Optical spectroscopy

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« Nanophysique et semiconducteurs » Group

Goal

Optical spectroscopy techniques

⇒ Some notions

⇒ QWs

⇒ Examples from literature (III-N mainly)

GaN peculiarities

⇒ Quantum Confined Stark Effect

⇒ Localization…

Books on the topic:

Semiconductor Optics, Springer
(C. F. Klingshirn)

Building Electro-Optical Systems : Making it all work, Wiley
P. C. D. Hobbs

Units

$$\lambda = \frac{c}{\upsilon} = \frac{hc}{E} = \frac{1}{\tilde{\upsilon}}$$

$$\lambda = 1\ \mu m$$

$$\Leftrightarrow$$

$$\upsilon = 3.10^{14}\ Hz$$

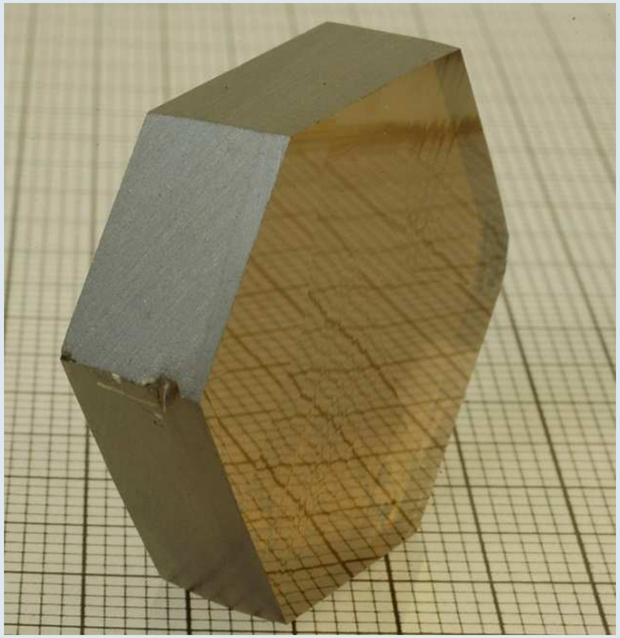
$$\Leftrightarrow$$

$$E = 1.24\ eV$$

$$\Leftrightarrow$$

$$\tilde{\upsilon} = 10^{4}\ cm^{-1}$$

Spectroscopy of GaN

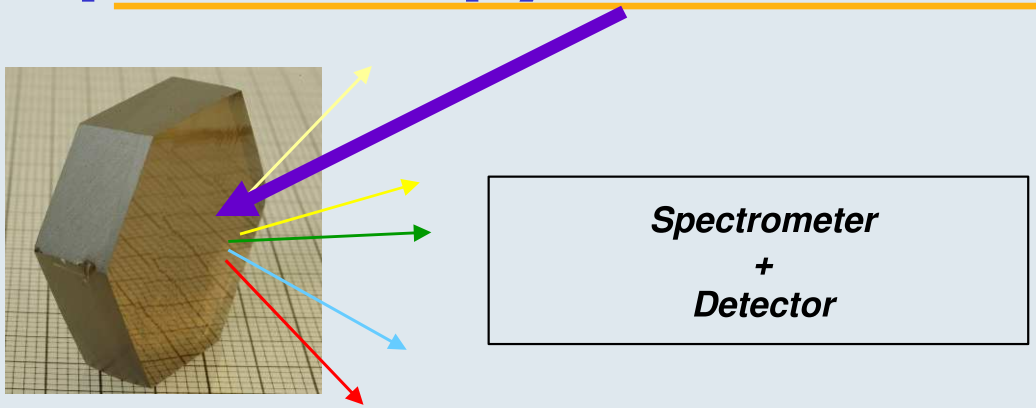


E&M, eanmint.co.jp

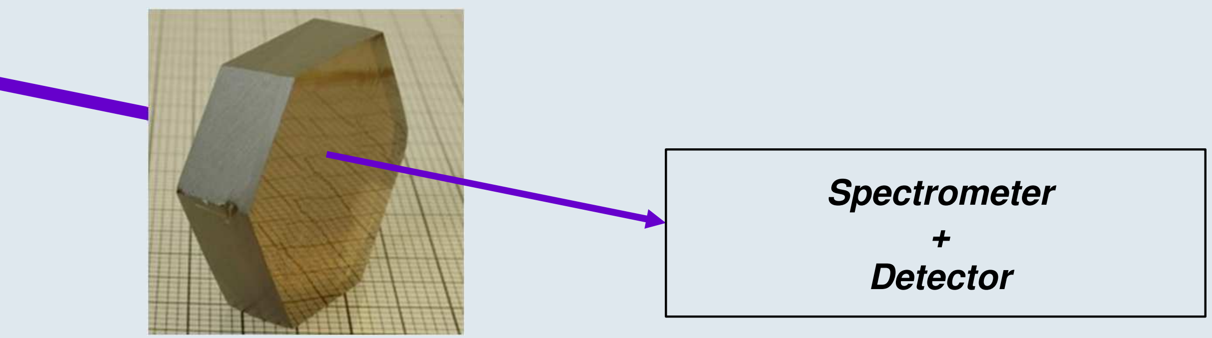
I have a piece of GaN and want to optically probe its optical properties…

Another wide band gap semiconductor

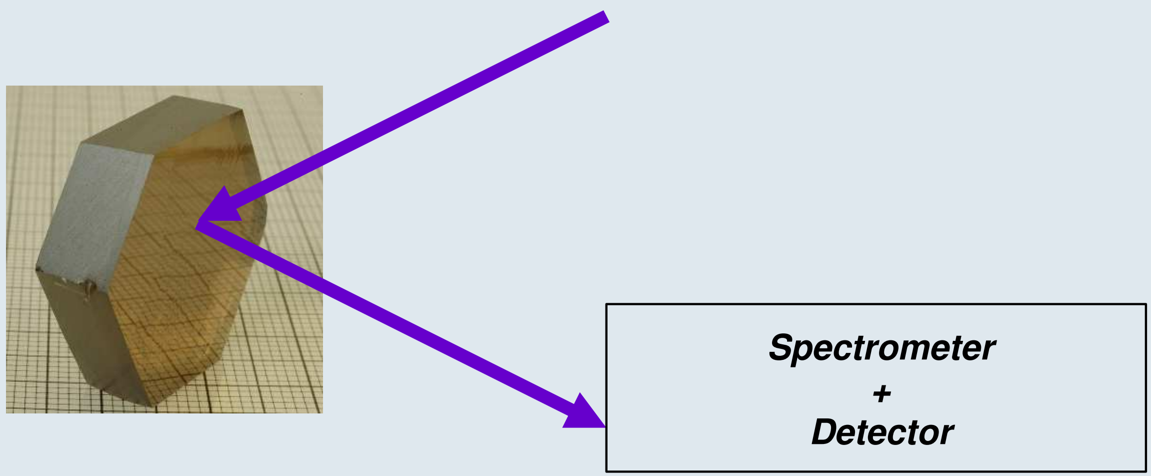
Spectroscopy of GaN



Photoluminescence

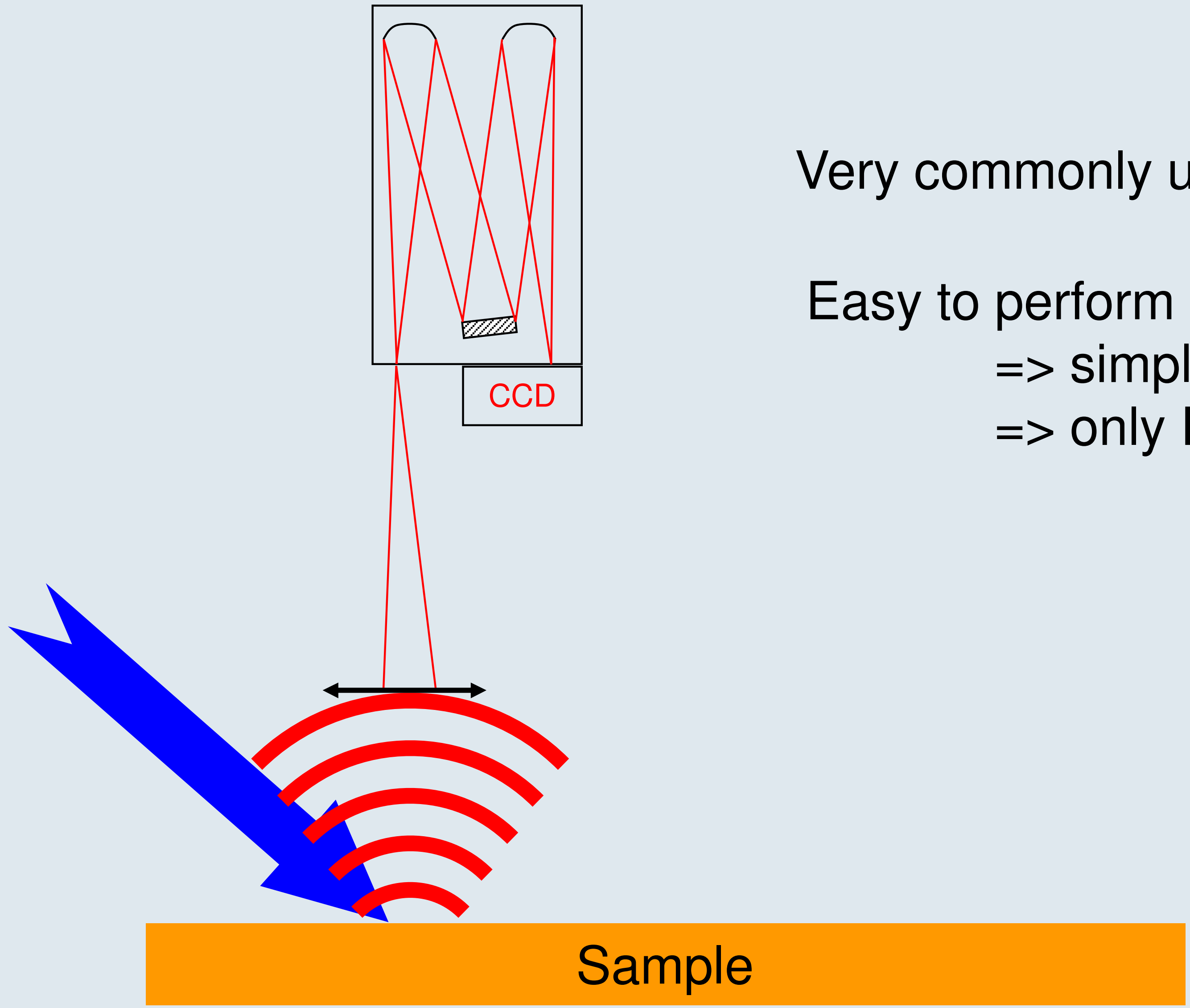


Absorption



Reflectivity

Spectroscopy of GaN : photoluminescence



Very commonly used

Easy to perform
=> simple set-up
=> only PL signal

The grating spectrometer

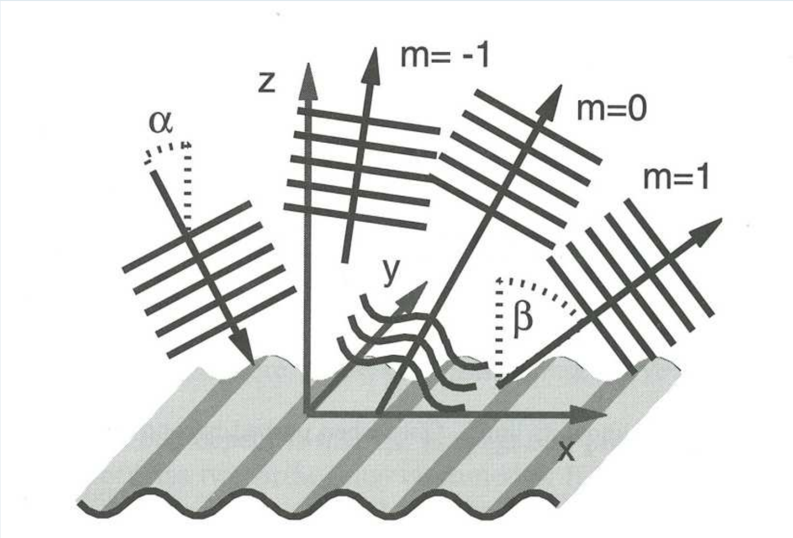


Figure 7.1 Plane diffraction grating.

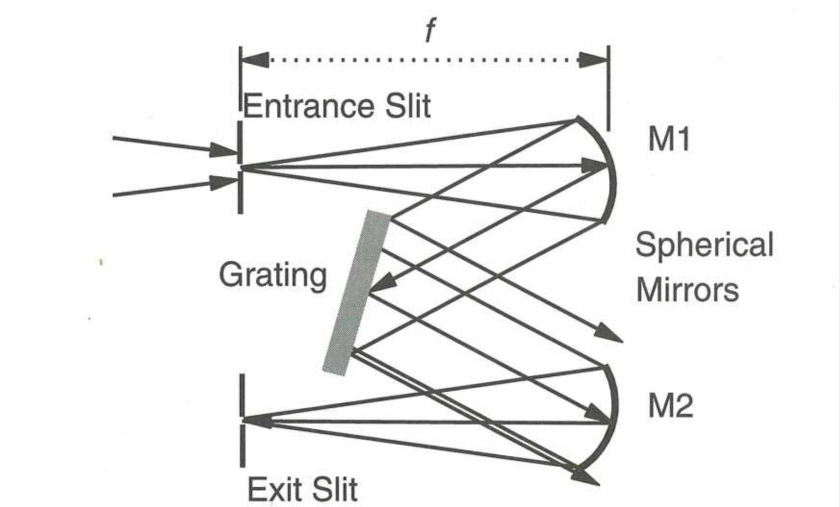
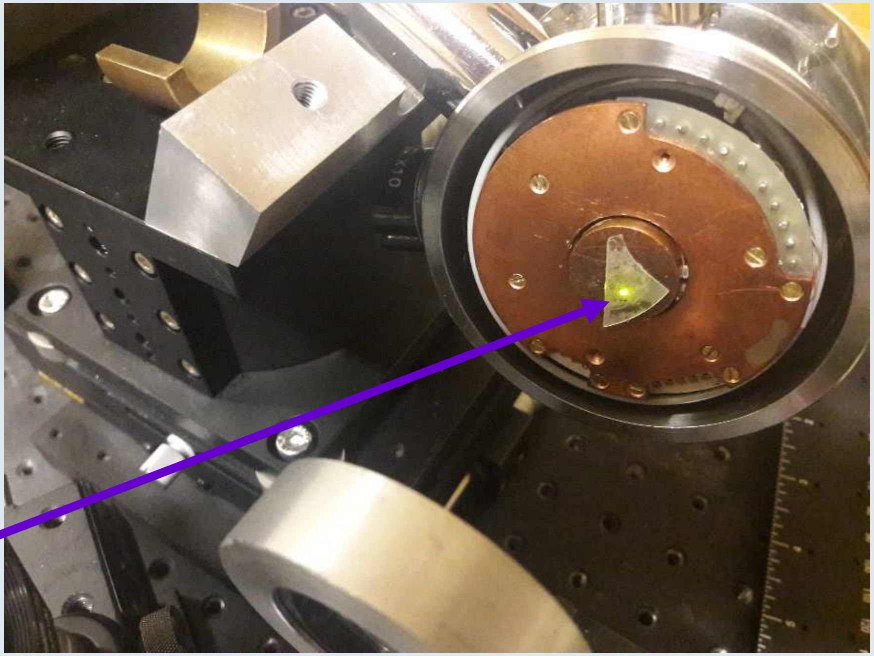


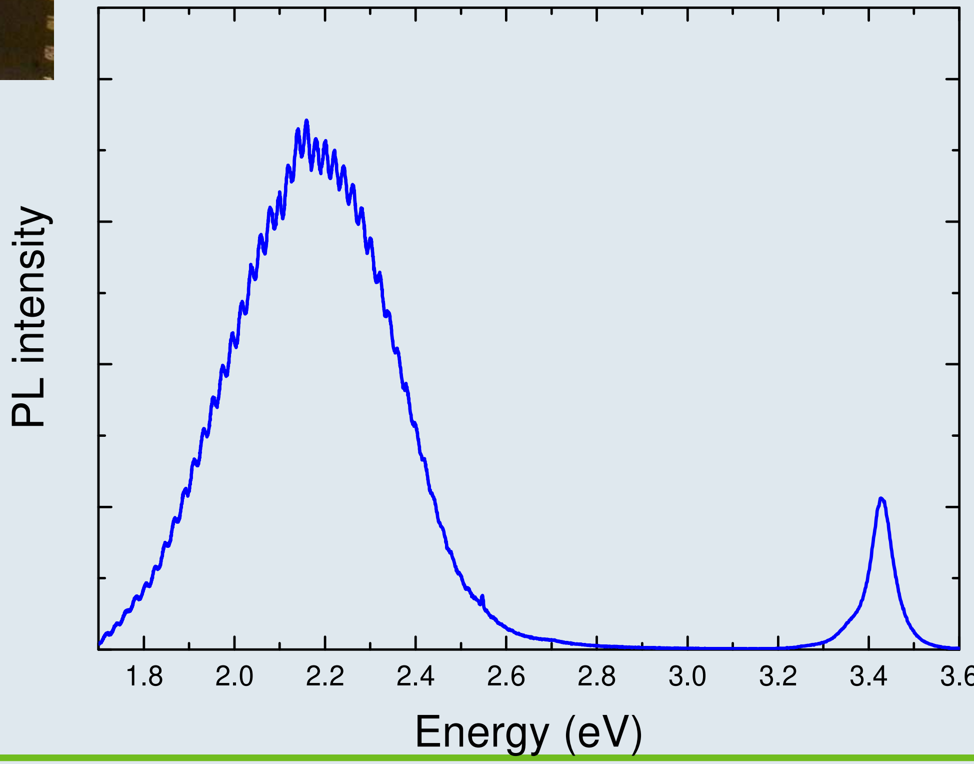
Figure 7.2 Czerny–Turner monochromator.

Spectroscopy of GaN : photoluminescence

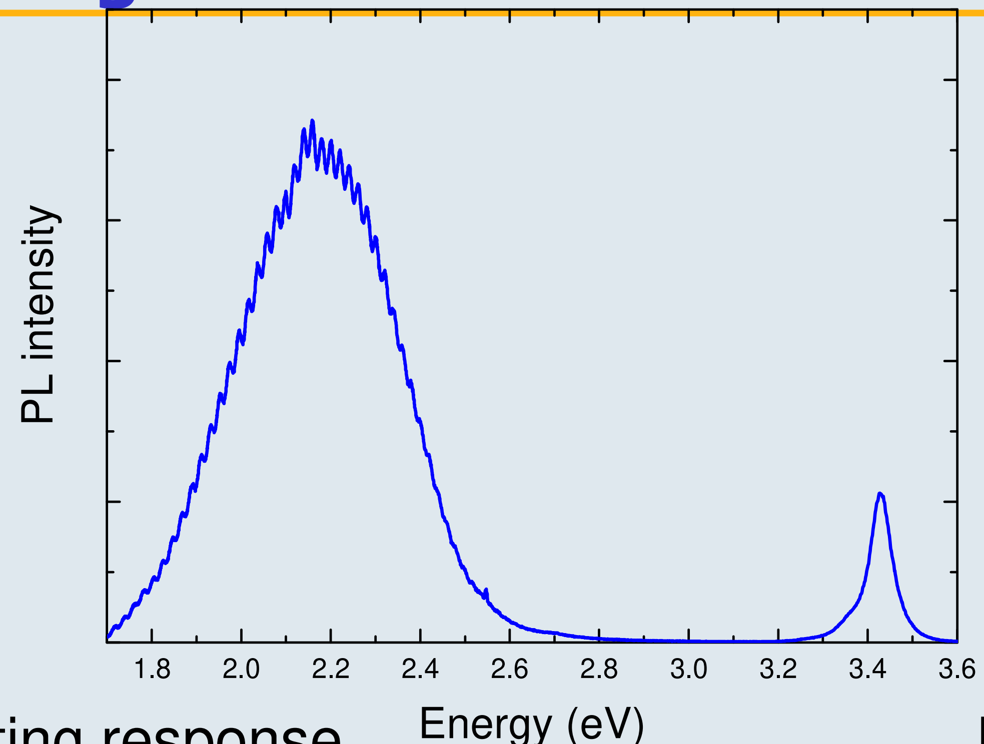


244 nm

300 K

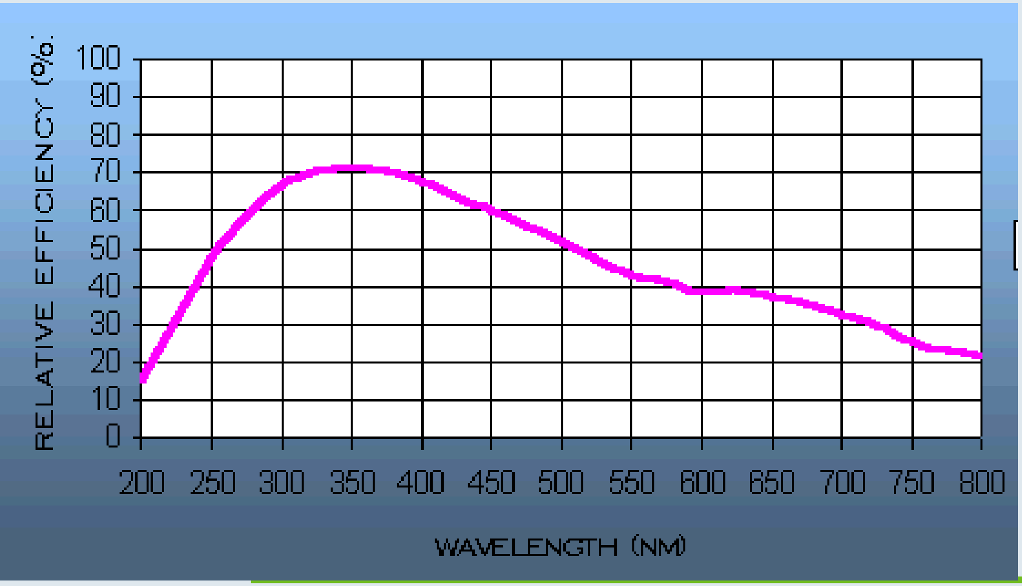


Comparing intensities…

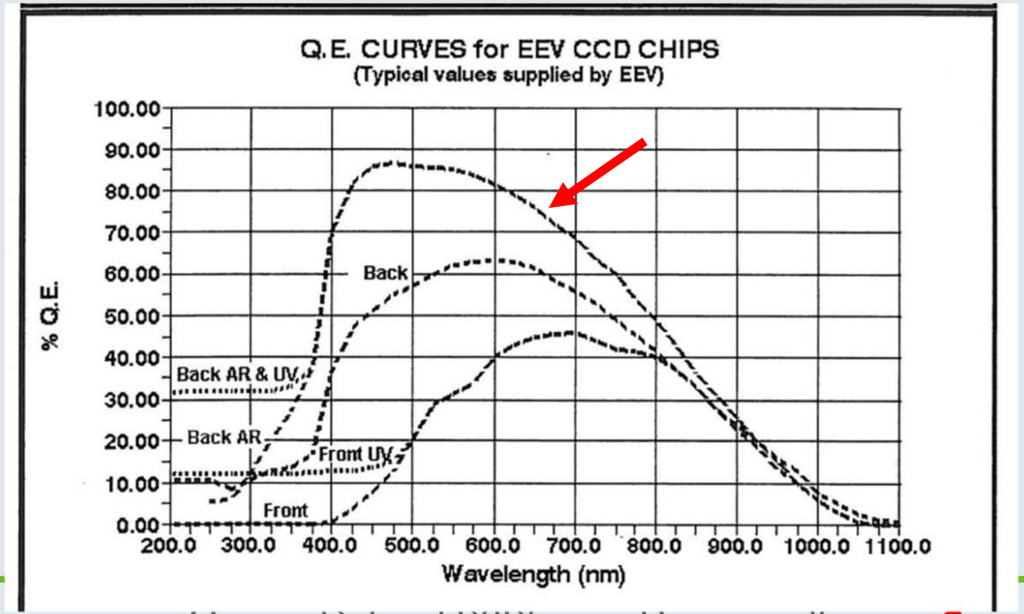


300 K, GaN on sapphire

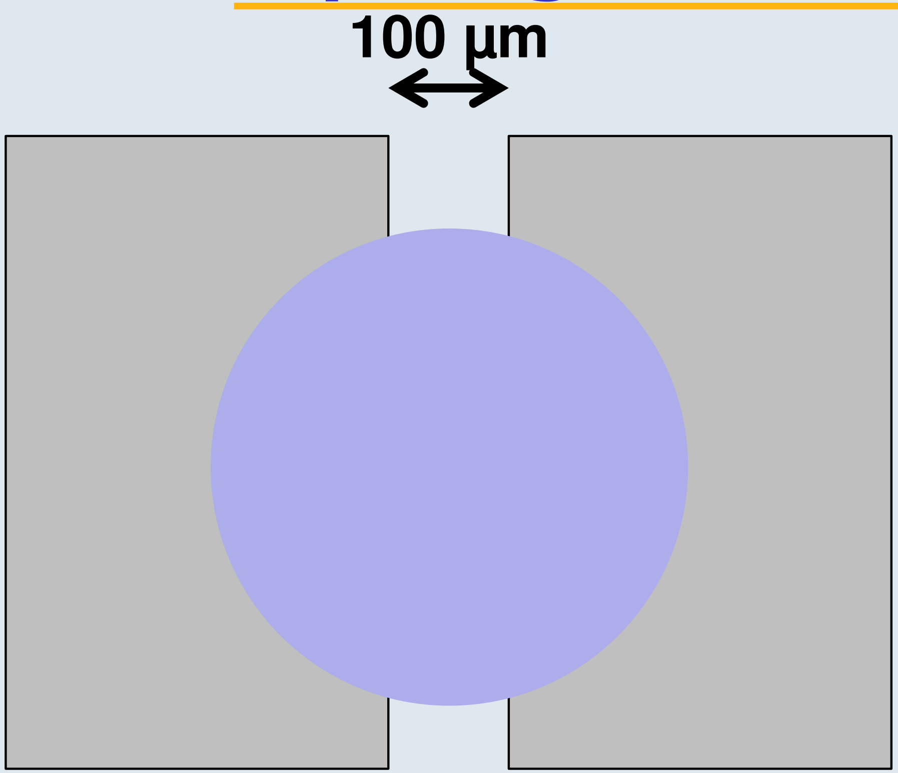
Grating response

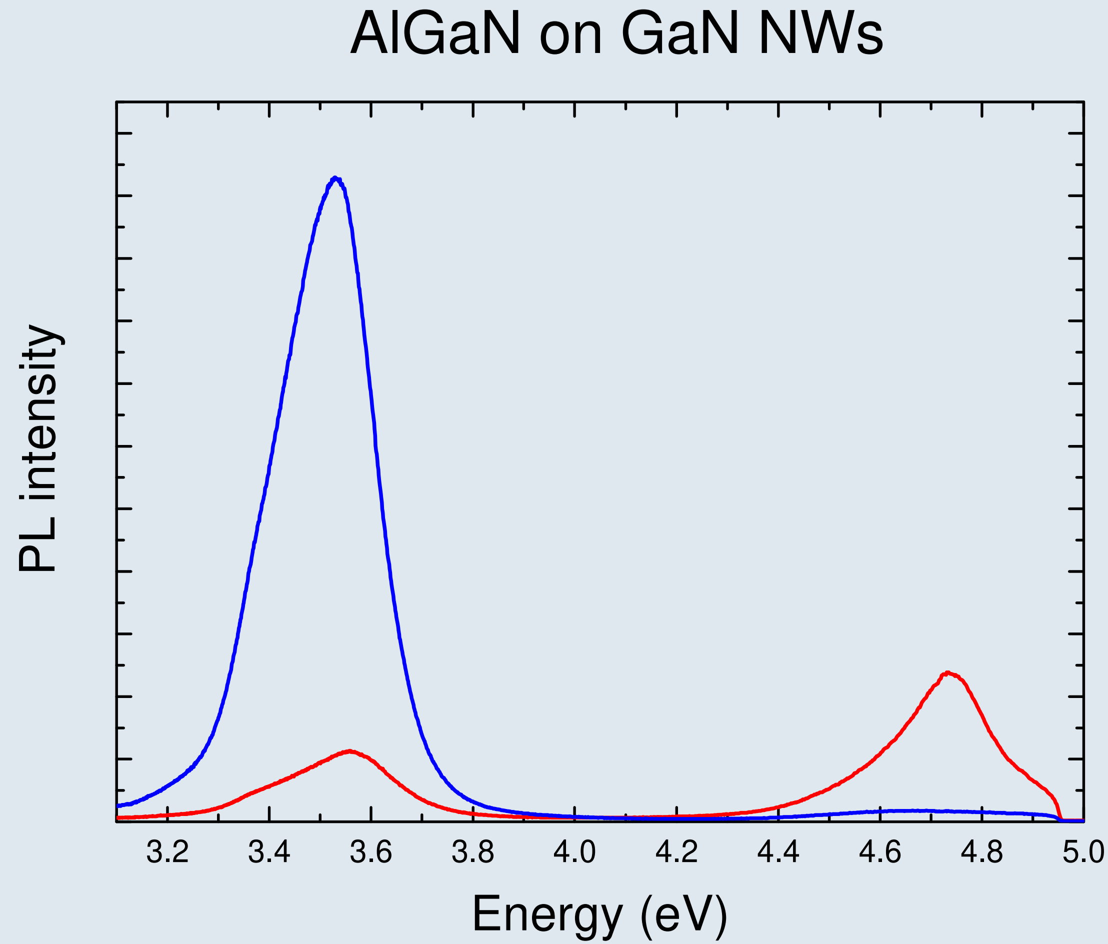


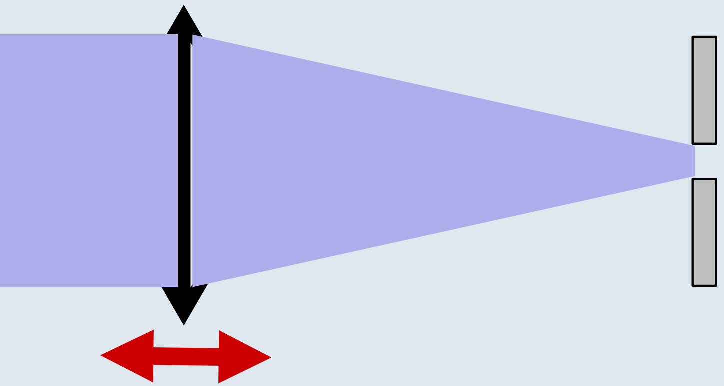
Detector response



Comparing intensities…



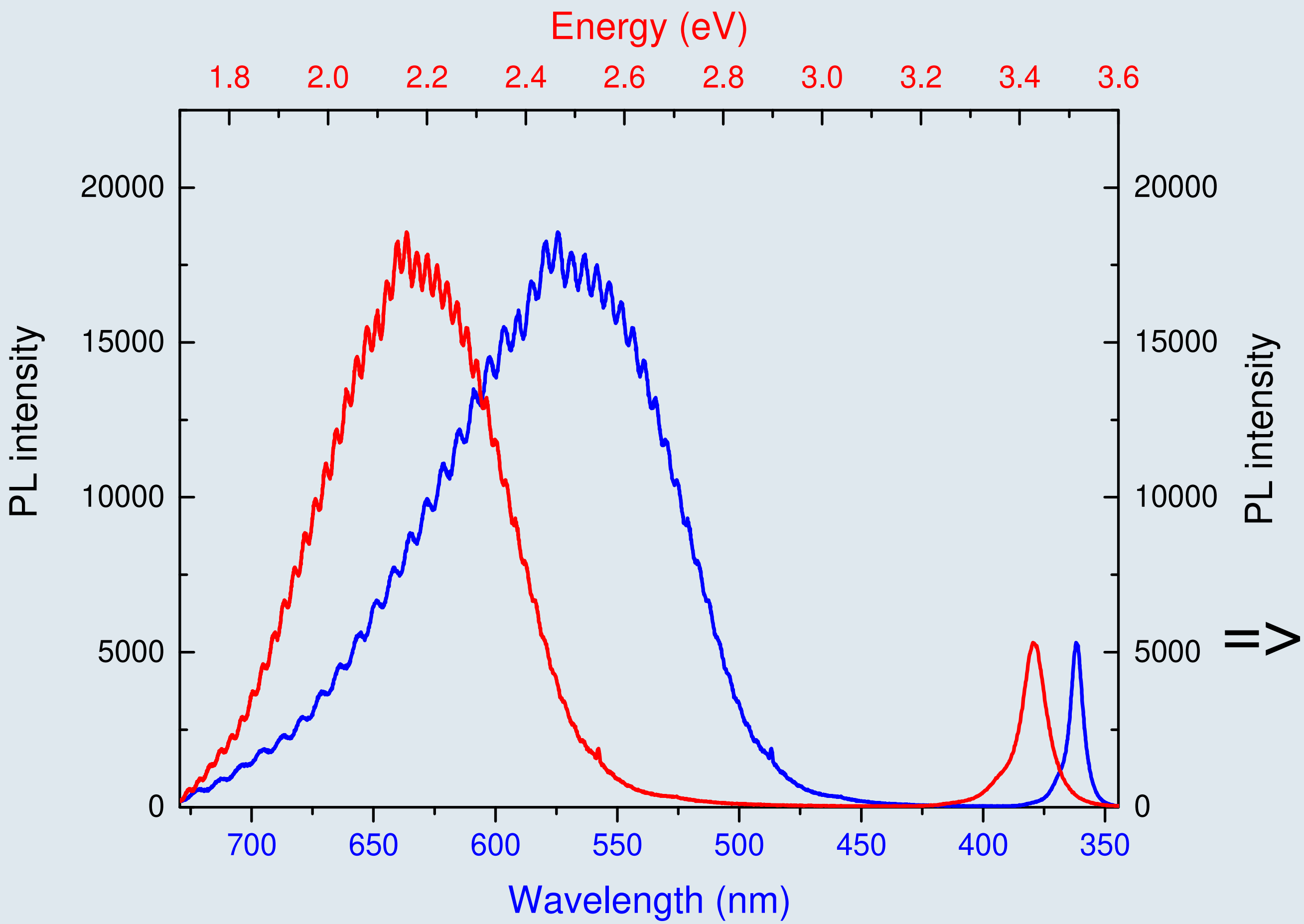




⇒ For wide spectral ranges (especially in UV) off-axis parabolic mirrors are recommended !

Comparing intensities…

$$\lambda(nm) = \frac{hc}{E} = \frac{1240}{E(eV)}$$



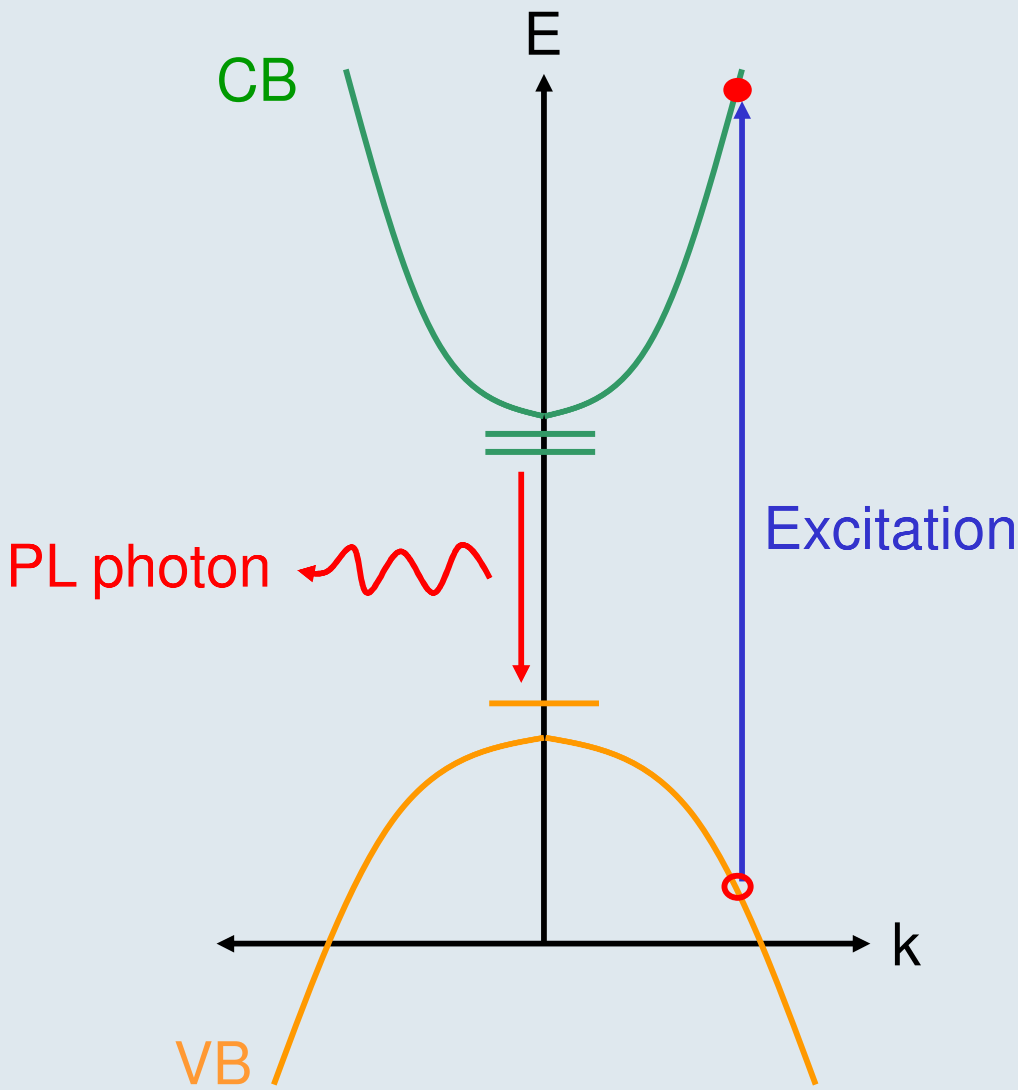
$$d\lambda \propto \frac{dE}{E^2}$$

=> Jacobian transformation

J. Mooney *et al.*, *J. Phys. Chem. Lett.* **4** 3316 (2013)

Spectroscopy of GaN : PL

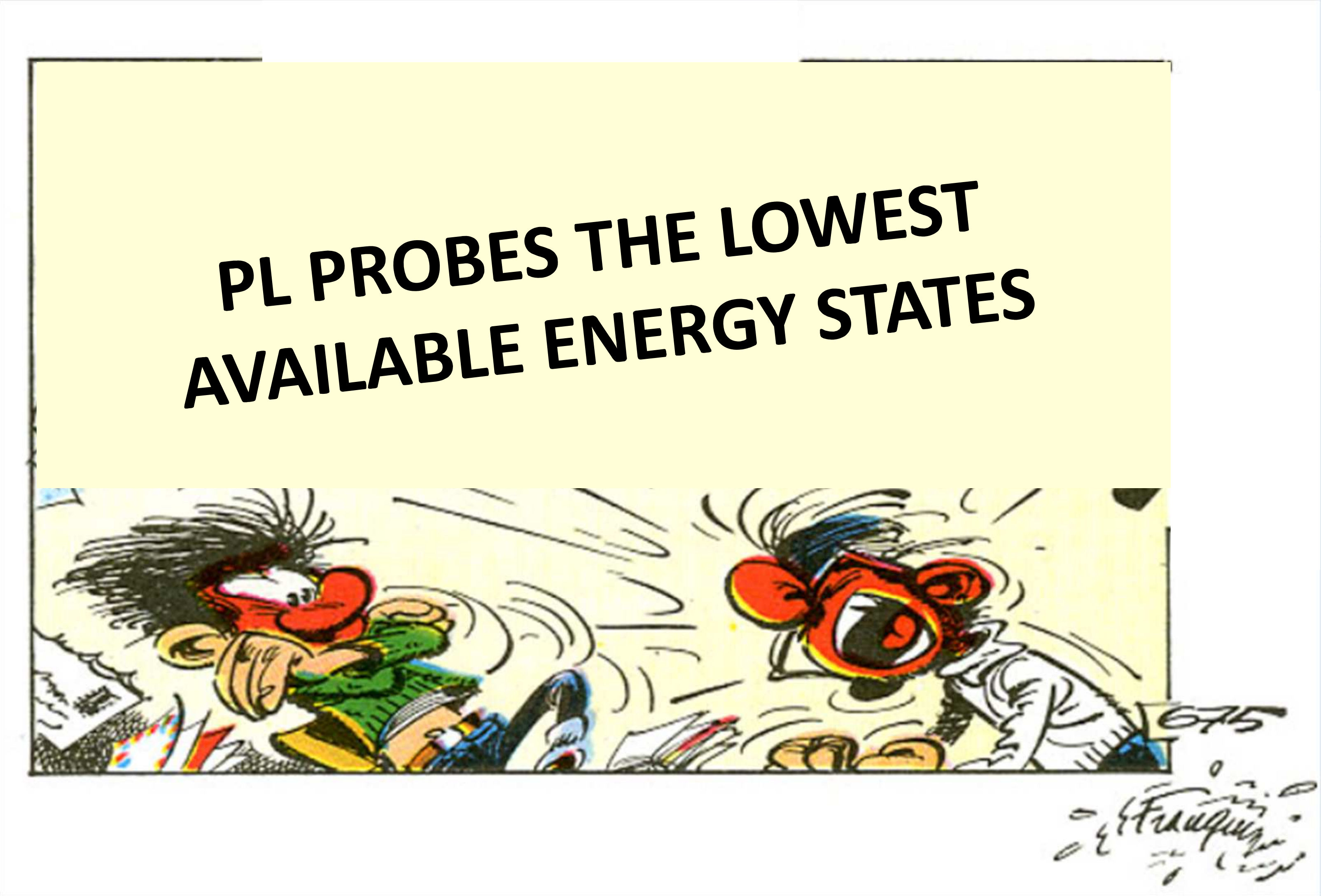
What is probed in PL??



In general, relaxation is very fast
=> much faster than radiative rates

=> PL probes the
lowest available energy states

Spectroscopy of GaN : PL



Spectroscopy of GaN : photoluminescence

Advantages of photoluminescence:

Very versatile and easy to set-up technique

Usually large (positive) signal

No issue with substrate

Limitations of photoluminescence:

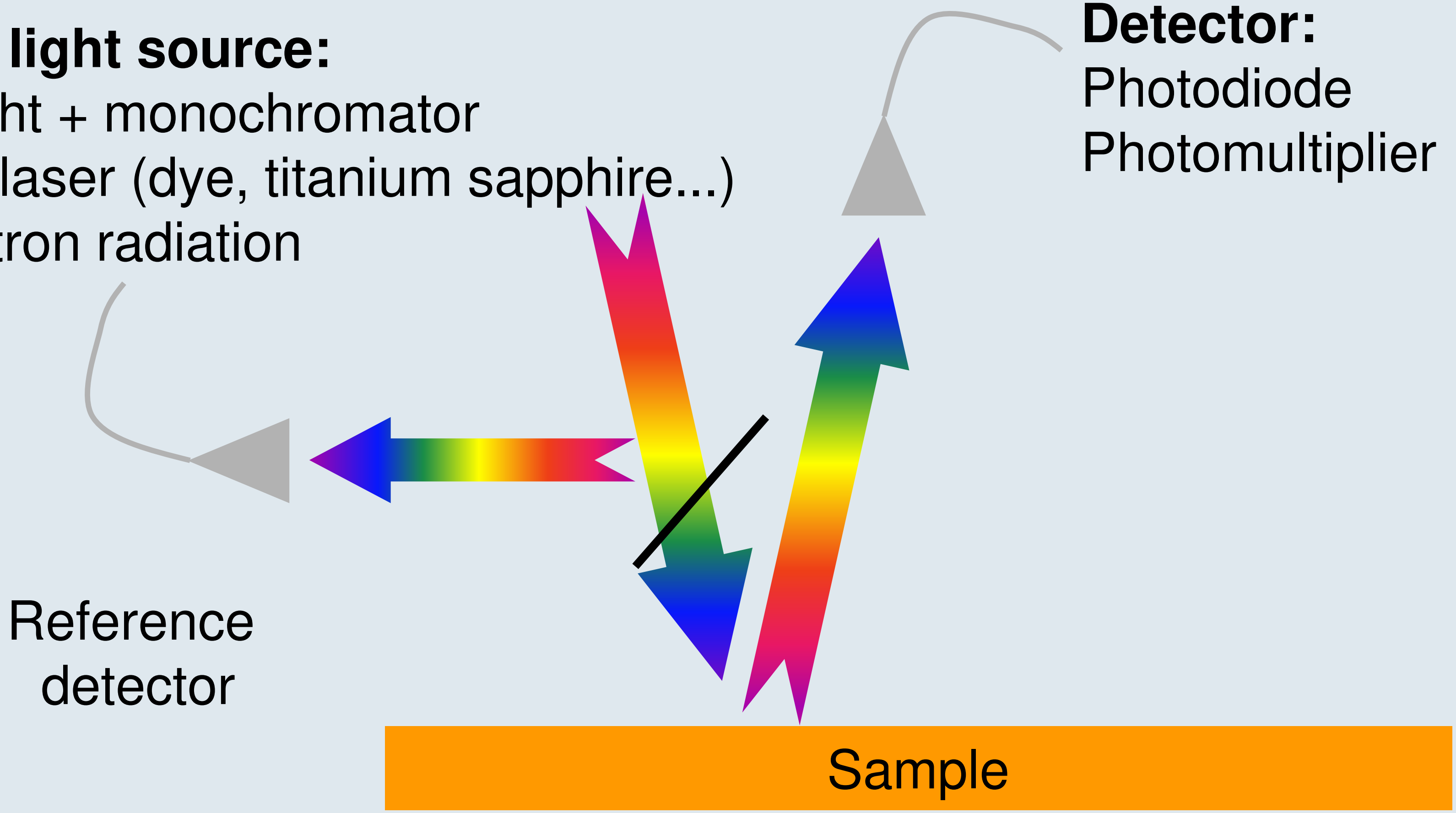
Only lowest energy state probed

Pump laser might affect the electronic properties

Data interpretation ?

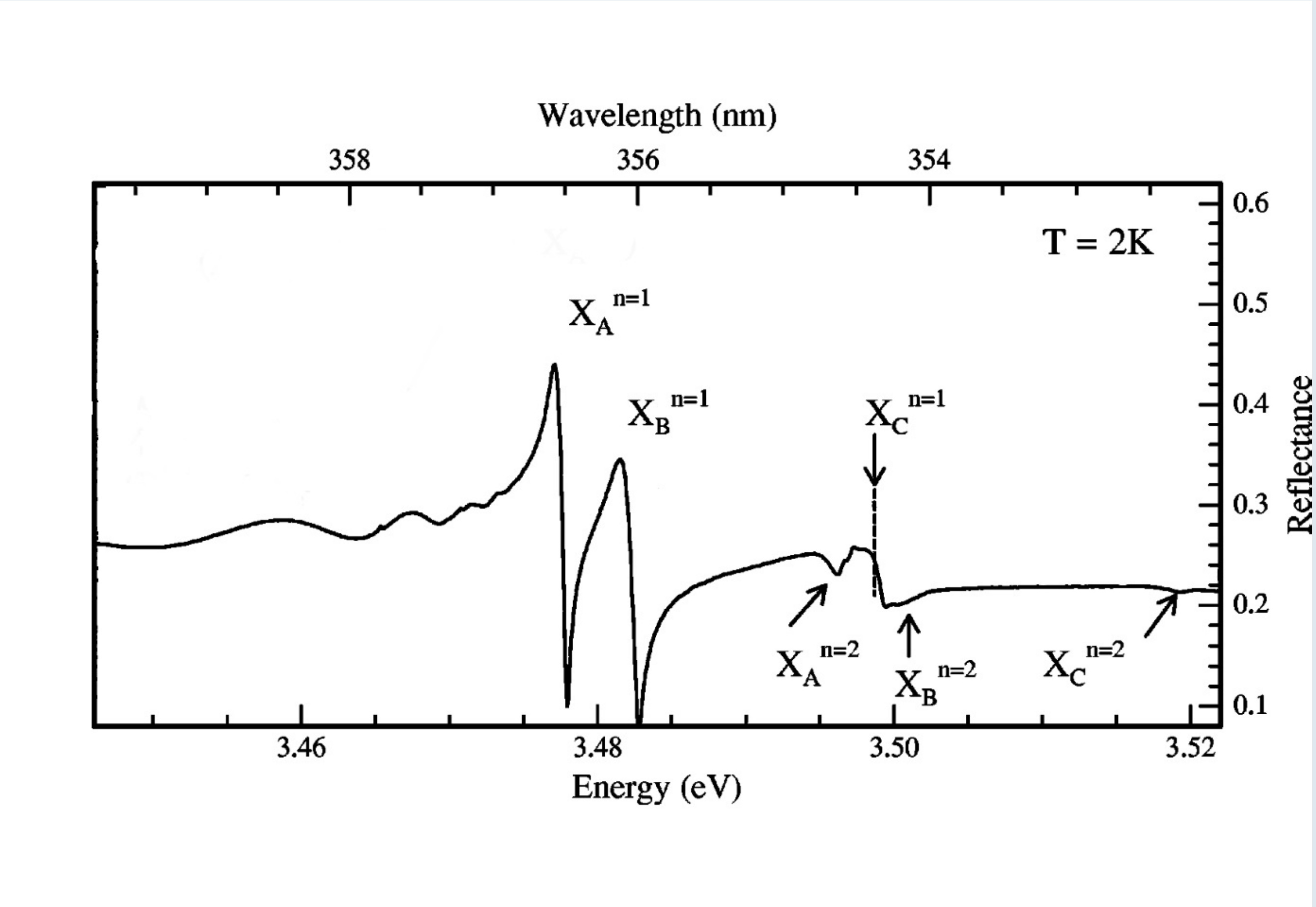
Spectroscopy of GaN : reflectivity

Tunable light source:
White light + monochromator
Tunable laser (dye, titanium sapphire...)
Synchrotron radiation



Often used in conjunction with modulation techniques
=> what is really measured?

Spectroscopy of GaN : reflectivity



1.5 µm GaN on bulk GaN substrate

Kornitzer *et al.* PRB **60** 1471 (1999)

Spectroscopy of GaN : reflectivity

Advantages of reflectivity:

Probing of the electronic states (coupled to the light!)

Measurement does not perturb the system at low power

No issue with substrate

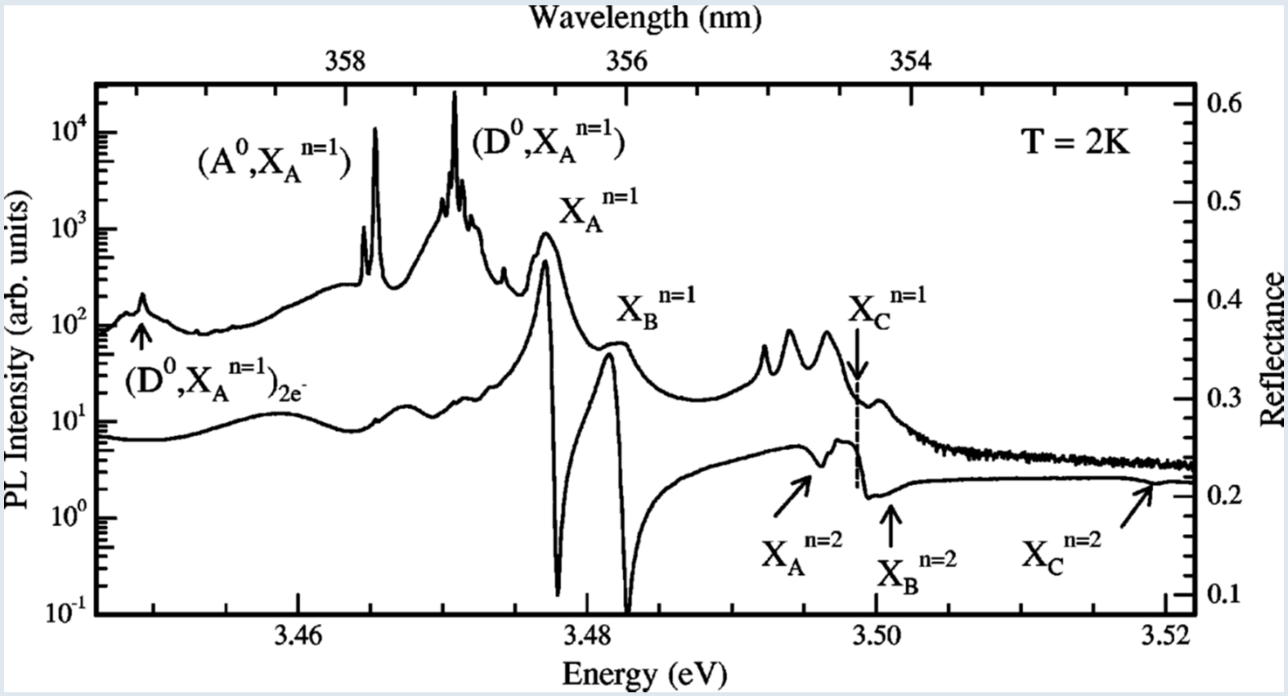
Limitations of reflectivity:

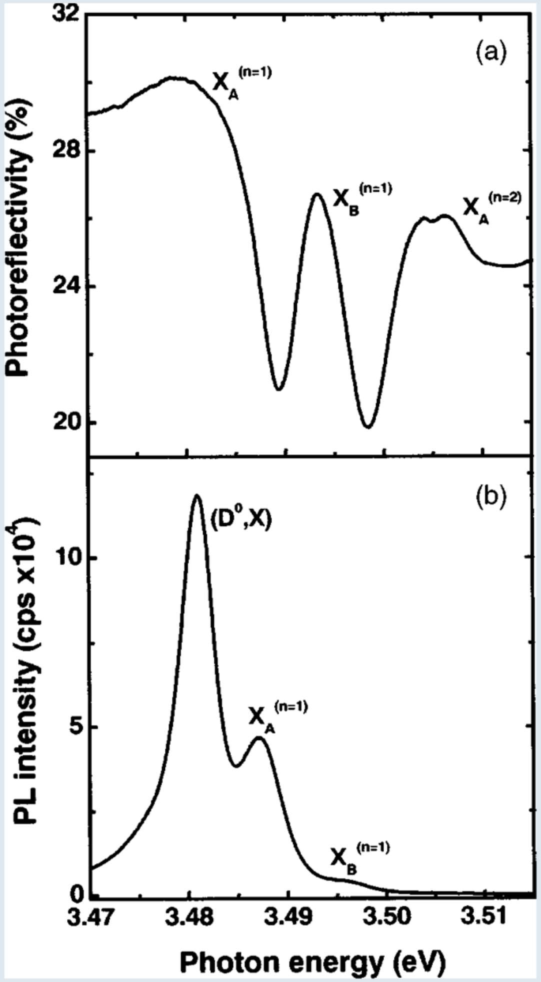
Weak signal (especially if large broadening)

Complex data interpretation

Spectroscopy of GaN : reflectivity vs PL

10 K
1.3 µm GaN on sapphire



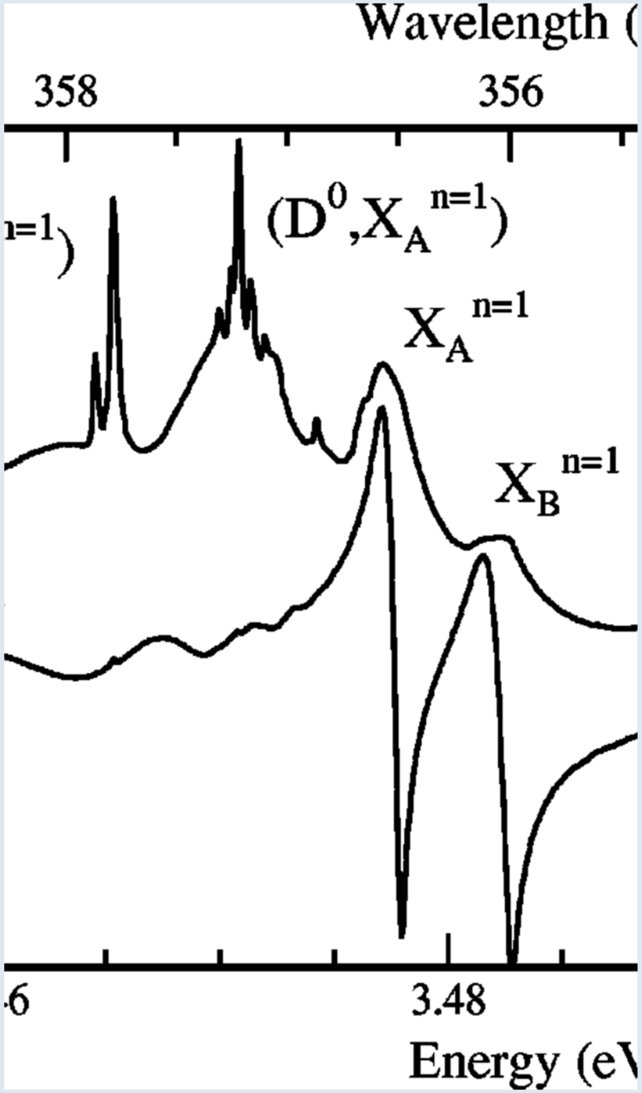


1.5 µm GaN on bulk GaN substrate

Kornitzer *et al.* PRB **60** 1471 (1999)

Ursaki *et al.* **JAP** 94 4813 (2003)

Spectroscopy of GaN : peak position

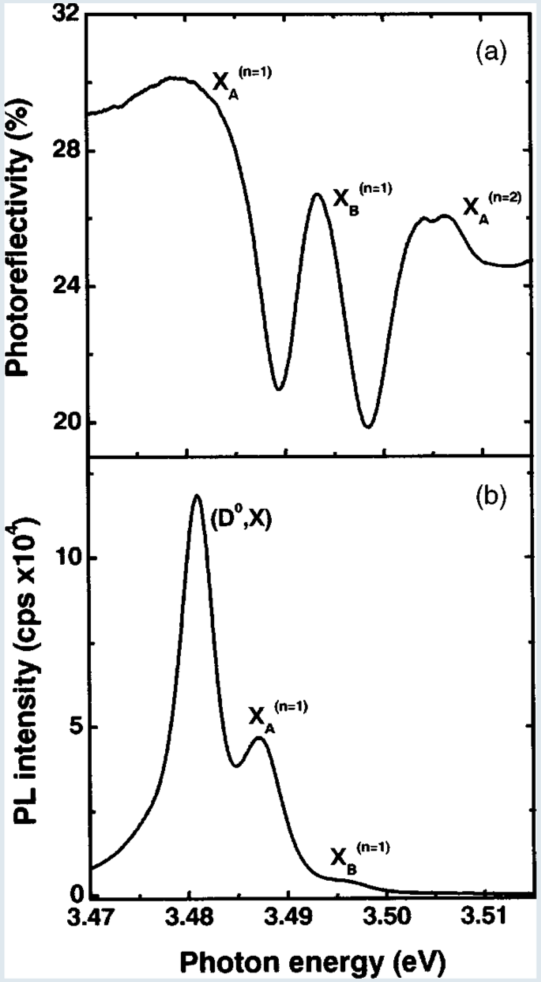


1.5 µm GaN on bulk GaN substrate

Kornitzer *et al.* PRB **60** 1471 (1999)

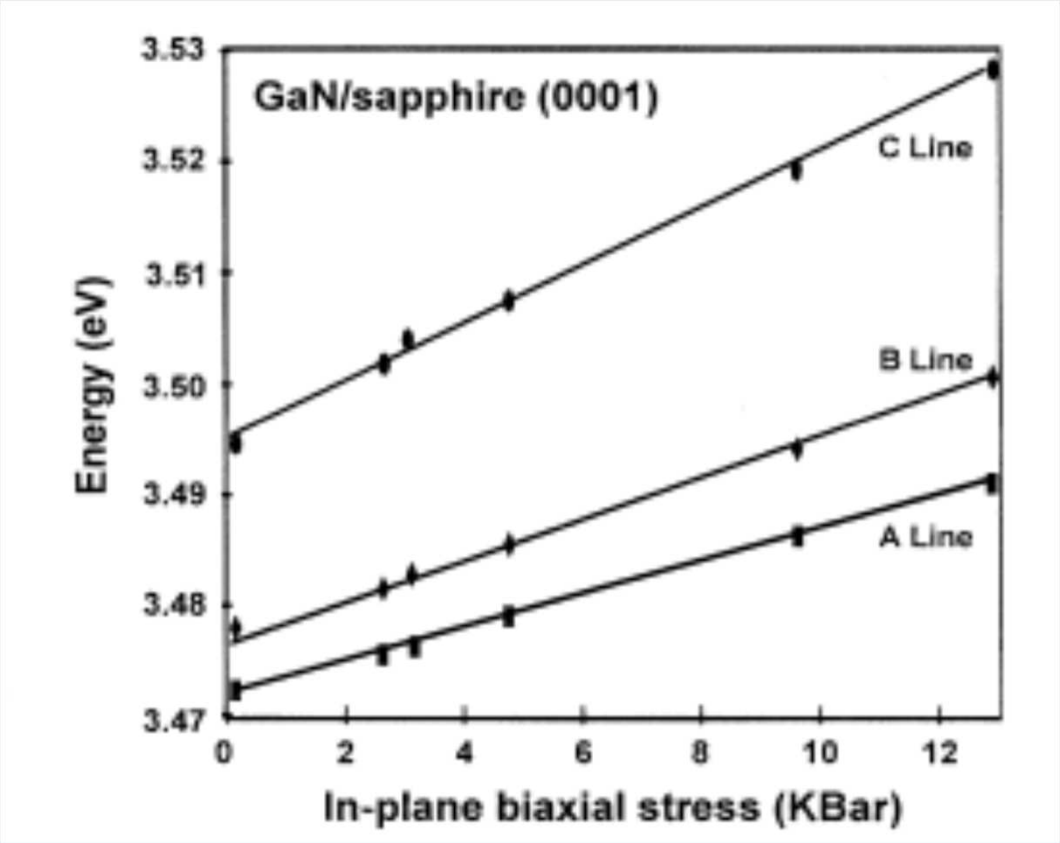
10 K

1.3 µm GaN on sapphire



Ursaki *et al.* **JAP** 94 4813 (2003)

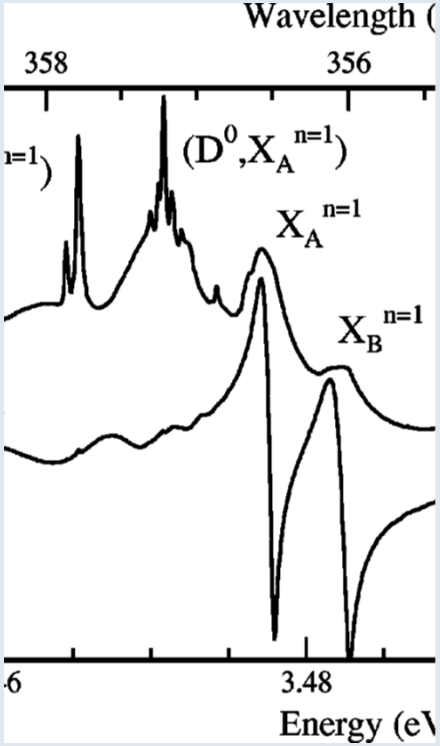
Spectroscopy of GaN : strain dependence



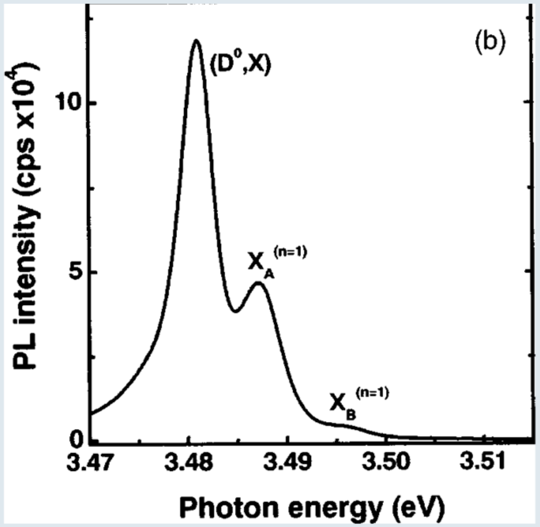
The « Bernard Gil » plot

Gil *et al.*, PRB **52** R17028 (1995)

Spectroscopy of GaN : broadening



100 µeV



5 meV

Temperature (kT@ 2K = 0.15 meV)

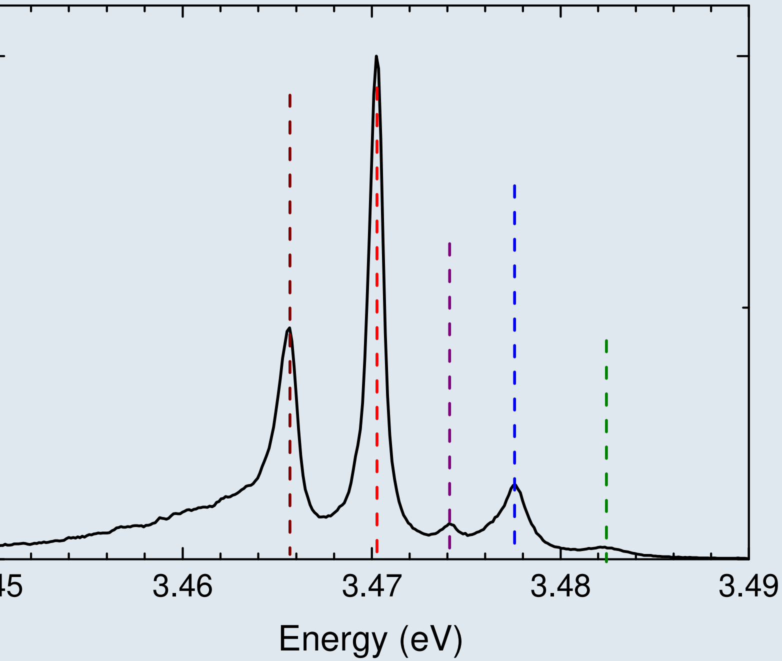
Strain inhomogeneity (due to extended defects, point defects….)

Lifetime ($\Delta E \, \Delta t > \hbar/2$)

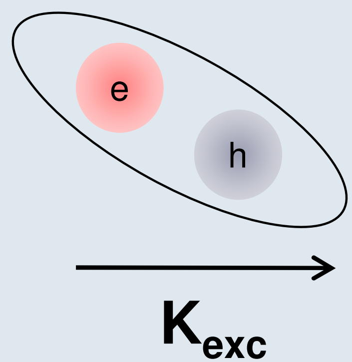
Kornitzer *et al.* PRB **60** 1471 (1999)

Ursaki *et al.* **JAP** 94 4813 (2003)

Excitons, what are they?



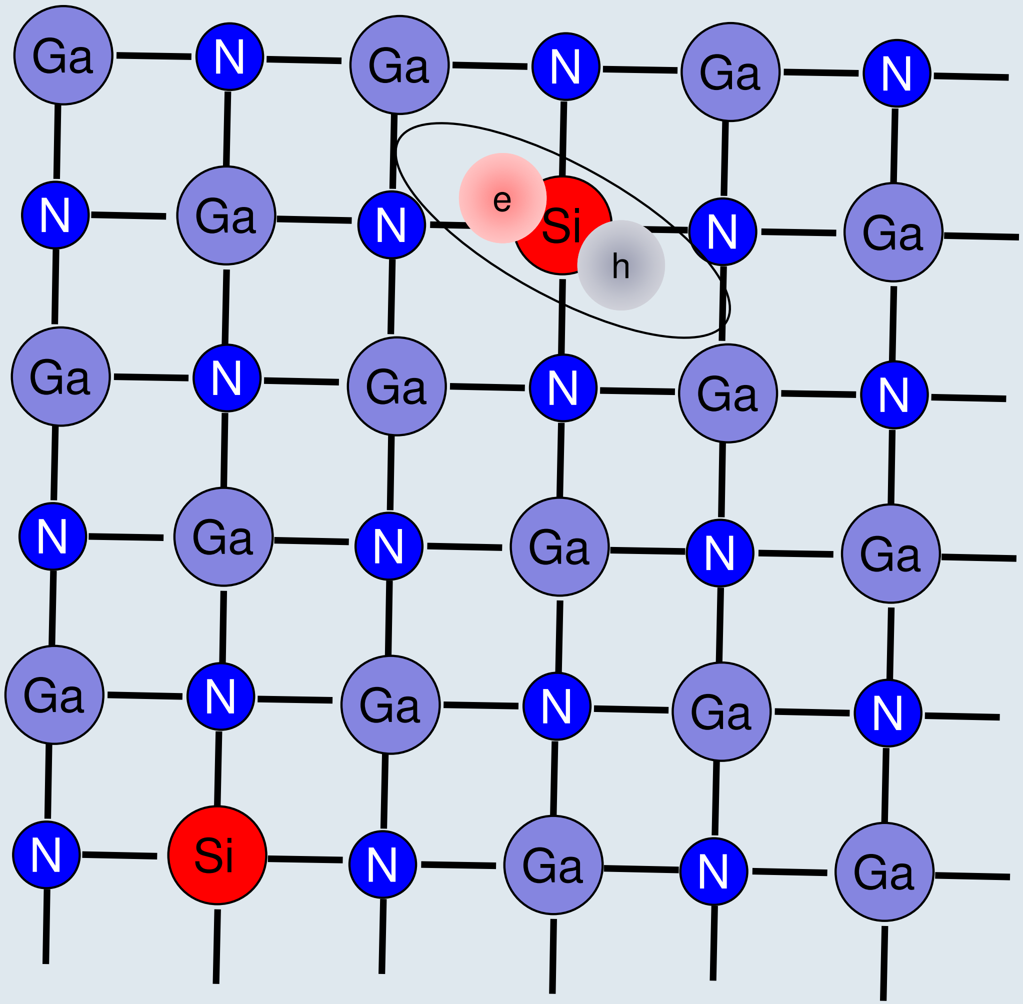
One electron + one hole
bound by Coulomb interaction
=> Hydrogen-like particle



	a (nm)	E_X (meV)
GaN	2.8	25
GaAs	12	4.8

kT @ 300K
25 meV

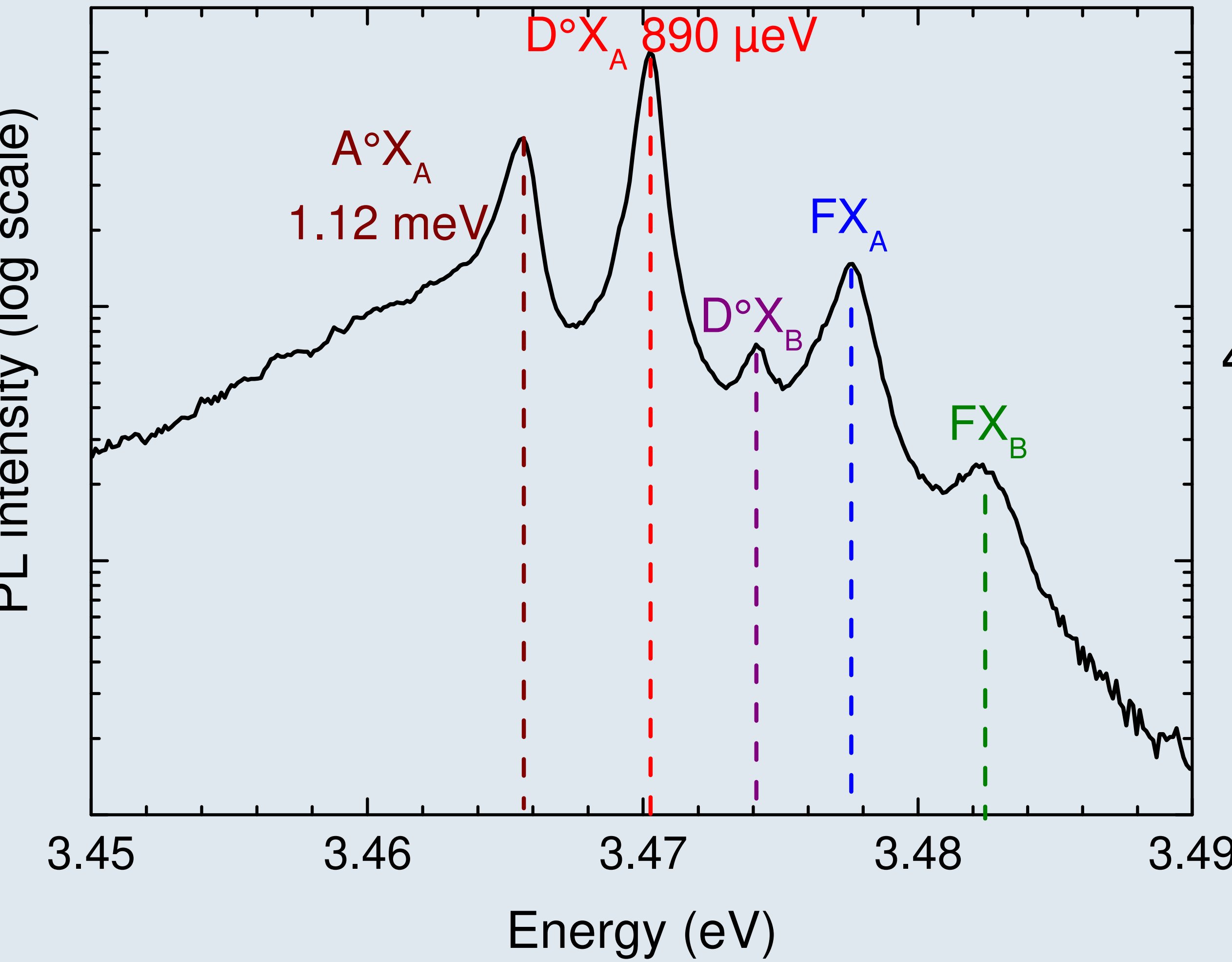
Excitons, what are they?



						helium 2 He 4.0026
	boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
	aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]

Neutral donor bound exciton D_0X

Photoluminescence of bulk GaN

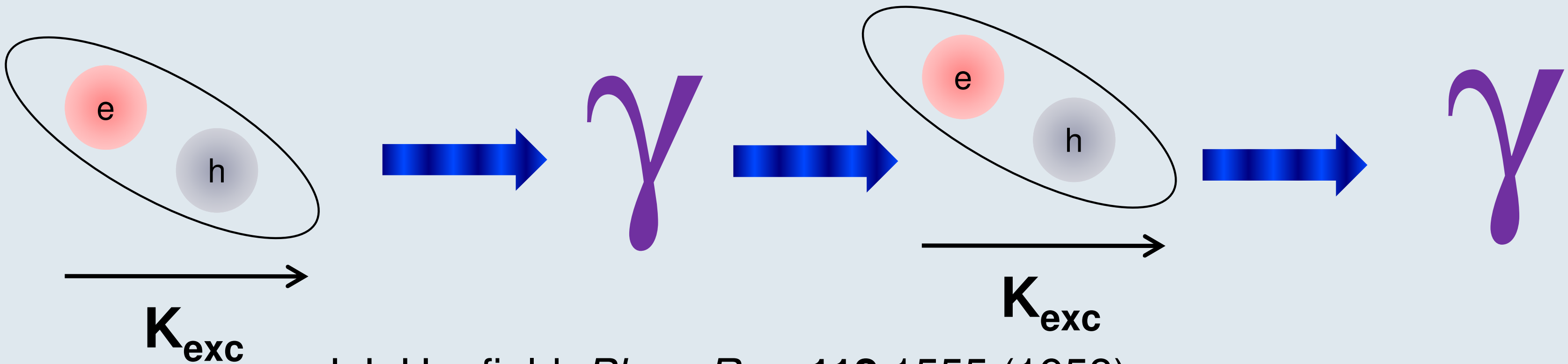


4 K nanowires

1 Si atom for 10^7 Ga atom (~10 per $(100\ nm)^3$) is enough to have a low temperature PL dominated by neutral donor bound exciton

Excitons and polaritons in GaN

Does the exciton really exist?



J.J. Hopfield, *Phys. Rev.* **112** 1555 (1958)
+ Pekar, Agranovich…

PHYSICAL REVIEW VOLUME 112, NUMBER 5 DECEMBER 1, 1958

Theory of the Contribution of Excitons to the Complex Dielectric Constant of Crystals*†

J. J. Hopfield‡
Physics Department, Cornell University, Ithaca, New York

(Received July 16, 1958)

Polariton = mixed exciton-photon particles

J.J. Hopfield, Annu. Rev. Condens. Matter Phys. Vol. 5, 1 (2014)

JJ Hopfield

Very numerous papers on the theory of semiconductor optics…

… but his most famous paper is :

Proc. Natl. Acad. Sci. USA
Vol. 79, pp. 2554–2558, April 1982
Biophysics

Neural networks and physical systems with emergent collective computational abilities

(associative memory/parallel processing/categorization/content-addressable memory/fail-soft devices)

J. J. Hopfield

Division of Chemistry and Biology, California Institute of Technology, Pasadena, California 91125; and Bell Laboratories, Murray Hill, New Jersey 07974

John J. Hopfield
Facts

© Nobel Prize Outreach.
Photo: Nanaka Adachi

John J. Hopfield
Nobel Prize in Physics 2024

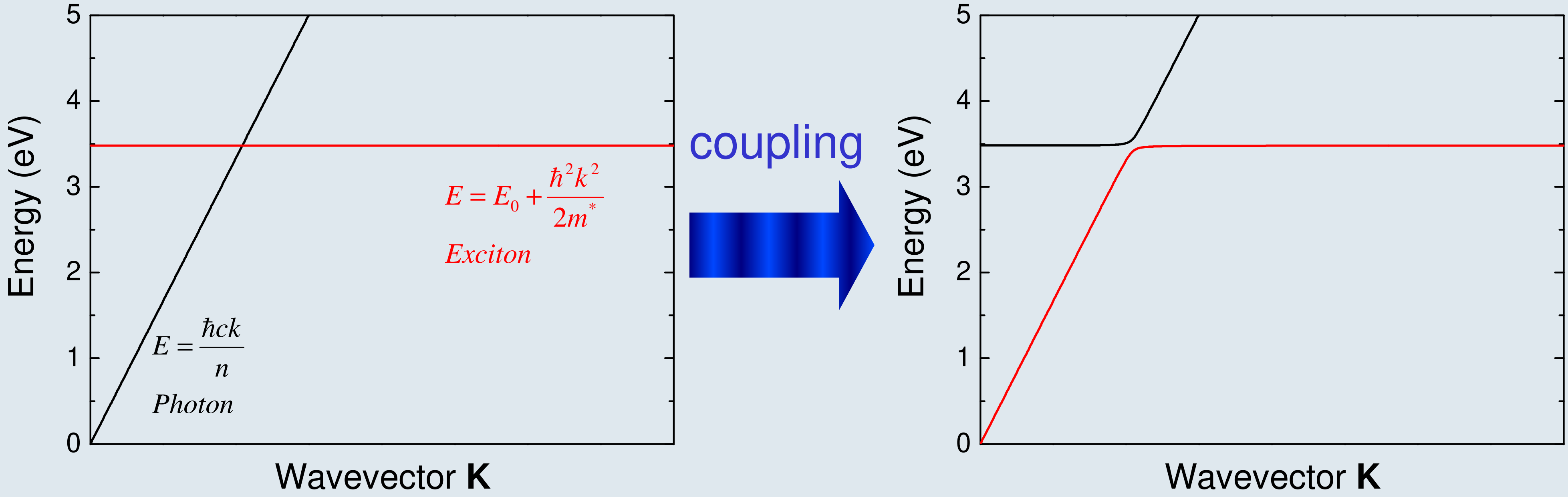
Born: 15 July 1933, Chicago, IL, USA

Affiliation at the time of the award: Princeton University, Princeton, NJ, USA

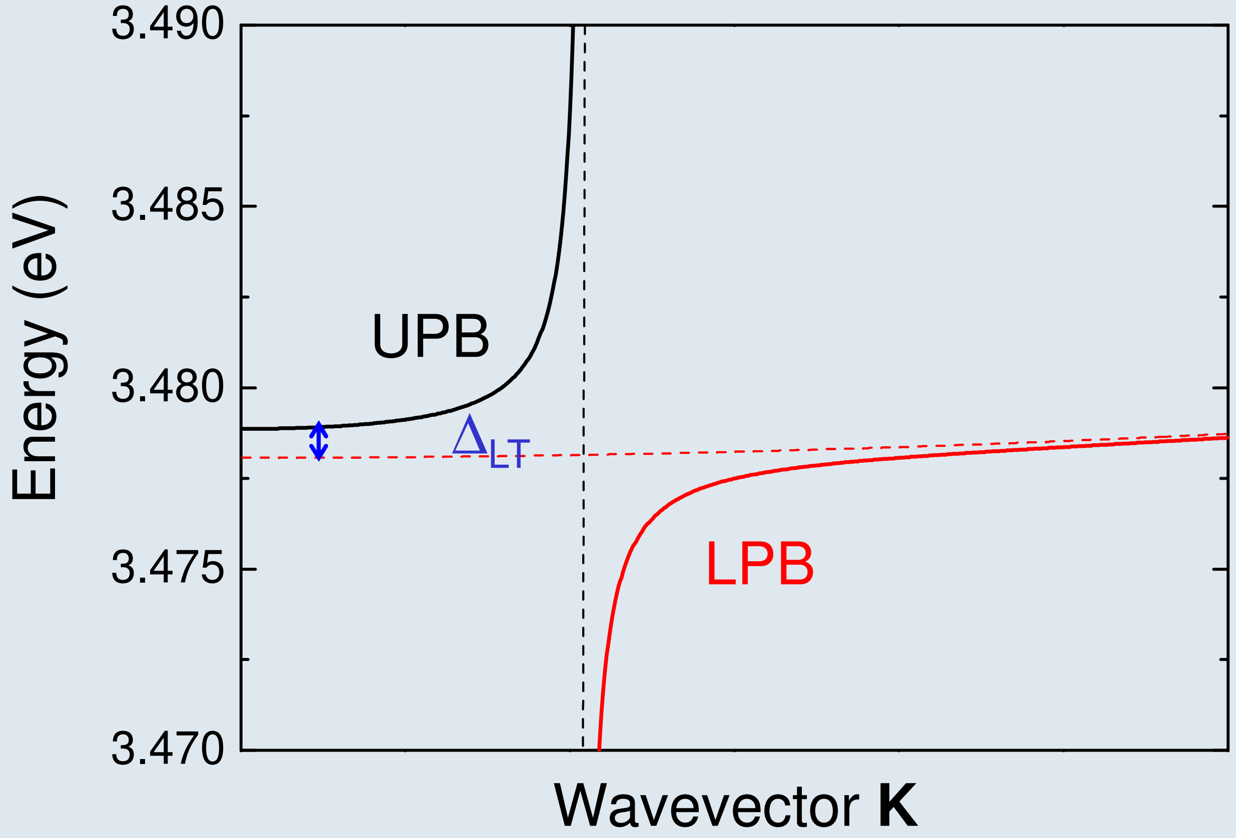
Prize motivation: “for foundational discoveries and inventions that enable machine learning with artificial neural networks”

Prize share: 1/2

Excitons and polaritons in GaN



Excitons and polaritons in GaN



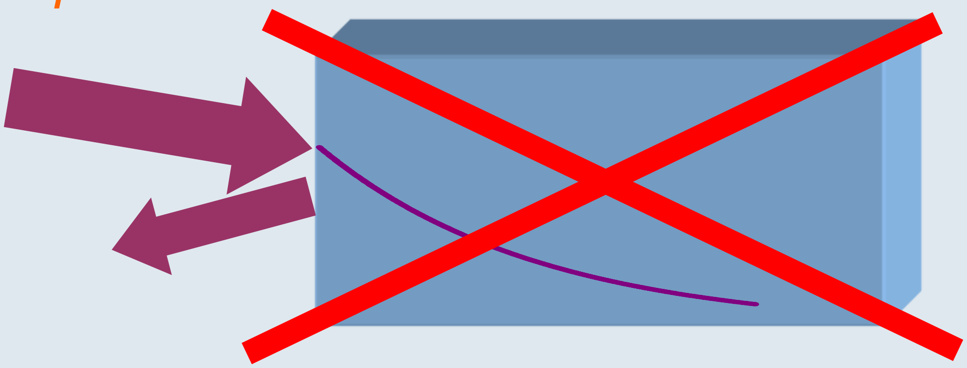
Δ_{LT} measures the intrinsic light-exciton coupling in the material

Note : in WZ GaN : A, B and C excitons + anisotropy

GaN : Δ_{LT}(A)=0.8 meV GaAs : Δ_{LT}=0.08 meV

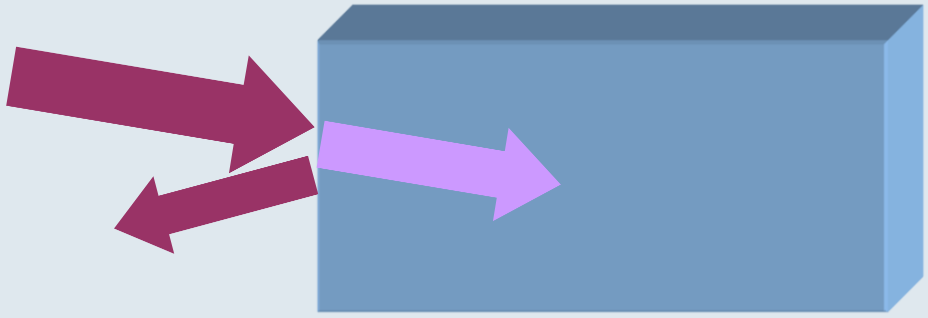
Consequences of the polariton picture

Absorption



Beer-Lambert law

$$I = I_0 e^{-\alpha L}$$

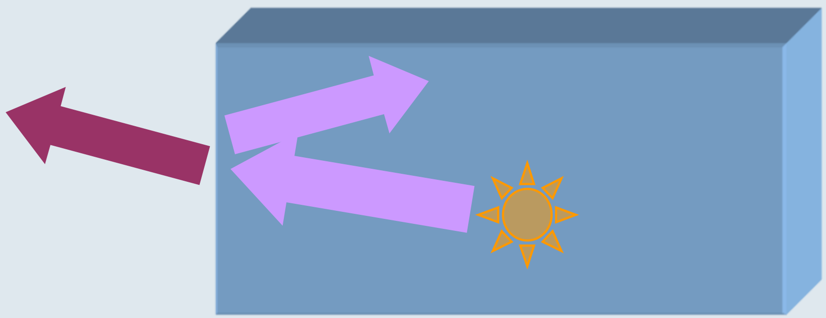


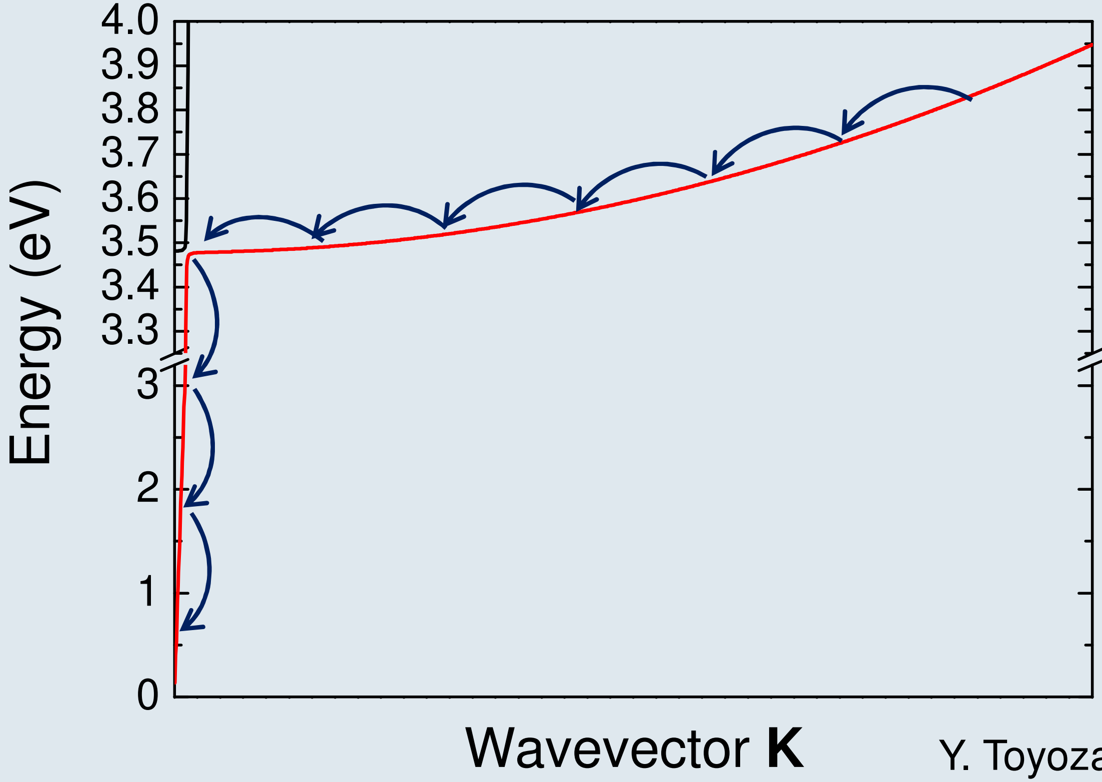
Propagating polariton
(attenuation = scattering)

Consequences of the polariton picture

Luminescence

Polariton propagating to
the surface !





Infrared catastrophy?

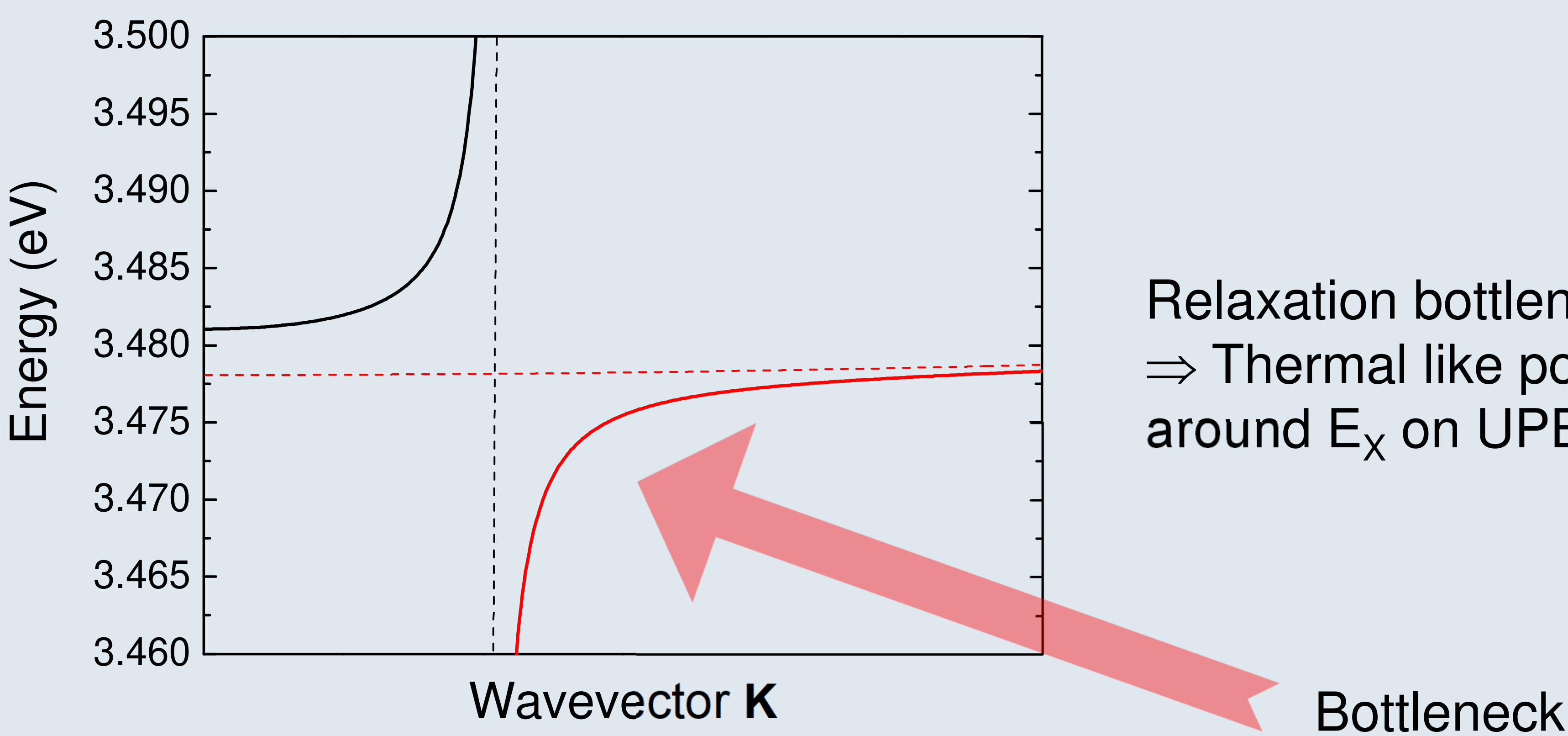
J. J. Hopfield, J. Phys. Soc. Jap. **21** 77 (1966)

Relaxation bottleneck
⇒ Thermal like population

Y. Toyozawa, Prog. Theor. Phys. Suppl. **12** 111 (1959)

Consequences of the polariton picture

Luminescence



Relaxation bottleneck
⇒ Thermal like population around E_X on UPB and LPB

Luminescence properties are very complex to model !!
(sample and experiments dependent…)

Consequences of the polariton picture

Luminescence

PHYSICAL REVIEW B VOLUME 34, NUMBER 2 15 JULY 1986

Effect of neutral donor scattering on the time-dependent exciton-polariton photoluminescence line shape in GaAs

T. Steiner* and M. L. W. Thewalt
Department of Physics, Simon Fraser University, Burnaby British Columbia, Canada V5A 1S6

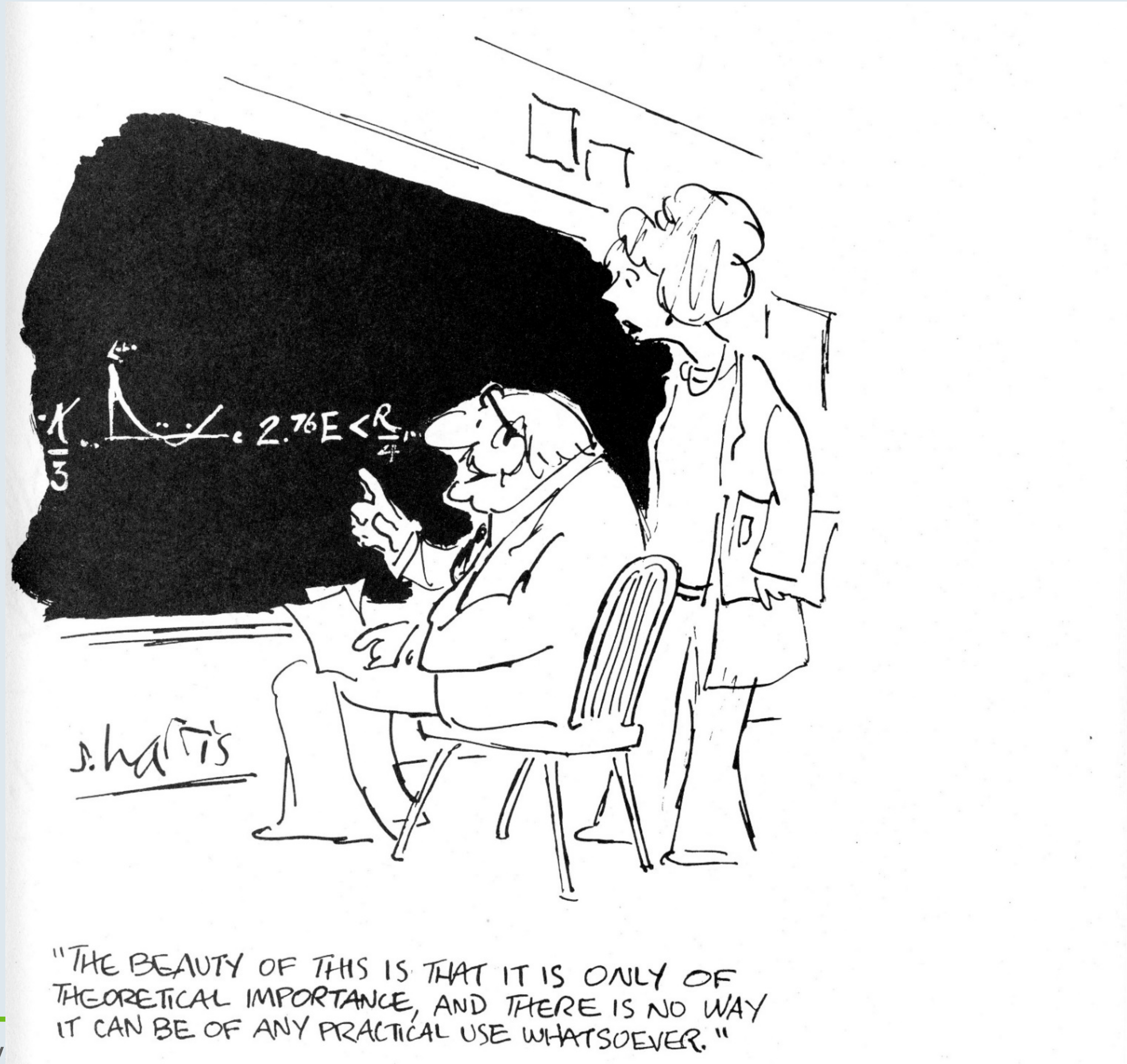
E. S. Koteles and J. P. Salerno
GTE Laboratories, Inc., Waltham, Massachusetts 02254

(Received 10 February 1986)

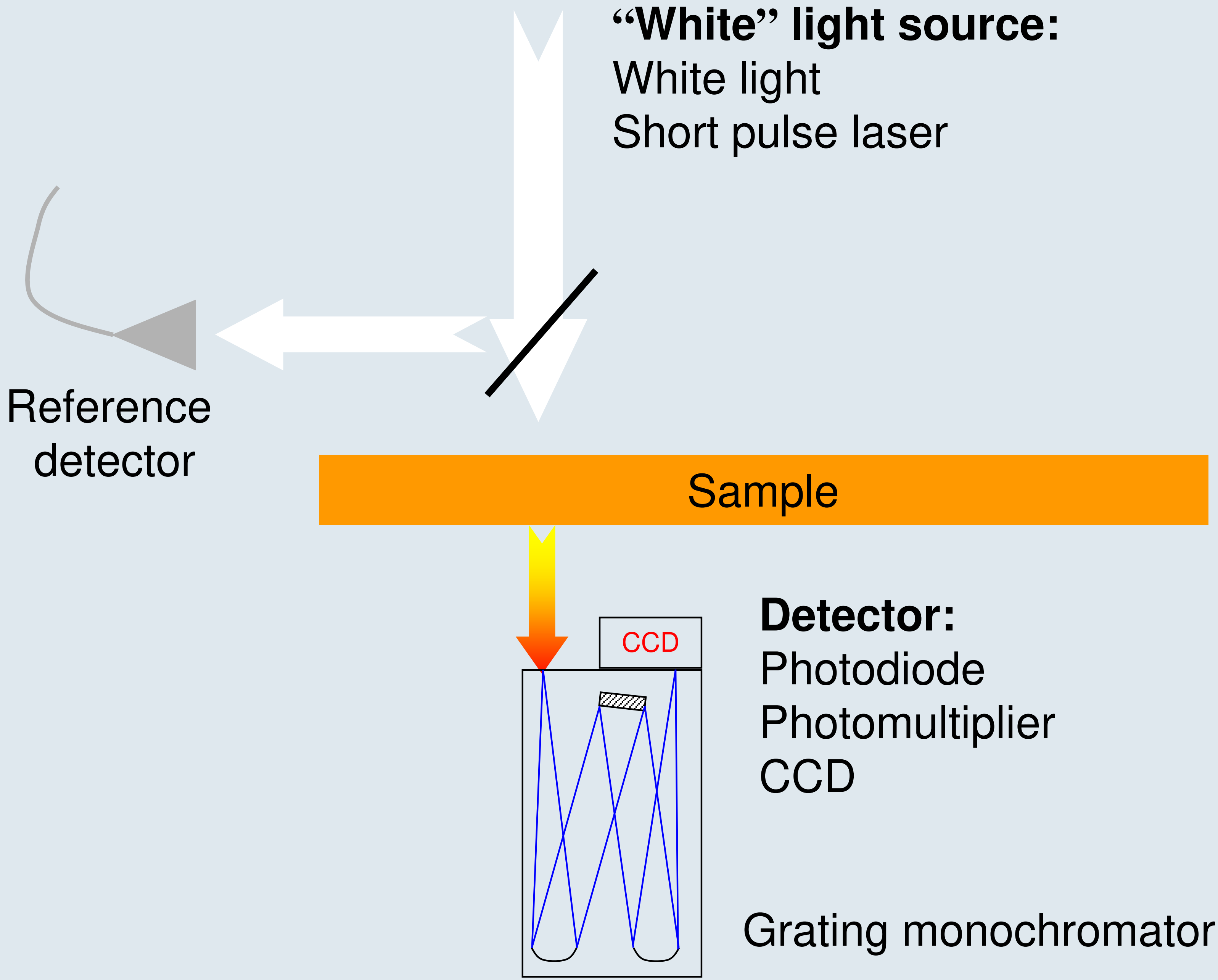
However, it is important to understand the complexity of the problem and hence the limitations of a simplified model. Any mechanism which affects the transport of polaritons to the sample surface, the probability of transmission at the surface, the distribution of polaritons in the crystal, or the polariton energy distribution can influence the observed polariton luminescence. Consequently, one can expect great variations in the observed emission with different samples, surface preparation, or experimental conditions.

"No single mechanism can explain the huge variety of observed polariton spectra in various crystals"

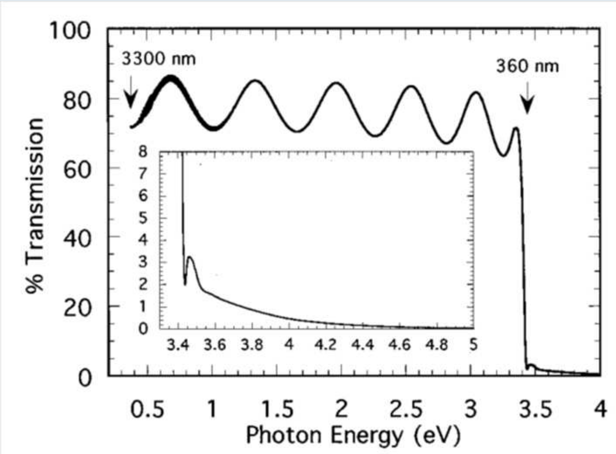
Excitons and polaritons in GaN

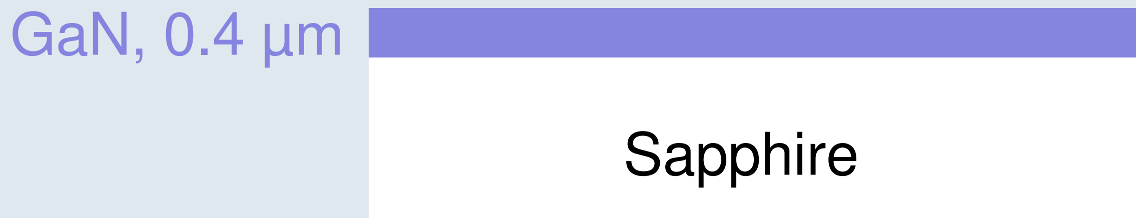


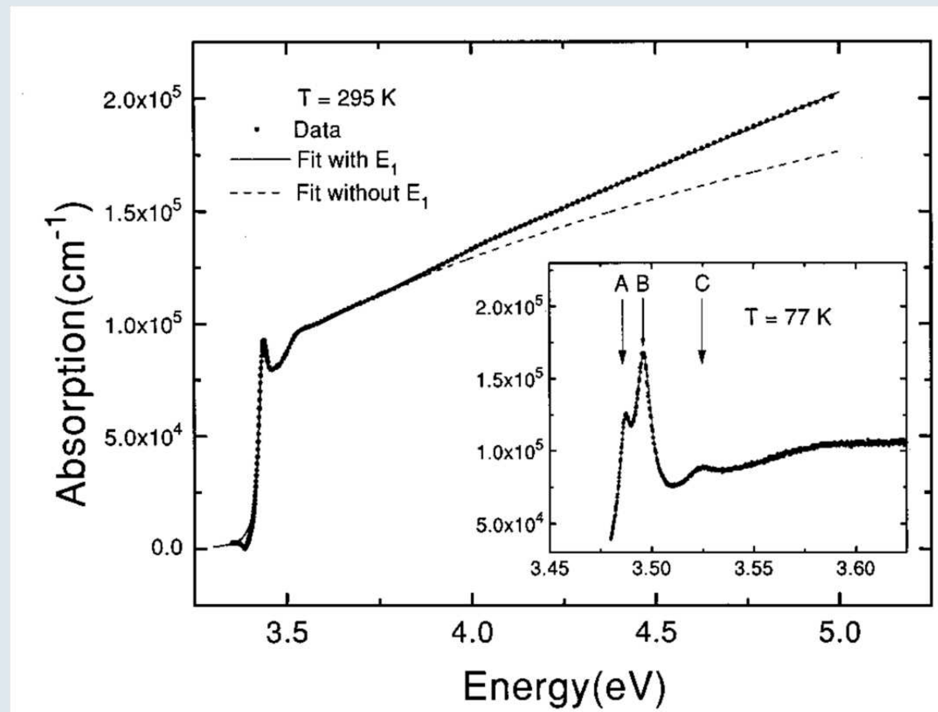
Spectroscopy of GaN : Absorption



Spectroscopy of GaN : Absorption







Muth *et al.* APL **71** 2572 (1997)

Spectroscopy of GaN : Reflectivity

Advantages of absorption:

Direct probing of the electronic states (coupled to the light!)

Measurement does not perturb the system at low power

Limitations of absorption:

Absorbing substrate (if substrate removal impossible)

Weak signal (especially if large broadening)

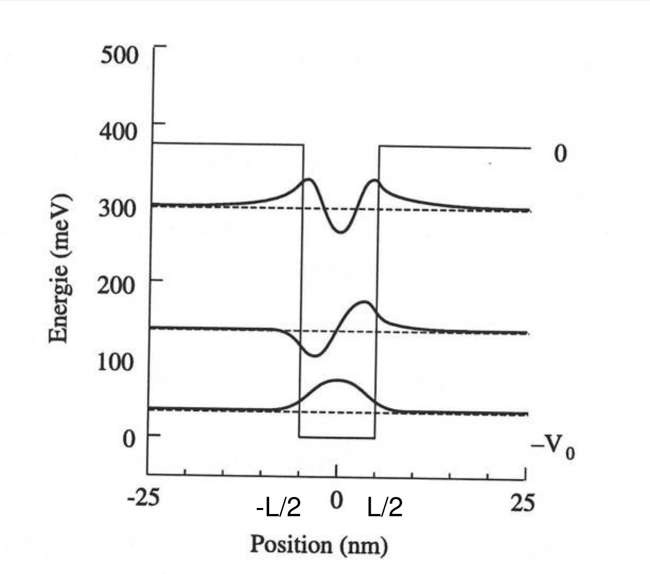
Complex structures

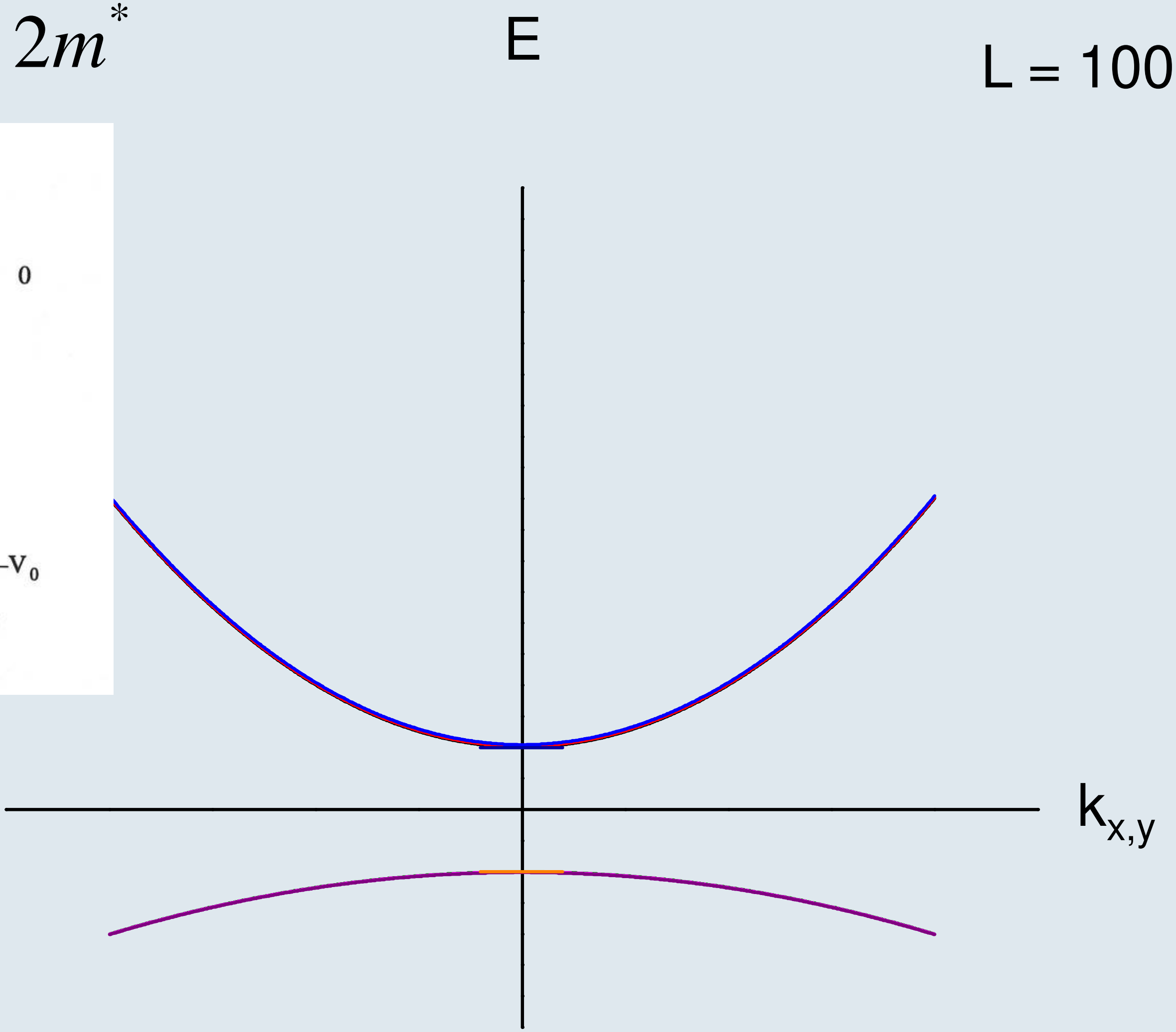
Quantum wells, quantum dots in III-N

Localization, quantum confined Stark effect, excitons and all that…

Quantum wells, the perfect case

$$E_{\vec{0},n} = \frac{\pi^2 \hbar^2 n^2}{2m^* L^2} + \frac{\hbar^2 k_{x,y}^2}{2m^*}$$

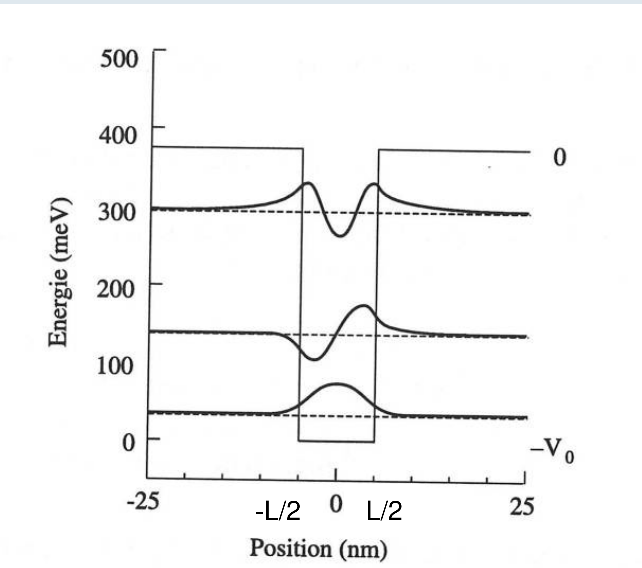


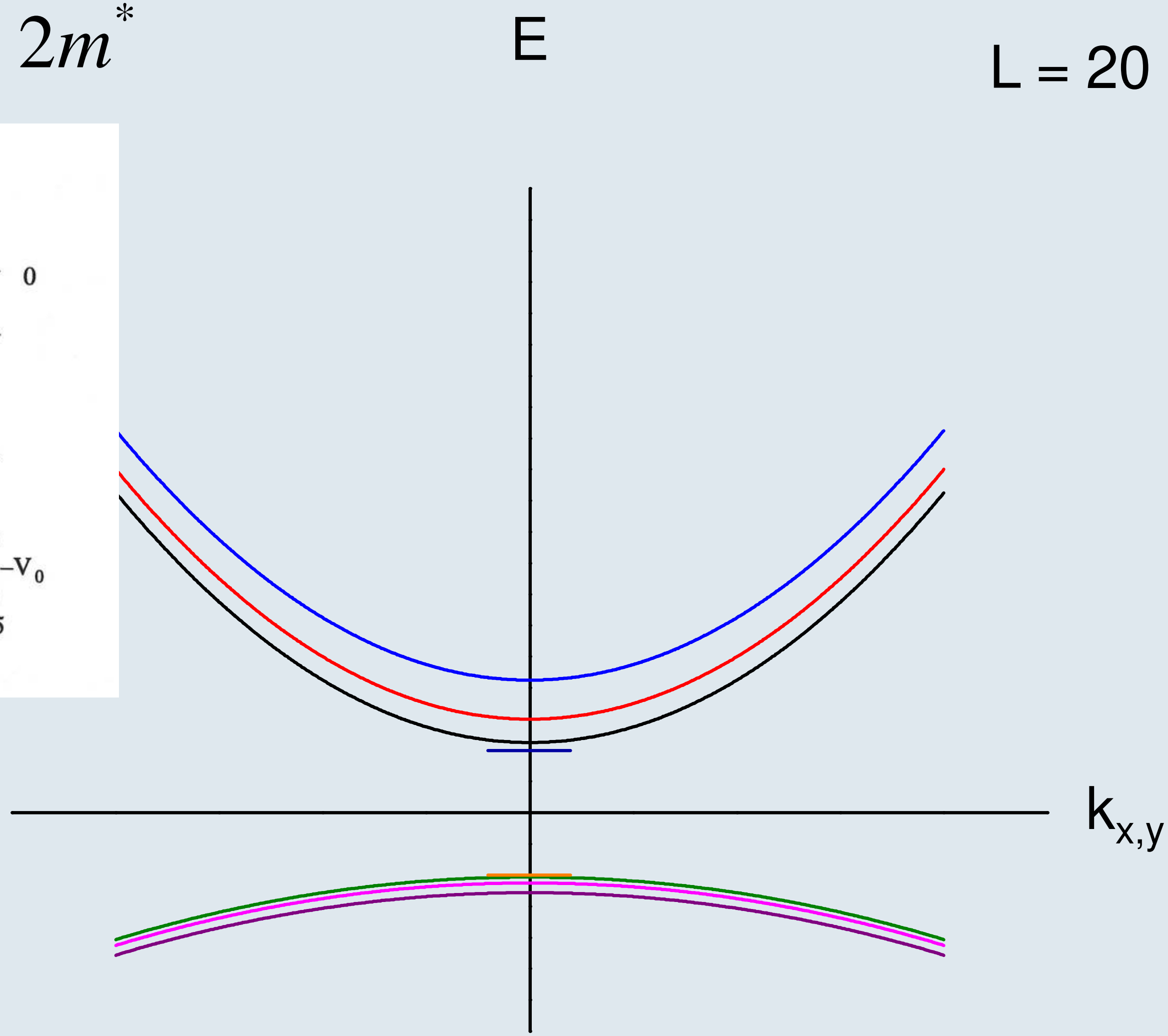


Quantum wells, the perfect case

$$E_{\vec{0},n} = \frac{\pi^2 \hbar^2 n^2}{2m^* L^2} + \frac{\hbar^2 k_{x,y}^2}{2m^*}$$

L = 20 nm





Quantum wells, the perfect case

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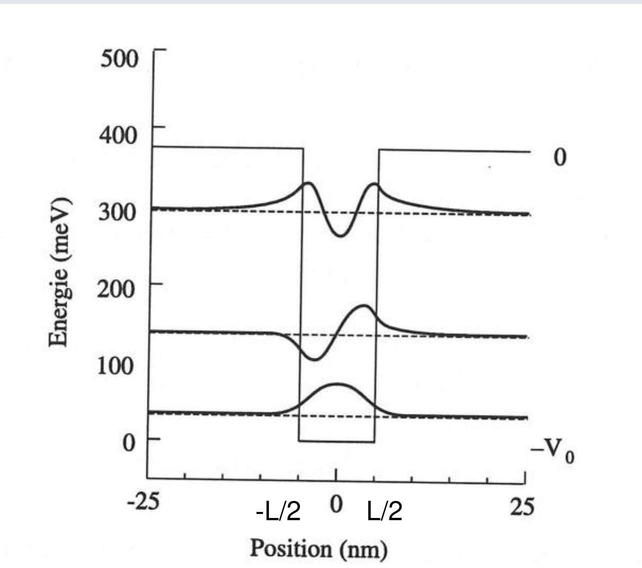
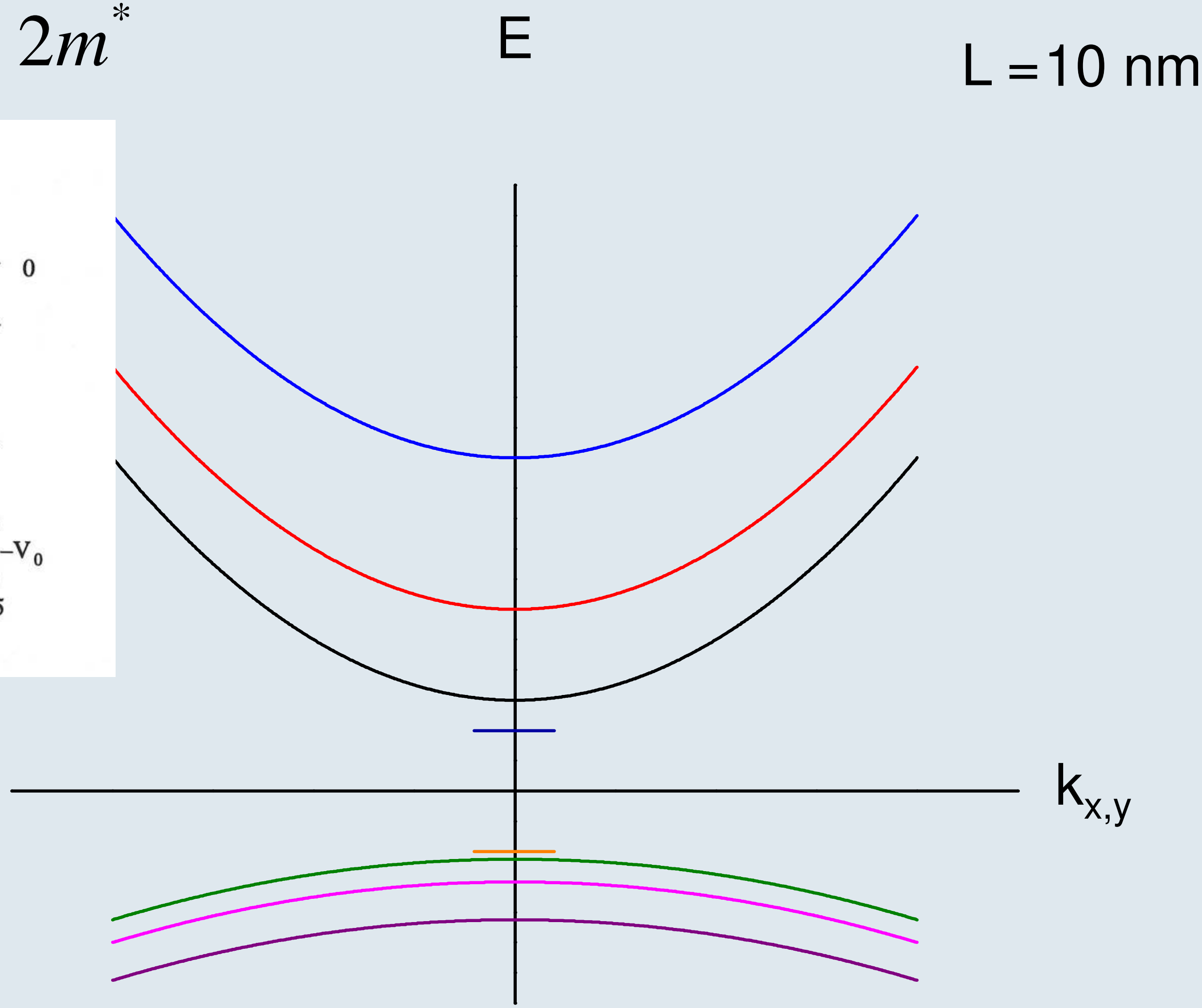
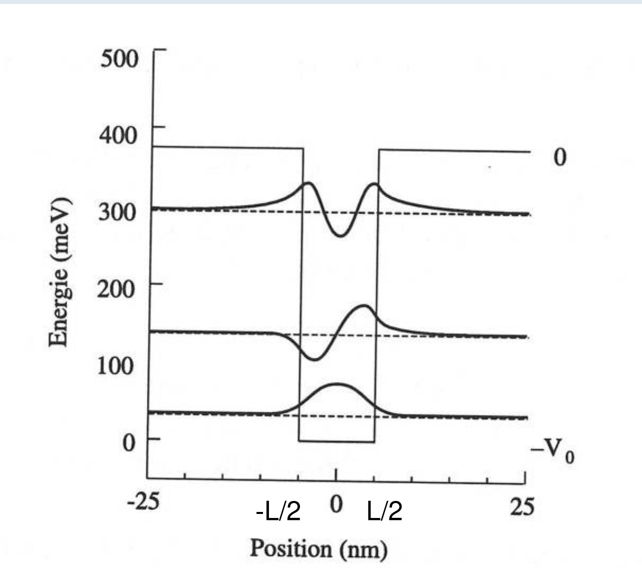


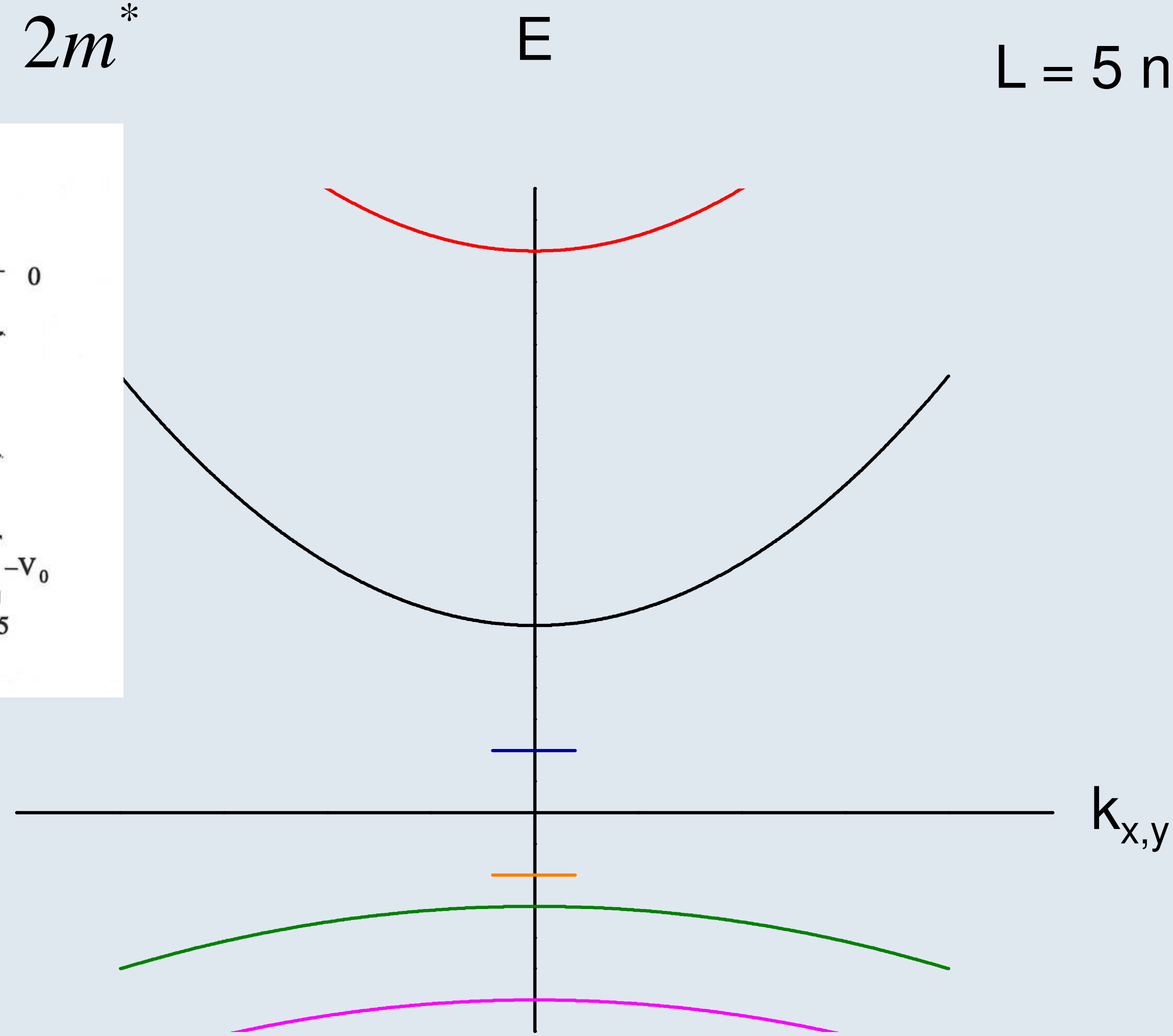


Quantum wells, the perfect case

$$E_{\vec{0},n} = \frac{\pi^2\hbar^2 n^2}{2m^* L^2} + \frac{\hbar^2 k_{x,y}^2}{2m^*}$$

L = 5 nm





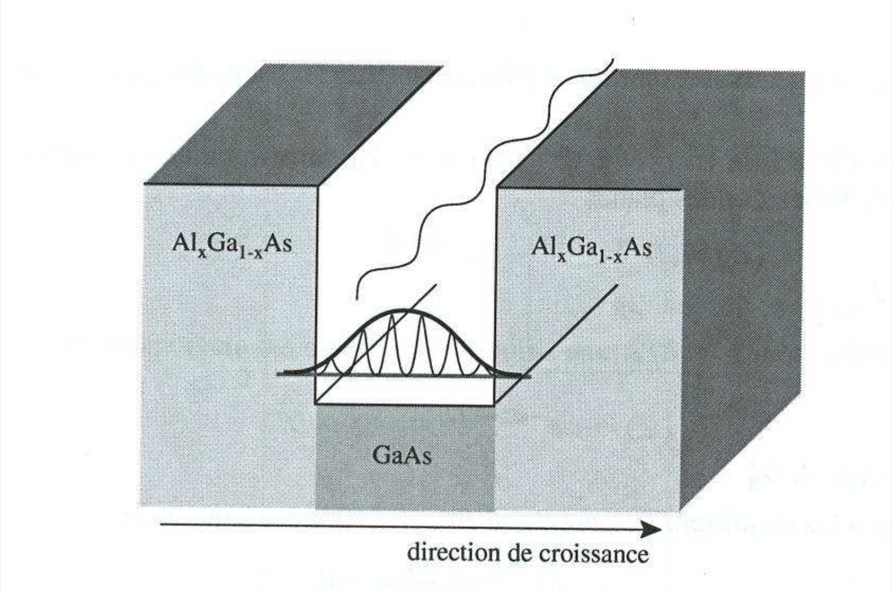
Quantum wells, the perfect case

Ideally, the quantum well exciton is laterally fully delocalized

⇒ A pure 2-D state
⇒ Note that the exciton binding energy is up to 4 times larger in 2D structures

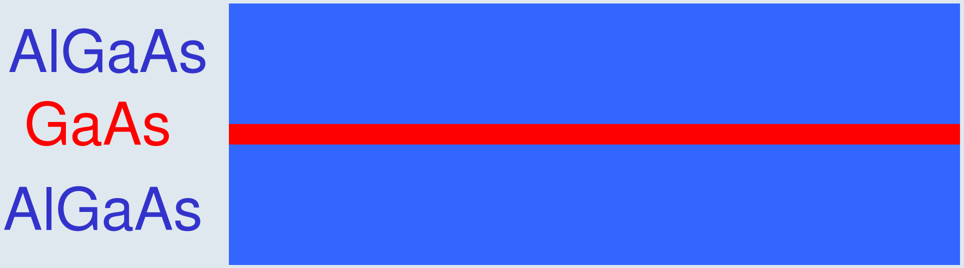
What about the Bohr radius ???

2 times smaller in 2D structures !!



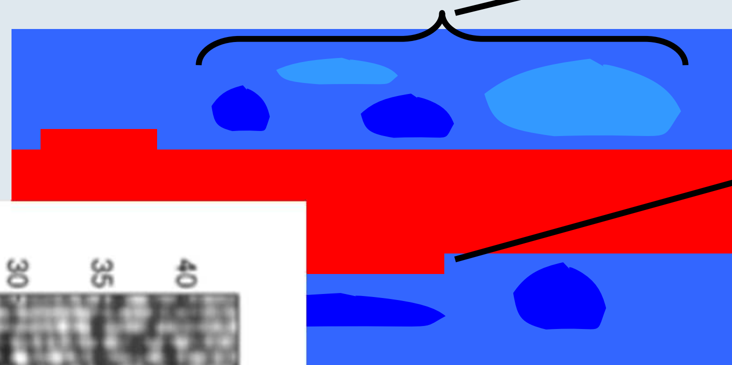
Quantum wells, reality

Stokes-shift for quantum wells:



Perfect QW:
electronic states
with a well defined
in-plane momentum

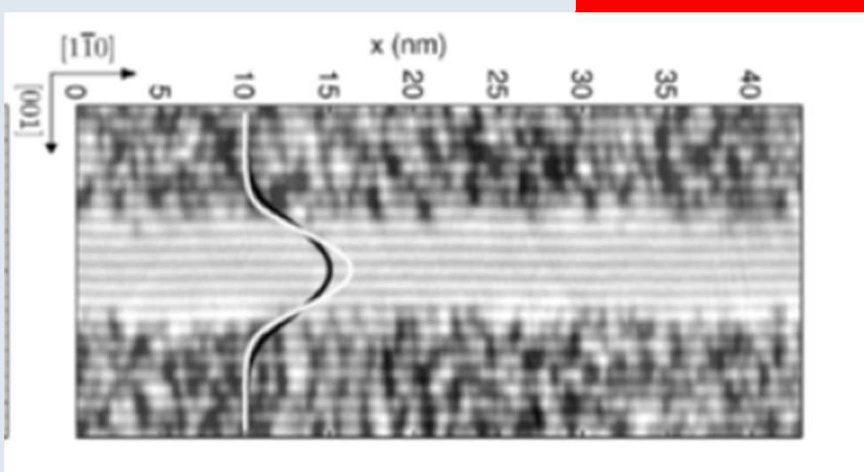
Reality:



Alloy fluctuations

Monolayer fluctuation

=> Localized states!!



GaAs/AlGaAs quantum well

See Nicolas Grandjean's lecture

Cultural pause : Sir George Gabriel Stokes, 1st Baronet

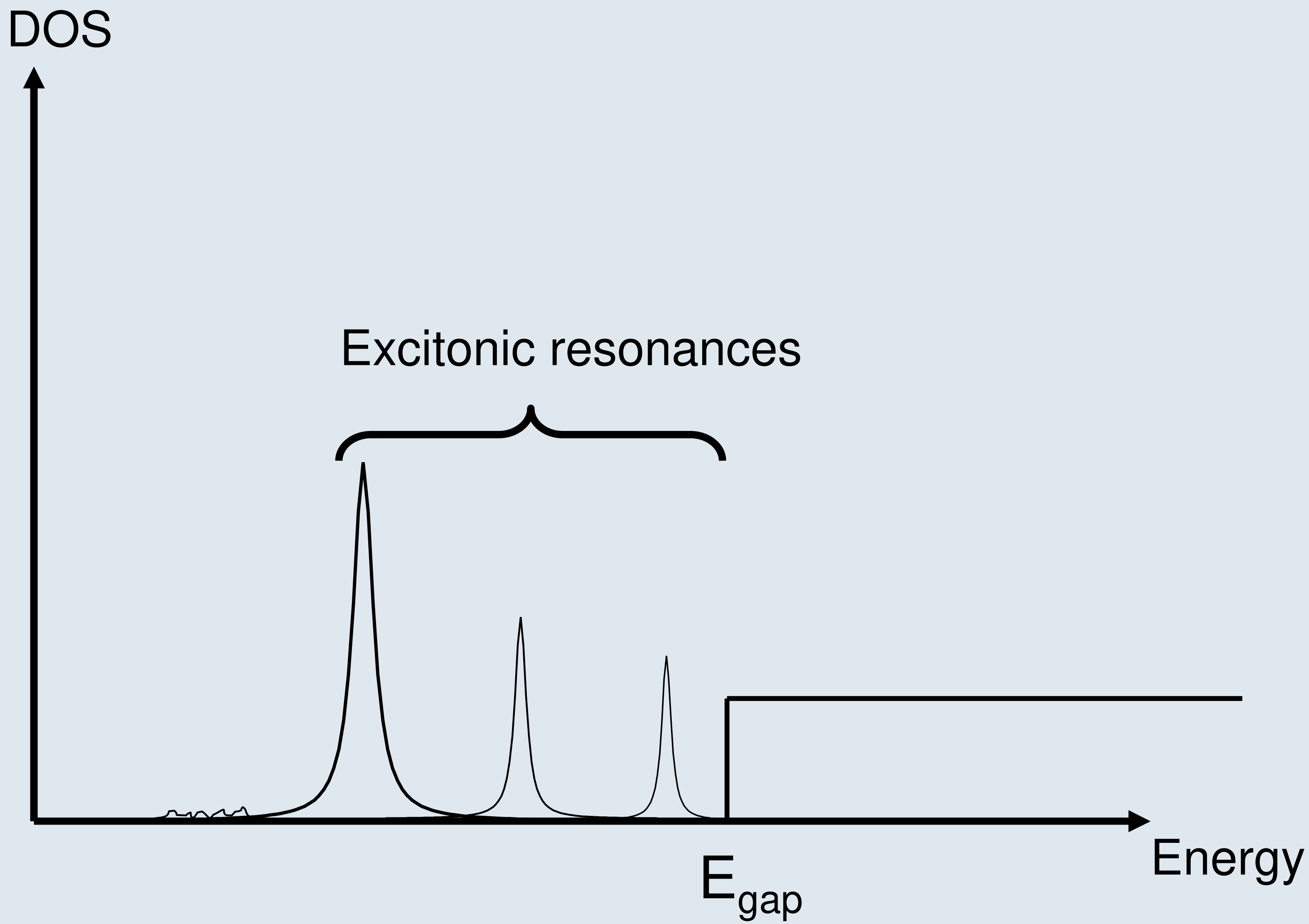
1819-1903

Major contributions in Mathematics (Stokes theorem), fluid mechanics (Navier-Stokes equation), optics (fluorescence, diffraction), biology (role of hemoglobin)…

We all admit that the book of Nature and the book of Revelation come alike from God, and that consequently there can be no real discrepancy between the two if rightly interpreted.

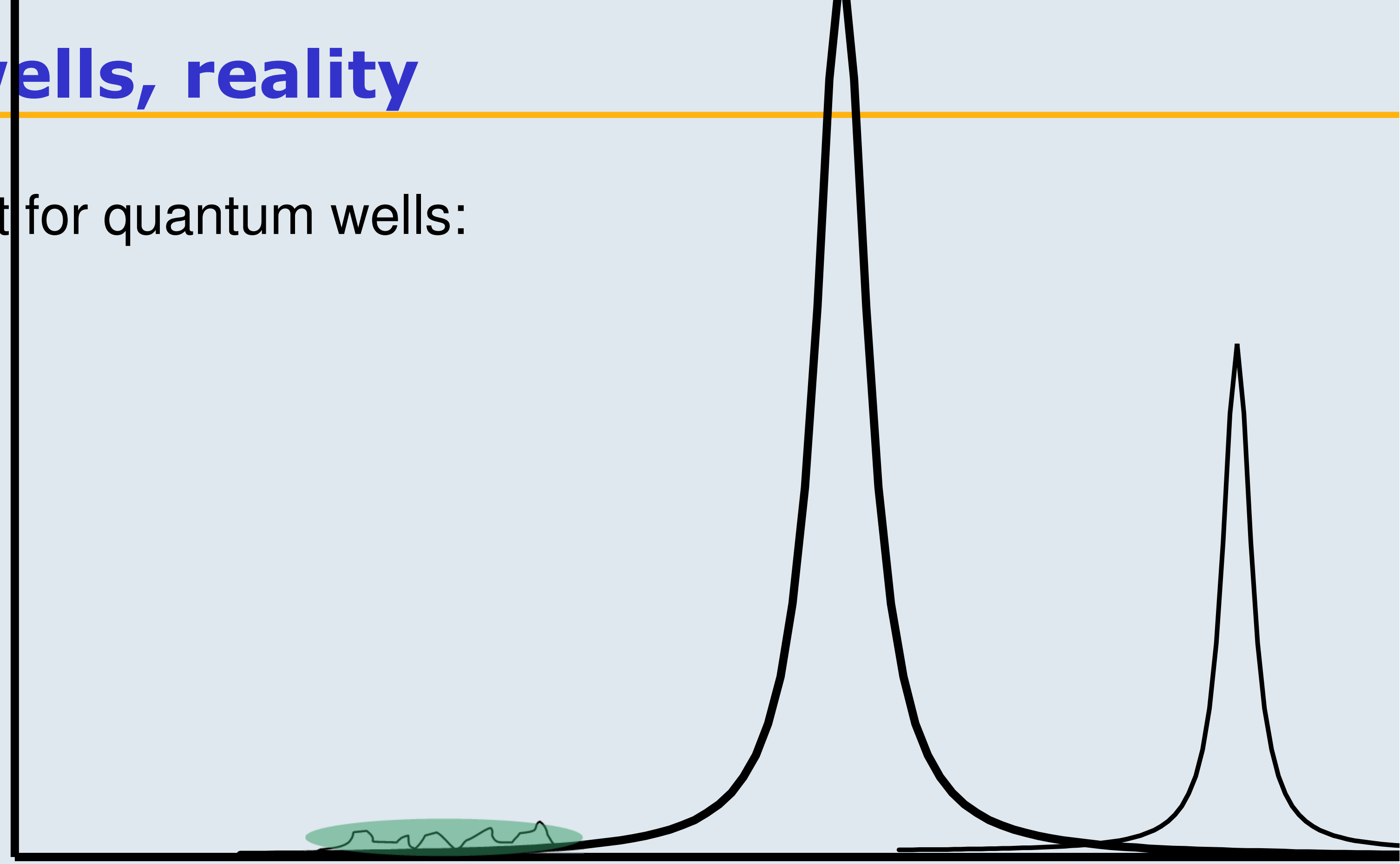
Quantum wells, reality

Stokes-shift for quantum wells:



Quantum wells, reality

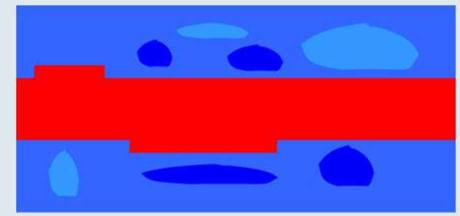
Stokes-shift for quantum wells:



Localized states
monolayer fluctuations
alloy fluctuations
impurity bound excitons

=> PL is not where the majority of states are

Quantum wells, reality

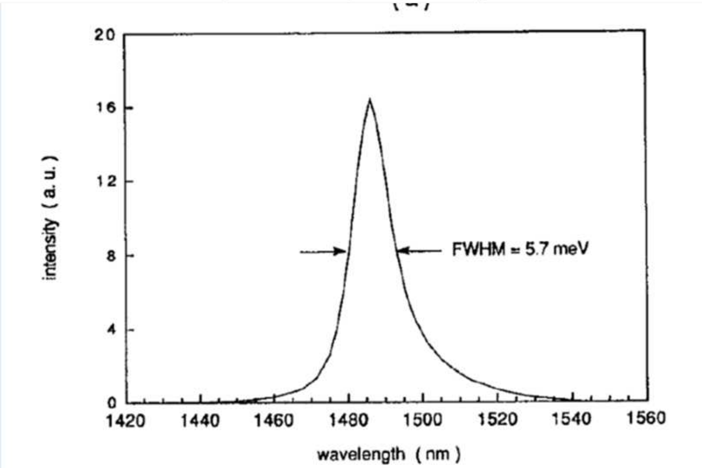
Ideal QW	Real QW
	
Fully in-plane delocalized exciton	More or less localized « exciton »
Very short intrinsic lifetime	Lifetime depends on lateral localization
Radiative lifetime / kT limited broadening	Broadening reflects potential inhomogeneities

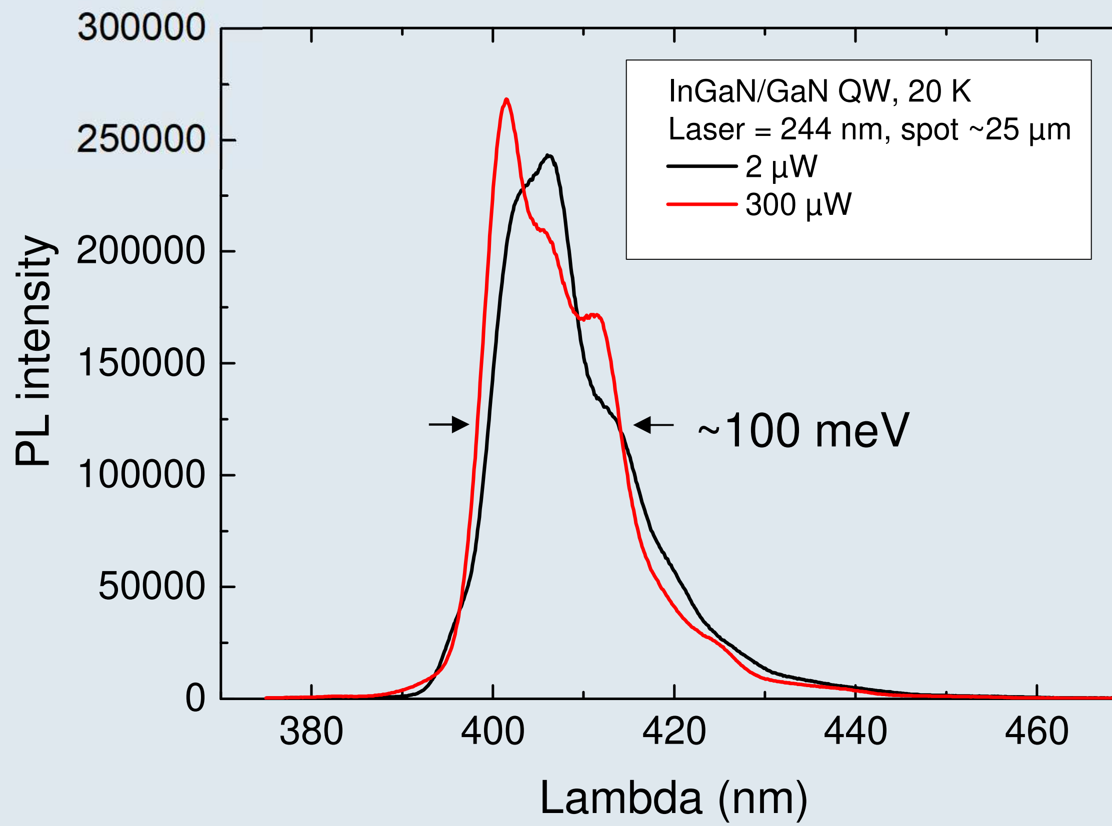
Quantum wells, InGaN/GaN QWs

Optical properties of high-quality InGaAs/InAlAs multiple quantum wells

S. Gupta, P. K. Bhattacharya, J. Pamulapati, and G. Mourou
Ultrafast Science Laboratory and Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109

(Received 12 September 1990; accepted for publication 6 December 1990)





Composition inhomogeneities at various scales

Quantum wells, InGaN/GaN QWs

Localization landscape theory of disorder in semiconductors III: Application to carrier transport and recombination in light emitting diodes

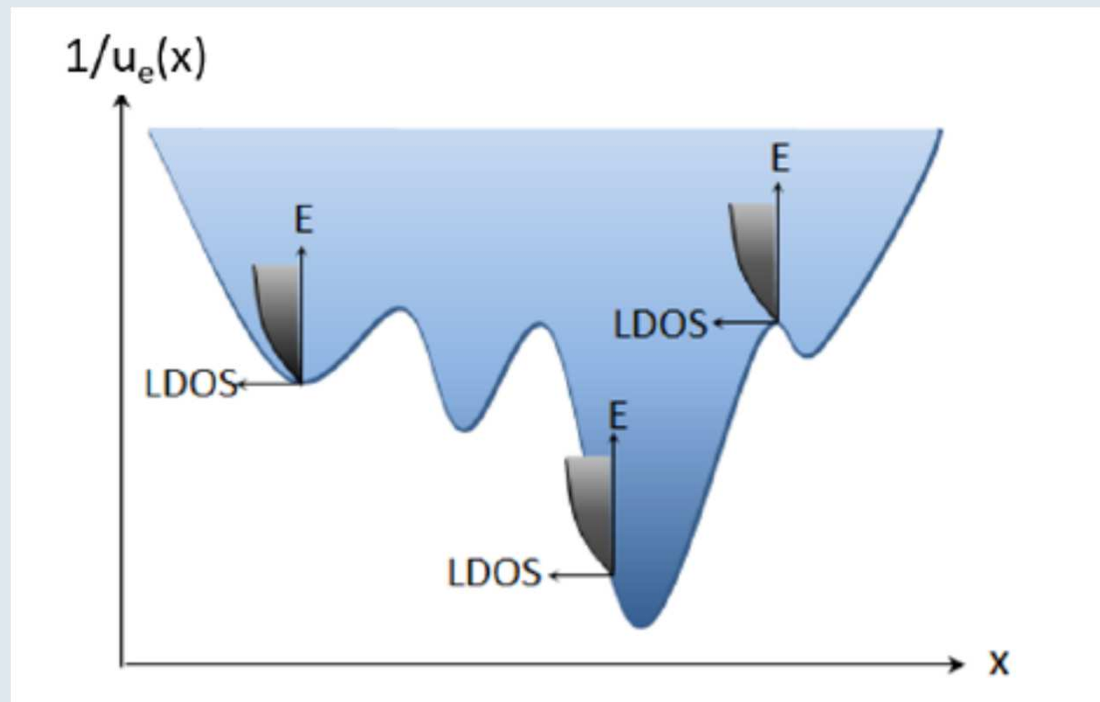
Chi-Kang Li,[1] Marco Piccardo,[2] Li-Shuo Lu,[1] Svitlana Mayboroda,[3] Lucio Martinelli,[2] Jacques Peretti,[2] James S. Speck,[4] Claude Weisbuch,[2,4] Marcel Filoche,[2] and Yuh-Renn Wu[1,*]

[1] *Graduate Institute of Photonics and Optoelectronics and Department of Electrical Engineering, National Taiwan University, Taipei 10617, Taiwan*

[2] *Laboratoire de Physique de la Matière Condensée, Ecole polytechnique, CNRS, Université Paris Saclay, 91128 Palaiseau Cedex, France*

[3] *School of Mathematics, University of Minnesota, Minneapolis, Minnesota 55455, USA*

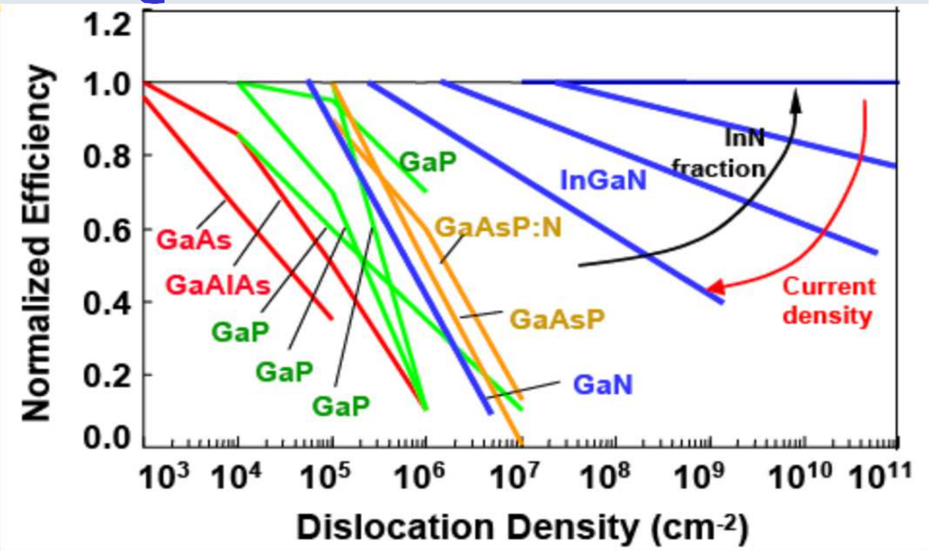
[4] *Materials Department, University of California, Santa Barbara, California 93106, USA*



Strong localization effects in InGaN QWs ??

Quantum wells, InGaN/GaN QWs

InGaN/GaN QWs are happily pathological



A vigorous debate in the last 20 years
…not settled yet (getting closer)

Dislocations are not NR centers

Indium clustering localization

Dislocations « protected » by V-pits

Localization intrinsic to random InGaN alloy

Quantum wells, InGaN/GaN QWs

InGaN quantum wells luminescence :

- Role of dislocations (=> V-pits)

- Role of point defects (=> Underlayer)

- Dependency on excitation density ("carrier temperature")

Corollary 1 : the most efficient semiconductor emitting structure, the most sold optoelectronic layer is still not yet well understood (…getting there !)

Corollary 2 : industrials have successfully spent big money to optimize InGaN/GaN QWs, with very little physical understanding of what’s going on

III-N quantum wells and the QCSE

Spontaneous polarization : it's complicated …

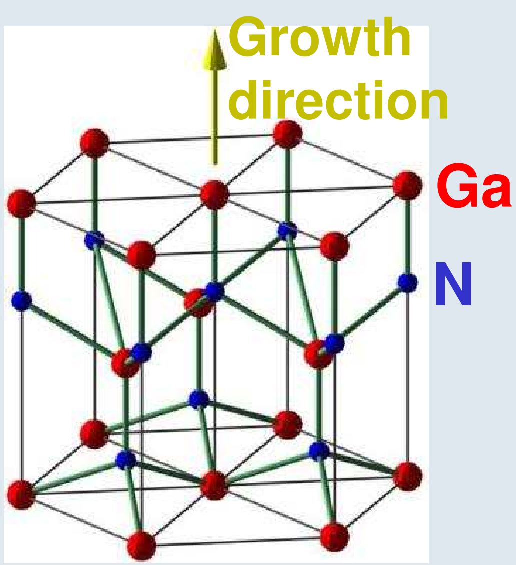
> Macroscopic electric polarization is a fundamental concept in the physics of matter, upon which the phenomenological description of dielectrics is based (Landau and Lifshitz, 1984). Notwithstanding, this concept has long evaded even a precise microscopic definition. A typical incorrect statement—often found in textbooks—is that the macroscopic polarization of a solid is the dipole of a unit cell. It is easy to realize that such a quantity is neither measurable nor model-independent: the dipole of a periodic charge distribution is in fact ill defined

R. Resta, Rev. Mod. Phys. **66**, 899 (1994)

Only polarization differences can be measured !

In materials with an inversion symetry, the spontaneous polarization is null (by convention)

[0001] = c-axis



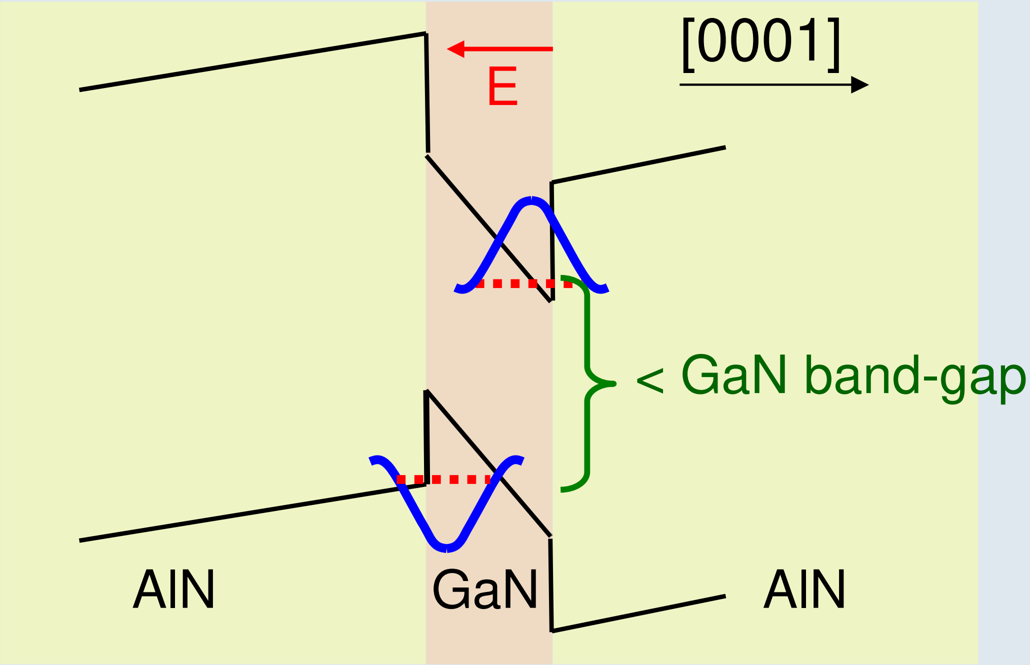
P

$$\vec{P} = \frac{1}{V}\left(-e\sum_l Z_l \vec{R}_l + \int d\vec{r}\,\rho(\vec{r}) \right)$$

$$\vec{F}_{QW} = \frac{\Delta \vec{P}}{\varepsilon_0 \varepsilon_r}$$

Review : Effects of Polarization in Optoelectronic Quantum Structures, R. Butté and N. Grandjean
In "Polarization Effects in Semiconductors: From Ab Initio Theory to Device Applications", Springer, 2008

III-N quantum wells and the QCSE



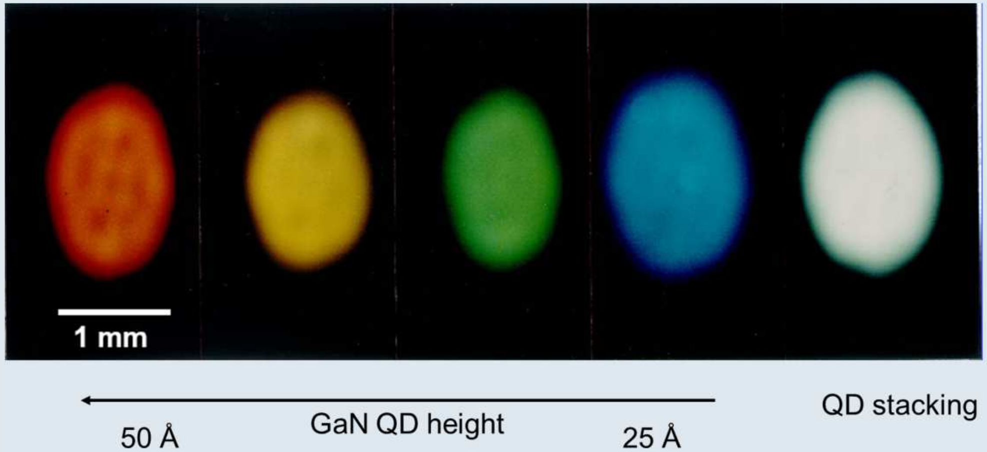
F. Bernardini *et al.*, Phys Rev B **56**, R10024 (1997)

Below well bandgap emission

Experimental result:

$P_{sp,GaN}+P_{pz,GaN}-P_{sp,AlN}-P_{pz,AlN}$

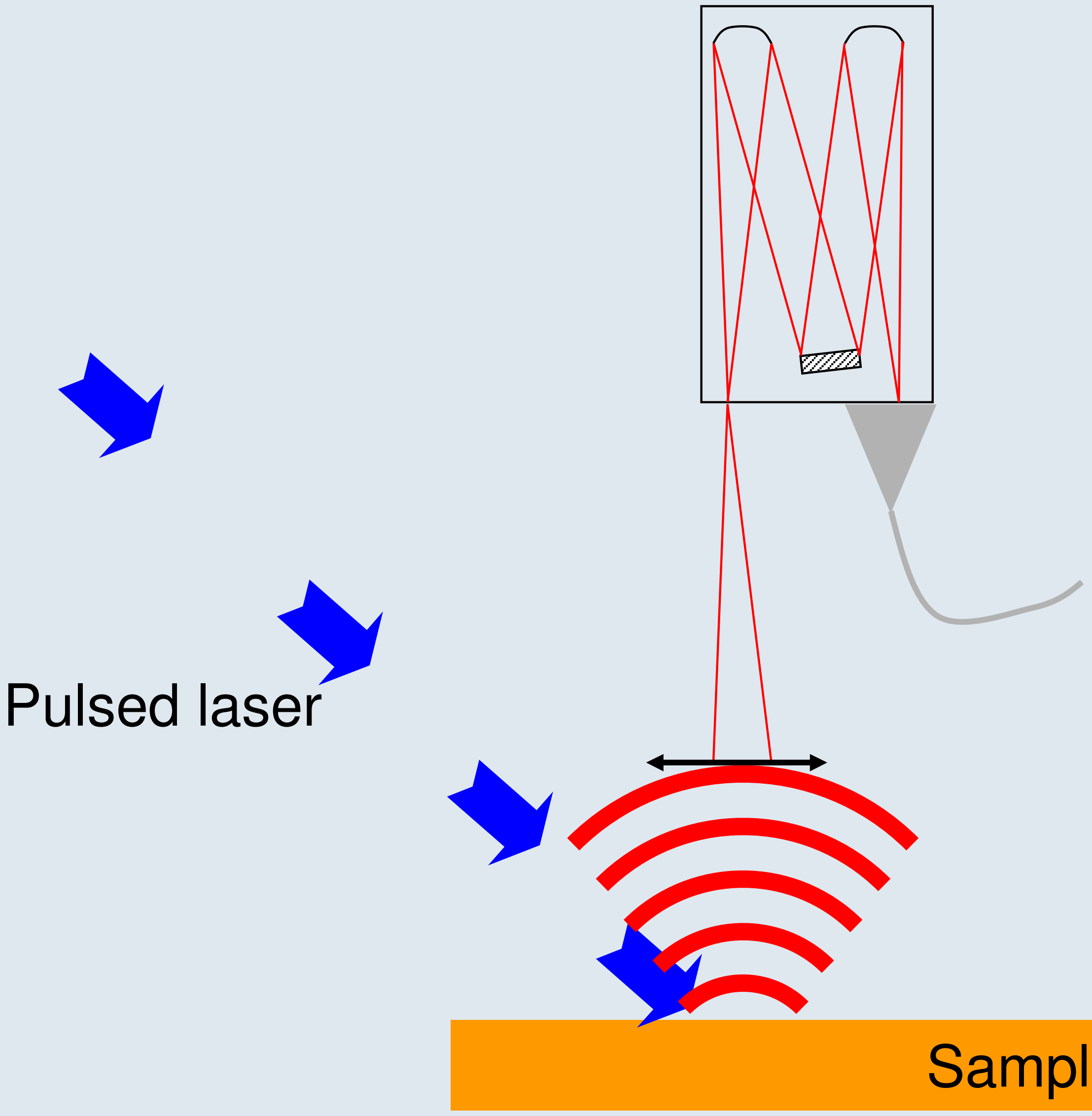
Reduced oscillator strength



Damilano *et al.*, Appl. Phys. Lett. **75** 962 (1999)

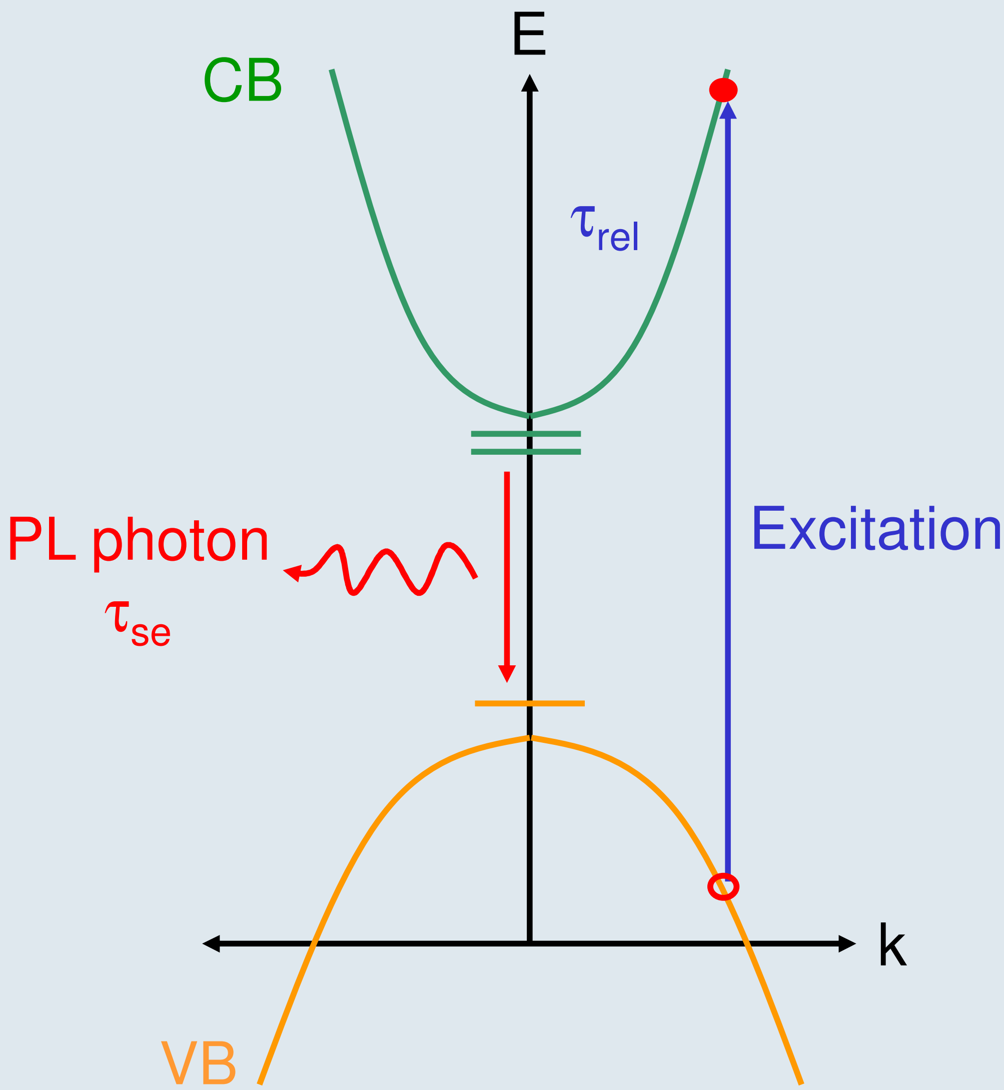
Most important effect = radiative lifetime
=> time-resolved PL

Experimental technique : time-resolved PL



Fast detector
Photodiode
Avalanche photodiode
Photomultiplier
Streak camera

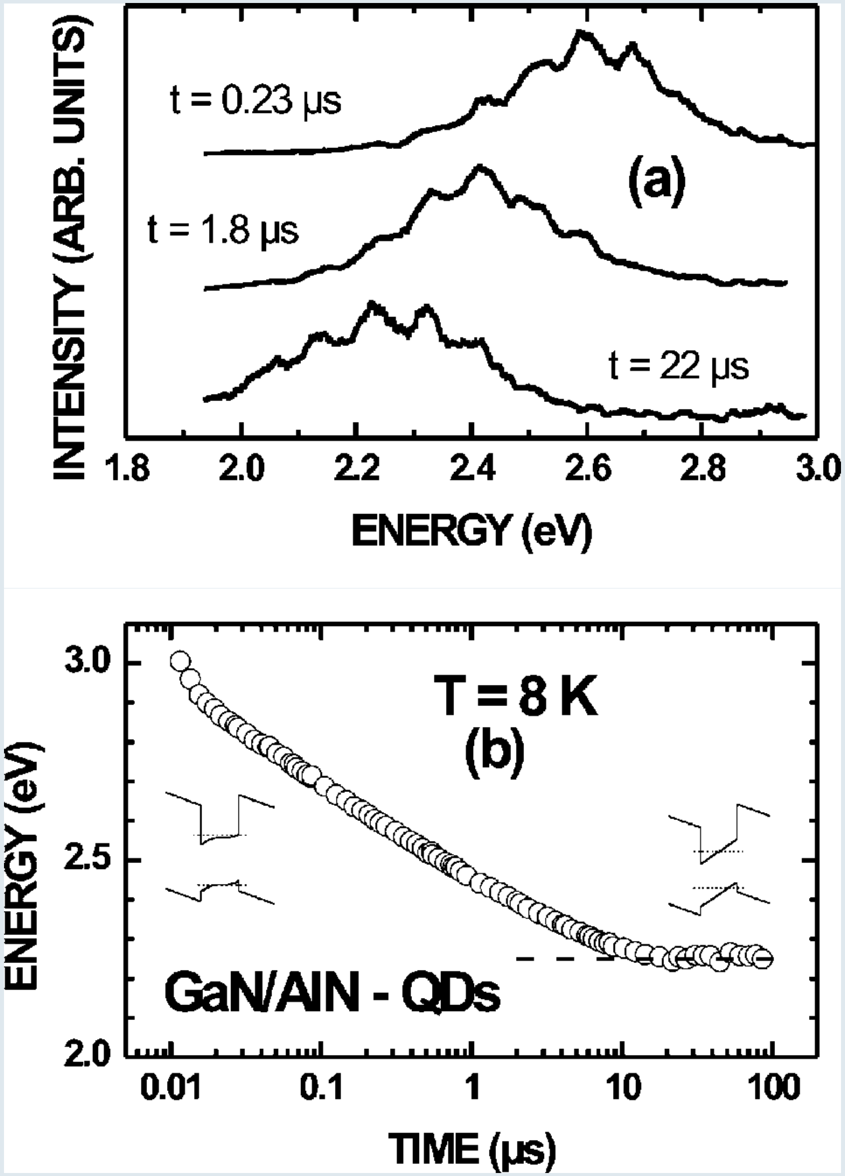
Experimental technique : time-resolved PL



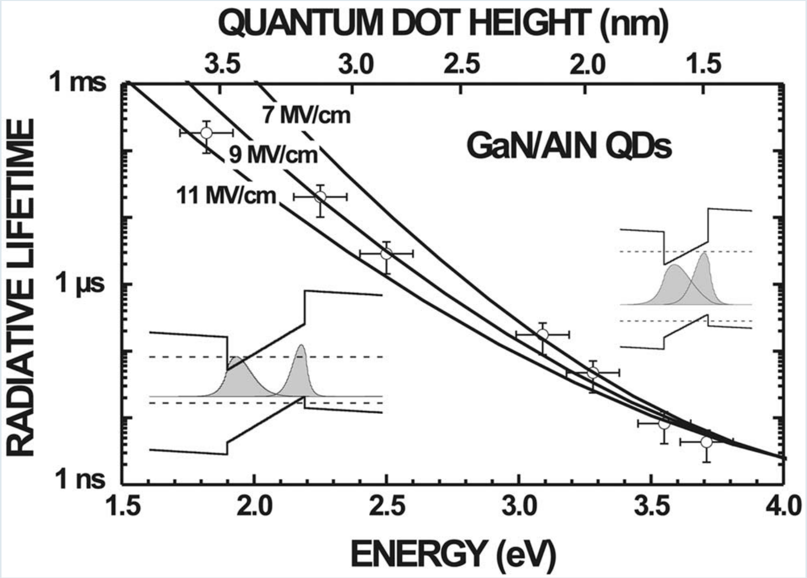
$$I(t,\lambda) \propto \frac{\tau_{se}}{\tau_{se}-\tau_{rel}}\left(e^{-\frac{t}{\tau_{se}}} - e^{-\frac{t}{\tau_{rel}}}\right)$$

$\Rightarrow$ Measurement of relaxation time and spontaneous emission time

III-N quantum wells and the QCSE



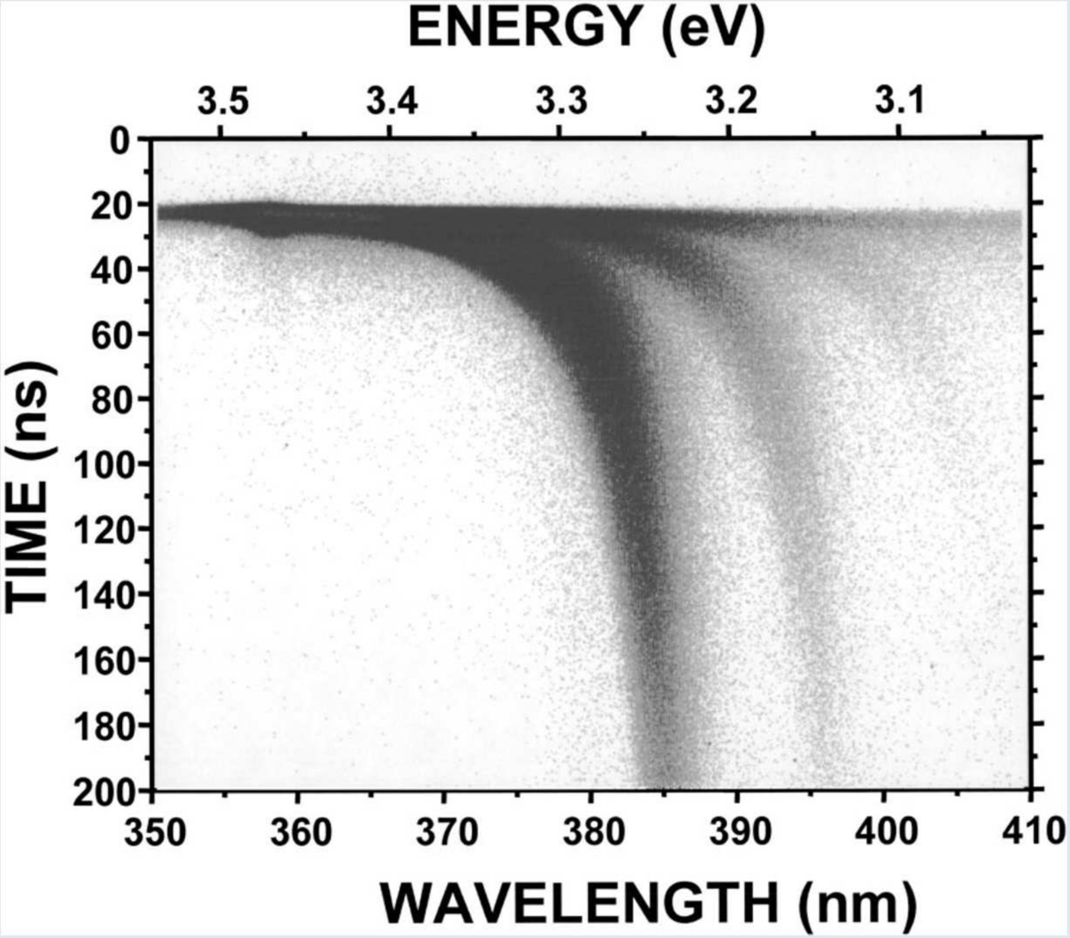
At « large » excitation density : screening of the QCSE



=> Extremely long lifetimes

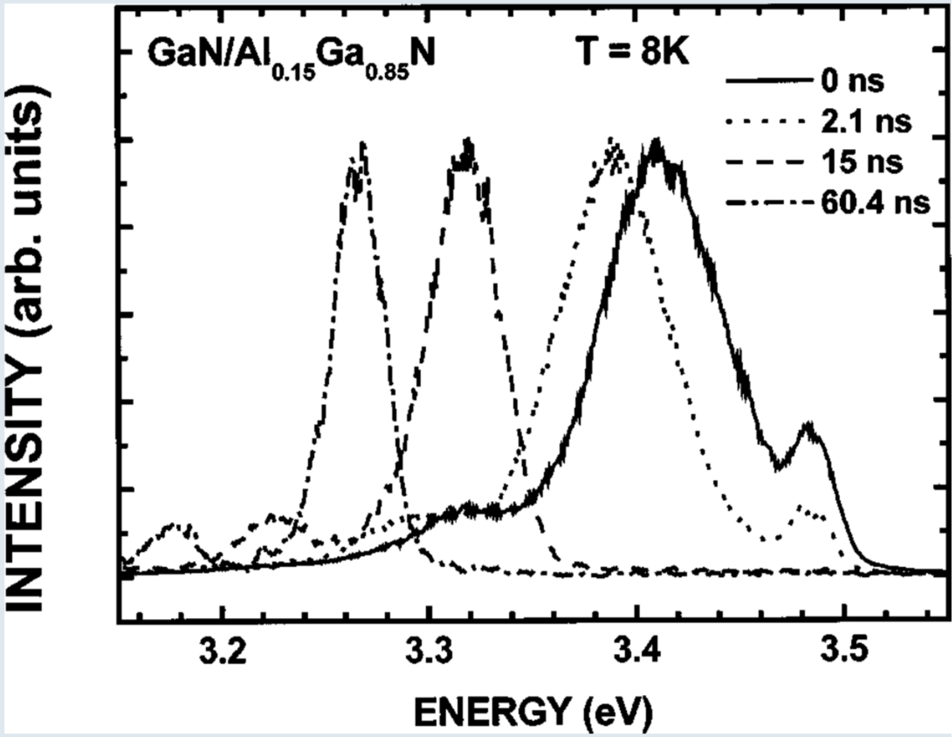
Bretagnon *et al.*, PRB **73**, 113304 (2006)

III-N quantum wells and the QCSE



Importance of the streak camera

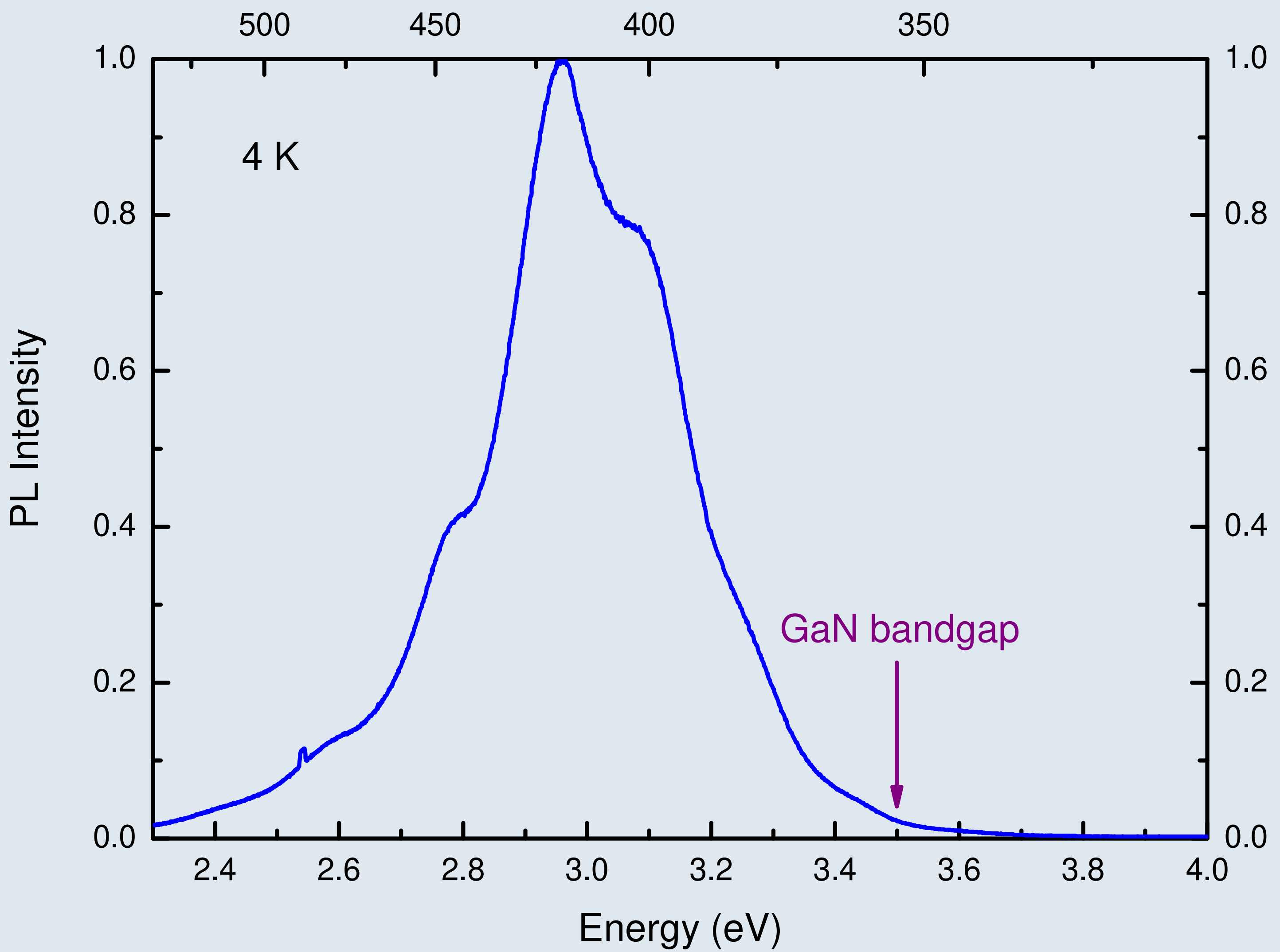
Beware of data interpretation!



Lefebvre *et al.* PRB **69** 035307 (2004)

III-N quantum wells and the QCSE

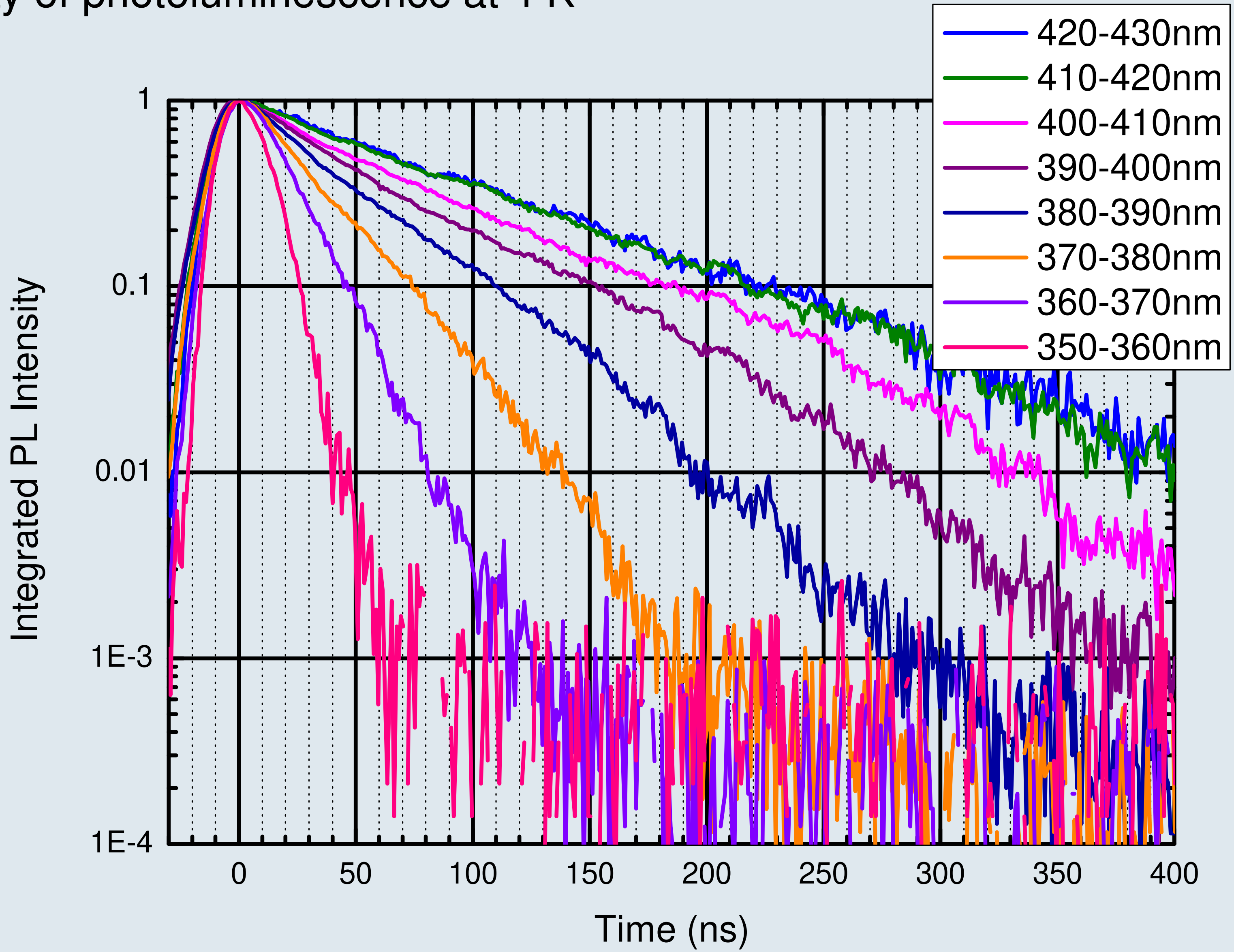
Inhomogeneously broadened GaN/AlN QDs



III-N quantum wells and the QCSE

Inhomogeneously broadened GaN/AlN QDs

Decay of photoluminescence at 4 K



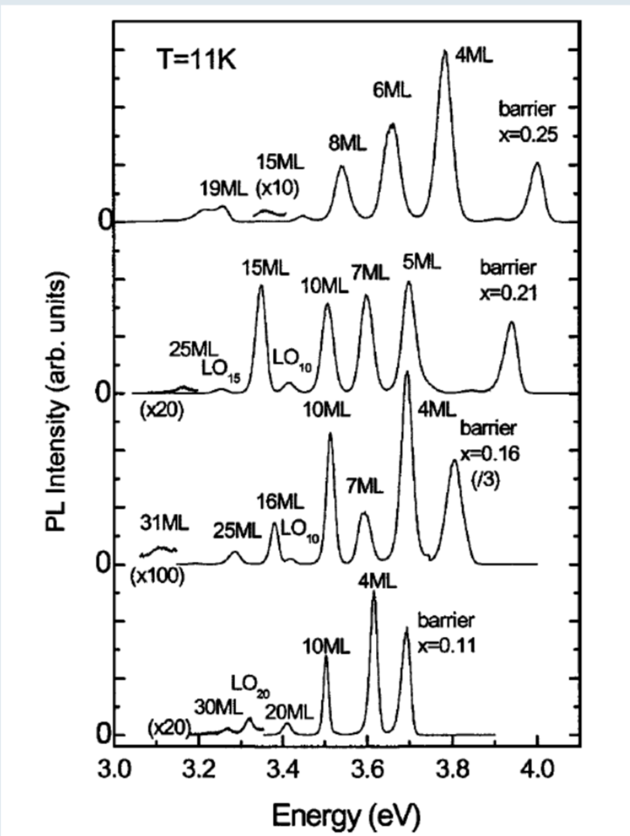
Quantum wells, GaN/AlGaN QWs

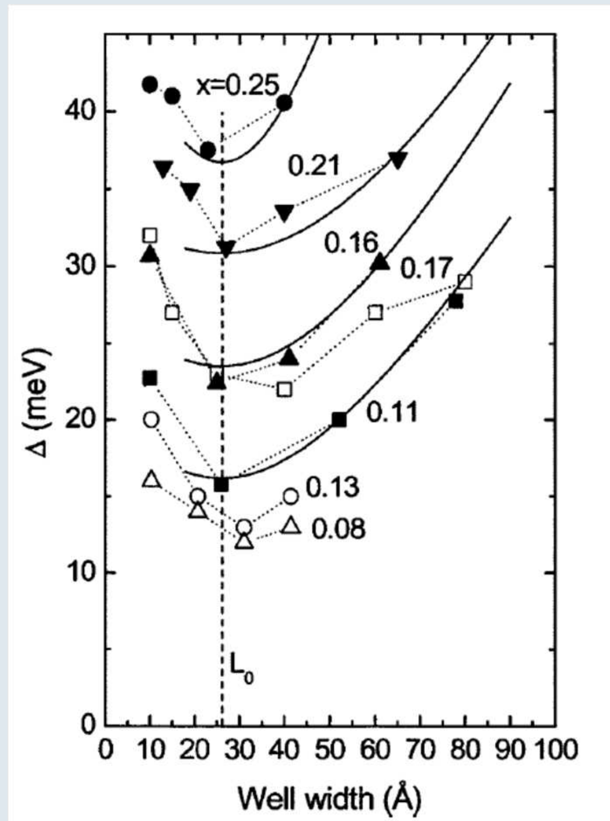
PHYSICAL REVIEW B **71**, 075311 (2005)

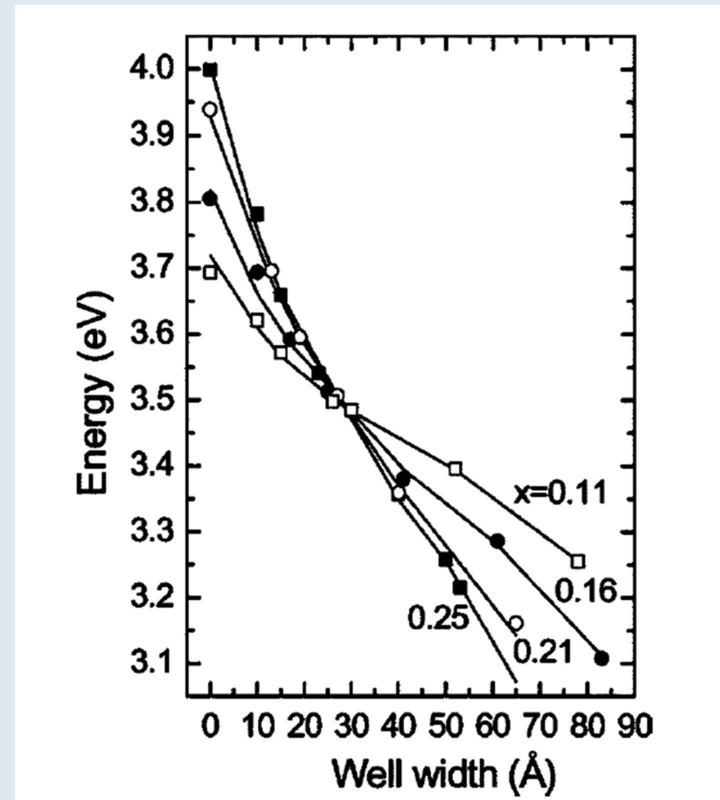
Inhomogeneous broadening of $Al_xGa_{1-x}N$/GaN quantum wells

F. Natali, D. Byrne, M. Leroux, B. Damilano, F. Semond, A. Le Louarn, S. Vezian, N. Grandjean, and J. Massies
Centre de Recherche sur l'Hétéro-Epitaxie et ses Applications–CNRS, Rue Bernard Grégory, 06560 Valbonne, France

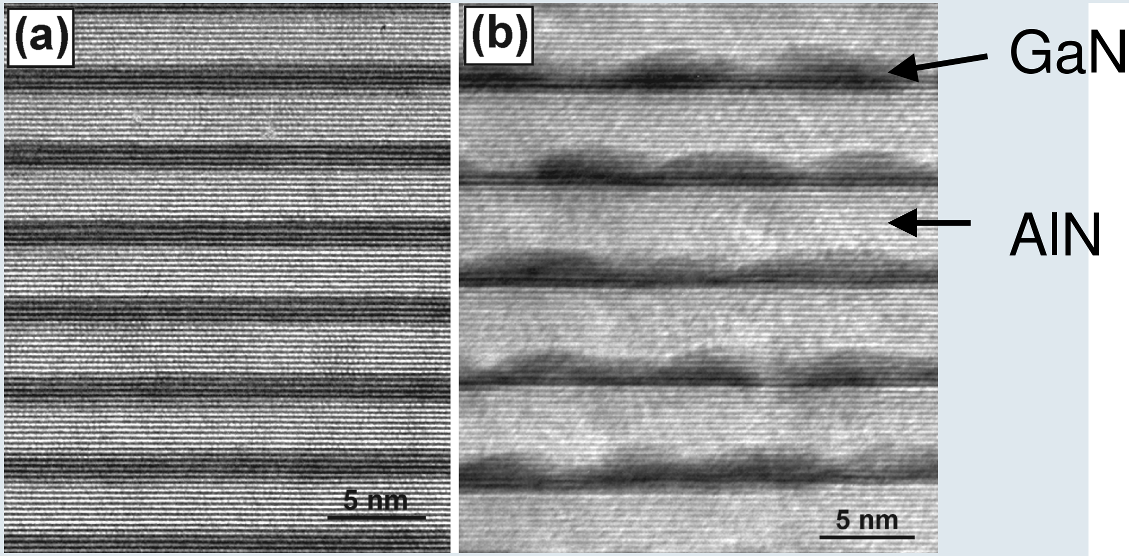
(Received 17 November 2003; revised manuscript received 10 September 2004; published 15 February 2005)

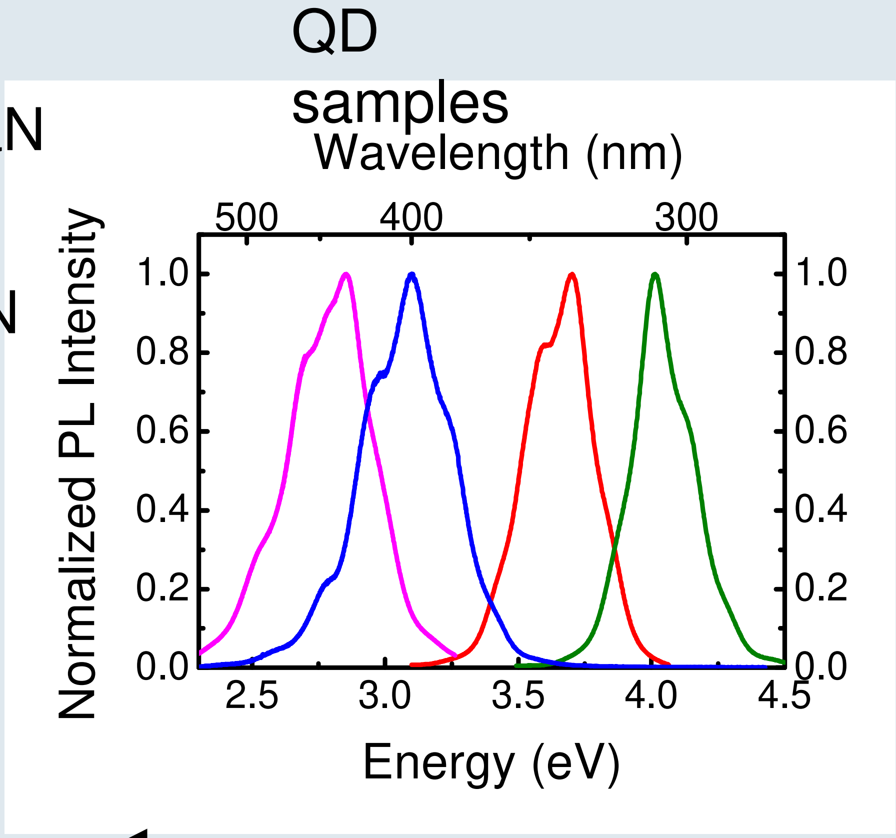






QDs vs QWs



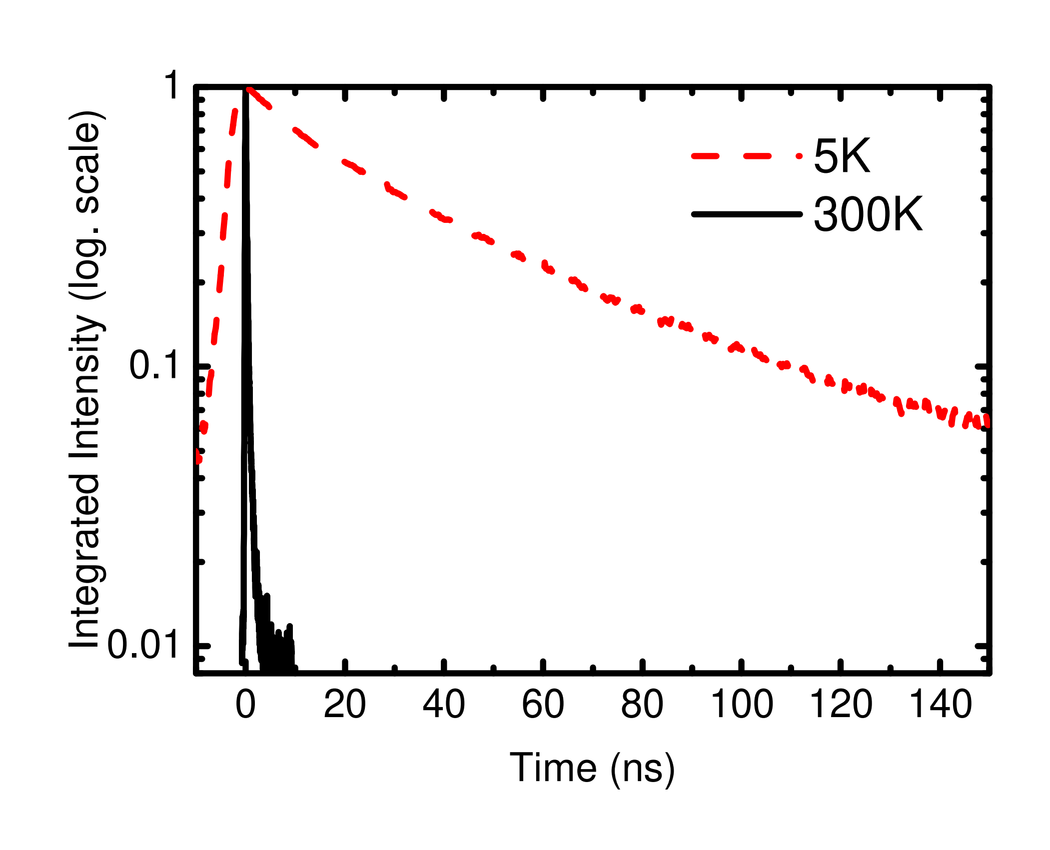


Increasing thickness (1-3 nm)

Large range of energy → large range of decay times (0.3 - 500 ns)

QDs vs QWs

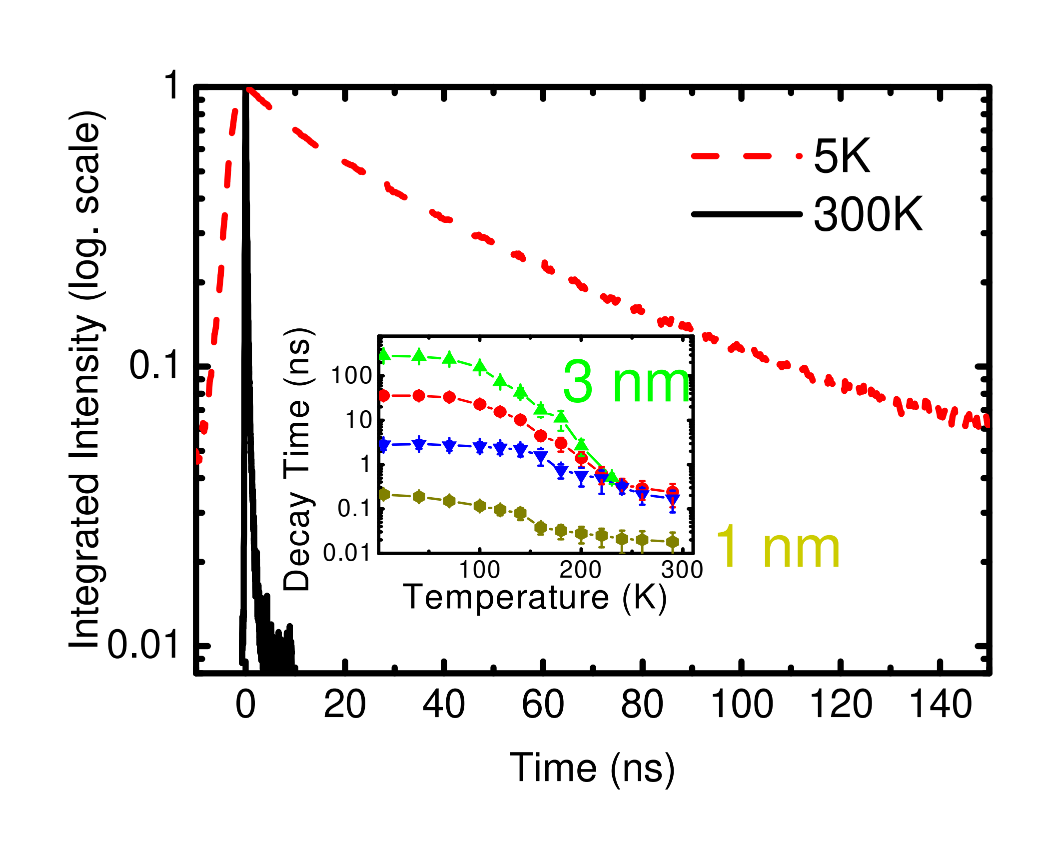
Quantum wells



QWs: strong decrease of the decay time → non radiative processes

QDs vs QWs

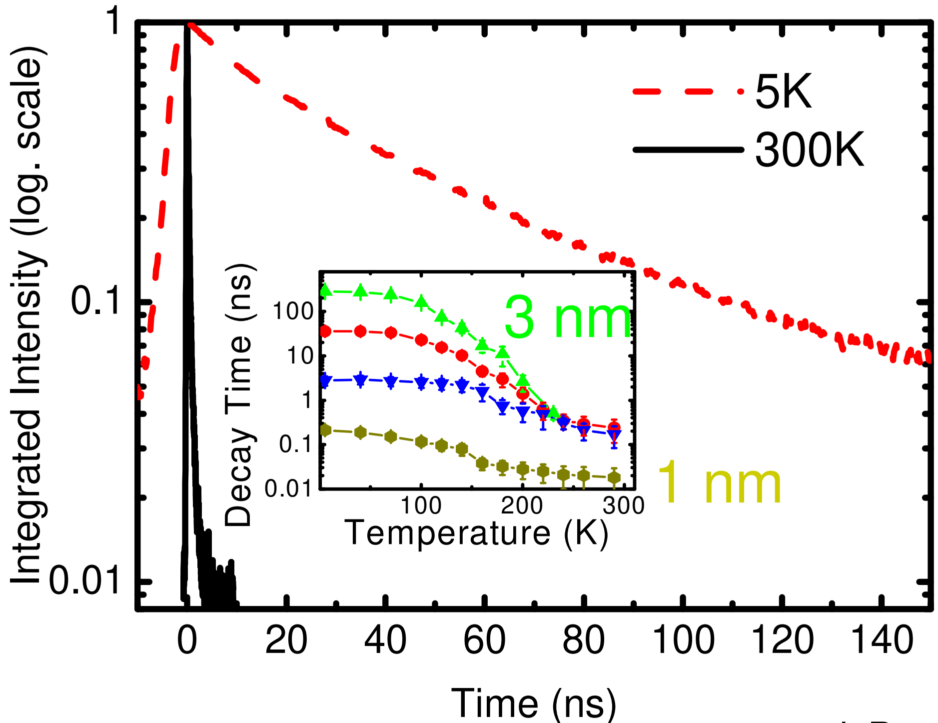
Quantum wells (1-3 nm)



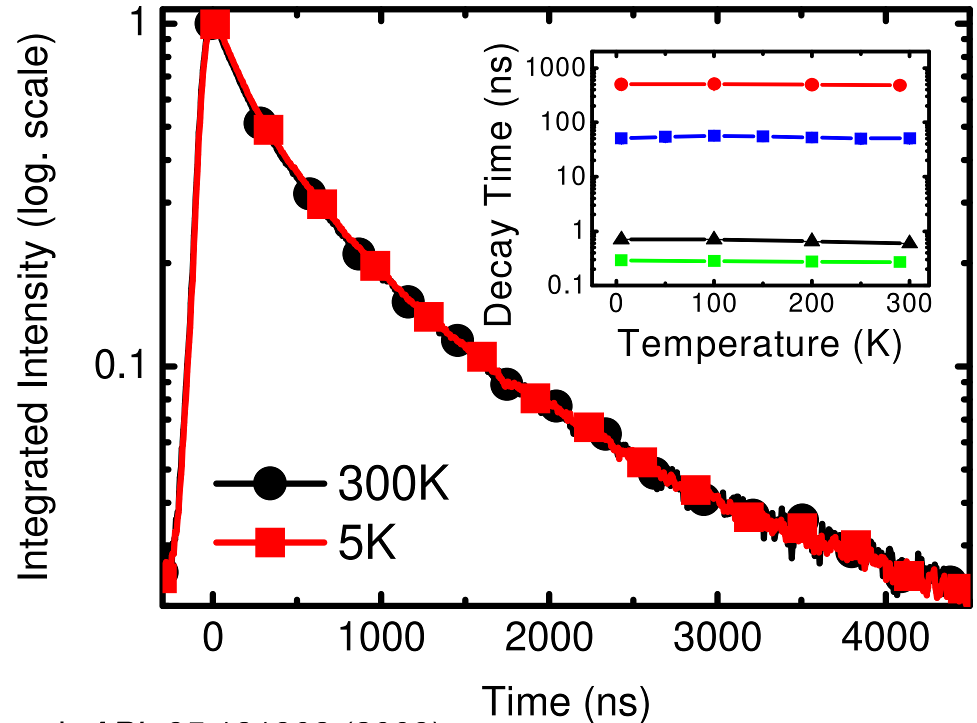
QWs: strong decrease of the decay time → non radiative processes

TRPL STUDY

Quantum wells (1-3 nm)



Quantum dots (3-5 MLs)



J. Renard et al. *APL* ***95*** *131903 (2009)*

QWs: strong decrease of the decay time → non radiative processes

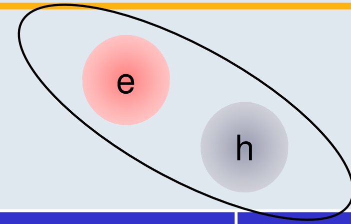
QDs**: constant decay time→ **negligible non radiative processes

Absence of thermal escape

Thermally activated !

Low radiative emission rate does not imply low efficiency !!!

The super exciton in GaN : it is useful?



	a (nm)	E_X (meV)
GaN	2.8	25
GaAs	12	4.8

kT @ 300K
25 meV

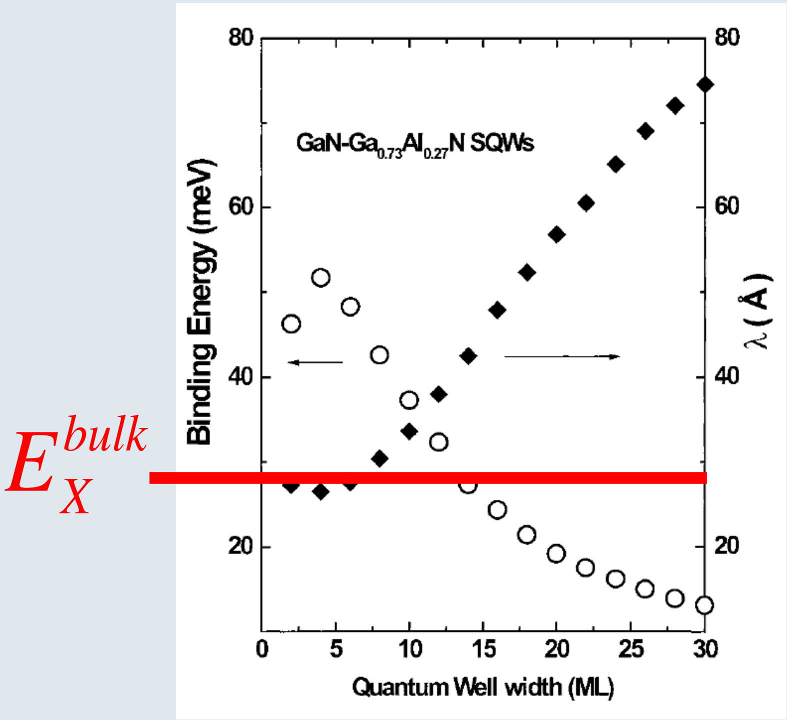
Why is it important ?
Is it useful ?

⇒ The binding energy of excitons in QW is up to 4 times larger than in bulk

M. Shinada and S. Sugano, J. Phys. Soc. Jpn. **21** 1936 (1966)

The super exciton in GaN : it is useful?

The QCSE reduces the exciton binding energy…



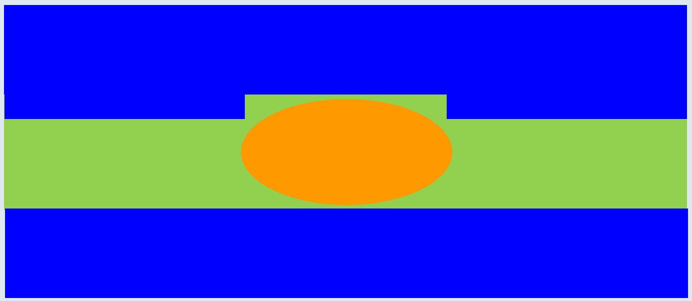
P. Bigenwald *et al.*, Phys. Stat. Sol. (b) **216** 371 (1999)

… but in thin QWs or non-polar QWs, the exciton binding energy can be large!

Excitonic effects in QWs

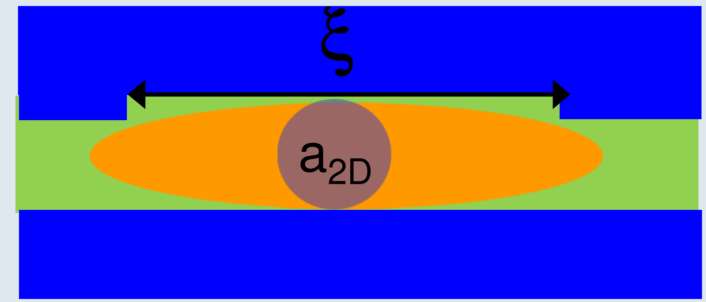
Do we get fast emission from a strong QW exciton?

$$\tau_{rad} \propto \frac{1}{nE^2 f}$$



Strong confinement

$$f = \frac{E_p}{E}$$



Lateral weak confinement

$$\psi_X(r_e, r_h) \propto f(z_e)\, g(z_h)\, e^{-r/a_{2D}}\, e^{-R_p^2/2\xi^2}$$

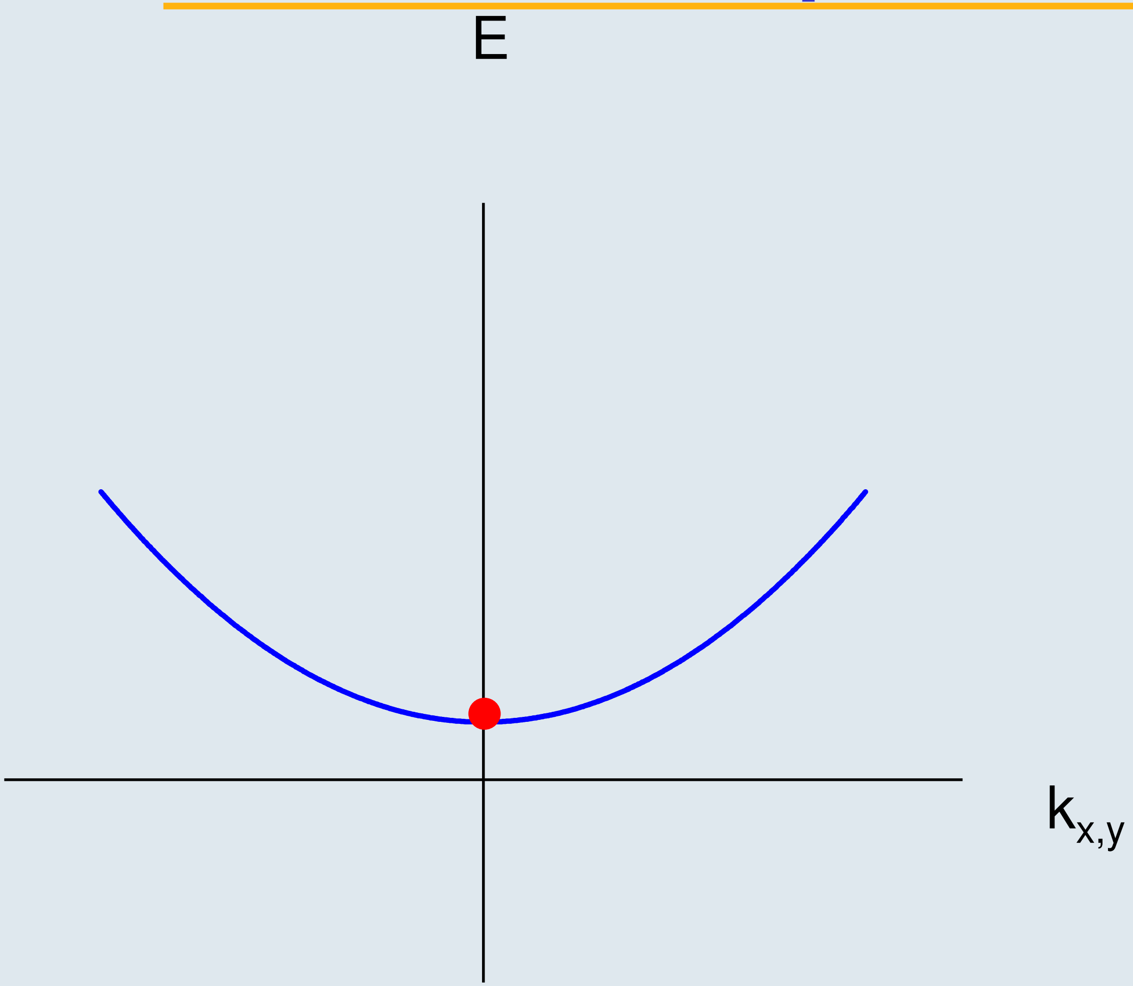
$$f = \frac{8E_p}{E}\left(\frac{\xi}{a_{2D}}\right)^2$$

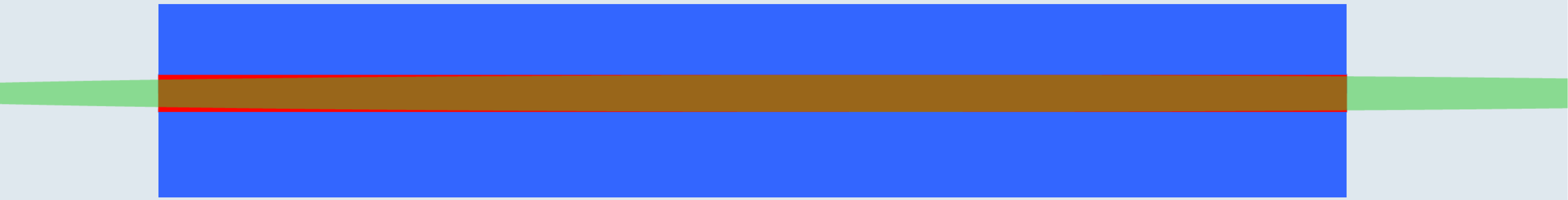
$\Rightarrow$ Giant oscillator strength

A. V. Kavokin, Phys. Rev. B, **50**, 8000 (1994).
L. C. Andreani *et al.*, Phys. Rev. B **60** 13276 (1999).

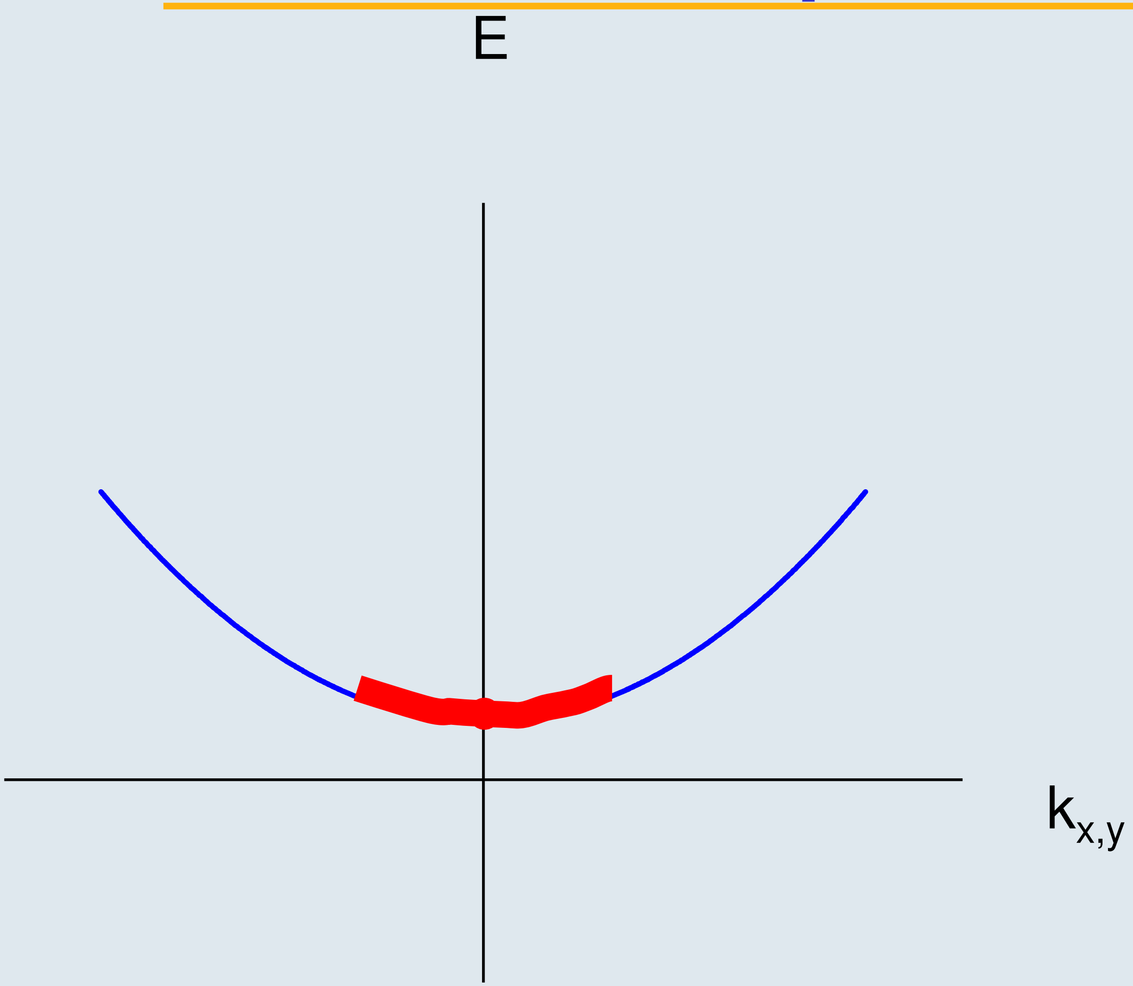
Robert C. Hilborn, "Einstein coefficients, cross sections, f values, dipole moments, and all that"
http://arxiv.org/ftp/physics/papers/0202/0202029.pdf

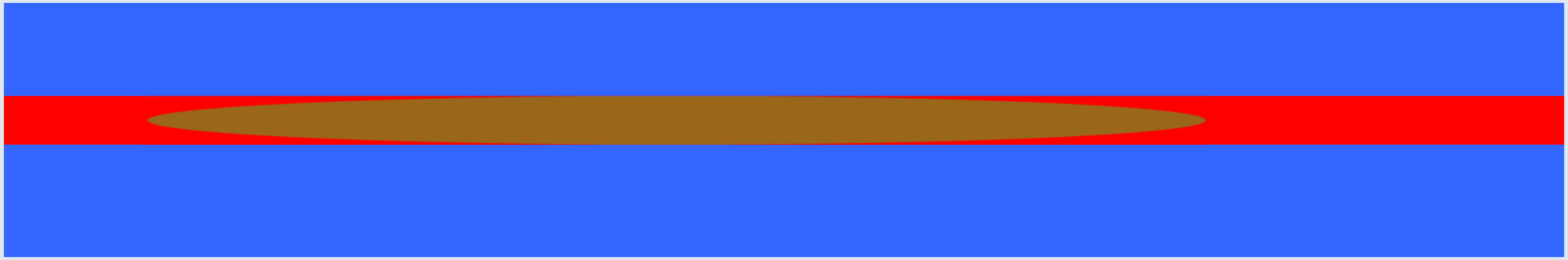
Localization in k-space and real space



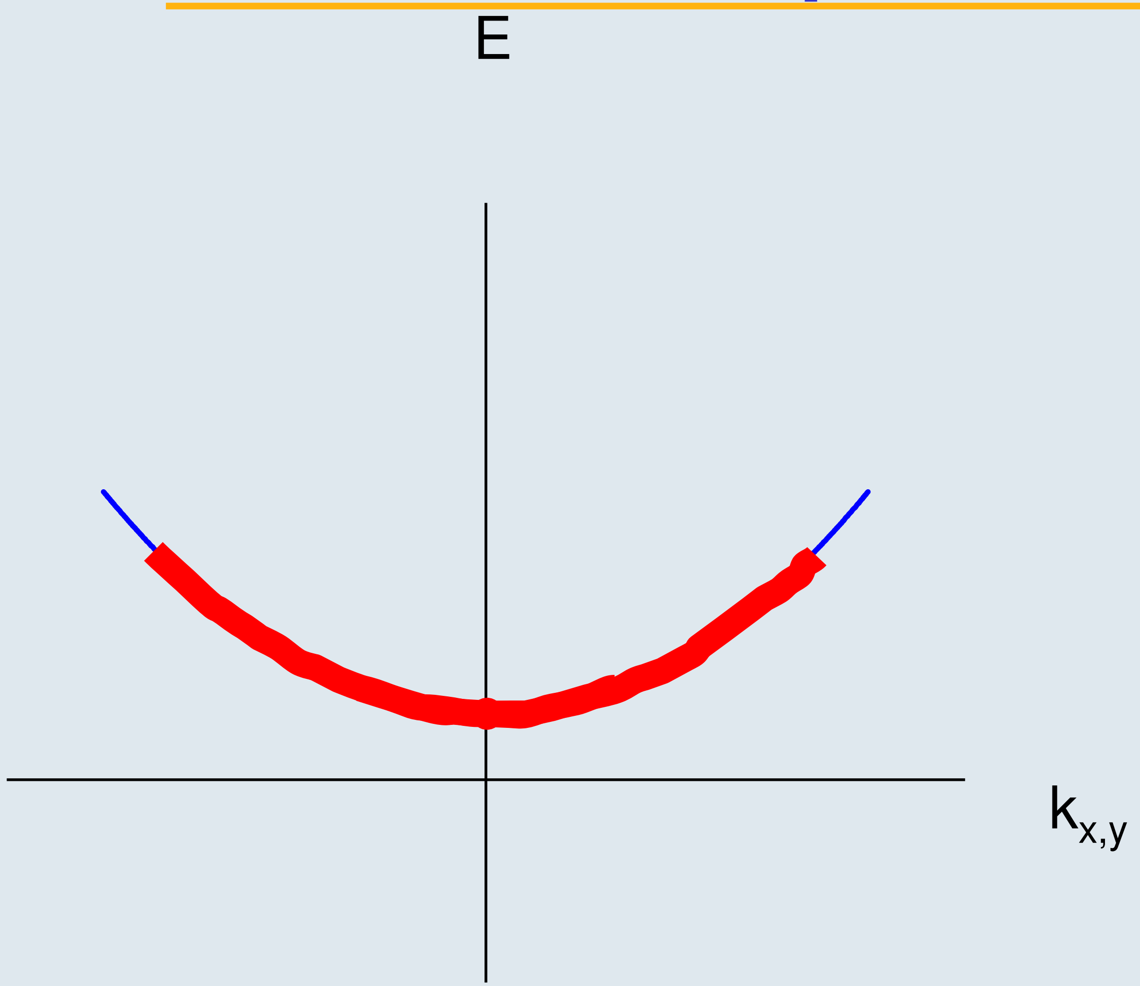


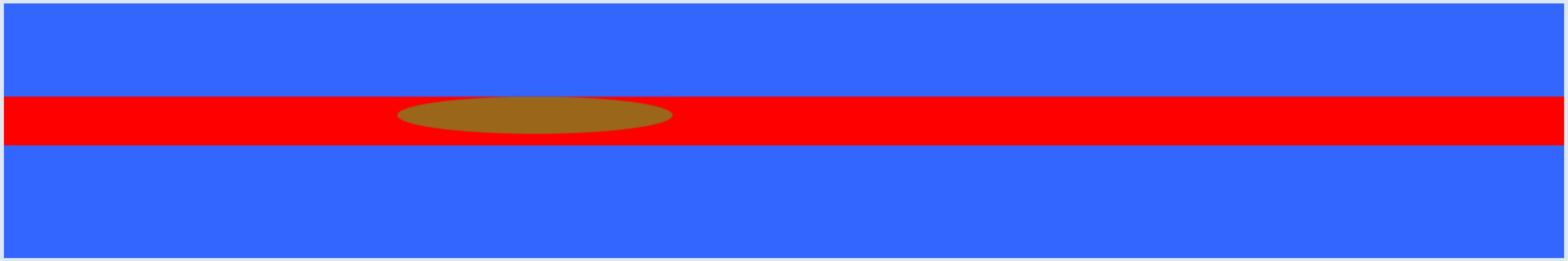
Localization in k-space and real space





Localization in k-space and real space





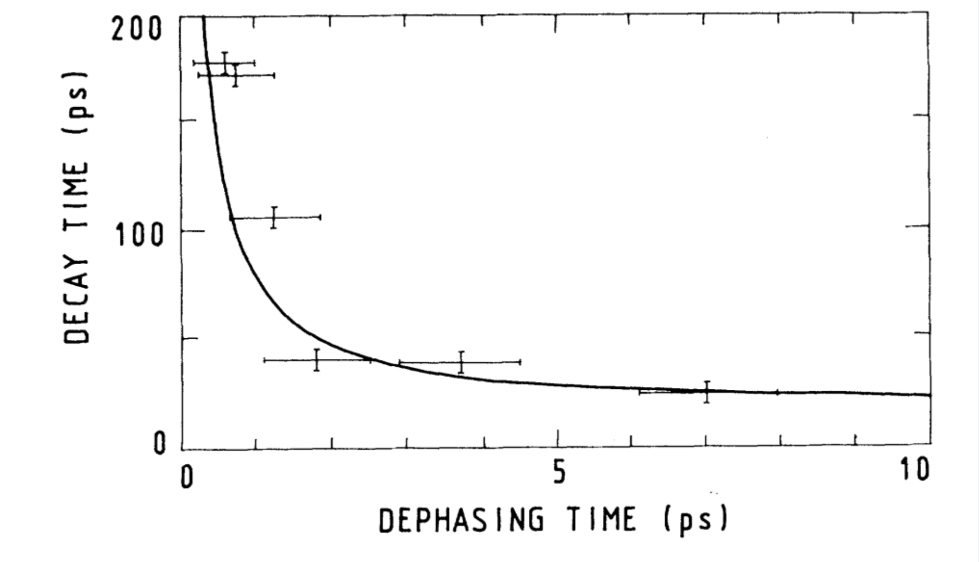
Excitonic effects in QWs

2D limit = intrinsic lifetime of two-dimensional exciton

~ 10 ps for a GaAs/AlAs QW

L. C. Andreani *et al.*, Solid State Commun. **77** 641 (1991)
B. Deveaud *et al.*, Phys. Rev. Lett. **67** 2355 (1991)

Dephasing (exciton-exciton or exciton-phonon scattering) limits the coherence surface and hence the radiative emission rate



Excitonic effects in QWs

The 2D quantum well excitons does couple efficiently to photons!

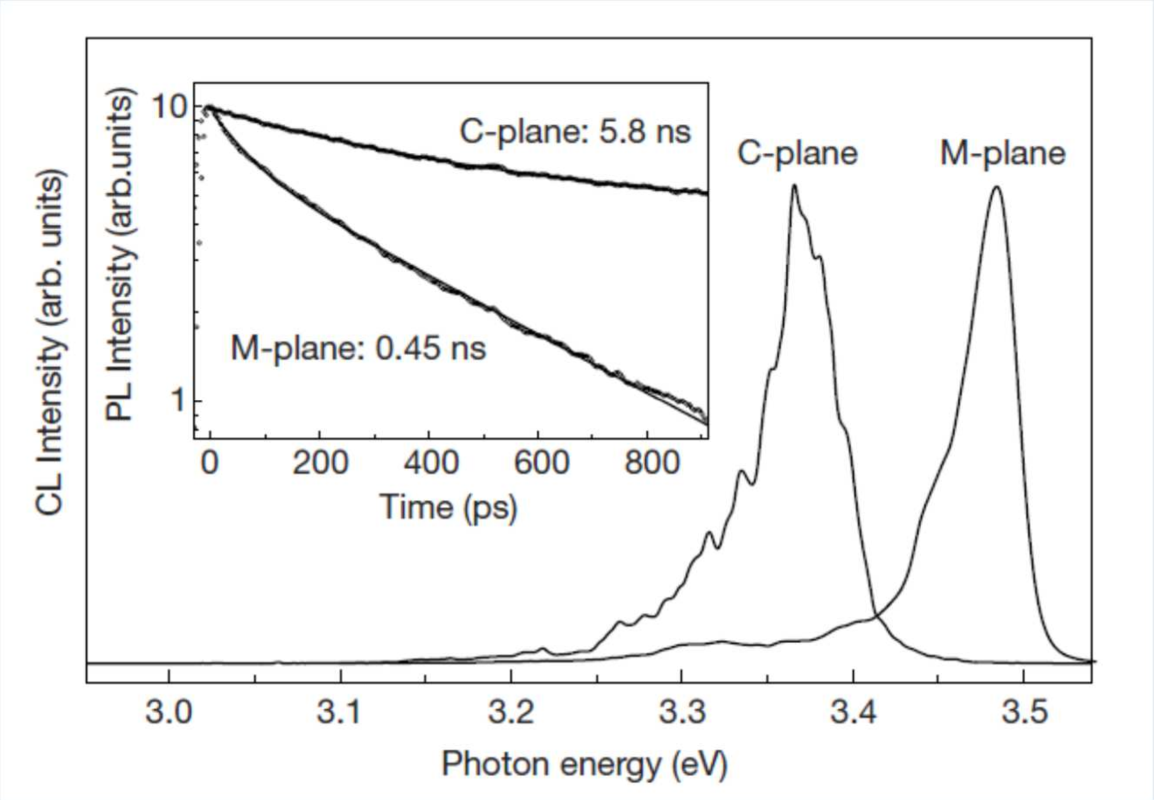
In a non perfect structure, the fundamental emitting states will be laterally localized states

Even in a very good (i.e. III-As) quantum well, it takes very peculiar experimental conditions to observe the intrinsic fast lifetimes of 2D excitons

- *Very low temperature (phonon scattering)*
- *Resonant and low excitation (carrier-carrier scattering)*

Excitonic effects in GaN QWs

Non-Polar QWs

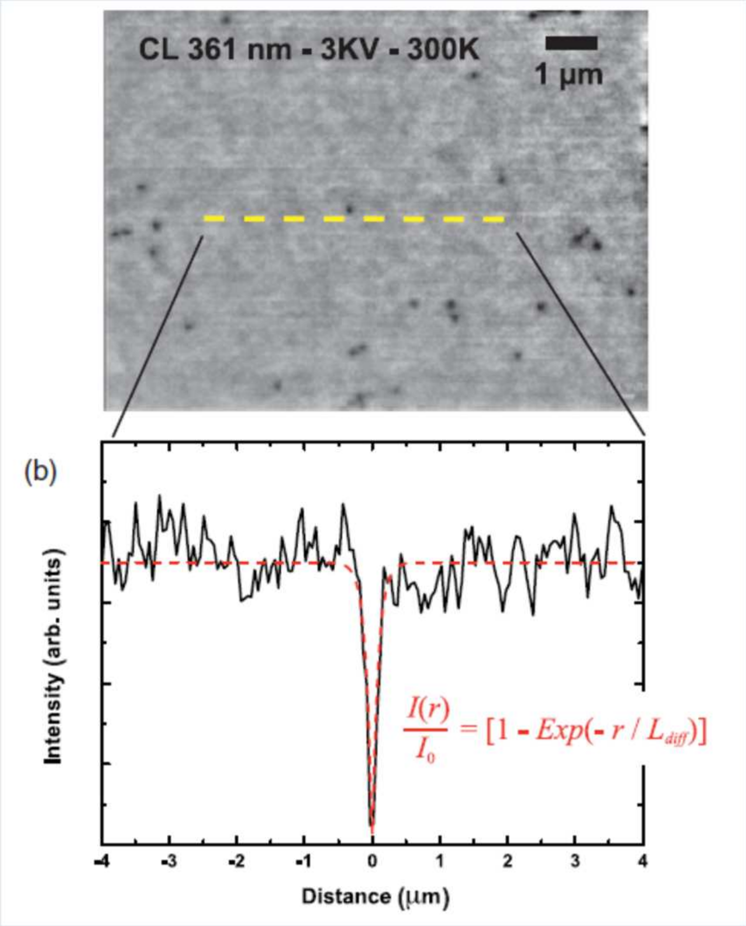


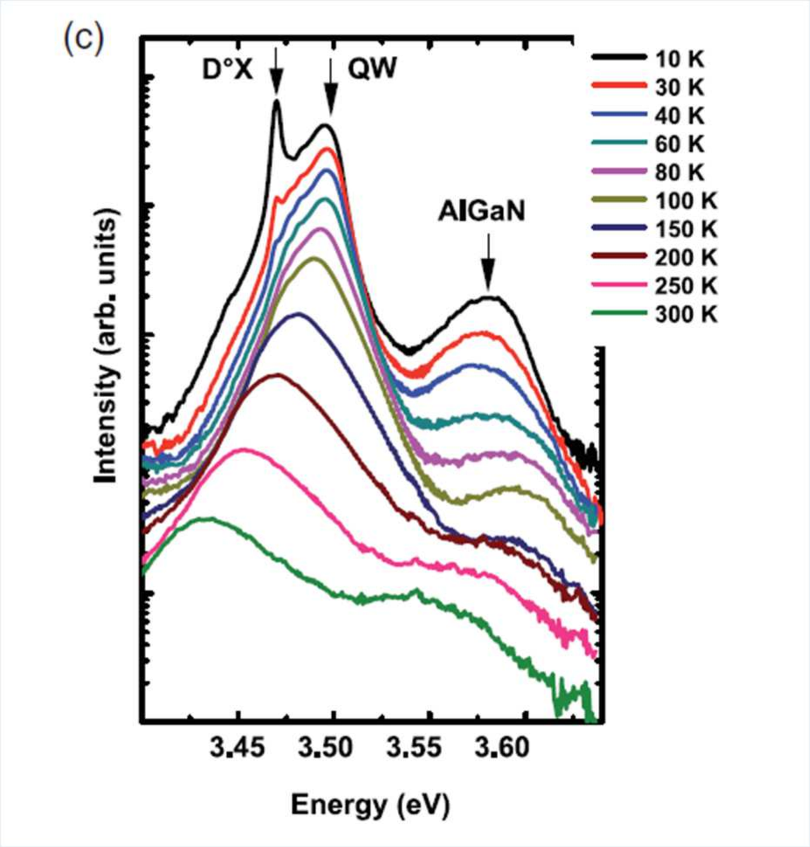
P. Waltereit *et al.*, Nature, **406** 865 (2000)

Excitonic effects in GaN QWs

Non-Polar QWs

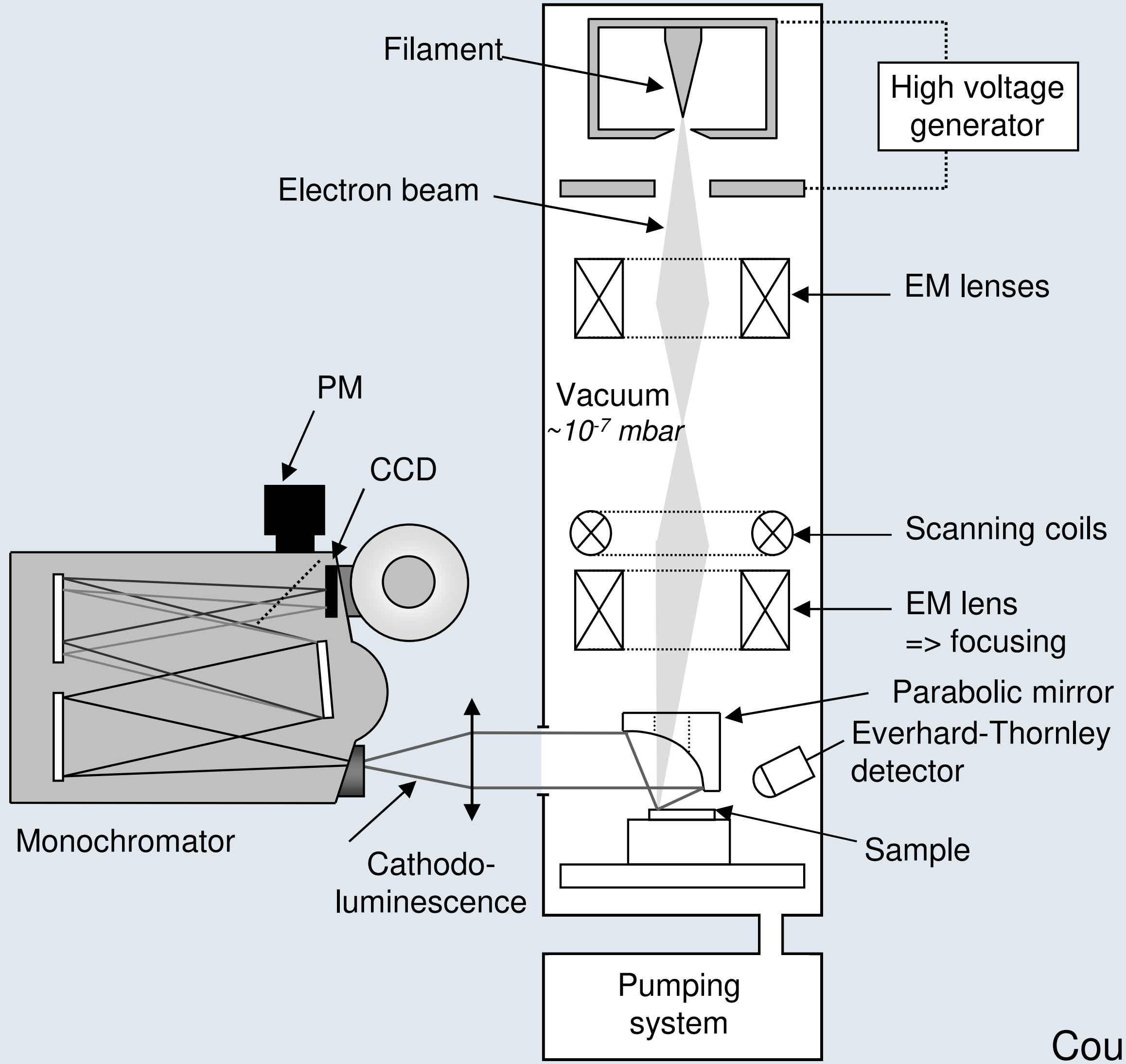
GaN/$Al_{0.06}Ga_{0.94}N$ QWs





P. Corfdir *et al.*, Phys. Rev. B **83** 245326 (2011)

Experimental technique : cathodoluminescence



Courtesy F. Rol, PhD thesis 2007

Experimental technique : cathodoluminescence

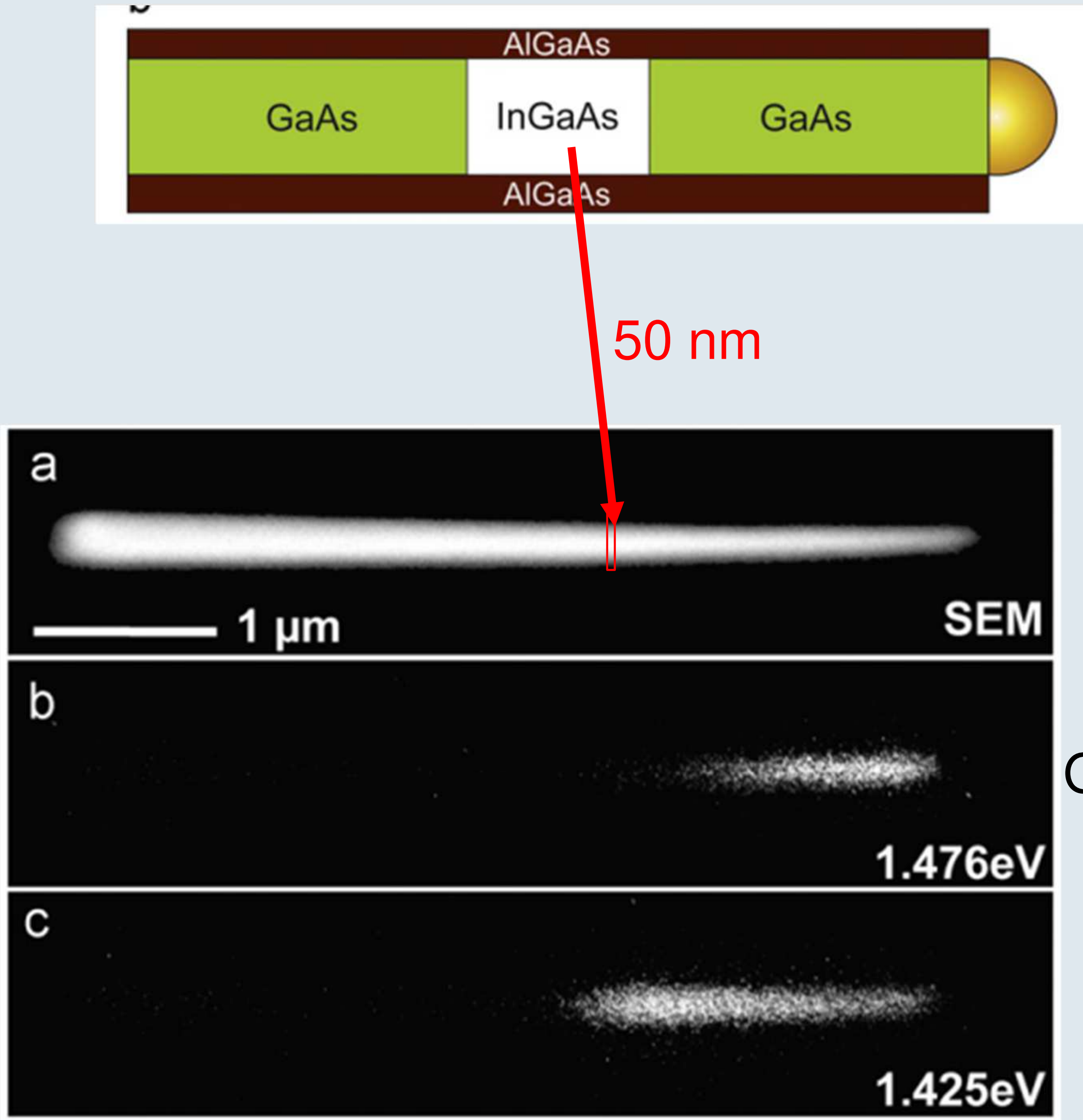
Advantages of CL :

- Excites any semiconductor (including large gap)
- High spatial resolution
- Easy scanning of sample

Limitations of CL :

- Requires a conducting substrate
- Messy excitation (lots of hot carriers created)
- Low collection efficiency

Cathodoluminescence ≠ imaging technique !



GaAs luminescence

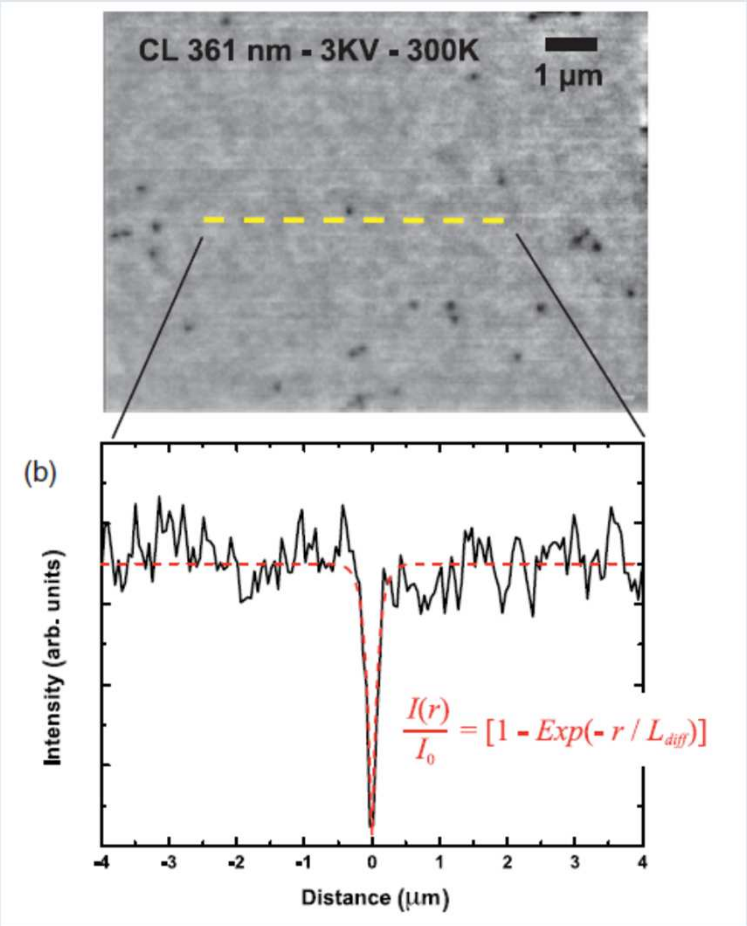
InGaAs luminescence

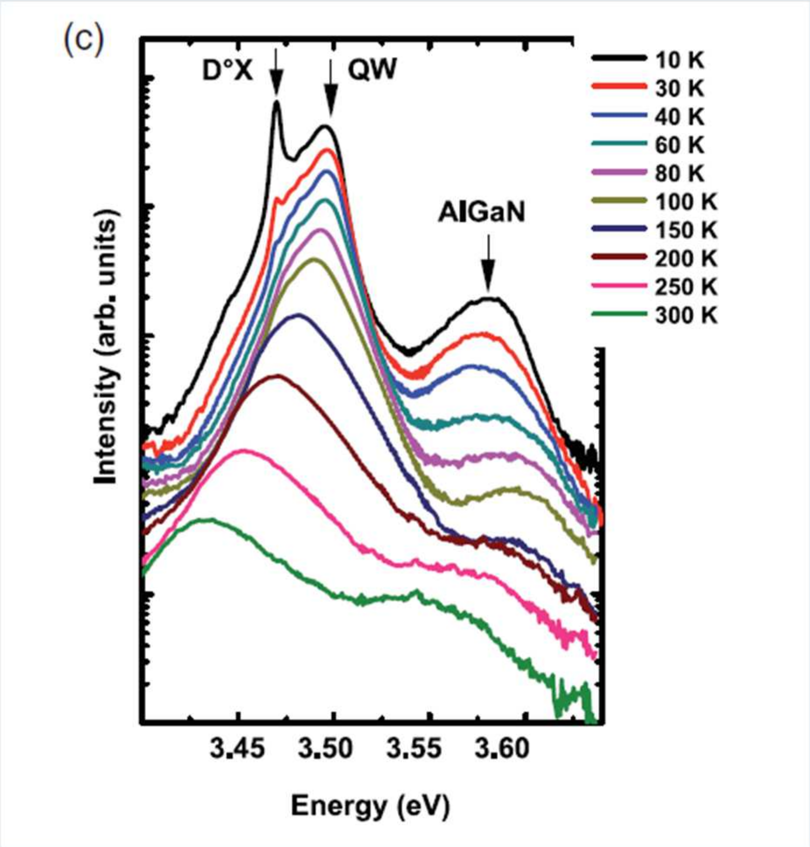
J. Bolinsson *et al. J. Cryst Growth* **315** 138 (2011)

Excitonic effects in GaN QWs

Non-Polar QWs

GaN/$Al_{0.06}Ga_{0.94}N$ QWs
grown on bulk GaN





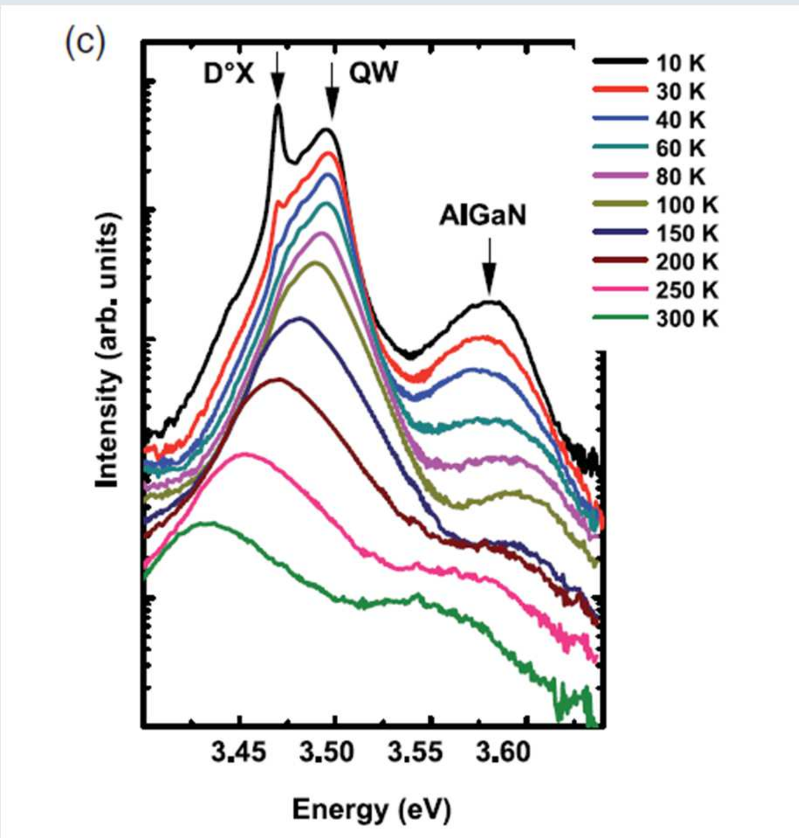
~100 nm in-plane diffusion length

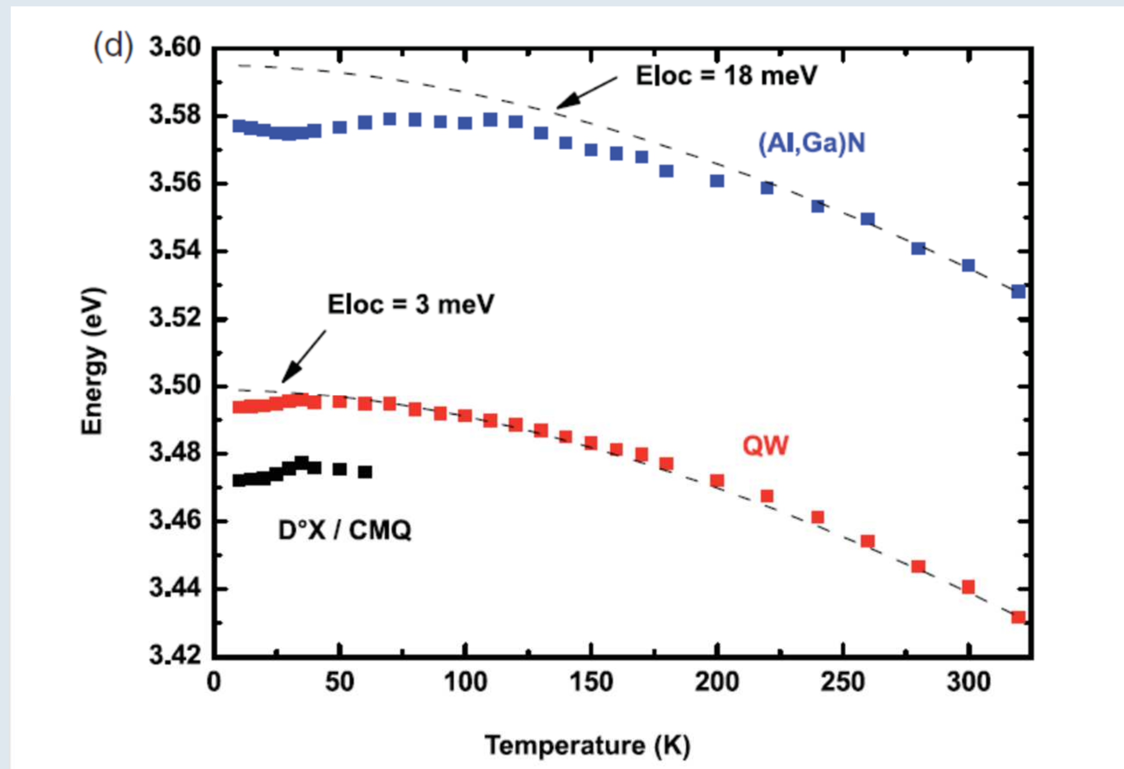
P. Corfdir *et al.*, Phys. Rev. B **83** 245326 (2011)

Excitonic effects in GaN QWs

Non-Polar QWs

$GaN/Al_{0.06}Ga_{0.94}N$ QWs





P. Corfdir *et al.*, Phys. Rev. B **83** 245326 (2011)

Temperature dependence of GaN bandgap

…. beyond the Varshni empirical law

phys. stat. sol. (b) **200**, 155 (1997)

Subject classification: 71.20.Nr; S5.11, S5.12, S7.12, S7.14, S8.11, S8.12

Basic Model Relations for Temperature Dependencies of Fundamental Energy Gaps in Semiconductors

R. Pässler [1])

Institut für Physik, Technische Universität Chemnitz–Zwickau, D-09107 Chemnitz, Germany

JOURNAL OF APPLIED PHYSICS VOLUME 90, NUMBER 8 15 OCTOBER 2001

Dispersion-related assessments of temperature dependences for the fundamental band gap of hexagonal GaN

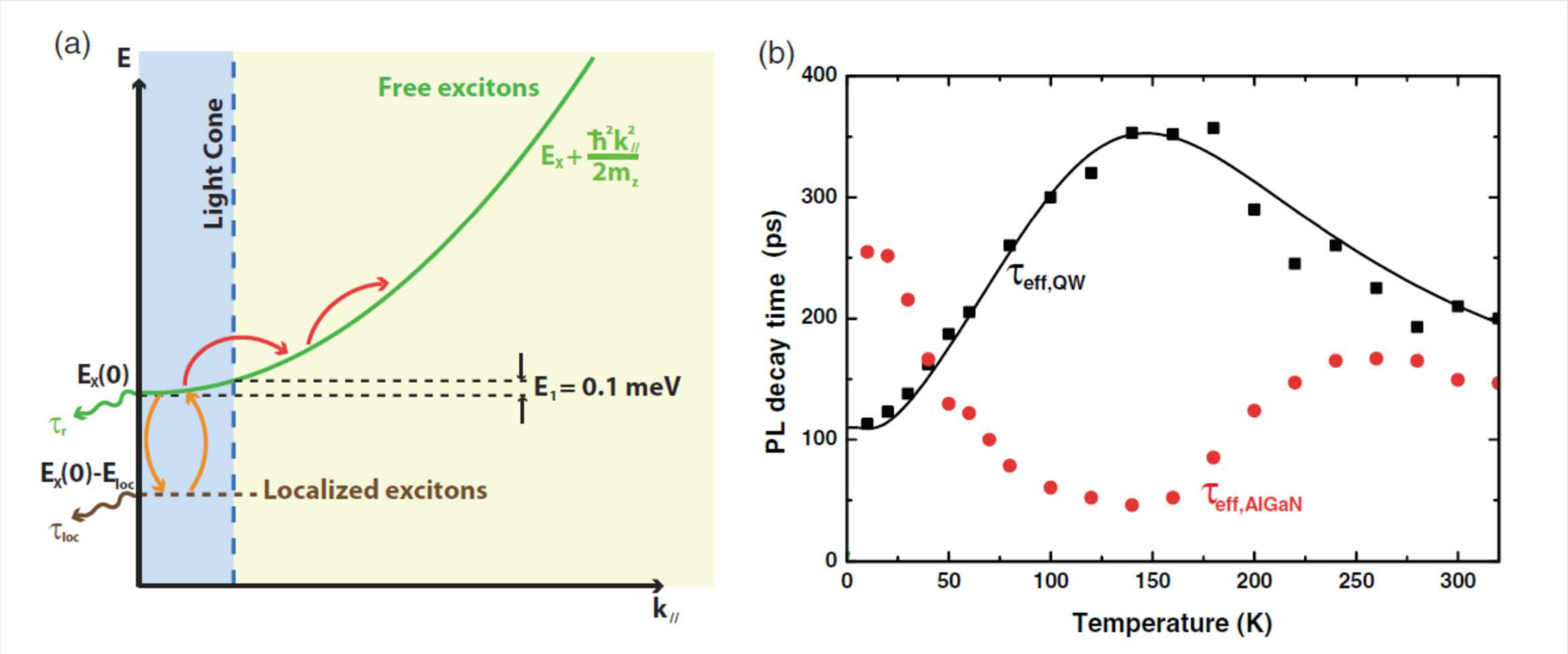
R. Pässler[a)]

Technische Universität Chemnitz, Institut für Physik, D-09107 Chemnitz, Germany

+ other references by R. Pässler

Excitonic effects in GaN QWs

Non-Polar QWs



P. Corfdir *et al.*, Phys. Rev. B **83** 245326 (2011)

Excitonic effects in GaN QWs

Is 100 ps @ 3.5 eV a fast recombination??

$$\tau_{rad} \propto \frac{1}{nE^2 f}$$

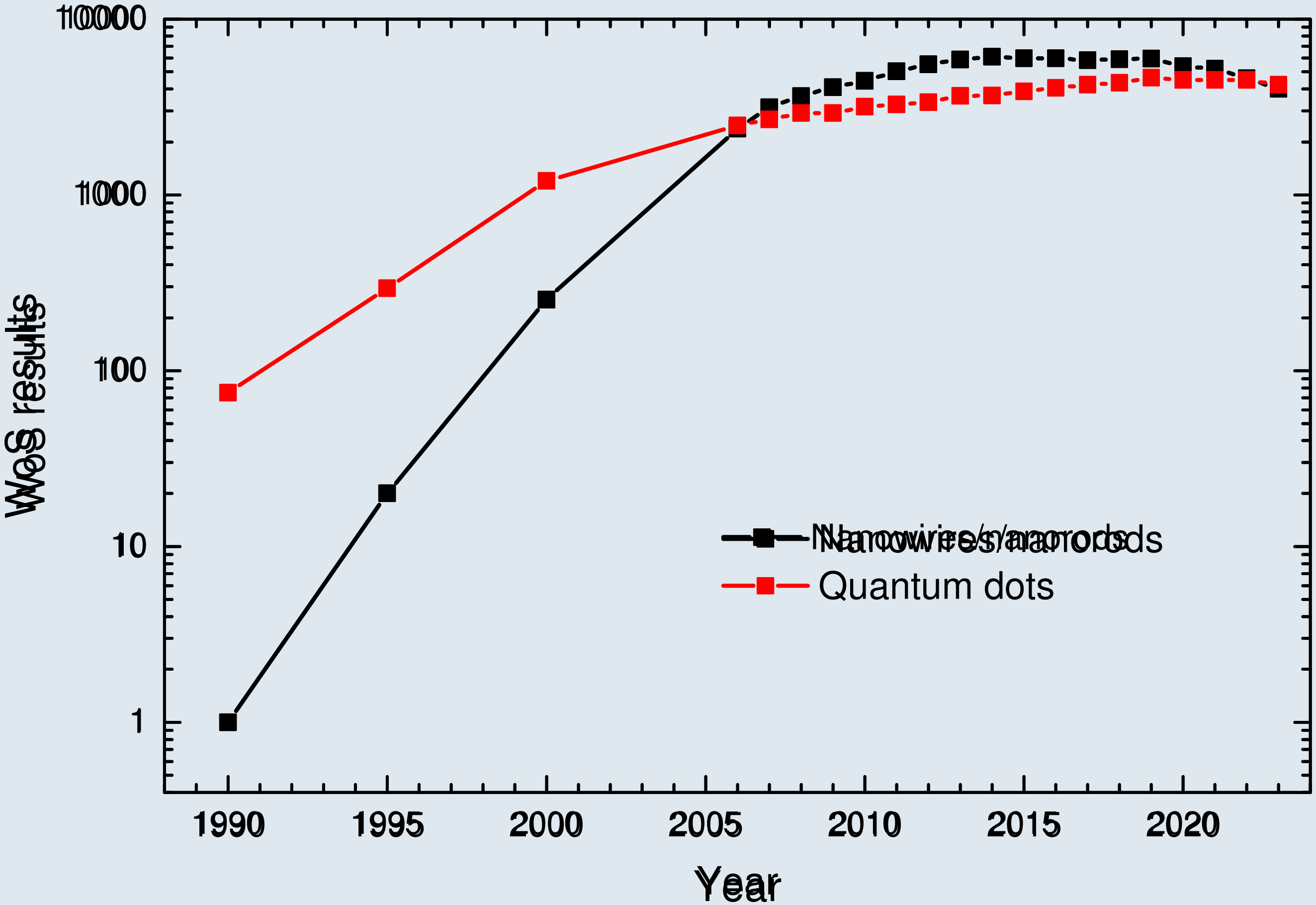
GaAs QW emitting at 1.7 eV with a lifetime of 25 ps : **f=320**

GaN QW emitting at 3.5 eV with a lifetime of 100 ps : **f=24**

⇒ Quite strong localization effects, no giant oscillator strength

⇒ Strong excitonic effects in III-N, but ordinary recombination rates

Context : Nanowires




OPINION

Fashions in Science and Technology

Rolf Landauer

Physics Today, 50(12), Dec. 1997, p. 62

Context : nitride nanowires

Jpn. J. Appl. Phys. Vol. 36 (1997) pp. L 459–L 462
Part 2, No. 4B, 15 April 1997

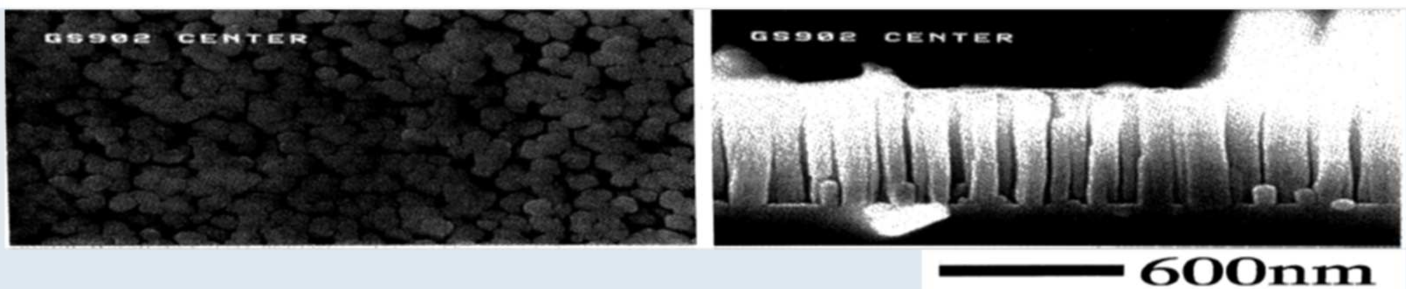
Growth of Self-Organized GaN Nanostructures on $Al_2O_3(0001)$ by RF-Radical Source Molecular Beam Epitaxy

Masaki YOSHIZAWA, Akihiko KIKUCHI, Masashi MORI, Nobuhiko FUJITA and Katsumi KISHINO
Department of Electrical and Electronics Engineering, Sophia University, 7-1 Kioi-cho, Chiyoda-ku, Tokyo 102, Japan

(Received July 18, 1996; accepted for publication February 28, 1997)

Columnar GaN nanostructures (GaN nanocolumns) were grown on $Al_2O_3(0001)$ by RF-radical source molecular beam epitaxy (RF-MBE) through a self-organization process. The nanocolumns were grown at high density, with the *c*-axis maintained perpendicular to the substrate surface. The dependence of column diameter and density on growth conditions was systematically investigated. The average diameter was minimized to 53 nm and the density of the GaN nanocolumns was 130×10^{12} columns per square meter.

KEYWORDS: self-organization, GaN, nanostructure, nanocolumn, $Al_2O_3(0001)$, RF-MBE



Context : nitride nanowires

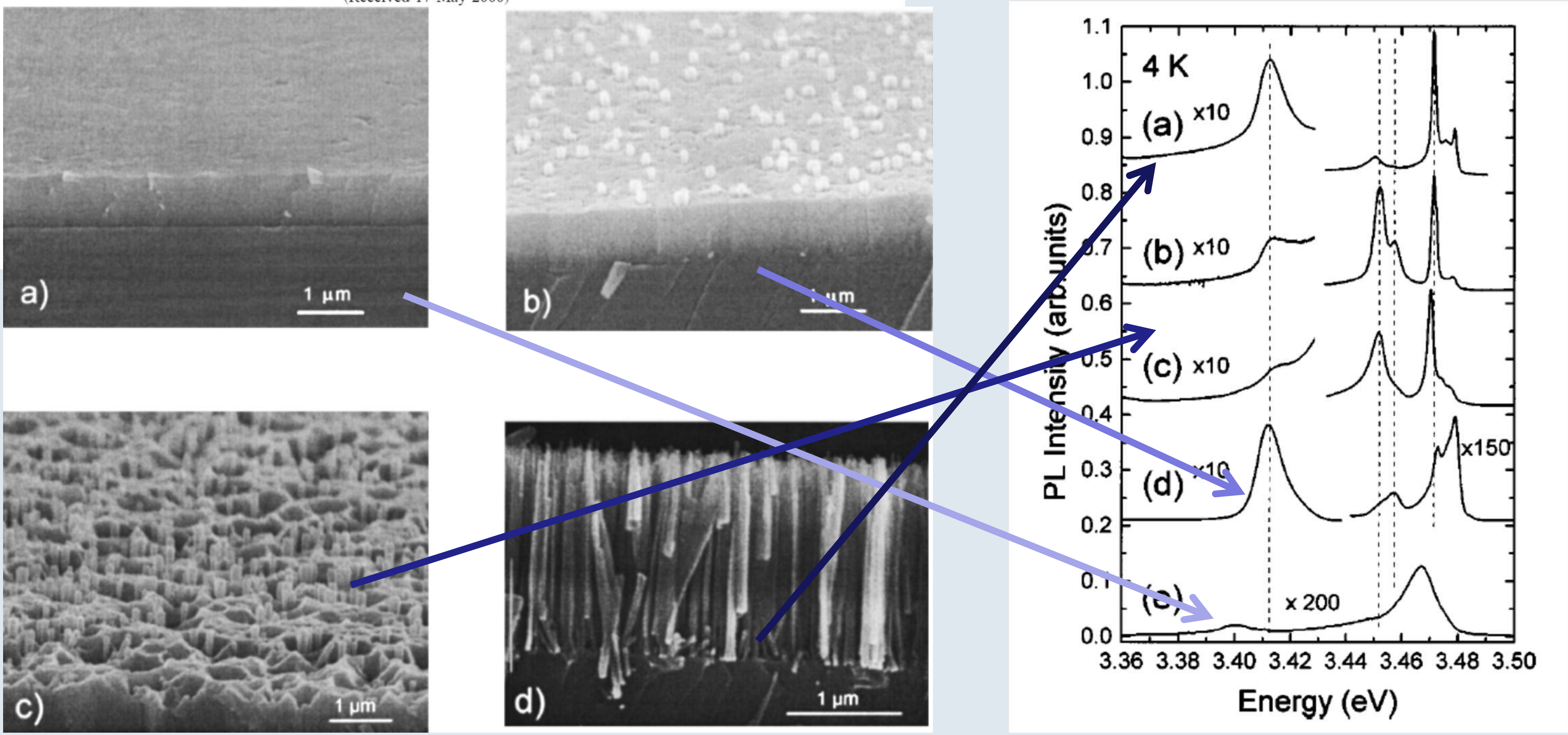
PHYSICAL REVIEW B VOLUME 62, NUMBER 24 15 DECEMBER 2000-II

Luminescence properties and defects in GaN nanocolumns grown by molecular beam epitaxy

E. Calleja, M. A. Sánchez-García, F. J. Sánchez, F. Calle, F. B. Naranjo, and E. Muñoz
Departamento Ingeniería Electrónica, ETSI Telecomunicación, Universidad Politécnica, 28040 Madrid, Spain

U. Jahn and K. Ploog
Paul Drude Institut für Festkörperelektronic, Hausvogteiplatz 5-7, D-10117 Berlin, Germany

(Received 17 May 2000)



GaN nanowires : fundamental studies

Can nanowires help answer fundamental questions about GaN?

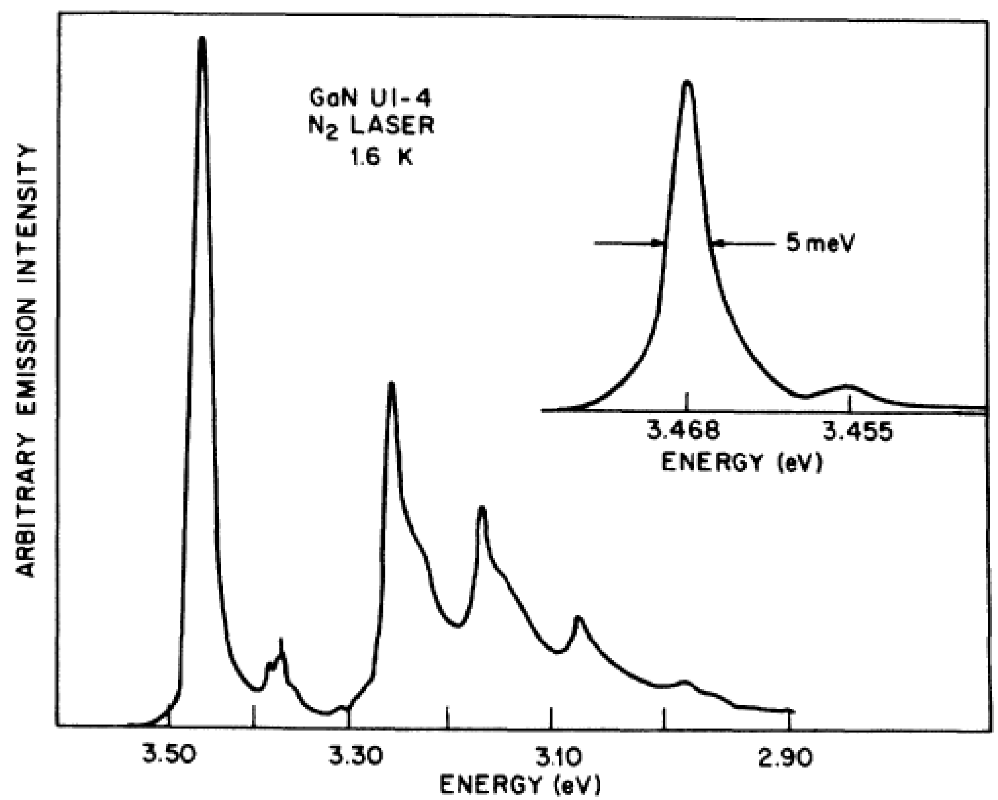
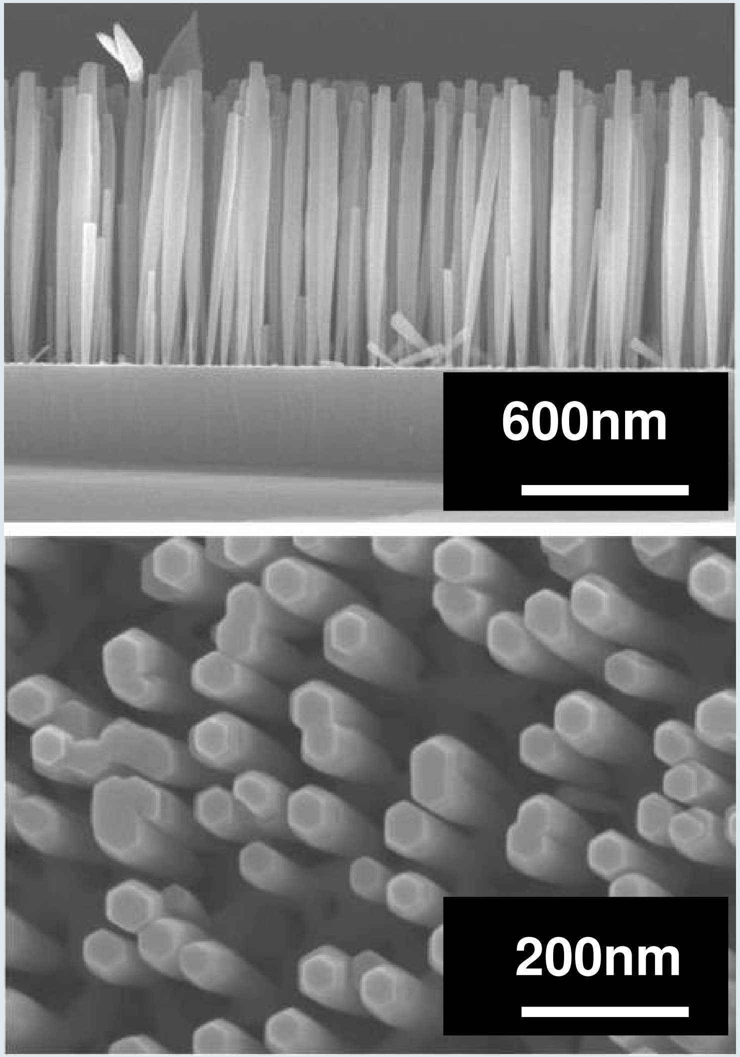


FIG. 5. Typical photoluminescence spectrum of type-I GaN at 1.6 K. The insert is a more detailed view of the strong high-energy peak near 3.468 eV, taken with low excitation intensity and high resolution.

R. Dingle *et al.*, Phys. Rev. B **4** 1211 (1971)

Fundamental properties of MBE grown GaN nanowires



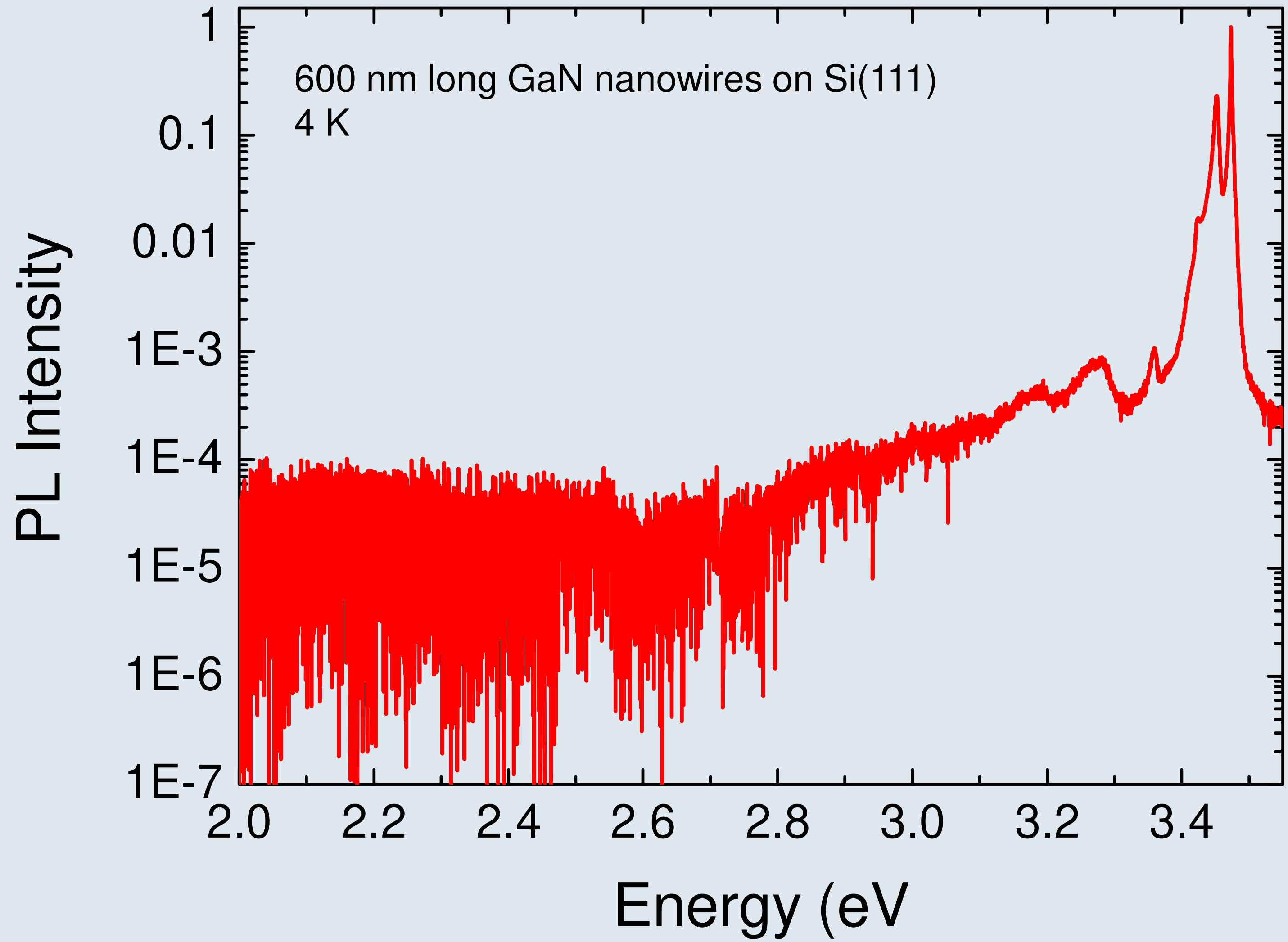
Plasma-assisted MBE
N-rich conditions
Si (111) substrate

M.A. Sanchez-Garcia *et al.*, J. Crystal Growth **183** 23 (1998)

Density : 10^{10} cm^{-2}
Diameter : ~40 nm

MBE growth: R. Songmuang *et al.* APL **91**, 251902 (2007)

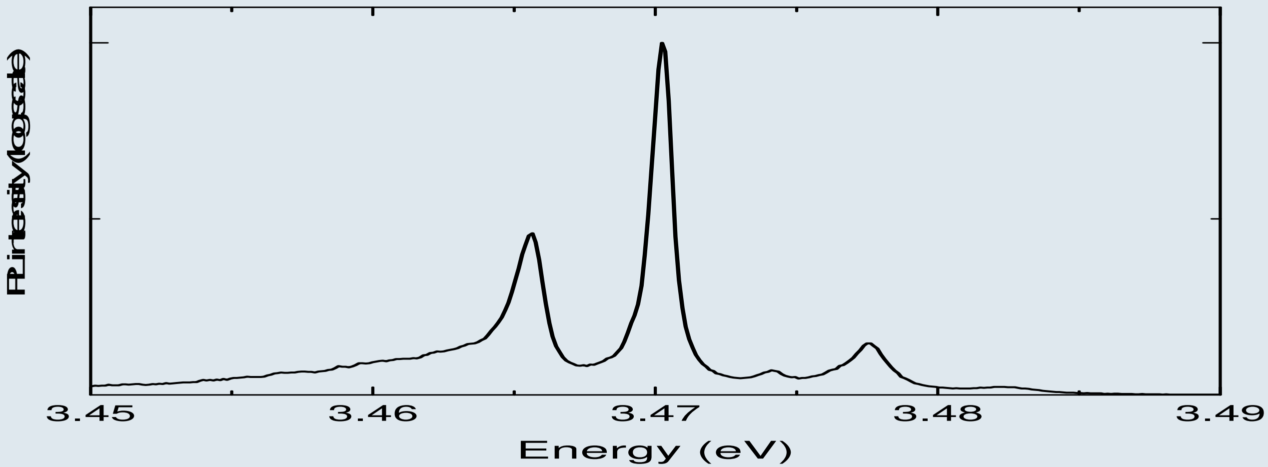
GaN nanowires : bulk properties

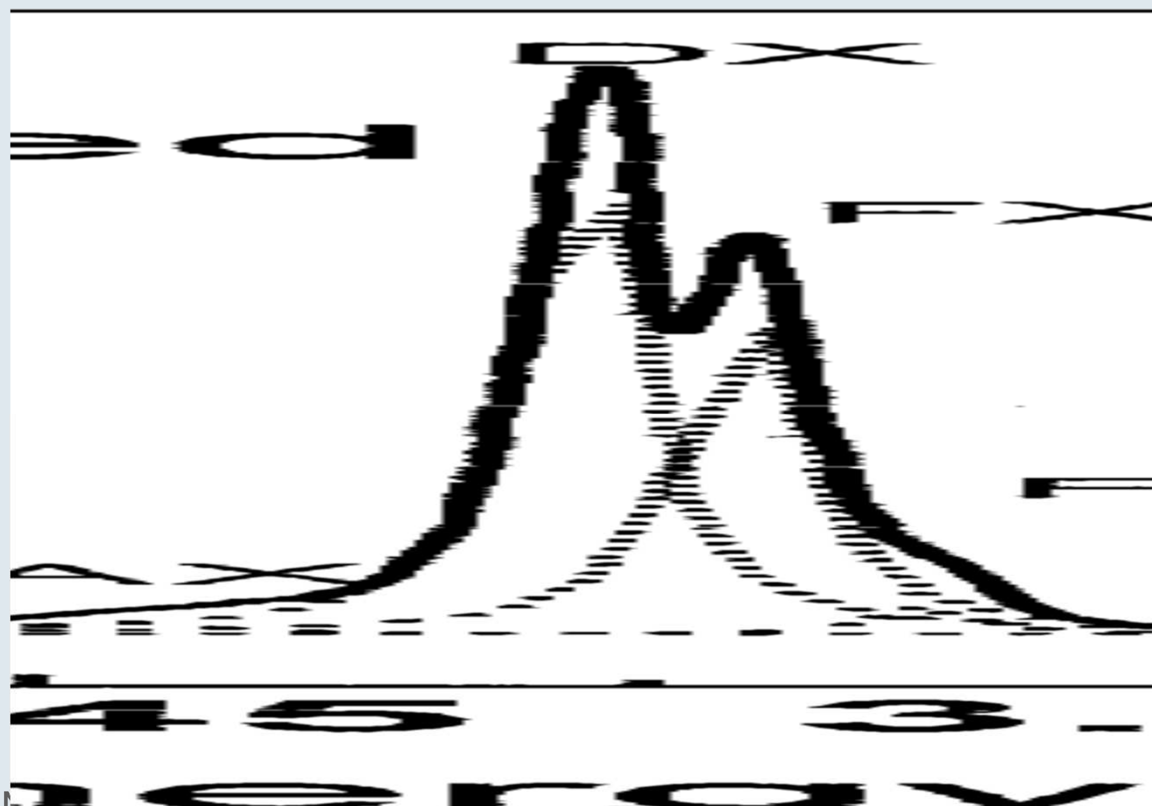


No deep defect (yellow) band

GaN nanowires : bulk properties

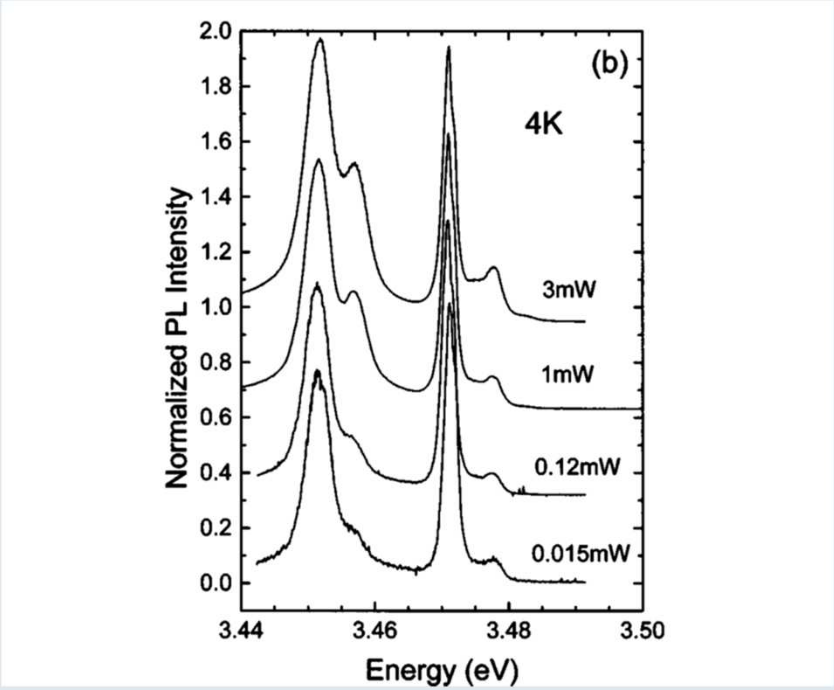
Near Band Edge PL of GaN:Mg nanowires, 4K





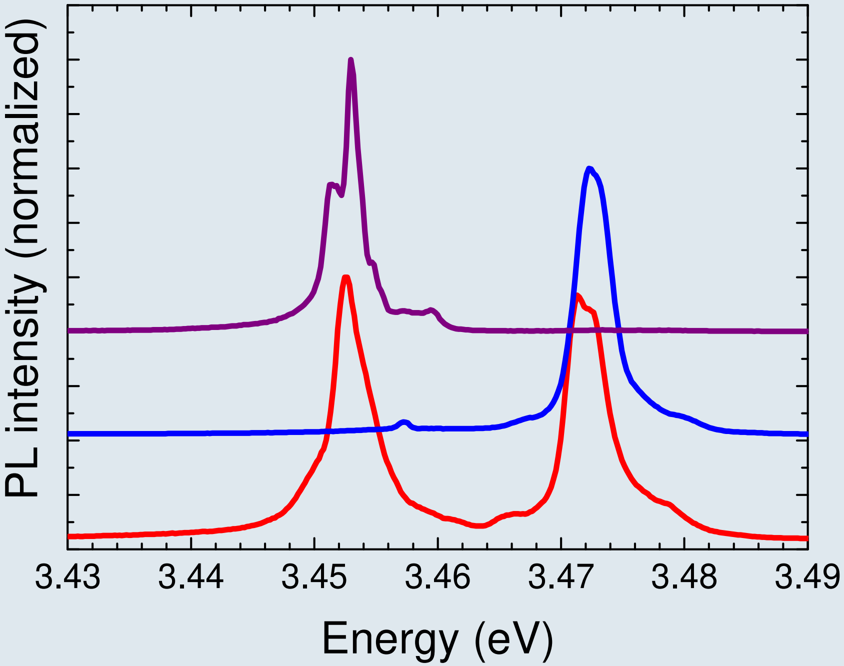
3 µm GaN on sapphire

Many discussions on **3.45 eV** luminescence line in PA-MBE-grown GaN nanowires



E. Calleja *et al.*, PRB **62** 16826 (2000)

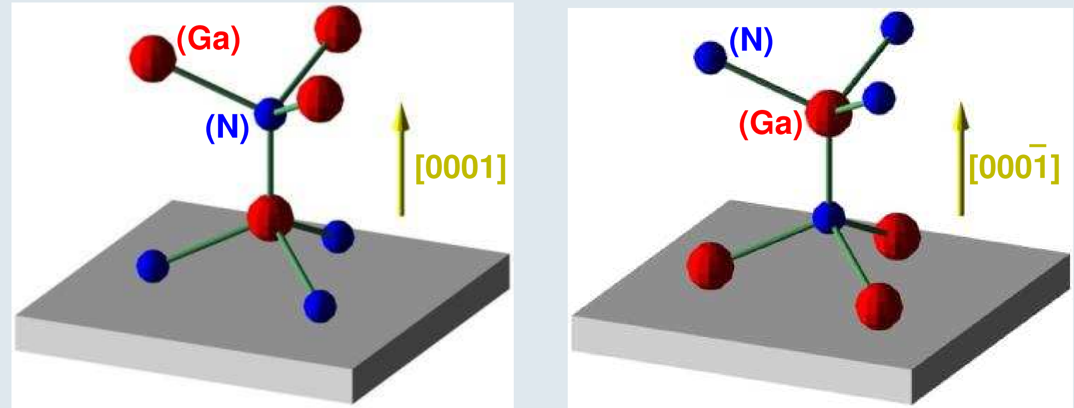
μPL on single NWs

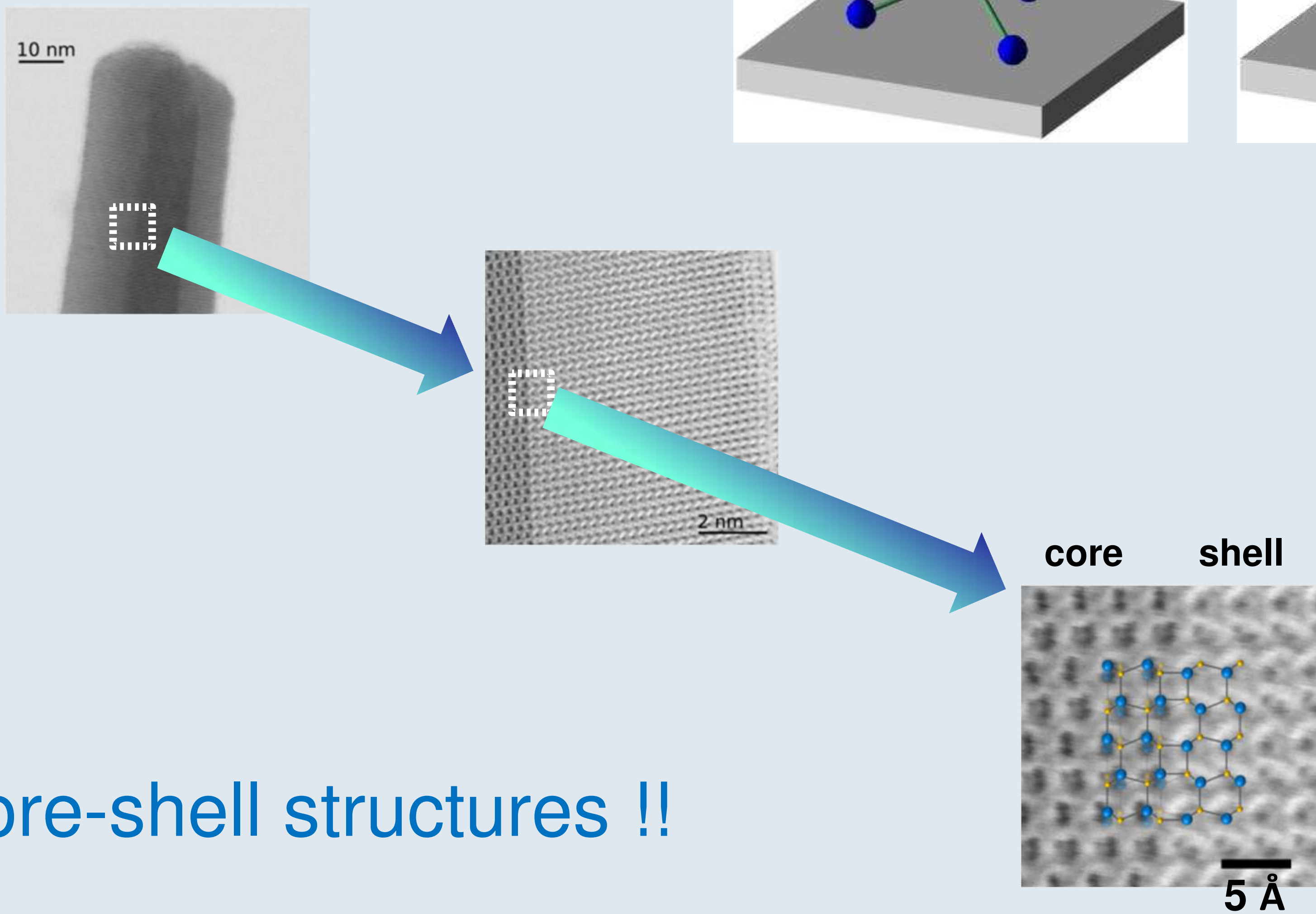


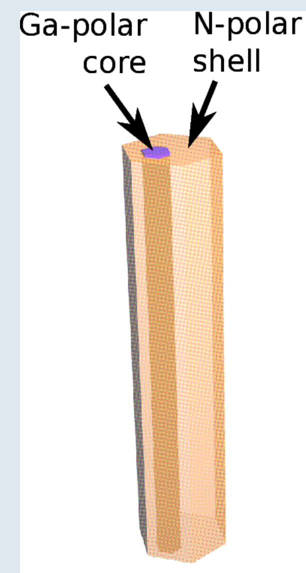
D. Sam-Giao *et al.*, JAP **113** 043102 (2013)

A mysterious emission line

Many discussions on **polarity** of PA-MBE-grown GaN nanowires -N or –Ga ??





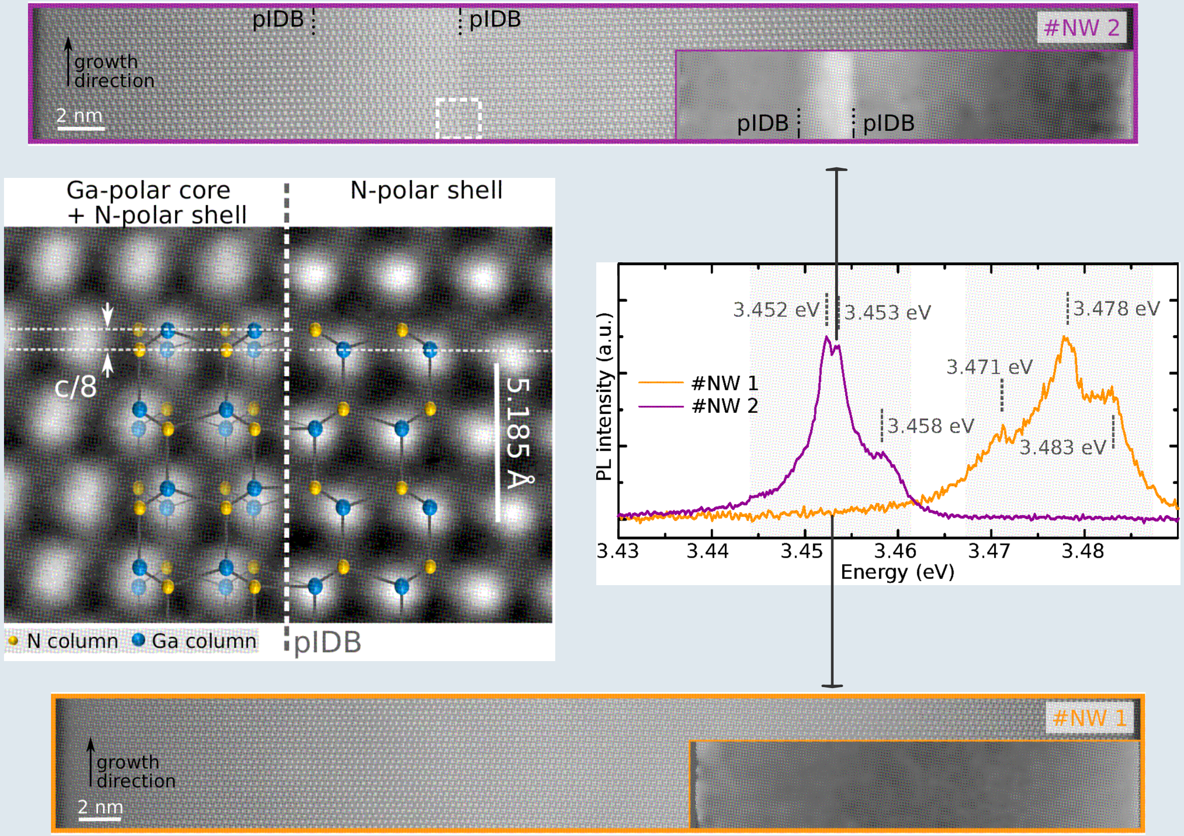


Core-shell structures !!

T. Auzelle *et al.*, J. Appl. Phys. **117**, 245303 (2015)

Inversion domain bound exciton

Correlated microPL and TEM studies on single nanowires

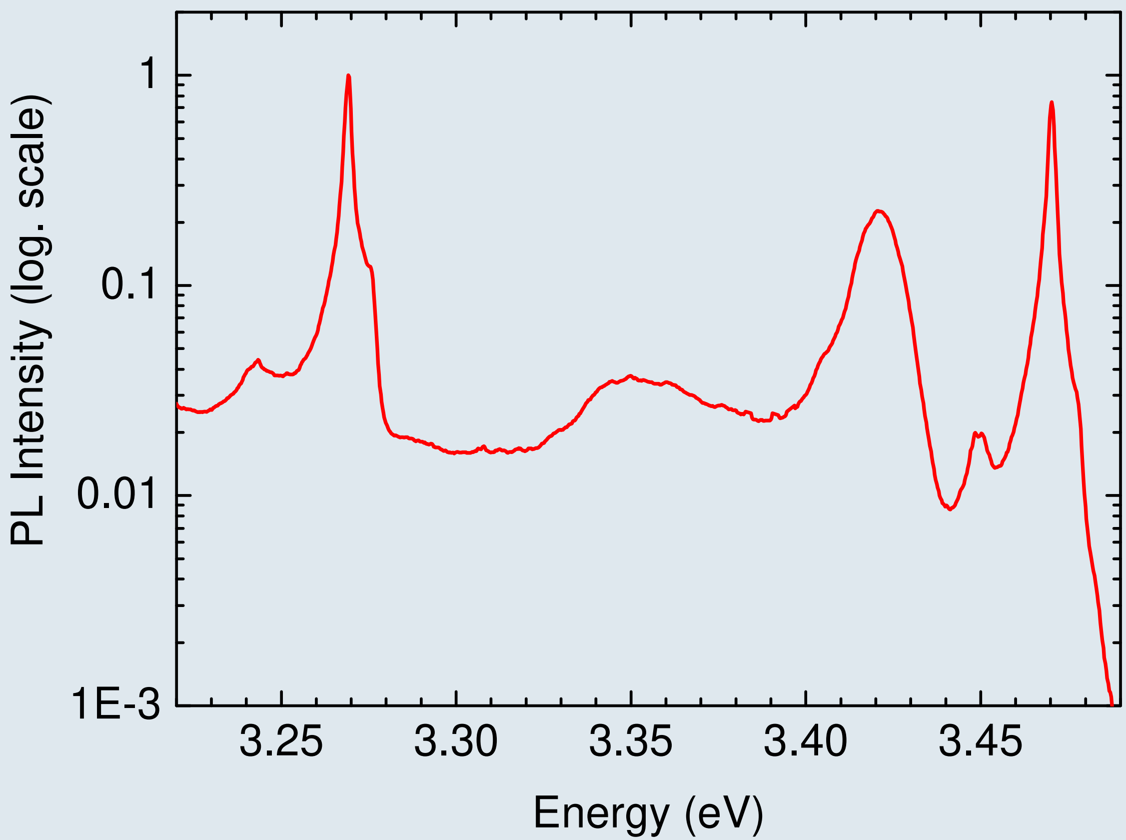


Systematic **correlated existence** of an inversion domain boundary (IDB) and a 3.45 eV luminescence.

T. Auzelle *et al.*, Appl. Phys. Lett. **107**, 051904 (2015)

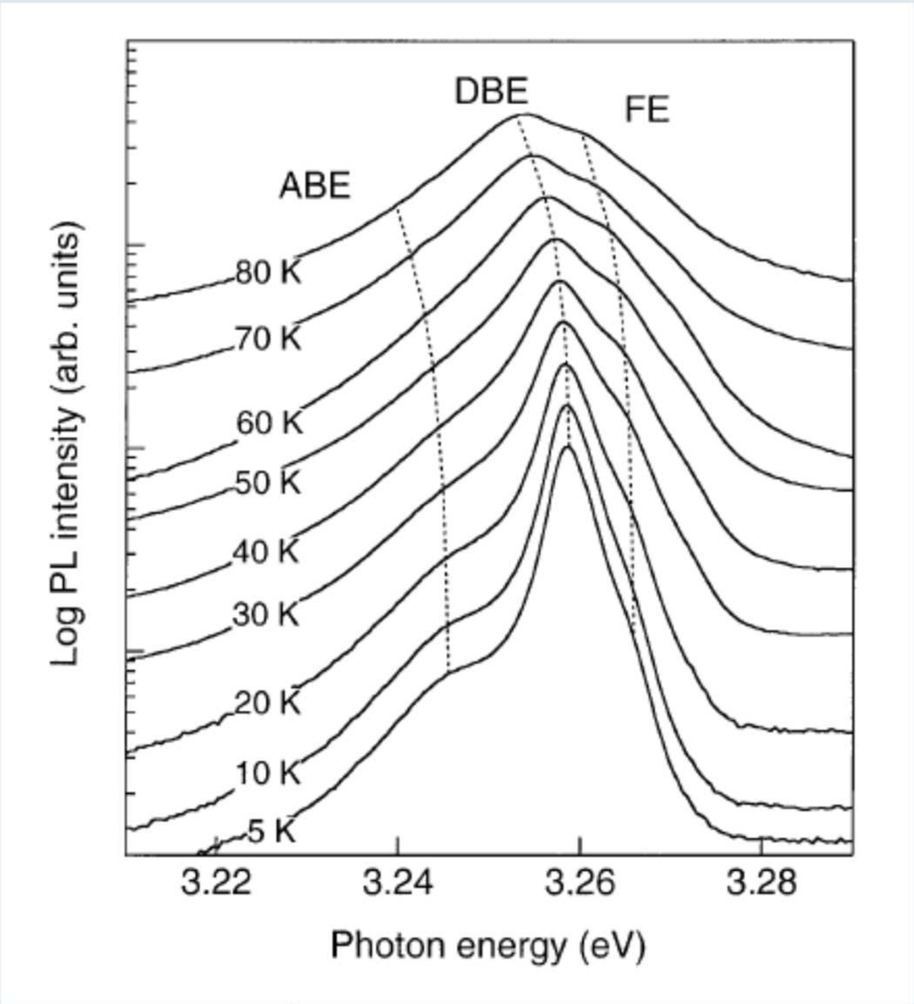
GaN nanowires : cubic phase

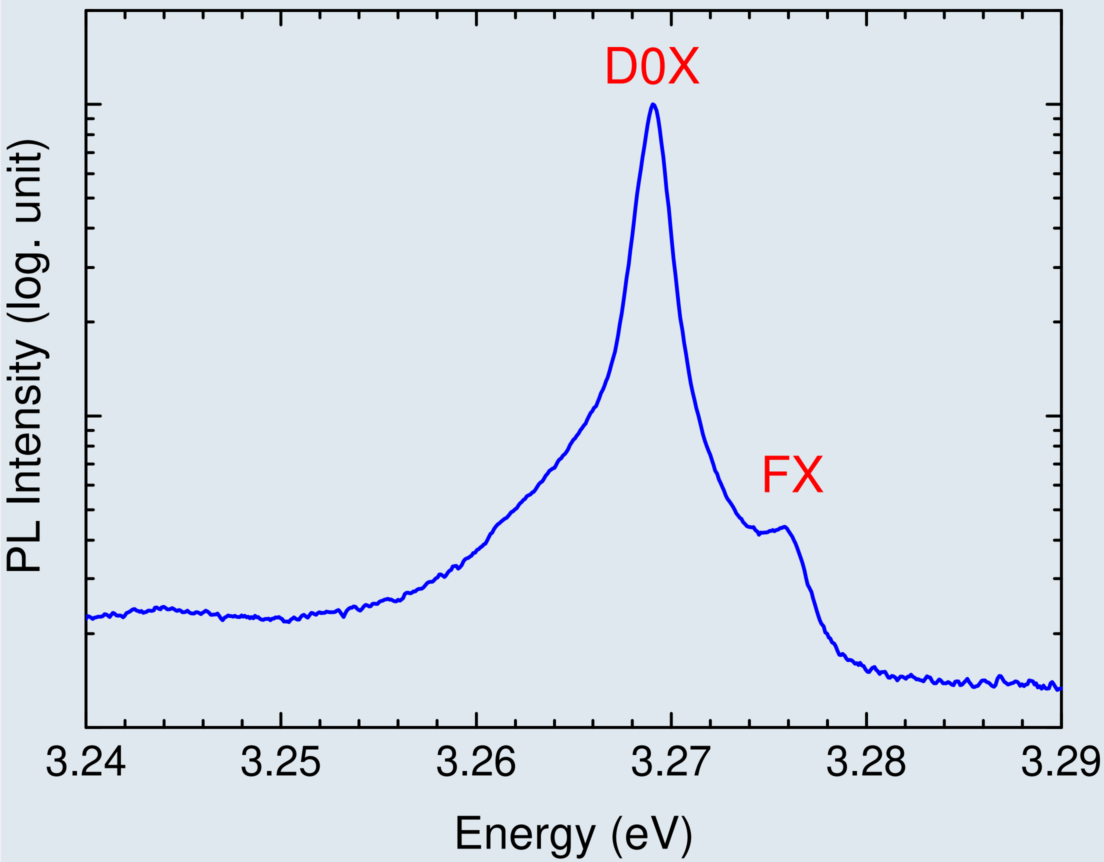
Cubic phase GaN by lowering the growth temperature



GaN nanowires : cubic phase

Cubic phase GaN by lowering the growth temperature





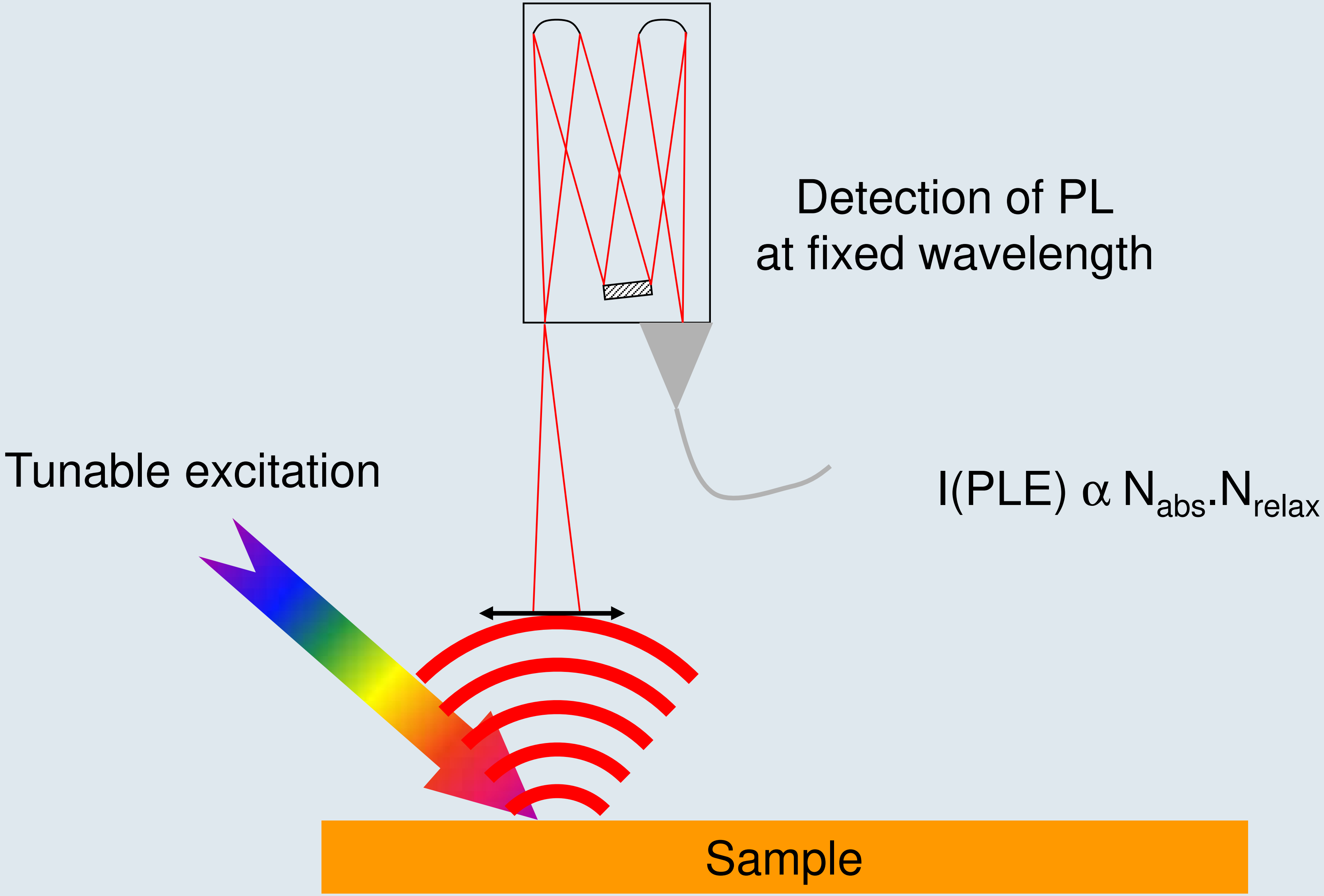
D0X FWHM : 1.6 meV

(previous state-of-the-art : 5 meV)

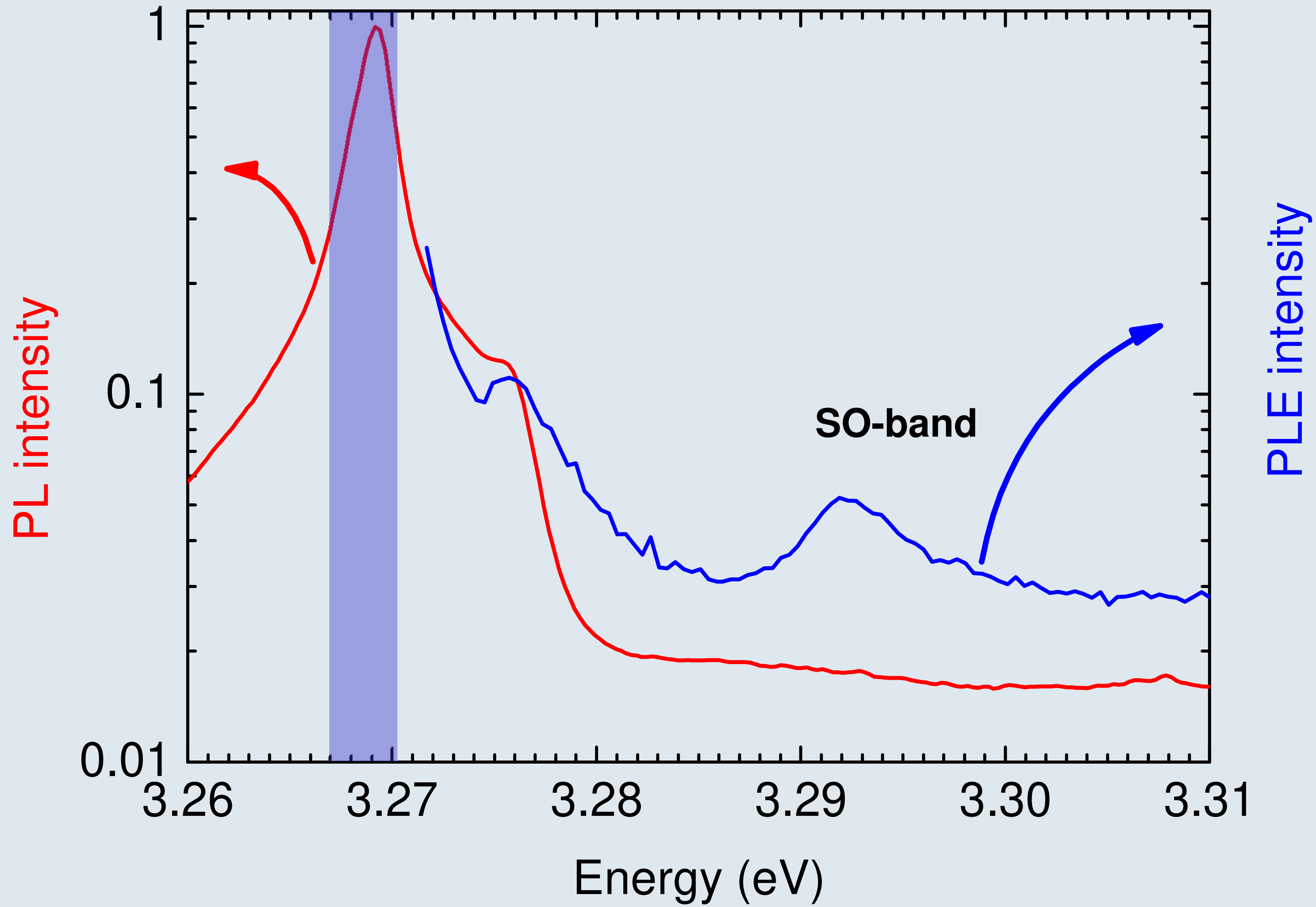
J. Renard *et al.*,
Appl. Phys. Lett. **97** 081910 (2010)

Experimental technique : PLE

=> Photoluminescence excitation



GaN nanowires : cubic phase



Measurement of split-off exciton spectral position