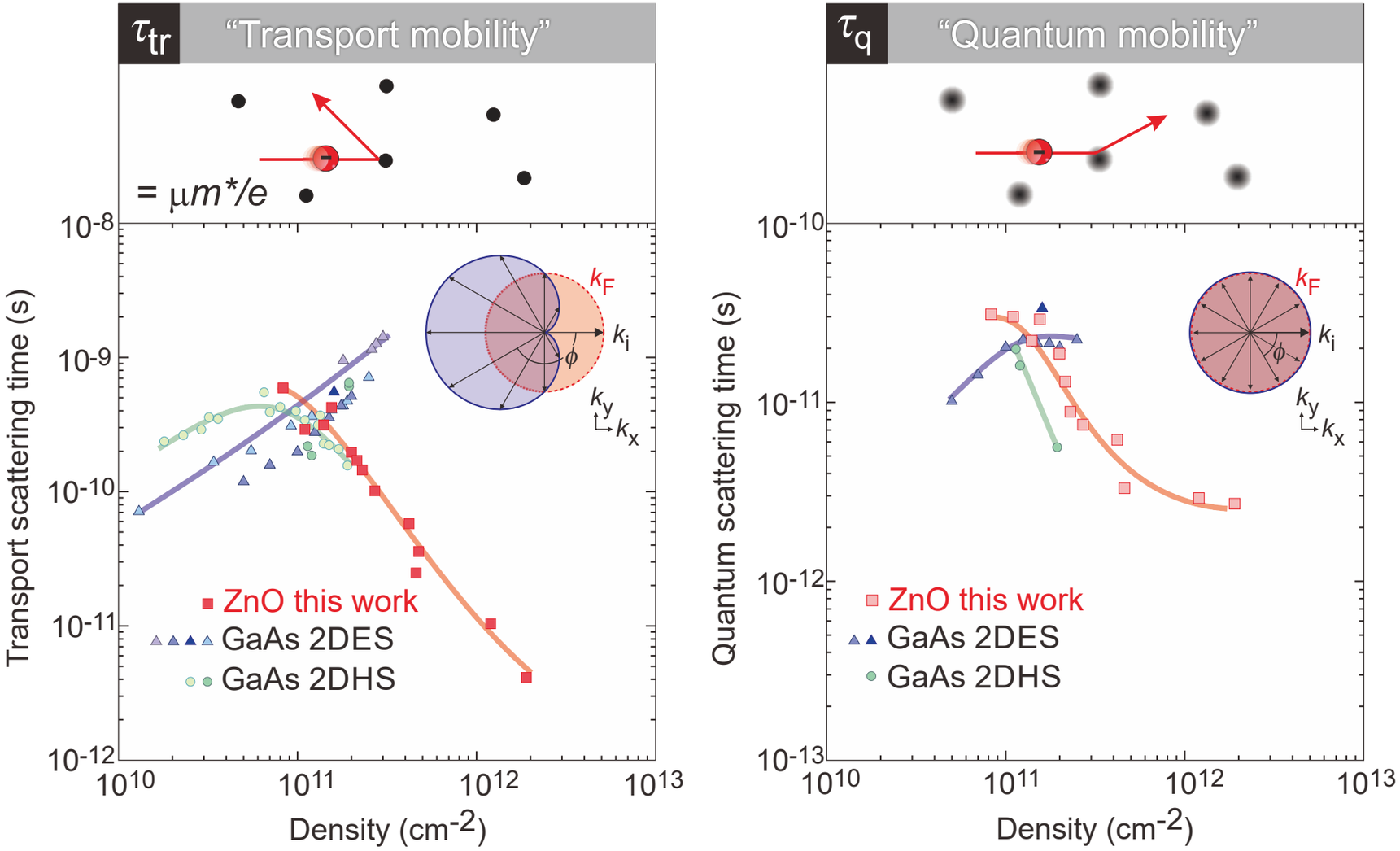
- Interface made rougher, wave-function pushed to interface as Mg is increased



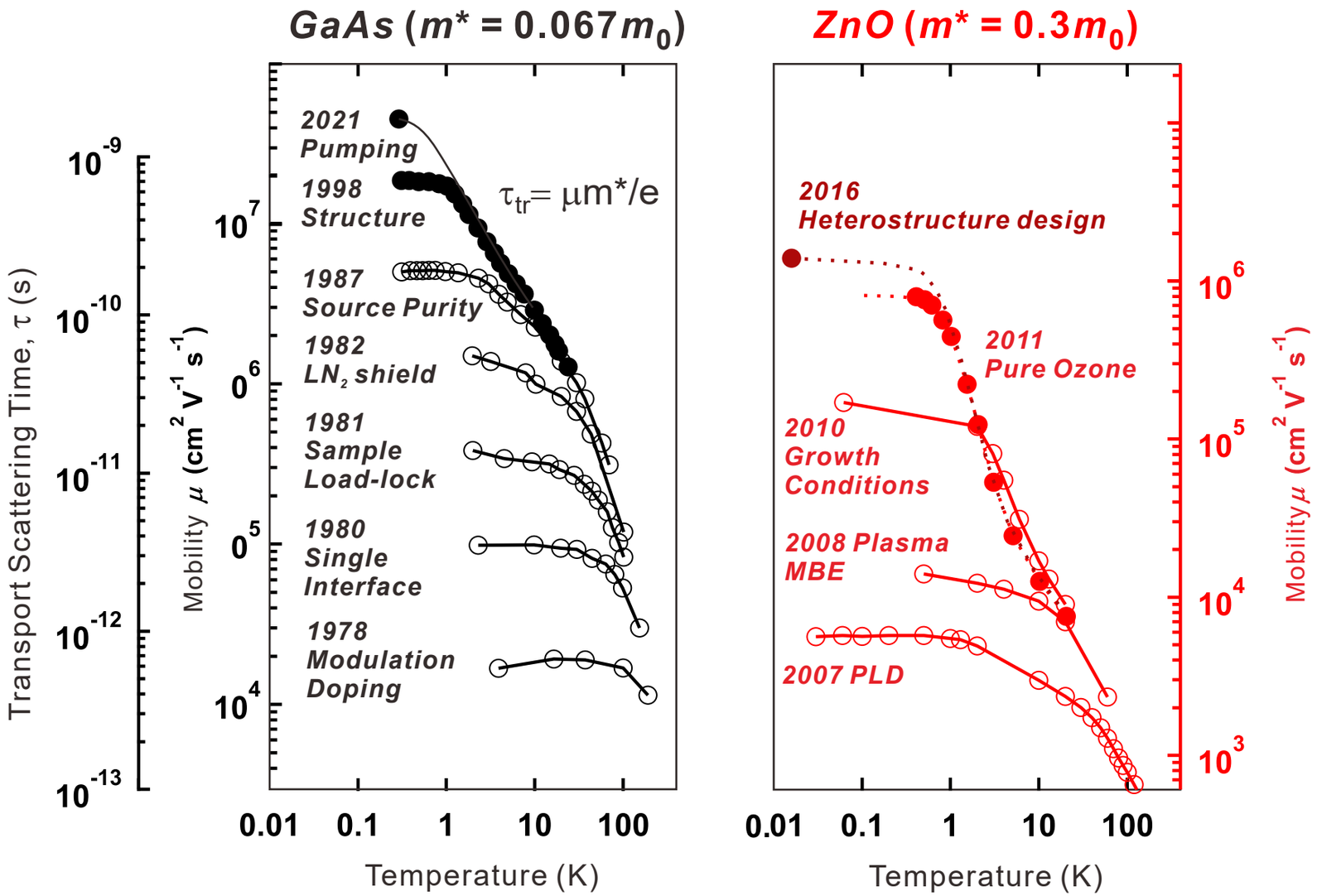
Electron scattering times

JF, et al.,
Appl. Phys. Lett. **107**, 082102 (2015).

$$\frac{1}{\tau_{TR}(\epsilon)} \equiv \Omega \int \frac{d^3\vec{k}'}{(2\pi)^3} W_{\vec{k}\vec{k}'}(1-\cos\theta_{\vec{k}\vec{k}'}), \qquad W_{\vec{k}'\vec{k}} = \frac{2\pi}{\hbar}|M_{\vec{k}'\vec{k}}|^2\delta(\epsilon_{\vec{k}'}-\epsilon_{\vec{k}})$$

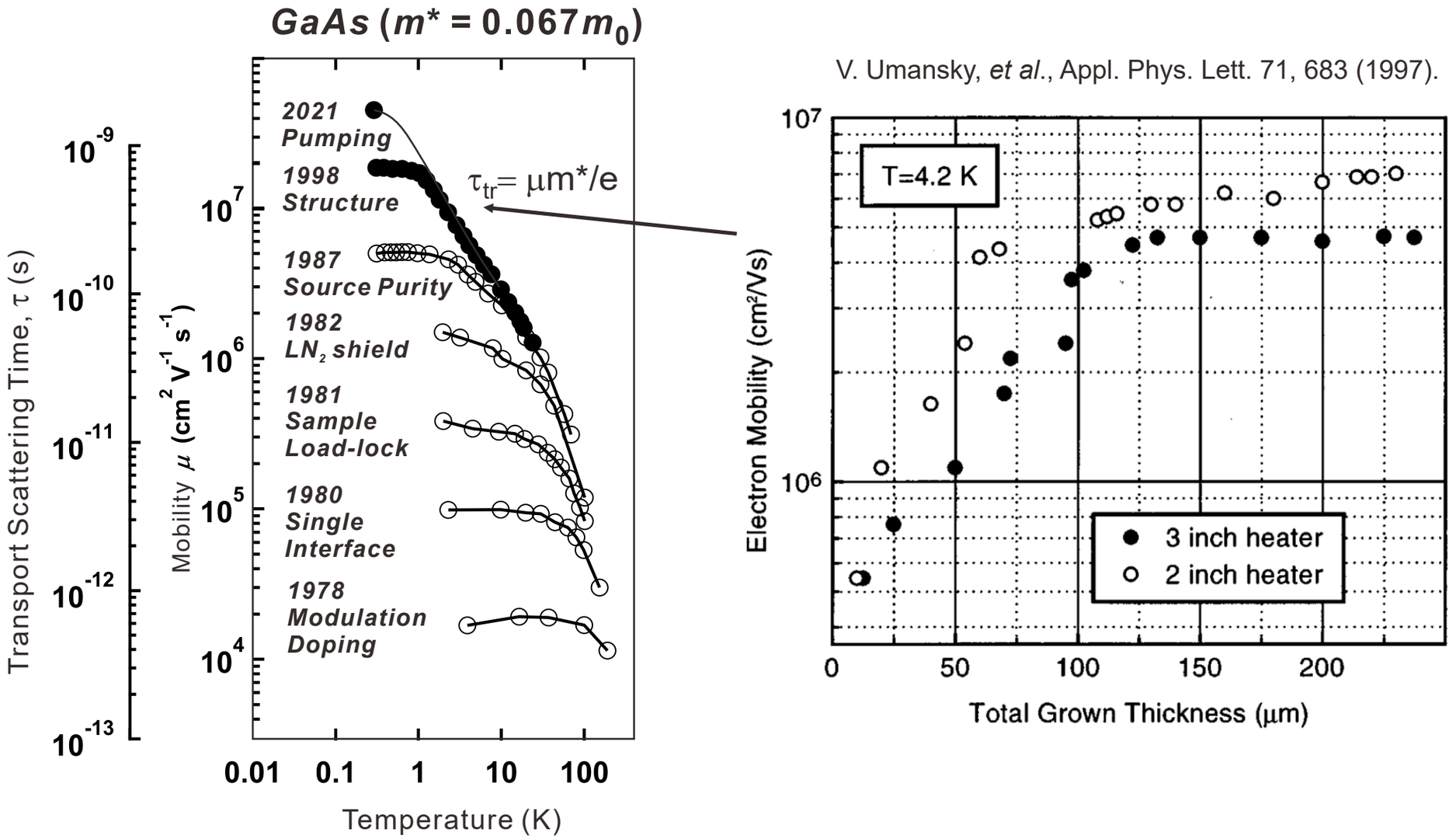


vs. GaAs 2DEG



D. Schlom and L. Pfieiffer, *Nature Materials* **9**, 881 (2010).
L.N. Pfeiffer, *et ai*., *Nature Materials* **20**, 632 (2021)

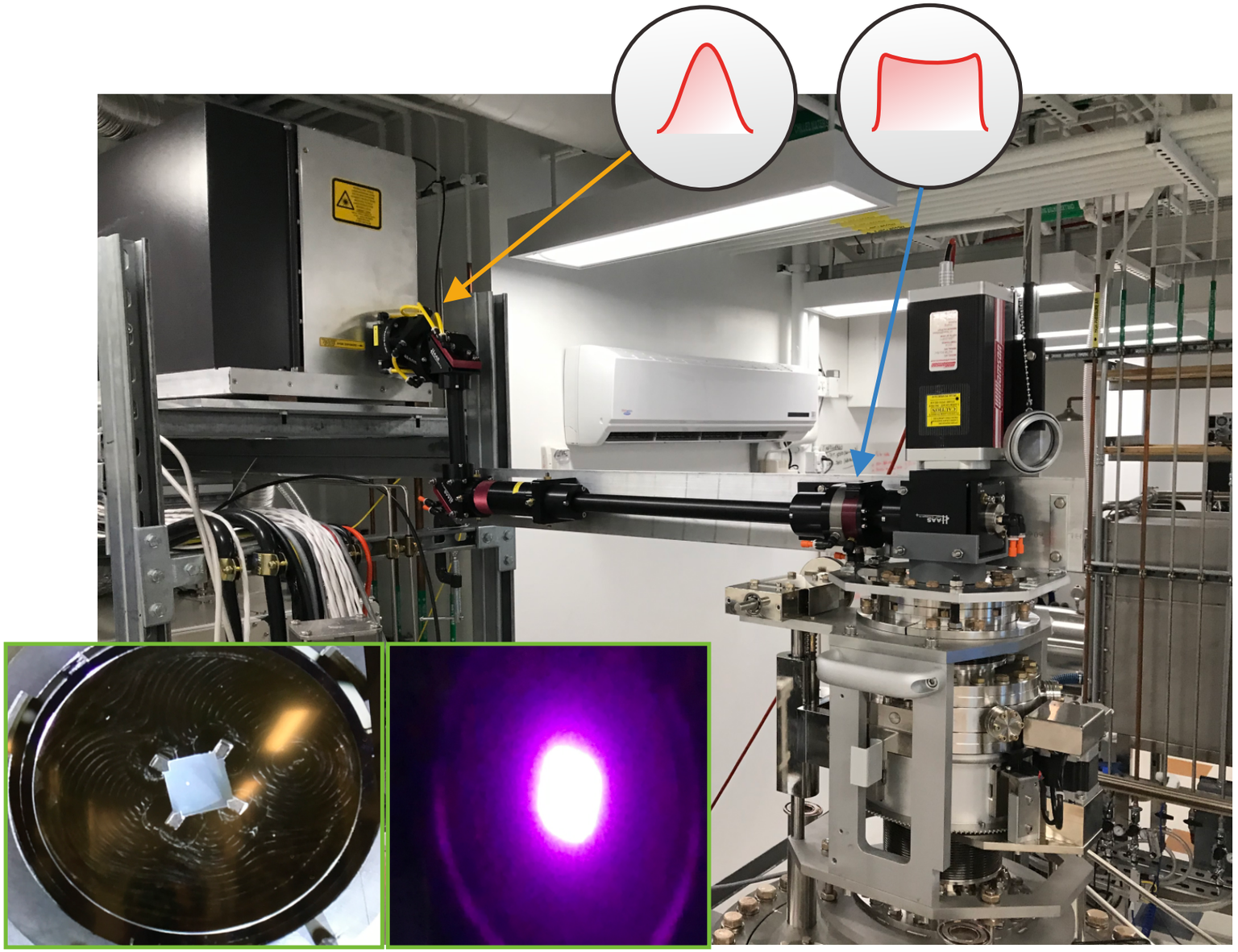
One step in the GaAs road

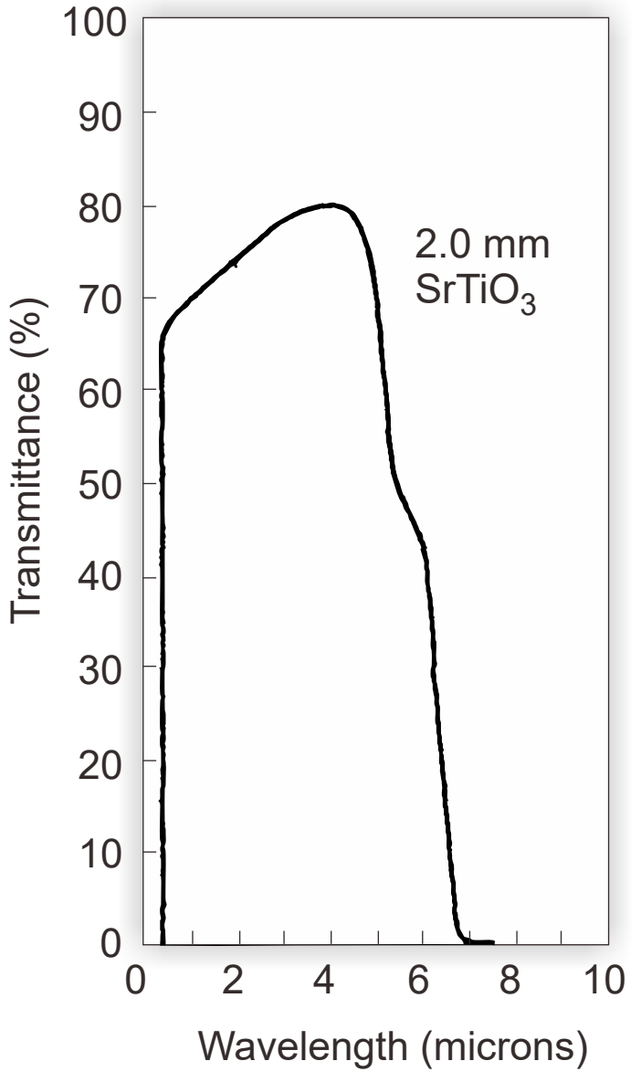


D. Schlom and L. Pfieiffer, *Nature Materials* **9**, 881 (2010).
L.N. Pfeiffer, *et ai*., *Nature Materials* **20**, 632 (2021)

The future is laser-based

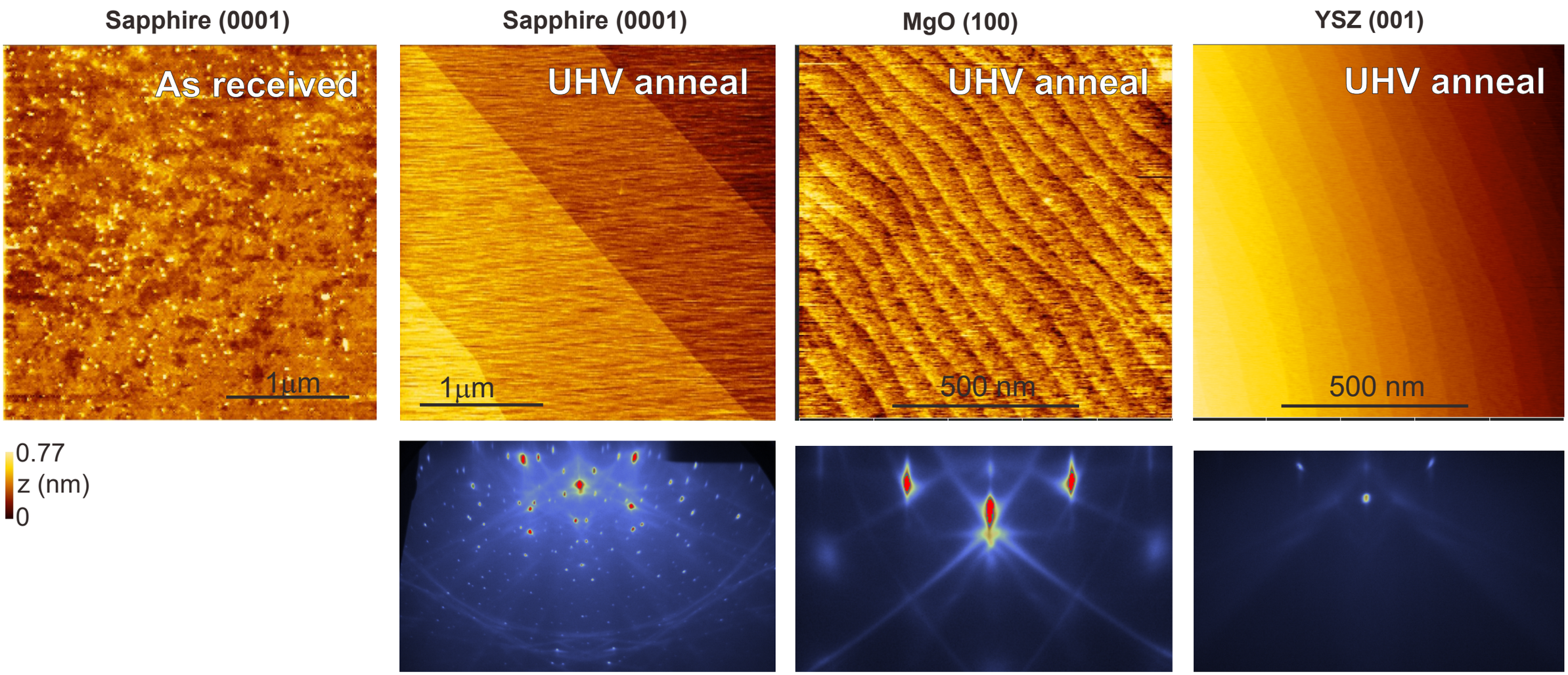
APL Materials **8**, 071112 (2020)



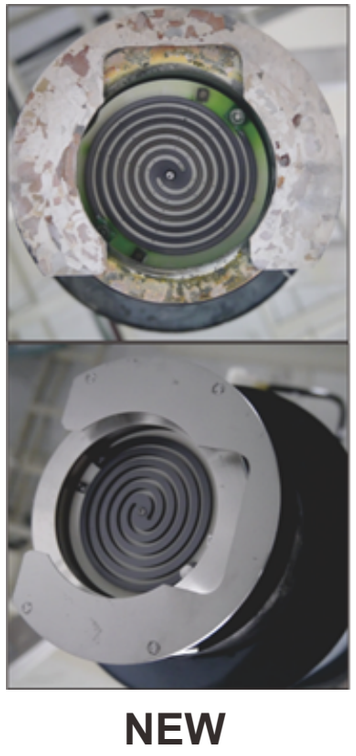


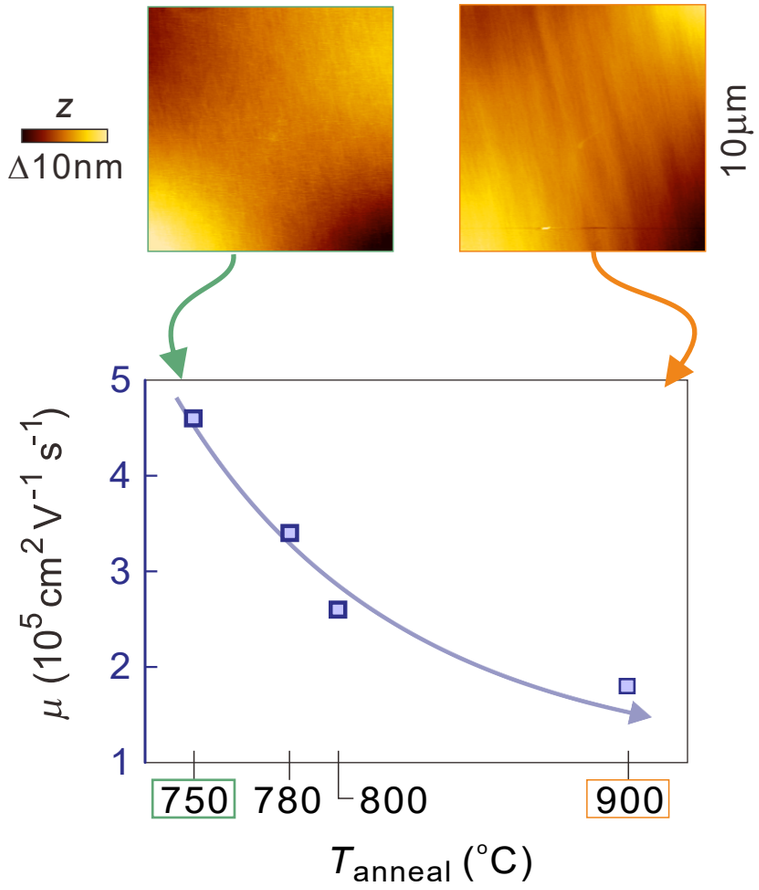
Widely useful for oxides

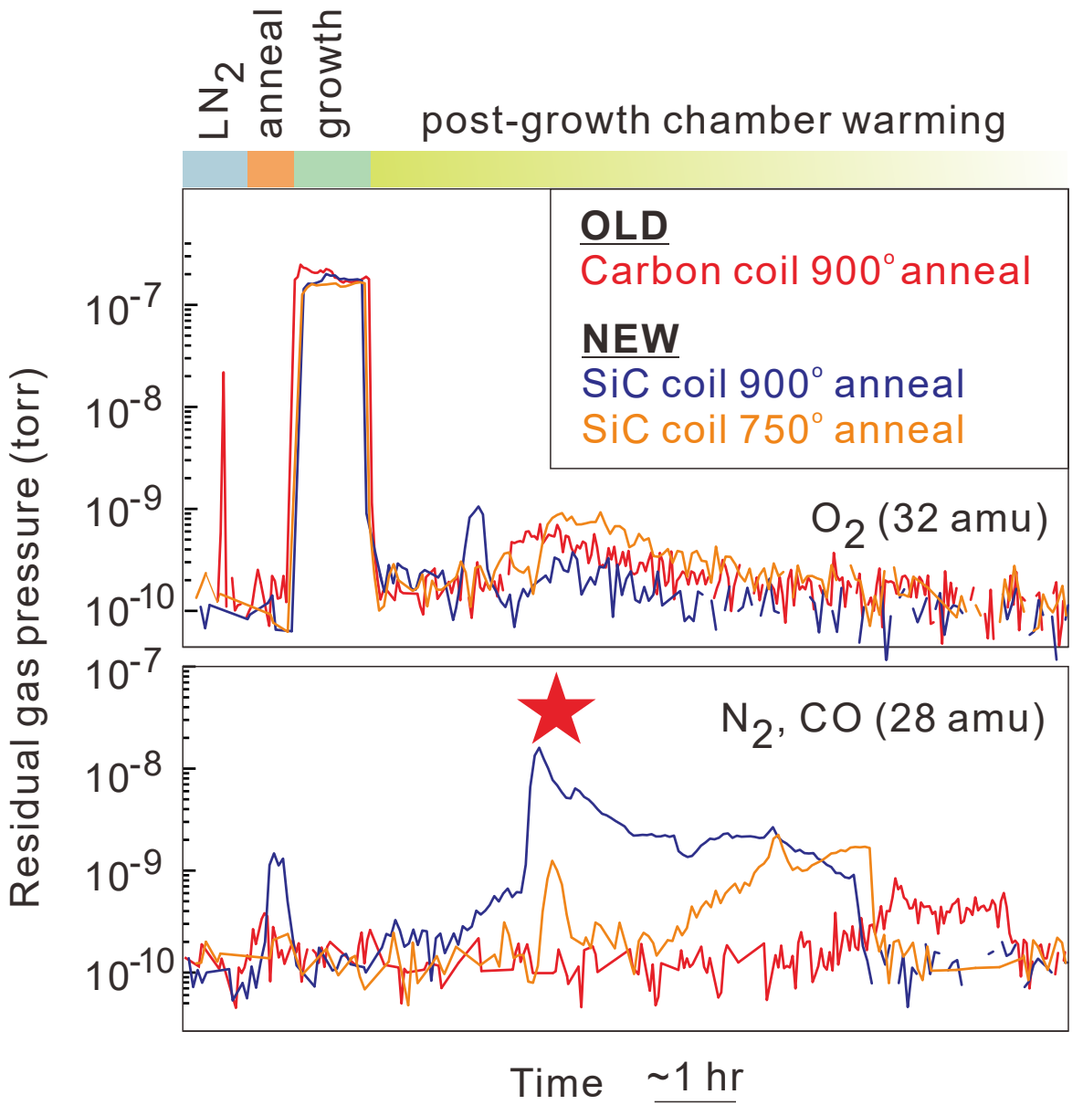
APL Materials **8**, 071112 (2020)



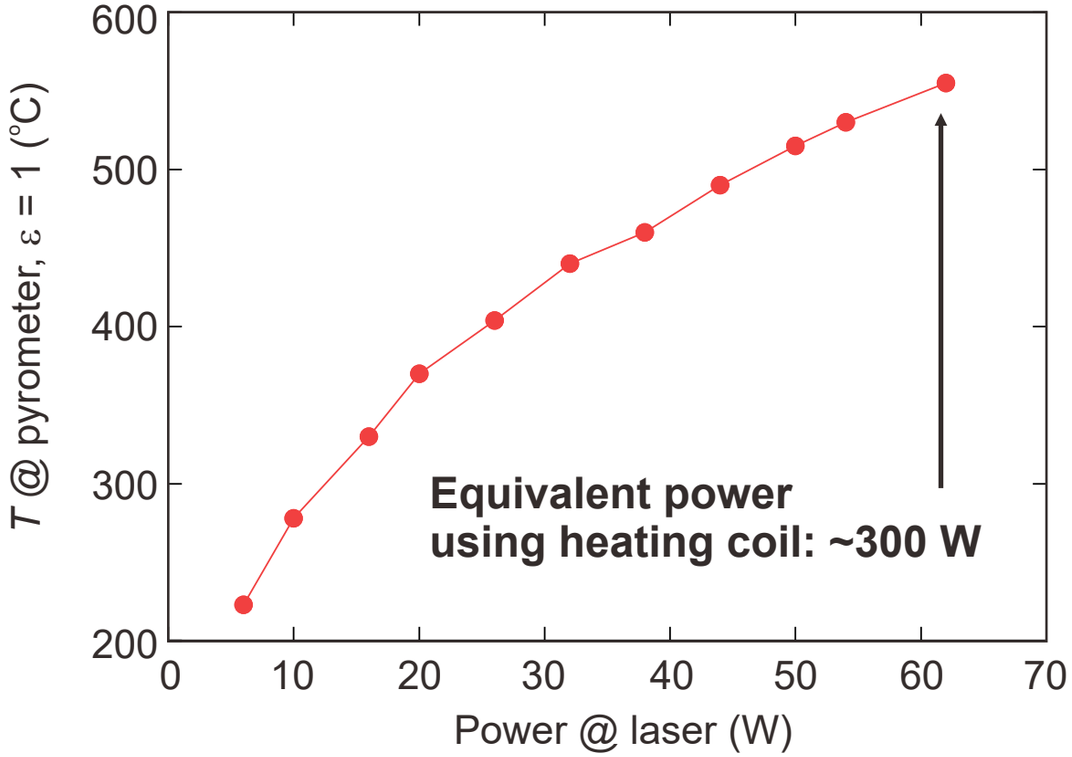
Contamination: Manipulator

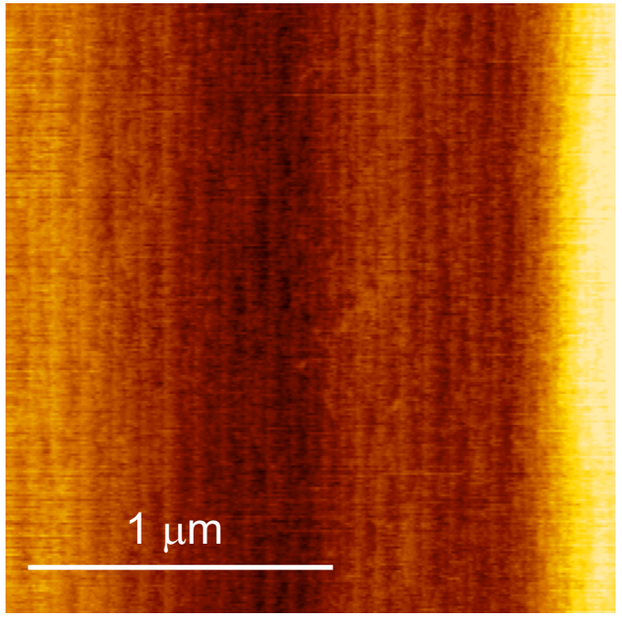


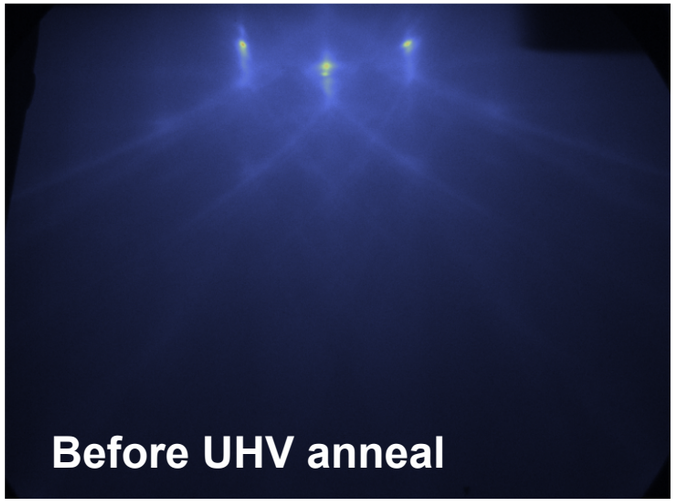


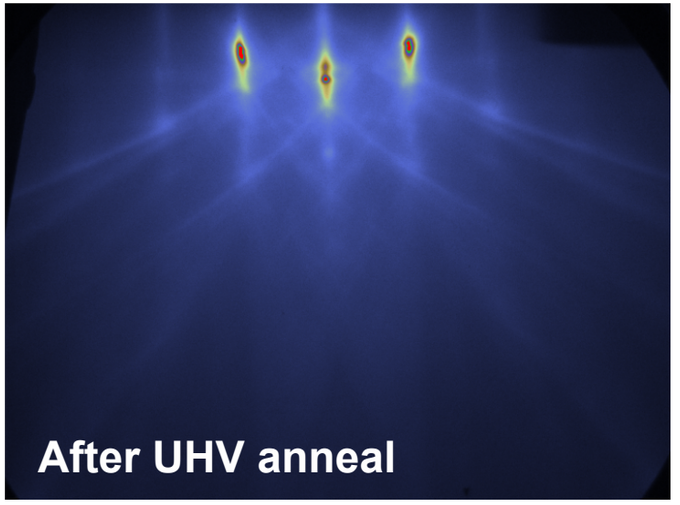


Preliminary tests on ZnO





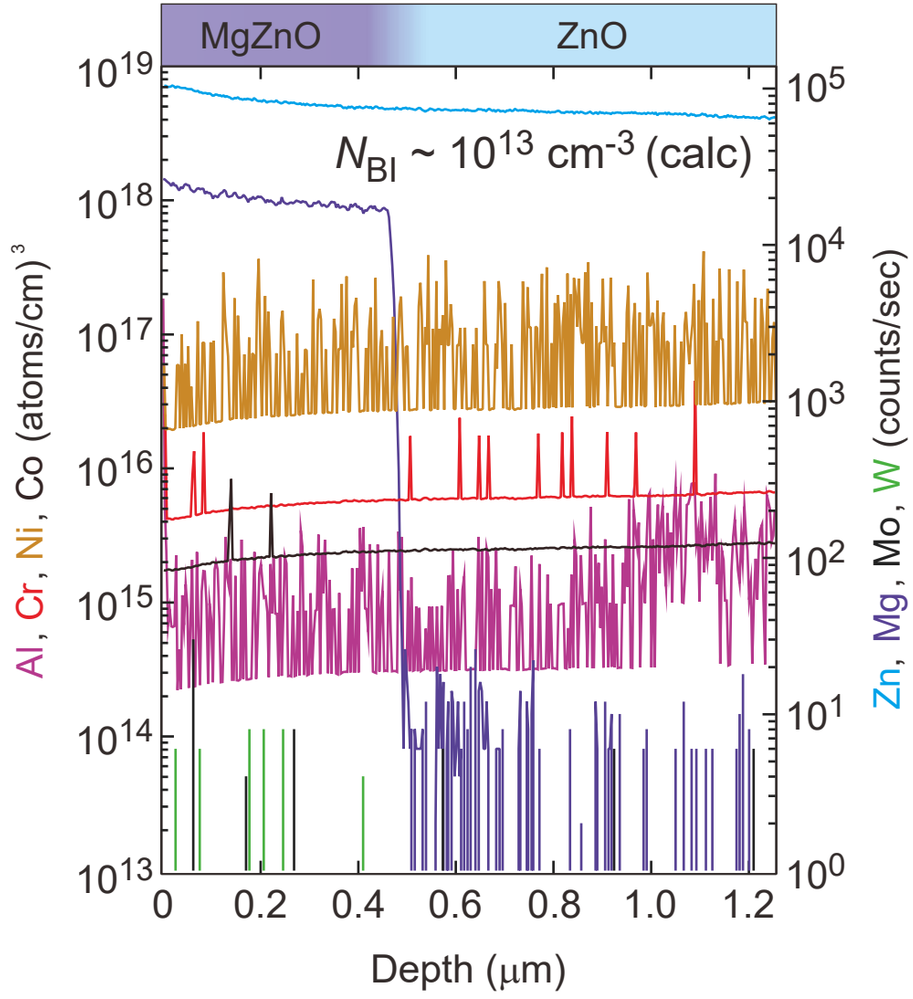


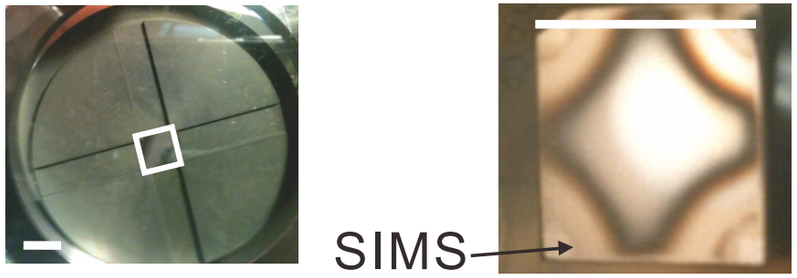


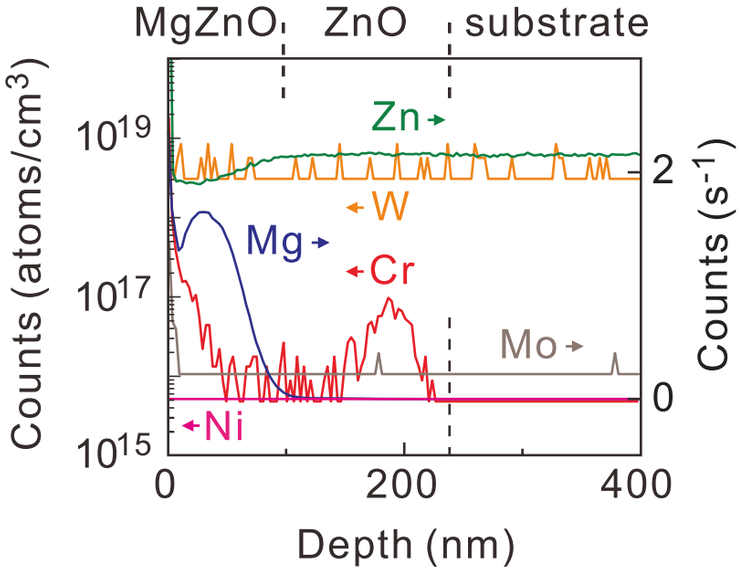
Contamination: Substrate holder

Falson, *et al.*, *Scientific reports* **6**, 26598 (2016).

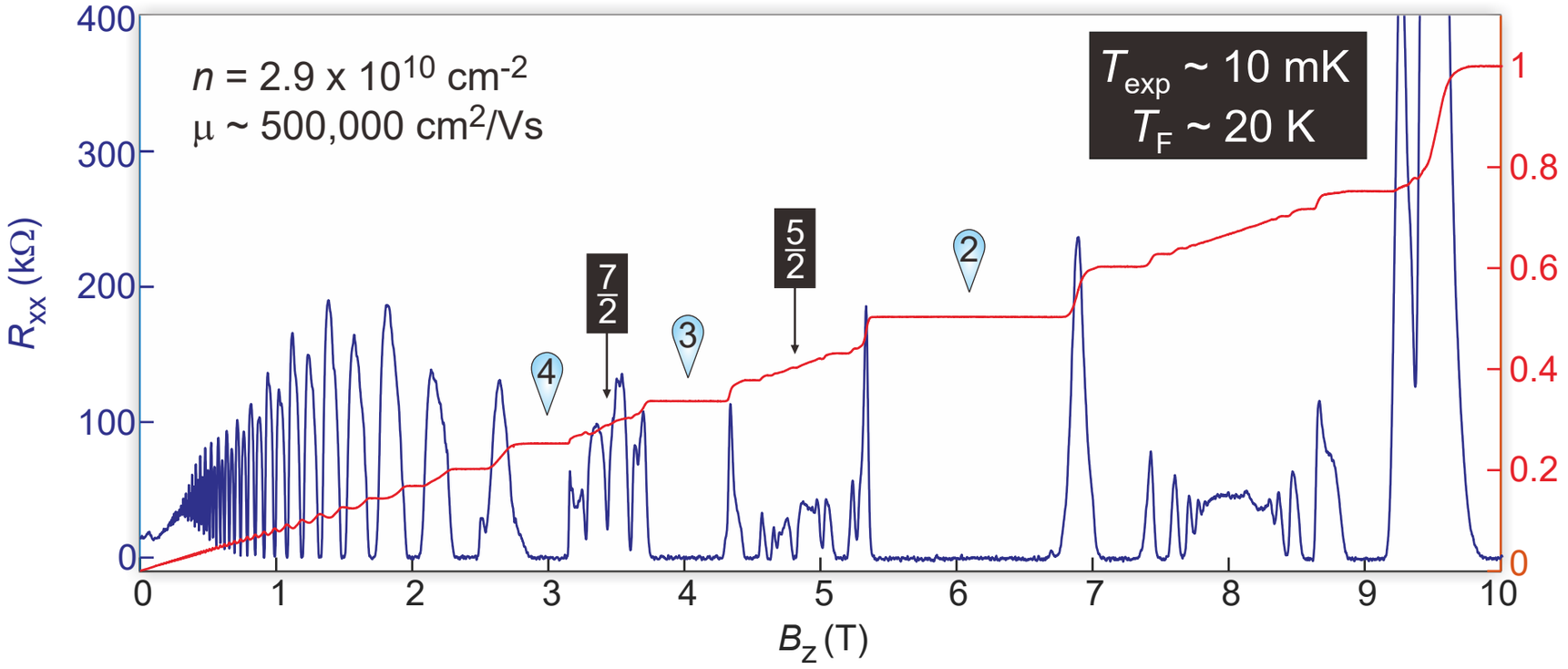
Success vs Failure

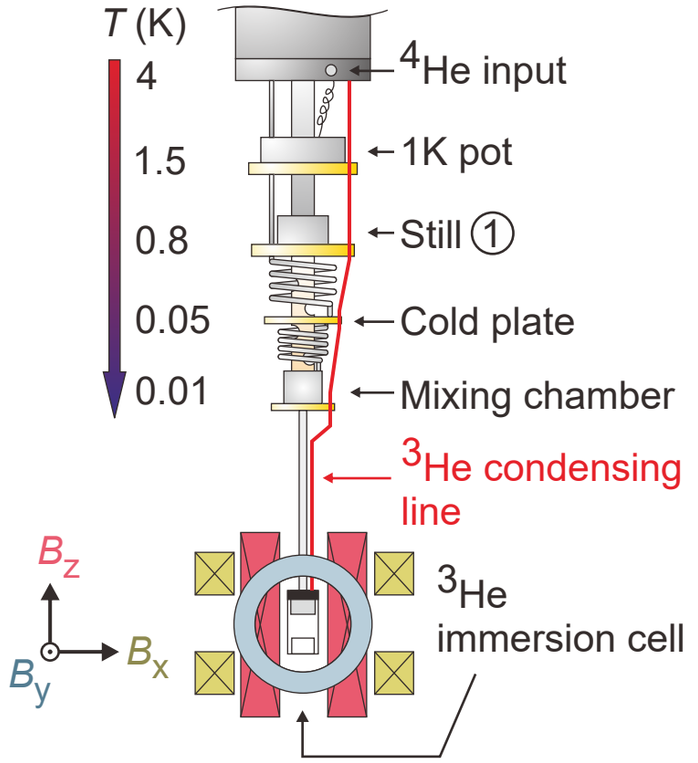


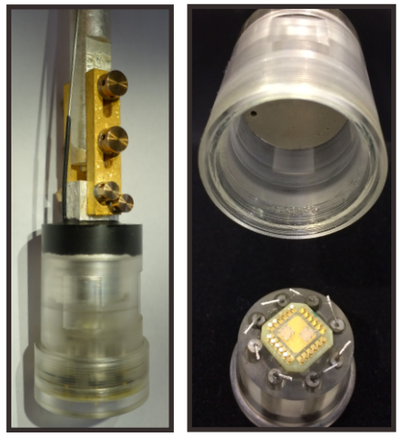




Pushing the limits

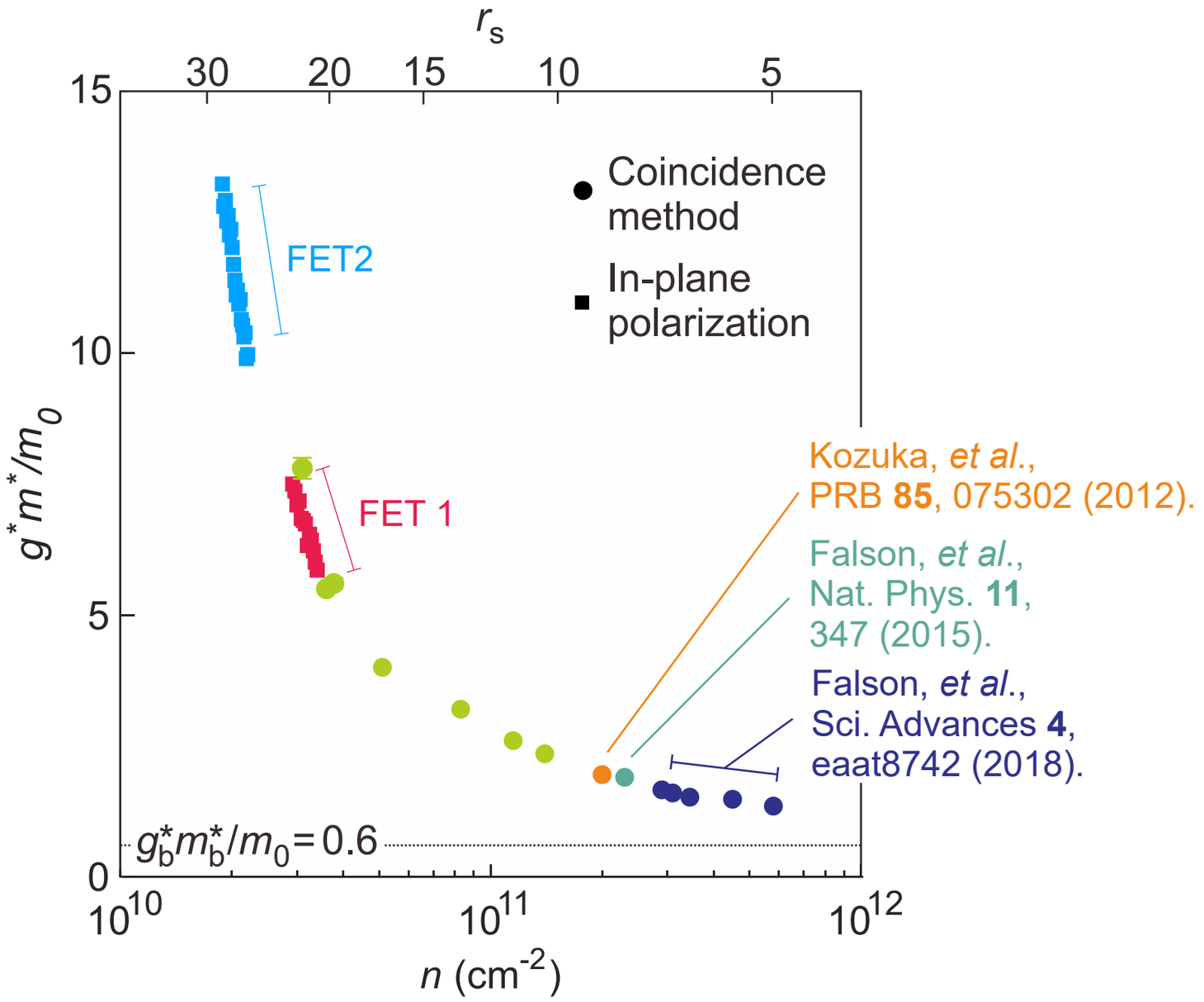






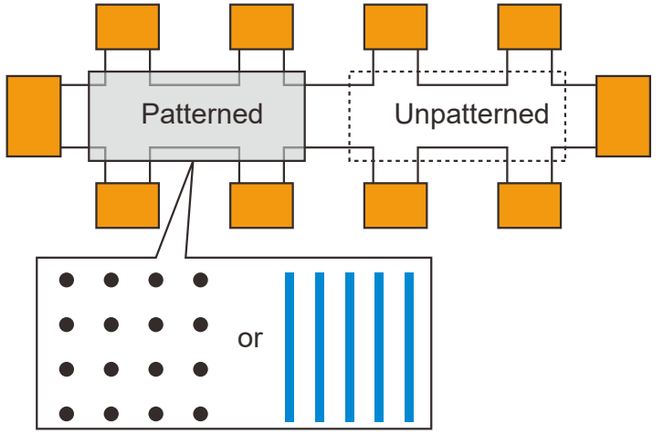
Fingerprints of correlation physics

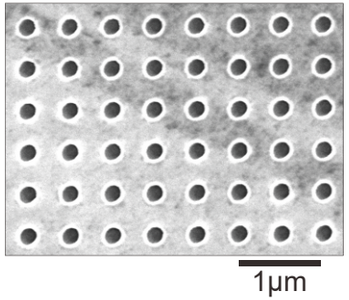
J. Falson, *et al.*,
Nature Materials **21**, 311 (2022).

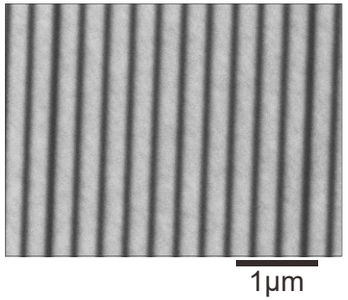


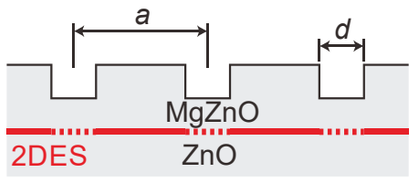
Glimpses of mesoscopic physics

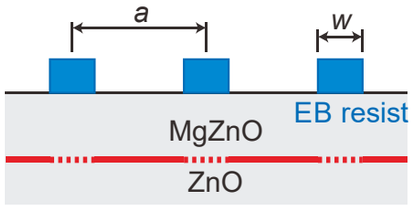
K. Tanaka, *et al.*,
Appl. Phys. Lett. 115, 153101 (2019)

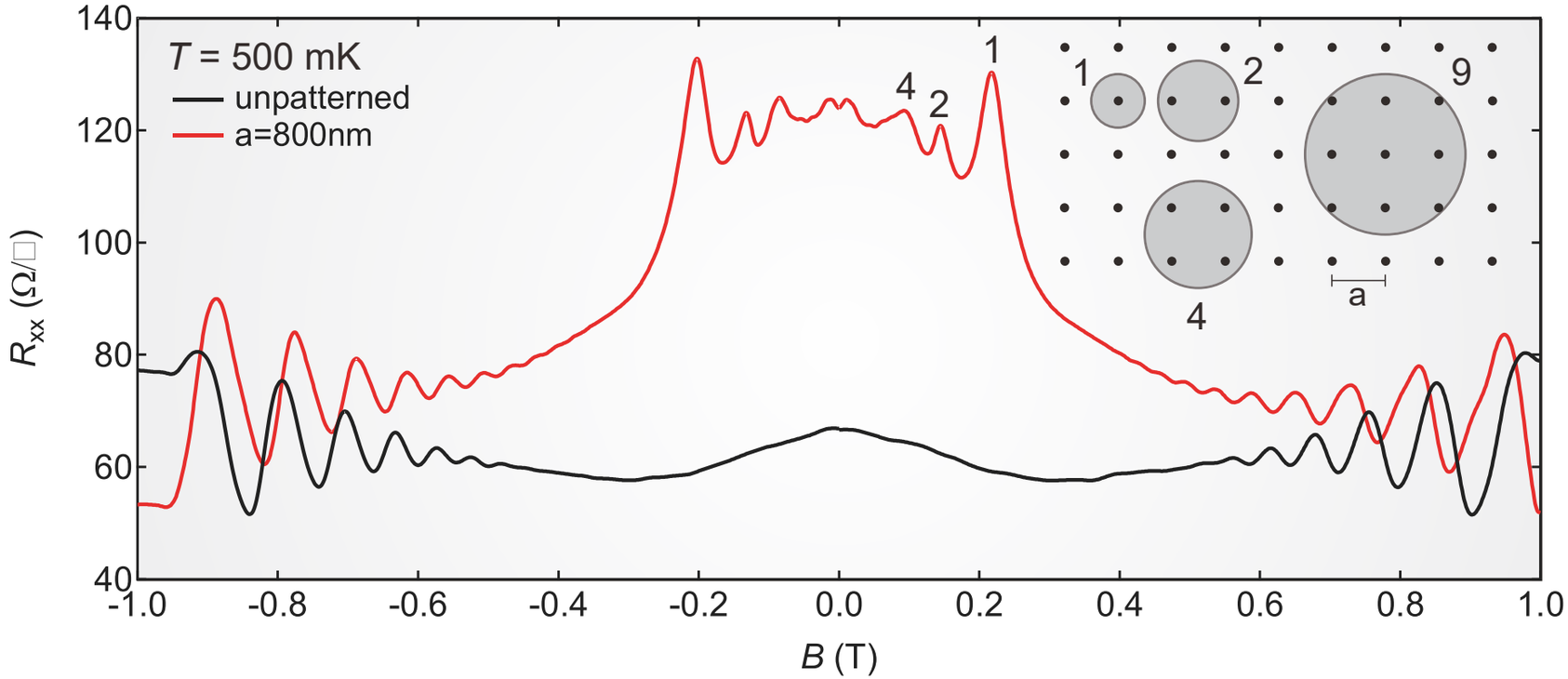












Summary & Outlook

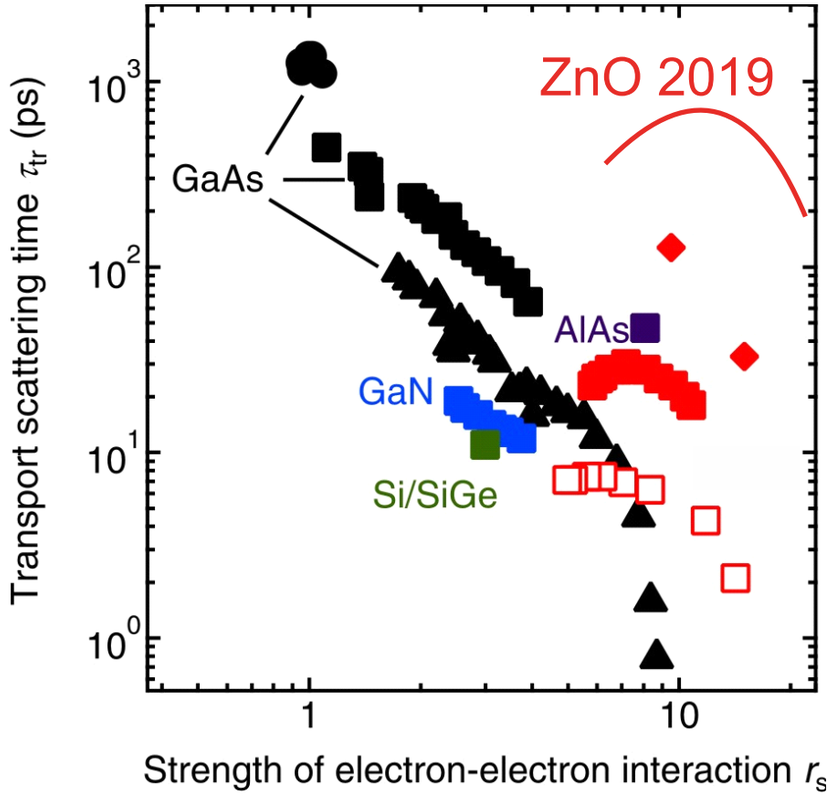
Simple chemistry, crystallography and device structure of ZnO enables pushing the limits of “clean” oxide MBE

ZnO enters a regime where electrical transport is the best means of quantifying crystallinity

Future challenges of MBE design refinement (slow and detailed experiments). *Towards 2(?) million mobility.*

Falson, *et al*., *Nature Physics* **11**, 347 (2015),
Falson, *et al., Science Advances* **4**, eaat8742 (2018)),
Falson, *et al*., Nature Materials 21, 311 (2022).

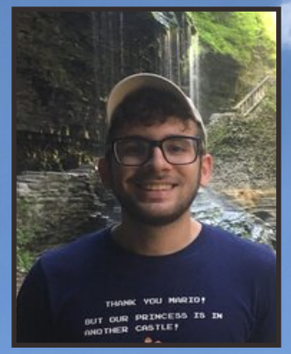
Strongly correlated electron physics: high mobility meets quantum criticality



Dr. Jeong Rae Kim

Adrian Llanos

Kaveh Pezeshki



Adam Abbas

Abigail Jiang

GORDON AND BETTY MOORE FOUNDATION

Thank you