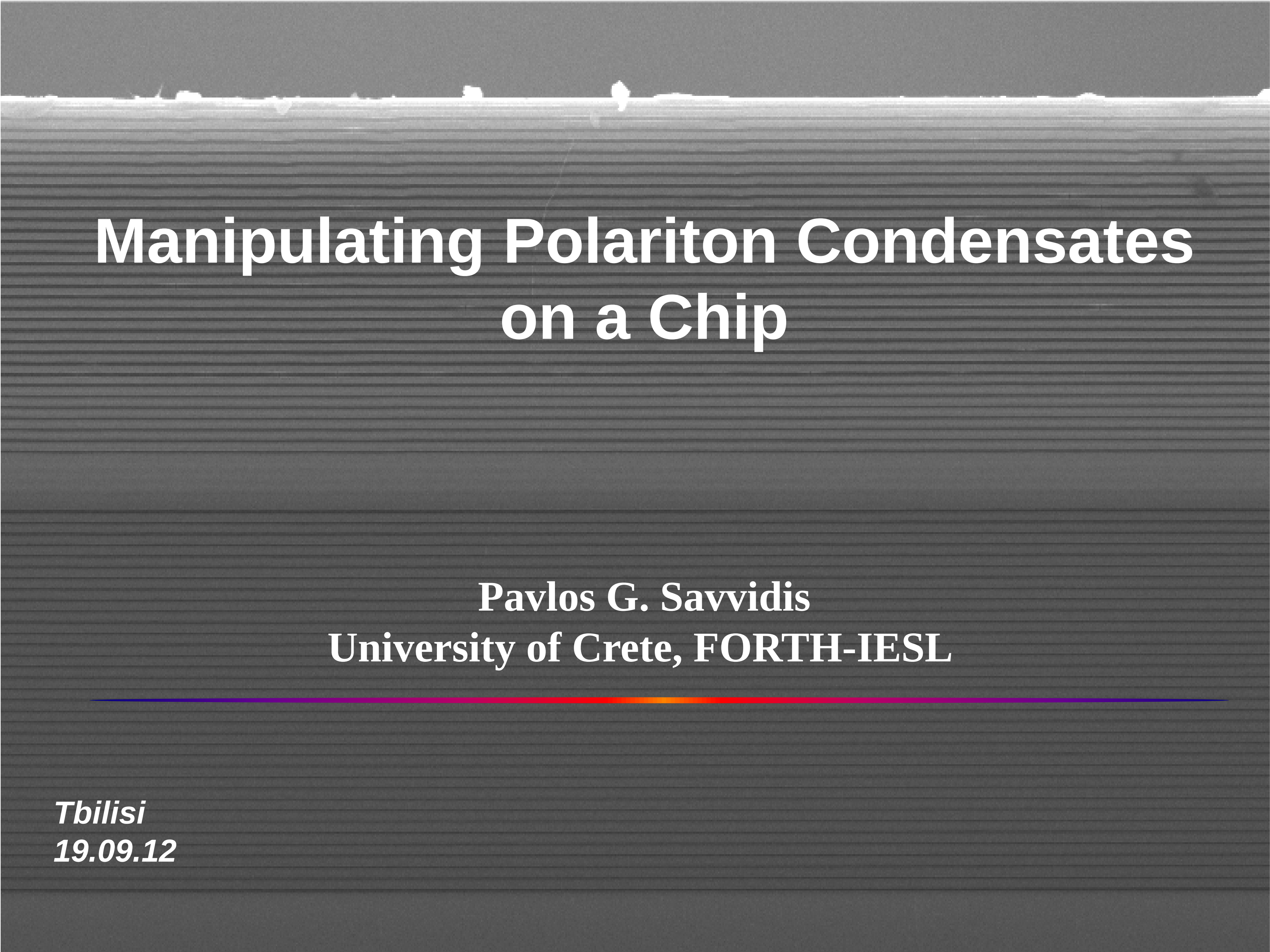

Manipulating Polariton Condensates on a Chip

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19.09.12

Acknowledgements

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Dr. Peter Eldridge
Dr. Simos Tsintzos
PhD Niccolo Somaschi
PhD Panos Tsotsis
PhD Tingge Gao
PhD Kostas Daskalakis
PhD Pramod Sharma

Dr. G. Kostantinidis
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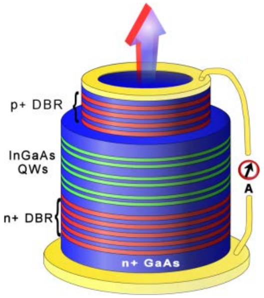
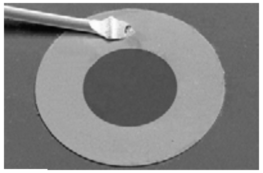
Singapore

Outline

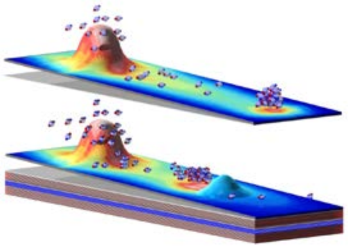
- New generation of semiconductor lasers operating in the so called strong light-matter coupling regime



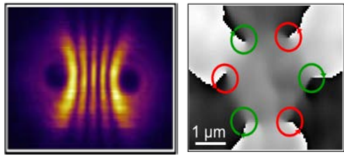
- Electrical and optical manipulation of polariton condensates on a chip



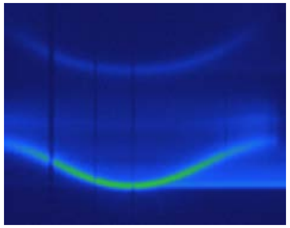
  - polariton condensate transistor



  - interactions between independent condensates



  - electrical control of polariton condensate



The History of Semiconductor Lasers

The concept of the semiconductor laser diode proposed by Basov in 1959
N. G. Basov, B. M. Vul and M. Popov
Soviet JETP, 37(**1959)**

First GaAs *laser diode* demonstrated by Robert N. Hall in 1962.

Pulsed operation at liquid nitrogen temperatures (77 K)

Bulk

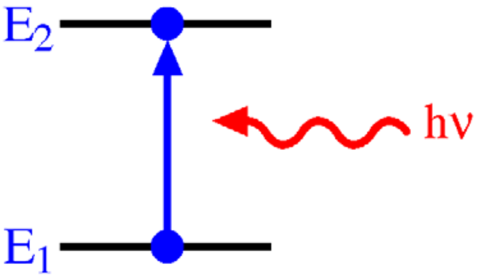
Electronic confinement in heterostructures

In 1970, Zhores Alferov, Izuo Hayashi and Morton Panish independently developed CW laser diodes at room temperature

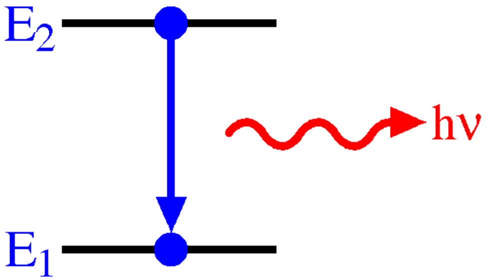
The laser disc player, introduced in 1978, was the first successful consumer product to include a laser, but the compact disc player was the first laser-equipped device to become truly common in consumers' homes, beginning in 1982.

Fundamental Optical Processes Involved in Operation of Semiconductor Lasers

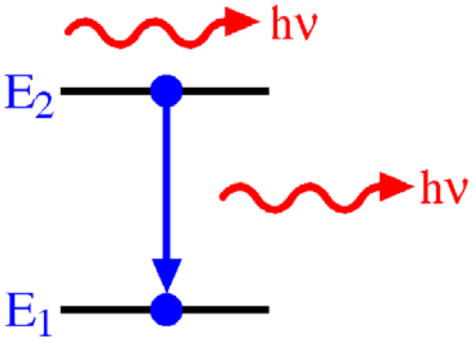
Absorption



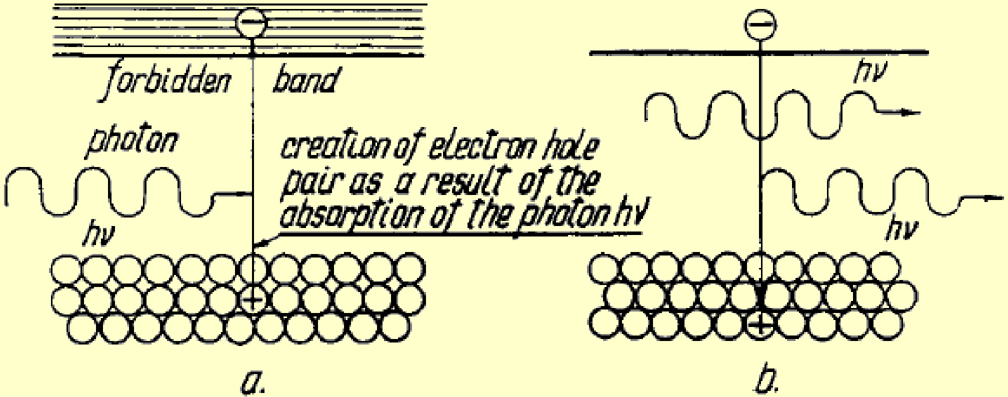
Spontaneous emission



Stimulated Emission



conduction band



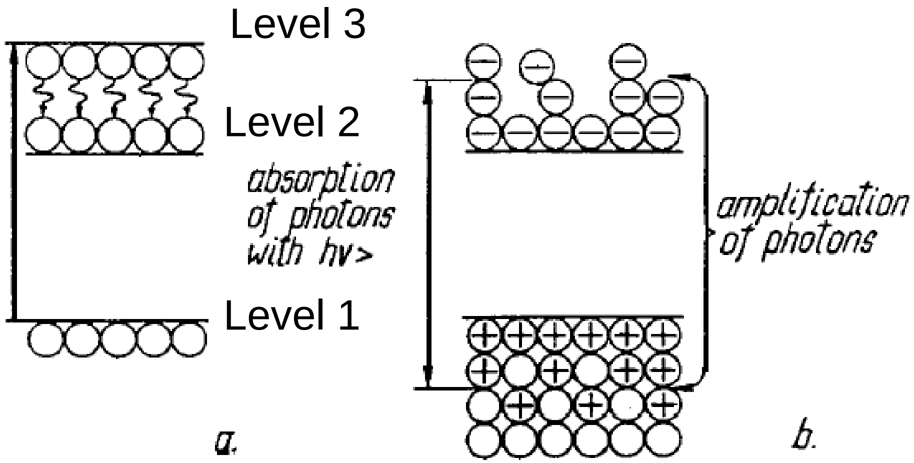
valence band

Negative Temperature & Population Inversion Lasing

To achieve non-equilibrium conditions, an indirect method of populating the excited state must be used.

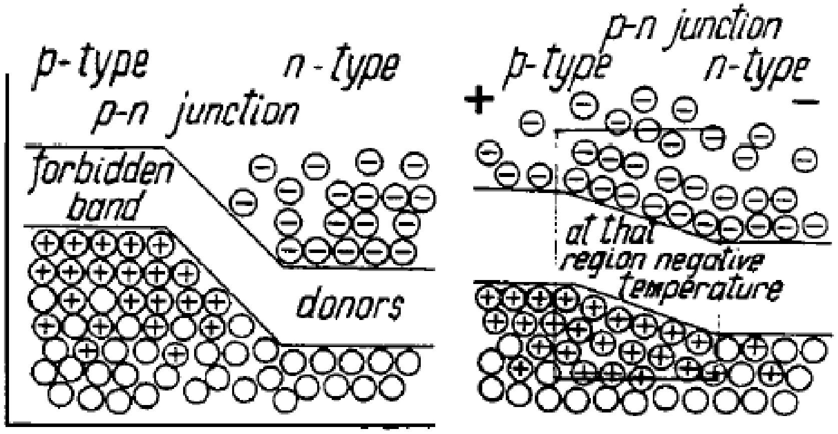
Three-level laser energy diagram

Basov Nobel Lecture



Atoms

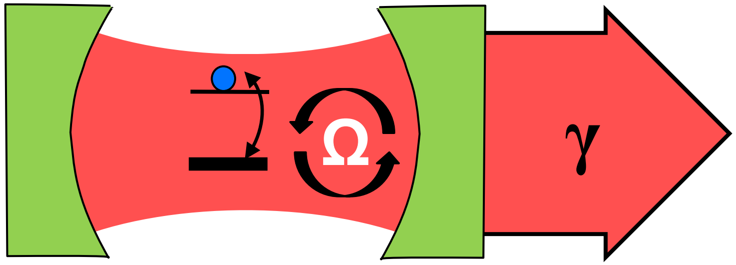
Semiconductors



p-n junction in the external electrical field

When population inversion ($N_2 > N_1$) between level 1 and 2 is achieved, optical amplification at the frequency ω_{21} can be obtained.
Because at least half the population of atoms must be excited from the ground state to obtain a population inversion, the laser medium must be very strongly pumped. **This makes three-level lasers rather inefficient.**

Strong Coupling Regime



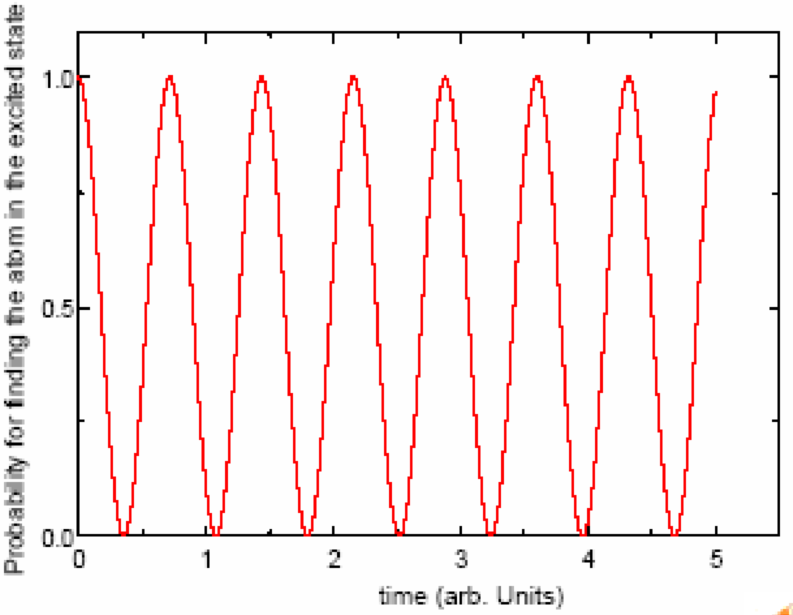
γ: loss channel

Ω coupling strength between optical transition of the material and the resonance photon mode

Strong Coupling Regime (Ω>>γ) :

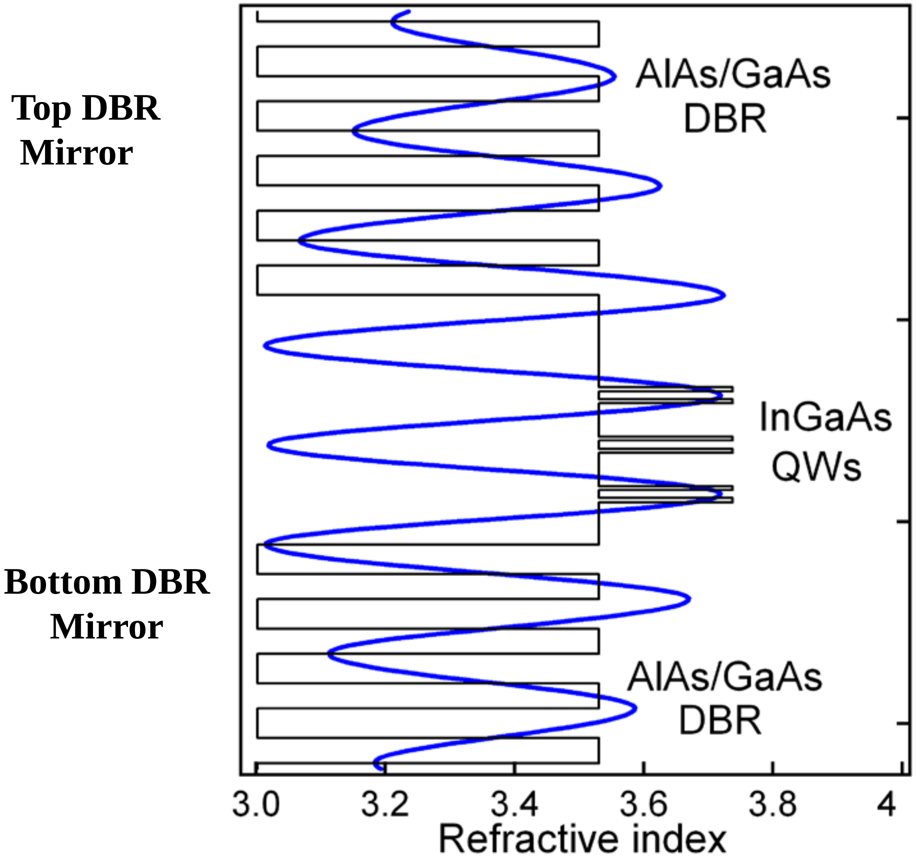
emitted photon will be reabsorbed before it leaves the cavity

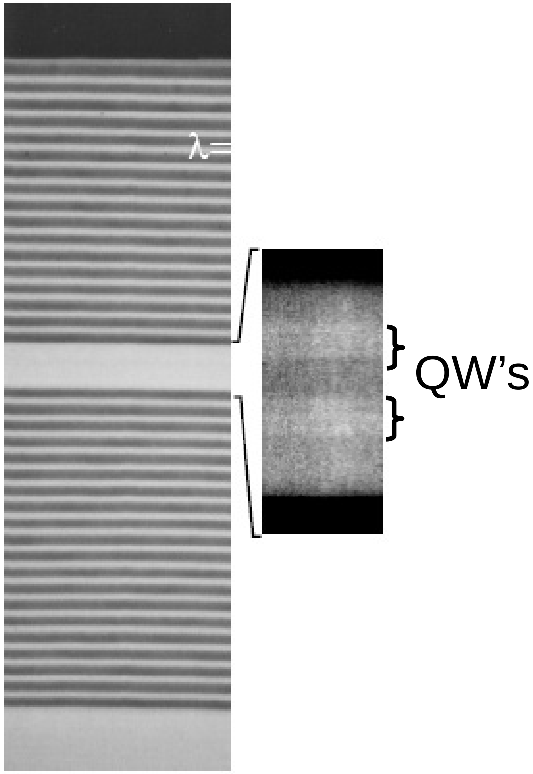
⇒ **Spontaneous Emission is a reversible process**



Monolithic Semiconductor Microcavity

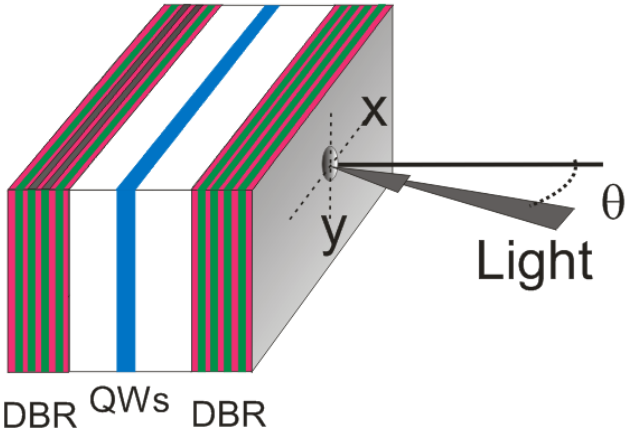
- QWs placed at the E-field maxima





- Combine electronic and photonic confinement in the same structure

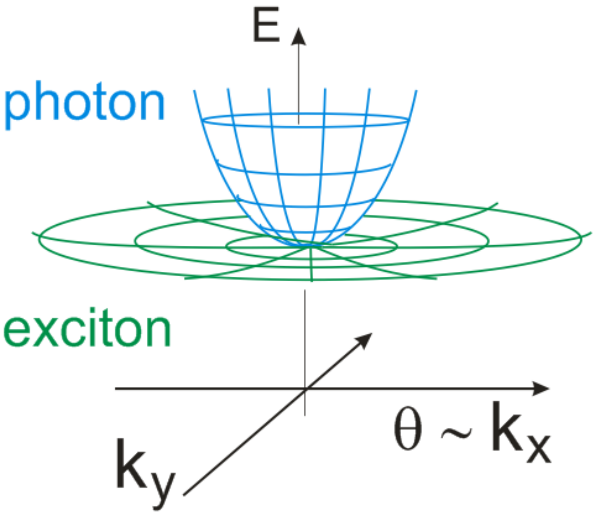
Strong Coupling Regime in Semiconductor Microcavity



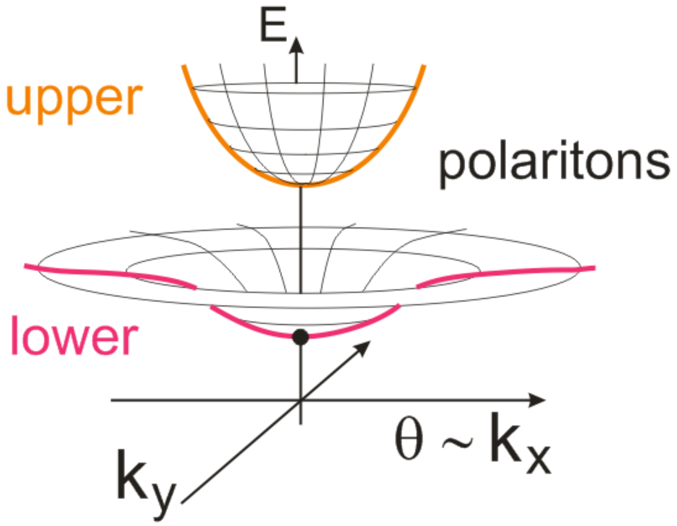
- Strongly modified dispersion relations
  new properties
- small polariton mass $m_{pol} \approx 10^{-4} m_e$
- strong non-linearities → χ^3 (exciton component)

$$E_{photon} = \frac{\hbar c}{n_c}\sqrt{\left(\frac{2\pi}{L_c}\right)^2 + k_{//}^2}$$

$$E_{ex}(k_{II}) = E(0) + \frac{\hbar^2 k_{//}^2}{2M_{exciton}}$$



Strong Coupling Regime



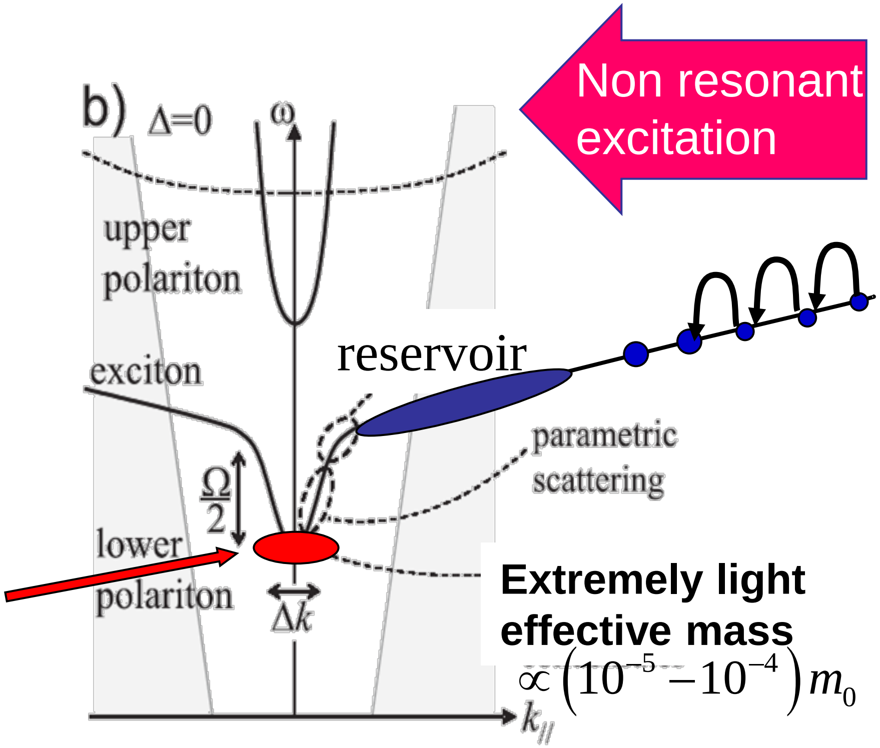
C. Weisbuch et al., Phys. Rev. Lett. 69, 3314 (1992)

Bose-Condensation and Concept of Polariton Lasing

Imamoglu et al., PRA 53, 4250 (1996)

Bosonic character of cavity polaritons could be used to create an exciton-polariton condensate that would emit coherent laser-like light.

Polariton condensate



Non resonant excitation

Extremely light effective mass

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

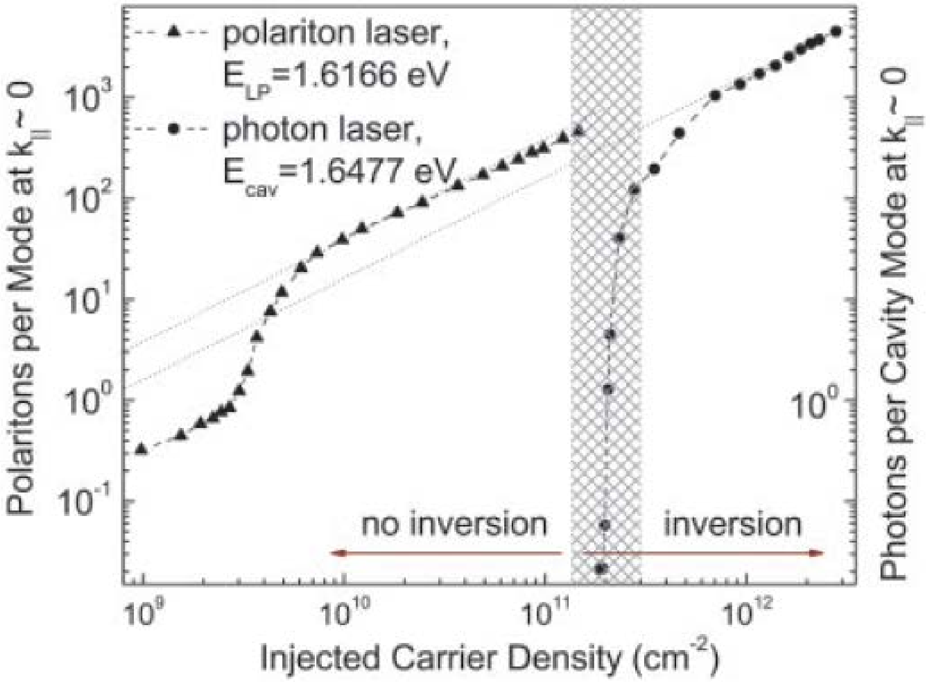
Polaritons accumulate in the lowest energy state by bosonic final state stimulation.

The coherence of the condensate builds up from an incoherent equilibrium reservoir and the BEC phase transition takes place.

The condensate emits spontaneously coherent light without necesity for population inversion

New Physics & Applications

- Strong-coupling provides a new insight into a number of very interesting fundamental physical processes and applications



Polaritons are Bosons

⇩

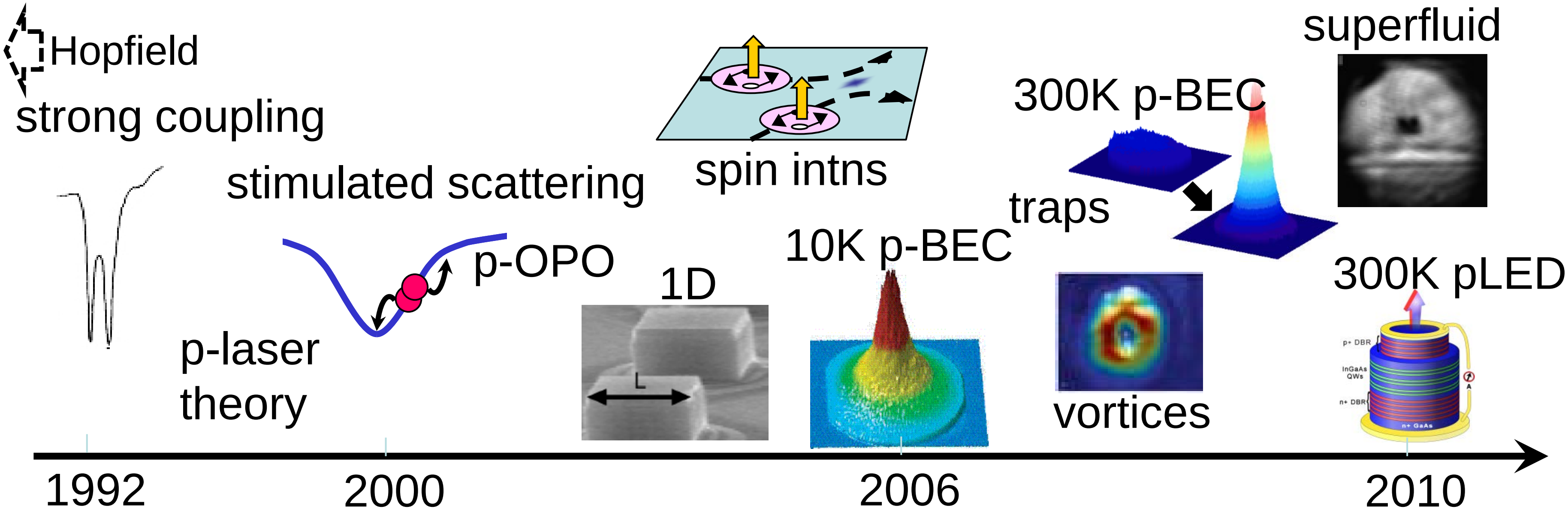
- Bose condensation
- stimulated scattering

Polariton vs Photon Laser

Deng, et al. Natl. Acad. Sci. 15318 (2003)

- ultralow threshold polariton lasers
- all optical switches and amplifiers

Polaritonics



Hopfield
strong coupling

stimulated scattering

p-laser
theory

p-OPO

1D

spin intns

10K p-BEC

traps

300K p-BEC

vortices

superfluid

300K pLED

1992
2000
2006
2010

From a device perspective:

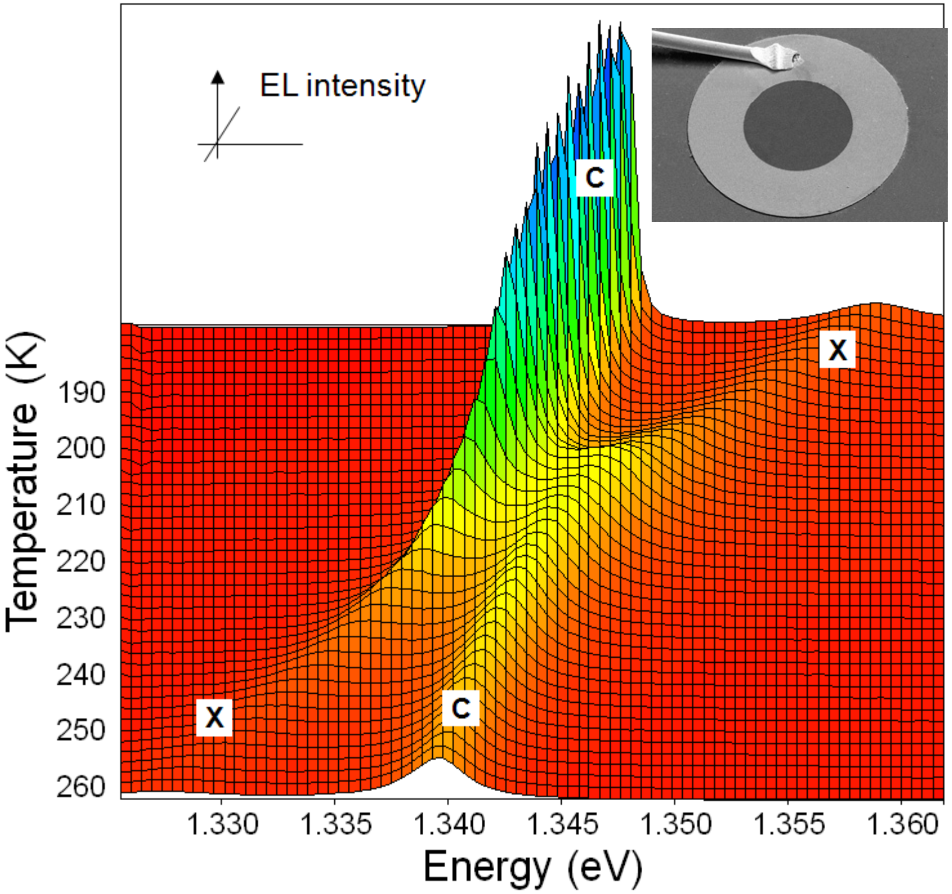
- Near speed of light lateral transport
- Light effective mass
- Condensate regime readily available on a chip even at RT

New directions: electrically driven polariton devices

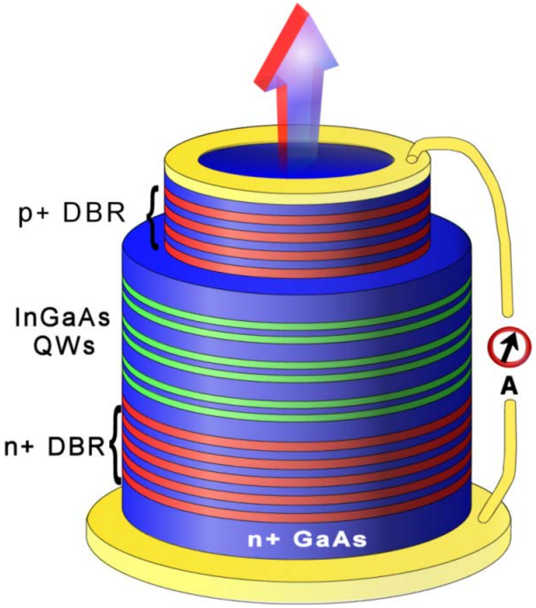
Polariton based Devices
“Polaritonics”

Room temperature Polariton LED

Emission collected normal to the device



- Clear anticrossing observed
- Direct emission from exciton polariton states

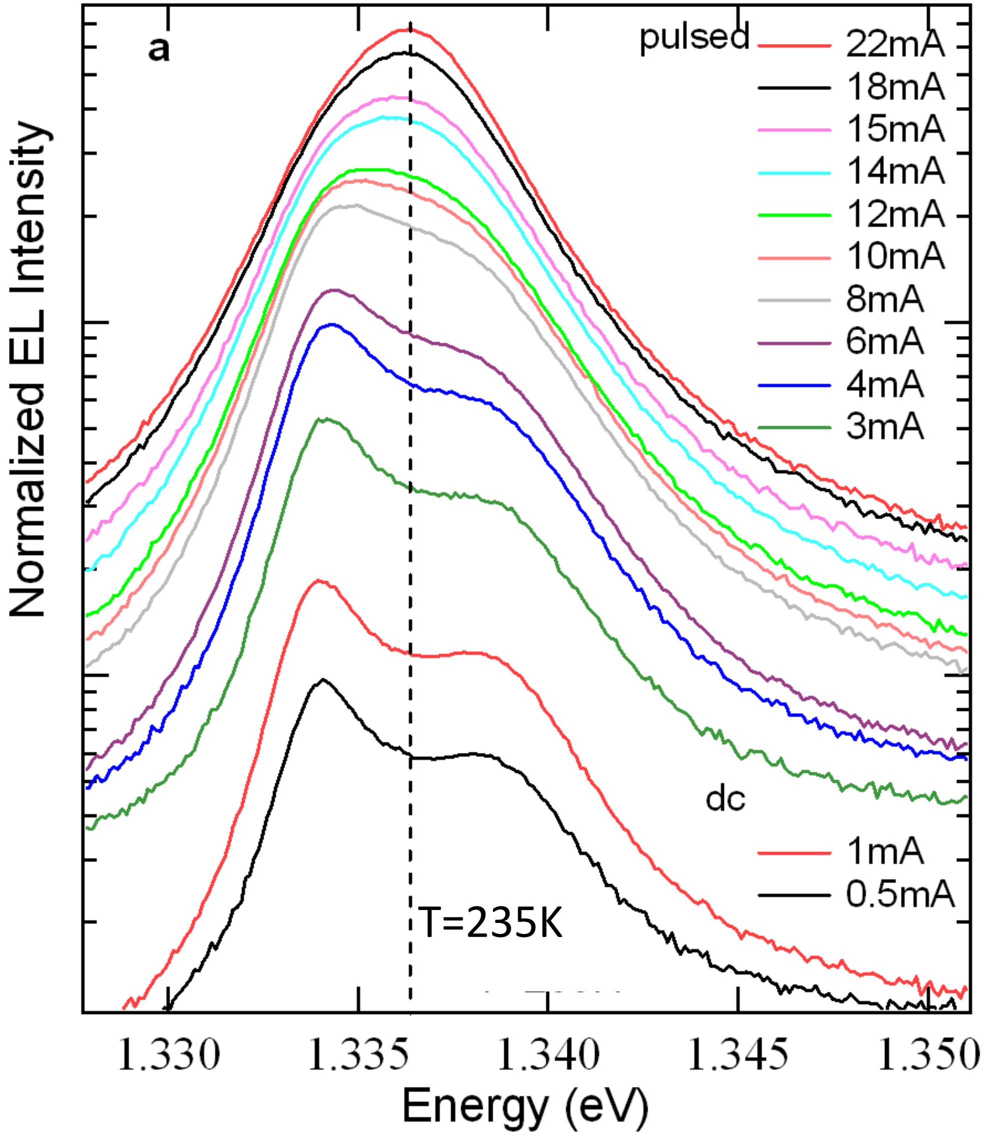


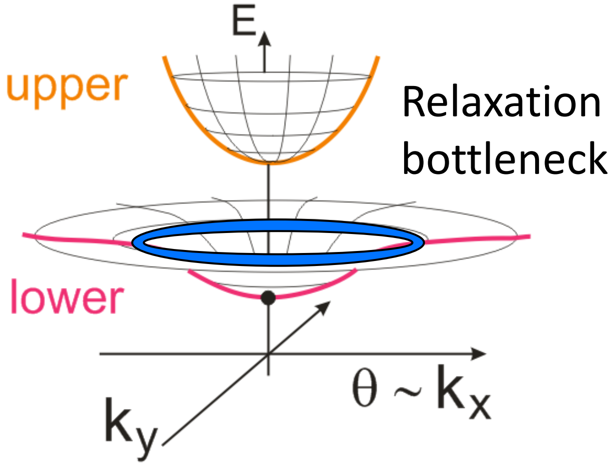
- Rabi splitting of 4.4meV at 219 K

Transport driven device

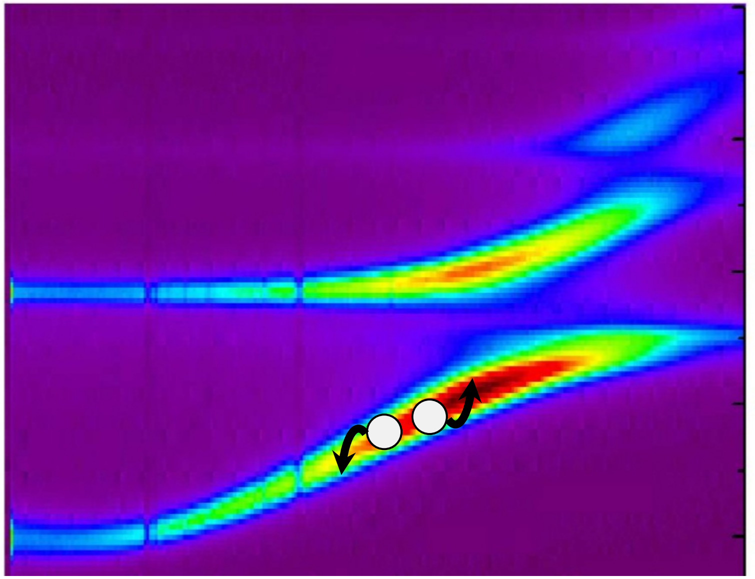
S. Tsintzos *et al.*, *Nature 453, 372* (2008)

Collapse of Strong Coupling Regime at High Densities



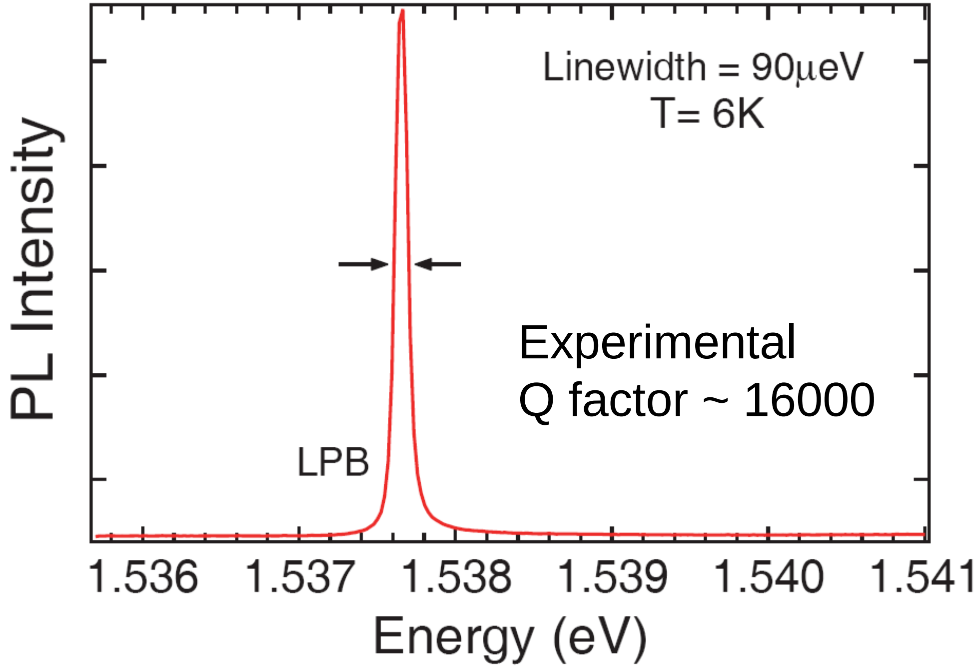


Relaxation on lower branch governed by polariton-polariton interactions (dipole-dipole)

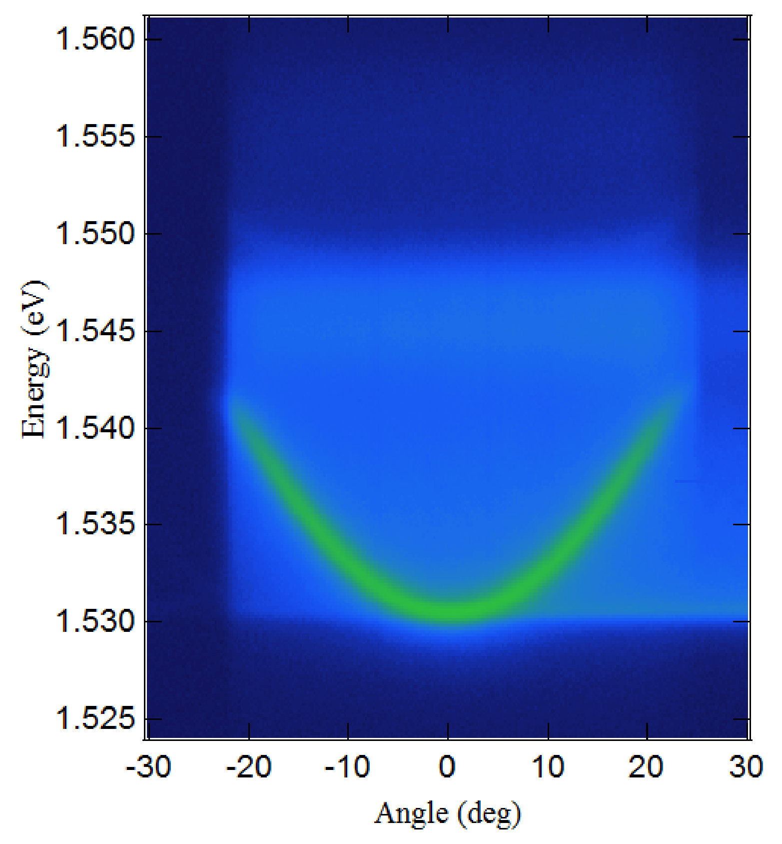


- **Injection density at 22mA ~ 10^{10} pol/cm^2**

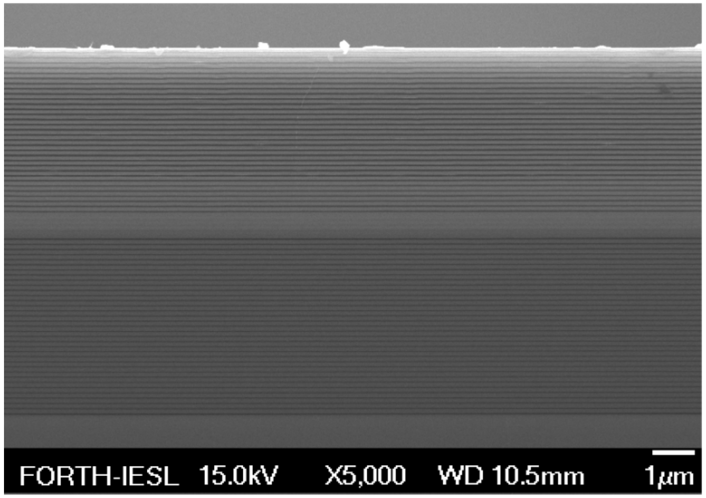
High finesse GaAs microcavity



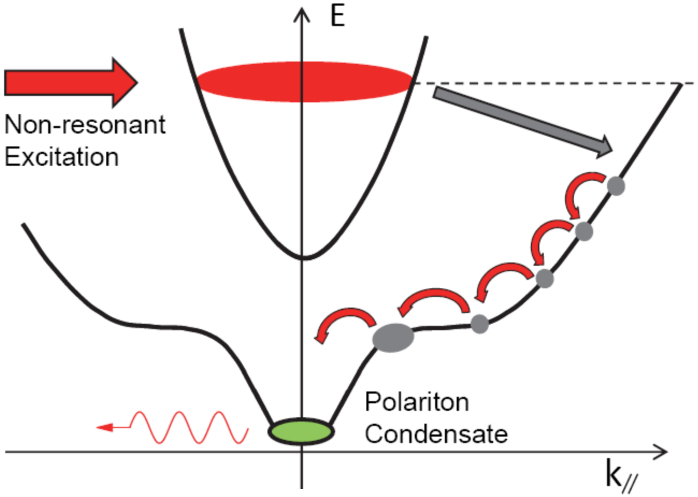
Experimental
Q factor ~ 16000

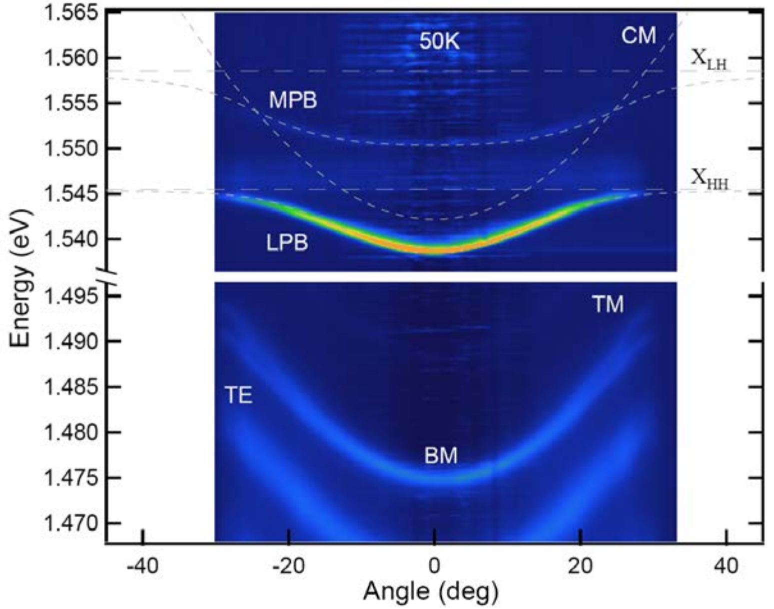


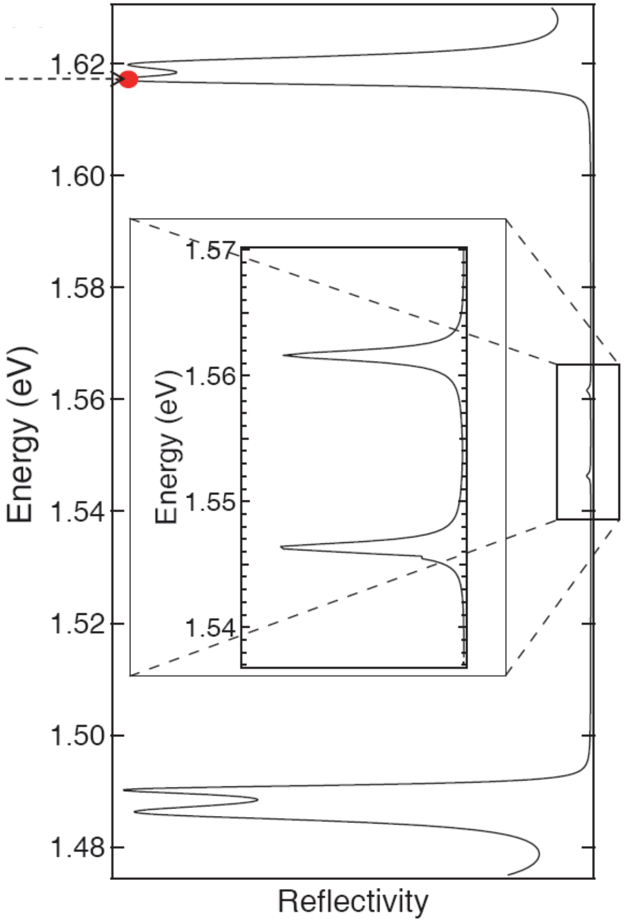
Modeled Q factor ~ 20000



Non-resonant optical excitation



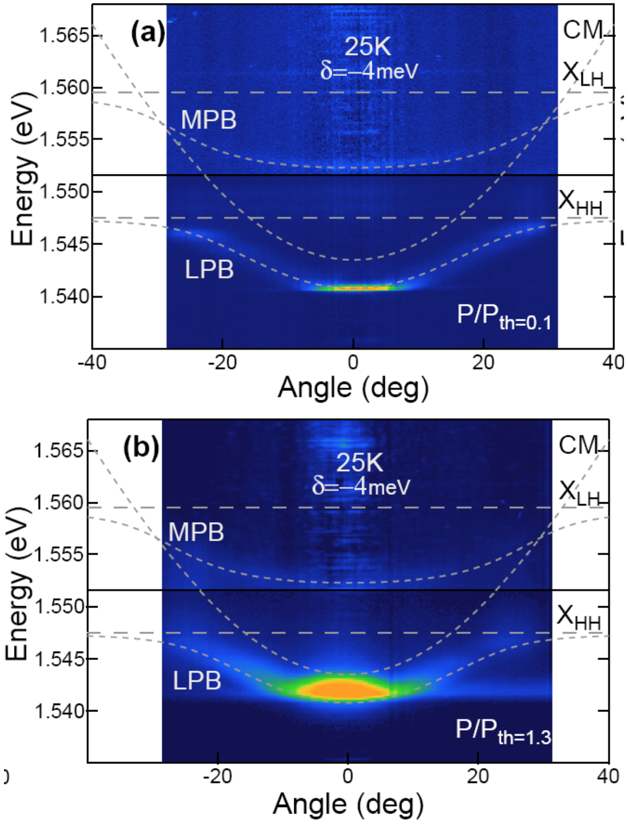


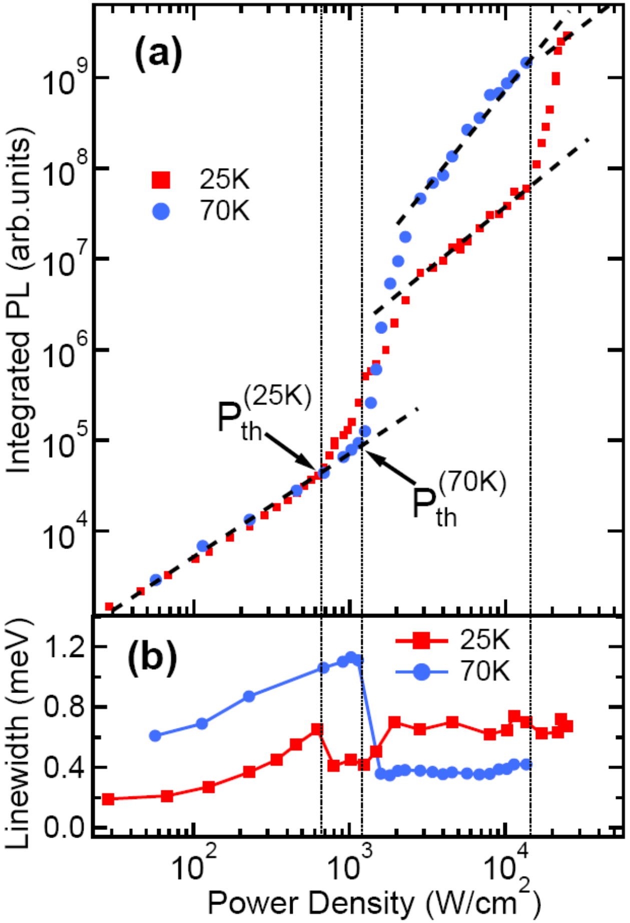


- Rabi splitting of 9.2meV at 50K
- Reflectivity dips relatively small

GaAs Polariton Laser 25K

- Nonresonant optical pumping above stopband





- Very low threshold at 25K ~ 6.5mW strong coupling

P. Tsotsis et al., New Jour. Phys. (2012)

Polariton Condensate Transistor Switch

Polariton Condensate Transistor Switch

Motivation: Although photonic circuits have been proposed, a viable optical analogue to an electronic transistor has yet to be identified as switching and operating powers of these devices are typically high

Common perception: In the future, charged carriers have to be replaced by information carriers that do not suffer from scattering, capacitance and resistivity effects

Approach: Polaritons being hybrid photonic and electronic states offer natural bridge between these two systems

Excitonic component allows them to interact strongly giving rise to the nonlinear functionality enjoyed by electrons

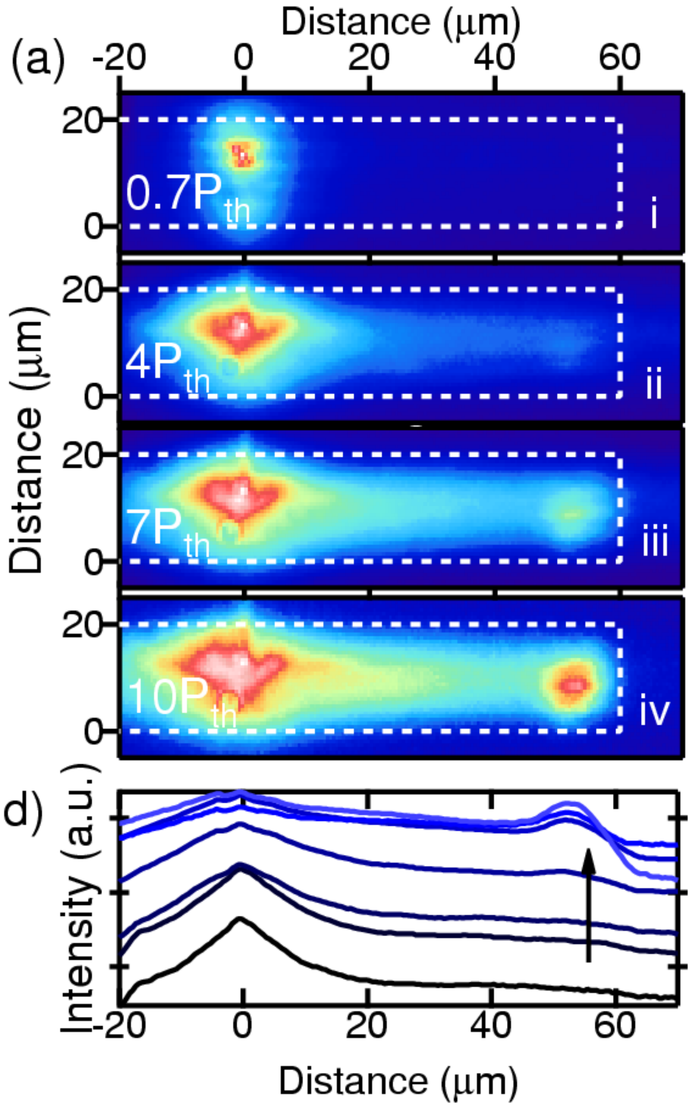
Photonic component restricts their dephasing allowing them to carry information with minimal data loss and high speed

Macroscopic quantum properties of polariton condensates make them ideal candidates for use in quantum information devices and all optical circuits

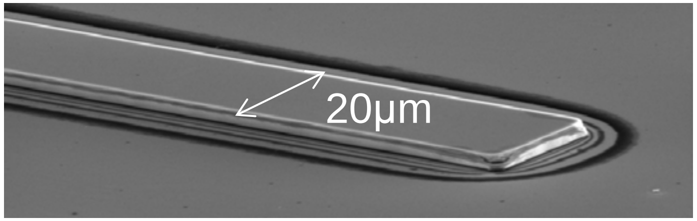
Gao et al.,PRB 85, 235102 (2012)
D.Ballarini et al. arXiv:1201.4071 (2012)

D.Sanvitto *et al.* Nature Photon. 5, 610 (2011)
E.Wertz *et al.* Nature Phys 6, 860 (2010)

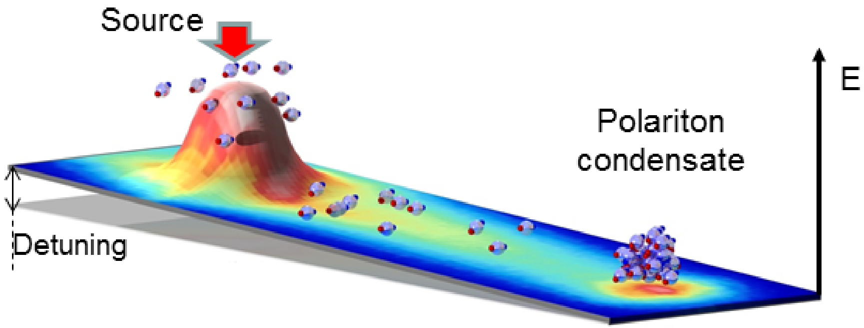
Generating Polariton Condensate Flow



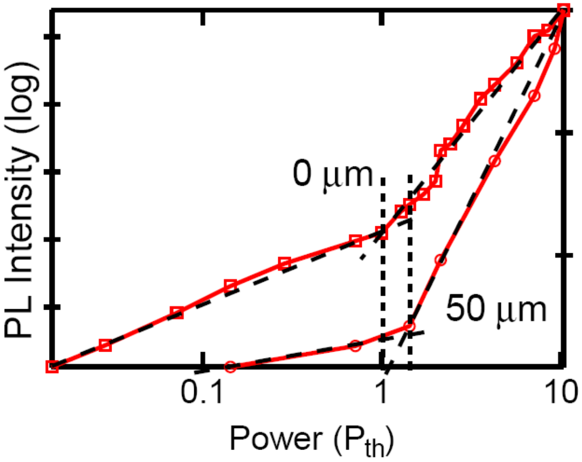
- Local pump induced blueshift and lateral confinement forces polariton flow along the ridge



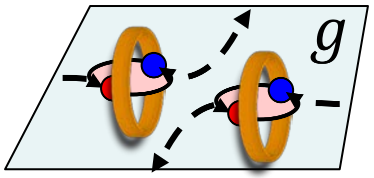
Only top DBR is etched



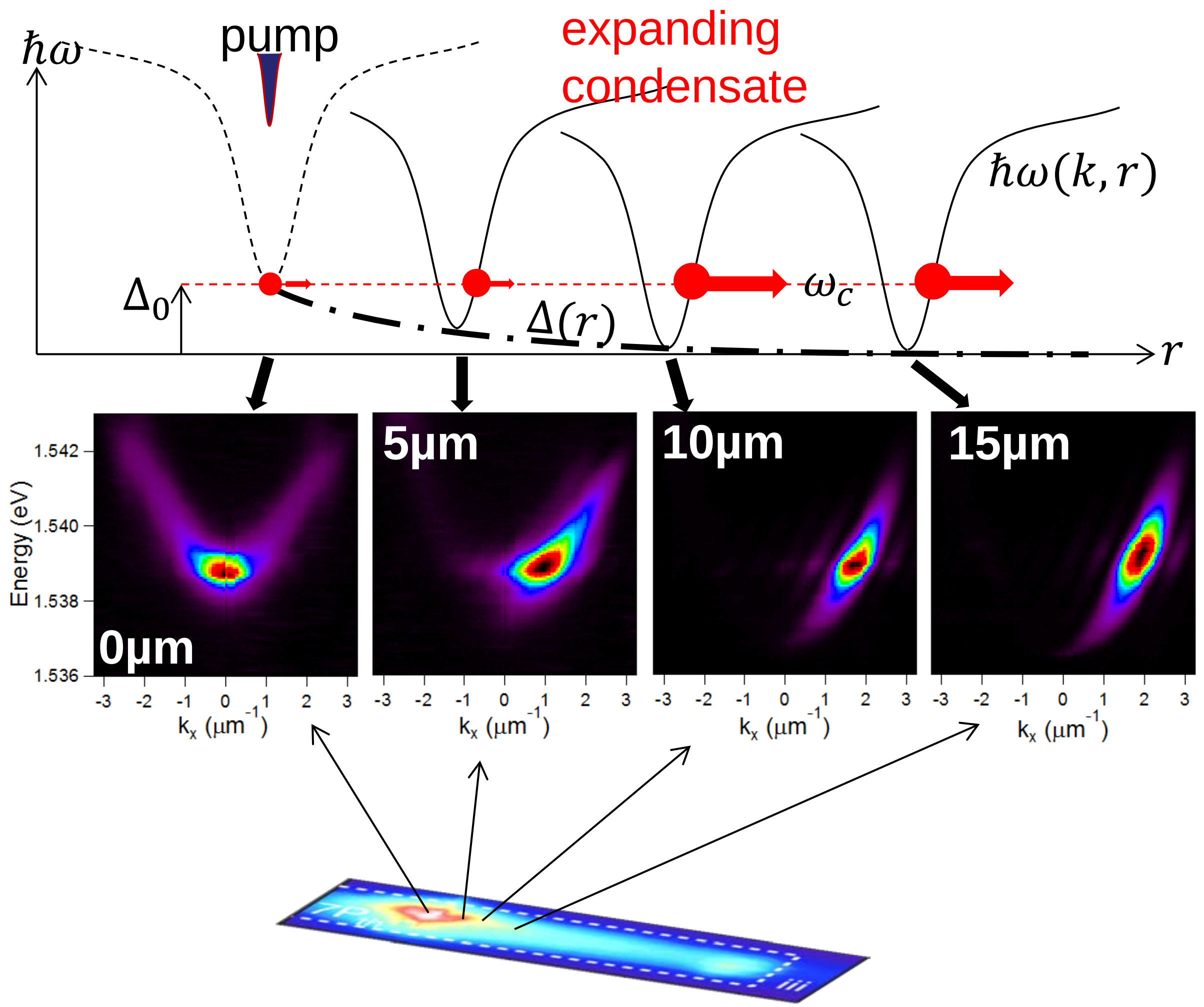
- Polariton condensate forming at the ridge end

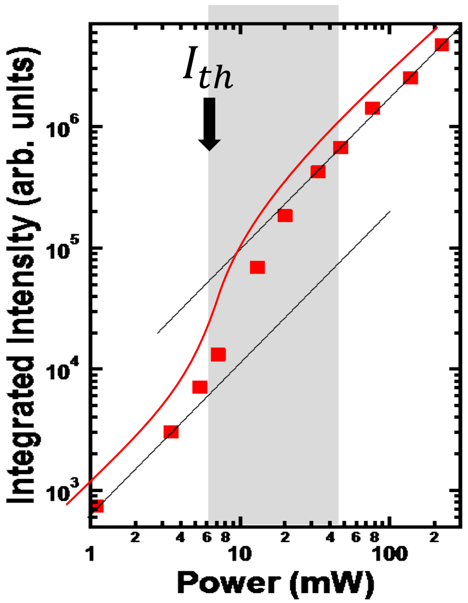


Ballistic Condensate Ejection



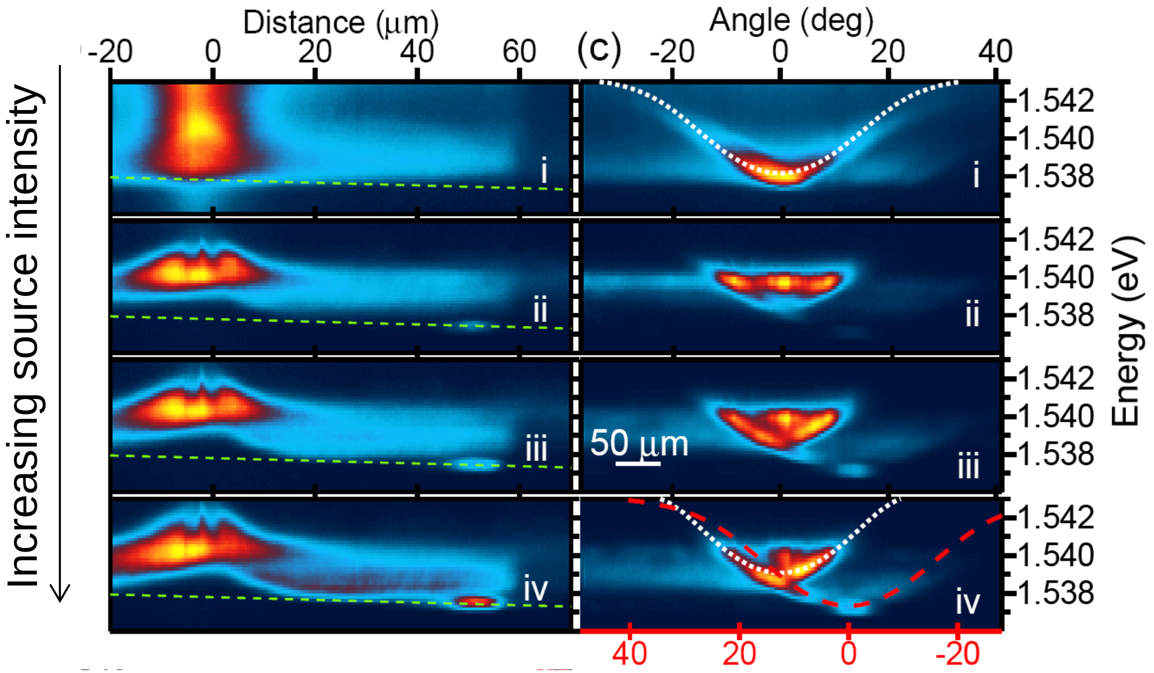
- blue shift at pump
  $$V_{max} = g|\psi|^2$$
- polaritons expand along the ridge



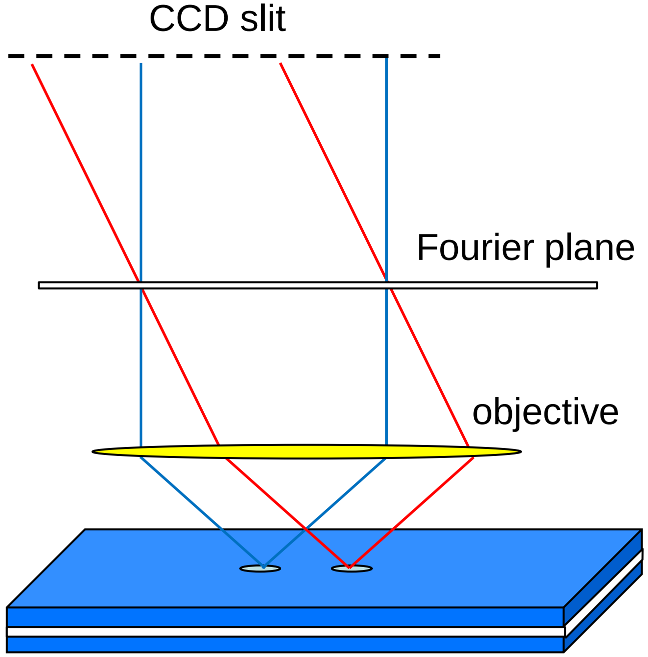


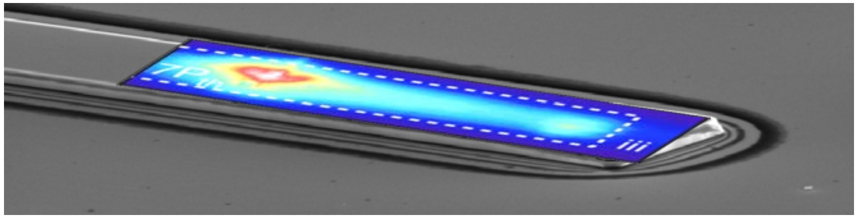
G. Christmann *et al.*, Phys. Rev. B 85, 235303 (2012)

Polariton Condensate Built-up



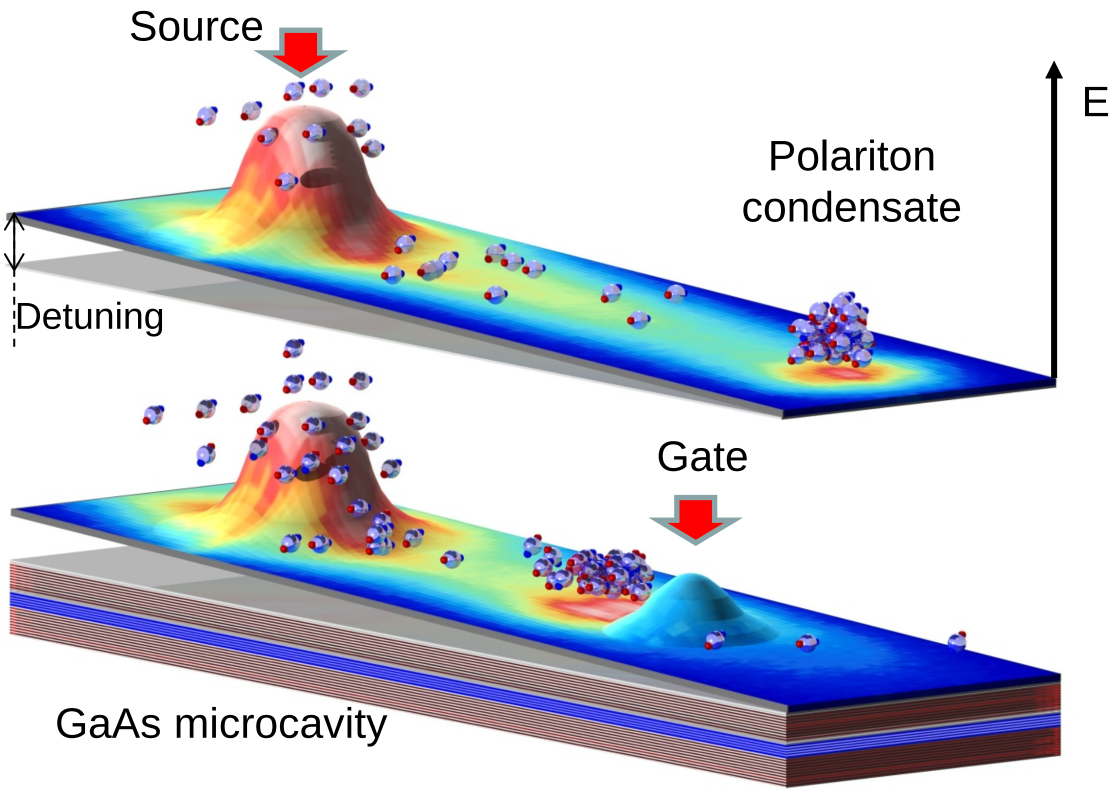
- spatially separated and angle resolved emission





- Ballistic transport of polaritons
- Polaritons flow and relax in the direction of negative detuning
- Condensate forming at the ridge end

Polariton Condensate Transistor Switch

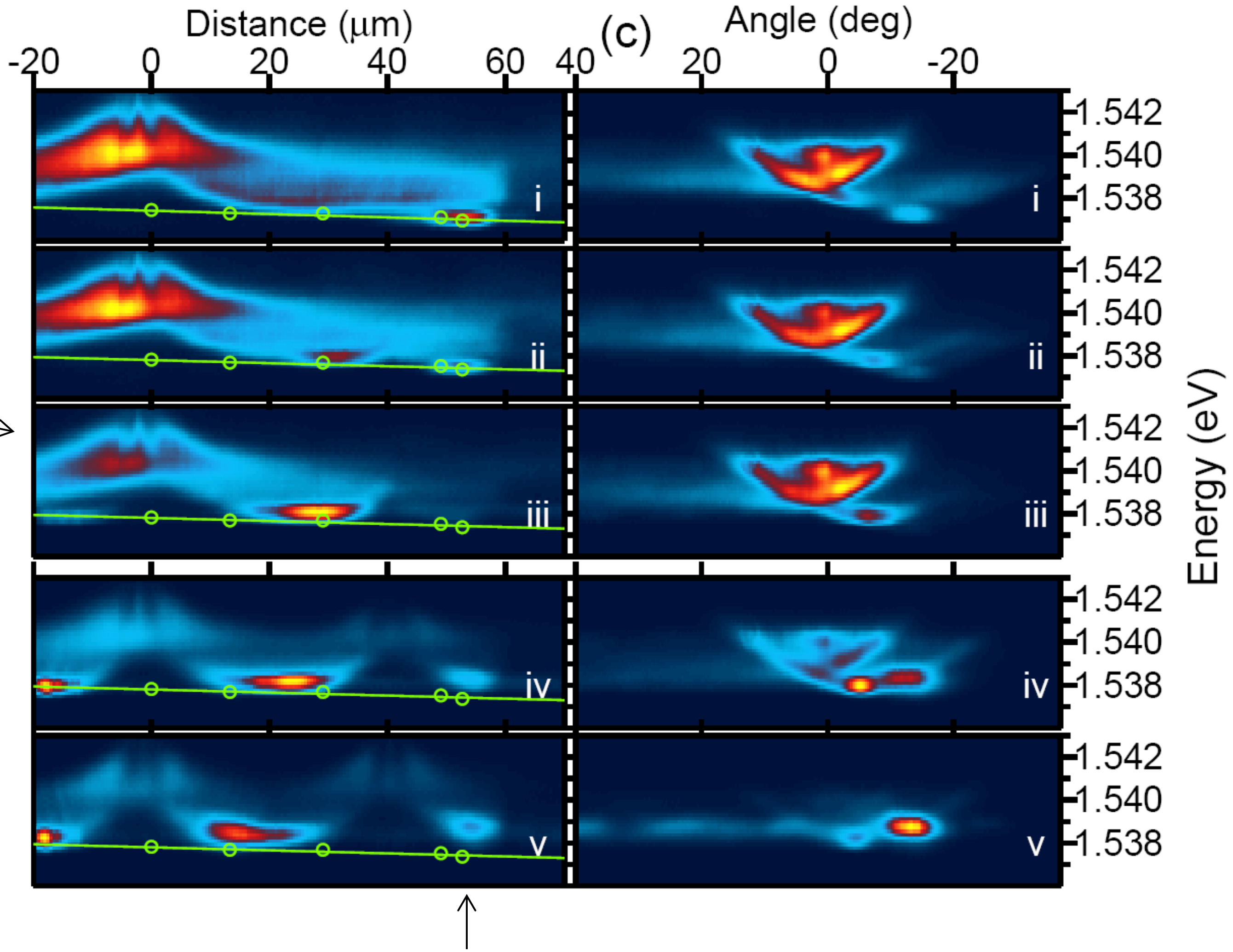


- Polariton propagation is controlled using a second weaker beam that gates the polariton flux by modifying the energy landscape

Gating Polariton Condensate Flow

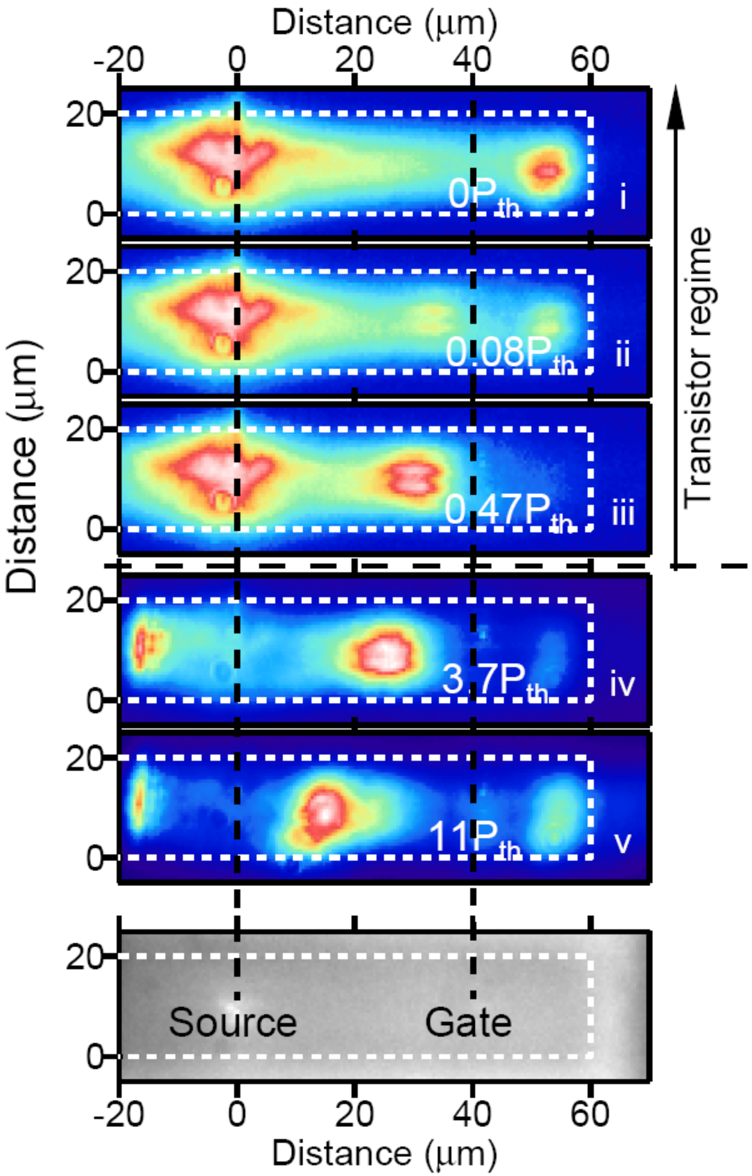
- Gate beam power 20 times weaker than source

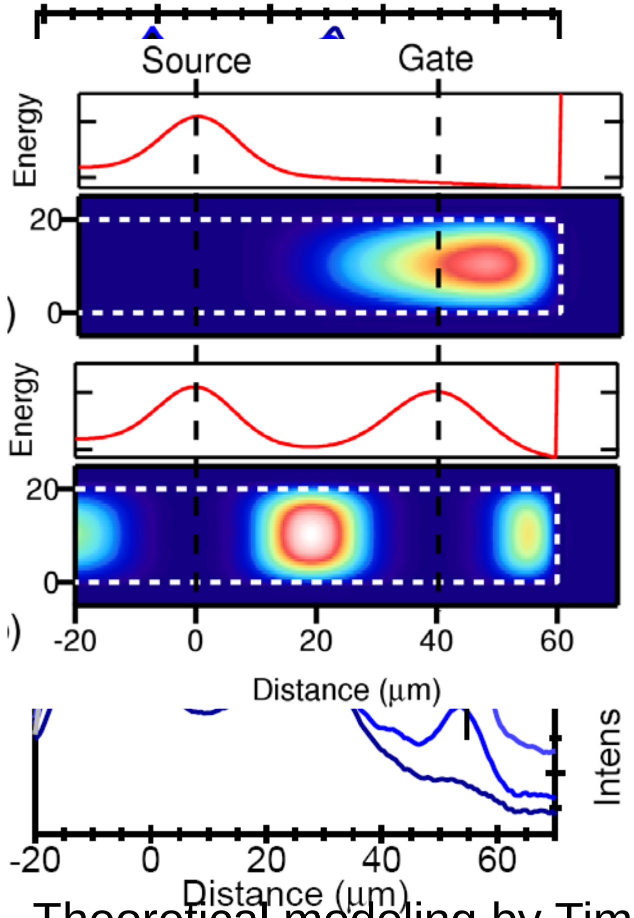
- Second condensate appears between source and gate at higher gate powers



- At higher powers gate re-pumps the condensate at the ridge end

Gating Polariton Condensate Flow





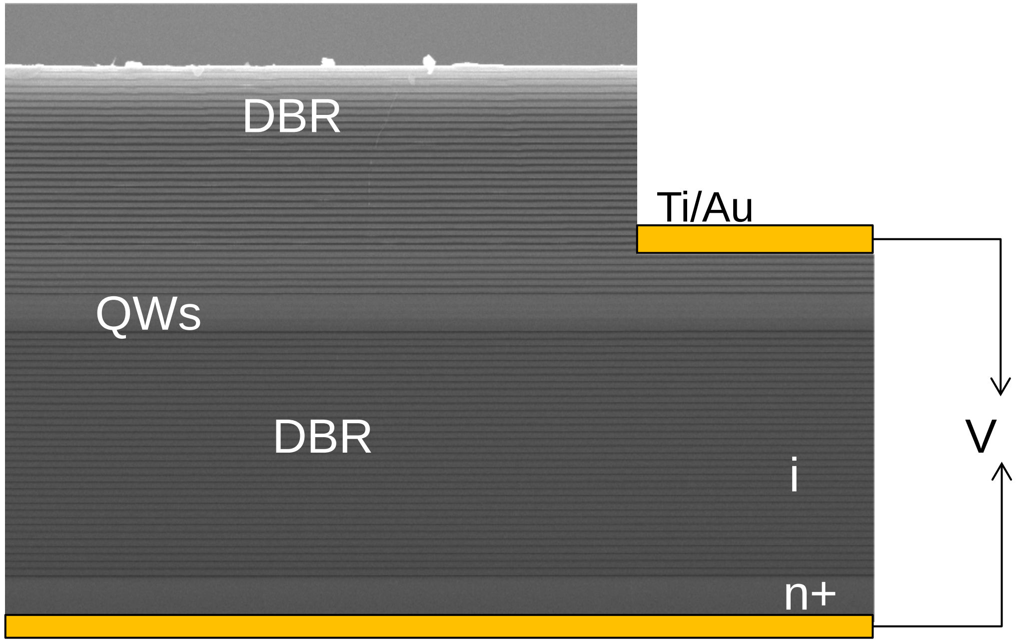
Theoretical modeling by Tim Liew

- gating efficiency up to 90% is demonstrated

Electrical and optical control of polariton condensates

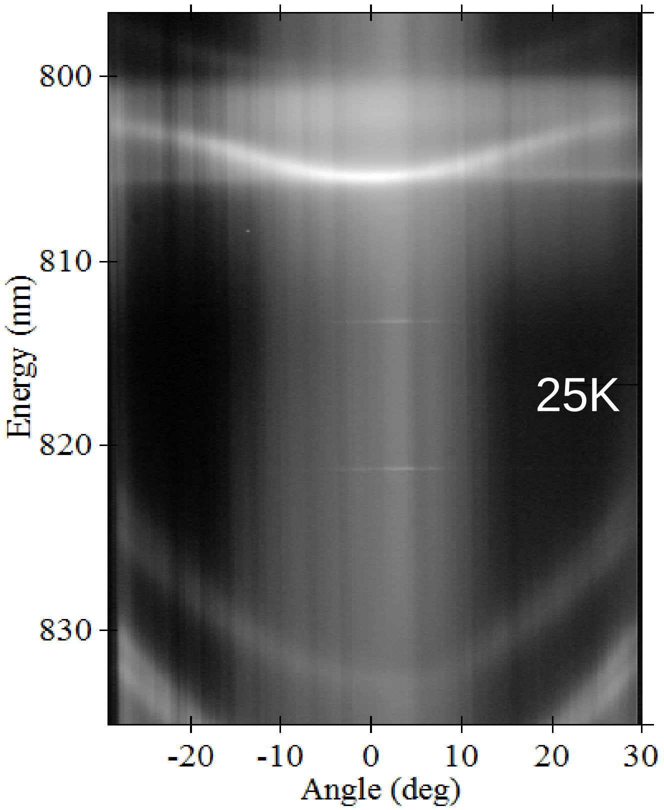
Electrical control of polariton dispersions

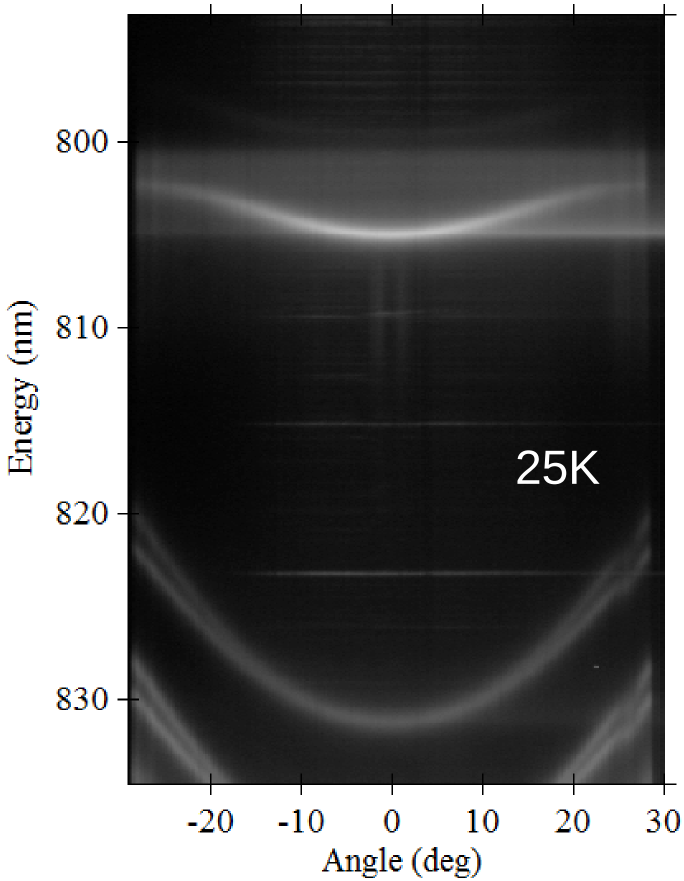
Schottky diode



- Application of electric field to the QW tunes the exciton energy through QCSE
- Reduction in exciton oscillator strength & Rabi splitting have to be considered

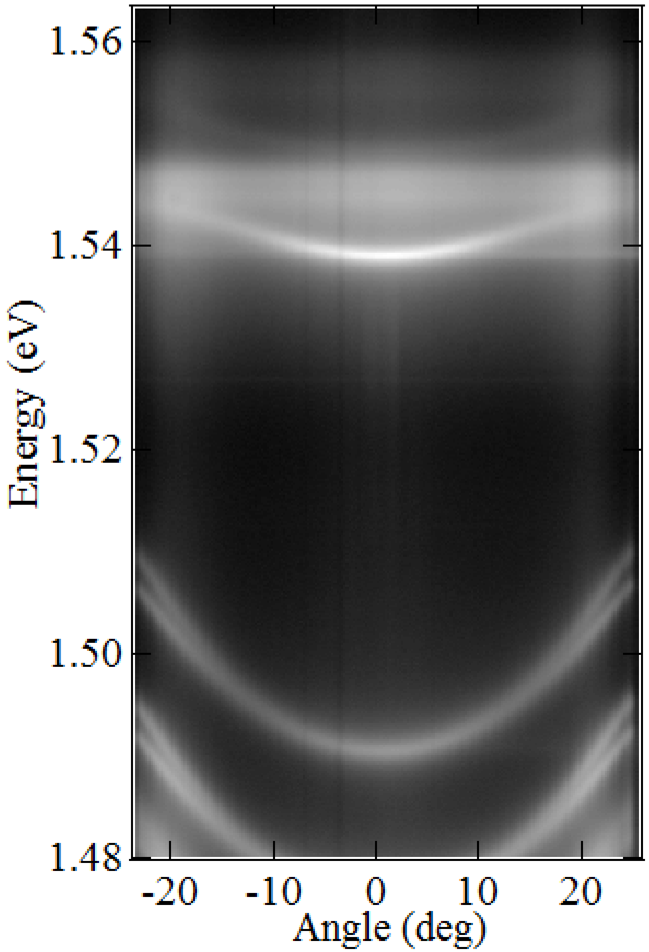
Electrical control of polariton dispersions

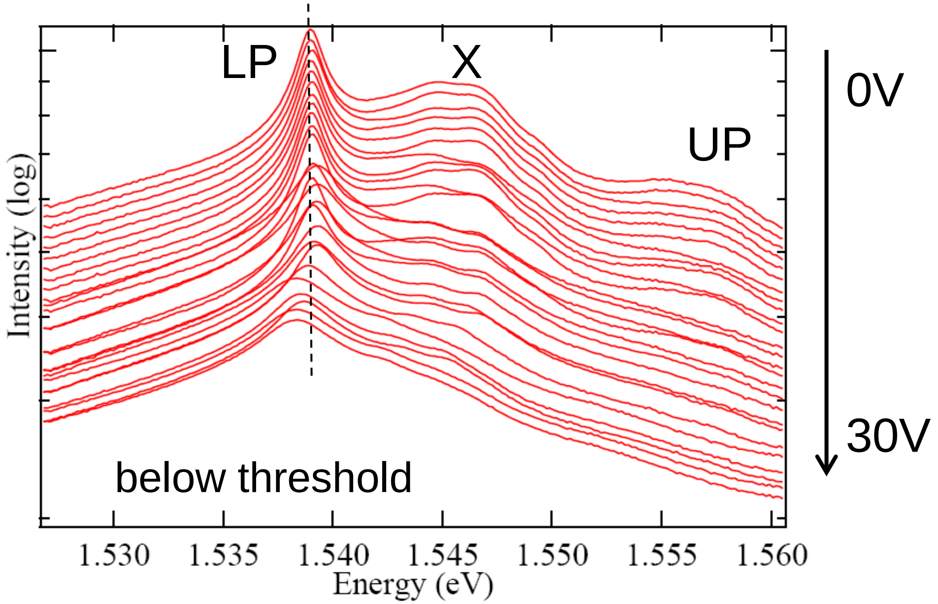

side contact

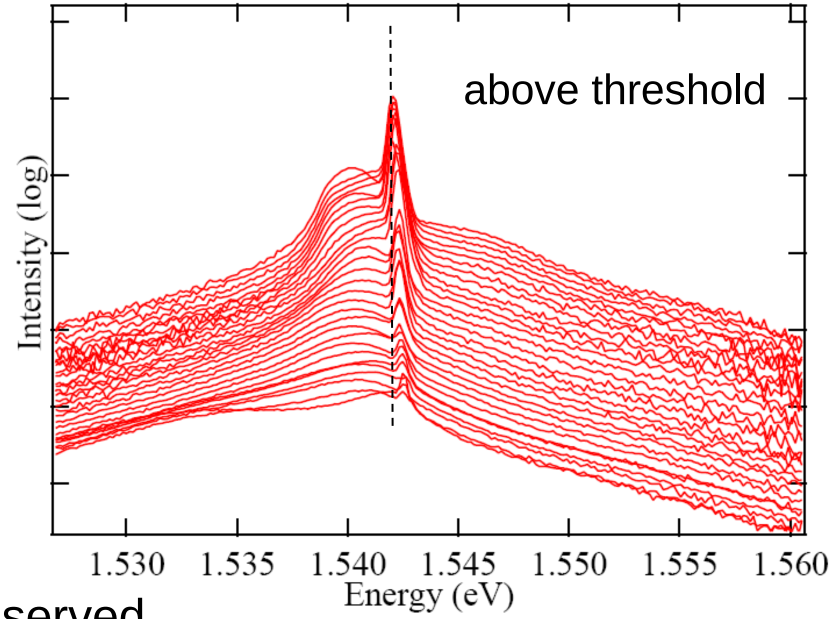

top contact

- Clear tuning of the lower polariton branch energy
- Schottky diode allows local spatial field to be applied

Control of polariton dispersions in nonlinear regime



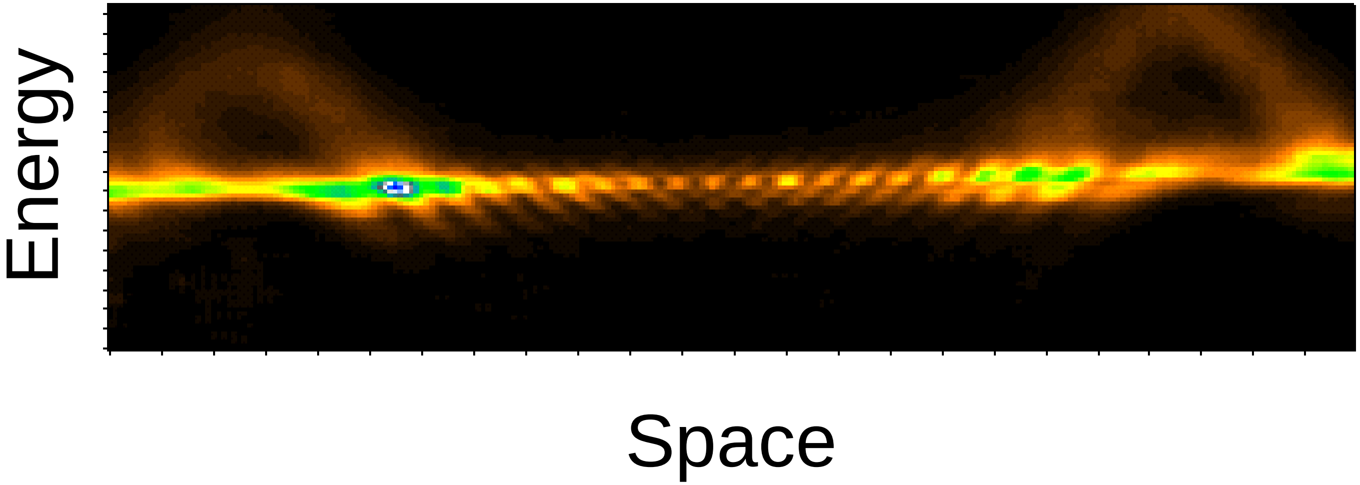


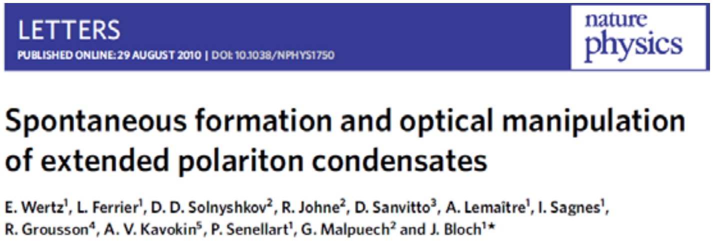


- electric tuning of the lasing energy observed

Interactions Between Condensates

- Can we make two independent condensates interact on a chip?
- What happens if we launch two condensates against each other





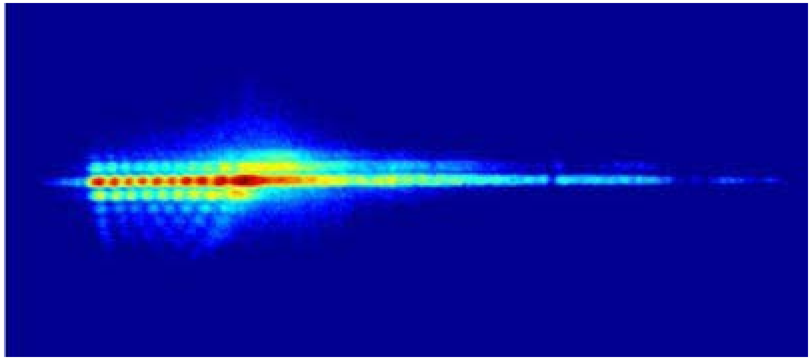
LETTERS

PUBLISHED ONLINE: 29 AUGUST 2010 | DOI: 10.1038/NPHYS1750

nature physics

Spontaneous formation and optical manipulation of extended polariton condensates

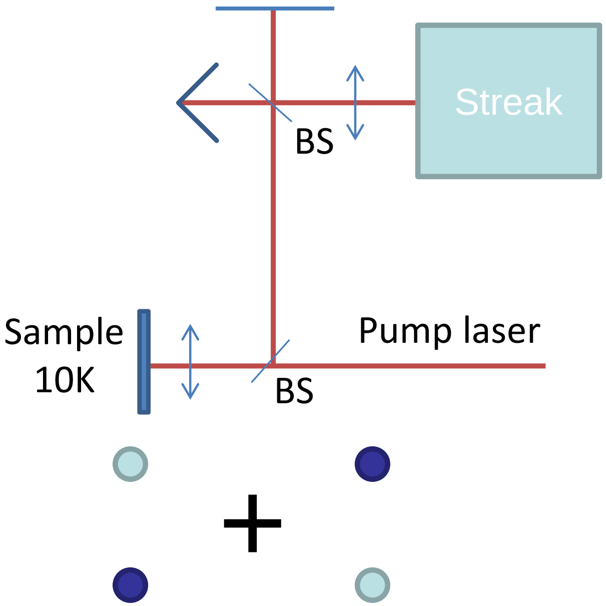
E. Wertz[1], L. Ferrier[1], D. D. Solnyshkov[2], R. Johne[2], D. Sanvitto[3], A. Lemaître[1], I. Sagnes[1], R. Grousson[4], A. V. Kavokin[5], P. Senellart[1], G. Malpuech[2] and J. Bloch[1]*

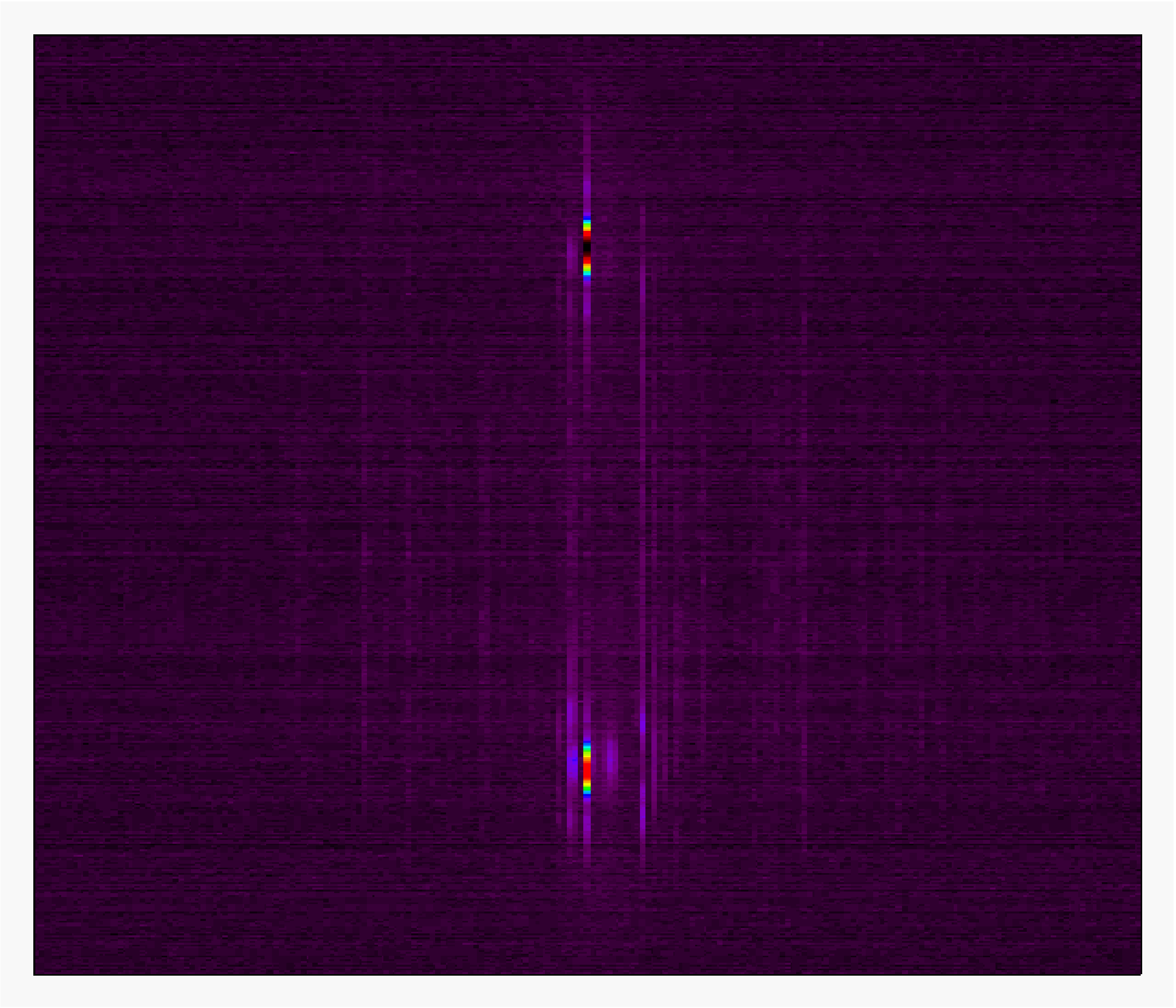


Buildup of Coherence and Phase Locking

Time resolved measurement & interferometry

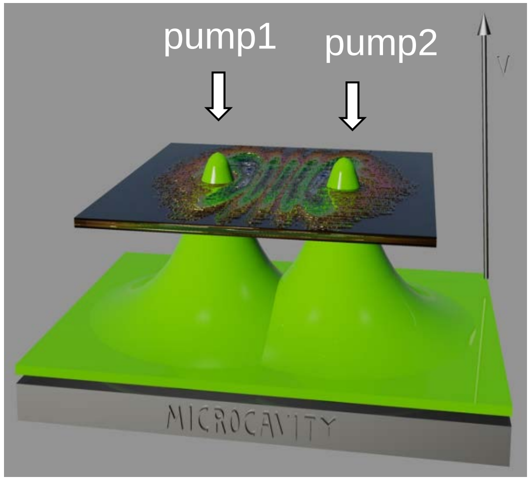
Pulsed excitation, interference of one with the other

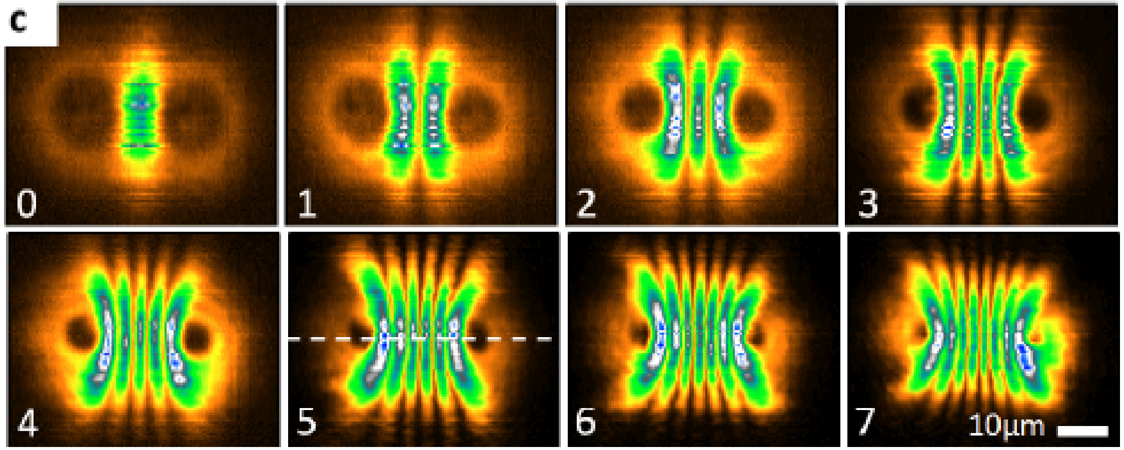


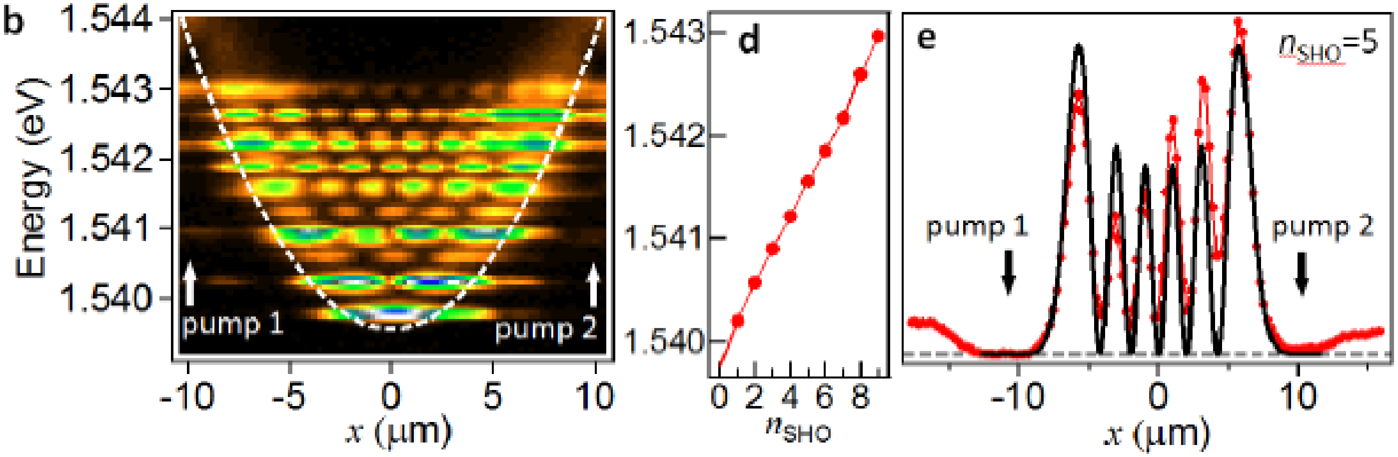


Polariton condensates in a parabolic optical trap

tomography







- equal spaced energies SHO wavefunctions
- harmonic potential - quantum pendulum

G. Tosi et al. Nature Physics 8, 190 (2012)

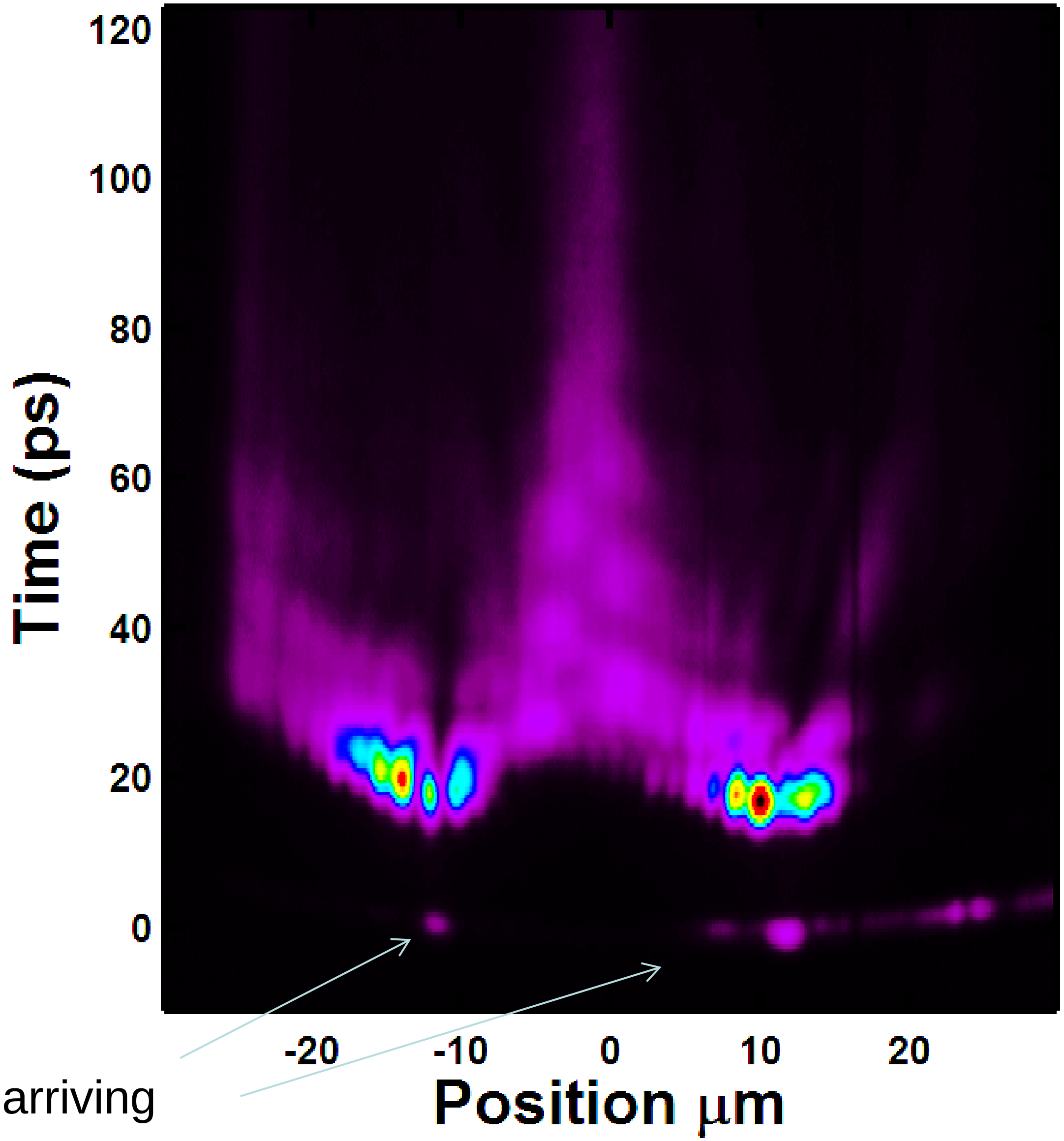
Polariton Quantum Pendulum

Oscillations observed under pulsed excitation regime

2 spots separated by 25 microns

Streak camera measurement

Increasing pump power



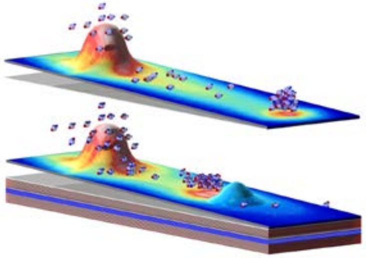
Laser arriving

Summary

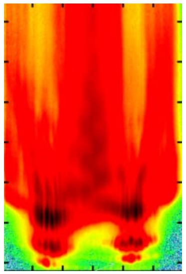
- Low threshold polariton lasing at 25K

- Electrical and optical manipulation of polariton condensates on a chip

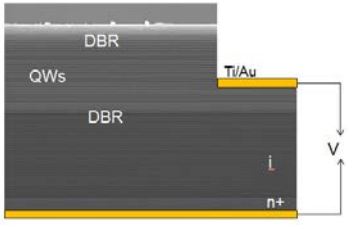
  polariton condensate transistor



  polariton condensate pendulum



Interactions between condensates in confining potentials



PostDoc positions at FORTH-IESL

3 Postdoctoral Research Fellow Positions on Polaritonic Devices

The aim is to develop novel class of electrically injected polariton devices.
Positions:
(1) Electrically injected polariton lasers
(2) Polaritonic circuits and transistors
(3) Design, growth and fabrication of microcavity structures

Living allowance under an employment contract: 21,600 €/year.
Highly motivated and qualified candidates with solid academic background and experimental experience are encouraged to apply.

For more info:
Prof. Pavlos Savvidis
Department of Materials Science &Technology, University of Crete
Senior Researcher at FORTH-IESL
http://quantopt.materials.uoc.gr
Implemented under the "ARISTEIA" Action co-funded by the (ESF) and National Resources.

“APOLLO” Aristeia grant

Thank you