OPTICS II
Nanophotonics and quantum optics

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« Nanophysique et semiconducteurs » Group

Goal

Light-matter coupling

$\Rightarrow$ Some notions, peculiarities of GaN

$\Rightarrow$ The “strong exciton” in GaN

Microcavity physics

$\Rightarrow$ From the weak to the strong coupling

$\Rightarrow$ Why do microcavity physics in GaN?

Books on the topic:

Semiconductor Optics, Springer
(C. F. Klingshirn)

Confined Electrons and Photons: New Physics and Applications, Springer
(E. Burstein and C. Weisbuch)

Units

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

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

$$\Leftrightarrow$$

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

$$\Leftrightarrow$$

$$E = 1.24\ eV$$

$$\Leftrightarrow$$

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

Excitons and polaritons in GaN

The excitons in GaN

⇒ See Optics I (M. Leroux)

⇒ A, B and C excitons

What does an exciton look like?

⇒ A well defined wavevector for the center of mass

⇒ The electron and hole are closely bound (Bohr radius)

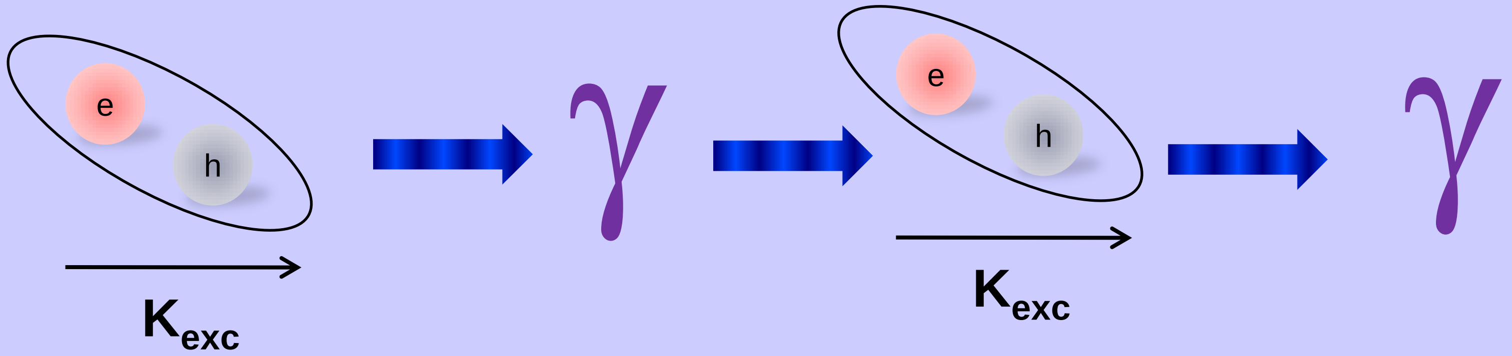
	a (nm)	E_X (meV)
GaN	2.8	25
GaAs	12	4.8

kT @ 300K
25 meV

Why is it important ?
Is it useful ?

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

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

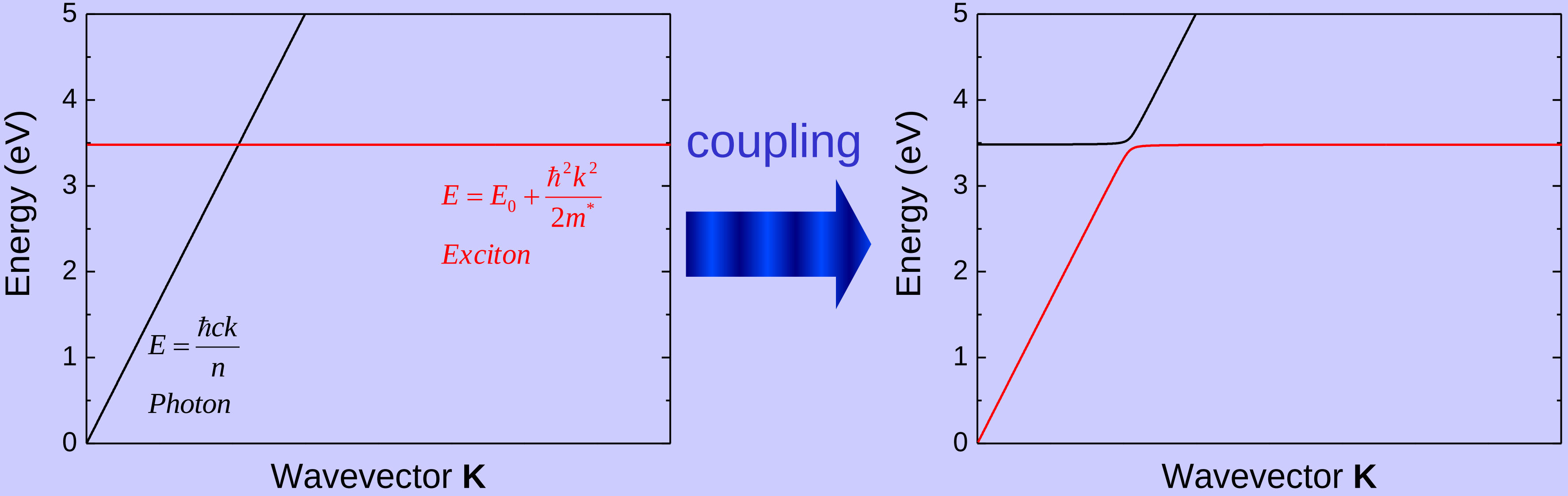
Neural networks and physical systems with emergent collective computational abilities

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

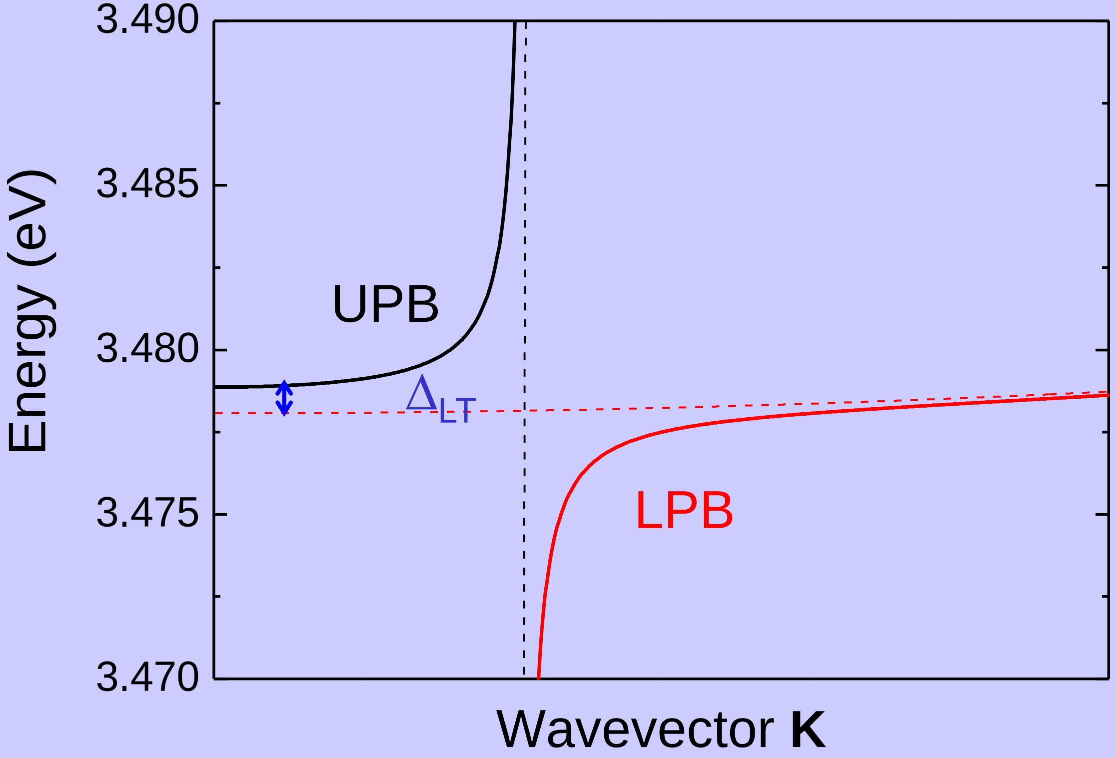
J. J. Hopfield

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

Excitons and polaritons in GaN



Excitons and polaritons in GaN



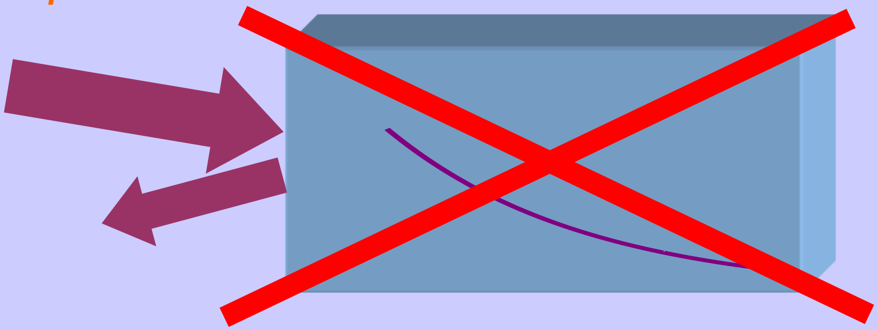
Δ_{LT} measures the intrinsic light-exciton coupling in the material

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

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

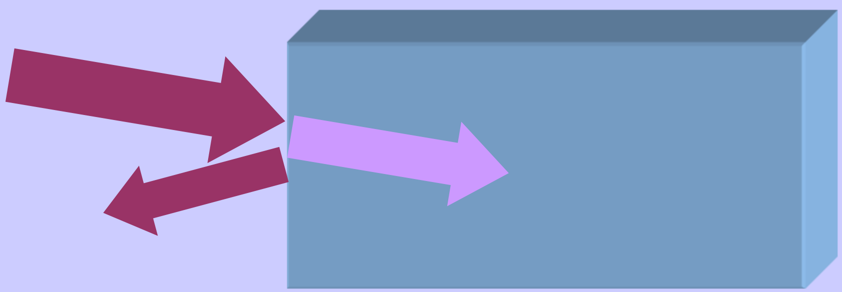
Consequences of the polariton picture

Absorption



Beer-Lambert law

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

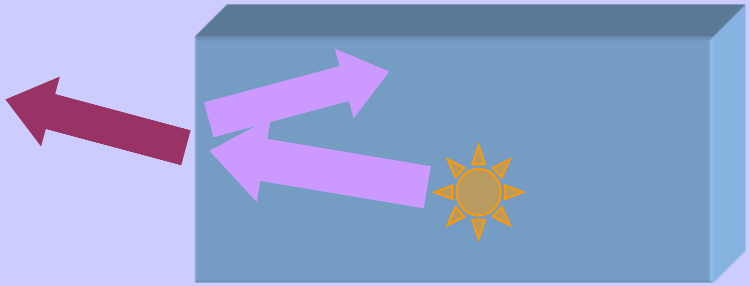


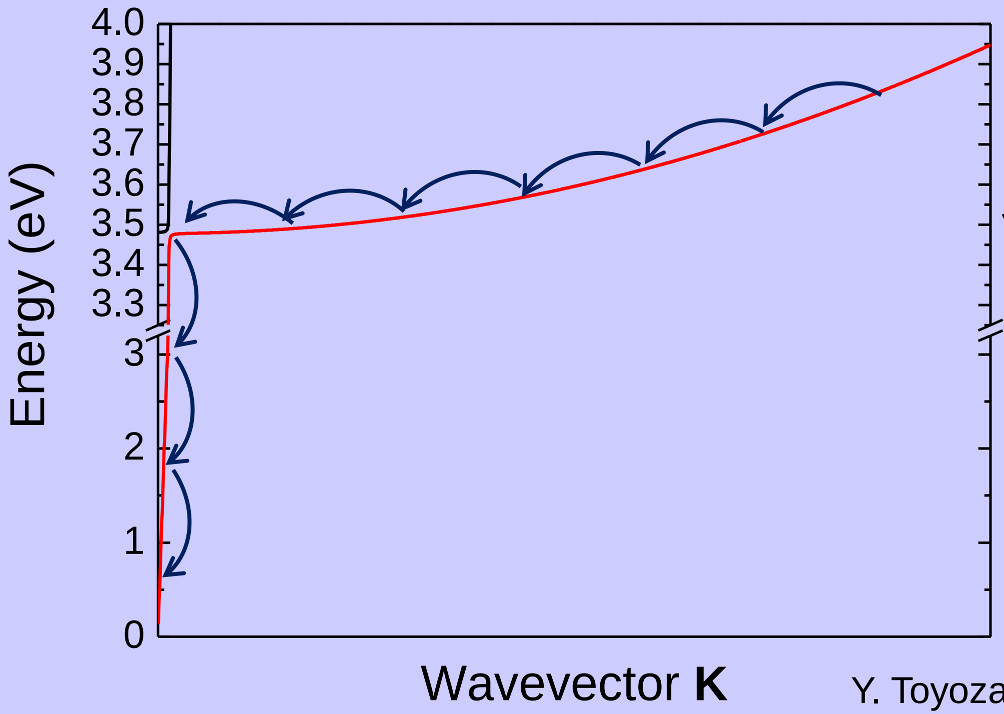
Propagating polariton
(attenuation = scattering)

Consequences of the polariton picture

Luminescence

Polariton propagating to
the surface !





Infrared catastrophy?

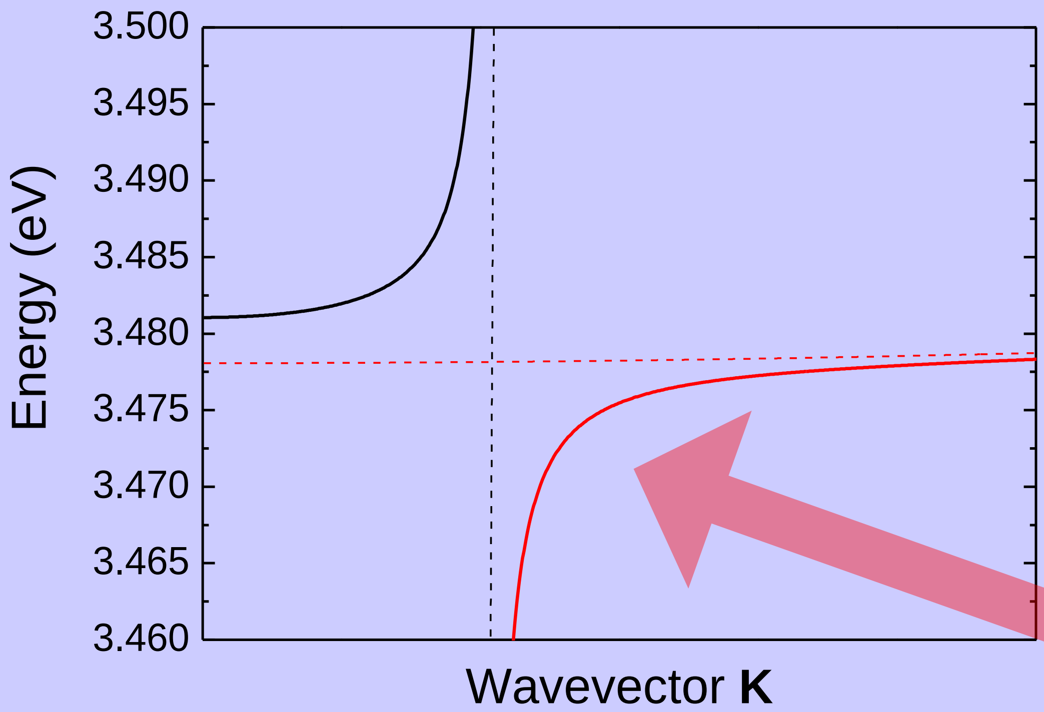
J. J. Hopfield, J. Phys. Soc. Jap. **21** 77 (1966)

Relaxation bottleneck
⇒ Thermal like population

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

Consequences of the polariton picture

Luminescence



Relaxation bottleneck
$\Rightarrow$ Thermal like population around E_X on UPB and LPB

Bottleneck

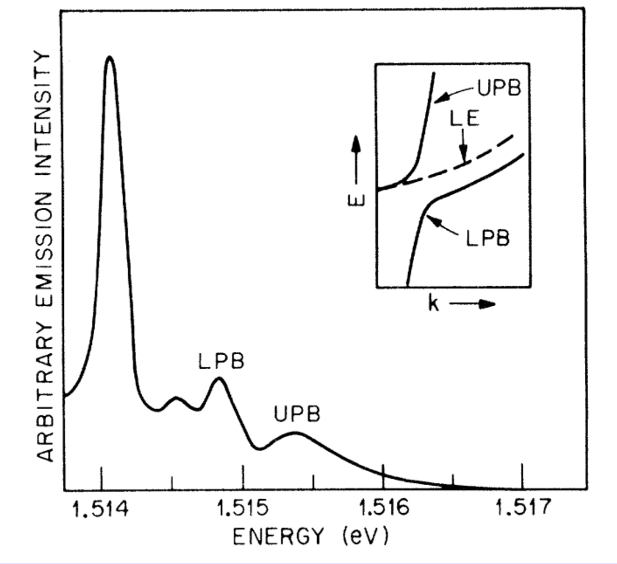
Luminescence properties are very complex to model !!
(sample and experiments dependent…)

The polariton in GaAs

VOLUME 27, NUMBER 24 PHYSICAL REVIEW LETTERS 13 DECEMBER 1971

Observation of Polaritons in GaAs: A New Interpretation of the Free-Exciton Reflectance and Luminescence

D. D. Sell, R. Dingle, S. E. Stokowski, and J. V. DiLorenzo
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 1 November 1971)



Excitons and polaritons in GaN

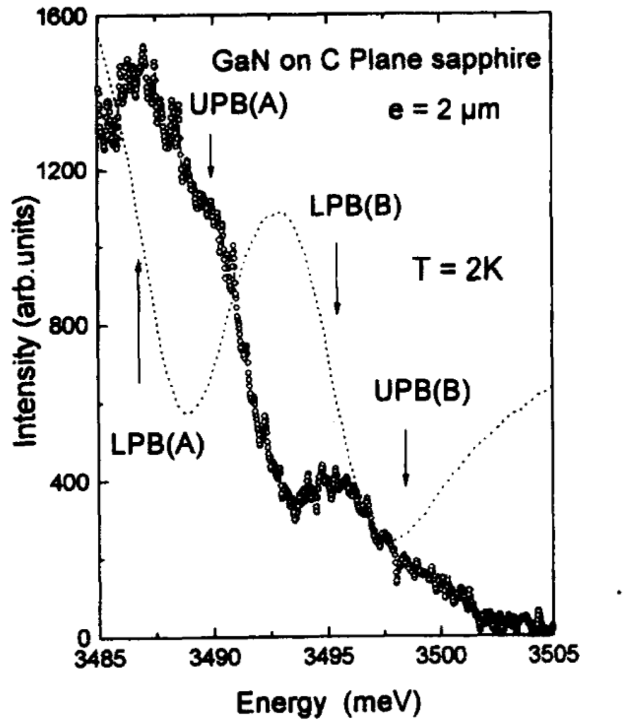
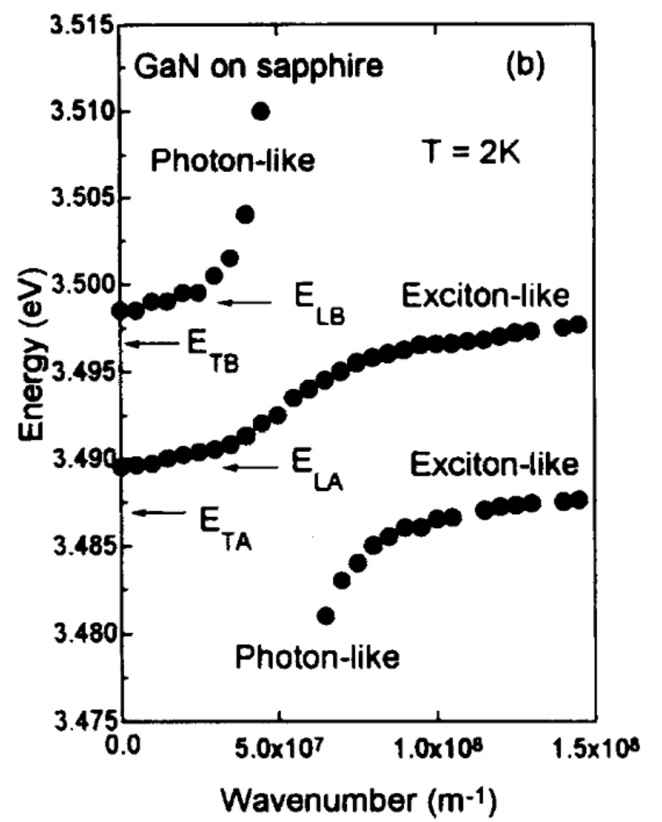


Fig. 1. 2 K reflectance spectrum (dashed line) and the corresponding 2 K photoluminescence (open circles) spectrum which shows the LPB and UPB contributions to the GaN fluorescence.



B. Gil *et al.*, Solid State Commun. **104** 264 (1997)

Confined electronic structures

The strong light-matter coupling in bulk GaN….

… creates strong polaritons, which are lousy emitters

What about QWs?

A confined exciton in a QW is coupled to a large number of photonic states
$\Rightarrow$ Luminescence allowed on the first order

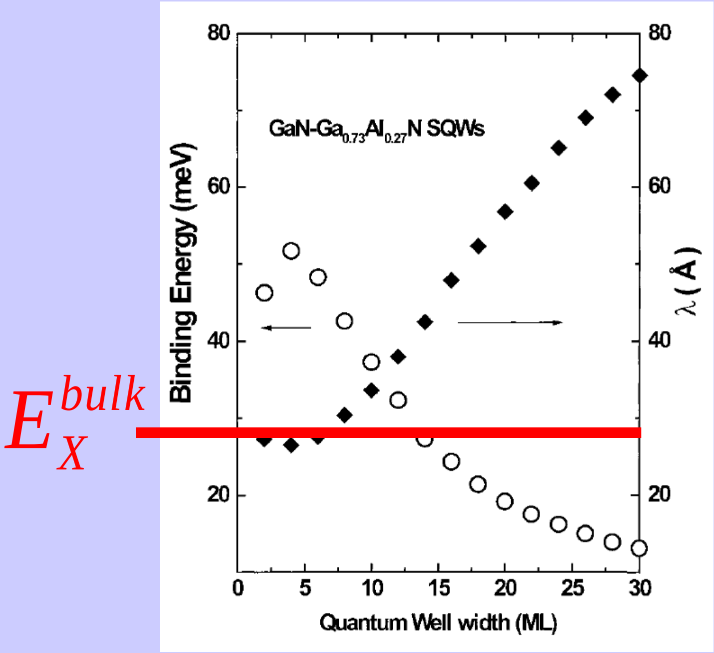
V. M. Agranovitch and O. A. Dubovskii, JETP Lett. **3**, 223 (1966)
C. Weisbuch *et al.*, Solid State Commun. **37**, 219 (1981)

$\Rightarrow$ 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)

Confined electronic structures : GaN

The QCSE reduces the exciton binding energy…



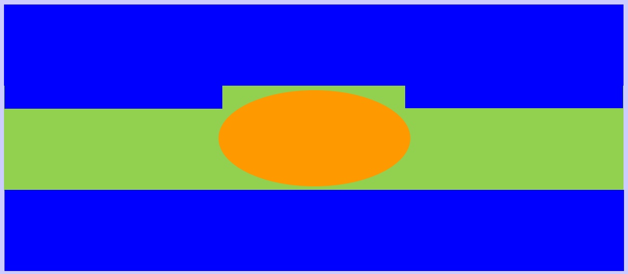
P. Bigenwald *et al.*, Phys. Stat. Sol. (b) **216** 371 (1999)

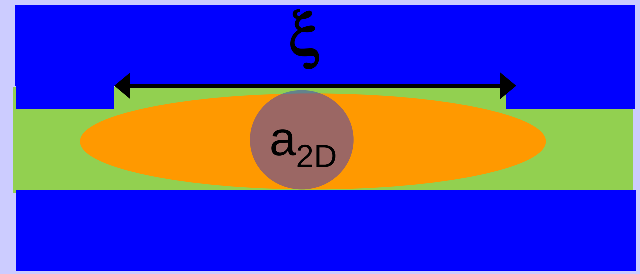
… but in thin QWs or non-polar QWs, the exciton binding energy can be large!

Excitonic effects in QWs

Do we get fast emission from a strong exciton?

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





Strong confinement

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

Lateral weak confinement

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

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

$\Rightarrow$ 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

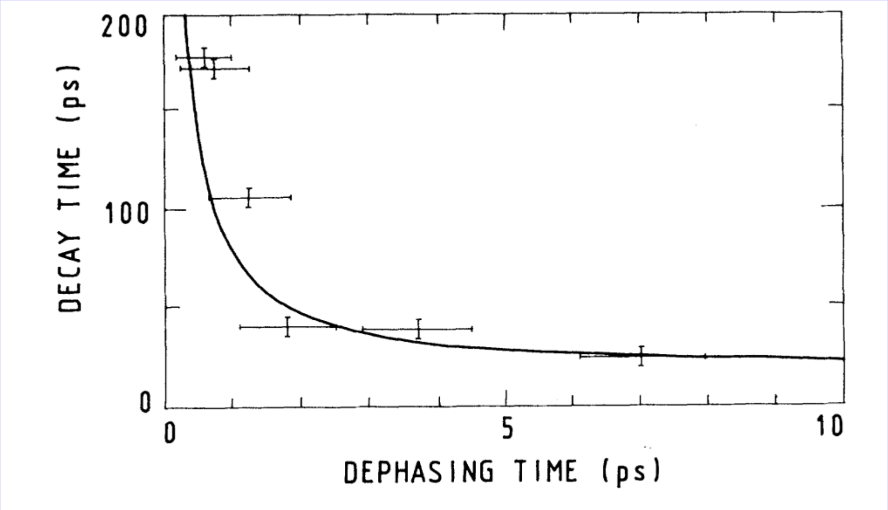
Excitonic effects in QWs

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!

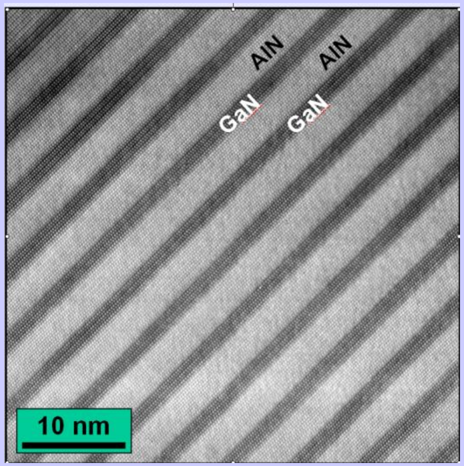
In a non perfect structure, the fundamental emitting state will be laterally localized states

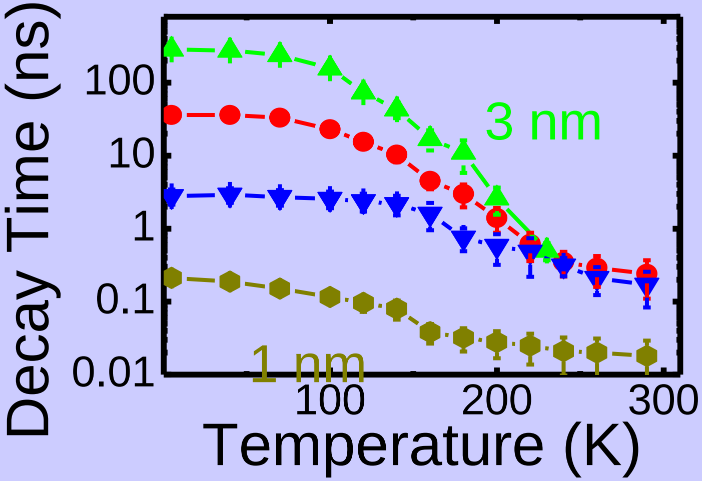
Even in a very good (i.e. III-As) quantum well, it takes very peculiar experimental conditions to observe the intrinsic fast lifetimes of 2D excitons

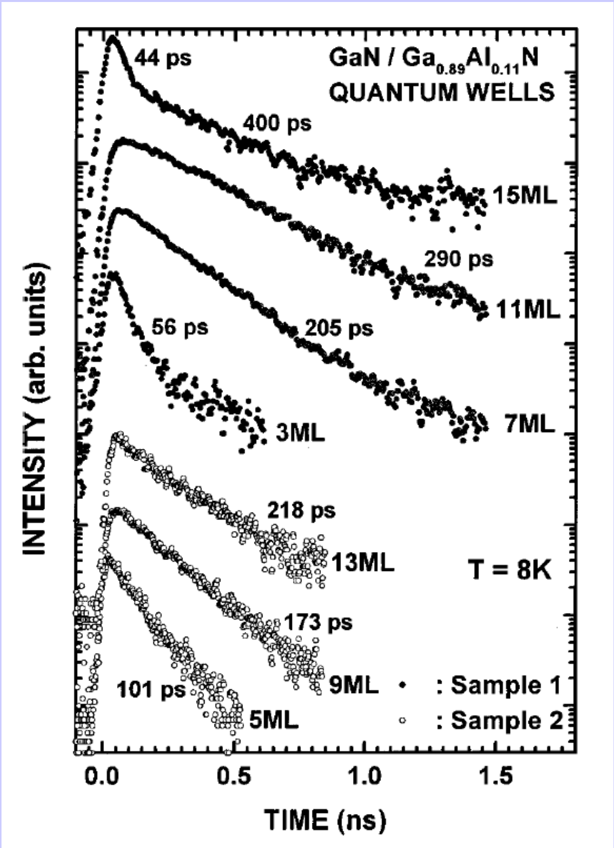
- *Very low temperature (phonon scattering)*
- *Resonant and low excitation (carrier-carrier scattering)*

Excitonic effects in GaN QWs

Polar QWs





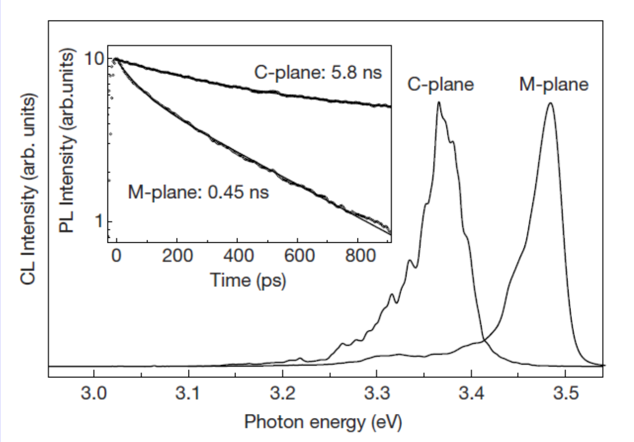


J. Renard *et al.*, Appl. Phys. Lett. **95** 131903 (2009)

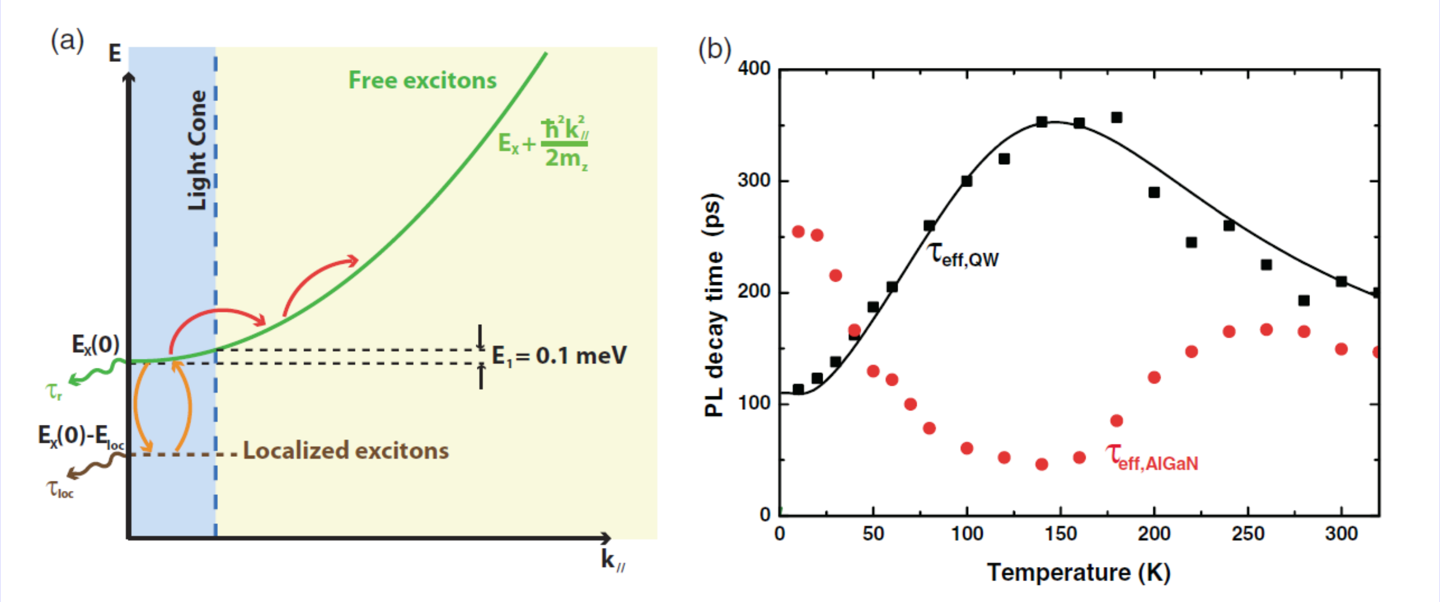
P. Lefebvre *et al.*, Phys. Rev. B 59 15363 (1999)

Excitonic effects in GaN QWs

Non-Polar QWs



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



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**

$\Rightarrow$ Quite strong localization effects, no giant oscillator strength

$\Rightarrow$ Strong excitonic effects in III-N, but ordinary recombination rates

Microcavity physics

More control on light-matter coupling

What are microcavities ?

How does an emitter in a microcavity behave ?

Strong coupling

Weak coupling

Two-dimensional microcavity polaritons

Peculiarities of the III-N system

Optical cavities

What is a mode of the E-M field?

$\Rightarrow$ A solution of Maxwell equations in the absence of source

What is a confined mode?

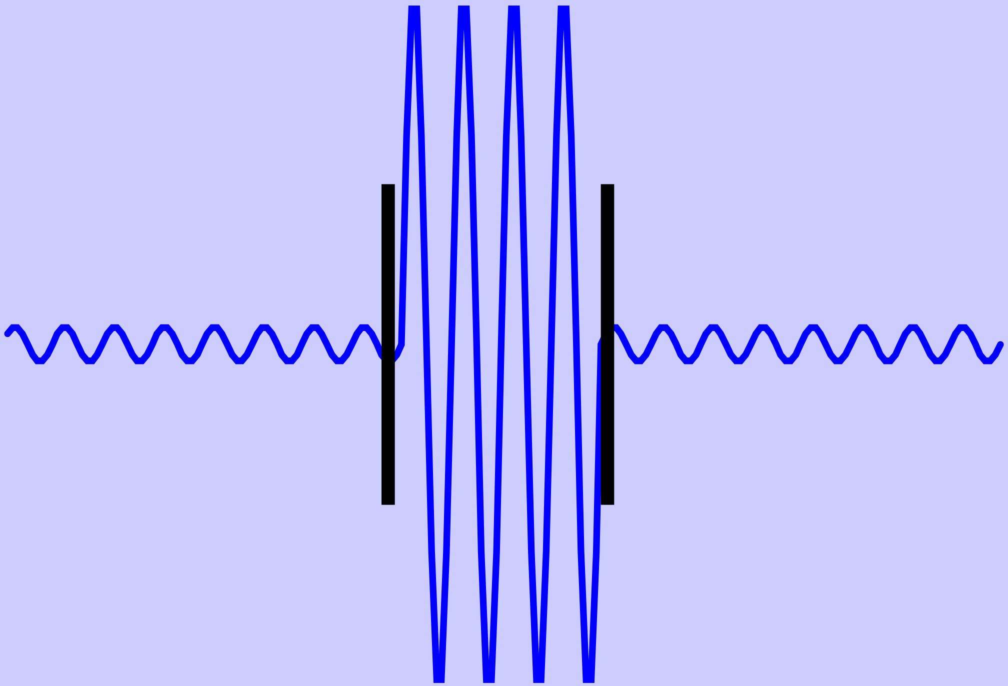
« An optical resonator, the optical counterpart of an electronic resonant circuit, confines and stores light at certain resonant frequencies »

« Fundamentals of photonics »
B.E.A. Saleh and M.C. Teich, Wiley ed.

« Optical resonators [...] are used primarily in order to build up large field intensities with moderate power inputs. They consist in most cases of two, or more, curved mirrors that serve to "trap," by repeated reflections and refocusing, an optical beam that thus becomes the mode of the resonator. »

« Optical electronics in modern communications »
A. Yariv, Oxford ed.

Optical cavities

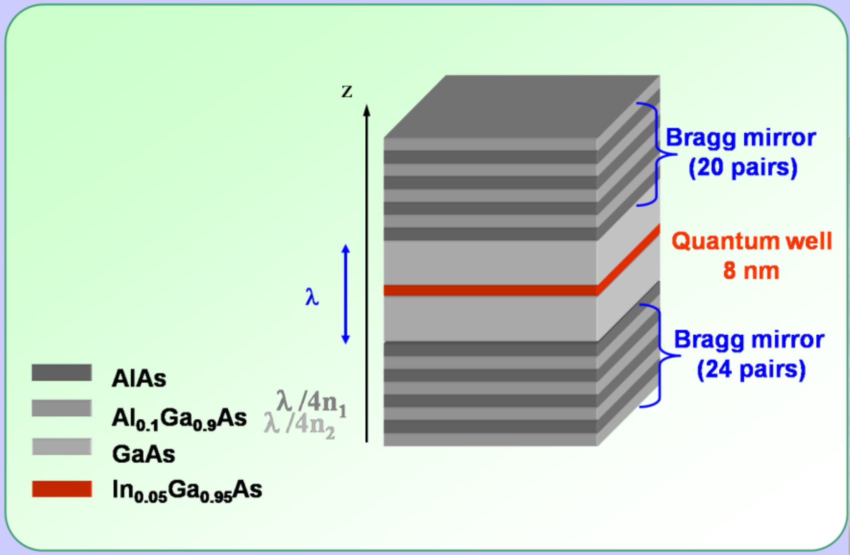


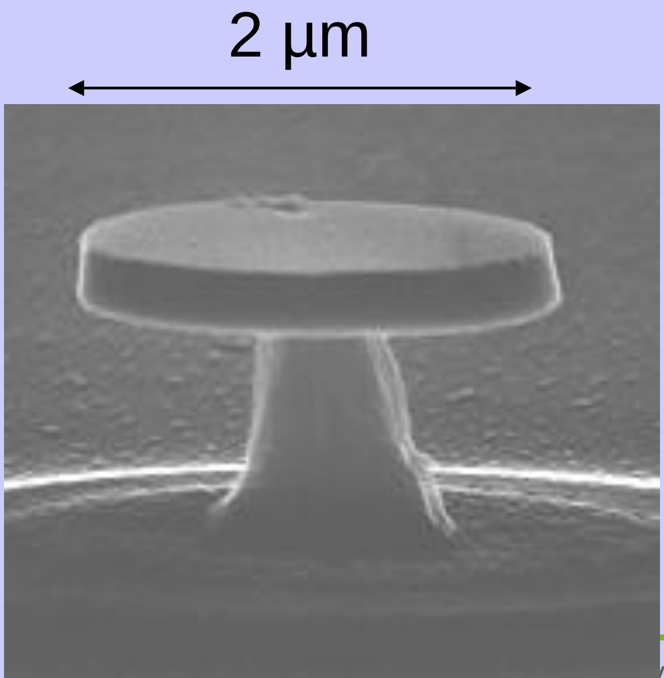
⇒ High intensity in a confined region of space for resonant frequencies

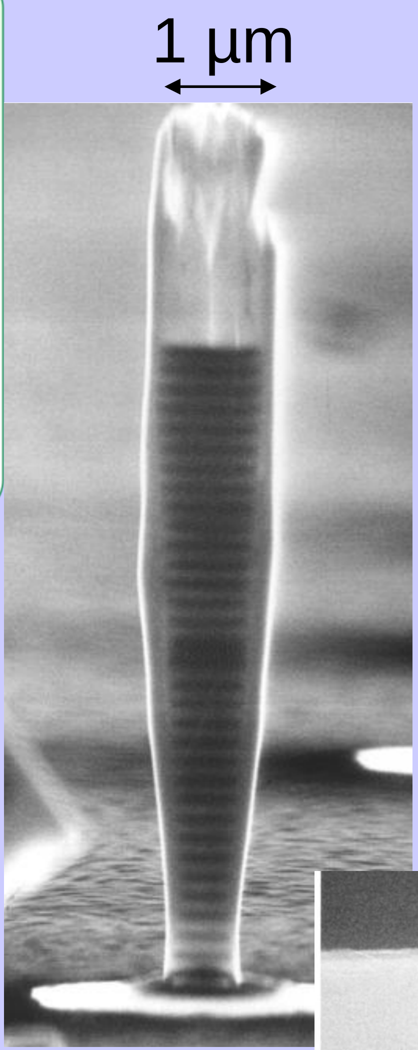
Quality factor measures the decay of stored E-M energy in mode :

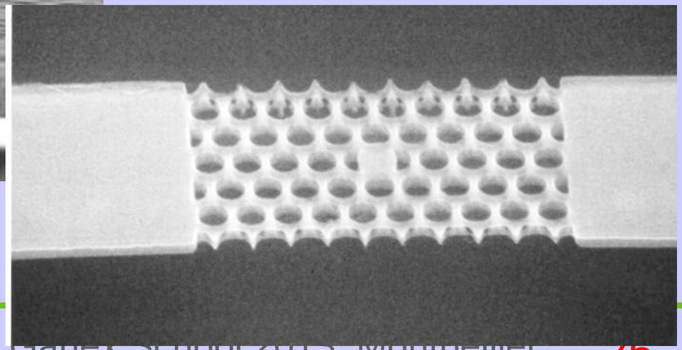
$$E = E_0 e^{-\frac{\omega t}{Q}}$$

Various semiconductor *micro*cavities



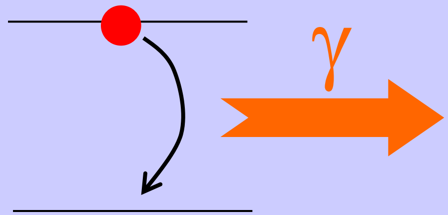






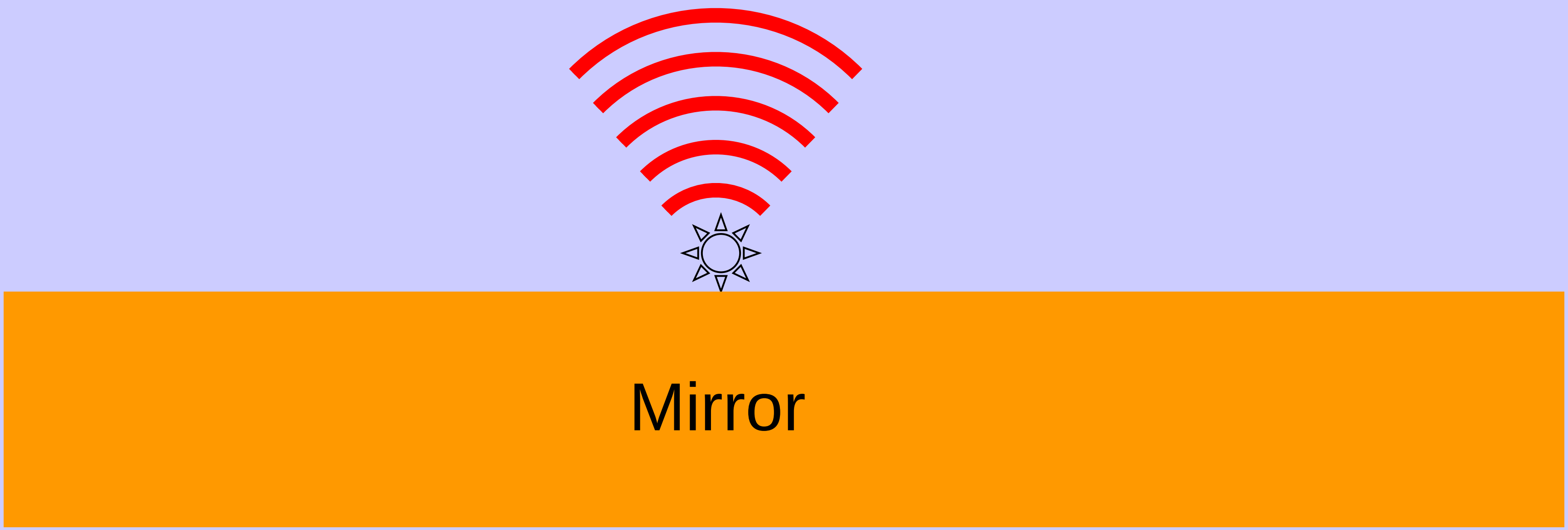
Spontaneous emission

Spontaneous emission : irreversible emission of a photon



$$\Gamma_{sp} = \frac{2\pi}{\hbar^2} \left| \langle f | H | i \rangle \right|^2 \rho(\omega)$$

Influence of the E-M surrounding:



Spontaneous emission

$$\Gamma_{sp} = \frac{2\pi}{\hbar^2} \left| \langle f | H | i \rangle \right|^2 \rho(\omega)$$

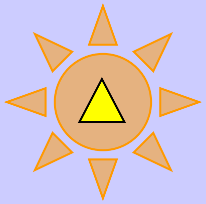
Control of the ***emitter-field coupling***

Control of the ***density of states*** for the EM field

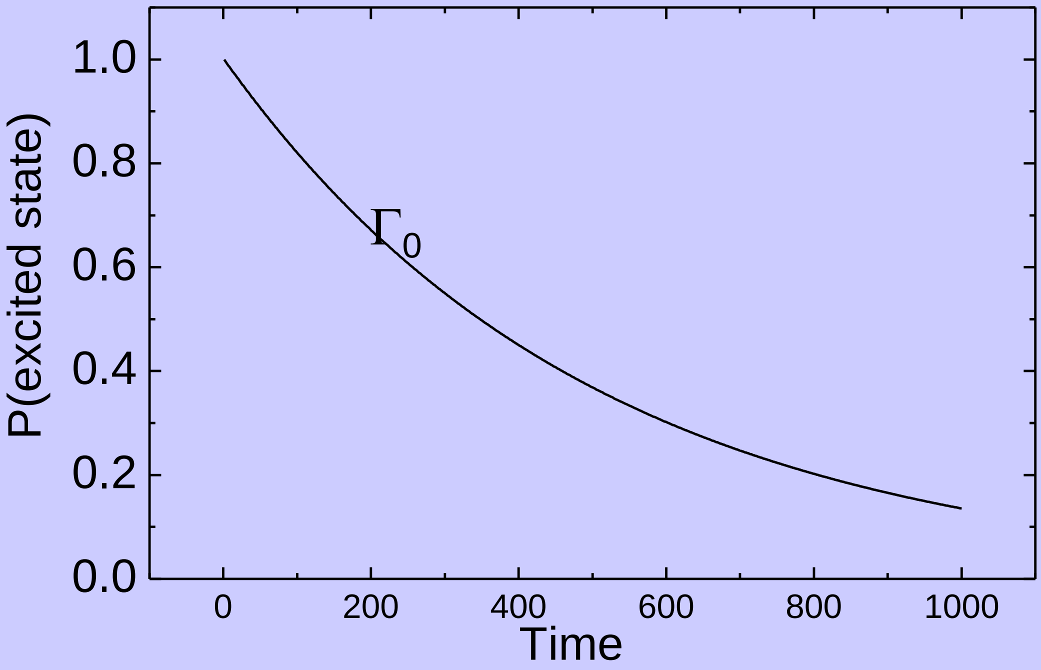
Cavity Quantum ElectroDynamics

Free space emission

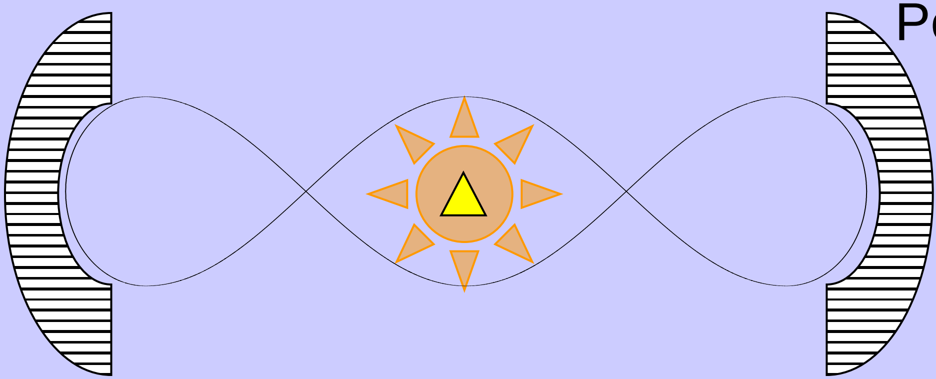
$$\Gamma_{sp} = \frac{2\pi}{\hbar^2}\left|\langle f|H|i\rangle\right|^2 \rho(\omega) = \frac{2\omega^3 d^2}{3\pi\hbar\varepsilon_0 c^3}$$



Free space



Strong coupling



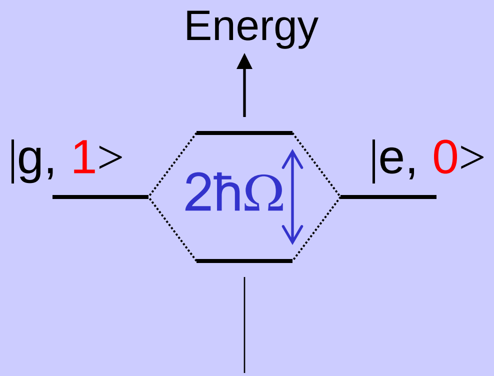
Perfect mirrors

Ω Rabi frequency

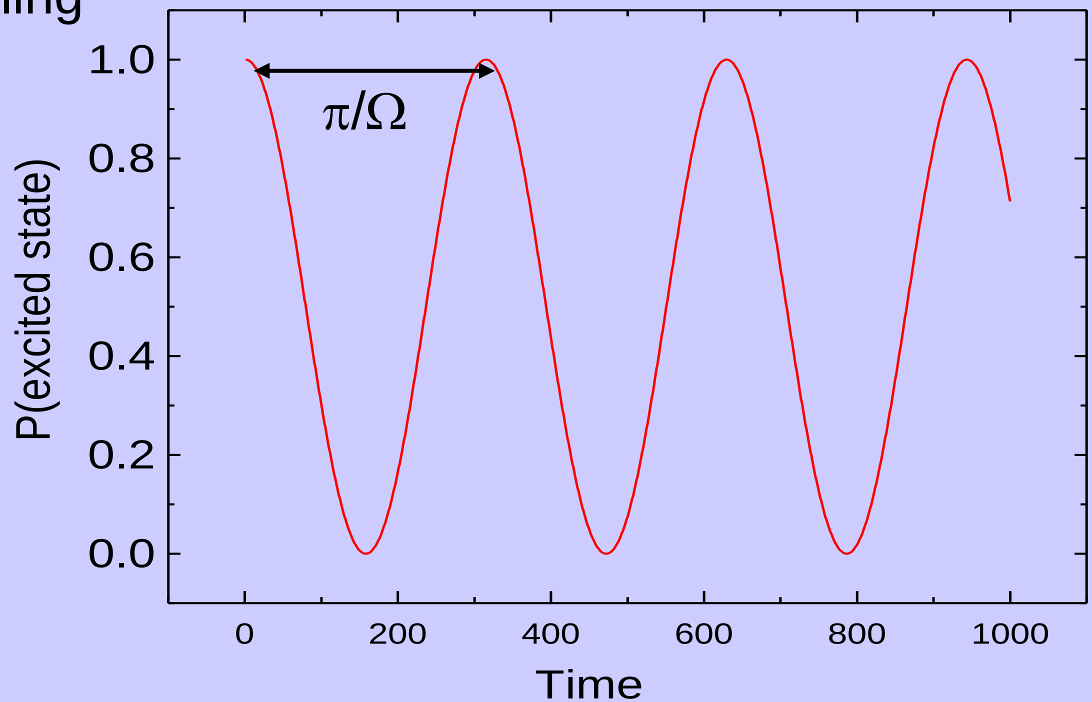
$$\Omega = \sqrt{\frac{\omega d^2}{2\hbar\varepsilon_0 V}}$$

d transition dipole, V mode volume

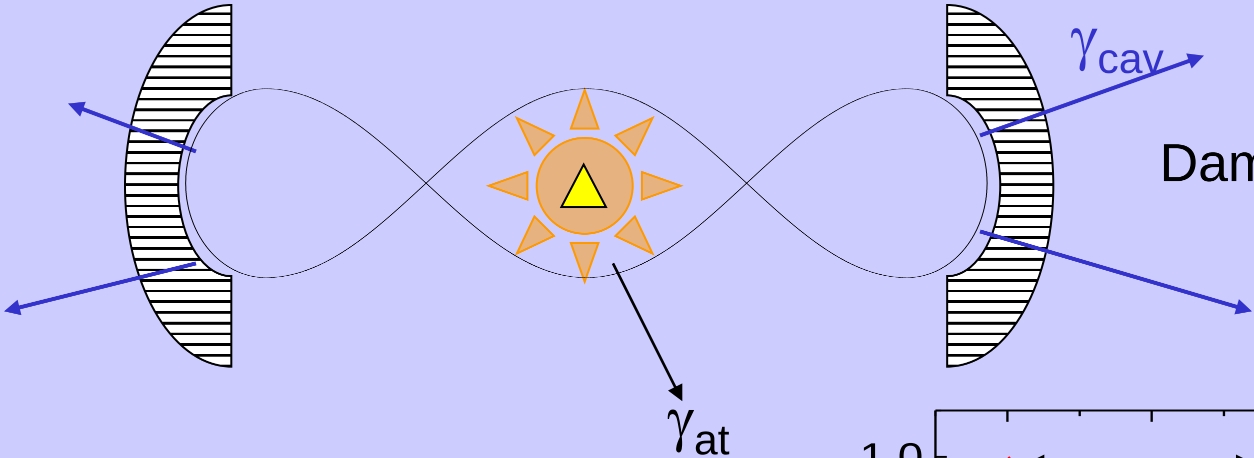
Isolated system : strong coupling



⇒ Photon/emitter hybrid eigenstates



Strong coupling

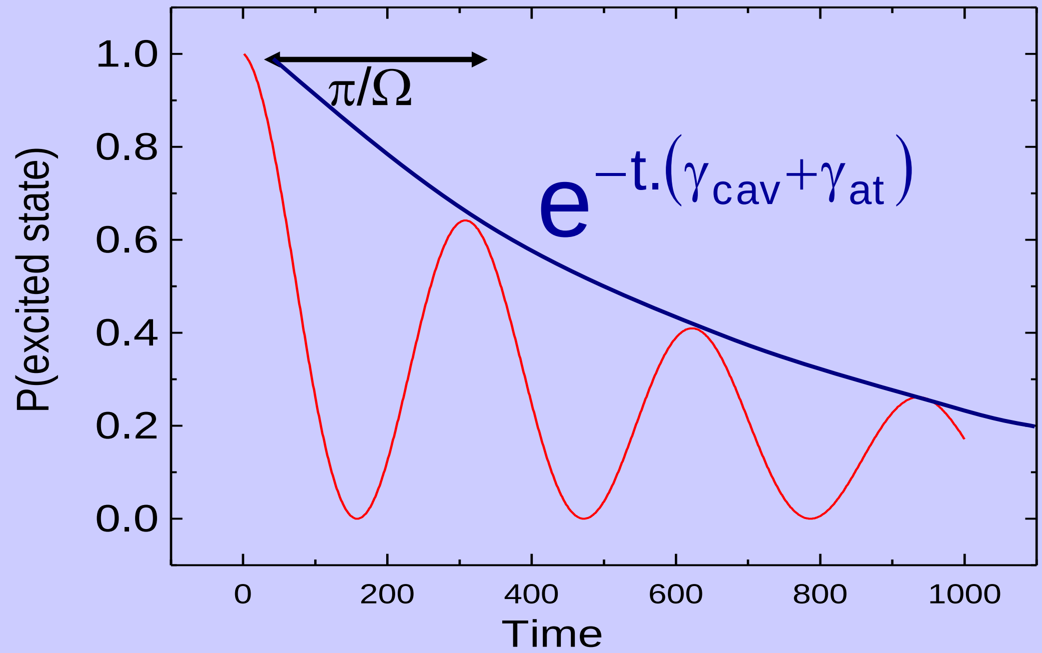


Damped strong coupling

Ω Rabi frequency

γ_{cav} cavity damping ($Q=\omega_{cav}/\gamma_{cav}$)

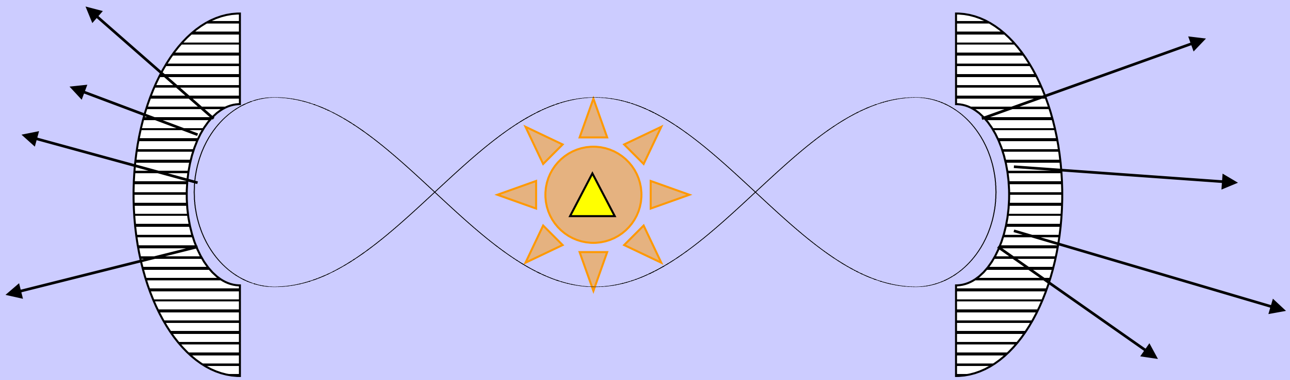
γ_{at} atomic decay in other modes



$\Omega>(\gamma_{cav}, \gamma_{at})$

In general $\gamma_{cav} >> \gamma_{at}$

Weak coupling, Purcell effect



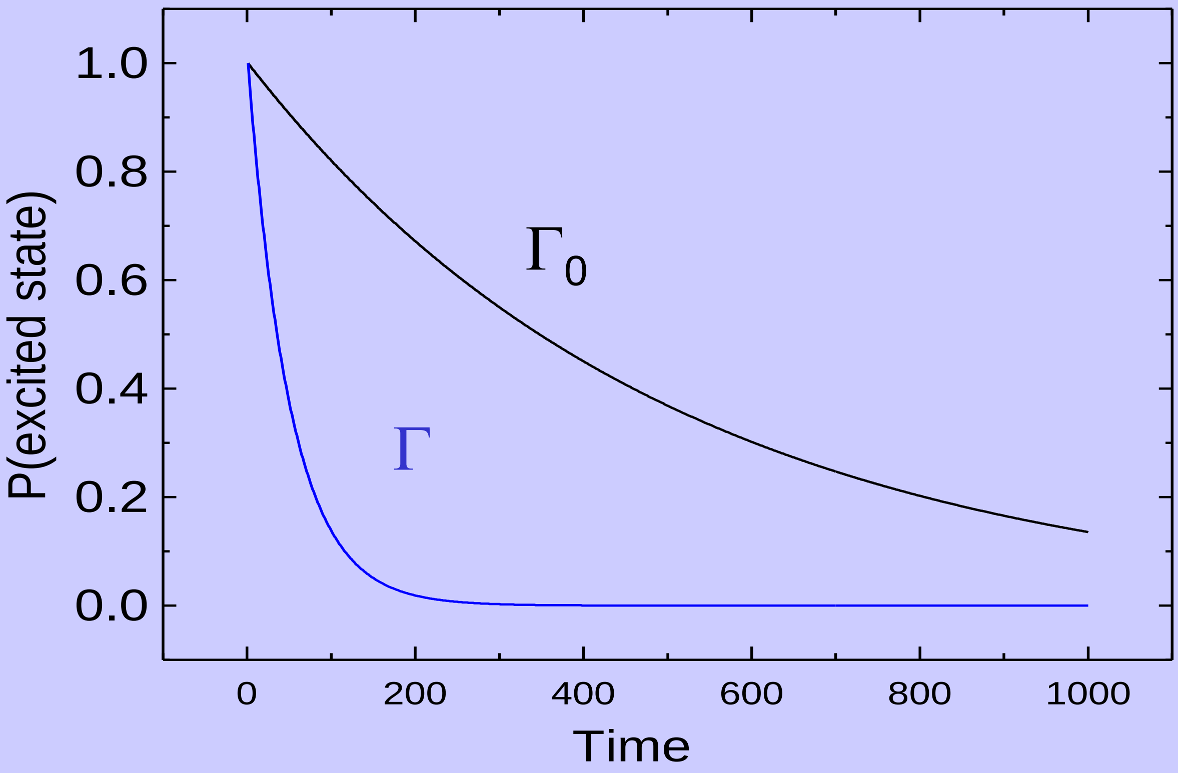
$\Omega < \gamma_{cav}$

2 unperturbed eigenstates

modified decay rates

$\Gamma = F_p \Gamma_0$

F_p Purcell factor



Weak coupling, Purcell effect

A famous paper :

B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. PURCELL, *Harvard University.*—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

$$A_\nu = (8\pi\nu^2/c^3)h\nu(8\pi^3\mu^2/3h^2) \text{ sec.}^{-1},$$

is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7$ sec.$^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical circuit, the factor $8\pi\nu^2/c^3$ no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now *one* oscillator in the frequency range ν/Q associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $f = 3Q\lambda^3/4\pi^2V$, where V is the volume of the resonator. If a is a dimension characteristic of the circuit so that $V\sim a^3$, and if δ is the skin-depth at frequency ν, $f\sim\lambda^3/a^2\delta$. For a non-resonant circuit $f\sim\lambda^3/a^3$, and for $a<\delta$ it can be shown that $f\sim\lambda^3/a\delta^2$. If small metallic particles, of diameter 10^{-3} cm are mixed with a nuclear-magnetic medium at room temperature, spontaneous emission should establish thermal equilibrium in a time of the order of minutes, for $\nu = 10^7$ sec.$^{-1}$.

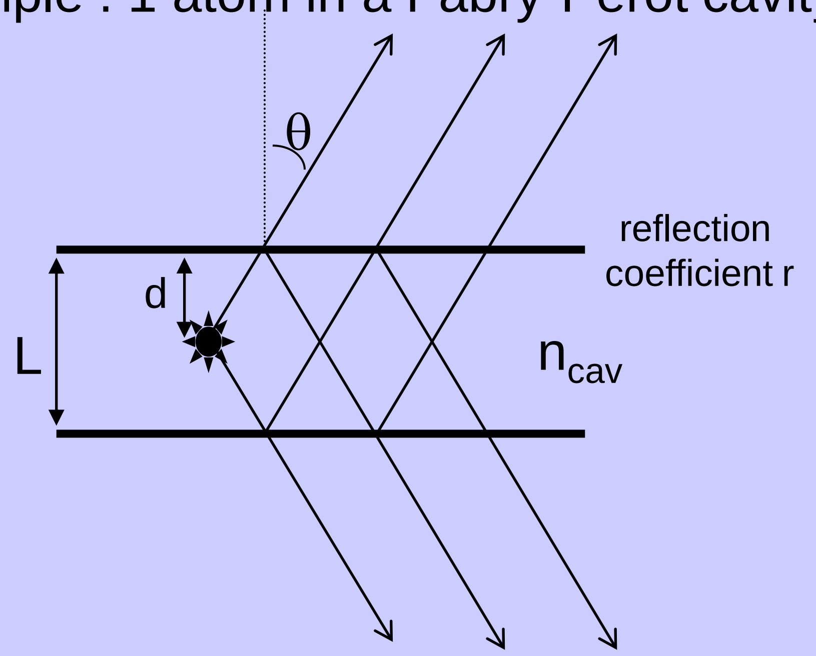
E.M. Purcell
Phys. Rev. **69**, 681 (1946)

Weak coupling, emission diagram modification

Atomes à l'Intérieur d'un Interféromètre Perot-Fabry

A. Kastler

Example : 1 atom in a Fabry-Pérot cavity, emitting at ω



$$I(\omega,\theta) = \frac{1 + r^2 + 2 * r\cos(2\phi_1)}{\left|1 - r^2 e^{-2i\phi}\right|^2}$$

$$\phi = n_{cav} L \cos(\theta)\frac{\omega}{c}$$

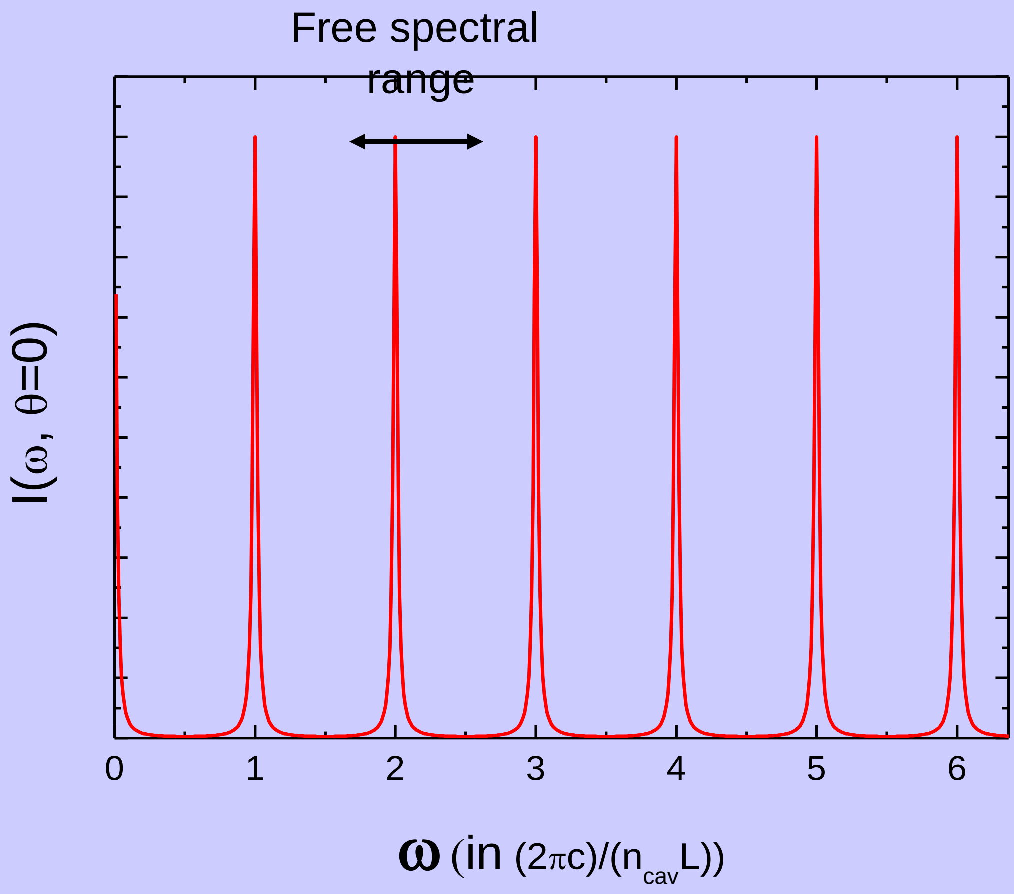
$$\phi_1 = n_{cav} d \cos(\theta)\frac{\omega}{c}$$

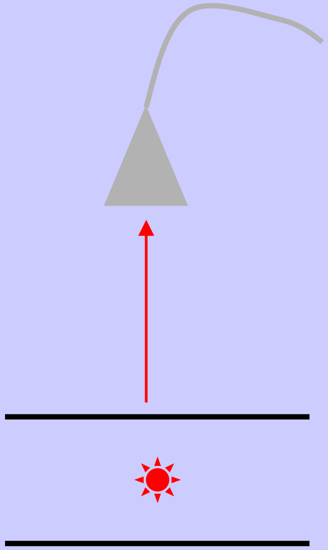
A. Kastler, Appl. Optics **1**,17 (1962)

Weak coupling, emission diagram modification

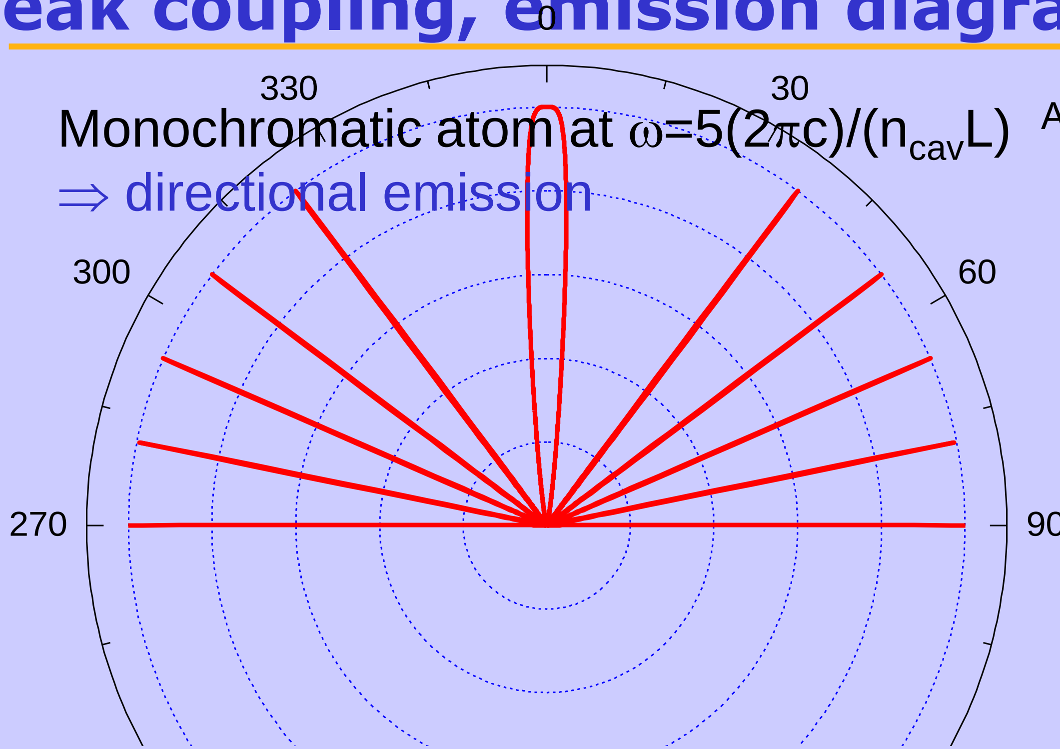
A. Kastler, Appl. Optics **1**,17 (1962)

Emission for a centered atom (varying ω) at normal incidence, r=0.9





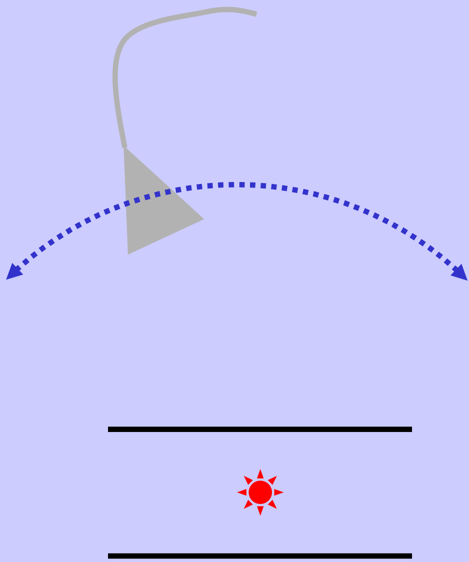
Weak coupling, emission diagram modification



Monochromatic atom at $\omega=5(2\pi c)/(n_{cav}L)$

$\Rightarrow$ directional emission

A. Kastler, Appl. Optics **1**,17 (1962)



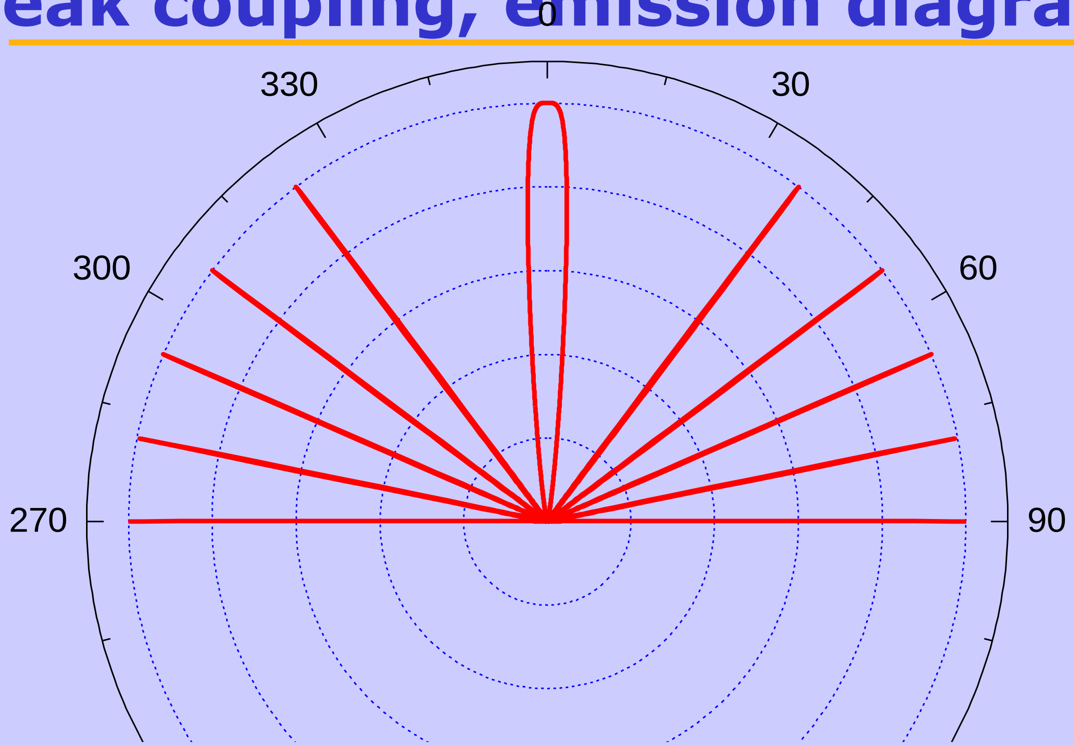
Only **spectral and angular intensity redistribution**

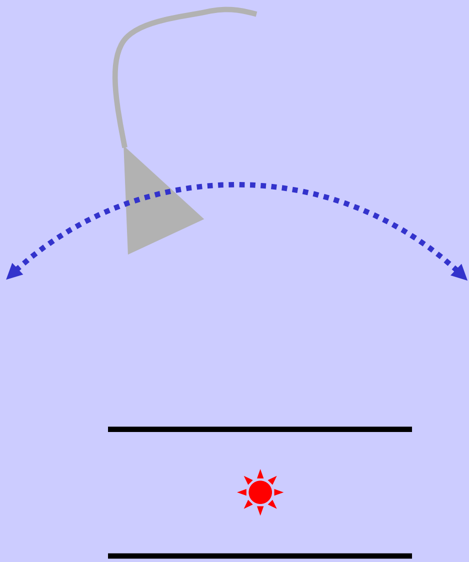
No spontaneous emission rate modification!!

$\Rightarrow$ But can be used to extract more light out of a high index material !!

H. Benisty, H. De Neve and C.Weisbuch, IEEE J. Quantum Electron., **34**, pp. 1612–1643 (1998)

Weak coupling, emission diagram modification





Grâce a l'interposition des faces semi-réfléchissantes, l'énergie lumineuse émise par la couche luminescente, au lieu d'être uniformément répartie dans toutes les directions, est concentrée dans des anneaux fins et extrêmement brillants.

A. Kastler, Appl. Optics **1**,17 (1962)

Weak coupling, emission diagram modification

Were you there? Some of the participants in the Paris ICO meeting July 1961

Photo: Harand

A. Kastler, Appl. Optics **1**,17 (1962)

Key ideas

Spontaneous emission depends on the E-M field **mode structure**

The SE **radiation pattern** is in general modified by the E-M field boundaries

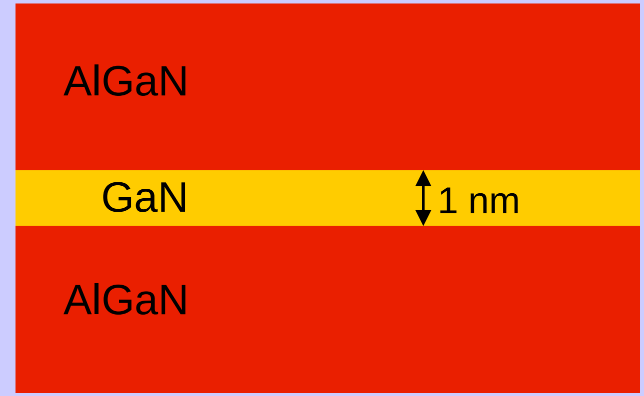
When resonantly coupled to a cavity mode, the SE rate can be modified:

- Weak coupling : **faster SE** in the « overdamped » regime
  => Purcell effect

- Strong coupling : damped reversible SE
  => **mixed emitter-photon modes**

Strong coupling in a planar cavity

Quantum Well



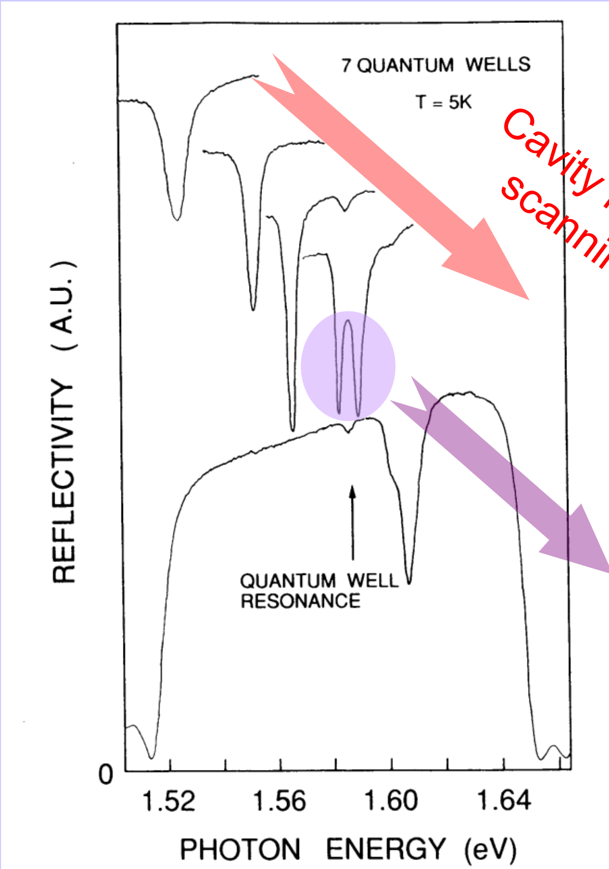
$$\psi_X(r_e,r_h) \propto f(z_e)\,g(z_h)\,e^{-r/a_{2D}}\,e^{i\vec{K}_{x,y}.\vec{R}_{x,y}}$$

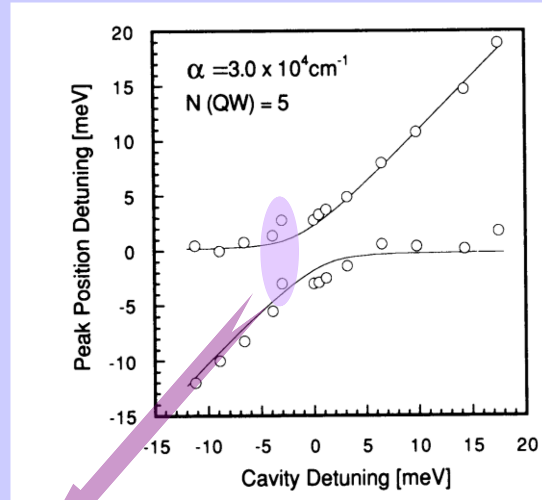
$$\vec{R}_{x,y} = \frac{m_e^*\vec{r}_e + m_h^*\vec{r}_h}{m_e^* + m_h^*}, \vec{K}_{x,y} = \vec{k}^e_{x,y} + \vec{k}^h_{x,y}, \vec{r} = \vec{r}_e - \vec{r}_h$$

In-plane translational invariance for confined field and QW excitons

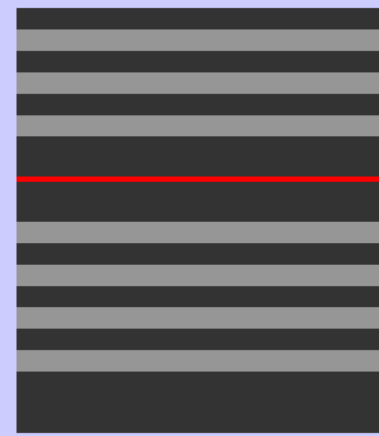
$\Rightarrow$ **one to one coupling** of confined modes and excitons of same $\mathbf{k}_{x,y}$

Strong coupling in a planar cavity





anticrossing at resonance



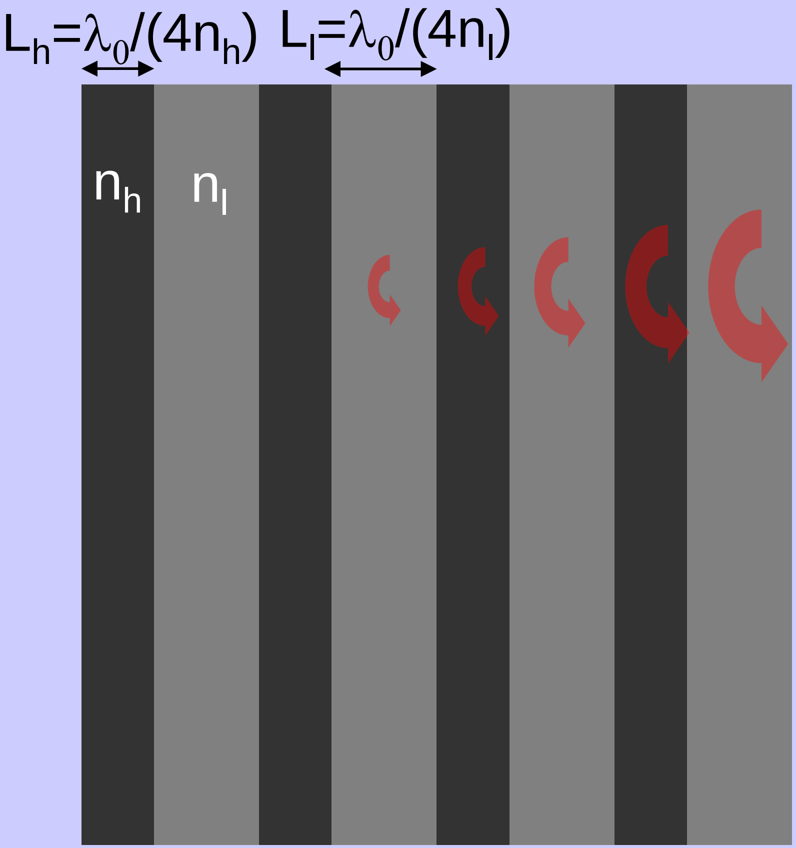
$\Rightarrow$ Creation of mixed exciton-photon states : **2D polaritons**

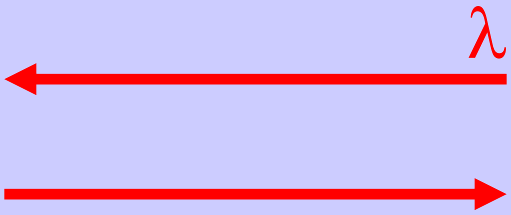
C. Weisbuch *et al.*, Phys. Rev. Lett. **69**, 3314 (1992)

Bragg mirrors

DBR = Distributed Bragg Reflector

$\Rightarrow$ rely on periodicity to have Bragg reflection





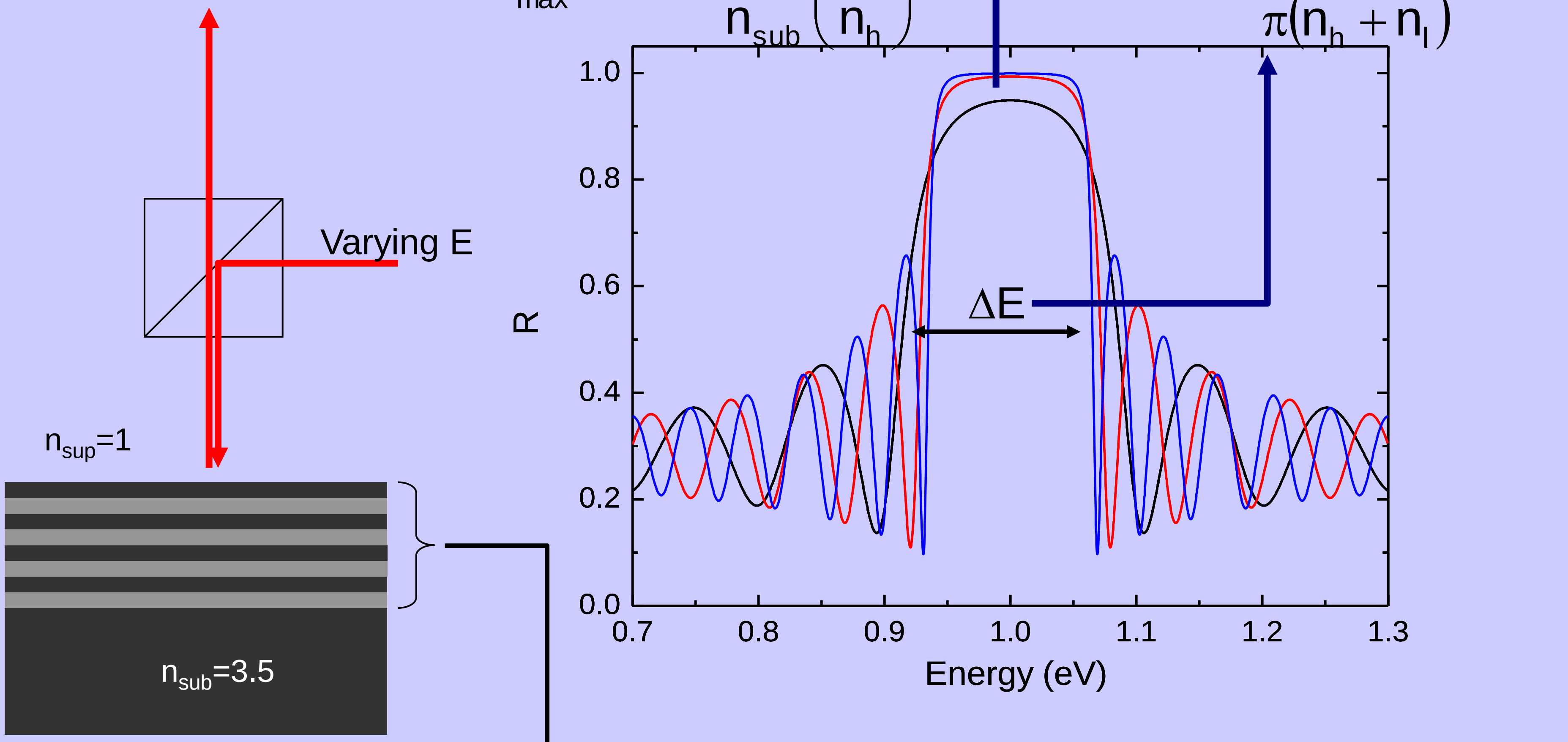
Reflection at each interface

At resonant wavelength:
- Constructive reflection interference
- Destructive propagation interference

Bragg mirrors

$$R_{max} = 1 - 4\frac{n_{sup}}{n_{sub}}\left(\frac{n_l}{n_h}\right)^{2N}$$

$$\Delta E = \frac{4E_{res}(n_h - n_l)}{\pi(n_h + n_l)}$$



DBR N pairs
n_h=3.5 (GaAs), n_l=2.95 (AlAs)
resonant at E=1eV (λ=1.24µm)

Comparison of III-N and III-As systems

$$R_{max} = 1 - 4\frac{n_{sup}}{n_{sub}}\left(\frac{n_l}{n_h}\right)^{2N}$$

III-As

n_{GaAs}=3.5, n_{AlAs}=3
Lattice-matched

R=99%
N=16

III-N

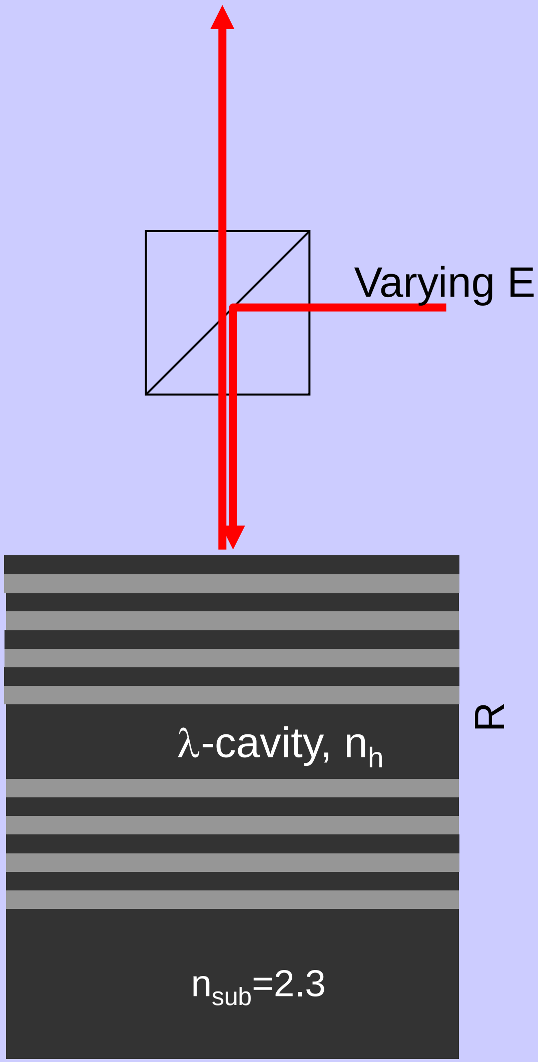
n_{GaN}=2.3, n_{AlN}=2.1
Lattice mismatch=2.4%

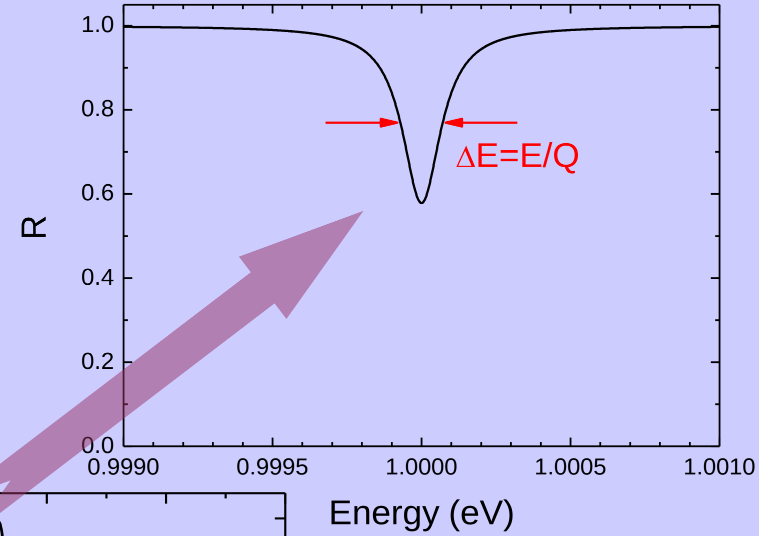
R=99%
N=20 to 60 for GaN/AlGaN DBR

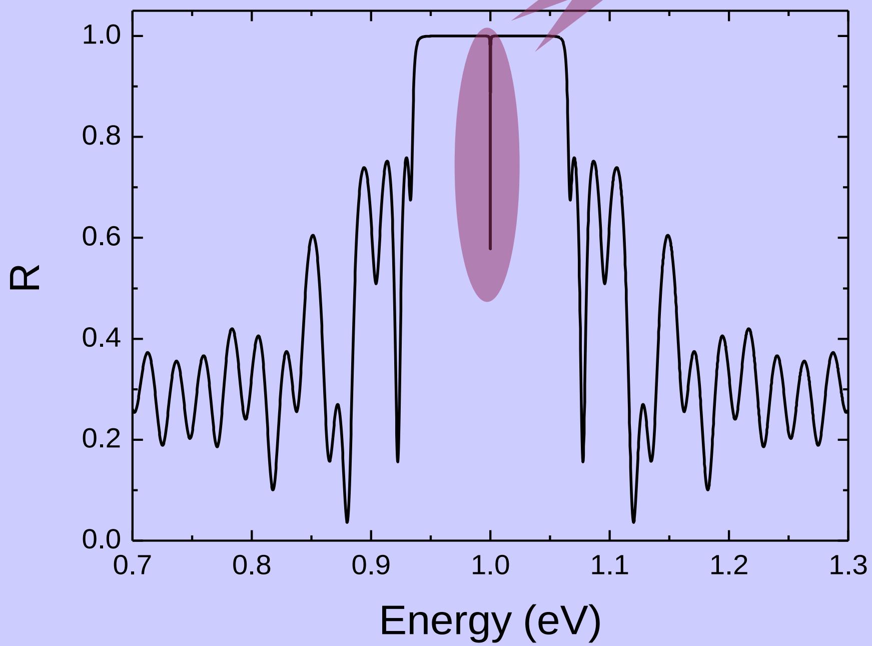
$Al_{0.2}Ga_{0.8}N/Al_{0.85}In_{0.15}N$
Lattice matched
R=99%
N=27

E. Feltin *et al.*, Appl. Phys. Lett. **88** 051108 (2006)

DBR based Fabry-Pérot







Q typically
10^3 => 10^4
(τ_{cav} : 0.5 => 5 ps)

Transmission=1
on resonance for
perfectly balanced
mirrors

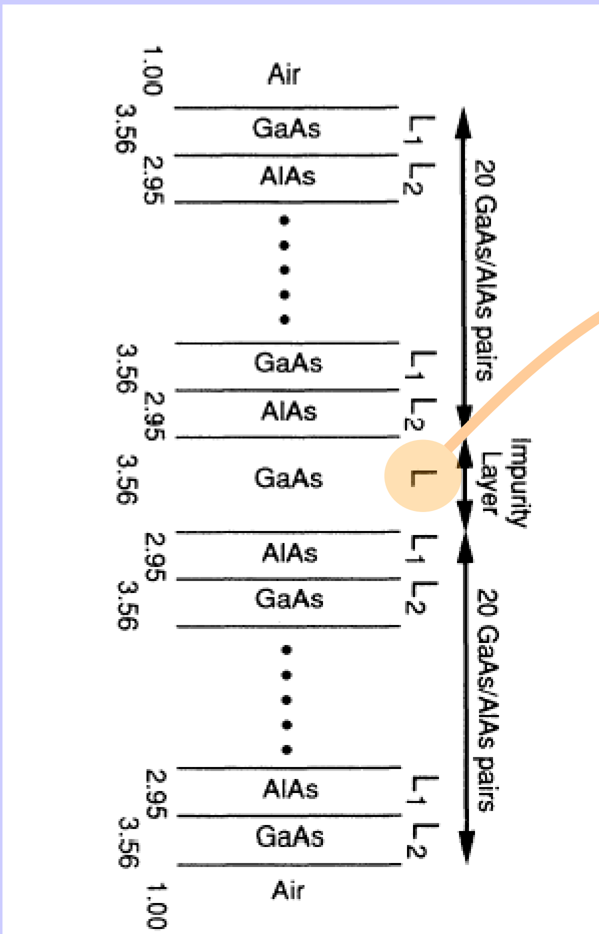
Bragg mirrors as 1D photonic band gap

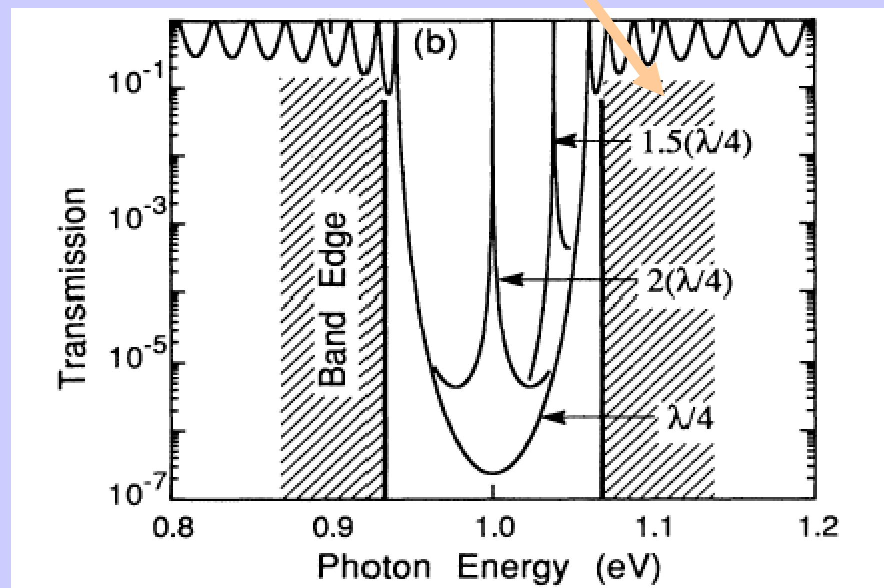
R. P. Stanley *et al.*, Phys. Rev. A **48**, 2246 (1993)

Analogy between Maxwell and Schrödinger equations

⇒ the Bragg reflector as a 1D photonic bandgap

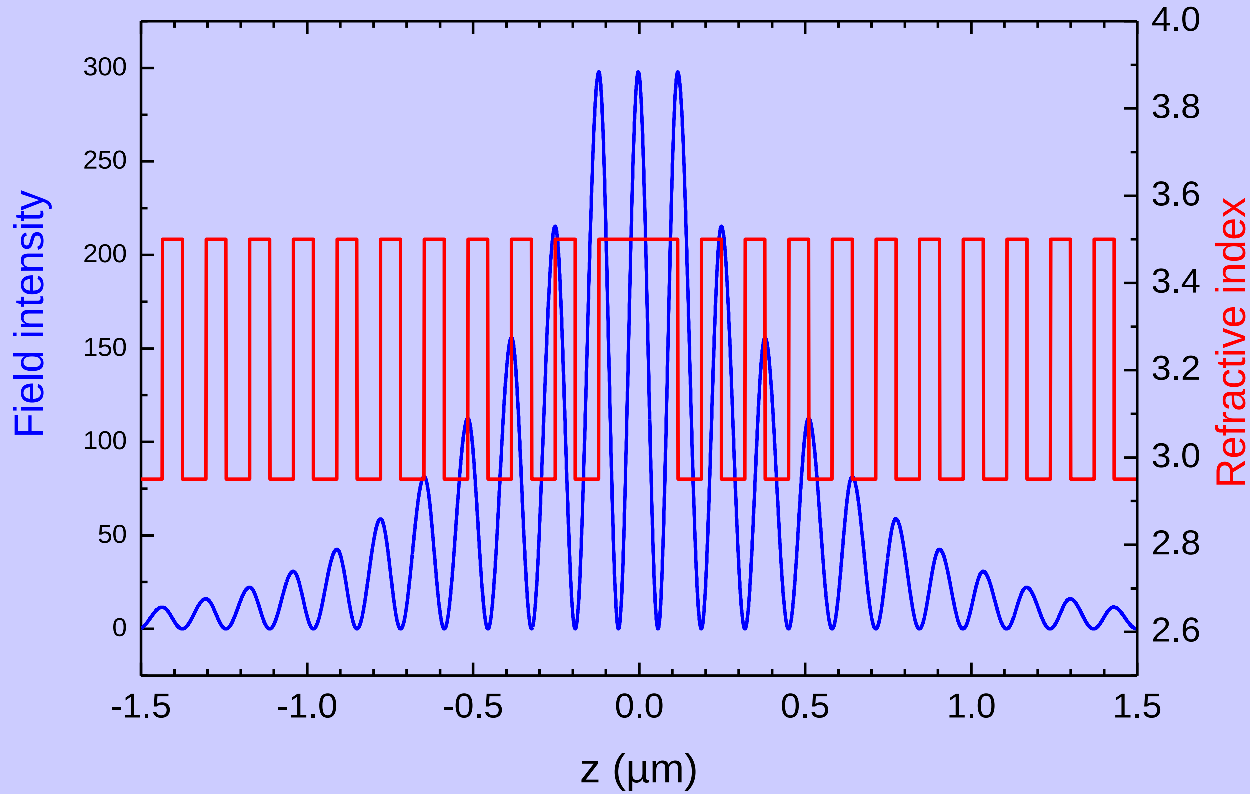
⇒ varying the height of one layer introduces an impurity state in the gap





DBR based Fabry-Pérot

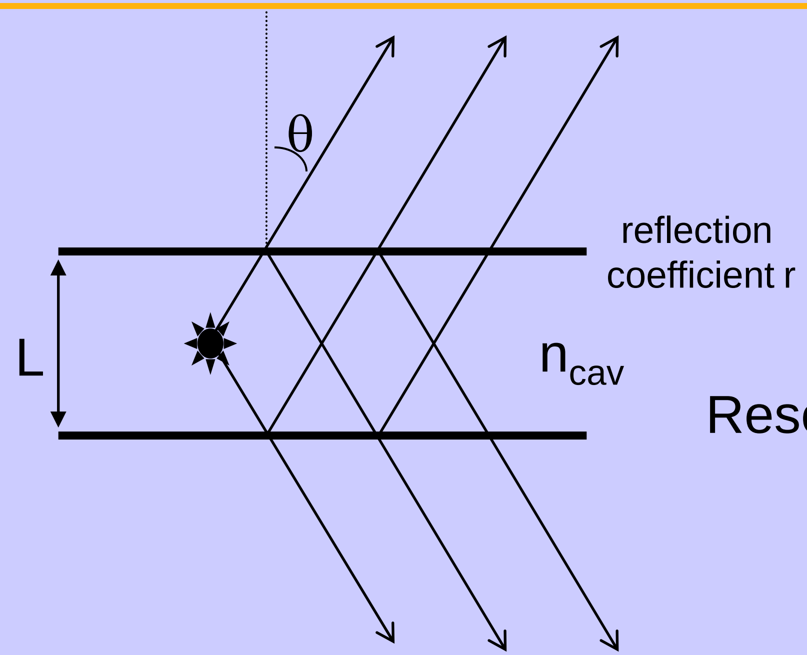
Longitudinal E-M field profile at resonance:



$\Rightarrow$ Field peaked at cavity center, exponential decay in the DBRs

Mode extent larger than for metal mirror cavity!

Planar microcavities : the photon effective mass



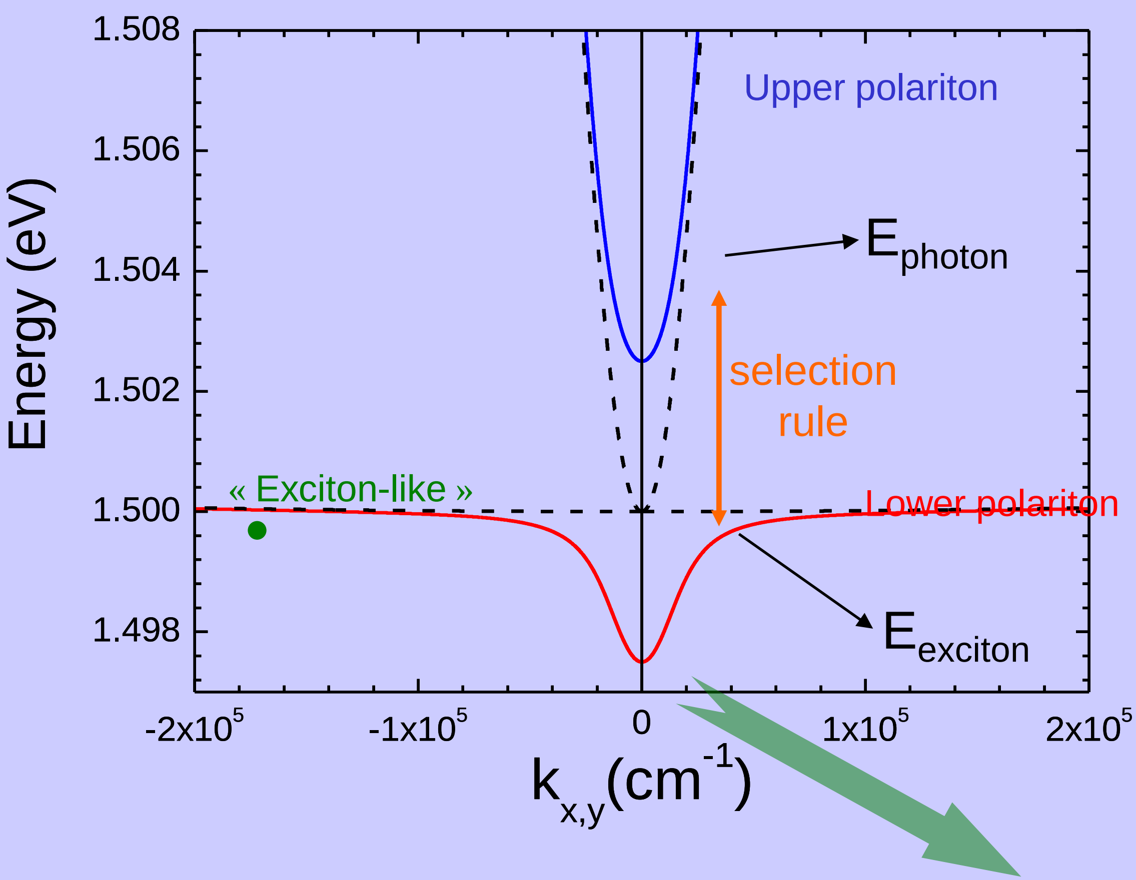
Resonance condition : $$k_z = \frac{p\pi}{L}$$

$$\Rightarrow E = \frac{\hbar c}{n_{cav}} \sqrt{\left(\frac{p\pi}{L}\right)^2 + k_{x,y}^2} \approx \frac{\hbar c p\pi}{n_{cav} L} + \frac{\hbar^2 k_{x,y}^2}{2m_{ph}^*}$$

$$m_{ph}^* = \frac{\hbar n_{cav} p\pi}{cL}$$

Strong coupling in a planar cavity

New dispersion relation :



$$E_X = E_{X,0} + \frac{\hbar^2 K_{//}^2}{2M_{X,//}}$$

$$E_{Ph} = E_{Ph,0} + \frac{\hbar^2 k_{//}^2}{2m_{Ph}^*}$$

$m_{ph} \sim 10^{-5}\ m_e$

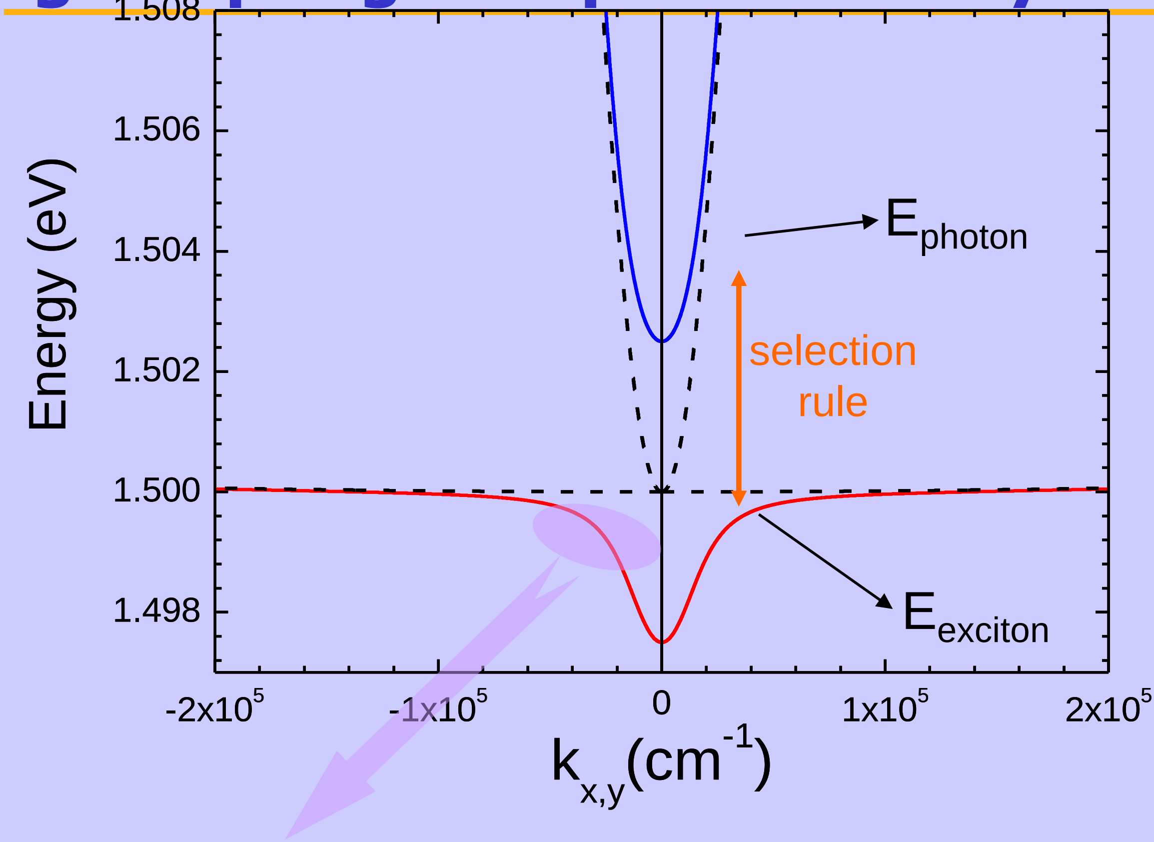
$m_{exc} \sim 10^{-1}\ m_e$

(confined photon + exciton)

$\Rightarrow$ Fast (~5 ps) desintegration through photon escape

$\Rightarrow$ 100% directional extraction through top mirror

Strong coupling in a planar cavity



$m_{ph} \sim 10^{-5}\ m_e$

$m_{exc} \sim 10^{-1}\ m_e$

Condition for condensation

$$\frac{n}{k_B T} > \frac{2m}{h^2}$$

Relaxation bottleneck
(high DOS vs low DOS at $k_{x,y} \sim 0$)

F. Tassone *et al.*, Phys. Rev. B **53**, R7642 (1996)

BUT excitons = bosons in the low density regime

⇒ Stimulated emission of polaritons : $R = R_0(1 + \langle N \rangle)$

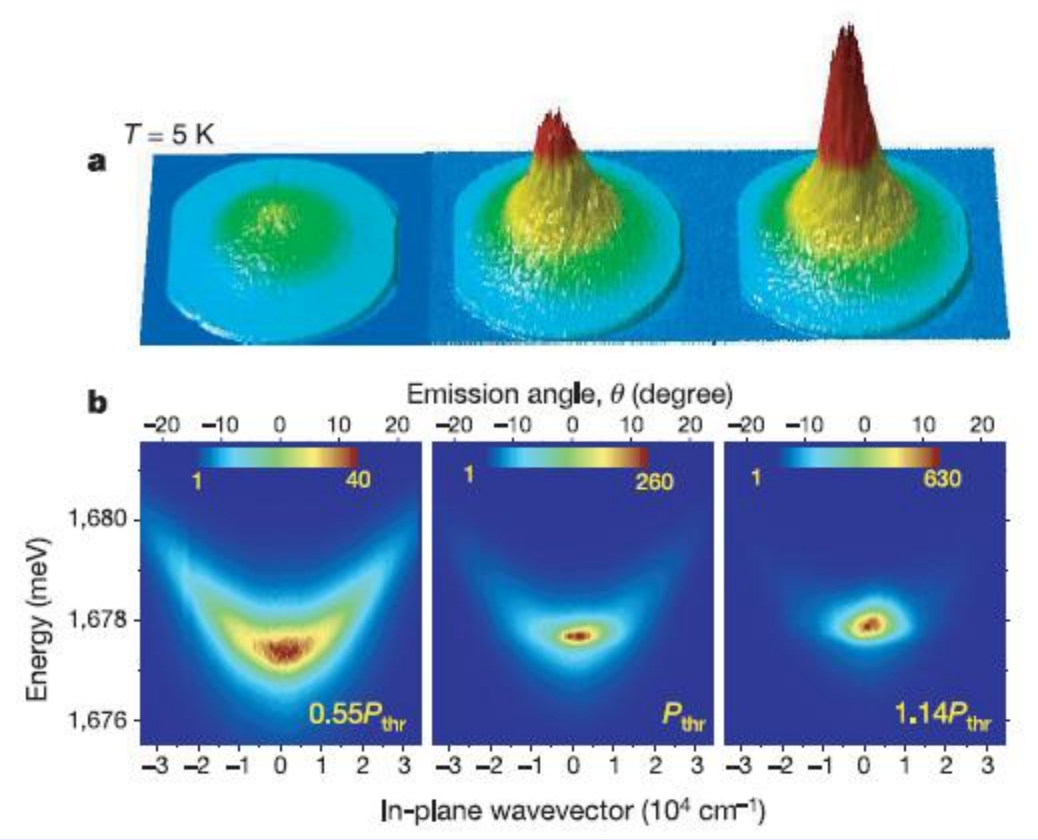
⇒ **Polariton laser or solid-state BEC**

A. Imamoglu *et al.*
Phys. Rev. A **53**, 4250 (1996)

Strong coupling in a planar cavity

"Bose–Einstein condensation of exciton polaritons"

⇒ reach stimulated relaxation of polaritons before exciton screening



J. Kasprzak *et al.*, Nature **443**, 409 (2006)

Polariton lasing and polariton condensation…

B. Deveaud-Plédran
"On the condensation of polaritons"
J. Opt. Soc. Am. B **29** A138 (2012)

It is central at this stage to correct a misuse of words: conventional lasing in semiconductors does not correspond to population inversion (which would mean having more electrons in the conduction band than electrons in the valence band). The lasing condition in semiconductors is the well-known Bernard–Durraffourg condition [63], i.e., that the distance between the quasi-Fermi levels for electron and holes is larger than the energy of the gap. **It is therefore misleading to talk, in semiconductors, about lasing without inversion.**

D. Bajoni
"Polariton lasers. Hybrid light-matter lasers without inversion"
J. Appl. Phys. D: Appl. Phys. **45** 409501 (2012)

The phenomenon of polariton condensation is exactly equivalent to the polariton lasing we have described in the previous section, and further investigation showed that thermal equilibrium is not achieved by the polariton gas, so that **the term Bose–Einstein condensate is not exact** and a weaker definition of condensation, which does not involve thermal equilibrium, has been applied to the justify the term condensation for polaritons

Strong coupling with nitrides

Reference system : GaAs/AlAs cavities, InGaAs QWs

⇒ Very large Q factors (10000-50000)
⇒ long polariton lifetime ~15 ps and little disorder induced localization

But : *restricted to low temperatures*
restricted to low pump powers

III-N system:

⇒ Large intrinsic light matter coupling
⇒ QW exciton stable at 300 K, more stable at large pump power

But : *high quality mirrors difficult to fabricate, much photonic disorder*

Strong coupling with nitrides

The "Mott density" for 2D excitons

$$n \approx \frac{1}{25\, a_B^2}$$

Smooth transition to e-h plasma, due to phase-space filling

	a (nm)	N_{mott}(cm-2)
GaN	2.8	$5\ 10^{11}$
GaAs	12	$2.5\ 10^{10}$

N. F. Mott, Philos. Mag. **6** 287 (1961)
S. Schmitt-Rink *et al.*, Phys. Rev. B **32** 6601 (1985)

Strong coupling with nitrides

APPLIED PHYSICS LETTERS VOLUME 81, NUMBER 3 15 JULY 2002

Room-temperature polariton lasers based on GaN microcavities

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Aldo Di Carlo
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Alexey Kavokin
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Jeremy J. Baumberg[b)]
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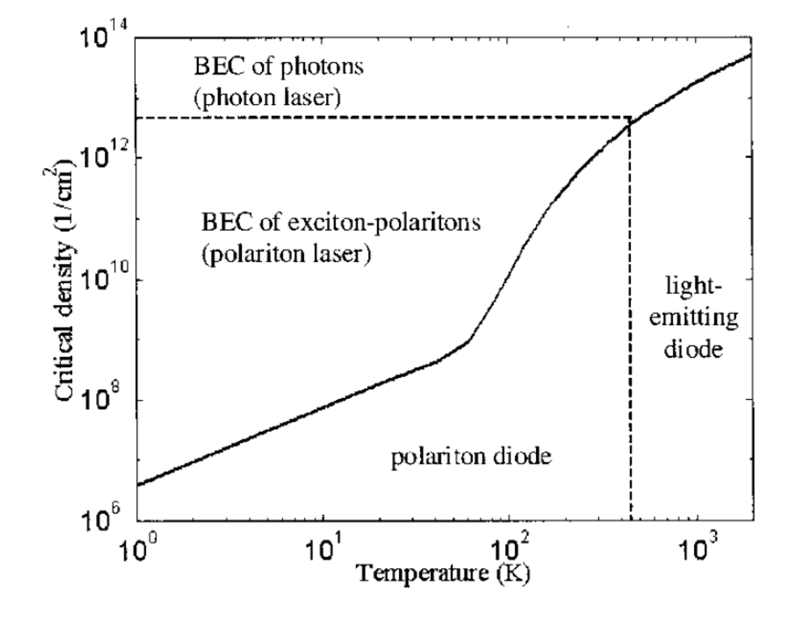
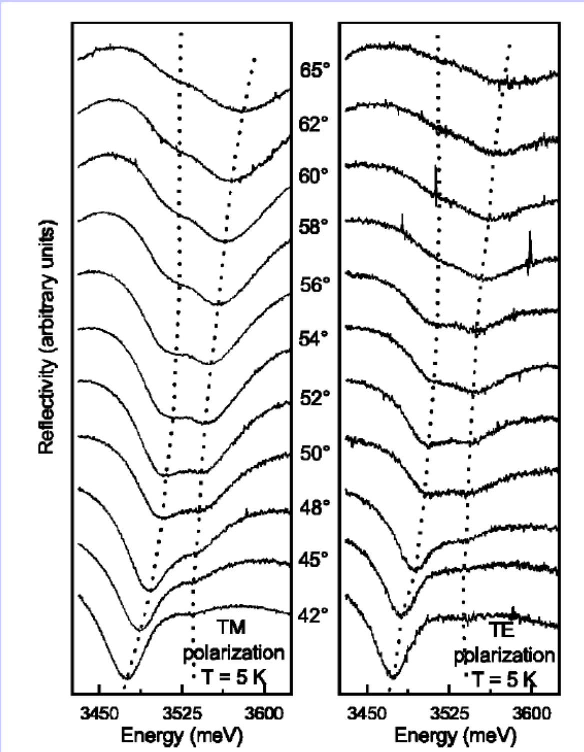
Paolo Lugli
INFM-Department of Electrical Ing., University of Rome "Tor Vergata," 110-I00133, Roma, Italy

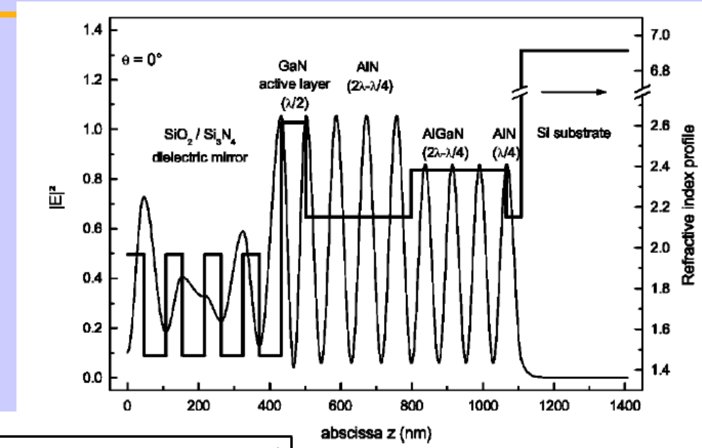
(1) GaN excitons are stable at room temperature;
(2) the light-matter coupling is enormously strong, as we will show below; and
(3) GaN technology is now increasingly well developed, and the observation of the strong coupling regime in such structures seems likely to be achieved.

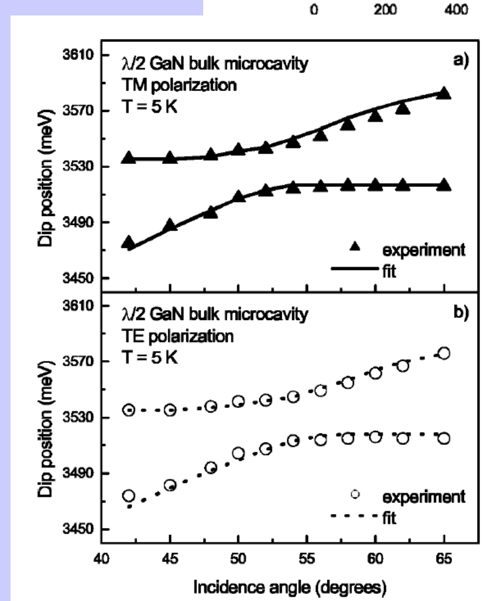


Strong coupling with nitrides

First demonstration:



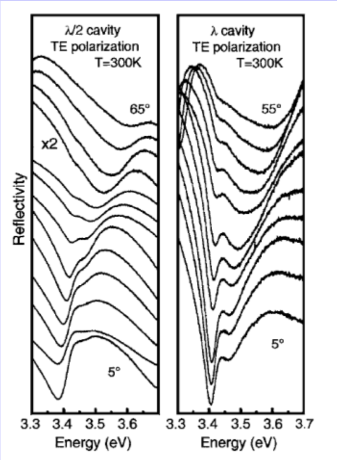




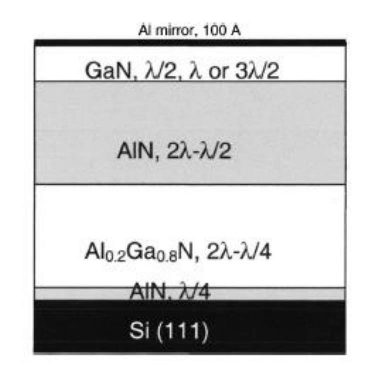
Bulk GaN, Q~100, 5 K, but strong coupling **Ω=30 meV**

A. Antoine-Vincent *et al.*, Phys. Rev. B **68** 153313 (2003)

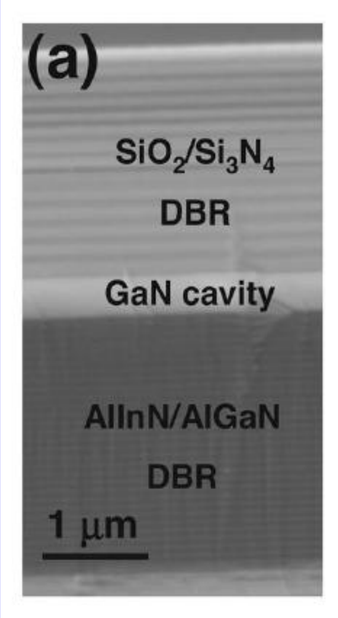
Strong coupling with nitrides

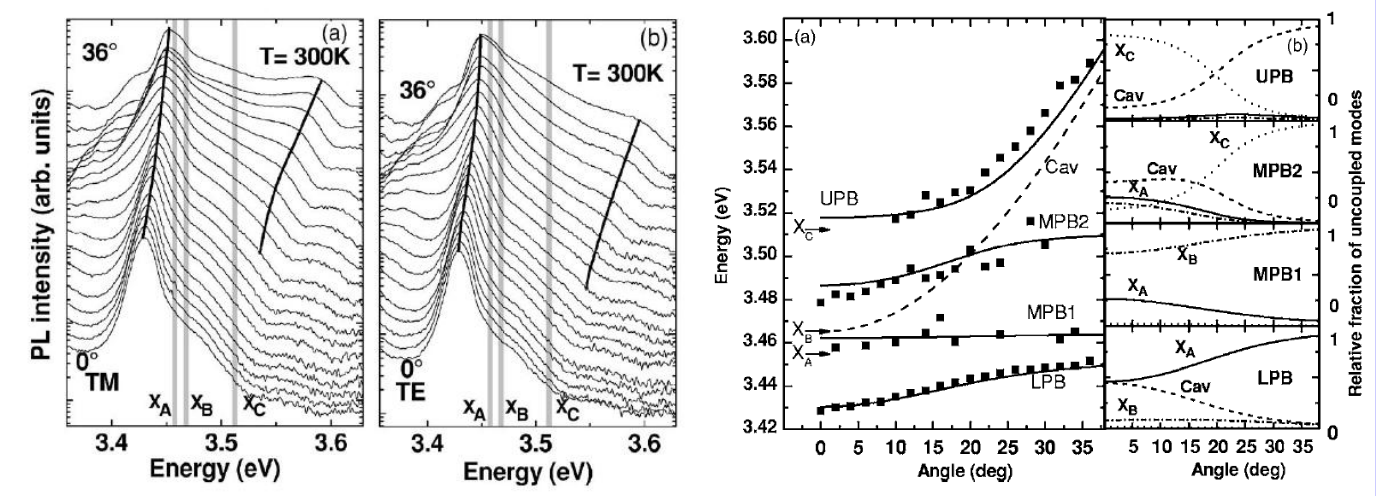


F. Semond *et al.*, Appl. Phys. Lett. **87** 021102 (2005)



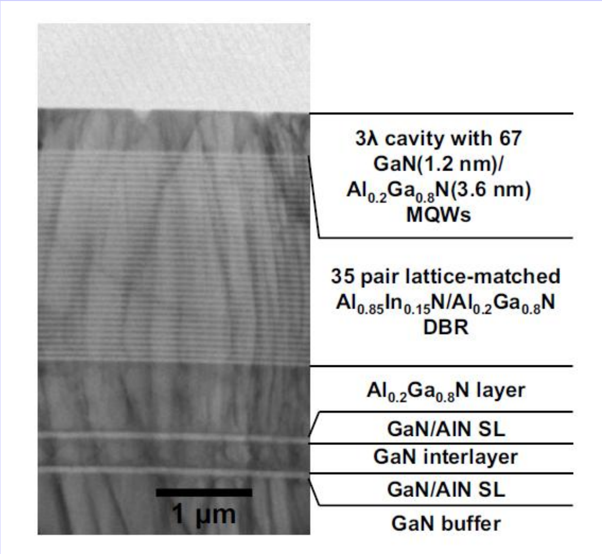
Room temperature strong coupling !





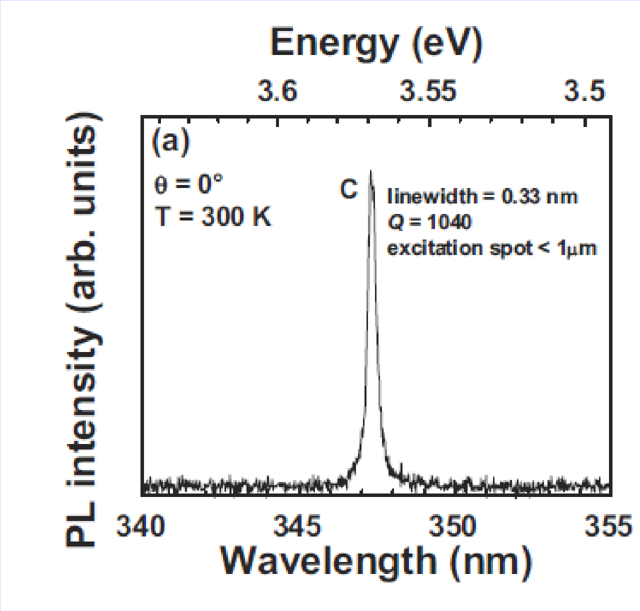
R. Butté *et al.*, Phys. Rev. B **73** 033315 (2006)

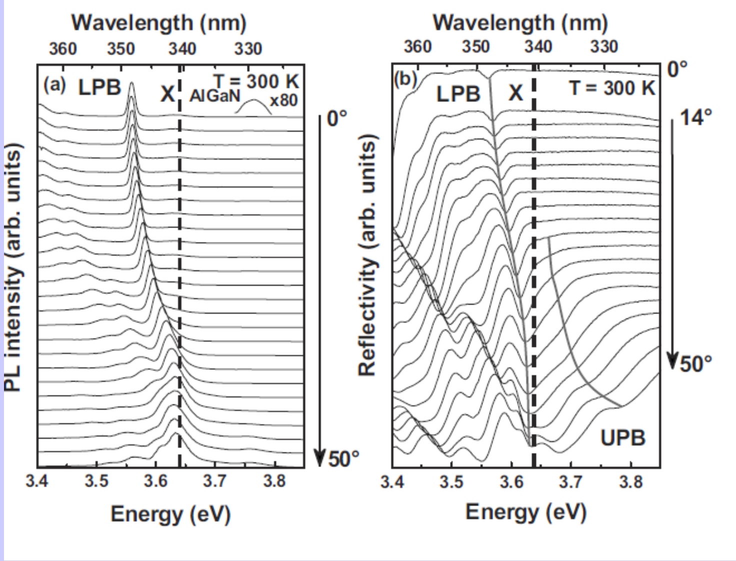
Strong coupling with nitrides



For N QWs

$$\Omega \propto \sqrt{N}$$

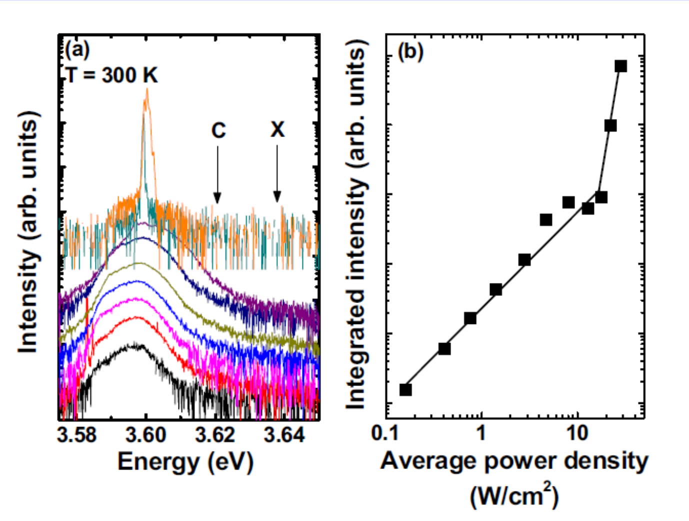


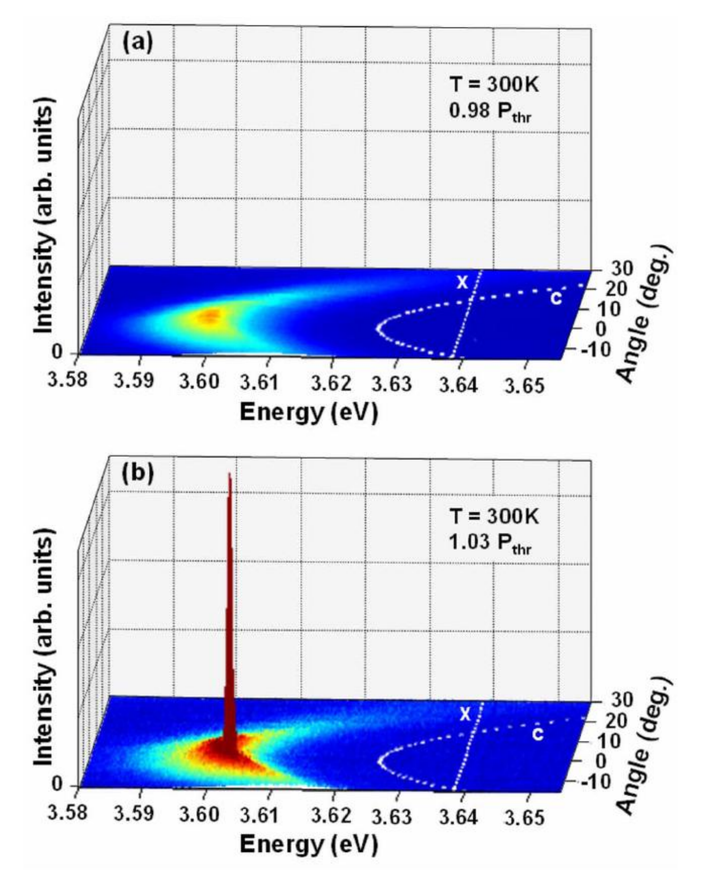


Ω=50 meV

G. Christmann *et al.*, Phys. Rev. B **77** 085310 (2008)

Strong coupling with nitrides



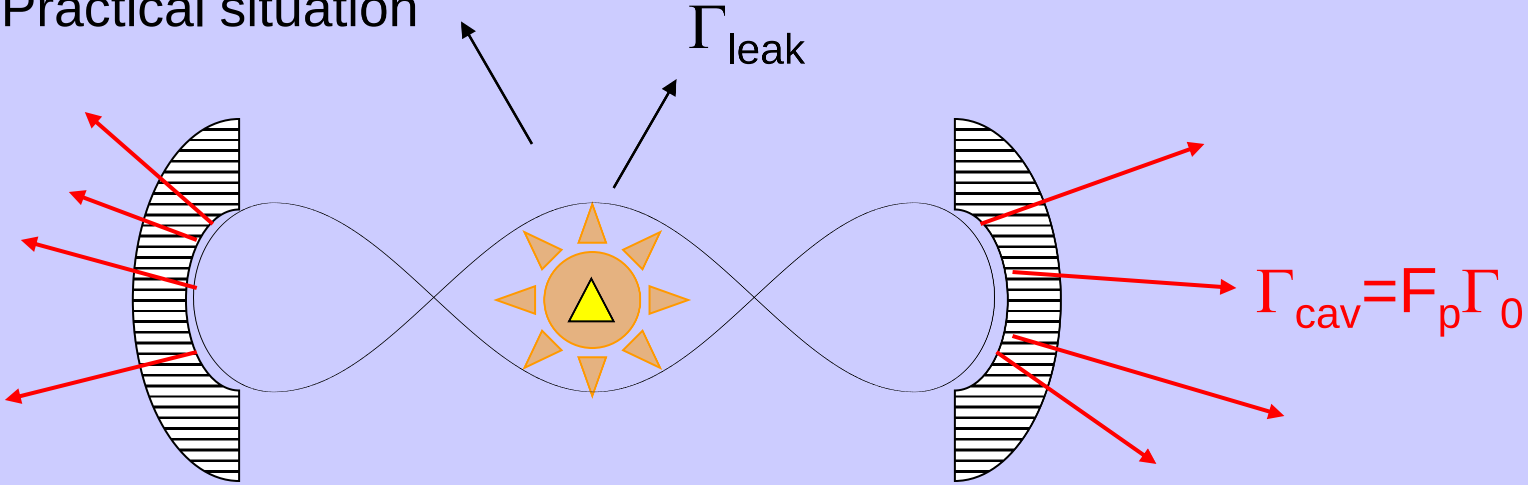


Room temperature polariton lasing

G. Christmann *et al.*, Appl. Phys. Lett. **93** 051102 (2008)

The Purcell effect

Practical situation



$$\Gamma=\Gamma_{cav}+\Gamma_{leak}\sim\Gamma_0(F_p+1)$$

β=(photons in confined mode)/(emitted photons)=Γ_{cav}/Γ

$$\boldsymbol{\beta=F_p/(F_p+1)}$$

$\Rightarrow$ For high Fp, **monomode emission** without inhibition!!

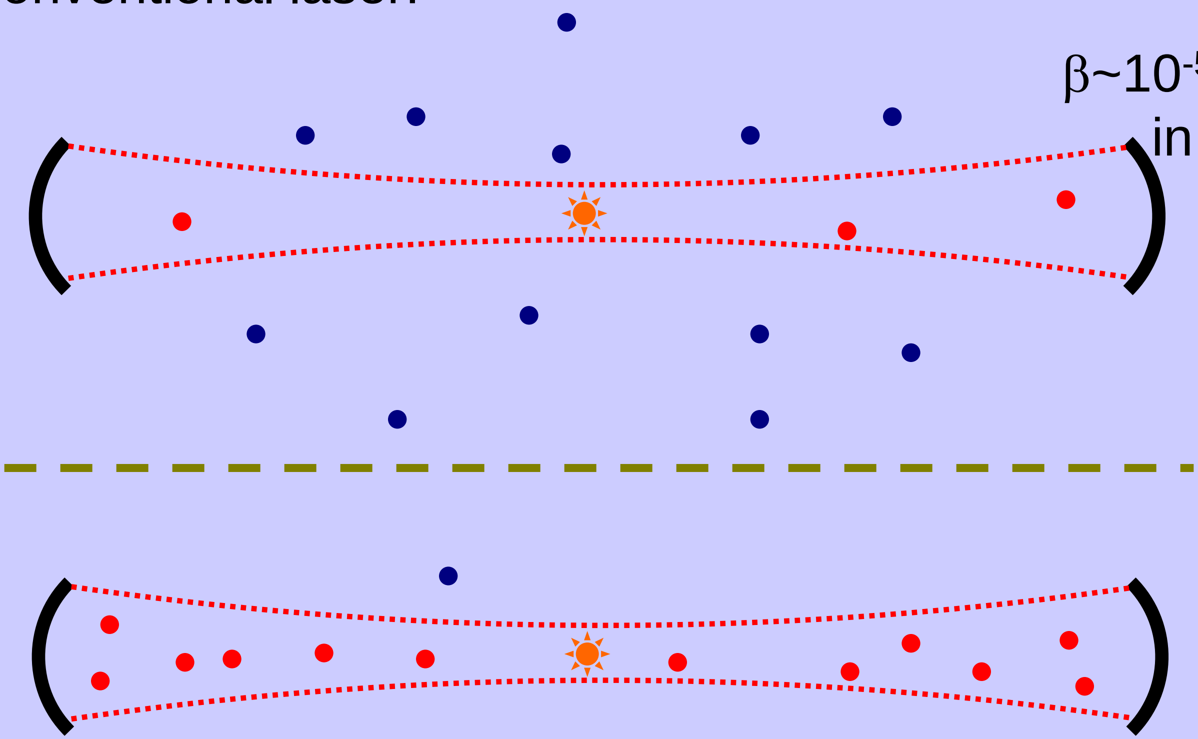
Application prospects

Thresholdless laser:

Conventional laser:

β~10^{-5} photons in mode

Below threshold:



Above threshold:

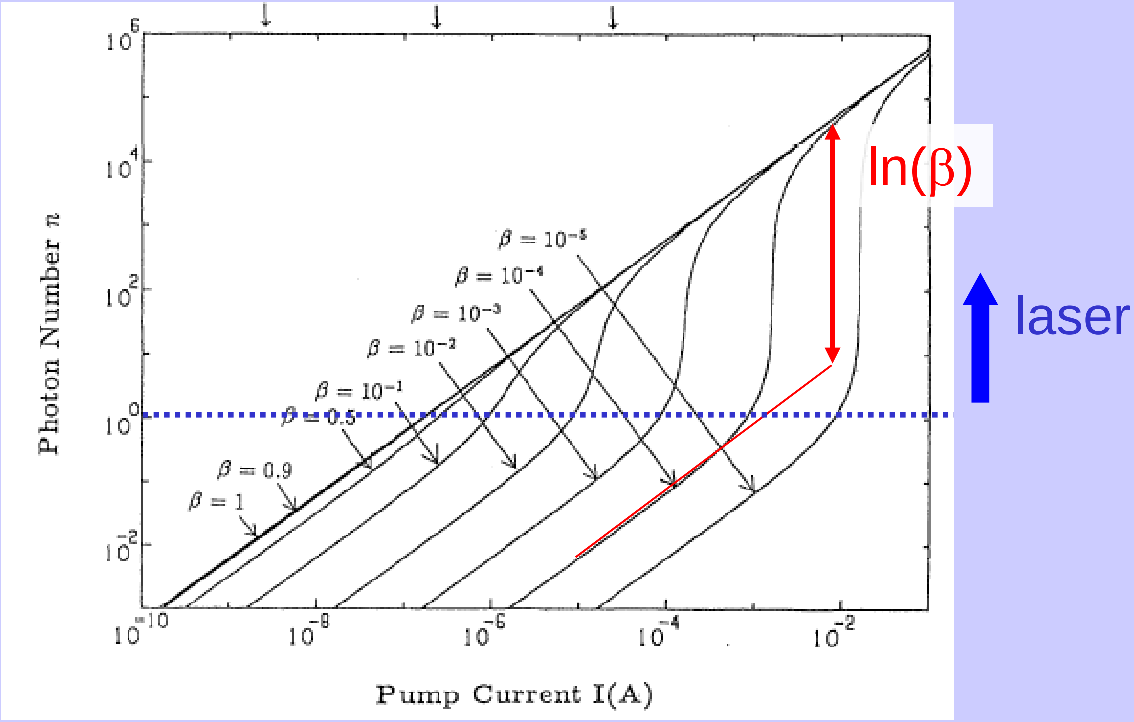
~all photons in mode

The Purcell effect

Thresholdless laser:

T. Kobayashi *et al.*, Tech. Dig. of 43rd Fall meeting of Japanese Applied Physics Society, paper 29a-B-6 (1982)

$$P_{in} = \frac{\gamma_{cav} n(1+\beta n)}{\beta(1+n)}$$



High β regime : all photons feed into mode *below threshold!!*

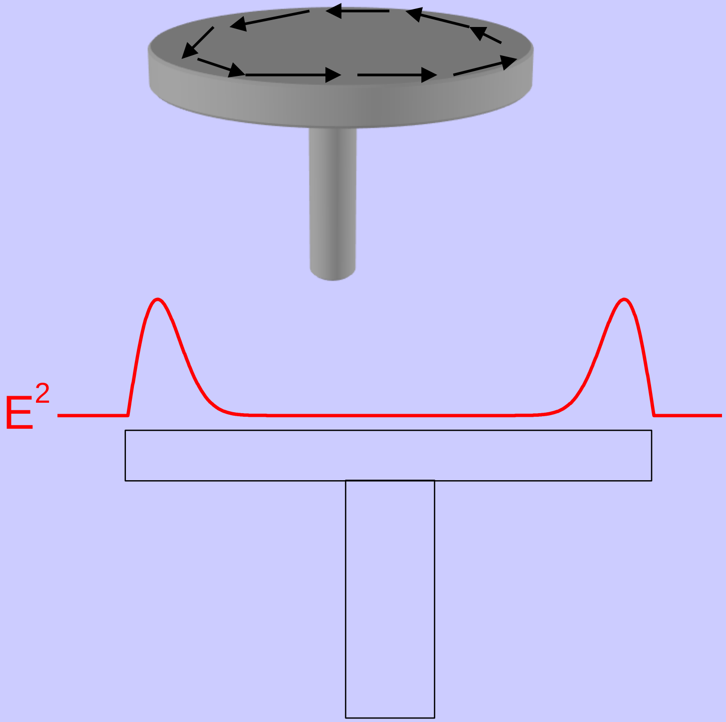
$P_{th} = \gamma_{cav}\,(1+\beta)/2\beta$ => P_{th} scales as $1/\beta$

For β~1 and Q~10000, P_{th} ~ 20 nA!

Y. Yamamoto *et al.*, Phys. Rev. A **44**, 657 (1991)

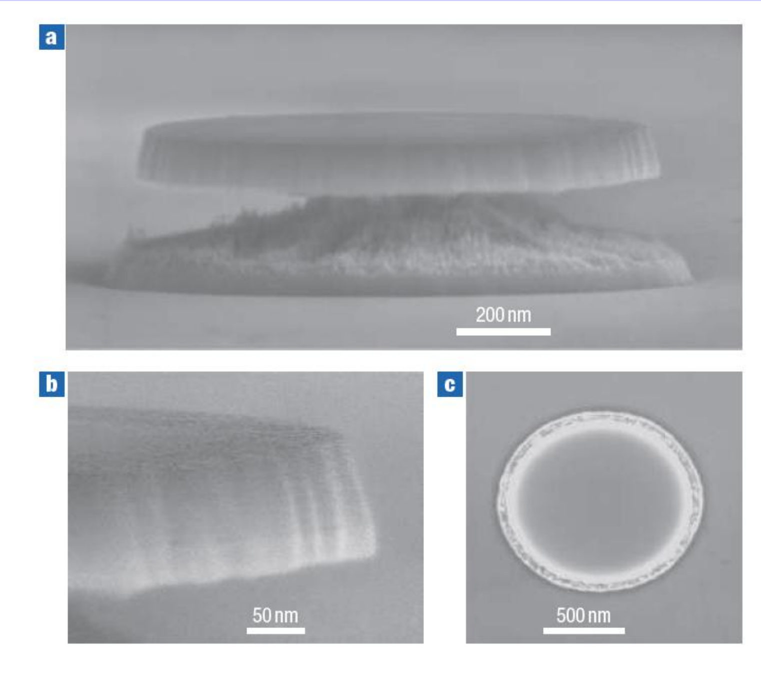
Various nitride microcavities

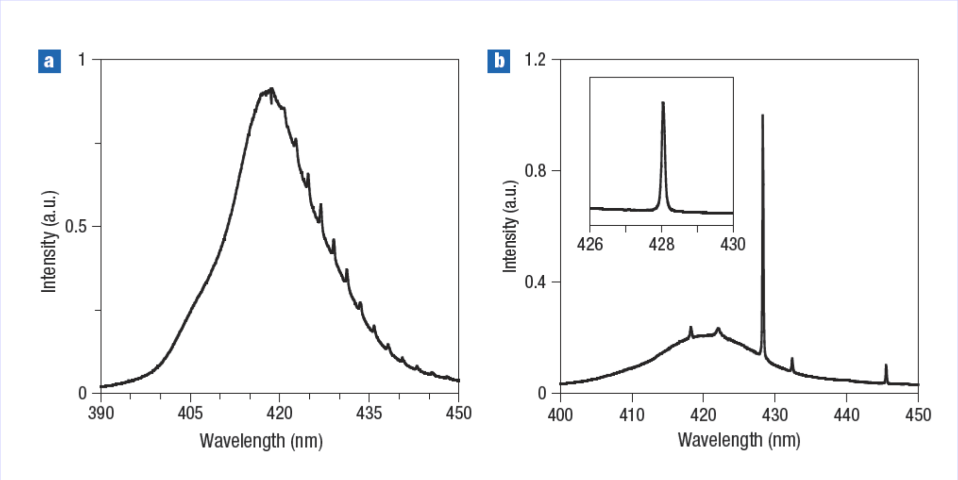
Whispering gallery modes confined by total internal reflection



G. Mie, Ann. Phys. (NY) **25**, 377 (1908)
Lord Rayleigh, « The problem of the whispering gallery », Scientic Papers **5**, 617 (1912)

Various nitride microcavities





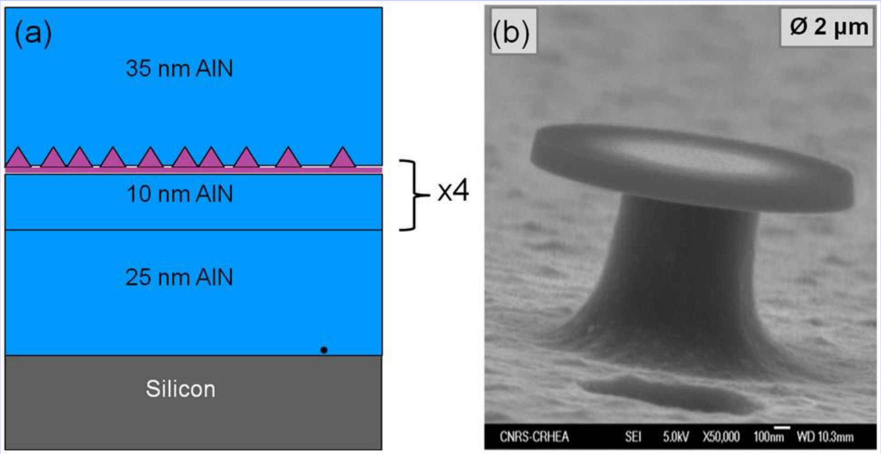
Q~4000

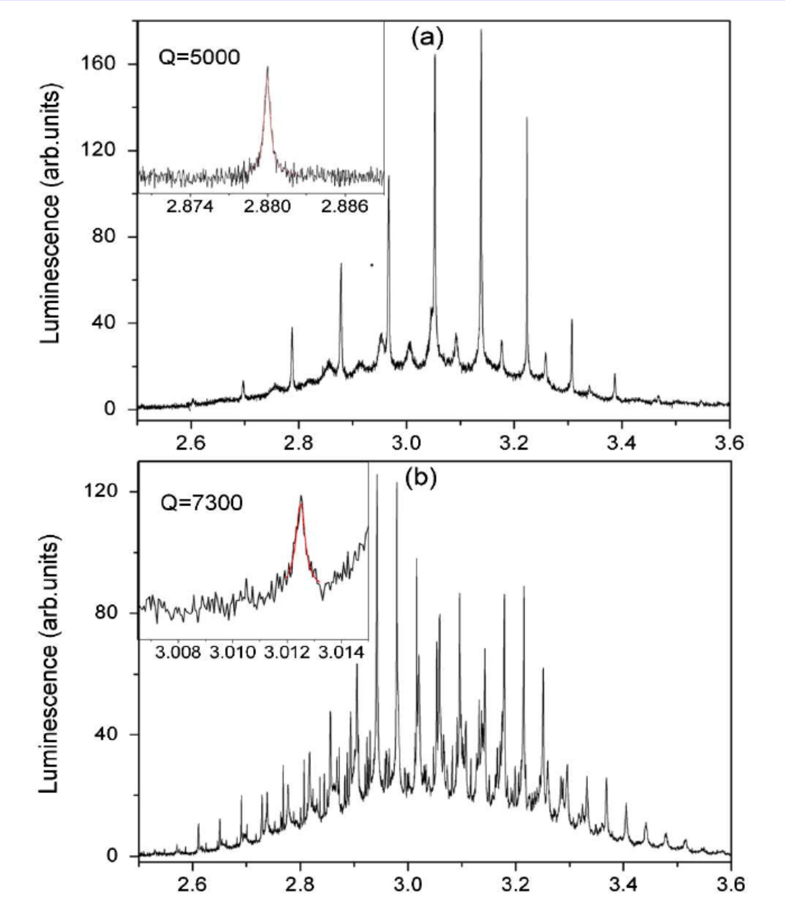
InGaN QWs in a GaN slab

Lasing at room temperature in a microlaser

A. C. Tamboli *et al.*, Nature Photon. **1** 61 (2007)

Various nitride microcavities

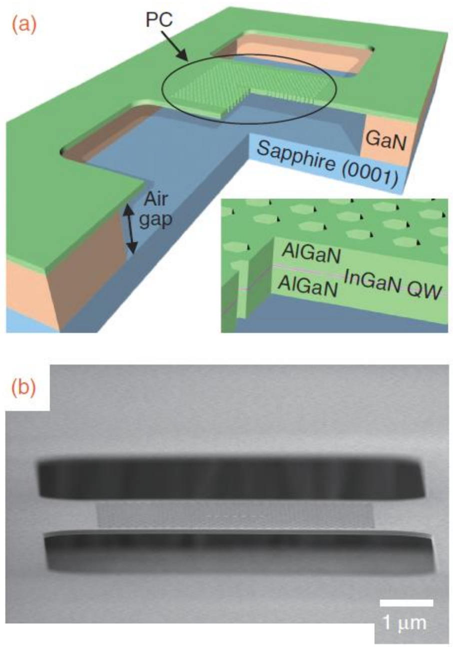


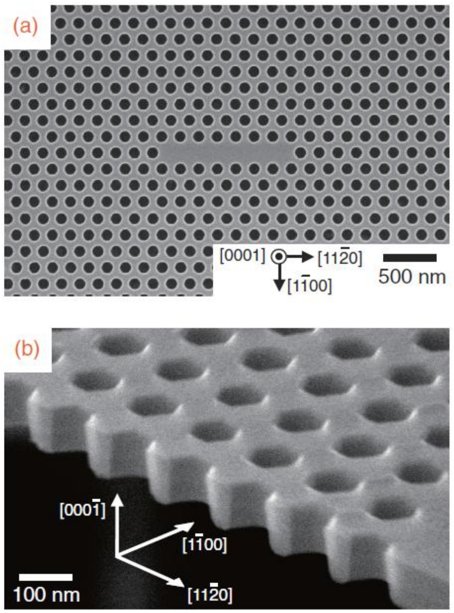


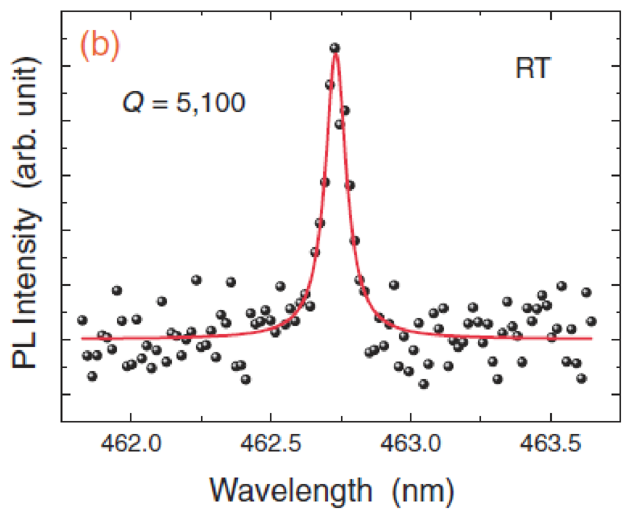
GaN quantum dots in AlN slab on Si

M. Mexis *et al.*, Opt. Lett. **36** 2203 (2011)

Various nitride microcavities

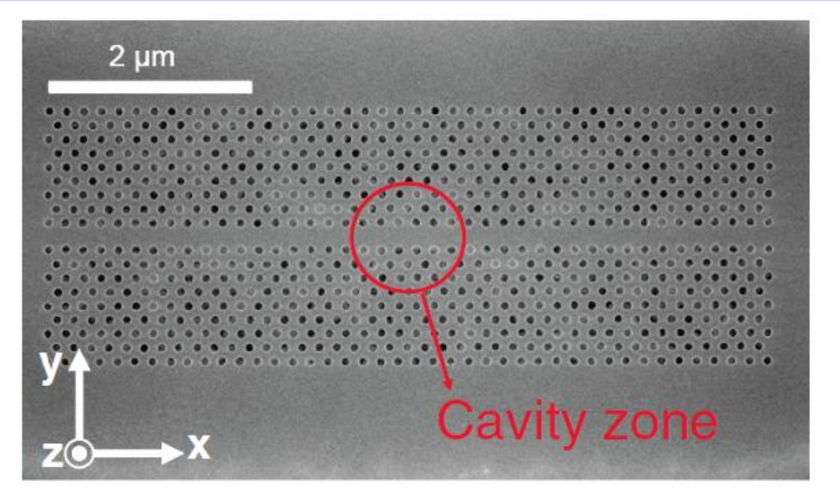




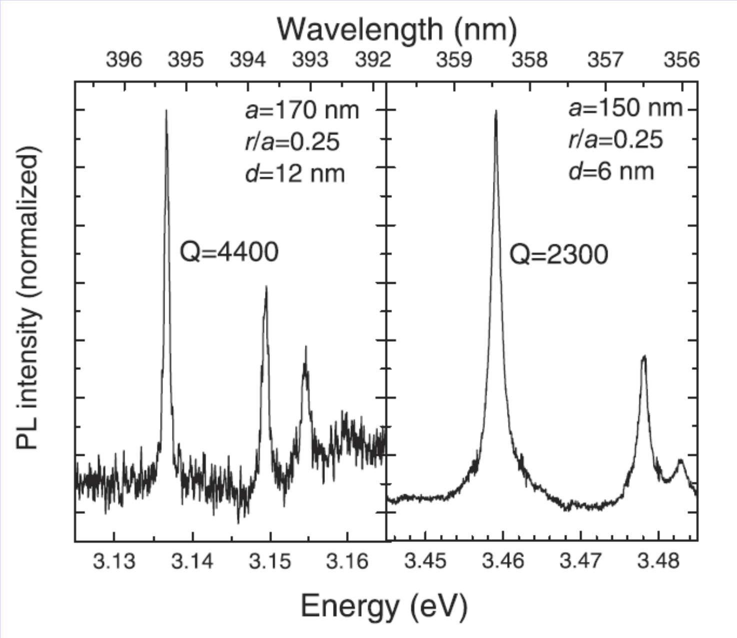


M. Arita *et al.*, Appl. Phys. Exp. **5** 126502 (2012)

Various nitride microcavities



GaN quantum dots in AlN on Si



D. Sam-Giao *et al.*, Appl. Phys. Lett. **100** 191104 (2012)

Various nitride microcavities

Prospects

- UV microlasers based on the Purcell effect

- Strong coupling in other geometries than planar cavity
  $\Rightarrow$ Strong coupling in photonic crystal slabs

Microdisk cavities

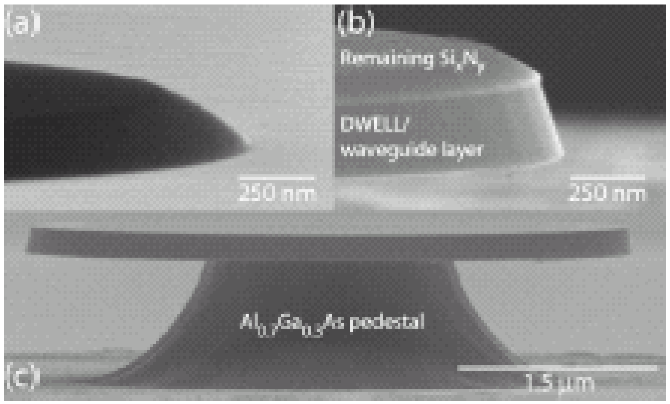
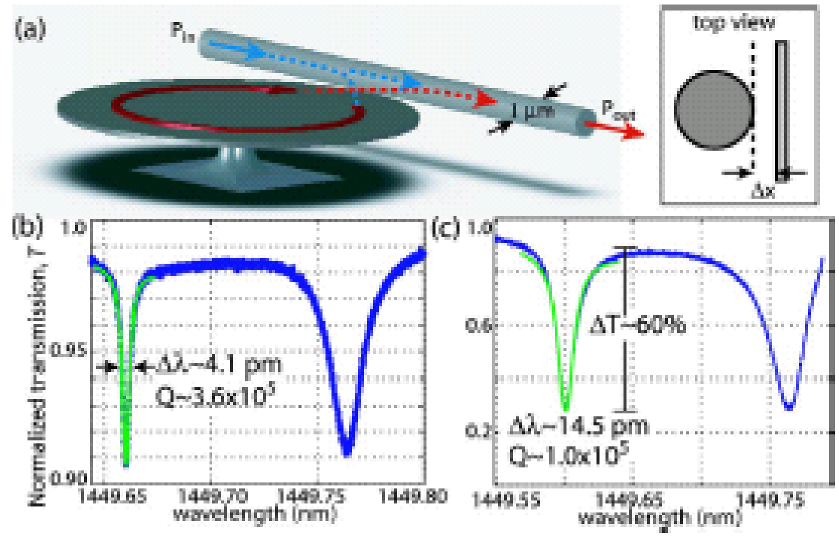


FIG. 1. Scanning electron microscope images of DWELL-containing microdisk cavities after the (a) Si_xN_y etch, and (b) and (c) AlGaAs etch and undercut.

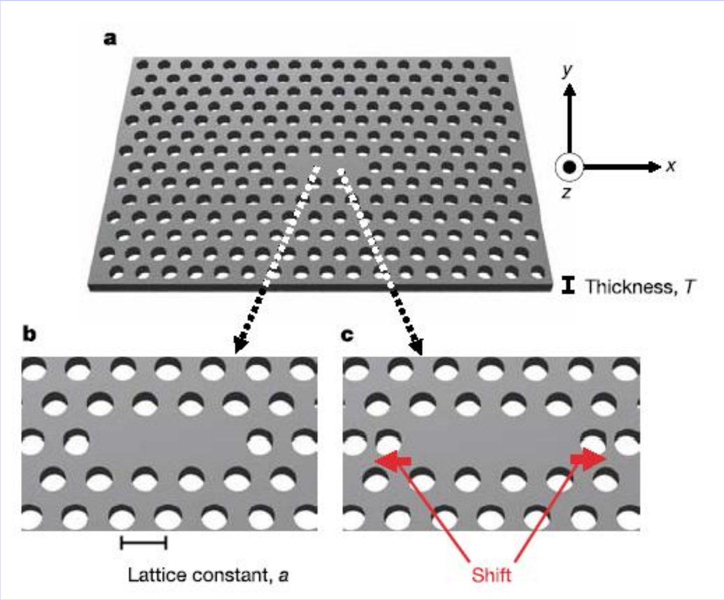


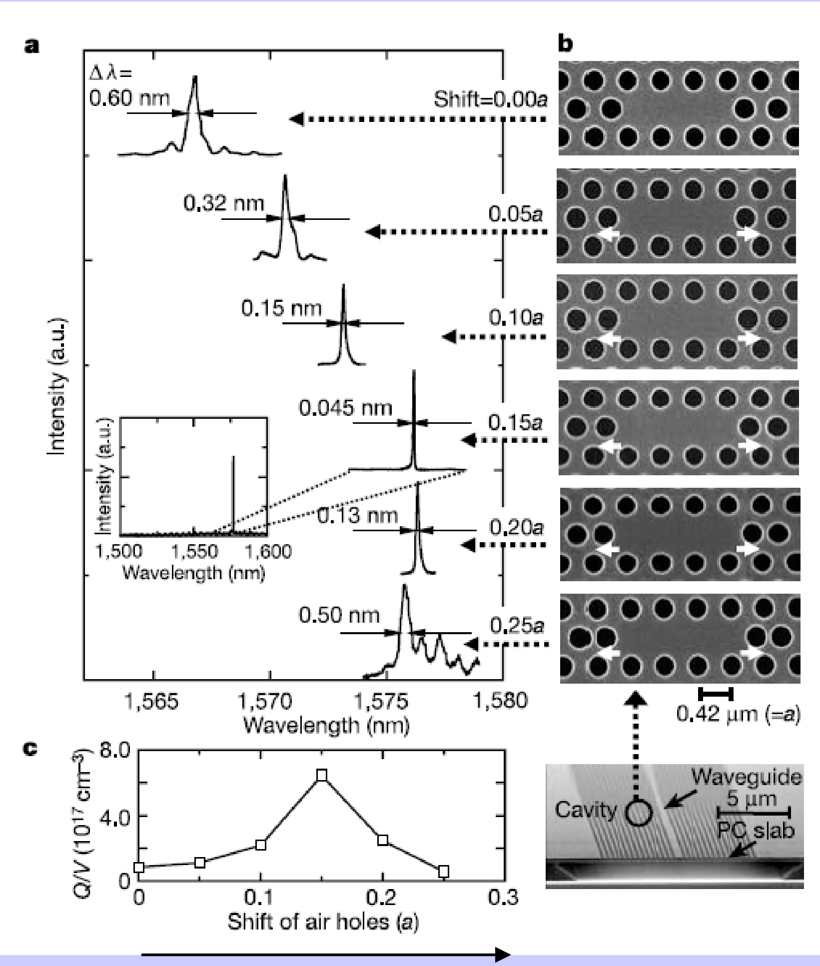
K. Srinivasan *et al.*, Appl. Phys. Lett. **86**, 151106 (2005)

d~ 4 µm, V~ 6 $(\lambda/n)^3$, Q=360000, F_p=4500 !

Remark : Result for empty cavities… probably less when QDs are inserted due to the increase of residual background absorption

2D photonic band gap cavities





Q=35000

F_p~4000

100 nm

Y. Akahane *et al.*, Nature **425**, 944 (2003)

Fundamental papers (my very subjective selection)

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)

Volume 27, Number 24 — PHYSICAL REVIEW LETTERS — 13 December 1971

Observation of Polaritons in GaAs: A New Interpretation of the Free-Exciton Reflectance and Luminescence

D. D. Sell, R. Dingle, S. E. Stokowski, and J. V. DiLorenzo
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 1 November 1971)

Volume 33, Number 14 — PHYSICAL REVIEW LETTERS — 30 September 1974

Quantum States of Confined Carriers in Very Thin $Al_xGa_{1-x}As$-GaAs-$Al_xGa_{1-x}As$ Heterostructures

R. Dingle, W. Wiegmann, and C. H. Henry
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 24 June 1974)

RAPID COMMUNICATIONS

PHYSICAL REVIEW B — VOLUME 30, NUMBER 2 — 15 JULY 1984

Reflectance of two-dimensional excitons in GaAs-AlGaAs quantum wells

L. Schultheis* and K. Ploog
Max-Planck-Institut für Festkörperforschung, D-7000 Stuttgart 80, Federal Republic of Germany
(Received 27 March 1984)

Fundamental papers (my very subjective selection)

VOLUME 58, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1987

Inhibited Spontaneous Emission in Solid-State Physics and Electronics

Eli Yablonovitch
Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701
(Received 23 December 1986)

VOLUME 67, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1991

Enhanced Radiative Recombination of Free Excitons in GaAs Quantum Wells

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Centre National d'Etudes de Télécommunications, 22300 Lannion, France

N. Roy, K. Satzke, and B. Sermage
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(Received 15 April 1991; revised manuscript received 15 August 1991)

VOLUME 69, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1992

Observation of the Coupled Exciton-Photon Mode Splitting in a Semiconductor Quantum Microcavity

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(Received 12 May 1992)

phys. stat. sol. (b) **424**, No. 111, 2345–2356 (2005) / **DOI** 10.1002/pssb.200560972

Feature Article

Microcavities in Ecole Polytechnique Fédérale de Lausanne, Ecole Polytechnique (France) and elsewhere: past, present and future

Claude Weisbuch[*,1,2,3] and **Henri Benisty**[**,4]

Fundamental papers (my very subjective selection)