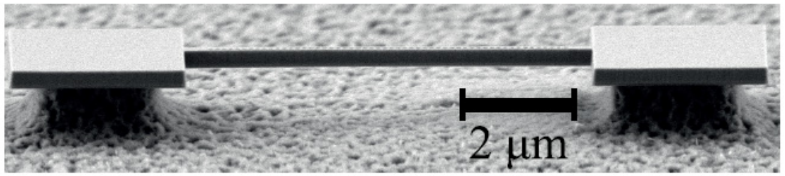
Benchmarking GaN-based photonic nanocavities: lasing features, quality factor quantification and surface effects

Raphaël Butté

Institute of Physics
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
SWITZERLAND



FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

raphael.butte@epfl.ch

III-nitrides, a brief overview

General features

- High luminous efficiency: > 200 lm/W (commercial, Nichia Inc.), > 300 lm/W (R&D, Cree)
- High wall-plug efficiency: 60% (blue LEDs), 50% (white LEDs)

 +  ⇒ 

Blue LEDs ⇒ InGaN/GaN QWs

- *World-most grown III-V heterostructures*
- High internal quantum efficiency despite large density of nonradiative recombination centers[1] (behavior similar to InAs dots on Si[2])

The Nobel Prize in Physics 2014

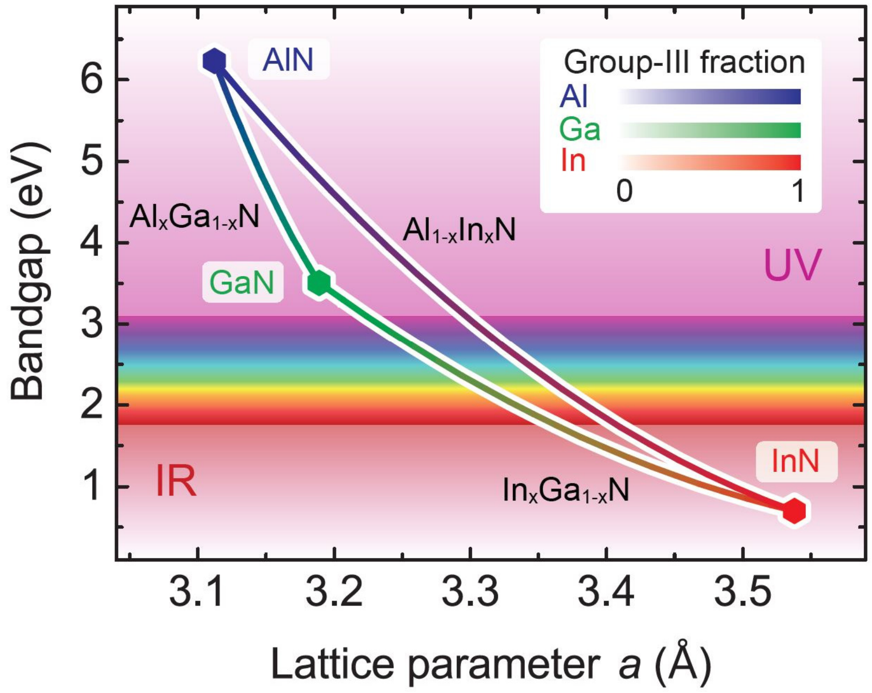
Photo: A. Mahmoud	Photo: A. Mahmoud	Photo: A. Mahmoud
Isamu Akasaki	**Hiroshi Amano**	**Shuji Nakamura**
Prize share: 1/3	**Prize share:** 1/3	**Prize share:** 1/3

[1]S. Nakamura, Science **281**, 956 (1998)
[2]J.-M. Gérard *et al.*, APL **68**, 3123 (1996)

III-N for integrated photonics

- ✓ Wide bandgap (~3.4 eV for GaN)
- ✓ Mechanical hardness
- ✓ Optoelectronics
- ✓ Industrial production
- ✓ Biocompatibility
- ✓ Single photon emission at 300 K[1]

- ✗ Heteroepitaxy
- ✗ “Low” refractive index



[1]M. J. Holmes *et al.*, Nano Lett. **14**, 982 (2014)

Outline

- III-N photonic nanocavities: a promising platform for high-β lasing
- GaN nanobeams: design, fabrication and main optical features
- Statistical analysis: a powerful approach for reconciling theory and experiment
- Surface effects: an unexpected prominence
- Conclusion and outlook

EPFL

Scrutinizing lasers[1]

- **Recent editorial in Nature Photonics (March 2017)**

Lasers play a pivotal role in photonics, but claims of lasing are not always as robust and informative as they should be. A new trial policy at *Nature Photonics* aims to rectify this shortcoming.

- **Laser checklist ⇒ evidence supporting claim of lasing**
  http://www.nature.com/authors/policies/laserchecklist.pdf

- **Do the listed criteria strictly apply to the case of nanolasers?**

Clear threshold behavior ⇒ not relevant for high-β lasers

Linewidth narrowing

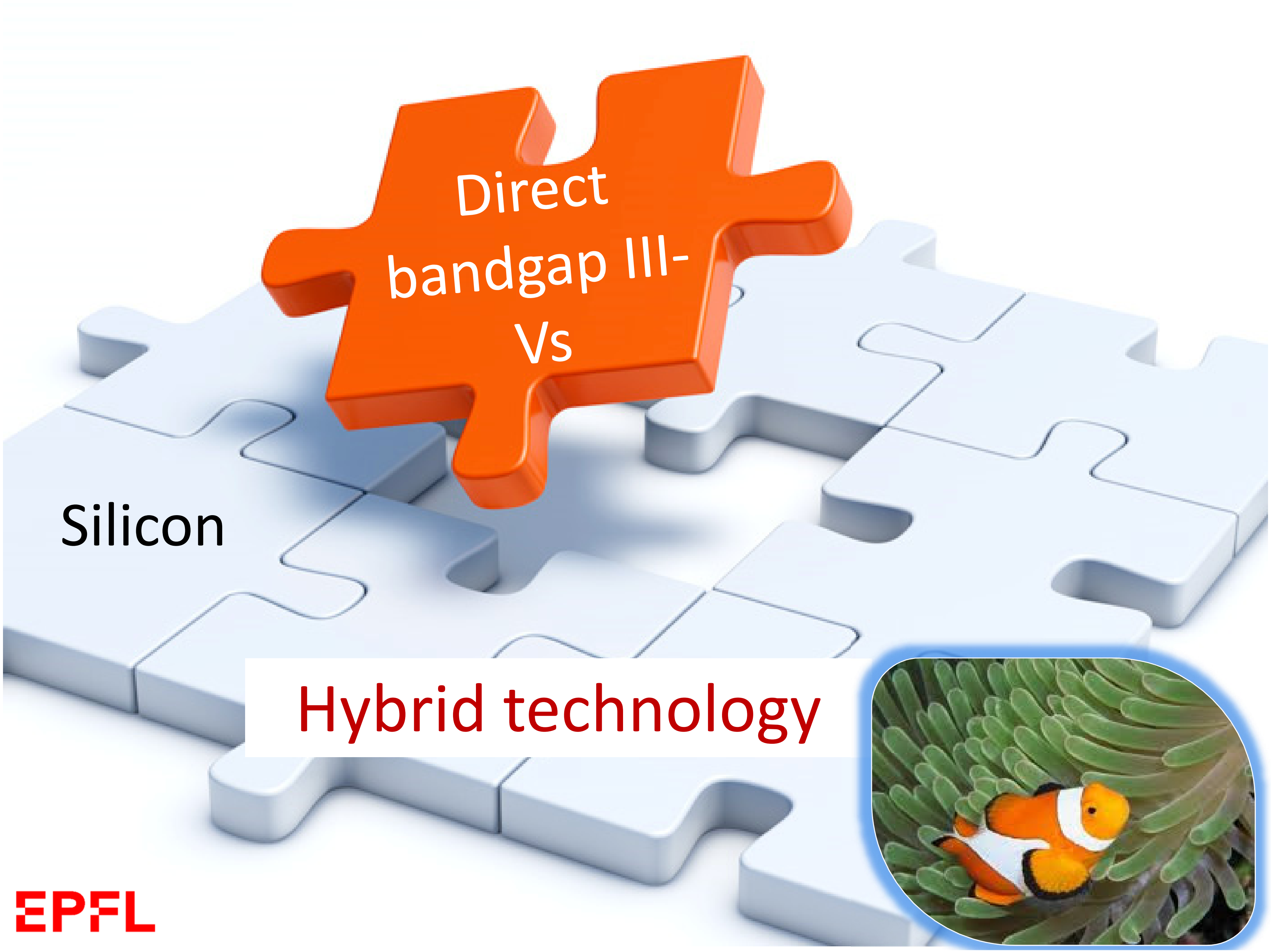
"Linewidth narrowing should bring you to the 1 Å level unless a spectrometer with inadequate resolution is used. If it is a multimode device, clear modal spectral resolution is required and the separation between modes should be determined by the cavity length. Here, poor spectral resolution is not to be tolerated,"

Coherent output

said so eloquently, 'No beam, no laser'. Beam images are really helpful, regardless of wavelength."

EPFL

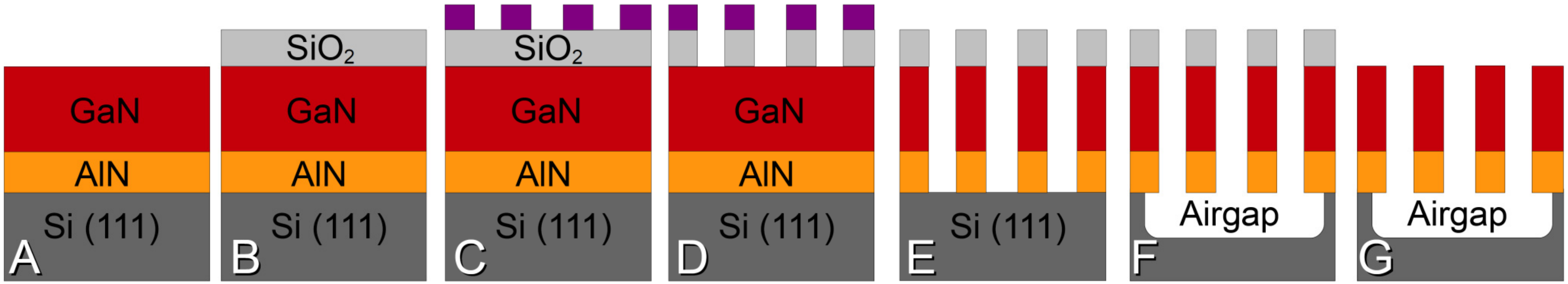
[1]Nature Photonics **11**, 139 (2017)



Hybrid technology

Growth and fabrication of GaN nanobeams[1]

A. Growth AlN/GaN MOVPE
B. Deposition SiO_2 PECVD
C. E-beam lithography
D. Dry etching SiO_2 RIE
E. Dry etching AlN/GaN ICP
F. Si substrate underetching by RIE
G. SiO_2 removal in HF solution



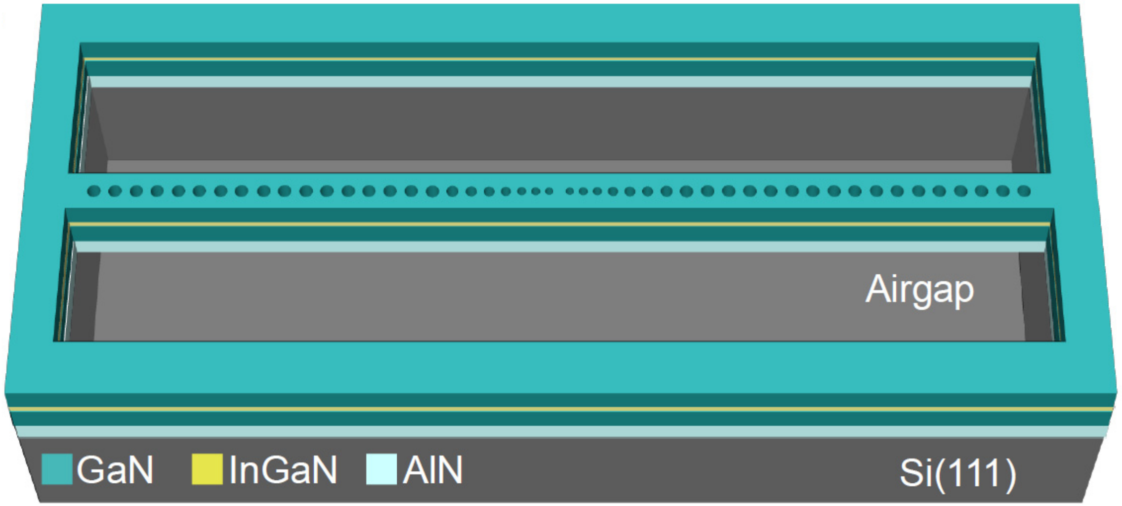
- ✓ Compatible with Si technology
- ✓ High airgaps (> 3 µm) achievable
- ✓ Suitable for visible and NIR structures

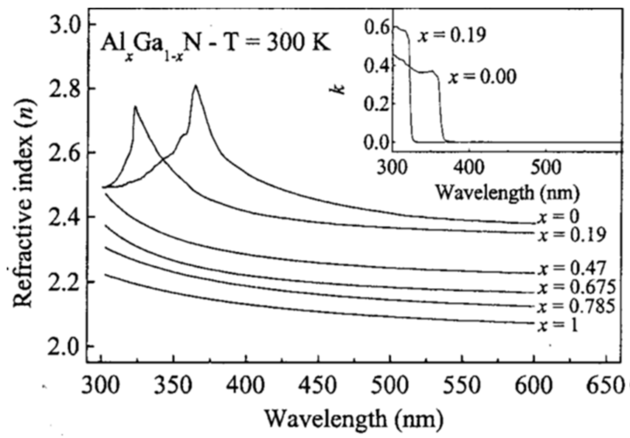
[1] N. Vico Triviño *et al.*, APL **100**, 071103 (2012); *ibid.*, APL **102**, 081120 (2013); *ibid.*, APL **105**, 231119 (2014); *ibid.*, Nano Lett. **15**, 1259 (2015)

EPFL

GaN nanobeam design

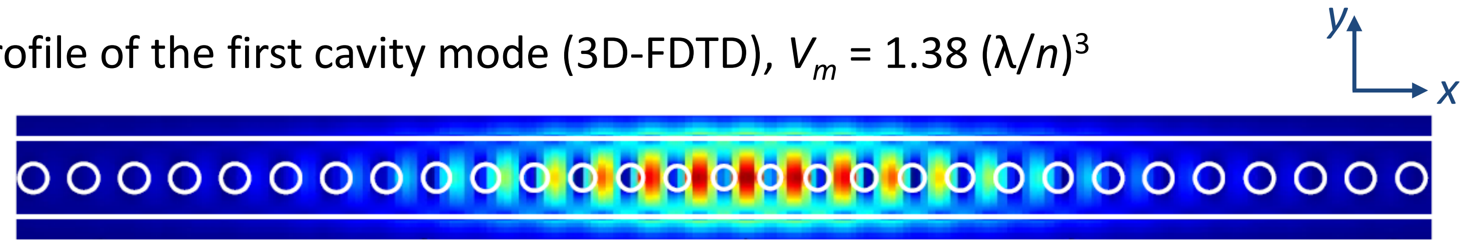
Challenge: fabricating high-*Q* 1D-nanobeam cavity @ short wavelength in low $n(\lambda)$ material





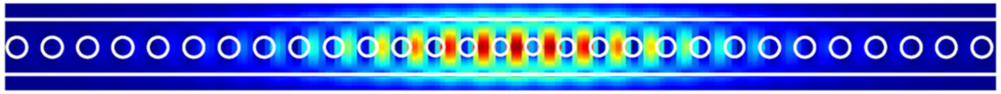
N. Antoine-Vincent *et al.*, JAP **93**, 5222 (2003)

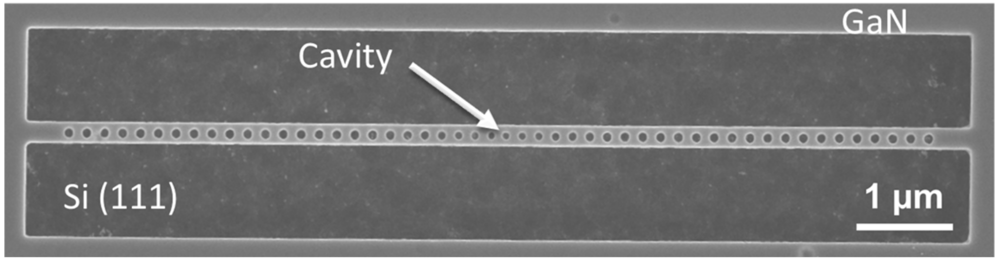
$|E_y|$ field profile of the first cavity mode (3D-FDTD), $V_m = 1.38\ (\lambda/n)^3$

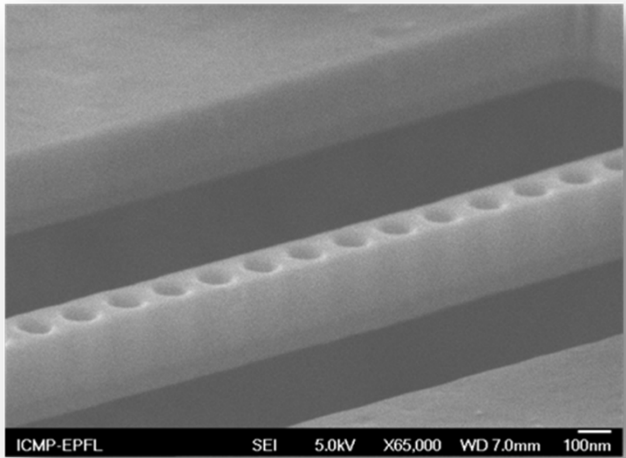


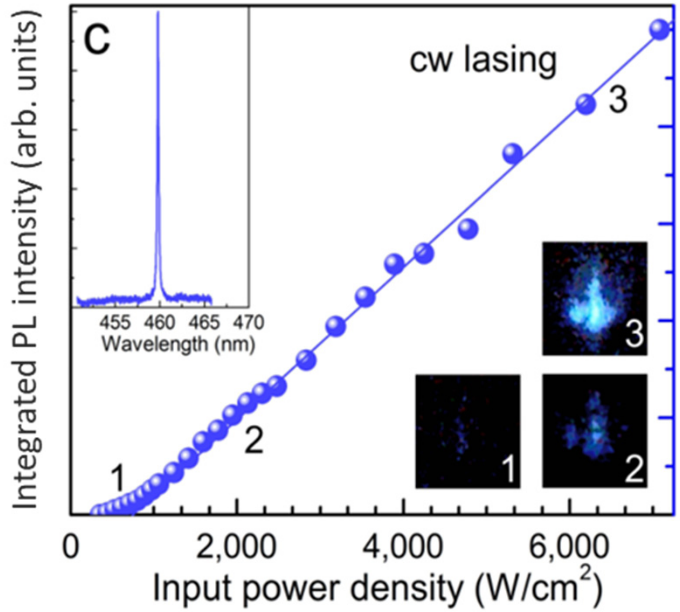
EPFL

High-β GaN nanobeam lasers @ 300 K[1]









- Single lasing mode
- Q ~ 2600
- P_{thr} ~ 740 W/cm² (2.3 µW)
- $\beta > 0.8$

[1]N. Vico Triviño *et al.*, Nano Lett. **15**, 1259 (2015)

Laser rate equation analysis[1]

$$\frac{dN}{dt} = R_{in} - \left(AN + BN^2 + CN^3\right) - v_g g N_p$$

$$\frac{dN_p}{dt} = \left[\Gamma v_g g - \frac{1}{\tau_p}\right] N_p + \Gamma \beta B N^2$$

- Logarithmic gain model

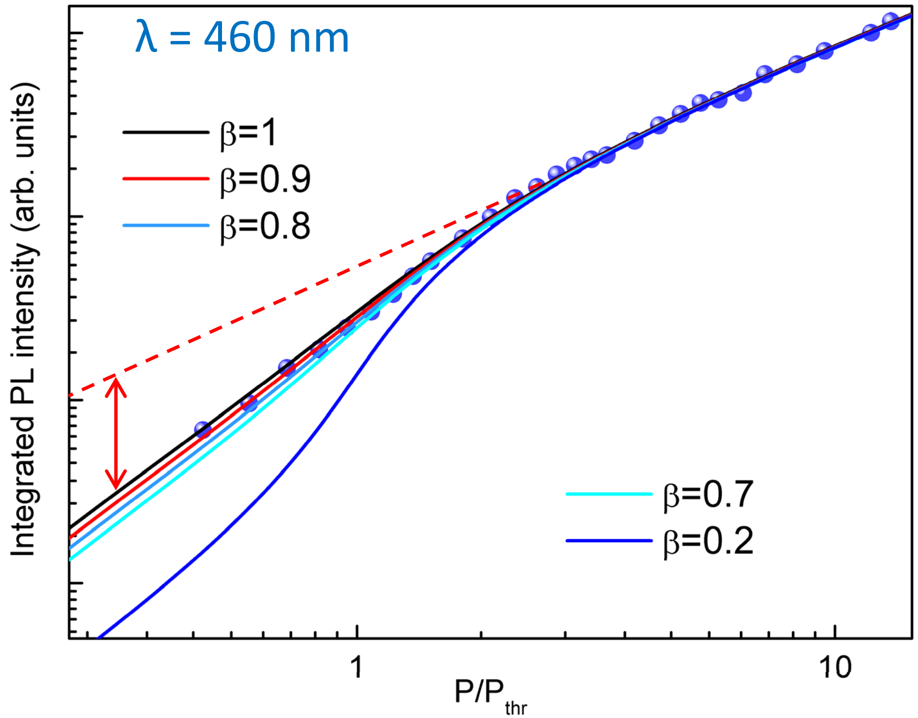
$$g(N) = g_0 \ln\left(\frac{N}{N_{tr}}\right)$$

- $\beta \rightarrow$ spontaneous emission coupling factor

$$\beta = A_0 \Big/ \sum_i A_i$$

- $\beta =$ 1 necessary (but not sufficient) condition for *thresholdless* lasing

$\beta > 0.8$[2]



Impact of nonradiative recombinations

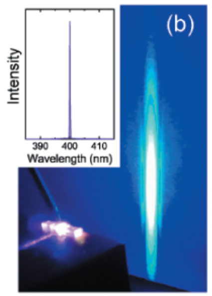
[2]N. Vico Triviño *et al.*, Nano Lett. **15**, 1259 (2015)

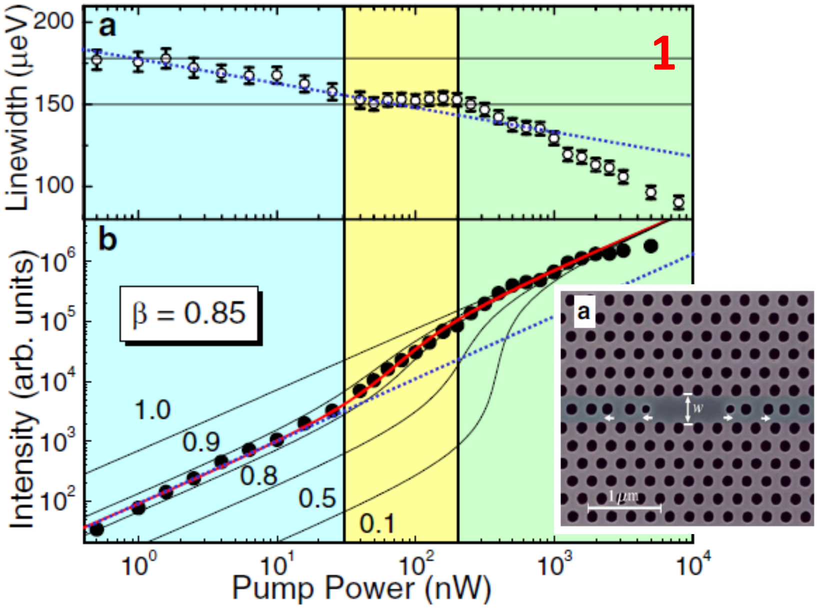
[1]L. A. Coldren *et al.*, *Diode Lasers and Photonic Integrated Circuits* (Wiley, New York, 2012)

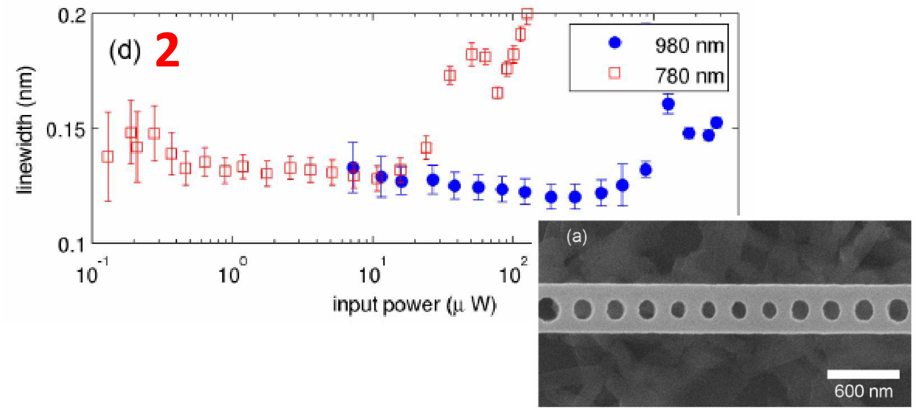
EPFL

Usual signatures of lasing

	Clear threshold	Linewidth narrowing	Far-field pattern
Conventional LDs	✓	✓	✓
High-β nanolasers	✗	Not always	Not straightforward







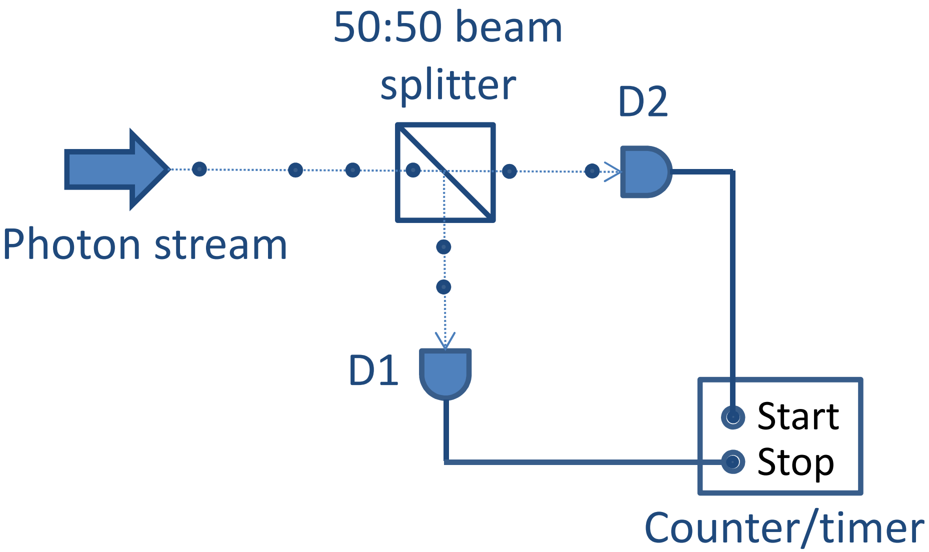
⇒ Need for an extra proof of lasing

[1]S. Strauf *et al.*, PRL **96**, 127404 (2006)
[2]Y. Gong *et al.*, Opt. Express **18**, 8781 (2010)

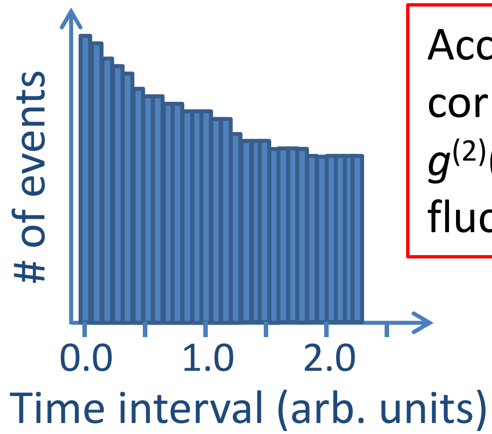
EPFL

Photon statistics as a tool to assess coherence

Hanbury Brown-Twiss experiment

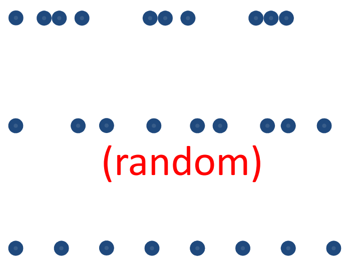


Histogram



Access to 2nd-order correlation function, $g^{(2)}(\tau)$, i.e., intensity fluctuations

- Bunched (chaotic) light: $g^{(2)}(0) > 1$
- Coherent light: $g^{(2)}(0) = 1$ (random)
- Antibunched light: $g^{(2)}(0) < 1$



The Nobel Prize in Physics 2005

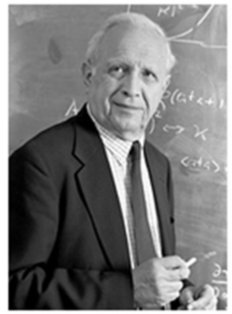
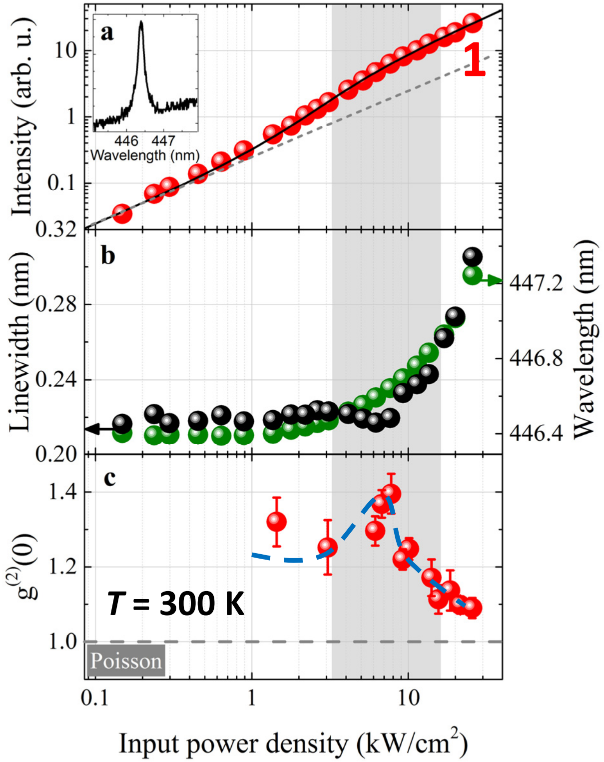


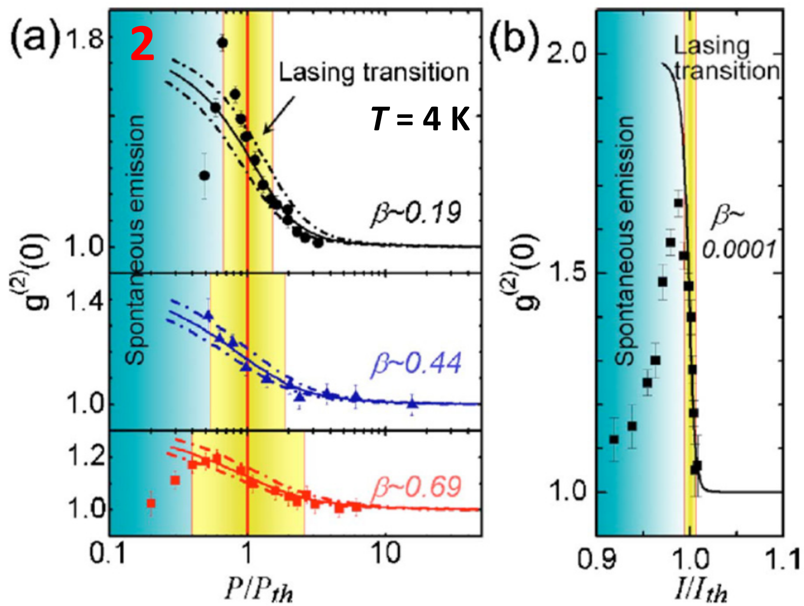
Photo: J.Reed
Roy J. Glauber
Prize share: 1/2

Quantum optics for true lasing assessment

Proof of high-β lasing up to 300 K via 2nd order autocorrelation function

$$g^{(2)}(\tau) = \frac{\langle I(t)I(t-\tau)\rangle}{\langle I(t)\rangle^2}$$





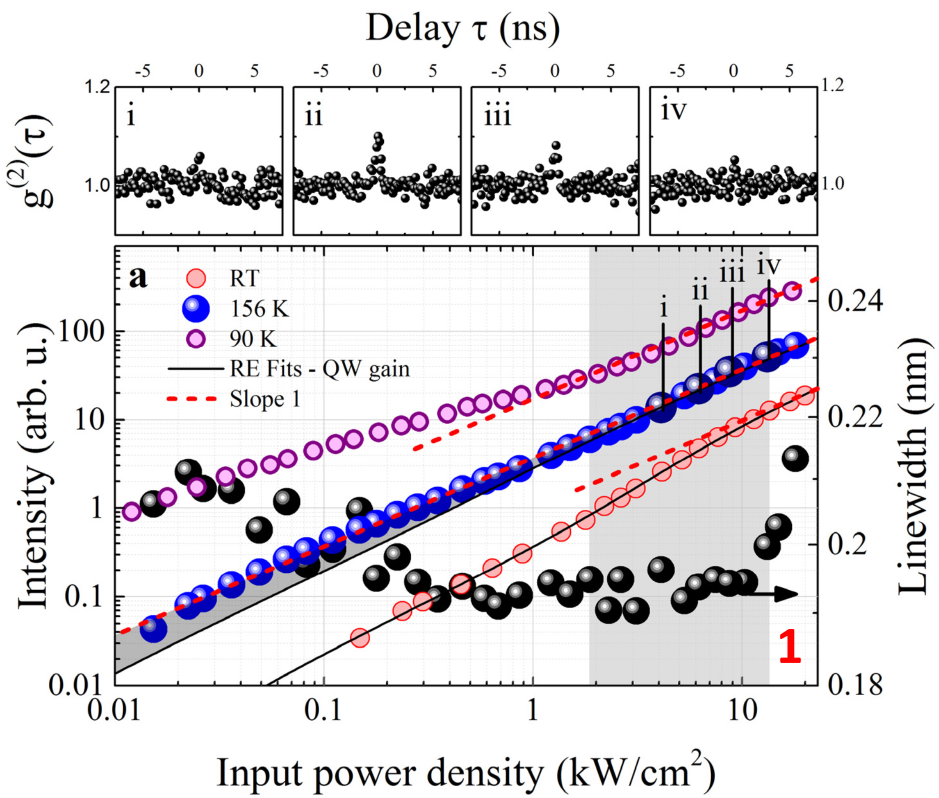
Increasing β coefficient ⇒

- Decreasing P_{thr} and blurred lasing transition
- $g^{(2)}(0)$ deviates from 2 below threshold
- Slow transition to Poisson limit

[1]S. T. Jagsch *et al.*, Nat. Commun. **9**, 564 (2018) [2]Y.-S. Choi *et al.*, APL **91**, 031108 (2007)

Lasing evolution vs temperature

Complexity of the gain medium revealed through temperature-dependent I-O curves



Upon decreasing temperature

- Softer s-shape

⇒ Modified weight of radiative and nonradiative channels

- Thresholdless I-O curve @ ~160 K despite β-factor below 1

⇒ **Two-component 0D-2D gain material**

⇒ I-O data not captured by temperature-dependent rate equations assuming pure 2D gain

⇒ **Need to rely on $g^{(2)}(0)$ measurements to probe the onset of lasing**

[1]S. T. Jagsch *et al.*, Nat. Commun. **9**, 564 (2018)

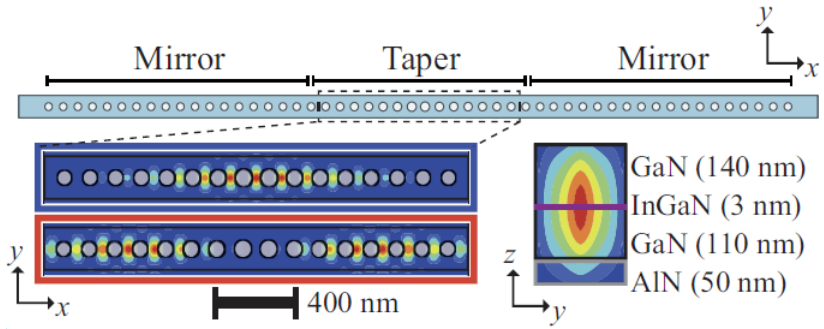
EPFL

Outline

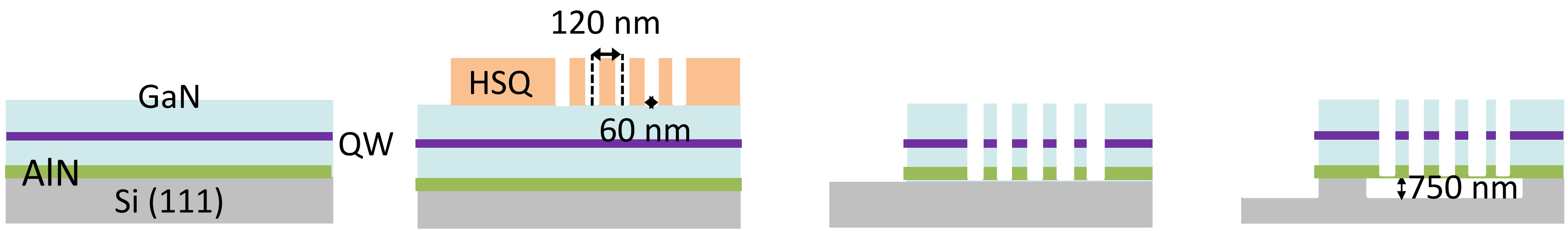
- III-N photonic nanocavities: a promising platform for high-β lasing
- GaN nanobeams: design, fabrication and main optical features
- Statistical analysis: a powerful approach for reconciling theory and experiment
- Surface effects: an unexpected prominence
- Conclusion and outlook

EPFL

New process flow for higher *Q* values



New taper design[1]

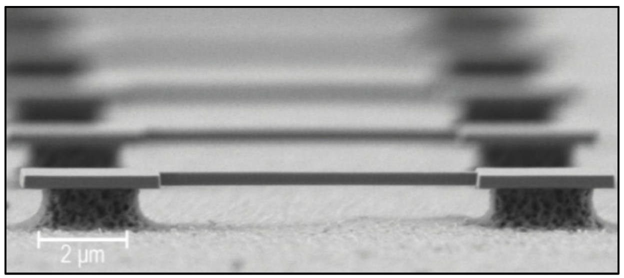


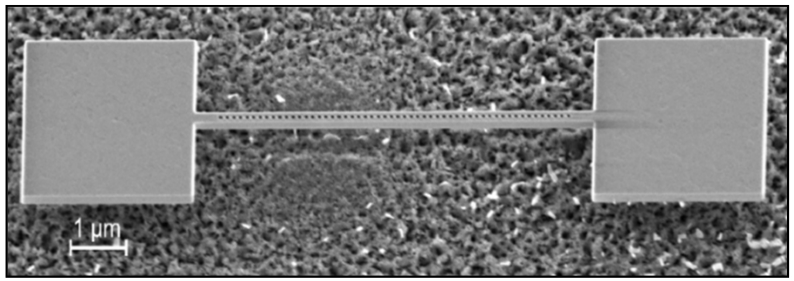
1. III-nitride growth by MOVPE

2. Electron beam lithography

3. ICP plasma etch in Cl_2/N_2

4. Membrane release in XeF_2 vapor



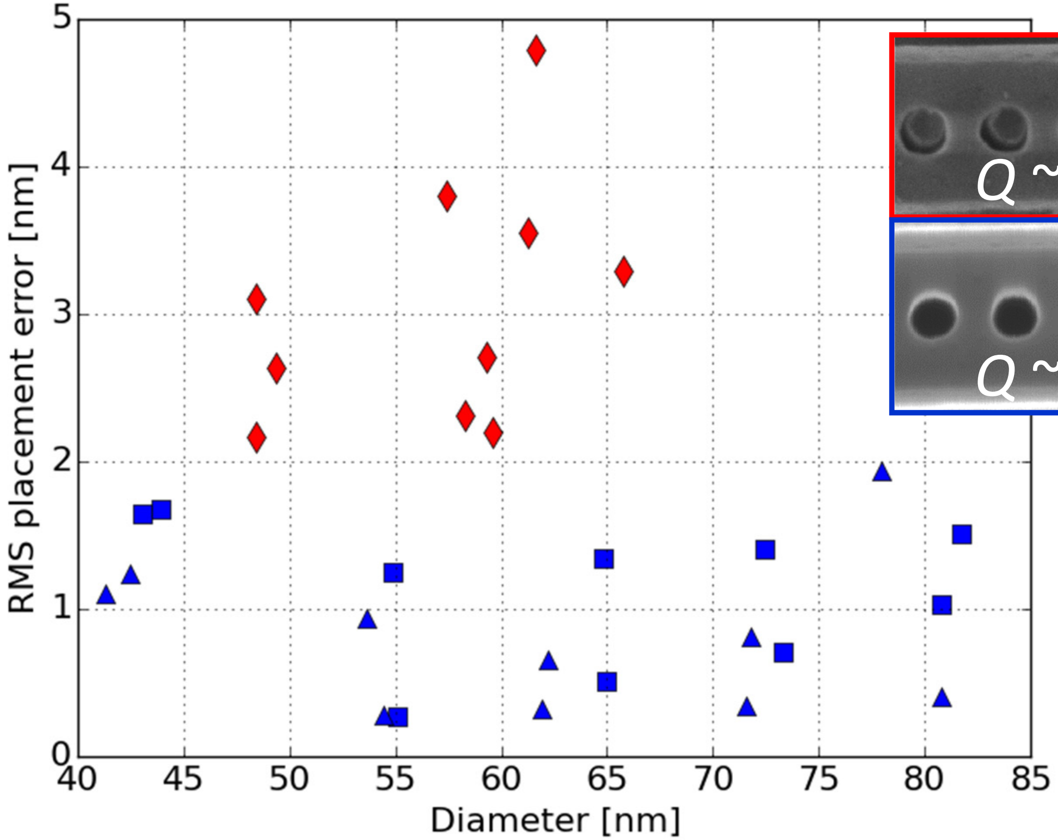


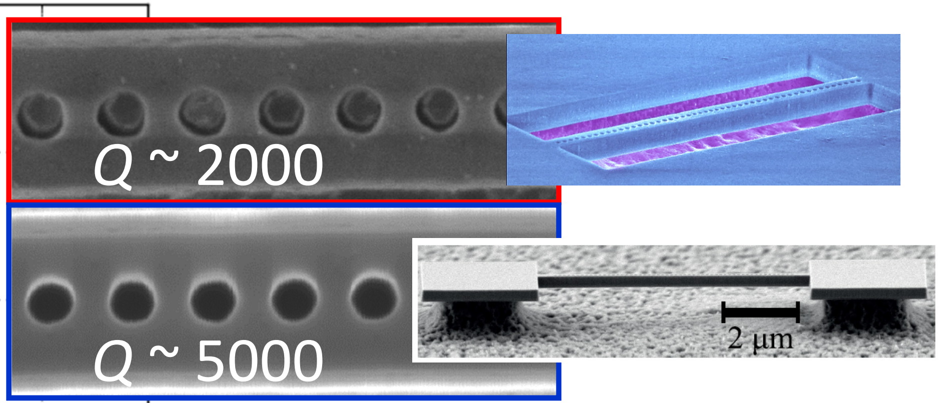
EPFL

[1]Q. Quan and M. Loncar, Opt. Express **19**, 18529 (2011)

New process flow for higher *Q* values

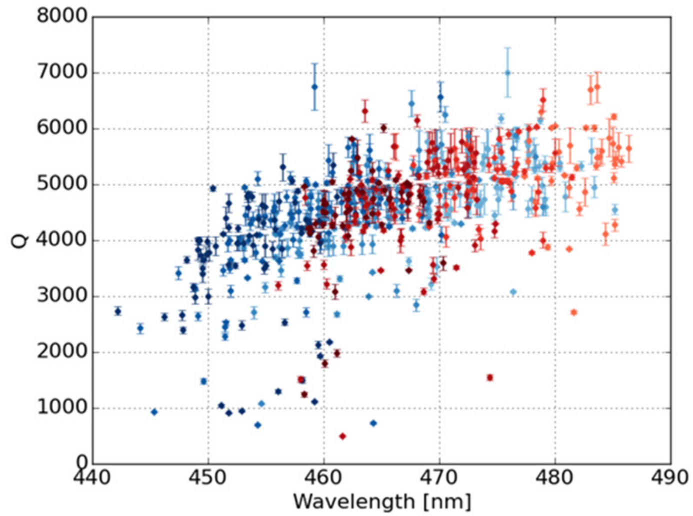
Single step pattern transfer process for e-beam lithography ⇒ improved rms shape error[1]





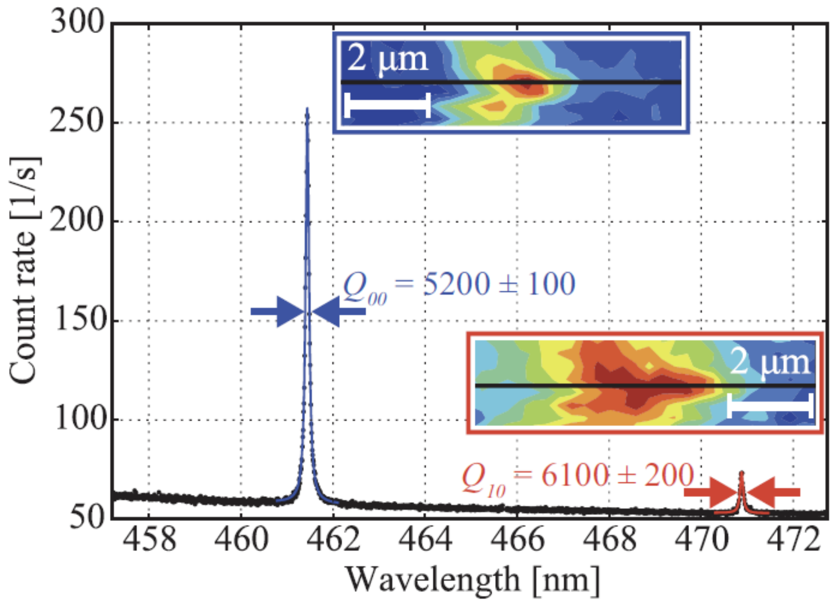
> twofold increase in *Q*

High fabrication yield (~ 97%)



[1] I. Rousseau *et al.*, PRB **95**, 125313 (2017)

Optical mode identification



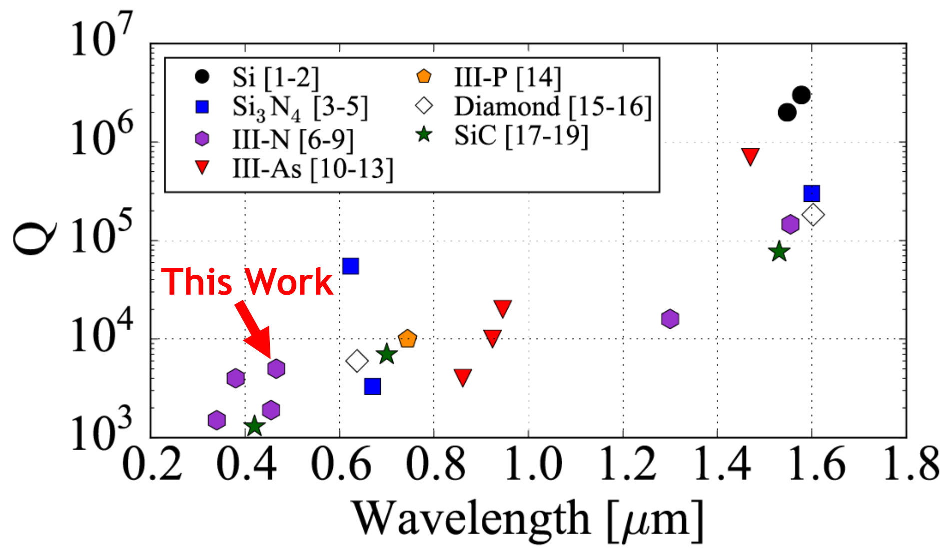
Optical mode identification using far-field μPL mapping[1]

- Symmetric fundamental cavity mode (Q_{00})
- Antisymmetric first-order cavity mode (Q_{10})

Decreasing *Q* in PhC cavities with decreasing wavelength[1]

- Qualitative trend independent of materials and cavity designs

⇒ **What are the limiting factors?**



[1] I. Rousseau *et al.*, PRB **95**, 125313 (2017)

Outline

- III-N photonic nanocavities: a promising platform for high-β lasing
- GaN nanobeams: design, fabrication and main optical features
- Statistical analysis: a powerful approach for reconciling theory and experiment
- Surface effects: an unexpected prominence
- Conclusion and outlook

Reconciling theory and experiment[1]

$$Q_{exp}^{-1} = Q_{th}^{-1} + Q_{fab}^{-1} + Q_{off}^{-1}$$

$Q_{00} = 10^6$

$Q_{10} = 10^5$

$$\Rightarrow Q_{th}^{-1} \approx 0$$

3D-FDTD calculations including σ-model[2] of disorder

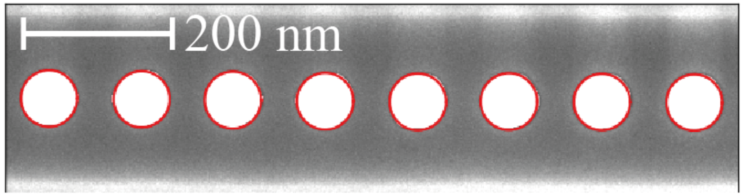
[1]N. Vico Triviño *et al.*, APL **105**, 231119 (2014)

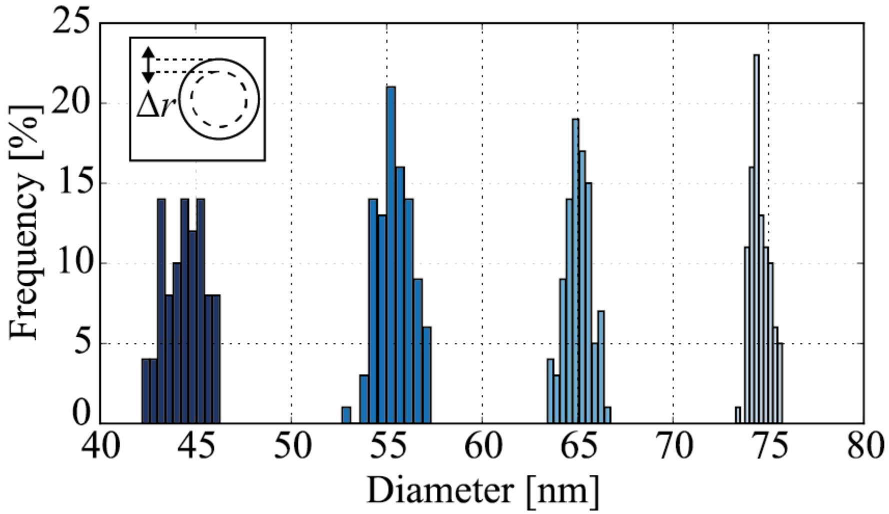
[2]D. Gerace and L. C. Andreani, Phot. Nano. Fund. Appl. **3**, 120 (2005)

EPFL

Fabrication tolerances

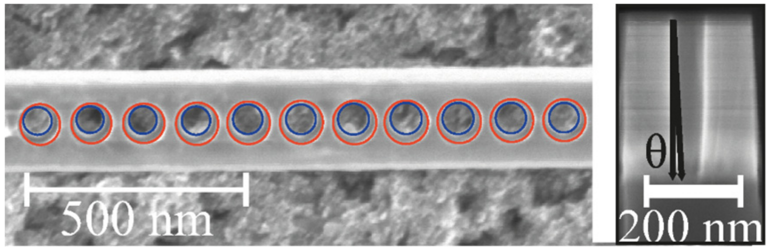
Algorithmic Hole Detection

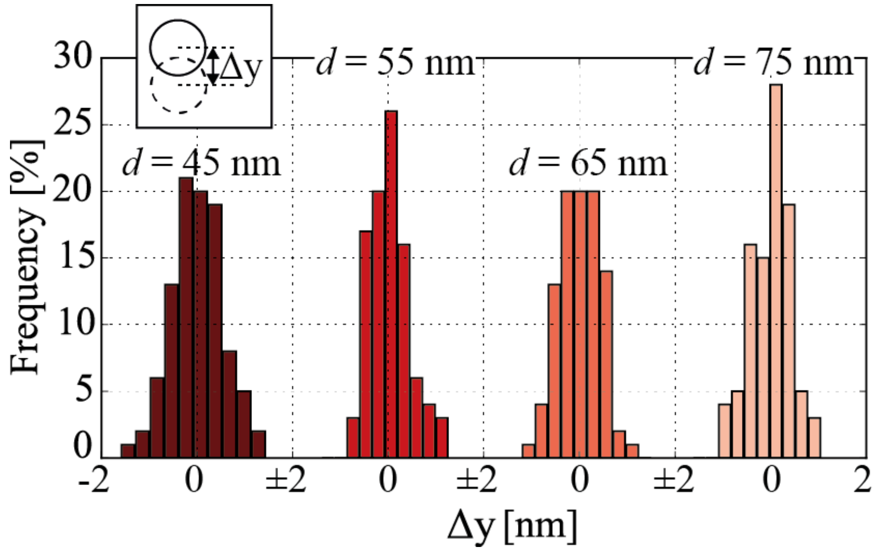




At the resolution limit of lithography technology

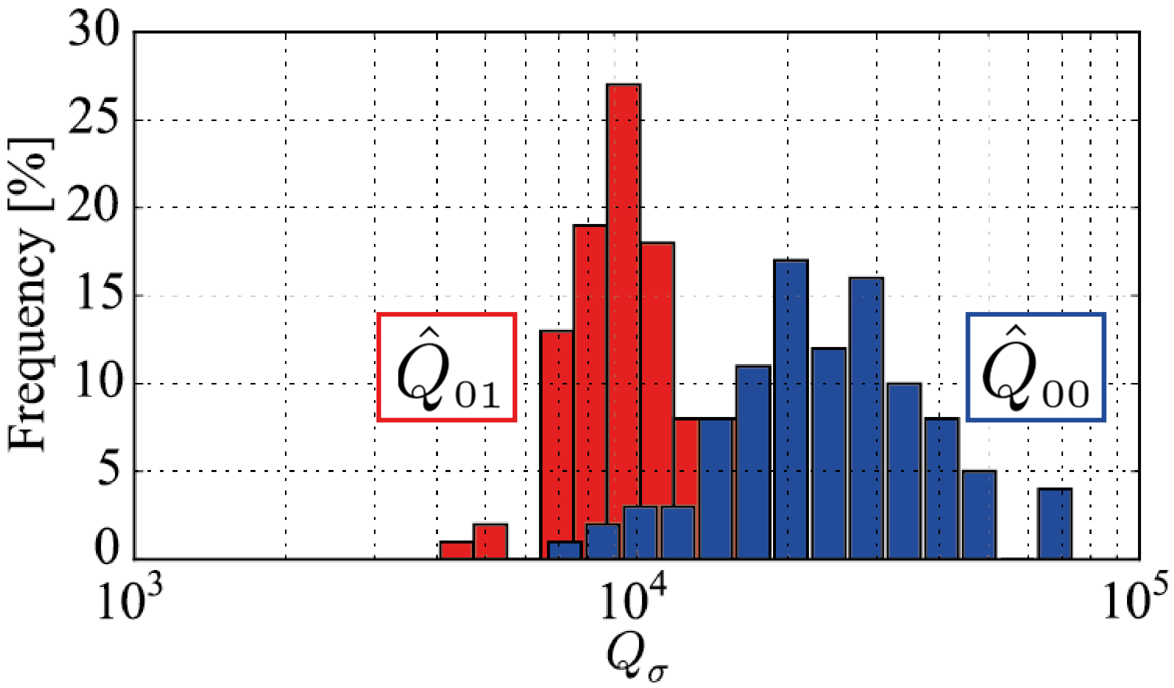
Sidewall Taper

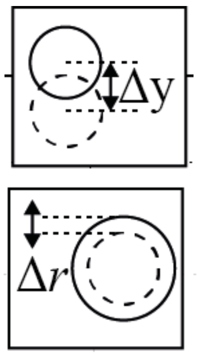




3D-FDTD simulations of fabrication disorder

$Q_{fab} \gg Q_{exp}$





$$\Delta x = \mathcal{N}(0, 1\ \mathrm{nm})$$
$$\Delta y = \mathcal{N}(0, 1\ \mathrm{nm})$$
$$\Delta r = \mathcal{N}(0, 1\ \mathrm{nm})$$

- 100 disorder realizations
- Geometrical parameters

EPFL

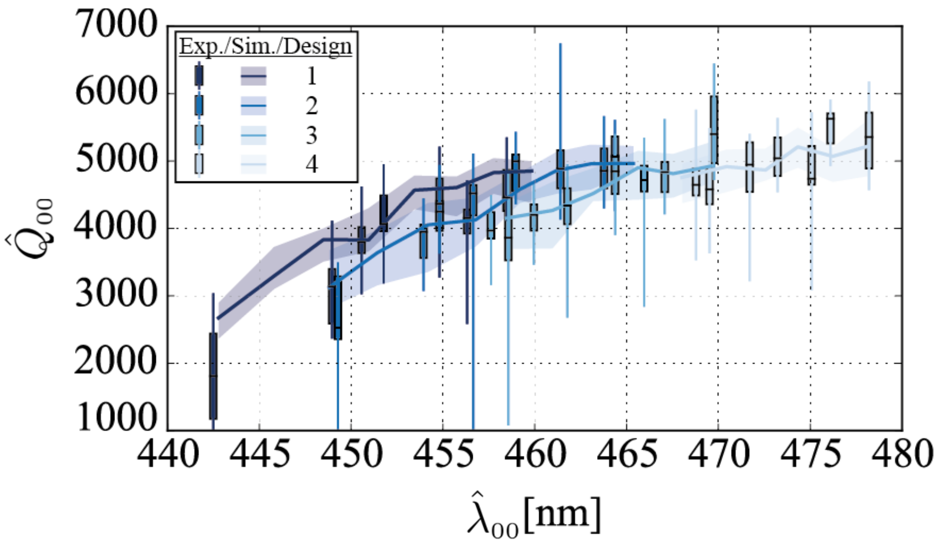
Experimental account of fabrication disorder

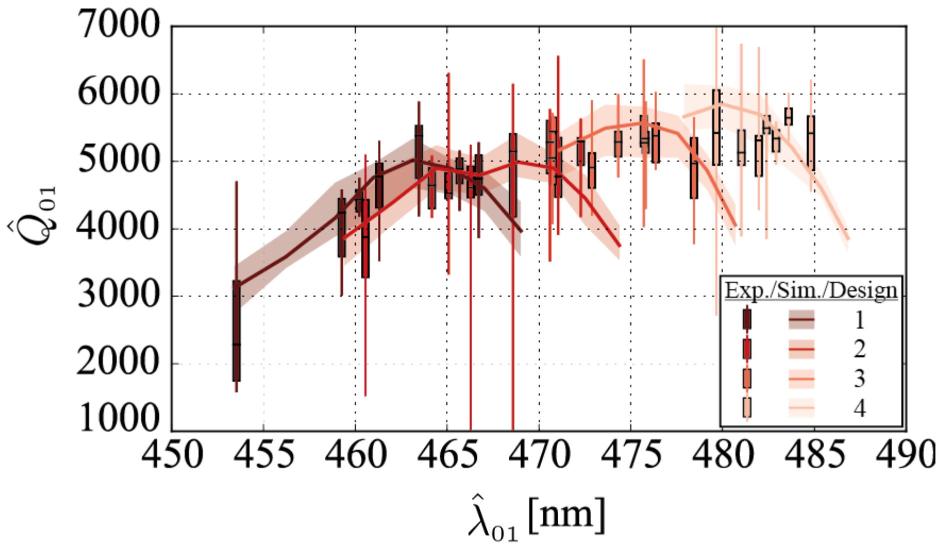
$$Q_{exp}^{-1} = Q_{fab}^{-1} + Q_{off}^{-1}$$

- 12 nanobeams
  - RT 351 nm cw pumping 1.6 kW/cm^2
- 20 disorder simulations
  - *N*(0,σ = 1 nm) for radius and position

$$Q_{off}^{00} = 6000$$

$$Q_{off}^{01} = 8500$$





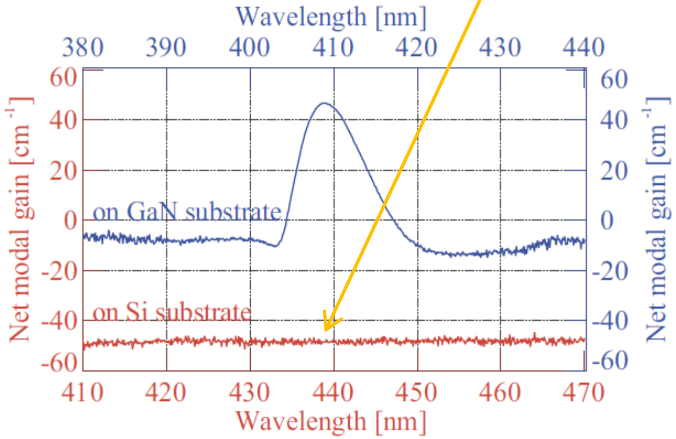
Reconciling theory and experiment

Surface roughness

$$Q_{off}^{-1} = Q_{bk}^{-1} + Q_{QW}^{-1} + Q_{sr}^{-1} + Q_{sa}^{-1}$$

At transparency

Surface absorption



$Q_{bk} \geq 16000$

Variable stripe length +

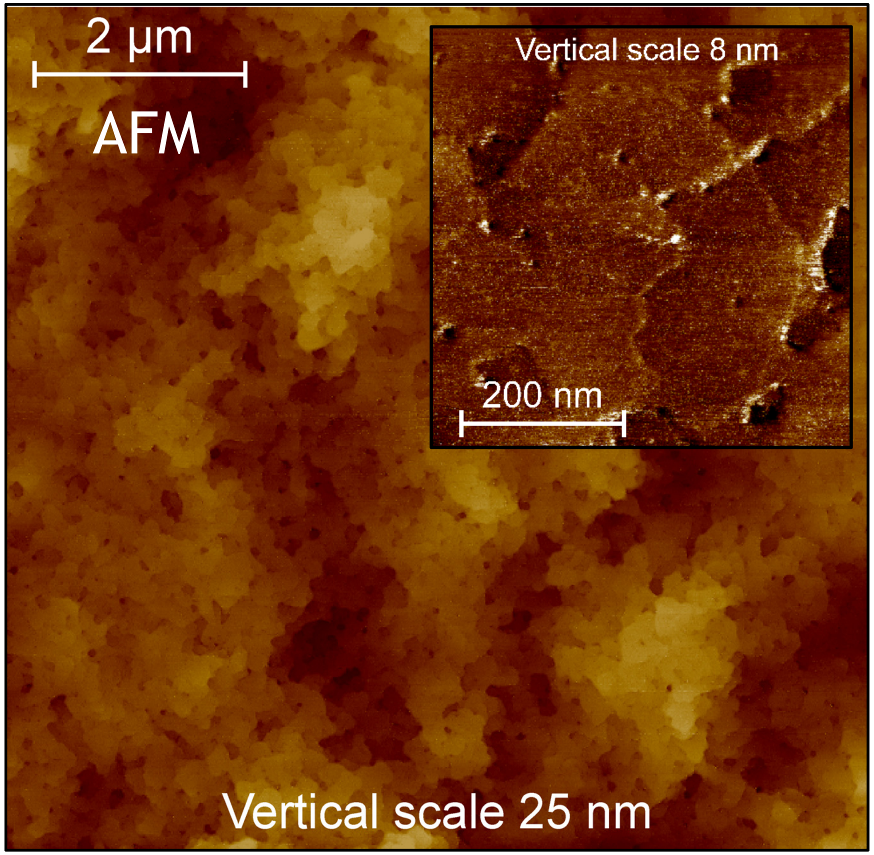
EM perturbation theory

Mode	Q_{off}	Surf. /Vol.
TE_{00}	6000	1
TE_{01}	8500	0.89

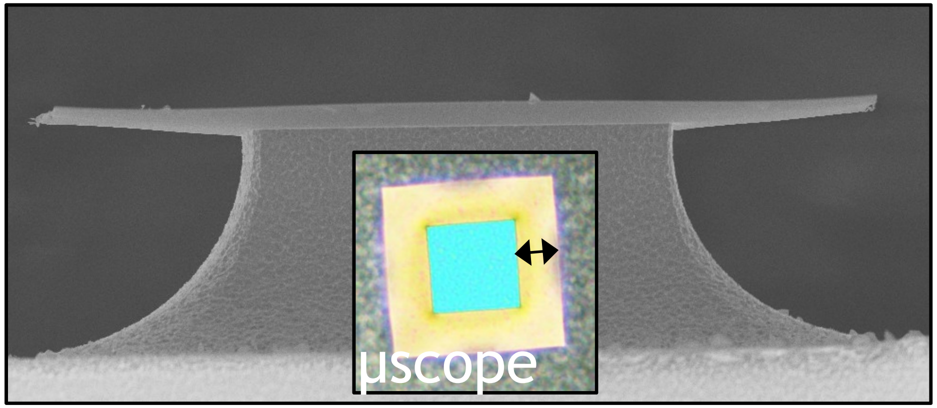
EPFL

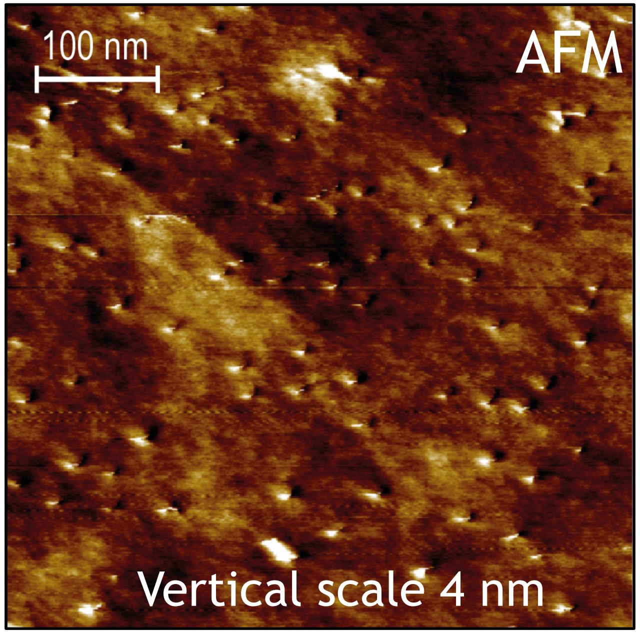
Surface roughness: experimental profiles

Top side



Back side



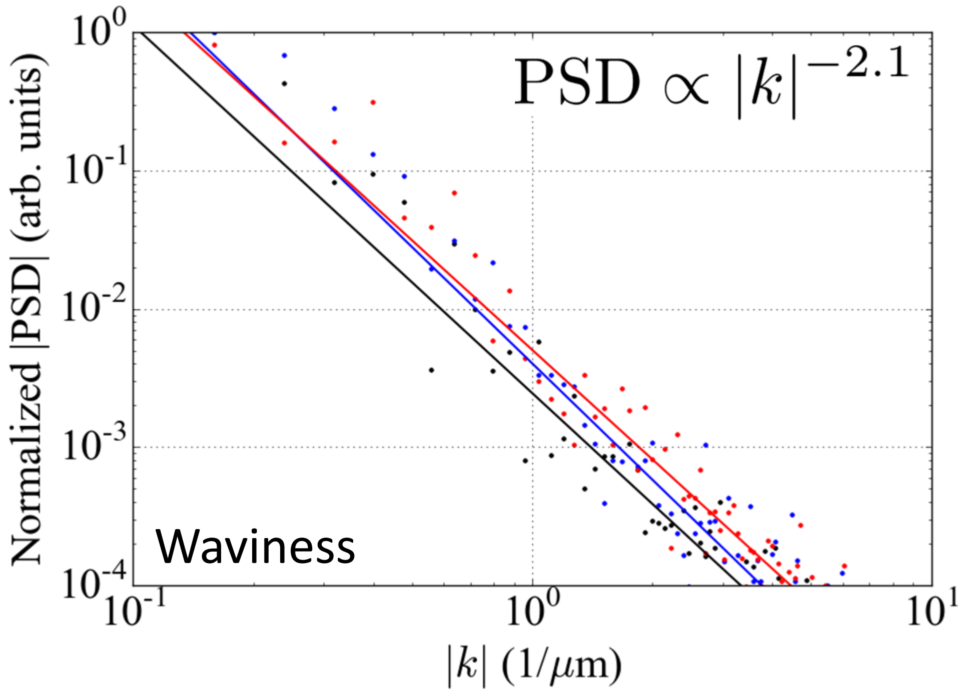


EPFL

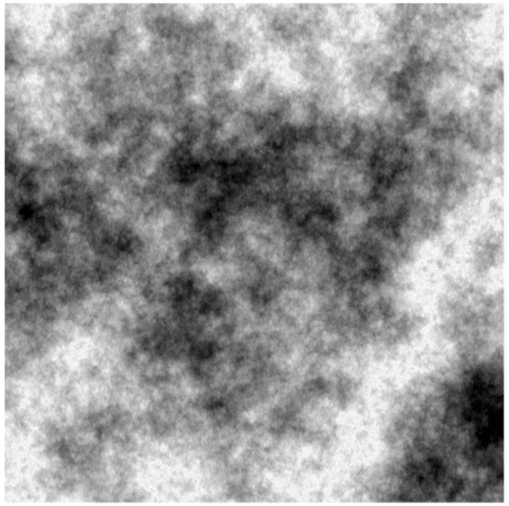
Surface roughness: simulated surfaces

Apodization of a random *k*-matrix

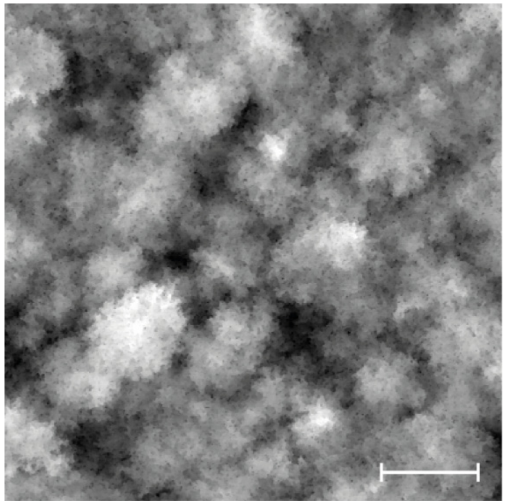
$$\mathcal{H}(x,y) = \mathrm{FFT}^{-1}\{[X(k) \sim \mathcal{U}(-k_0,k_0)] \cdot |k|^{-2.1}\}$$



Simulated



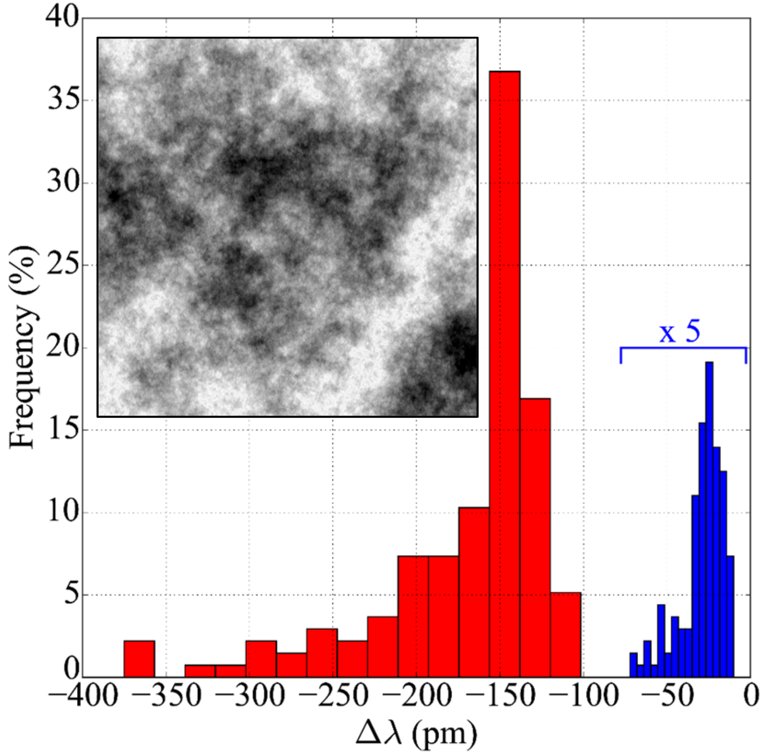
Experimental



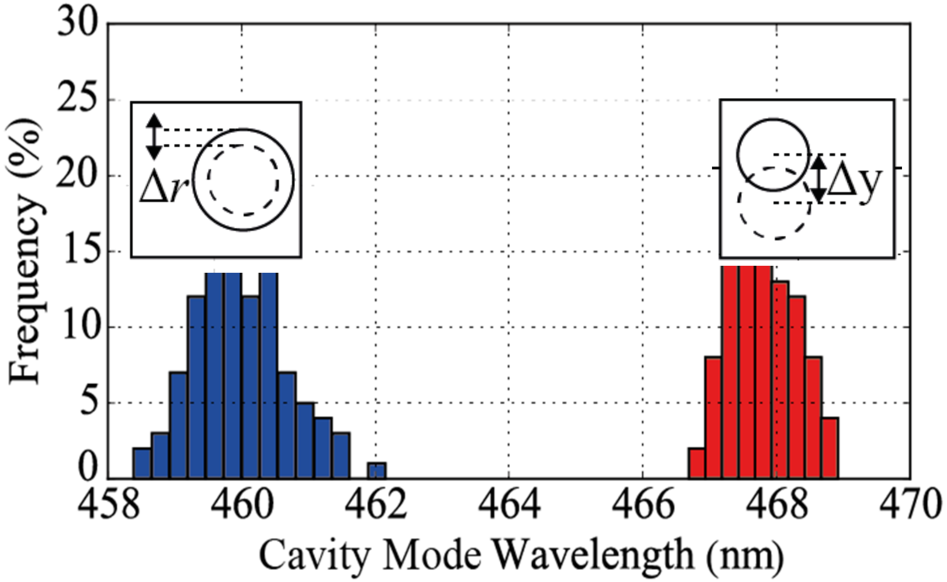
Surface waviness: frequency shifts

Surface waviness ($\mathbf{E}_{||}$ only)[1]

$$\Delta\nu = -\frac{\nu_0}{2}\frac{\int_V \varepsilon^{(1)}(\mathbf{r})|\mathbf{E}(\mathbf{r})|^2 d^3\mathbf{r}}{\int_\Omega \varepsilon_r^{(0)}(\mathbf{r})|\mathbf{E}(\mathbf{r})|^2 d^3\mathbf{r}}$$



Hole disorder (FDTD)

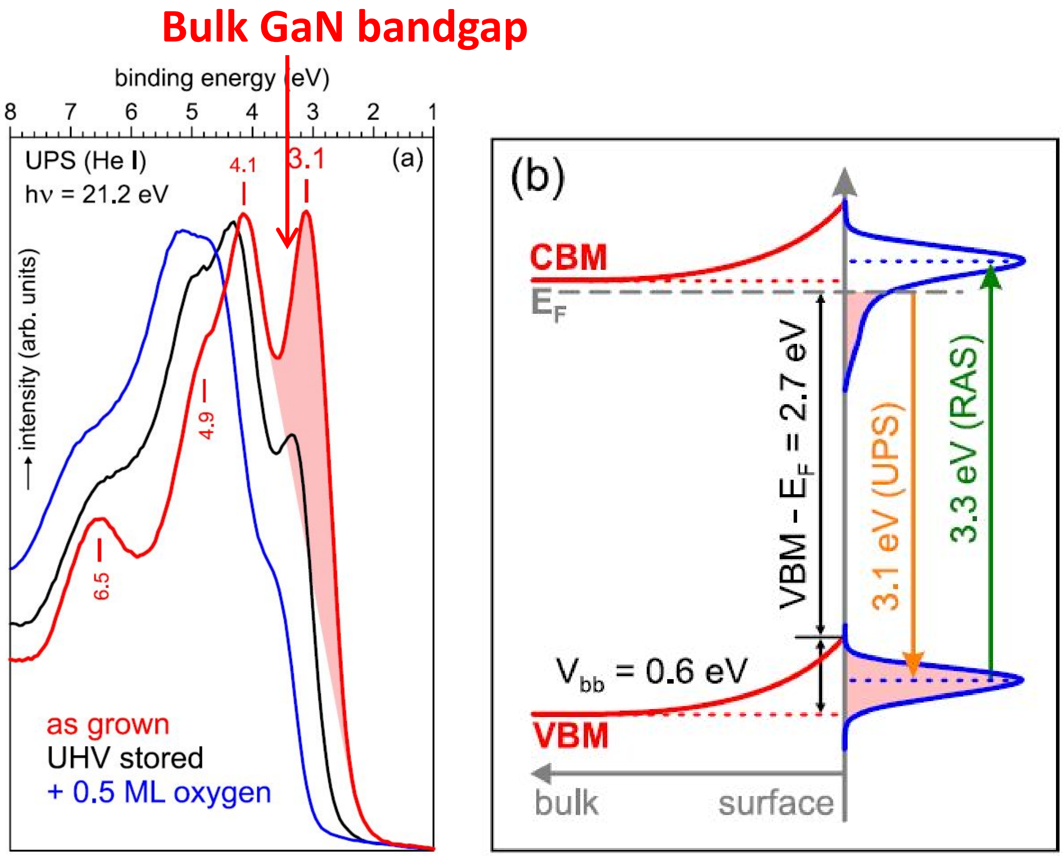


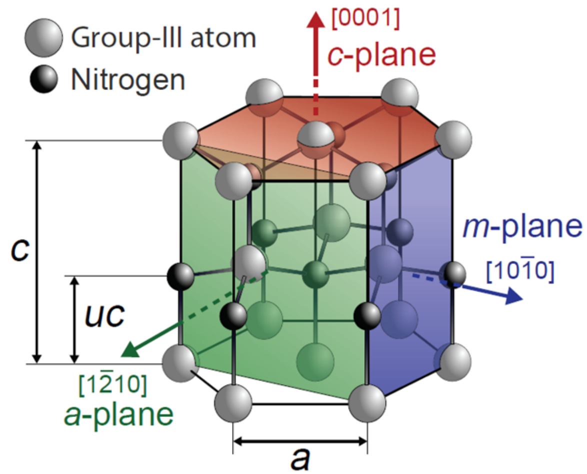
Hole disorder stronger than surface waviness

[1]S. Johnson *et al.*, PRE **65**, 066611 (2002)

Surface state absorption

Electronic states at GaN (1-100) surface[1] (sidewalls photonic nanocavities)





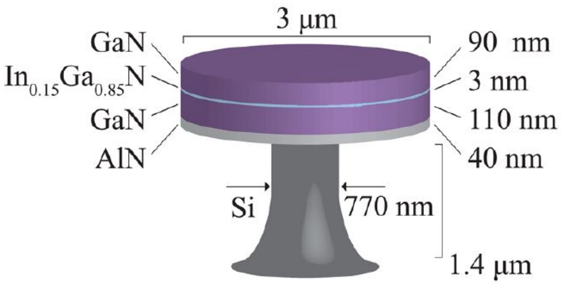
- Strong sub-bandgap absorption from *m*-plane GaN surface
- 3.1 eV absorption peak suppressed by oxygen adsorption

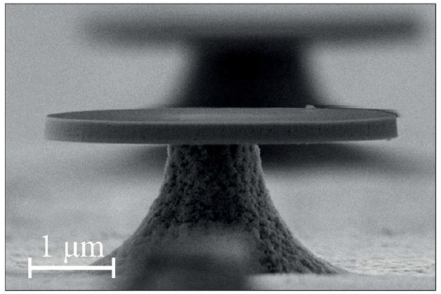
⇒ **Role of oxygen on photonic properties of GaN-based nanocavities**

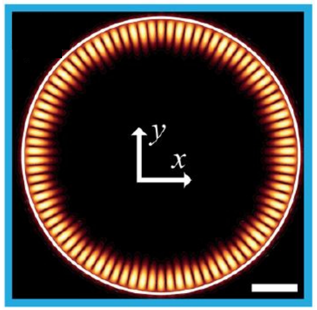
[1]M. Himmerlich *et al.*, APL **104**, 171602 (2014)

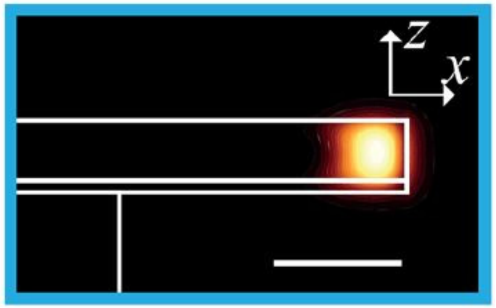
EPFL

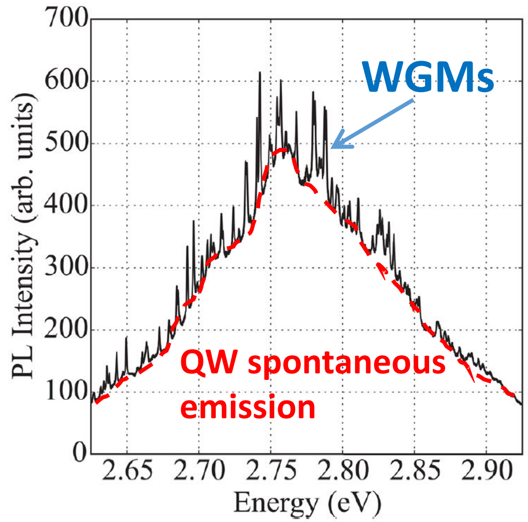
Microdisks: an ideal probe of surface states[1]

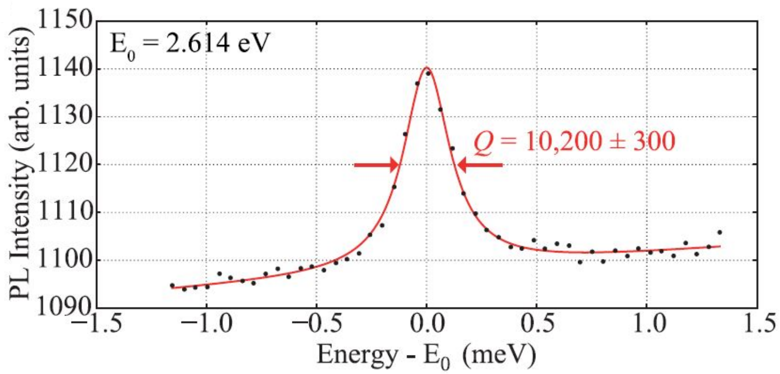












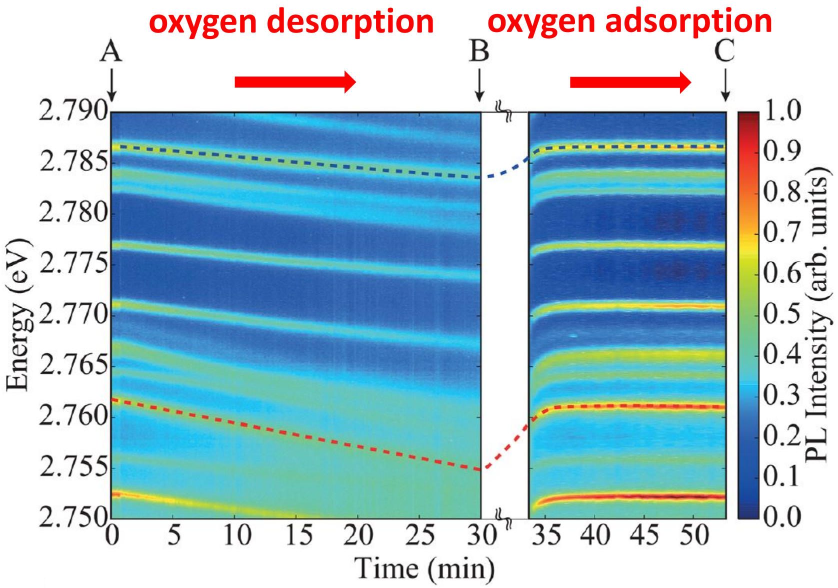
- Simple multimodal nanophotonic structures
- Vertical nonpolar sidewalls
- High *Q* factor for samples exposed to oxygen

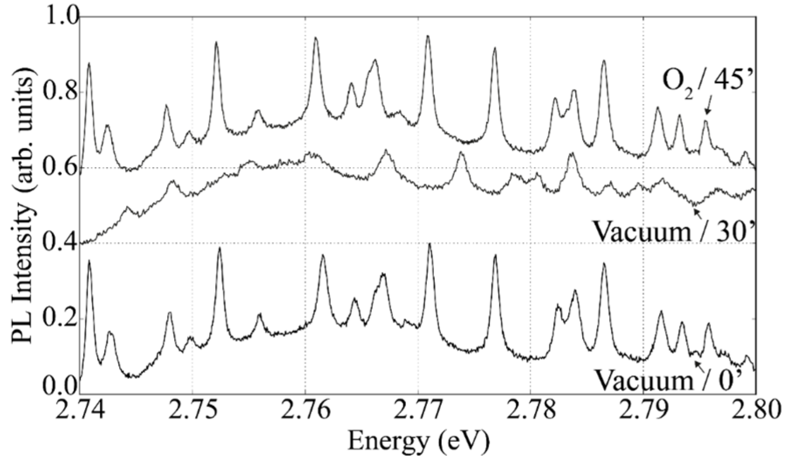
⇒ Ideal platform to probe the impact of surface states

[1]I. Rousseau *et al.*, JAP **123**, 113103 (2018)

EPFL

Photoinduced oxygen desorption

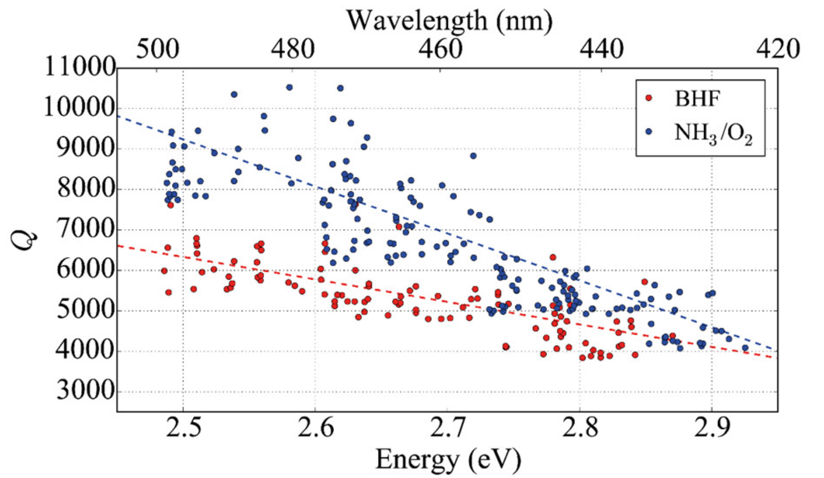




- 295 K
- Non-resonant optical pumping
- Vacuum < 1 x 10^{-4} mbar

O_2 desorption
⇒ > 100 cm^{-1} surface state absorption

Q factor with/without surface passivation



EPFL

[1]I. Rousseau *et al.*, JAP **123**, 113103 (2018)

Potential cavity quantum electrodynamic studies

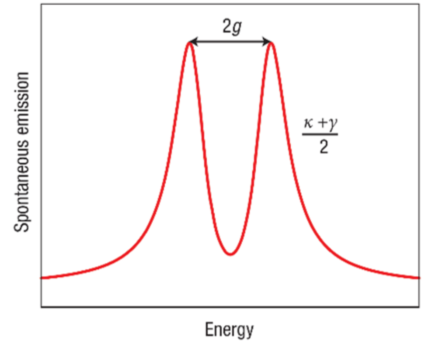
Can we consider the strong coupling regime to be within reach?

$$\Omega = 2g > \frac{\gamma + \kappa_{cav}}{2} \quad \text{with} \quad g = \frac{\mu E_{vac}}{\hbar}$$

Light-matter coupling strength

$$E_{vac} = \frac{1}{n_{op}} \left[\frac{\hbar \omega_{vac}}{2\varepsilon_0 V_m} \right]^{1/2}$$

Vacuum field amplitude

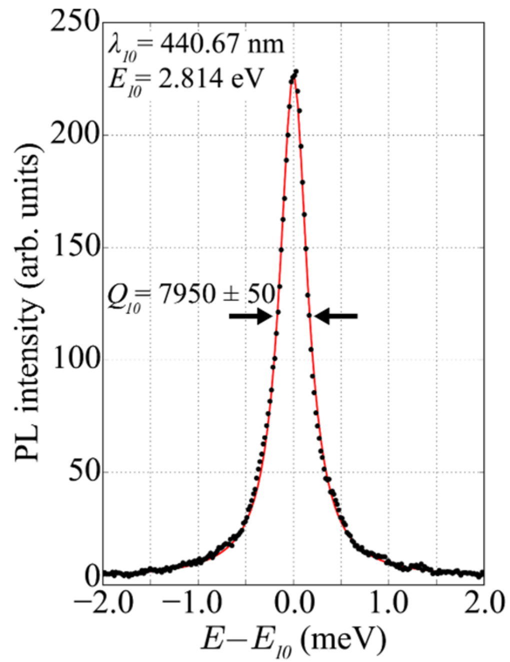


$$\gamma \approx F_P \gamma_{em} \quad \text{with} \quad F_P = \frac{3}{4\pi^2} \frac{\lambda_{cav}^3}{n_{op}^3} \frac{Q_{cav}}{V_m} \quad \text{and} \quad \gamma_{em} = \frac{1}{\tau_{em}} = \frac{n_{op} \omega_{em}^3 \mu^2}{3\pi \varepsilon_0 \hbar c^3}$$

Bare spontaneous emission rate

Purcell factor

$$\kappa_{cav} = \frac{1}{\tau_{cav}} = \frac{\omega_{cav}}{Q_{cav}}$$



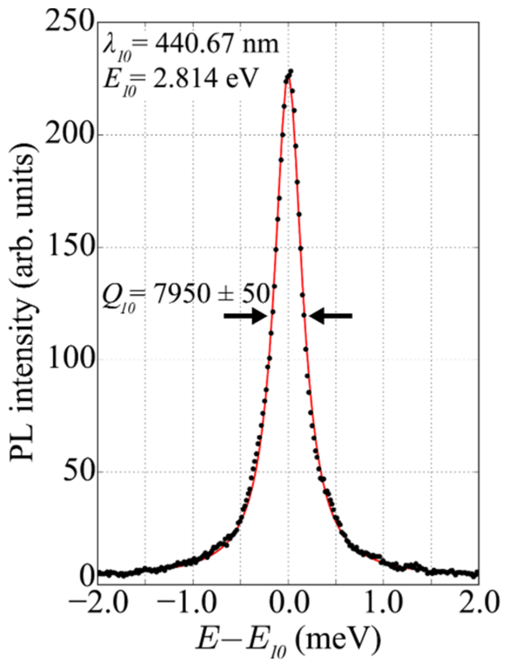
$$\Rightarrow \quad Q_{cav} > \frac{\lambda_{cav}^{3/2}}{\mu} \left[\frac{\varepsilon_0 \hbar \omega_{cav}}{2 n_{op}} \right]^{1/2} \approx 7400 \quad @ \quad \lambda_{cav} = 450\,\text{nm} \text{ and } \tau_{em} = 1\,\text{ns}$$

⇒ Quest for a suitable quantum emitter!

EPFL

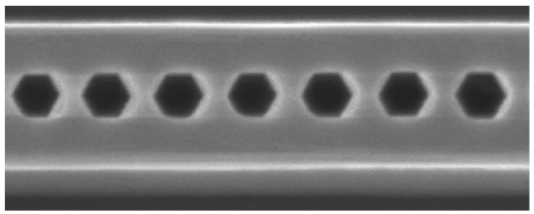
Conclusion and outlook

- **CW lasing** in high-β **blue nanobeam cavities** revealed via $g^{(2)}(0)$ measurements
- **High-*Q* factors** in the **blue spectral range** (Q = 8000 nanobeams; Q = 10200 microdisks) **well accounted for by statistical analysis**
- Large **sub-bandgap absorption** from **GaN surface** ⇒ **oxygen passivation**



Outlook

- **Stabilize the GaN surface** in high S/V cavities
- **Investigate quantum optical emission features** of high-*Q* GaN-based **nanophotonic cavities**



EPFL

Acknowledgments

EPFL

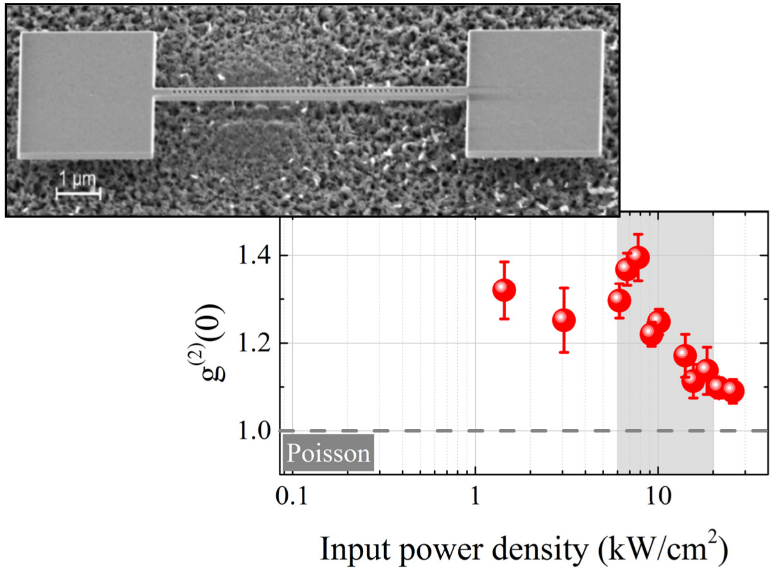
- Ian Rousseau, Noelia Vico Triviño (IBM), Gordon Callsen, Irene Sánchez-Arribas (Konstanz), Kanako Shojiki, Jean-François Carlin, Vincenzo Savona, Momchil Minkov (Stanford) and Nicolas Grandjean

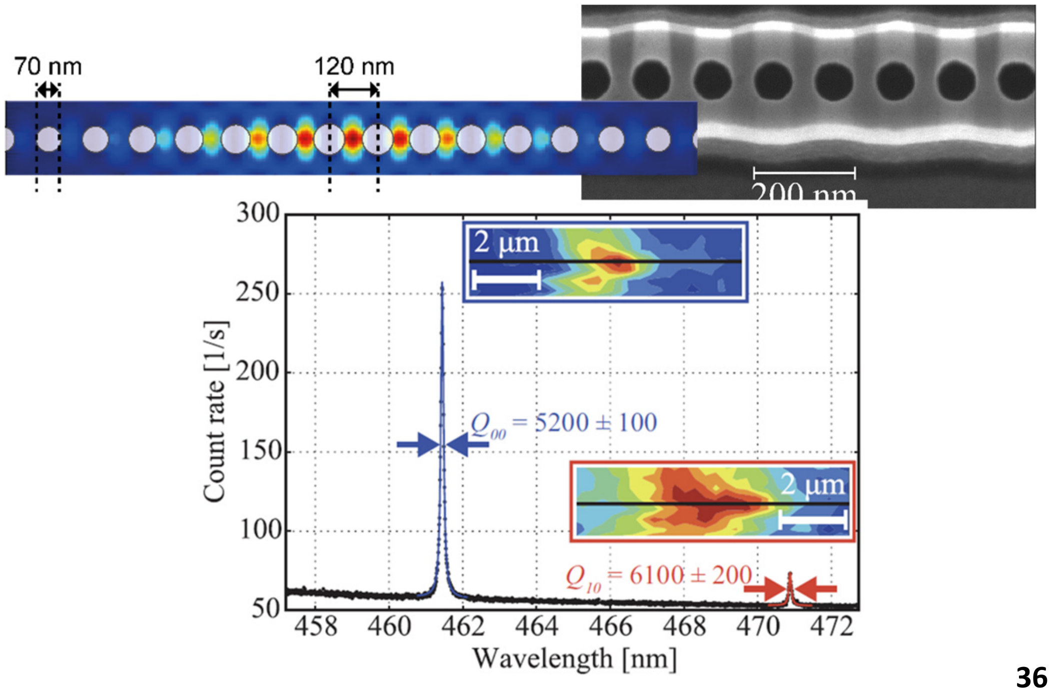
TU Berlin, Germany

- Stefan Jagsch, Stefan Kalinowski, Axel Hoffmann and Stephan Reitzenstein

Otto von Guericke Univ. Magdeburg, Germany

- Martin Feneberg, Stefan Freytag, and Rüdiger Goldhahn





EPFL LASPE

Thank you for your attention!