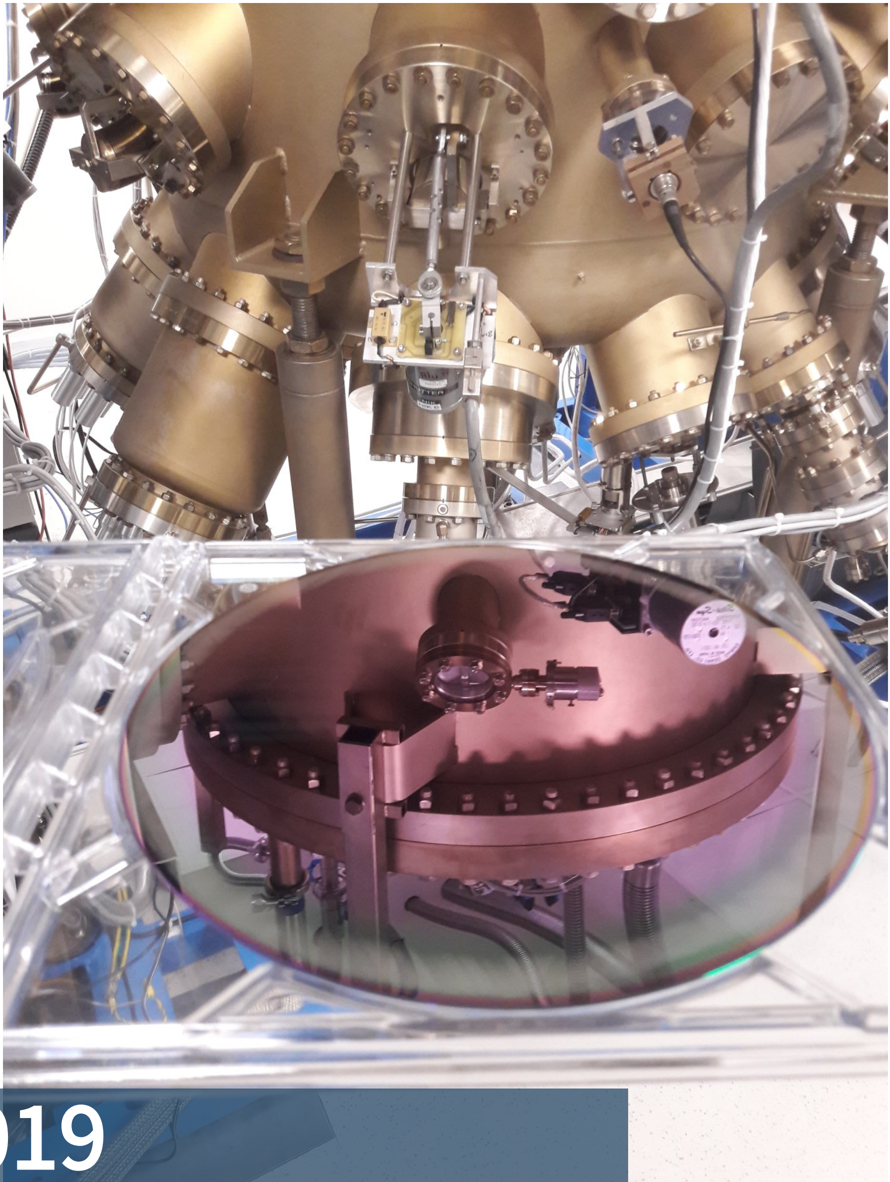
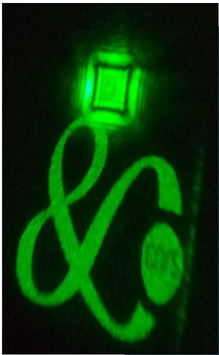


2019

UNE ANNEE AVEC LE CRHEA

UNIVERSITÉ CÔTE D'AZUR

EDITORIAL



2019 has been a very productive year for CRHEA. This booklet presents some of the most significant results that have been published and we are delighted to share them with you.

What this booklet does not show are the new projects that have been initiated or concluded during this year. To cite a few: a new ICP etching reactor has been ordered and we are extending the cleanroom to host this new equipment. After more than two years of negotiation, we have finally secured the funding for a new transmission electron microscope. The 8 inches molecular beam epitaxy reactor delivered by Riber is now fully operational and ready to grow high quality III-nitrides on silicon.

Many projects have been labeled in 2019: An ERC proof of Concept for the development of Lidars, an European project to establish new metrology standards with graphene, a Flag-Era project on the MBE growth of transition metal dichalcogenides, two French National Research Agency projects. The laboratory of Excellence Ganex has been renewed for five more years. CRHEA has joined the Integrated Project of Common European Interest Nano2022. New PhDs and post-docs have started on innovative ideas.

Research at CRHEA relies on international collaborations. This year, we have more specifically developed collaborations with NTT and Fukui University in Japan, UCSB in the US, University of Bath in the UK, University of Hong Kong, NTU in Singapore, University of Wellington in New Zealand, Beijing University of Technology in China and with different partners in Germany. Two distinguished professors from Germany as well as from China have been present in CRHEA for long-term stays.

The national collaborations obviously are ongoing. Our connections with laboratories from Université Côte d'Azur have been strengthened. Unfortunately, one of our colleagues from INPHYNI, Marc de Micheli, has passed away this year. We still keep him in our heart and acknowledge his remarkable contributions to build links between different communities.

2020 looks bright, not only because CRHEA's building should be renovated. Be prepared for a transition period with heavy work. Many new projects are emerging. CRHEA is committed to develop new ideas that will help to address the societal challenges we are facing. Let's say: Physics and Engineering for humanity. Sustainable, Creative, Connected. It is a nice motivation.

Philippe Boucaud
Director of CRHEA

Record power density RF HEMT on GaN

1

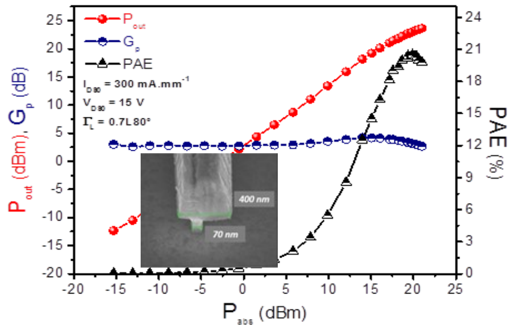


***Fig 1:** Output power, power gain and power added efficiency versus absorbed power at 40 GHz for a 2 × 50 × 0.07 µm² AlGaN/GaN HEMT on Free-Standing GaN substrate. The insert shows the 0.07 µm footprint gate.*

A new record power density at 40 GHz on commercial GaN substrate

The development of performant and reliable GaN high-electron-mobility transistors (HEMTs) on high crystal quality GaN is hampered by the lack of large lattice matched substrates available at reasonable cost. In this context, the growth of GaN HEMTs on commercial free-standing GaN substrates previously developed for high brightness light emitting diodes has been investigated as an alternative approach for high frequency applications. After the demonstration of high quality surface despite the growth of 10 to 40 µm thick highly resistive GaN buffer layer to limit the capacitive coupling between the active regions at the top and the conductive substrate at the bottom, 70 nm gate footprint transistors have been successfully fabricated.

A 100 GHz maximum intrinsic cutoff frequency f_T, and a maximum intrinsic oscillation frequency f_{Max} of 125 GHz are obtained from S-parameters measurement. A record output power density of 2 W/mm, associated with 20.5 % power added efficiency and a linear power gain (Gp) of 4.2 dB is demonstrated at 40 GHz.

Breakthroughs

Record power density at 40 GHz on commercial GaN substrate doubles the previous state of the art.

Perspectives

Further enhance the performance by optimizing the epitaxial structure.

Collaborations : IEMN, LUMILOG, LAAS (ANR-11-LABX-0014, Investissements d'Avenir, 'GaNeX')
More information : Semicond. Sci. and Technol, https://doi.org/10.1088/1361-6641/ab4e74
Contact : Yvon Cordier | yc@crhea.cnrs.fr

Thin channel GaN HEMT with 10 kV capability

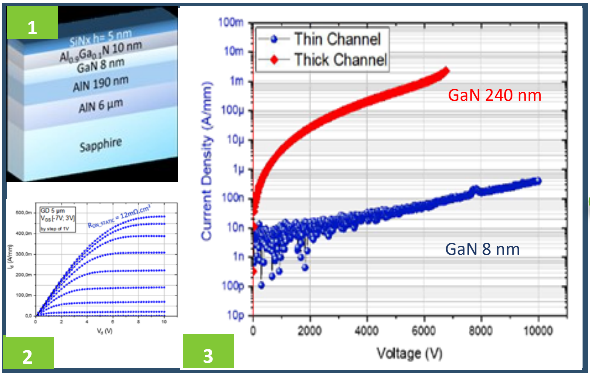


Fig 1: *Cross section view of the Aluminum-rich HEMT structure with thin channel on AlN .*

Fig 2: *Output characteristics of a transistor with 8 nm thin channel.*

Fig 3: *Lateral leakage current recorded between two isolated ohmic contact pads for HEMTs*

For power, the thinner channel is the better

AlN is investigated as the basement of new high-electron-mobility transistors (HEMTs) for high-power and high-voltage electronic applications. Thanks to a very large band gap energy beyond 6 eV and high thermal conductivity, such semiconductor is very promising to overcome the limitations encountered with GaN based electron devices. Recently, Aluminum-rich AlGaN/GaN HEMTs have been grown on AlN-on-Sapphire templates to study the influence of various parameters such as the channel thickness on the electrical properties. It appeared that reducing the GaN channel thickness was a key for reaching high breakdown voltages. For a HEMT with thin (8 nm) channel, the buffer assessment revealed a remarkable lateral breakdown field of 5 MV/cm for short contact distances, which is far beyond the theoretical limit of GaN-based material system. 1 kV breakdown voltage was achieved with a contact distance of 2 µm, whereas 10 kV were reached for 96 µm. The static on-resistance R_{on} of the transistor scaled as expected with the gate-drain distance to reach 12 mΩ.cm² for 5 µm.

Breakthroughs

1kV (10kV) breakdown voltage between contacts separated by 2µm (96µm) on a thin channel device structure.

Perspectives

Evaluations on other substrates (bulk AlN, SiC).

Collaborations : IEMN, Institut Néel (ANR-17-CE05-00131 BREAKUP)
More information : Micromachines 2019, 10 (10), 690, https://doi.org/10.3390/mi10100690
Contact : Yvon Cordier | yc@crhea.cnrs.fr

Group-III nitride nanowire arrays made by sublimation for nanophotonic

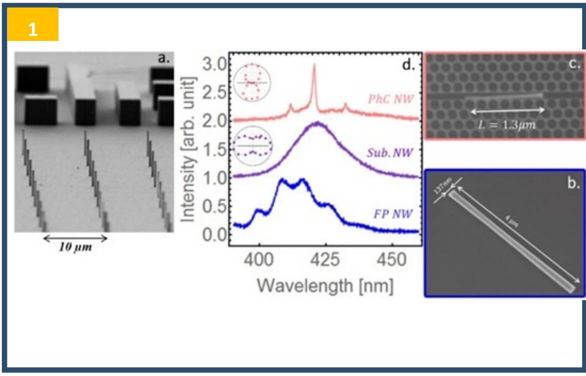


Fig 1 : SEM images of (a) bird's eye view of a NW array obtained after selective-area sublimation. (b) A NW transferred on SiN. (c) A subwavelength NW embedded in a slotted photonic crystal. (d) Room-temperature μPL spectra of the NW shown in panel b (blue line), a subwavelength NW transferred on SiN (purple line) and the subwavelength NW embedded in a photonic crystal shown in panel c (pink line)

High yield top-down fabrication of InGaN/GaN NWs

We have demonstrated that selective-area sublimation (carried out in a MBE chamber) together with electron beam lithography or displacement Talbot lithography can be a powerful and versatile method to realize precisely defined GaN-based NW arrays in a top-down approach. We have shown that it not only allows for high yield and homogeneity on a macroscale but also for a fine nanoscale control in terms of position, shape, and dimensions.

Despite this top-down approach, we have been able to demonstrate the high material and optical quality of these NWs. The existence of intrinsic Fabry–Pérot resonances in thick NWs (4-7 μm) lead to room-temperature lasing in the near-ultraviolet range. We have shown that subwavelength NWs including precisely positioned InGaN quantum disks can be integrated into a hybrid nanophotonic platform.

Breakthroughs

First demonstration of InGaN/GaN NW-induced nanocavities in slotted SiN photonic crystal.

Perspectives

Taking advantage of the ultrahigh vacuum environment in which the sublimation is carried out to realize more complex NW designs, including core−shell and hollow-core structures as well as radial heterostructures.

Collaborations : NTT, **Japan**. University of Bath, UK.
More information : S. Sergent, B. Damilano, S. Vézian et al. ACS Photonics (2019).
B. Damilano, S. Vézian et al. APEX 12, 045007, (2019). P.M. Coulon, B. Damilano, et al. Microsyst. Nanoeng., 5 (2019).
Contact : Benjamin Damilano | bd@crhea.cnrs.fr

AlGaN Quantum Dots for deep UV emission

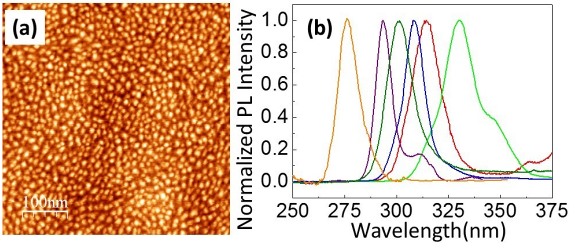


Fig (a) : Atomic force microscopy image of AlGaN quantum dots grown by molecular beam epitaxy.

Fig (b) : Photoluminescence spectra of AlGaN quantum dots emitting in the UVC, UVB and UVA regions from 275 nm to 340 nm.

High quantum efficiency ultra-violet emitters

As the replacement of mercury lamps by environmentally safe UV sources is required, AlGaN based LEDs are expected to fulfil this goal, in particular in the UVB (280-320 nm) and UVC (< 280 nm) regions where strategic medical and environmental applications are targeted. As lower cost processes should be privileged, monolithic growth approaches and thin layer structures could be well adapted for the development of UV LEDs. However, such a design leads to high dislocation densities (which are non radiative recombination centers) of 10^9— 10^{10} cm^{-2} and internal quantum efficiencies (IQE) below 1%. As a solution, we have grown AlGaN quantum dots (QD)— i.e. nanometer-sized islands (fig.(a))— active regions to efficiently confine the carriers and favour their radiative recombination. By varying the Al composition, the emission can be tuned from 340 nm to 275 nm (fig.(b)). The IQE, determined by combining temperature dependent and time resolved photoluminescence, has been shown to be higher for QD emitting between 276 and 308 nm, with a highest IQE value of 20% at 276 nm.

Breakthroughs

AlGaN QDs with highest internal quantum efficiency obtained in the UVB and UVC range have been fabricated by molecular beam epitaxy.

Perspectives

Quantum dots based LEDs with high internal quantum efficiency in the UVB and UVC regions for medical (dermatology) and environmental (water purification) applications.

Collaborations : Laboratoire Charles Coulomb (L2C), RIBER SA
More information : J. Brault et al., Journal of Applied Physics 126, 205701 (2019)
Contact : Julien Brault | jb@crhea.cnrs.fr

Topological photonics with ZnO

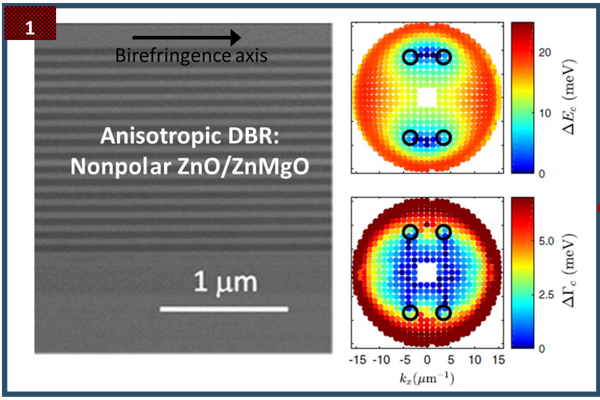


***Fig 1**: Cross-section SEM image of an anisotropic optical microcavity based on nonpolar ZnO/ ZnMgO DBR (left) displaying Voigt Exceptional points. Energy difference (top right) and FWHM difference (bottom right) between the two eigenmodes of the cavity as a function of in-plane momentum. The four exceptional points are indicated by*

Making planar optical microcavities “Exceptional”

Voigt points represent propagation directions in anisotropic crystals along which optical modes degenerate, leading to a single circularly polarized eigenmode.

By employing an appropriately-designed dielectric, anisotropic optical microcavity based on nonpolar ZnO/ZnMgO Bragg reflectors, we have been able to implement a non-Hermitian system and mimic thereby the behavior of Voigt points in natural crystals.

To prove the exceptional nature of these particular locations in momentum space, we have monitored the complex-square-root topology of the mode eigenenergies (real and imaginary parts) around the Voigt points. As illustrated in the figure above, when approaching the exceptional points the eigenenergies of the two eigenmodes coalesce, and so do the eigenvectors (not shown). Polarization state analysis shows that these artificially - engineered Voigt points behave as vortex cores for the linear polarization and sustain chiral modes.

Breakthroughs

We have designed and fabricated a planar optical microcavity displaying exceptional points in momentum space.

Perspectives

Our findings apply to any planar microcavity with broken cylindrical symmetry and, thus, pave the way for exploiting exceptional points in optoelectronic devices such as VCSELs and resonant cavity light emitting diodes.

Participants : C. Deparis, J. Zuniga-Perez
Collaborations : Universität Leipzig (Prof. Dr. M. Grundmann)
More information : Phys. Rev. Lett. **123**, 227401 (2019)
Contact : Jesus Zuniga-Perez | jzp@crhea.cnrs.fr

Epitaxial growth of Fe_3O_4 on ZnO nanostructures

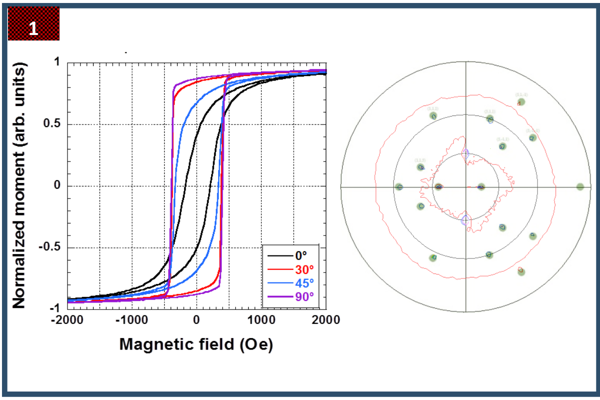


Fig 1: in-plane magnetization loops (rt) and XRD pole figure of a 150 nm-thick Fe_3O_4 epilayer grown on m-plane nonpolar ZnO. The pole figure taken at 2Θ = 57° shows the (5,1,1) and (3,3,3) reflections of only one single Fe_3O_4 domain oriented along the (1-12) direction.

Single-domain growth of ferrimagnetic Fe_3O_4 on nonpolar ZnO

There is currently a worldwide effort to integrate semiconductors and magnetic materials, as an efficient spin injection and detection of spin in semiconductors is essential to the field of spintronics, but remains an unsolved issue.

The research project “SPINOXIDE” aims at taking advantage of both ZnO compatibility for the epitaxy of highly spin-polarized oxide ferromagnets and the potentially exceptional spin coherence lengths and spin lifetimes in ZnO nanostructures.

Convincing preliminary results (see figure) have been obtained regarding the growth of the semi-metal Fe_3O_4 (magnetite, T_C =860K) for which a spin-polarization of 100% is expected.

High-quality Fe_3O_4 epilayers have been grown both on polar c- and, for the first time, nonpolar m-ZnO showing the importance of the stoichiometry control of the first 1-2 ML and even the orientation of atomic steps on the ZnO surface.

Breakthroughs

- Tuning of the stochiometry at the interface to tailor structural and magnetic isotropy and band offsets.

- Single-domain growth on nonpolar ZnO either in the (111) or (1-12) Fe_3O_4 orientations.

Perspectives

Efficient spin injection(and detection) in ZnO nanostructures owing to 100% spin-polarization in Fe_3O_4 and interface control

Collaborations : O. Popova, V. Sallet, Y. Dumont (GeMac, Versailles) and colleagues at CRHEA
More information : Project Spinoxide (ANR-19-CE24-0020)
Contact : Christian Morhain | cm@crhea.cnrs.fr

Vectorial Holography

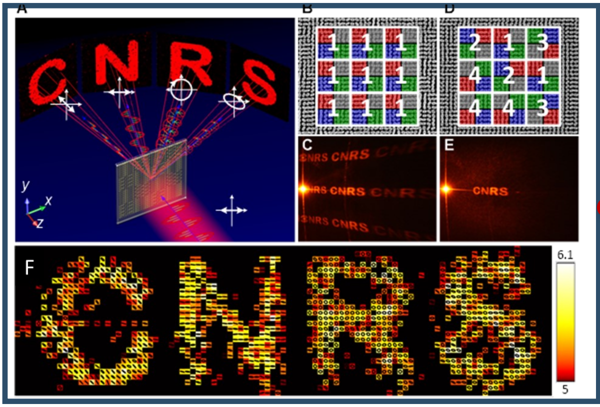


Fig : (A) Schematic of the polarization-reconstructed and multi-directional meta-hologram. (B, D) SEM image of the fabricated meta-hologram with uniformly and randomly distributed sub-pixels. (C,E) Photograph of the holographic image with a series of ghost images and unique image respectively. (F) Intensity values (arbitrary units), together with the corresponding local state of polarization. The reconstructed vectorial far-field of the metasurface have been obtained using ptychographic measurements.

Metasurfaces enable wavefront shaping with arbitrary output polarization

Polarization reconstruction, which is based on the superposition of two orthogonal polarization bases, has been widely used in optical science. Circular polarization (CP), respectively linear polarization (LP), can be generated based on the superposition of two orthogonal LP, respectively CP.

However, full-polarization-reconstruction cannot be obtained based on such phase-only difference between two orthogonal bases and its application to arbitrary wavefront control have not been realized.

Here, we demonstrate a full-polarization-reconstructed metasurface that can produce arbitrary polarization for wavefront shaping based on a given LP incidence light. The approach relies on pixelated metasurfaces, in which each pixel acts as a deflector able to encode both the polarization and the holographic phase information, resulting in a holographic image in a specific angle with arbitrary polarization. The experimental demonstrations, based on the metasurface Jones matrices extraction, are supported by state-of-the-art vectorial ptychography for full electromagnetic field characterization.

Breakthroughs

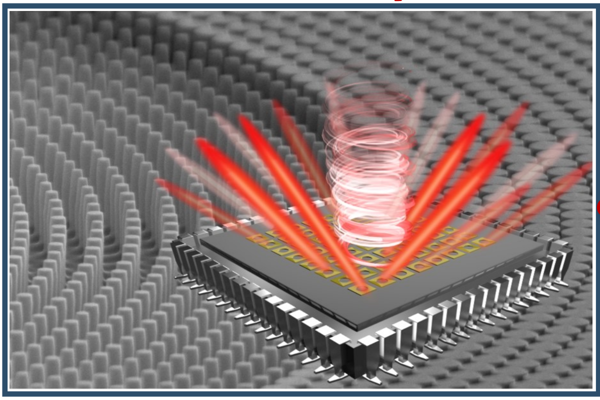
A multidirectional meta-hologram is able to multiplexed the polarization channels in different directions.

Perspectives

Vectorial holograms that address different polarization channels have been integrated into a shared aperture to display several arbitrary polarized images, leading to promising new applications in vector beam generation, full color display and augmented/virtual reality imaging.

Collaborations : Patrick Ferrand, Institut Fresnel, Marseille
More information : (paper submitted) Patrice Genevet
Contact : Patrice Genevet | pg@crhea.cnrs.fr

Metasurface integrated Vertical Cavity Surface Emitting Lasers



***Programmable lasers array for wide-range dynamic beam steering**. The image shows a schematic of the metasurface integrated vertical surface emitting array (MS-VCSELs). The array of MS-VCSELs is mounted onto a PCB board, indicating different deflection angles for wide-range dynamic beam steering applications. .Below, a SEM of the nanopillars forming the beam shaping metasurfaces.*

Monolithic integration of dielectric metasurfaces with VCSELs enables arbitrary control of the laser beam profiles

Vertical-cavity surface-emitting laser (VCSEL) has experienced a soaring development over the last 30 years and become one of the most versatile laser sources for a large number of applications. The exploding development of modern optoelectronic technologies places stringent requirements for lower power consumption devices with high efficiency and more compact integrated system. However, due to the narrow aperture of the laser, their emission is generally highly divergent, spreading the signal after only few hundreds of microns from the laser source.

The emerging ultra-thin flat optical structures, namely metasurfaces, offer a powerful technique to manipulate electromagnetic fields with exceptional spectral and spatial controllability, unique planar configuration, and complementary-metal-oxide-semiconductor processing compatibility, making them promising candidates for ultra-compact optoelectronic integration. Here, we demonstrate a wafer-level non-intrusive and monolithic integration that solves the issues of arbitrary beam shaping VCSELs by directly sculpturing their emitting surfaces into metasurfaces.

Breakthroughs

Metasurface integrated Vertical Cavity Surface Emitting Lasers (MS-VCSELs): the first realization of programmable laser-array emitting with fully-arbitrary beam profiles.

Perspectives

The arbitrary wavefront control directly at the wafer-level and the programmability of Metasurface VCSELs would significantly promote applications in various wide-field applications, such as optical fibre communications, laser printing, smartphones, optical sensing, face recognition, directional displays and ultra-compact light detection and ranging (LiDAR).

Collaborations : Key Laboratory of Optoelectronics Technology, Beijing University of Technology, Ministry of Education, China
More information : (paper accepted, Nature Nanotechnology)
Contact : Patrice Genevet | **pg@crhea.cnrs.fr**

$Al_{5+\alpha}Si_{5+\delta}N_{12}$, a new Nitride semiconductor

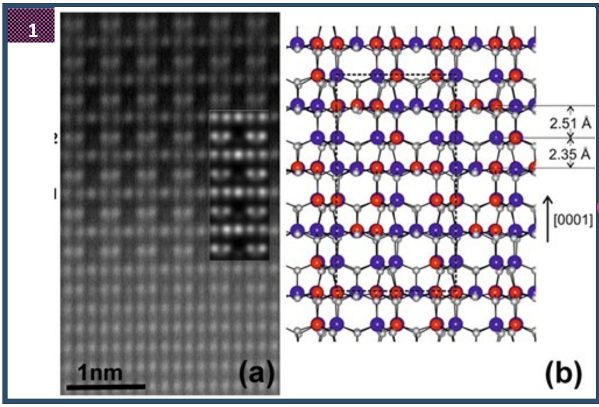


***Fig 1**: (a) High resolution high angle annular dark field image of a $Al_{5+\alpha}Si_{5+\delta}N_{12}$ layer epitaxied on AlN. The insert shows a simulated image using the model presented in (b).*

(b) Schematic representation of the structural model of $Al_{5+\alpha}Si_{5+\delta}N_{12}$ relaxed by DFT calculations. Large red and blue spheres denote Si and Al atoms,

New material, new properties?

A new semiconductor, $Al_{5+\alpha}Si_{5+\delta}N_{12}$, was synthesized by high temperature annealing of aluminum nitride films under silicon flux. A high resolution transmission electron microscopy study combined with theoretical calculations allowed to determine the crystalline structure of this new material. This structure is derived from the AlN parent one with the anion sublattice fully occupied by N-atoms whereas the cation sublattice is
the stacking of 2 different planes along <0001>: The first one exhibits a ×3 periodicity along <11–20> with 1/3 of the sites being vacant. The rest of the sites in the cation sublattice are occupied by an equal number of Si and Al atoms. The calculated band structure shows that $Al_{5+\alpha}Si_{5+\delta}N_{12}$ has a gap around 4 eV and suggests that this new semiconductor may have applications for the emission and detection of UV light as well as for the realization of normally-off transistors

Breakthroughs

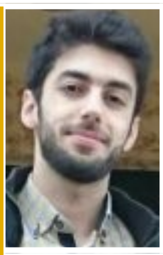
A new semiconductor has been synthetized which opens the way to new properties and new applications

Perspectives

The next step of the study will be the synthesis of thicker $Al_{5+\alpha}Si_{5+\delta}N_{12}$ layers by annealing and growth processes to study their properties and envisage applications.

Collaborations : MPI Stuttgart; CEA-LETI Grenoble; C2N Palaiseau
More information : https://www.nature.com/articles/s41598-019-52363-7
Contact : Philippe Vennéguès | pv@crhea.cnrs.fr

PhD : defense of Rami Mantach



Rami Mantach defended his PhD work on "Semipolar GaN pseudo-substrates" in the conference room of CRHEA on September 10th, 2019.

PhD : defense of Gauthier Brière

Gauthier Brière defended his PhD work on "Development of meta-optics based on III-V semiconductor materials for applications in the visible range".
The defense took place in the amphitheater of CRHEA November 28th, 2019.

PhD : defense of Nolwenn Le Biavan

Nolwenn Le Biavan defended her PhD work on "Toward a zinc oxide based quantum cascade laser" on November 13th, 2019 in the amphitheater of CRHEA.

PhD : defense of Mario Ferraro

Mario Ferraro defended his PhD work on "Integration of metasurfaces in optoelectronic devices and control of laser emission".
The defense took place in the amphitheater of CRHEA December ,12th 2019.

Arrival : Samira Khadir

Associate professor coming at Université Côte d'Azur from Marseille. She joins the Nano team under the supervision of Patrice Genevet .

MT180 : Victor Fan Arcara in regional final

Victor Fan Arcara, participated to the regional final of "My PhD in 180 seconds" with his "work on Jonctions tunnel" on March 5th, 2019.

CRHEA in numbers

- 63 researchers, professors, engineers, technicians, PhDs and post-docs
- 2 M€ annual budget without salaries
- 45 publications in 2019
- 48 patents
- 6 European projects (1 ERC - 1ERC POC) and 18 ANR projects on going
- Coordination of one laboratory of excellence

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