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► **To cite this version:**

Loïc Méchin, François Médard, Joël Leymarie, Martine Mihailovic, Jesús Zúñiga-Pérez, et al.. Photoluminescence of Two-Dimensional Hole Gas (2DHG) in GaN-based polariton waveguide. 18th edition of the Optics of Excitons in Confined Systems conference (OECS18), Jun 2023, Lecce (ITALY), Italy. hal-04680336

HAL Id: hal-04680336

<https://hal.science/hal-04680336>

Submitted on 28 Aug 2024

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Photoluminescence of Two-Dimensional Hole Gas (2DHG) in GaN-based polariton waveguide

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Context

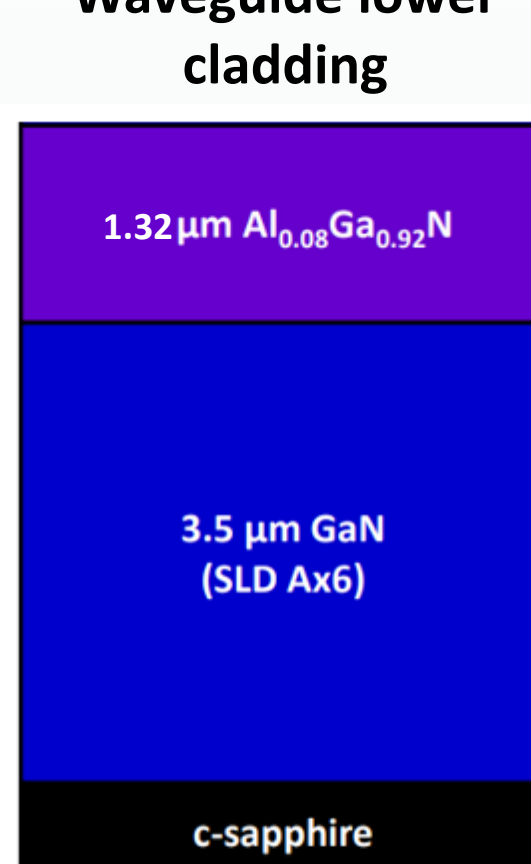
The Bose-Einstein condensation of polaritons has been studied for over two decades with the aim of developing light emitters that can eventually be integrated into optoelectronic devices. The polariton laser effect was initially investigated in microcavities. However, the complex nature of these structures make difficult their integration into devices. To address this issue, waveguides have been proposed. The objective of this study is to better understand the relaxation dynamics of guided polaritons, ultimately leading to the achievement of the polariton laser effect.

Sample and Setup

Sample 1 : GaN waveguide



Sample 2 : Waveguide lower cladding



Sample 3 : GaN buffer



Samples informations

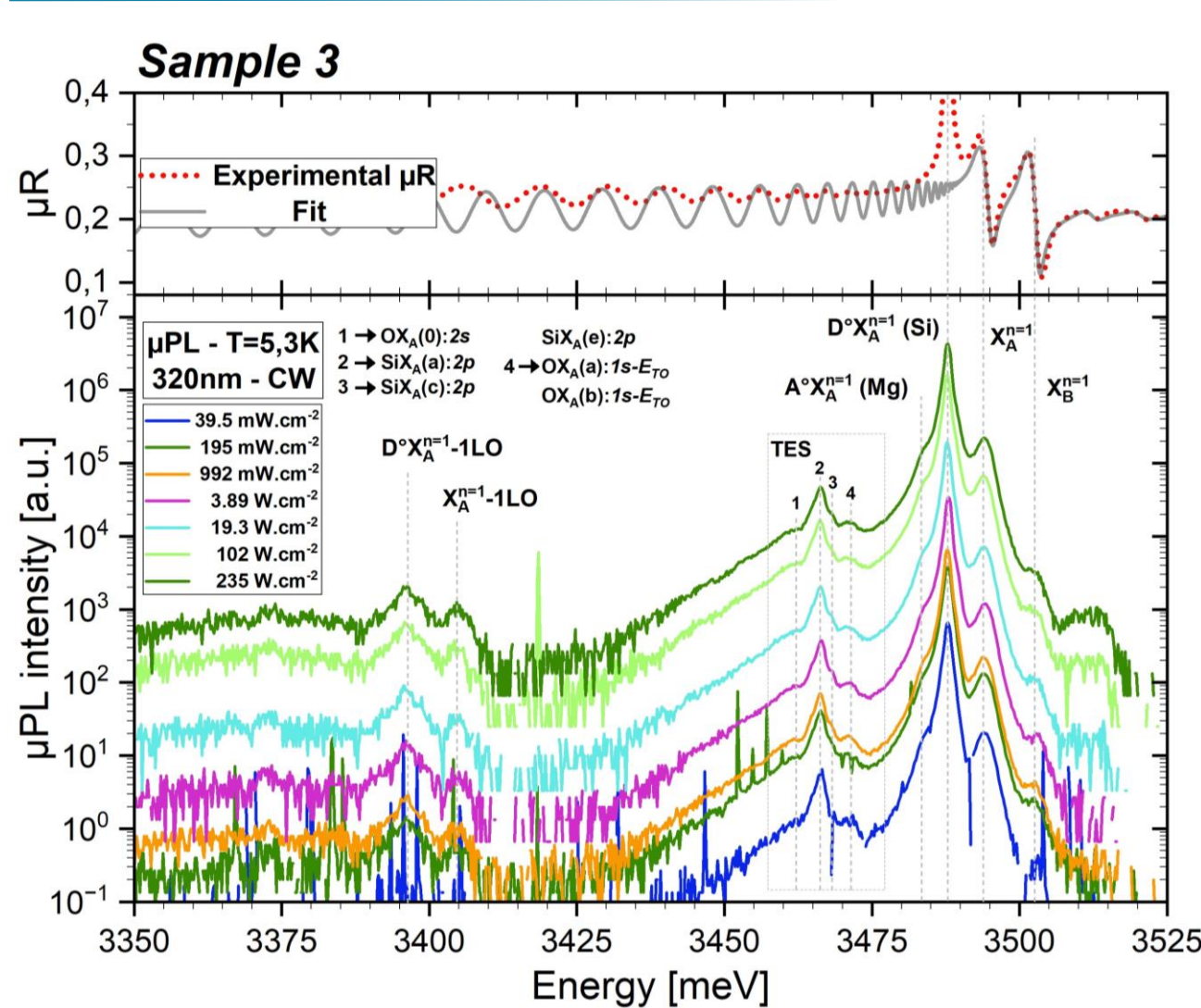
- All samples are grown by MOCVD on c-plane sapphire substrate
- Dislocation density : 10^7 cm^{-2}
- Donor density : 10^{17} cm^{-3}
- On the sample 2, the GaN layer has been removed by plasma etching

Experimental Setup

- μ PL with quasi-continuous wave excitation and continuous wave excitation :
 - QS 349 nm – 4 ns
 - Hübner-Photonics Cobolt cw laser (320 nm)
- TRPL with the third harmonic of a Ti:Sapphire 150 fs laser (266 nm)

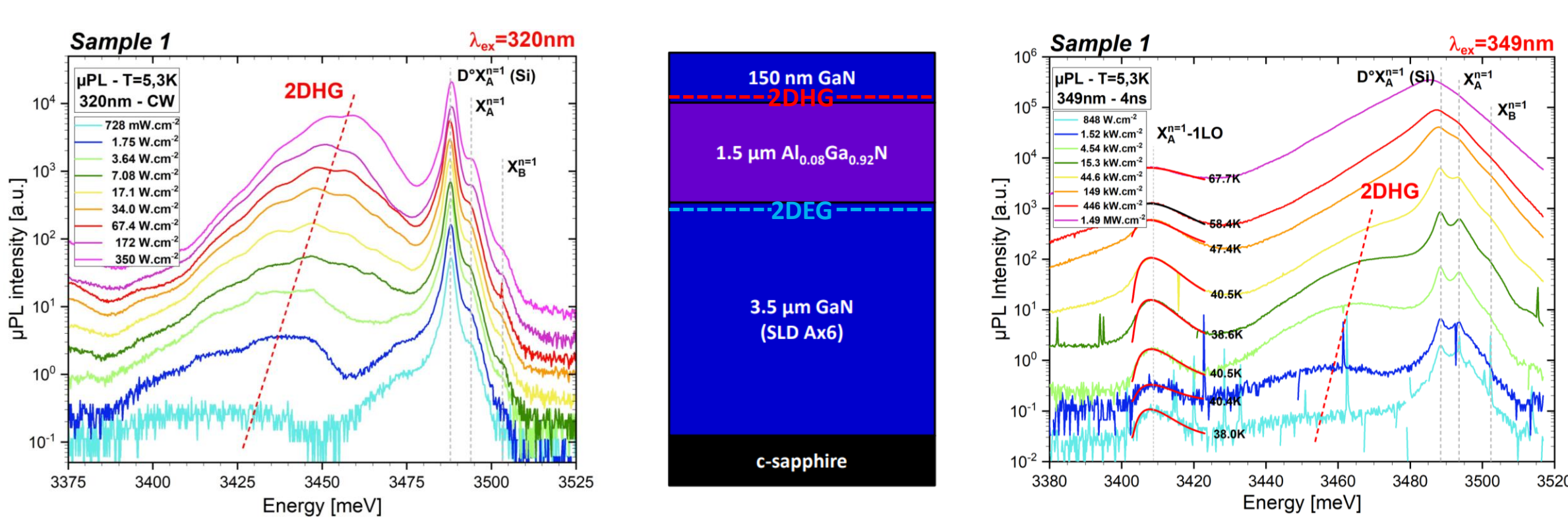
Experimental results

① μ PL under continuous wave excitation at 320nm :

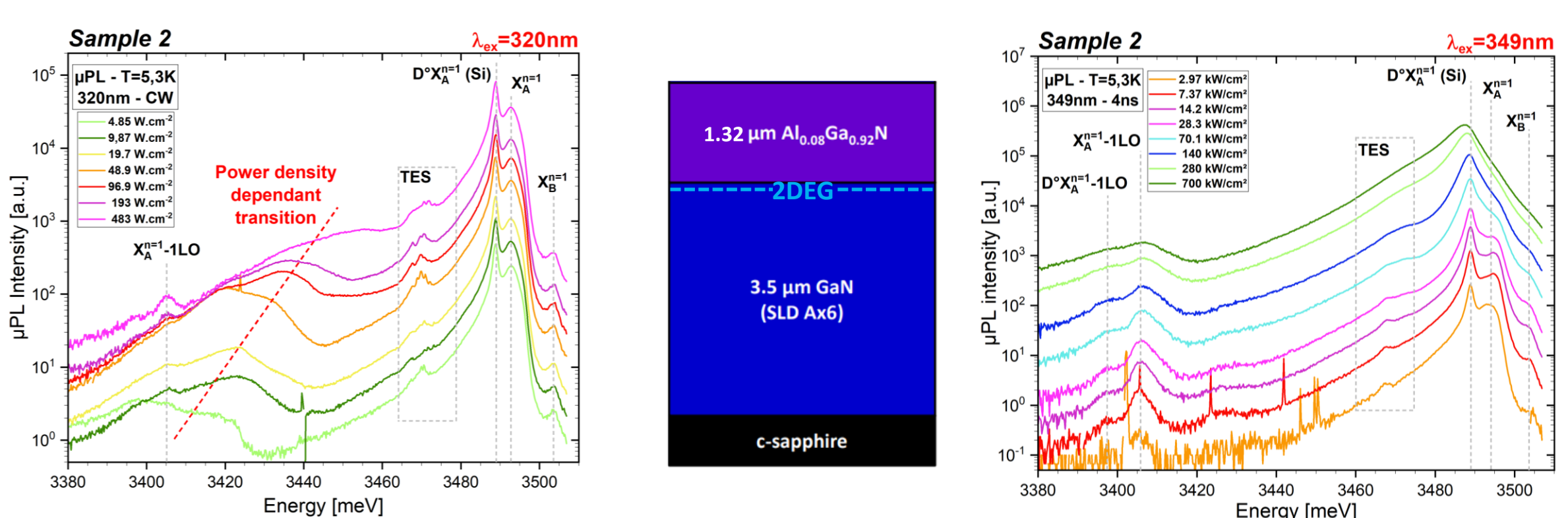


- Accurate identification of excitonic transitions. [J. Appl. Phys. 97, 061301 (2005)] [Physical Review B 66, 233311 (2002)]
- Micro-reflectance (μ R) experiments and simulations allowed us to determine the energies of free-exciton transitions.
- In the waveguide, the excitonic transitions have the same energies as those in the template. Therefore, the GaN luminescence in the waveguide primarily originates from the buffer layer.

② Study of photoluminescence as a function of power density

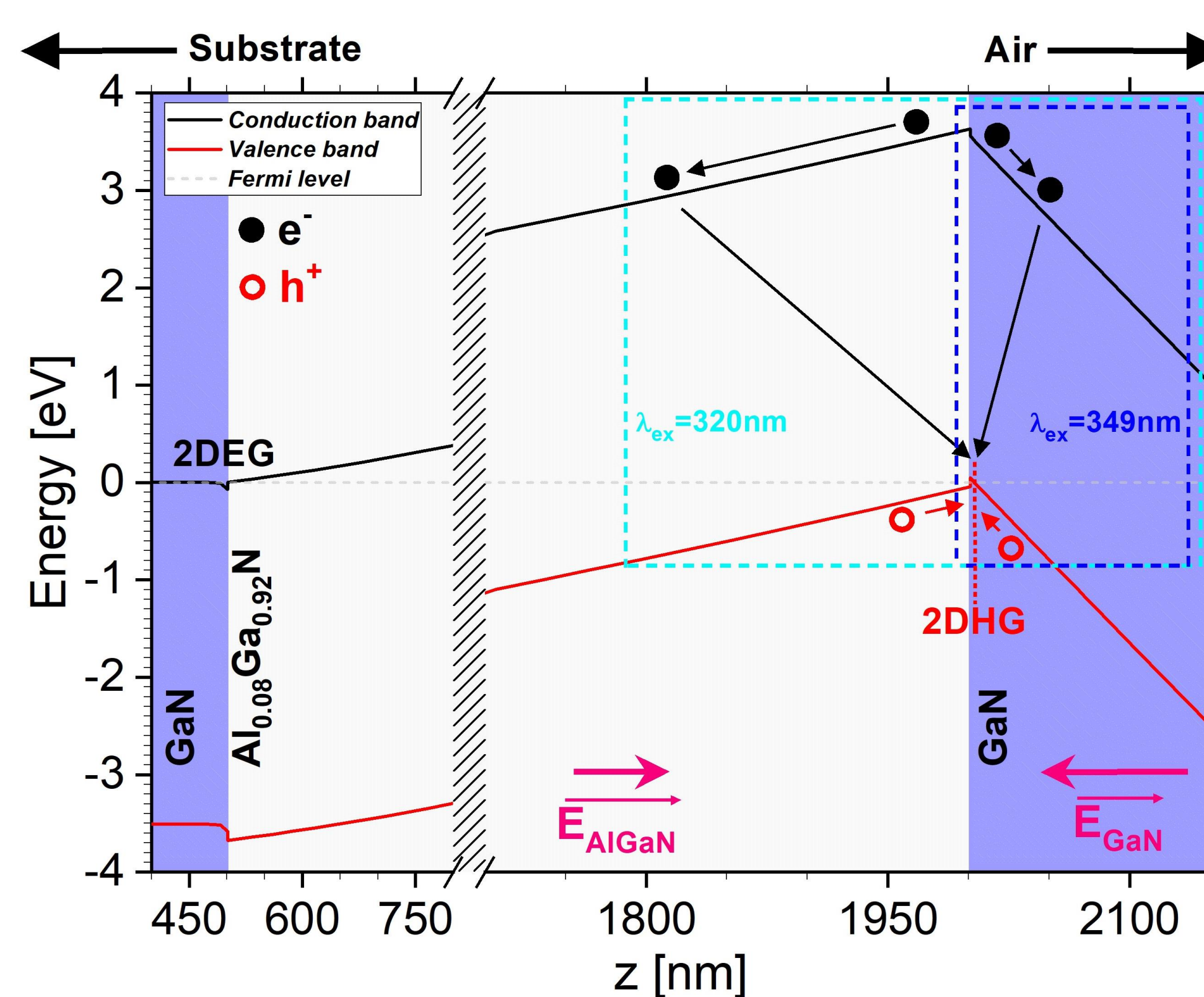


- On the waveguide, a specific transition that is not observed in the template show a rapid blue-shift with increasing peak power density. After reaching 150 kW.cm^{-2} , this transition becomes no longer visible. These characteristics are typically associated with electric field effects, specifically with two-dimensional carrier gases (2DHG or 2DEG).



- When using a pulsed laser at 349 nm, this transition is no longer detectable on sample 2. → The luminescence does not come from GaN buffer layer.
- Power density dependant transition observed when using CW laser at 320nm is associated with recombinations of electrons and holes localized on surface states.

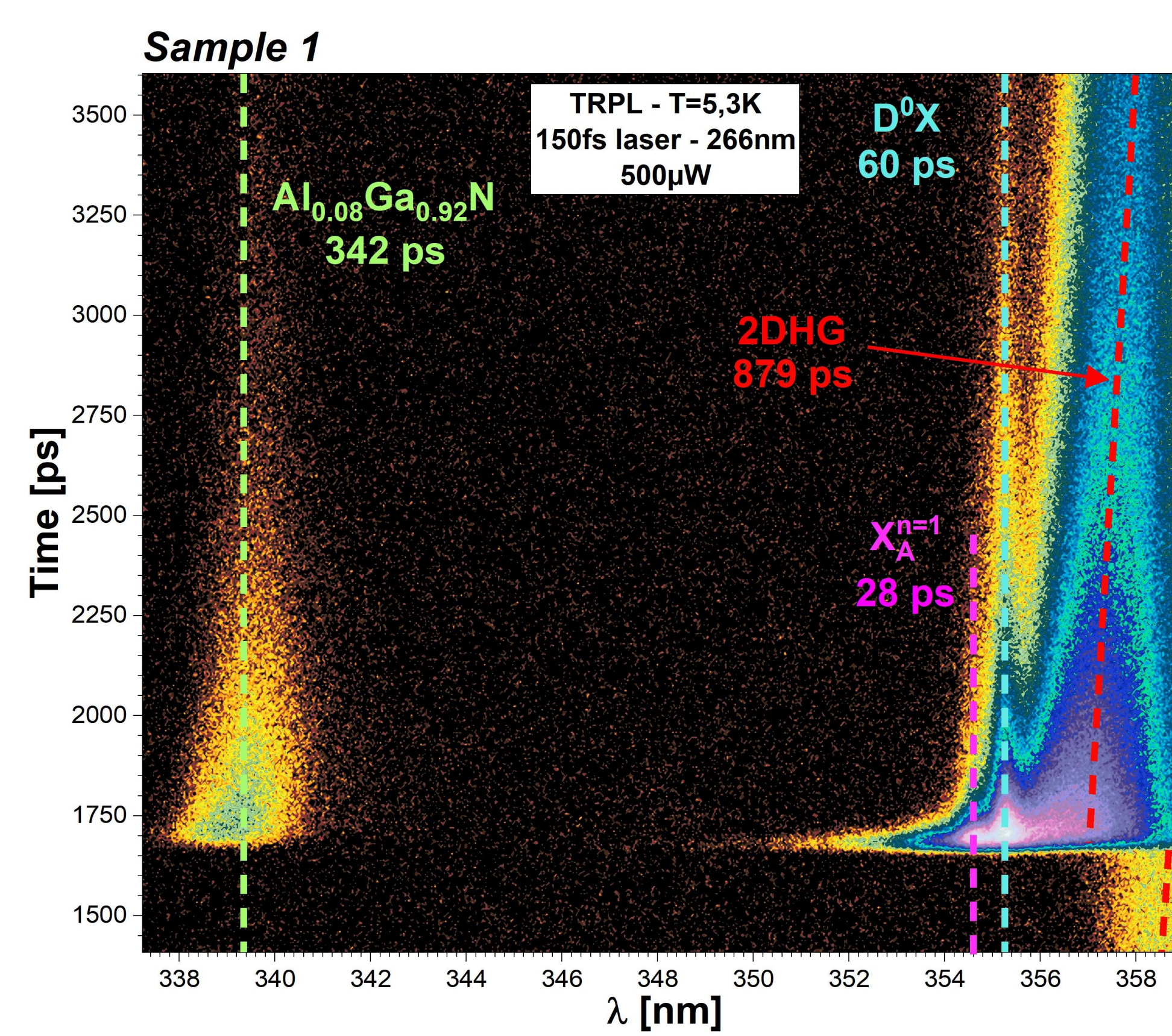
③ Band alignment and TRPL measurements



- Strained würtzite structure: spontaneous and piezoelectric polarizations. → sheet charge at the interfaces : $\sigma_{pol} = \|P_{AlGaN}\| - \|P_{GaN}\|$
- Band alignment calculation with a self consistent resolution of Schrödinger and Poisson equations.
- Electrostatic equilibrium is achieved by the accumulation of holes and electrons at the interfaces, creating potential wells in the valence band and conduction band, respectively.

Internal electric field :

1. Electrons drift away from the interface.
2. Holes accumulate into the potential well (2DHG)



TRPL measurement :

1. Electrons and holes not localized at the same position :
 - Large decay time ↔ weak overlap of the wavefunctions
2. Large internal electric field :
 - Red-shift of the transitions

Conclusion

- First optical observation of a two-dimensional hole gas (2DHG) in a GaN- $\text{Al}_x\text{Ga}_{1-x}\text{N}$ heterostructure.
- Previous observations only by :
 - Contactless Electroreflectance (CER) [Phys. Status Solidi RRL 2021, 15, 2000573]
 - Magnetotransport measurement [Science 365, 1454–1457 (2019)]

Perspectives

Photoluminescence measurements on SiO_2 extraction gratings deposited on the surface of the waveguide have allowed, through Fourier plane imaging on a CCD camera, the determination of guided mode dispersion. Comparison with 2DHG luminescence shows clearly that :

Guided polaritons modes are fed by the 2D hole gas.

This result is important because the low intensity and long lifetime of this transition enable the preservation of a polaritonic mode in the waveguide beyond an optical density of 1 MW.cm^{-2} . This represents an advancement in the field, as it is known that such structures can exhibit polariton laser effects at room temperature. [Phys. Rev. Appl. 18, 044029 (2022)]

