

Tuning the secondary electron yield and electronic conductivity properties by Atomic layer deposition

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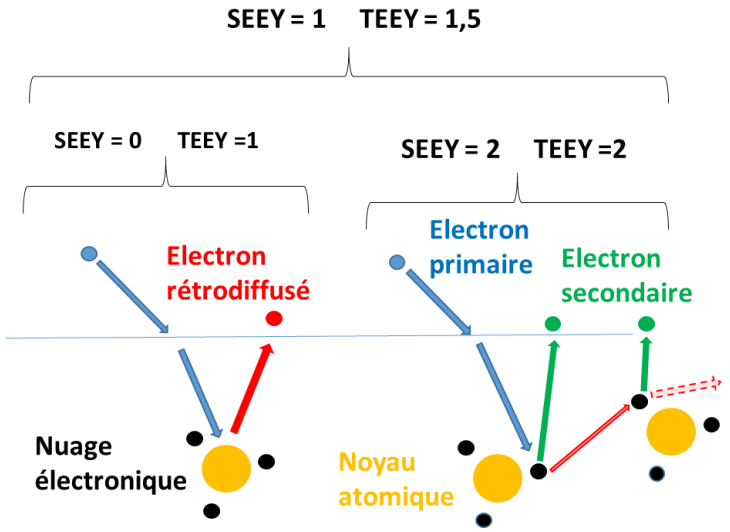
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Thin film Workshop 2026 – Chester, UK.

Outline

1. Context: charging and multipacting in SRF, space, detector applications
2. Tuning chemical and structural properties by ALD multilayers
3. Tuning conductivity and TEEY by ALD multilayers
4. Conclusions and perpectives

Secondary electron yield and multipacting



TEEY = Total electron emission yield

⇒ Number of secondary electron retro diffused emitted from the surface for each incident electron at a given energy.

⇒ TEEY > 1 avalanche.

⇒ TEEY < 1 do not start.

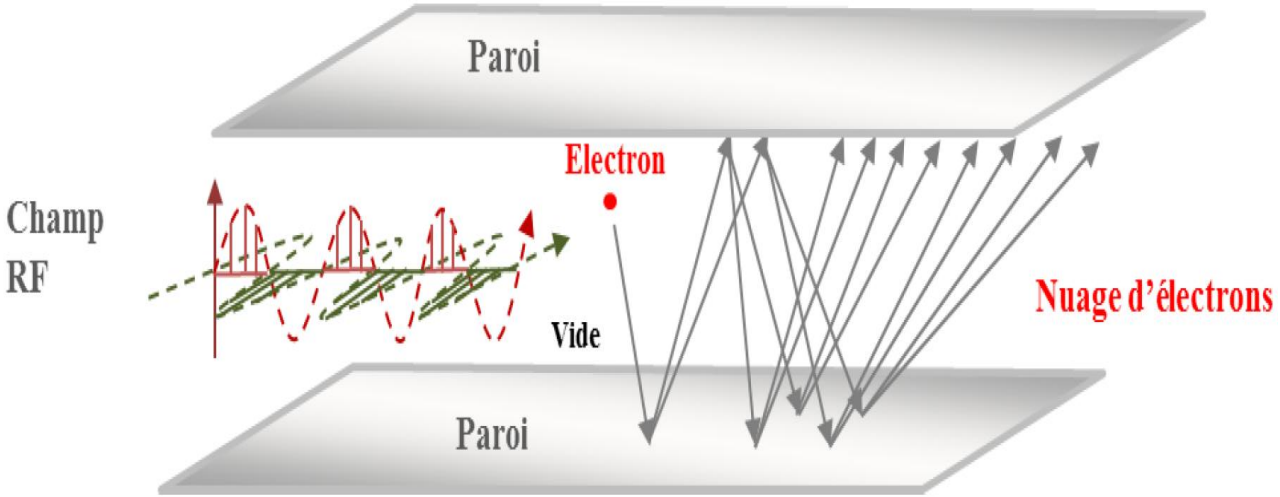
⇒ TEEY is dominated by the first 1 to 10 nm of the surface.

Electronic emission

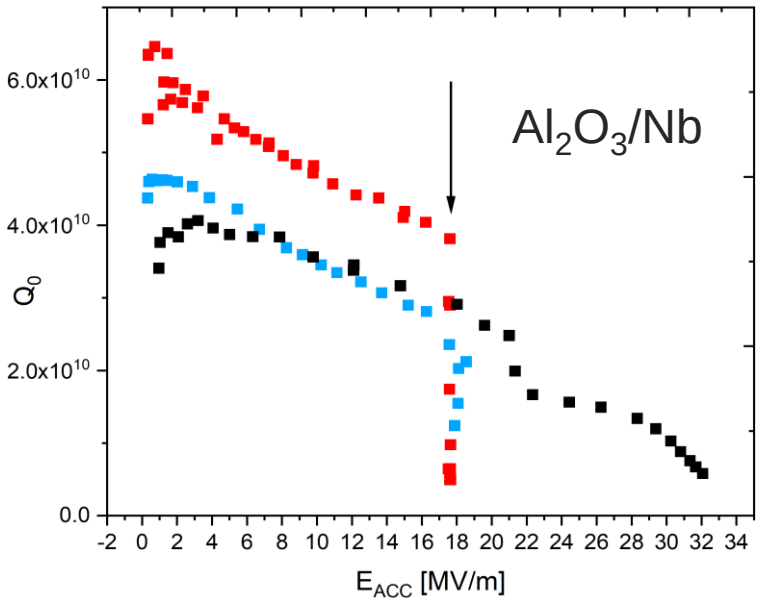
Synchronized multiplication of electrons with RF field

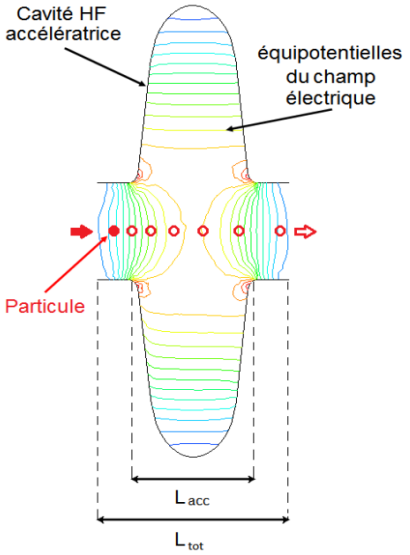
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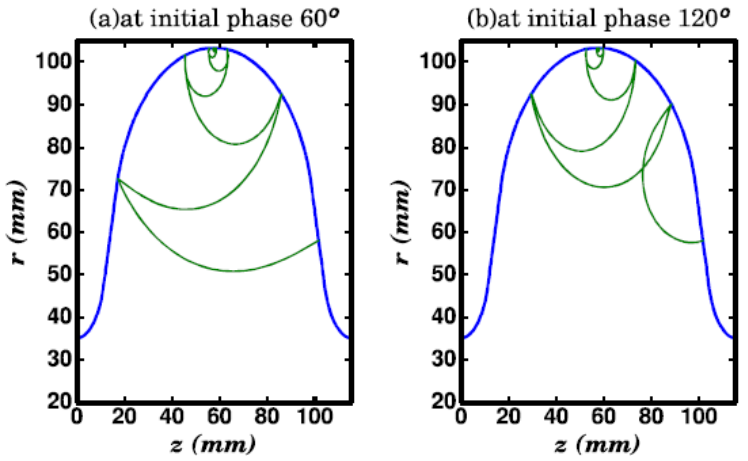
Multipacting

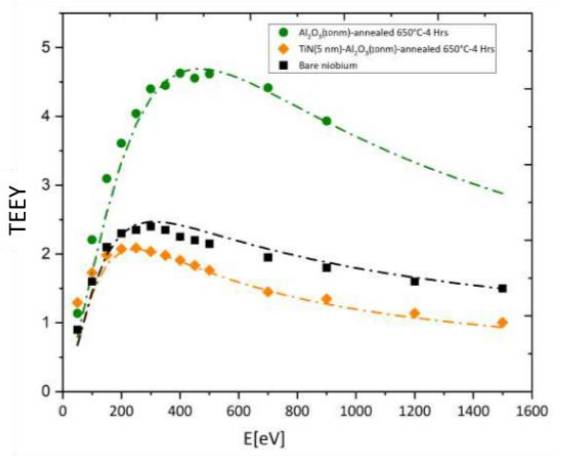


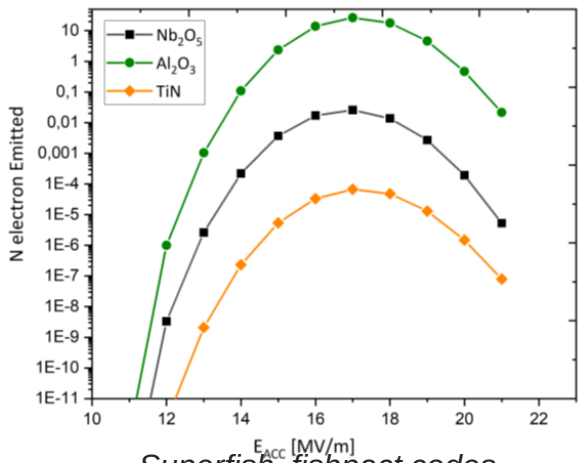
Multipacting in SRF cavities.











Superfish, fishpact codes

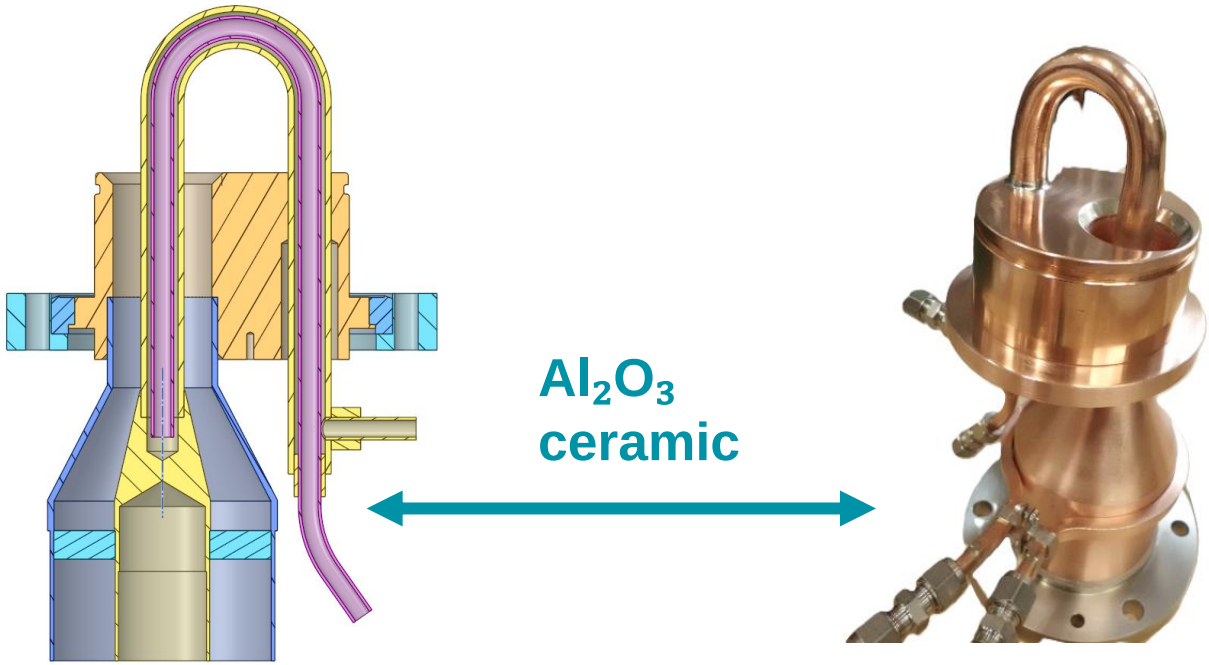
- Synchronization between RF field and electronic emission.
- Limit performances of SRF cavities + irreversible decrease of Q.
- Exponential dependence on the surface (~nm) TEEY (total electron emission yield).
- How to mitigate this effect: Low TEEY thin film – TiN by ALD.
- Ph.D Thesis Y. Kalboussi. https://theses.fr/2023UPASP029

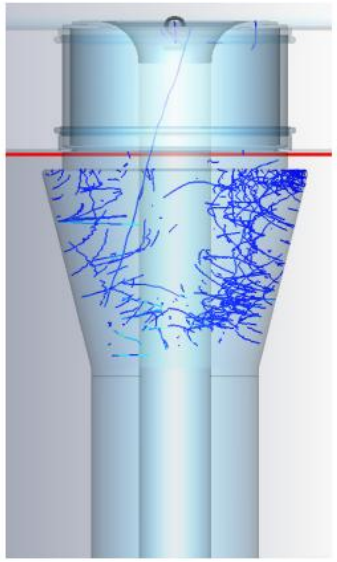
❑ Requirements are **Low TEEY and low conductivity** to avoid joule heating

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Multipacting in RF couplers

- Multipacting is a very detrimental phenomena to RF systems.
- Near the ceramic window, RF-accelerated electrons strike the Al_2O_3 surface, generating secondary electrons and sustaining multipacting as the SEY of Al_2O_3 is ~ 4.5.
- Coating with low SEY film such as TiN is an established solution.



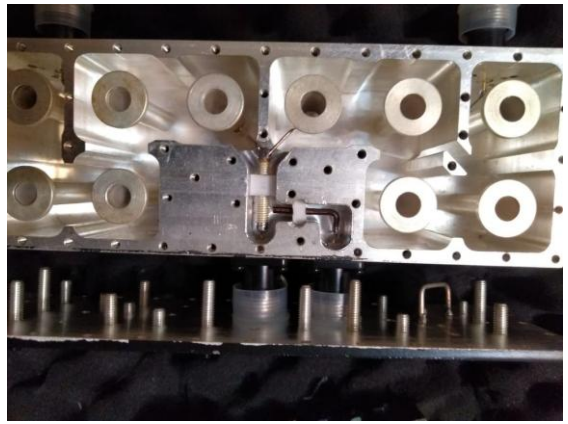


Electron trajectoires
Inside a power coupler [1]

- Requirements are **Low TEEY and controled conductivity (low)** to avoid joule heating

Charging in space applications

Multipacting embarked RF system



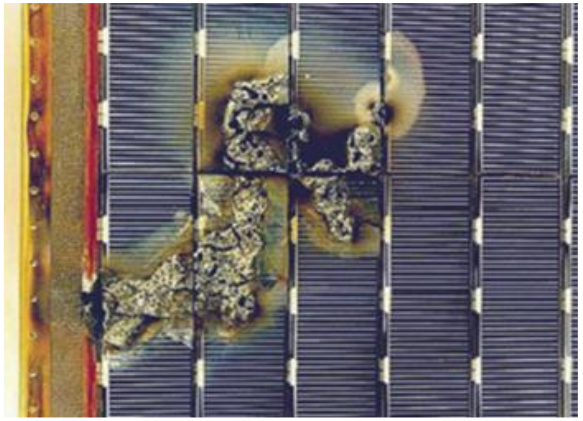
RF filters

Pertub the function damages risks

Sun light exposure

ESD risk on solar panels

Irreversible dammages



ESD Damages

Electron emission yield (TEEY)

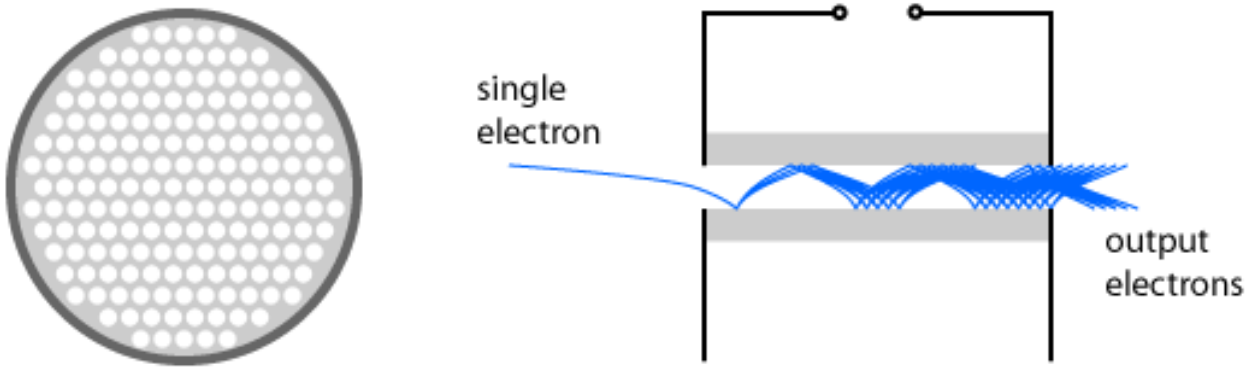
Risk perturbation instruments outside the craft (Langmuir probes)



Langmuir probe

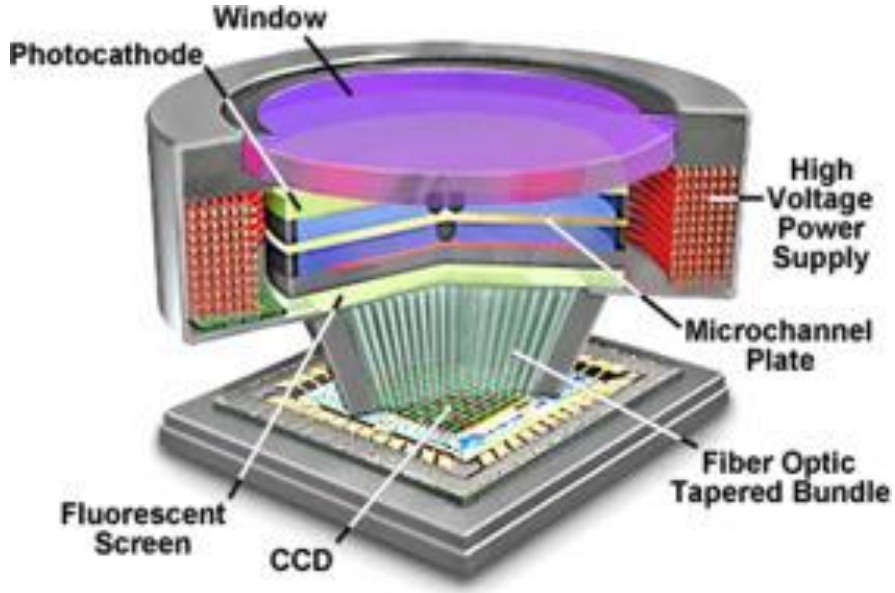
❑ Requirements are **Low TEEY and high or Low conductivity.**

Microchannel plate multipliers



a) front view of microchannel plate

b) electron avalanche in a single channel



- MCPs are Part of detector electronic and is based on electron multiplication
- Requirements are **High TEEY and controled conductivity (semi metallic)** to avoid surface charging

Dr. Rüdiger Paschotta –rp Photonic - https://www.rp-photonics.com/microchannel_plates.html

TEEY and electical conductivity

Dielectric

Large band gap

Low carrier density

Low conductivity

Large escape depth ~ 10 nm
No electron screening

High TEEY

Conductor

Filled conduction band

High carrier density

High conductivity

Small escape depth ~ nm
Electron screening

Low TEEY

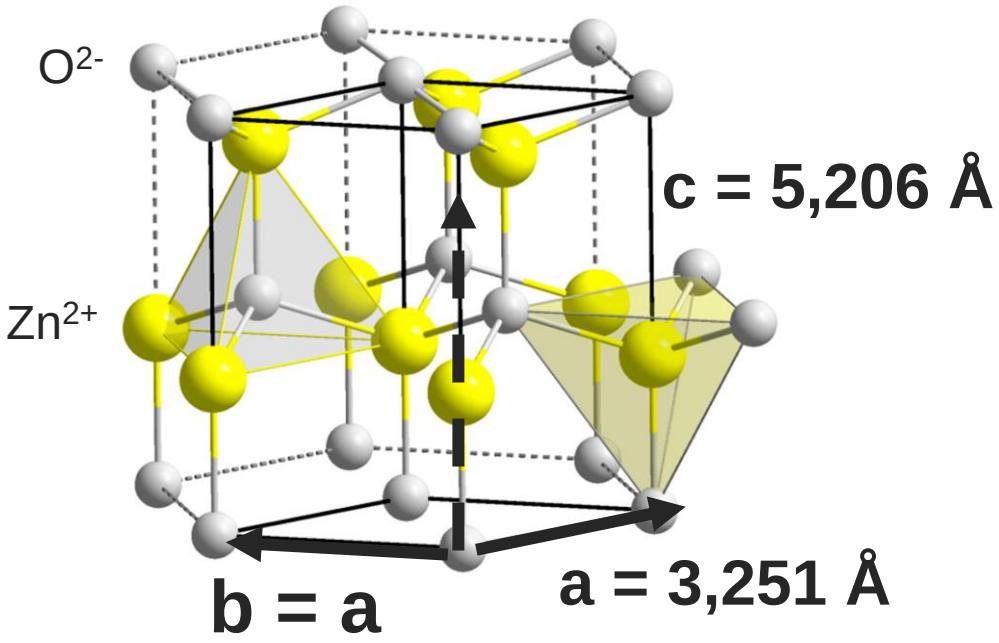
Approach

Main constraints		Solutions
TEEY dominated by first 10 nm	→	Use nanometric films
Complex geometry and surfaces	→	ALD synthesis
TEEY and electrical conductivity can hardy be modulated in single phase materials.	→	Heterostructure combining different alloys
Combining two materials at the sub nm level	→	Intermixing at the atomic level by ALD

Choice of materials: why ZnO and MgO

ZnO :

- **TEEY = 2.5**
- **Conductivity = 10^4 $\Omega^{-1}.m^{-1}$**
- GPC = 0,177 nm.cycles^{-1}
- Précursors : DEZ + H_2O
- Temperature = 150 °C✓



Large Differences

TEEY

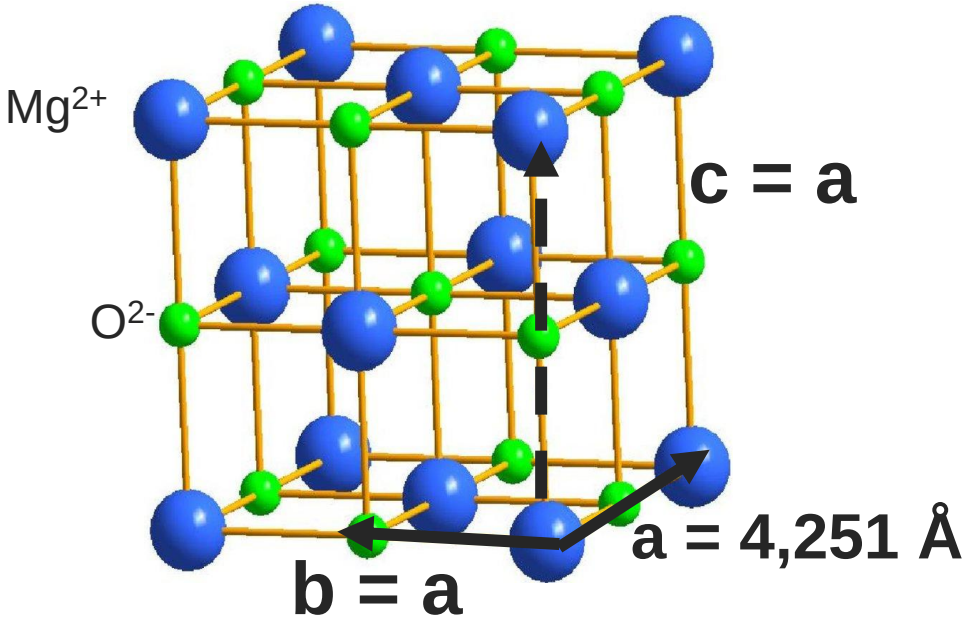
electrical conductivity

GPC

cristallinity

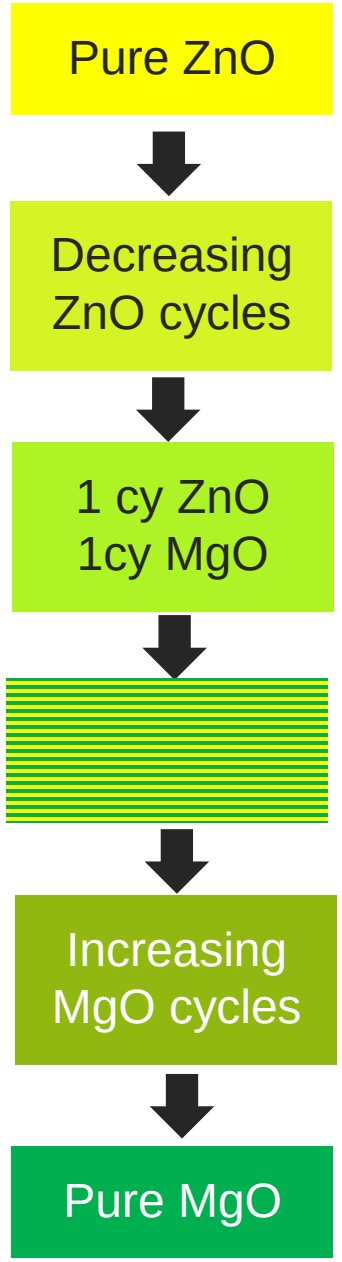
MgO :

- **TEEY = 6,2**
- **Conductivity = 10^{-13} $\Omega^{-1}.m^{-1}$**
- GPC = 0,12 – 0,14 nm.cycles^{-1}
- Précursors : $Mg(EtCp)_2$ + H_2O
- Temperature = 150 °C✓



ALD growth sequences

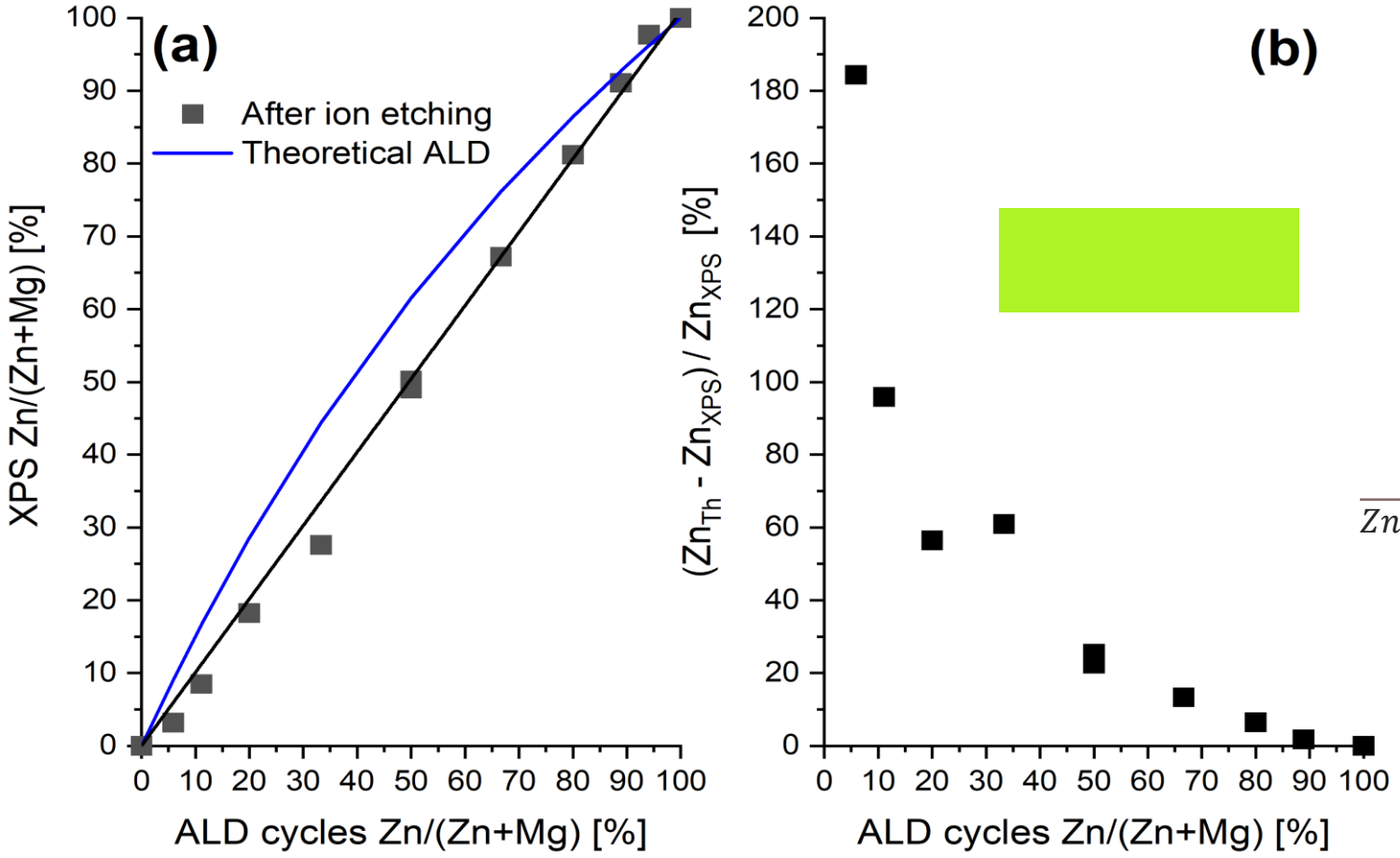
Nomenclature	Supercycle description	Supercycles	Surface layer (ALD cycles)
ZnO	200 cycles of ZnO	1	ZnO
1/16*	1 cycle of MgO + 16 cycles of ZnO	12	ZnO (16)
1/8*	1 cycle of MgO + 8 cycles of MgO	24	ZnO (8)
1/4*	1 cycle of MgO + 4 cycles of ZnO	42	ZnO (4)
1/2*	1 cycle of MgO + 2 cycles of ZnO	72	ZnO (2)
1/1*	1 cycle of MgO + 1 cycle of ZnO	112	ZnO (1)
2/2*	2 cycles of MgO + 2 cycles of ZnO	56	ZnO (2)
4/4*	4 cycles of MgO + 4 cycles of ZnO	28	ZnO (4)
8/8*	8 cycles of MgO + 8 cycles of ZnO	14	ZnO (8)
16/16*	16 cycles of MgO + 16 cycles of ZnO	7	ZnO (16)
32*/32	32 cycles of ZnO + 32 cycles of MgO	6	MgO (32)
16*/16	16 cycles of ZnO + 16 cycles of MgO	7	MgO (16)
12*/12	12 cycles of ZnO + 12 cycles of MgO	9	MgO (12)
8*/8	8 cycles of ZnO + 8 cycles of MgO	14	MgO (8)
4*/4	4 cycles of ZnO + 4 cycles of MgO	28	MgO (4)
1*/1	1 cycle of ZnO + 1 cycles of MgO	112	MgO (1)
1*/2	1 cycle of ZnO + 2 cycles of MgO	77	MgO (2)
1*/4	1 cycle of + 4 cycles of MgO	48	MgO (4)
1*/8	1 cycle of + 8 cycles of MgO	28	MgO (8)
1*/16	1 cycle of ZnO + 16 cycles of MgO	15	MgO (16)
MgO	250 cycles of MgO	1	MgO



- ❑ Tailor composition (1 cyles-n cycles): ***series 1 samples***
- ❑ Fixed composition tailor growth sequence – structure: ***series 2 samples***
- ❑ How both influences TEEY – Electrical conductivity

Chemical composition control – series 1

XPS conc. Zn vs Zn ALD cycles

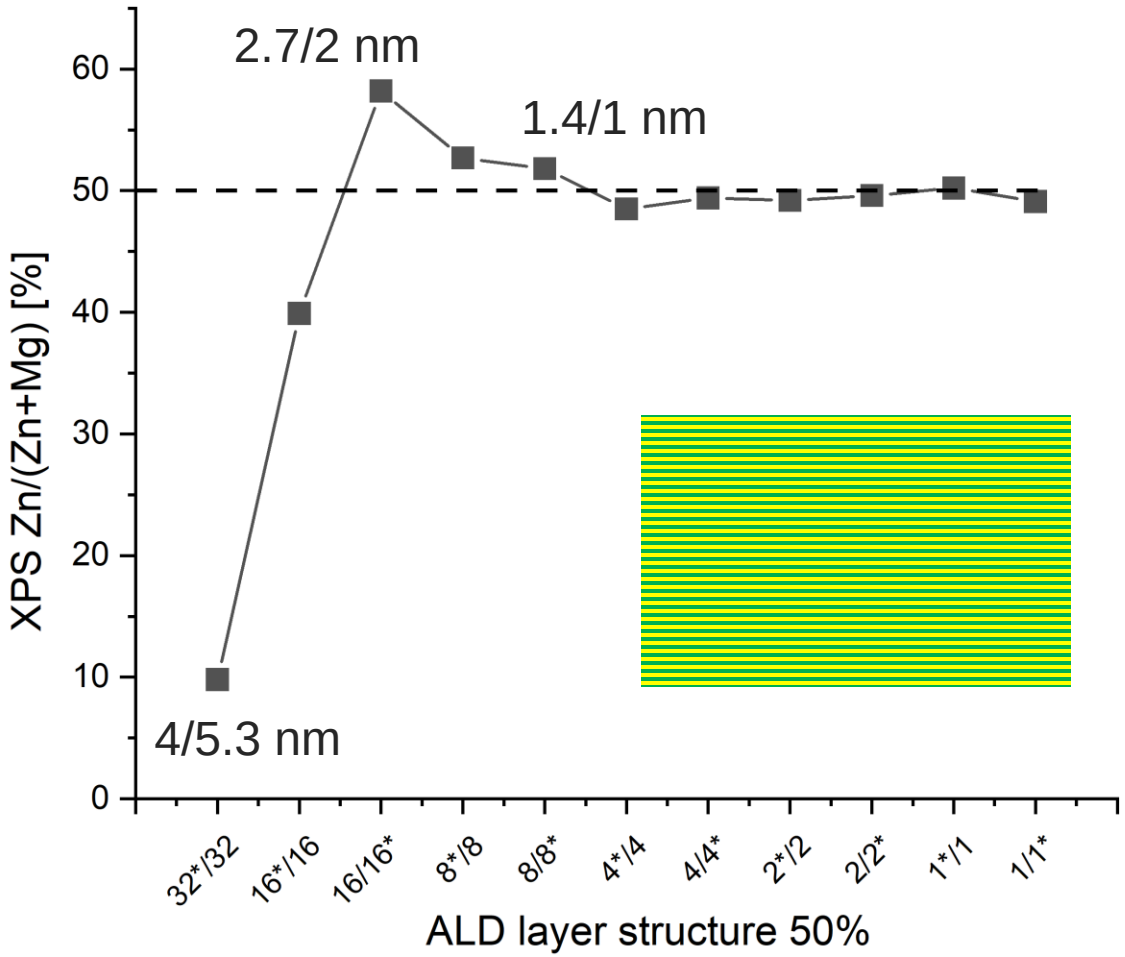


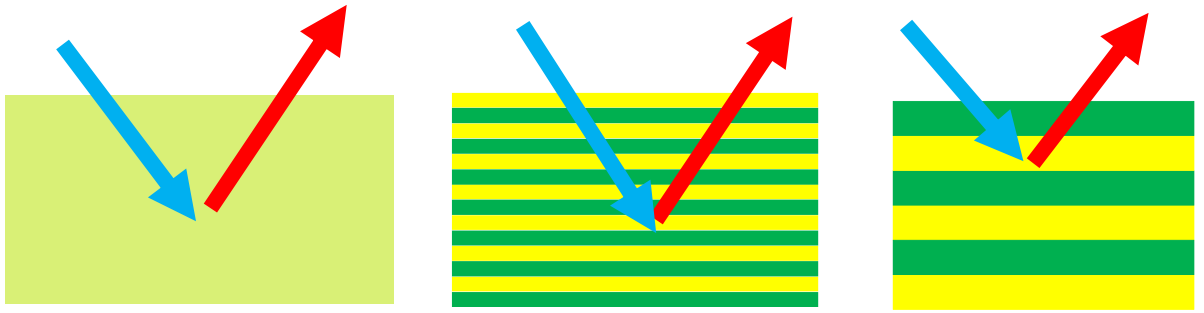
- Series 1 samples
- Slight surface erosion to decrease adventitious C contamination:15-25% down to 1-4%.
- XPS conc prop to Intended (ALD cycles) But far from expected: Theory.

$$\frac{ZnO\ cycles\ \times\ ref\ ZnO\ GPC}{ZnO\ cycles\ \times\ ref\ ZnO\ GPC + MgO\ cycles\ \times\ ref\ MgO\ GPC}$$

- Deviation -> lower Growth rate per cycle and increase with # MgO Cycles

Chemical composition control – series 2



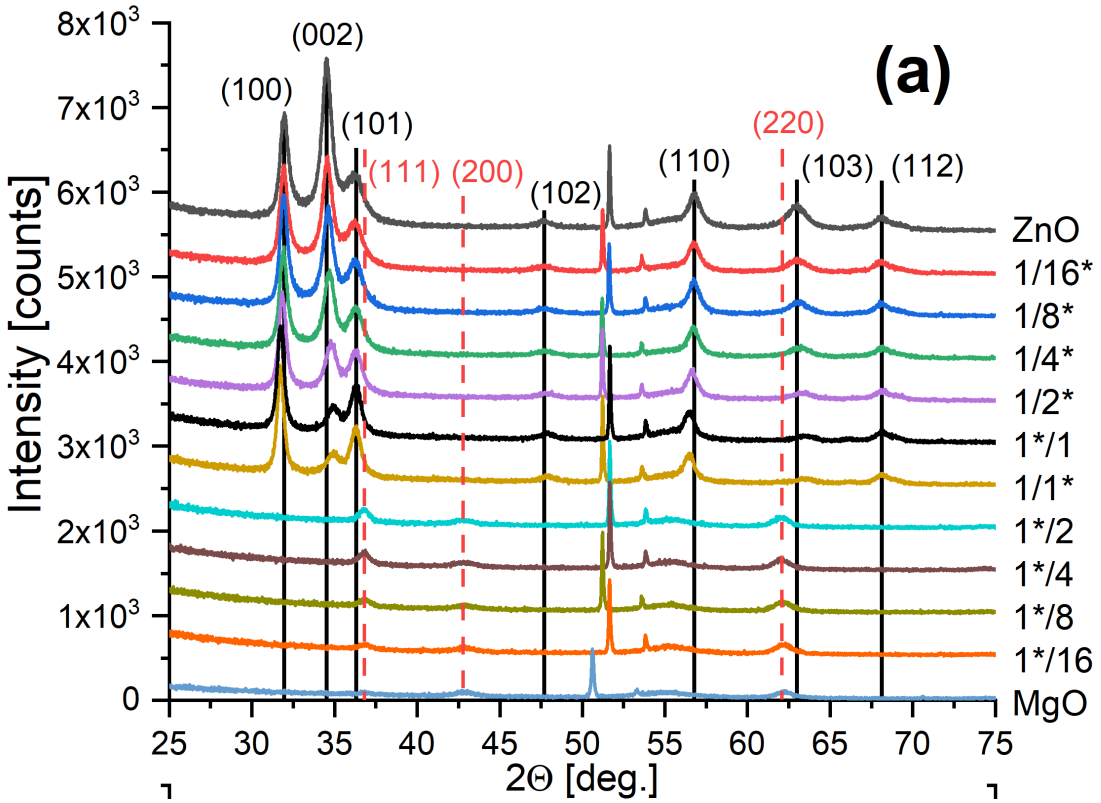


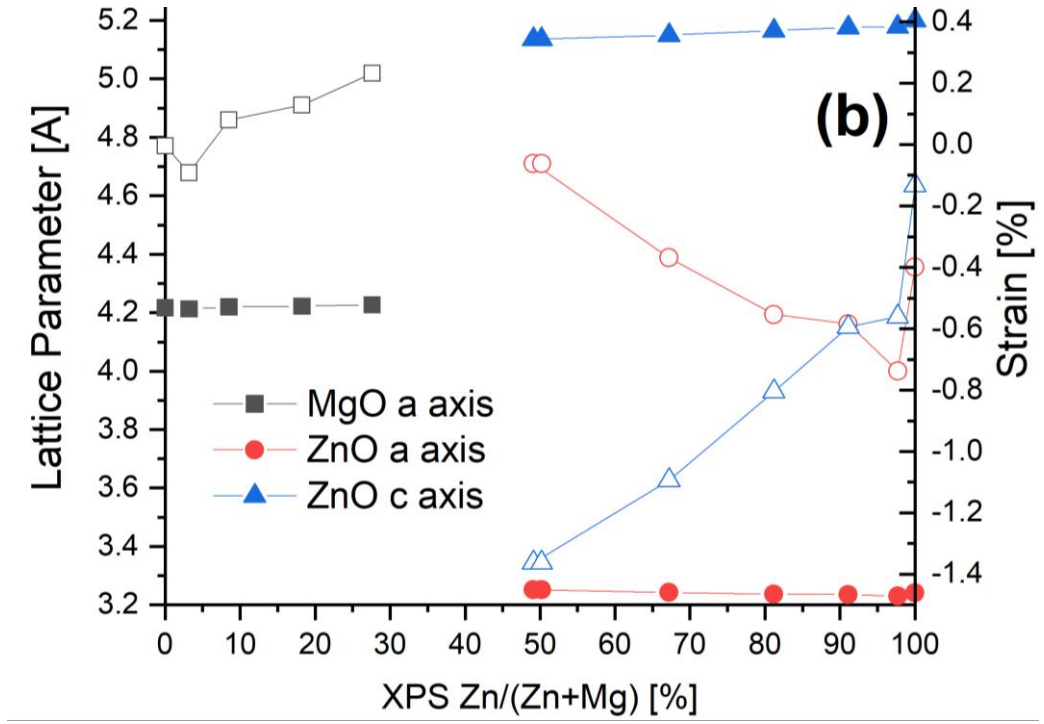
- Layer thickness, d, vs depth probed by XPS, λ (escape electronic depth – insulator ~ 10 nm / metal ~ 1 nm):

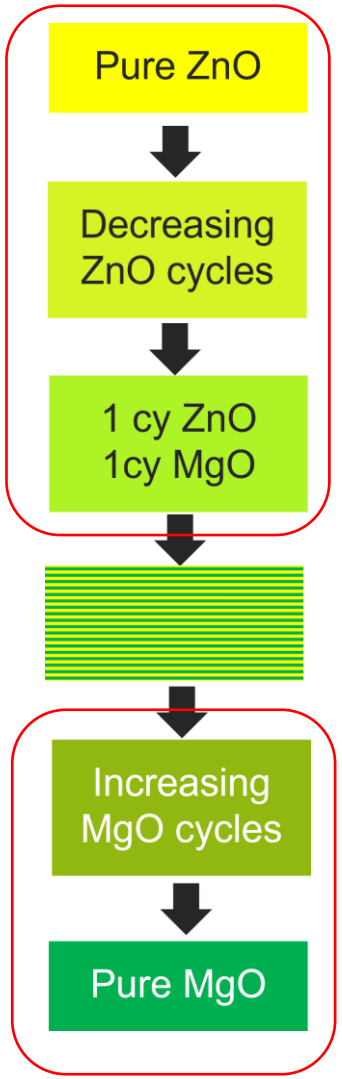
  d << λ -> average over multiple1 bilayer.

  d ~ λ -> the last layer dominate the conc. probed by XPS

Structural evolution – series 1

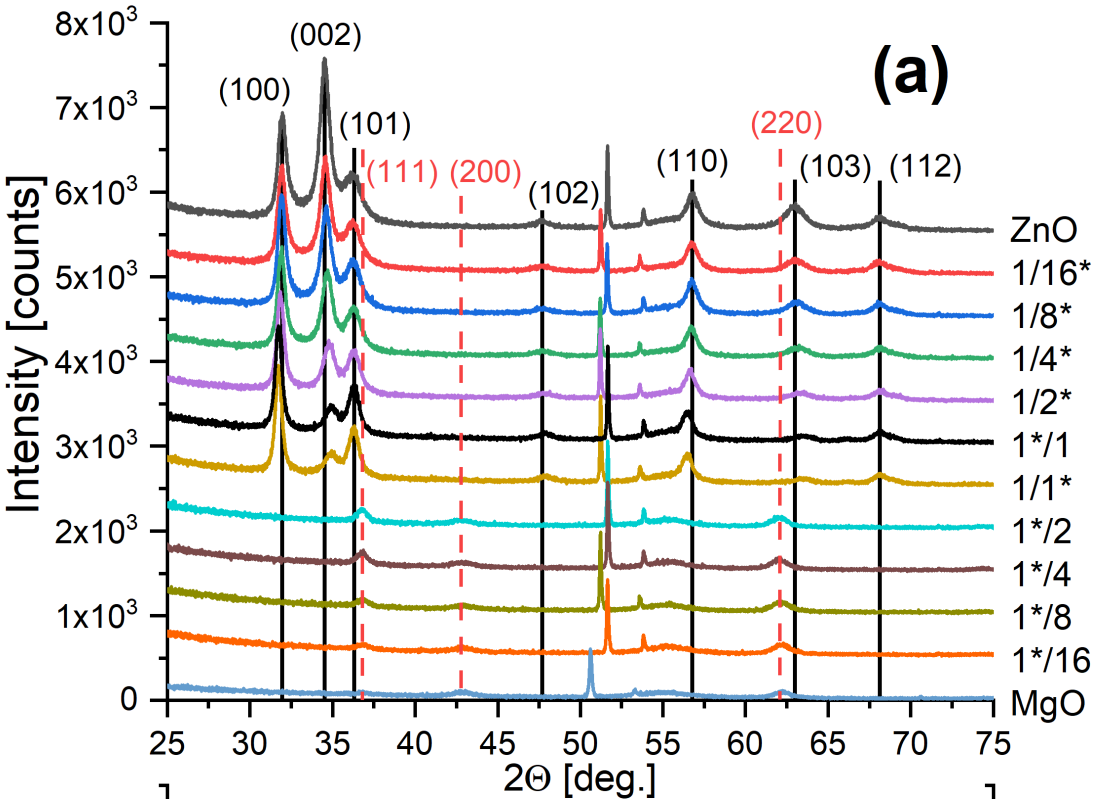


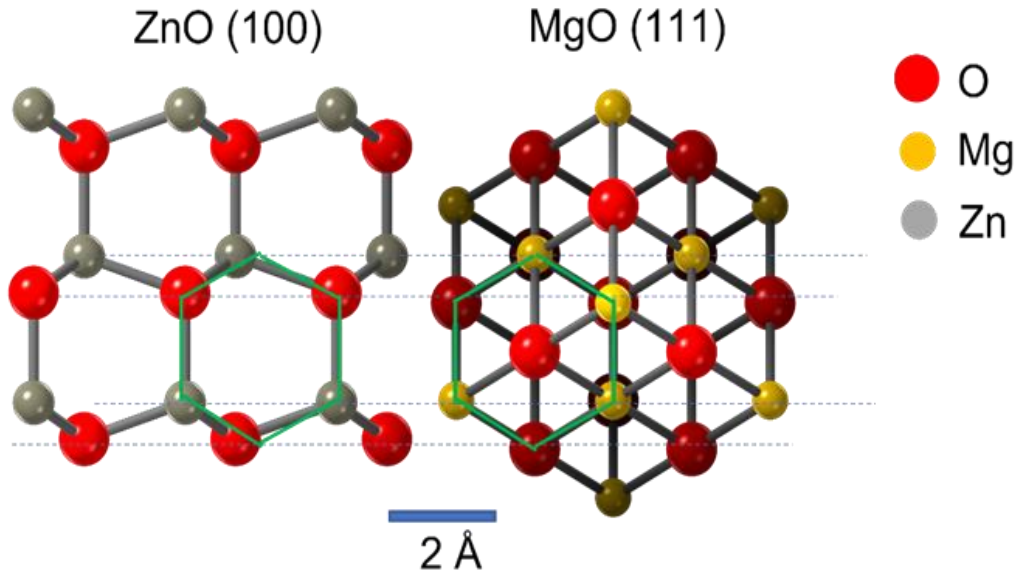


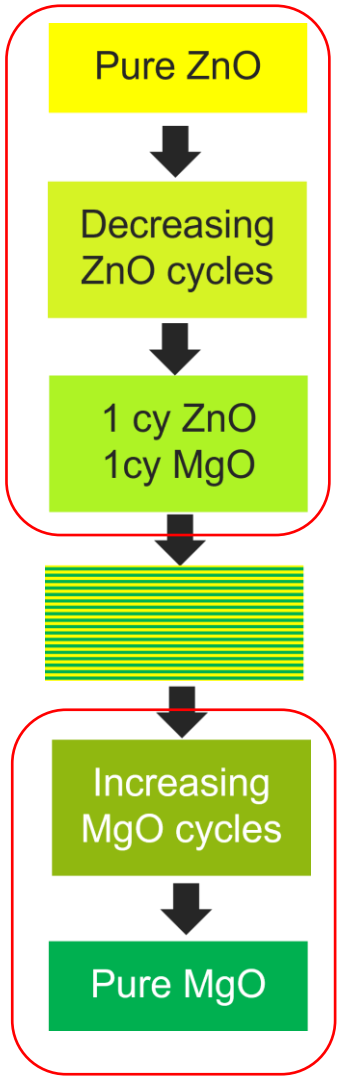


- In ZnO rich film multilayer crystallinity is ZnO hex. Wurtzite
- In MgO rich film dominated by the cubic.
- Abrupt crystalline transition from MgO to ZnO rich films.
- As mix goes to 50% MgO - 50% ZnO, MgO -> (200) to (111) and ZnO (002) to (100)
- MgO and ZnO adapt to each other.

Structural evolution – series 1

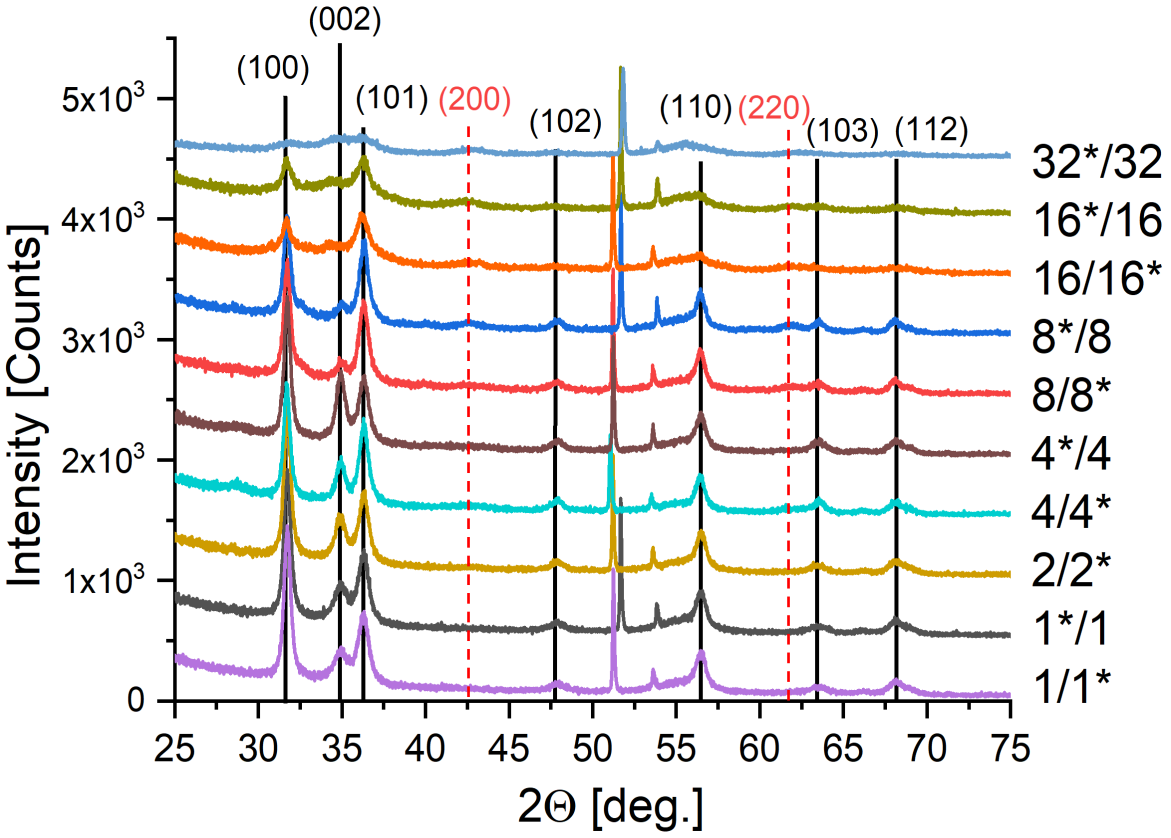


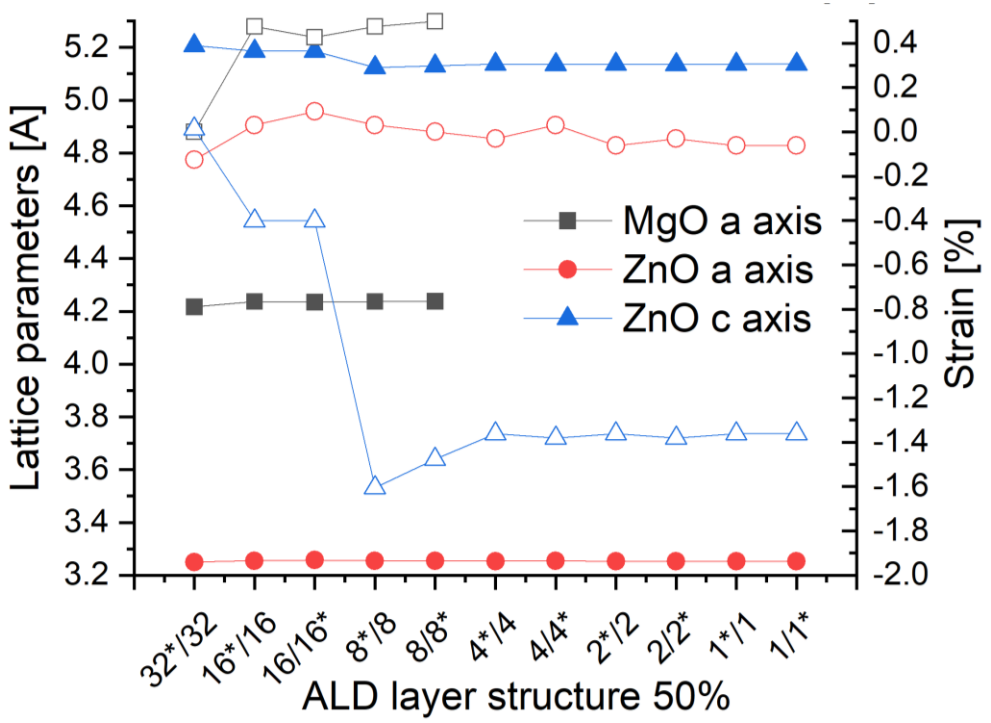


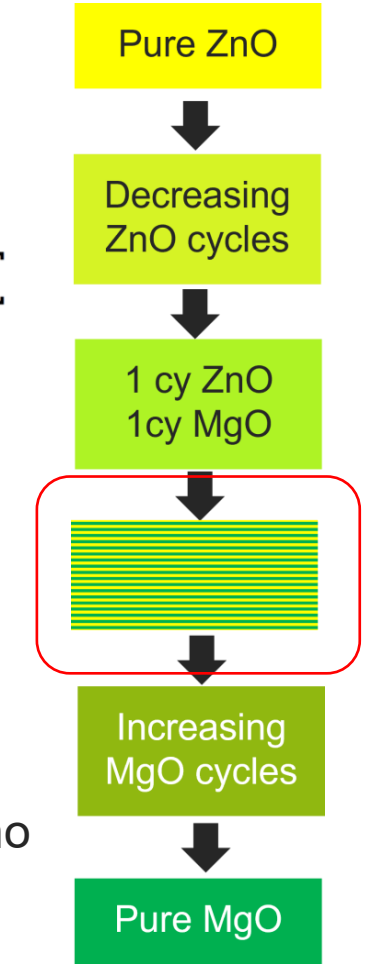


- In ZnO rich film multilayer crystallinity is ZnO hex. Wurtzite
- In MgO rich film dominated by the cubic.
- As mix goes to 50% MgO - 50% ZnO, MgO -> (200) to (111) and ZnO (002) to (100)
- Cubic MgO -> hex 111 sym but the ZnO can only adapt it lattice parameters to match MgO.

Structural evolution – series 2

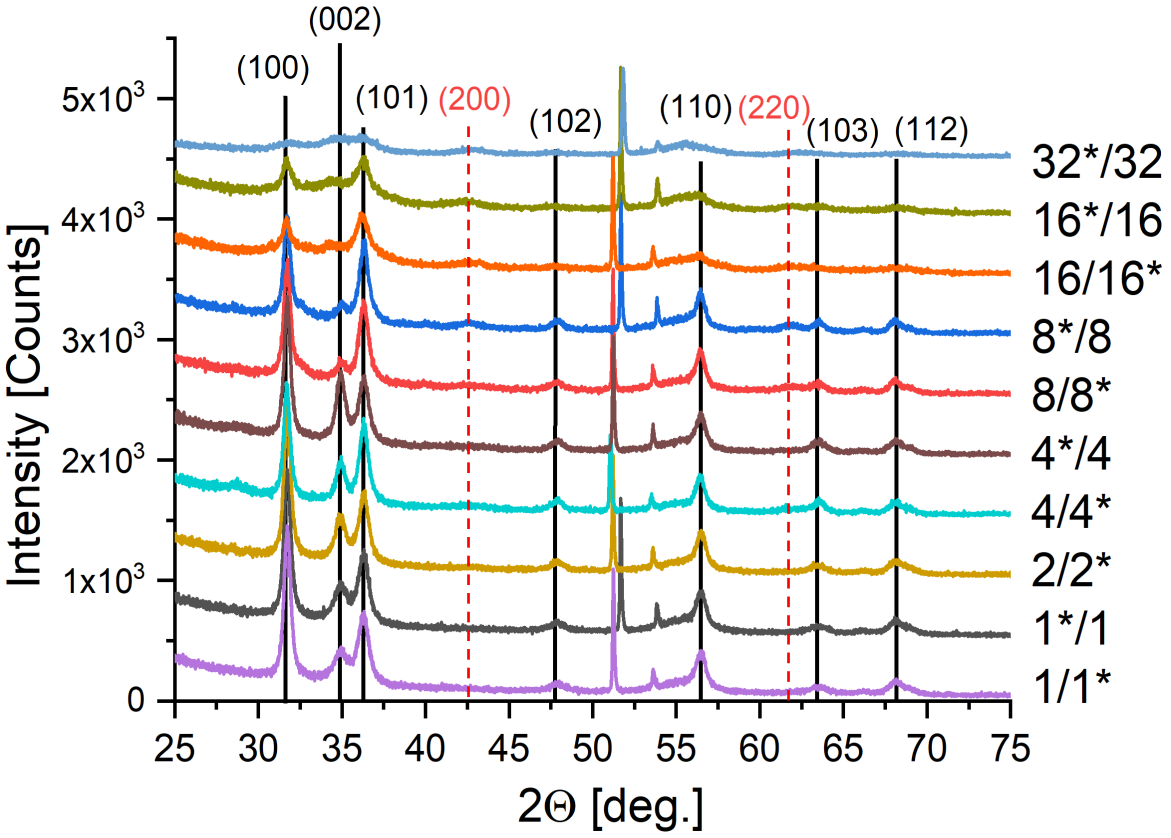


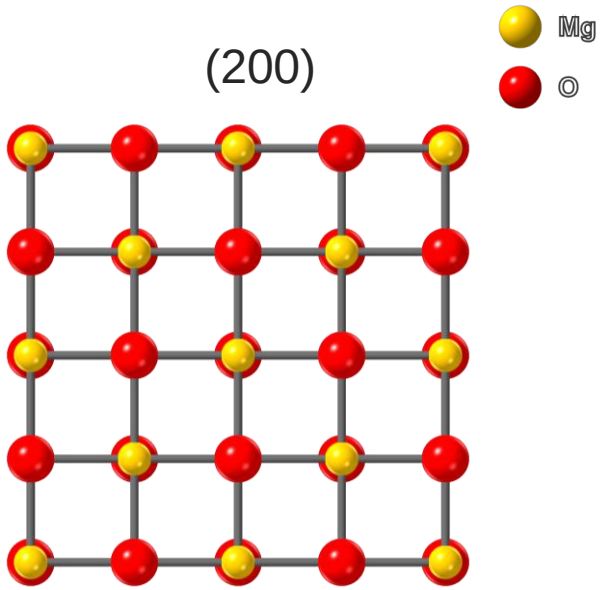


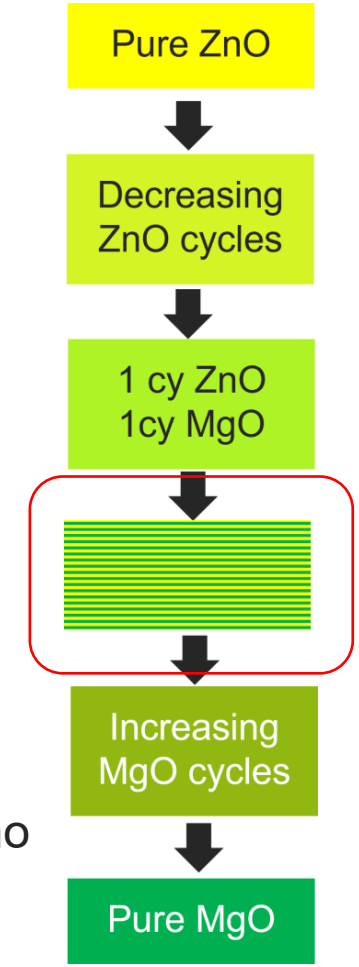


- As layer thicknesses increase -> MgO tends towards in pur form (200) and ZnO wants to but…no
- ZnO in losing crystallinity: (200) is incompatible with any ZnO hex direction.
- Strong strain relaxation of the ZnO c axis.

Structural evolution – series 2

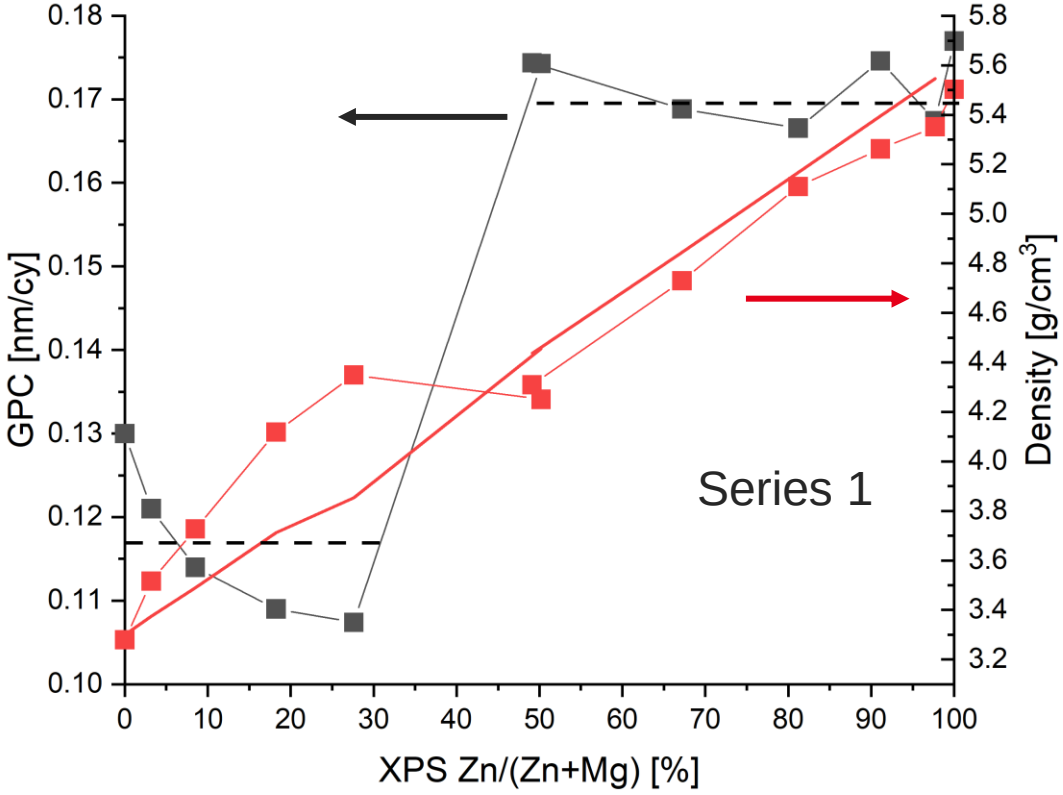


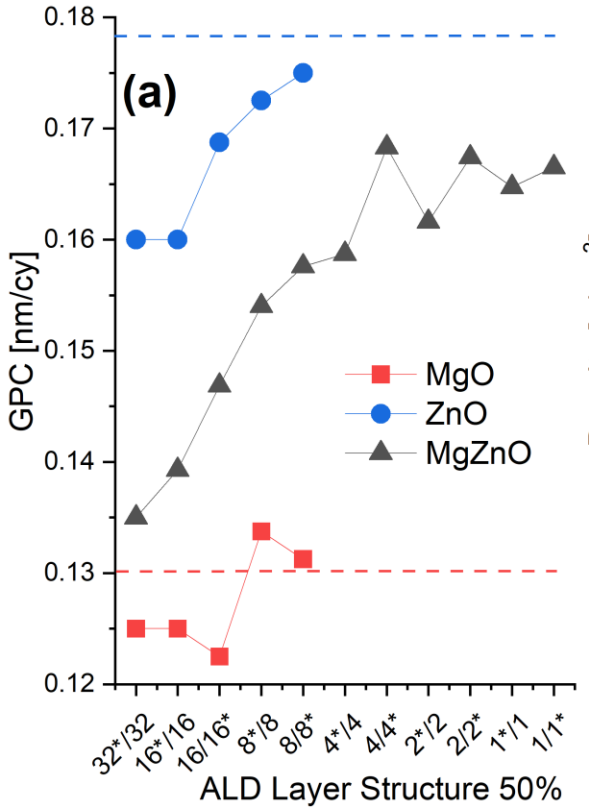


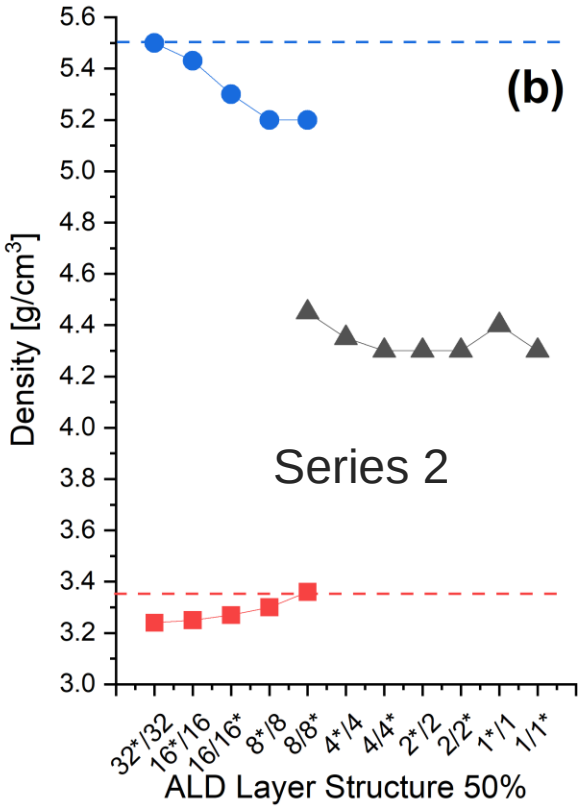


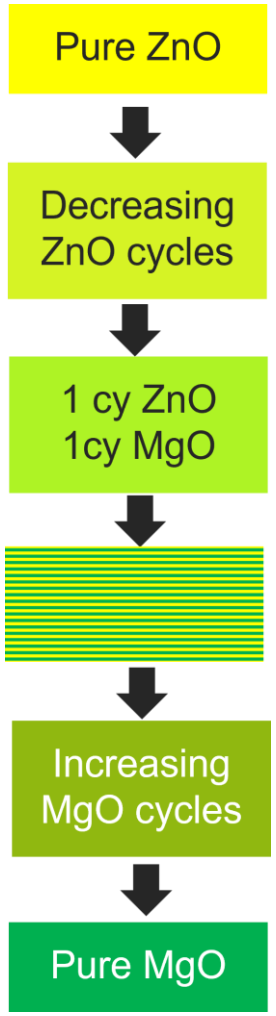
- As layer thicknesses increase -> MgO tends towards in pur form (200) and ZnO wants to but…no
- ZnO in losing crystallinity: (200) is incompatible with any ZnO hex direction.
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Structure influence growth



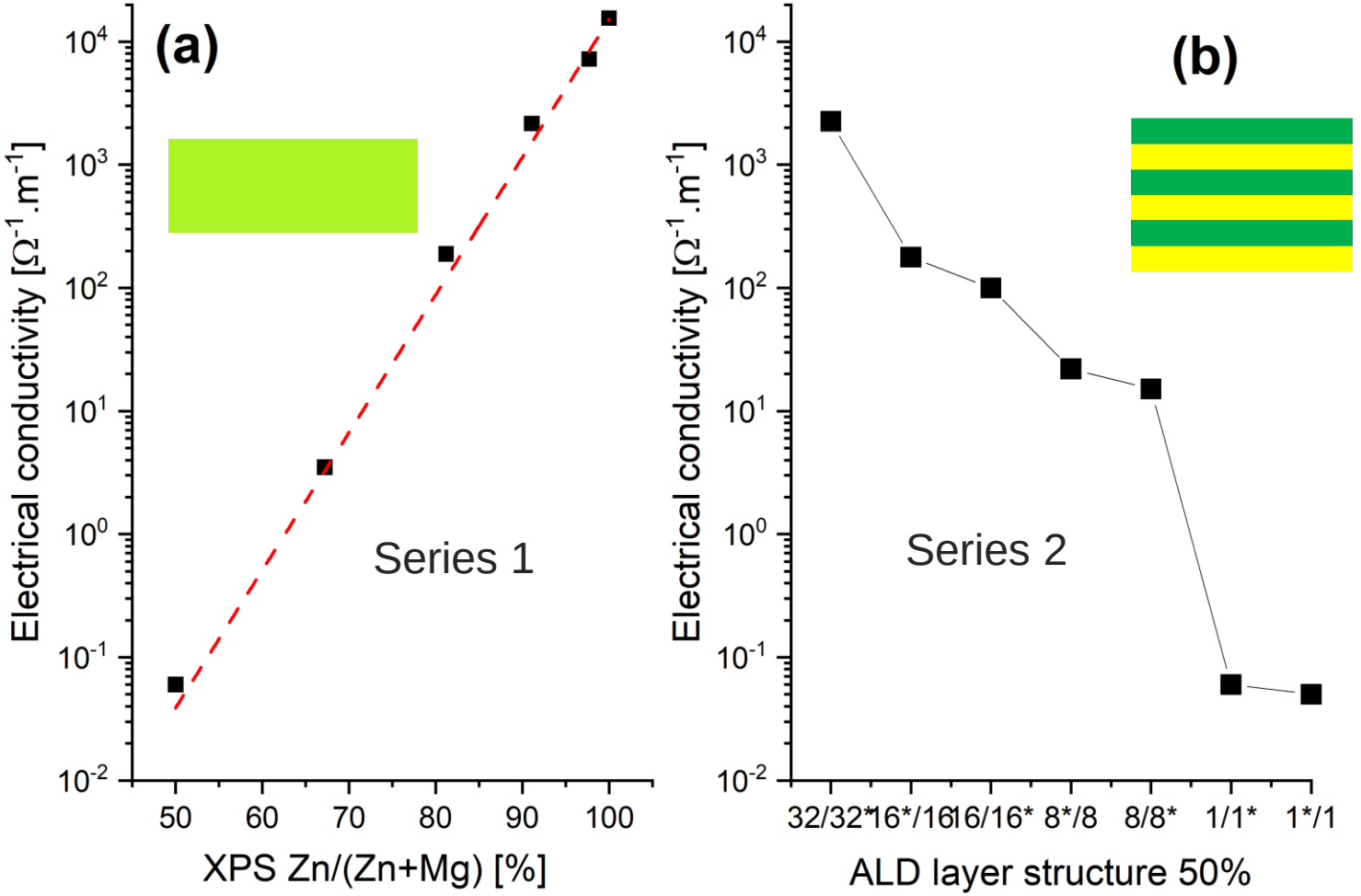


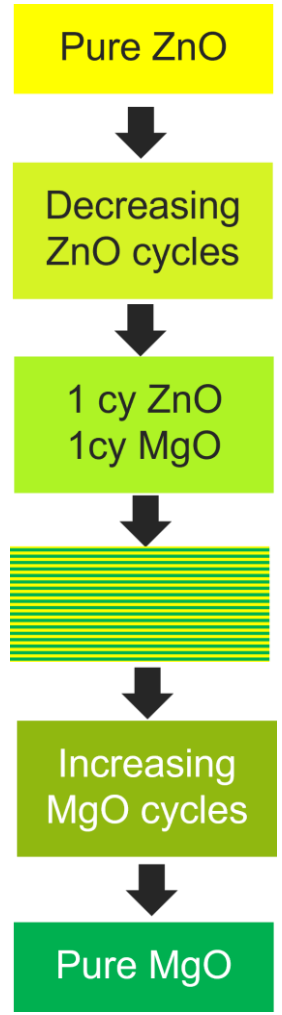




- Find this binary transition between MgO rich and ZnO rich films.
- Affects growth rate and density: As the number of atom per cycle is constant : density x GPC = 40±2 ng/cm^2 is cst. As MgO switch from (200) to (111) -> densest plan then GPC is decreasing

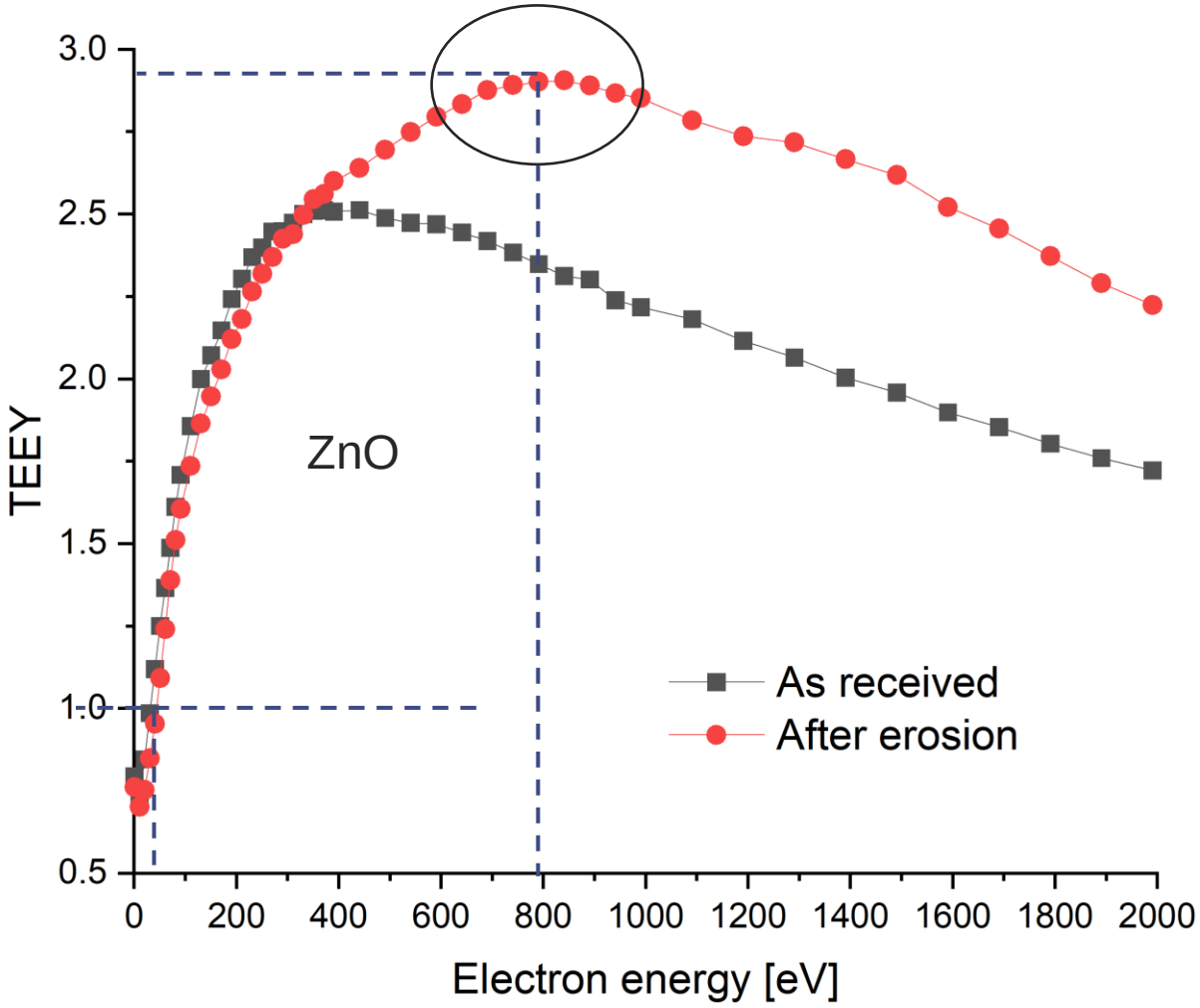
Electrical conductivity





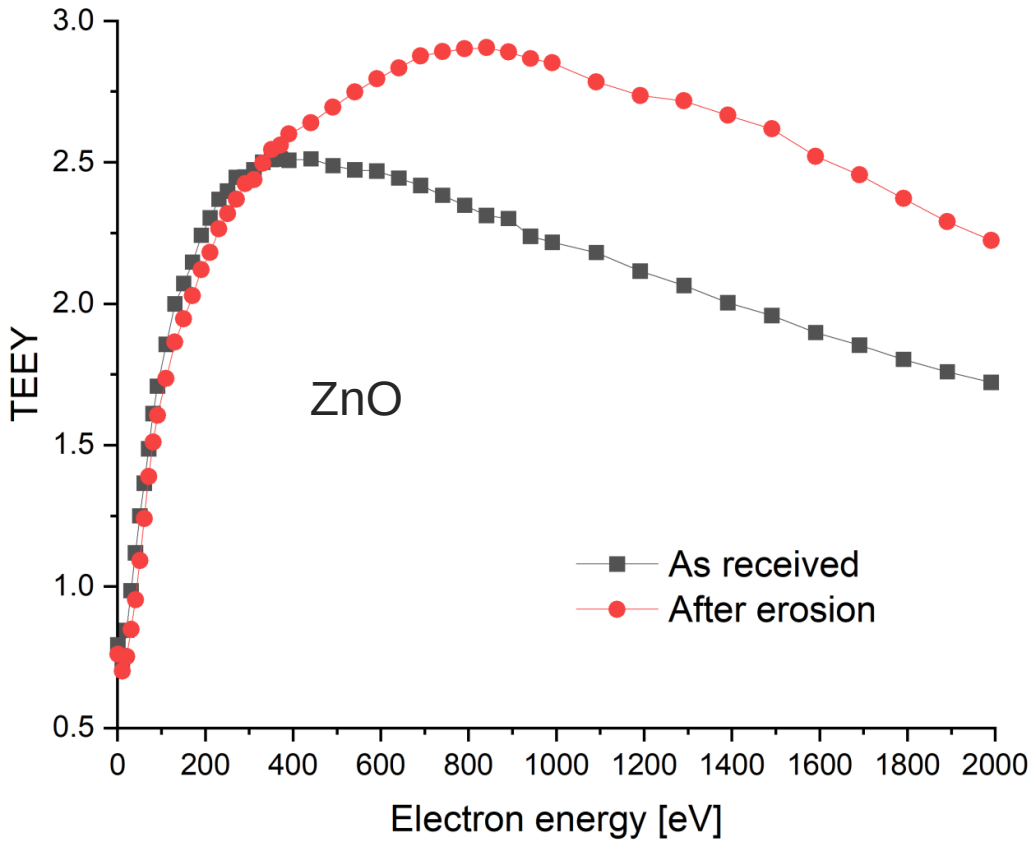
- Tuning the conductivity by controling chemical composition (series 1) and layered structure -> layer thickness (series 2) .

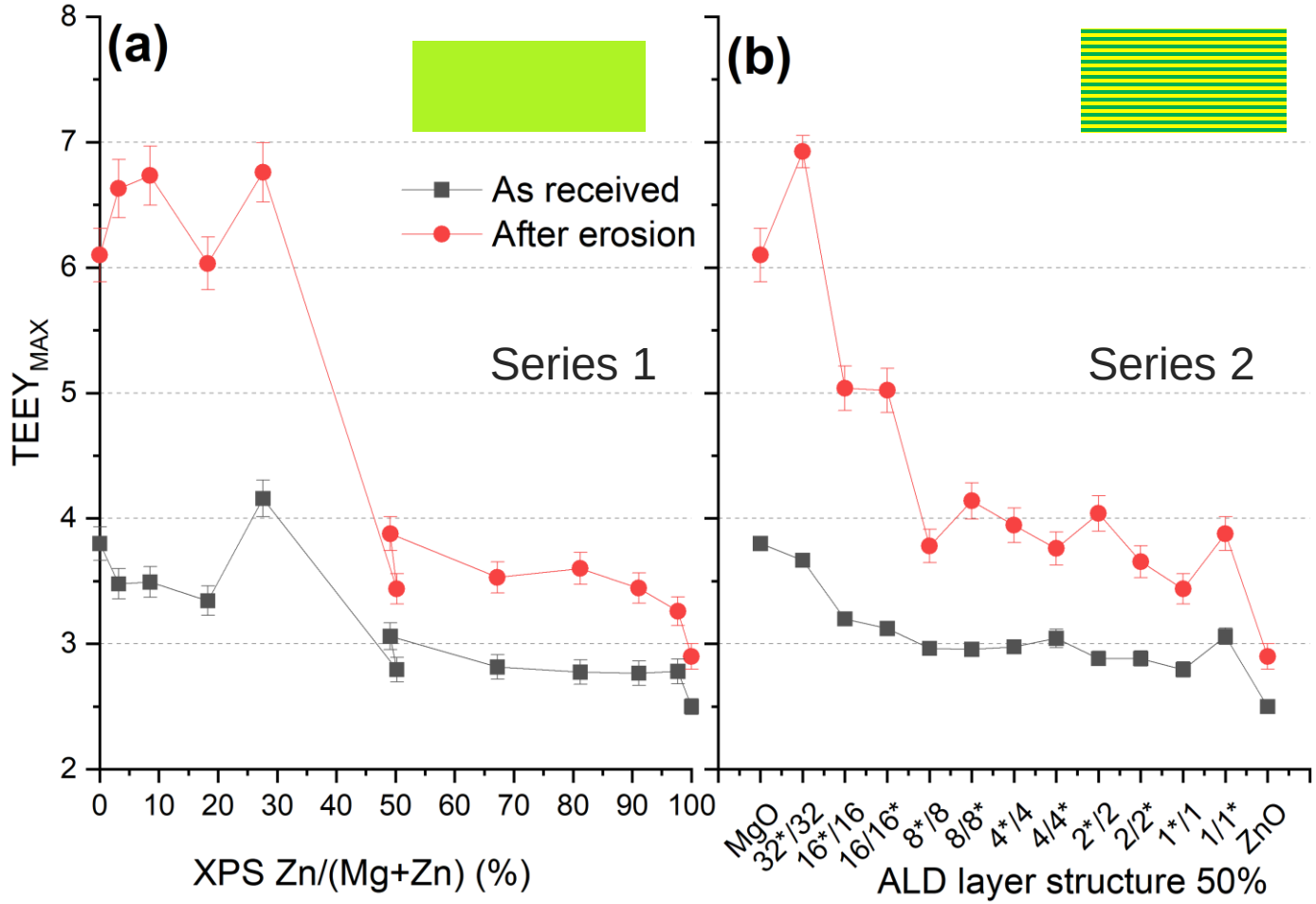
TEEY measurements



- Extract the maximum TEEY .
- Careful when measuring TEEY for Insulators:
  Charging induce artefacts.
- Light surface Ar+ insitu erosion to remove surface adventitious carbon that hinder instrinc TEEY properties.
- C contamination from 15-25% to 1-4%

TEEY measurements

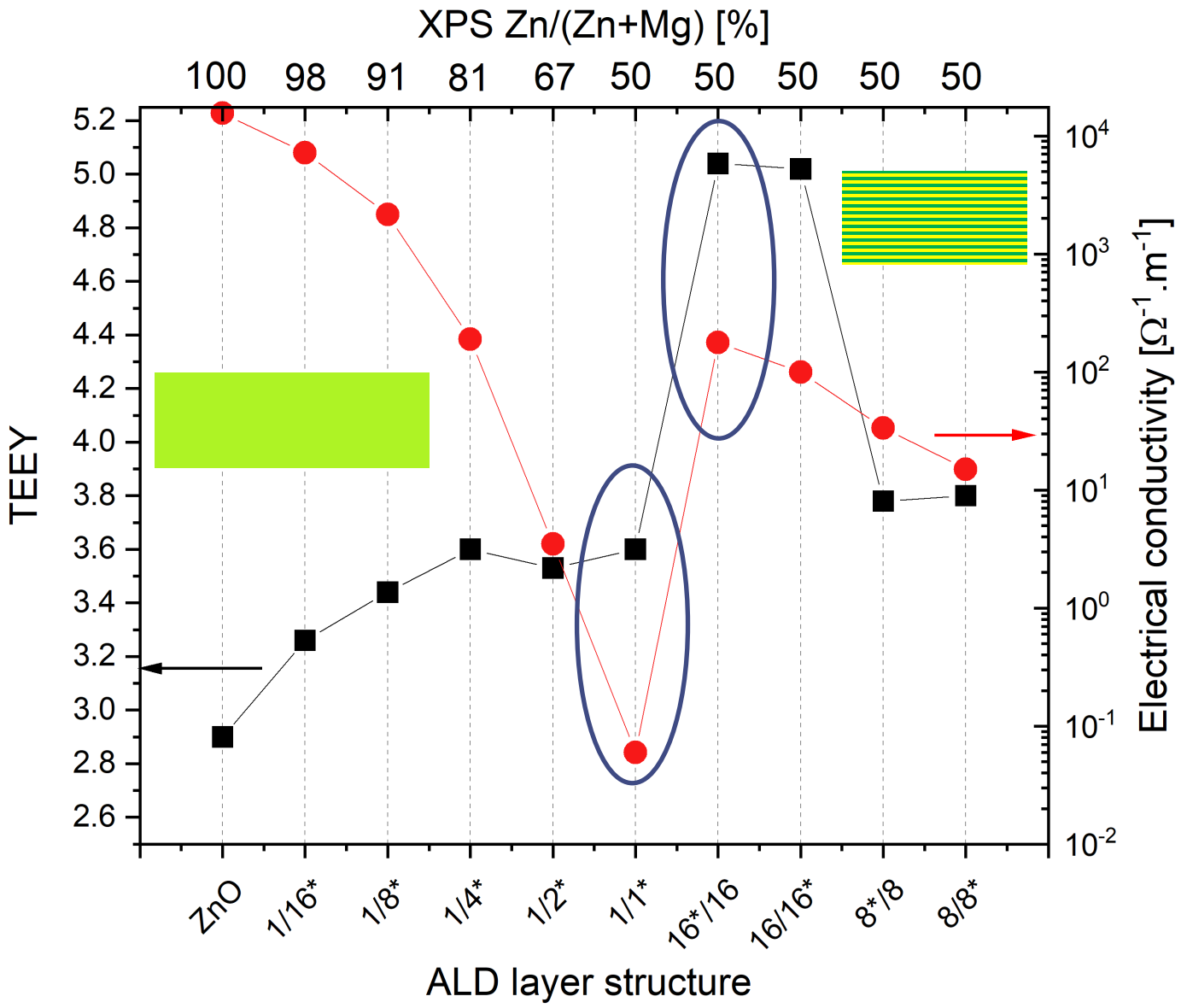




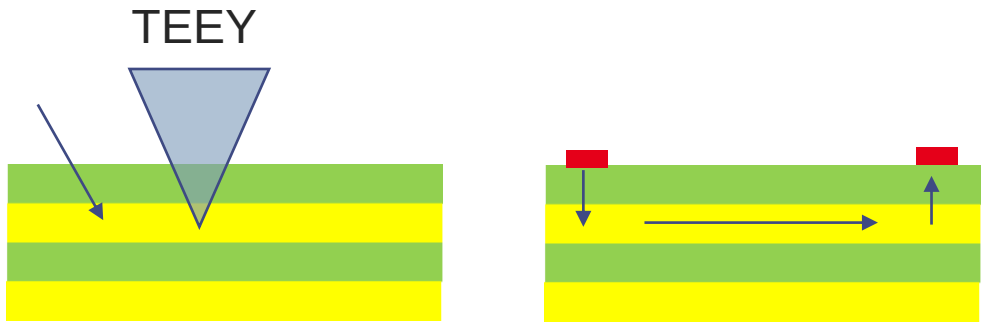
- ❑ Find this binary transition between MgO rich and ZnO rich films.
- ❑ Tuning the TEEY by controling the chemical composition and structure.

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Tuning TEEY and resistivity: Composition control



- Depending on the micro and macrostructuration o the meta material we can obtain:
  - TEEY close to ZnO and conductivity 5 orders of magnitude lower than pur ZnO.
  - TEEY close to MgO and conductivity 10 orders of magnitude higher



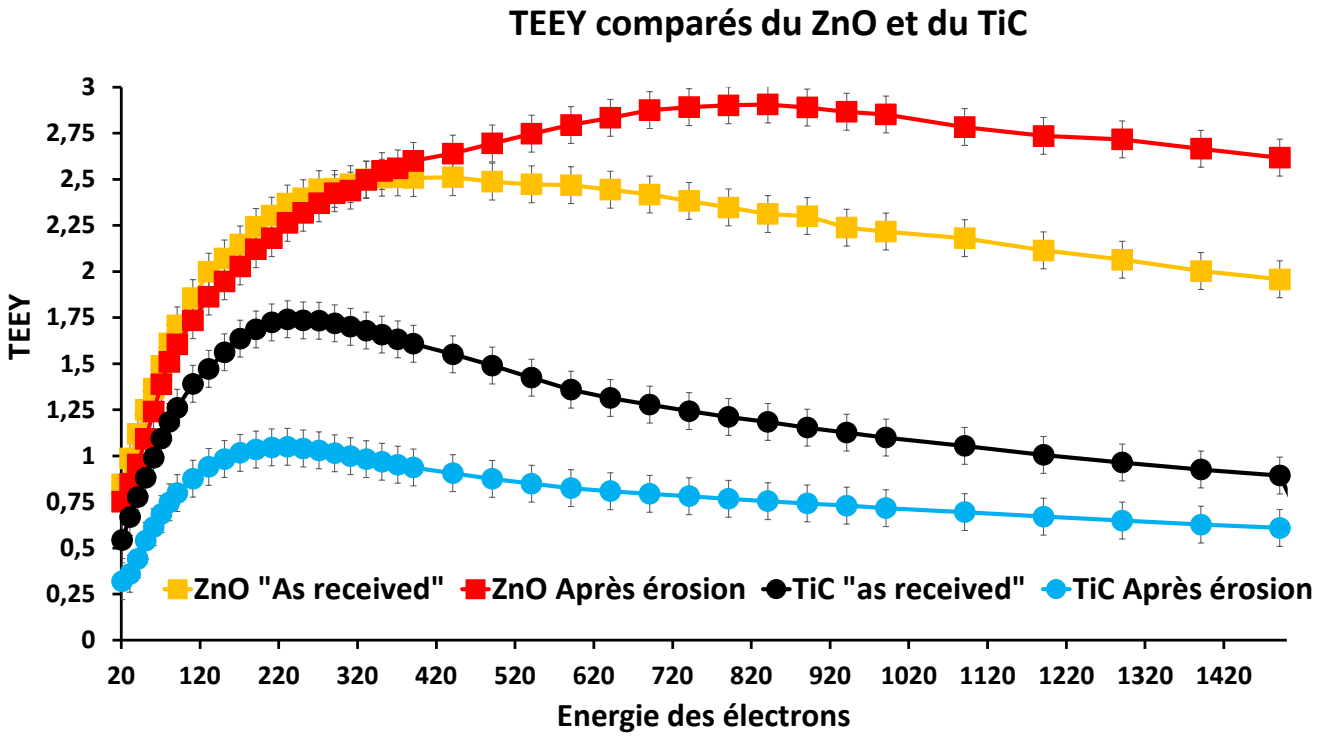
https://depozit.isae.fr/theses/2025/2025_Lafarie_Mathieu.pdf
Article: Arxiv.

Conclusion - perspectives

- Demonstrated chemical and structural control by ALD.
- Their interplay and influence of growth and electrical properties.
- One step further with multilayers:

  Obtain combinaison of TEEY and conductivities not reachable in pure forms.
- Interplay bewteen the sample structural anisotropy and the phenomenon probed -> bidimensionality.
- Other materials: Carbides TiC (– MgF_2) : towards a control of E_{C1} for RF filters.

Perspectives : un nouveau couple prometteur, TiC / MgF_2

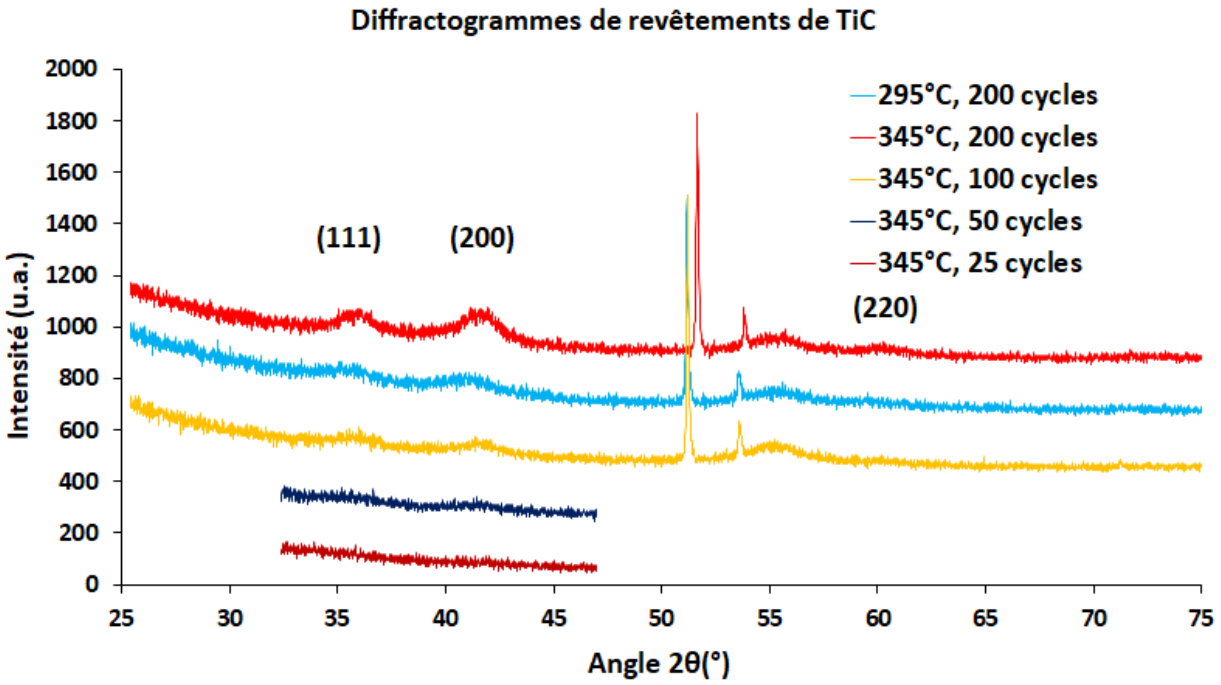


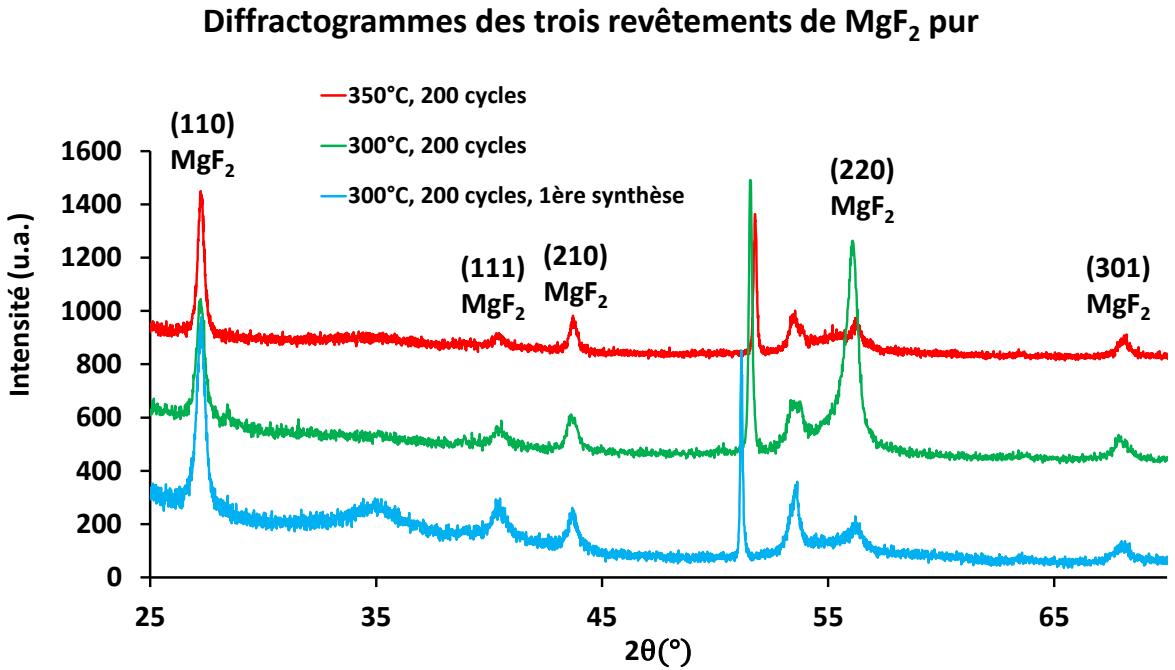
	ZnO « As received »	ZnO après érosion	TiC « As received »	TiC après érosion
E_{C1} (eV)	33	45	62,5	162
$TEEY_{max}$	2,5	2,9	1,7	1,05

- **TiC :**
  - Low TEEY = 1.05
  - High E_{C1}
  - High electrical Conductivity (5 x ZnO)
- **MgF_2 :**
  - TEEY and conductivity close to MgO
- Grow crystalline and on each other (Tretragonal – cubic system).

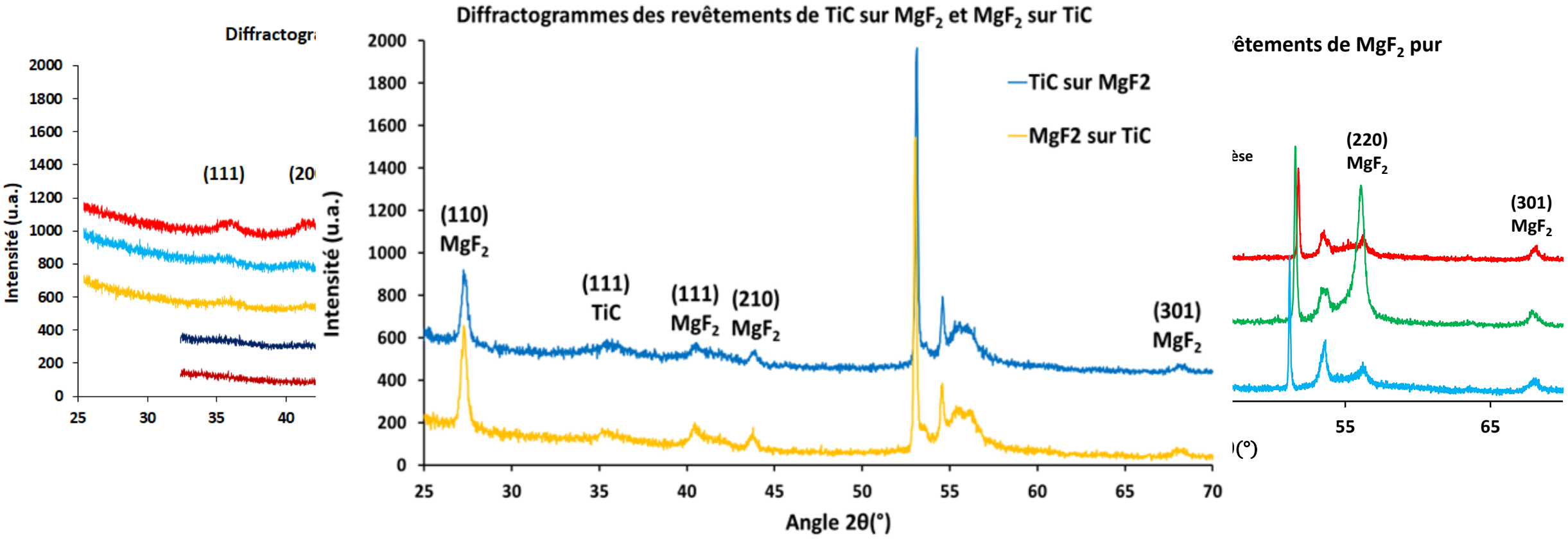
Promissing couple for multilayer approach.

TiC / MgF_2


Diffractogrammes de revêtements de TiC
Intensité (u.a.)
Angle 2θ(°)
295°C, 200 cycles
345°C, 200 cycles
345°C, 100 cycles
345°C, 50 cycles
345°C, 25 cycles
(111)
(200)
(220)


Diffractogrammes des trois revêtements de MgF2 pur
Intensité (u.a.)
2θ(°)
350°C, 200 cycles
300°C, 200 cycles
300°C, 200 cycles, 1ère synthèse
(110) MgF2
(111) MgF2
(210) MgF2
(220) MgF2
(301) MgF2

TiC / MgF_2


Diffractogr
Intensité (u.a.)
(111)
(20
Diffractogrammes des revêtements de TiC sur MgF2 et MgF2 sur TiC
Intensité (u.a.)
TiC sur MgF2
MgF2 sur TiC
(110) MgF2
(111) TiC
(111) MgF2
(210) MgF2
(301) MgF2
Angle 2θ(°)
êtements de MgF2 pur
èse
(220) MgF2
(301) MgF2
(°)

Thank you

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Atomic Layer Deposition

Thin film synthesis technique. **Self-limiting** chemical surface reactions between two or more precursors in the **vapor phase** introduced sequentially. Deposition in a molecular layer fashion.

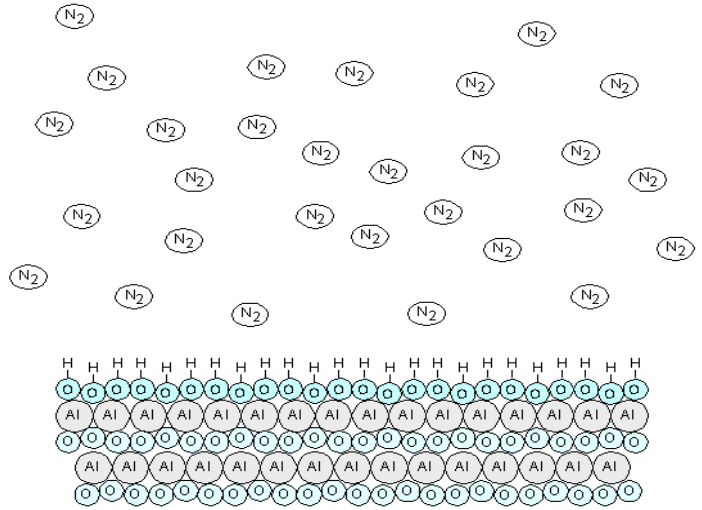
$Al_2O_3 = TMA(Al(CH3)_3) + H_2O$

Advantages:

- Control of chemical composition and thickness at the atomic level
- Intermixing of different alloys.
- Films smooth and pin hole free
- Excellent conformality on arbitrary complex structures.
- Large palette materials available
- Low temperature.

Limits:

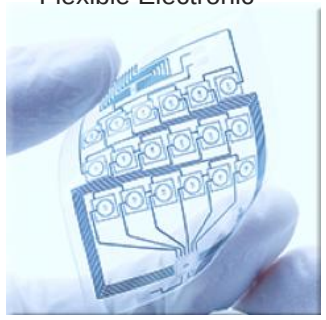
- Slow Deposition (~ 0,2 - 1 nm/min)
- New materials require new chemistries.



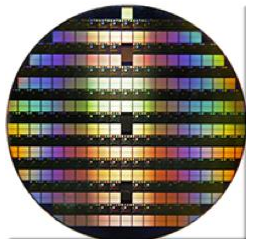
Applications:

- Micro-electronic, Biomedical, Batteries, Catalysis…
- Detectors.
- Photovoltaïc.
- Diffusion barriers/corrosion.
- Superconducting Qubits

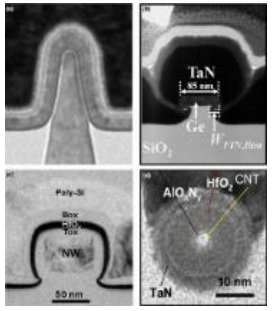
Flexible Electronic



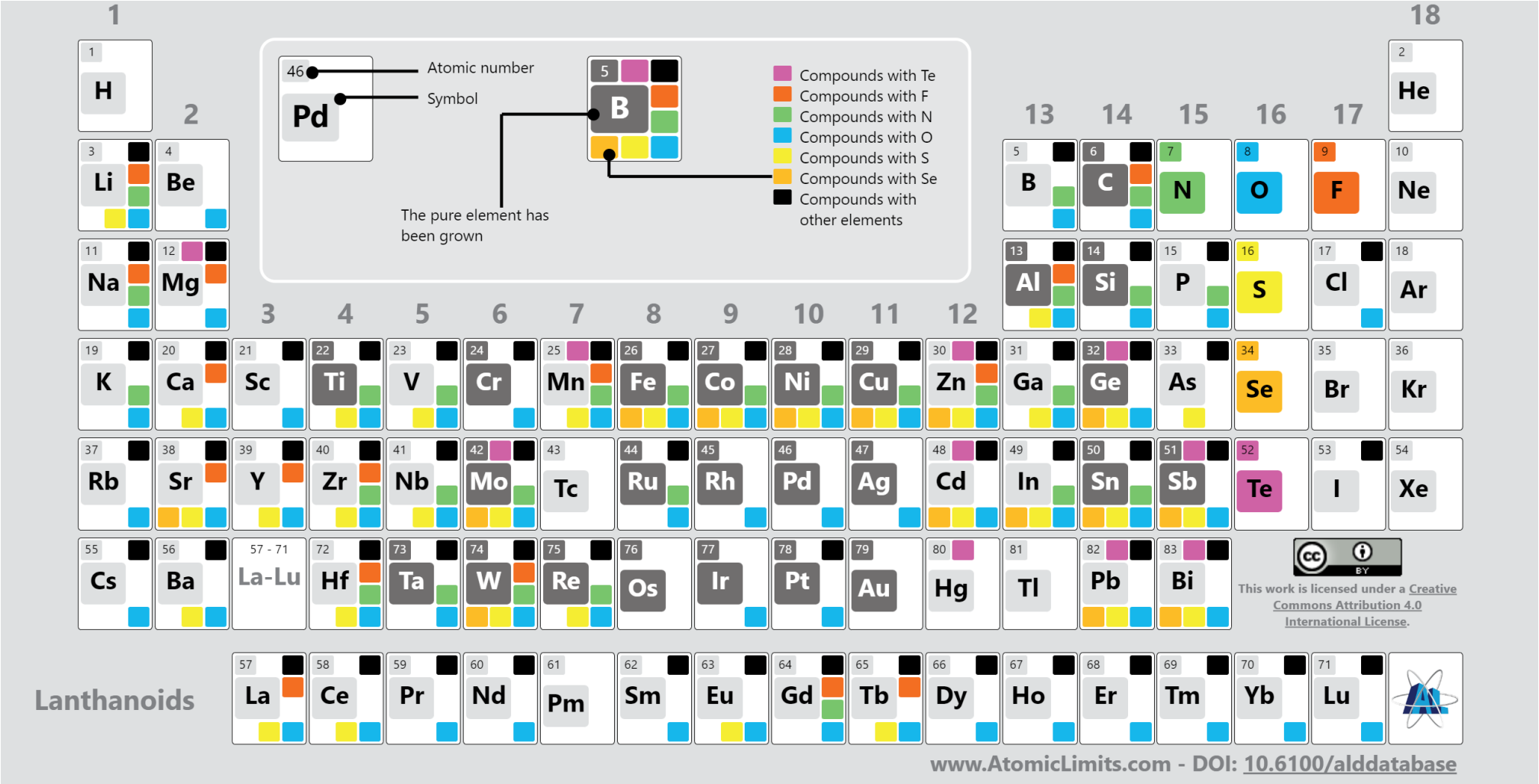
Microelectronic



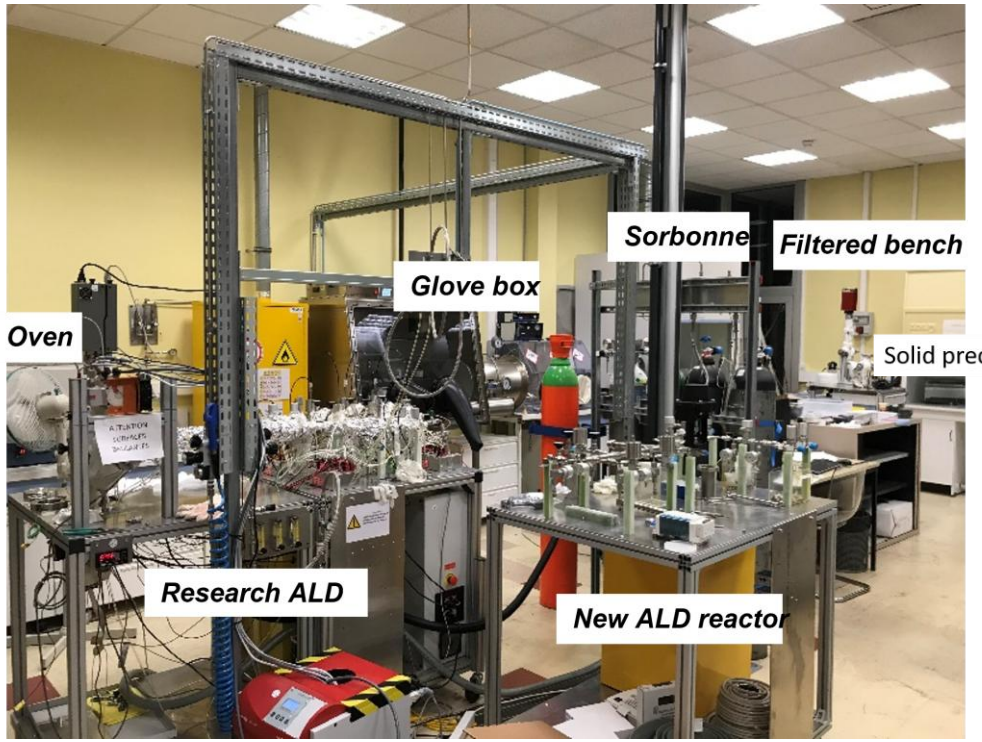
Electronic-nanotubes

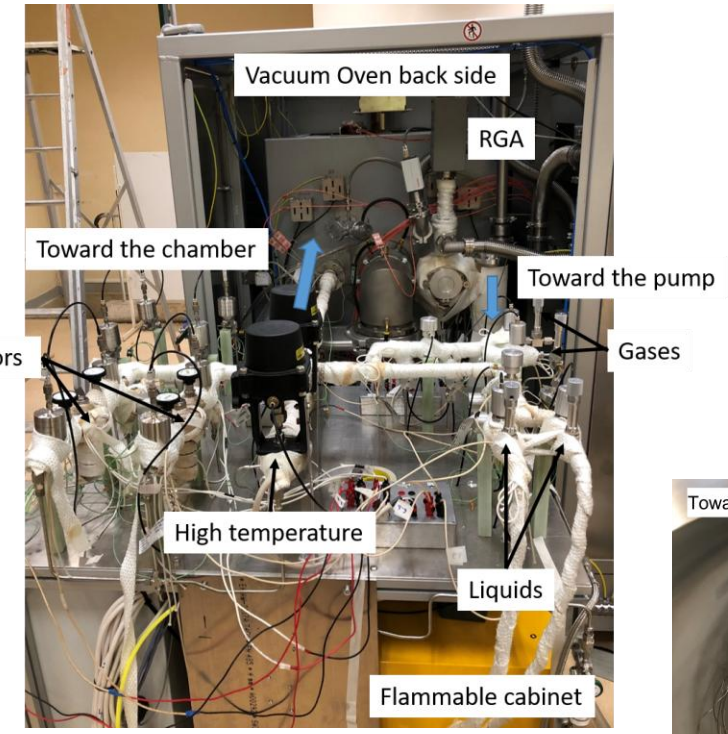


Atomic Layer deposition

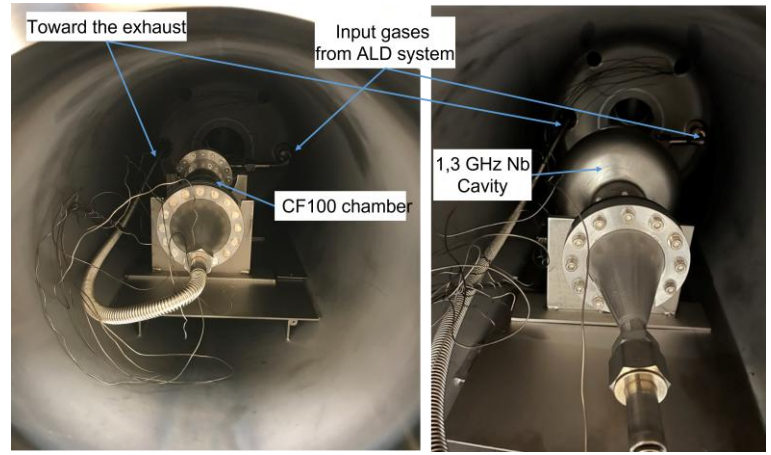


ALD lab at CEA









Two ALD apparatus:

- A research scale for prospection (new chemistries, optimize processes…)
- A development scale for applications

Research themes: Particle accelerators, Qubits, filters, nuclear waste management…

Mesures de TEEY : focus sur ALCHIMIE

ONERA
THE FRENCH AEROSPACE LAB

