The Abdus Salam
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2234-8

Meeting of Modern Science and School Physics: College for School Teachers of Physics in ICTP

27 April - 3 May, 2011

Excitons: artificial hydrogen atoms in crystals

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Excitons: artificial hydrogen atoms in crystals

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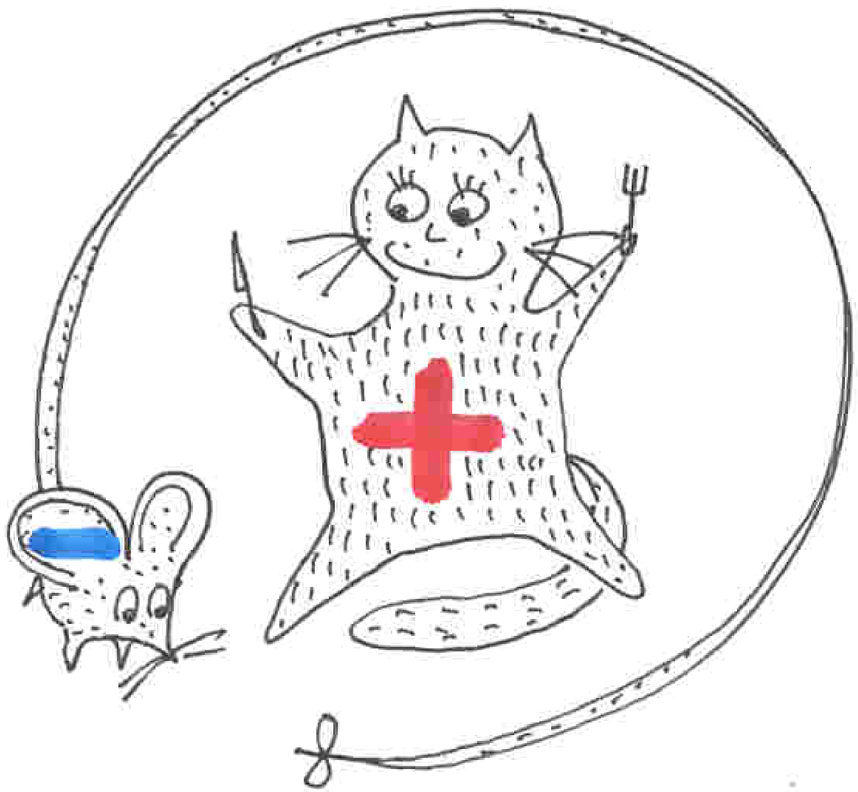
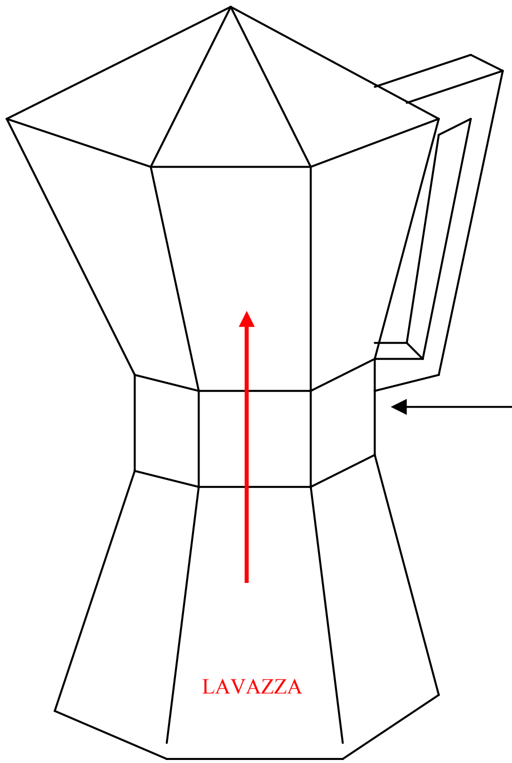
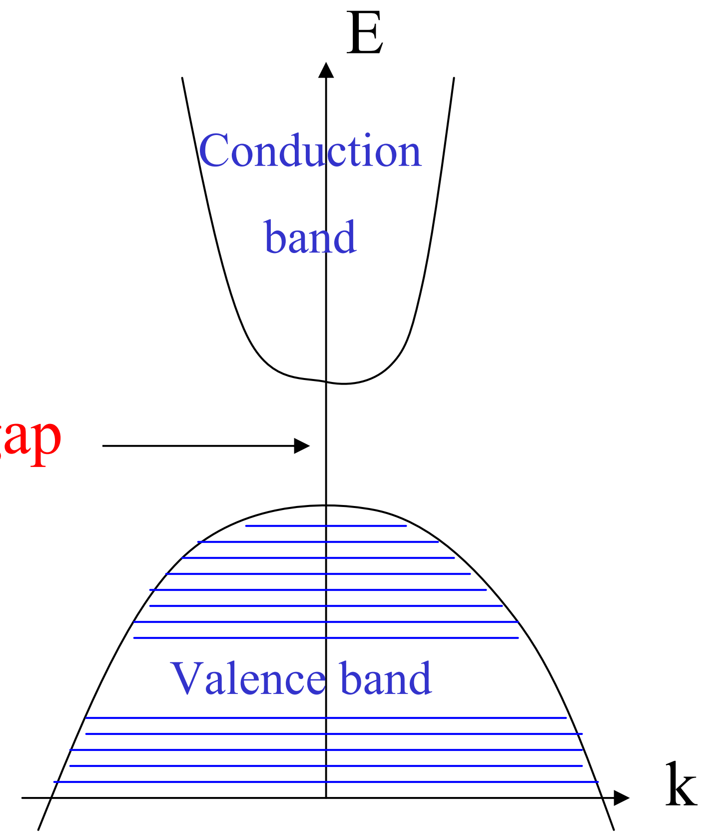


Italian coffee machine

Semiconductor band structure

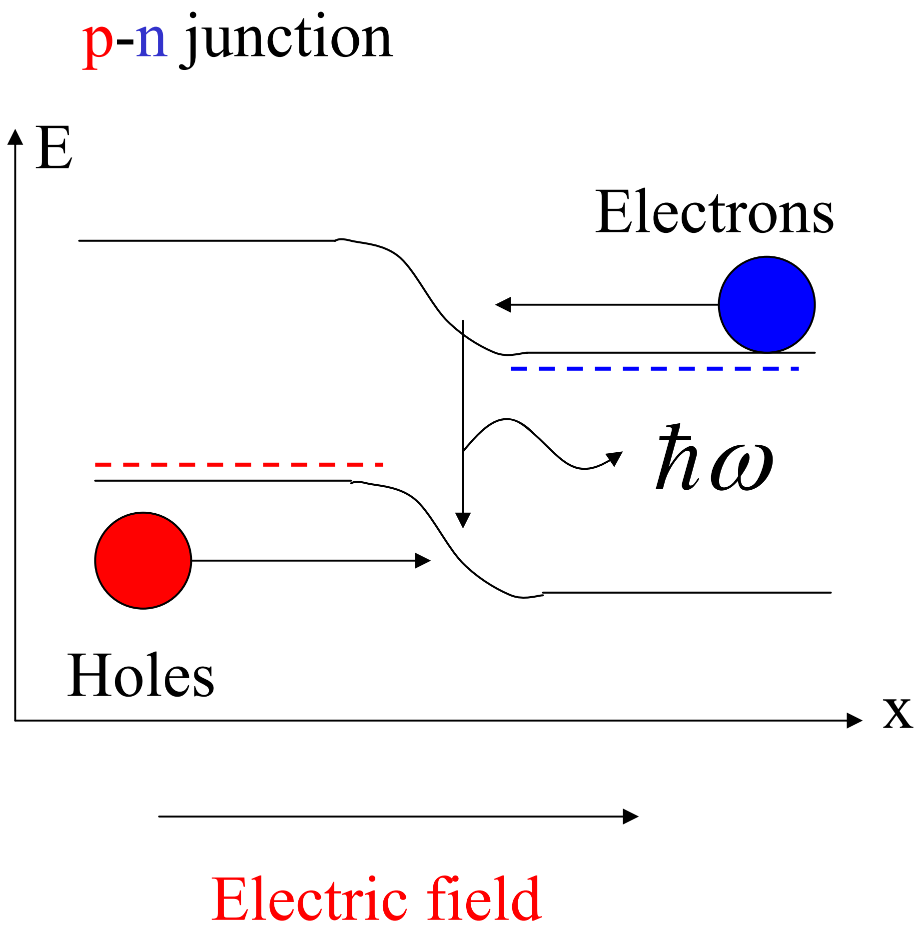


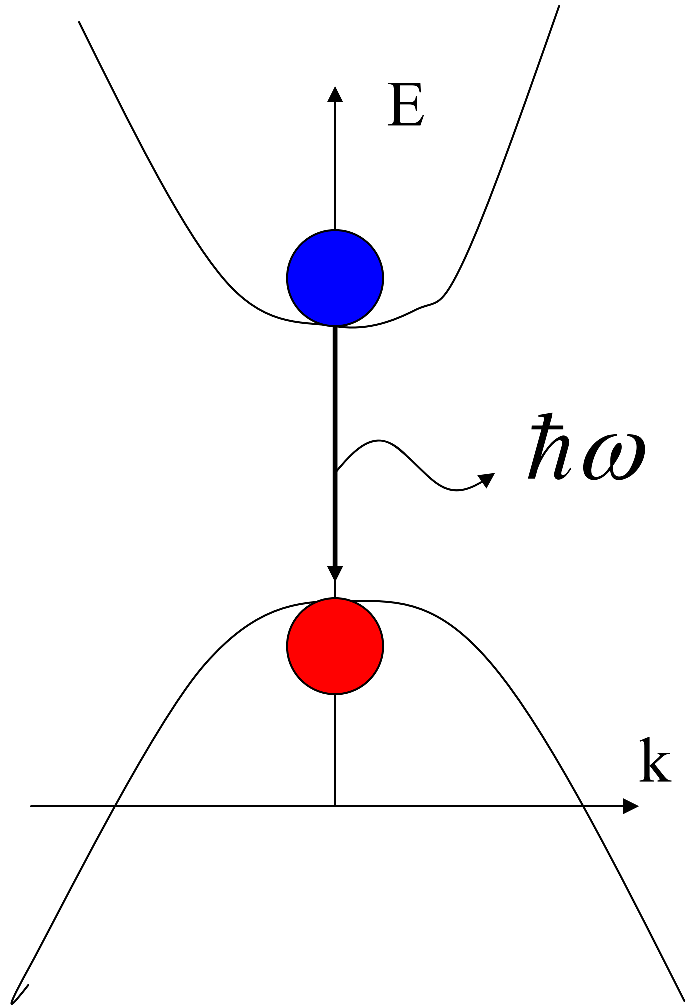
Energy gap



All modern electronics is based on semiconductors...

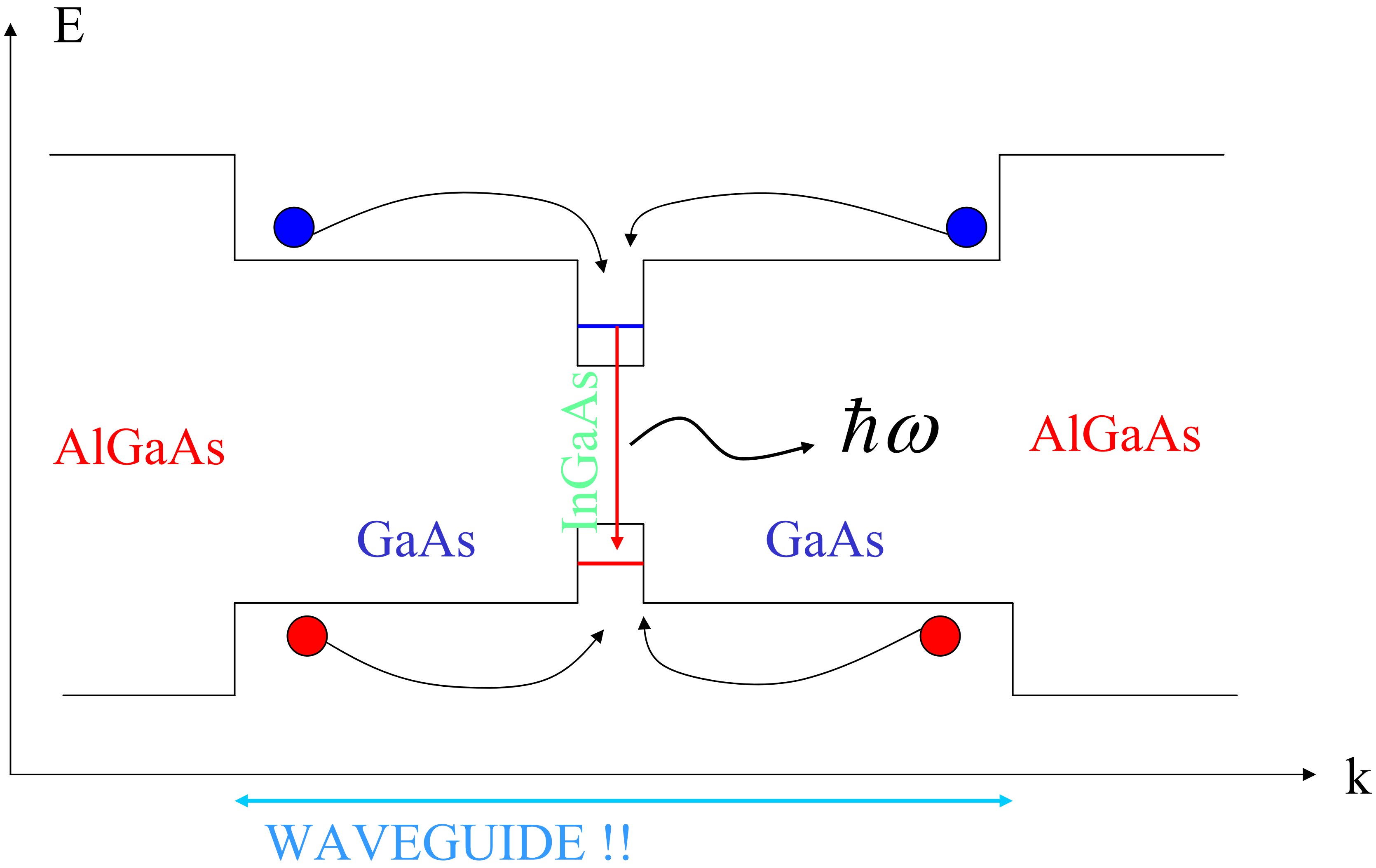
Semiconductor lasers



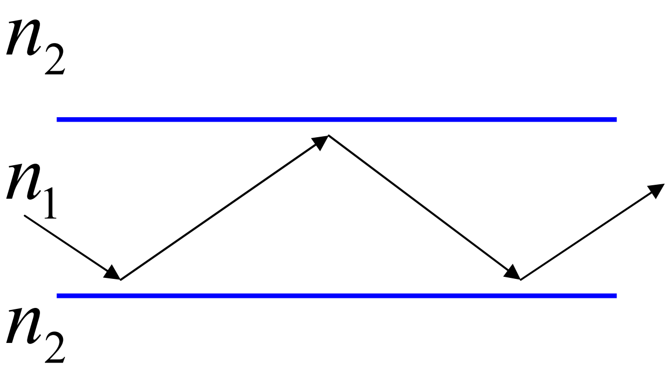


Lasers on heterostructures

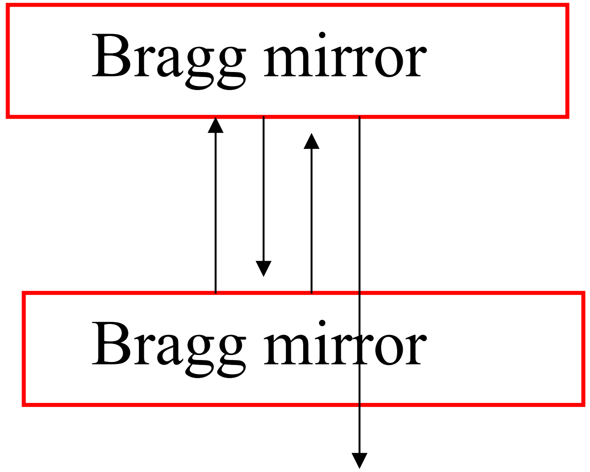
Zh. Alferov, 1972



« Horisontal » and « Vertical » lasers



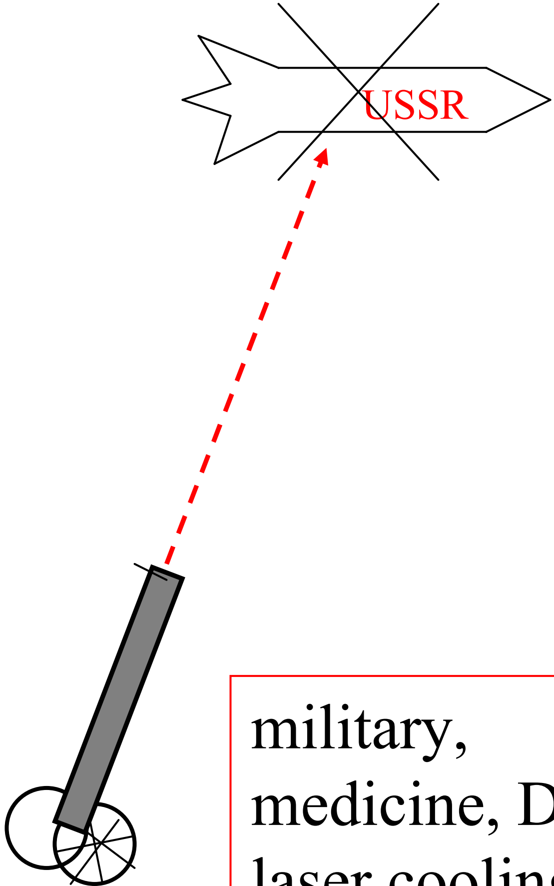
Horisontal lasers emit in guided modes



Vertical lasers emit across the mirrors

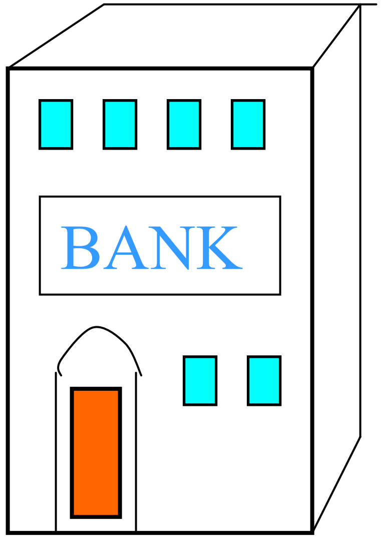
Microlasers, screens...

High power lasers and low power lasers



military,
medicine, DVD,
laser cooling...

A P P L I C A T I O N S

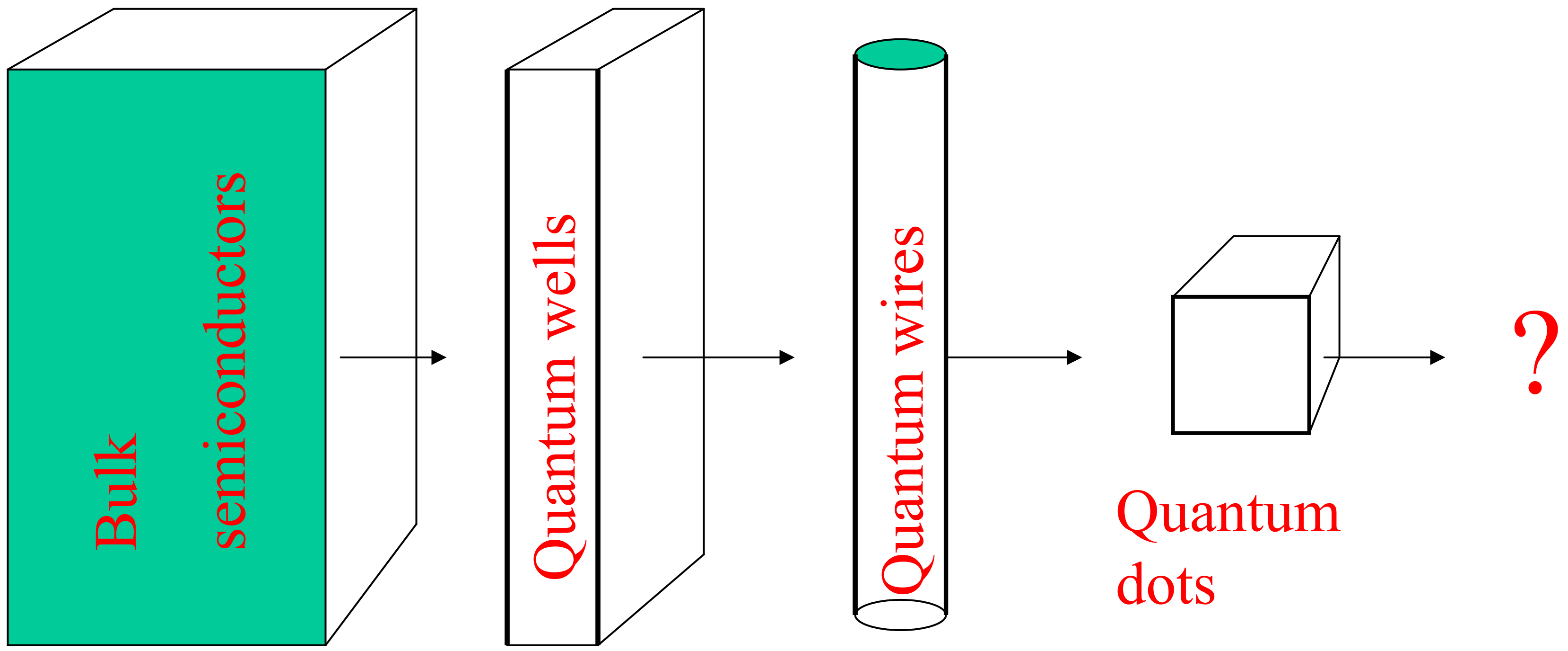


Single photon sources,
quantum cryptography,
quantum computing...

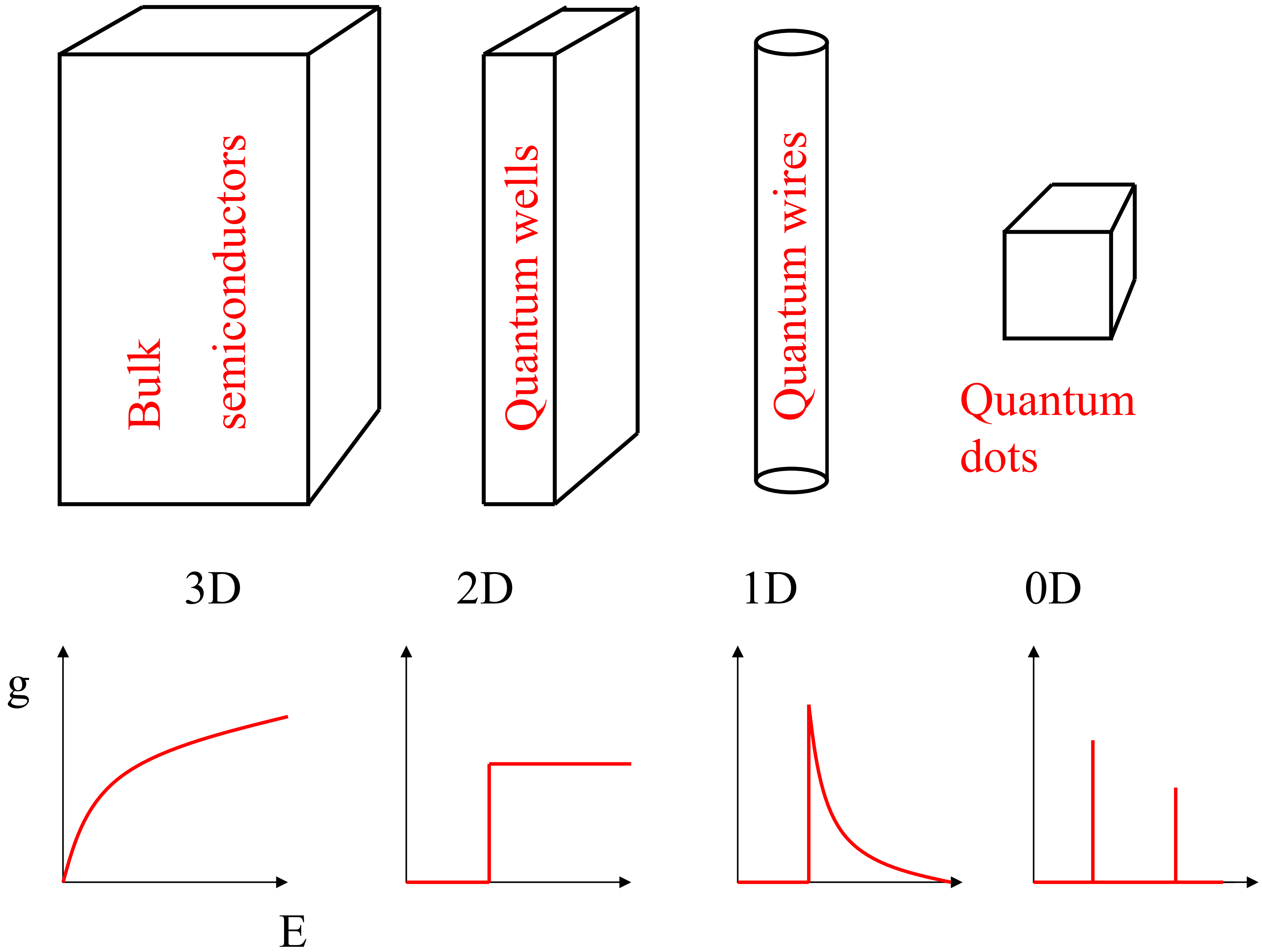
Each laser has a threshold...

Threshold comes from the population inversion...

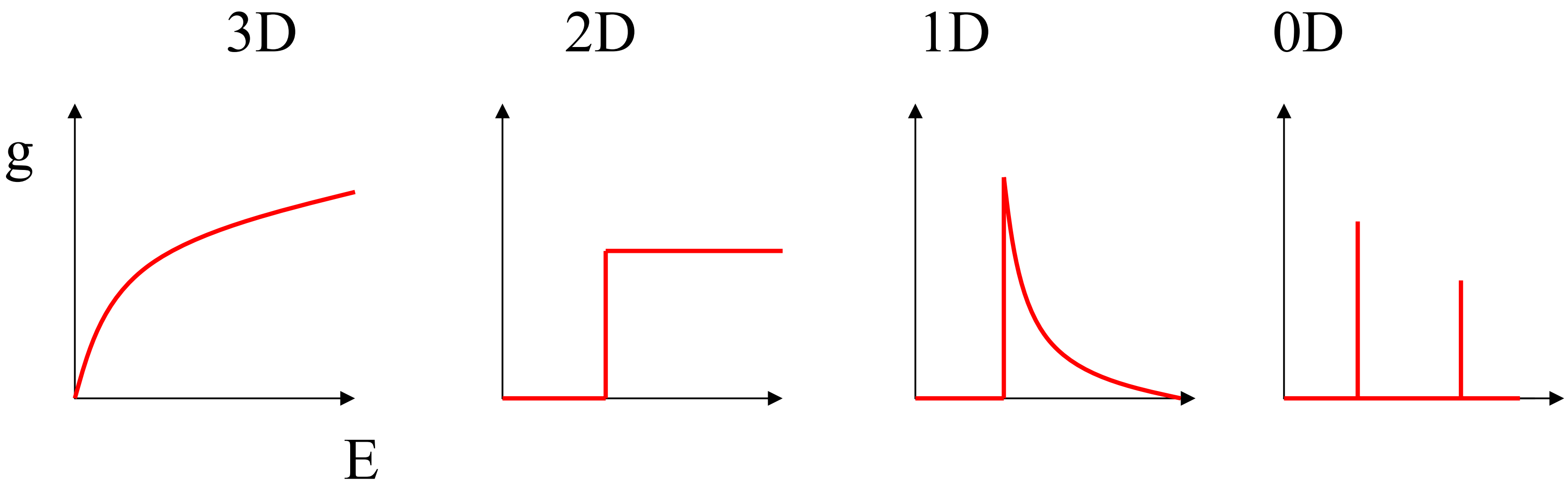
How to make it lower ???



...reducing the density of electronic states !

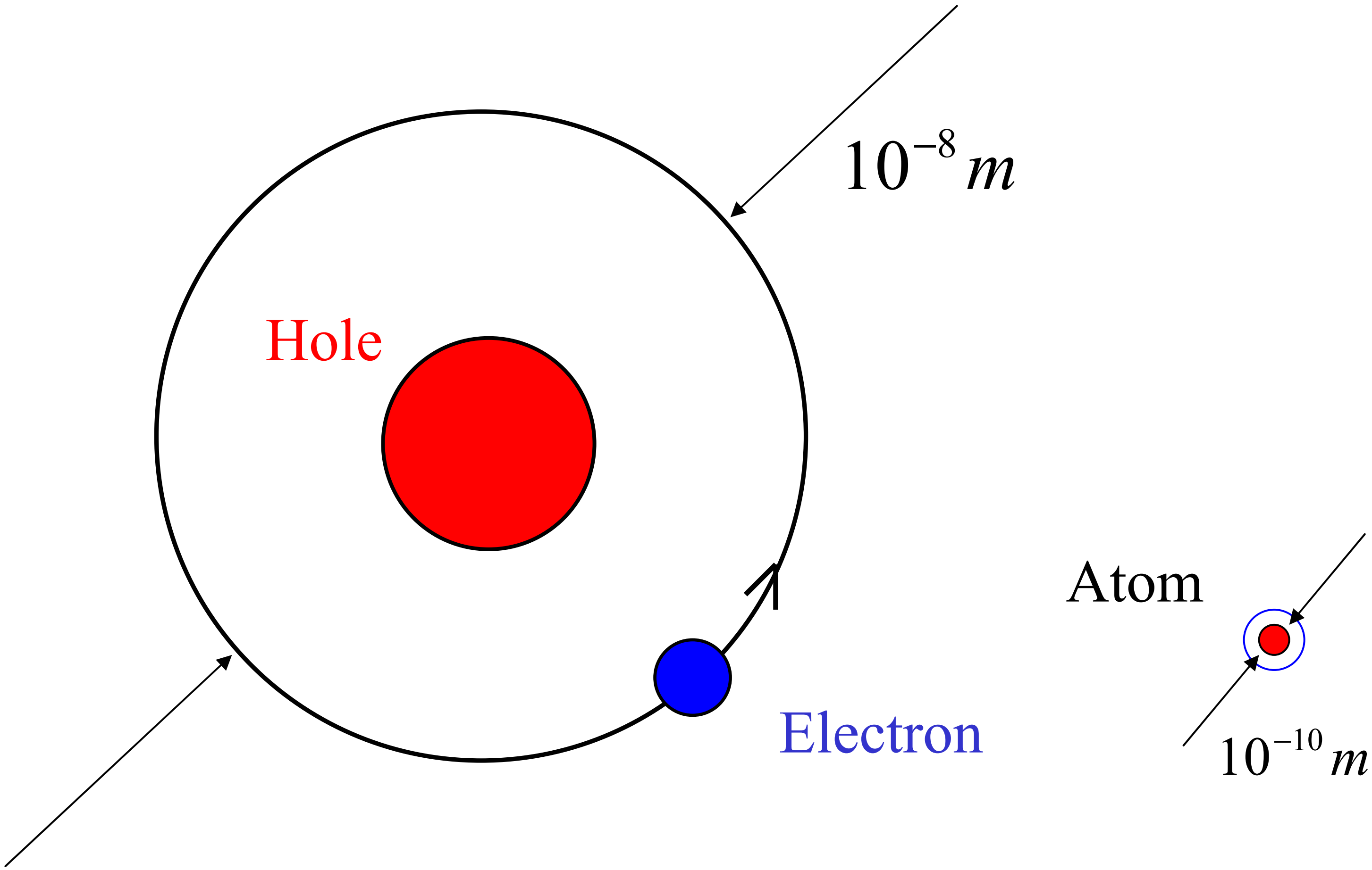

Bulk semiconductors
Quantum wells
Quantum wires
Quantum dots
3D
2D
1D
0D
g
E

Electron density of states



New idea: non-Einstein laser

EXCITON: an artificial ATOM !

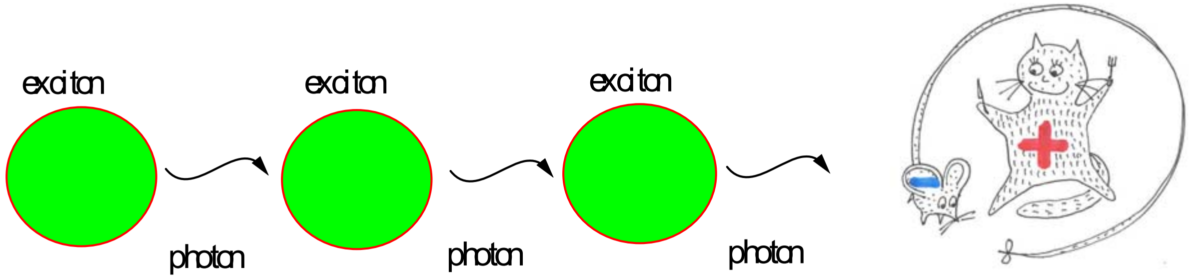


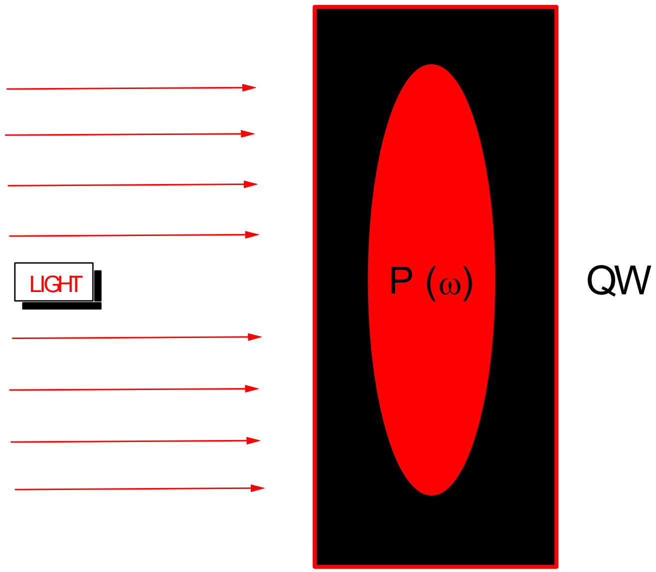
EXCITON + PHOTON = EXCITON-POLARITON

Exciton-polaritons: quantum and classical pictures

Virtual chain of emission-absorption acts

(quantum optics)





(semi-classical approach)

Time- and space-dependent dielectric polarization

LIGHT-MATTER COUPLING IN SOLIDS

Maxwell equations

$$\nabla \cdot \mathbf{D} = \frac{\rho}{\varepsilon_0}\,, \qquad \nabla \times \mathbf{E} = -\frac{1}{c}\partial_t \mathbf{B}\,,$$

$$\nabla \cdot \mathbf{B} = 0\,, \qquad \nabla \times \mathbf{B} = \frac{1}{\varepsilon_0 c^2}\partial_t \mathbf{J} + \frac{1}{c^2}\partial_t \mathbf{D}\,.$$

Electric displacement field $\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} = \boldsymbol{\varepsilon}\mathbf{E}$

and Lorentz oscillator model

$$m_0 \ddot{x} + m_0 2\gamma \dot{x} + m_0 \omega_0^2 x = -eE(t)$$

damping

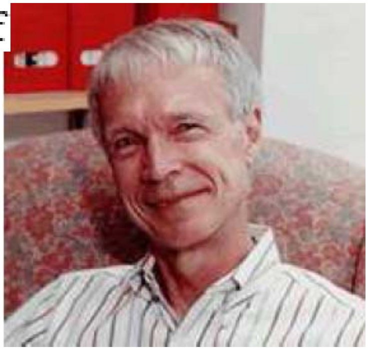
potential

driving force

Solution: $x(t \to \infty) = \mathcal{A}\cos(\omega t - \phi)$

$$\mathcal{A}(\omega) = \frac{-eE_0}{m_0} \frac{1}{\sqrt{(\omega^2 - \omega_0^2)^2 + (2\gamma\omega)^2}} \qquad \phi(\omega) = \arctan\left(\frac{2\gamma\omega}{\omega_0^2 - \omega^2}\right)$$

Hopfield, J. J. (1958). Theory of the contribution of excitons to the complex dielectric constant of crystals, *Phys. Rev.* **112**: 1555.



Hopfield equations

$$\nabla \cdot \mathbf{D} = \frac{\rho}{\varepsilon_0}, \qquad \nabla \times \mathbf{E} = -\frac{1}{c}\partial_t \mathbf{B},$$

$$\nabla \cdot \mathbf{B} = 0, \qquad \nabla \times \mathbf{B} = \frac{1}{\varepsilon_0 c^2}\partial_t \mathbf{J} + \frac{1}{c^2}\partial_t \mathbf{D}$$

Maxwell equations

Displacement field

$$\mathbf{D} = \varepsilon_{\mathrm{B}}\mathbf{E} + \mathbf{P} = \boldsymbol{\varepsilon}\mathbf{E}$$

$$\frac{\varepsilon_{\mathrm{B}}}{c^2}\frac{\partial^2}{\partial t^2}\mathbf{E}(\mathbf{r},t) + \nabla \times \nabla \times \mathbf{E}(\mathbf{r},t) = -\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\mathbf{P}(\mathbf{r},t)$$

1st Hopfield equation

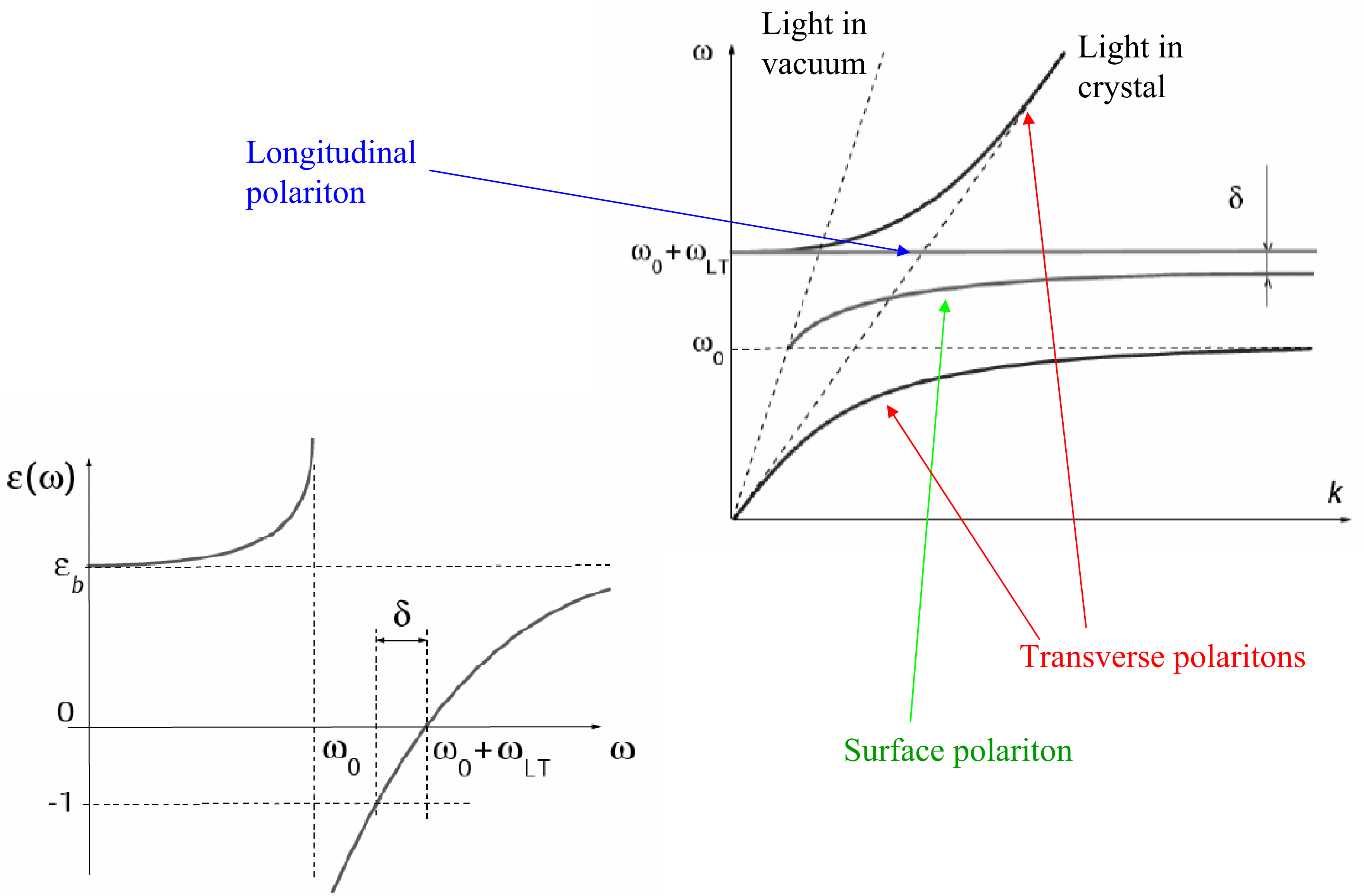
Lorentz oscillator

$$m_0\ddot{x} + m_0 2\gamma\dot{x} + m_0\omega_0^2 x = -eE(t)$$

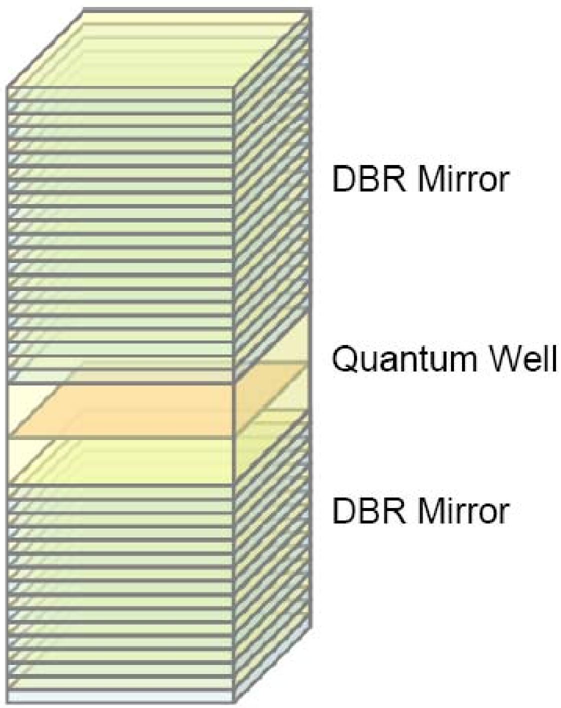
$$\left[\frac{\partial^2}{\partial t^2} + 2\gamma\frac{\partial}{\partial t} + \omega_0^2 - \frac{\hbar\omega_0}{M_x}\nabla^2\right]\mathbf{P}(\mathbf{r},t) = \varepsilon_{\mathrm{B}}\omega_{\mathrm{p}}^2\mathbf{E}(\mathbf{r},t)$$

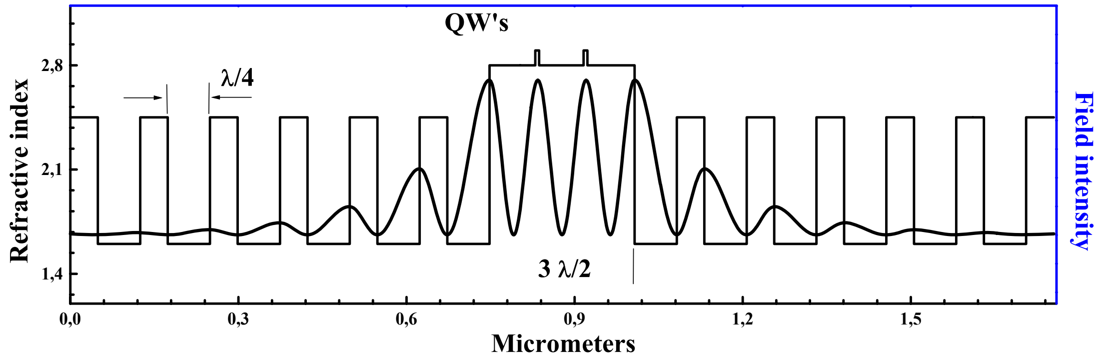
2nd Hopfield equation

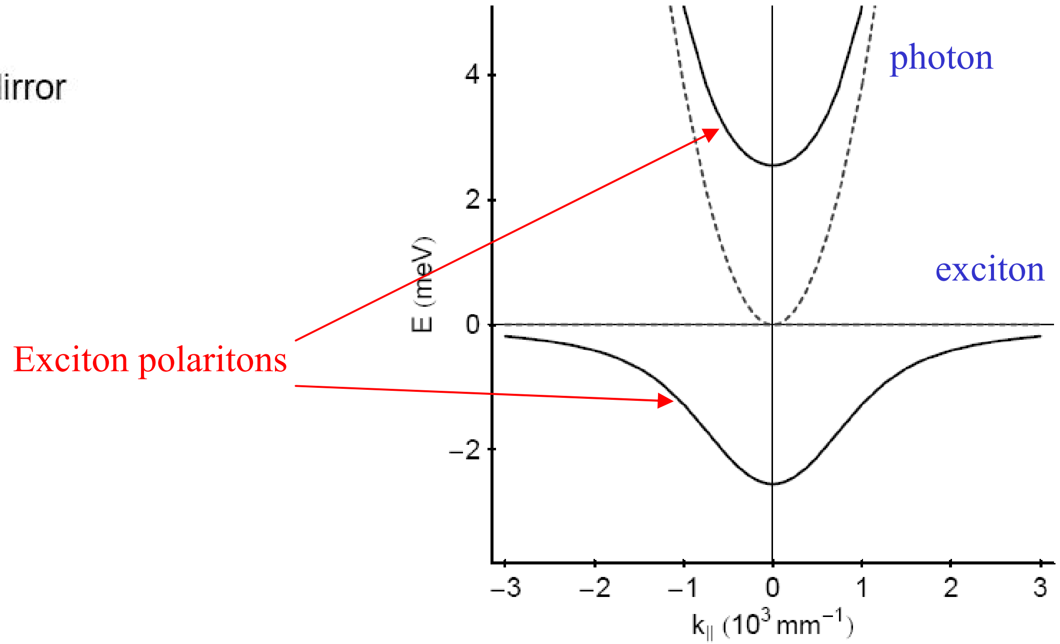
Dispersion of bulk exciton-polaritons in the limit $M_x \rightarrow \infty \quad \gamma \rightarrow 0$



Polaritons in microcavities







Concept of polariton lasing:

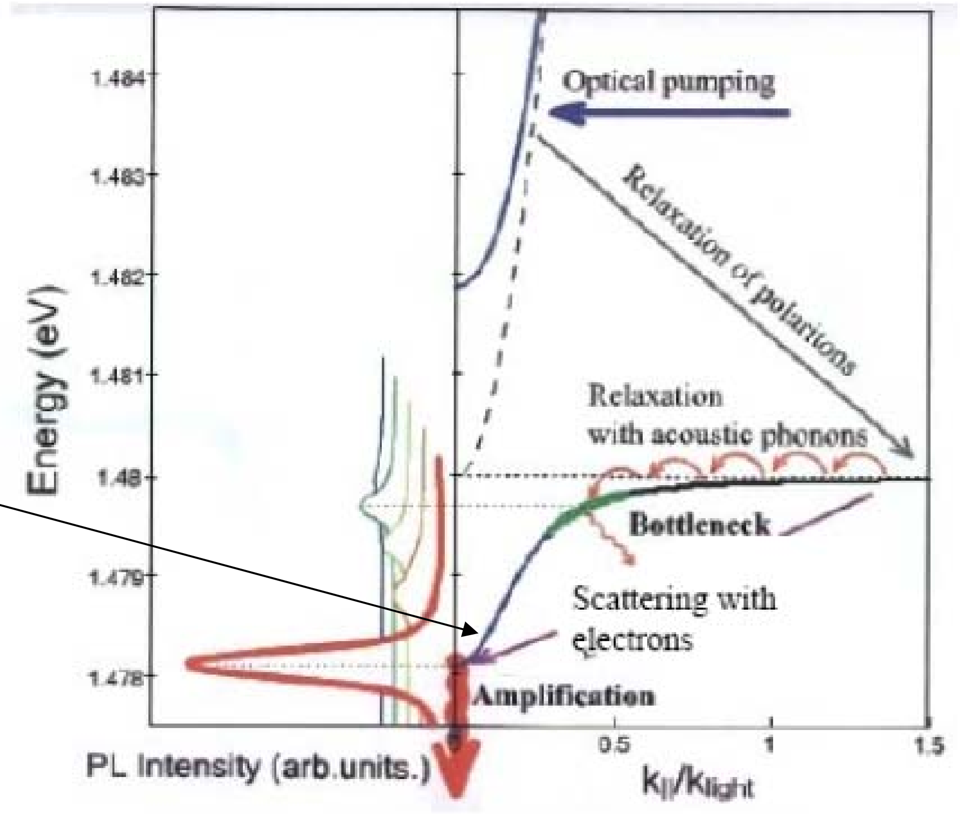
A. Imamoglu, et al, Phys. Lett. A 214, 193 (1996).

Photon mode dispersion

$$\frac{\omega}{c}n = \sqrt{\left(\frac{2\pi}{L}\right)^2 + k_\parallel^2}$$

Extremely light effective mass

$$\propto \left(10^{-5} - 10^{-4}\right) m_0$$



Optically or electronically excited exciton-polaritons relax towards the ground state and Bose-condense there. Their relaxation is stimulated by final state population. The condensate emits spontaneously a coherent light

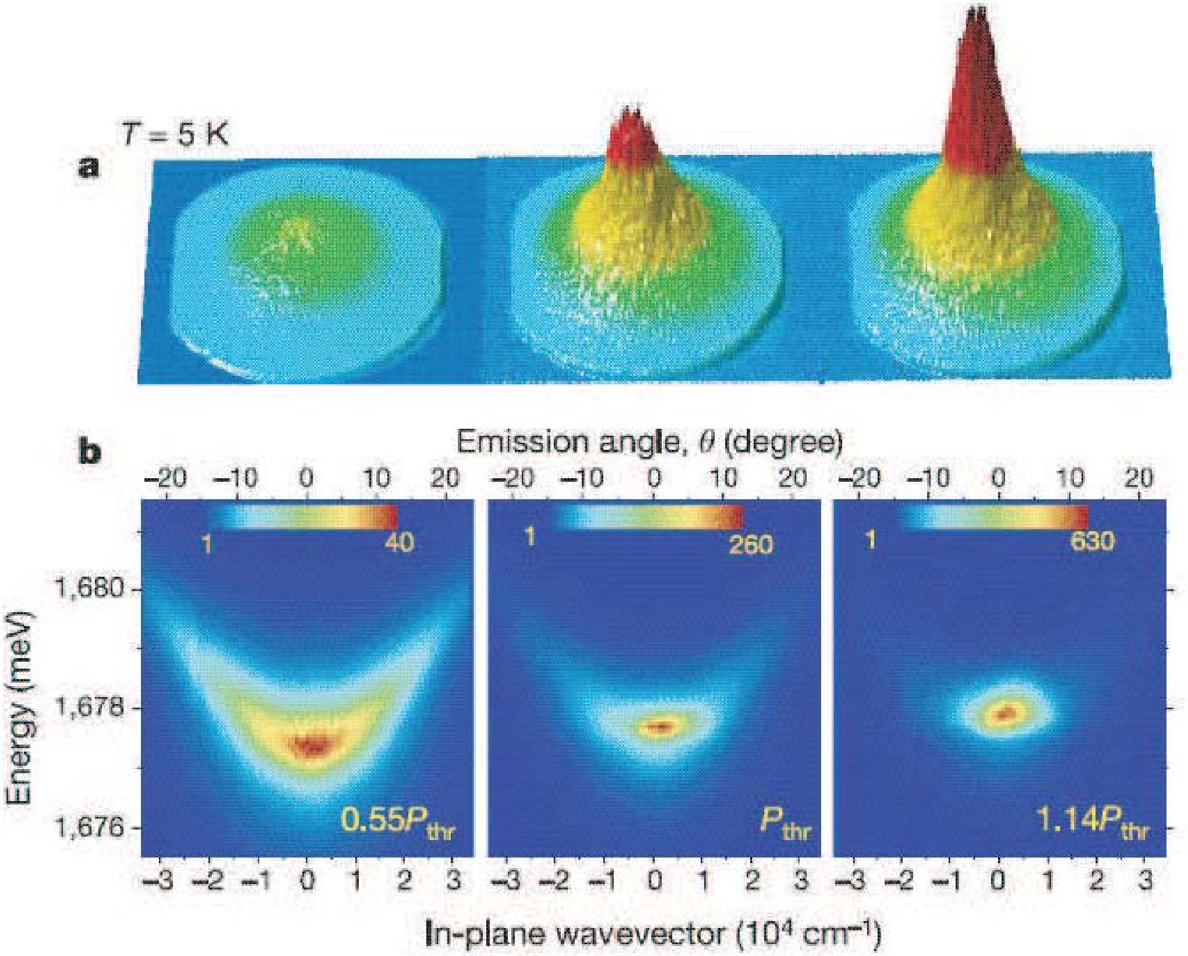
Polariton lasing vs polariton BEC

Criteria	Polariton laser	Polariton BEC
Strong coupling regime	yes	yes
Formation of a macroscopically occupied coherent polariton state	yes	yes
Stimulated scattering	yes	yes
Polaritons with low k at thermal equilibrium	not necessarily	yes
Thermodynamic phase transition	not necessarily	yes
Order parameter build up	not necessarily	yes
Spontaneous symmetry breaking	not necessarily	yes

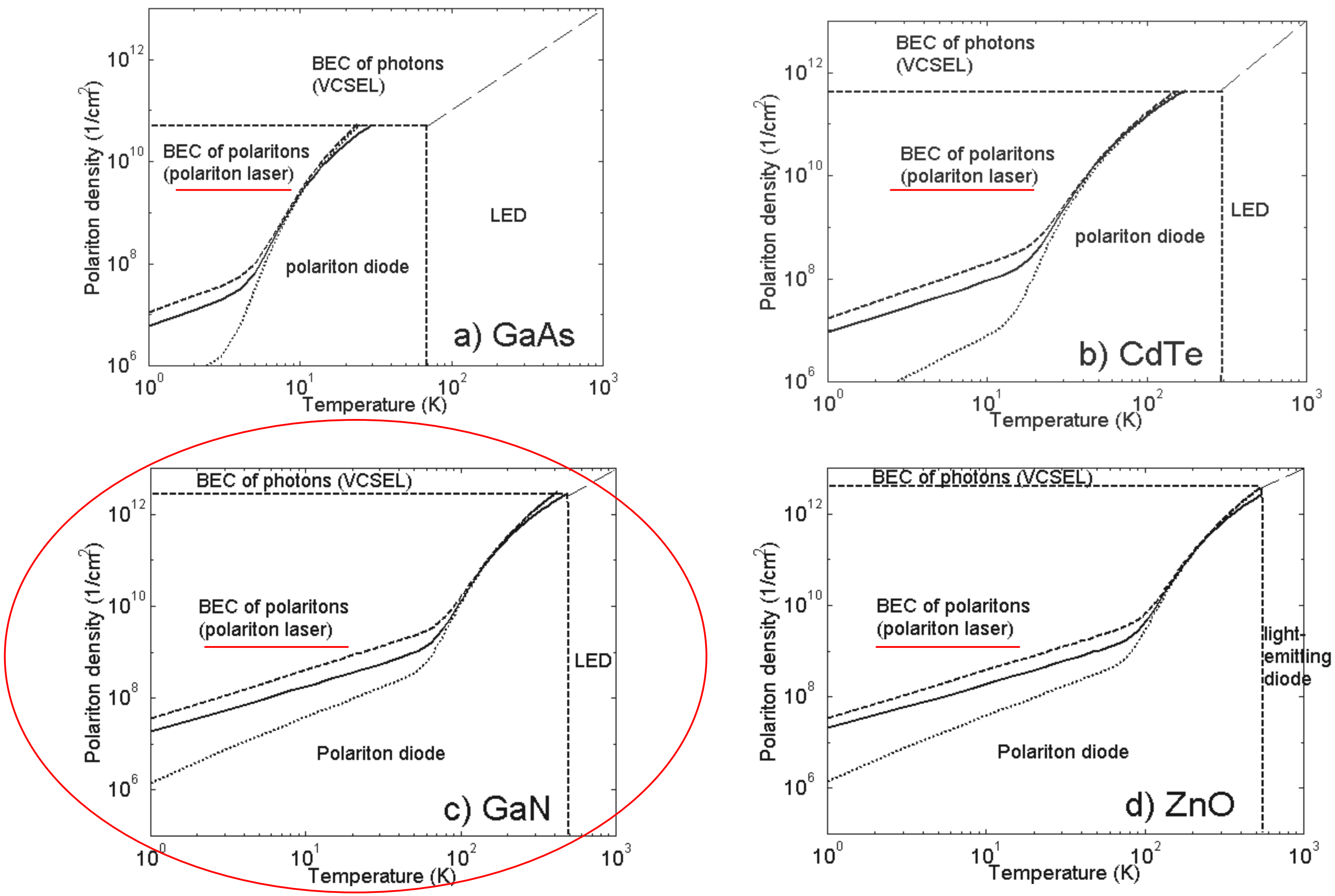
ARTICLES

Bose–Einstein condensation of exciton polaritons

J. Kasprzak[1], M. Richard[2], S. Kundermann[2], A. Baas[2], P. Jeambrun[2], J. M. J. Keeling[3], F. M. Marchetti[4], M. H. Szymańska[5], R. André[1], J. L. Staehli[2], V. Savona[2], P. B. Littlewood[4], B. Deveaud[2] & Le Si Dang[1]



Phase diagrams for BEC of exciton-polaritons in different model cavities



Solid lines show the critical concentration N_c versus temperature of the polariton KT phase transition. Dotted and dashed lines show the critical concentration N_c for quasi condensation in 100 µm and 1 meter lateral size systems, respectively.

*Kavokin A, Malpuech G, Gil B, Semiconductor microcavities: towards polariton lasers, MRS Internet Journal of Nitride Semiconductor Research **8** (3): 3 (2003)*

GaN-based microcavities

Exciton binding energy = 28 meV

↓

Excitons are stable at room temperature!

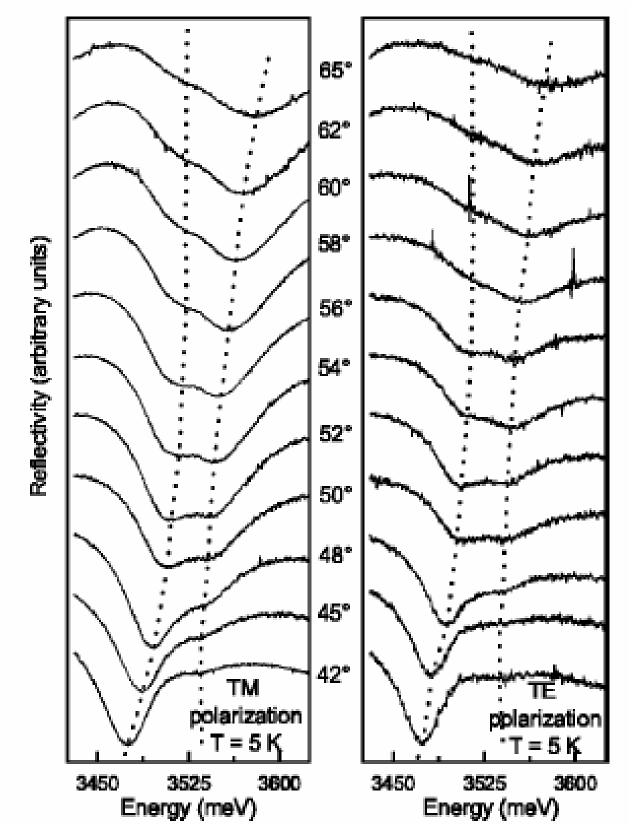
RESEARCH

Strong coupling in GaN-based microcavities: experimental realisation

CLERMONT (1999-2003)

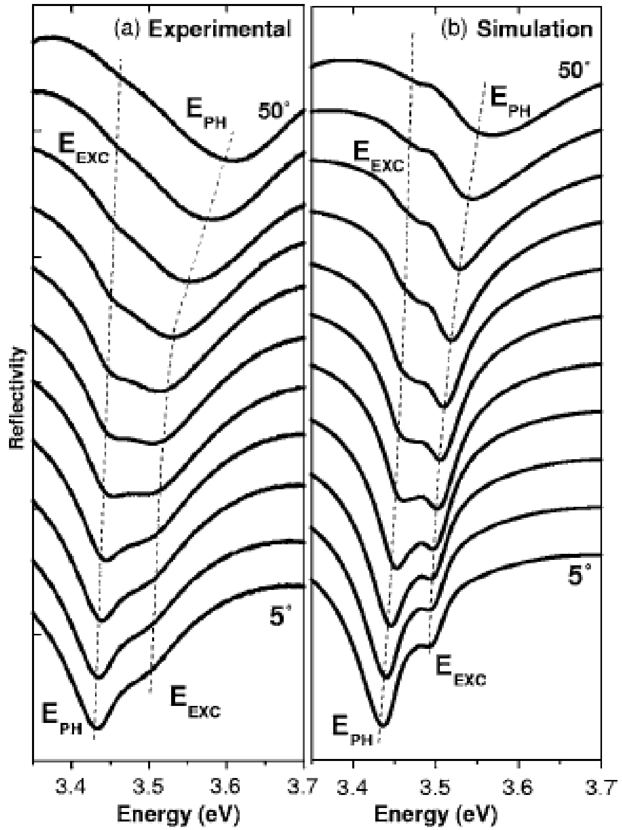
CLERMONT2 (2003-2007)

CLERMONT4 (2009-2013)



T=5K

T=300K

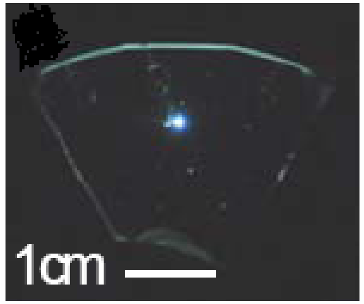


N. Antoin-Vincent et al, PRB 68, 153313 (2003)

I. Sellers et al, Phys. Rev. B73, 033304 (2006)

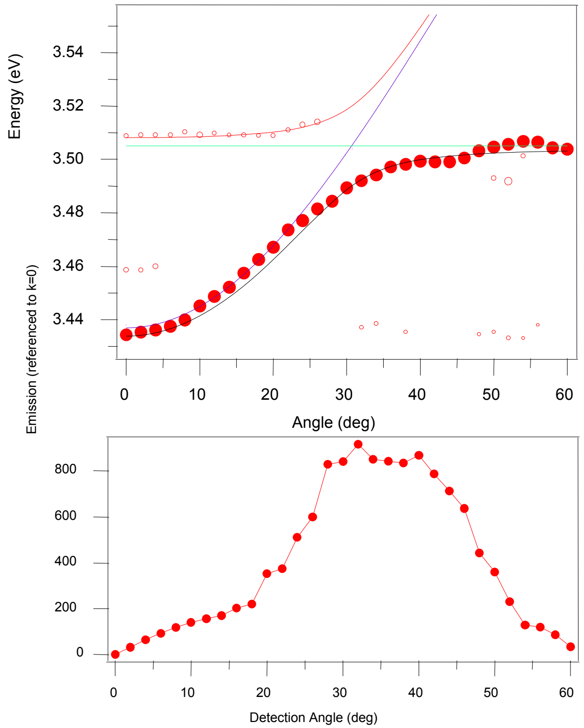
Polariton lasing in GaN microcavities

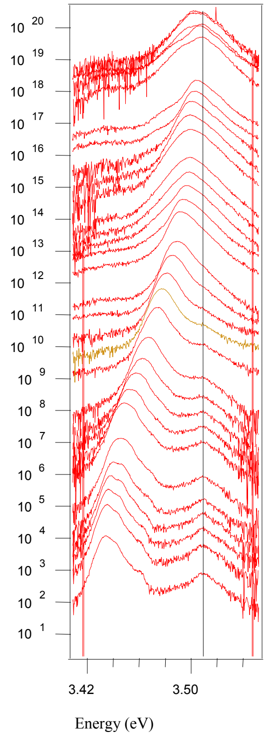
S. Christopoulos *et al.*, *Phys. Rev. Lett.* **98**, 126405 (2007).

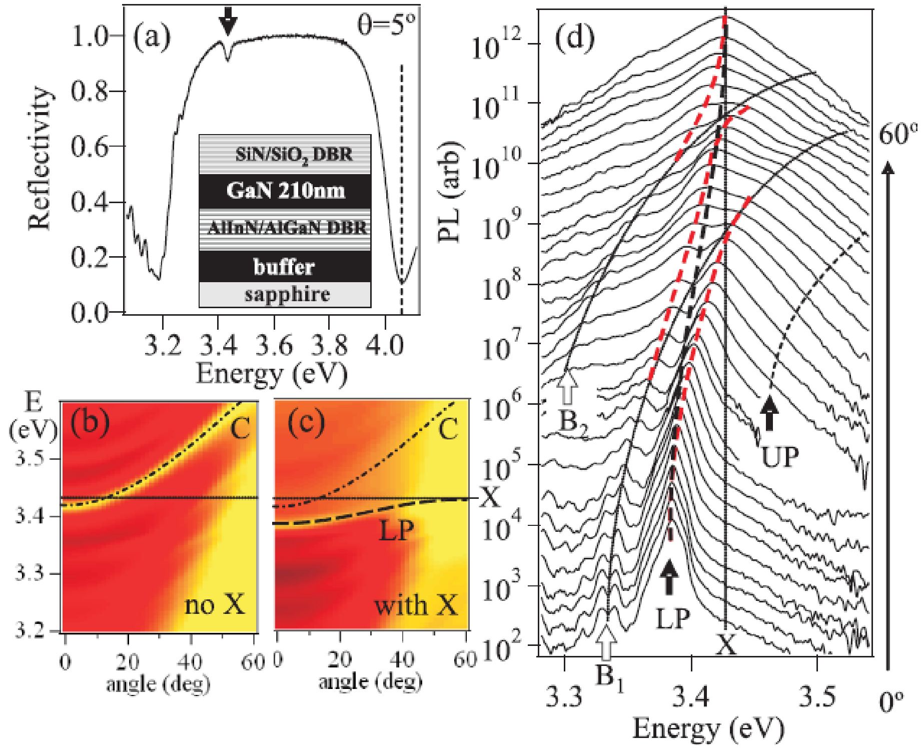


T=77K

T=300 K

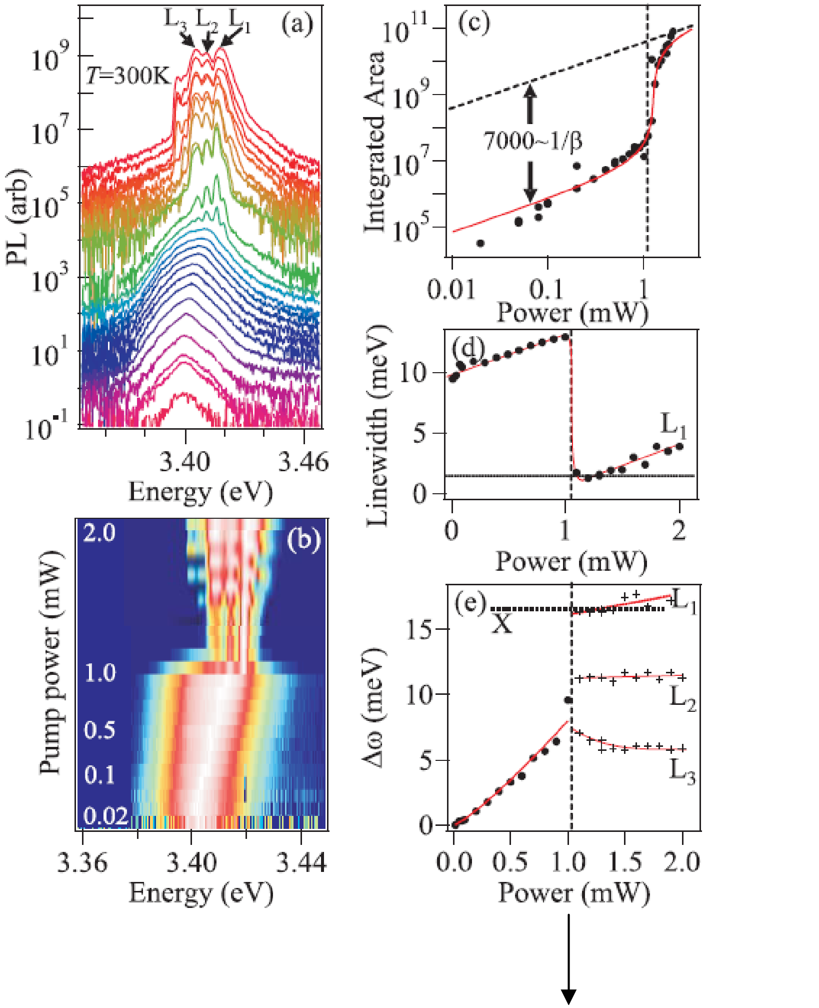






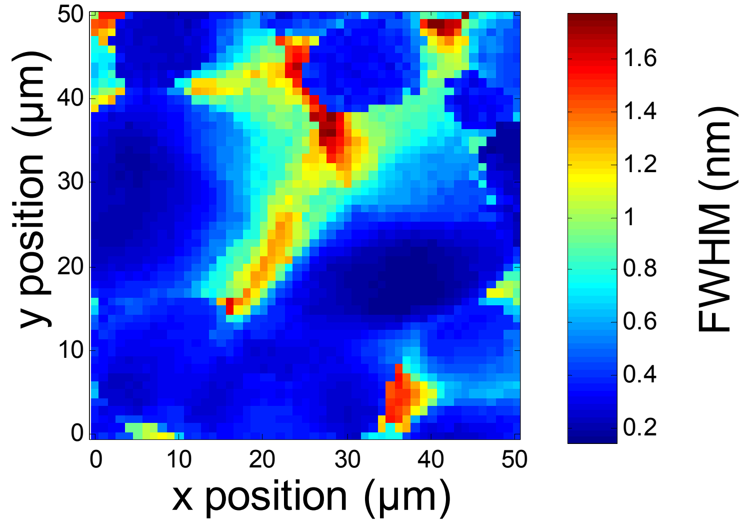
S. Christopoulos, G. Baldassarri von Högersthal, A. J. Grundy, P. G. Lagoudakis, A. V. Kavokin, J. J. Baumberg, G. Christmann, R. Butté, E. Feltin, J.-F. Carlin, and N. Grandjean, *Room-Temperature Polariton Lasing in Semiconductor Microcavities*, **Phys. Rev. Lett. 98**, 126405 (2007).

Polariton lasing



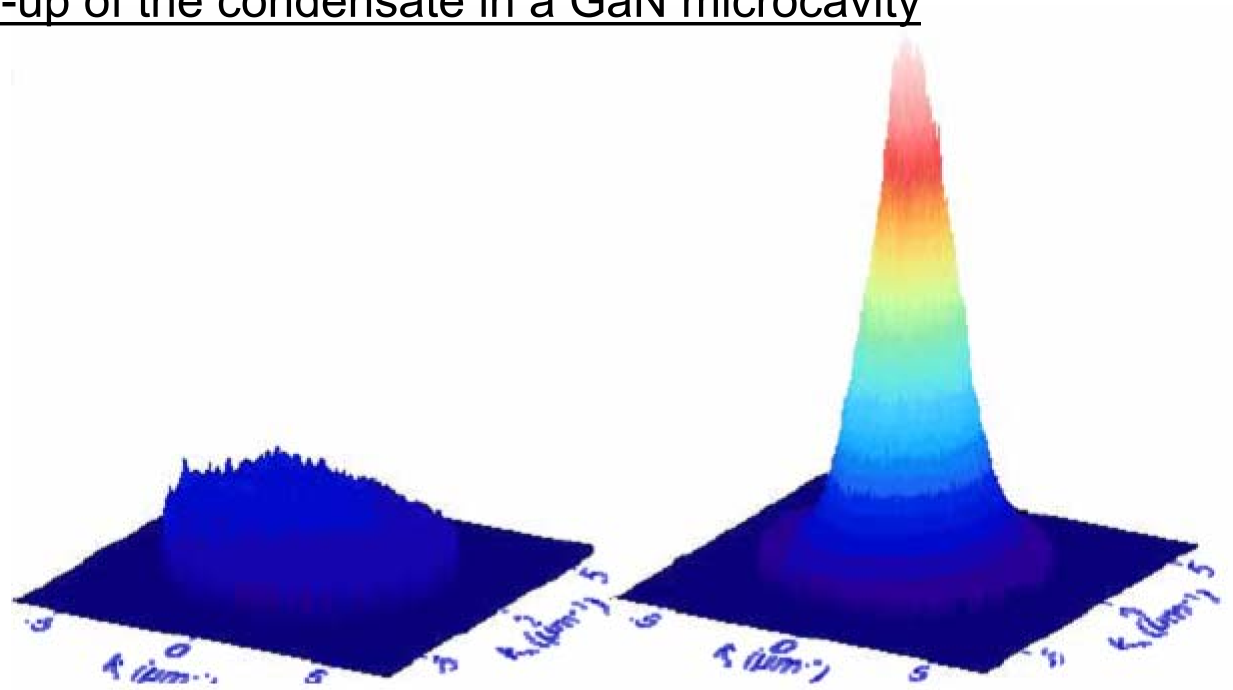
$$I_{\text{th}} = 1.0 \text{ mW} \qquad N_{3D} \sim 8 \times 10^{17} \text{ cm}^{-3}$$

Photonic disorder

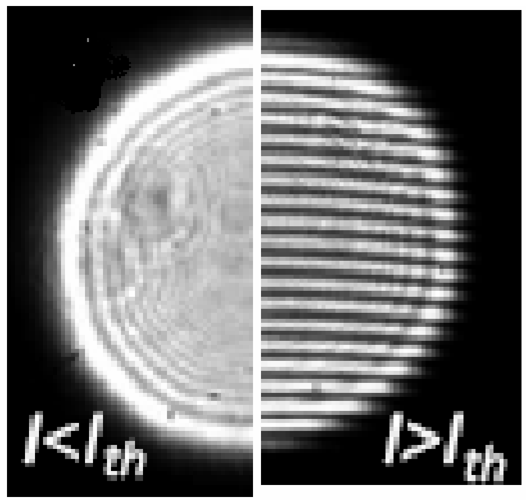


Micro-transmission maps of the cavity linewidth of a GaN bulk microcavity, with a negatively-detuned cavity of resonant wavelength around 418nm. The spot size is 8μm.

Build-up of the condensate in a GaN microcavity

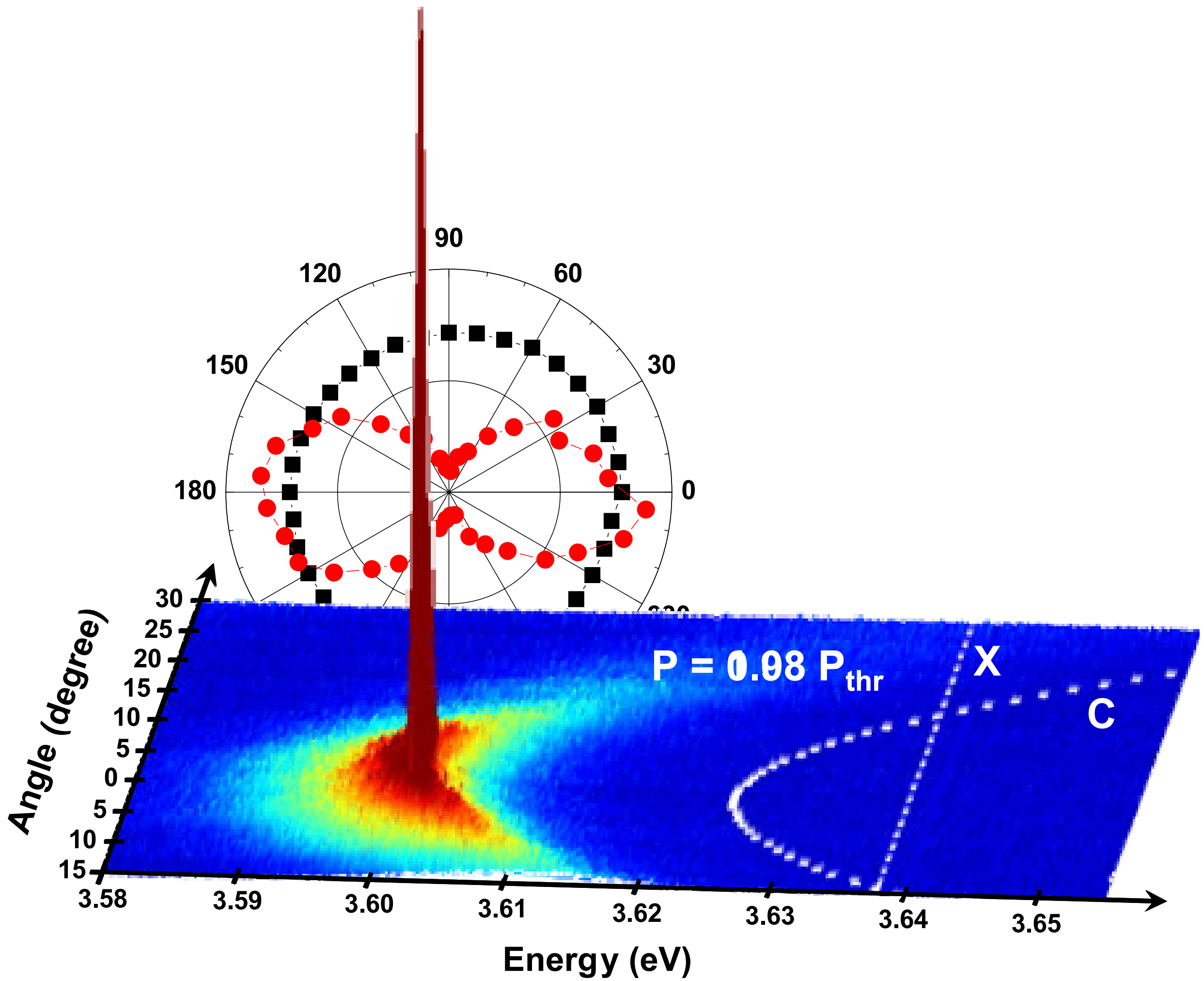


Below threshold Above threshold



J. J. Baumberg, A. V. Kavokin, S. Christopoulos, A. J. Grundy, R. Butté, G. Christmann, D. D. Solnyshkov, G. Malpuech, G. Baldassarri Höger von Högersthal, E. Feltin, J.-F. Carlin, and N. Grandjean, Spontaneous Polarization Buildup in a Room-Temperature Polariton Laser, **Phys. Rev. Lett. 101**, 136409 (2008).

Room temperature polariton lasing



Nonlinear emission peaked at $k_{//} = 0$

Linearly polarized emission above threshold (polarization degree: 80%)

Emission still in the strong coupling regime

Polarization splitting: ~150 µeV

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