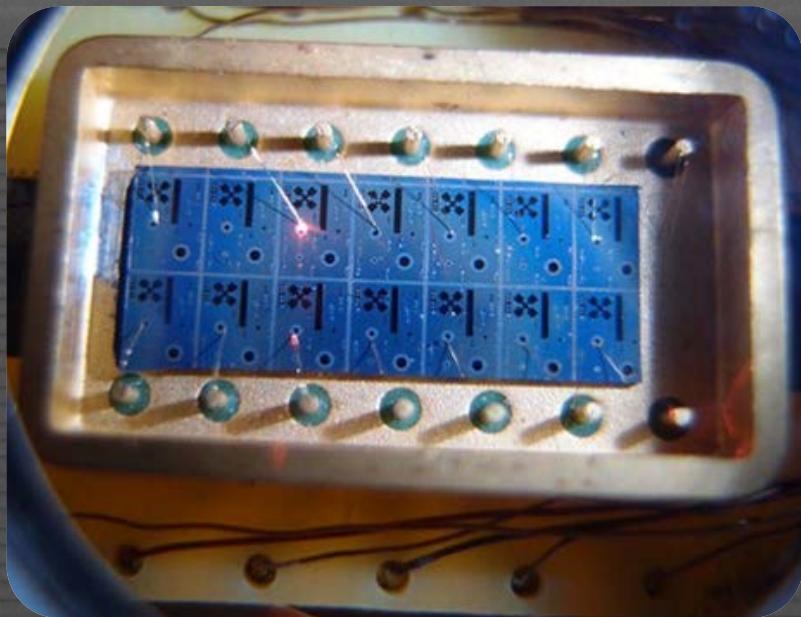


Polariton Based Devices

Pavlos G. Savvidis
University of Crete, FORTH-IESL

Peterhoff
18.06.13



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G. Tosi
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Department of Materials Science / IESL-FORTH



Collaborations

IESL-FORTH



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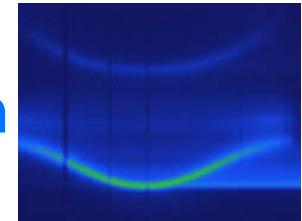
Luis Vina
Carlos Anton



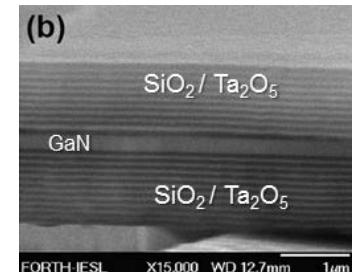
David Lidzey
D. Cole

Outline

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

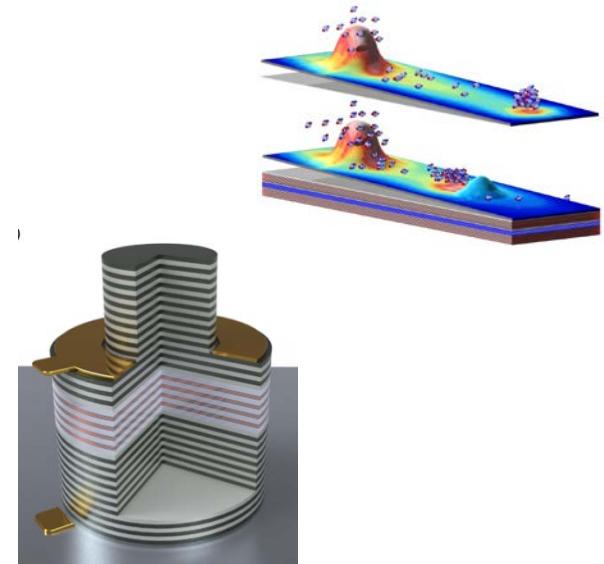


- Polariton lasing at room temperature in hybrid GaN dielectric mirror microcavities



- Electrical and optical manipulation of polariton condensates on a chip

- polariton condensate transistor
 - electrical control of polariton condensate



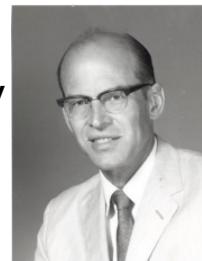
The History of Semiconductor Lasers

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

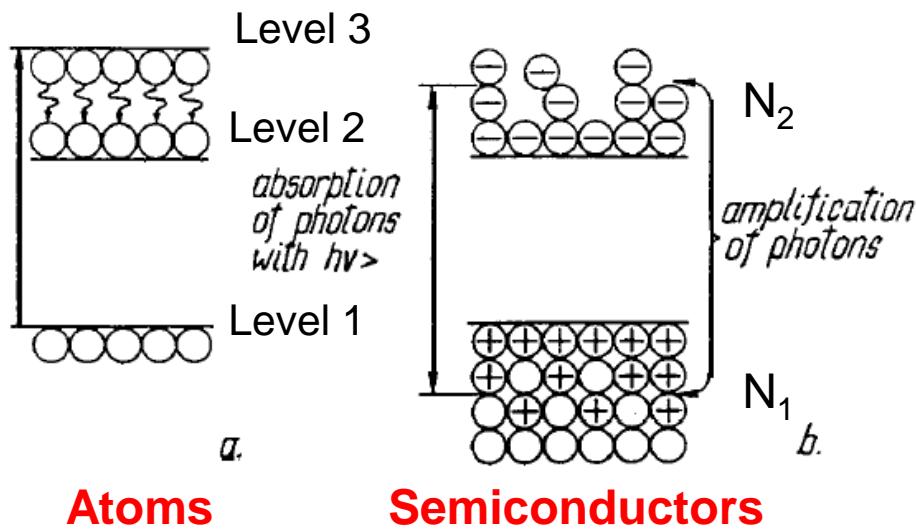
In 1970, Zhores Alferov, Izuo Hayashi and Morton Panish independently developed CW laser diodes at room temperature

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.

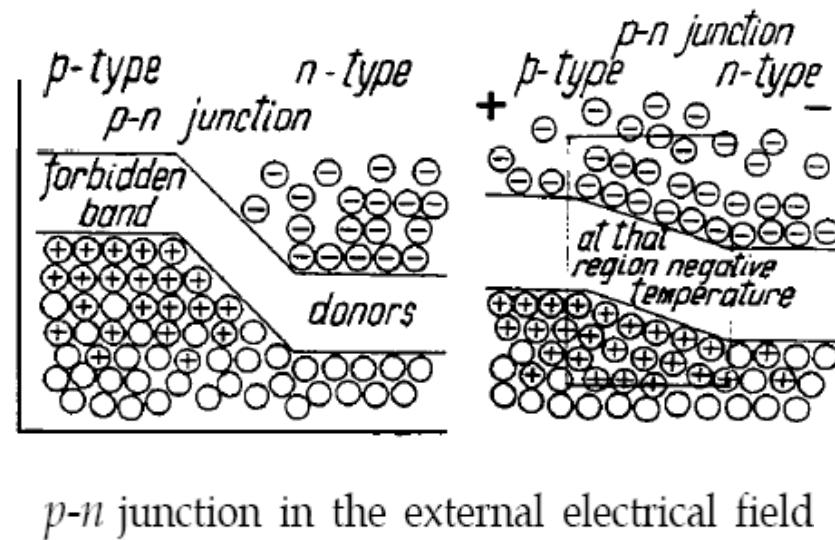
Negative Temperature & Population Inversion Lasing

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

Three-level laser energy diagram



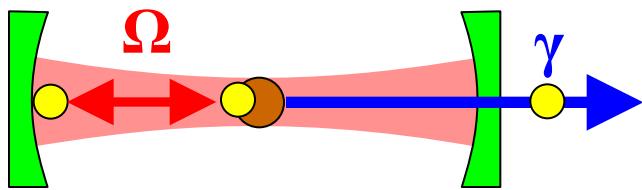
Basov Nobel Lecture



- 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.

Weak Coupling Regime



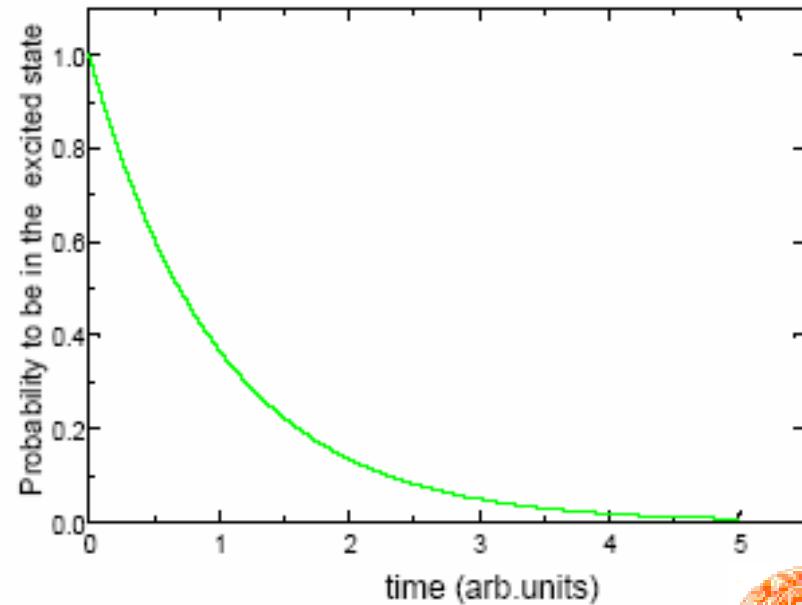
γ : loss channel (e.g. imperfect mirror)

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

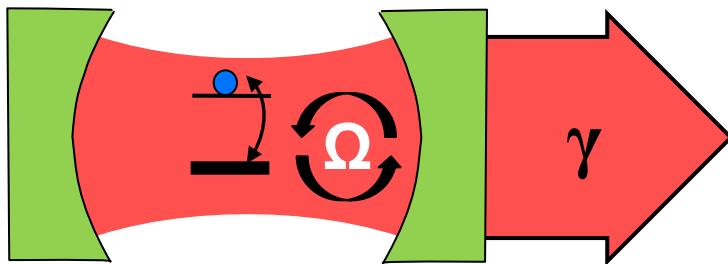
Weak Coupling Regime ($\gamma \gg \Omega$) :

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

⇒ Spontaneous Emission is irreversible



Strong Coupling Regime

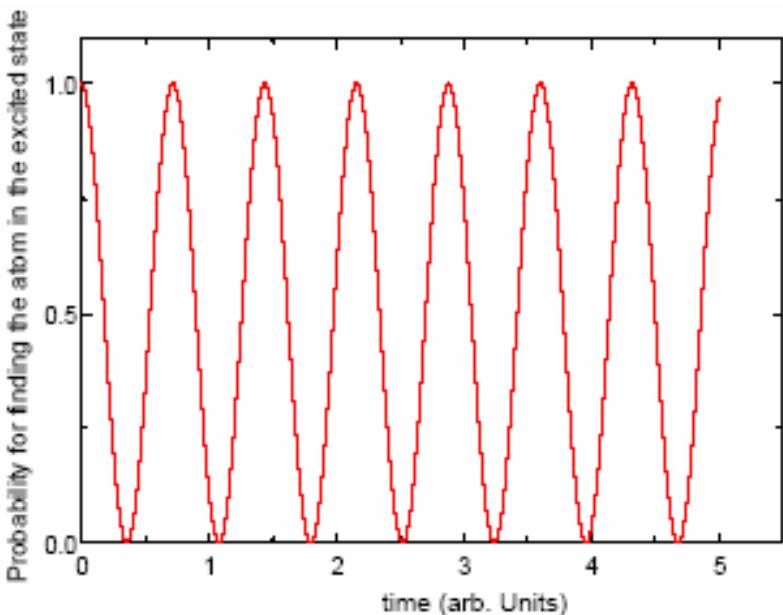


γ : loss channel

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

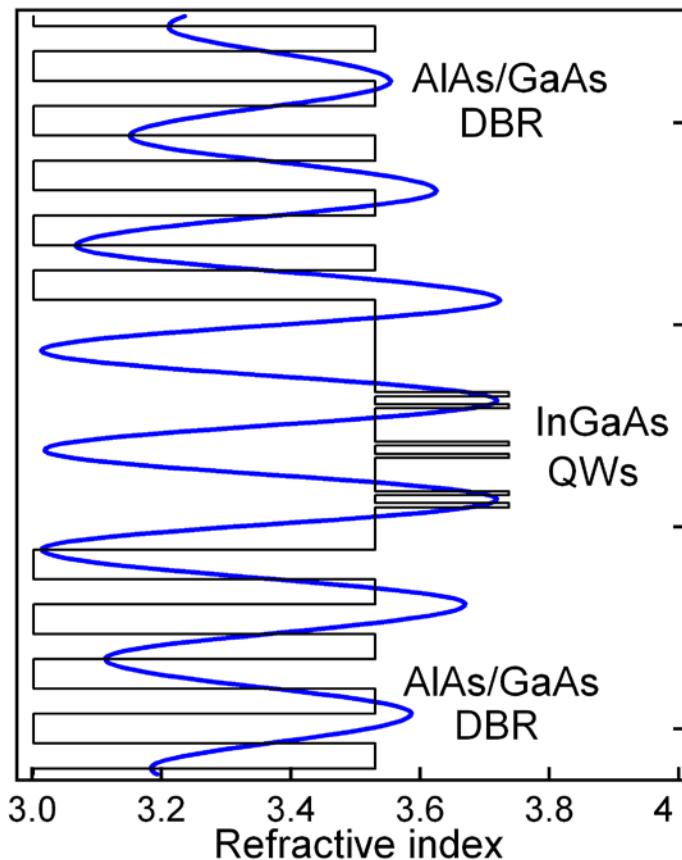
emitted photon will be reabsorbed before it leaves the cavity

⇒ Spontaneous Emission is a reversible process

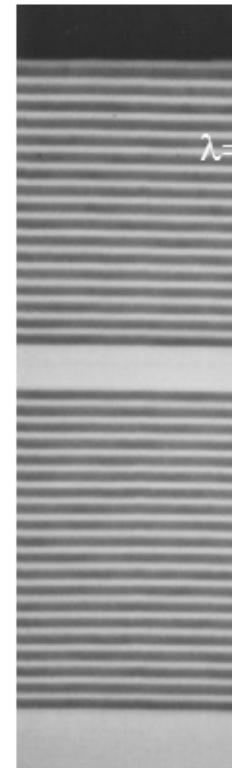


Monolithic Semiconductor Microcavity

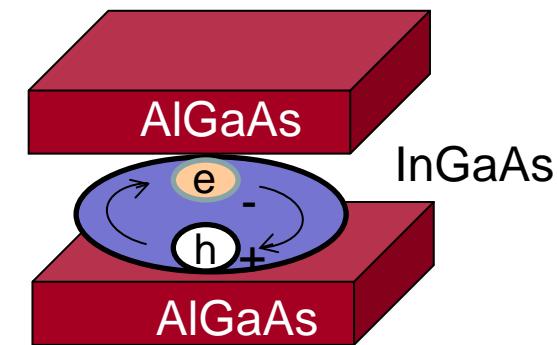
Top DBR Mirror



- QWs placed at the E-field maxima



Bottom DBR Mirror



- Combine electronic and photonic confinement in the same structure



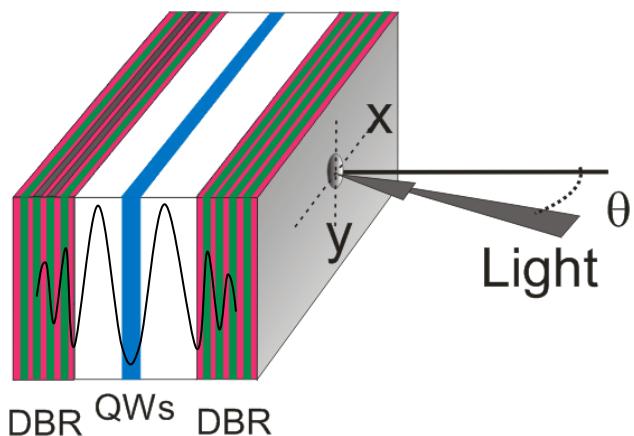
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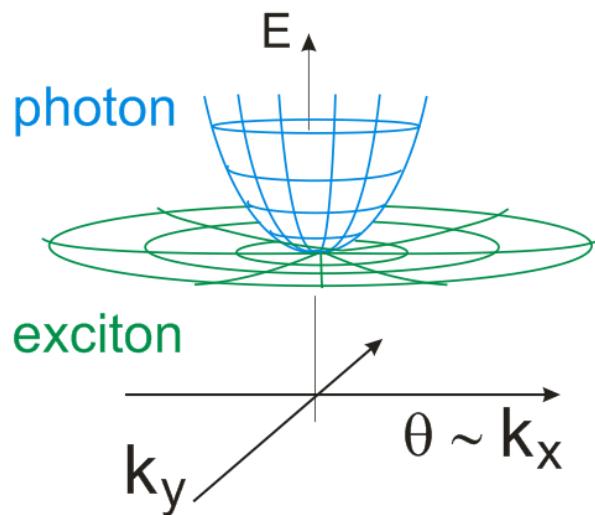
Strong Coupling Regime in Semiconductor Microcavity



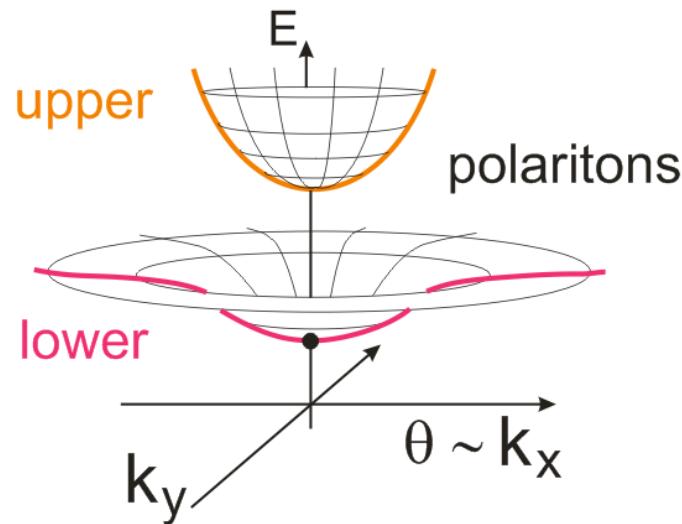
- Strongly modified dispersion relations
reduced density of states near $k_{\parallel}=0$
- small polariton mass $m_{\text{pol}} \approx 10^{-4}m_e$
- strong non-linearities $\rightarrow \chi^3$ (exciton component)

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

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



Strong Coupling Regime



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



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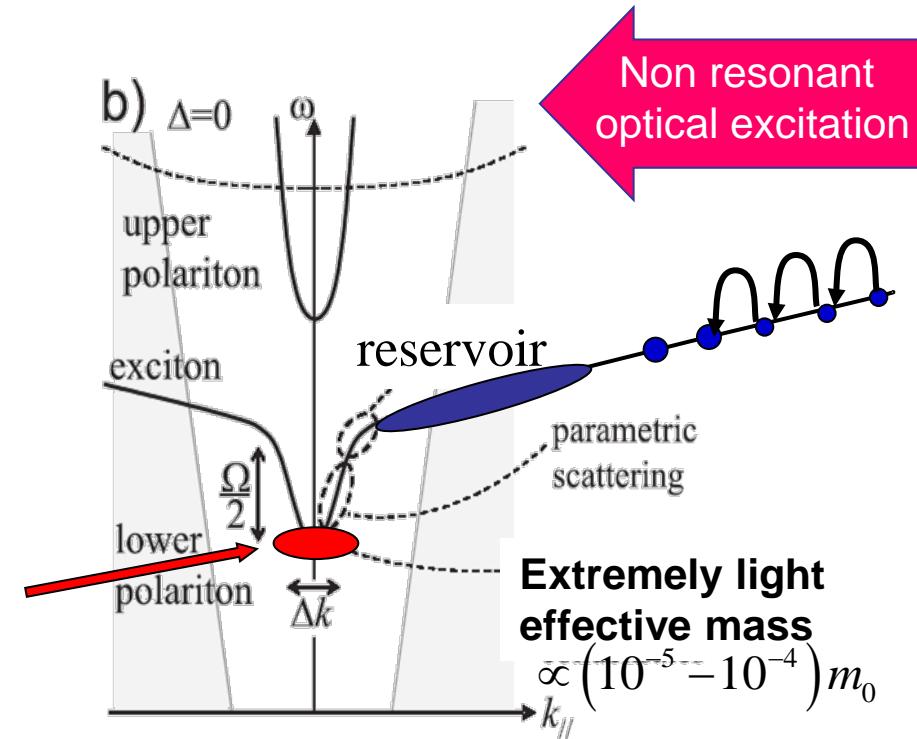


Bose-Condensation and Concept of Polariton Lasing

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



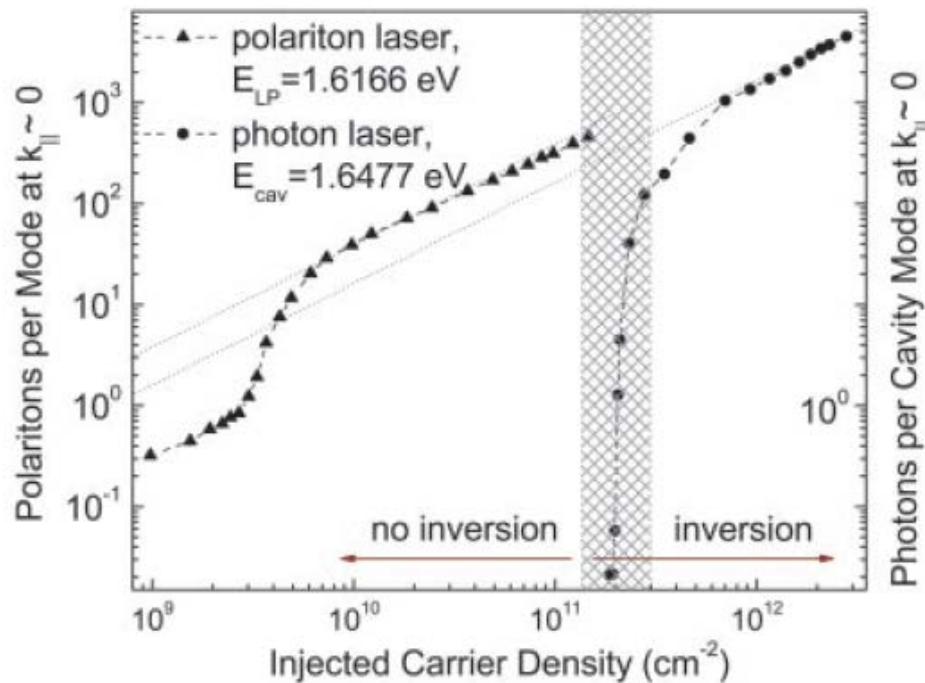
Polaritons accumulate in the lowest energy state by bosonic final state stimulation.

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



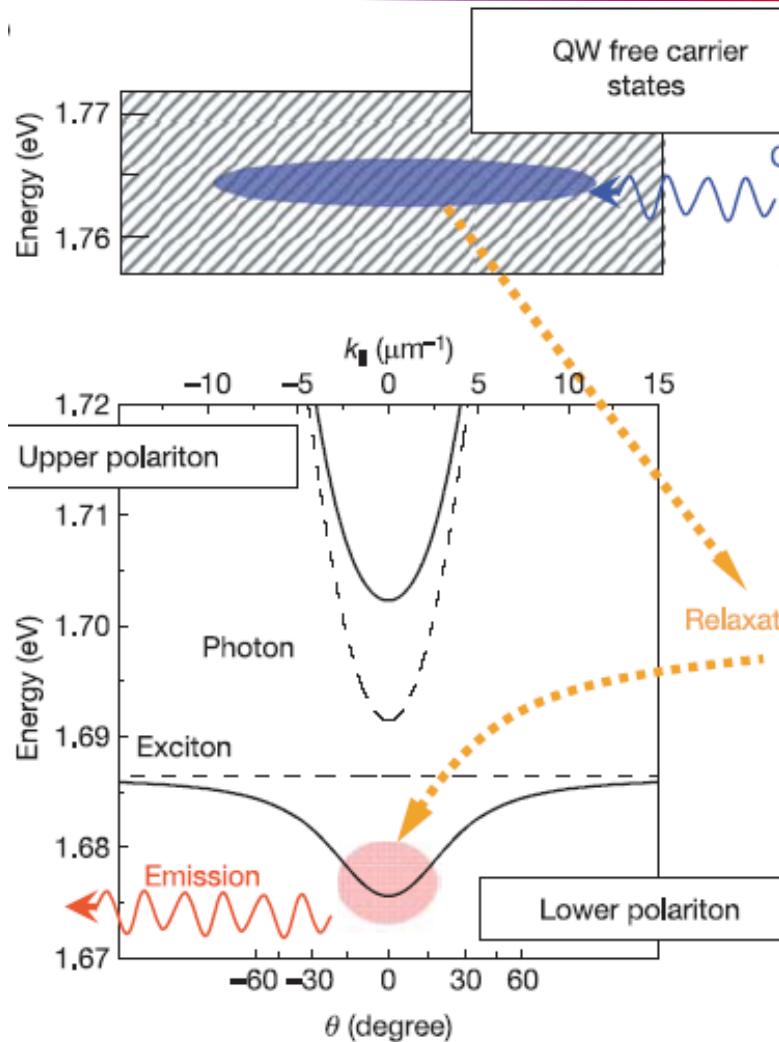
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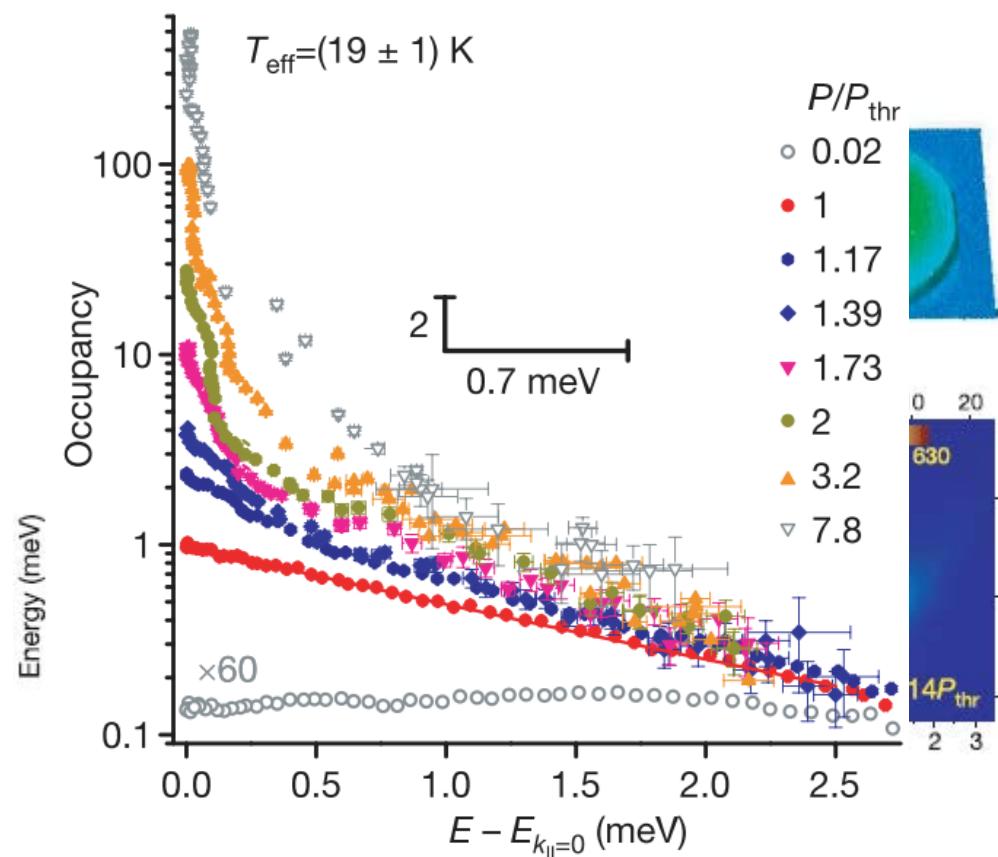


Polariton Condensation in CdTe/CdMnTe MC



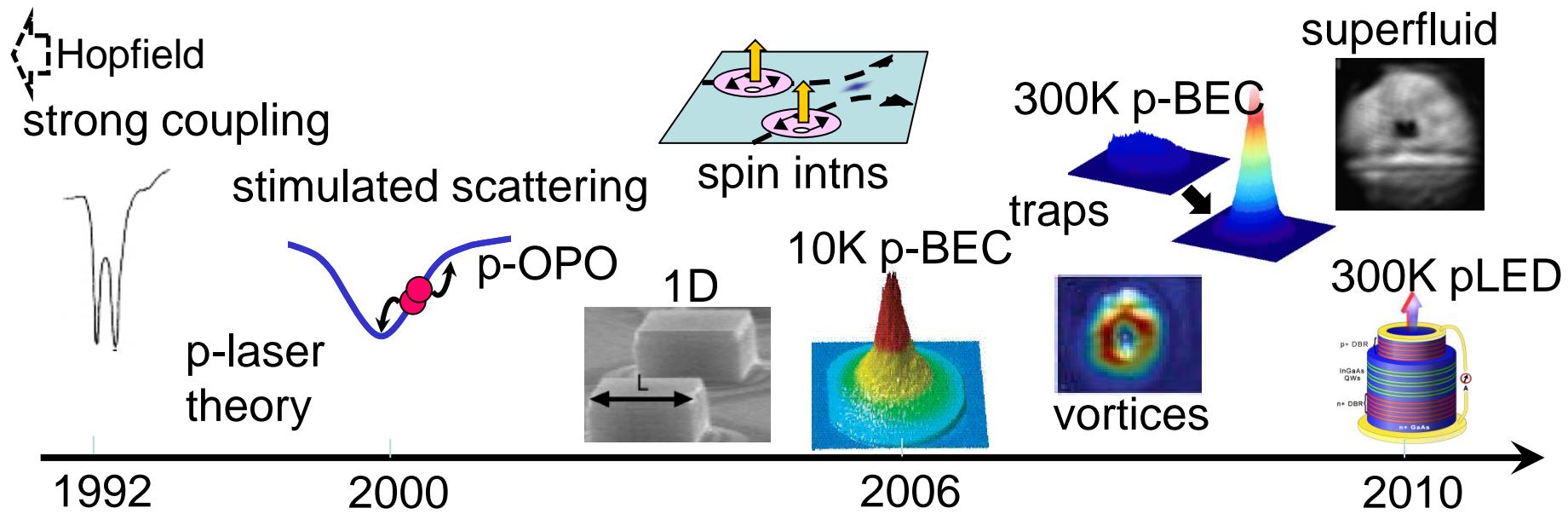
J. Kasprzak et al. Nature 443, 409 (2006)

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

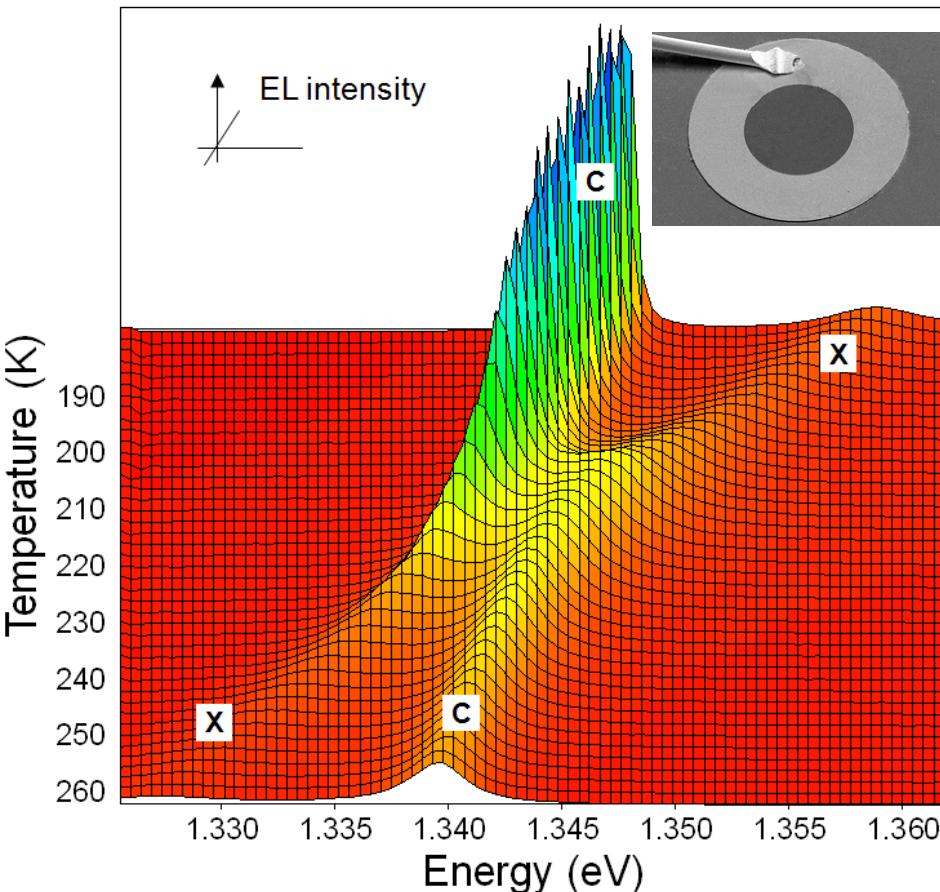
New directions: electrically driven polariton devices

Polariton based Devices

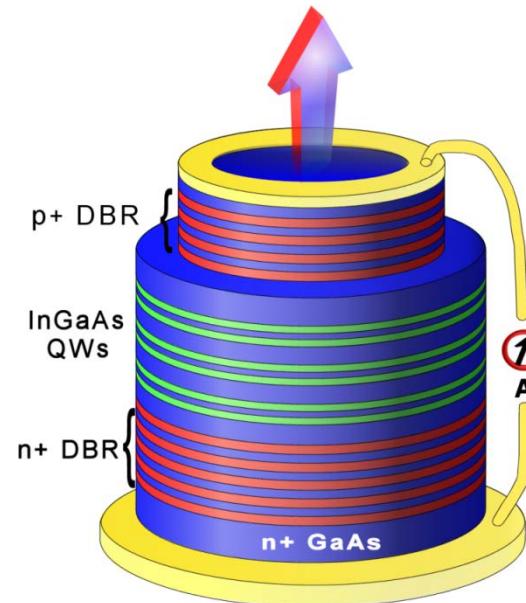
“Polaritonics”

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

Transport driven device

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



N. Pelekanos



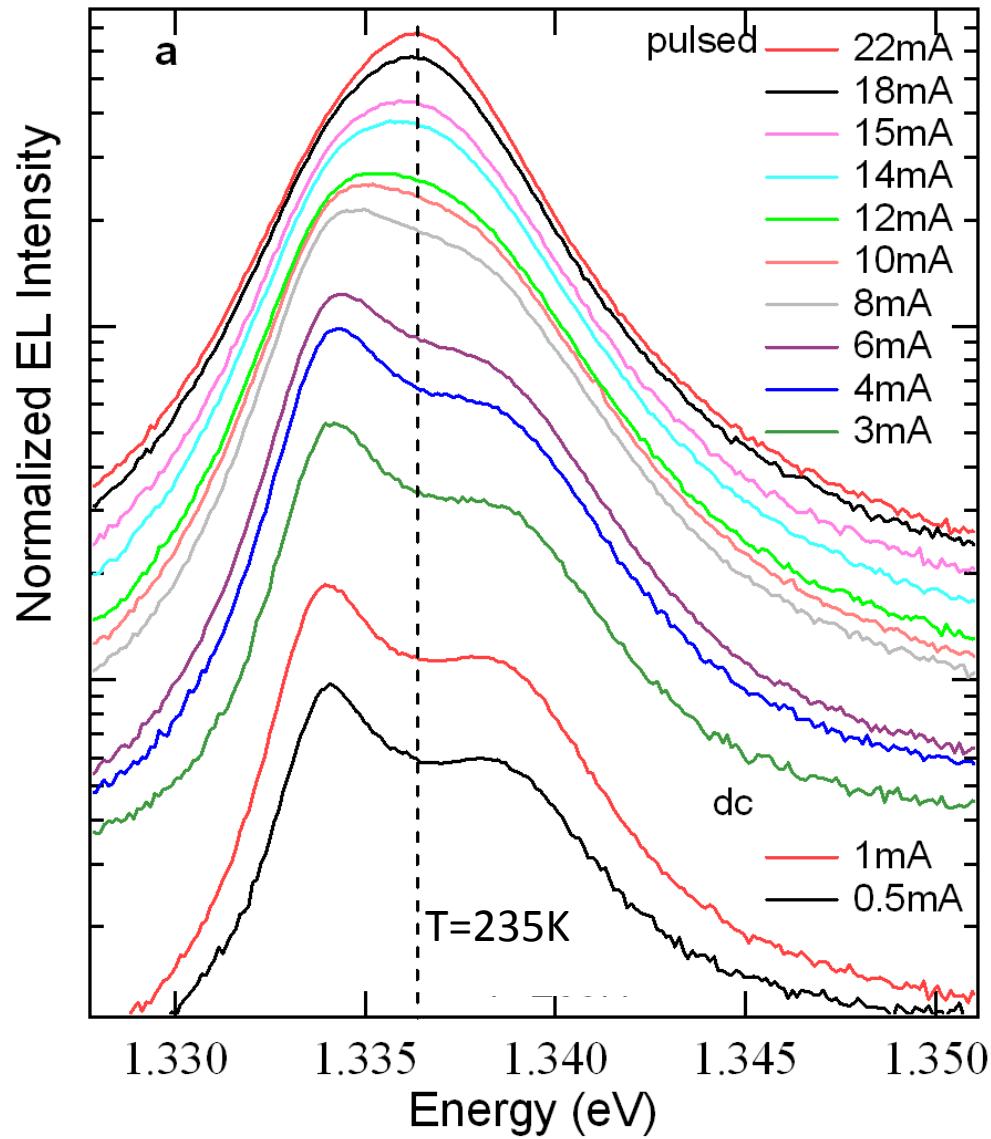
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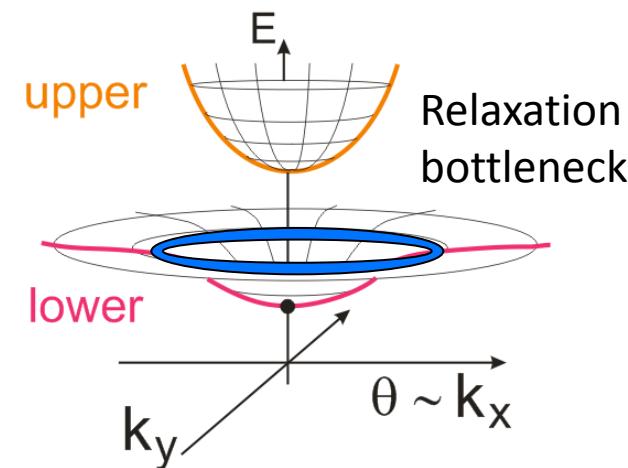
Univ. of Crete



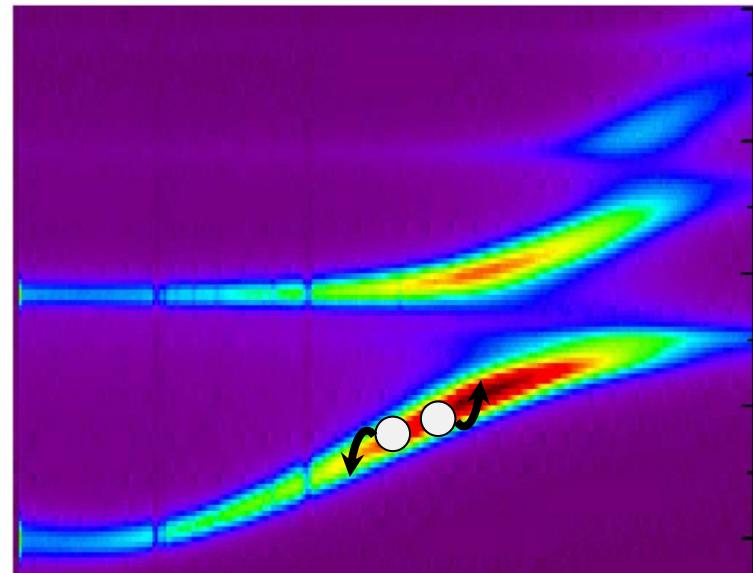
Collapse of Strong Coupling Regime at High Densities



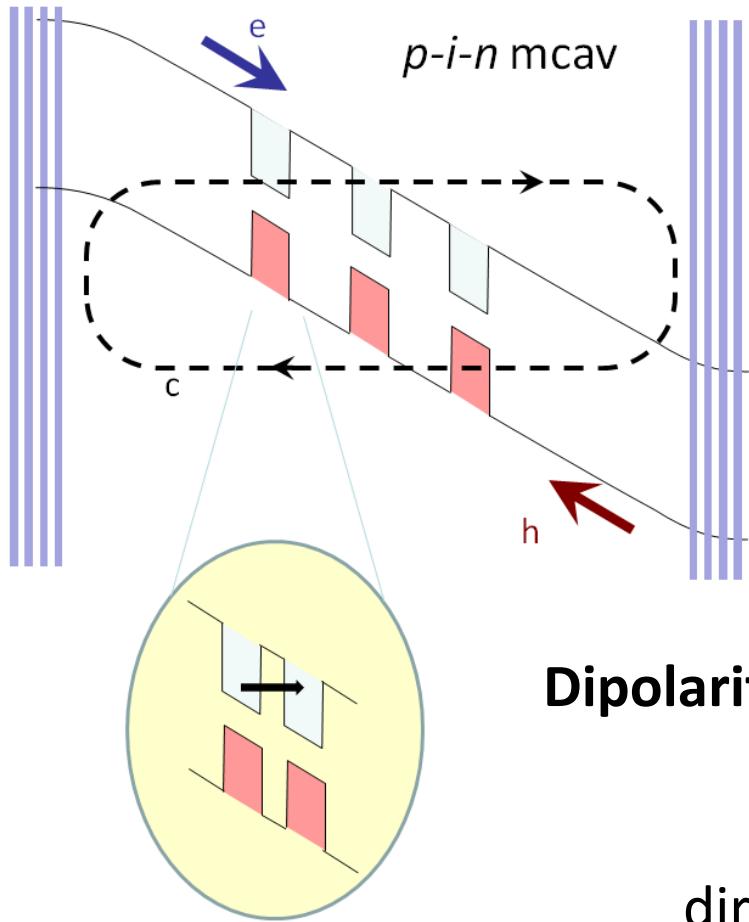
- Injection density at 22mA $\sim 10^{10}$ pol/cm²



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

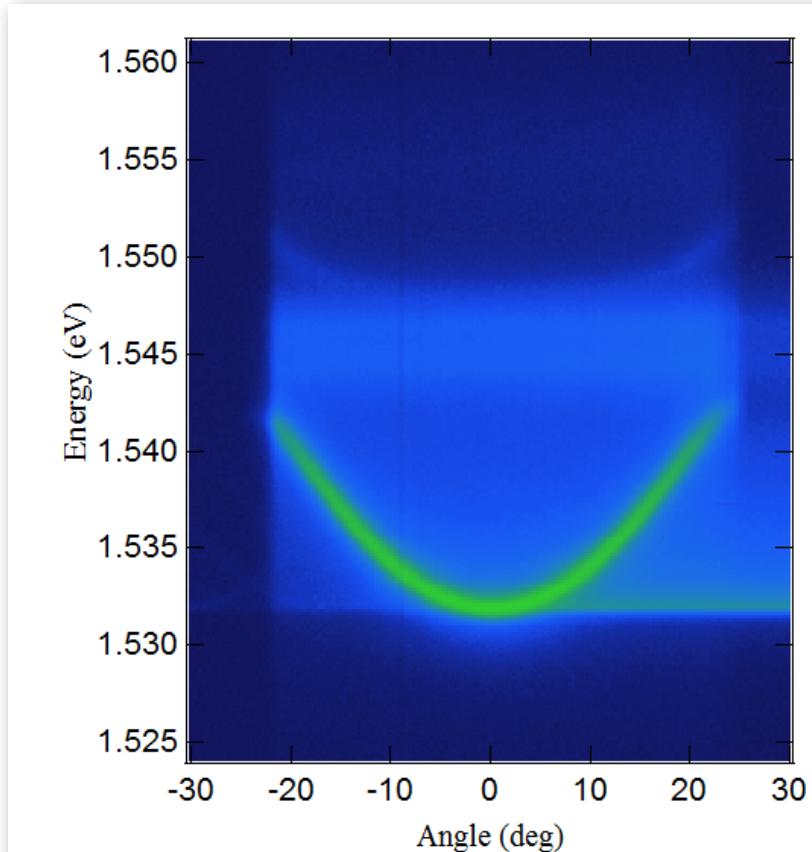
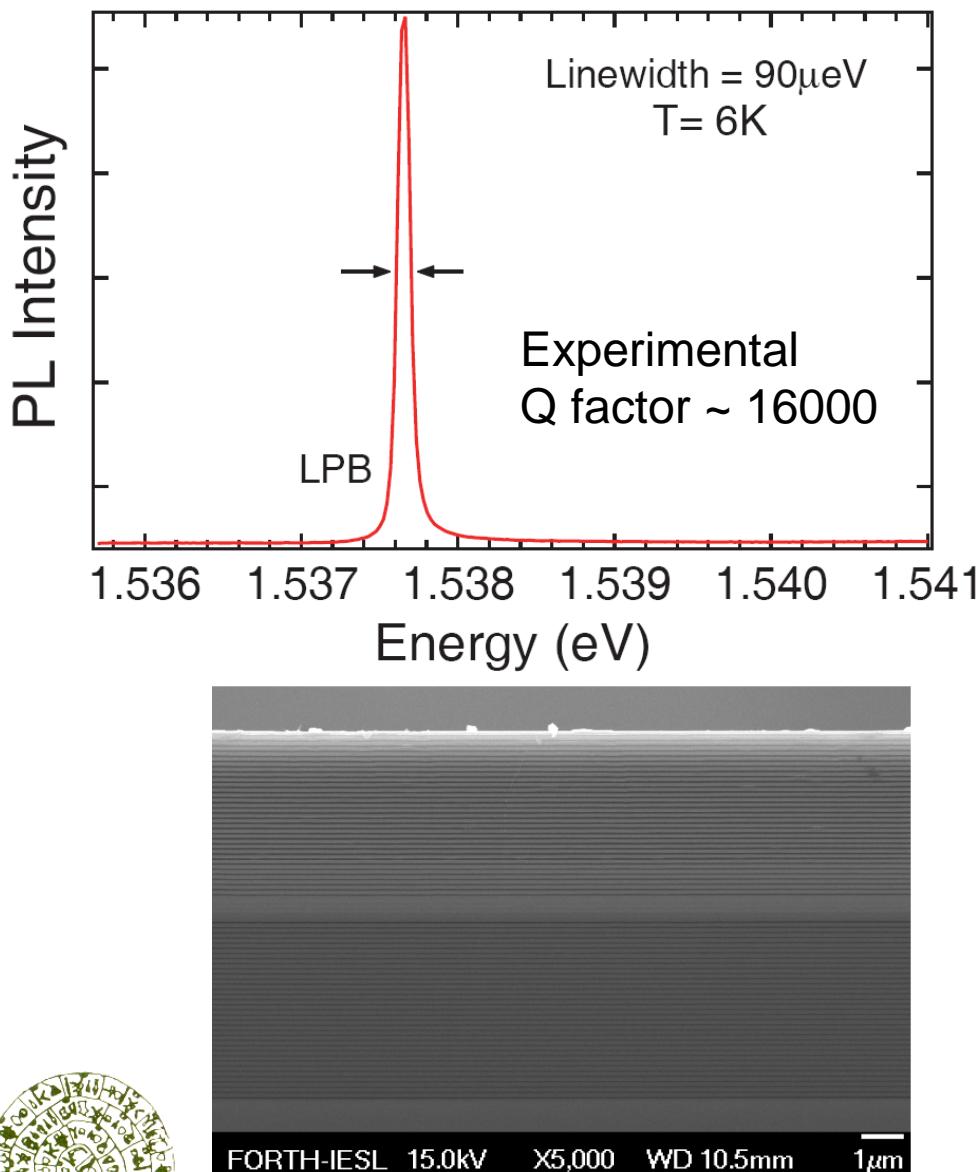


direct control of polariton dipole

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

dipole-dipole

High finesse GaAs microcavity



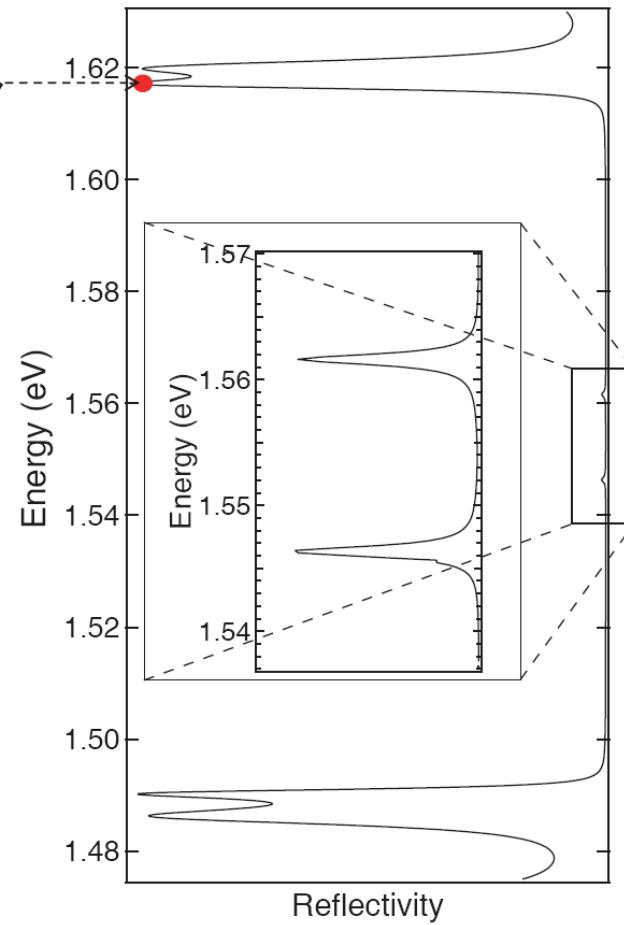
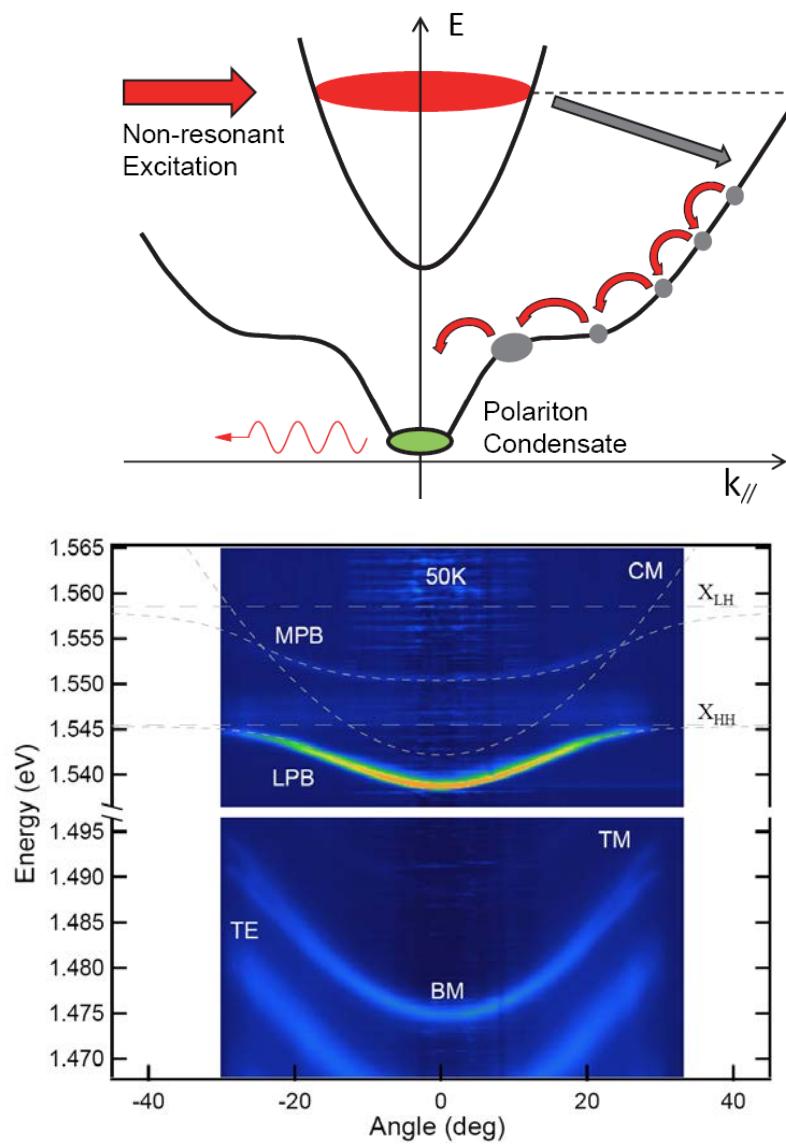
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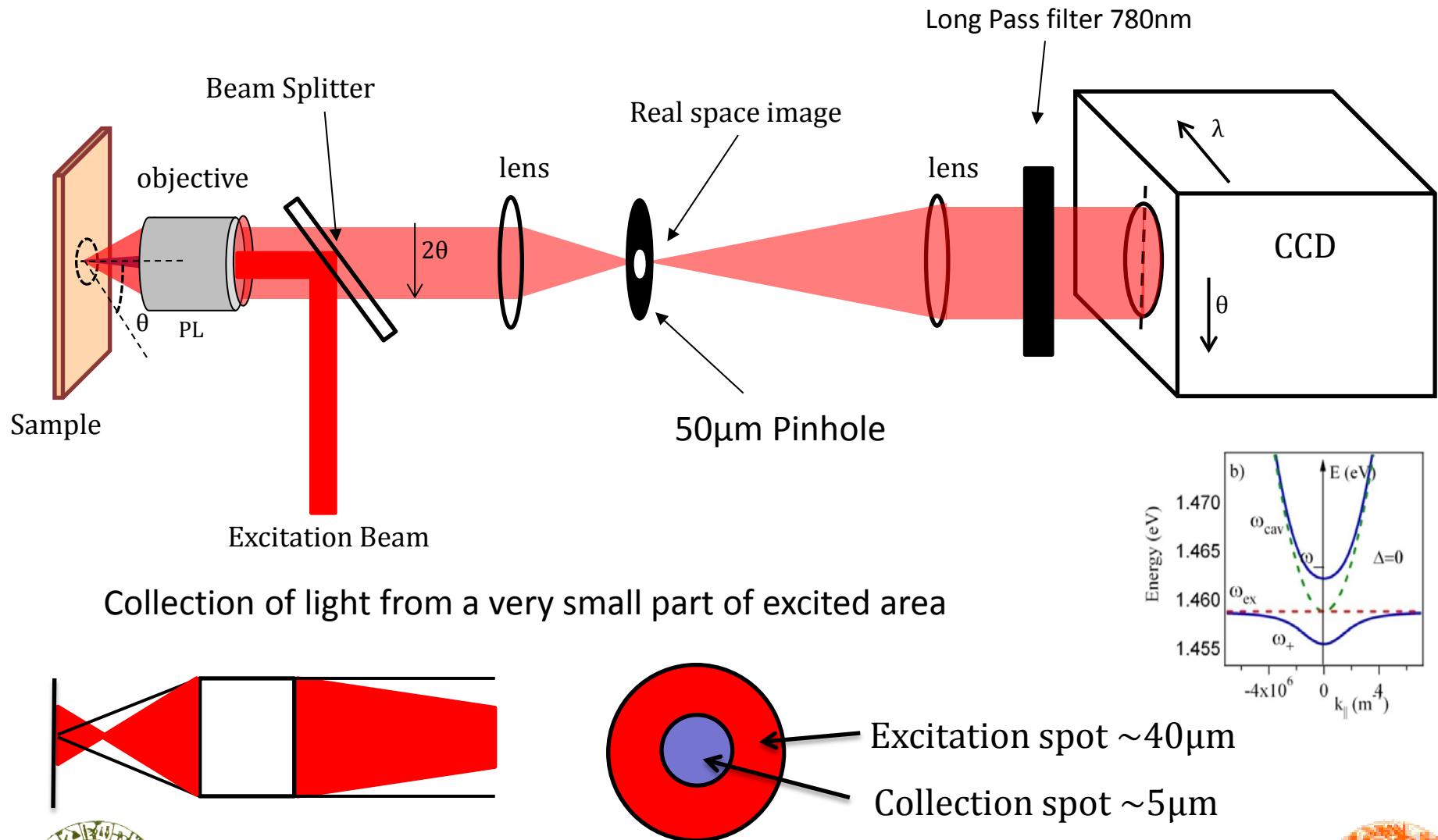
Non-resonant optical excitation



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



PL imaging Setup



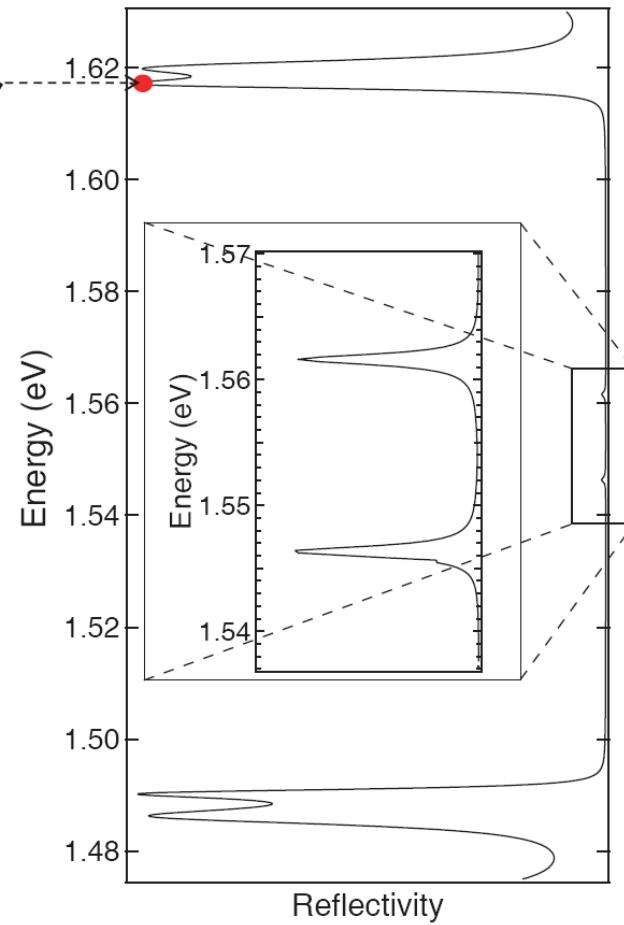
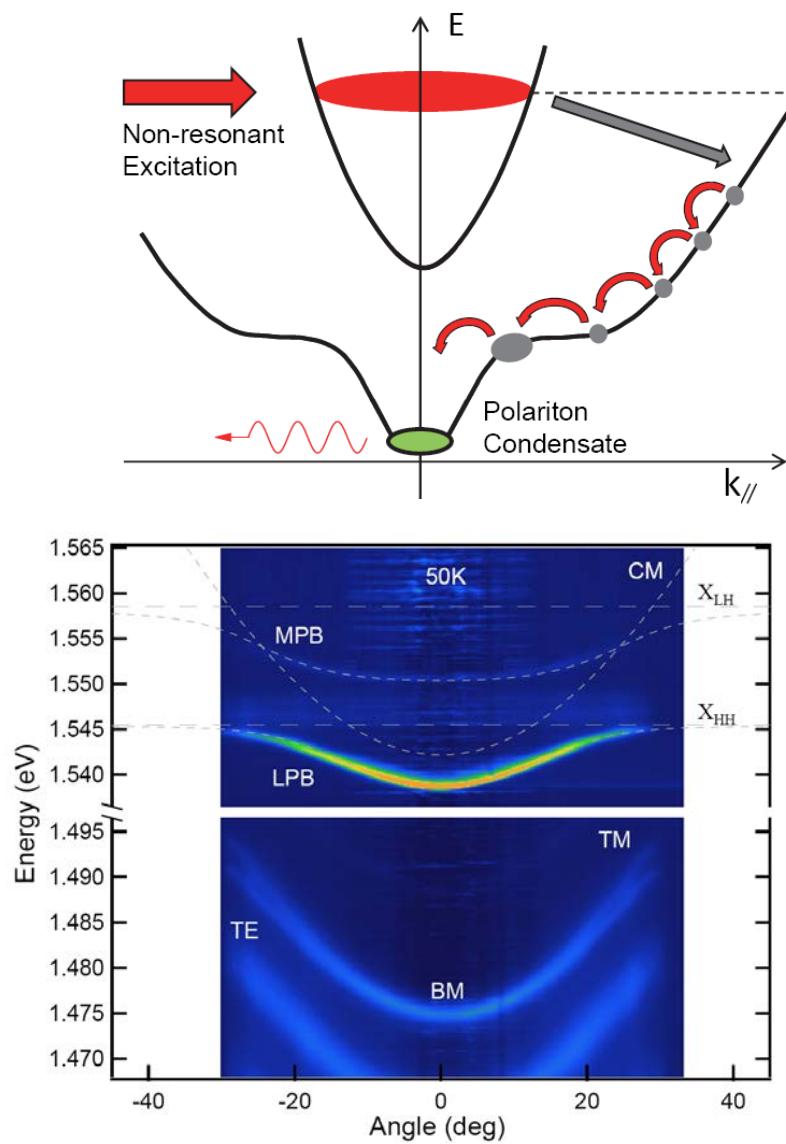
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Non-resonant optical excitation

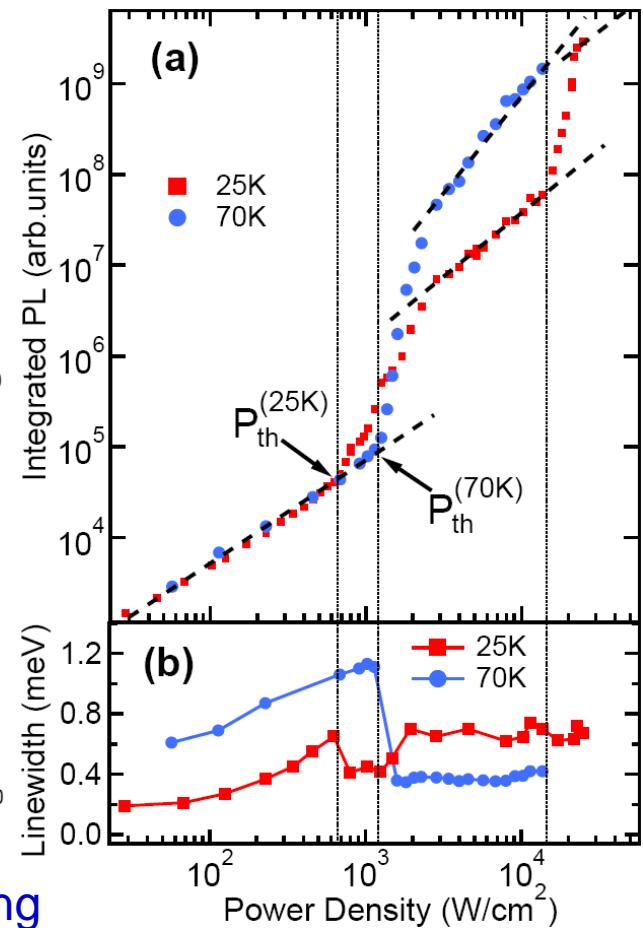
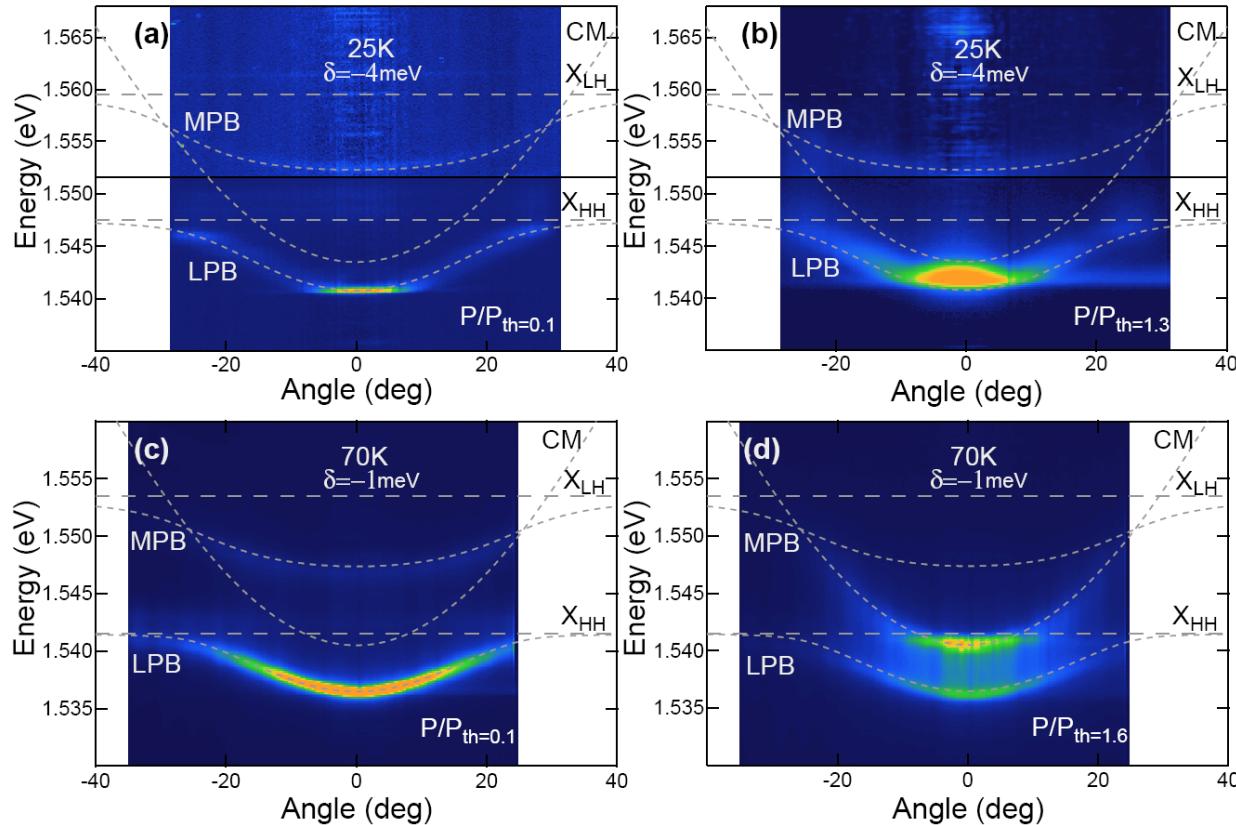


- Rabi splitting of 9.2meV at 50K
- Reflectivity dips relatively small



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

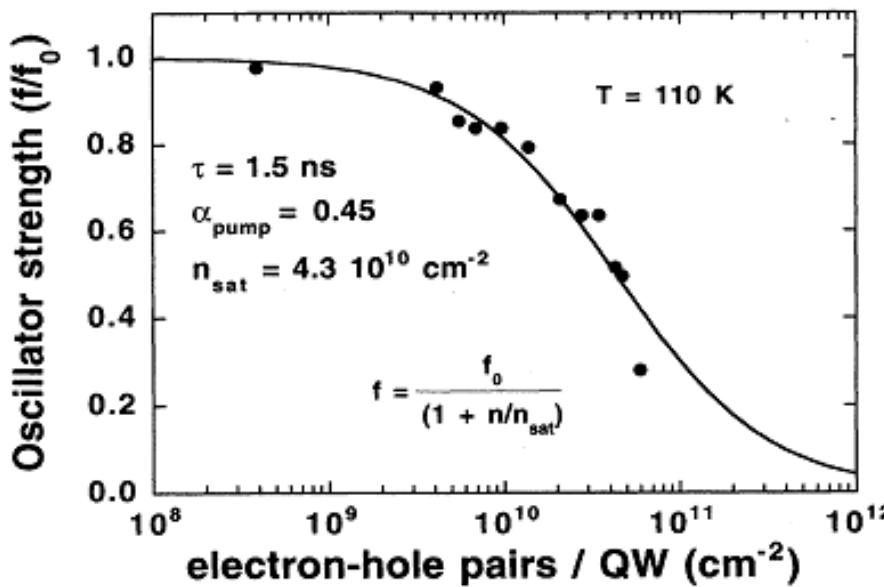
Rabi Splitting vs Density

$$\Omega = \sqrt{4V^2 - (\gamma_X - \gamma_C)^2}$$

$$\hbar V = \hbar \sqrt{\frac{1+\sqrt{R}}{\sqrt{R}} \frac{c\Gamma_0}{n_{cav} L_{eff}}}$$

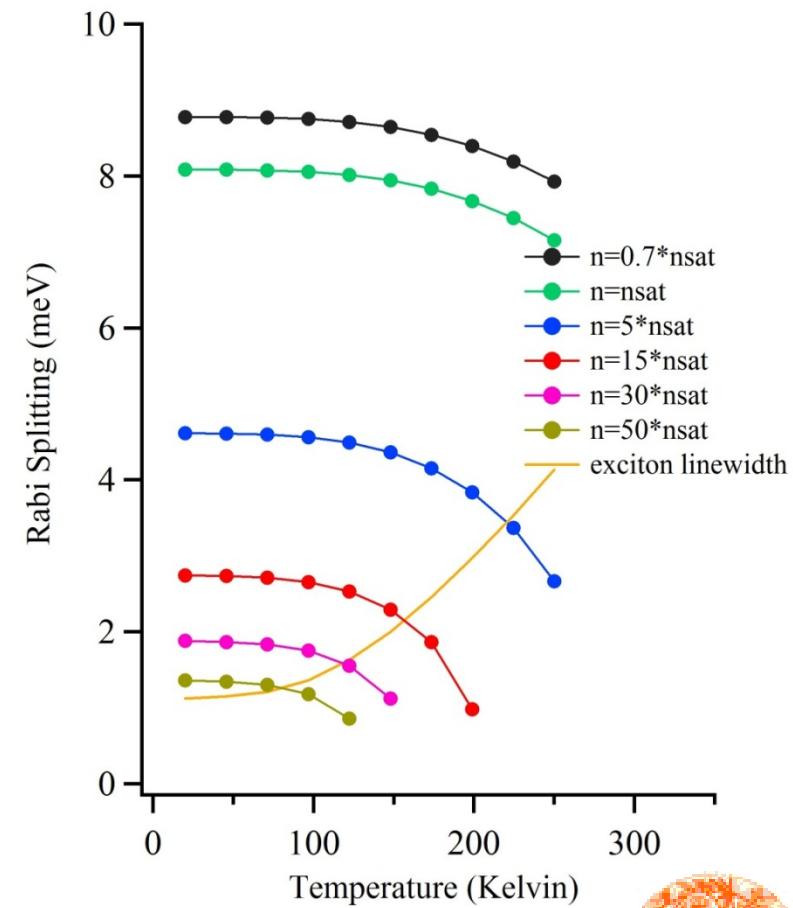
$$f = \frac{f_0}{1 + \frac{n}{n_{sat}}}$$

$$\Gamma_0 = \frac{e^2}{4\epsilon_0 n_{cav} m_0 c} \frac{f}{S}$$



(PRB , M. Illegems)

f : exciton oscillator strength
 n : carrier density
 n_{sat} : saturation density



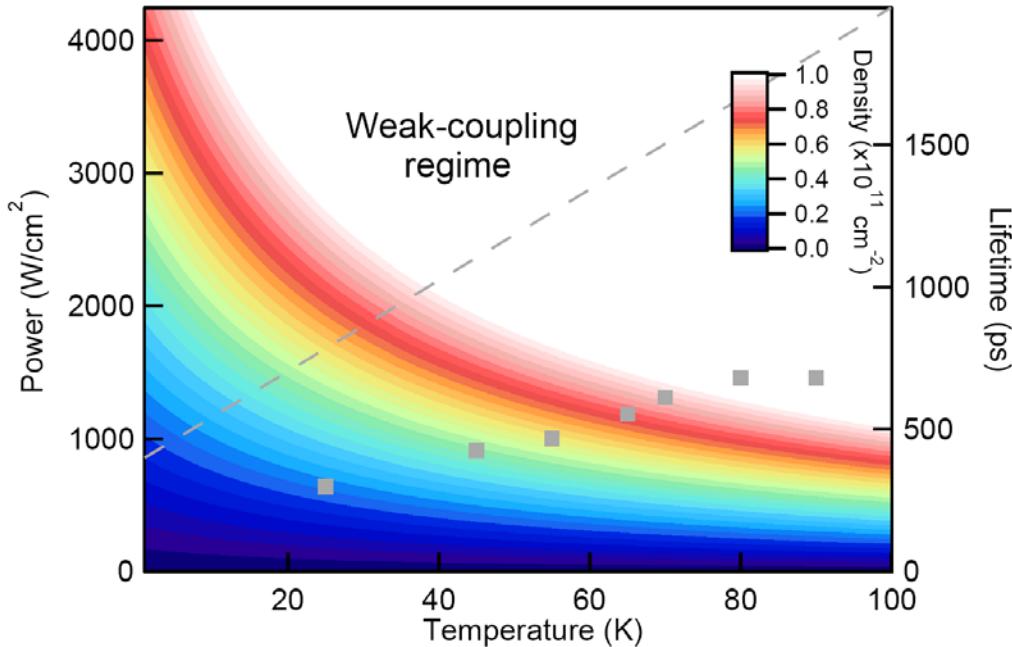
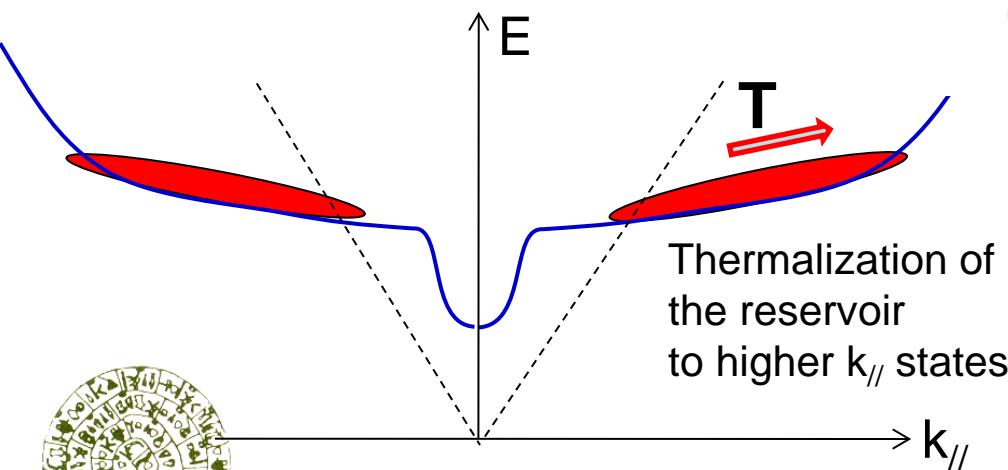
Crossover from Strong to Weak coupling Lasing

$$\frac{dN}{dt} = g - \frac{N}{\tau} \Rightarrow N = g \cdot \tau \quad (\text{steady state})$$

↑
pump

Exciton lifetime τ increases with temperature
(PRB M.Gurioli,
V. Savona)

- For same pumping rate carrier density increases dramatically with increasing T



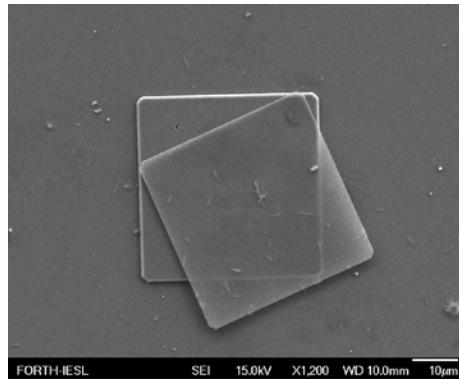
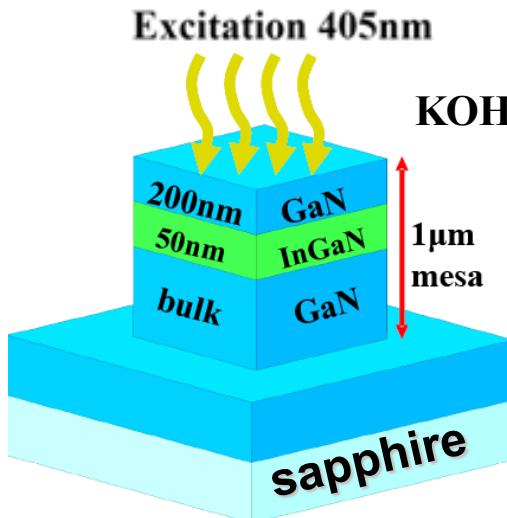
P. Tsotsis et al., New Jour. of Physics
14, 023060 (2012)



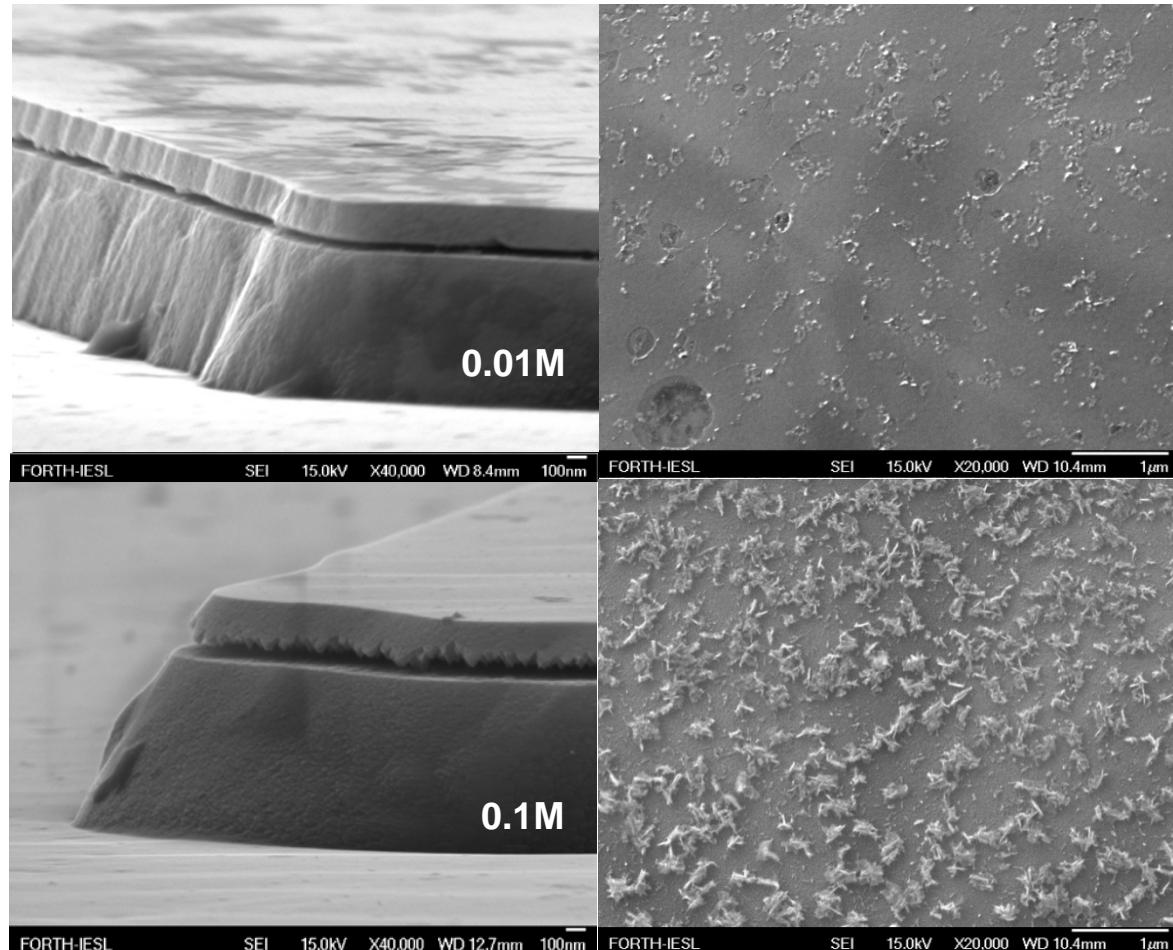
Polariton Lasing in GaN

At room temperature

Freestanding GaN membranes by Lateral Etching of InGaN



- Optical quality GaN membranes



Trichas et. al, APL **94**, 173505 (2009)
Trichas et al. APL **98**, 221101 (2011)



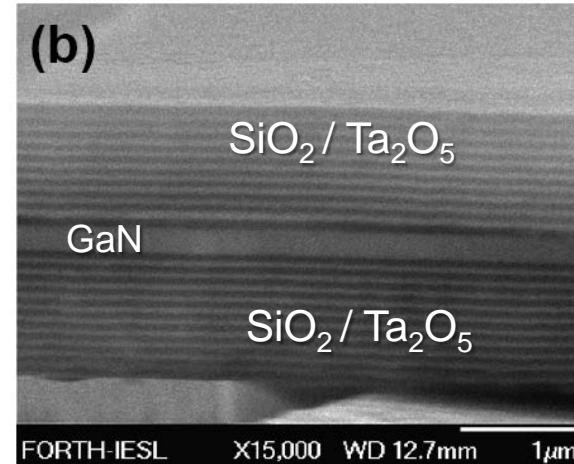
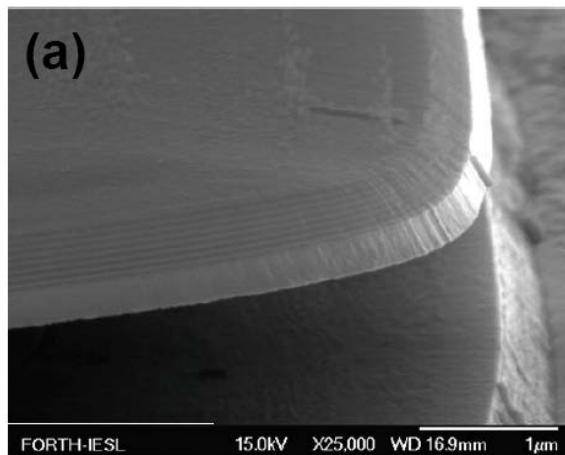
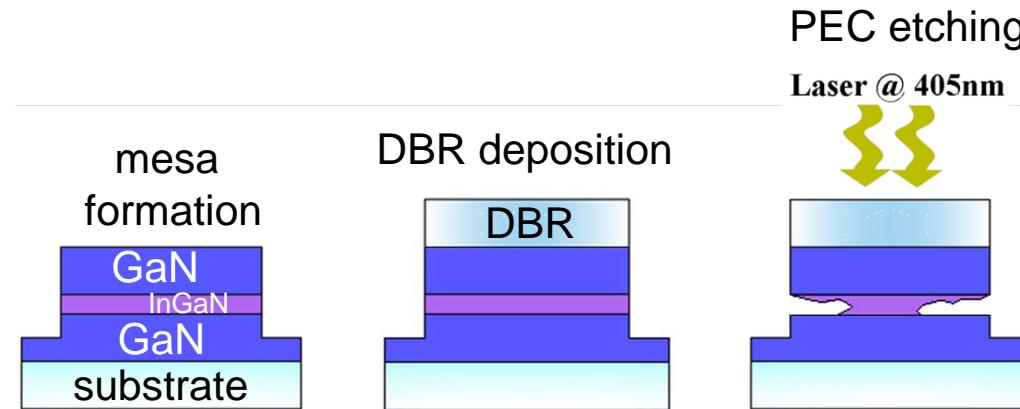
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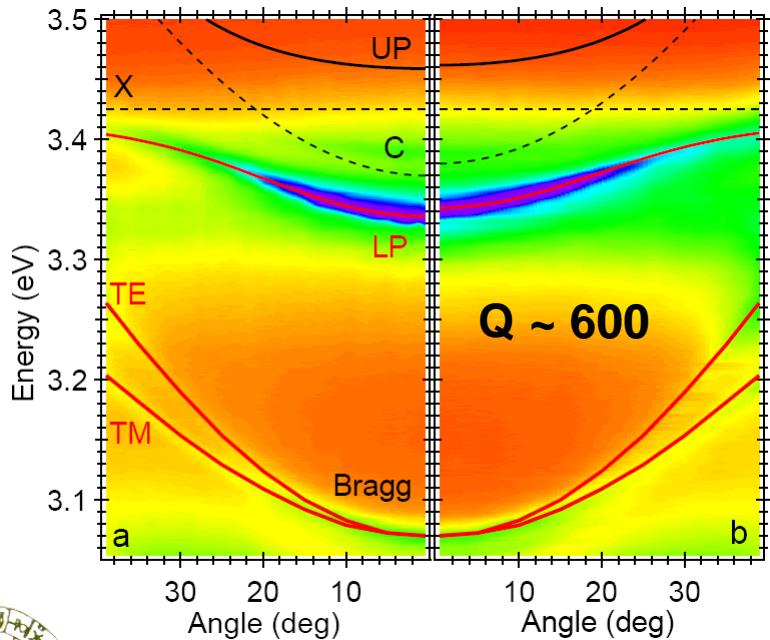
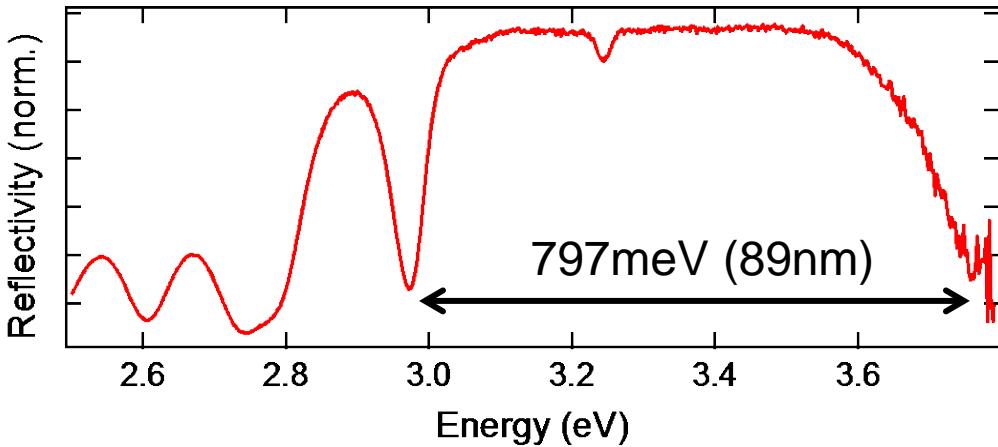
Bragg Luminescence in All Dielectric Microcavity



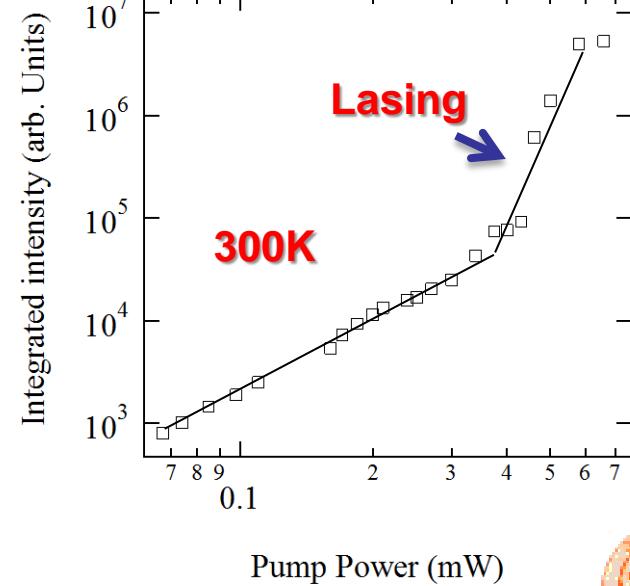
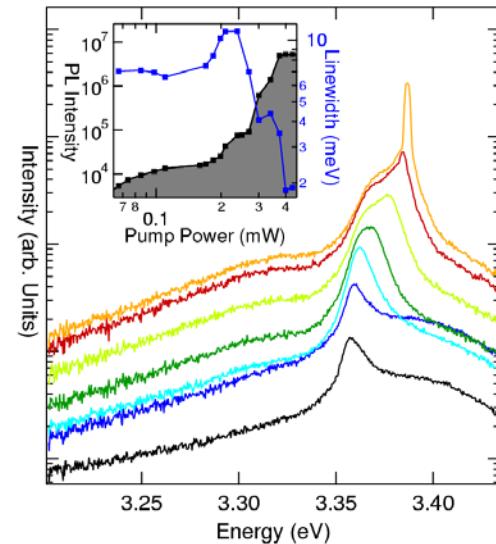
SEM of the free standing
GaN membrane/DBR

E. Trichas, Appl. Phys. Lett. 98, 221101 (2011)

Room temperature GaN based polariton laser



Appl. Phys. Lett. 102, 101113 (2013)



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Polariton Condensate Transistor

Polaritonic Circuits

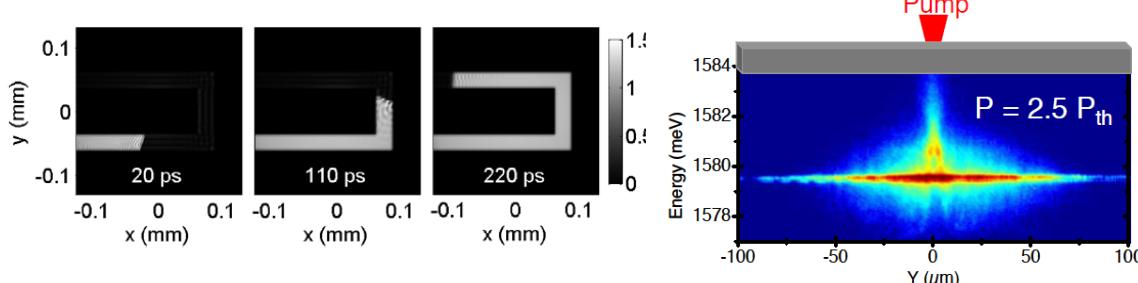
In the future, charged carriers have to be replaced by information carriers that do not suffer from scattering, capacitance and resistivity effects

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

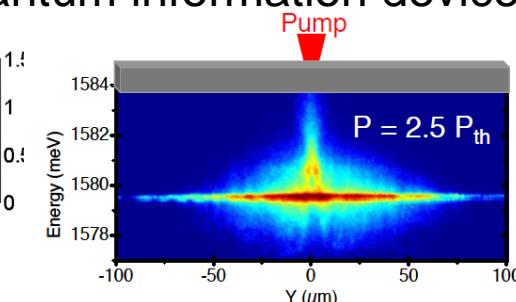
Excitonic component allows them to interact strongly giving rise to the nonlinear functionality enjoyed by electrons

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

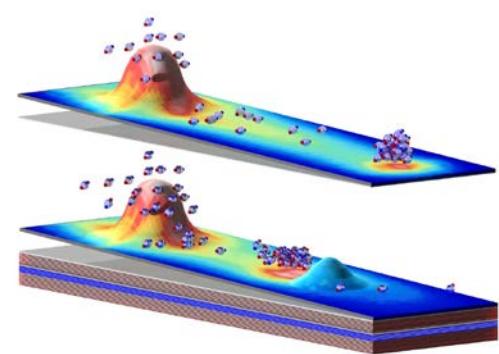
Macroscopic quantum properties of polariton condensates make them ideal candidates for use in quantum information devices and all optical circuits



Liew PRL **101**, 016402 (2008)

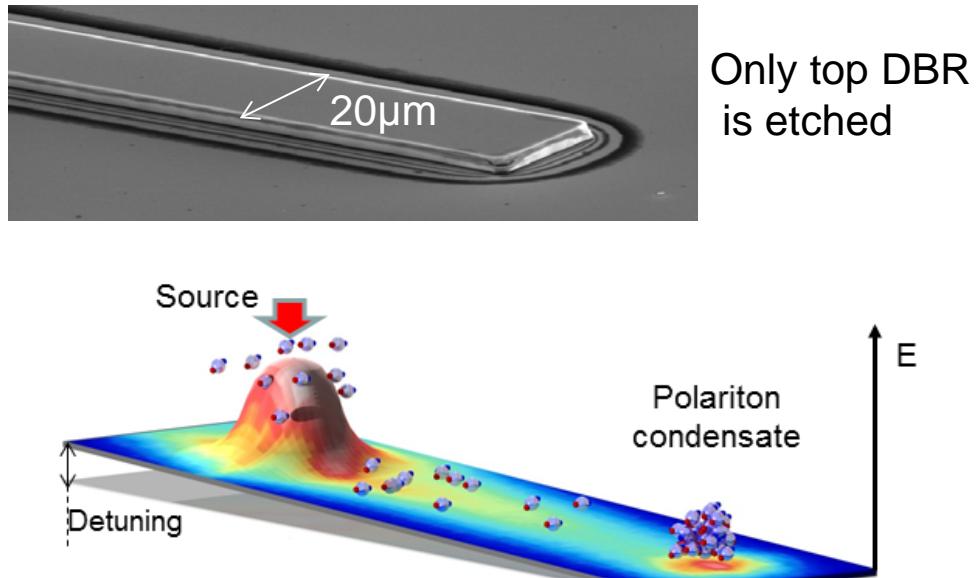
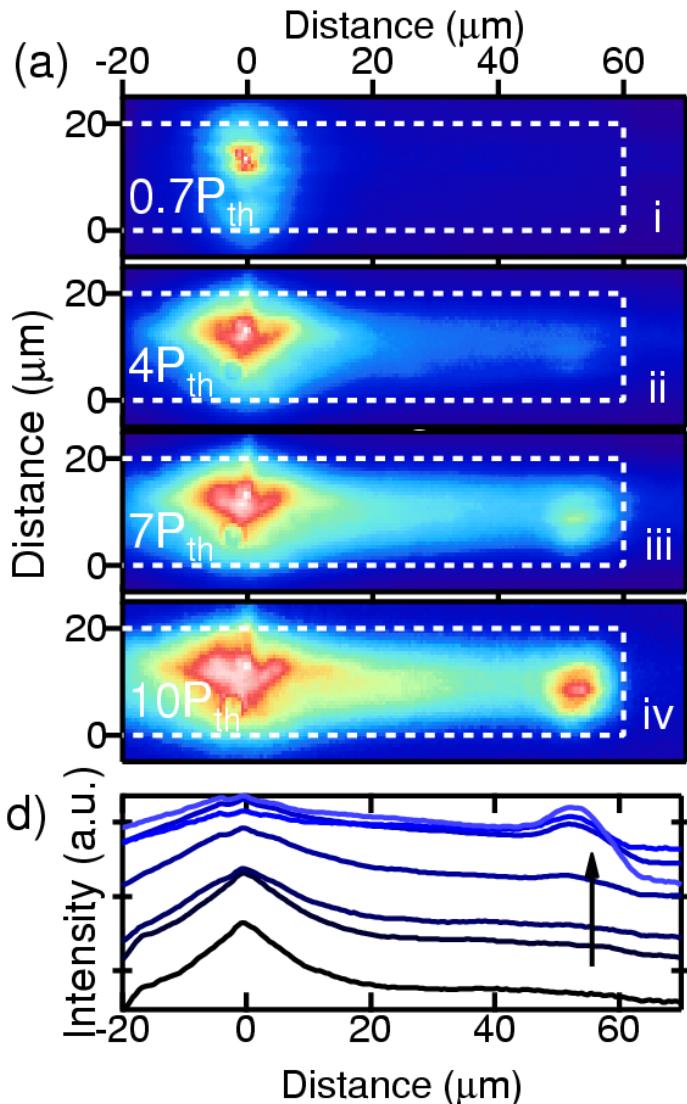


Wertz , Nature Phys **6**, 860 (2010)



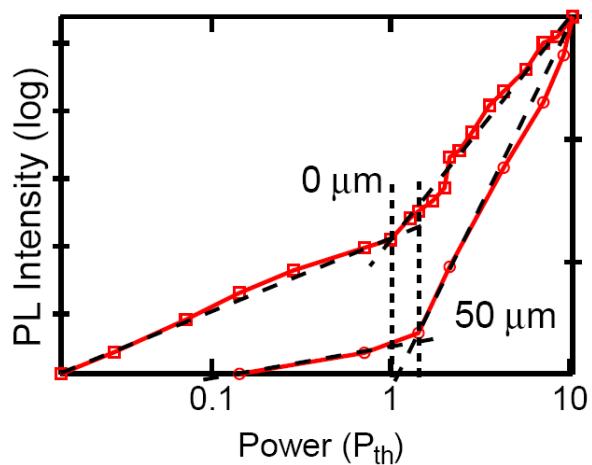
Gao, Phys. Rev. B **85**, 235102 (2012)

Generating Polariton Condensate Flow

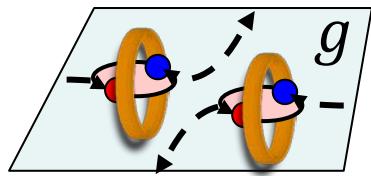


- Polariton condensate forming at the ridge end

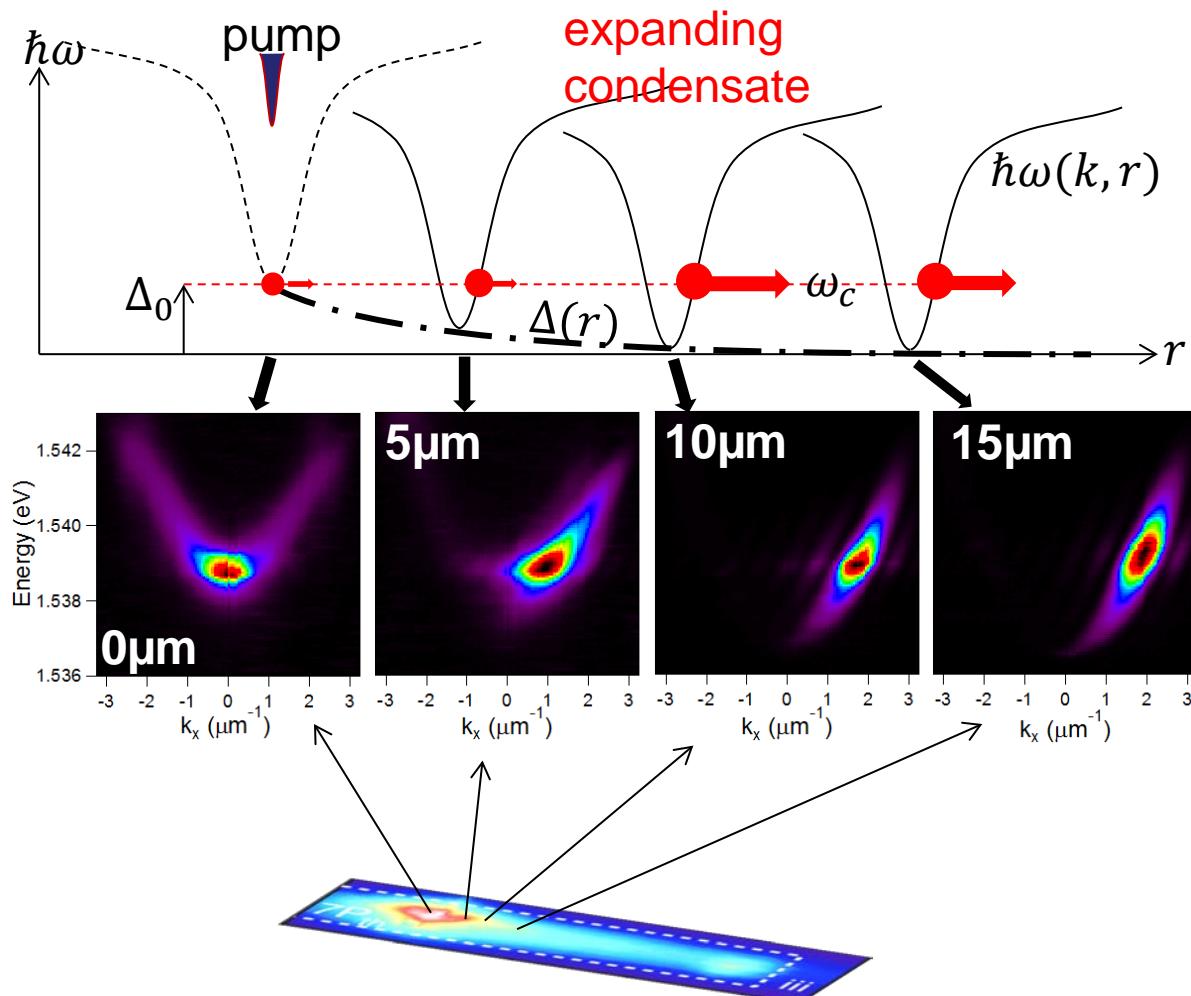
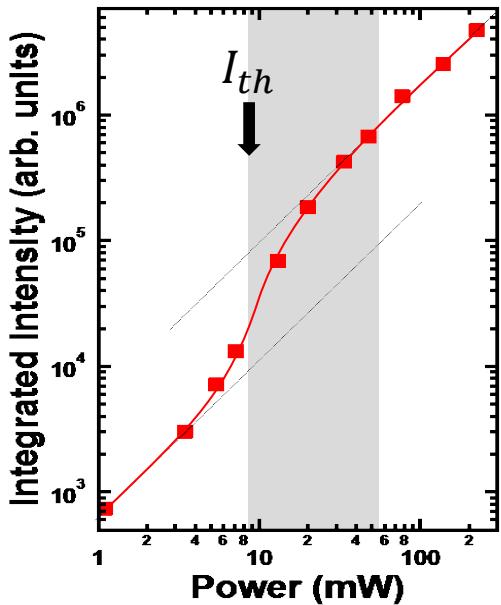
- Local pump induced blueshift and lateral confinement forces polariton flow along the ridge



Ballistic Condensate Ejection

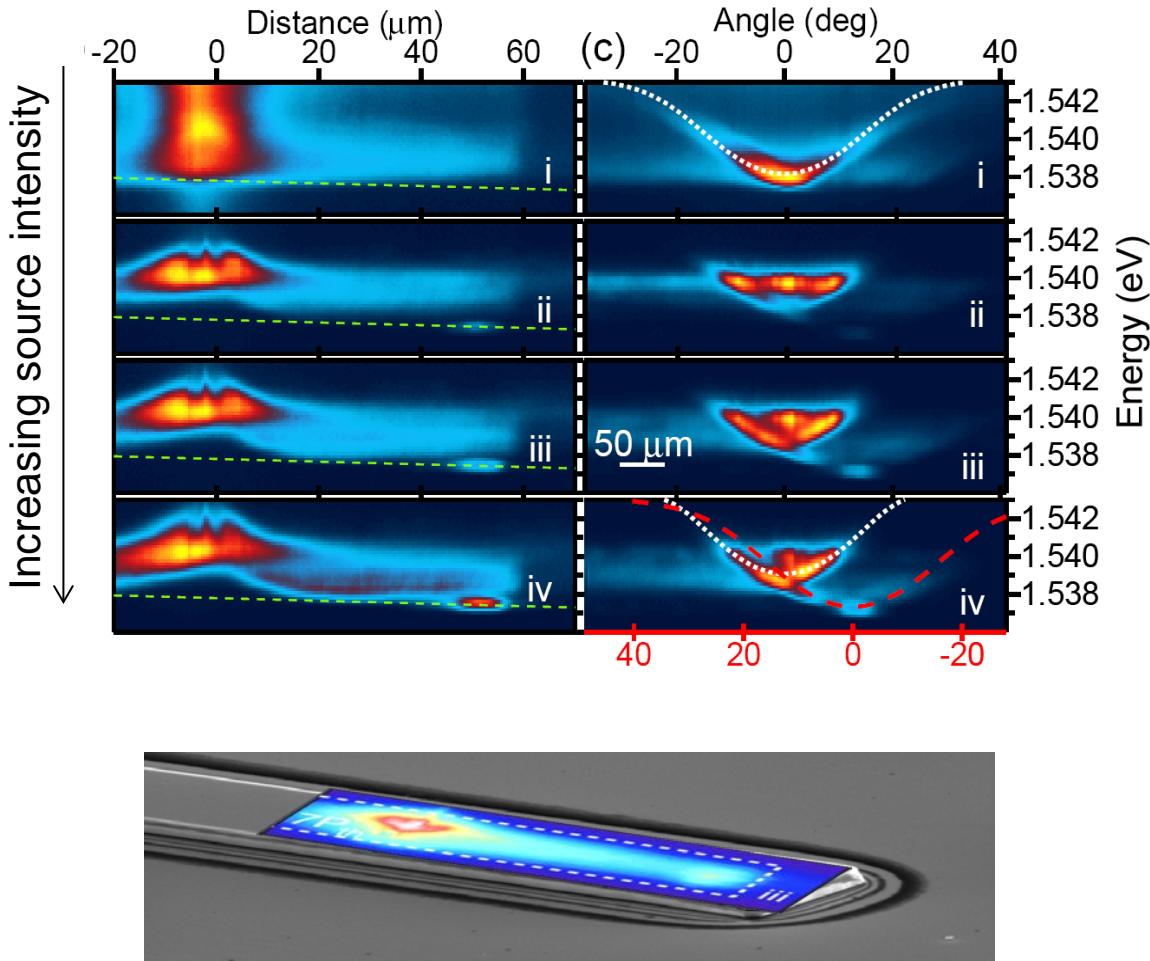


- blue shift at pump
 $V_{max} = g|\psi|^2$
- polaritons expand along the ridge

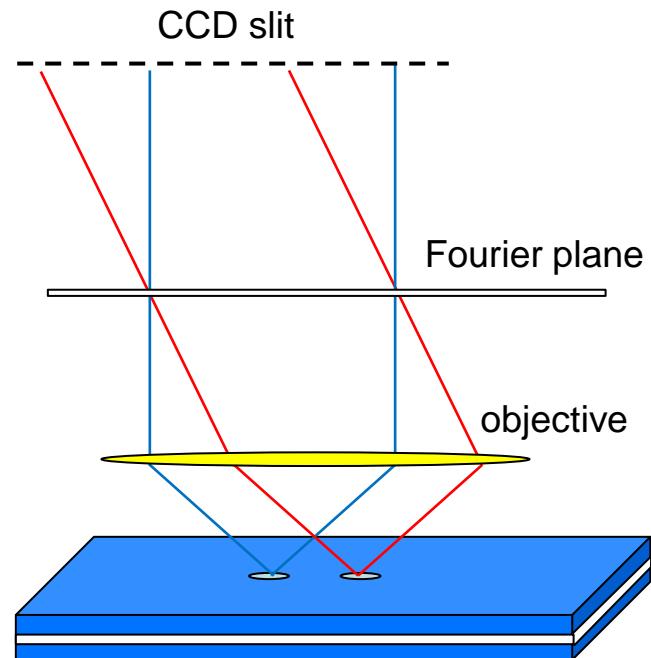


G. Christmann *et al.*, Phys. Rev. B 85, 235303 (2012)

Polariton Condensate Built-up



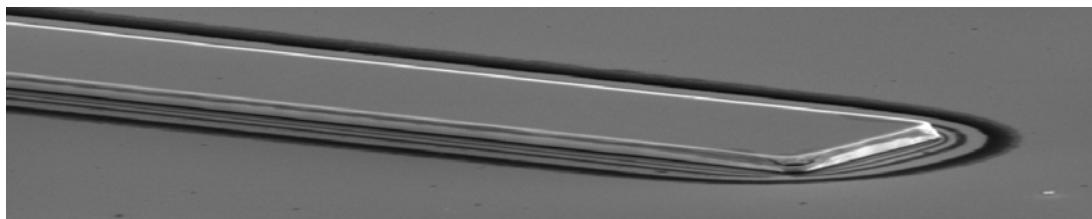
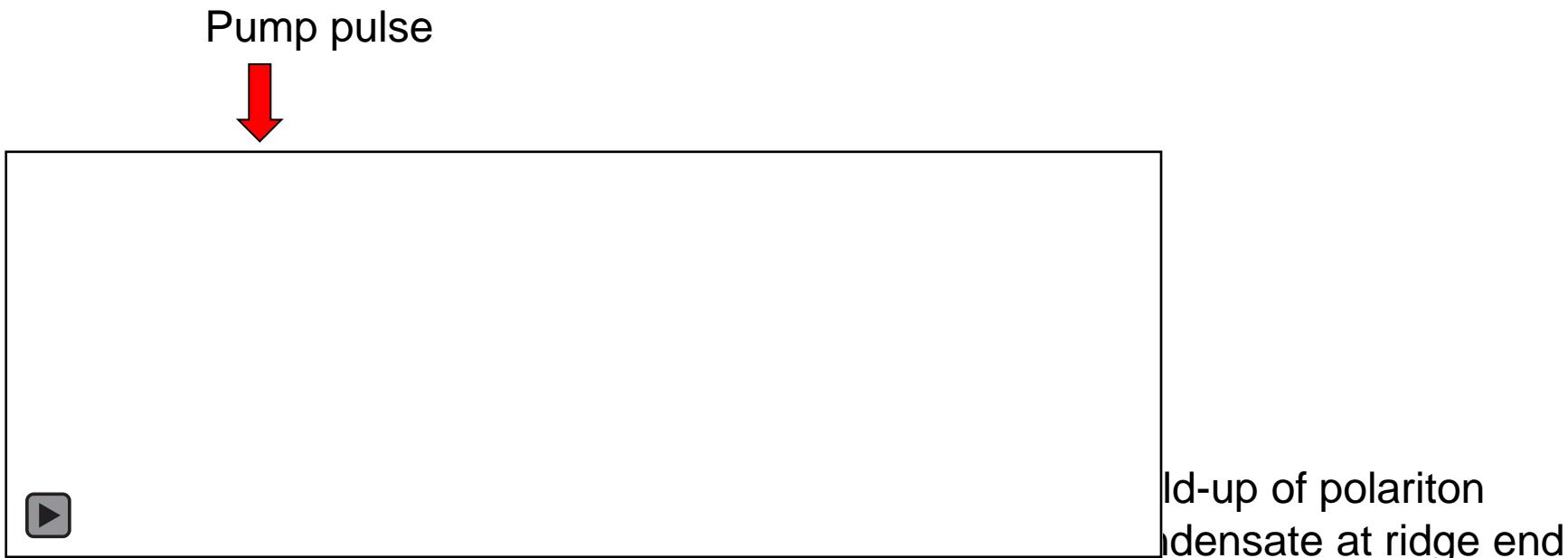
- spatially separated and angle resolved emission



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



Time Resolved Polariton Condensate Dynamics



Luis Vina

Anton et al., Appl. Phys. Lett. (accepted 2012)



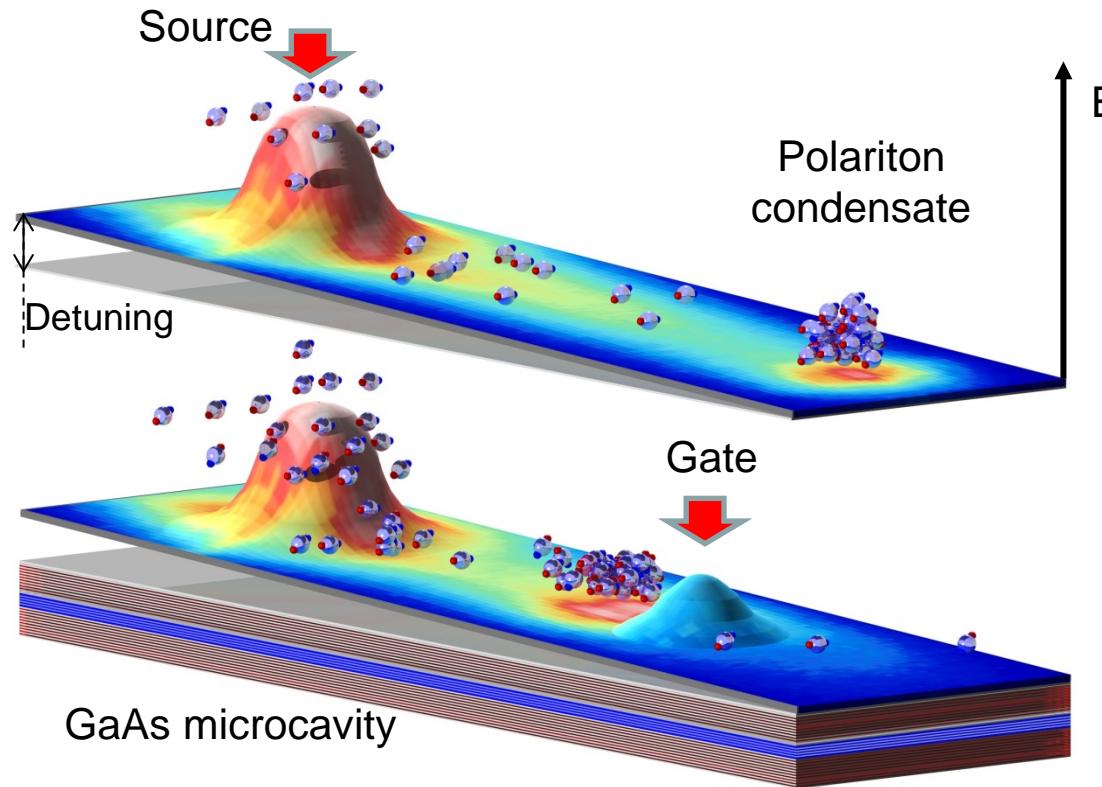
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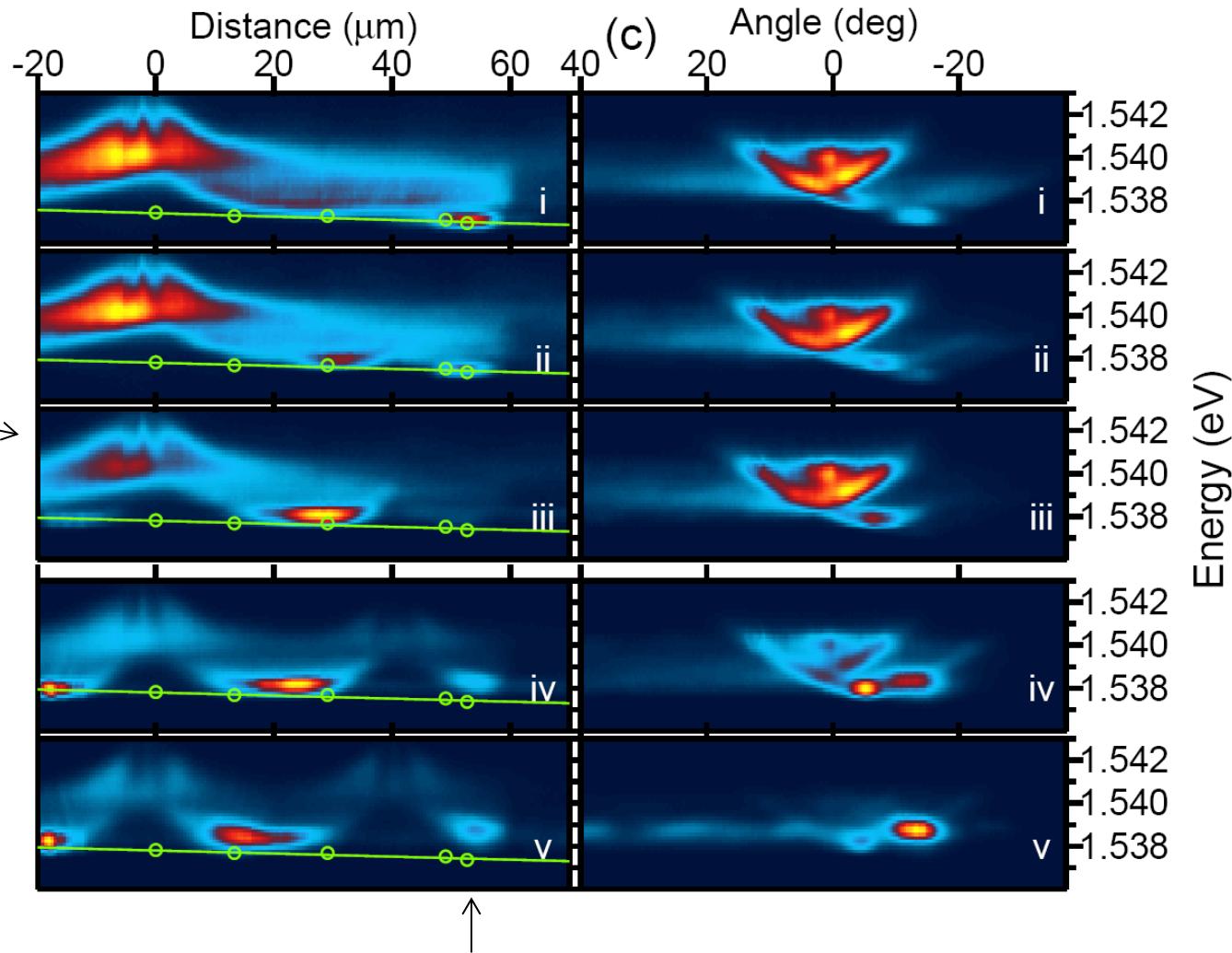
Polariton Condensate Transistor Switch



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



Gating Polariton Condensate Flow

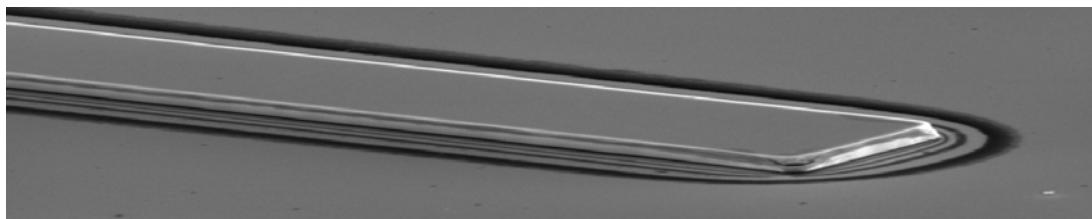
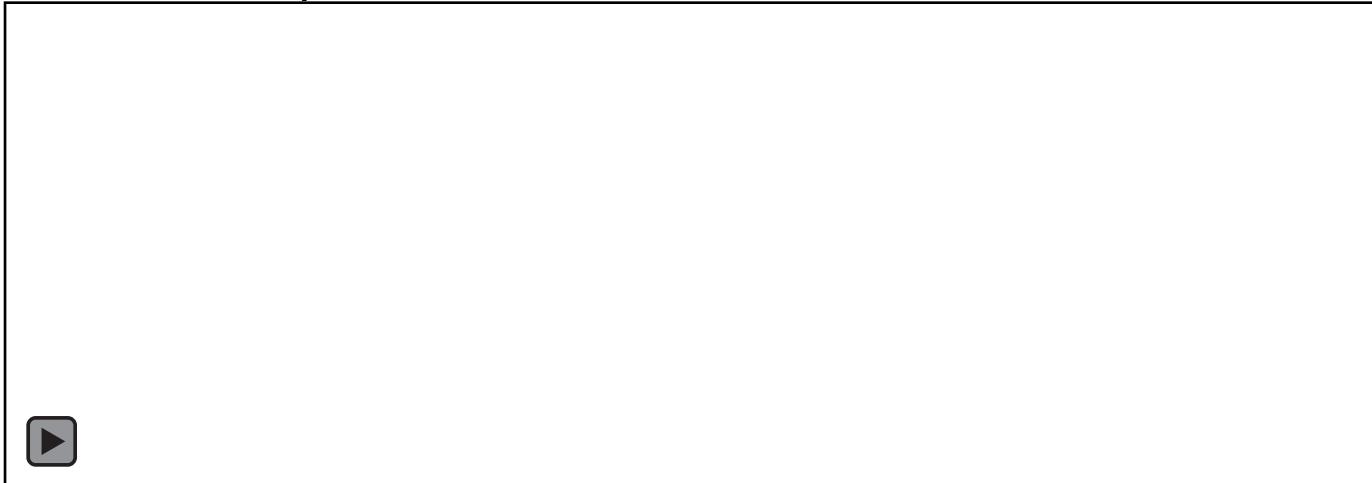


Time Resolved Gating Dynamics

Pump pulse



90% gating of the polariton condensate flow



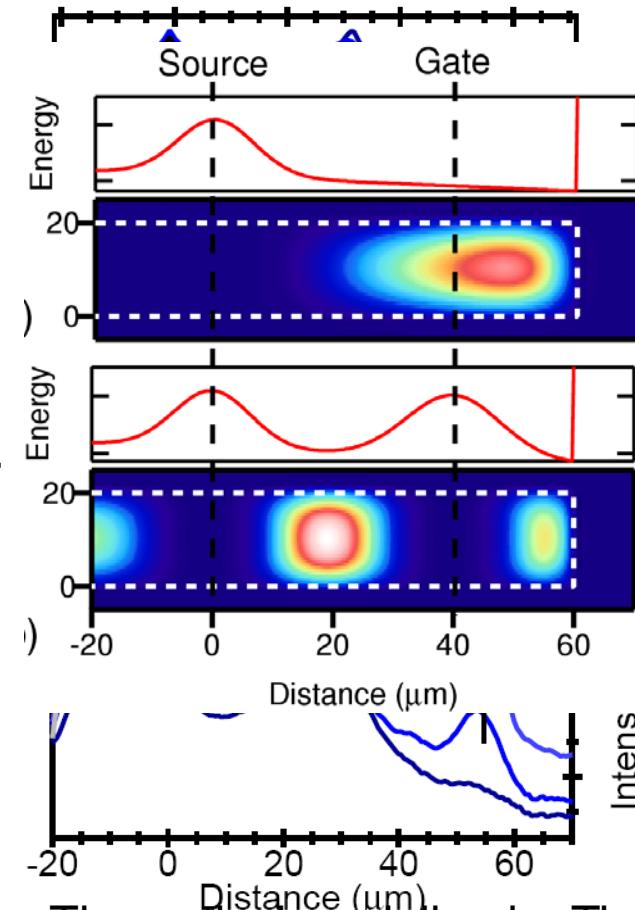
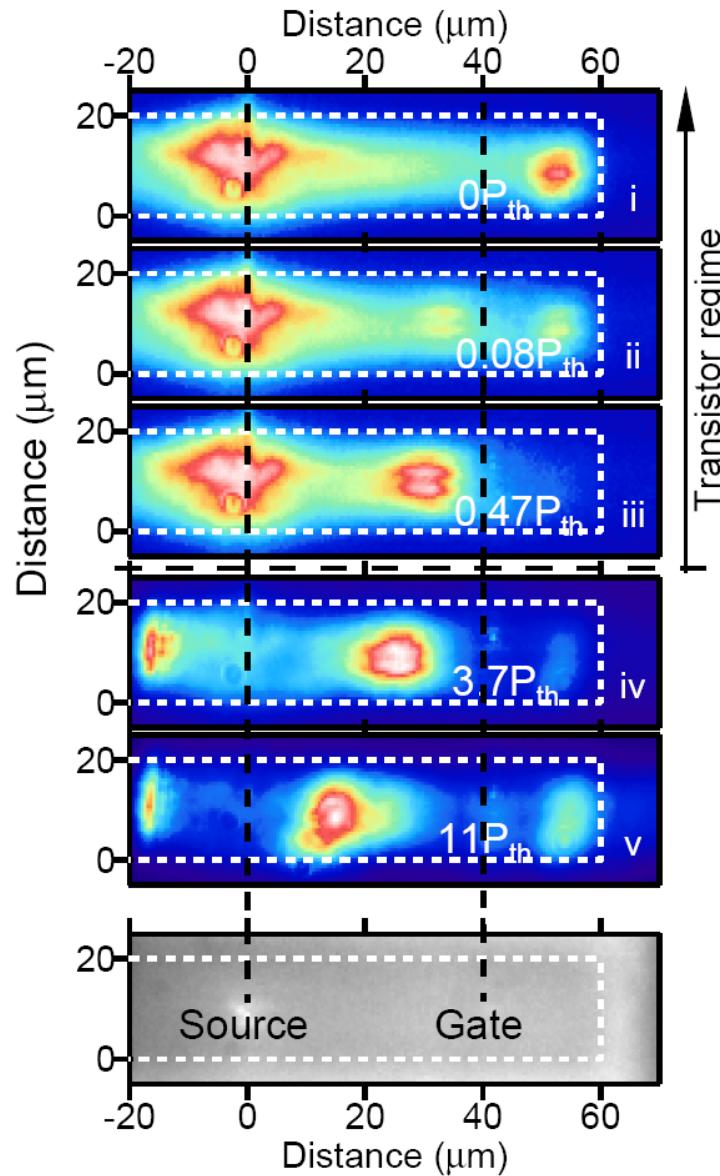
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Gating Polariton Condensate Flow

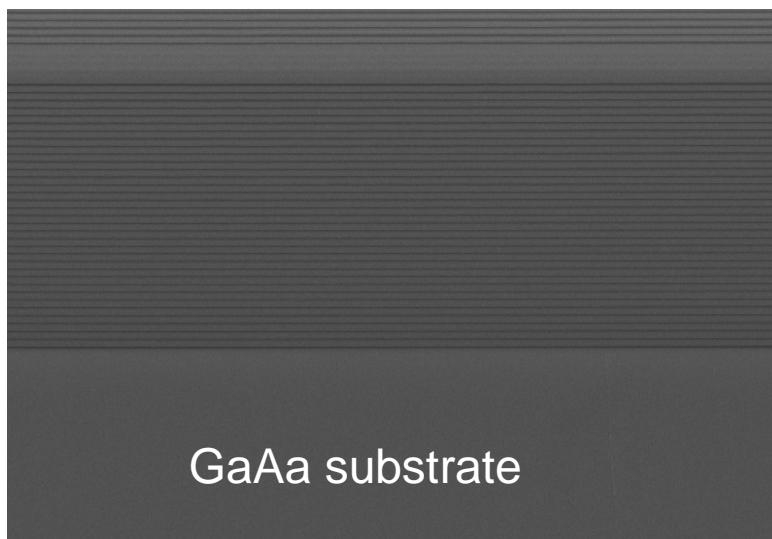


Theoretical modeling by Tim Liew

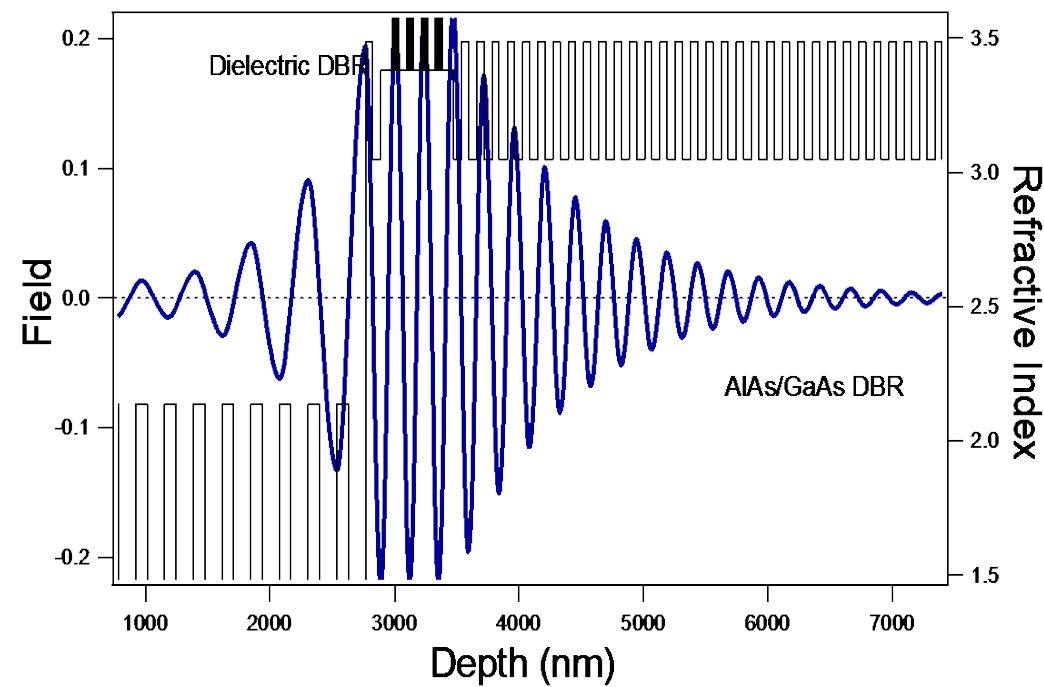
- gating efficiency up to 90% is demonstrated

High Q hybrid GaAs/dielectric microcavity

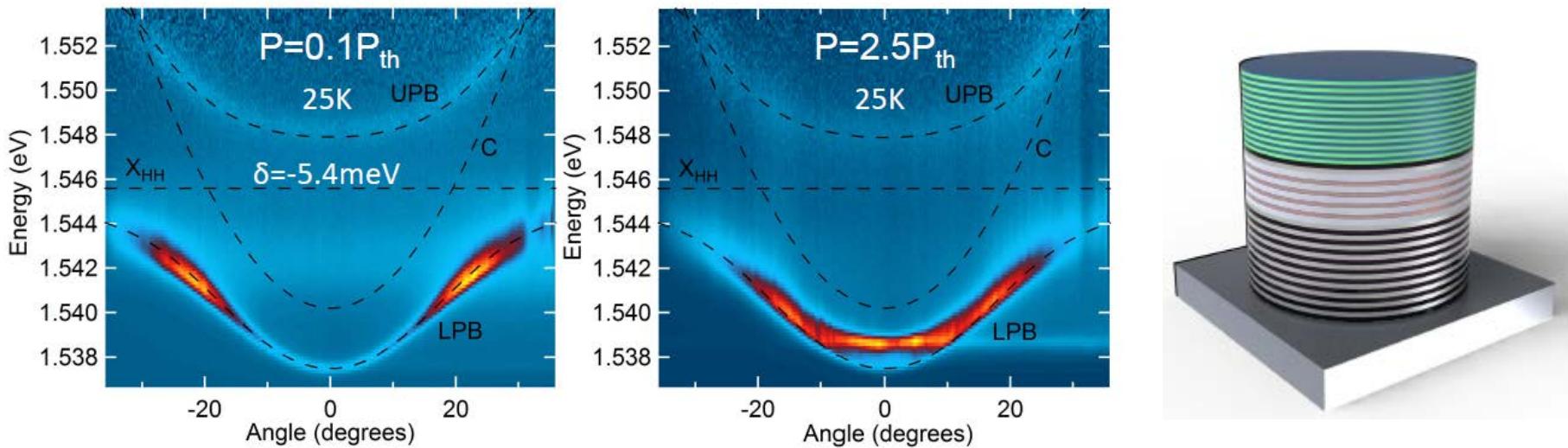
- Dielectric DBR mirrors in hybrid microcavity
- Allows precise control of electrical contact close to the cavity



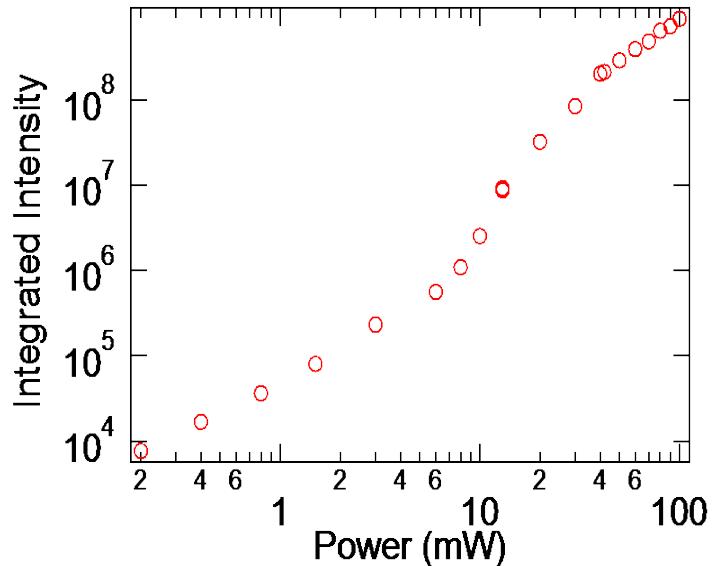
Half microcavity structure



Polariton Laing in Hybrid Microcavities



- Observation of the formation of a polariton condensate
- Contacts can be easily deposited close to the cavity region

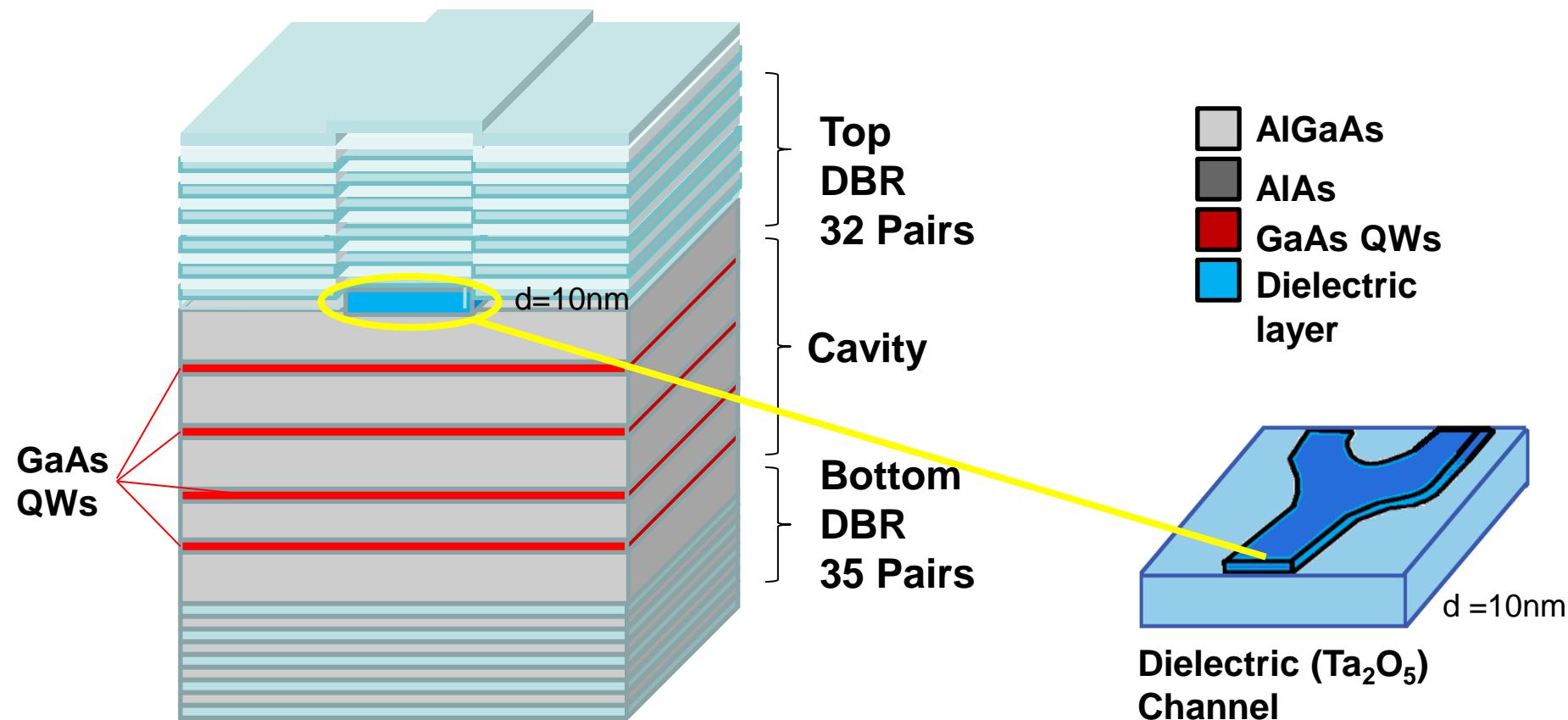


Electric field tuning of a polariton condensate



Writing Polariton Circuits with dielectric Channels

- Dielectric DBR mirrors in hybrid microcavity
- polariton confinement in dielectric channels
- Allows precise control of electrical contact close to the cavity



Polariton Confinement in the channel: SiO_2

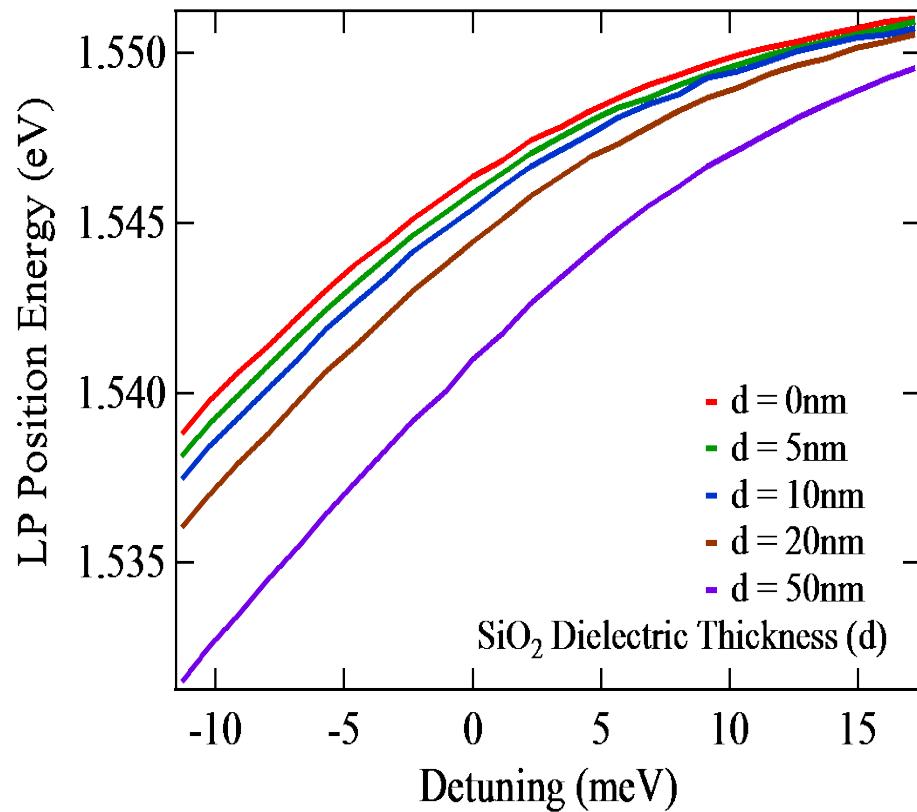


Figure: Lower Polariton Position Vs Detuning on varying dielectric (SiO_2) thickness

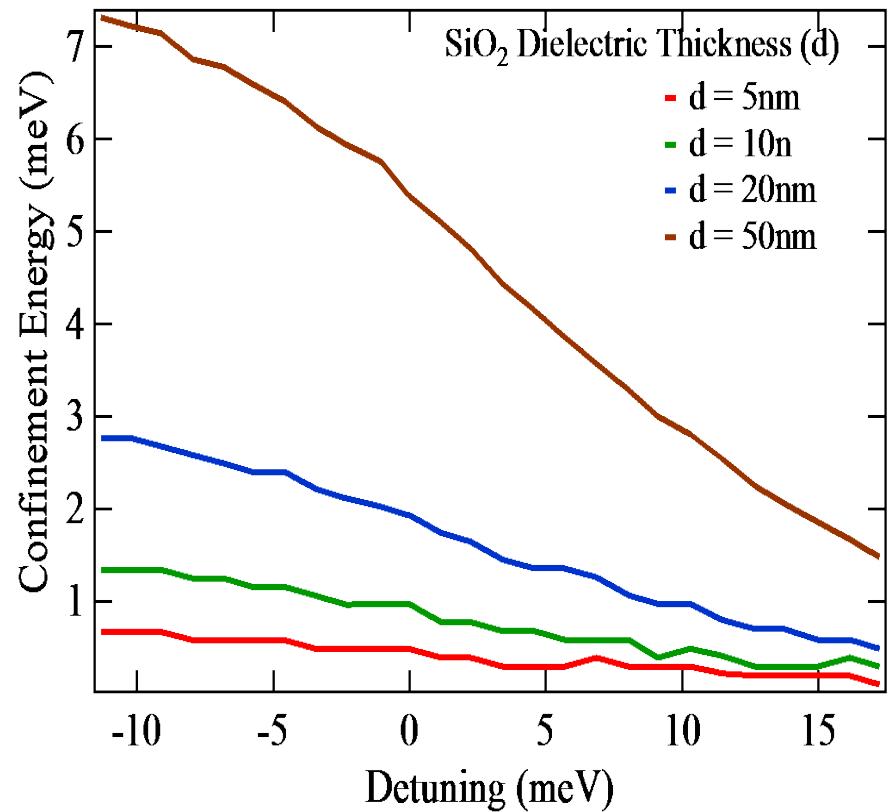


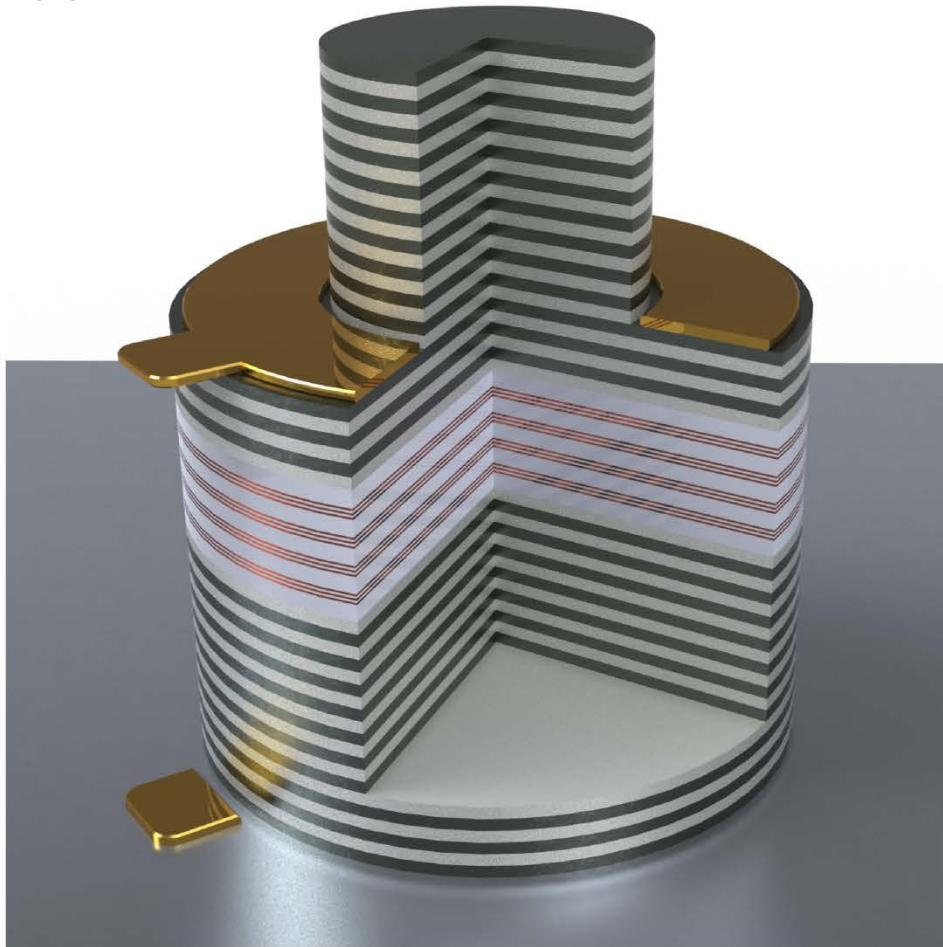
Figure: Confinement Energy Vs Detuning on varying dielectric (SiO_2) thickness

Electrical and optical control of polariton condensates

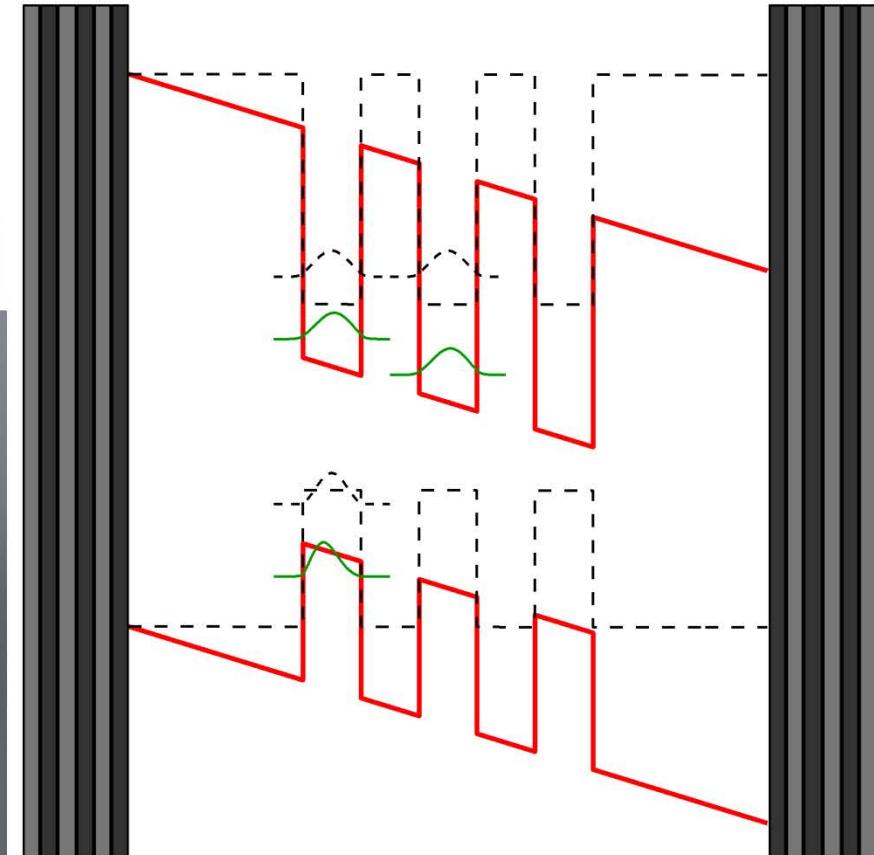
Is electric gating of transistor feasible ?

Electrical control of a polariton condensate

(a)



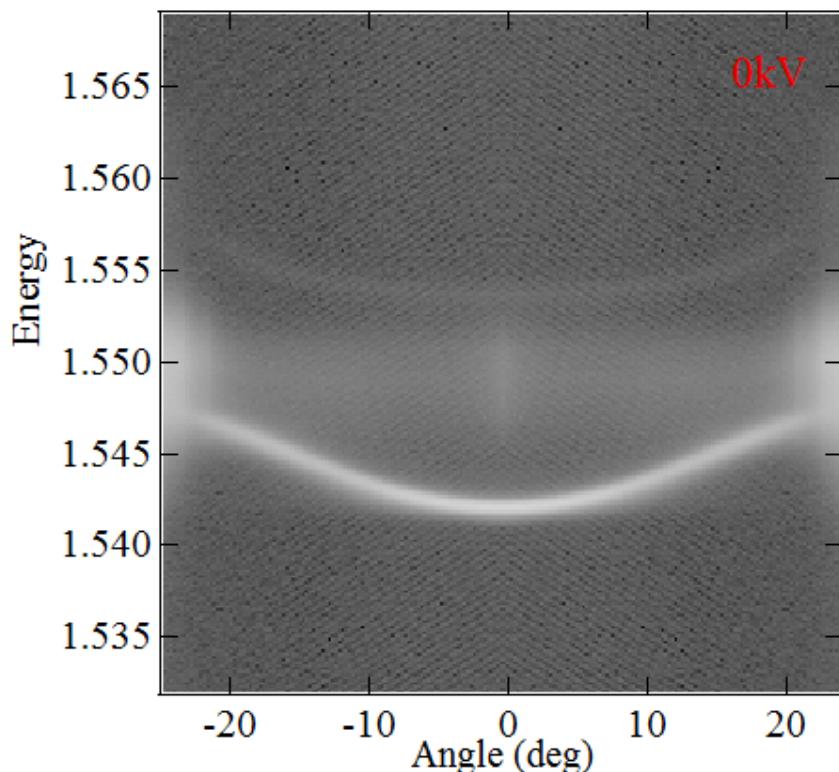
(b)



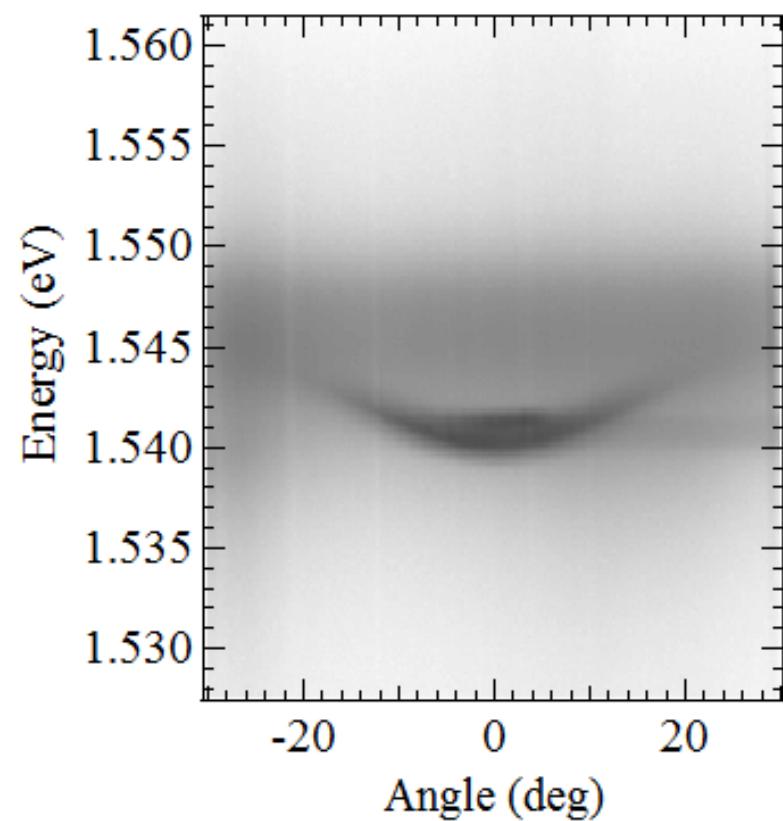
- AlGaAs/GaAs quantum wells- 10nm well , 10nm barrier

Linear and non-linear regimes

Below Threshold

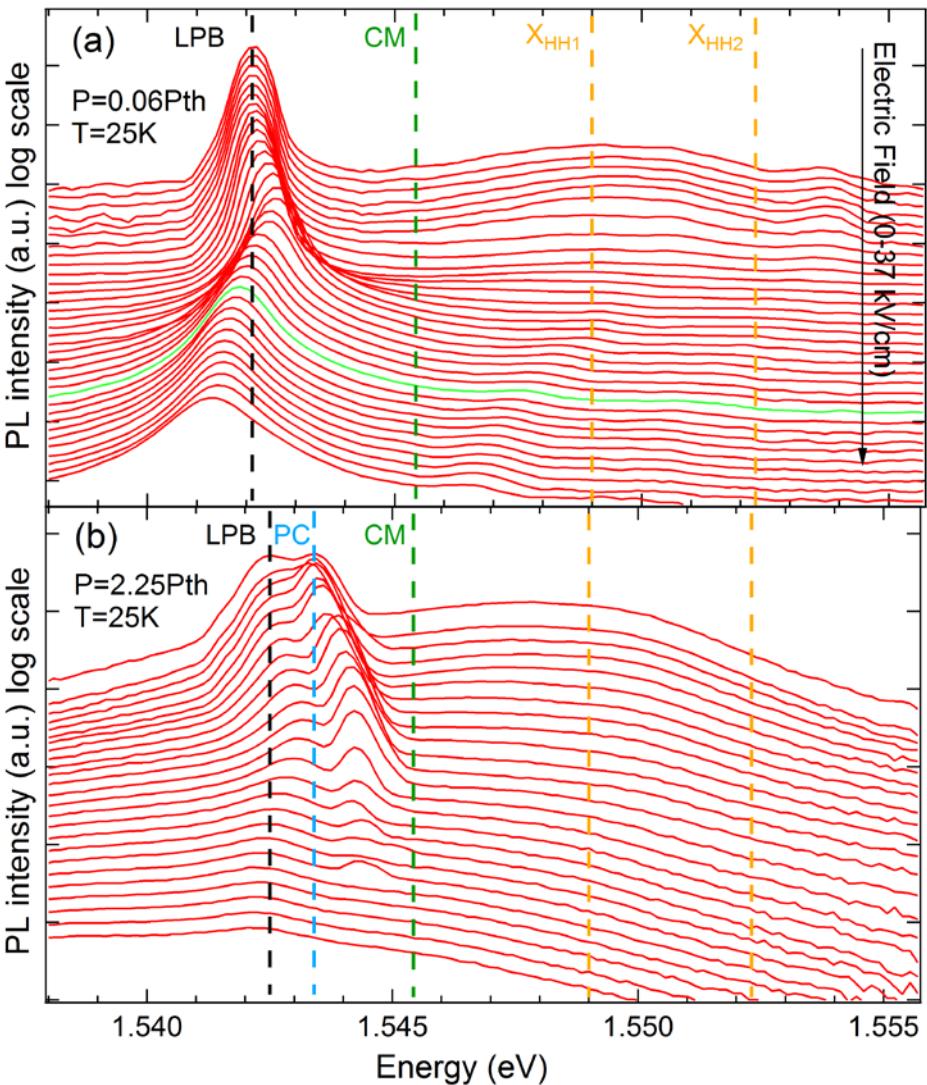


Above Threshold

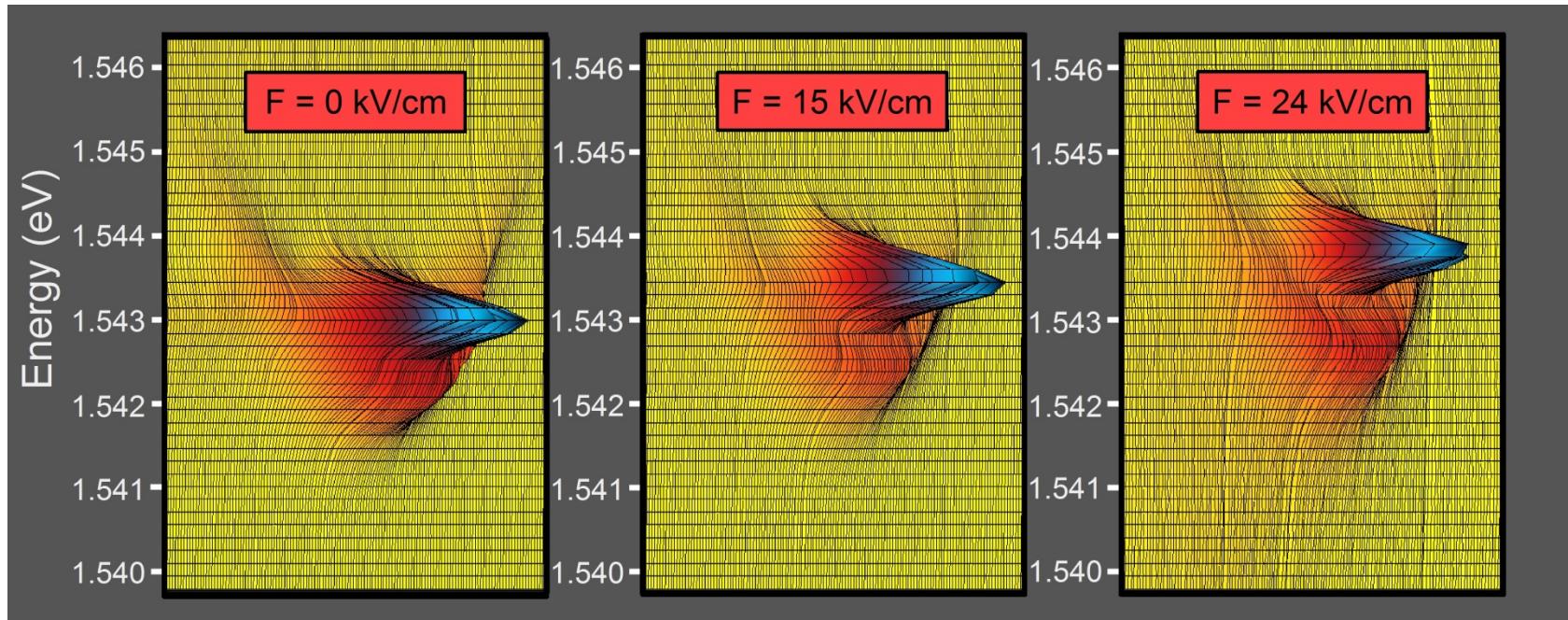


Linear and non-linear regimes

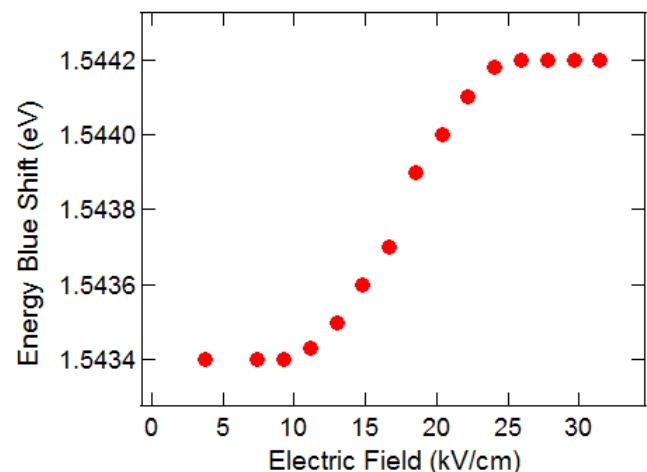
- Linear regime
 - Small fields-blueshift
 - Large fields-redshift
- Non-linear regime
 - Small fields- blueshift
 - Large fields- Emission quenching
- Interpretation
 - Reduction in oscillator strength
 - Quantum confined Stark Effect
 - Contribution of indirect exciton



Non-linear regime

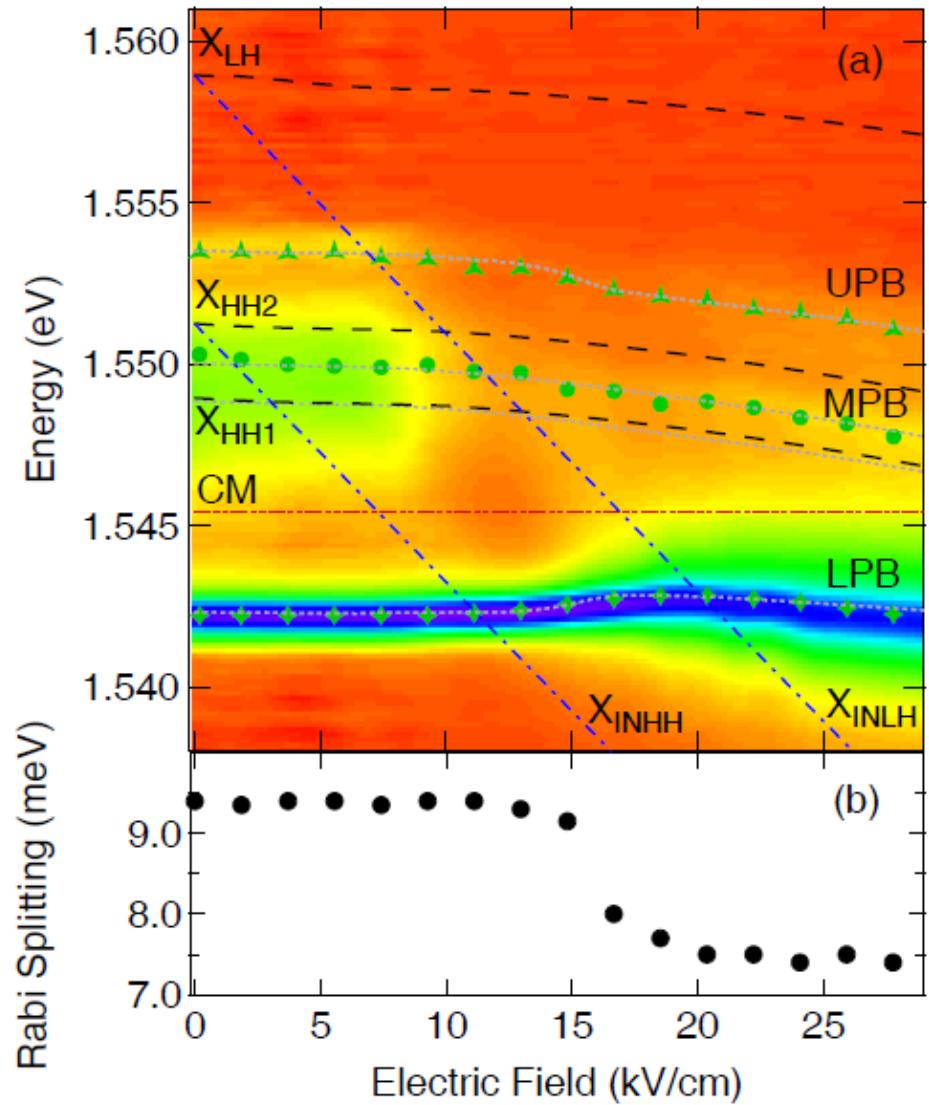
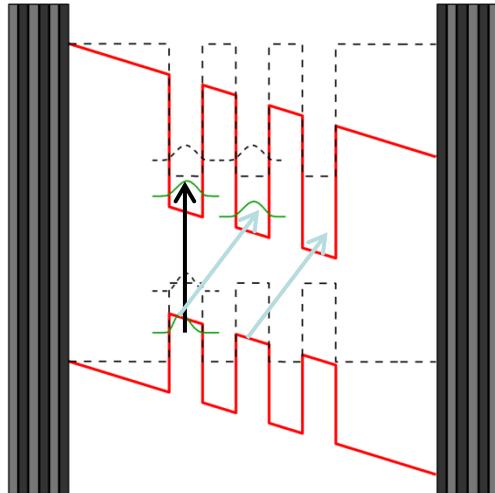


- Blueshift 0.8meV
- Larger Rabi splitting should allow larger tuning

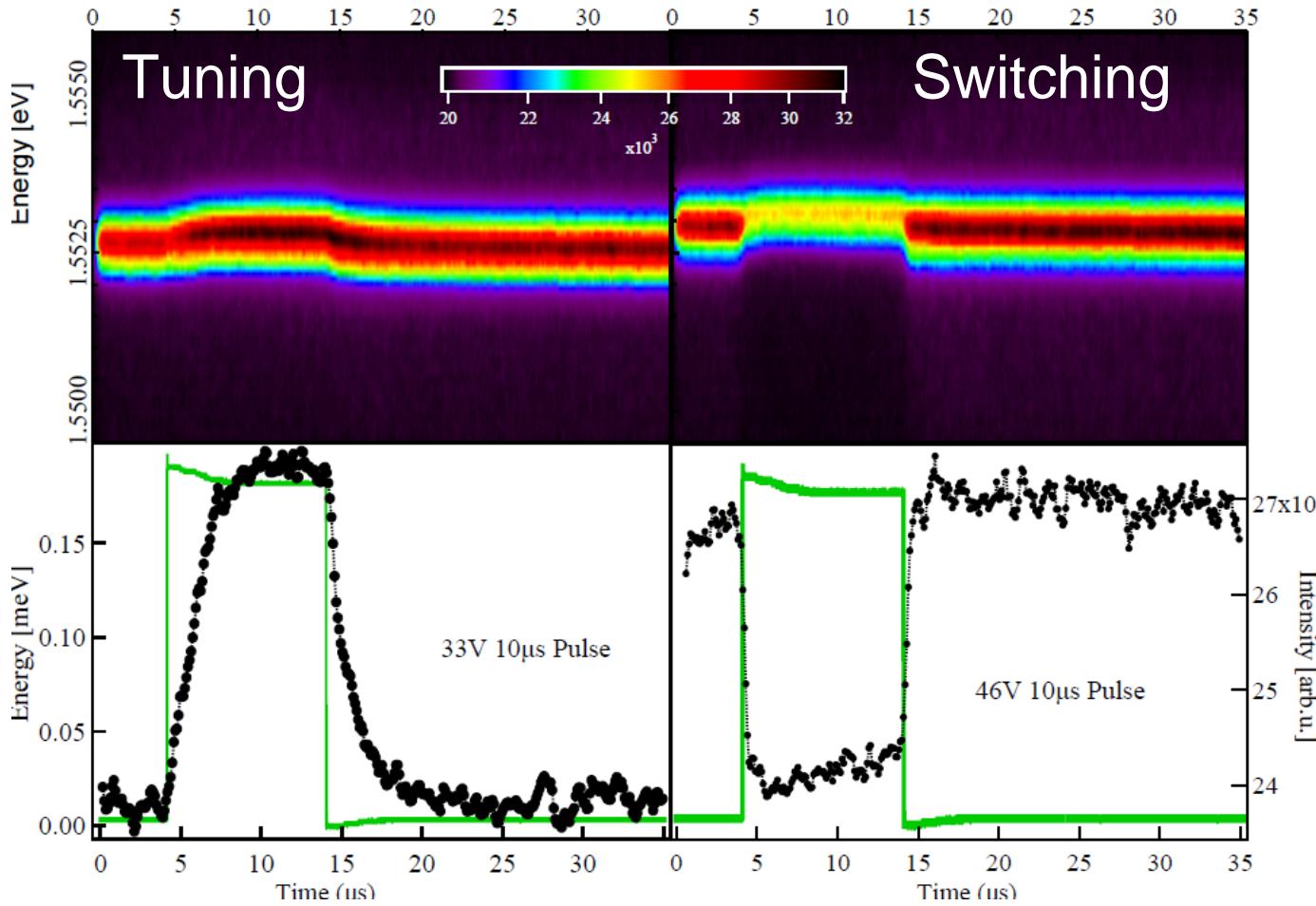


Linear Regime

- Origin of blueshift under investigation
 - Indirect exciton



Dynamical Response

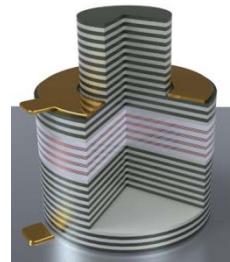
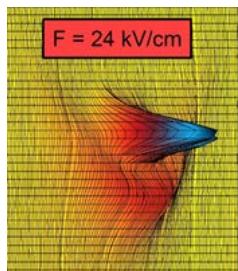
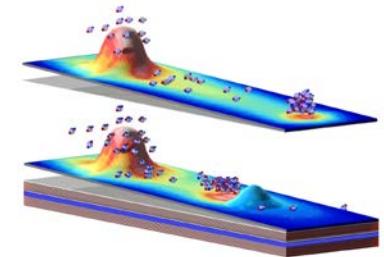
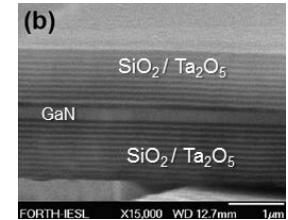


In collaboration
with Southampton
A. Askitopoulos
A. V. Kavokin
P. G. Lagoudakis

- Different modulation regimes are possible
- Voltage dependent response may indicate screening effects

Summary

- Low threshold polariton lasing at 25K and RT in GaN
- Electrical and optical manipulation of polariton condensates
 - propagation of polariton condensates in waveguides
 - polariton condensate transistor
- Demonstration of the electric field tuning of the energy of a polariton condensate.



Thank you

