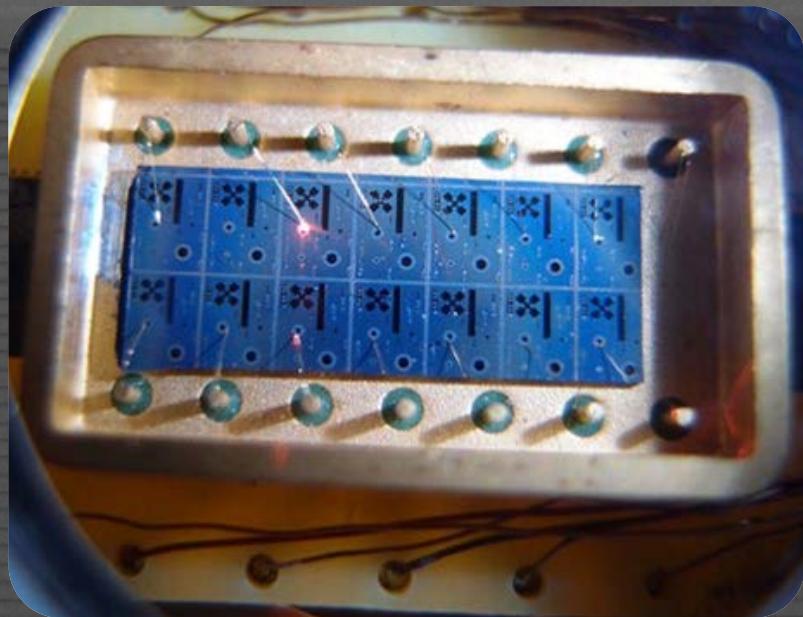


Dipole Oriented Polaritons

Pavlos G. Savvidis
University of Crete, FORTH-IESL

Ioffe
17.06.13



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G. Tosi
P. Cristofolini

Department of Materials Science / IESL-FORTH



Collaborations

IESL-FORTH



P. Lagoudakis
A. Kavokin
A. Askitopoulos



T. Liew



Daniele Sanvitto

UOC



Z. Hatzopoulos
N. Pelekanos
E. Iliopoulos
A. Georgakilas
I. Perakis

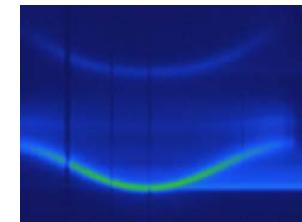
Luis Vina
Carlos Anton



David Lidzey
D. Cole

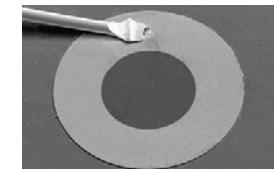
Outline

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



- Electrical control of polariton interactions and nonlinearities in biased semiconductor microcavities

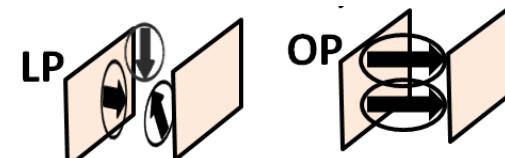
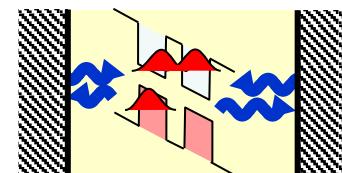
- Forward bias **GaAs Polariton LED**



- Reverse bias **Dipolaritons: dipole oriented polaritons**

- exploit tunneling to create oriented polaritons with enhanced dipole moments

- enhance nonlinearities



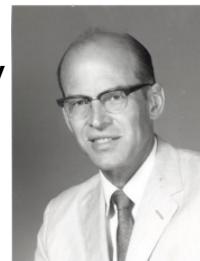
The History of Semiconductor Lasers

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

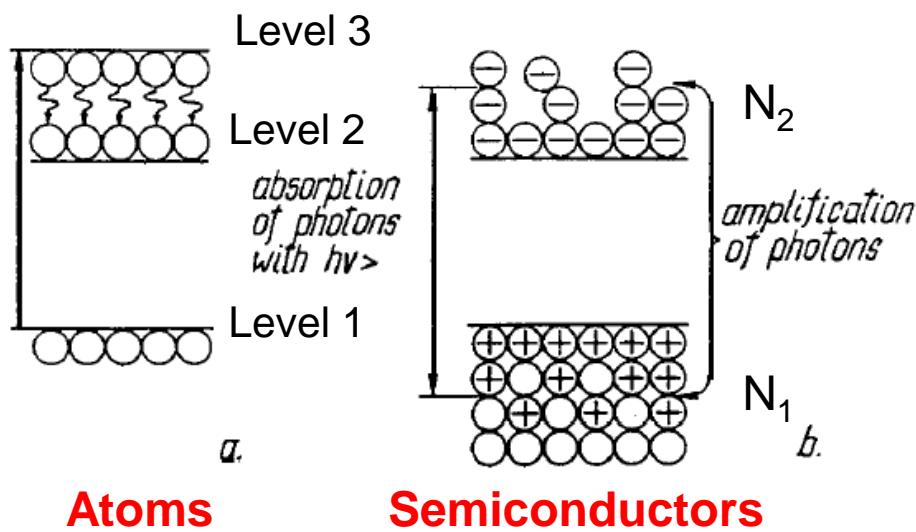
In 1970, Zhores Alferov, Izuo Hayashi and Morton Panish independently developed CW laser diodes at room temperature

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

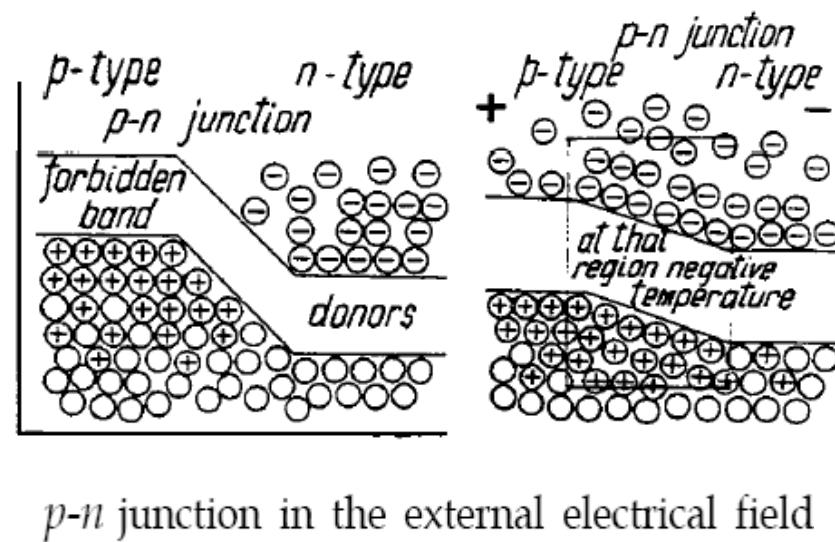
Negative Temperature & Population Inversion Lasing

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

Three-level laser energy diagram



Basov Nobel Lecture



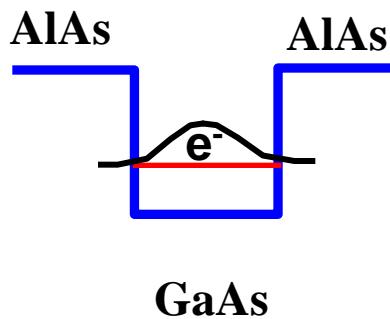
- Population inversion when $(N_2 > N_1) \rightarrow$ optical amplification at the frequency ω_{21}
- At least half the population of atoms must be excited from the ground state
 - to get population inversion laser medium must be very strongly pumped

This makes three-level lasers rather inefficient.

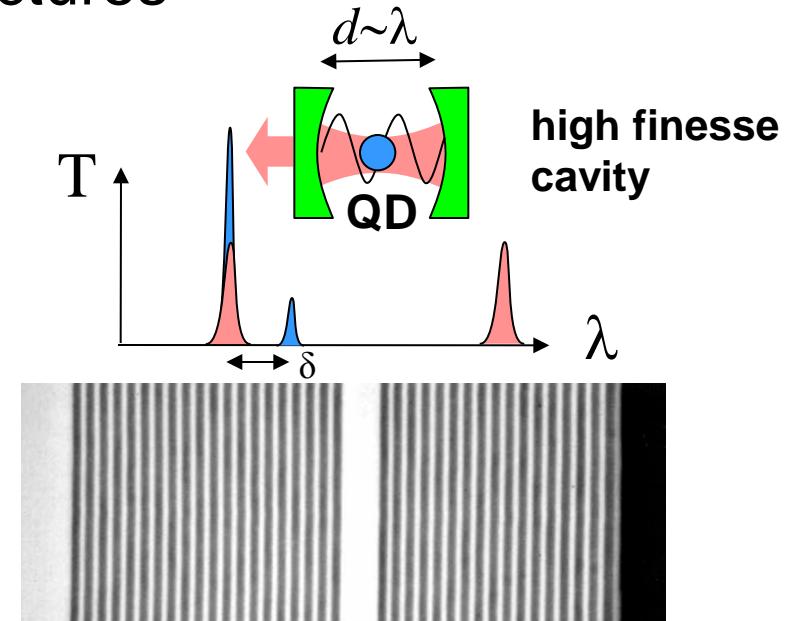


Engineering Light Matter Interactions

- modify photonic and electronic wavefunctions in semiconductor heterostructures



Confined electronic states:
band gap energy modulation

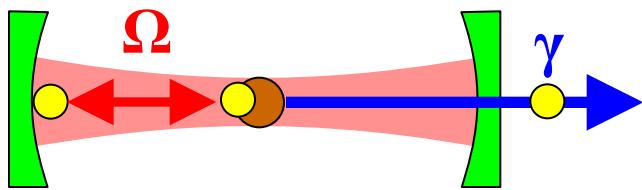


photons: refractive index modulation

- enhance, inhibit spontaneous radiation
- new properties, novel interactions, novel emitters



Weak Coupling Regime



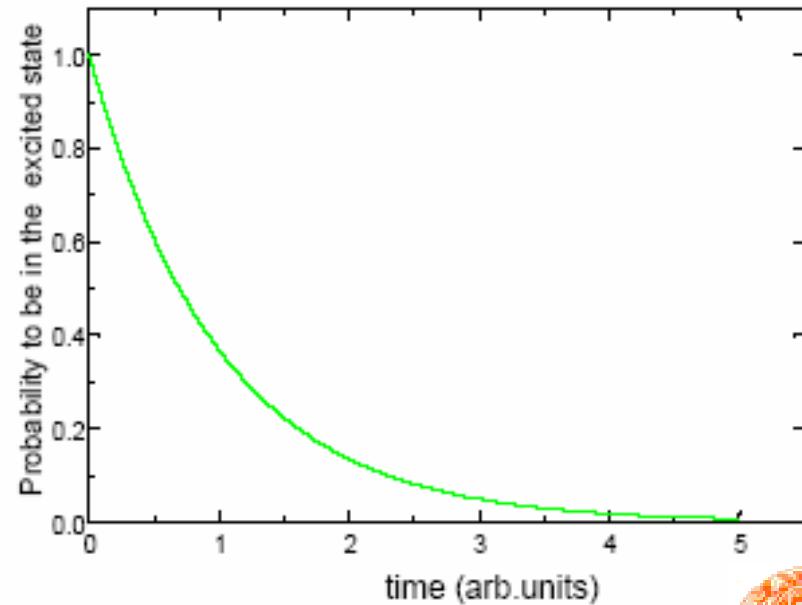
γ : loss channel (e.g. imperfect mirror)

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

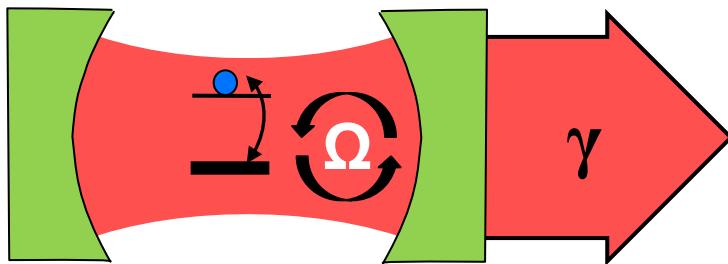
Weak Coupling Regime ($\gamma \gg \Omega$) :

emitted photon leaves the resonator
(after some reflections) no
reabsorption

⇒ Spontaneous Emission is irreversible



Strong Coupling Regime

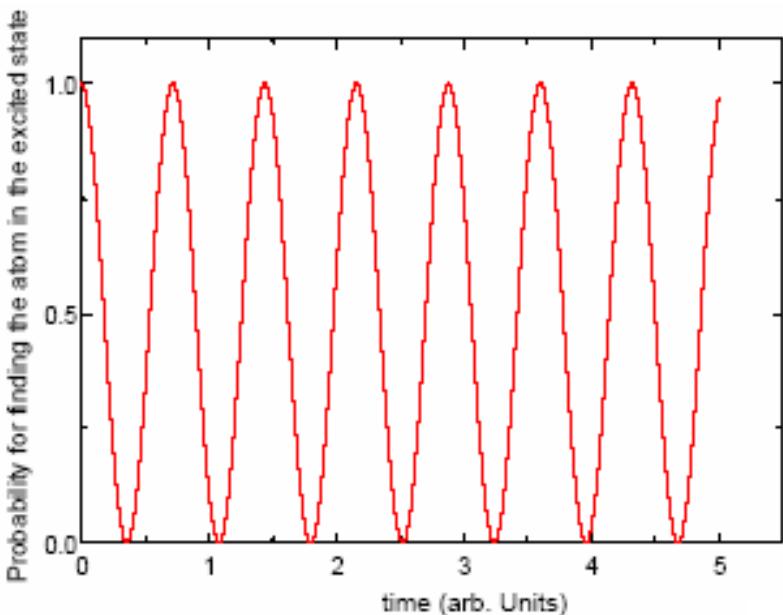


γ : loss channel

Strong Coupling Regime ($\Omega \gg \gamma$) :

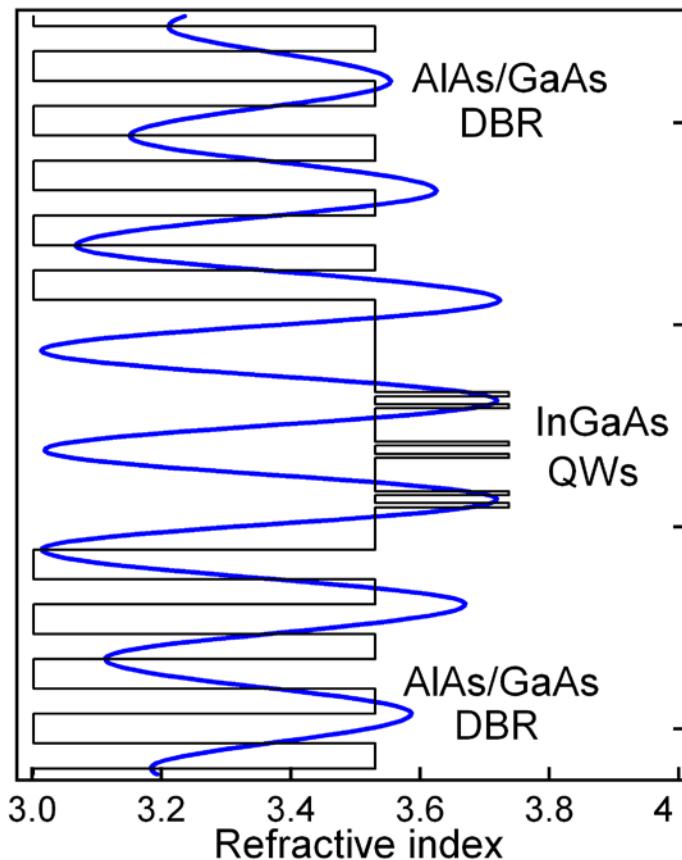
emitted photon will be reabsorbed before it leaves the cavity

⇒ Spontaneous Emission is a reversible process

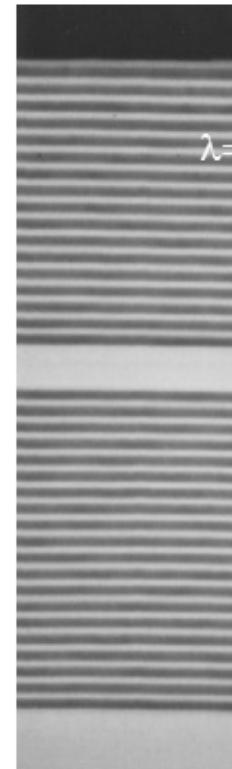


Monolithic Semiconductor Microcavity

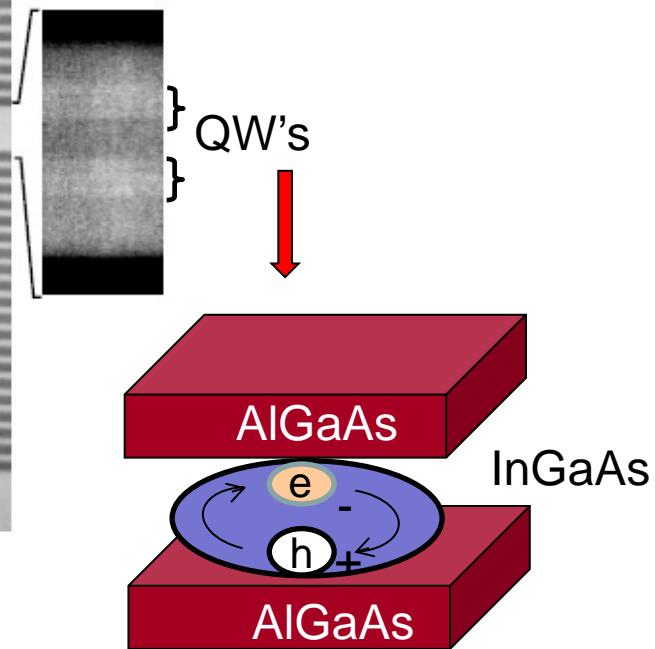
Top DBR Mirror



- QWs placed at the E-field maxima



Bottom DBR Mirror



- Combine electronic and photonic confinement in the same structure



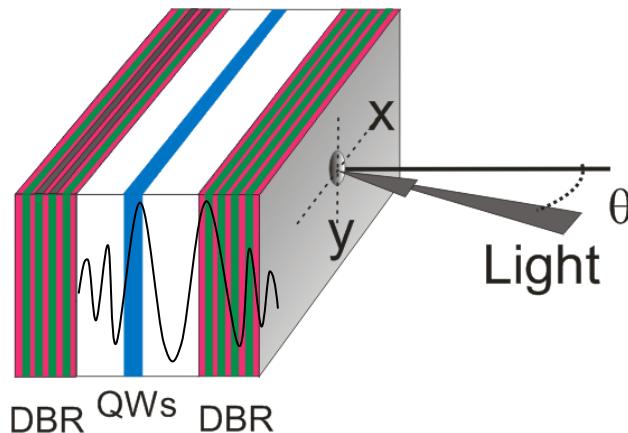
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Strong Coupling Regime in Semiconductor Microcavity

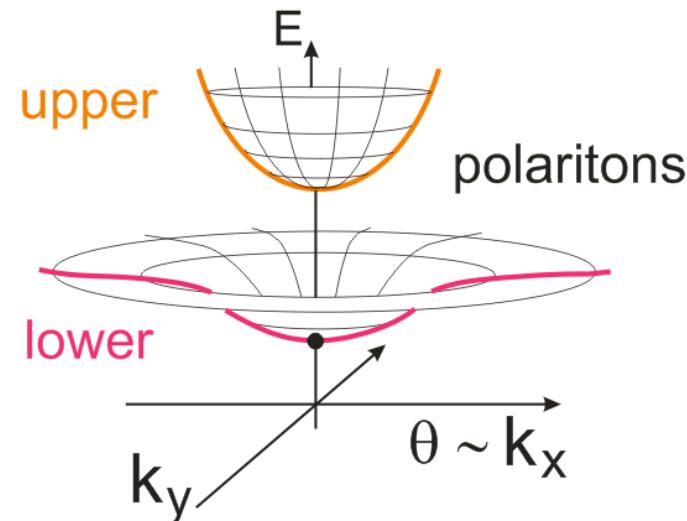
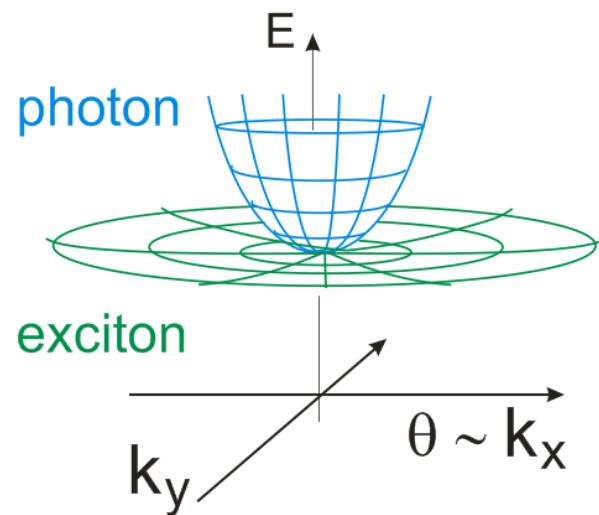


- Polaritons directly accessible by shining light on MC
- Strongly modified dispersion relations
reduced density of states near $k_{\parallel}=0$
- small polariton mass $m_{\text{pol}} \approx 10^{-4}m_e$
- strong non-linearities $\rightarrow \chi^3$ (exciton component)

Strong Coupling Regime

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

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



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



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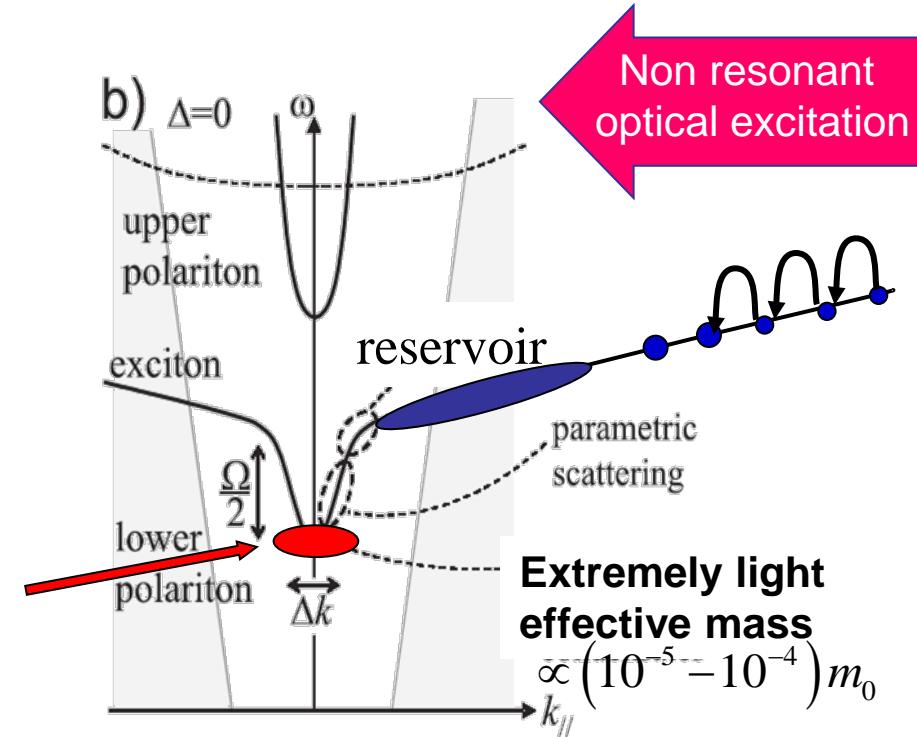


Bose-Condensation and Concept of Polariton Lasing

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



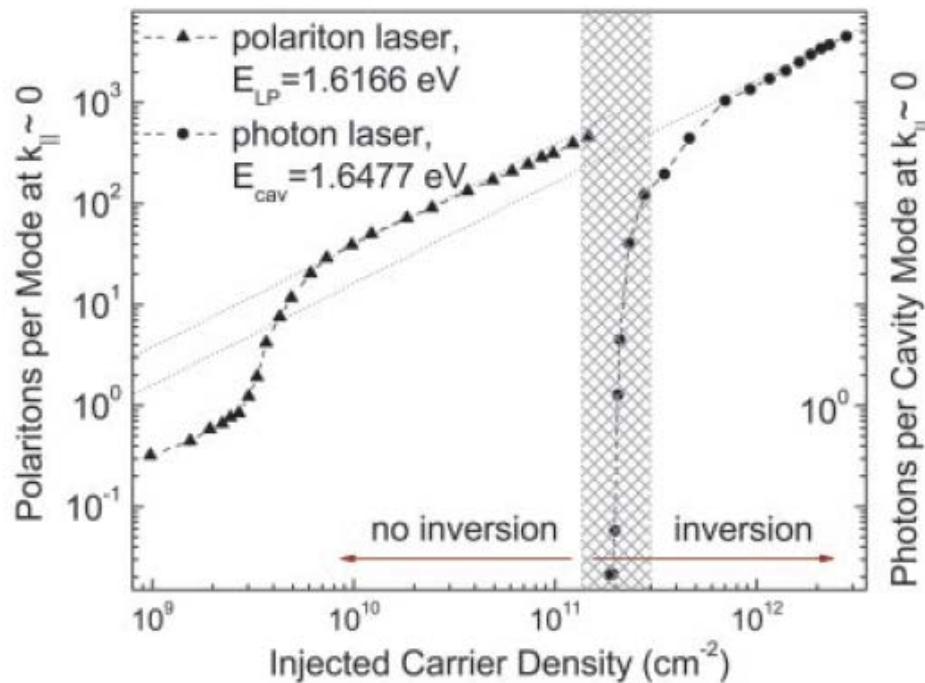
Polaritons accumulate in the lowest energy state by bosonic final state stimulation.

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 necessity 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. 100, 15318 (2003)

- ultralow threshold polariton lasers
- all optical switches, transistors and amplifiers



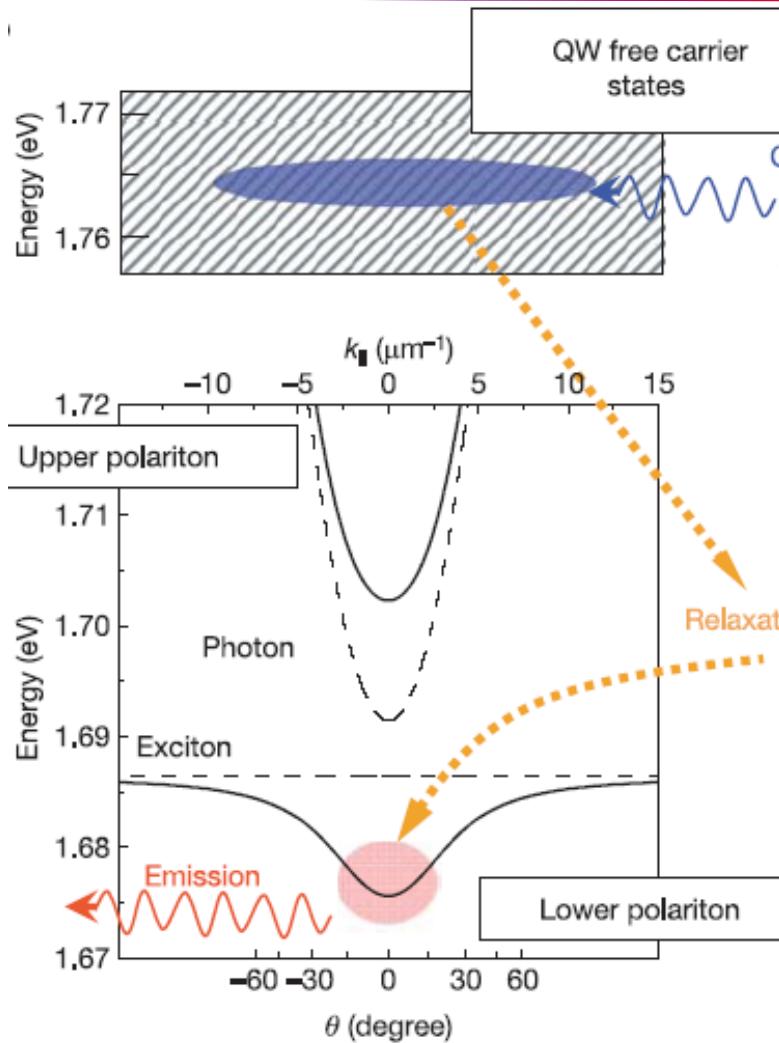
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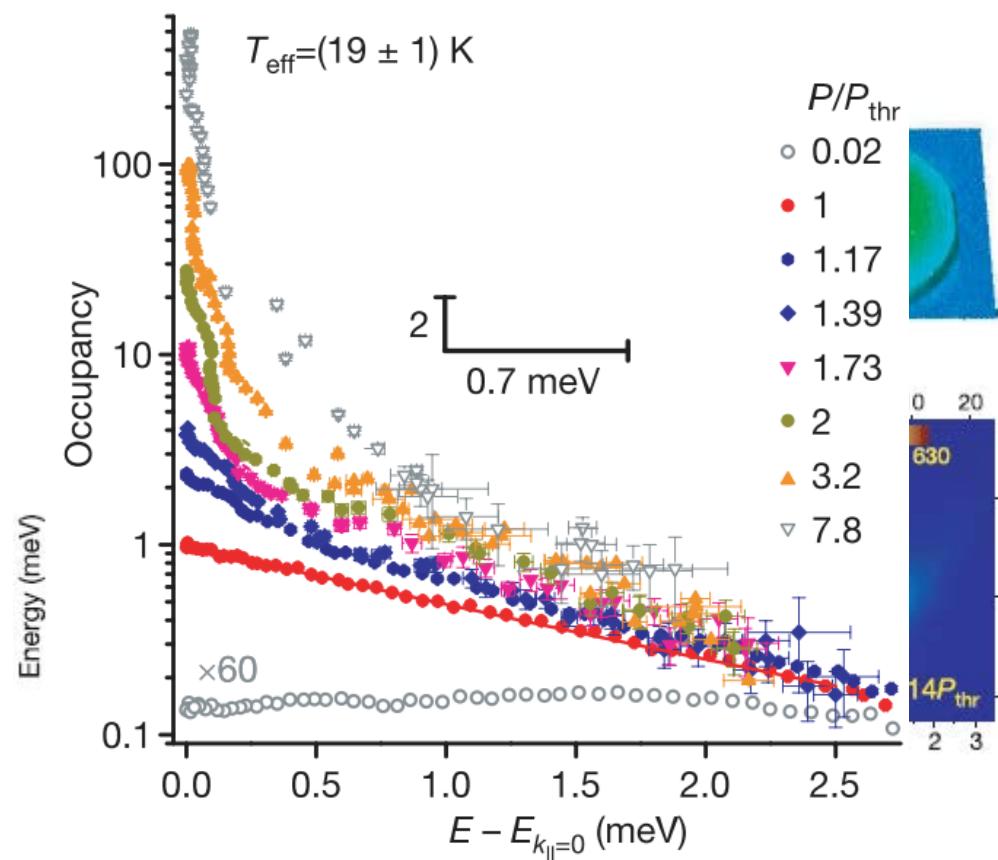


Polariton Condensation in CdTe/CdMnTe MC



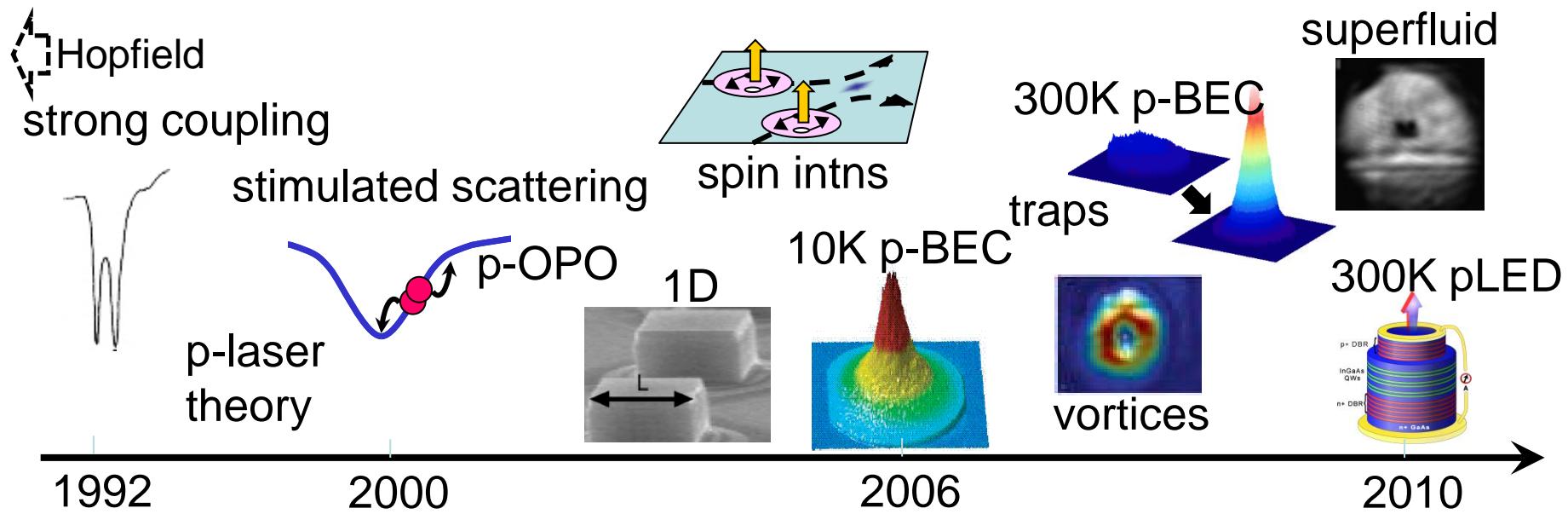
J. Kasprzak et al. Nature 443, 409 (2006)

Narrowing of the momentum distribution



- polaritons 10^9 times lighter than Rubidium atoms
- observation of polariton BEC at cryogenic temperature is possible

Polaritonics



From a device perspective:

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

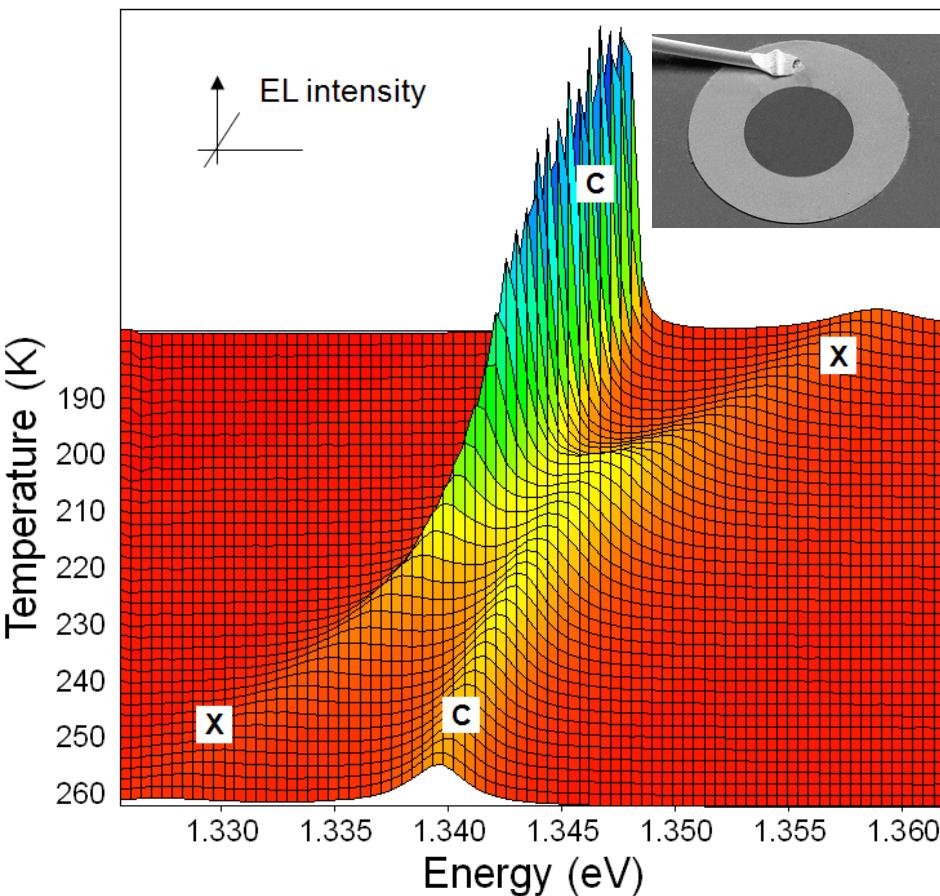
New directions: electrically driven polariton devices

Polariton based Devices

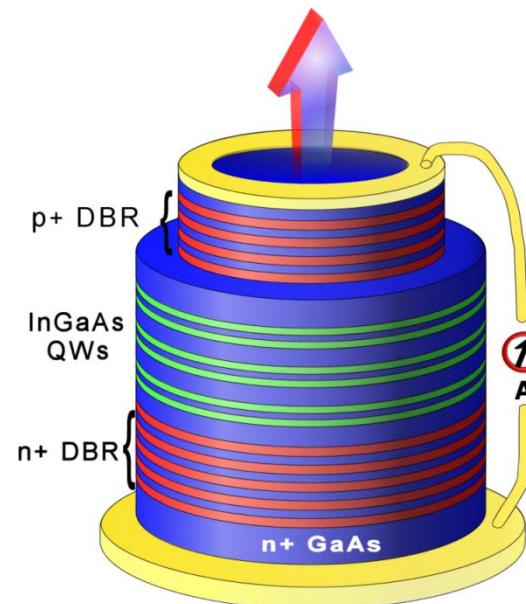
“Polaritonics”

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

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

N. Pelekanos



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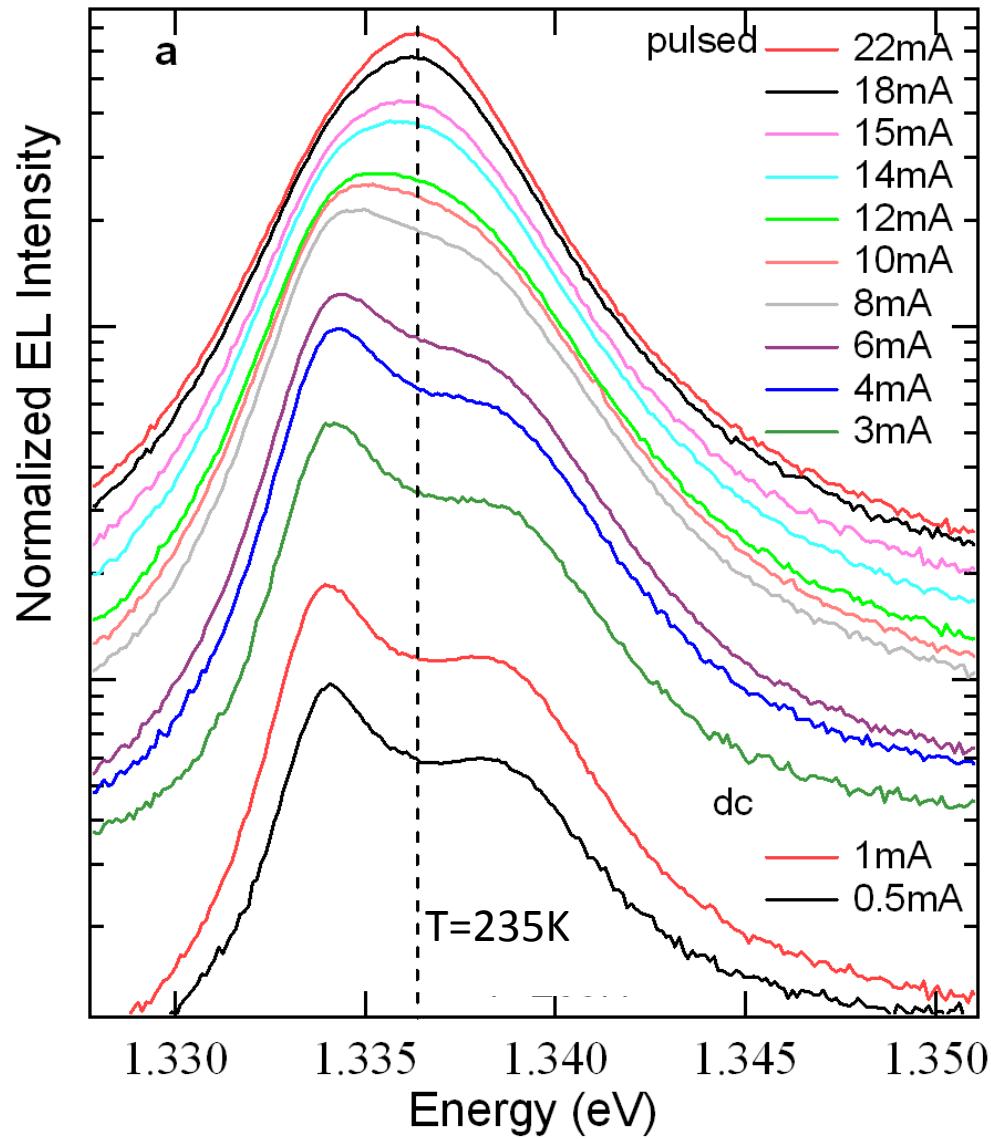
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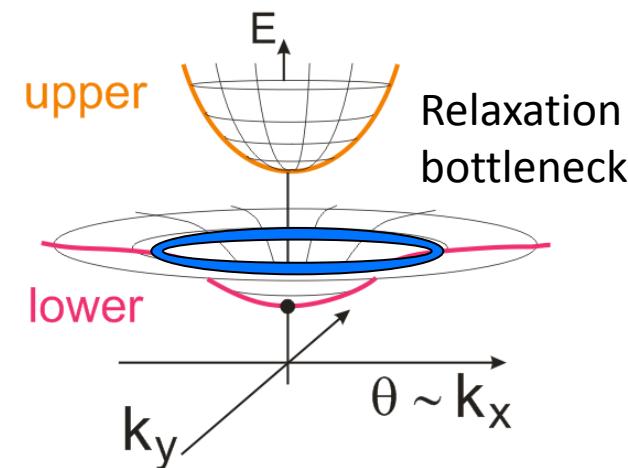




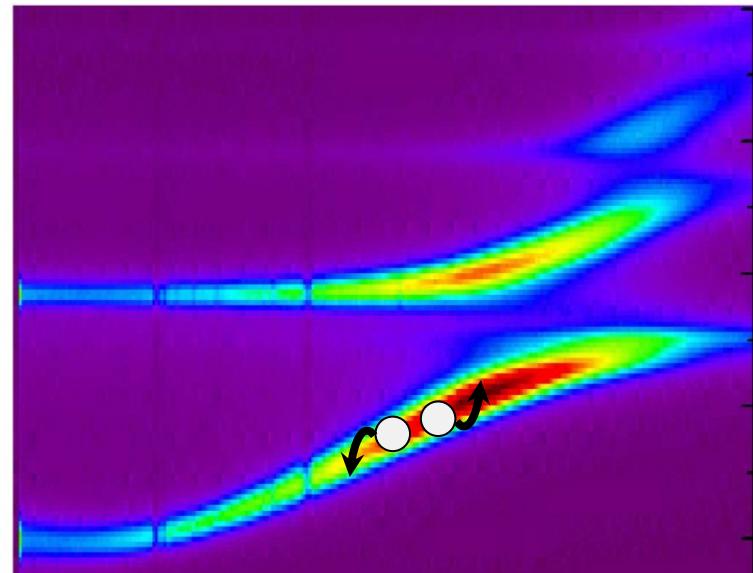
Collapse of Strong Coupling Regime at High Densities



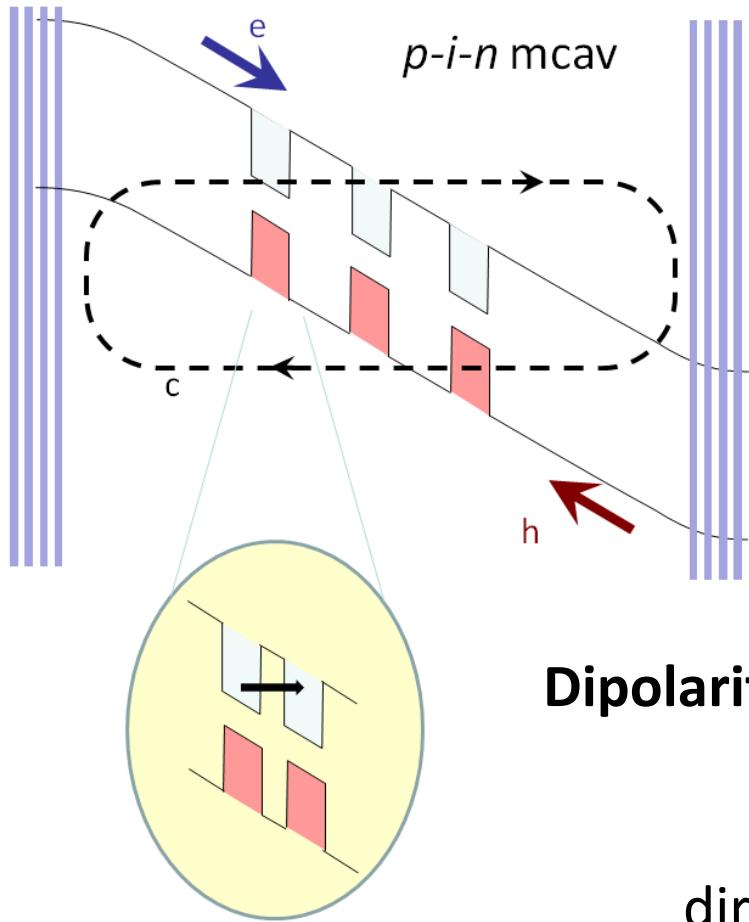
- Injection density at 22mA $\sim 10^{10}$ pol/cm²



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



Electrically pumped polariton lasers



new challenges:

- strong coupling in high finesse doped microcavities structures
- injection bypassing relaxation bottleneck
- control of polariton dispersions and scatterings

Dipolariton approach: weakly-coupled double quantum wells

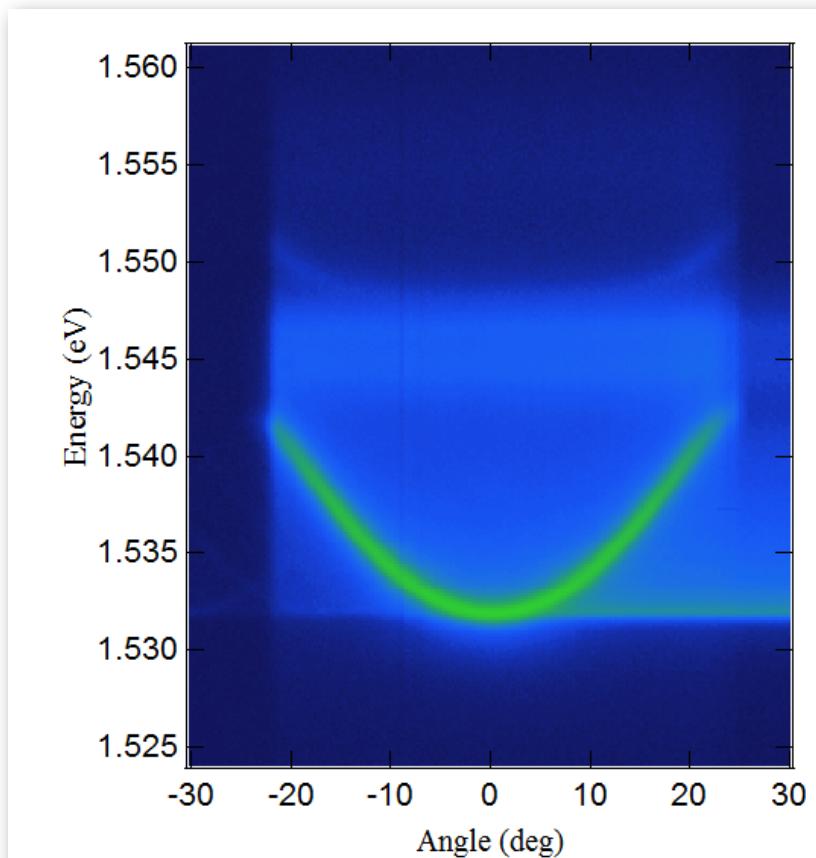
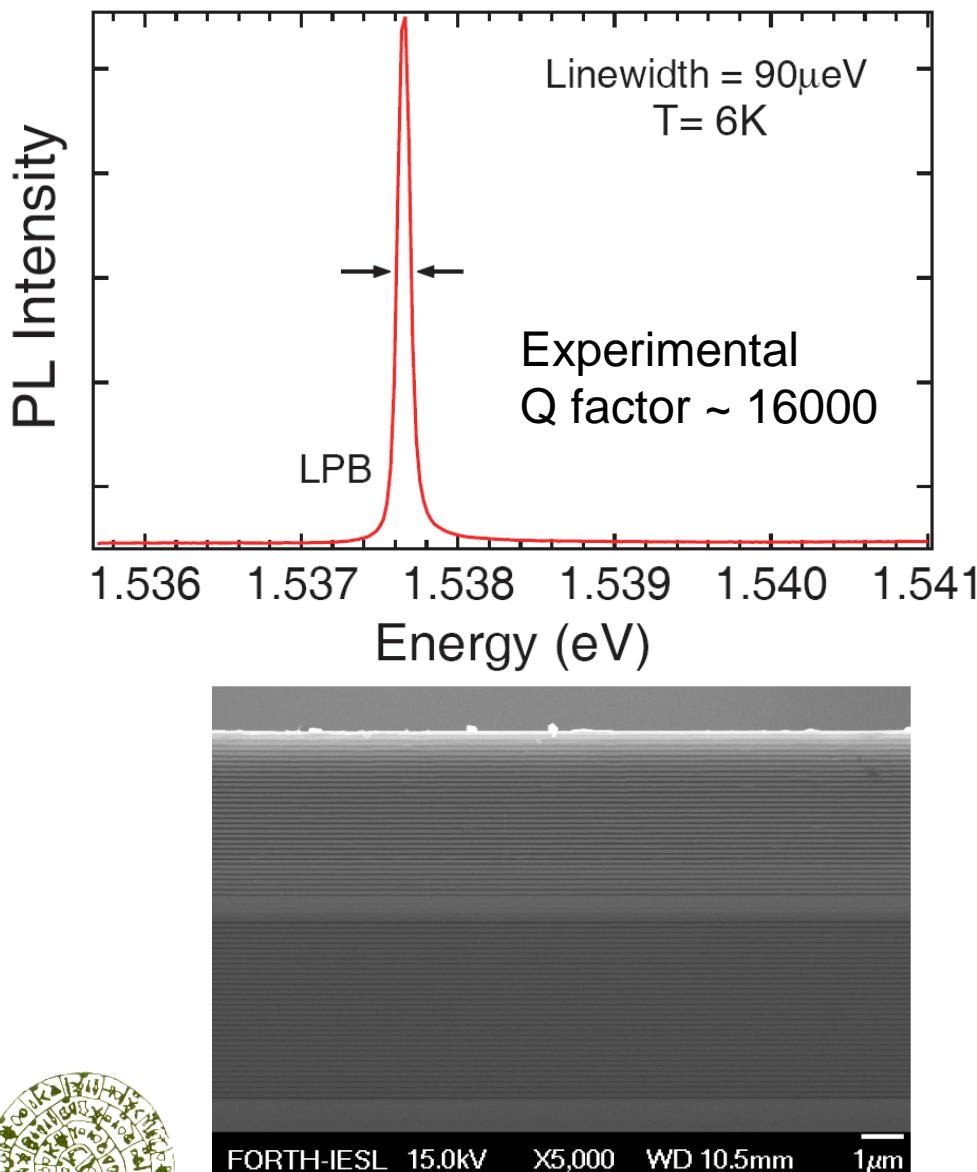


direct control of polariton dipole

$$H_{PP}^{eff} = \frac{1}{2} \sum_{k,k',q} \frac{a_B^2}{A} V_{k,k',q}^{PP} \hat{p}_{k+q}^+ \hat{p}_{k'-q}^+ \hat{p}_k^- \hat{p}_{k'}^-$$

dipole-dipole

High finesse GaAs microcavity



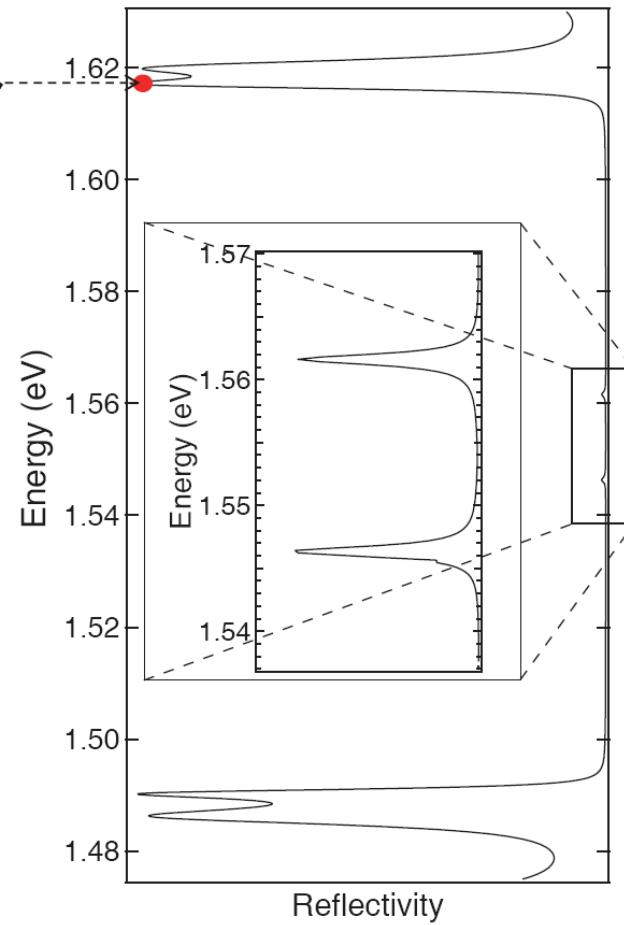
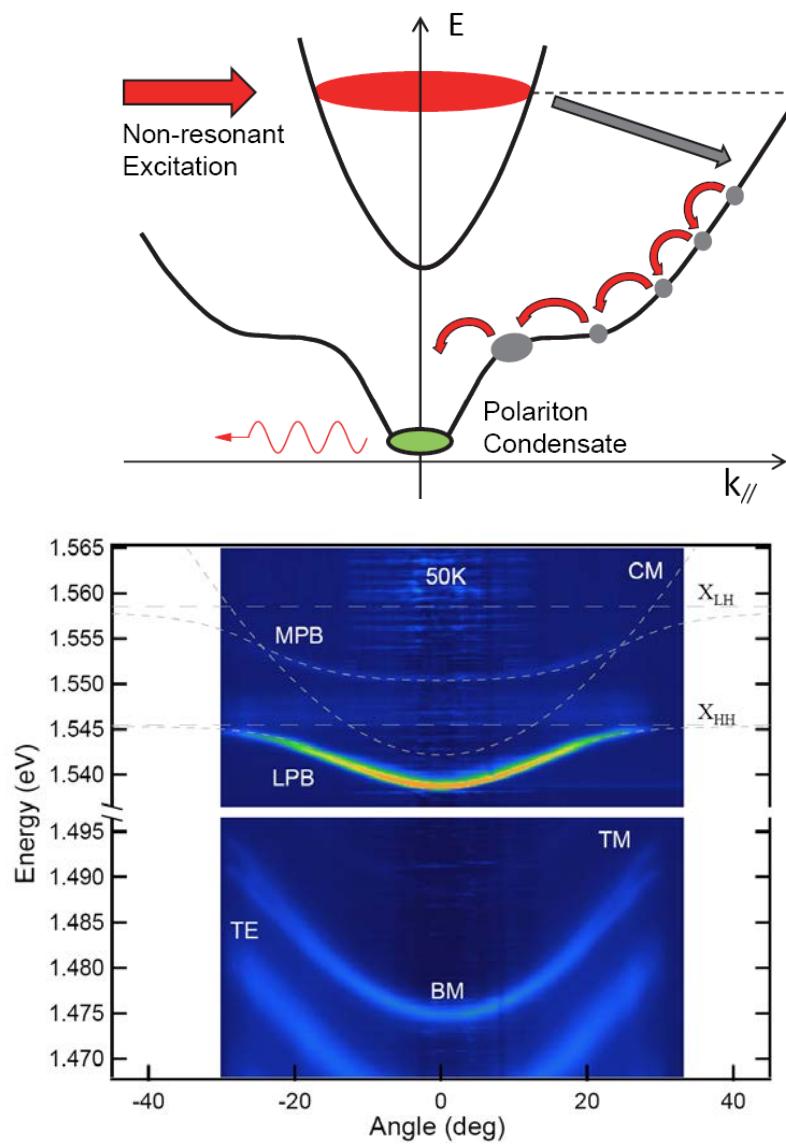
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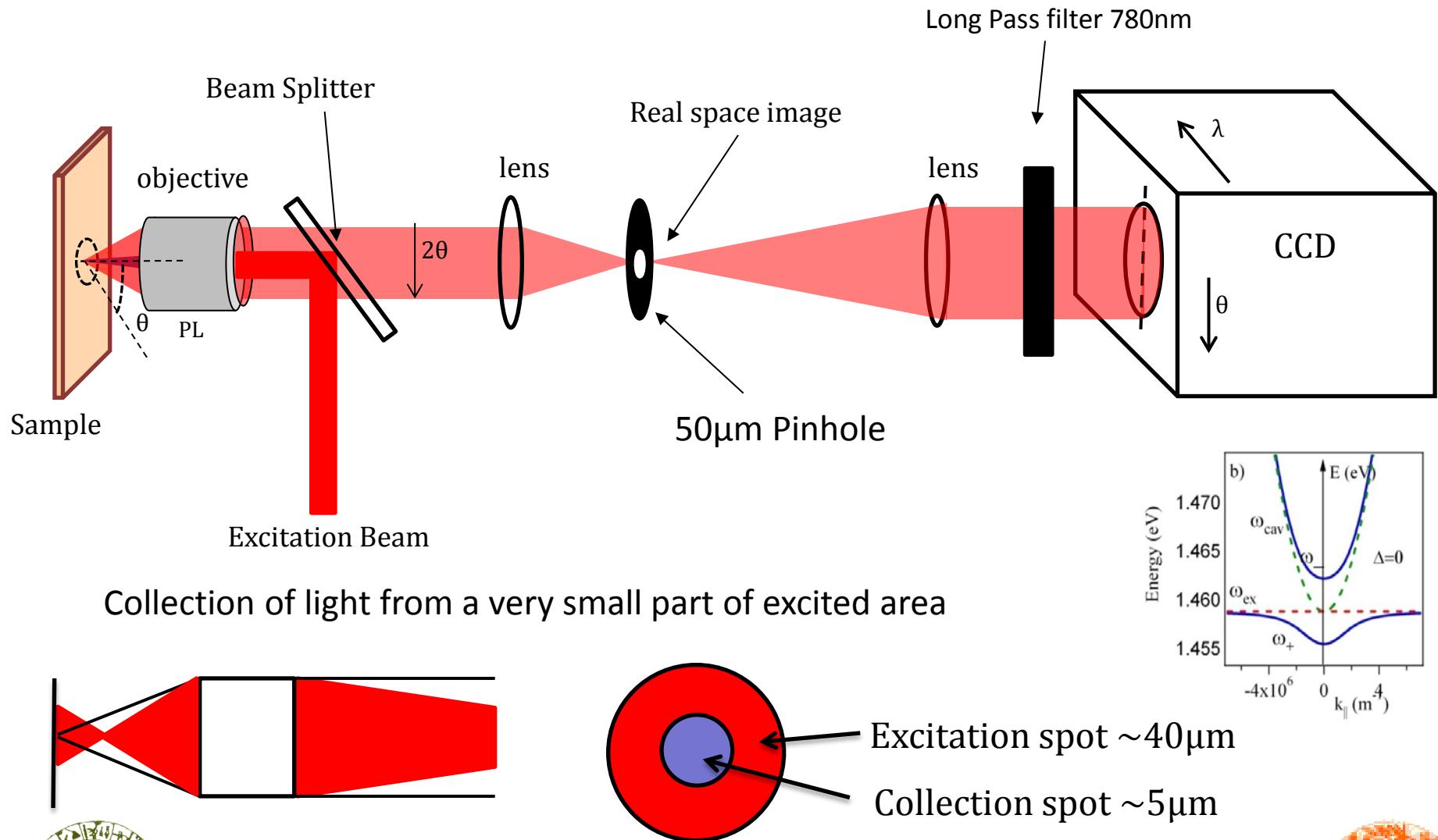
Non-resonant optical excitation



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



PL imaging Setup



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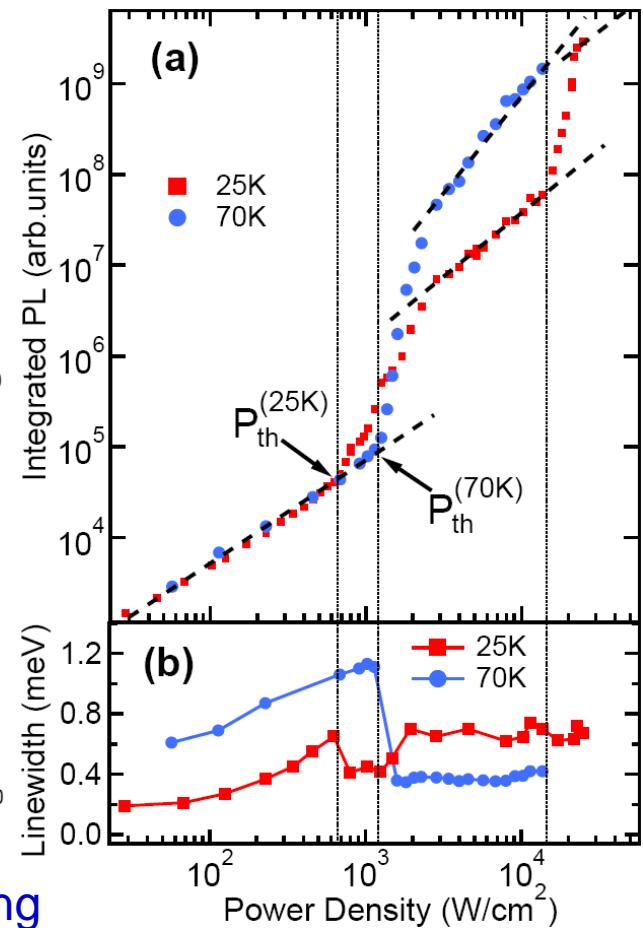
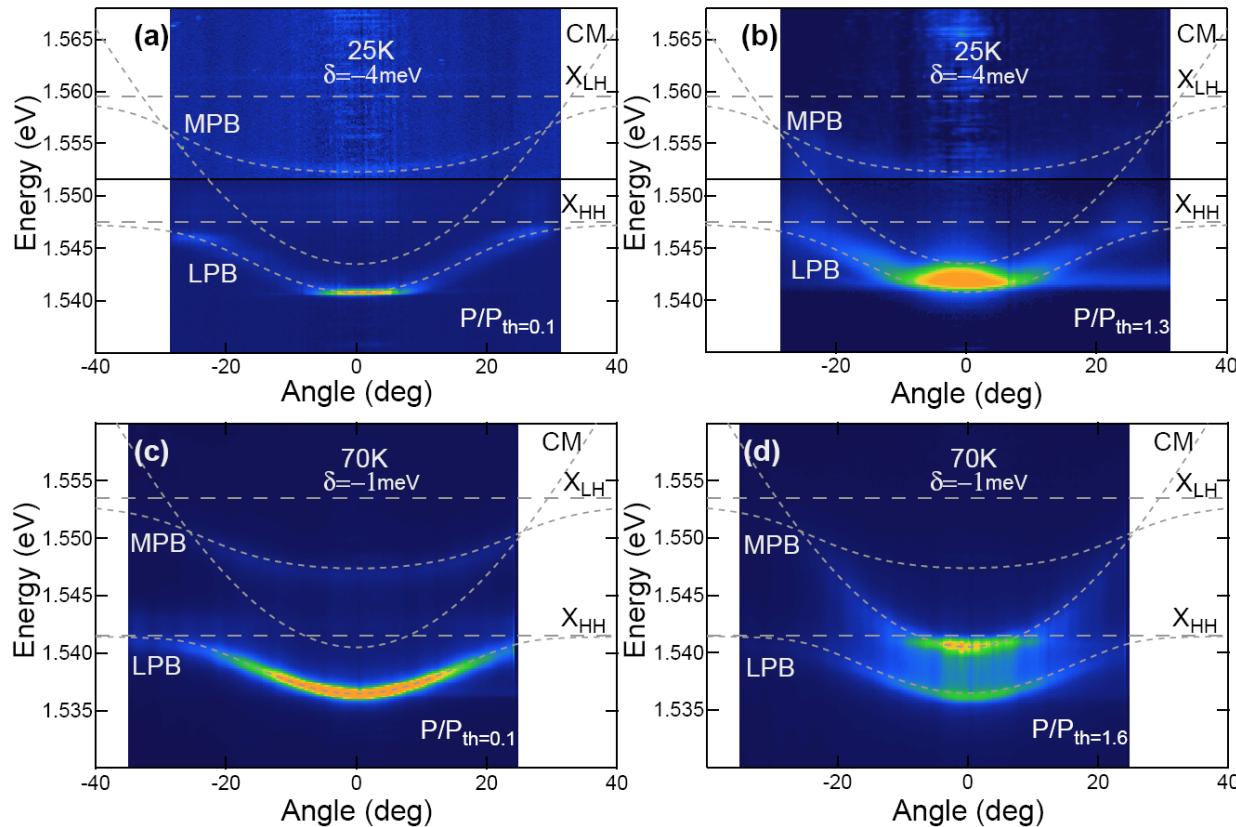
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GaAs Polariton Laser 25K vs 70K

- Nonresonant optical pumping above stopband

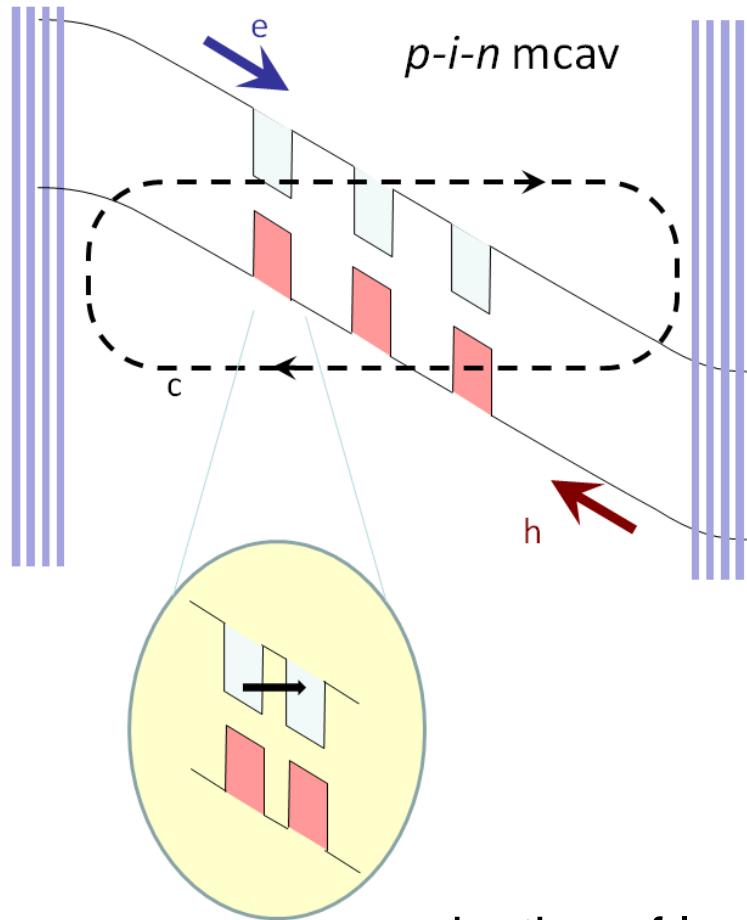


- Lowest Threshold at 25K ~ 6.5mW strong coupling
at 70K ~ 13mW weak coupling
- Lasing threshold only **doubles** between polariton laser at 25K and photon laser at 70K

Dipole Oriented Polaritons

Oriented polaritons in strongly-coupled
asymmetric DQW microcavities

Indirect polaritons: Dipolaritons



Dipolariton approach:
weakly-coupled double quantum wells

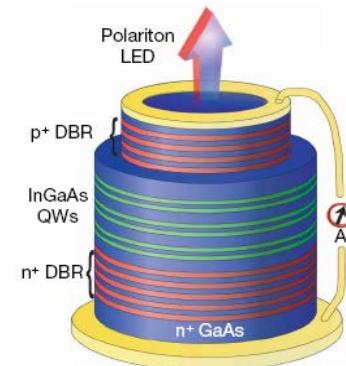


direct control of polariton dipole

$$H_{PP}^{eff} = \frac{1}{2} \sum_{k,k',q} \frac{a_B^2}{A} V_{k,k',q}^{PP} \hat{p}_{k+q}^+ \hat{p}_{k'-q}^+ \hat{p}_k \hat{p}_{k'}$$

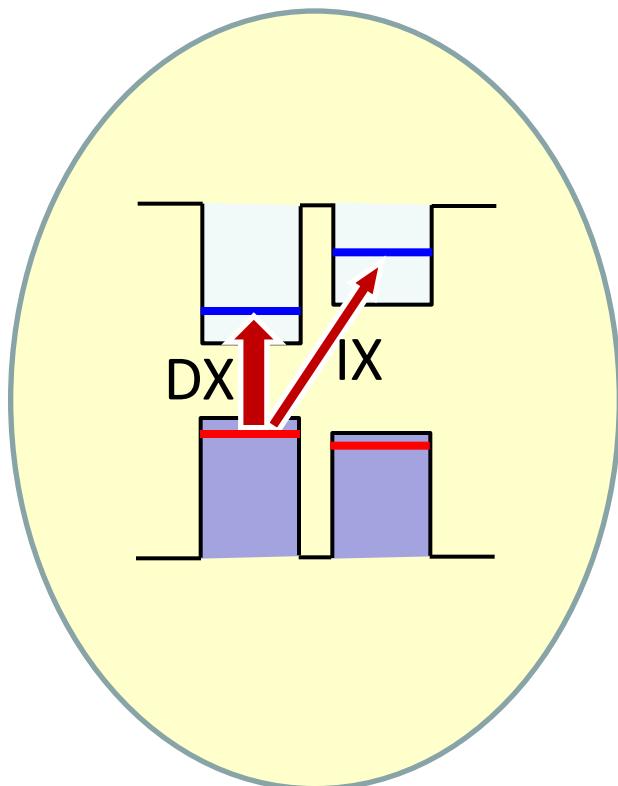
dipole-dipole

- reduction of lasing threshold
- electrically-pumped polariton lasers and BECs

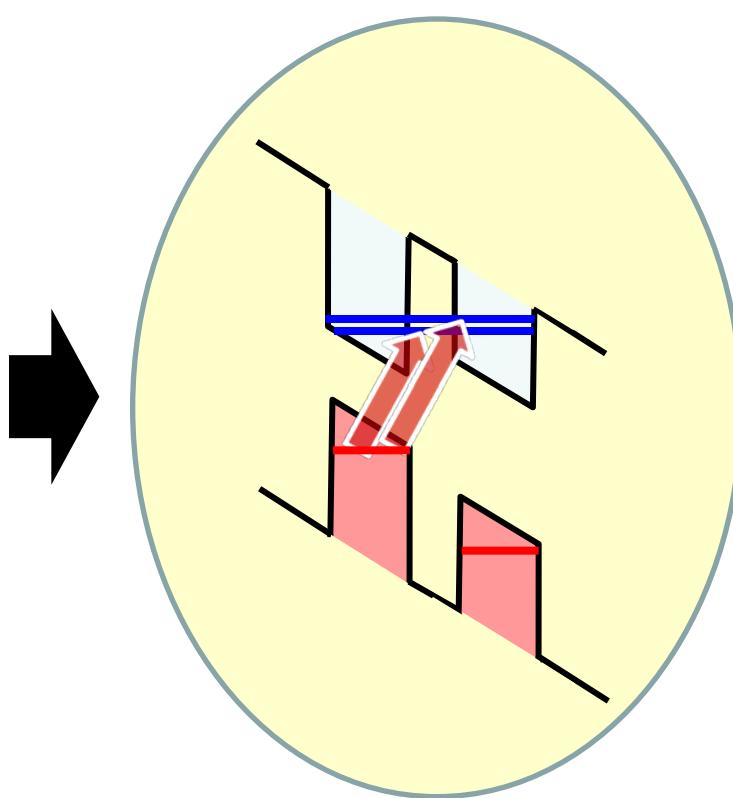


Double Quantum Wells

- asymmetric vs. symmetric DQWs



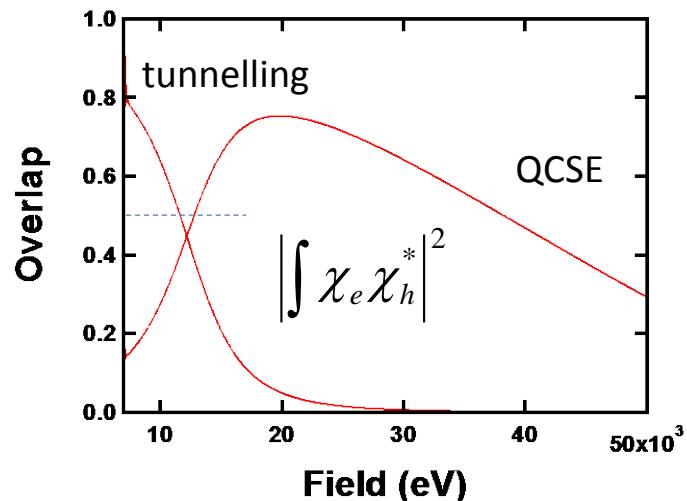
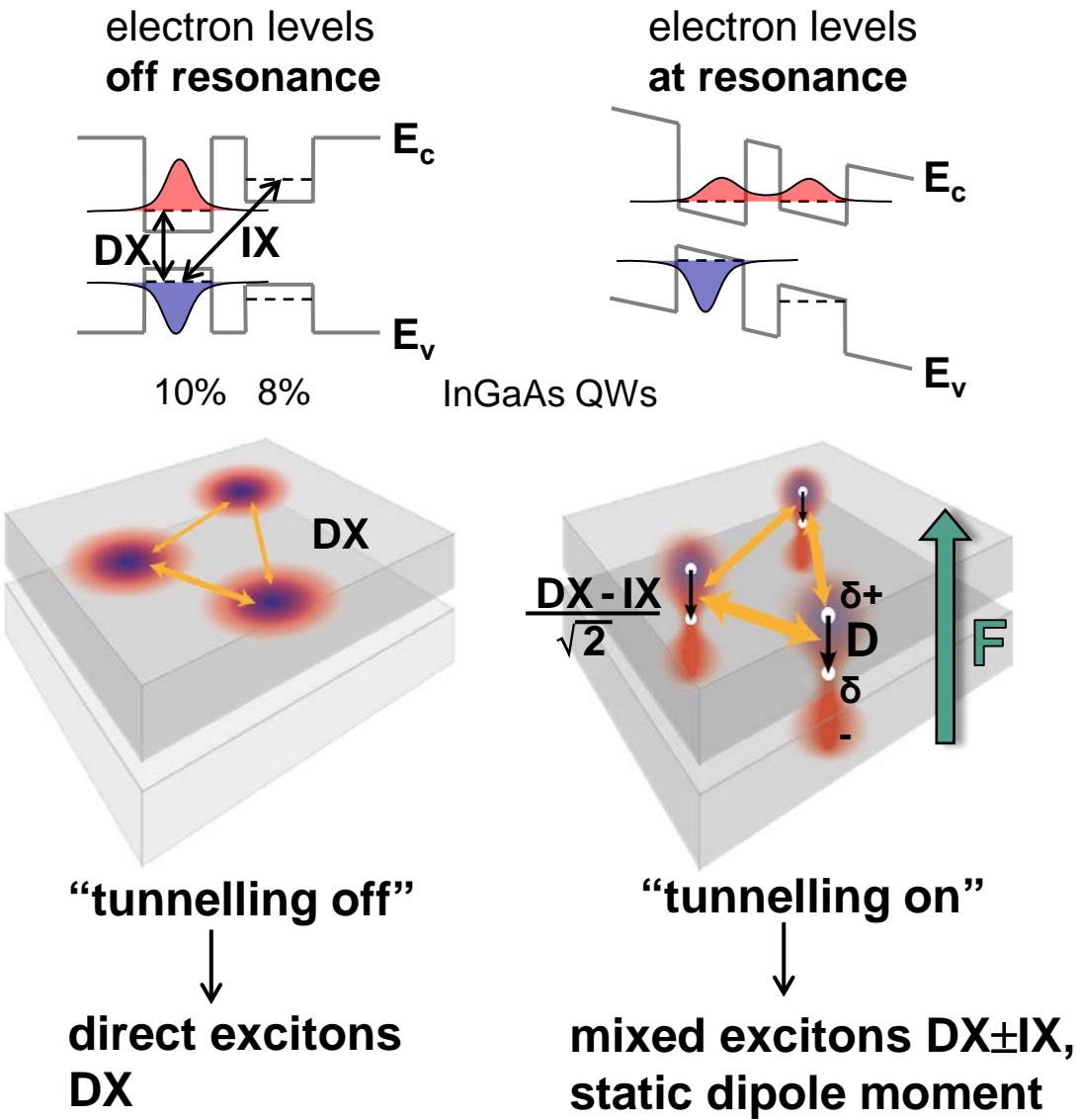
LQW: Rabi coupled to C



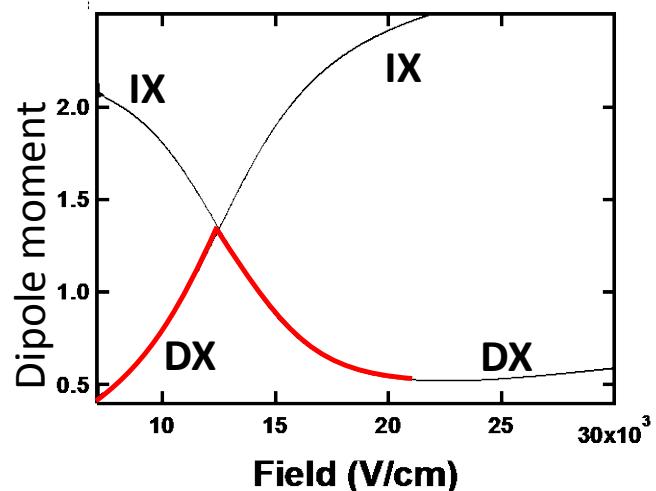
2 mixed states Rabi couple to C

- asymmetric DQWs: large field at resonance
- symmetric DQWs: small field at resonance

Dipolaritons

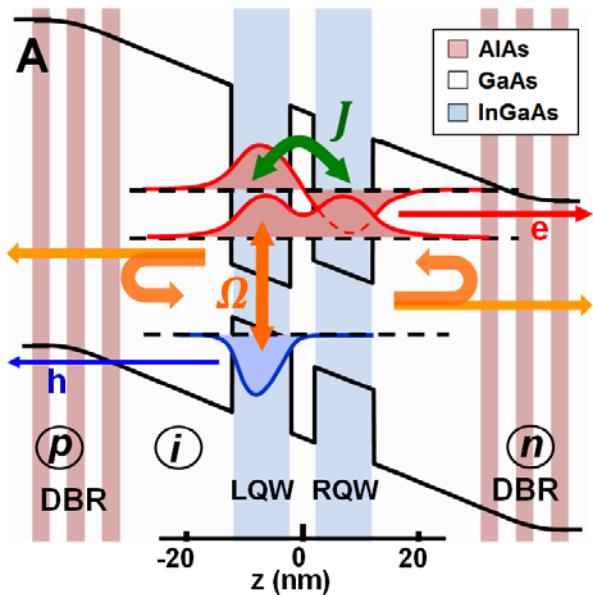


Oscillator strength is kept



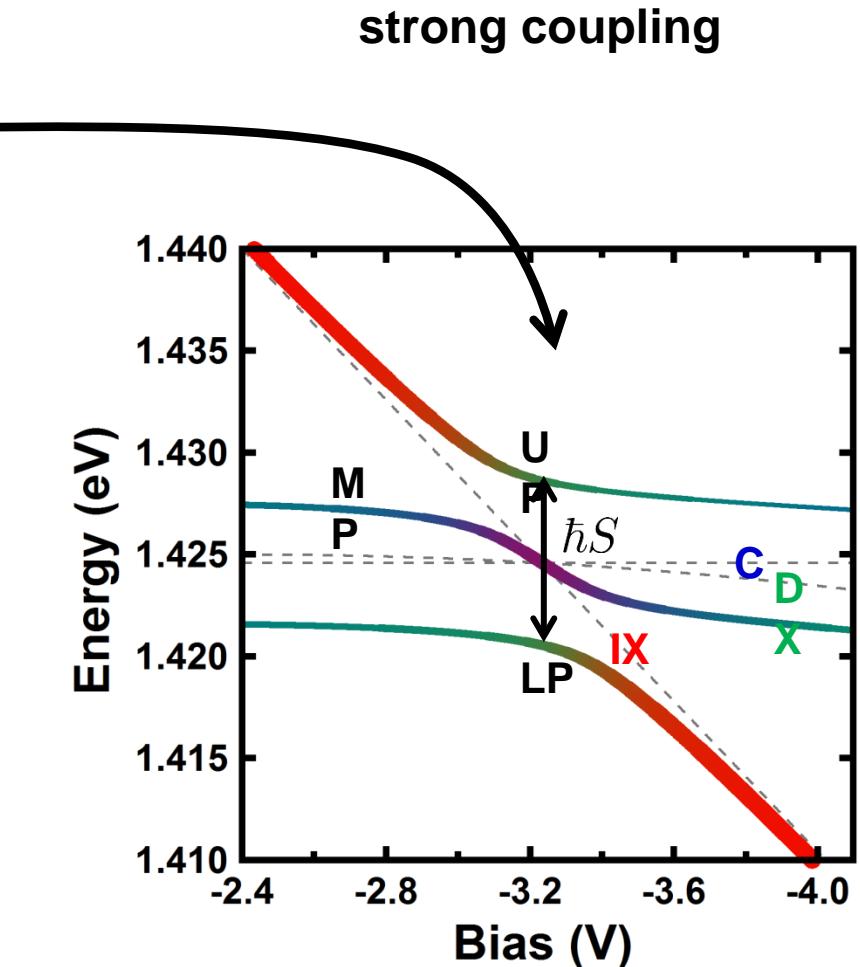
Strong dipole moment

Dipolaritons



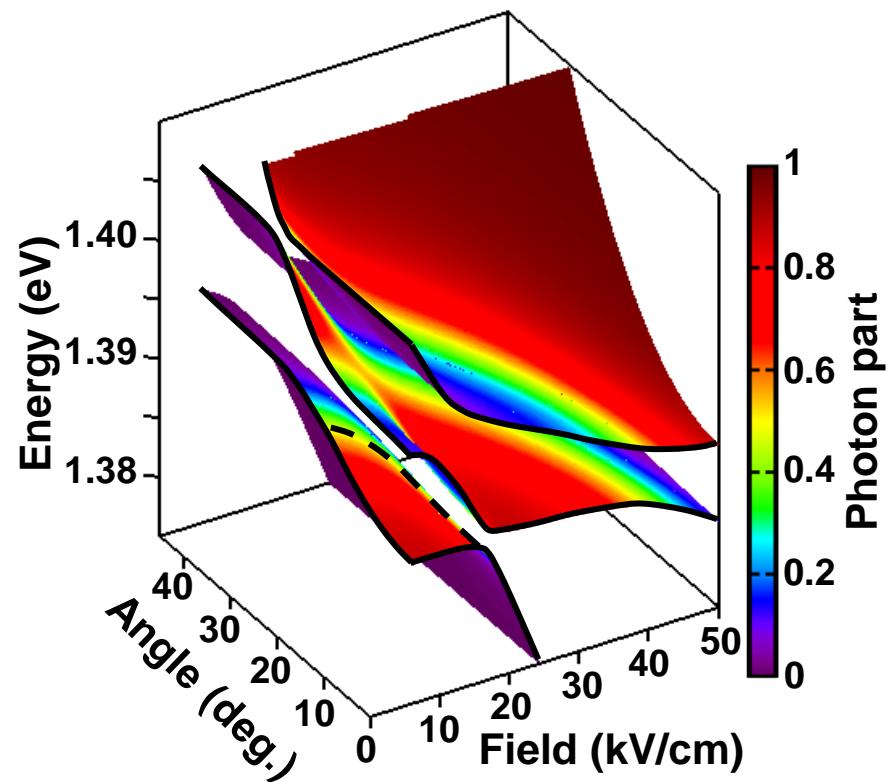
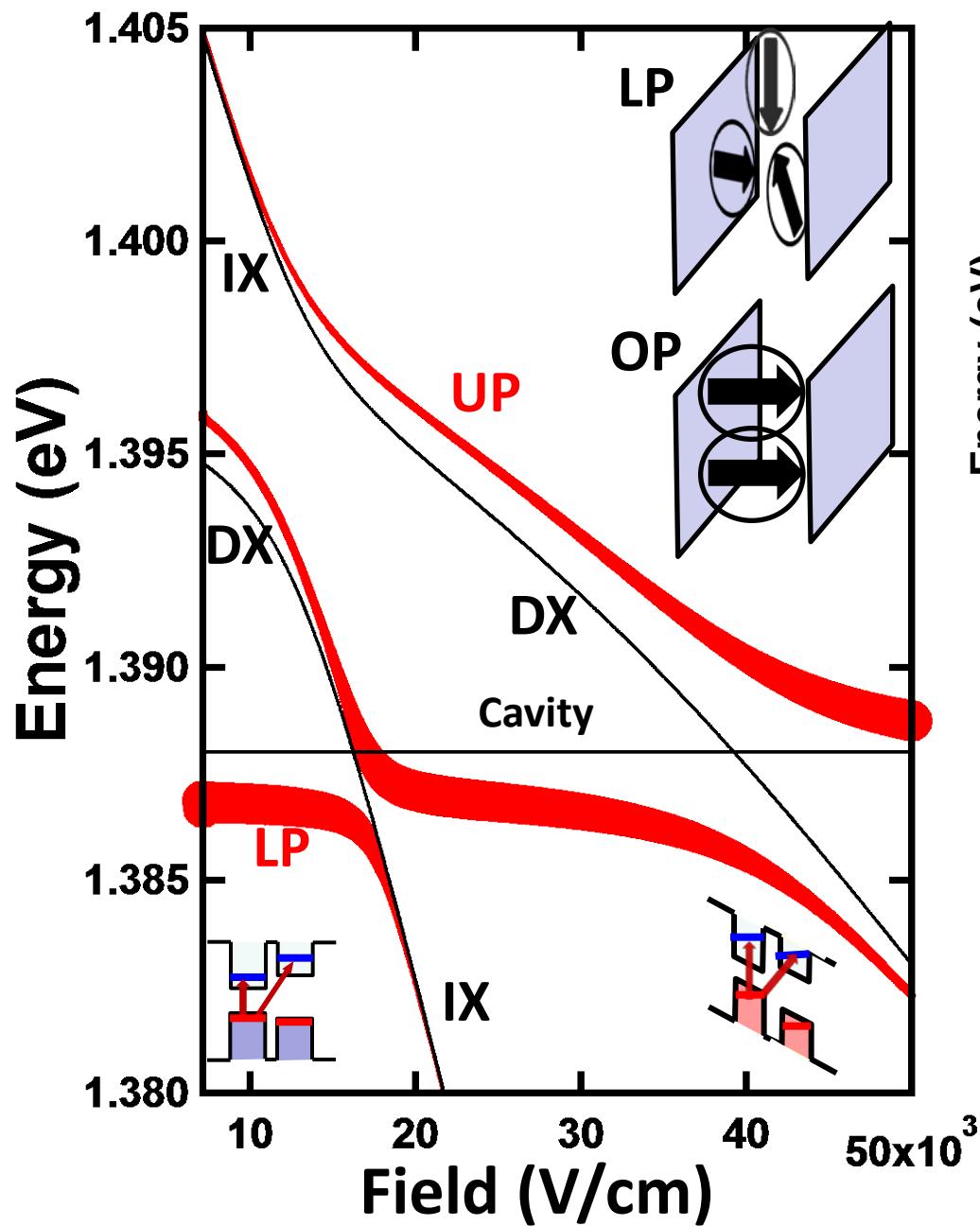
Combining tunnel coupling (J)
and Rabi splitting (Ω)

$$H = \begin{pmatrix} E_C & \Omega/2 & 0 \\ \Omega/2 & E_{DX} & J/2 \\ 0 & J/2 & E_{IX} \end{pmatrix}$$



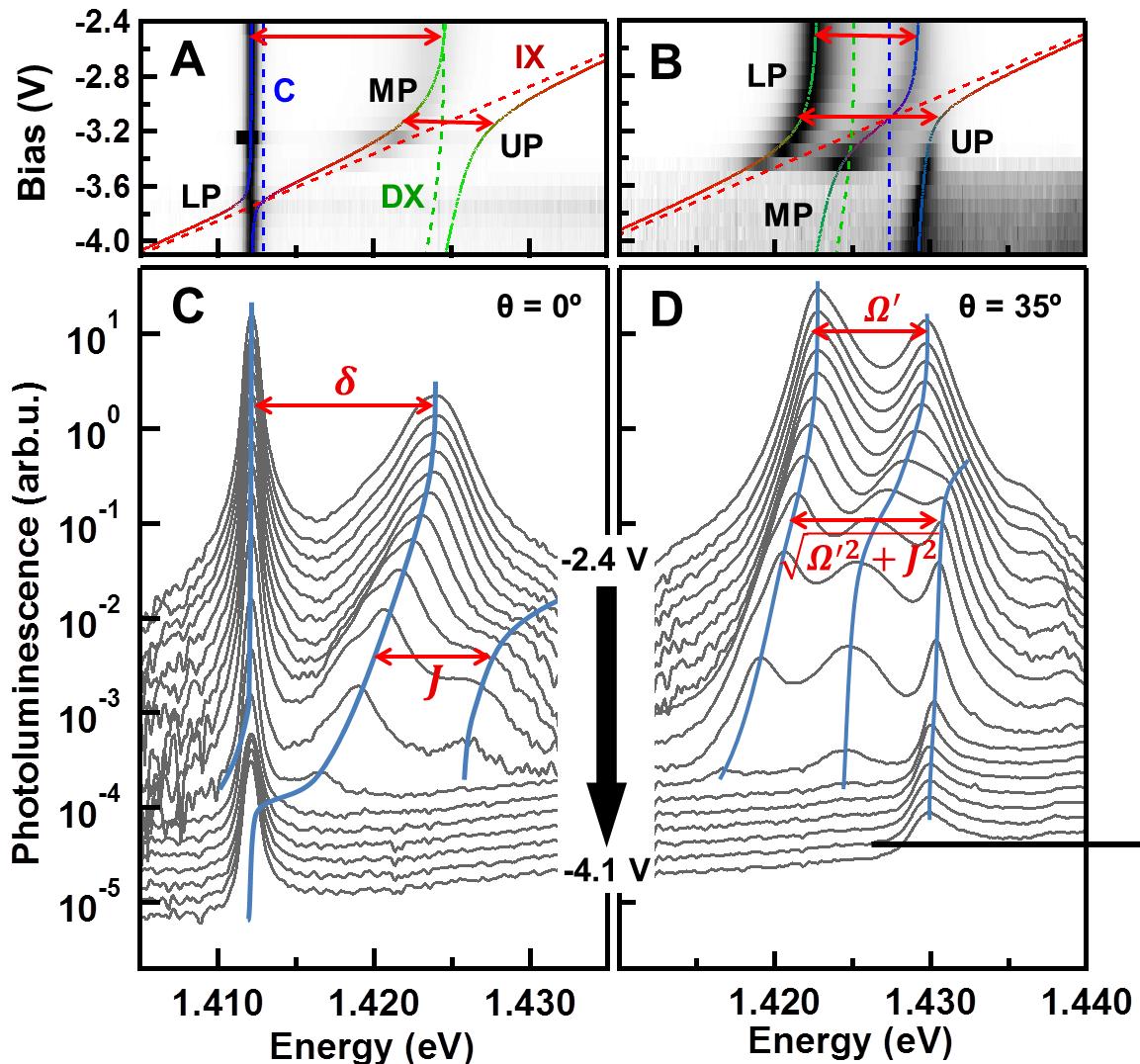
Coupled harmonic oscillator model

Dipolariton Dispersions



- vertical polariton dipole
- enhanced polariton-polariton coupling

Observation of dipolaritons



tunnel-split
excitons,
uncoupled cavity

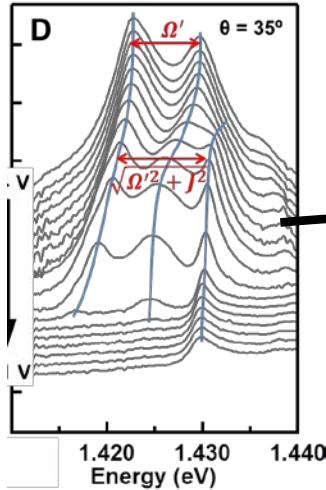
dipolaritons,
strong coupling of
 J and Ω

Photoluminescence of
the system versus
increasing bias for
detuned and resonant
cavity

PL is lost because
electron tunnel out
of the system

“Coupling Quantum Tunneling with
Cavity Photons”
Science 336, 704 (2012)

Dipolaritons at resonance



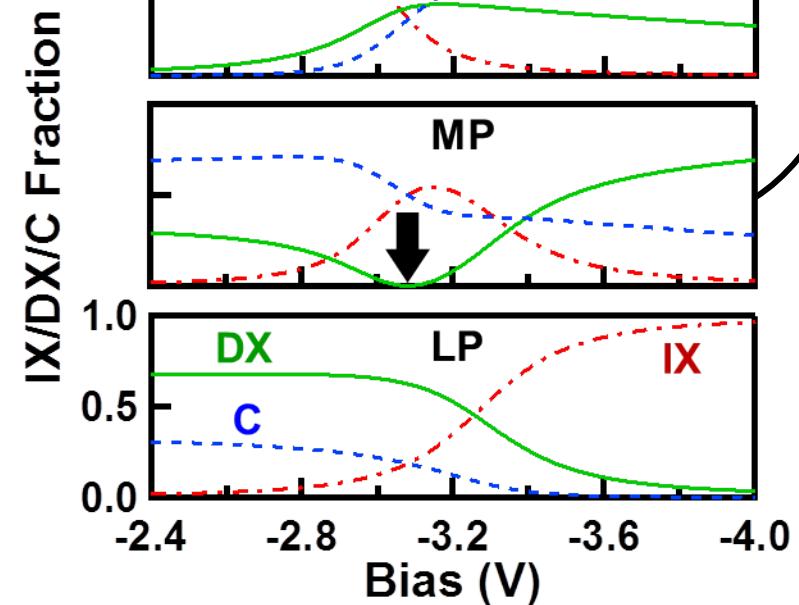
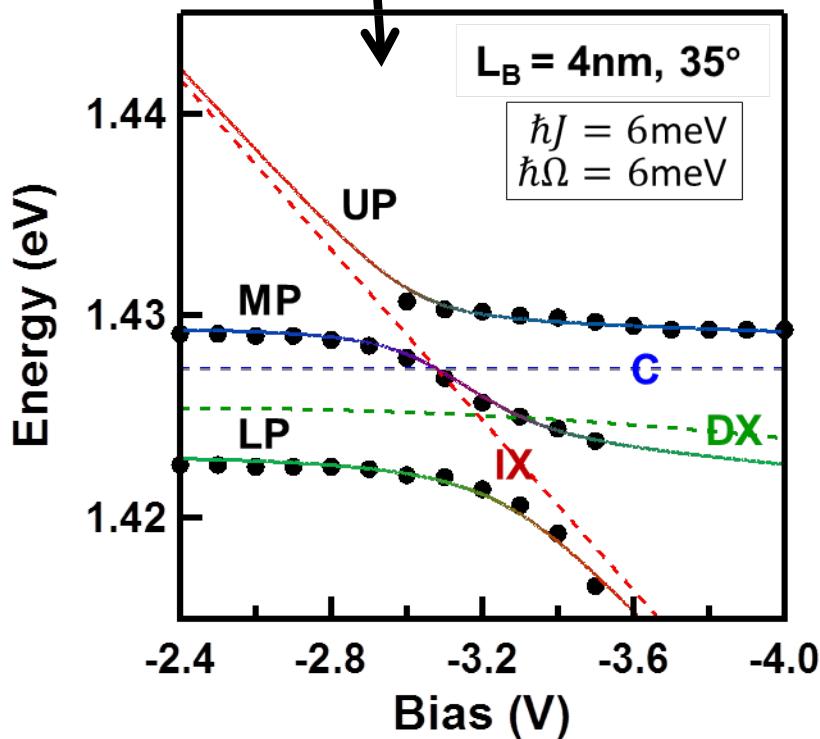
peak extraction

+

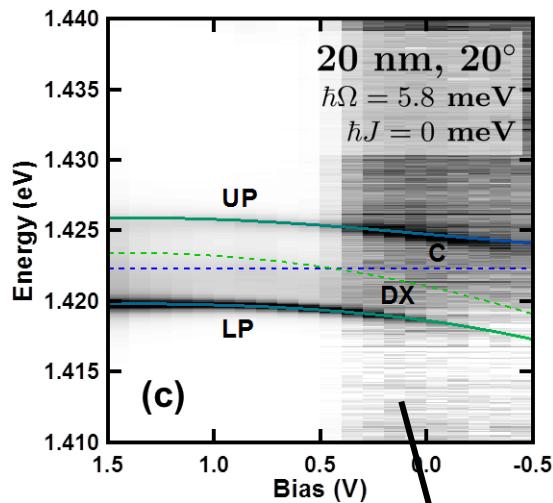
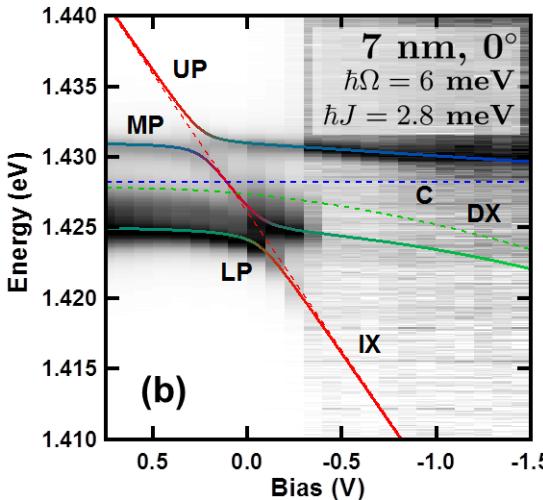
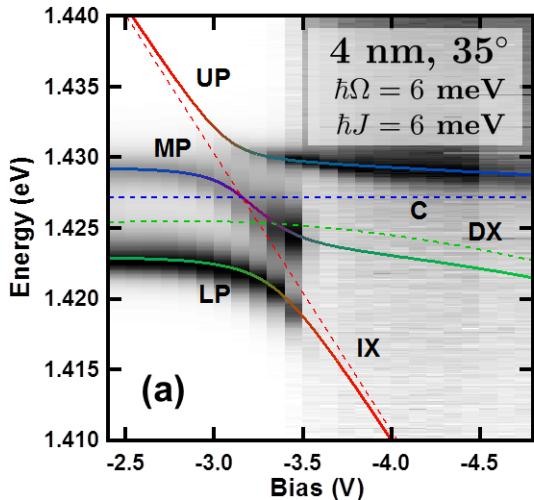
$$H = \begin{pmatrix} E_C & \Omega/2 & 0 & J/2 \\ \Omega/2 & E_{DX} & J/2 & E_{IX} \\ 0 & J/2 & E_{IX} \end{pmatrix}$$

MP – state: no DX!

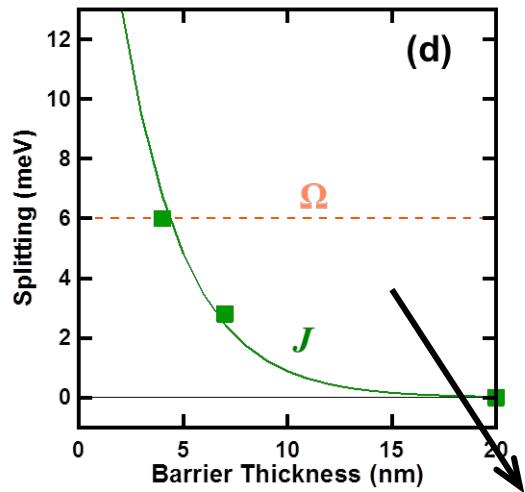
$$|MP\rangle = \frac{\Omega|IX\rangle - J|C\rangle}{S}$$



Barrier width dependence



no tunnel coupling normal polariton regime



ADQW simulation from solving Schrödinger equation

Influence of the tunnelling barrier thickness (4,7,20nm) on the bare tunnelling rate J

Excellent agreement with solution of the Schrödinger equation for tunnel coupling

Applications of Dipolaritons

| 4 Apr 2013

Continuous THz lasing from dipolaritons

K. Kristinsson,¹ O. Kyriienko,^{1,2} T. C. H. Liew,¹ and I. A. Shelykh^{1,2}

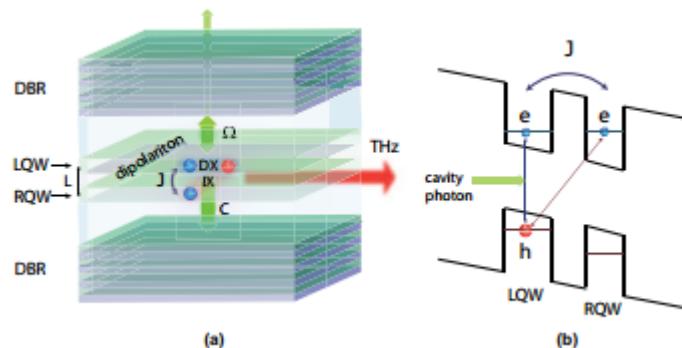
¹*Division of Physics and Applied Physics, Nanyang Technological University 637371, Singapore*

²*Science Institute, University of Iceland, Dunhagi-3, IS-107, Reykjavik, Iceland*

(Dated: April 5, 2013)

We propose a scheme of continuous tunable THz emission based on dipolaritons — mixtures of strongly interacting cavity photons and direct excitons, where the latter are coupled to indirect excitons via tunnelling. We investigate the property of multistability under continuous wave (CW) pumping, and the stability of the solutions. We establish the conditions of parametric instability, giving rise to oscillations in density between the direct exciton and indirect modes under CW pumping. In this way we achieve continuous and tunable emission in the THz range, in a compact single-crystal device, which is expected to operate at high temperatures. We show that the emission frequency can be tuned in a certain range by varying an applied electric field and pumping conditions. Finally, we demonstrate the dynamic switching between different phases in our system, allowing rapid control of THz radiation.

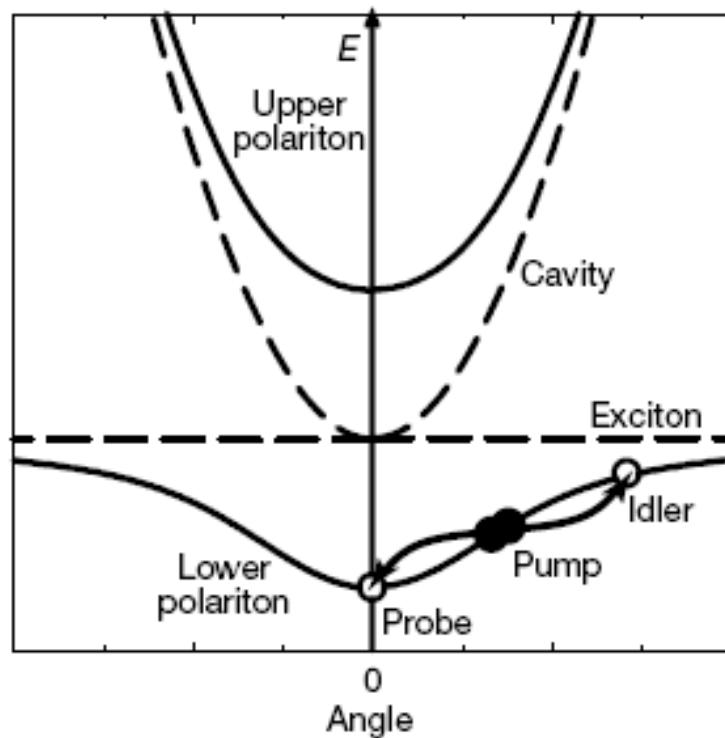
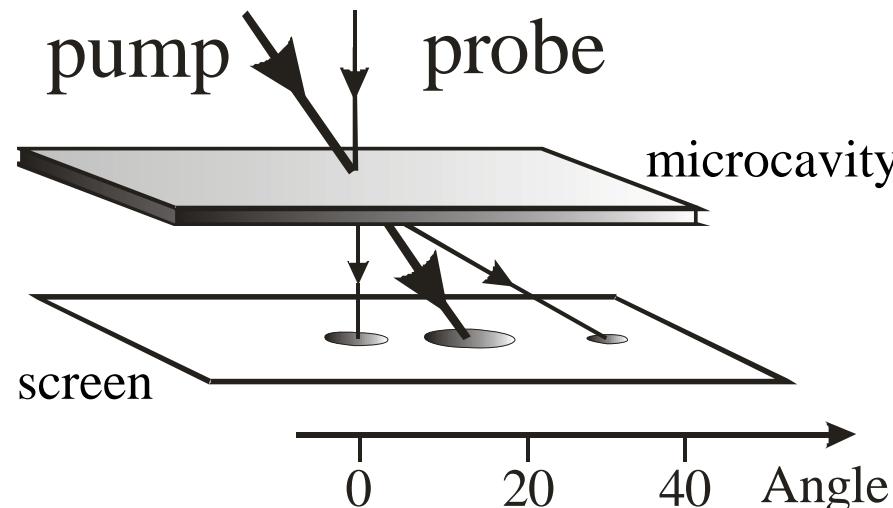
PACS numbers: 71.36.+c, 78.67.Pt, 42.65.-k, 71.35.Lk



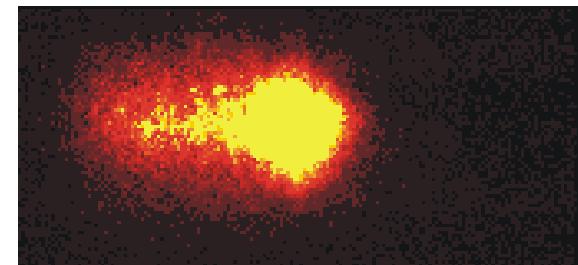
Nonlinear properties of Tunnelling Polaritons

**Control of polariton scattering in resonant-tunnelling
symmetric DQW semiconductor microcavities**

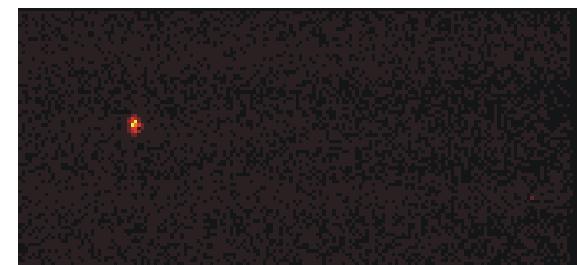
Polariton Parametric Amplification



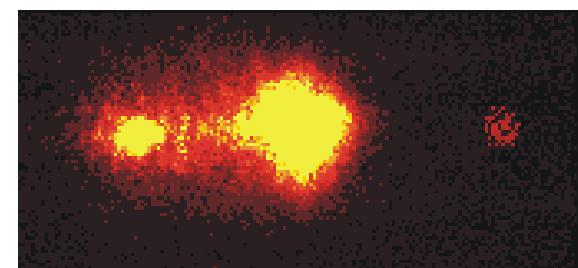
pump
only



probe
only



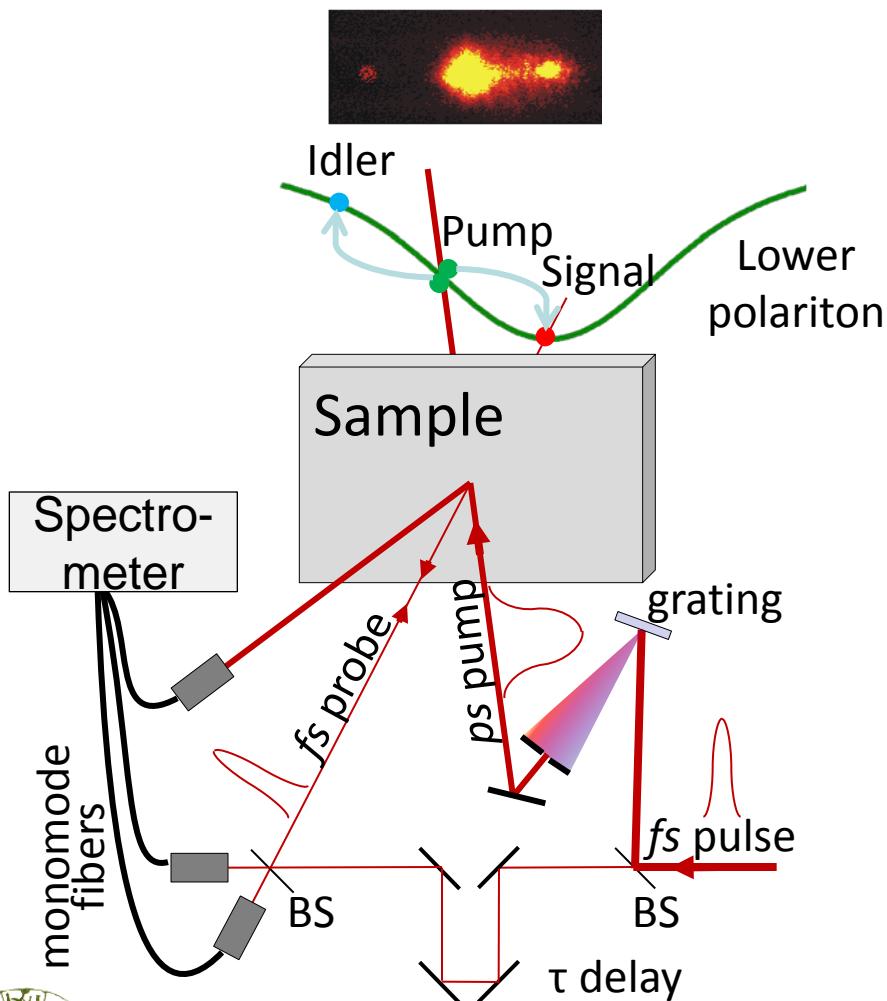
pump &
probe



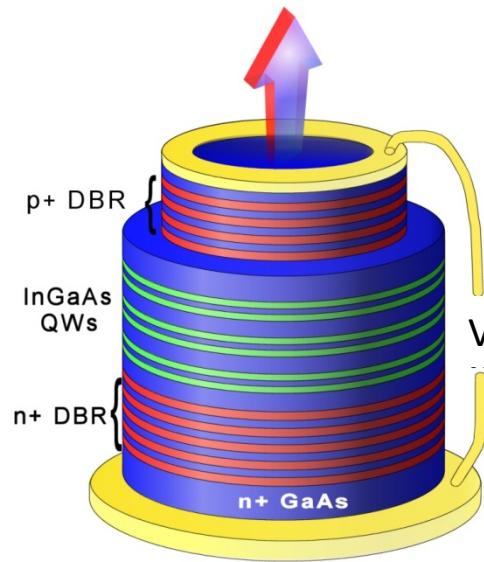
- Stimulated scattering of polaritons
- ultrafast amplification process

Savvidis et. al. PRL 84, 1547 (2000)

Electrical control of parametric amplification



- 100fs OPO regime
- spectrally-filtered pump at θ_m
- monitor probe gain at $k=0$



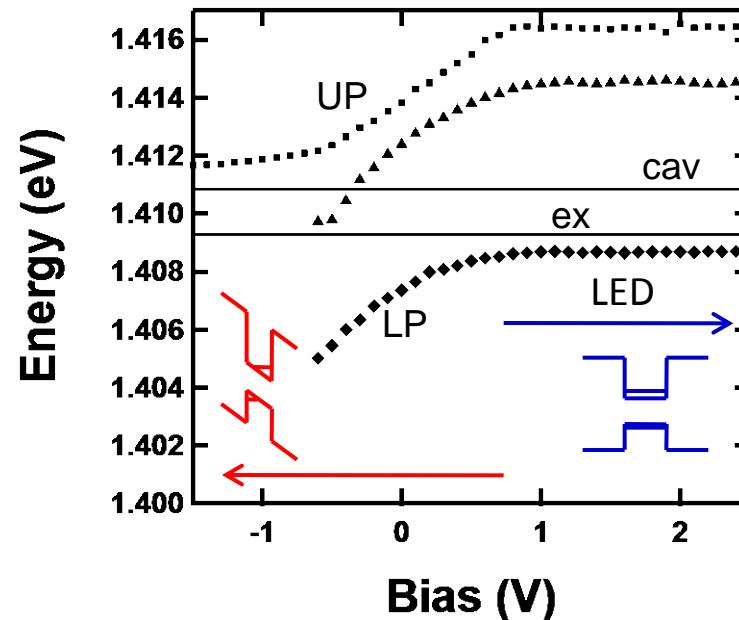
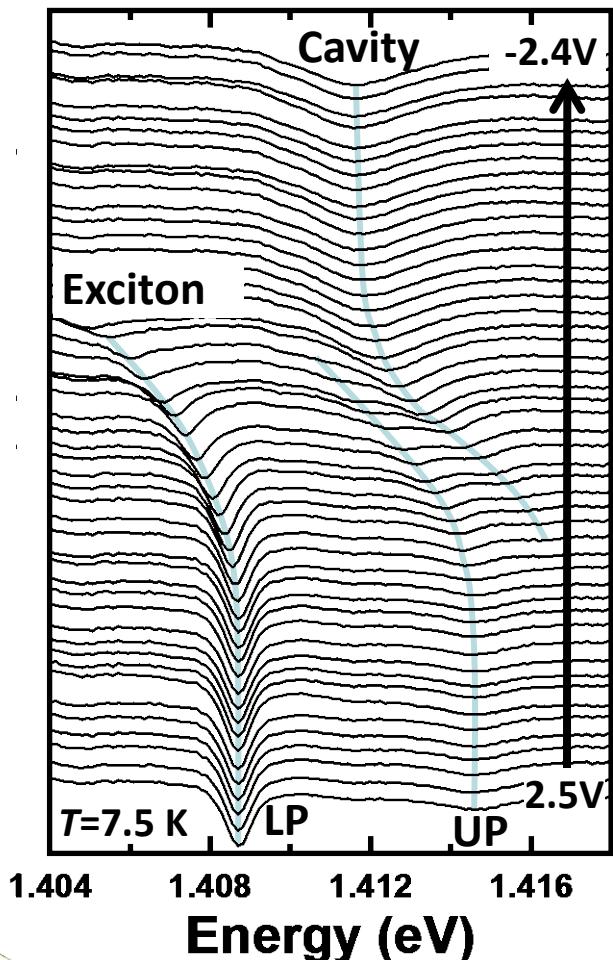
Electrical control: reverse bias

Quantum confined Stark effect



Stark tunable polariton modes

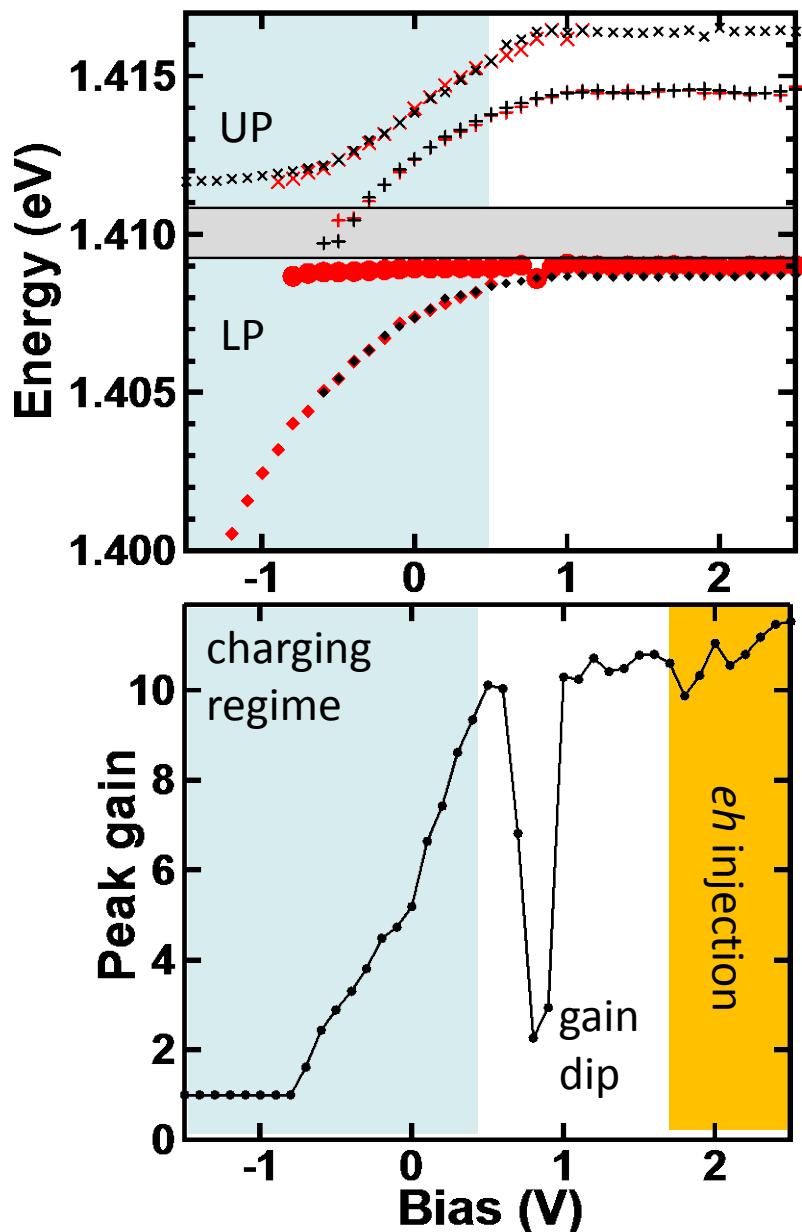
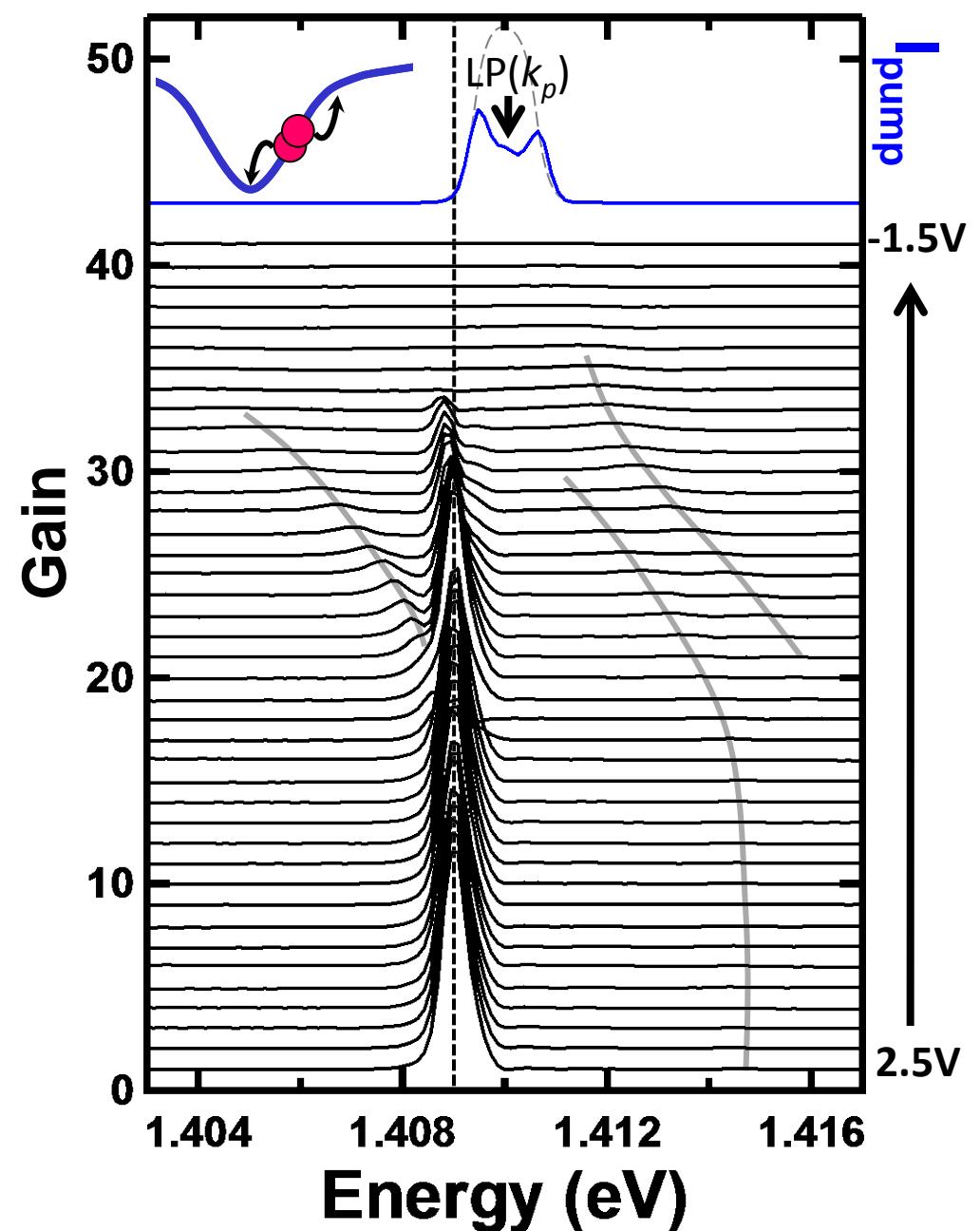
Probe reflectivity



Stark tuning of the excitons
Rabi splitting 6 meV

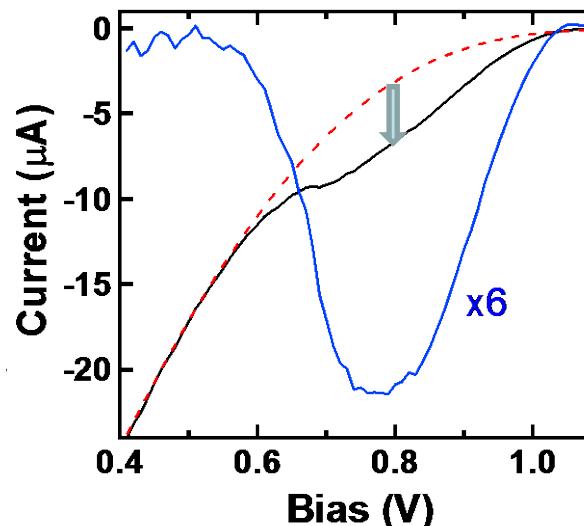
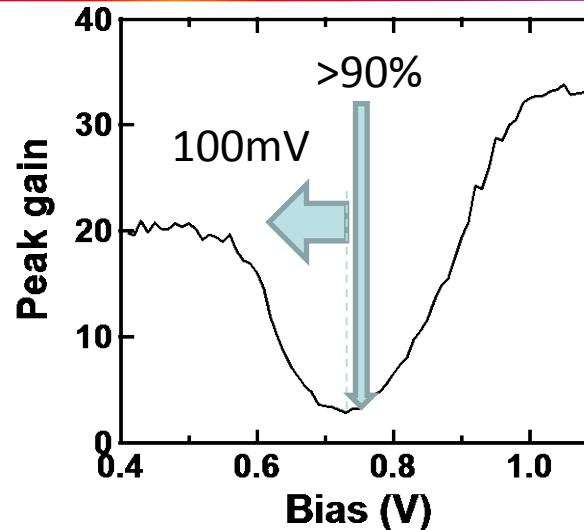
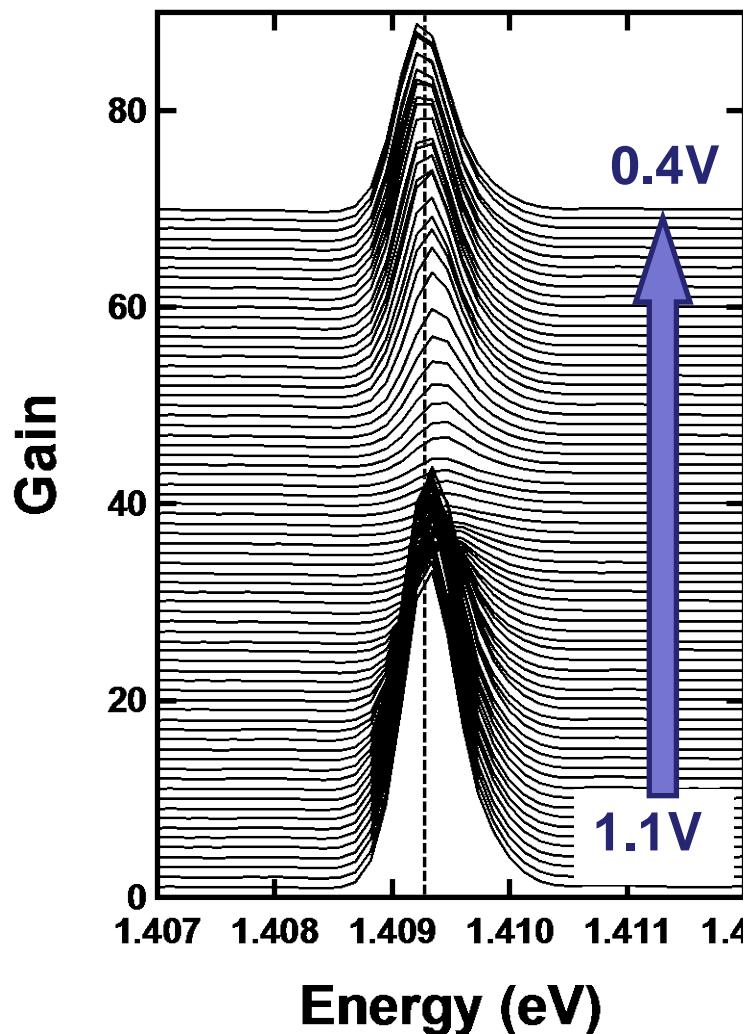


Ultrafast Gain



- dispersion-less gain peak
- gain dip at 0.7V

Gain dip

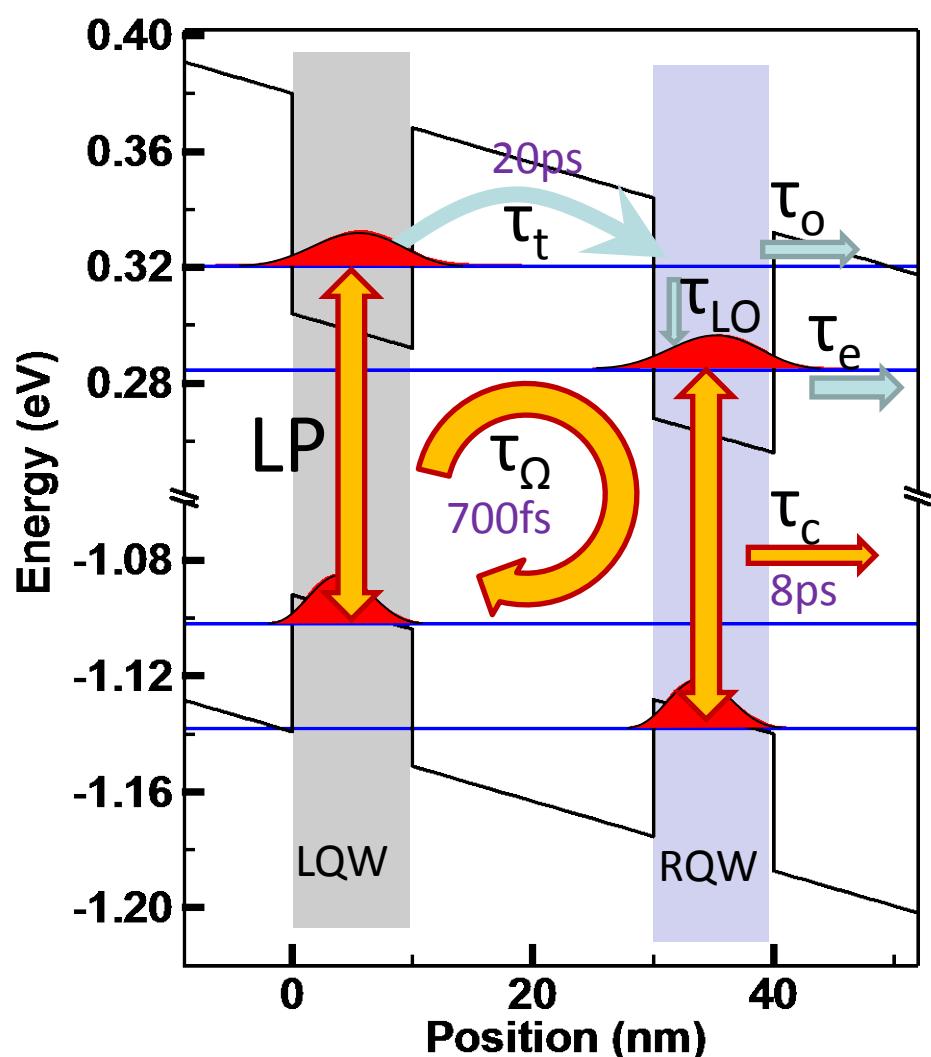


sharp dip in gain

extra
photocurrent
at same bias

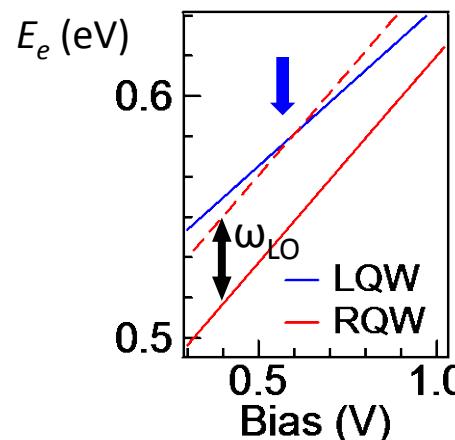
- tunnelling-induced gain quenching

Tunnelling in microcavities



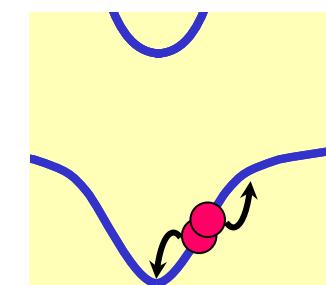
transport competition:

- tunnelling separates e and h
- Rabi coupling: polaritons redistribute eh pairs between QWs



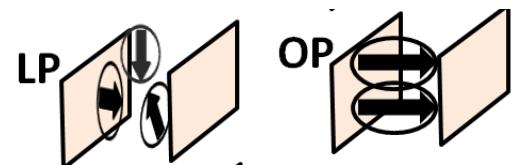
- LO phonon-induced tunnelling 100fs
- carrier escape 180ns, 250fs

- extra e^- population creates extra scattering
- OPO gain very sensitive to damping: phonon vs e^-



Summary

- **New regime: polaritons and quantum tunneling**
 - bias controlled dispersion
- **Dipolaritons: Oriented polaritons**
 - vertically-oriented polaritons
 - new possibilities for enhancing nonlinear Interactions
threshold reduction, control of parametric scattering



Thank you !

Thank you



FORTH

Microelectronics Research Group

Univ. of Crete

