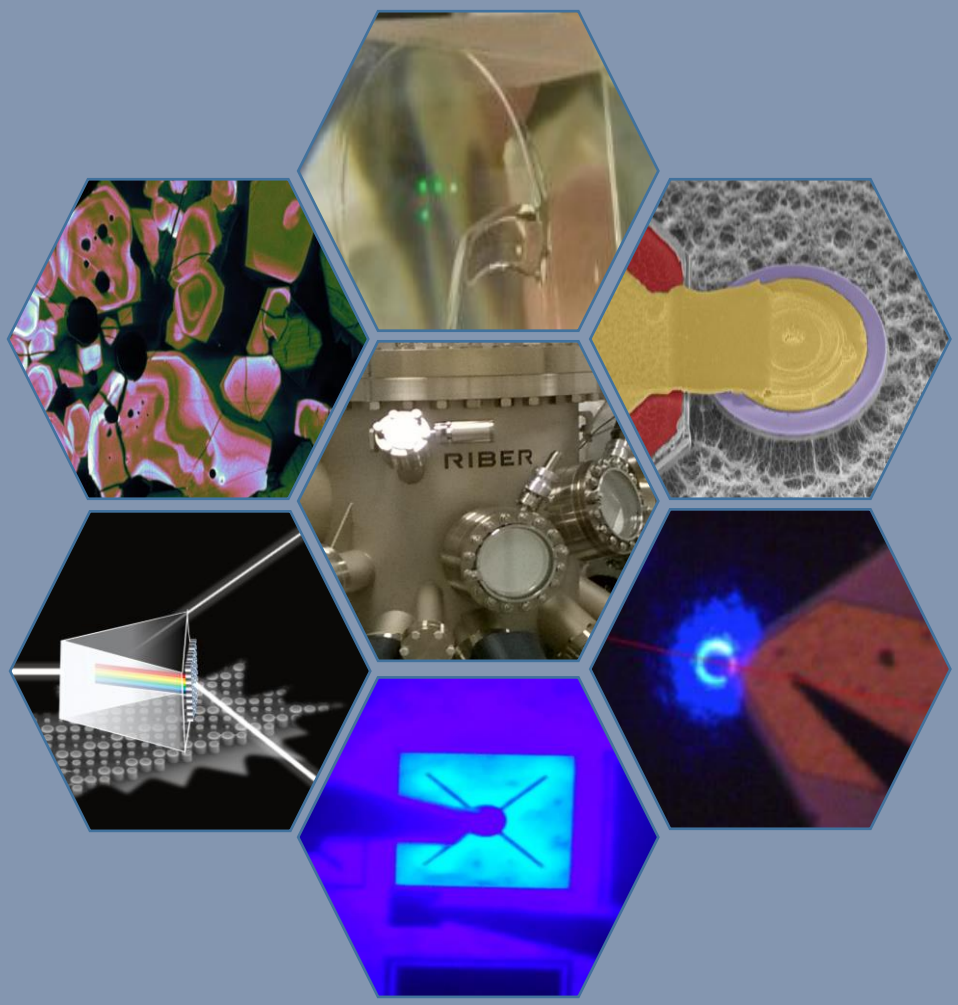
CRHEA

Centre de Recherche sur l'Hétéro-Epitaxie et ses Applications



Highlights 2018

cnrs

UNIVERSITÉ CÔTE D'AZUR

Introduction

This booklet gives an overview of the most striking results obtained at CRHEA in 2018. These highlights cover all the scientific domains where CRHEA is active, from basic physics and photonics to most advanced optoelectronics or microelectronics devices.

The activity of the laboratory is not limited to publications or patents. In 2018, a new molecular beam epitaxy reactor, compatible with 8 inches wafers, has been installed at CRHEA. The delivery of this reactor from Riber has been enabled through an agreement between CRHEA, Riber and an SME. The reactor opens promising perspectives for the development of GaN on silicon for high frequency and power devices.

The R49 reactor is not the only ambitious program managed by CRHEA. The funding for a new ICP-plasma Etching tool has been secured and we expect this clean room equipment to be delivered in 2019.

A network between seven partners of Université Côte d'Azur and two SMEs has been set up with the objective to reinforce the capabilities on material characterizations by microscopy. This advanced material characterization platform has organized a kick-off meeting on September 2018. An application was submitted to receive European fundings in order to purchase a novel high resolution transmission electron microscope that will be managed by CRHEA.

Beginning of 2019, we have received confirmation that the laboratory of Excellence « Ganex » will continue for five more years. Ganex has been over the last decade a real success and we are more than happy to see such ambitious program pursuing the collaboration between academic and industrial partners on III-nitrides.

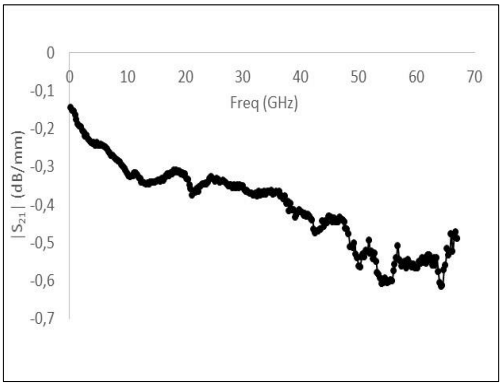
The science cannot be successful without skilled collaborators. A new clean room engineer has joined CRHEA in 2018, reinforcing the manpower and the development capabilities of CRHEATEC.

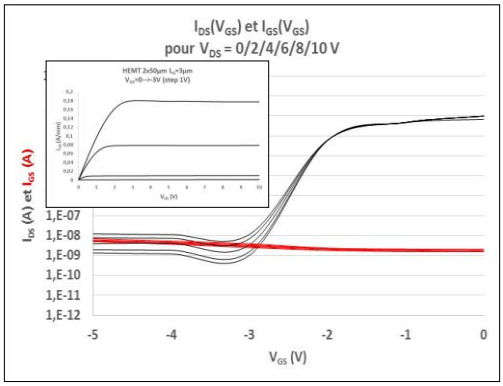
In 2018, CRHEA's website has been fully transformed, you can have a look at http://www.crhea.cnrs.fr/.

Dynamic, responsive, all the spirits that drive CRHEA's activity.

Philippe Boucaud
Director of CRHEA

GaN RF HEMT structures grown by MOCVD on CVD 3C-SiC/Si





Left: *RF propagation losses measured on co-planar wave guides fabricated on GaN-on-3C-SiC/Si buffer.*

Right: *DC transfer and output characteristics of a transistor fabricated with a GaN HEMT on 3C-SiC/Si.*

(Process and device characterizations performed at IEMN).

CVD templates for low cost GaN RF circuits

Volume production of high performance GaN high electron mobility transistor (HEMT) heterostructures on large diameter substrates is a key point for the large scale development of high frequency telecommunications like 5G. In spite of large availability of low cost Silicon substrates, the high surface reactivity and the large mismatch in crystal lattice parameter and thermal expansion coefficient with GaN make the growth tricky. An original solution to overcome these difficulties has been developed with techniques recognized as suitable for the epitaxy at industrial scale. Cubic Silicon Carbide (3C-SiC) templates grown by CVD on high resistivity Silicon with diameter up to 100 mm have enabled the MOCVD epitaxy of AlGaN/GaN structures with high resistivity buffer inducing low RF propagation losses and compatible with the fabrication of transistors.

Breakthroughs

Low RF propagation losses (0,4-0,8 dB/mm at 40 GHz) in a GaN HEMT compatible buffer layers grown by MOCVD on 3C-SiC/Si.

Perspectives

Fabrication of RF circuits with GaN HEMTs on Silicon.

Collaborations : NOVASiC, IEMN

More information : http://www.crhea.cnrs.fr/GoSiMP/

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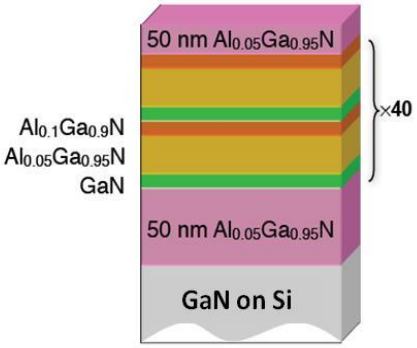
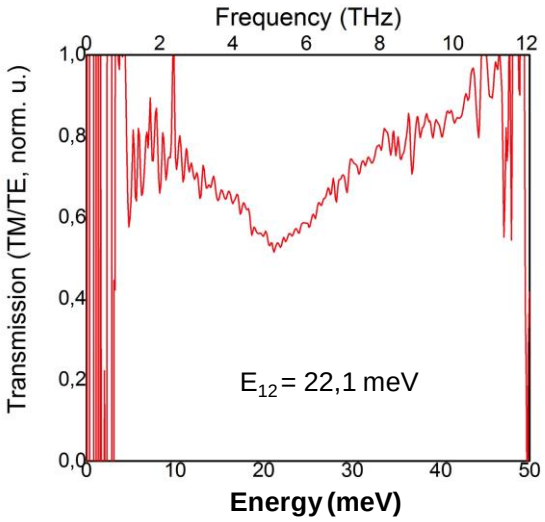
THz intersubband absorption in GaN based heterostructures grown on Silicon substrate

ELECTRO OPTO





Left: *schematic cross section view of the AlGaN/GaN step multiquantum well structure grown on Silicon at CRHEA.*

Right: *TM polarized ISB absorption in a structure grown by MOCVD on Si(110). Measurements performed at C2N.*

GaN on Silicon for THz detectors

AlGaN/GaN heterostructures present interesting features for optoelectronic devices working in the TeraHertz (THz) range:

1. the possibility to build periodic heterostructures with energy levels separated with few tens of meV;
2. a large optical phonon energy which may enable the electron population inversion in quantum cascade lasers (QCLs) at room temperature. Furthermore, the fabrication of AlGaN/GaN quantum cascade detectors (QCDs) on a THz transparent substrate like high resistivity Silicon is very interesting for use at large scale. The demonstration of TM polarized absorption of THz radiations within AlGaN/GaN heterostructures grown either by MOCVD or by MBE is a proof of inter-subband (ISB) absorption process and is a first step in the development of such devices.

Breakthroughs

ISB absorption in structures grown on Si(111) and Si(110) either by MOCVD or by MBE.

Perspectives

Development of GaN based THz quantum cascade detectors on Silicon; development of THz emitters.

Collaborations : C2N, III-V lab

More information : http://www.crhea.cnrs.fr/OptoTeraGaN/ ; A.Jollivet, PhD thesis Univ. Paris Saclay, 18 Feb. 2019

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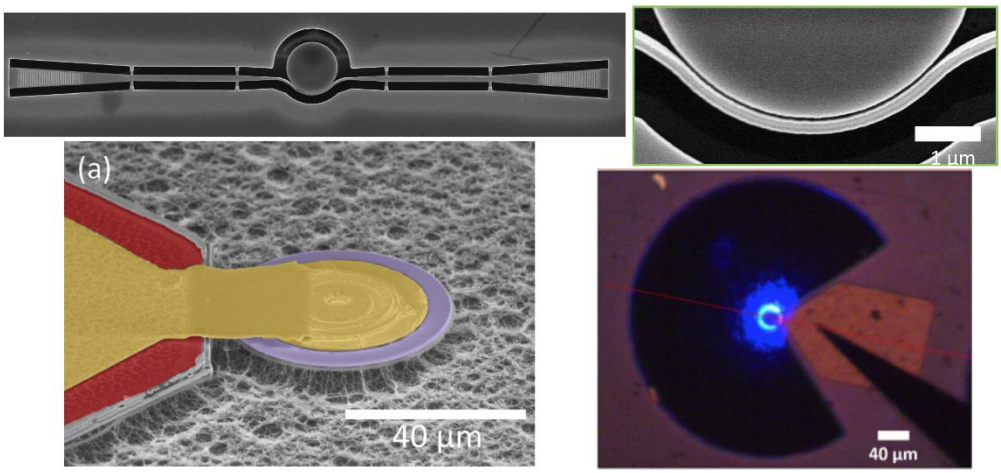
III-nitride on silicon nanophotonic platform: electrical injection and microlaser photonic circuits

OPTO



***Top**: A III-nitride photonic circuit combining a microdisk resonator with bus waveguides for light collection and outcoupling gratings. The distance between the microdisk and the bus waveguide is in the tens of nm range.*

***Bottom:** A III-nitride microring resonator with electrical injection. Electroluminescence is shown at the bottom right.*

A novel photonic plateform on Silicon enabled by III-Nitride Semiconductors

The group III-nitrides on silicon platform is promising for photonics as it is the only one that can simultaneously combine passive and active circuits operating in the UV and visible spectral range with monolithically integrated active emitters like lasers and LEDs.

Combining microdisk lasers under electrical injection with passive devices represents a major challenge in realizing a viable III-nitride nanophotonic platform on silicon. We have demonstrated two major achievements that will strengthen the viability of the III-nitride photonics platform on silicon.

We have successfully fabricated suspended active III-N photonic circuits containing a microdisk laser, a bus waveguide with a gap size as small as 80 nm and terminated on both sides by out-coupling gratings (See reference).

We have demonstrated electroluminescence from suspended microrings on silicon. The developed process enables to bypass the insulating AlN buffer layers and to inject current from the sample backside. The next step will be the coupling of a monolithic blue microdisk laser emitter with a full photonic circuitry on silicon.

Breakthroughs

Photonic circuit with suspended III-nitride on silicon Microdisk laser emission collected by bus waveguide Electrical injection in microring resonators

Perspectives

Microlasers on silicon under electrical injection.

Full photonic circuit with microlasers driven by electrical injection

Collaborations : C2N, CEA-INAC, L2C

More information: F. Tabataba-Vakili, L. Doyennette, C. Brimont, T. Guillet, S. Rennesson, E. Frayssinet, B. Damilano, J.-Y. Duboz, F. Semond, I. Roland, M. El Kurdi, X. Checoury, S. Sauvage, B. Gayral and P. Boucaud. "Blue Microlasers Integrated on a Photonic Platform on Silicon". ACS Photonics, 2018 5 (9), 3643-3648.

Contact: Fabrice Semond - fs@crhea.cnrs.fr ; Philippe Boucaud - pbo@crhea.cnrs.fr

Tunnel better than holes

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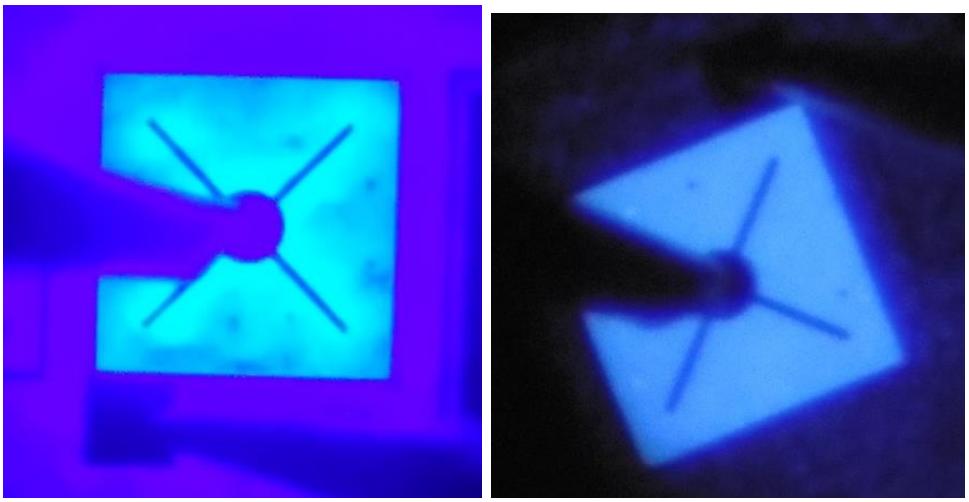

Light emission from a visible (left) and UV (right) LEDs based on a tunnel junction. The tunnel junction allows for a better hole injection in the LED and provides a better current spreading, leading to a uniform emission across the device

Tunnel junctions for visible and UV diodes

The low density of holes in GaN and even more in AlGaN induces a reduced performance of nitride LEDs. First, access resistances increase the operating voltage and degrade the wall plug efficiency. Second, the carrier injection in the quantum well of the active region is unbalanced and its efficiency is reduced. When a tunnel junction is grown on top of an LED and operated in reverse bias when the LED is under forward bias, it injects holes in the p region of the LED by tunnel effect from the conduction band of the top n contact. In the frame of the DUVET and NANOGANUV projects and the GaNeX PhD work of Victor fan Arcara, we demonstrated tunnel junction based LED in GaN and AlGaN materials, for LED emitting at 440, 360 and 300 nm. Various approaches have been successfully tested, including an original all MOCVD and also MBE/MOCVD hybrid growths. The tunnel injection has been applied to active regions based on QWs, QDs and heterojunctions. Differential resistance on the order of 10^{-3} Ωcm^{-2} at 1 $kAcm^{-2}$ have been obtained.

Breakthroughs

Tunnel junctions in GaN and AlGaN for visible and UV (300 nm) LEDs based on quantum wells, quantum dots and heterojunctions

Perspectives

UVC LEDs at 275 nm based on AlGaN tunnel junction

Collaborations : LETI, IEMN

More information : V. fan Arcara et al, 2019, submitted.

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Optical phase transition in semiconductor quantum metamaterials

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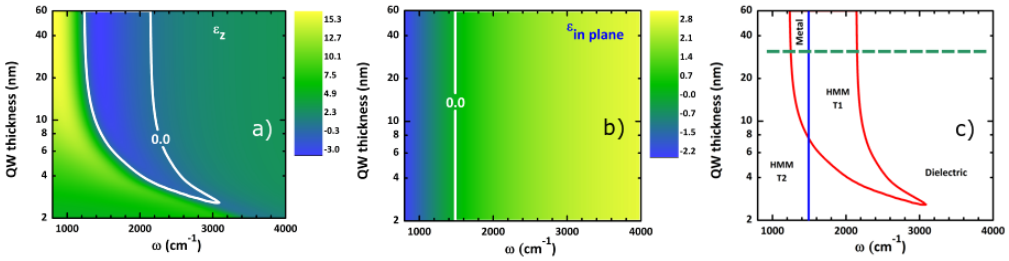

Hyperbolic metamaterial condition with a nominal doping of $n \sim 5 \cdot 10^{19} cm^{-3}$ *and* $l_{ZnO}/l_{MgZnO} = 3$.
(a,b) *Real part of the effective permittivity out-of-plane (a) and in-plane* ***(b)*** *as a function of the frequency and QW thickness. The white solid curves show the sign inversions.*
(c) *Optical phase transition diagram of the system as a function of frequency and QW thickness.*

Prediction and observation of an optical phase transition in a quantum metamaterial based on heterostructured semiconductors

The direction of refracted light at an interface between two media generally follows the conventional Snell-Descartes law. By stacking subwavelength-thick metallic and dielectric layers to form metamaterials, it is possible to realize unexpected behavior such as negative refraction. These effects result from the interaction with metallic or dielectric / amorphous nanostructured materials. Here we report on the optical phase transition in quantum metamaterials based on heterostructured semiconductors. We demonstrate that the hyperbolic response in quantum superlattices is generic and can be unambiguously attributed to the electronic quantum confinement of the electrons in quantum wells, acting as an adjustable resonance to achieve negative refraction behaviour at mid-infrared wavelength. We show theoretically and demonstrate experimentally that both the thicknesses and the doping levels, carefully chosen for each layer to feature strong intersubband transitions, lead to type 1 and type 2 hyperbolic response in highly doped ZnO/(Zn,Mg)O semiconductor material. Taking into consideration these results would enable new designs of mid-IR and THz quantum devices.

Breakthroughs

This work connects for the first time the concepts of intersubband plasmons with the photonic response of hyperbolic metamaterials. This work highlights the role of quantum confinement in the photonic response of quantum heterostructured materials, and proves that the electronic intersubband resonance in some of the most conventional heterostructured materials could lead to unexpected metamaterial behavior such as optical phase transitions.

Perspectives

- Extension of the wavelentgth operation in the THz and visible.
- Active optical response of the metamaterial

Collaborations : ISOM-Madrid

More information : funded by ERC "Flatlight" GA No 639109 (https://2dphotonics.weebly.com/) and FET-OPEN "Zoterac" GA No 665107 (www.Zoterac.eu)

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Hybrid-metasurfaces

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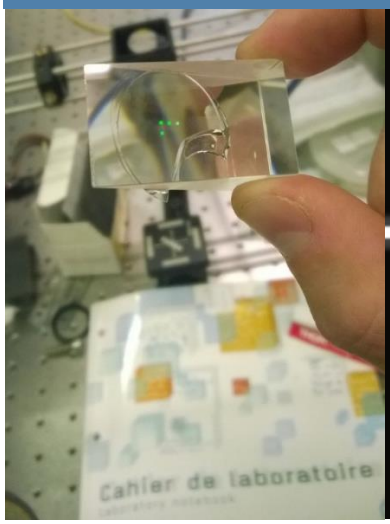

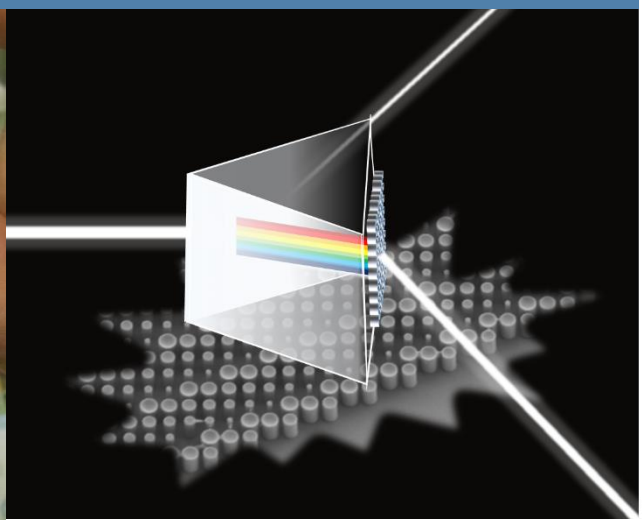

Metasurfaces can successfully mitigate the dispersion of refractive optical components leading to new achromatic applications in the visible wavelength.

Metasurfaces reorganize dispersed rays and restore the color of light

Metasurfaces control various properties of light via scattering across a large number of subwavelength-spaced nanostructures. Wavelength-dependent diffraction and resonant scattering effects usually limit their working operation wavelengths. In refractive optics, chromatic dispersion is a significant problem and is generally treated by cascading multiple lenses into achromatic doublets, triplets, and so on. Recently, broadband achromatic metalenses in the visible have been proposed to circumvent chromatic aberration but their throughput efficiency is still limited.

Here, the dispersion of refractive components is corrected by leveraging the inherent dispersion of metasurfaces. Hybrid refractive-metasurface devices, with nondispersive refraction in the visible, are experimentally demonstrated. The dispersion of this hybrid component, characterized by using a Fourier plane imaging microscopy setup, is essentially achromatic over about 150 nm in the visible.

Breakthroughs

We show that the diffractive properties of simple phase gradient metasurfaces are sufficient to mitigate the dispersive behavior of a prism. Coupling it with phase gradient metasurfaces, we obtain identical refraction angle for all colors within a certain range of wavelength around the designed frequency. We extend this study to the design of a metasurface planar-convex lens

Perspectives

Addressing the problem of chromatic dispersion in multilayer/cascaded optical systems, these hybrid metasurface devices could challenge the performances of binary optics designs.

Collaborations: Capasso Group, Harvard University

More information: R. Sawant, P. Bhumkar, A. Y. Zhu, P. Ni, F. Capasso and P. Genevet, ***Adv. Mater.*** **2019** 31, 1805555

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Polariton lasing competition

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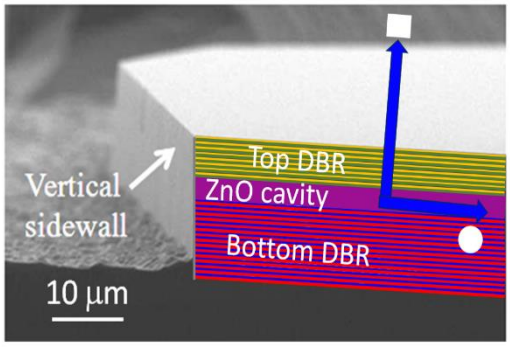

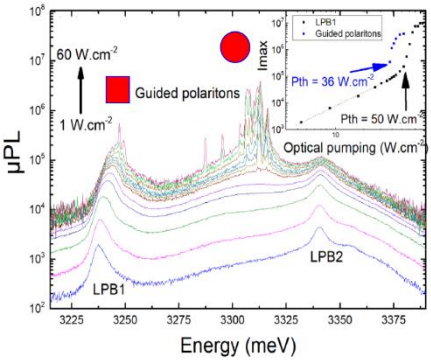

SEM image of a microcavity containing an (AlN/AlGaN) DBR, a ZnO active region cavity and a top (SiO_2/HfO_2) DBR grown on a patterned Si substrate. Photoluminescence spectra as a function of pumping power, displaying vertical (square) and horizontal (circle) polariton lasing.

First demonstration of concomitant vertical and in-plane polariton lasing

Polaritons are the quasiparticles resulting from the strong coupling between a confined photonic mode and an excitonic resonance. Since their observation in 1992, most studies have been carried out in vertical microcavities, which are usually fabricated by introducing an active region between two Bragg mirrors. In 2017/2018 we demonstrated for the first time the possibility of achieving polariton condensation on in-plane guided modes, suggesting the possibility of observing within the same microcavity polariton condensation on vertical and on guided modes.

To demonstrate this competition we have studied a vertical microcavity grown on a patterned Si substrate and measured it near a vertical sidewall of one of the mesas (see left panel). As shown by spectrally- (right panel) and angular-resolved measurements (not shown), polariton condensation can indeed occur in both kinds of polaritons branches (circle and square), one or the other being preferred depending on the actual exciton-photon detuning.

Breakthroughs

First ever demonstration of concomitant polariton condensation (lasing) on vertically-confined and horizontal propagative polariton modes.

Perspectives

This competition might have existed in previous reports on polariton condensation, calling for a revision of some accepted ideas, and point towards new cavity designs optimizing (ie. minimizing) such competition.

Participants : B. Alloing, M. Al-Khalfioui, S. Chenot, M. Leroux, F. Semond, J. Zuniga-Perez

Collaborations : C2N (S. Bouchoule), Institut Pascal (J. Leymarie and G. Malpuech), and L2C (T. Guillet)

More information : O. Jamadi et al., Light Sci. Appl **7**, 82 (2018), O. Jamadi et al., Phys. Rev. B **99**, 085304 (2019) and ANR Plug-And-Bose (ANR-16-CE24-0021)

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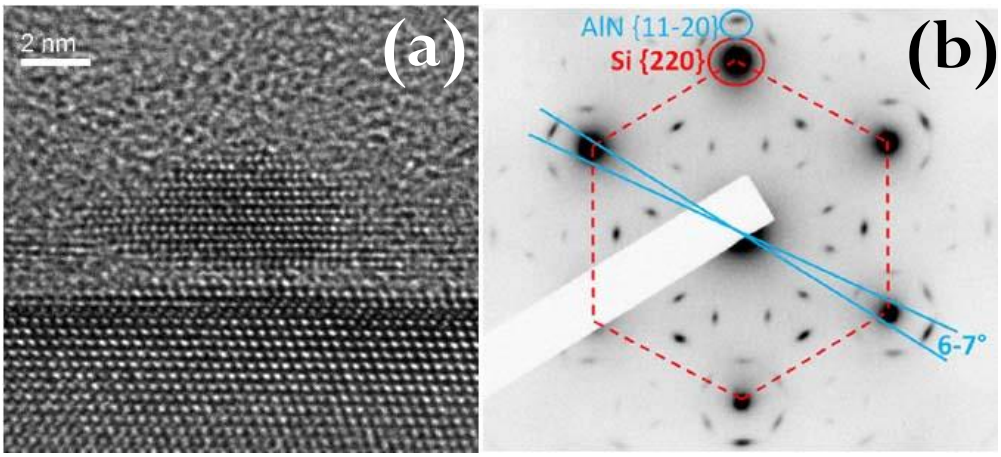
Towards the comprehension of dislocations generation in epitaxially-grown (0001) wurtzite layers

Common Research Service (SCR)



(a) Side view of an AlN island deposited on Si (111).

(b) Top view electron diffraction pattern revealing the twist between AlN islands.

Why twisted columns in wurtzite thin films?

Materials with a hexagonal wurzite structure (III-Nitrides, ZnO-based…) have a lot of applications in optoelectronic and microelectronic. Due to the lack of available large size and low price substrates, wurtzite films are most of the time heteroepitaxially-grown on foreign substrate. The microstructure of these films is dominated by threading dislocations which have detrimental effects on their properties and whose origin remains unclear. Our study of the growth of AlN on Si (111) allow us to propose a model explaining their formation. Firstly, AlN growth is 3D with the formation of relaxed islands. The relaxation occurs trough the introduction of in-plane mixed dislocations. The screw components of these dislocations induce the twist of the islands. The angle distribution of the twist may be quantitatively correlated to the lattice mismatch between the deposited film and the substrate. Threading dislocations are formed at the coalescence of the 3D-islands to compensate their relative twist. Their density depends on the islands twist (intrinsic to a material system) and size (growth dependent).

Breakthroughs

We propose an original model explaining the twist of crystalline domains in wurtzite films and therefore the origin of threading dislocations.

Perspectives

The proposed model has been quantitatively verified for AlN on Si (111). The study has to be extended to other wurtzite films/substrate systems with different lattice mismatches.

Collaborations : CEA-LETI ; CNRS-C2N

More information : *N. Mante et al., J. Appl. Phys.,* ***123****, 215701 (2018)*

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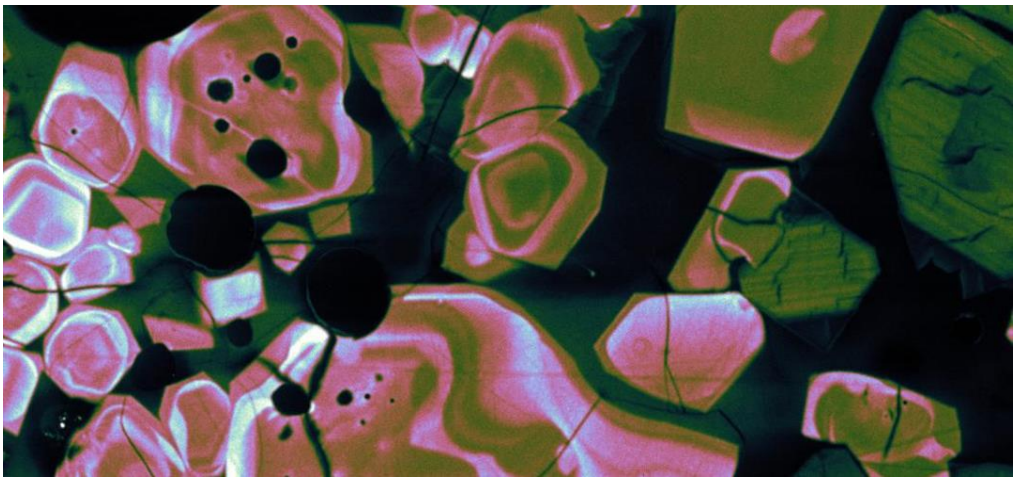
Cathodoluminescence

Common Research Service (SCR)



Unraveling early solar protoplanetary disk evolution using high resolution cathodoluminescence images

A new Vision on the primitive objects of the solar system

To understand the first stages of the formation of the solar system has always animated the community of physicists, astrophysicists and cosmochemists. In this research, the analysis of the main constituents of so-called primitive meteorites represents a major challenge in view of their potential role as witnesses of the mechanisms that occurred in the first 5 million years of the life of our solar system. To gather multidisciplinary knowledge and know-how becomes a decisive asset. Thanks to the use of high sensitivity cathodoluminescence (CL), new internal structures have been observed in olivines (Mg_2SiO_4), one of the constituents of meteorites. This study makes it possible to highlight a mechanism of epitaxial growth of these objects at high temperature. The very high sensitivity acquired on the images of CL brings a new light on the formation of olivines. These results and their many implications have been published on July 11, 2018 in Science Advances.

Breakthroughs

For the first time, the use of a cathodoluminescence system, suitable for the analysis of semiconductor structures, allowed access to an unmatched level of reading, up to now, to the fine structure of extraterrestrial olivines.

Collaboration : Laboratoire Lagrange (UMR 7293/Observatoire de la Côte d'Azur, Nice)

More information : « Chondrules as direct thermochemical sensors of solar protoplanetary disk gas», Science Advances, 11 Jul 2018 Vol. 4, no. 7, eaar3321 DOI: 10.1126/sciadv.aar3321

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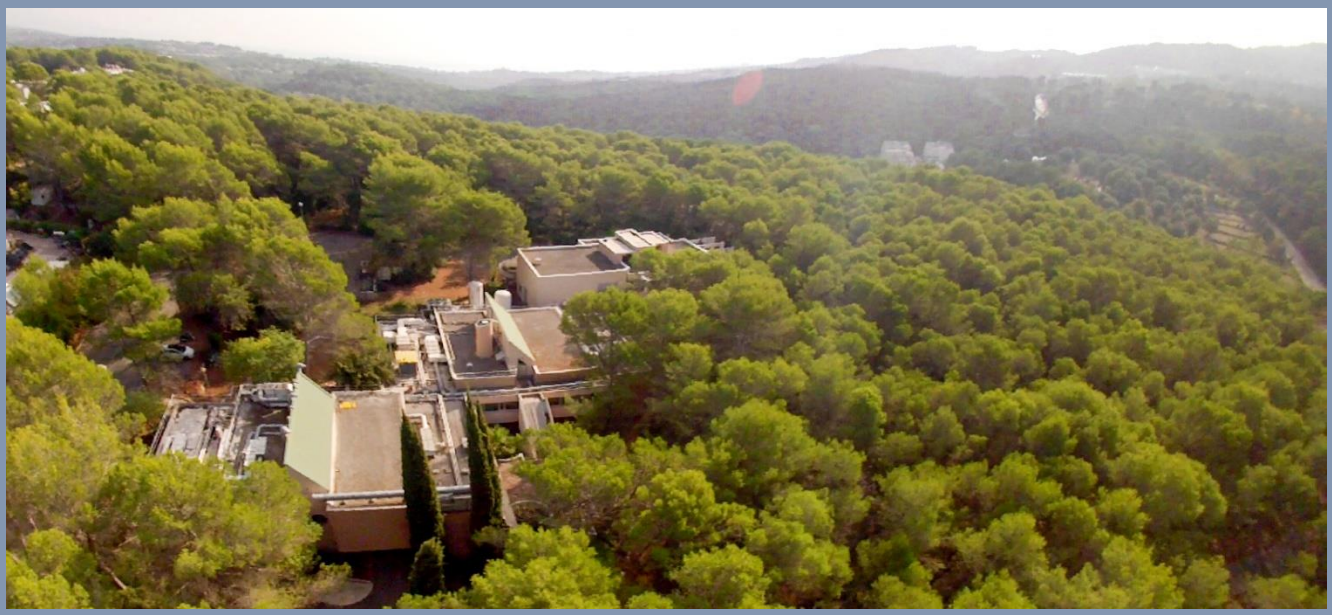
CRHEA in numbers

- 58 researchers, professors, engineers, technicians, PhDs and post-docs
- 2 M€ annual budget without salaries
- 36 publications in 2018
- 47 patents
- 4 European projects (1 ERC) and 16 ANR projects on-going
- Coordination of one laboratory of excellence



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