

LIGHTinPARIS	Marie Skłodowska-Curie Actions Second call for COFUND PhD fellowships
Employer	University Paris-Saclay
Doctoral School	EOBE (Electrical, Optical, Bio-Physics and Engineering)
Selection Domain	EOBE (Electrical, Optical, Bio-Physics and Engineering)
Supervision	
Thesis Director	Charles RENARD
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Group / Team (website)	SEEDs /Dept Matériaux
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3i Institution - Country	ETH Zurich - Switzerland
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PHD THESIS PROJECT	
SYNOX - Symmetry-Driven Nonlinear Optics in Hexagonal Polytype Semiconductors	
Summary / Abstract	
This project explores crystal-phase control to engineer material properties and unlock new functionalities. Building on a patented breakthrough enabling the growth of metastable hexagonal semiconductor thin films, we will investigate their nonlinear optical behaviour. The anisotropic hexagonal symmetry is expected to provide strong $\chi(2)$ and intrinsic birefringence, enhancing SHG and SPDC for applications in frequency conversion, optical modulation, sensing and quantum photonics. As a first demonstrator, the SYNOX project aims to develop disruptive sources of correlated photon pairs via SPDC in subwavelength AlGaAs-hex films, a key enabler for secure quantum communication. Our vision is to design and integrate miniaturized nonlinear optical devices, paving the way toward fully integrated and scalable on-chip quantum light sources for practical quantum technologies. Principal 3i dimension: international. Second 3i dimension: interdisciplinary Keywords • Information and Communication Technologies (optoelectronics) • Quantum technologies; Nanophotonics (metamaterials, surfaces and interfaces) • Materials (inorganic semiconductor) • Metastable crystal phase, polytypism • Thin layer epitaxy • Nonlinear optics • Secondary harmonic generation, spontaneous parametric down conversion and entangled photons	

SYNOX - Symmetry-Driven Nonlinear Optics in Hexagonal Polytype Semiconductors

Key Objectives

SYNOX 's key objectives are to:

- (i) Grow device-quality AlGaAs-hex thin films
- (ii) Identify the nature of defects and evaluate the hexagonality yield
- (iii) Acquire fundamental nonlinear parameters of AlGaAs-hex specifically SHG response
- (iv) Demonstrate SPDC in AlGaAs-hex thin films

The PhD will extend the synthesis of GaAs-4H (patent) toward GaAlAs-2H films on CdS-2H substrates, addressing Ga diffusion that limits film quality. The candidate will optimize UHV-VPE growth, study optical and electrical properties through advanced characterization, and probe nonlinear responses via SHG and SPDC mapping using an HBT setup.

Project

Context and state-of-the-art of Scientific Research project

The control of crystal phases is an emerging pathway to modify material properties and create on demand new functionalities. The project leverages a recent patented breakthrough achieved by our group [1,2], allowing for the growth of metastable hexagonal-phase semiconductor thin films. This opens large benefits to achieve standard experimental characterization of this new class of materials in thin-film form. First, we aim at providing a full comprehension of the optical properties especially band gap values, nature of light emission lines, carrier dynamics, lifetime of excited states and energy transfer. Importantly, the anisotropic hexagonal symmetry gives rise to strong second order nonlinear susceptibility $\chi(2)$ combined with intrinsic birefringence which will likely enhance the secondary harmonic generation (SHG) and spontaneous parametric down conversion (SPDC) efficiencies [3,4]. Indeed, such new material platform will have strong potential for applications such as frequency conversion, optical modulation and switching, high-speed signal processing, sensing, and quantum photonic circuits. A subwavelength thickness of hexagonal phase of semiconductor is expected to provide a promising pathway on-chip integration for miniaturization and electronic compatibility toward scalable quantum technologies. As a first demonstrator of this platform's capabilities, we aim to demonstrate the emission of entangled photon pairs via spontaneous parametric down conversion.

Description

The synthesis of metastable hexagonal polytype of GaAs-4H has been specifically demonstrated on stabilized ZnS-4H substrates as a proof of principle and the process has been patented. The aim of this doctoral project is to build on this expertise by transferring and optimising the method for the fabrication of GaAlAs-2H thin films on commercially available, stable CdS-2H substrates. A primary major challenge lies in the significant interdiffusion of Ga into CdS, which must be mitigated to prevent the formation of an SGA layer that may hinder the growth of GaAs-2H films. We aim to grow AlGaAs-2H planar thin films with reduced defect density and low impurity level satisfying the requirement of pure crystal hexagonal phase with controlled composition offering a tunable band-gap based on the concentration of Al. The density of stacking faults and dislocations will be considered as a function of growth parameters. Since nonlinear properties

are sensitive to surfaces, interfaces and defects, a particular study will be devoted to analyze the defect nature that will be correlated to the optical response

A thorough theoretical and experimental investigation of the electronic and nonlinear optical properties is necessary to understand how the crystal symmetry and composition affect the nonlinear optical performance of hexagonal AlGaAs-2H for quantum light generation. According to the hexagonal lattice symmetry, for 6mm class crystals only three elements of the nonlinear tensor are expected: d_{33} , $d_{15}=d_{24}$, $d_{31}=d_{32}$. Establishing the relative magnitude of these tensor components will guide the generation of entangled states. Since the c-axis should be in plane with the growth of the 2H crystalline films, we will probe the d_{33} component to have a type 0 emission.

The ETH Zurich team has recently demonstrated background-free bi-photons emission from GaAs-3C nanowires from SPDC in a HBT setup [5]. Here, we aim at measuring the bi-photons emission from $\text{Al}_x\text{Ga}_{(1-x)}\text{As}$ -hex thin films, as promising platforms to have a higher coincidence rate, as well as hyper-entanglement. As reported in [6] tremendous efforts are currently made at miniaturizing the SPDC sources without losing on the conversion efficiency, in order to achieve integrated quantum devices. We will take advantage of the theoretical analysis of the susceptibility tensors $\chi(2)$ as well as the experimental analysis of the SHG response to efficiently probe the $\text{Al}_x\text{Ga}_{(1-x)}\text{As}$ -hex films to generate bi-photons at the near infrared (at 1555 nm) with a continuous wave linearly polarized pump laser emitting at 778 nm. We also aim at characterizing the quantum state with quantum tomography to retrieve the density matrix. The phase matching condition being relaxed in thin films (for thicknesses below the coherence length), we expect a broad spectrum of the emitted bi-photons, which we plan to measure via fiber spectroscopy.

The selected candidate will perform cutting-edge fundamental research in material science and solid state. The PhD student is expected to contribute to:

- improve the crystalline quality of metastable GaAs thin films with UHV-VPE by optimizing the growth parameters (substrate preparation, growth temperature, precursor flow) and limit the Ga diffusion in CdS. A primary challenge lies in reducing extended defects — dislocations and stacking faults.
- identify the nature of the defects and study their optical signature
- investigate the electro-optical properties with various standard characterization methods (ellipsometry, photoluminescence, cathodoluminescence, electroluminescence, Raman spectroscopy, $I(V)$, $C(V)$, EBIC...) to assess the refractive index, the charge carrier concentration, the identification of optically active defects...SNOM provides high-resolution local optical maps that reveal nanoscale inhomogeneities and establish correlations between the crystal structure and the resulting optical response. Complementary techniques (IR absorption, ARPES) can be implemented, and our partners in SOLEIL synchrotron.
- conduct a detailed investigation of the nonlinear response using a prototype polarized SHG [7,8] and a Hanbury Brown and Twiss (HBT) set-up for SPDC mapping [7].

Demonstrating nonlinear optical processes in AlGaAs hexagonal material will open an entirely new research domain in integrated nonlinear optics and quantum photonics, providing a key platform for on-chip quantum light generation. By enabling low-cost, energy-efficient, and industry-compatible quantum photonic technologies, the project strengthens Europe's strategic leadership in next-generation quantum communication and computation. These advancements promise applications in sensing, spectroscopy, infrared imaging, LIDAR, communication and more, potentially impacting fields like metrology, communication and medicine.

Bibliography

- 1) L. Vincent et al., Adv. Materials Interfaces 9, 2102340 (2022) / <https://doi.org/10.1002/admi.202102340>
- 2) H. Melhem et al. Thin Solid Films 812 (2025) 140609. / DOI: 10.1016/j.tsf.2025.140609
- 3) R. Chen et al. Applied Physics Letters 96(5) (2010) / <https://doi.org/10.1063/1.3304118>
- 4) B. Zhang et al. Advanced Functional Materials 31 (2021) / DOI: 10.1002/adfm.202104671
- 5) G. Saeuens et al. Nano Letters 23(8) (2023) 3245-3250/ <https://doi.org/10.1021/acs.nanolett.3c00026>
- 6) Okoth et al. Physical Review Letters 123(26) (2019) 26360 / <https://doi.org/10.1103/PhysRevLett.123.263602>
- 7) A. Mahmoudi et al., PRB110(16) (2024) 165418. / <https://doi.org/10.1103/PhysRevB.110.165418>
- 8) G. Kremer et al. PRM7(7) (2023) 074601 / <https://doi.org/10.1103/PhysRevMaterials.7.074601>

Facilities and quality of research environment available for the researcher

The position is at C2N, a research center in the field of material science, nanophotonics, nanoelectronics, and nanotechnologies. A cleanroom of 2900 m² is dedicated to fabrication processes, growth, epitaxy and characterization. The researcher will benefit from an original home-made cluster tool for the epitaxial growth of III-V and group IV semiconductors equipped with surface analysis probes (XPS and AES). The C2N is equipped with all necessary structural characterization tools (HR-XRD, STEM) as well as all standard optical characterizations such as ellipsometry, FTIR, photoluminescence, electroluminescence and cathodoluminescence. As part of a collaboration with Horiba, a second-harmonic generation (SHG) prototype set-up has been installed on an HR Evolution system at C2N. This implementation enables to perform SHG mapping and polarization-dependent measurements as well as Raman polarized measurements with a commercial set-up.

The PhD will be member of SEEDs group (Visit our website <https://seeds.c2n.universite-paris-saclay.fr/en/research/>). Large part of the optical measurements will be done with the collaboration of the MAT2D team (<https://mat2d.c2n.universite-paris-saclay.fr/en/news/>). It should be emphasized that the collaboration with theorists (in Bochum university) will give the opportunity of comparing and interpreting the results with ab-initio theoretical calculations.

The PhD candidate will carry out short research visits to CEMES in Toulouse (<https://www.cemes.fr/>) to perform complementary TEM and SNOM analyses. These measurements will provide structural and optical characterization at the nanoscale, enabling direct correlations between the crystal quality and the optical properties of the investigated materials.

A secondment is planned in ETH Zurich for one year under the supervision of Rachel Grange (<https://ong.ethz.ch/research.html>). The candidate will investigate bi-photon emission via SPDC in the grown layers by using a HBT set up specifically developed by the team. They can also do quantum tomography to fully characterize the state and retrieve the density matrix. See website for full description of the group (<https://ong.ethz.ch/the-group.html>).

3i Dimension - international

Description and expected outcomes

The success of the SYNOX project relies on the complementary expertise on material growth and optical characterisation. A multidisciplinary consortium with complementary expertise has therefore been established to cover the full value chain from material synthesis to photonic device demonstration. SEEDs team brings unique expertise in the synthesis of metastable semiconductors while the synergy with nonlinear optical characterization (SHG and SPDC) experts ensures that the PhD candidate will receive interdisciplinary training while developing strong experimental and analytical skills. The ETH Zurich group is internationally recognized for its expertise in nonlinear optics and integrated photonics, and will lead the demonstration of SPDC in ultrathin AlGaAs-hex films as well as the proof-of-principle generation of entangled photon pairs.

This project represents a unique opportunity to strengthen a newly forming international consortium, as the ETH Zurich co-supervisor brings indispensable and complementary expertise, enhancing both the scientific scope and the collaborative dimension of the project. Additionally, the collaboration with HORIBA will support the upgrade of the polarized SHG setup and leverage their expertise in these advanced measurements, further reinforcing the project's experimental capabilities and impact.

The project aims to provide the scientific foundation for a future EIC Pathfinder project, targeting potential applications of this new material in nonlinear optics.

Approximate timeline of internships / external stays corresponding to the 3i dimension

- Year 1 (October 2026 – September 2027)

C2N, Palaiseau: Material growth of AlGaAs-4H and 2H thin layers and standard structural and optical characterisations (SEM, Raman, TEM, FTIR...)

- Year 2 (October 2027 – March 2028)

Optimisation of thin layer crystal quality and comprehensive optical characterization, including SHG response of thin films, polarised raman, ellipsometry and cathodoluminescence, SNOM (coll. CEMES). Identification of defect nature (coll. CEMES)

- Year 2 (April 2028 – March 2029)

ETH Zurich: SPDC characterization, demonstration of correlated photon emission, and manuscript preparation. A 12-month secondment is planned at ETH Zurich. The researcher is expected to relocate independently to Zurich for the duration of the secondment, covering their own housing and living expenses. The €150/month allowance will cover minor travel expenses; other costs required for the scientific exchange will be supported by C2N under separate arrangements. ETH Zurich will provide all necessary facilities and consumables for the research and may provide additional salary (that would be necessary (to be defined)).

- Year 3 (March 2029 – September 2029)

C2N, Palaiseau: Final studies of characterisation and manuscript writing.

Profile of PhD fellow

PhD studies and research work require curiosity, creativity, rigour, teamwork, and organisational skills. A minimum B2 level of English is mandatory. The below criteria are specific to the thesis project.

pre-requisite	Applicants with a Master degree in Physics, materials science or solid state physics with strong knowledge in semiconductor physics and optical properties
pre-requisite	Academic background in crystal structures
pre-requisite	Theoretical and / or experimental knowledge in non-linear optics
advantageous	Experience working with laser set up
advantageous	Experience working with epitaxy reactors

Ethics issues in the project as per Horizon Europe Ethics Self-assessment

Section 1. Human embryonic stem cells (hESCs) and human embryos (hEs)			No
Section 2. Humans	No	Section 3. Human cells and tissues	No
Section 4. Personal data	No	Section 5. Animals	No
Section 6. Third Countries	Yes	Section 7. Environment, health and safety	Yes
Section 8. Artificial Intelligence	Yes	Section 9. Other ethics issues	No
Section 10. Crosscutting issue: potential misuse of results			No

6. Third Countries

Collaborations with third countries, in a non-EU or non Horizon Europe associated country, is based on an existing scientific collaboration. ETH Zurich (Switzerland) works in collaboration with the C2N laboratory on this project.

7. Environment, health and safety

All French labs are required to have health and safety procedures in place, which takes into account the use of high-energy light sources such as lasers of class 3 and above, and the use of hazardous / toxic chemical and biological products. The institution and the laboratory comply with the highest safety requirements, and PhD fellows have mandatory health and safety training, with additional training if required.

8. Artificial intelligence

The use of machine learning and artificial intelligence is used to fit data and analyse results. This is typically used to improve fits and complex models with multiple parameters. The data in question is related to physical experiments and is not human data.