Tailoring oxide thin films by ion beam

Shengqiang Zhou
s.zhou@hzdr.de

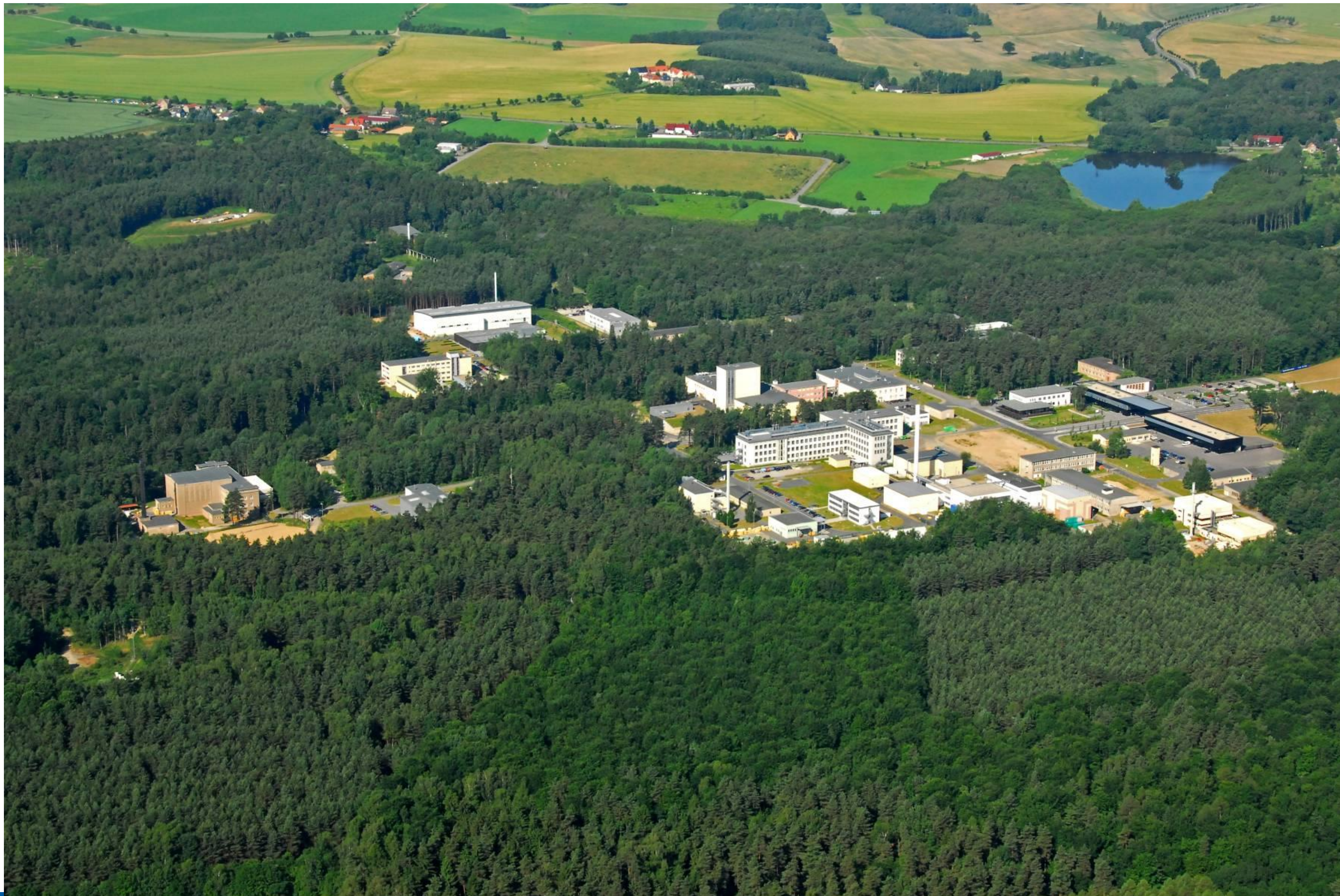
Department Head, Semiconductor Materials
Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

Always along a river

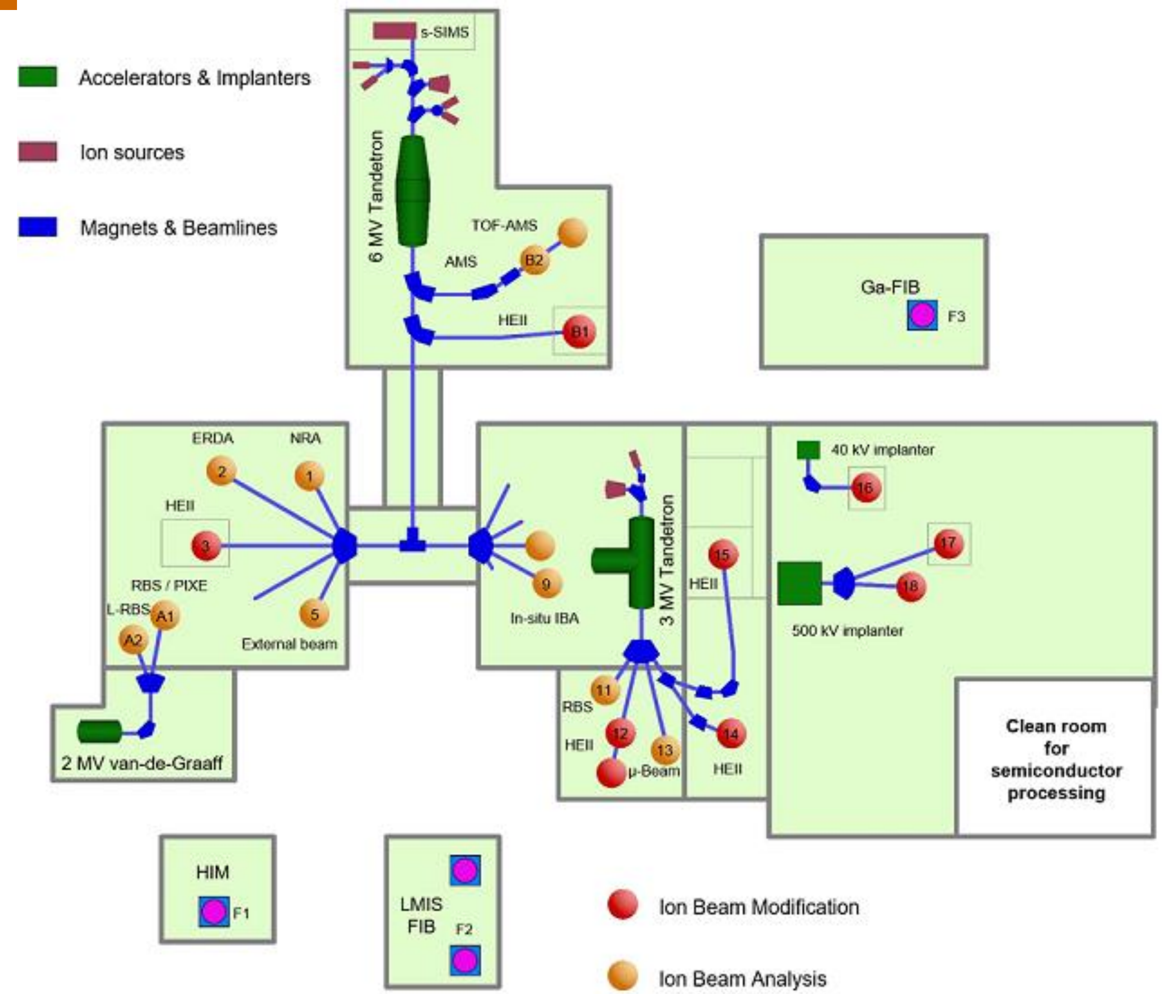
Dresden

HELMHOLTZ ASSOCIATION

Aerial View

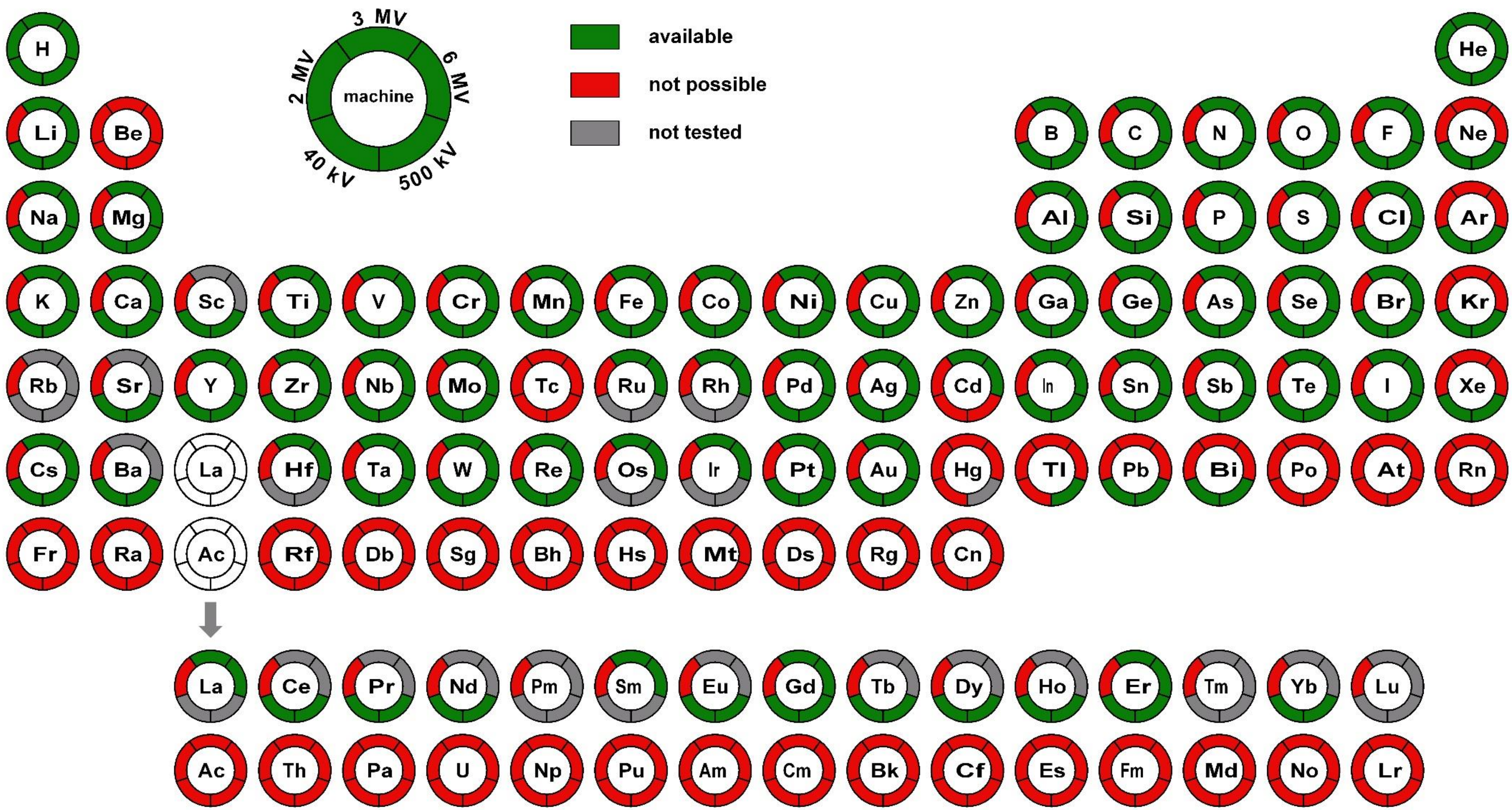


Ion Beam Center



HELMHOLTZ | ASSOCIATION

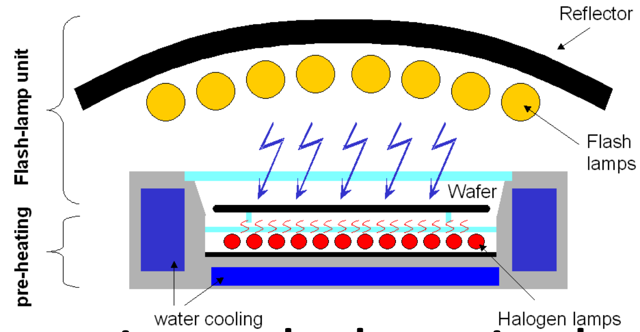
Ion Beam Center



Department of Semiconductor Materials

Resources: Semiconductor materials

Material processing: laser and flash lamp annealing



Material characterization: magnetic and electrical

SQUID-VSM
SQUID-MPMS
Lakeshore Hall Measurement system
1.8-400 K
up to 7 T

Material characterization: optics

Raman, PL and attoCube-dry

And the user facilities: ion beam center

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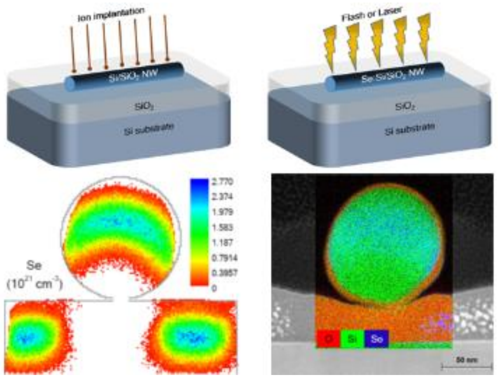
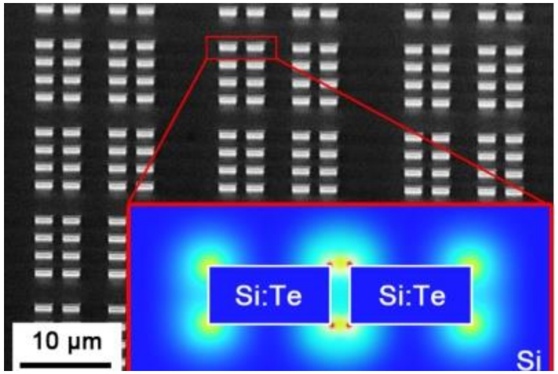
Department of Semiconductor Materials

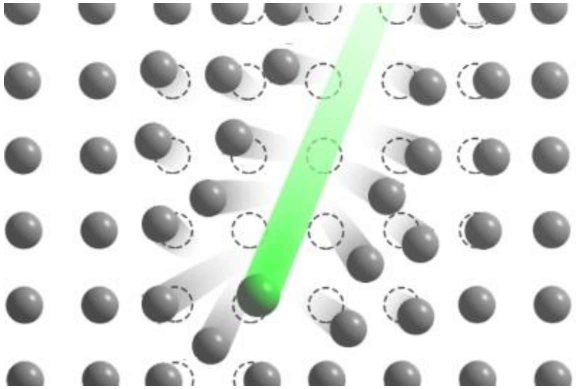
Hyperdoped semiconductors



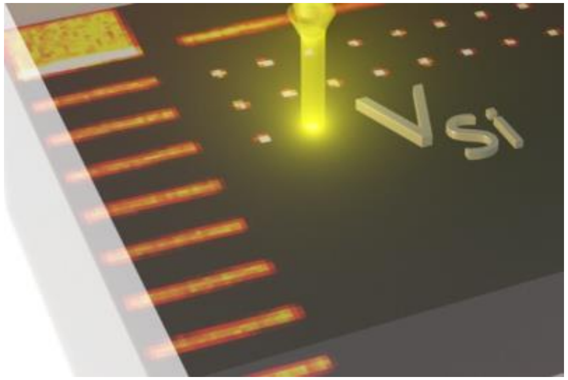
Optoelectronics



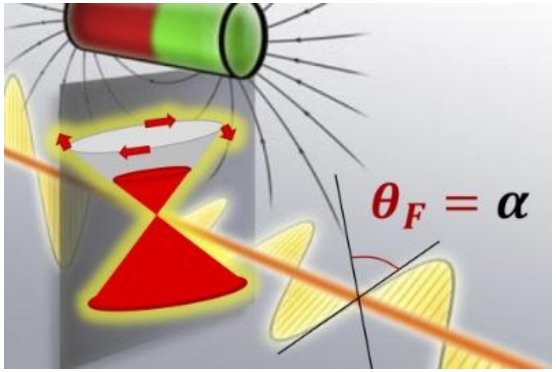
Defect engineering by ions



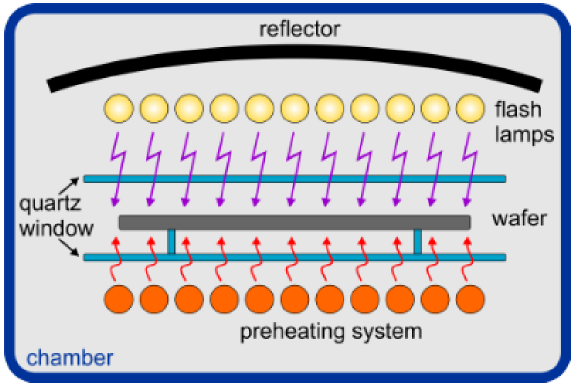
Quantum technology



Quantum metrology

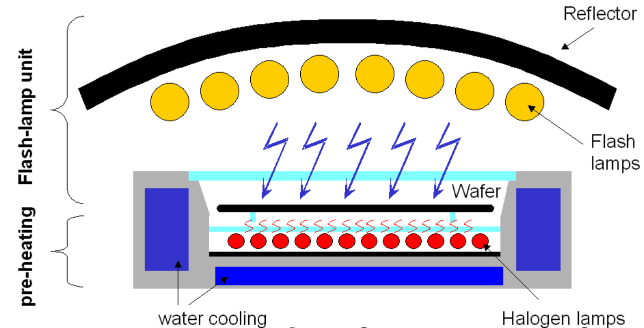


Flash lamp and pulsed laser



Resources in my department: semiconductor materials

Material processing: laser and flash lamp annealing



Material characterization: magnetic and electrical

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Lakeshore Hall Measurement system
1.8-400 K
up to 7 T

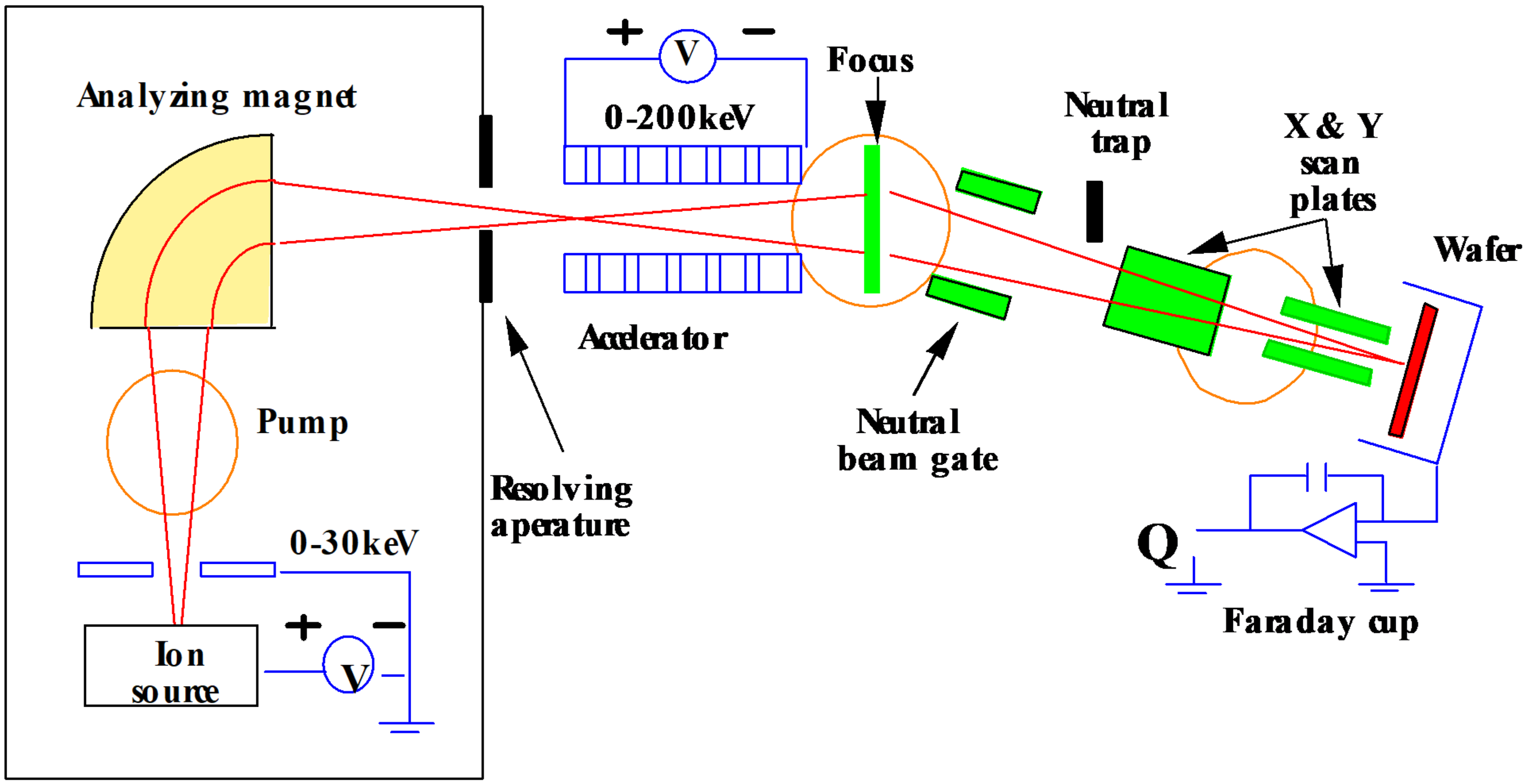
Material characterization: optics

Raman, PL and attoCube-dry

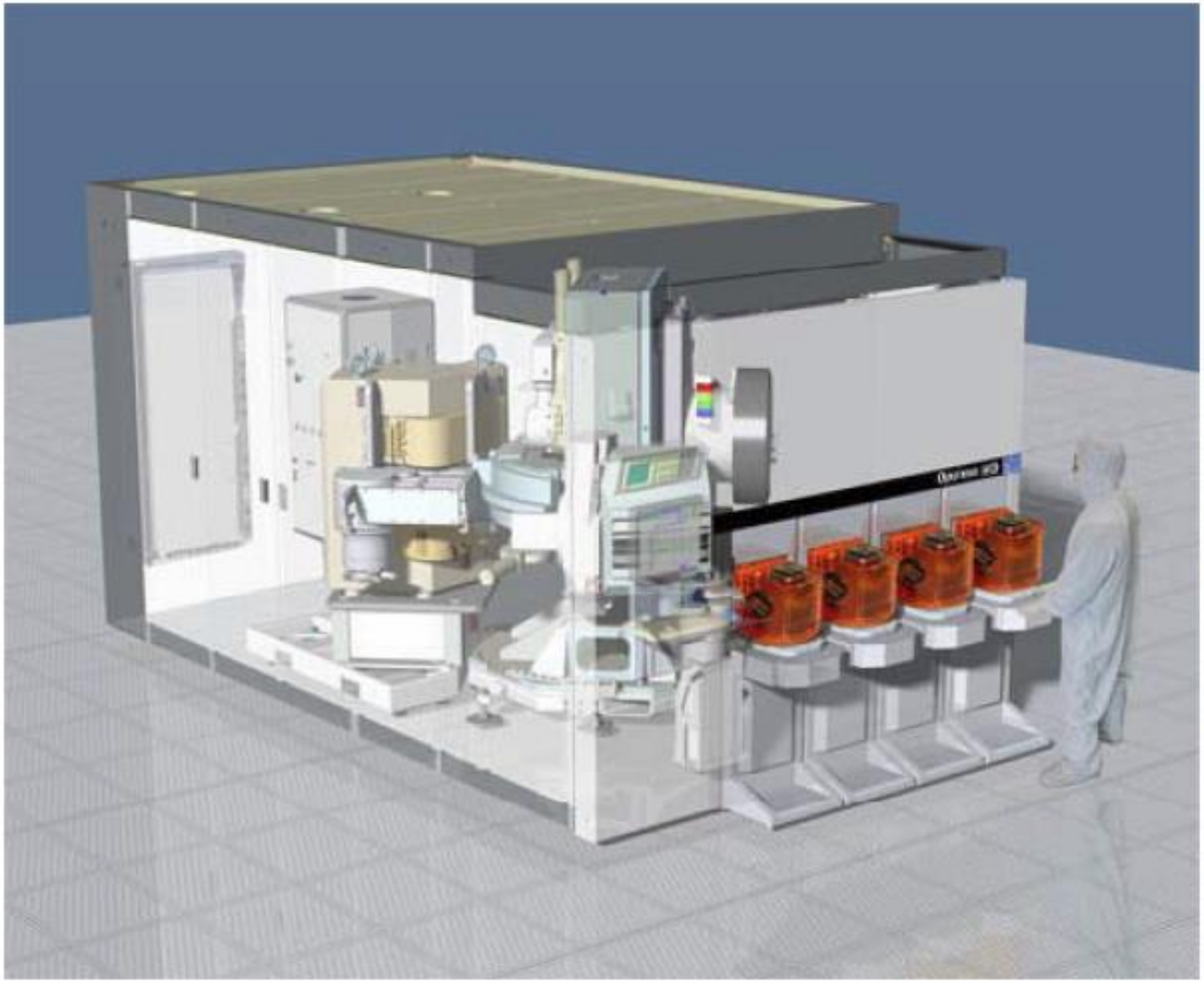
And the user facilities: ion beam center

Ion irradiation effect in matter

Ion implantation: basic layout



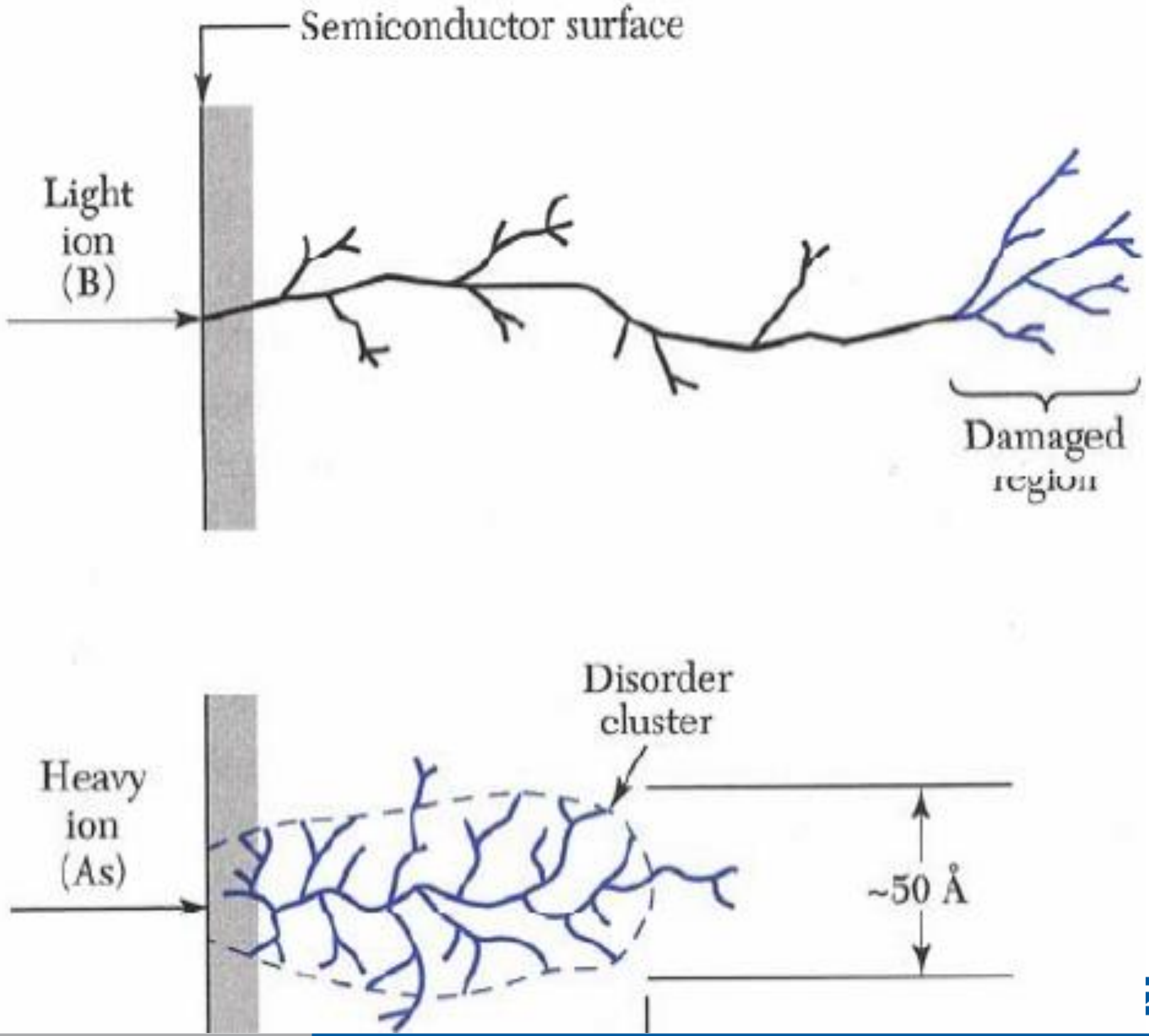
Ion Implanter



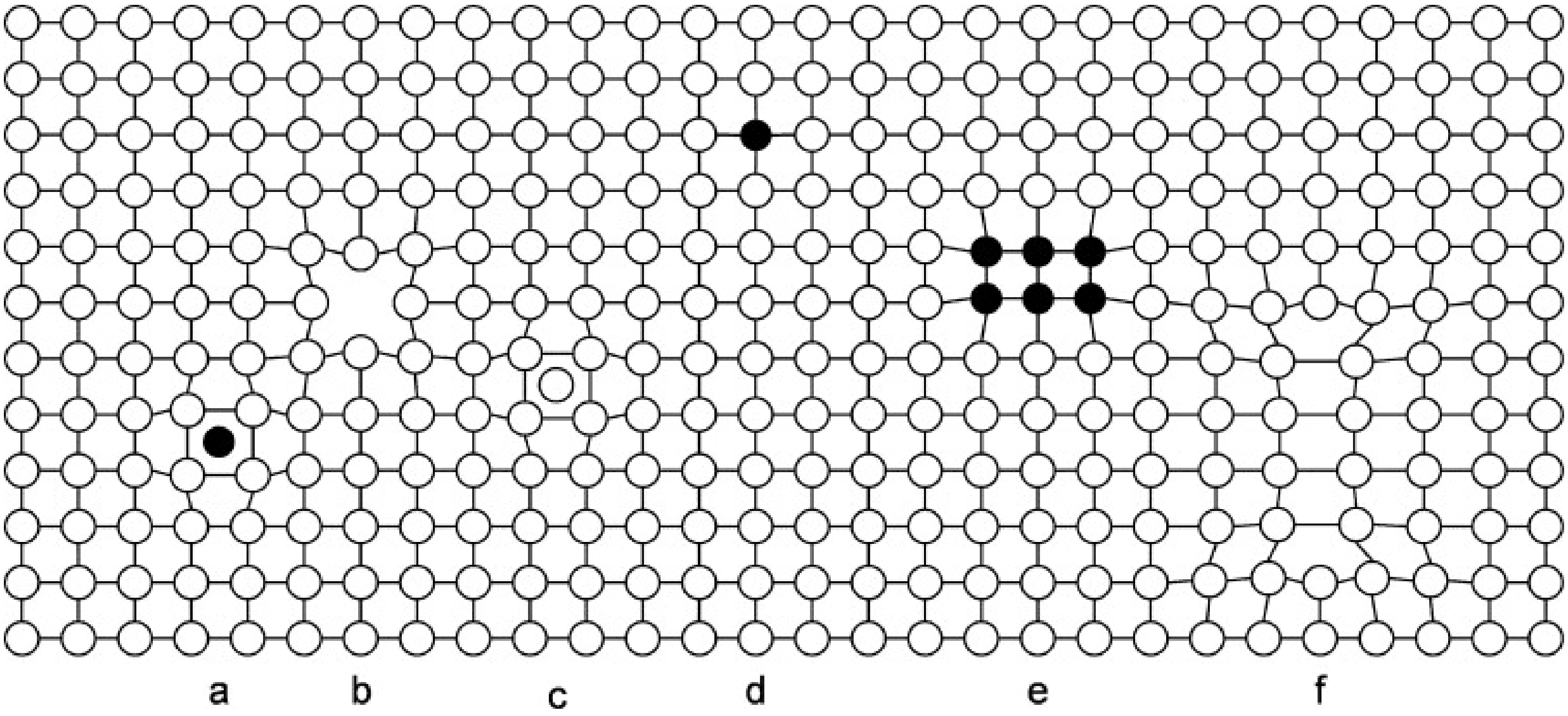
Axcelis Ultra
Wafer Loading Station

Axcelis, Optima HD: High-Dose Implanter

Ion implantation: effect



Ion implantation: effect

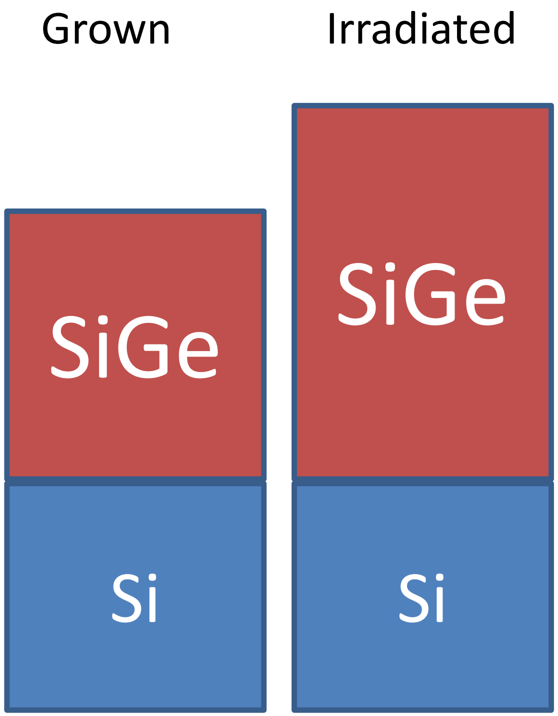


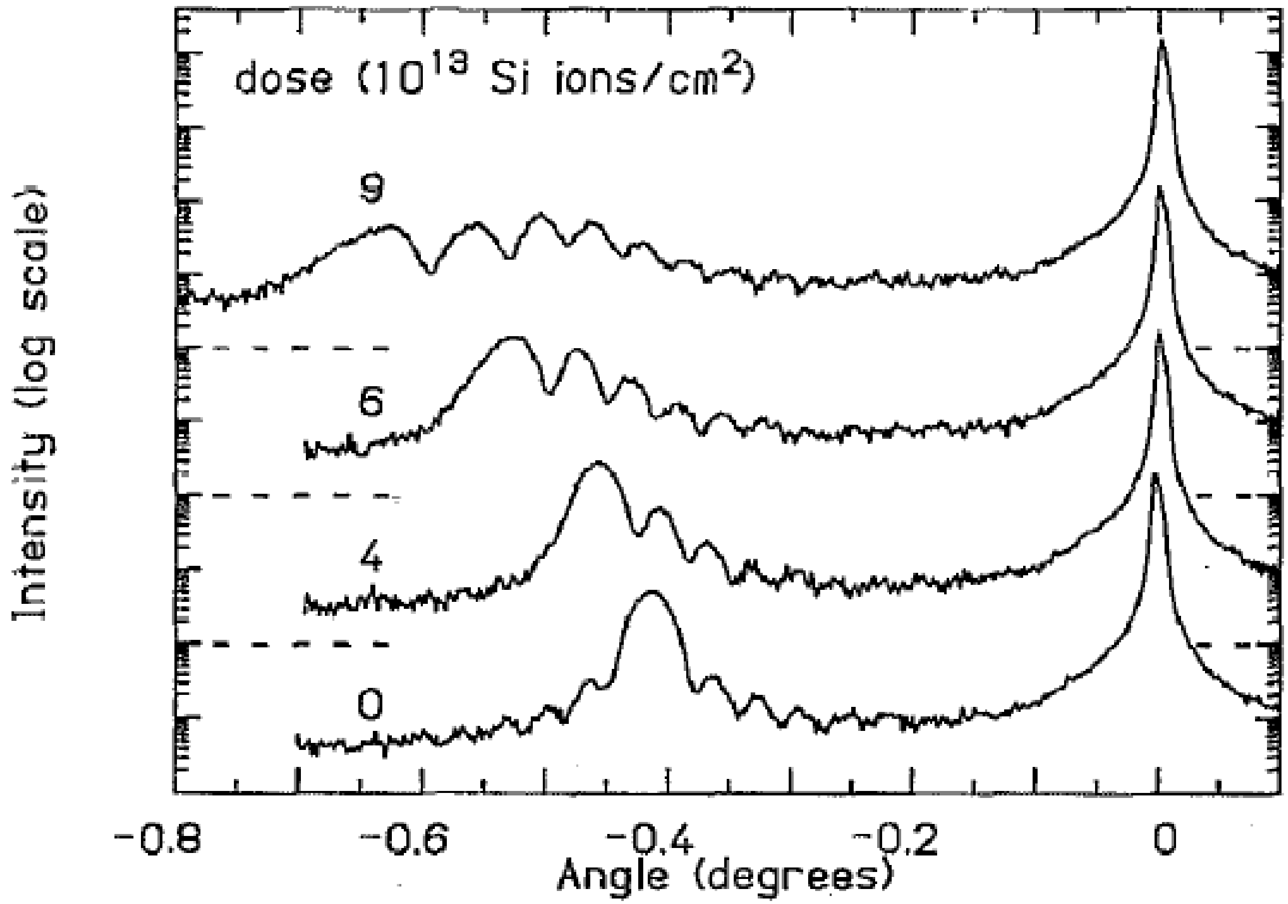
Common defects in materials

Wang et al., J. Appl. Phys. 115, 17C104, (2014)

Ion implantation: effect

More than 20 years ago in Si…





Lie et al, J. Appl. Phys. 74, 6039 (1993)

Ion implantation: effect

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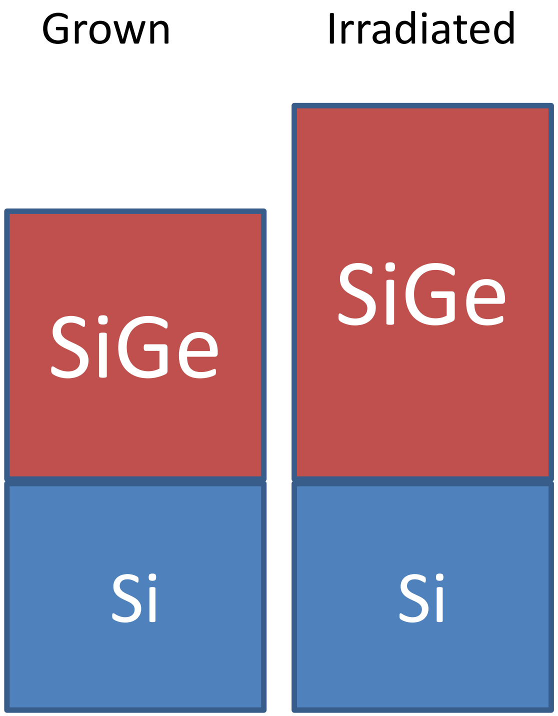
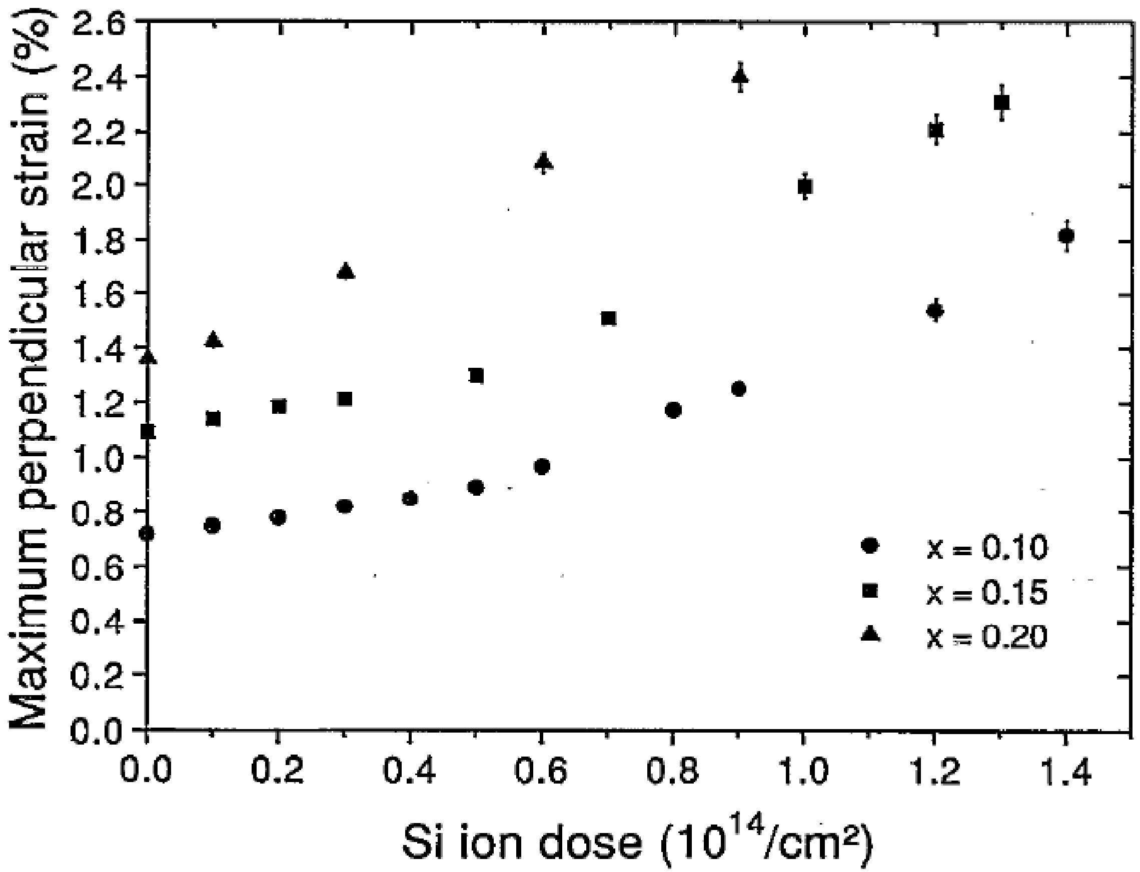


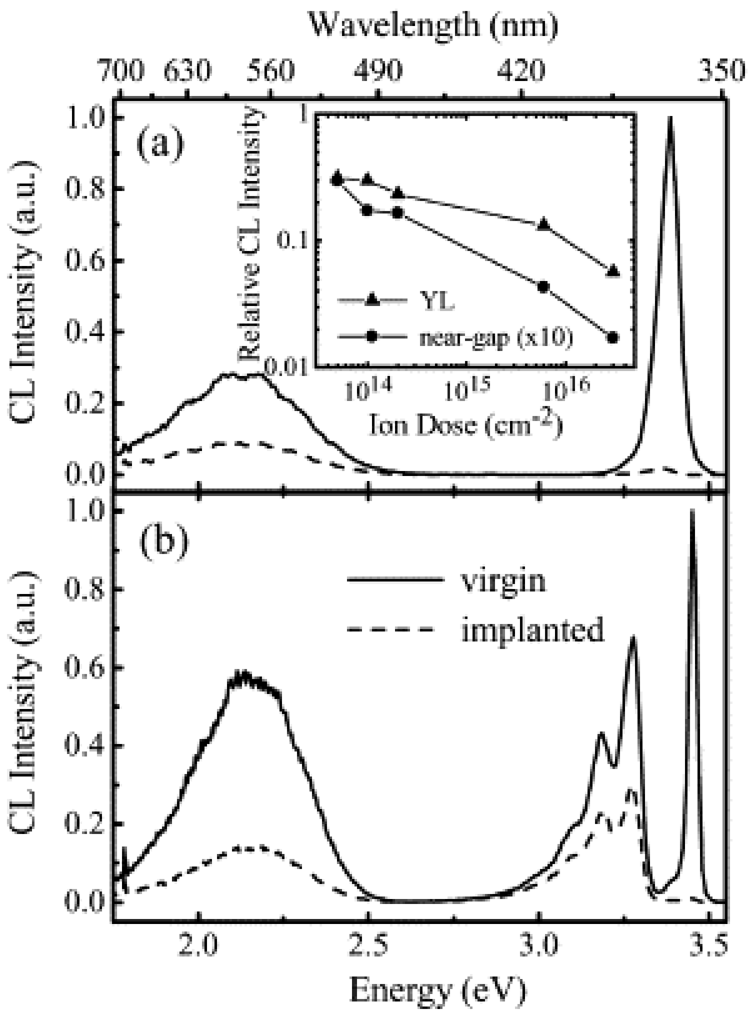


Lie et al, J. Appl. Phys. 74, 6039 (1993)

Ion implantation: effect

More than 20 years ago in Si, GaAs and GaN

- Mobility ↘
- Photoluminescence ↘

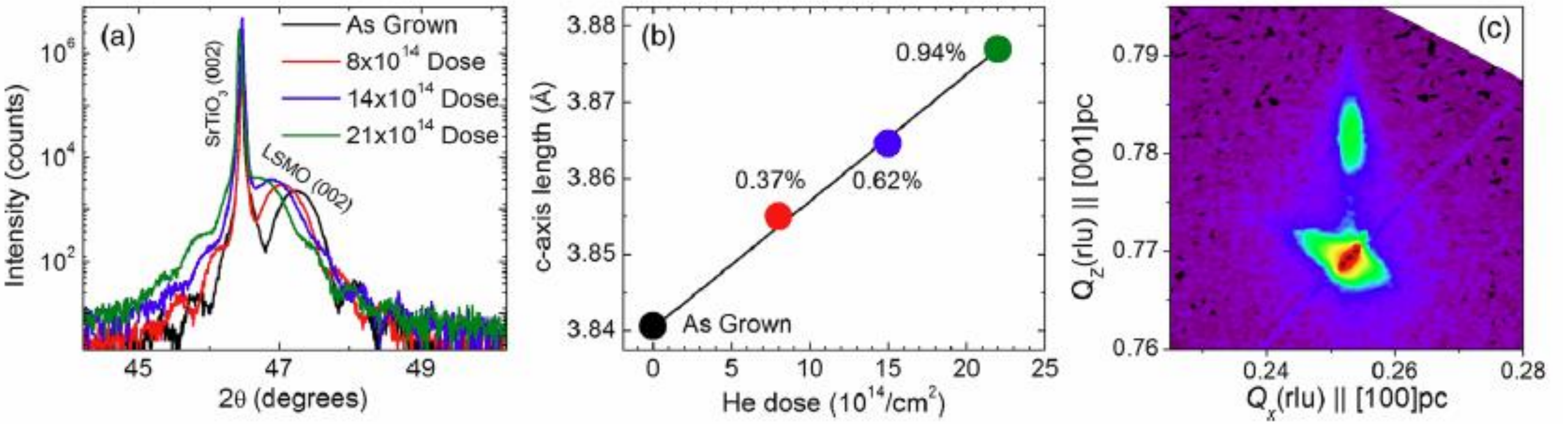


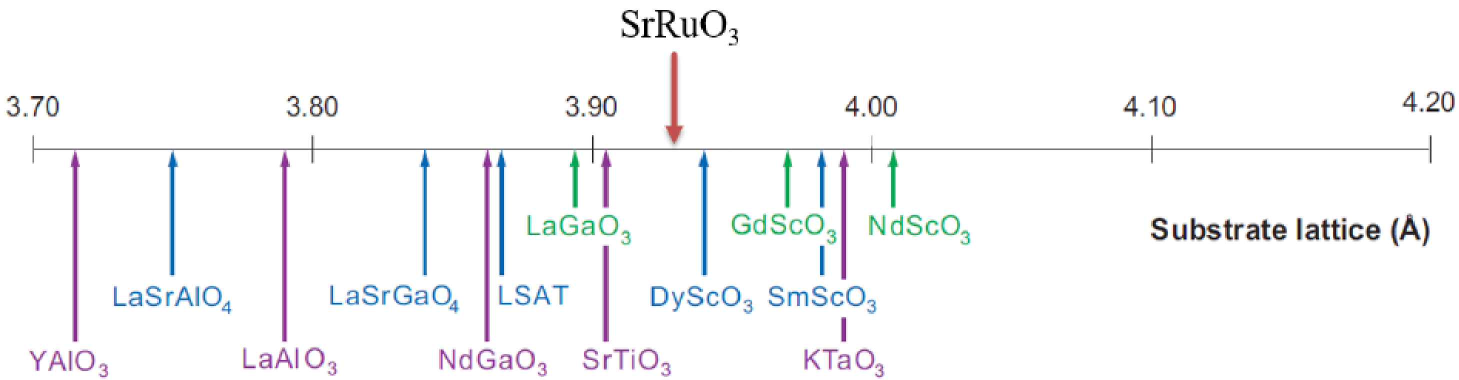
Carbon ion dose: $1x10^{14}$ cm^{-2}

Kucheyev et al, Mat. Sci. Eng. R 33, 51 (2001)

Ion implantation: effect

Recently: in oxides

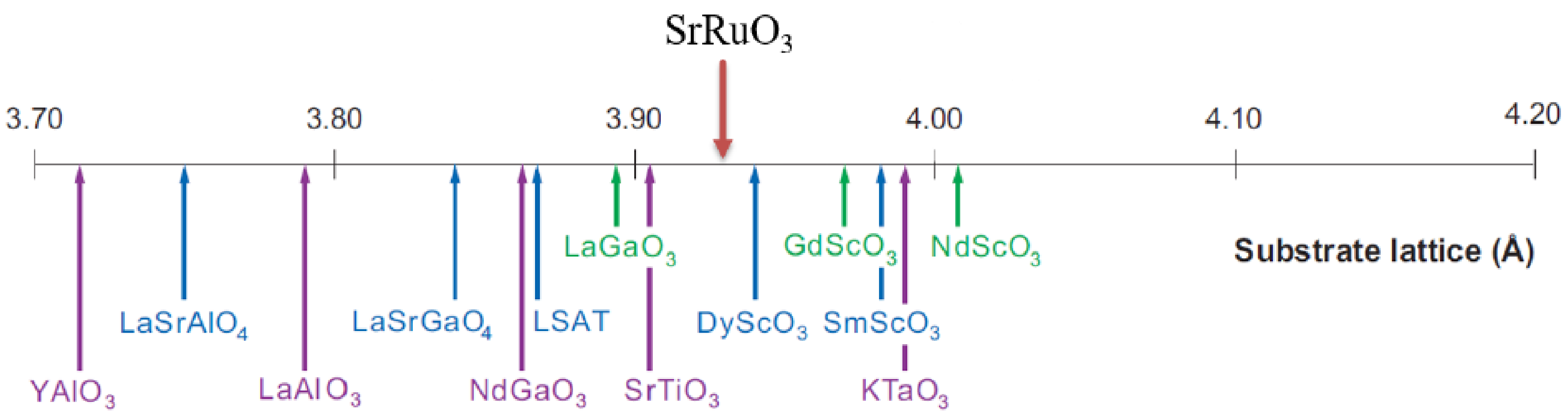




01 (2015)

Ion implantation: effect

Recently: in oxides

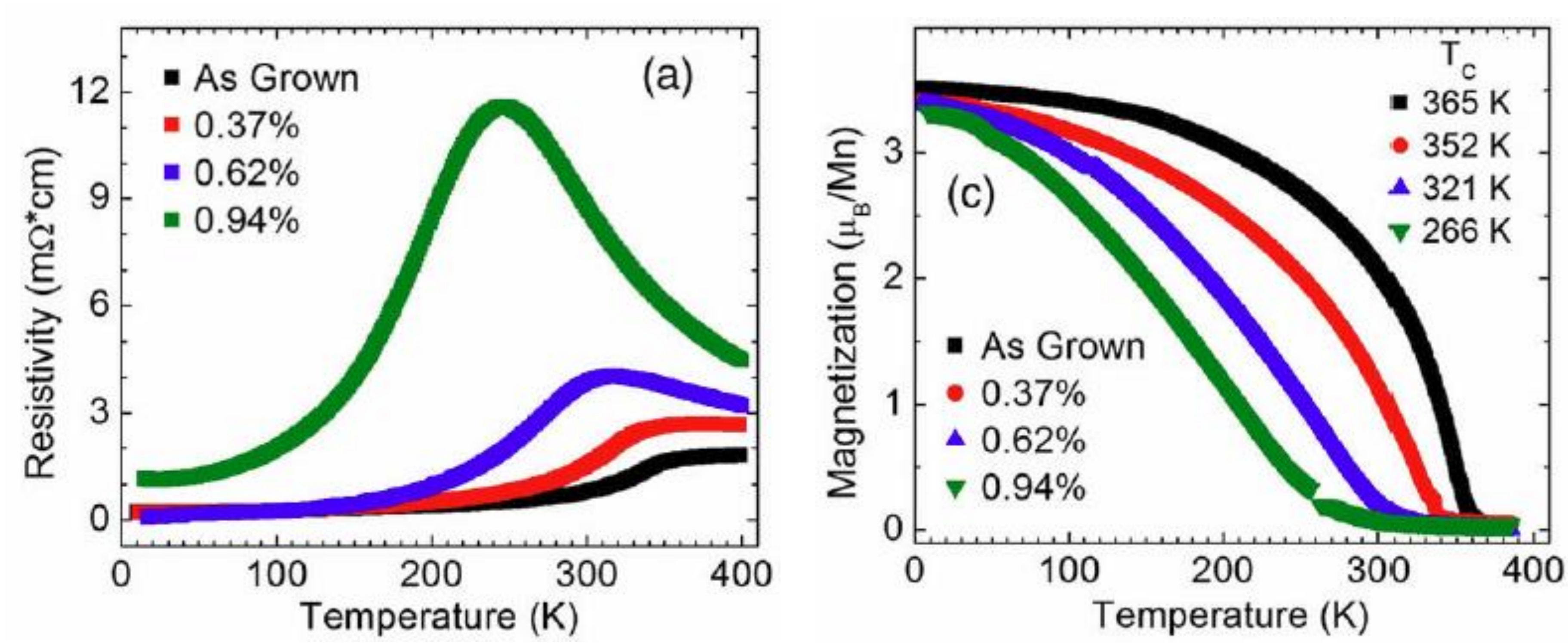


Using different substrates: only discrete choice

http://dx.doi.org/10.5772/intechopen.70125

Defect engineering by irradiation

Helium irradiation shifts the metal-insulator transition and Curie temperature in $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) film.

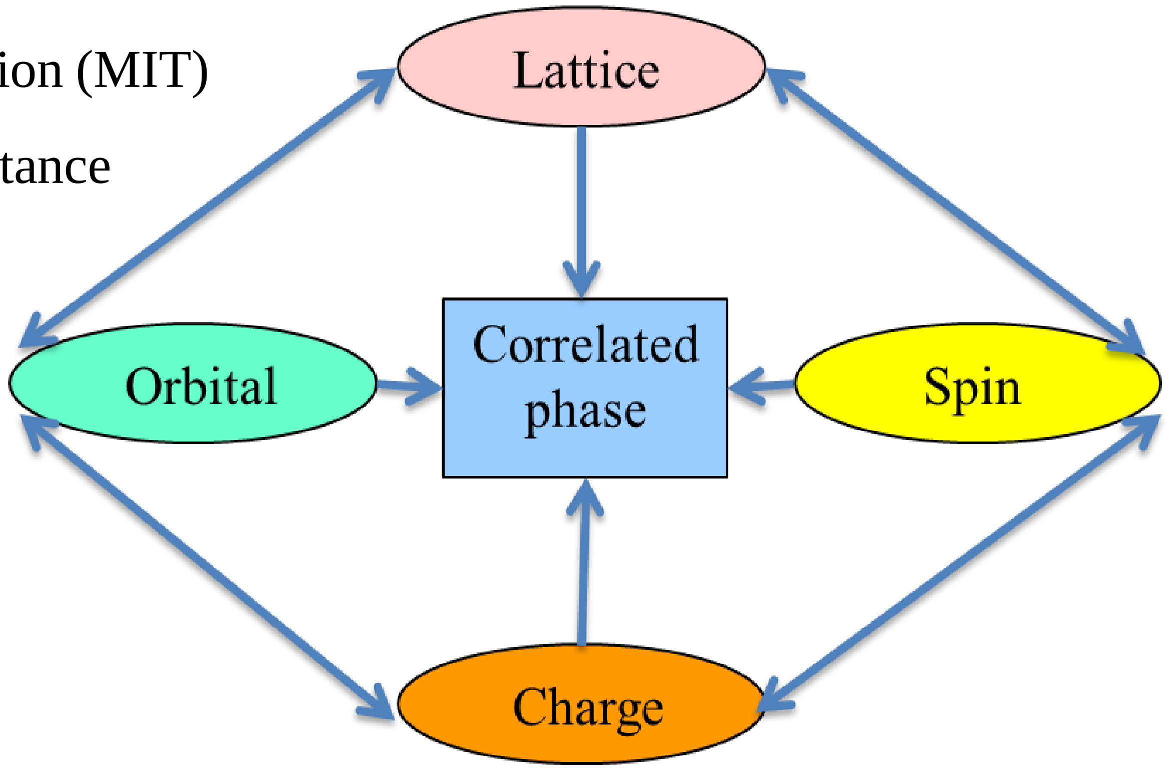


H. Guo. et al. Phys. Rev. Lett **26**, 256801 (2015)

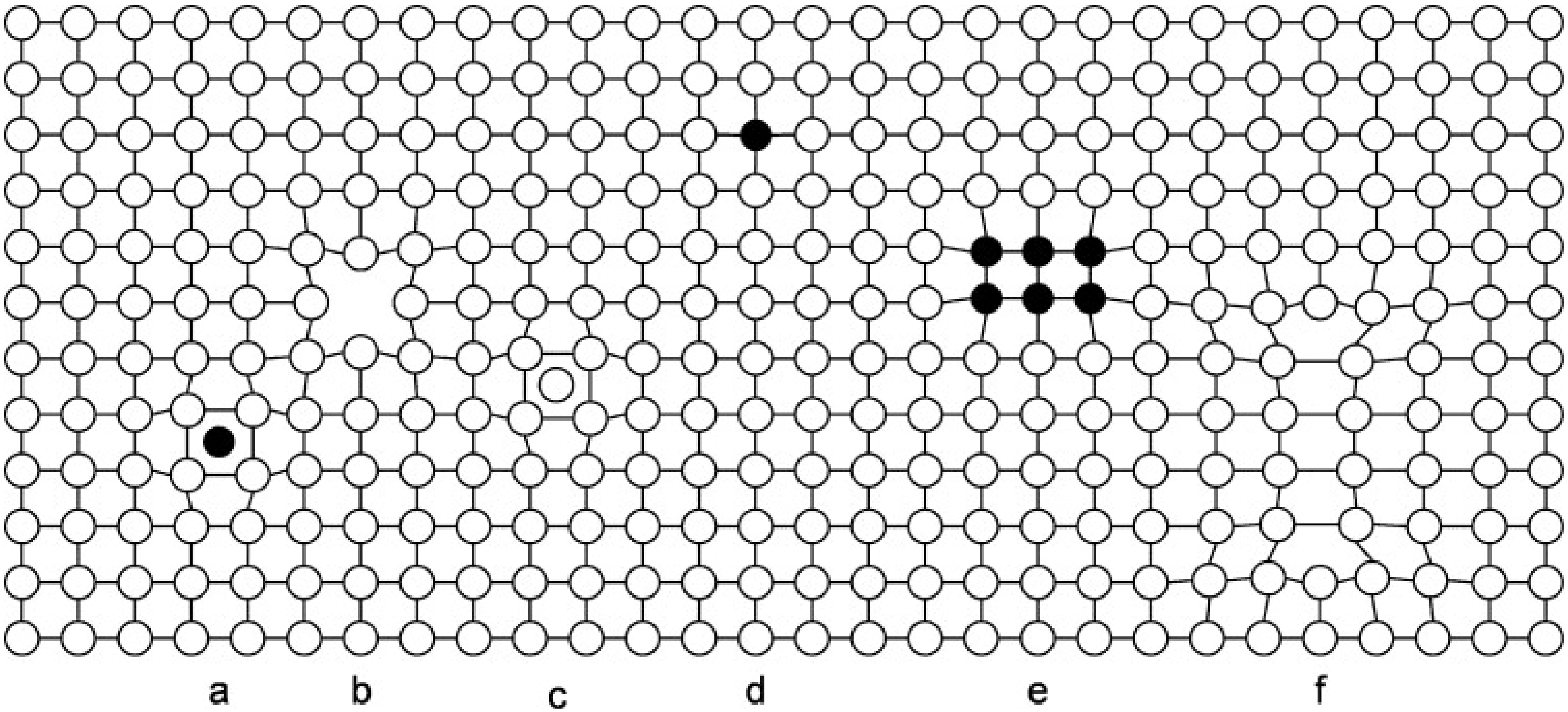
Correlated oxides

Complex oxides show strong correlations among spin, charge, lattice and orbital degrees of freedom.

- Superconductivity
- Metal-insulator transition (MIT)
- Colossal magnetoresistance
- Multiferroicity



Ion implantation: effect

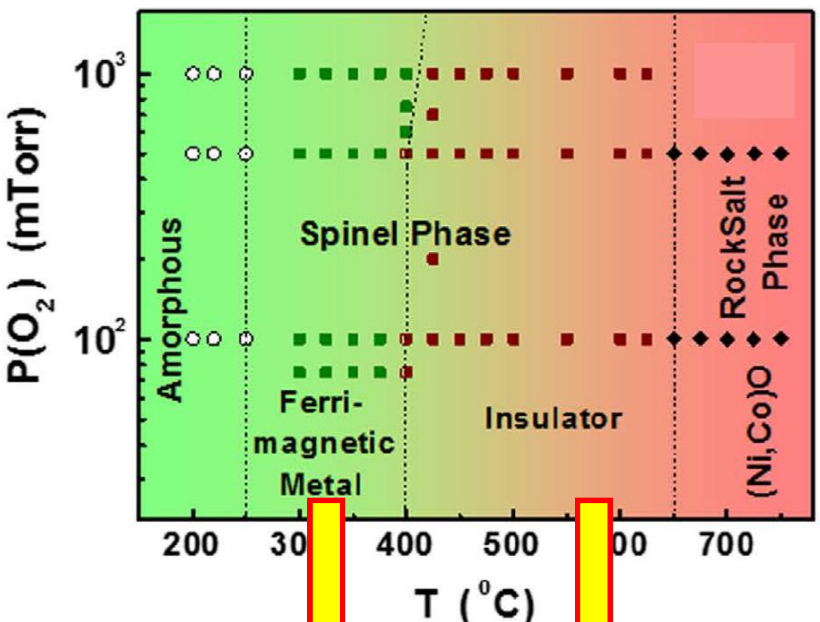


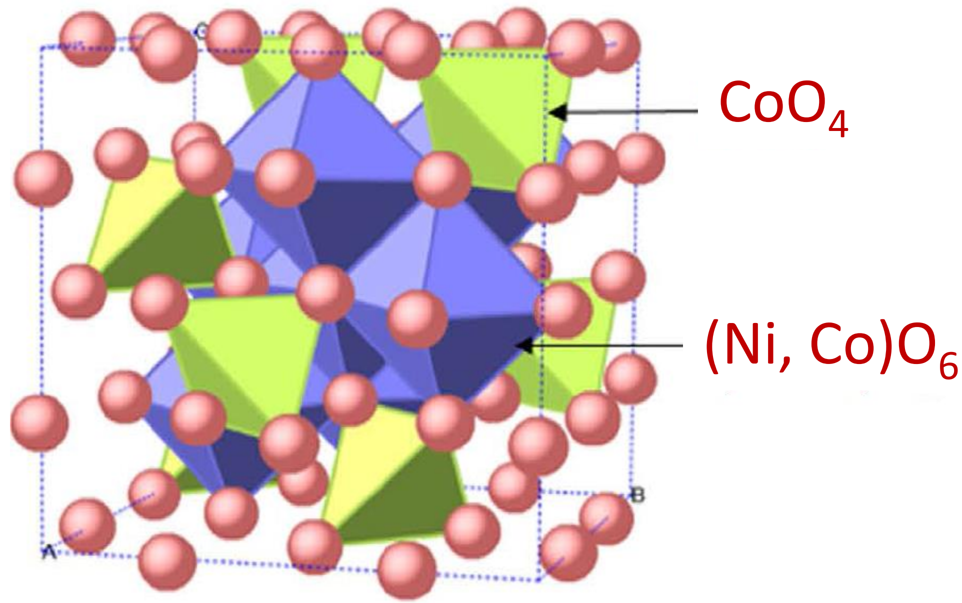
Common defects in materials

Wang et al., J. Appl. Phys. 115, 17C104, (2014)

1. $NiCo_2O_4$

- $NiCo_2O_4$ (NCO) exhibits an inverse spinel structure. NCO displays better electronic conductivity.
- NCO is widely used in various technological applications such as photo-detector, infrared-transparent electrode, supercapacitor





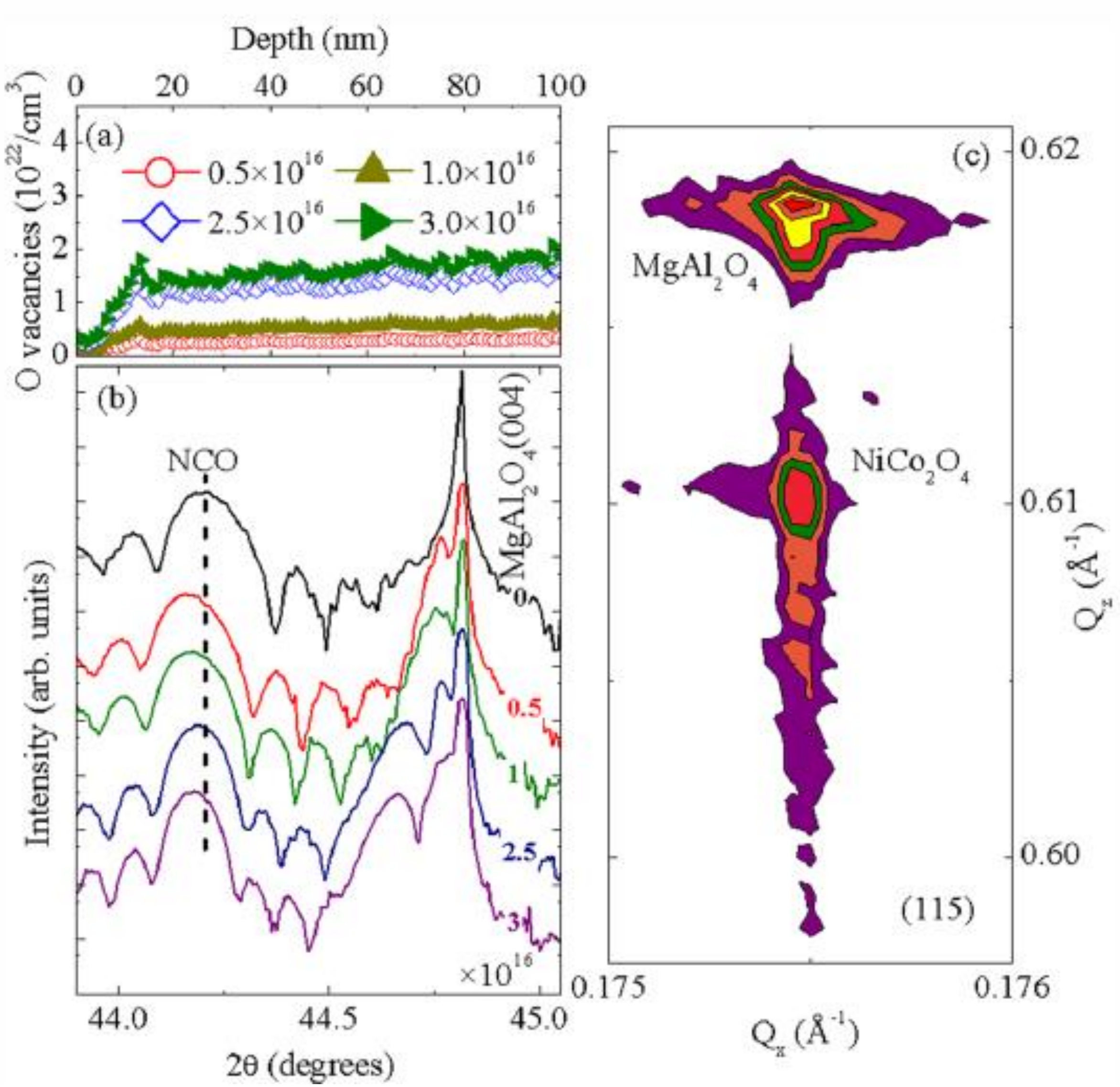
T_C = 305 K

T_C = 90 K

$Co^{2+}_{0.54}Co^{3+}_{0.46}[Ni^{2+}_{0.62}Ni^{3+}_{0.38}Co^{2+}_{0.05}Co^{3+}_{0.95}]$ $Co^{2+}_{0.54}Co^{3+}_{0.46}[Ni^{2+}_{0.82}Ni^{3+}_{0.18}Co^{2+}_{0.13}Co^{3+}_{0.87}]$

Bitla *et al*. SREP **5**,15201 (2015)

1. $NiCo_2O_4$



APL Mater. **6**, 066109 (2018)

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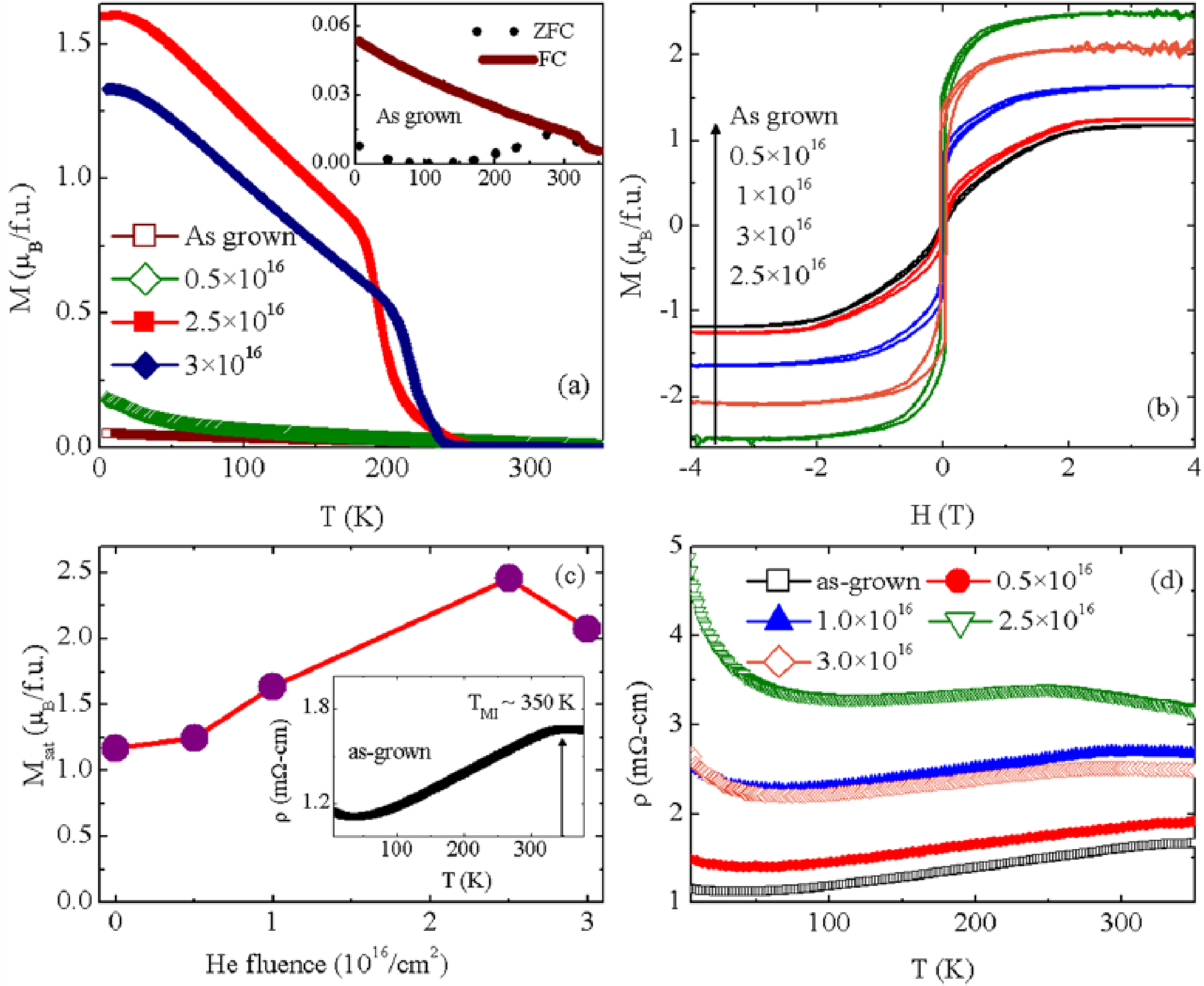


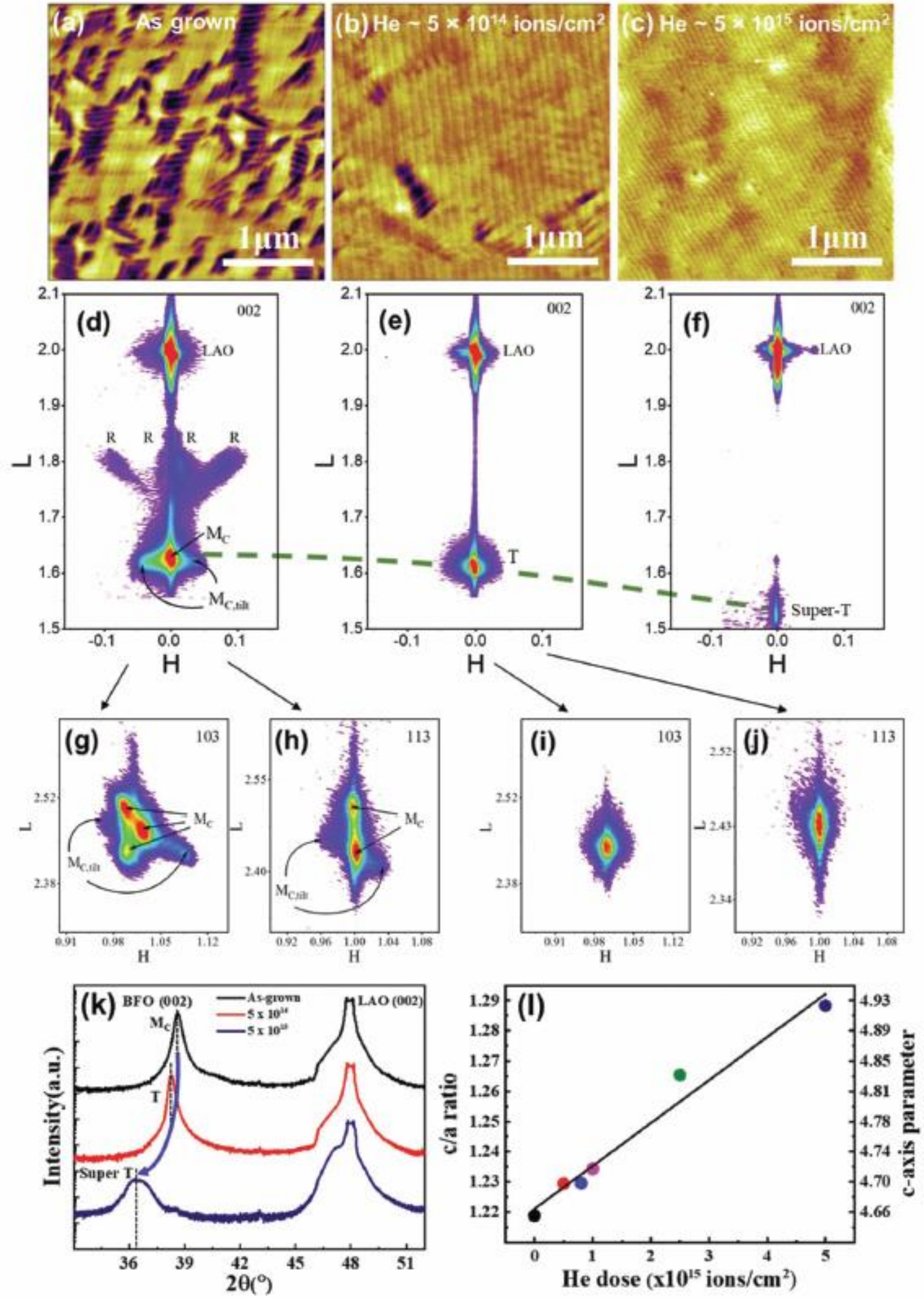
APL Mater. **6**, 066109 (2018)

2. BiFeO$_3$

Phase transition from the as-grown mixed rhombohedral-like (R) and tetragonal-like (M_C) phase to true tetragonal (T) symmetry.

The stripe multi-nanodomains to a single domain state

Nanoscale 11, 8110 (2019)



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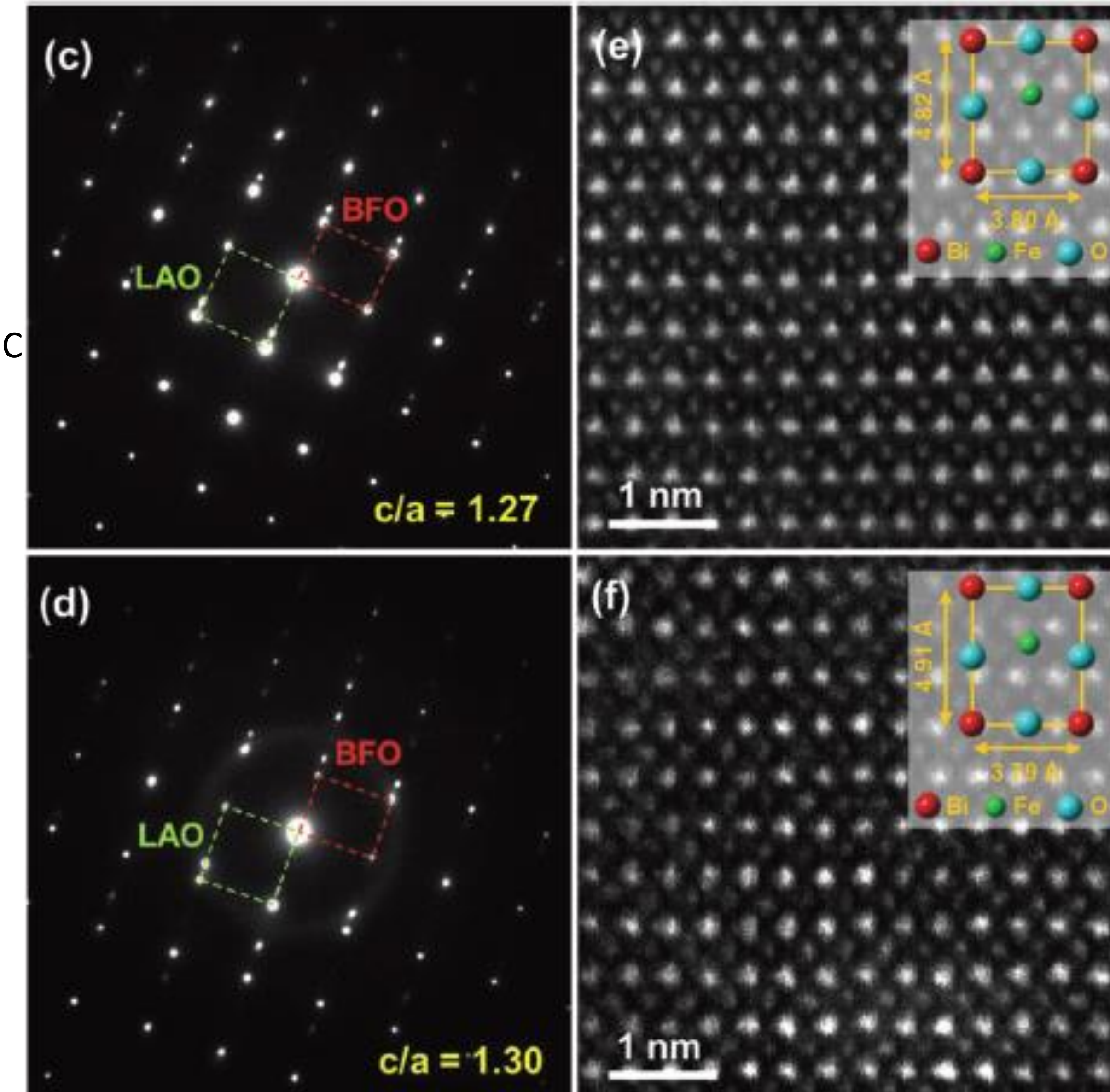
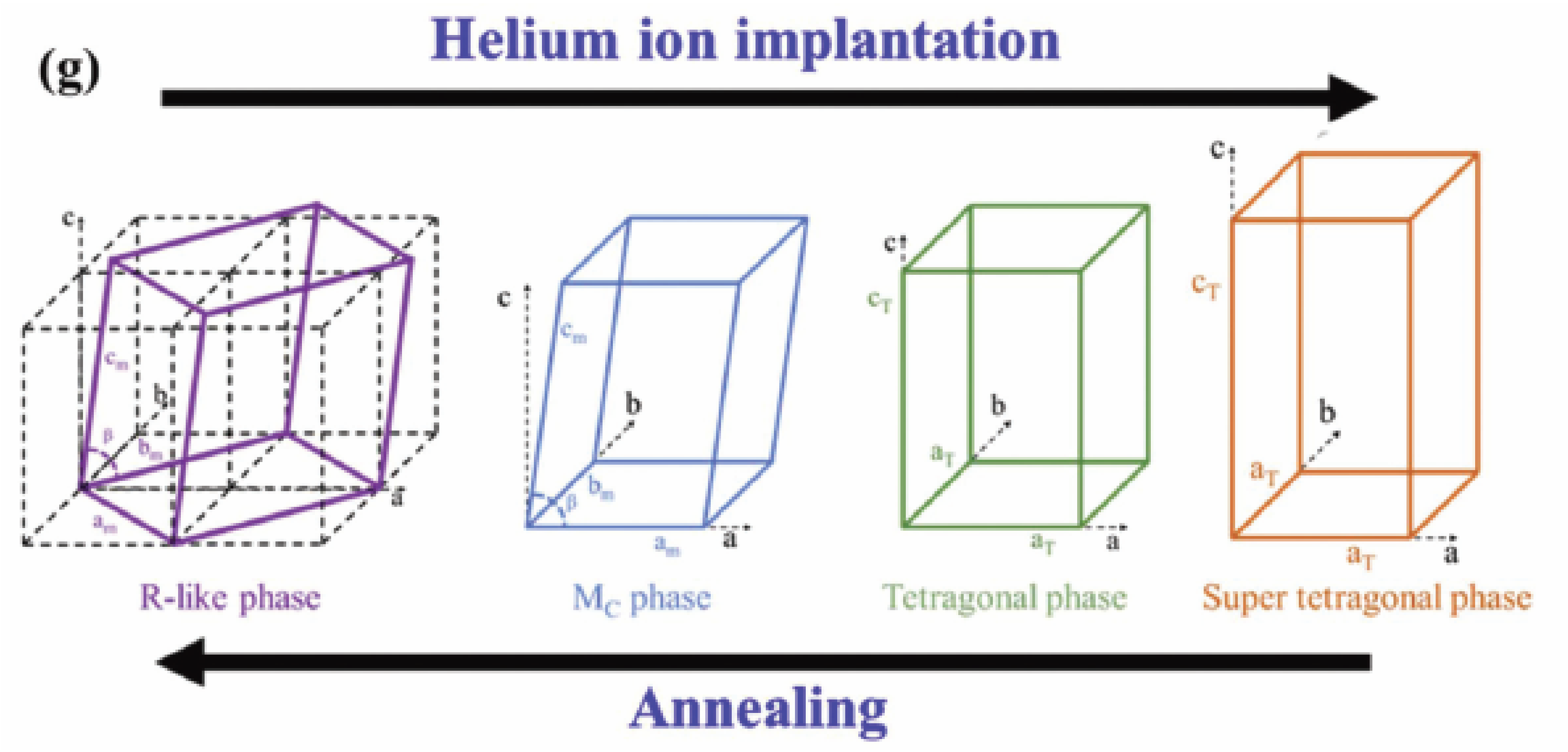


Nanoscale 11, 8110 (2019)

2. $BiFeO_3$

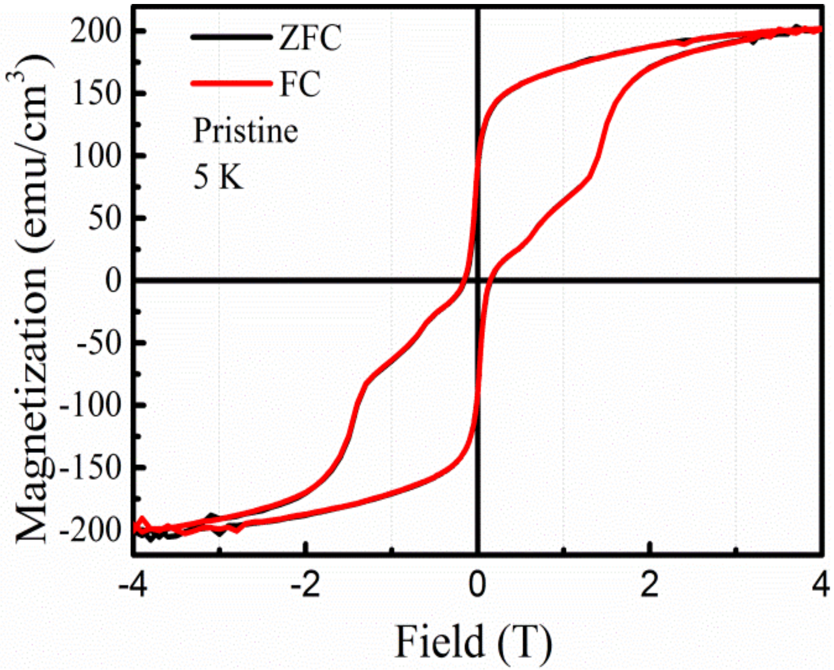
Transition is reversible



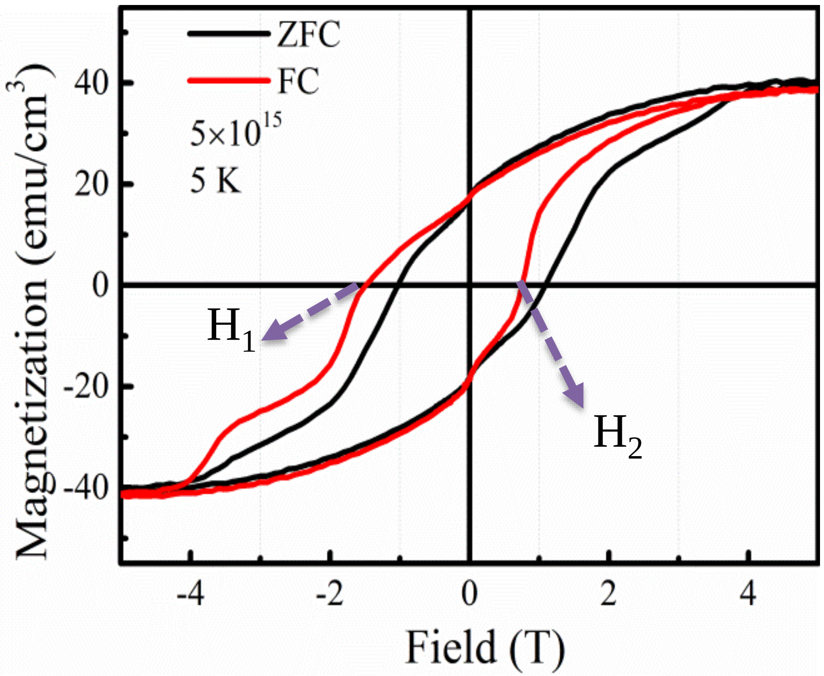
Nanoscale 11, 8110 (2019)

3. $SrRuO_3$

ZFC: zero-field cooling



FC: field cooling

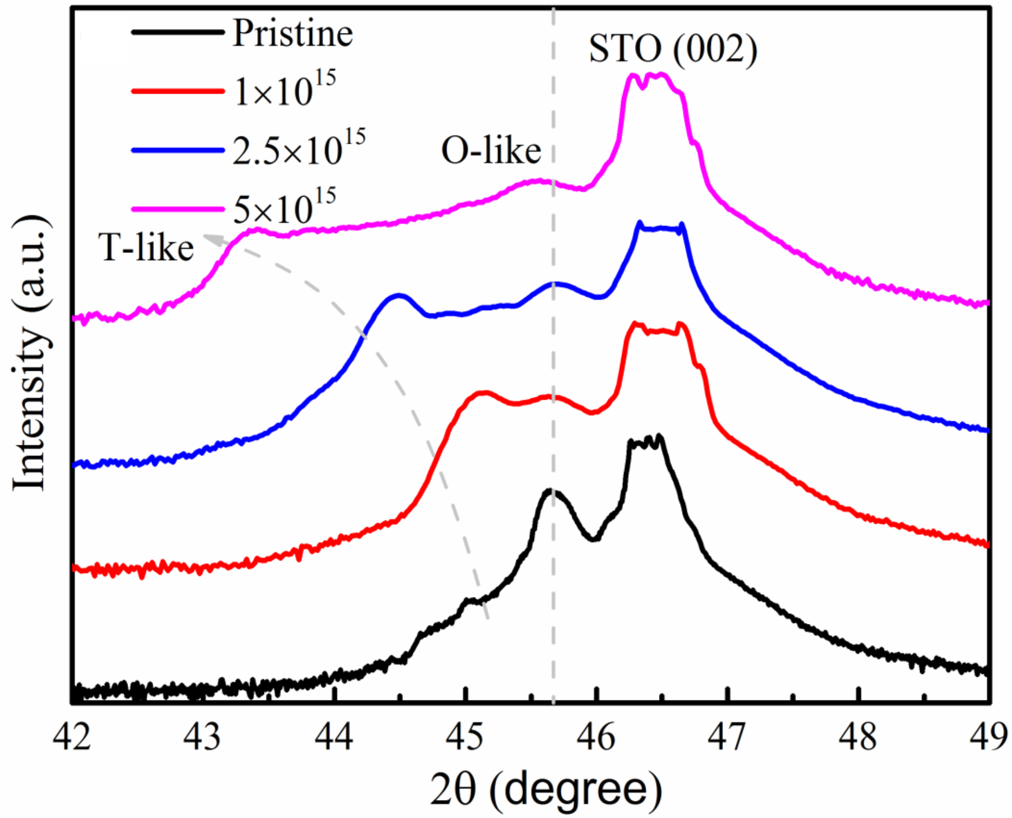


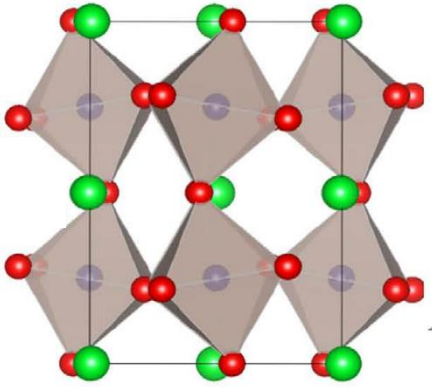
$$H_{EB} = |(H_1+H_2)/2|$$

A large exchange bias field H_{EB} up to ~0.36 T.

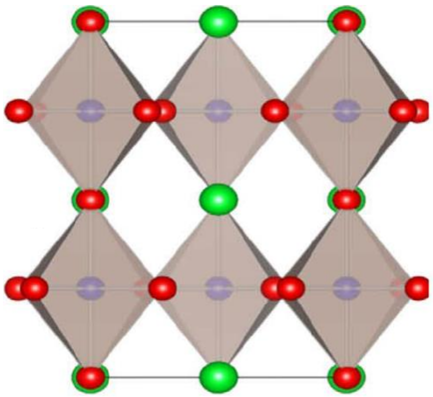
C. A. Wang et al., ACS Appl. Mater. Interfaces 10, 27472-27476 (2018).

3. $SrRuO_3$





O-like:orthorhombic-like

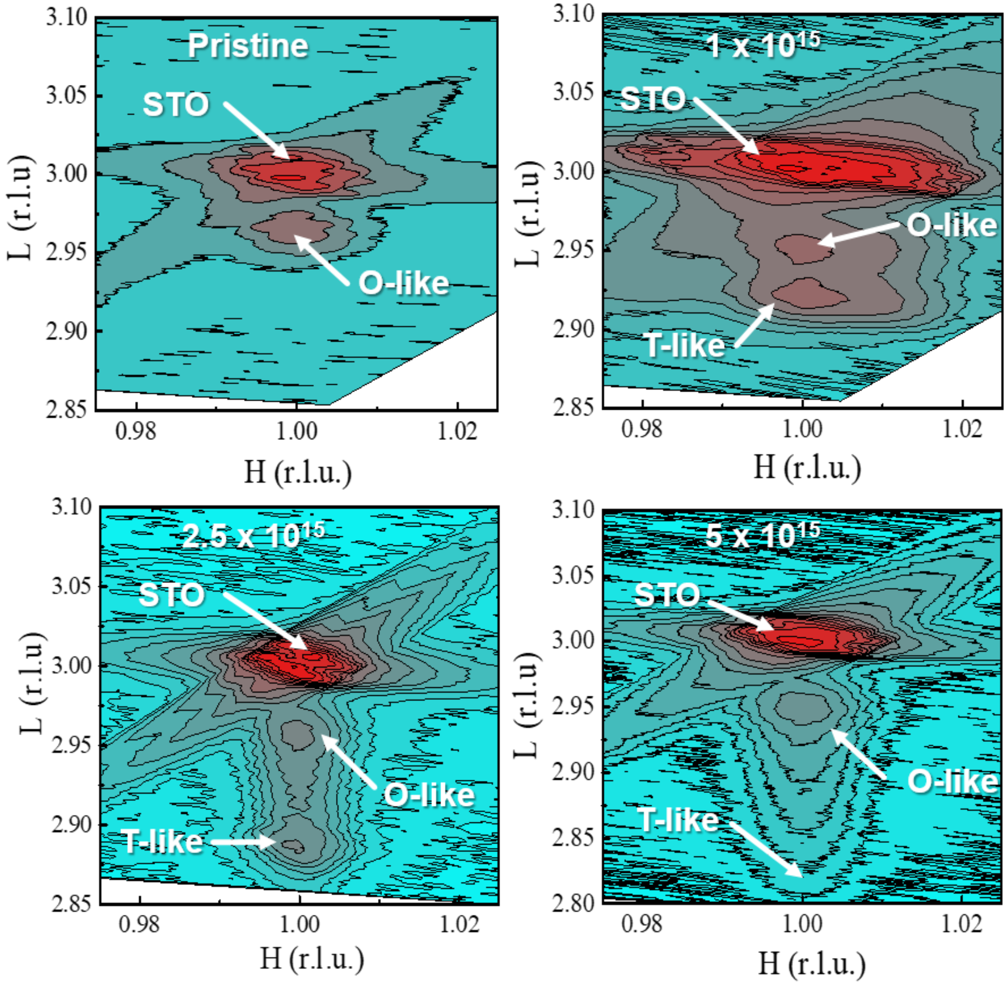


T-like:tetragonal-like

The irradiation triggers a transition from an O-like phase to a T-like one.

C. A. Wang et al., ACS Appl. Mater. Interfaces 10, 27472-27476 (2018).

3. $SrRuO_3$

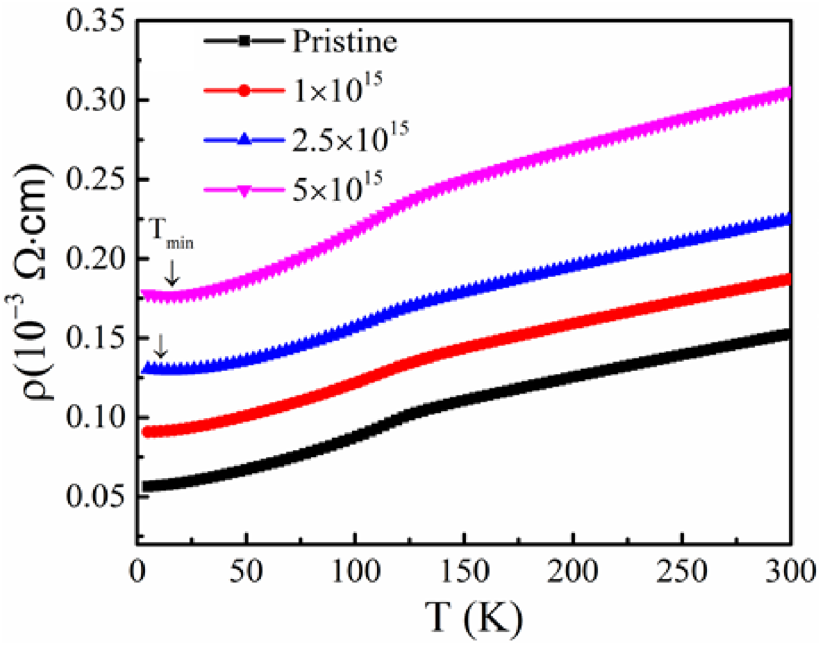


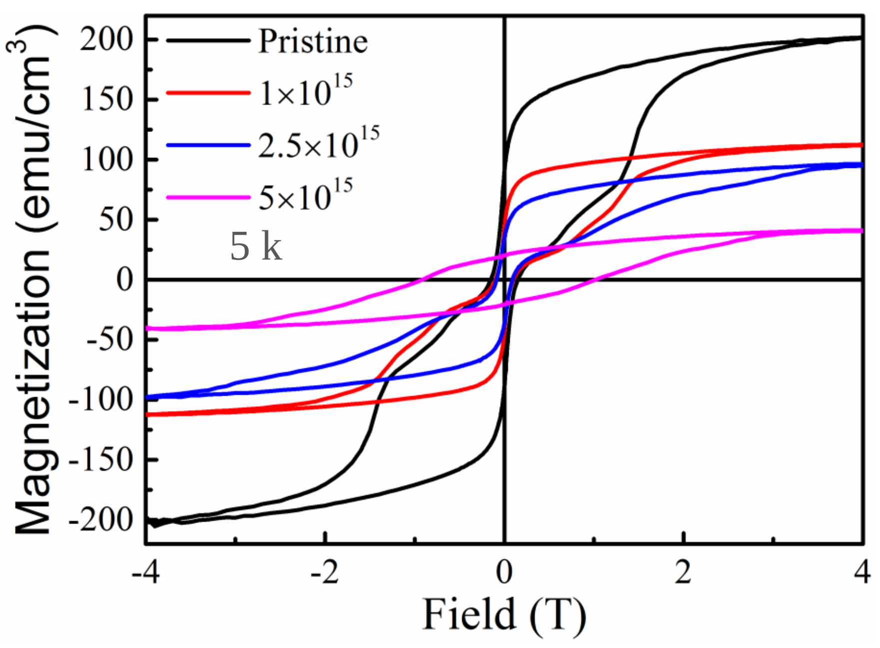
- The irradiation only induces uniaxial lattice expansion.
- Two peaks for irradiated SRO films in RSMs indicate the existence of two phases.

C. A. Wang et al., ACS Appl. Mater. Interfaces 10, 27472-27476 (2018).

3. $SrRuO_3$

➢ Electrical and magnetic properties in SRO films with He ion irradiation.





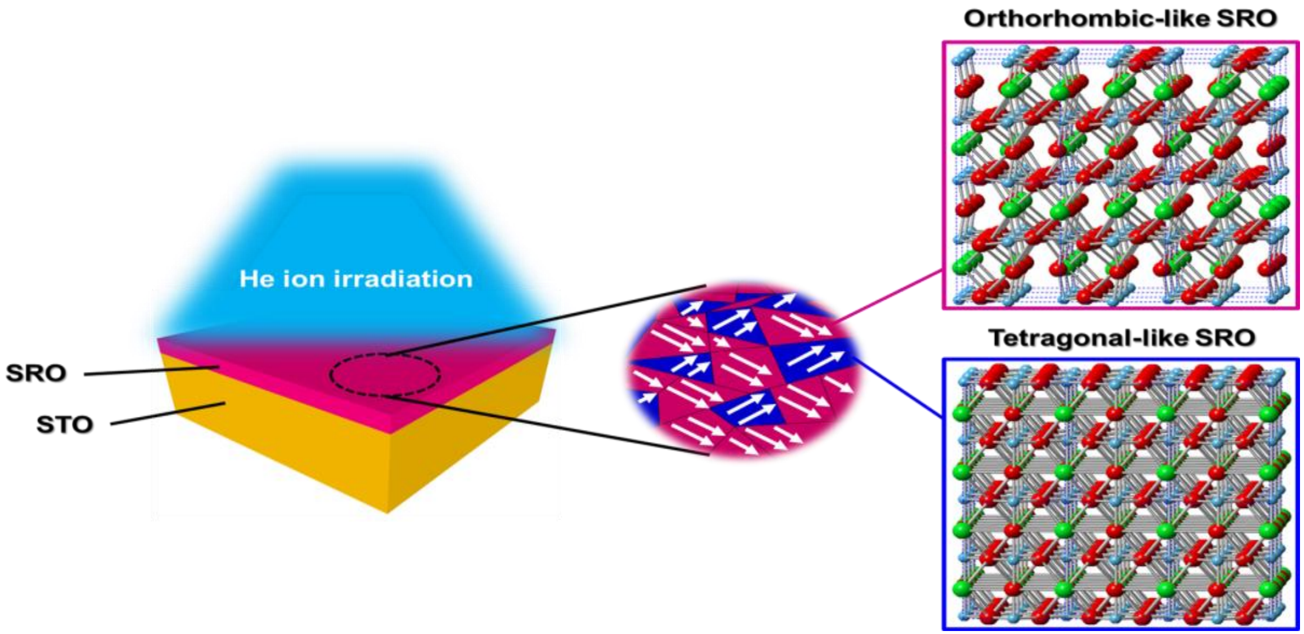
- The resistivity increases continuously as the fluence of ions increases.
- The magnetization decrease with the increase of the irradiation fluence.

C. A. Wang et al., ACS Appl. Mater. Interfaces 10, 27472-27476 (2018).

3. $SrRuO_3$

➢ How to understand exchange bias in irradiated SRO films?

The magnetic phases with different easy axes in an irradiated SRO film.



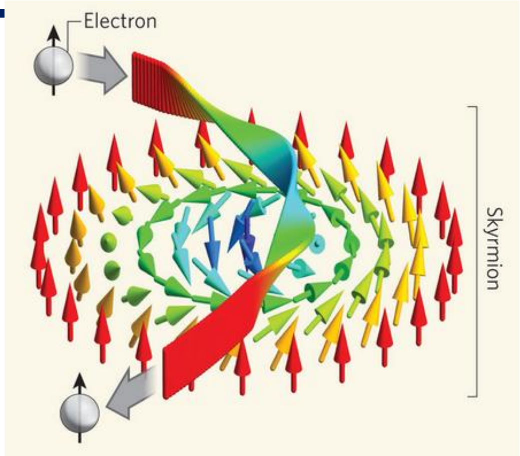
1. The O-like phase and the T-like phase have different magnetic anisotropy.

2. Disorder induced by the ion irradiation may drive an antiferromagnetic phase in SRO.

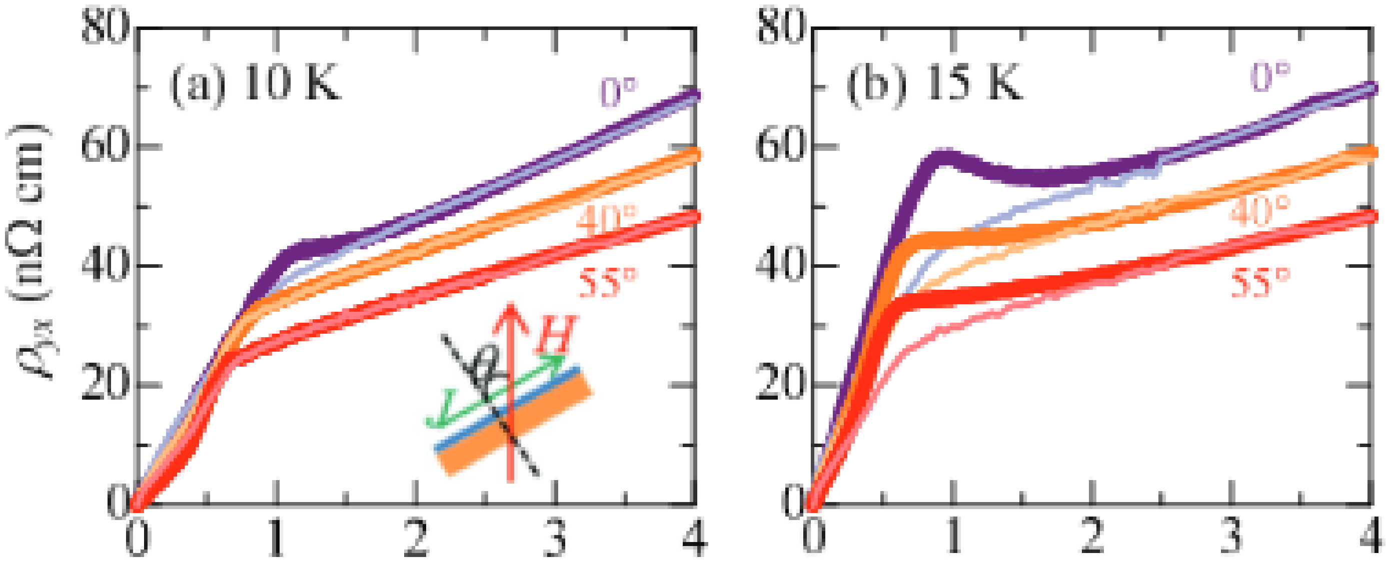
C. A. Wang et al., ACS Appl. Mater. Interfaces 10, 27472-27476 (2018).

3. $SrRuO_3$

Topological Hall effect (THE) is proportional to neither magnetic field nor magnetization. It is generated by non-coplanar or non-collinear spin arrangements such as domain walls, helices or skyrmions.



$$\rho_{xy} = R_H B + R_S M + \rho_H^T$$



$Mn_{0.96}Fe_{0.04}Si$ film (thickness 20 nm)

T. Yokouchi et al. *Phys. Rev. B.* **89**, 064416 (2014)

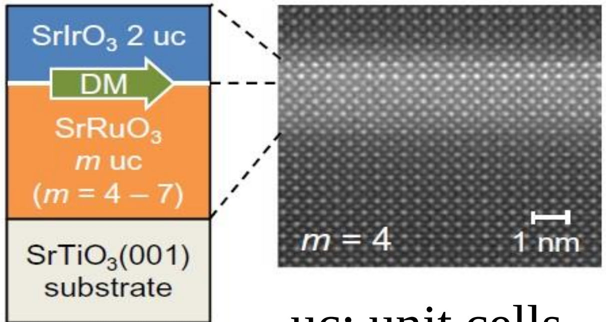
T. Yokouchi et al. *Phys. Rev. B.* **89**, 064416 (2014)

www.christophschuette.com/physcis (Introduction to emergent electrodynamics)

3. $SrRuO_3$

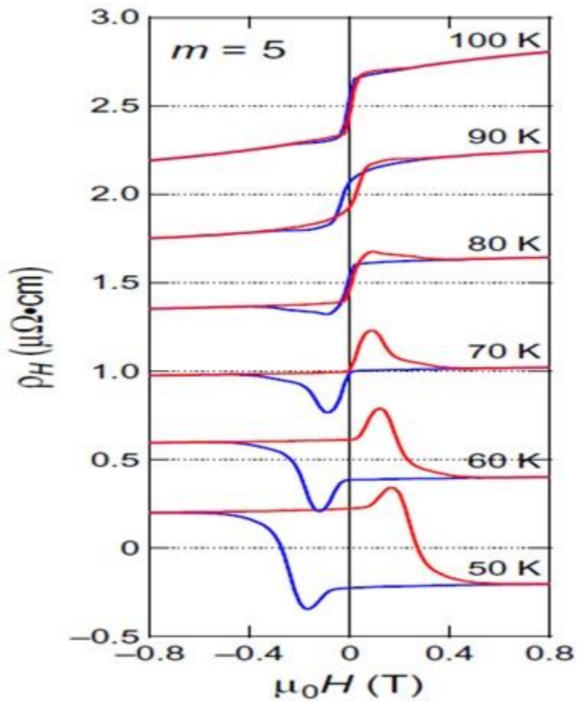
In previous report:

Heterostructure:

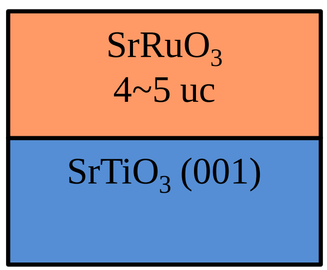


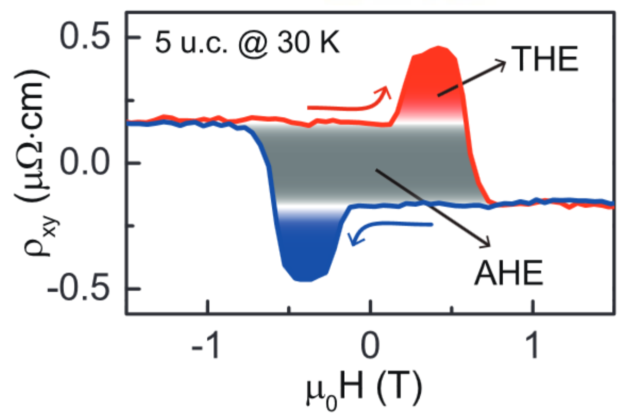
uc: unit cells

DM: Dzyaloshinskii-Moriya interactio



Ultrathin SRO system:



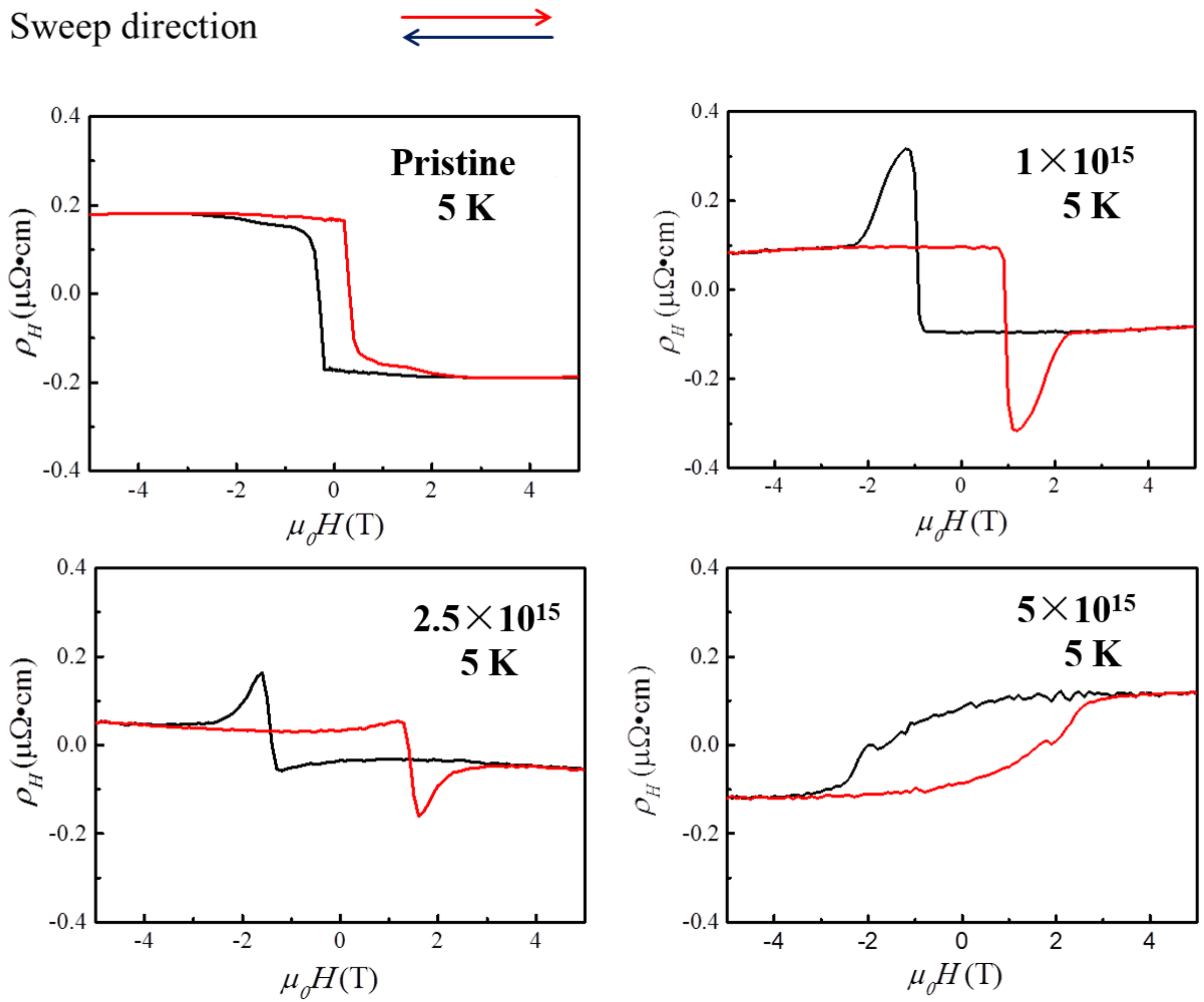


A heterostructure system or the SRO layer thickness is limited to only a few nanometers to show a measurable THE

J. Matsuno et al. *Sci.Adv.* 2016; 2: e1600304; B. Sohn, et al. arXiv: 1810.01615

3. $SrRuO_3$

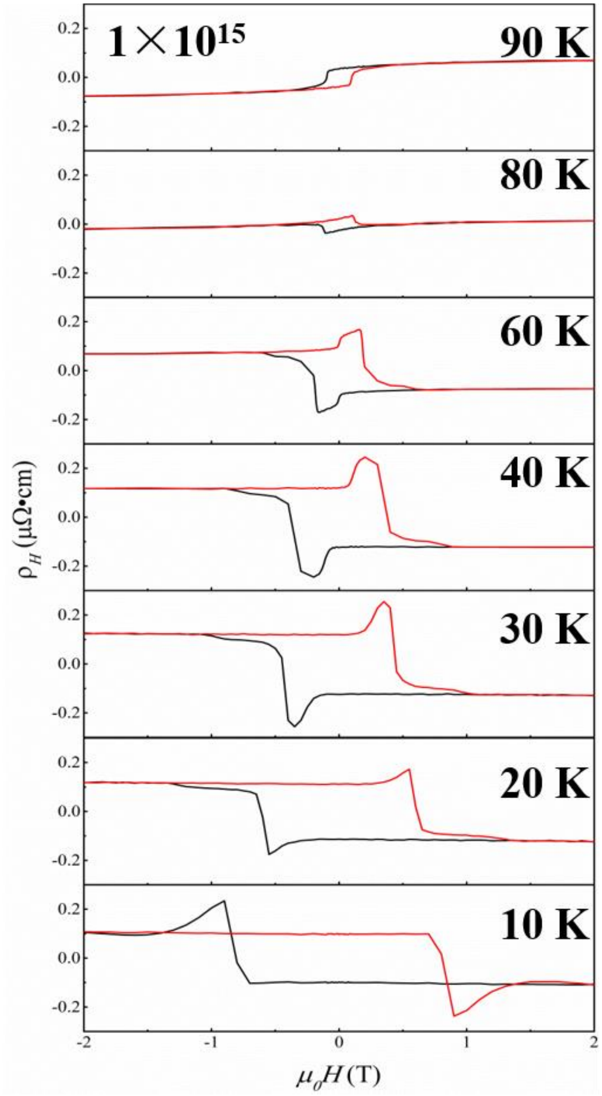
- THE appear in a single and thick (~ 60 nm) SRO films with He ion irradiation.



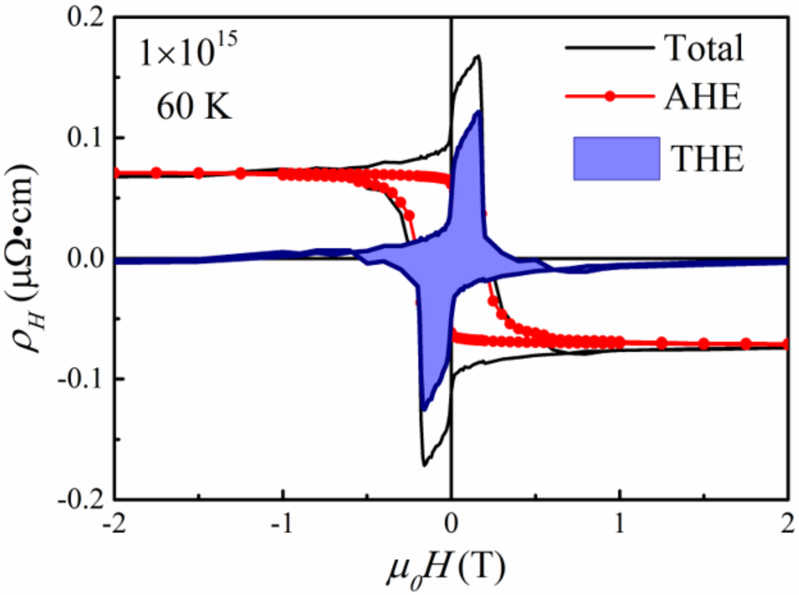
C. A. Wang et al., Adv. Electron. Mater. 2020, 2000184

3. $SrRuO_3$

- Hall effect for the sample **1×10^15^**



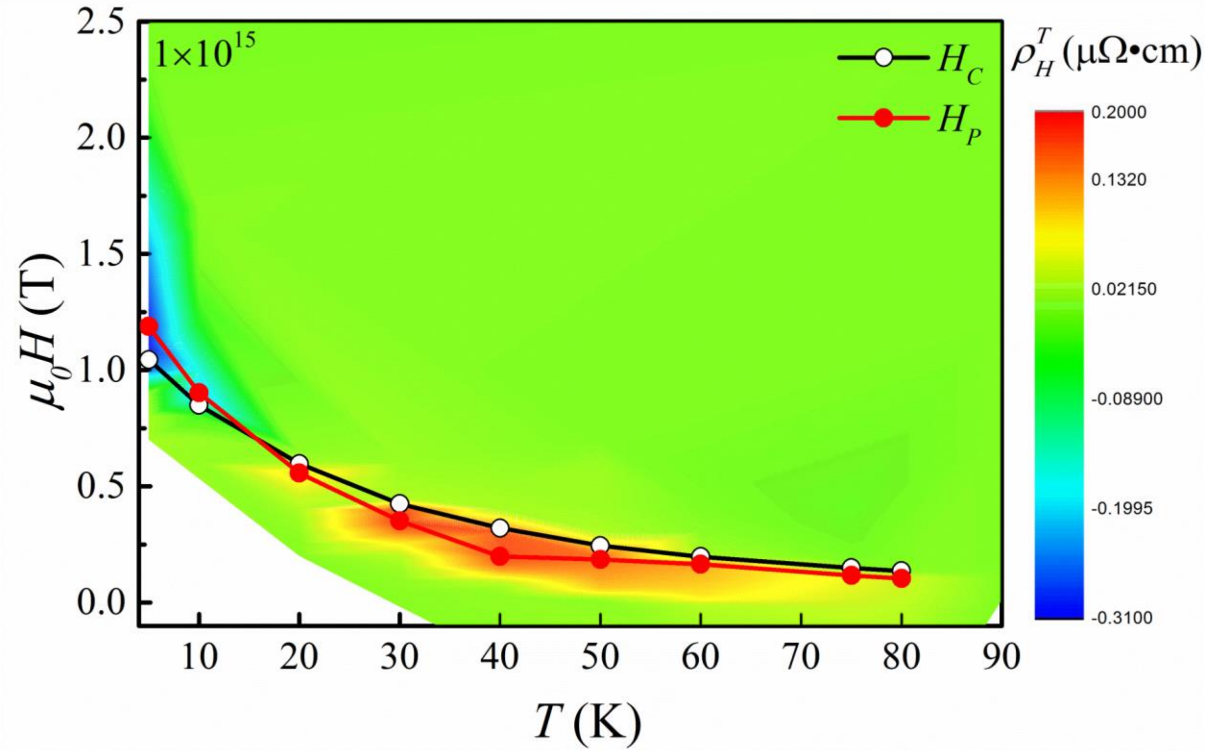
Contribution from AHE and THE for the **1×10^15^**



C. A. Wang et al., Adv. Electron. Mater. 2020, 2000184

3. $SrRuO_3$

- Color map of topological Hall resistivity in the T-H plane for the sample **1×10[15]**



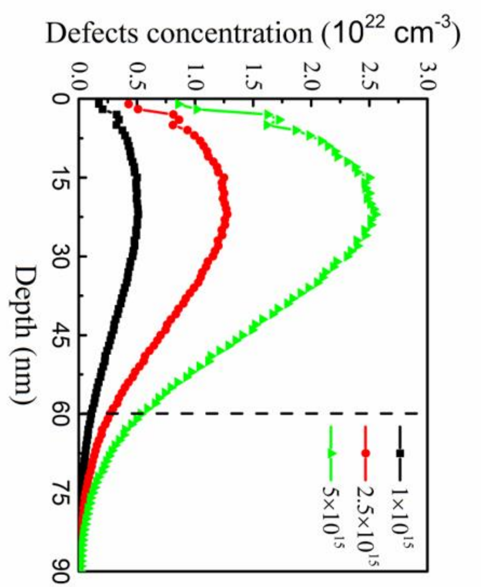
H_C: coercivity at M-H loops H_P: magnetic field of peak at THE

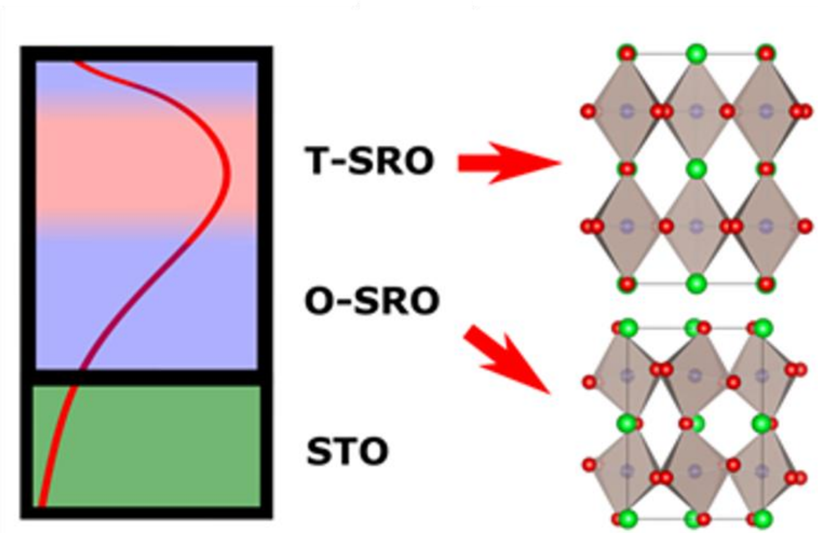
A pronounced THE is observed in a wide temperature range from 5 to 80 K.

C. A. Wang et al., Adv. Electron. Mater. 2020, 2000184

3. $SrRuO_3$

- The observed THE is attributed to inversion symmetry breaking due to defect engineering.

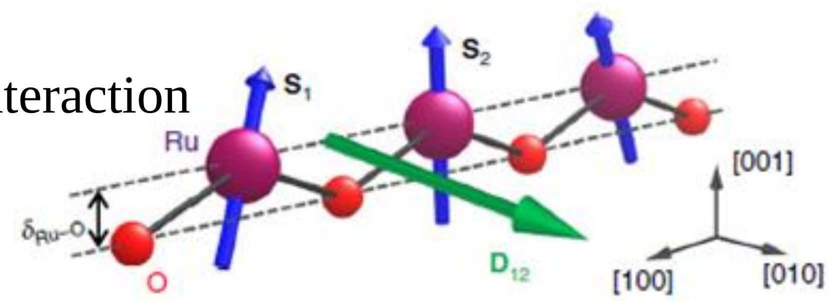




A gradient in the density of defects lead to the local structural distortion.

The change of oxygen octahedral rotation at the O-T phase boundary.

Dzyaloshinskii-Moriya interaction



L. F. Wang et al. *Nat. Mater*. 2018, 7, 1087-1094

C. A. Wang et al., Adv. Electron. Mater. 2020, 2000184

Ion irradiation effect in complex oxides: Another degree of freedom or complexity?

Who play the major role?

Defects? Strain? Oxygen-vacancy? Ion occupations?

Acknowledgement

From my group: Changan Wang, Dr. Parul Pandey

Prof. Ching-Hao Chang:
Prof. Ying-Hao Eddie Chu: National Jiaotong University
Prof. Deyang Chen: South China Normal University

ZH 225/10-1

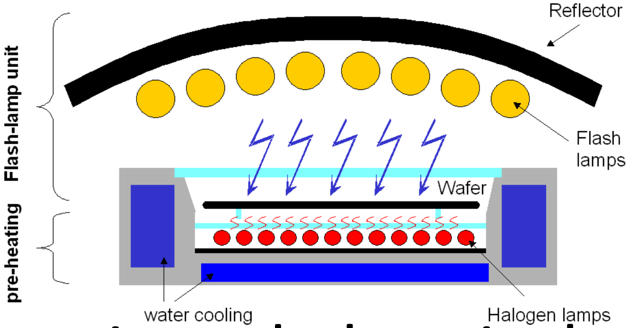
s.zhou@hzdr.de

Thank you for your attention!
Looking forward to cooperation!

s.zhou@hzdr.de

Resources: Semiconductor materials

Material processing: laser and flash lamp annealing



Material characterization: magnetic and electrical

SQUID-VSM
SQUID-MPMS
Lakeshore Hall Measurement system
1.8-400 K
up to 7 T

Material characterization: optics

Raman, PL and attoCube-dry

And the user facilities: ion beam center

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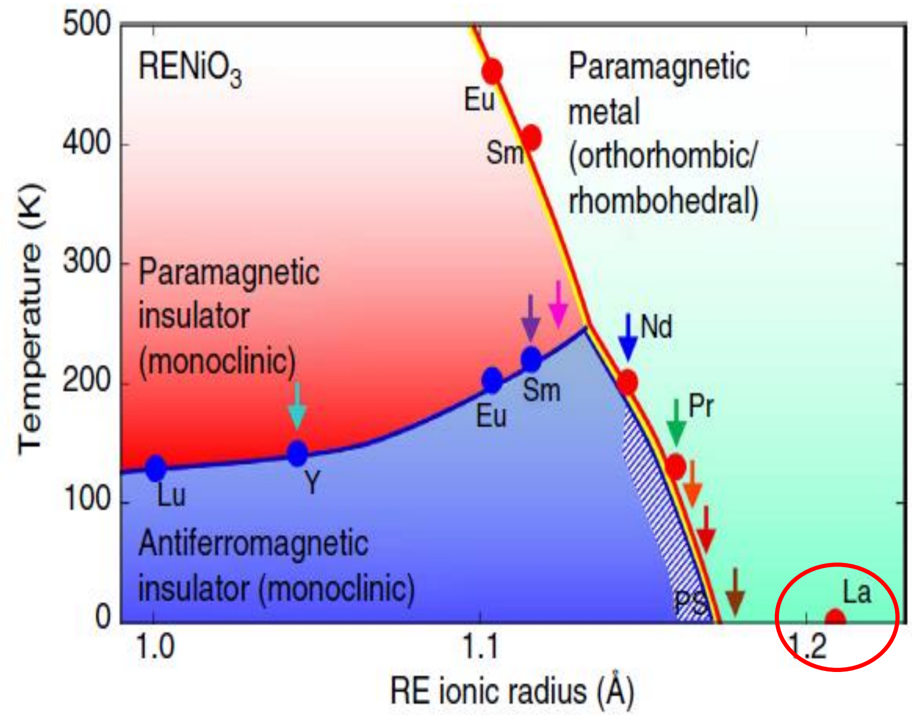
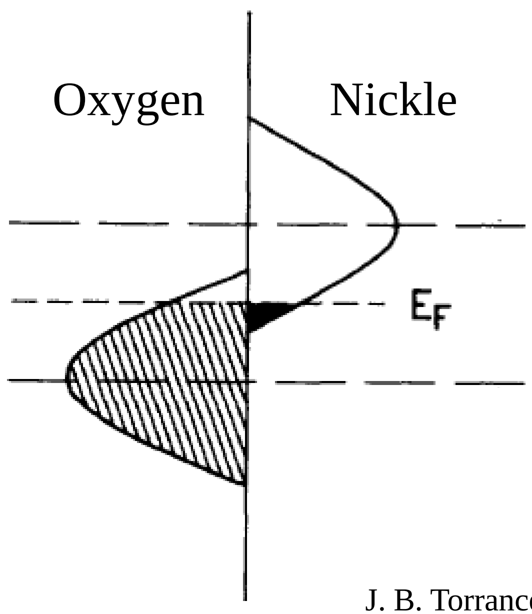
3. $LaNiO_3$

- Paramagnetic oxide
- No metal insulator transition
- Metallic behavior down to 0.4 K

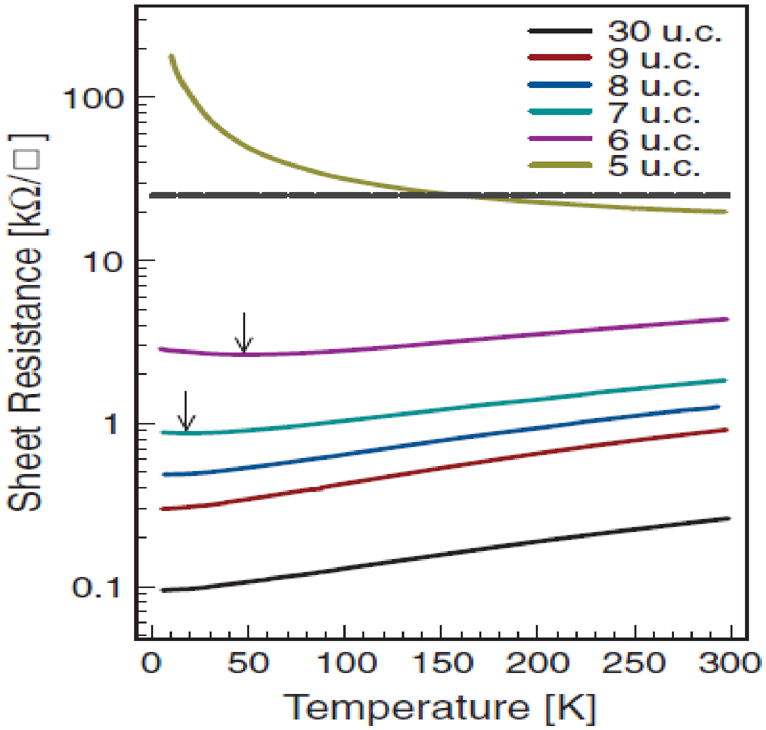


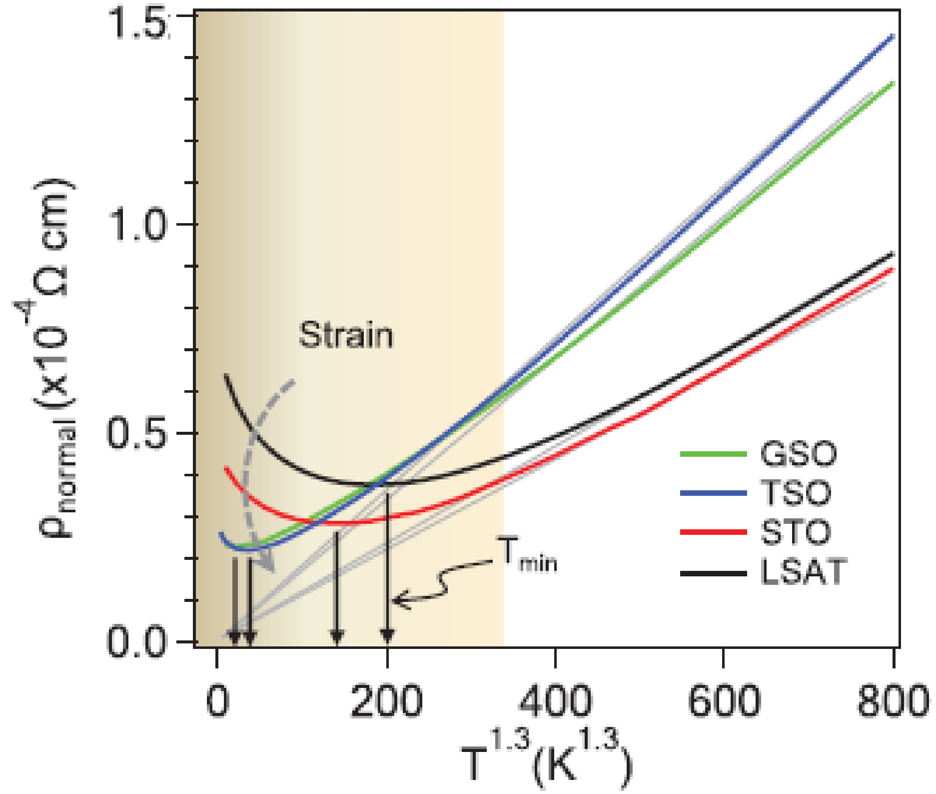
B. A. Frandsen. et al. Nat. Commun **7**, 12519 (2016)



J. B. Torrance. et al. Phys. Rev. B **45**, 8209 (1992)

3. $LaNiO_3$



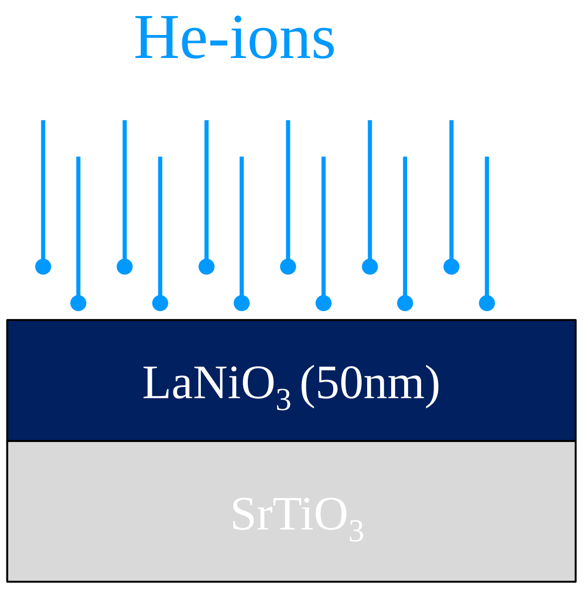


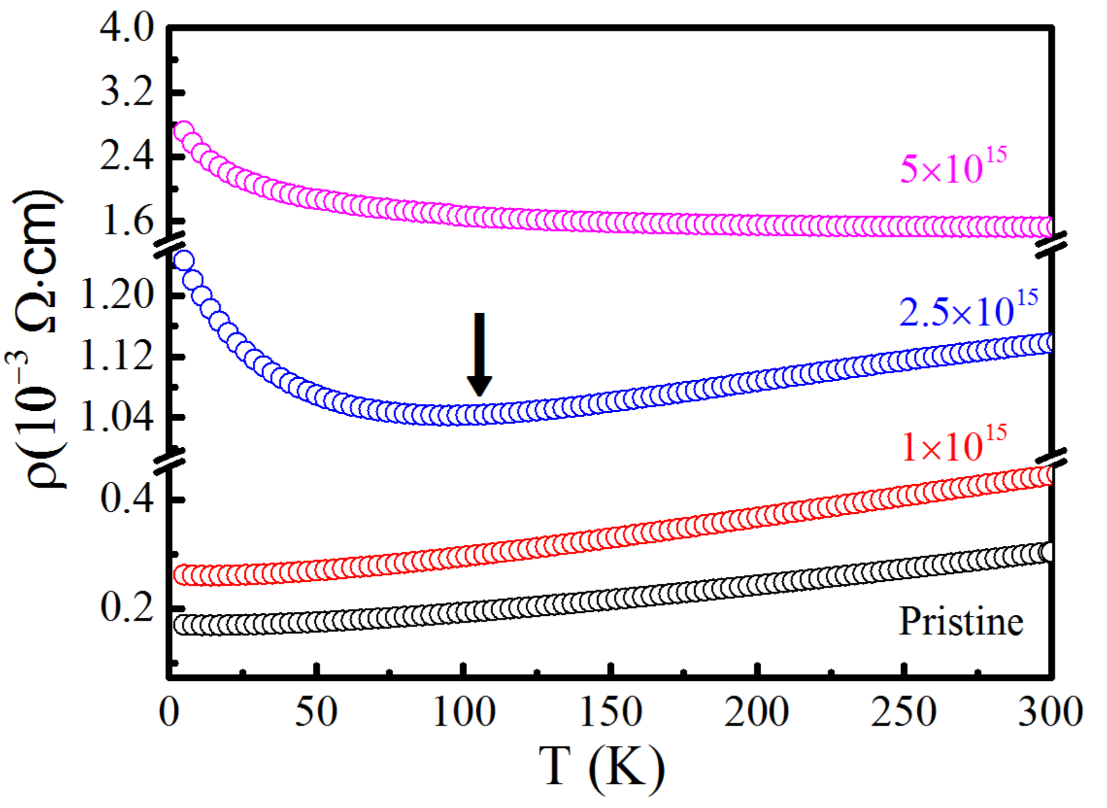
LNO-based heterostructures have been grown and transport measurements have revealed a MIT as the thickness is reduced to 3-5 monolayer.

Weak localization can also be driven in LNO films by strain.

R. Scherwitzl. et al. Phys. Rev. Lett **106**, 246403 (2011)
E. J. Moon. et al. New. J. Phys. 13, 073037(2011)

3. $LaNiO_3$





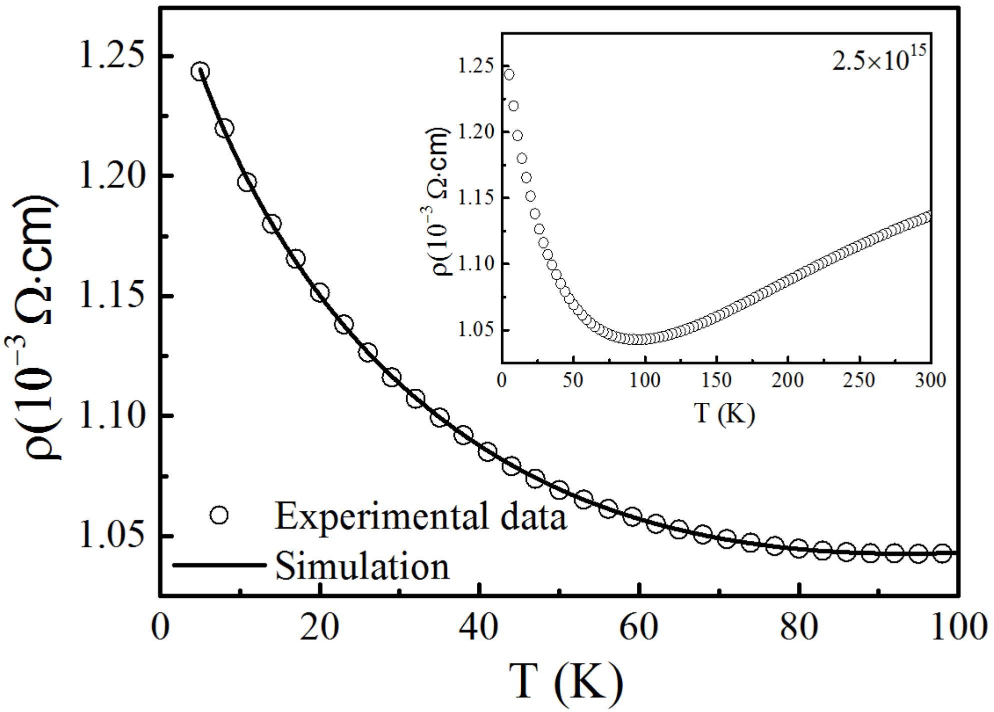
Pristine and 1×10^{15} show metallic behavior ($d\rho/dT > 0$).

2.5×10^{15} displays an upturn in resistivity at around 100 K.

5×10^{15} shows insulating behavior ($d\rho/dT < 0$).

Phys. Rev. Mater. 3, 053801 (2019)

3. $LaNiO_3$



- ρ_0: the remnant resistance;
- the second and third terms represent the weak localization correction in three dimensions and inelastic scattering due to electron-boson interaction;
- bT^2 is the classical Boltzmann term.

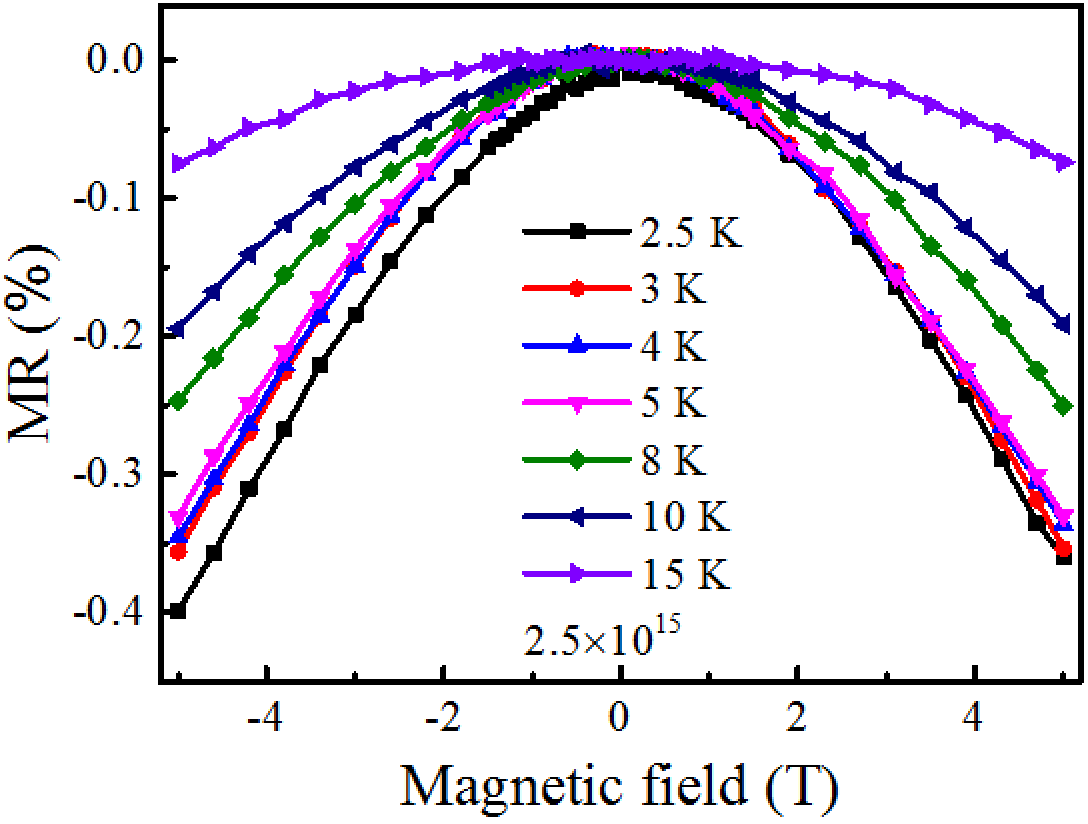
$$\rho=\rho_0 - \alpha T^{3/4}+\beta T^{3/2}+bT^2$$

Dominated by electron-defects interaction rather than the electron-electron interaction

N. Gayathri. et al. J. Phys.: Condens. Matter **10**, 1323 (1998)

Phys. Rev. Mater. 3, 053801 (2019)

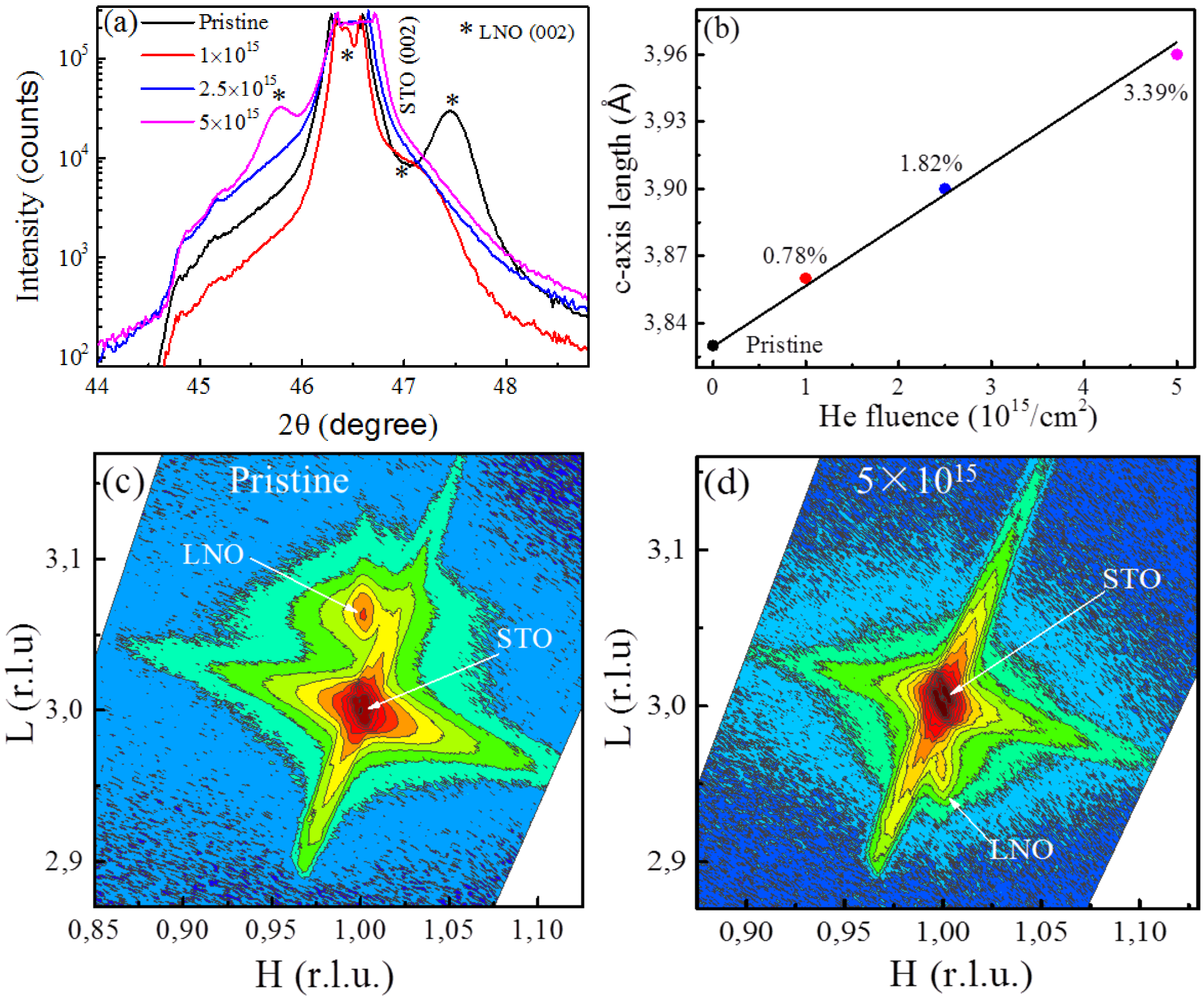
3. $LaNiO_3$



The negative MR is also an evidence that the dominant scattering mechanism is not electron-electron interaction.

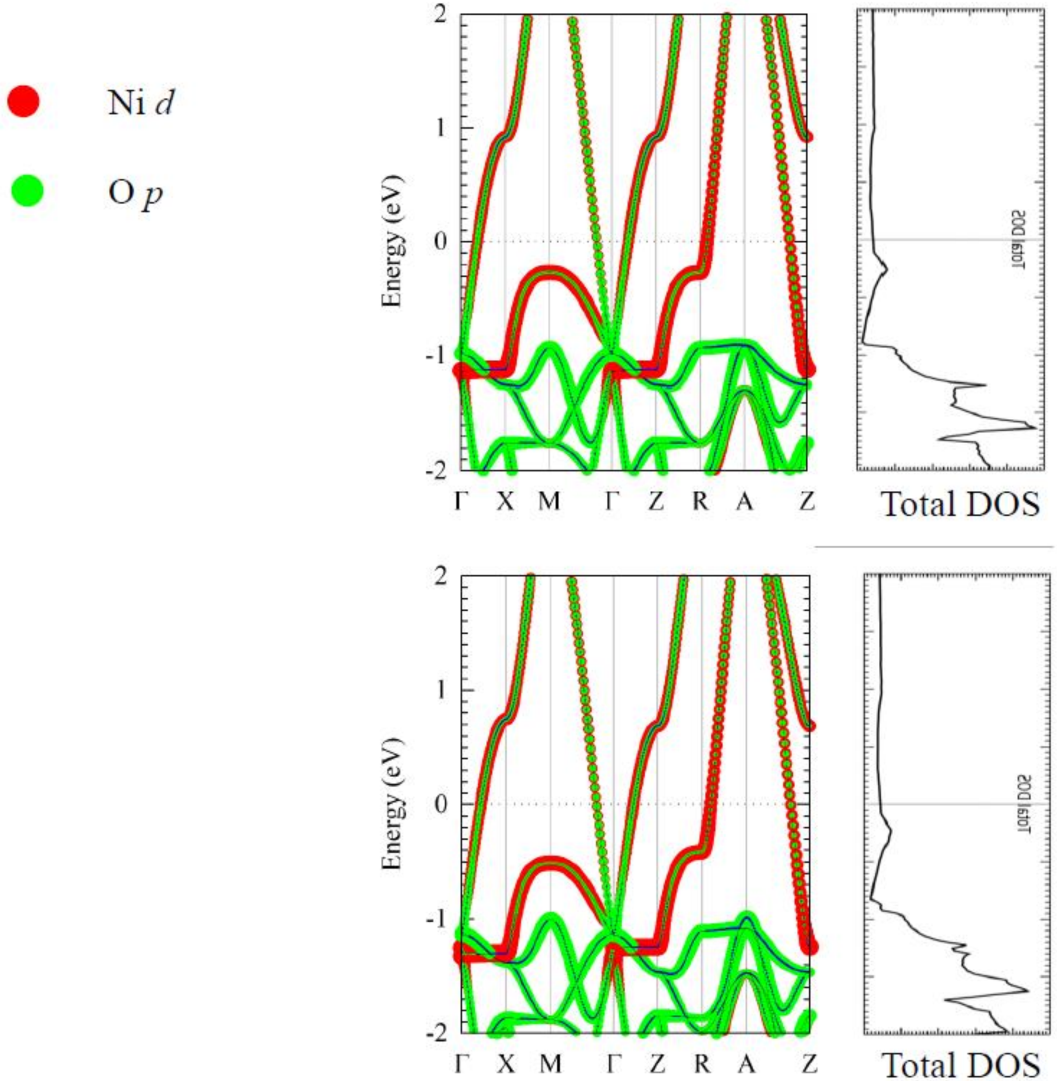
Phys. Rev. Mater. 3, 053801 (2019)

3. $LaNiO_3$

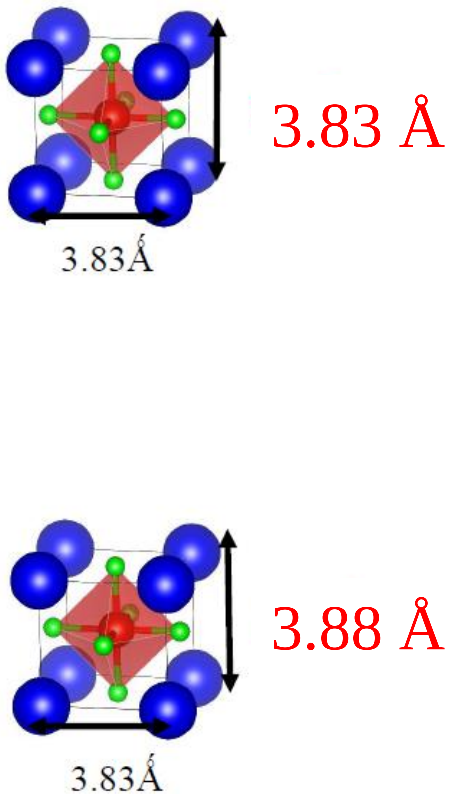


Phys. Rev. Mater. 3, 053801 (2019)

3. $LaNiO_3$



$LaNiO_3$ (stress in c axis)



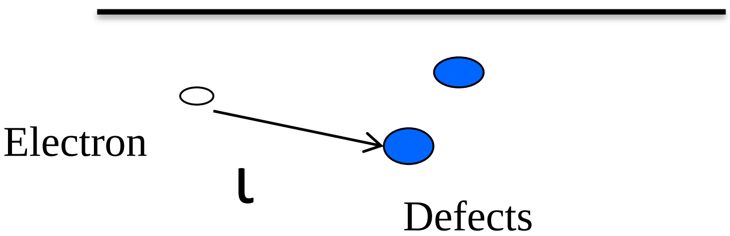
Strain induced by defects does not open the band gap in LNO.

Done by Ching-Hao Chang (IFW)

Phys. Rev. Mater. 3, 053801 (2019)

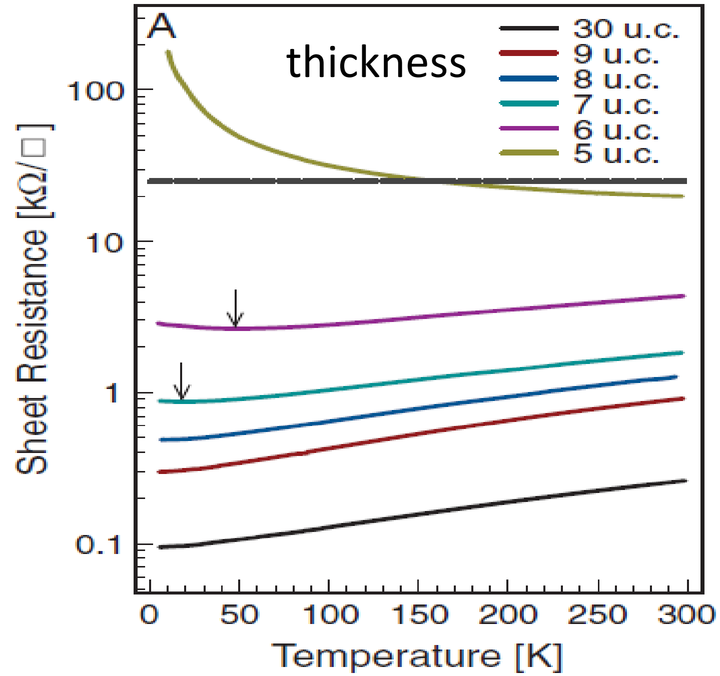
3. $LaNiO_3$ Defects / impurties are winners

Defects are responsible for electrical phenomena in LNO



Mean free path : ι

Analogy



R. Scherwitzl. et al. Phys. Rev. Lett **106**, 246403 (2011)

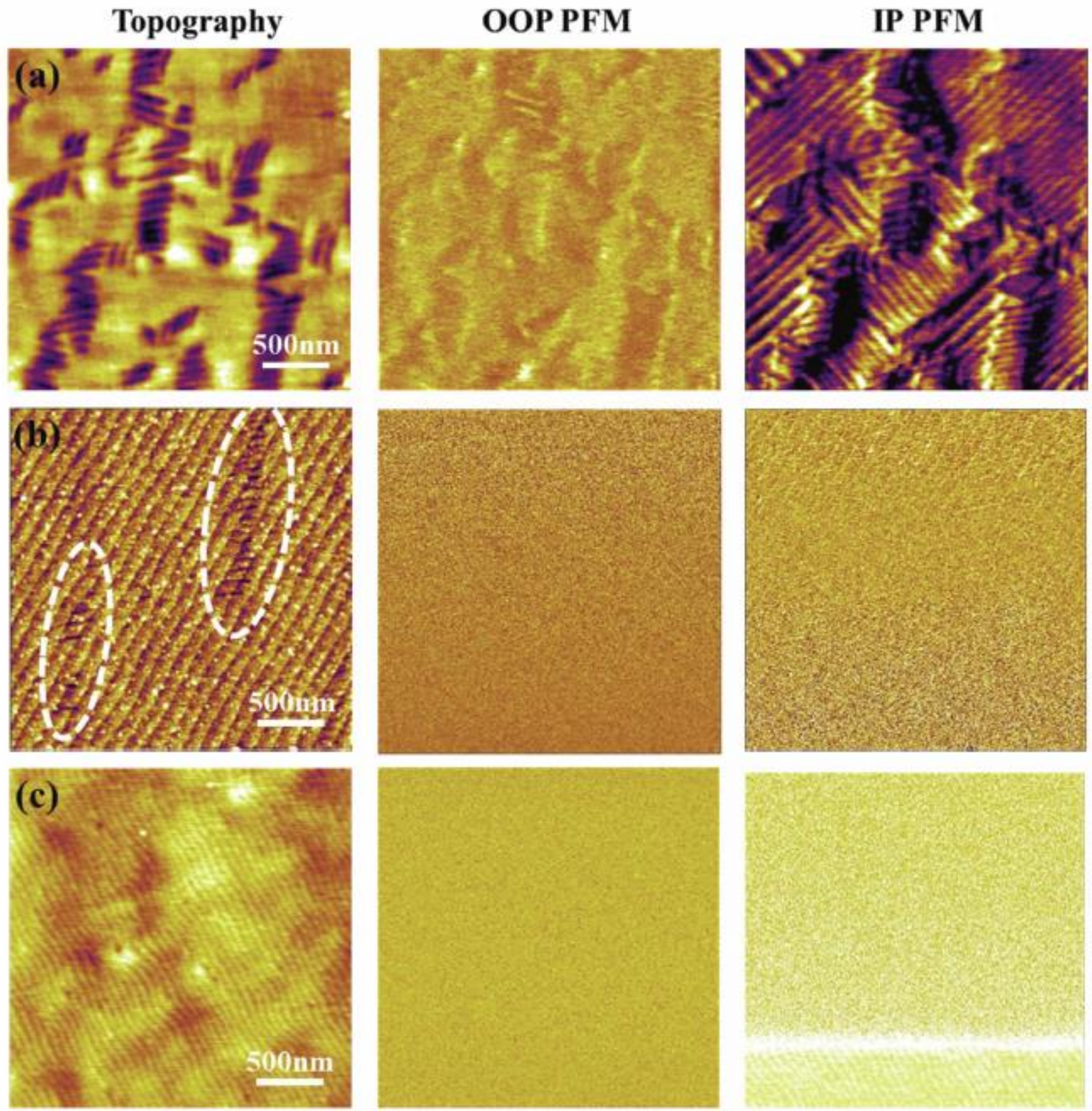
Mean free path reduced, then rise the resistivity as $\rho \propto \iota^{-1}$

ι approaches the interatomic spacing a

The usual transport theory (the Drude formula) break down.
This is so-called Mott-Ioffe-Regel (MIR)

Phys. Rev. Mater. 3, 053801 (2019)

2. $BiFeO_3$



Nanoscale 11, 8110 (2019)