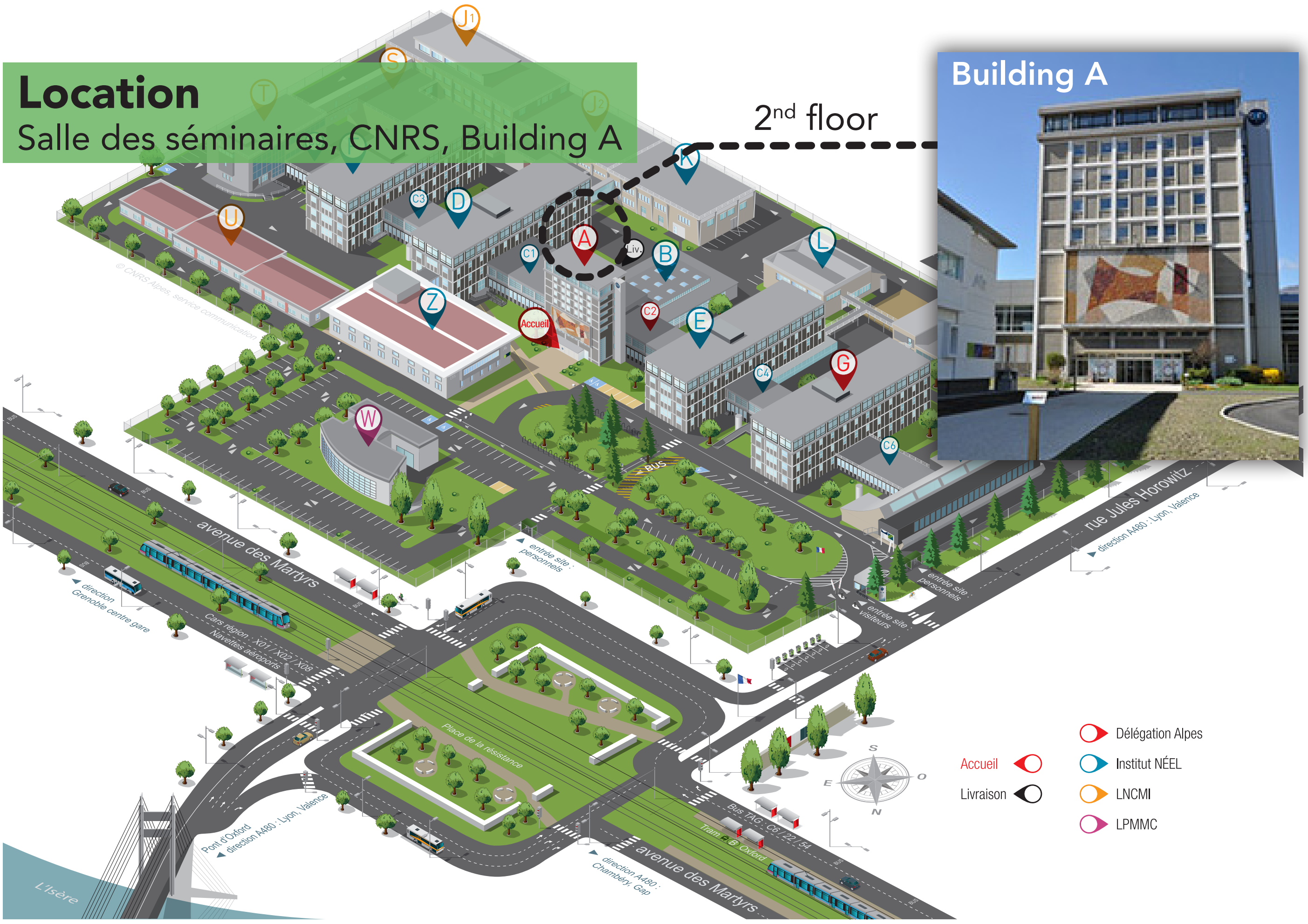
Workshop on Gallium Oxide and Related Materials

September 29-30, 2025
Grenoble - France

Salle des séminaires, CNRS, Building A
CNRS, 25 Avenue des Martyrs,
38042 GRENOBLE

Workshop on Gallium Oxide and Related Materials

Location
Salle des séminaires, CNRS, Building A



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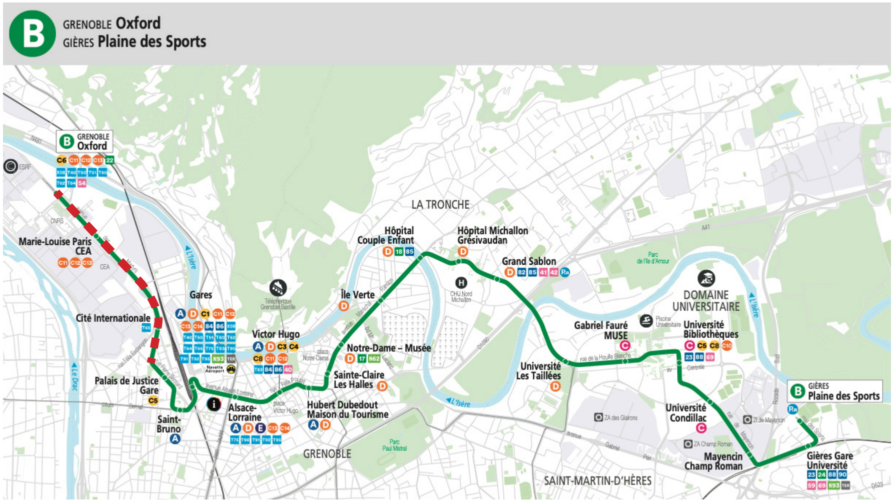

WORKSHOP ON GALLIUM OXIDE AND RELATED MATERIALS

	Time	September 29, 2025
	13:30 – 13:50	**Workshop introduction**
		Growth and structural characterization 1
Chairman **Vincent Consonni (LMGP)**	13:50 – 14:15	***Andy SÉGURET***, CEA-IRIG-PHELIQS & LMGP ALD of epitaxial (002) κ-Ga_2O_3 thin films on c-plane sapphire
	14:15 – 14:40	***Ilyass JELLAL*** - LMGP κ- and β-phases of Ga_2O_3 thin films grown by atomic layer deposition: a study of their phase transition using thermal annealing
	14:40 – 15:05	***Alexandre JAUD***, LMI Ga_2O_3 thin films on c-plane Sapphire by Low-Pressure MOCVD. From Epitaxial Growth to Devices
	15:05 – 15:30	***Marielena VELASCO-ENRIQUEZ,*** LMGP & Institut NEEL Pulsed-Liquid Injection MOCVD of epitaxial Ga_2O_3 thin films
	15:30 – 15:55	***Julien BOSCH,*** CEA-IRIG-PHELIQS Plasma-Assisted Molecular Beam Epitaxy of β-Ga_2O_3/NiO Heterojunctions
	15:55 – 16:25	**Coffee break**
		Growth and structural characterization 2
Chairwoman **Ekaterine Chikoidze (GEMaC)**	16:25 – 16:50	***Vincent CONSONNI,*** LMGP Ga_2O_3 Nanomaterials & Thin Films by Chemical Bath Deposition
	16:50 – 17:15	***Eva MONROY,*** CEA-IRIG-PHELIQS Molecular Beam Epitaxy of Al-Polar Wurtzite AlN(0001) on β-Ga_2O_3(-201)
	17:15 – 17:40	***Enora VUILLEMET,*** AMPERE Raman and photoluminescence characterization of β-Ga_2O_3 for power electronic application
	17:40 – 18:05	***Marcin KONCZYKOWSKI,*** LSI Thermal Stability and Doping Effect of Electron Irradiation Induced Defects in β-Ga_2O_3 and GaN Crystals
		Heterostructures
Chairwoman **Eirini Sarigiannidou (LMGP)**	18:05 – 18:30	***Adrien ROTH,*** CEA-LETI & Institut NEEL Investigating the blistering mechanisms of β-Ga_2O_3 under light ion implantation
	18:30 – 18:55	***Emilien LEFEBVRE,*** LMGP & Institut NEEL Core Shell ZnO-Ga_2O_3 Nanowire Heterostructures for Piezoelectric Devices
	18:55 – 21:00	**Diner**

WORKSHOP ON GALLIUM OXIDE AND RELATED MATERIALS

Chairman	Time	September 30, 2025
		Electrical characterization
Chairman Philippe Ferrandis (Institut Néel)	08:30 – 08:55	***Ekaterina CHIKOIDZE***, GEMaC The Beauty of Ga_2O_3 and $ZnGa_2O_3$ Electronic Properties
	08:55 – 09:20	***Akash PATNAIK*** - GEMaC Thin Film Deposition and Simulation of β-Ga_2O_3 Power Devices for High Voltage Applications
	9:20 – 09:45	***Ouissal HERIBI***, INL A New Route to Efficient β-Ga_2O_3 p–n Junctions: Electrical and Defect Characterization of Phosphorus Ion Implantation
	09:45 – 10:15	**Coffee break**
		Technological steps and devices
Chairman Jean-François Michaud (GREMAN)	10:15 – 10:40	***Changzi LU,*** AMPERE Technology Optimization for a Ga_2O_3 power Schottky diode fabrication
	10:40 – 11:05	***Juan-Carlos TRUJILLO-YAGUE,*** Institut NEEL & LMGP Optimization of Ti/Au Ohmic Contacts on β-Ga_2O_3
	11:05 – 11:30	***Philippe FERRANDIS,*** Institut NEEL Study of the Schottky barrier height distribution in β-Ga_2O_3 diodes
	11:30 – 11:55	***Tom MICOTTIS,*** IEMN Emerging Vertical Ga_2O_3 PiN Diodes for High-Power Conversion and Protection
	11:55 – 12:20	***Patrick PITTET,*** INL New perspectives for the development of Ga_2O_3-based detectors for dosimetry in FLASH radiotherapy
	12:20 – 13:50	**Lunch**
		Short presentations
Chairman Taoufik Slimani Tlemcani (GREMAN)	13:50 – 13:55	***David Muñoz-Rojas,*** LMGP New processes for the Spatial Atomic Layer Deposition (SALD) of functional materials: Ga_2O_3 from DMP-based non-pyrophoric precursors
	13:55 – 14:00	***Marty VOLANT,*** LMGP & CEA-IRIG-MEM Advanced Transmission Electron Microscopy for optimization of gallium oxide thin films
	14:00 – 14:05	***Catarina MATOS,*** LMGP & NOVA Lisboa Heterostructures Made of Ga_2O_3 for self-powered UV photodetection and power electronics
	14:05 – 14:10	***Thomas RIBAULT,*** GEMaC/INSP $Ni_{1-x}O/Ga_2O_3$ Heterostructures for Next-Generation Power Electronics
	14:10 – 14:15	***Dimitri BEBIEN,*** GREMAN Conception, realization and comparison of gallium nitride and gallium oxide based vertical power diodes
	14:15 – 14:20	***Vijay THAKUR,*** LGP Optimized Packaging of 10 kV Ga_2O_3 Power Module
	14:20 – 15:00	**Workshop conclusion**

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ALD of epitaxial (002) κ-Ga_2O_3 thin films on c-plane sapphire

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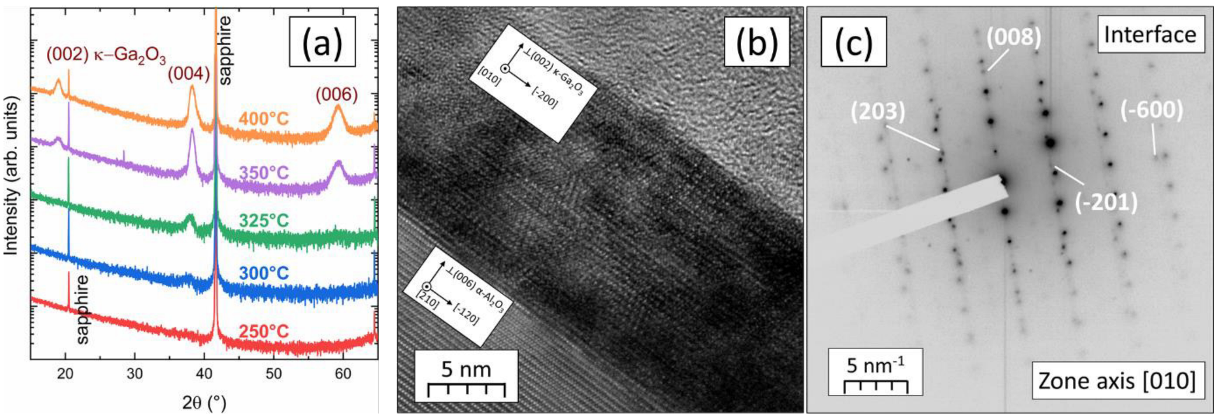
Ultra-wide bandgap semiconductors such as diamond, AlN and Ga_2O_3 have been emerging as strong contenders to overcome the limits of current power electronics, based on SiC and GaN. Ga_2O_3 is particularly interesting, with a high (>8 MV/cm) breakdown electric field, leading to a large Baliga's figure of merit[1]. Atomic Layer Deposition (ALD), as a self-limiting growth method, results in the formation of conformal thin films with low surface roughness, using a low thermal budget. In contrast to other vapor phase deposition techniques, the ALD of Ga_2O_3 has been much less explored, and studies have mainly been limited to the use of chemical precursor combinations such as trimethylgallium (TMGa) and ozone or triethylgallium (TEGa) and oxygen plasma. In particular, the ALD of Ga_2O_3 using TEGa and O_3 precursors has not yet been thoroughly investigated on the substrates that are widely used in the semiconductor industry.

In this study, Ga_2O_3 thin films are grown by ALD on sapphire(0001) in the temperature range from 150°C to 450°C using TEGa and O_3 precursors. The ALD window is found to lie between 250°C and 400°C, with a growth rate of approximately 0.4 Å/cycle. This study focuses on 16 nm thick samples and aims at understanding and controlling the epitaxial deposition and structural arrangement of the layers. All films display sub-nm surface roughness. The optical bandgap energy of the films is evaluated at 4.8 eV via direct transmittance spectrophotometry. XRD θ-2θ scans reveal that films grown between 350°C and 400°C are crystalline with the (001) κ-Ga_2O_3 phase. The ω-scan of the (004) κ-Ga_2O_3 reflection presents a linewidth of 0.1°, comparable to values reported in the literature for thick κ-Ga_2O_3 grown using CVD techniques. In-plane XRD measurements allow the determination of the in-plane epitaxial relationships as [010] κ-Ga_2O_3 || [1-100] α-Al_2O_3 and [100] κ-Ga_2O_3 || [11-20] α-Al_2O_3. It is also found that κ-Ga_2O_3 is arranged in 3 distinct domains corresponding to grains with ±120° in-plane rotations. TEM and XANES data provide further confirmation of the pure κ-Ga_2O_3 nature of the films. These results show the high potential of ALD to obtain epitaxial κ-Ga_2O_3 thins films with a high crystalline quality at relatively low temperatures.

References

(1) Zhou, H.; Zhang, J.; Zhang, C.; Feng, Q.; Zhao, S.; Ma, P.; Hao, Y. A Review of the Most Recent Progresses of State-of-Art Gallium Oxide Power Devices. *J. Semicond.* **2019**, *40* (1), 011803. https://doi.org/10.1088/1674-4926/40/1/011803.

Fig 1. *(a) XRD scans for samples grown between 250 and 400°C. (b) TEM image and (c) SAED diffraction pattern of a 350°C-grown sample.*



κ- and β-phases of Ga_2O_3 thin films grown by atomic layer deposition: a study of their phase transition using thermal annealing

I. Jellal[1,*], A. Séguret[1,2], H. Roussel[1], I. Gélard[1], S. Ortega[1], E. Sarigiannidou[1], E. Monroy[2], V. Consonni[1]

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The development and study of ultra-wide-bandgap Ga_2O_3 thin films has attracted many attention for the new generation of electronic and optoelectronic devices. In this work, we present the growth of Ga_2O_3 thin films on *c*-plane sapphire substrate using atomic layer deposition (ALD). The Ga_2O_3 thin films are grown at 350 °C using 1000 cycles. A growth per cycle of approximately 0.5 Å/cycle is obtained. X-ray diffraction (XRD) data confirms that the as-grown Ga_2O_3 thin films are well-crystallized into the metastable κ-phase, specifically with a (002) preferred orientation.

We further investigate the thermal stability of the κ-Ga_2O_3 thin films by performing both the *ex situ* and *in situ* analyses of the thermal annealing under an air atmosphere using XRD and Raman scattering. Our findings demonstrate a phase transition from the metastable κ-phase to the thermodynamically stable β-phase, starting at a temperature as low as 600 °C. A complete transformation to the β-phase is subsequently observed from the temperature of 800 °C. The surface RMS roughness of as-grown and thermally annealed Ga_2O_3 thin films is also investigated by atomic force microscopy, along with the chemical composition and inter-diffusion processes using X-ray photoelectron spectroscopy and secondary ion mass spectrometry.

These results highlight the potential of ALD to grow crystalline Ga_2O_3 thin films at low temperature and provide an insightful information about their thermal stability and the way to select the most appropriate phases.

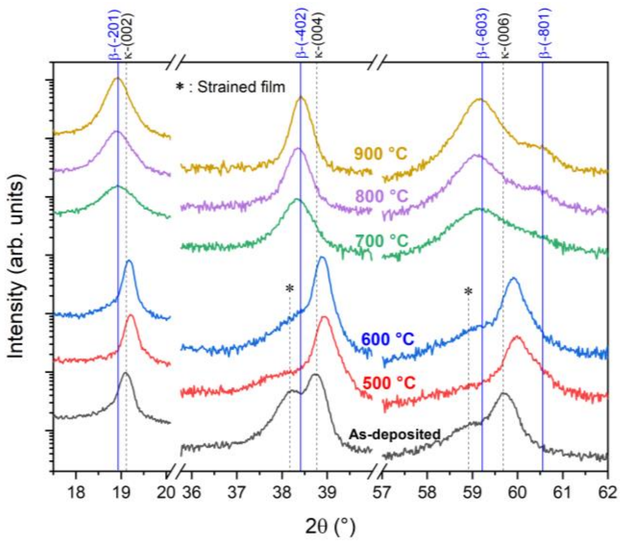

Figure 1. XRD diffractograms of Ga_2O_3 thin films deposited at 350 °C and after ex-situ annealing at 500, 600, 700, 800, and 900 °C.

Ga_2O_3 thin films on c-plane Sapphire by Low-Pressure MOCVD From Epitaxial Growth to Devices

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Due to its ultra-wide bandgap (4.9 eV), thermal stability, and high breakdown electric field (8 MV/cm), gallium oxide Ga_2O_3 is considered as a promising semiconductor material for power electronics and UV detection. The Center for Quantum Devices (CQD) at Northwestern University (Illinois, US), headed since its founding in 1992 by Professor Manijeh Razeghi, has been working along the past decade on the development of Ga_2O_3 for applications in Solar Blind UV photodetectors and transistors.

This work presents epitaxial growth of Ga_2O_3:Si thin films on c-plane sapphire (0001) by Metal-Organic Chemical Vapor Deposition (MOCVD) at low pressure (50 mbar), using a commercial Aixtron 200/4-RF reactor. The precursors used are : trimethylgallium (TMG), ultra-pure deionized H_2O, silane (SiH_4). The carrier gases are H_2 or N_2. Systematic parametric optimization studies have been performed, varying the main growth parameters: temperature, III/VI ratio, and the SiH_4 dopant flux. All layers have been characterized by structural, optical, and electrical methods.

Prior to MOCVD, annealing the sapphire substrate under H_2 at 1100 °C enables the formation of a smooth step-and-terrace surface, which facilitates subsequent deposition. In addition, it has been identified that a Ga pre-deposition step enhances the crystalline quality of the eventual Ga_2O_3 films. Using N_2 as a carrier gas leads to the deposition of relatively smooth and conductive κ-Ga_2O_3 layers [1], whereas H_2 promotes the growth of smoother, better crystallized, but electrically insulating κ-Ga_2O_3 layers [2]. Following further annealing under N_2, the layers exhibit n-type conductivity and, upon annealing above 1000 °C, undergo a phase transition from κ-Ga_2O_3 to β-Ga_2O_3 [2-3].

These Ga_2O_3:Si layers enable the production of MSM photodiodes [4] and MOSFET transistors [3,5]. Ga_2O_3 metal-semiconductor-metal (MSM) photodetectors exhibited a peak responsivity at 261 nm with a maximum EQE of 41.7% at -2.5 V. The related I-V measurements showed a photocurrent nearly three orders of magnitude higher than the dark current under the same bias [4]. κ-Ga_2O_3 MOSFETs exhibited I_D values of 26.7 and 9.12 mA/mm with breakdown voltage values of 360 V and 390 V, respectively, together with on/off ratios exceeding 10^7–10^8 [5]. β-Ga_2O_3:Si MOSFETs, on the other hand, achieved a maximum I_D of 100 mA/mm with a breakdown voltage of 400 V at V_{GS} = - 40 V, along with an on/off ratio of ~10^{11} and gate leakage as low as 1.5 pA/mm [3].

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[2] J. Lee, H. Kim, L. Gautam, K. He, X. Hu, V. P. Dravid and M. Razeghi, Photonics **8**(1),17 (2021)
[3] J.H. Park , R. McClintock, **A. Jaud**, A. Dehzangi and M. Razeghi, Applied Physics Express **12**, 095503 (2019)
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Proc. SPIE 11288, Quantum Sensing and Nano Electronics and Photonics XVII, 1128803 (2020)
[5] J.H. Park, R. McClintock and M. Razeghi, Semicond. Sci. Technol. **34** (2019)

Pulsed-Liquid Injection MOCVD of epitaxial Ga_2O_3 thin films

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The epitaxial growth of Ga_2O_3 thin films has emerged as a research focus within the power electronics community, due to its promising properties, including an ultra-wide bandgap energy (4.8-4.9 eV), a high critical breakdown field (8 MV/cm), etc. Among several growth methods, metal-organic chemical vapor deposition (MOCVD) is highly attractive for achieving Ga_2O_3 thin films with a high structural quality at high growth rates, compared to their counterparts, making it suitable for industrial-scale production [1].

Moving beyond conventional MOCVD equipped with a bubbler-based system for introducing the chemical precursors, the pulsed–liquid injection MOCVD technique incorporates a vaporizer prior to the reactor chamber. This configuration allows the use of chemical precursors with low vapor pressure and poor thermal stability, by pulsing micro-amounts of the liquid precursor into the vaporizer, ensuring homogeneous evaporation, hence precise dosing before entering the reactor chamber [2]. In-house studies have shown some key advantages of using this innovative approach for the growth of various oxide materials, as it prevented the accumulation of condensed high-k oxide precursor [3] and to enable great control over morphology and polarity transitions in ZnO structures [4].

In this study, we report the epitaxial growth of Ga_2O_3 thin films on *c*-plane sapphire substrates *via* PLI-MOCVD using a semi-industrial ANNEALSYS MC200 reactor with triethylgallium (TEGa) and O_2 as chemical precursors. The epitaxial quality, defect nature, and interfacial properties are characterized by FESEM, AFM, XRD, TEM, XPS and cathodoluminescence spectroscopy. The present findings open perspectives for the growth of epitaxial Ga_2O_3 thin films with a high quality using PLI-MOCVD.

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References

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[2] "PROCEDE ET DISPOSITIF D'INTRODUCTION DE PRECURSEURS DANS UNE ENCEINTE DE DEPOT CHIMIQUE EN PHASE VAPEUR (Brevets) - Data INPI." Accessed: Nov. 27, 2023. [Online]. Available: https://data.inpi.fr/brevets/FR2707671?q=#FR2707671
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Plasma-Assisted Molecular Beam Epitaxy of β-Ga_2O_3/NiO Heterojunctions

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With the increasing demand for power electronics, ultra-wide bandgap materials such as diamond, AlN and Ga_2O_3 are emerging as strong contenders to surpass the performance limits of SiC and GaN. Among them, β-Ga_2O_3 is particularly interesting, with a 4.9 eV bandgap energy and breakdown field above 8 MV/cm, which lead to large figures-of-merit for power electronics. For the growth of oxide materials, plasma-assisted molecular-beam epitaxy (PAMBE) provides an ultra-high-purity environment, monolayer-scale thickness control and reduced inter-diffusion effects.

Here, we report the PAMBE growth of Ga_2O_3 on GaN and AlN templates on c-sapphire, at temperatures in the range of 580-780°C. Although β-Ga_2O_3 has a monoclinic lattice, its (-201) plane presents hexagonal symmetry with reduced in-plane lattice mismatch with the hexagonal (0001) plane of III-nitrides: ~2.4 % along [010]β-Ga_2O_3 ‖ [11-20]AlN [1]. *In-situ* reflection high-energy electron diffraction (RHEED) is consistent with this structural arrangement, and reveals a relaxation of the lattice within the first few nanometers of growth of β-Ga_2O_3.

The growth of Ga_2O_3 using PAMBE is hampered by the formation of the volatile Ga_2O sub-oxide, which slows down the deposition. However, this particularity can be exploited as a precise in-situ thickness calibration tool: Ga_2O_3 can be decomposed by exposure to Ga, in a time that is proportional to the layer thickness. Complete desorption is easily identified by the emergence of the GaN or AlN RHEED pattern, with a slightly different parameter. We have used this technique to assess the growth rate as a function of substrate temperature and Ga flux. Then, a flux of In has been introduced to prevent the formation of Ga_2O. A small In flux (beam-equivalent pressure ≈ 10^{-8} Torr) boosts the growth rate by a factor of 2.5 without incorporating In in the layer. The resulting Ga_2O_3 layers present surface roughness in the range of 2.8 nm to 1.0 nm, with a surface morphology that is dependent upon the substrate temperature. X-ray diffraction measurements and scanning transmission electron microscopy images confirm that all the layers are (-201)-oriented β-Ga_2O_3, containing 60°-rotated domains with [010]β-Ga_2O_3 ‖ <11-20>AlN

Because of its intrinsic n-doping [2] and high hole effective mass [3], Ga_2O_3 is not well adapted for the fabrication of p-doped structures. Therefore, we also investigated the growth of NiO on (100) β-Ga_2O_3, in order to establish a process window for the fabrication of high-quality p-n heterojunctions.

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Ga_2O_3 Nanomaterials & Thin Films by Chemical Bath Deposition

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The growth of Ga_2O_3 nanomaterials and thin films has mainly been developed using vapor phase deposition techniques, including molecular beam epitaxy, pulsed-laser deposition, and metal-organic chemical vapor deposition to name a few [1]. For the sake of simplicity and sustainability, a promising, alternative way consists in achieving their chemical synthesis using a low-temperature chemical route in aqueous solution [2]. However, the physicochemical processes at work have not yet been elucidated.

Here, we develop a double-step process involving the growth of α-GaOOH on silicon using chemical bath deposition and their further structural conversion into α-Ga_2O_3 or β-Ga_2O_3 by thermal annealing at high temperature [3]. By using gallium nitrate and sodium hydroxide in aqueous solution, we show that the structural morphology of GaOOH deposits is thoroughly tunable in terms of both dimensions, density, and nature by varying the initial pH value from acidic to basic conditions [4]. In the low-pH region where Ga^{3+} ions represent the dominant Ga(III) species, GaOOH microrods with a low aspect ratio. In the intermediate-pH region where $GaOH_2^+$ ions represent the dominant Ga(III) species, GaOOH prismatic nanorods with a high aspect ratio. In the high-pH region where $Ga(OH)_4^-$ complexes are predominantly formed, the growth of partially crystallized GaOOH thin films with a typical thickness of about 1 μm proceeds. Interestingly, the structural conversion into the α- and β-phases of Ga_2O_3 is further investigated using an in situ analysis by Raman scattering and X-ray diffraction, which is combined with X-ray near-edge structure absorption spectroscopy using synchrotron radiation. These findings show the correlation between the characteristics of the chemical bath and the resulting structural morphology of GaOOH deposits. They further open great perspectives to grow GaOOH and hence Ga_2O_3-based materials on silicon with a dedicated structural morphology for engineering devices in the fields of gas sensing, solar-blind UV-C photo-detection, and power electronics.

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Molecular Beam Epitaxy of Al-Polar Wurtzite AlN(0001) on β-Ga_2O_3(-201)

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Ultrawide bandgap semiconductors such as β-Ga_2O_3 and AlN are emerging as promising candidates for next-generation power electronics. Combining these materials into high-quality heterostructures could enable devices with polarization-induced two-dimensional electron gases (2DEGs) of unprecedented density, thereby overcoming the intrinsic mobility limitations of β-Ga_2O_3.

Here, we report on the heteroepitaxial growth of Al-polar wurtzite AlN(0001) on monoclinic β-Ga_2O_3(-201) substrates by plasma-assisted molecular beam epitaxy (PAMBE). The growth process was systematically investigated with respect to nucleation conditions and Al/N flux ratio. We demonstrate that that N-rich growth conditions combined with substrate nitridation produce smooth AlN layers with sharp heterointerfaces, while Al-rich conditions lead to rougher surfaces and highly twisted grains. High-resolution X-ray diffraction and scanning transmission electron microscopy demonstrate that under optimized N-rich growth the AlN layer is epitaxially aligned with AlN[2-1-10] ‖ β-Ga_2O_3[020] and exhibits homogeneous Al polarity, with an abrupt monoclinic–wurtzite transition. Chemical mapping indicates that careful nitridation is required to suppress interfacial reactions and limit the formation of intermediate (Al,Ga)N or $(Al,Ga)_2O_3$ phases. Theoretical band-structure calculations further show that the polarization discontinuity at the AlN/β-Ga_2O_3 interface can generate a 2DEG with an interface charge density exceeding 10^{13} cm^{-2}, strongly dependent on the strain relaxation of the AlN layer. These results demonstrate a viable pathway toward integrating nitrides with β-Ga_2O_3, opening perspectives for high-performance high-electron-mobility transistors and power devices based on ultrawide bandgap hybrid heterostructures.

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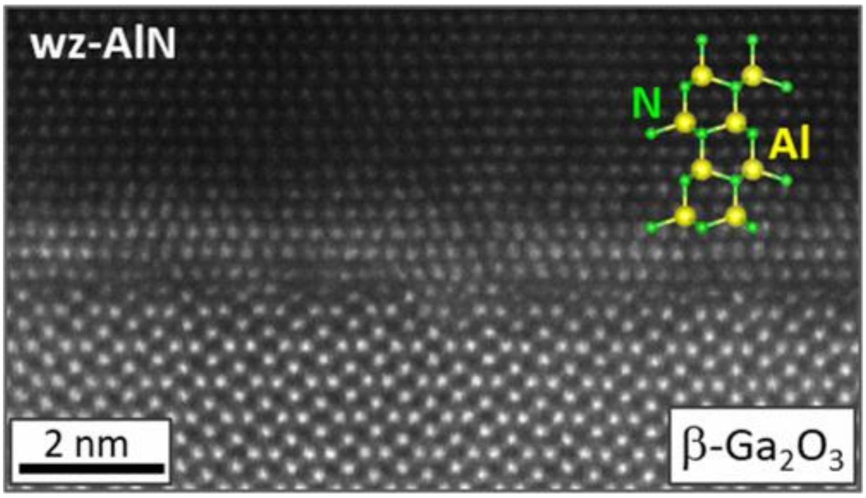

Figure 1. High-angle annular dark field scanning transmission electron microscopy image of the AlN/Ga_2O_3 interface.

Raman and photoluminescence characterization of β-Ga_2O_3 for power electronic application

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The ultra-wide bandgap (Eg ~ 4,5 eV), high breakdown field (up to 8 MV/cm) [1], and short absorption edge of β-Ga_2O_3 have raised strong interest for high-voltage and low-loss power electronics, as a complement or potential alternative to wide-bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN). Despite recent progress in bulk and epitaxial growth [2], the effects of doping and growth conditions on the structural and optical properties of β-Ga_2O_3 are still not fully understood. Identification and spatial distribution of defects such as, dislocations, doping impurities, or point defects, are also still a subject of discussion in recent publications [3,4].
The objective of this work is to better understand the impact of material defects and substrate orientation on β-Ga_2O_3 power devices performance. To this end, µ-Raman and photoluminescence (PL) measurements were realized respectively under green (532nm) and UV (325nm) laser excitation, to investigate the crystallinity and defects of β-Ga_2O_3 single crystals and epitaxial layers. While doping has little impact on the Raman spectra, the low symmetry of β-Ga_2O_3 monoclinic lattice leads to variations in Raman peaks depending on substrate orientation. Raman mappings show small shifts in peak position at the border of the samples, indicating minor stress variations and overall good crystalline quality of the samples. On the other side, PL measurements allow the identification and localization of point defects that are not visible by Raman spectroscopy. Furthermore, PL mappings show inhomogeneous defect distribution within the Fe-doped β-Ga_2O_3 substrate, both laterally and in depth (Fig.1), which could impact the performance of β-Ga_2O_3 power devices.

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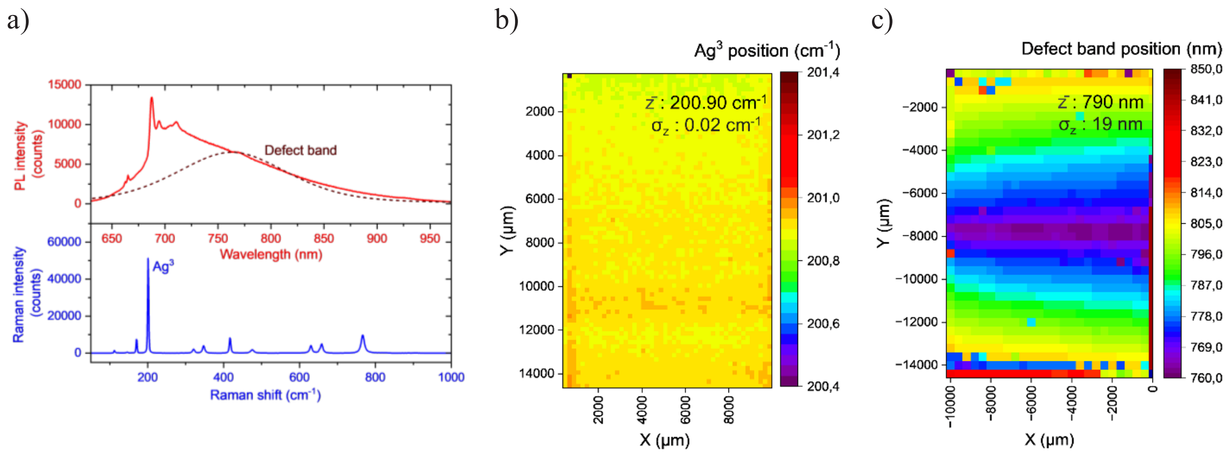

Figure 1. (a) Raman and PL spectra at the center of the of Fe-doped β-Ga_2O_3 sample under respective laser excitation of 532 and 325nm. (b) Raman mapping of the Ag^3 band position at 532nm and (c) PL mapping of the defect band position at 325nm of a Fe-doped β-Ga_2O_3 sample.

Thermal Stability and Doping Effect of Electron Irradiation Induced Defects in ß-Ga_2O_3 and GaN Crystals

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Doping by elementary defects (vacancies and interstitials) significantly contributes to the electronic transport of ultra-wide bandgap semiconductors (UWGS). Understanding their properties, in particular their thermal stability, is a key issue in power electronics. In order to identify the nature of doping by single defects and their migration energy, we have carried out a systematic study of the electronic transport and electron paramagnetic resonance (EPR) of UWGS irradiated at low temperature (20 K), with fast and relativistic electrons. The subsequent isochronous annealing allows us to deduce information on the thermal stability of the created defects. The evolution of the EPR following the same isochronous annealing protocol allows us to identify the nature of the defects involved in their migration.

Our experimental platform consists of a Pelletron accelerator delivering an electron beam up to 2.5 MeV coupled to a closed-cycle hydrogen liquefier. Immersion of the samples in liquid hydrogen during irradiation prevents defect migration and agglomeration. In our previous experiments, consisting of incremental irradiation intercalated with Hall effect and resistivity measurements, we demonstrated that in Ga_2O_3 and GaN, the doping effect of vacancies on the Ga sublattice is of acceptor type, leading to a downward shift of the Fermi level upon low-temperature electron irradiation. Isochronous annealing of Ga_2O_3 irradiated at low doses (below 200 mC/cm²) revealed a defect migration threshold at 120 °C, followed by a full recovery of the initial free carrier concentration. Complete recovery from irradiation damage occurring during the single annealing step, is attributed to Ga vacancy migration. Surprisingly, we do not observe the expected annealing of the donor-type oxygen vacancy. A possible explanation is the migration of these defects occurring below room temperature and their annihilation during transfer from the irradiation chamber filled with liquid hydrogen.

The same annealing protocol applied to samples irradiated at higher doses (above 1 C/cm²) results in a shift of the annealing step towards higher temperatures, resulting in the appearance of defects with higher migration energy. This reduction in thermal stability is attributed to the formation of defect aggregates.

Investigating the blistering mechanisms of β-Ga_2O_3 under light ion implantation

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The current energy transition is accelerating the electrification of uses. It is estimated that 30% of the global electricity undergoes a conversion through power electronic devices [1]. Improving the energy efficiency of these devices is therefore crucial. SiC and GaN wide bandgap semiconductors are already being used to meet this challenge. However, their bulk crystal growth processes are expensive and energy-intensive [2]. This is where β-Ga_2O_3 stands out. In addition to having a wide bandgap (4.8 eV) and a high breakdown field (8 $MV.cm^{-1}$), it can be manufactured by liquid phase crystal growth [3], which is more energy-efficient and cost-effective than the growth of other wide bandgap materials. However, Ga_2O_3-based power devices suffer poor thermal management capabilities, due to the very low thermal conductivity (0.15 $W.cm^{-1}.K^{-1}$) [4] of this material, preventing this technology from being widely adopted in the industry.

To address this issue, we study the transfer of a thin layer of β-Ga_2O_3 onto a high thermal conductivity substrate, such as Si or SiC. The transfer is based on the Smart Cut™ technology, which involves implanting the β-Ga_2O_3 substrate with light ions (H^+ or He^+) to create defects near the surface, bonding it to the receiver substrate, and then annealing. During annealing, gas blisters form at the defects and propagate a crack leading to the transfer of a thin layer of material [5].

In this study, we characterized the initial (001)-oriented β-Ga_2O_3 substrates, notably highlighting line-shaped defects oriented along the [010] axis [6]. Then, several ion implantation conditions were explored (He^+ and H^+ at different fluence values) to achieve the blistering of β-Ga_2O_3. The presence of blisters upon ion implantation and annealing on a free surface confirms the possibility of material transfer if bonded on a receiver substrate.

At this stage, He^+ implantation seems to indicate better results with the presence of larger and exfoliated bubbles. Additional studies on implantation conditions are ongoing in order to evaluate the impact on the crystalline quality of the Ga_2O_3 thin film after layer transfer. These preliminary studies will enable the fabrication of β-Ga_2O_3/β-Ga_2O_3 homostructure and β-Ga_2O_3/Si and β-Ga_2O_3/SiC heterostructures in the near future.

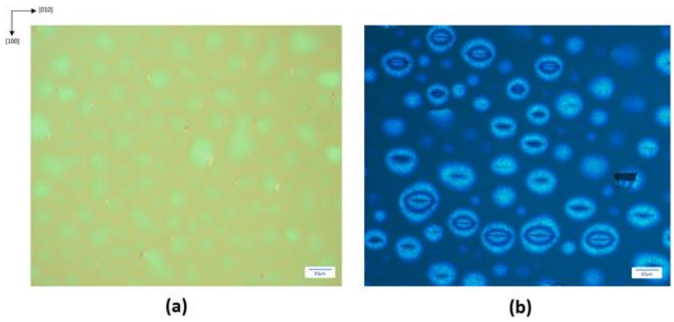

Figure 1. Optical top view microscopy images of blistered β-Ga_2O_3 (001) after annealing at 850°C for 1h of (a) He^{2+} implanted and (b) H^+ implanted samples.

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Core Shell ZnO-Ga_2O_3 Nanowire Heterostructures for Piezoelectric Devices

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ZnO nanowire arrays are promising building blocks for a wide variety of applications, including piezoelectric devices harvesting the ambient mechanical energy [1]. In that context, the piezoelectric performance of ZnO nanowires is strongly governed by the screening effect coming from the high density of free electrons in their centre [2] and by the passivation effect originating from the high density of surface traps [3]. However, the coupling of both effects and their exact role on the piezoelectric potential generated under mechanical solicitation are still under debate.

To address that issue, we perform the unexplored growth of ZnO nanowires coated with a Ga_2O_3 amorphous shell by using chemical bath deposition and atomic layer deposition, respectively (*Figure 1*). The thickness of the Ga_2O_3 amorphous shell is tuned in the range of 1-10 nm by varying the cycle number by ALD. A further thermal annealing under O_2 atmosphere at different temperatures is achieved to assess the crystallization process of the amorphous Ga_2O_3 shell. The structural morphology of core shell ZnO nanowire heterostructures is investigated using scanning and transmission electron microscopy, as well as X-ray diffraction and Raman spectroscopy. The chemical composition of the shell is assessed by X-ray photoelectron spectroscopy, while the optical properties along with their surface properties are measured by 5K cathodoluminescence spectroscopy in both continuous and time-resolved modes. Eventually, the piezoelectric potential in core shell ZnO nanowire heterostructures is carefully determined by piezoelectric force microscopy measurements. The findings open new perspectives based on the development of core shell ZnO-Ga_2O_3 nanowire heterostructures, which are poorly investigated for piezoelectric devices.

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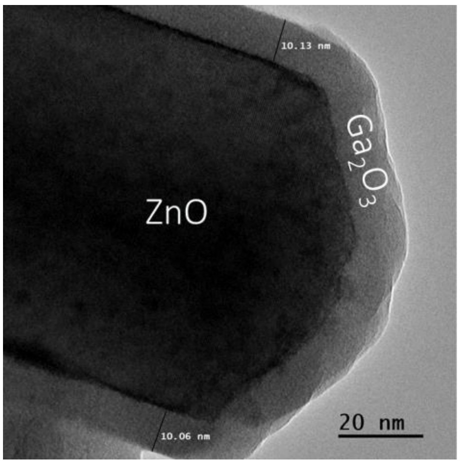

Figure 1. HRTEM image of a single core-shell ZnO-Ga_2O_3 nanowire.

The Beauty of Ga_2O_3 and $ZnGa_2O_4$ Electronic Properties

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A new generation of UWBG semiconductors will open new territories for higher power rated power electronics and solar-blind deeper ultraviolet optoelectronics. Gallium oxide - Ga_2O_3 (4.5-4.9 eV), has recently emerged pushing the limits set by more conventional WBG (~3 eV) materials such as SiC & GaN as well as for transparent conducting oxides (TCO) like In_2O_3, ZnO and SnO_2 to name a few. While there are several *n*-type transparent semiconductor oxides (TSO) for optoelectronic applications their required *p*-type counterpart oxides are known to be more challenging. We have demonstrated that Ga_2O_3 is also the intrinsic (or native) *p*-type TSO. [1] A low activation energy of conductivity as E_{a2} = 170 ± 2 meV was determined, associated to the $V_O^{++} - V_{Ga}^{-}$ native acceptor defect complex. The incorporation of Zinc impurity effects the electronic properties of Ga_2O_3 thin films grown by MOCVD technique in a very divers way. When Zn is <1%, ie. doping case, the conductivity of Ga_2O_3:Zn film was remarkably increased by three orders of magnitude, showing a long-time stable room-temperature hole conductivity with the conductivity activation energy of around 86 meV.[2] While "alloying" case resulting to $ZnGa_2O_4$ (Eg~5eV) spinel structure with both n and p type native conductivity thanks to cation inversion. [3,4,5]

In 2019, we first reported [6] a two-dimensional electron gas (2DEG) onto beta-Ga_2O_3, a solid that is a pure insulator in its bulk but has a metallic conductive termination presenting a two-dimensional conductive channel at its surface. β-Ga_2O_3 thin films exhibited degenerate semiconductor conduction with a room temperature $n = 8\times10^{18}$ cm^{-3} electron concentrations and μ = 19 cm^2/Vs Hall electron mobility. Under the Thomas-Fermi approximation, the sheet charge concentration of the 2DEG is $n_s \sim 2\times10^{14}$ cm^{-2}. This 2DEG was found to be resistant to high dose proton irradiation (2 MeV, 5×10^{15}cm^{-2} dose) and was largely invariant (metallic) over the phenomenal temperature range of 2 K -850 K. In 2023, we first reported [7] a two-dimensional hole gas (2DHG) onto beta-Ga_2O_3. Although two-dimensional electron gases have been realized in a number of semiconductor surfaces, examples of two-dimensional hole gases (2DHG) - the counterpart to 2DEG - are still very limited.

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Thin Film Deposition and Simulation of β-Ga_2O_3 Power Devices for High Voltage Applications

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β-Ga_2O_3 is a Wide Bandgap material (~4.7eV) with high critical field (~7 MV/cm) and High Baliga's Figure of Merit (~3484), which finds application in high power devices [1]. β-Ga_2O_3 MOSFETs suffers from premature breakdown due to the catastrophic dielectric failure at the drain side of the gate [2]. The electric field at the drain side of the gate, should be normalized, to achieve smooth electric field profile, which will enhance the breakdown voltage. In this work, design exploration of β-Ga_2O_3 MOSFET is performed to improve the breakdown voltage and Baliga's Figure of Merit (BFoM). High-κ dielectric material TiO_2 helps to reduce the electric field peak at the gate edge towards the drain side. Incorporating high-κ dielectric TiO_2, stacked with Al_2O_3, hence Stacked dielectric gate (SDG) oxide, helps to improve the breakdown voltage by 20%. On reducing the doping concentration, the breakdown voltage increases at the cost of increased R_{ON}. At channel doping of $8\times10^{16}cm^{-3}$, the Al_2O_3(5nm)/TiO_2 (20nm) dielectric configuration achieves 40% more BFoM than standalone Al_2O_3(25nm) dielectric. Subsequently, the effect of the box channel layer on the SDG oxide comprising a high-κ dielectric TiO_2 layer is systematically explored to enhance the breakdown voltage. The BFoM reaches 126.1 MW/cm^2 for device having channel doping of $2\times10^{17}cm^{-3}$ with box thickness and doping of 200nm and $2\times10^{16}cm^{-3}$, respectively. Subsequently, for the box doping of 2×10^{16} cm^{-3}, the BFoM increases 25.5 times, for the channel doping of 8×10^{17} cm^{-3}. Thus, introducing a low doped box layer configuration significantly improves the breakdown voltage and BFoM of the SGD β-Ga_2O_3 MOSFET. Subsequently, deposition of Sn doped β-Ga_2O_3 thin film on Fe:doped Ga_2O_3 substrate is performed using MOCVD. The Sn doped thin film is characterized using Hall instrument to check the carrier concentration and activation energy.

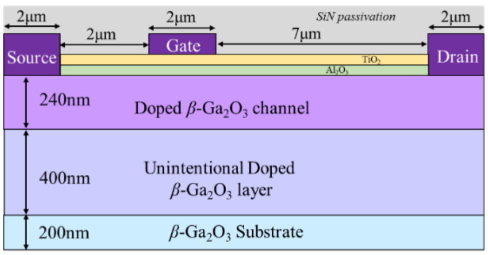

Fig. 1 Schematic Structure of the Stacked Gate Dielectric

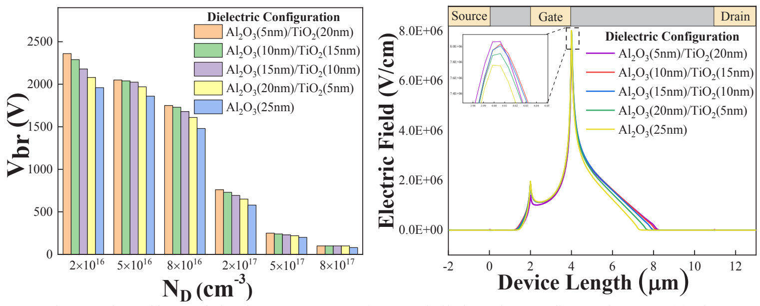

Fig. 2 The effect of doping concentration and dielectric configuration on (a) the breakdown voltage (b) electric field distribution at V_{DS}=700V.

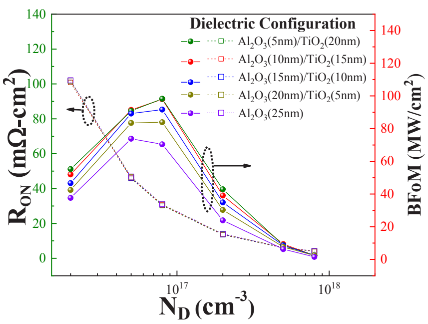

Fig. 3 The effect of doping concentration and dielectric configuration on the BFoM and R_{ON}

Fig. 4 point Vander Pauw configuration performed with Ag paste and wire leading to ohmic contact.

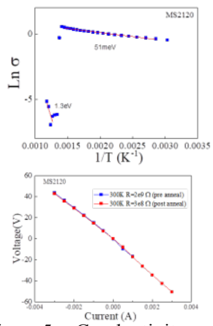

Fig. 5 Conductivity and Ohmicity measurement Sn doped β-Ga_2O_3 thin film.

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A New Route to Efficient β-Ga_2O_3 p–n Junctions: Electrical and Defect Characterization of Phosphorus Ion Implantation

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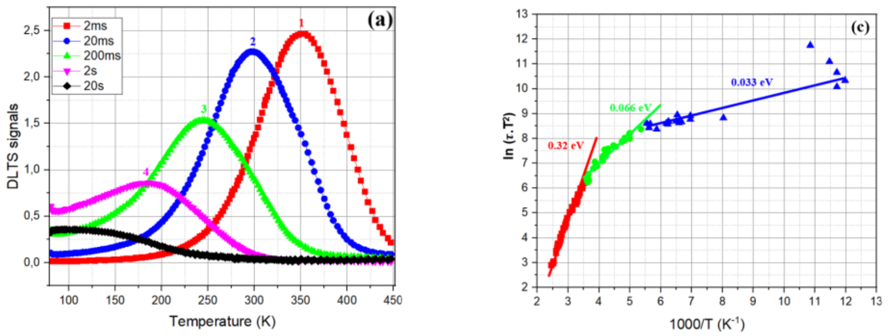
β-Ga_2O_3, an ultra-wide bandgap (UWBG) semiconductor, holds great promise for power electronics due to its exceptional properties and the availability of large-area wafers [1]. However, achieving stable and efficient p-type conductivity remains challenging, restricting the advancement of bipolar devices. Recently, phosphorus (P) ion implantation has been proposed as a promising technique to induce room-temperature p-type conduction [2,3].

In this work, we report the electrical behavior and deep-level defect characterization of vertical p–n diodes fabricated by phosphorus (P) implantation in a 600 nm undoped β-Ga_2O_3 homoepitaxial layer grown by MOCVD on a Sn-doped (010) β-Ga_2O_3 substrate ($N_D \sim 10^{19}$ cm^{-3}). Multi-energy (40–100 keV) and multi-dose (1×10^{13} to 1.6×10^{14} ions/cm^2) implantation resulted in a flat phosphorus profile. Rapid thermal annealing at 1100 °C for 10 s activated the dopants and enabled p-type conduction. The devices, realized with Ni/Au (p-type) and Ti/Al/Ni/Au (n-type) ohmic contacts, were characterized by I–V, C–V, and deep-level transient spectroscopy (DLTS). C–V profiling showed a built-in potential of 3.64 V and an acceptor concentration of approximately 4.5×10^{18} cm^{-3}, consistent with previous reports [2]. DLTS revealed multiple trap states between 0.033 eV and 0.32 eV above the valence band, rather than a single dominant defect level. These traps were localized in the implanted region and are likely related to the implantation process. Recent studies have also reported the observation of shallow acceptor levels associated with Anderson disorder in similar samples [4].

Current studies aim to investigate the origin of the defect distribution and its link to p-type conductivity. These results highlight the key role of phosphorus implantation in deep-level defects and its impact on β-Ga_2O_3 p–n junction performance, offering insights for improving UWBG devices.



Figures: DLTS response at varying time windows – Arrhenius plot

[1] Qin, Yuan, et al. " *Japanese Journal of Applied Physics* **62**. SF, SF0801 (2023)
[2] Horng, Ray Hua, et al, *Materials Today Advances* **20**, 100436 (2023)
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WORKSHOP ON GALLIUM OXIDE AND RELATED MATERIALS

Technology Optimization for a Ga2O3 power Schottky diode fabrication

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Monoclinic β-Ga2O3 is an ultra-wide bandgap (UWBG) semiconductor (Eg=~4.8 eV) with a high breakdown electric field (8MV/cm) [1]. These properties result in a Baliga Figure of Merit (BFOM) 10 times higher than SiC and 4 times higher than GaN [2]. These characteristics together with the feasibility of largescale wafer (4 inches nowadays) make Ga2O3 a very promising candidate for high power electronics towards the 10 kV range. Nevertheless, p type material is still not available. Consequently, in order to develop Ga2O3 technology and demonstrate material potential we target the realization of a vertical Schottky diode (Fig1a) with passivation and optimized edge termination.

Toward this end, the following steps have been or will be studied:

- Ohmic contact for RON optimization (circular transfer length method (CTLM) for specific contact resistivity)
- Schottky contact optimization (I-V, C-V for barrier height, ideality factor, leakage mechanism evaluations)
- Plasma etching optimization for MESA or etched guard ring realization
- Passivation material choice and optimization
- Diode structure and design optimization by TCAD simulation

Results on CTLM for different metal stacks (Ti/Al, Ti/Al/Pt, Ti/Au) after rapid thermal annealing (RTA) will be presented. The results show ohmic contacts with very low total resistances within 1Ω. The extracted specific contact resistivities are in the range of $10^{-4}\Omega \cdot cm^2$.

For the Schottky diode, Ni and Pt have been selected from literature results. Both metals will be deposited by sputtering and results will be compared in order to evaluate the performance of each metal.

Optimization of Inductive Coupled Plasma Reactive Ion Etching (ICP-RIE) using BCl_3/Ar is in progress. Initial results show etch rates of 35 nm/min (Oxford ICP) and 89 nm/min (Sentech ICP), compared to 135 nm/min reported in literature [3] for a Sentech ICP system under similar etch conditions. The discrepancy is due to the sample's orientation, (001) in our case versus (−201) in the literature. AFM and SEM characterization of side walls and etched surfaces will be presented. A sidewall angle around 82° has been observed. (Fig1b)

Finally, the 1D simulation of a vertical punch-through structure using impact ionization method with Sentaurus parameters have shown good accordance of the theoretical data within the literature regarding breakdown voltage. Thanks to this first calibration, simulations have been next used for evaluation of different structures' optimization.

[1] A. J. Green et al., "β-Gallium oxide power electronics," APL Materials, vol. 10, no. 2, p. 029201, Feb. 2022

[2] S. J. Pearton et al., "A review of Ga2O3 materials, processing, and devices," Applied Physics Reviews, vol. 5, no. 1, p. 011301, Mar. 2018

[3] Amit P. Shah, Arnab Bhattacharya, "Inductively coupled plasma reactive-ion etching of β-Ga2O3: Comprehensive investigation of plasma chemistry and temperature." J. Vac. Sci. Technol. A 1 July 2017; 35 (4): 041301.

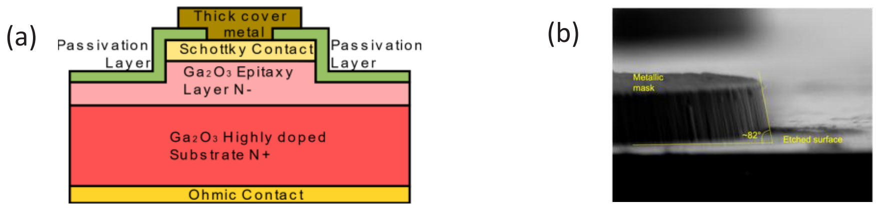

Figure 1. (a) Previewed Schottky diode's structure (b) Cross-sectional SEM image of an etched sample by Sentech ICP system

Optimization of Ti/Au Ohmic Contacts on β-Ga_2O_3

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β-Ga_2O_3 is an ultra–wide-bandgap (UWBG) semiconductor (E_g ≈ 4.7–4.9 eV) with a high theoretical critical field (~ 8 $MV.cm^{-1}$) and a unipolar Baliga figure of merit exceeding that of GaN and SiC. Combined with the availability of low-cost, melt-grown bulk substrates (Edge Defined Film Fed Growth, Czochralski method), these attributes make β-Ga_2O_3 a compelling platform for scalable power electronics [1]. However, the intrinsically low thermal conductivity of β-Ga_2O_3 (~ 11–27 $W.m^{-1}.K^{-1}$) magnifies the thermal impact of resistive losses, therefore, contact resistance becomes a key loss channel. Minimizing the specific contact resistivity ρ_c mitigates the interfacial voltage drop and Joule heating and thereby enhances current density, reduces on-resistance, accelerates switching, and improves reliability [2]. In this work, the post-metallization annealing temperature is optimized for Ti/Au contacts on β-Ga_2O_3 (–201) with a doping level of 2.2×10^{17} cm^{-3} to reduce the contact resistance, where the specific contact resistivity is extracted by using the circular transfer length method (C-TLM). Ti/Au (30/150 nm) test structures were subjected to 60 s rapid thermal annealing (RTA) between 400 and 550°C in high vacuum and in N_2. Figure 1 shows the representative current-voltage (IV) characteristics at a fixed gap of d = 40 µm for the different anneal temperatures and atmospheres. The optimization identifies a vacuum window of 400–460°C. At 460°C, we obtain a low specific contact resistivity of $\rho_c = (3.92 \pm 1.02)\times10^{-4}$ $\Omega.cm^2$, whereas a nominally lower value is determined at 400°C with $\rho_c \approx 5\times10^{-5}$ $\Omega.cm^2$, but the associated uncertainty is large, nevertheless, it exhibits the best IV characteristics. On the other hand, contacts degrade and become non-Ohmic in N_2 at 550°C indicating interfacial over-reaction. Overall, vacuum annealing produces lower ρ_c than annealing in N_2.

[1] Green et al, *APL MATERIALS* No 2, 029201 (2022)
[2] Huan et al., *Nanoscale Res. Lett.* 13, 246 (2018)

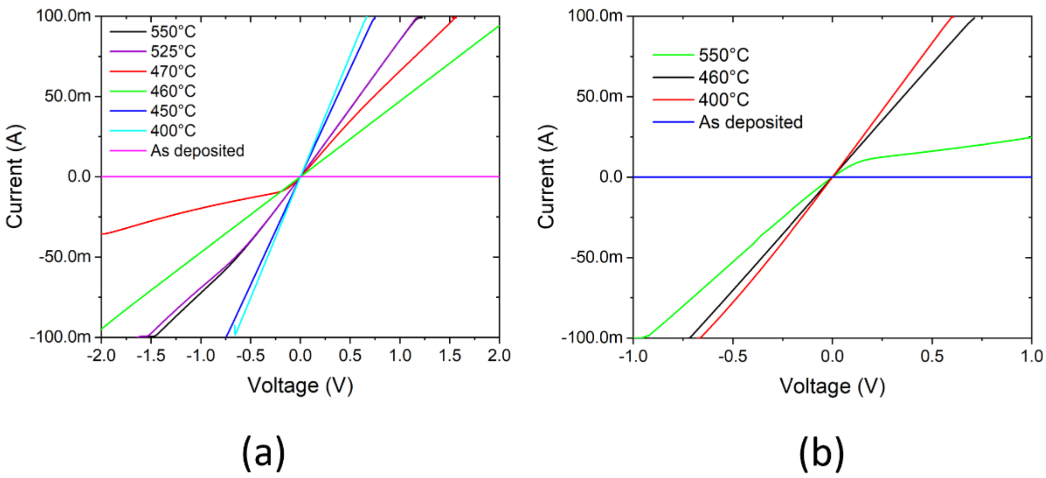

Figure 1. I-V characteristics of CTLM structures at a fixed gap d = 40 µm and different annealing temperatures in a) vacuum and b) N_2.

Study of the Schottky barrier height distribution in β-Ga_2O_3 diodes

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Schottky contacts are widely used for power rectification, voltage clamping, high-speed switching circuits and solar photodetectors. Interface defects between metal and semiconductor are known to reduce the barrier height, thus degrading the rectifying behavior of the junction. In this work, we demonstrate that bulk defects can also contribute to Schottky contact degradation.

Vertical Schottky barrier diodes have been performed using Ti/Au for the Ohmic contact on the back side and Ni/Au for the Schottky contact on the top. The first set of diodes was carried out with a commercial β-Ga_2O_3 (-201) substrate grown by Edge defined Film fed Growth (EFG) from Novel Crystal Technology with a doping level at 4.3×10^{17} cm^{-3}. The second set of diodes was realized with an 11 µm epitaxial layer grown by Hydride Vapor-Phase Epitaxy (HVPE) on a Sn-doped β-Ga_2O_3 (001) substrate. The doping levels of the epitaxial layer and Sn-doped substrate are 2.1×10^{16} cm^{-3} and 7×10^{18} cm^{-3}, respectively.

Deep Level Transient Spectroscopy (DLTS) has allowed the detection of bulk deep traps in both sets of diodes. Three main traps E2, E2* and E3 were identified with a concentration of the order of 10^{15} cm^{-3} in the EFG commercial substrate, whereas traps E1, E2 and E2* were detected in the HVPE epitaxial layer with a concentration of the order of 10^{13} cm^{-3}.

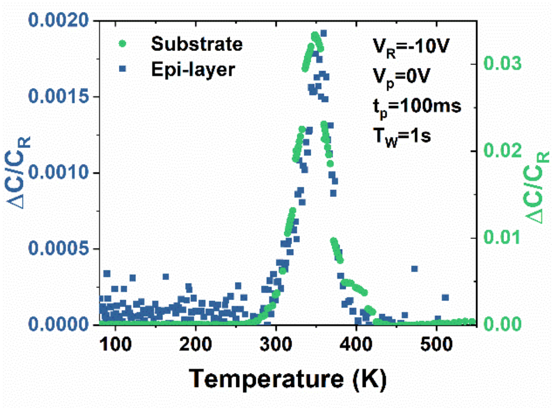

Figure 2 : DLTS spectra obtained on EFG substrate and HVPE epitaxial layer.

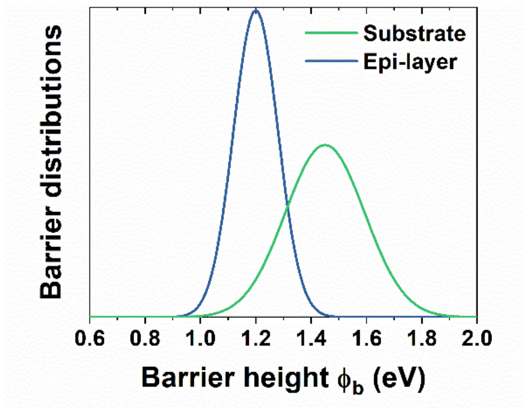

Figure 1 : Distribution of Schottky barrier heights at 0 V for diodes performed on EFG substrate and HVPE epitaxial layer.

Barrier heights and ideality factors extracted from current-voltage measurements are temperature dependent. Assuming barrier inhomogeneities at the Schottky contacts [1-2], we were able to fit the experimental data by considering a Gaussian distribution of barrier heights. We found a correlation between Gaussian barrier height distributions and the concentrations of deep traps. In diodes performed on the EFG substrate, the higher concentration of traps (Figure 1) is associated with a broader Gaussian distribution of Schottky barrier heights (Figure 2). Furthermore, the standard deviation is more sensitive to voltage variation for diodes fabricated on the EFG substrate than for those performed on the HVPE layer. Barrier height inhomogeneities are therefore greater for diodes realized on the EFG substrate. This result can be explained by the higher concentration of defects observed from the bulk to the surface.

[1] J. H. Werner and H. H. Güttler, J. Appl. Phys. 69, 1522 (1991); doi: 10.1063/1.347243
[2] T.-H. Yang, H. Fu, H. Chen and al., J. Semicond. 40, 012801 (2019); doi: 10.1088/1674-4926/40/1/012801

Emerging Vertical Ga_2O_3 PiN Diodes for High-Power Conversion and Protection

Tom Micottis[1], Katir Ziouche[1], Farid Medjdoub[1]

[1] IEMN, WIND group, CNRS, University of Lille, Villeneuve-d'Ascq, France

Societies worldwide are increasingly shifting toward electricity-based systems. This transition drives a growing demand for advanced power devices. Components based on Wide BandGap (WBG) materials already cover applications in the 600 V/1200 V range, while other fields require devices operating beyond 3 kV, relevant to High Voltage (HV) conversion and protection in electricity distribution, SMART grids, onshore wind (3.3 kV) offshore (6.5 kV), rail transport, and charging electric vehicles from HV (22 kV) lines.

Recently, three Ultra-Wide BandGap (UWBG) materials have attracted considerable attention for HV applications. Among them, Gallium Oxide (Ga_2O_3) stands out, compared to GaN and SiC, as the only material that can be produced via liquid-phase growth using conventional drawing processes.

Theoretical predictions indicate that Ga_2O_3-based devices can outperform other WBG and UWBG counterparts for very high-power applications. Furthermore, the expected cost reduction of 6-inch substrates to around \$300 by 2030 will enhance their commercial viability.

This project focuses on the design and fabrication of Ga_2O_3-based devices using TCAD Silvaco tools, combined with experimental validation. The primary objective is a PiN diode with a breakdown voltage of 10 kV and a high on-state current above 10A, integrated into a dedicated packaging solution.

The initial phase of this project has addressed the optimization of Ga_2O_3 etching processes and the fabrication of Schottky diodes with mesa structures as a preliminary step toward PiN diodes as the Figure 1 is describing it.

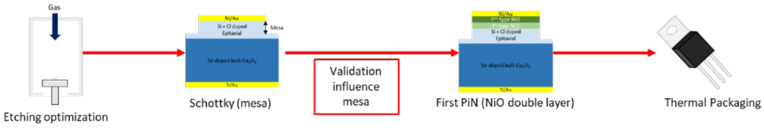

Figure 1: Schematic of the different steps of the first phase of the project

The key innovation of this work is the quantitative determination of the mesa depth required to achieve a substantial increase in breakdown voltage, thereby providing a practical design rule for Ga_2O_3 HV devices. The Figure 2 shows the breakdown voltage of Schottky diodes compared to different mesa thickness. Diodes have a 226µm diameter and have the same drift thickness as well as the same doping level. In parallel, a tailored thermal management packaging solution is being developed to significantly improve heat dissipation, which directly enables higher on-state current capability. The next steps involve fabricating additional Schottky diodes to confirm the influence of the mesa geometry, followed by the realization of PiN diodes with a double-layer p-doped NiO structure. Finally, packaging concept will be validated on Ga_2O_3 high power.

Thickness Etched (µm)	Breakdown Voltage (V)
0,5	864
0,5	1001
3,4	1033
2	1118
2	1243
3,4	1283
3,1	1437
3,4	1604

Figure 2: Table of breakdown voltage vs mesa thickness for Schottky diodes of 226µm diameter.

New perspectives for the development of Ga_2O_3-based detectors for dosimetry in FLASH radiotherapy

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Ga_2O_3 is currently being extensively studied for X-ray detection, whether used as a photodetector or as a scintillator [1]. In this study, we investigate the possibility of developing X-ray detectors for dosimetry in FLASH radiotherapy in which Ga_2O_3 is used simultaneously as a radioelectric and radioluminescent transducer. To establish this proof of concept, we developed a metal-semiconductor-metal structure, which is coupled to an optical fiber on its edge as illustrated in Figure 1.a. The photocurrent was collected at the device electrodes, while the scintillation photons at the output of the optical fiber were detected by a photomultiplier tube. Signals from these two channels were acquired simultaneously as shown in figure 1.b. This prototype was characterized during irradiation with a synchrotron micro-radiotherapy beam at dose rates between 183Gy/s and 4749Gy/s, with average beam energies between 52 and 95keV.
The results of this study confirm the good properties of the Ga_2O_3 transducer for dosimetry in FLASH radiotherapy in terms of linearity, measurement dynamics, and radiation hardness. In addition, they also show (i) that it is possible to detect the scintillation signal and the radioelectric signal simultaneously, and (ii) that for the same irradiation, the characteristics of these signals differ in terms of response speed and transduction efficiency, as shown in figure 1.c. This proof of concept opens up new perspectives for the design of innovative Ga_2O_3-based detectors for dosimetry in FLASH radiotherapy, as well as for studying the aging mechanisms of this material under high dose rate irradiation.

[1] Venkata Prasad et al, *Materials Today Physics* **35**, 101095 (2023)

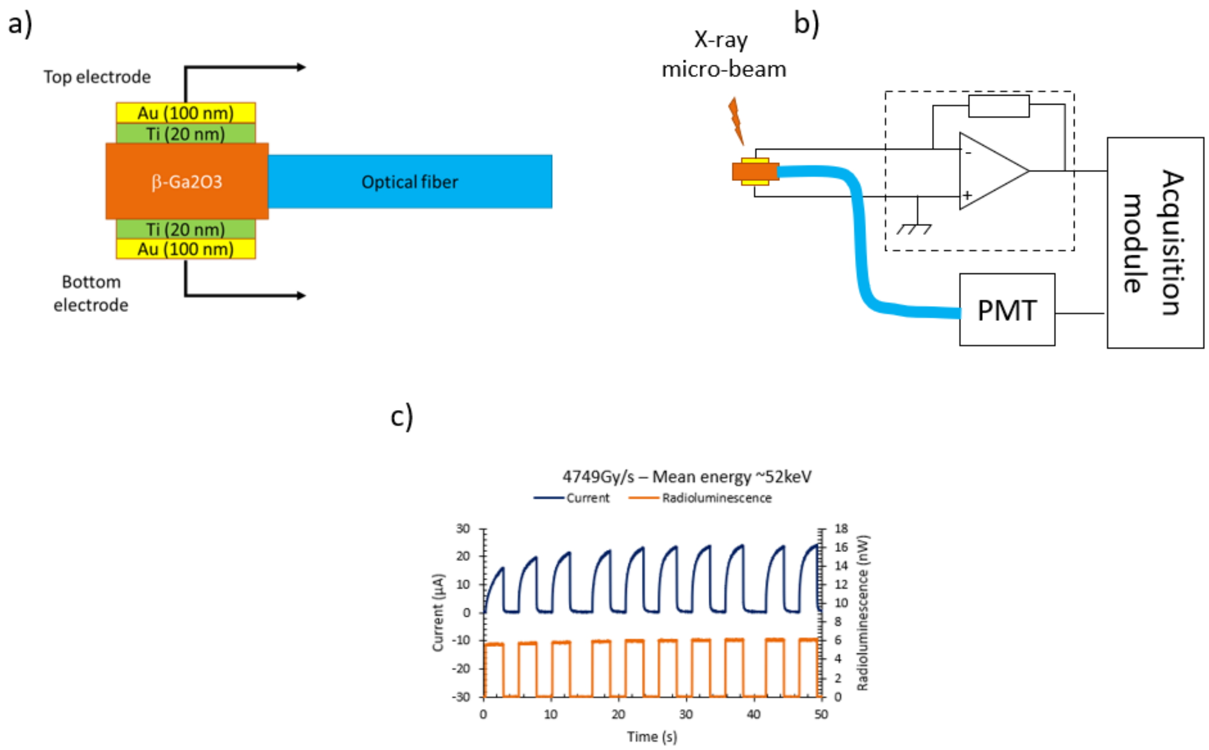

Figure 1. a) Detector structure, b) Readout diagram and c) transient radiolelectric and radioluminescent response to pulsed irradiations

New processes for the Spatial Atomic Layer Deposition (SALD) of functional materials: Ga_2O_3 from DMP-based non-pyrophoric precursors

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Spatial Atomic Layer Deposition is a variant of ALD offering the same unique assets but at deposition rates up to two orders of magnitude faster, thus being more appealing for industrial mass production.[1,2] This is achieved by having a continuous injection of precursors in different regions of the reactor separated by inert gas regions. SALD can be performed using many different engineering approaches and both at low and atmospheric pressure, and even in the open air, i.e. without the need of a deposition chamber, when using close proximity manifold approaches.[3] Finally, it has a lower environmental impact than conventional ALD.[4,5] While common ALD precursors are in principle suitable for SALD, when working at atmospheric pressure, some precursors may lack sufficient volatility or stability. Additionally, in the case of open-air approaches the use of highly-reactive, pyrophoric or highly-toxic precursors can seriously jeopardize the transfer of SALD processes form lab to fab.

I collaboration with Prof. Devi's team at IFW Dresden, we are developing new SALD processes using original, non-pyrophoric precursors. In particular, we have shown that $Zn(dmp)_2$ (bis-3-(N,N-dimethylamino)propyl zinc) is a suitable alternative to the commonly used pyrophoric DEZ (dyethylzinc).[6] Currently we are exploring the use of $Ga(dmp)Me_2$ as an alternative to pyrophoric TMGa (trimethylgallium) for the SALD deposition of Ga_2O_3. Our preliminary results will be shown in this presentation.

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4. Niazi, M. F. K., *et al. ACS Sustain. Chem. Eng.* **11**, 15072 (2023).
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Advanced Transmission Electron Microscopy for optimization of gallium oxide thin films

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In 2018, it was estimated that nearly 30% of global electrical energy was passed through power electronics systems [1]. In this context, Wide Band Gap (WBG) and Ultra-Wide Band Gap (UWBG) semiconductors are emerging as the next generations of materials, enabling significantly higher efficiency compared to silicon. Despite its widespread use, silicon exhibits substantial power losses, with up to 90% dissipated as heat [1].

Among UWBG semiconductors, gallium oxide stands out as a promising candidate due to its high breakdown field of 8 $MV \cdot cm^{-2}$ and its potential for cost-effective large-scale production [2].Despite significant progress over the past decades, the crystalline quality, impurity control, and electron mobility achieved to date remain insufficient for the fabrication of high-performance vertical devices on an industrial scale. A major challenge lies in increasing the growth rate while preserving high electron mobility and excellent crystalline quality, particularly in thick epitaxial layers. Achieving industrial maturity will require a comprehensive understanding of growth techniques, process parameters, and the mechanisms governing material properties [3]. A detailed characterization of material properties requires a technique that combines high spatial resolution with high precision, capable of resolving atomic structures and resolving features from atomic defects to extended structures while also providing insights into their chemical nature. Scanning/Transmission Electron Microscopy ((S)TEM) fulfills these requirements, with its strength lying in the extensive range of advanced characterization methods now available.

The objective of this thesis is to contribute to the improvement of β-Ga_2O_3 layer quality through advanced (S)TEM techniques - including ptychography, holography and differential phase contrast (DPC), that have been implemented at Grenoble.

[1] Shivani, D. Kaur, A. Ghosh, et M. Kumar, *Materials Today Communications*, vol. 33, p. 104244, déc. 2022
[2] J. Y. Tsao *et al.*, *Advanced Electronic Materials*, vol. 4, nº 1, p. 1600501, 2018.
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Heterostructures Made of Ga_2O_3 for self-powered UV photodetection and power electronics

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[2] *i3N/CENIMAT, Department of Materials Science, NOVA School of Science and Technology and CEMOP/UNINOVA, NOVA University Lisbon, Campus de Caparica, Portugal*

Ultra-wide bandgap semiconductors have attracted a lot of attention in the past decade for applications in UV photodetection and power electronics. The monoclinic β phase of Ga_2O_3, which is the most stable of five crystalline structures, has the advantages of attractive properties, potential low cost and availability of large size substrates through the melt-grown method, as well as the easy control of *n*-type doping [1]. So far, the heterostructures including $(Ga,Al)_2O_3/ZnO$ for self-powered UV photodetection (λ‹280nm) and $(Ga,Al)_2O_3$/diamond for power electronics with a varying chemical composition (from Ga_2O_3 to Al_2O_3) have not been investigated despite their high potential.

This PhD project aims to: **(1)** explore and develop the atomic layer deposition (ALD) of Ga_2O_3 and $(Ga,Al)_2O_3$ thin films to optimize their overall morphological, structural, surface, optical, and electrical properties, and **(2)** achieve an innovative combination with (i) ZnO thin films grown by ALD to form all-oxide heterostructures for self-powered UV photodetectors [2], and with (ii) diamond through the implementation of $(Ga,Al)_2O_3$ thin films as insulator in Metal-Insulator-Metal (MIM) capacitor architectures [3].

[1] S. J. Pearton *et al.*, “A review of Ga_2O_3 materials, processing, and devices,” *Appl. Phys. Rev.*, vol. 5, no. 1, p. 011301, Mar. 2018, doi: 10.1063/1.5006941.
[2] T. Cossuet *et al.*, “ZnO/$CuCrO_2$ Core–Shell Nanowire Heterostructures for Self-Powered UV Photodetectors with Fast Response,” *Adv. Funct. Mater.*, vol. 28, no. 43, p. 1803142, 2018, doi: 10.1002/adfm.201803142.
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[4] A. J. Green *et al.*, “β-Gallium oxide power electronics,” *APL Mater.*, vol. 10, no. 2, p. 029201, Feb. 2022, doi: 10.1063/5.0060327.

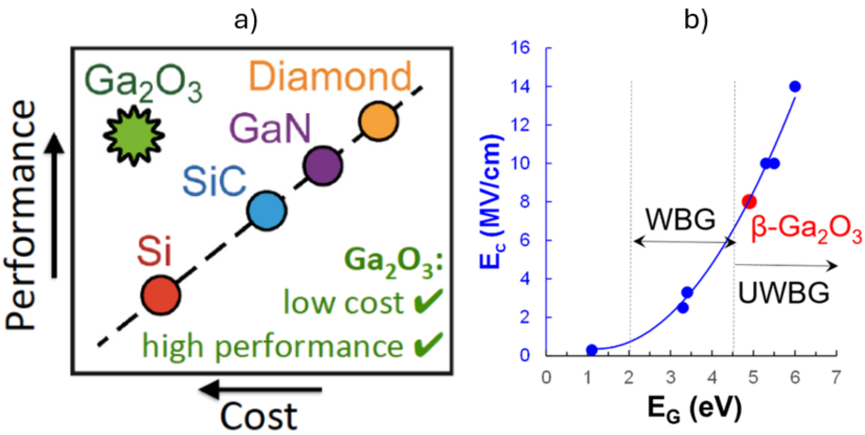

Figure 1. a) performance vs cost of selected semiconductors and b) breakdown electric field vs bandgap identifying WBG (wide bandgap) and UWBG (ultra wide bandgap) ranges [4].

$Ni_{1-x}O/Ga_2O_3$ Heterostructures for Next-Generation Power Electronics

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The transition toward sustainable energy systems and the reduction of CO_2 emissions require power electronic devices capable of operating at higher voltages with enhanced efficiency and reduced switching losses. Wide band gap (WBG) semiconductors such as SiC and GaN have enabled major advances in medium-power applications, including automotive and renewable energy conversion. However, their intrinsic material limits motivate the exploration of ultra-wide band gap (UWBG) semiconductors (Eg > 4 eV) for next-generation, high-voltage applications such as smart grids and transport infrastructures.

Among UWBG oxides, β-Ga_2O_3 (Eg ≈ 4.9–5.3 eV) stands out due to its high critical electric field (>8 MV/cm), good thermal/chemical stability, and the relative ease of achieving n-type conductivity [1]. For high-power electronics, efficient p–n junctions are essential, since they provide strong rectification, high breakdown voltages, and low leakage currents, which are crucial for switching and power conversion efficiency. In this context, NiO is an attractive choice as a p-type partner: it is a wide band gap oxide (Eg ≈ 3.6–4.0 eV), naturally prone to p-type conductivity due to nickel vacancies, and its electrical properties can be tuned via non-stoichiometry or extrinsic dopants [2]. Moreover, NiO has already demonstrated compatibility with oxide thin-film growth techniques and favourable band alignment with Ga_2O_3, enabling the formation of rectifying p–n junctions [3].

My PhD project aims to fabricate and optimize vertical $Ni_{1-x}O$/β-Ga_2O_3 diodes structure, combining epitaxial growth of $Ni_{1-x}O$ thin films by RF sputtering and Sn:Ga_2O_3 by MOCVD, with in-depth characterization of their structural, chemical, optical, and electrical properties. Particular emphasis will be placed on identifying and controlling point defects (donors, acceptors, compensators) in both materials and at the heterointerface.

My work is carried out within the framework of the ANR/PEPR project GOTEN, dedicated to the development of next-generation UWBG semiconductors for power electronics.

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[3] H. Gong et al., *IEEE Transactions on Electron Devices*, 67, 8, 3341-3347 (2020)

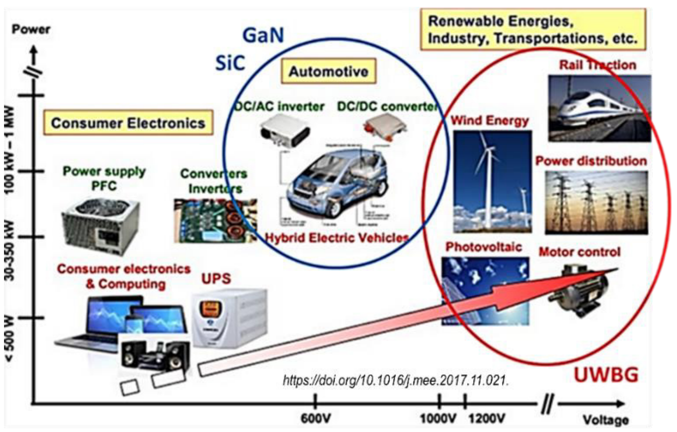

Fig. 1. Major application areas of WBG power devices in a plot of the power vs voltage operation range

Conception, realization and comparison of gallium nitride and gallium oxide based vertical power diodes

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Power converters, essential in numerous application fields, rely heavily on power diodes. However, silicon-based converters face intrinsic limitations in terms of energy efficiency, device miniaturization, and production cost. To overcome these challenges, Wide and Ultra-Wide Band Gap (WBG and UWBG) semiconductors such as gallium nitride (GaN) and gallium oxide (Ga_2O_3) have emerged as promising alternatives [1], [2]. Despite their potential, the realization of devices, particularly vertical architectures, remains difficult on these materials. Mainly due to their low availability and the difficulty of achieving reliable p-type doping [3]. Yet, vertical devices are crucial to achieving compact, high-efficiency components capable of competing with already established wide-band-gap solutions such as silicon carbide (SiC) [4].
The GREMAN laboratory has extensive expertise in the design of lateral and vertical devices on SiC and GaN, and is now extending this work to β-Ga_2O_3 substrates. This thesis proposes to characterize the structural and morphological properties of GaN and Ga_2O_3, realize vertical Schottky diodes (Figure 1) with the aim of comparing the performance of these two materials for microelectronics applications. For this thesis, GaN substrates are provided by CRHEA-CNRS of Valbonne and Ga_2O_3 substrates by Leibniz IKZ of Berlin. Initial characterizations, including AFM and XRD analyses, have already been performed on the provided materials.
In order to finally realize these vertical Schottky power diodes, several technological steps have been undertaken or are currently being considered to identify the technological solutions to be favored for each process step : Cleaning and surface treatment, wet and dry etching of the semiconductors and dielectric materials associated, determination of metals arrangements for electrodes (ohmic and rectifier contacts) with the thermal treatments. The outcomes of this work will contribute to assessing and comparing the potential of GaN and β-Ga_2O_3 for next-generation power electronics.

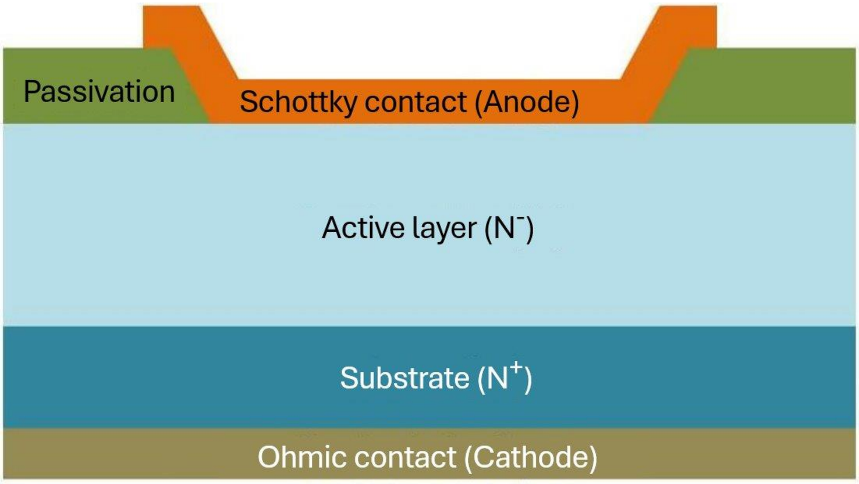

Figure 1. Cross-sectional schematic of a vertical Schottky diode (translated from [4])

[1] F. Roccaforte et al., Microelectronic Engineering 187-188, 66 (2018)
[2] M. Higashiwaki et al., Applied Physics Letters 100, 013504 (2012)
[3] S. J. Pearton et al., Applied Physics Reviews 5, 011301 (2018)
[4] J. Biscarrat, PhD thesis, Université de Tours (2015)

Optimized Packaging of 10 kV Ga_2O_3 Power Module

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Abstract :

Gallium oxide (Ga_2O_3) is an ultra-wide bandgap semiconductor with a critical electric field far exceeding that of SiC and GaN, making it highly attractive for next-generation high-voltage power devices. Within the GOTEN (PEPR Électronique ANR-23-PEEL-0002), my PhD research focuses on the development of packaging solutions for Ga_2O_3 vertical diodes. The project's target is a laboratory-scale diode prototype (TRL4) capable of withstanding 10 kV while delivering forward currents above 10 A. The well-known major challenge for Ga_2O_3 is its low thermal conductivity, nearly an order of magnitude lower than SiC, which complicates heat management under high-power operation. Strategies such as double-sided cooling, diamond integration, and advanced heat sink architectures are under consideration. Indeed, the packaging design is playing a decisive role in enabling effective thermal dissipation while ensuring electrical insulation at 10 kV. The PhD started in June 2025m supervised by LGP for packaging integration and AMPERE for characterization. My work to date has focused on preliminary package design using Catia V5, which will guide upcoming multi-physics thermal simulations using ABAQUS and later experimental validation. This presentation will introduce the GOTEN project context, discuss Ga_2O_3 thermal management challenges, and present initial design activities as the foundation for future simulation and experimental studies.

References:

[1] Catalano, Antonio Pio, et al. "Optimum thermal design of high-voltage double-sided cooled multi-chip SiC power modules." *2019 25th International Workshop on Thermal Investigations of ICs and Systems (THERMINIC)*. IEEE, 2019.

[2] Qin, Yuan, et al. "Recent progress of Ga2O3 power technology: large-area devices, packaging and applications." *Japanese Journal of Applied Physics* 62 SF (2023): SF0801.

Advantages: high thermal package,
SiC die integration
Challenges: electric field insulation

Figure 1. TO-254 Package with SiC integration for preliminary work