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LABORATORY HAXPES OF GAN STRUCTURES FOR POWER ELECTRONICS

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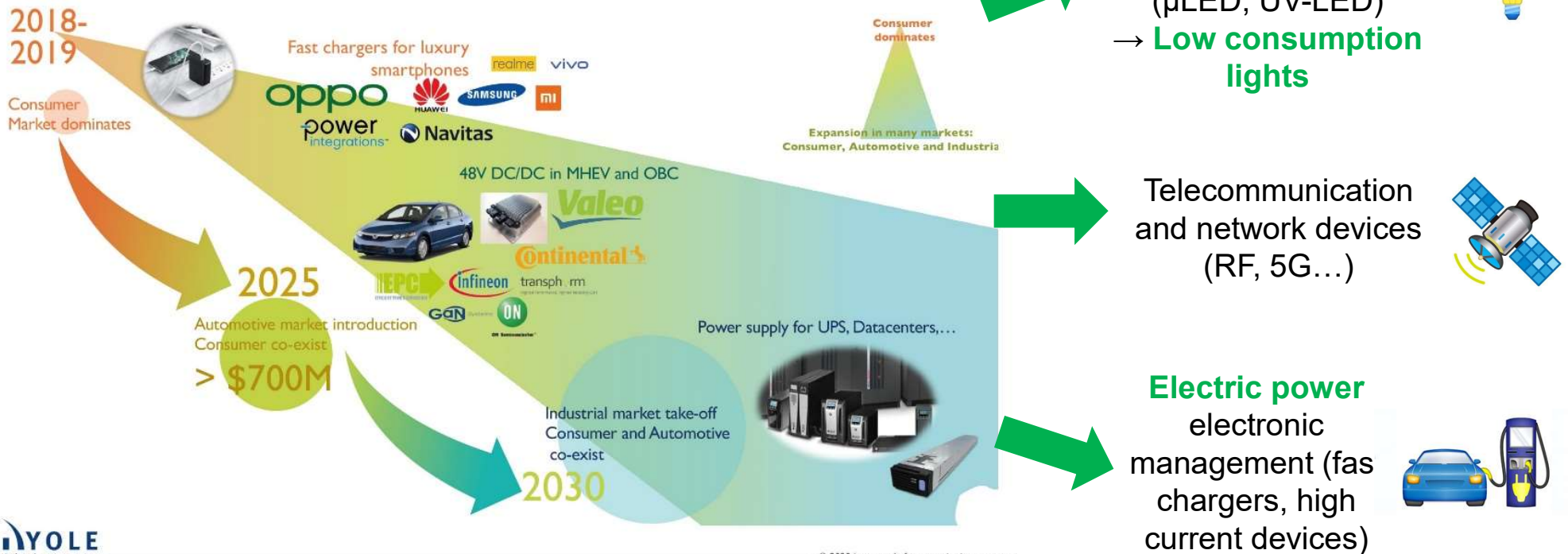
²Univ. Grenoble Alpes, CNRS, LTM, 38000 Grenoble, France



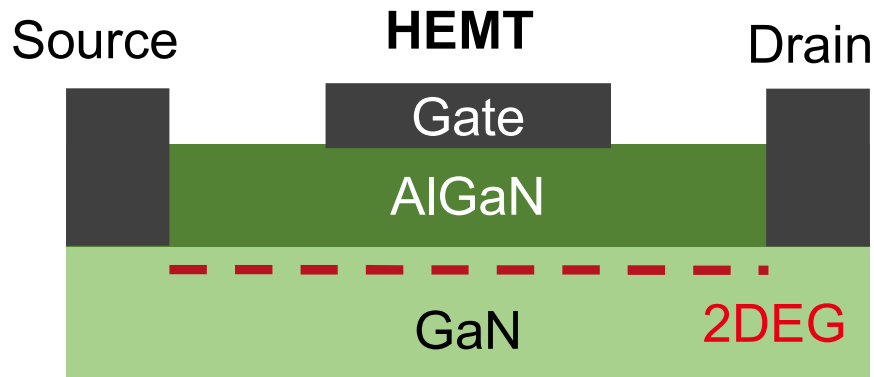
NEW TECHNOLOGY FOR THE FUTURE

Power GaN - Entering: a new era

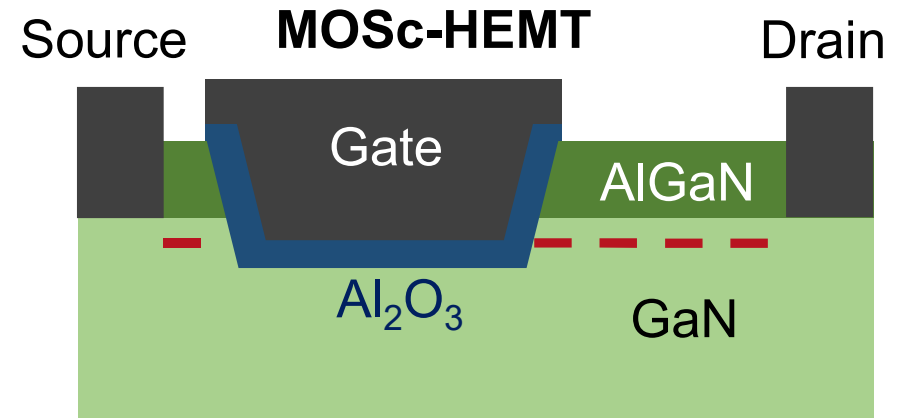
(Source: Power GaN: Epitaxy, Devices, Applications & Technology Trends report, Yole Développement? 2019)



HIGH ELECTRON MOBILITY TRANSISTOR (HEMT)



- Maximum voltage (~ 650V)
- Low energy loss at ON-state = **Low R_{ON}**
- OFF-state = negative V_{Gate} → **Normally-On**



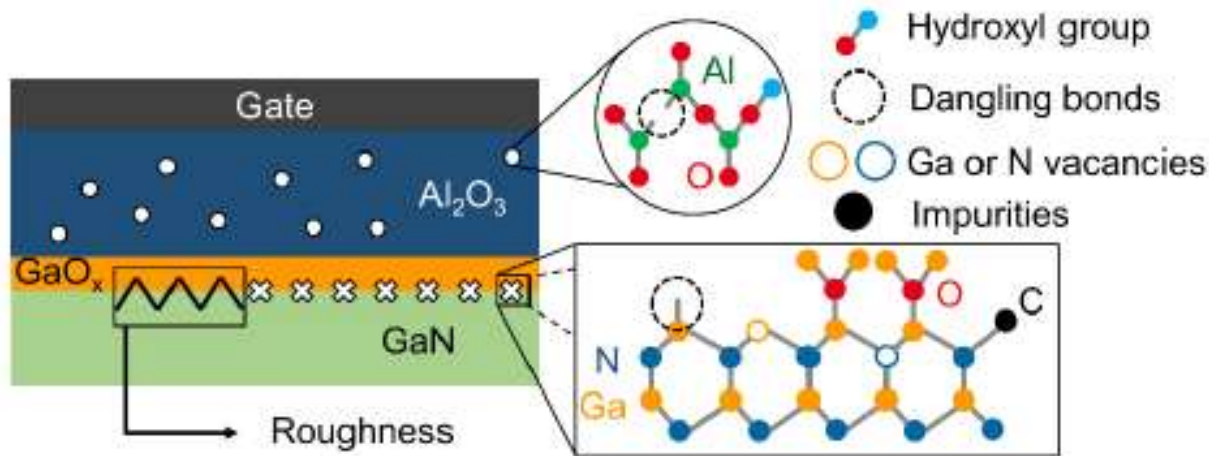
Normally-Off by depleting the 2DEG

→ **MOSc-HEMT**

- AlGaN etch = 2DEG depletion
- Dielectric deposition (e.g. Al_2O_3)
- Metal deposition

✓ **Positive Threshold voltage (V_{TH})**

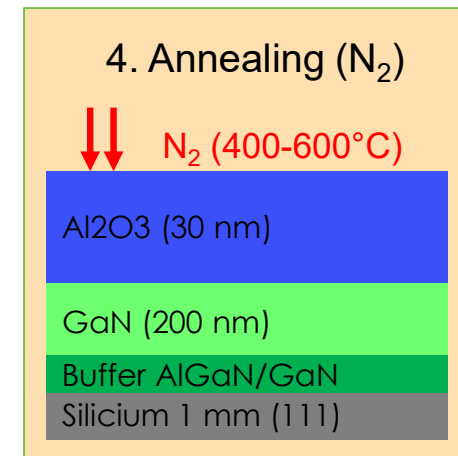
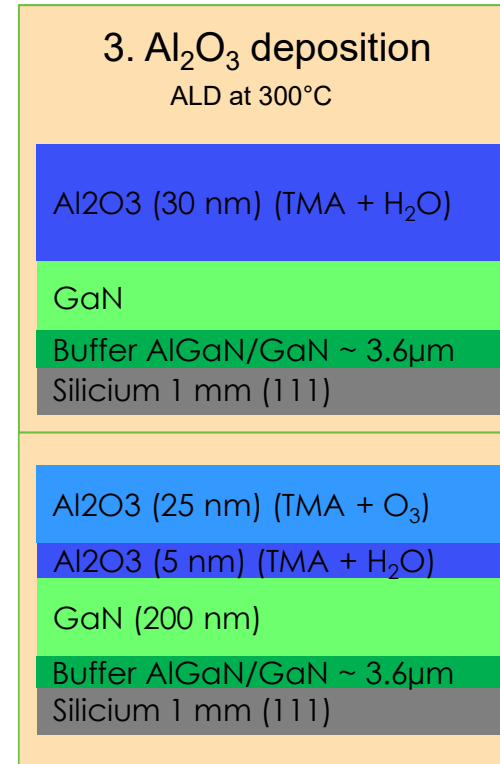
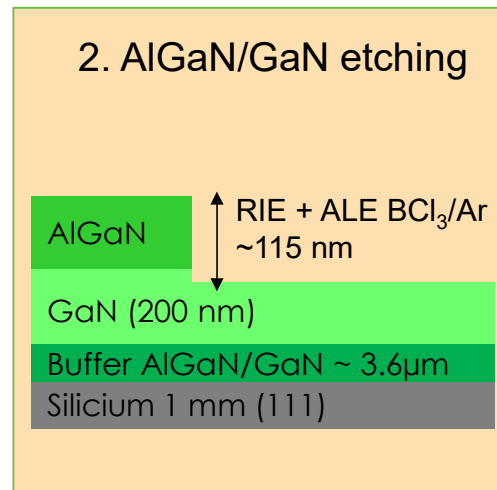
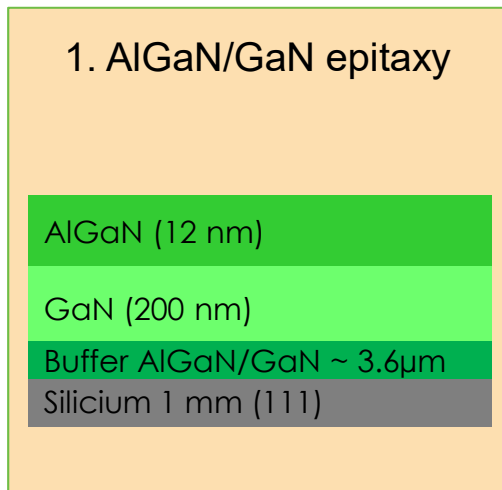
CRITICAL BURIED $\text{Al}_2\text{O}_3/\text{GaN}$ INTERFACE



- Ga oxydation $\Rightarrow \text{GaO}_x$
- Defects \Rightarrow dangling bonds, vacancies (Ga, N), impurities
- Roughness
- ✓ Impact on electrical properties (V_{TH} , ΔV_{TH} , R_{ON})

□ The $\text{Al}_2\text{O}_3/\text{GaN}$ interface quality needs to be improved for good transistors performances

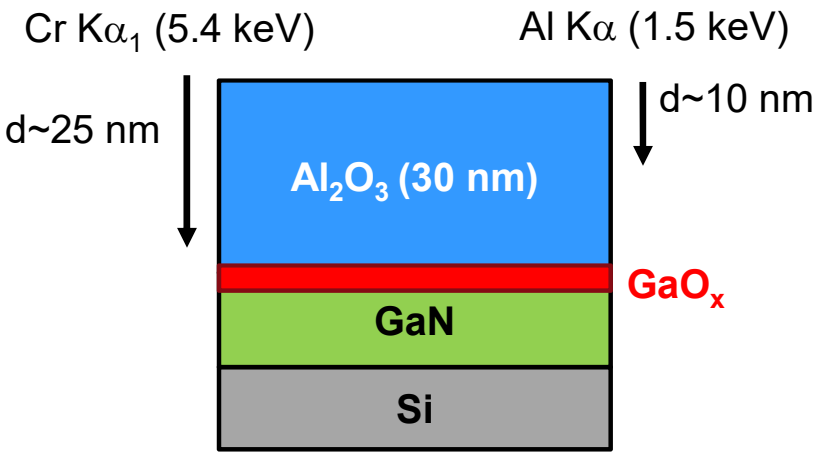
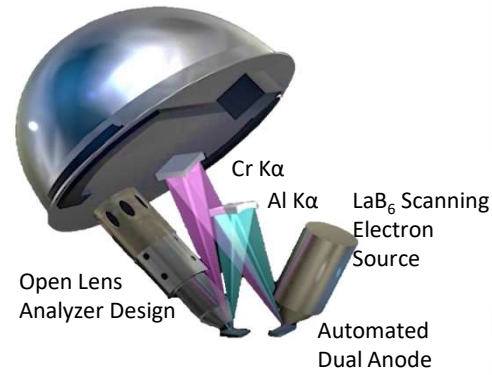
IMPACT OF PROCESS STEPS



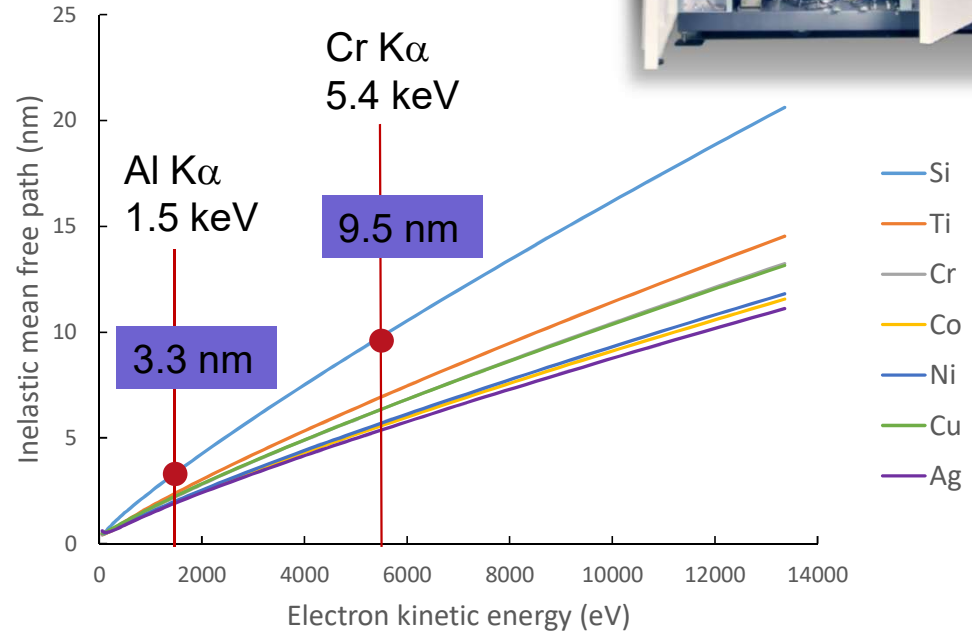
□ The AlGaIn etching, GaN cleaning, Al_2O_3 deposition and annealing must be optimized

LABORATORY HAXPES Cr K α

Dual confocal Al K α_1 & Cr K α_1 sources

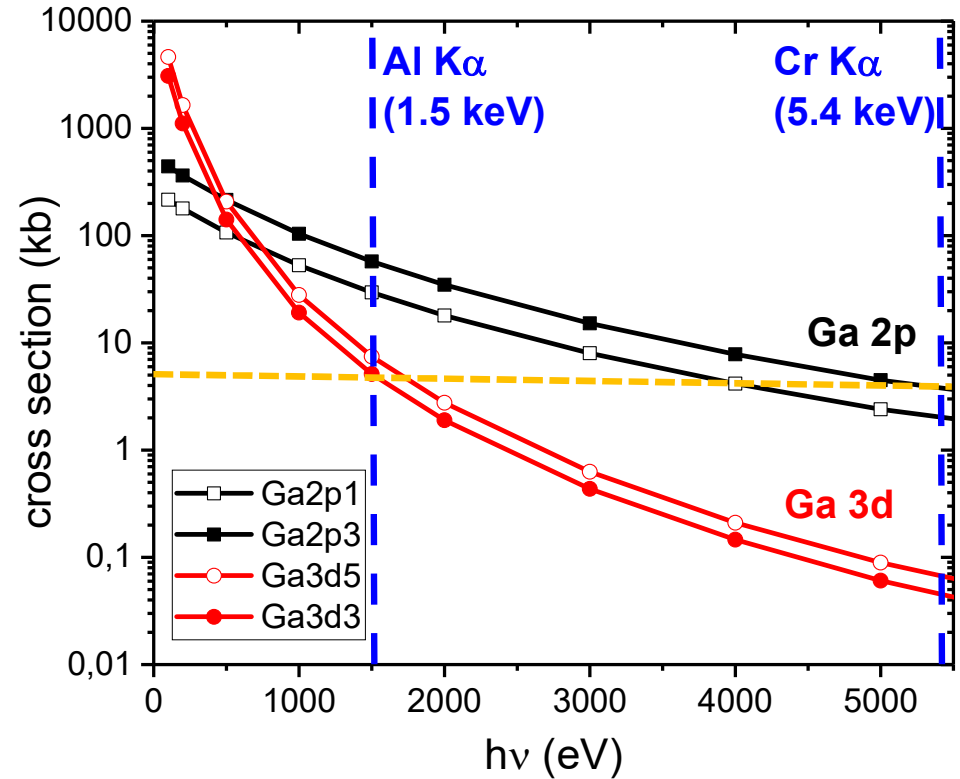
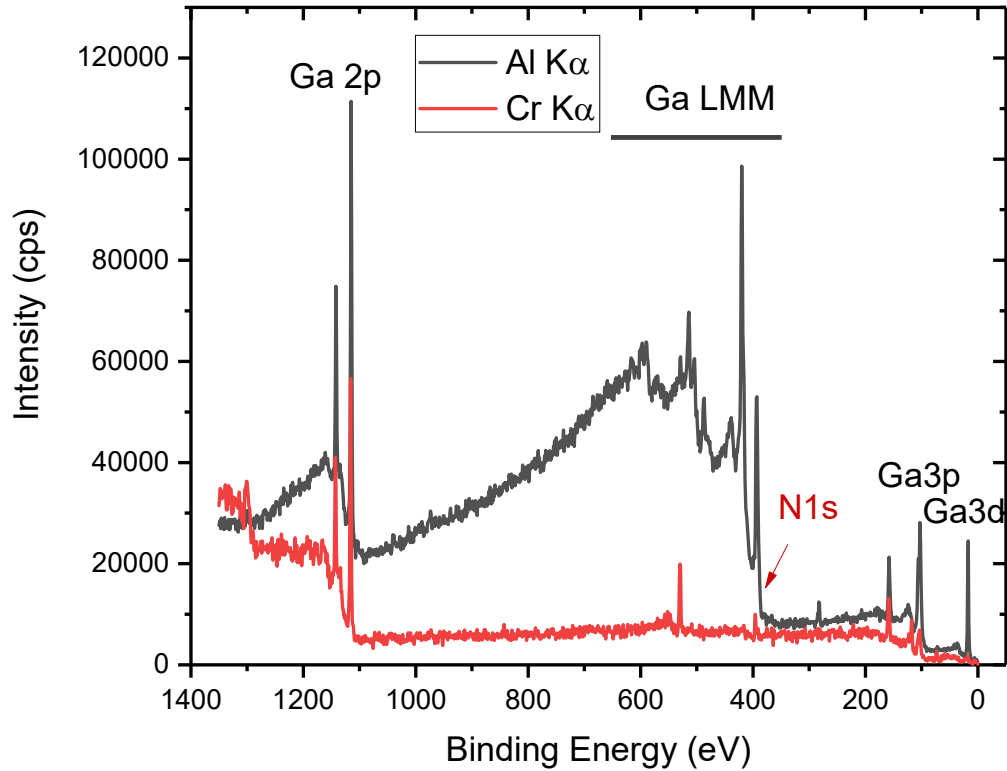


Analysis of buried interfaces



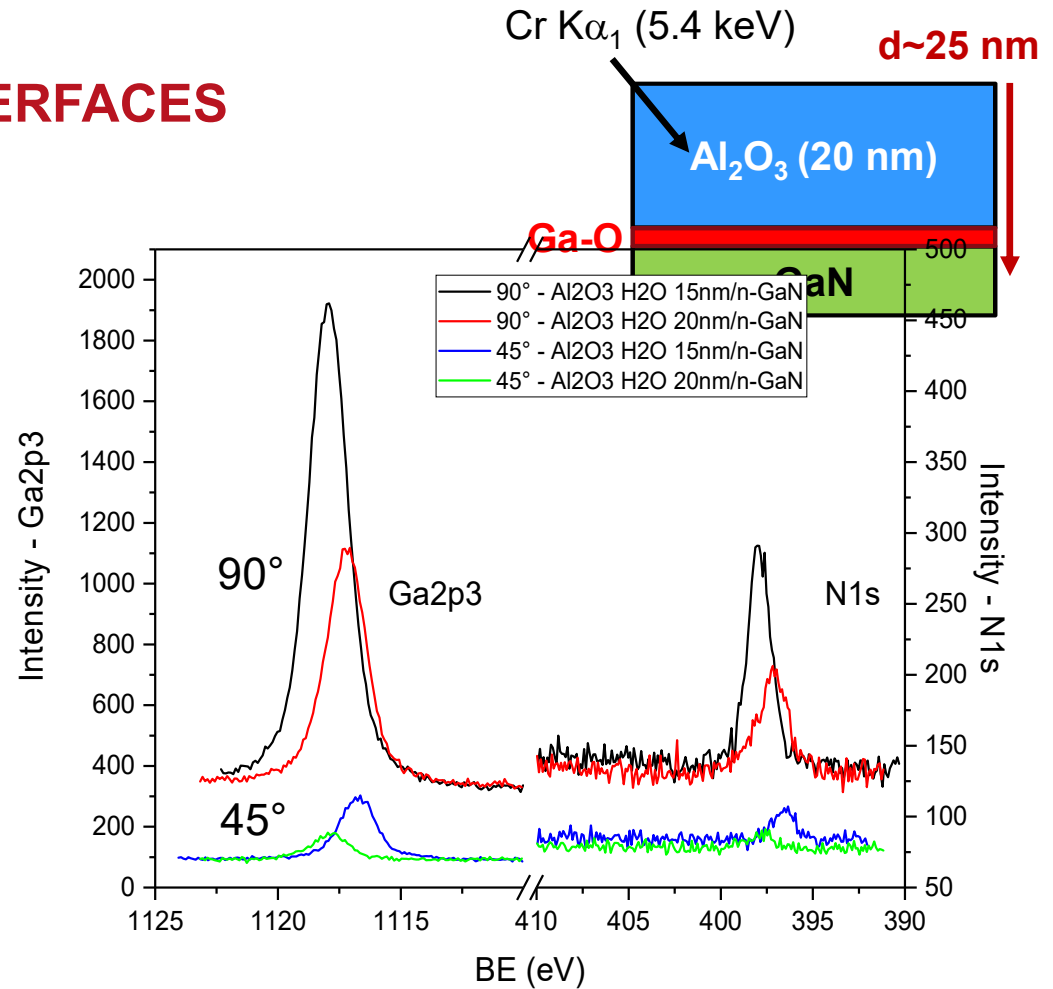
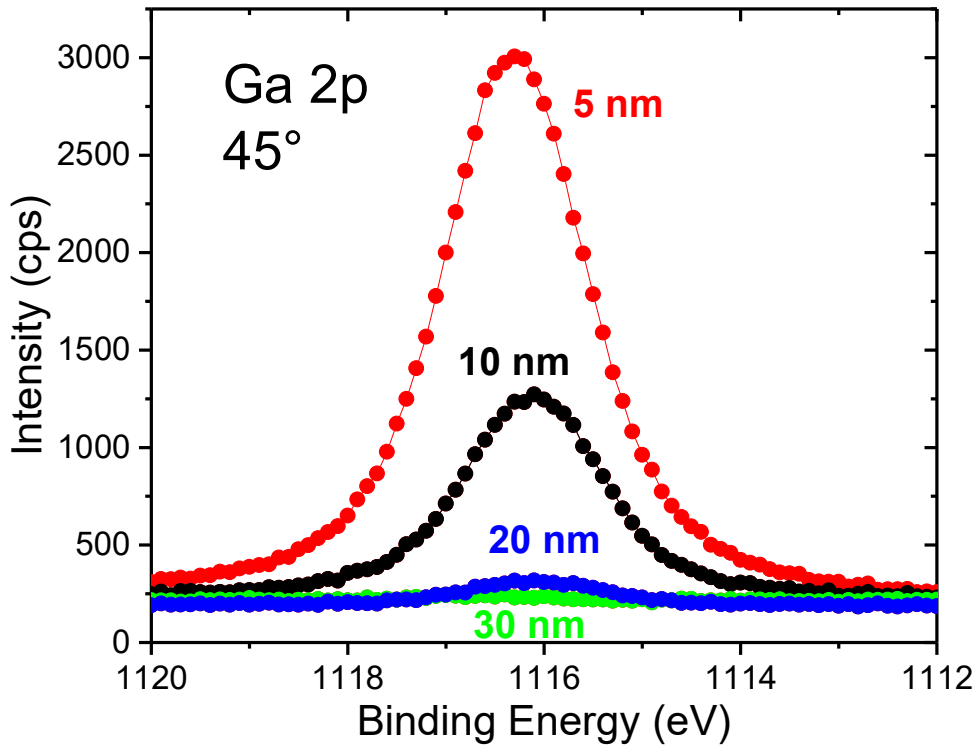
Shinotsuka *et al.* Surf. Int. Anal. **47**, 871 (2015)

INTEREST OF HAXPES FOR GAN



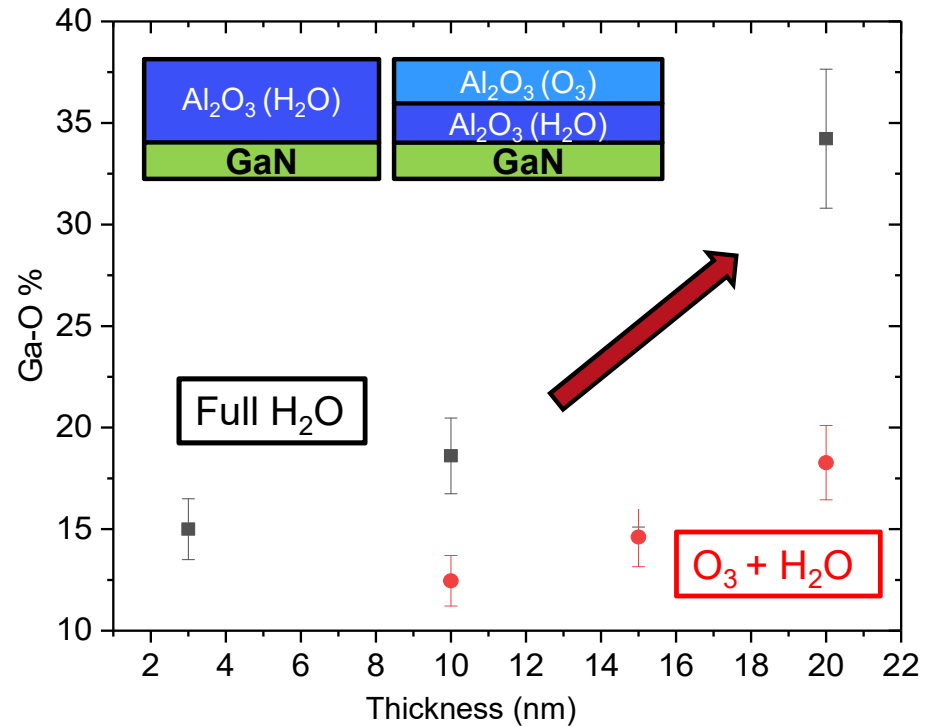
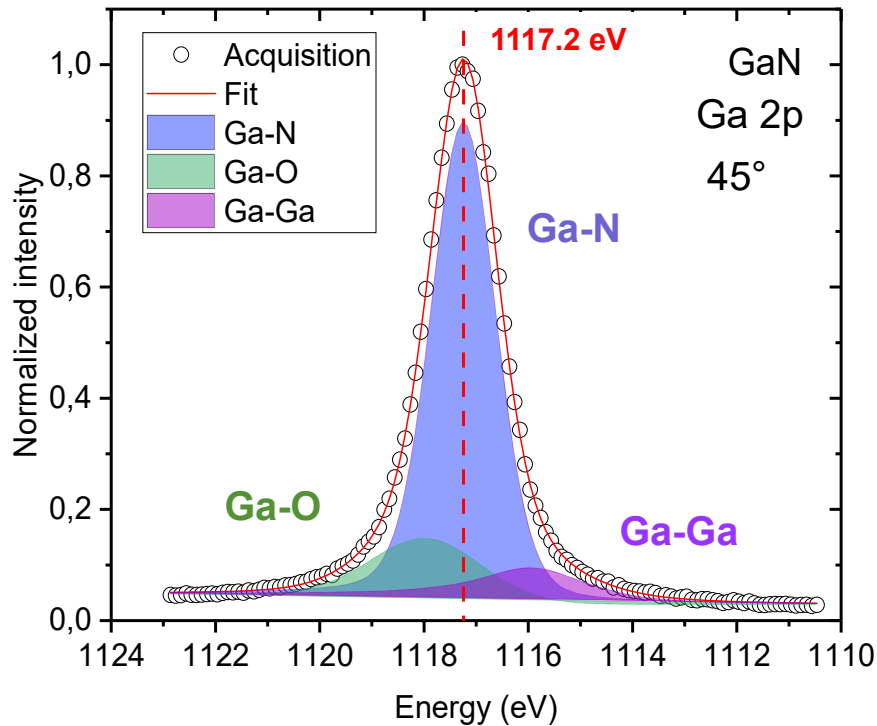
- Avoid the overlap between N 1s & Ga LMM
- Trade-off between sensitivity & probing depth with Ga 2p / Ga 3d

ANALYSIS OF BURIED INTERFACES



□ Investigate the GaN surface with a 20 nm-thick Al₂O₃ upper layer

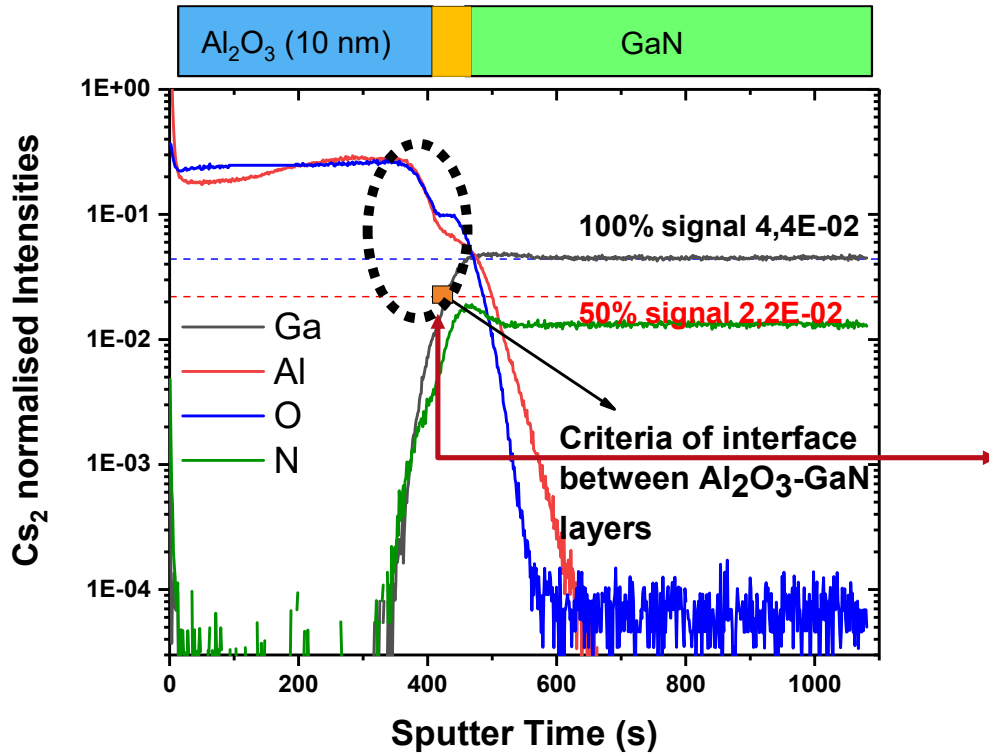
IMPACT OF AL₂O₃ THICKNESS ON GAN OXIDATION



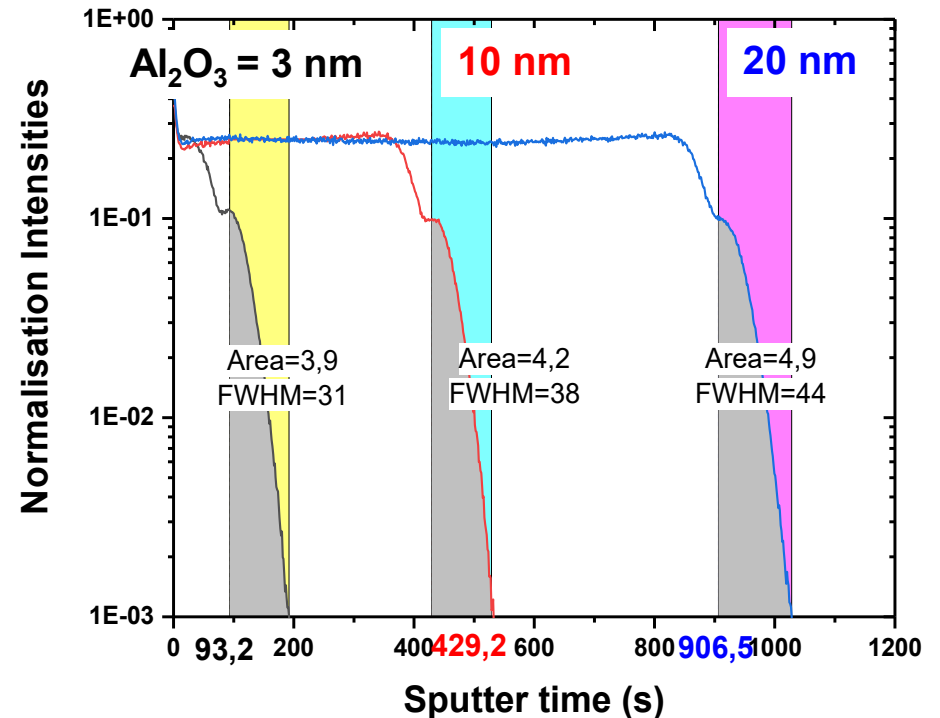
□ Increase of Ga-O bonds at the GaN surface with increasing Al₂O₃ thickness

O. Renault et al., Faraday Discuss. (2022), <https://doi.org/10.1039/D1FD00110H>

CORRELATION WITH TOF-SIMS

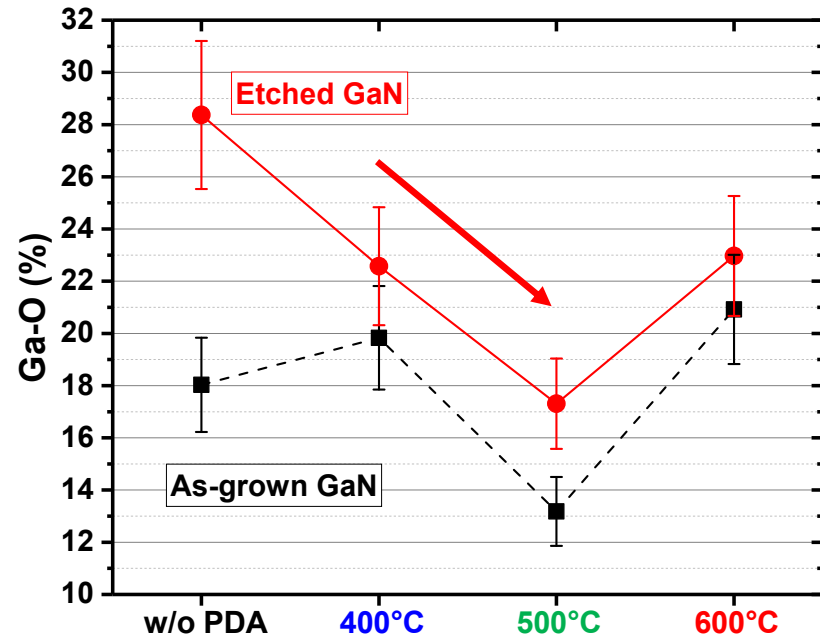
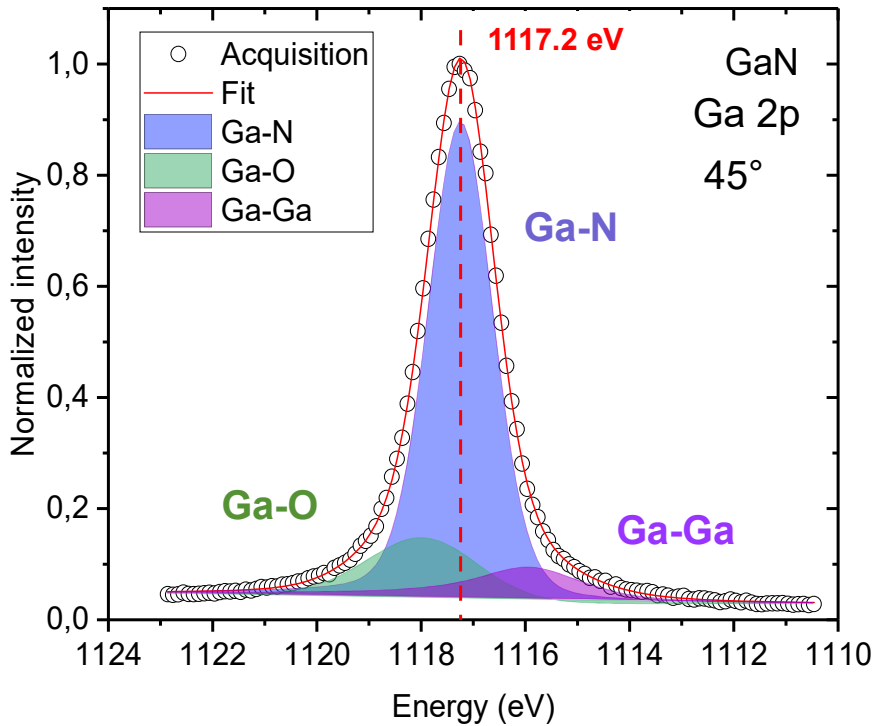
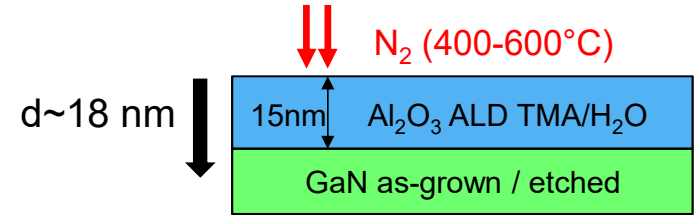


¹⁶OCs₂ normalisation intensities versus Al₂O₃ thickness



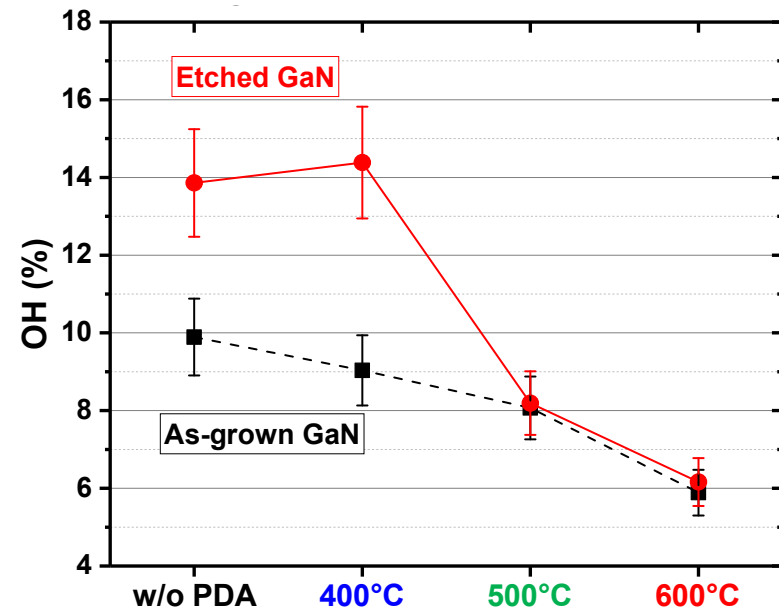
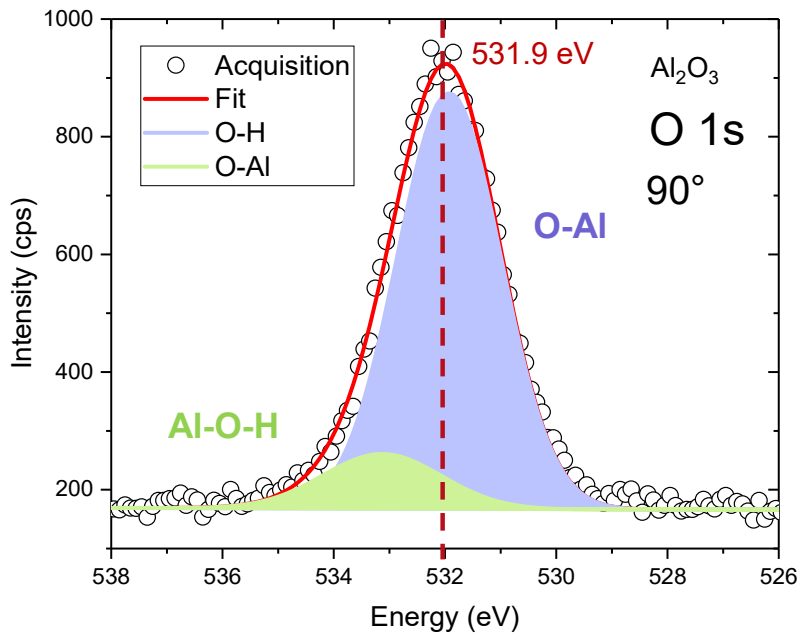
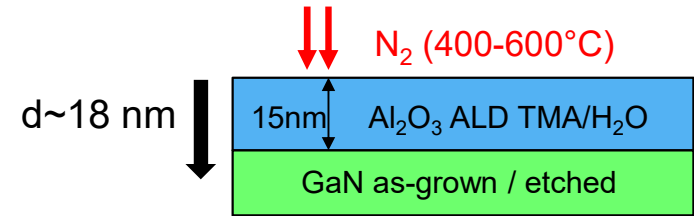
- Increasing area under O profiles with Al₂O₃ thickness
- Consistent with GaO_x increase observed by HAXPES

IMPACT OF POST DEPOSITION ANNEAL (1)



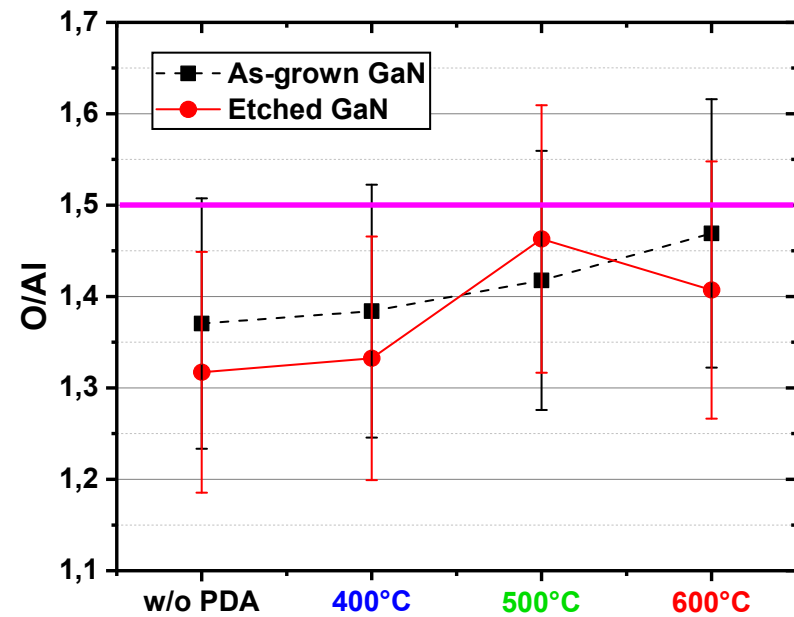
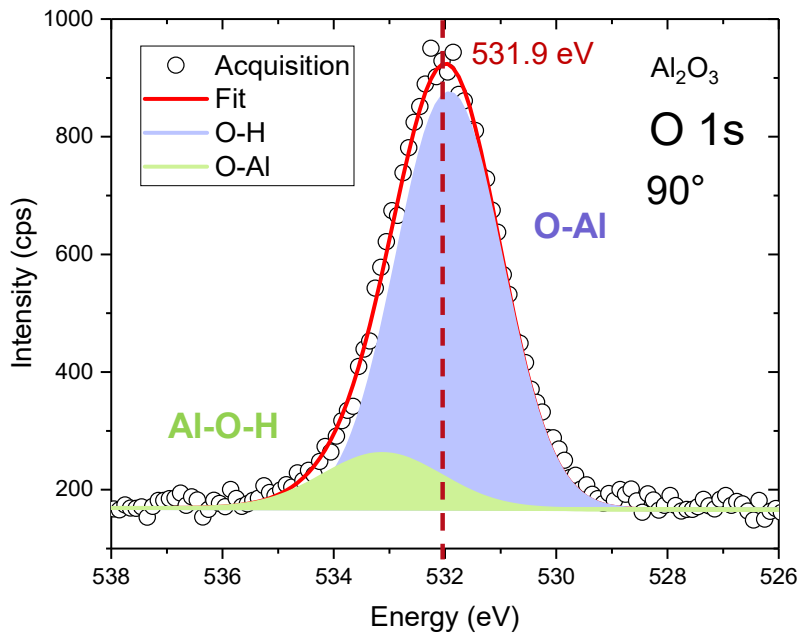
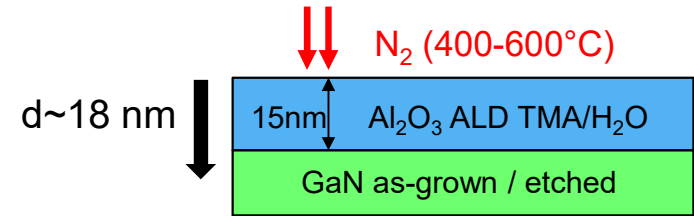
□ Reduction of Ga-O bonds at $\text{Al}_2\text{O}_3/\text{GaN}$ interface until 500°C

IMPACT OF POST DEPOSITION ANNEAL (2)



□ Reduction of -OH groups in Al_2O_3 with increasing PDA temperature

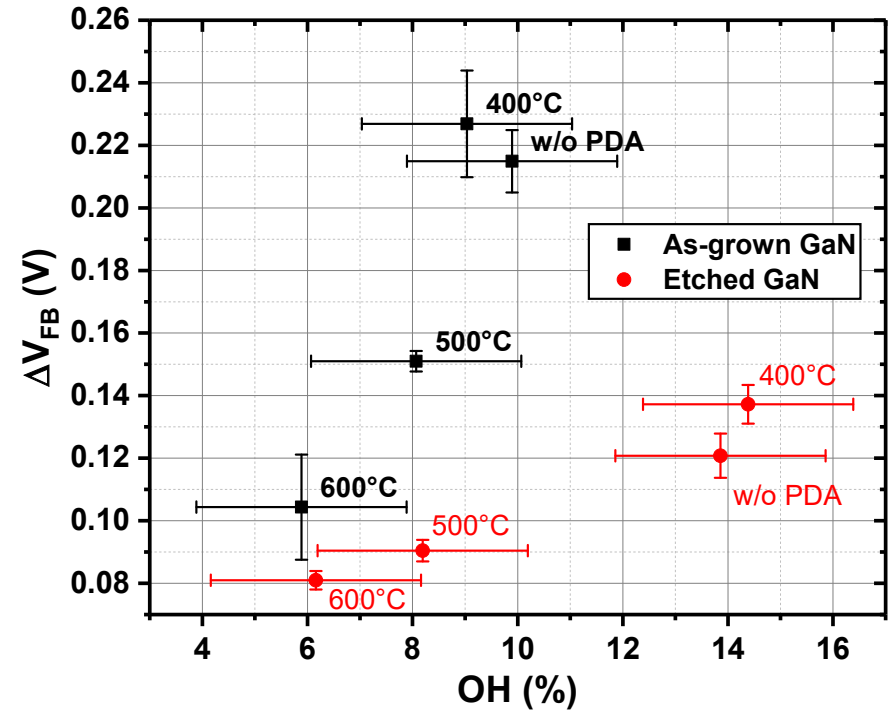
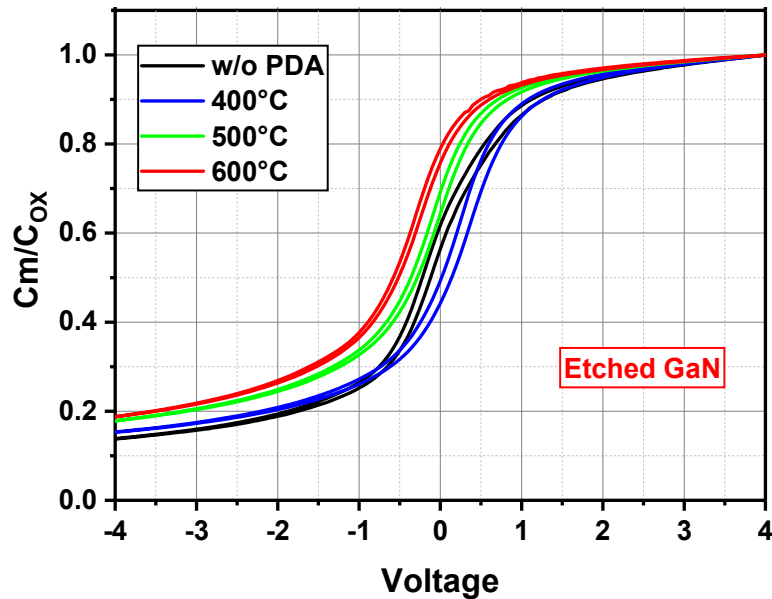
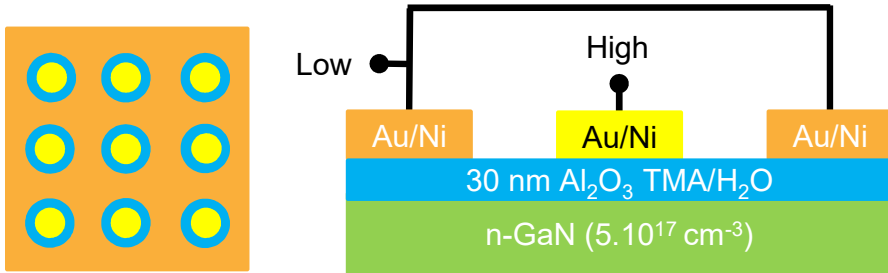
IMPACT OF POST DEPOSITION ANNEAL (3)



□ Better stoichiometry of Al₂O₃ with PDA temperature

P.M. Deleuze et al., Surf. Sci. Spectra 29, 014003 (2022)

CORRELATION WITH C(V) MEASUREMENTS



□ Correlation of -OH groups decrease with hysteresis decrease

P. Fernandes et al., Proceedings GaN Marathon (2022)

- **Gate-first MOSc-HEMT technology is currently optimized for power electronics**
- **Final devices properties rely on the quality of the $\text{Al}_2\text{O}_3/\text{GaN}$ interface**
- **Non destructive HAXPES is particularly interesting:**
 - Remove Ga LMM Auger lines from N1s
 - Get closer to the real buried interface (Al_2O_3 30 nm)
- **HAXPES main results:**
 - Increase of GaN oxydation with Al_2O_3 thickness as confirmed by ToF-SIMS
 - Reduction of $-\text{OH}$ groups in Al_2O_3 with increasing PDA temperature
- **Strong interest in developing laboratory HAXPES for such devices technology**



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Thank you for your attention

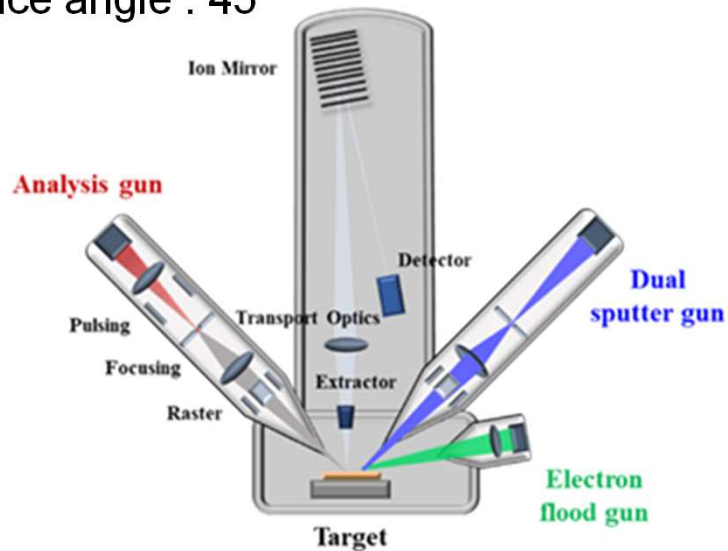
Some questions ?

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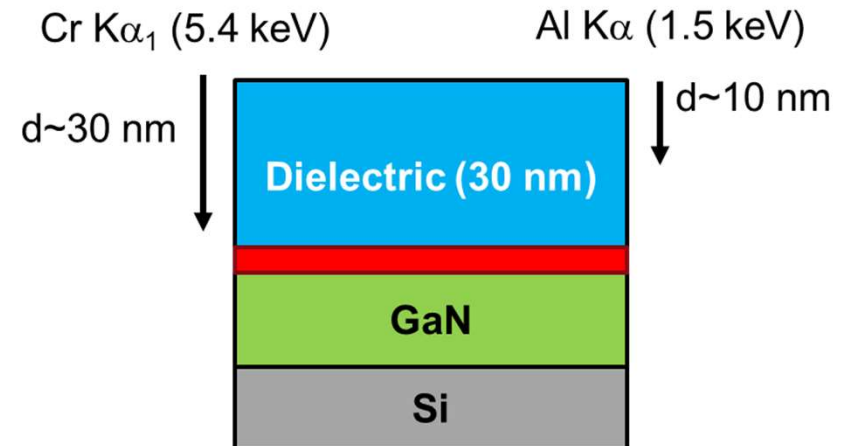
Tof SIMS Analysis conditions :

Analyze gun : Bi^{3+} 15 KeV current : $0.6 \pm 0,02\text{pA}$
 Sputter gun : Cs 500 eV current : $24.3 \pm 0,2 \text{ nA}$
 Sputter area : $300\mu\text{m}$ Analysis area : $80\mu\text{m}$
 Incidence angle : 45°



HAXPES Analysis conditions :

Source energy : Cr $K\alpha$ 5415 eV
 Pass-energy : 55eV
 Take-off angle : $42^\circ - 90^\circ$
 Probe depth : 24nm
 Pics studied : Ga2p, N1s, O1s, Al1s



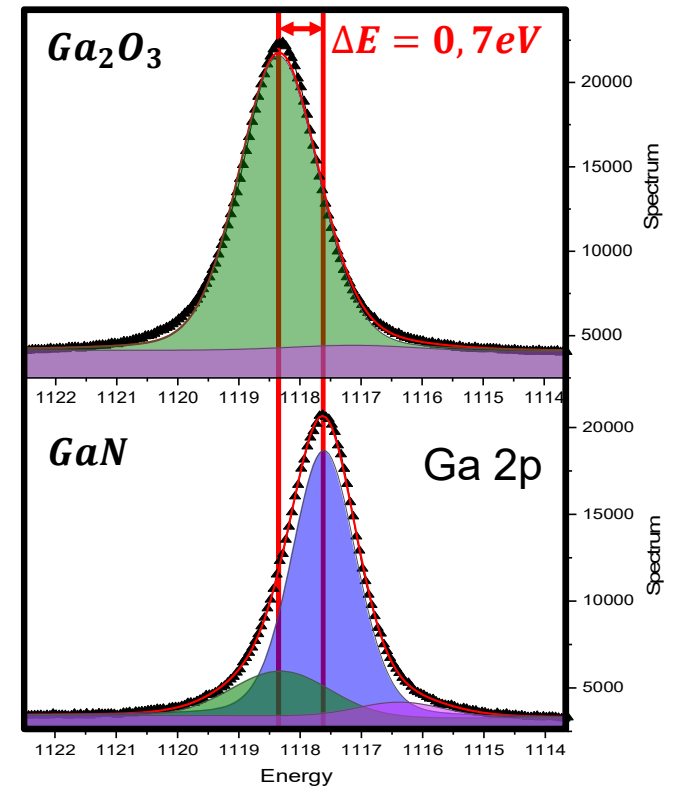
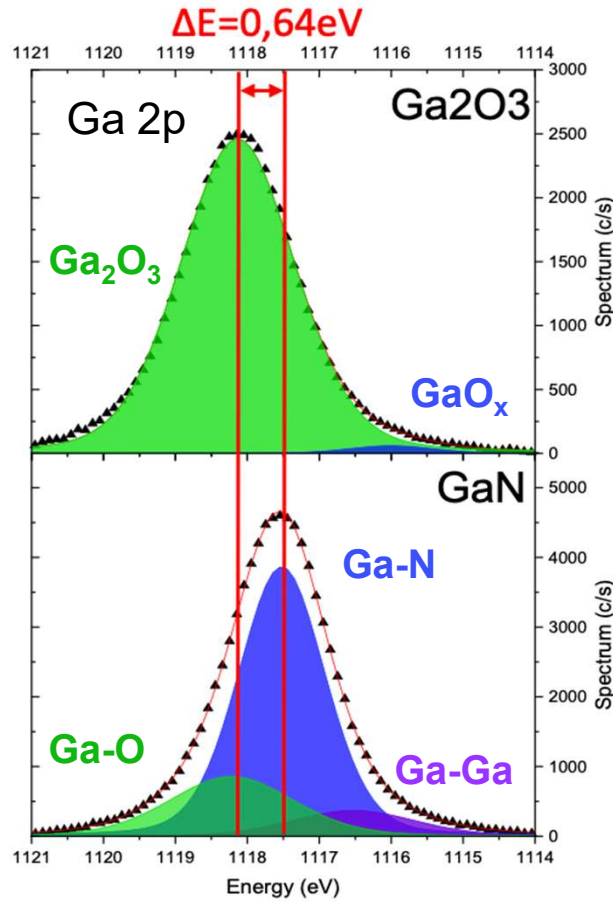
FIT OF GA2p – ANALYSIS OF REFERENCES

Cr K α = 5,4 KeV (Quantes)

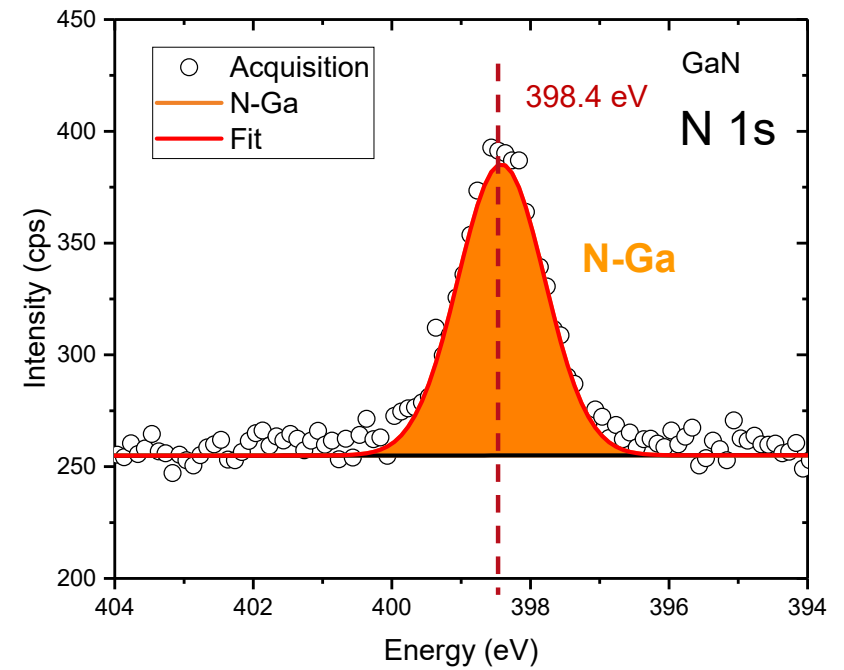
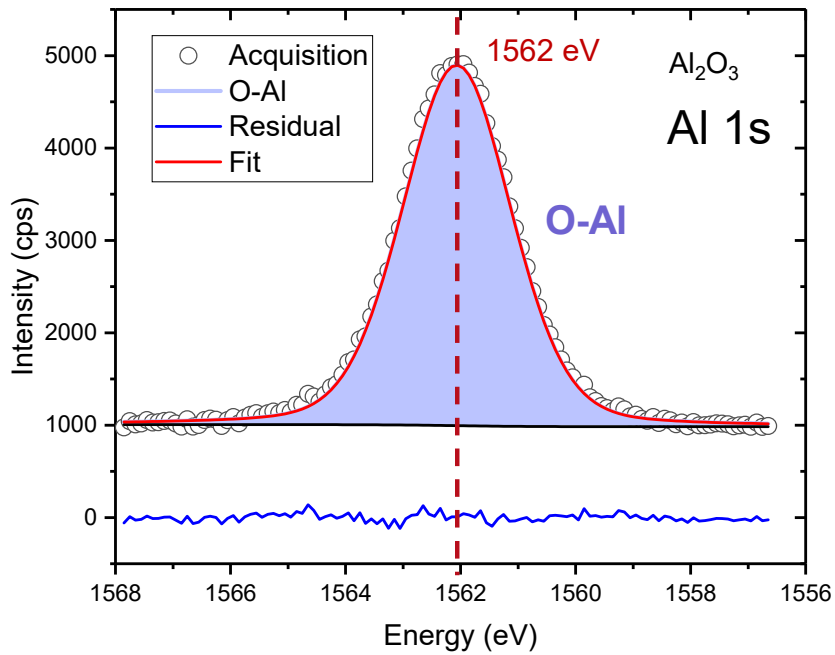
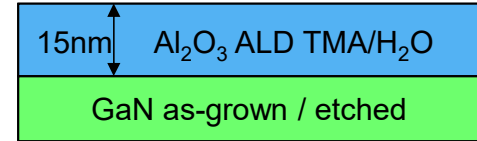
Al K α = 1486 eV (VP II)

Ga₂O₃ (bulk)

GaN (70 nm)
Si



SOME EXAMPLES OF OTHER SPECTRA

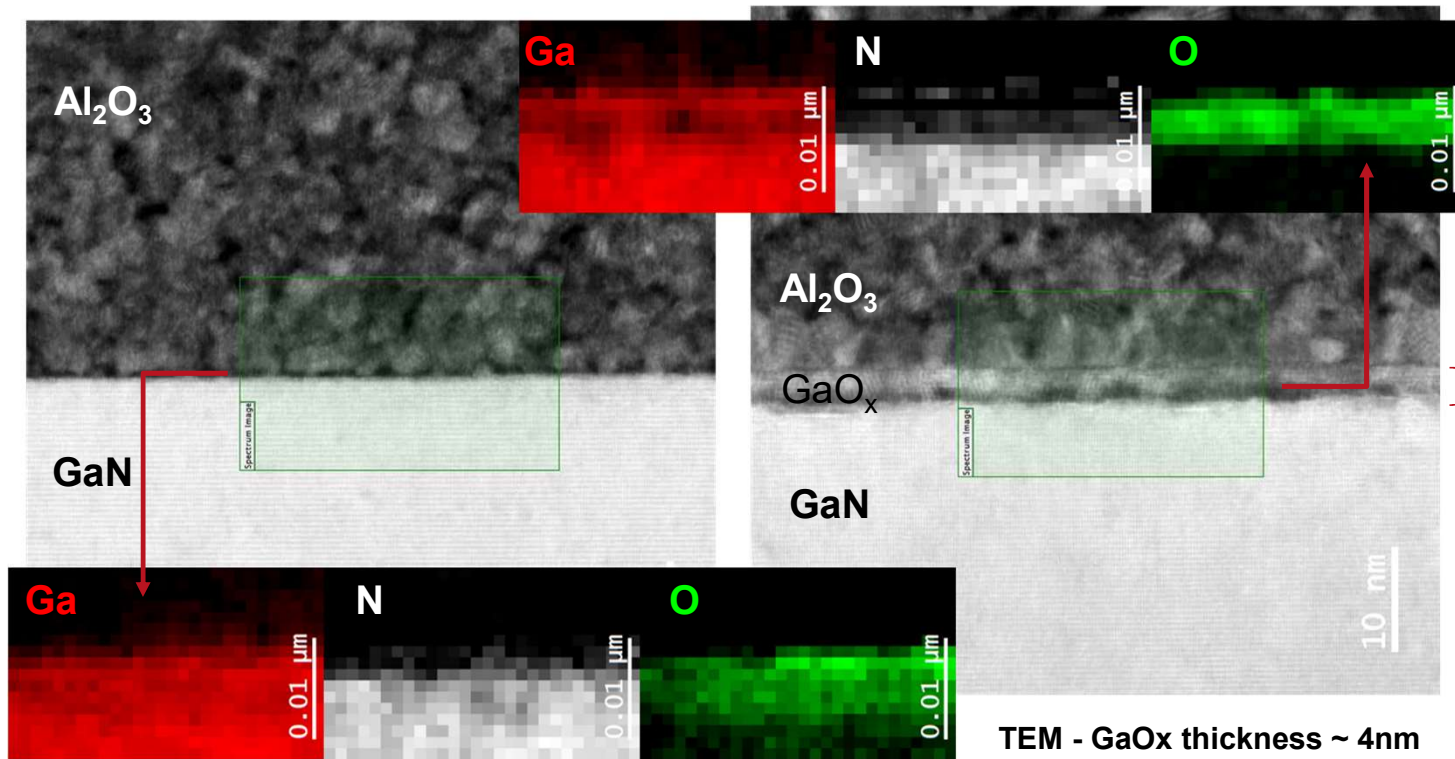


Some STEM-EELS results

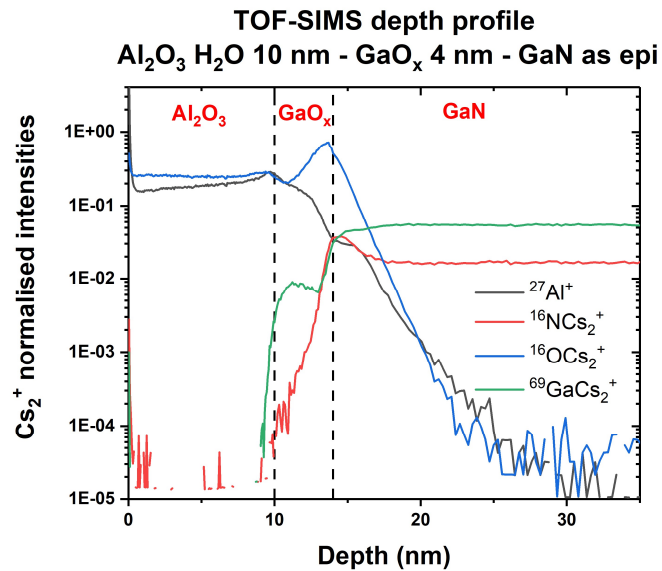
EELS mapping

0 W

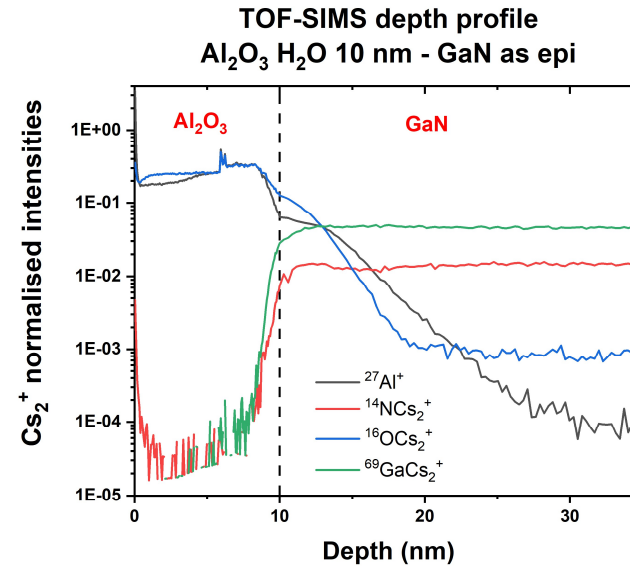
40 W



ToF-SIMS results



$$\text{At depth}=13 \text{ nm } \frac{16 \text{ O Cs}_2^+}{69 \text{ Ga Cs}_2^+} = 90$$

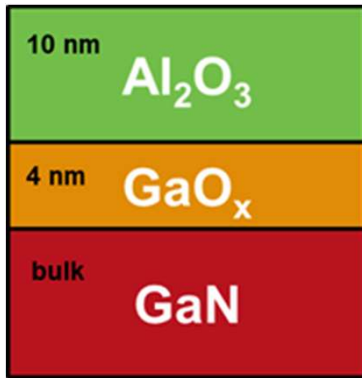


$$\text{At depth}=10 \text{ nm } \frac{16 \text{ O Cs}_2^+}{69 \text{ Ga Cs}_2^+} = 5$$

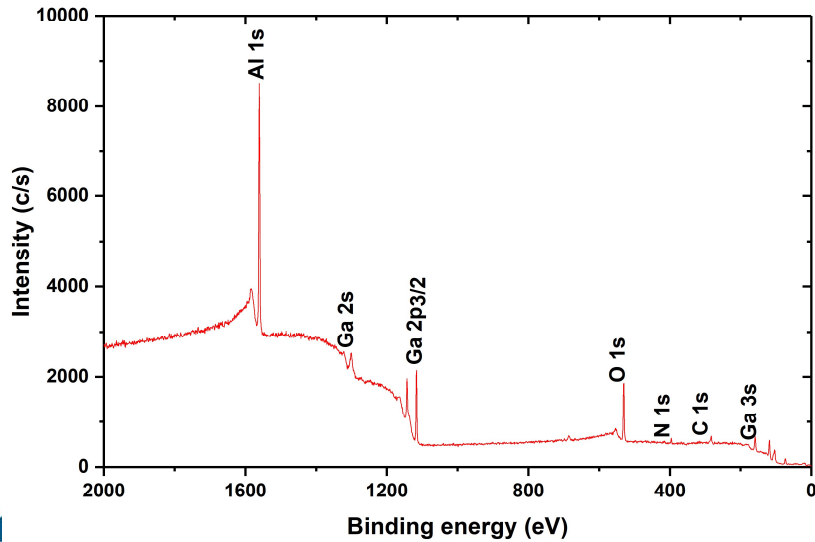
From the above depth profiles we can suppose from the Ga₂O₃ reference sample that :

- Al₂O₃ 10 nm – GaO_x 4 nm – GaN interface is poorer of ¹⁶O and richer in ⁶⁹Ga
- Al₂O₃ 10 nm – GaN etched interface is really poor in ¹⁶O and richer in ⁶⁹Ga
- Same observation for the etched sample

AR-HAXPES results



Al₂O₃ H₂O 10 nm - GaO_x 4 nm - GaN as-epi



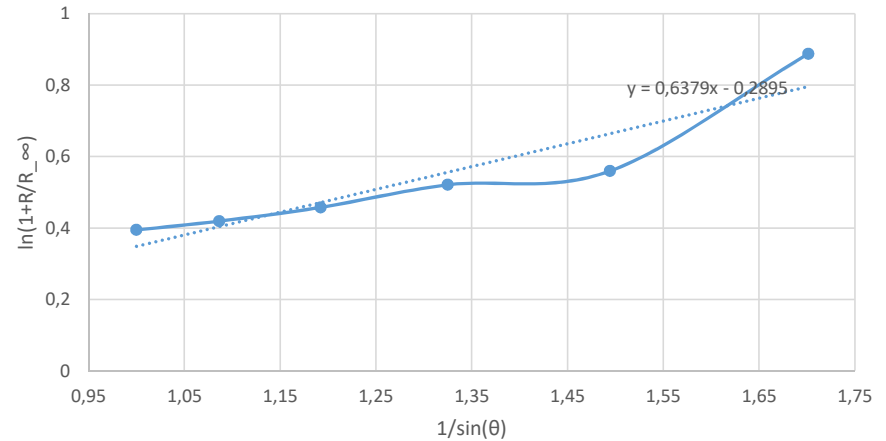
$$\ln \left[1 + \frac{R}{R_\infty} \right] = \frac{t}{\lambda * \sin(\theta)}$$

θ : take off angle
 $\frac{t}{\lambda}$: slope of the curve

$t = \text{slope} * \lambda \sim 4.6 \text{ nm}$

AR-HAXPES Gallium oxide thickness estimation

Al₂O₃ H₂O 10 nm - GaO_x 4 nm - GaN as-epi



GaO_x thickness assessment by HAXPES on Al₂O₃/GaN structures

Al ₂ O ₃ 10 nm O ₃ /H ₂ O – GaN etched	~ 0.2 nm
Al ₂ O ₃ 10 nm H ₂ O – GaN etched	~ 0.6 nm
Al ₂ O ₃ 10 nm H ₂ O – GaN as-epi	~ 0.8 nm