



SMR 1760 - 5

**COLLEGE ON
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***Acoustically induced superlattices: from photons
and electrons to excitons and polaritons***

Presented by:

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Acoustically induced superlattices: from photons and electrons to excitons and polaritons



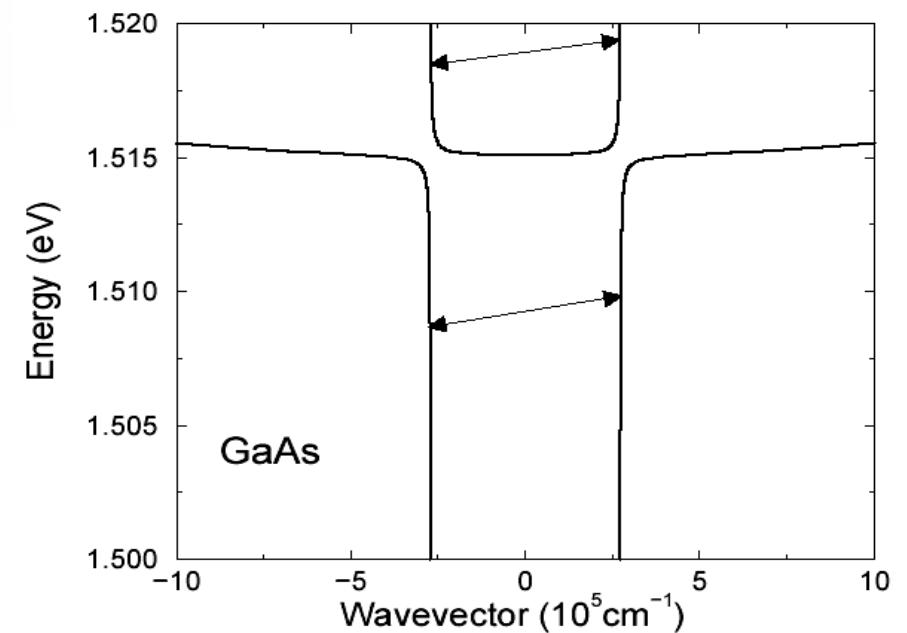
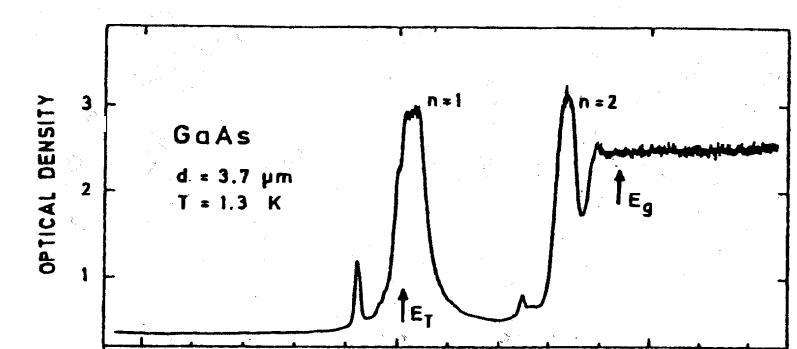
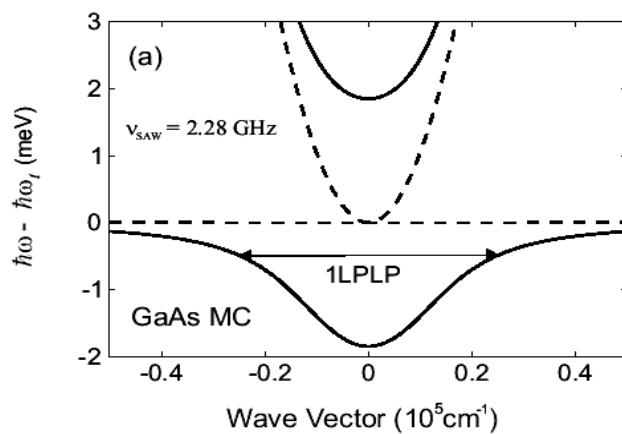
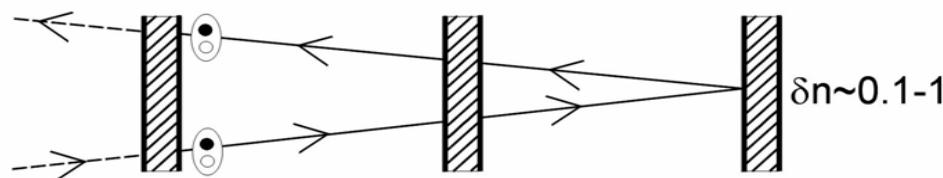
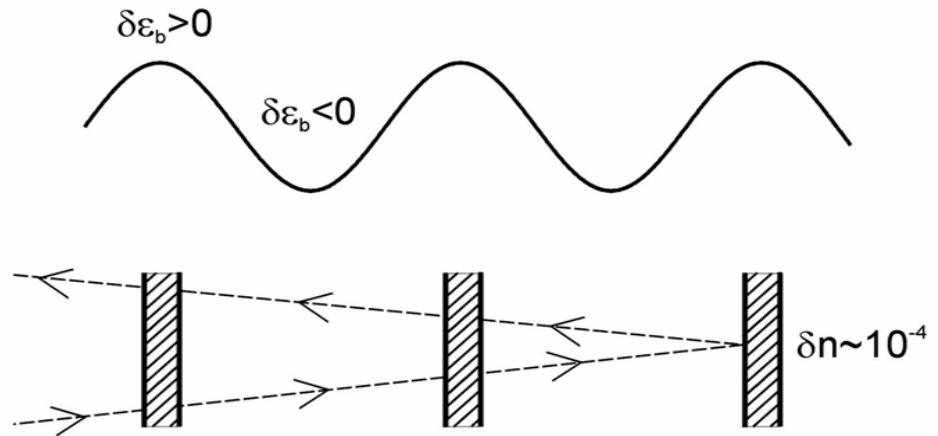
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Outline

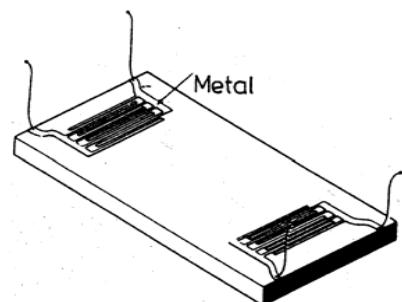
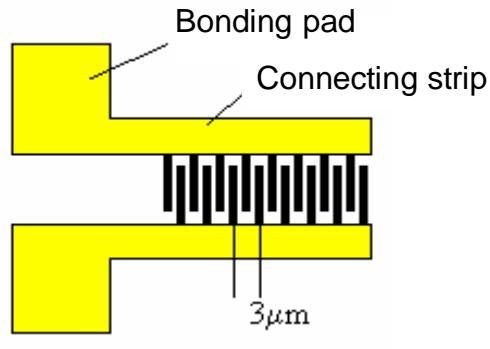
- Resonant acousto-optics: concept and general ideas
- Surface acoustic waves (SAWs)
- Acoustically induced Bragg scattering of photons and electrons
- Optics of SAW-driven bulk and microcavity polaritons
- Acoustic versus optical pumping
- Resonant acousto-optics for device applications
- Conclusions

Resonant acousto-optics of photon-dressed excitons



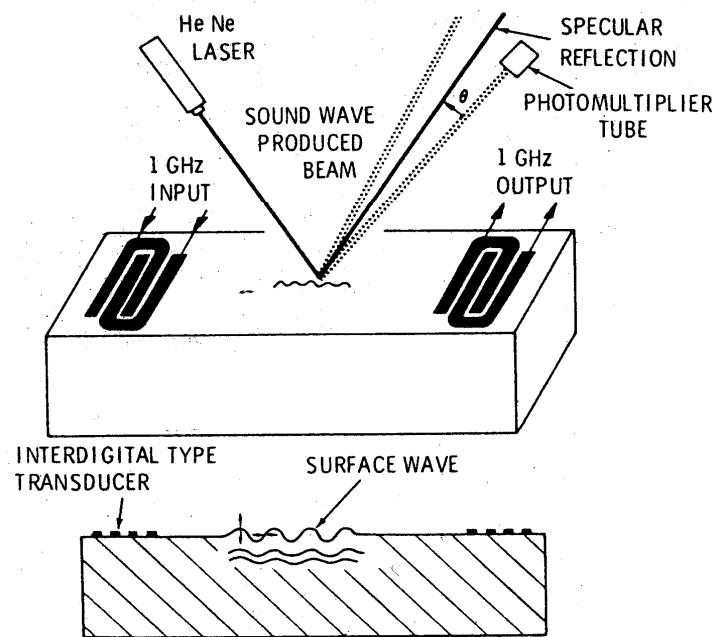
Surface acoustic waves and ITD technique

Interdigital transducer



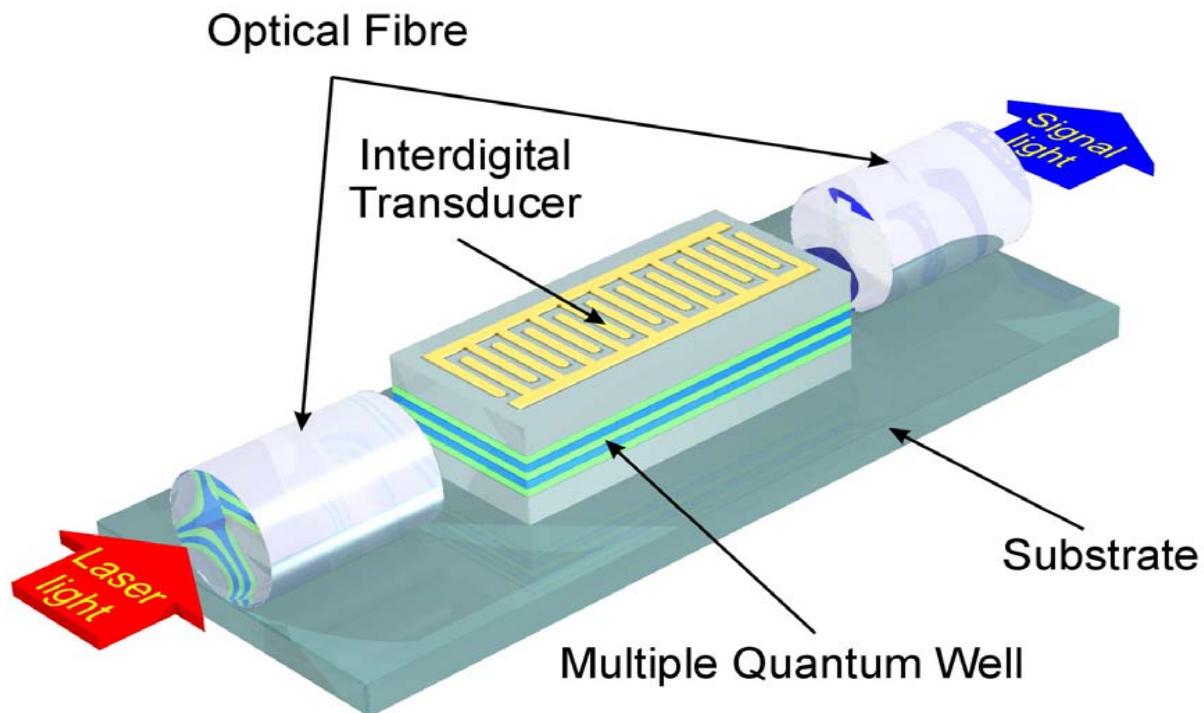
A Rayleigh SAW propagating between the transducers

GaAs : $\nu_{\text{SAW}} = 0.1 - 3.0 \text{ GHz}$ (routine use) ;
 $\nu_{\text{SAW}} = 2 - 9 \text{ GHz}$ (quantum Hall effect) ;
AlN : $\nu_{\text{SAW}} \simeq 32 \text{ GHz}$.



SAW-mediated acousto-optic spectroscopy

Schematic of a SAW-driven semiconductor microcavity for optical modulation and switching



Non-resonant acousto-optical interaction

- L. Brillouin, Ann. Phys. (Paris) **17**, 88 (1922):

$$\left[\varepsilon(\mathbf{r}, t) \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \Delta \right] \mathbf{E}(\mathbf{r}, t) = 0 .$$

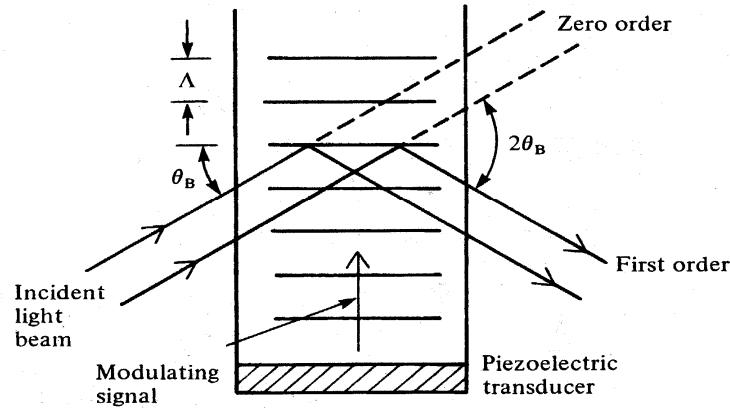
$$\rightarrow \varepsilon(\mathbf{r}, t) = \varepsilon_b + \delta\varepsilon_b \cos(\Omega_{\mathbf{k}}^{\text{ac}} t - \mathbf{k}\mathbf{r}) ;$$

$$\rightarrow \delta\varepsilon_b = 4\pi \chi_{\gamma-\text{ac}}^{(2)} I_{\text{ac}}^{1/2} ;$$

→ Strong coupling regime (nonperturbative solution):
the solution is given in terms of the Mathieu function.

- Typical acousto-optic materials: LiNbO₃, PbMoO₄, GaAs.
- L. Brillouin (1938): "... these Mathieu functions are terribly inconvenient."

Diffraction of the light field by an acoustic grating



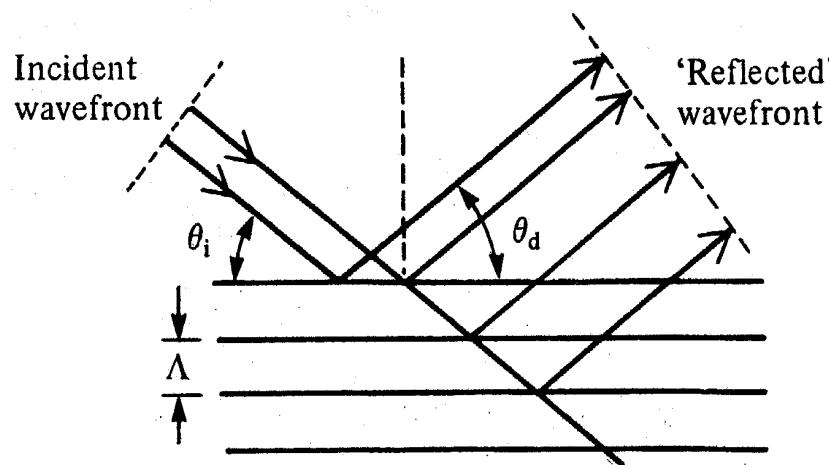
- Raman-Nath regime (transmission-type) :

$$n\lambda_\gamma = \Lambda \sin \Theta_n , \quad \text{where } n = 0, \pm 1, \pm 2, \dots \text{ and } \Lambda \equiv \lambda_{ac} .$$

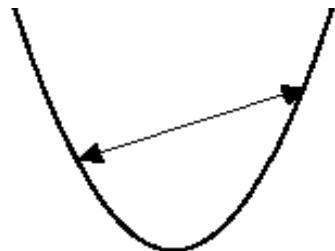
- Bragg regime (transmission-type) :

$$\sin \Theta_i = \sin \Theta_d = \frac{n\lambda_\gamma}{2\Lambda} , \quad \text{where } n = 0, \pm 1, \pm 2, \dots$$

- The Bragg angle: $\sin \Theta_B = (1/2)(\lambda_\gamma/\Lambda)$;
- A nearly normal interaction geometry ($\mathbf{k}_\gamma \perp \mathbf{k}$): $\sin \Theta_B \ll 1$;
- $\mathbf{k}_\gamma \pm n\mathbf{k} = \mathbf{k}_\gamma^{(\pm n)}$.



Effect of ultrasonics on the electron spectrum



- L. V. Keldysh, Sov. Phys. Solid State **4**, 1658 (1962).

$$i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi + [V \cos \omega(t - x/v_s)] \psi.$$

- The solution is given in terms of the Mathieu function.

Hamiltonian approach

- Classical acoustic field $\rightarrow c_{\mathbf{k}} = \sqrt{N_0^{\text{ph}} V} \exp(-i\Omega_{\mathbf{k}}^{\text{ph}} t)$:

$$H^{\text{eff}} = \sum_{\mathbf{p}} [\hbar\omega_{\mathbf{p}}^e a_{\mathbf{p}}^\dagger a_{\mathbf{p}} - im_{\mathbf{k}}(a_{\mathbf{p}}^\dagger a_{\mathbf{p}-\mathbf{k}} e^{-i\Omega_{\mathbf{k}}^{\text{ph}} t} - a_{\mathbf{p}-\mathbf{k}}^\dagger a_{\mathbf{p}} e^{i\Omega_{\mathbf{k}}^{\text{ph}} t})] ,$$

$$m_{\mathbf{k}} = m_{\mathbf{k}}(I_{\text{ac}}) = D_e \left(\frac{\hbar k N_0^{\text{ph}}}{2\rho v_s} \right)^{1/2} \quad \text{and} \quad N_0^{\text{ph}} = \frac{I_{\text{ac}}}{\hbar \Omega_{\mathbf{k}}^{\text{ph}}} \frac{1}{v_s} .$$

- Acoustically coupled “two-level” systems $\{\mathbf{p}, \mathbf{p} - \mathbf{k}\}$.

Truncated scheme for the quasi-energy spectrum

- Canonical transformation S :

$$S = \exp \left[it \sum_{\mathbf{p}} \Omega_{\mathbf{k}}^{\text{ph}} \left(\frac{\mathbf{kp}}{k^2} \right) \right], \quad a_{\mathbf{p}} = \tilde{a}_{\mathbf{p}} e^{-i(\mathbf{v}_{\mathbf{s}\mathbf{p}})t}.$$

- Time-independent Hamiltonian:

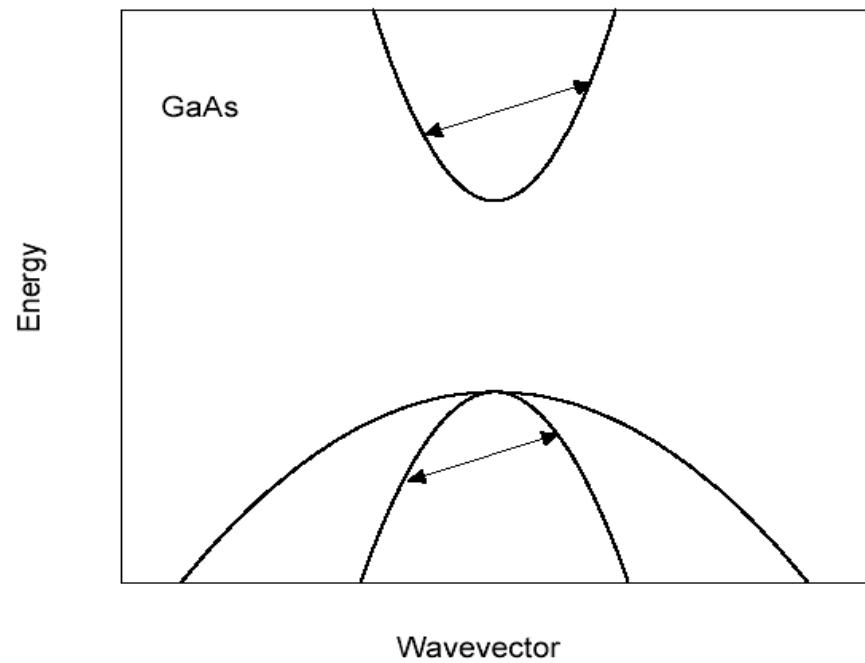
$$\tilde{H}^{\text{eff}} = \sum_{\mathbf{p}} [\hbar \tilde{\omega}_{\mathbf{p}}^e \tilde{a}_{\mathbf{p}}^\dagger \tilde{a}_{\mathbf{p}} - im_{\mathbf{k}} (\tilde{a}_{\mathbf{p}}^\dagger \tilde{a}_{\mathbf{p}-\mathbf{k}} - \tilde{a}_{\mathbf{p}-\mathbf{k}}^\dagger \tilde{a}_{\mathbf{p}})],$$

where $\tilde{\omega}_{\mathbf{p}}^e = \omega_{\mathbf{p}}^e - \hbar \Omega_{\mathbf{k}}^{\text{ac}} \left(\frac{\mathbf{kp}}{k^2} \right)$.

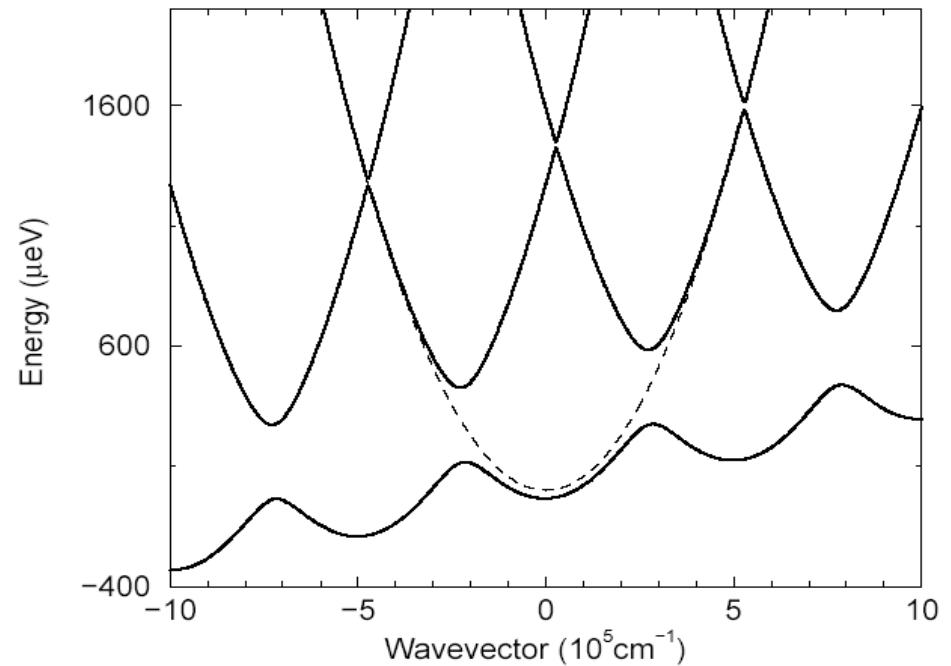
- Acoustically-induced quasi-energy spectrum:

$$(\omega - \tilde{\omega}_{\mathbf{p}}) - \frac{|m_{\mathbf{k}}|^2}{\omega - \tilde{\omega}_{\mathbf{p}+\mathbf{k}} - \frac{|m_{\mathbf{k}}|^2}{\omega - \tilde{\omega}_{\mathbf{p}+2\mathbf{k}} - \frac{|m_{\mathbf{k}}|^2}{\omega - \tilde{\omega}_{\mathbf{p}+3\mathbf{k}} - \dots}}} \\ - \frac{|m_{\mathbf{k}}|^2}{\omega - \tilde{\omega}_{\mathbf{p}-\mathbf{k}} - \frac{|m_{\mathbf{k}}|^2}{\omega - \tilde{\omega}_{\mathbf{p}-2\mathbf{k}} - \frac{|m_{\mathbf{k}}|^2}{\omega - \tilde{\omega}_{\mathbf{p}-3\mathbf{k}} - \dots}}} = 0.$$

Acoustically-pumped bulk GaAs

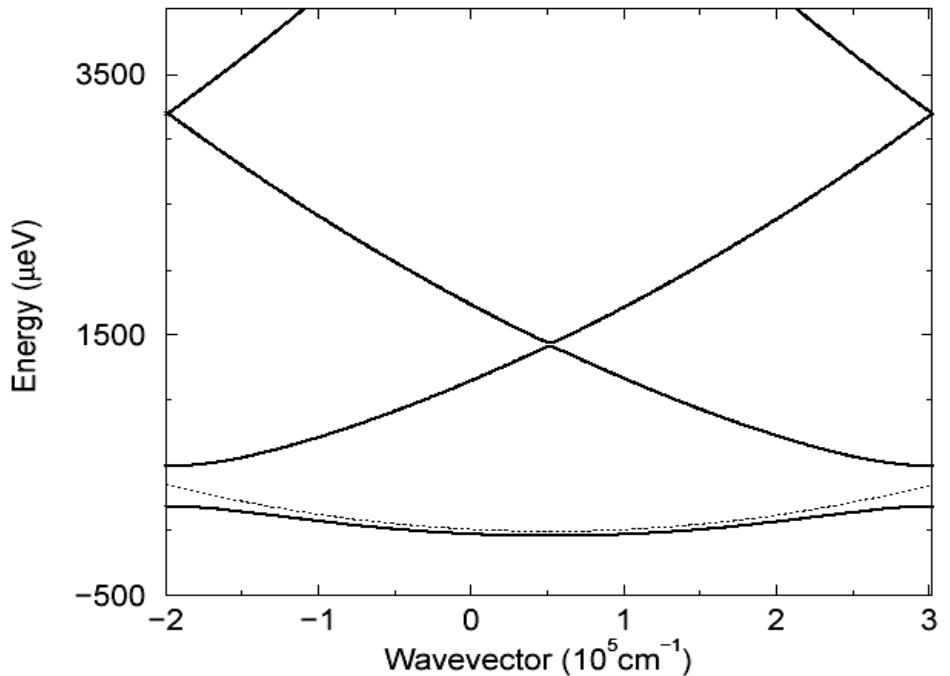
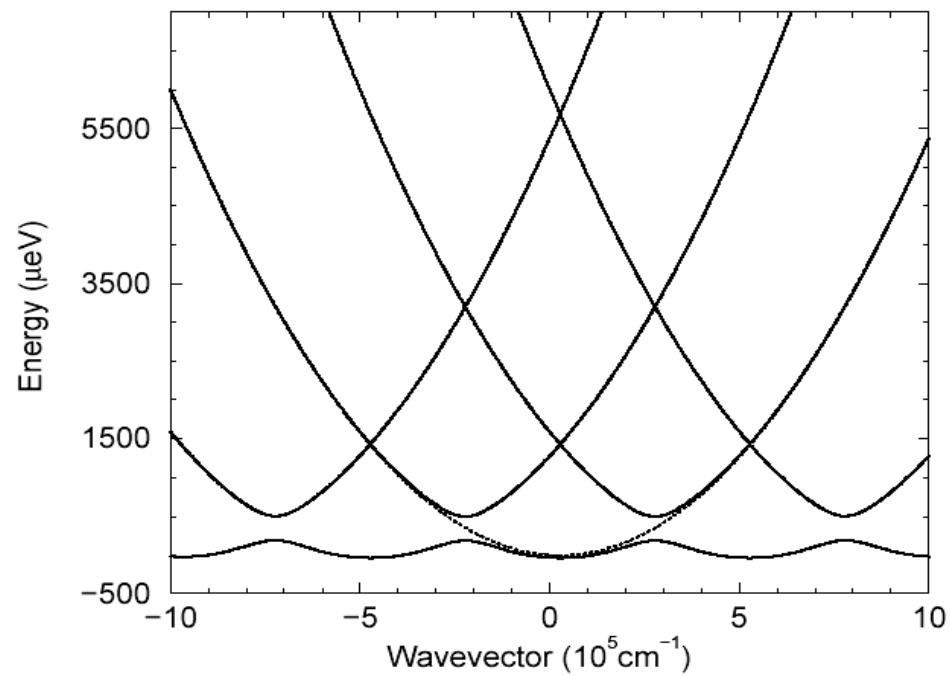


$$\nu_{\text{ac}} = 1 - 40 \text{ GHz} \quad (\hbar\Omega_{\mathbf{k}}^{\text{ph}} = 5 - 175 \text{ } \mu\text{eV})$$
$$I_{\text{ac}} = 0.1 - 1000 \text{ W/cm}^2$$



$$k_{\text{ac}} = 50000 \text{ cm}^{-1}$$
$$I_{\text{ac}} = 42.2 \text{ W/cm}^2$$

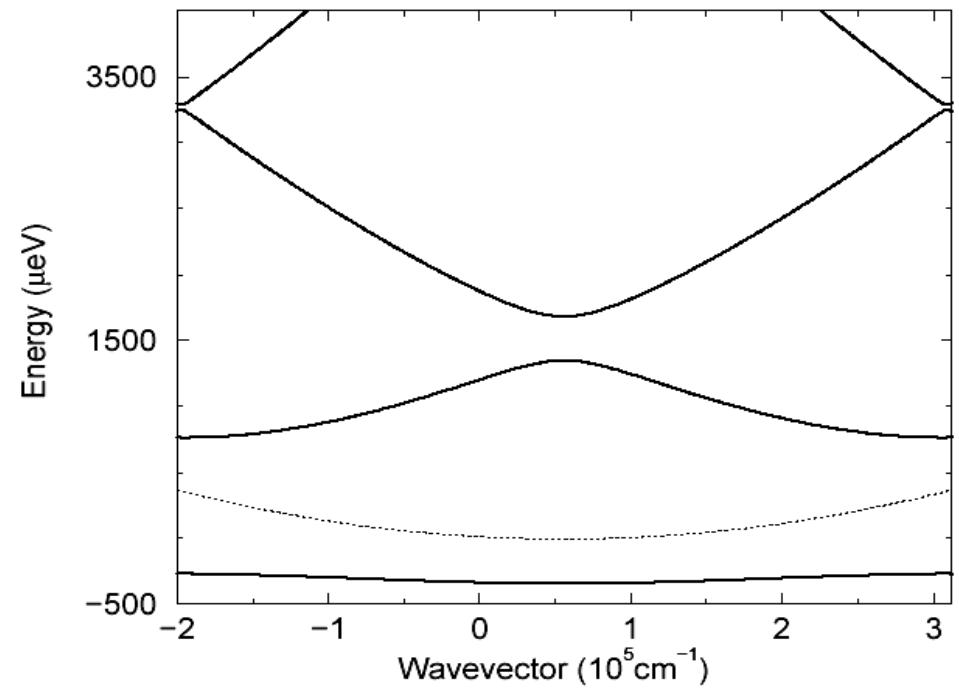
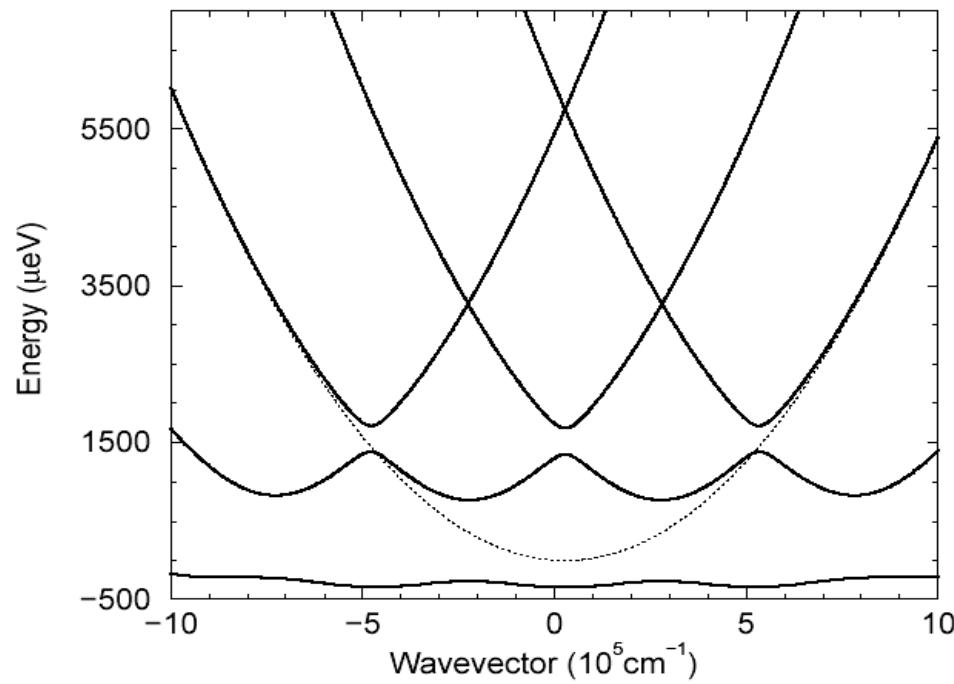
The quasi-energy spectrum of the acoustically-pumped conduction band of bulk GaAs



$$k_{\text{ac}} = 50000 \text{ cm}^{-1}$$

$$I_{\text{ac}} = 42.2 \text{ W/cm}^2$$

The quasi-energy spectrum of the acoustically-pumped conduction band of bulk GaAs



$$k_{\text{ac}} = 50000 \text{ cm}^{-1}$$

$$I_{\text{ac}} = 500 \text{ W/cm}^2$$

Accuracy of the truncated scheme

- Truncated scheme :

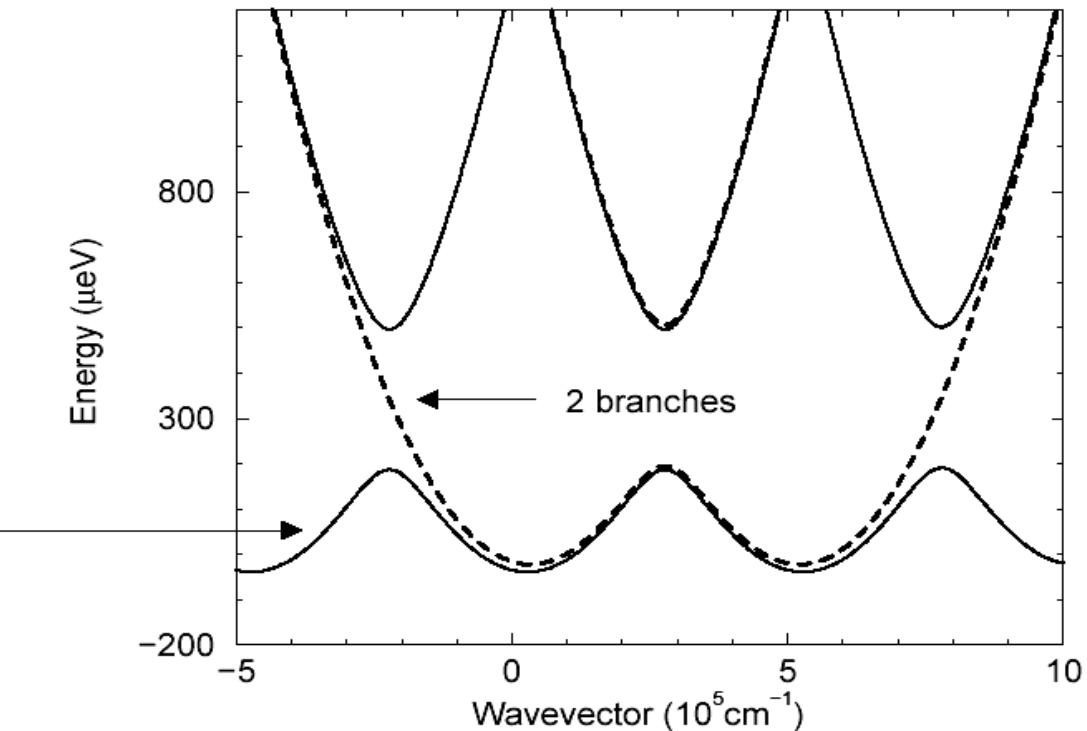
$$(\omega - \tilde{\omega}_p) - \frac{|m_k|^2}{\omega - \tilde{\omega}_{p+k} - M_{p+2k}} - \frac{|m_k|^2}{\omega - \tilde{\omega}_{p-k} - M_{p-2k}} = 0 ,$$

$$M_{p\pm 2k} = \frac{|m_k|^2}{\omega - \tilde{\omega}_{p\pm 2k} - M_{p\pm 3k}} , \dots , M_{p\pm jk} = \frac{|m_k|^2}{\omega - \tilde{\omega}_{p\pm jk} - M_{p\pm (j+1)k}} .$$

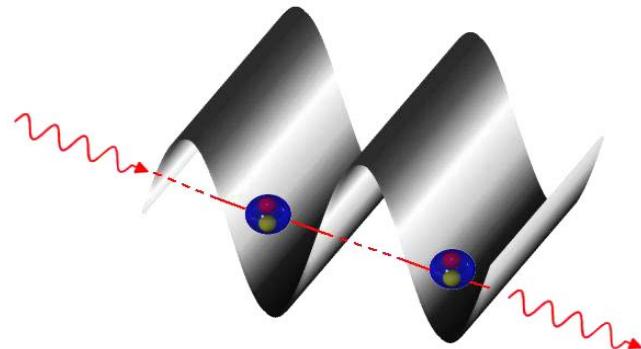
$$\begin{aligned}\Delta = \Delta(I_{ac}) &= 2|m_k| \\ &= 2^{3/2}\pi D_e \frac{\delta u}{\lambda_{ac}} \propto \sqrt{I_{ac}} .\end{aligned}$$

In bulk GaAs, $D_e = 7.8$ eV

5 branches



Resonant acousto-optics of the polariton eigenstates



- A. L. Ivanov and P. B. Littlewood :

Phys. Rev. Lett. **87**, 136403 (2001) - bulk polaritons ;

Semicond. Sci. Technol. **18**, S428 (2003) - MC polaritons .

- Macroscopic equations :

$$\left[\frac{\varepsilon_b}{c^2} \frac{\partial^2}{\partial t^2} - \Delta \right] \mathbf{E}(\mathbf{r}, t) = - \frac{4\pi}{c^2} \frac{\partial^2}{\partial t^2} \mathbf{P}(\mathbf{r}, t) ,$$

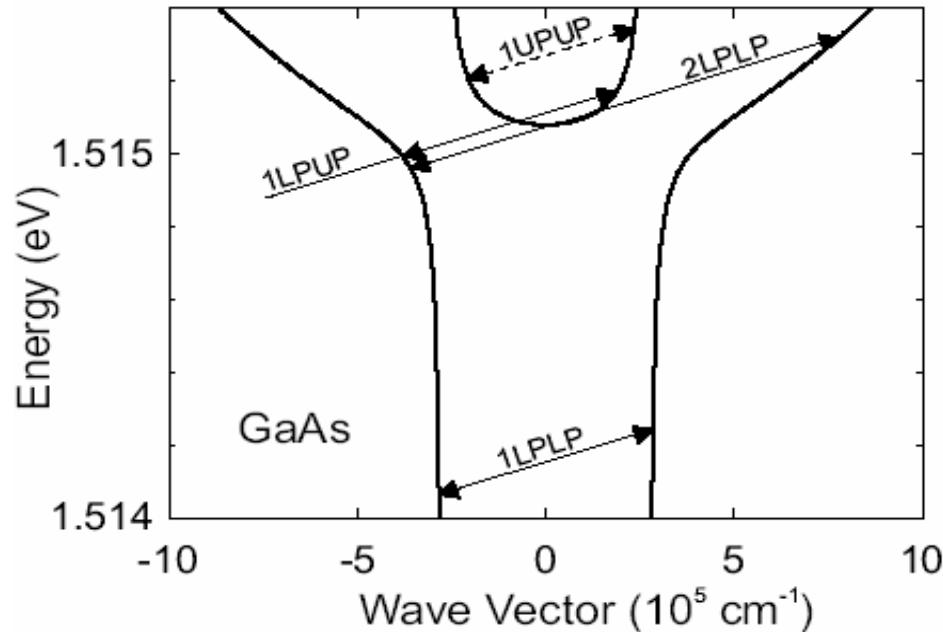
$$\left[\frac{\partial^2}{\partial t^2} + \omega_t^2 - \frac{\hbar\omega_t}{M_x} \Delta - 4 \frac{m_{\mathbf{k}}^x}{\hbar} \omega_t \cos(\Omega_{\mathbf{k}}^{\text{ac}} t - \mathbf{k}\mathbf{r}) \right] \mathbf{P}(\mathbf{r}, t) = \frac{\varepsilon_b \Omega_c^2}{4\pi} \mathbf{E}(\mathbf{r}, t) .$$

- Polaritons parametrically driven by an ultrasonic wave (e.g., SAW) ;
- Quantum diffraction of optically-dressed excitons by a coherent acoustic wave ;
- The giant acousto-optic nonlinearities : interaction of two “matter” waves is effective ;
- Both resonant interactions should be treated non-perturbatively (strong coupling regime) and in an equal basis.
- Solution of the equations cannot be given in terms of the Mathieu function .

Polaritons parametrically driven by an acoustic wave

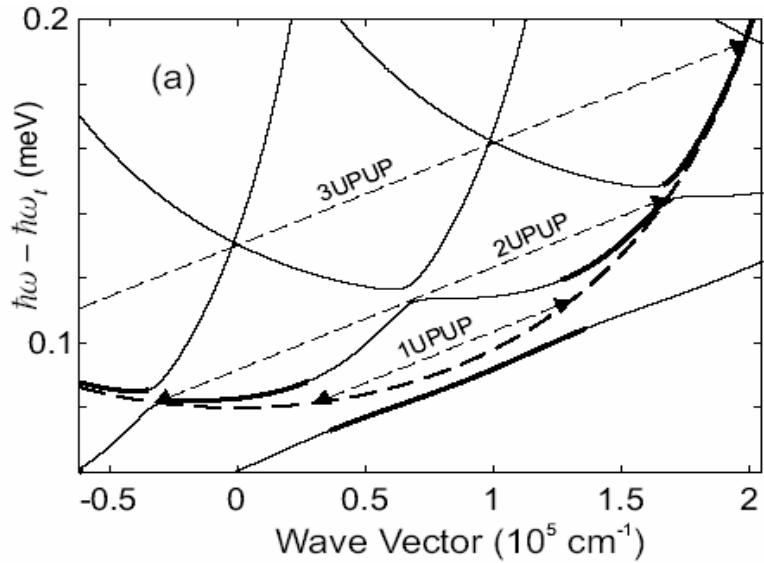
- The reduced Hamiltonian:
$$H^{\text{eff}} = \sum_{\mathbf{p}} \left[\hbar\omega_{\mathbf{p}}^x B_{\mathbf{p}}^\dagger B_{\mathbf{p}} + \hbar\omega_{\mathbf{p}}^\gamma \alpha_{\mathbf{p}}^\dagger \alpha_{\mathbf{p}} + \frac{\Omega_c}{2} (\alpha_{\mathbf{p}}^\dagger B_{\mathbf{p}} - B_{\mathbf{p}}^\dagger \alpha_{\mathbf{p}}) \right. \\ \left. - im_{\mathbf{k}}^x (B_{\mathbf{p}}^\dagger B_{\mathbf{p}-\mathbf{k}} e^{-i\Omega_{\mathbf{k}}^{\text{ph}} t} - B_{\mathbf{p}-\mathbf{k}}^\dagger B_{\mathbf{p}} e^{i\Omega_{\mathbf{k}}^{\text{ph}} t}) \right],$$

where $m_{\mathbf{k}}^x = m_{\mathbf{k}}^x(I_{\text{ac}}) = (D_e - D_h) \left(\frac{\hbar k N_0^{\text{ph}}}{2\hbar\rho v_s} \right)^{1/2}$ and $N_0^{\text{ph}} = \frac{1}{V} \langle c_{\mathbf{k}}^\dagger \rangle \langle c_{\mathbf{k}} \rangle = \frac{I_{\text{ac}}}{\hbar\Omega_{\mathbf{k}}^{\text{ph}}} \frac{1}{v_s}$.

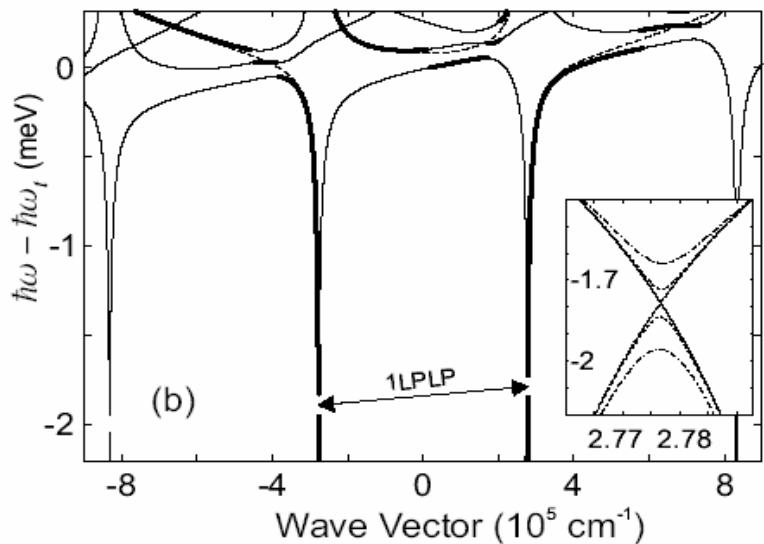


Solid arrows: $\nu_{\text{ac}} = 43.4 \text{ GHz}$,
Dashed arrow: $\nu_{\text{ac}} = 33.6 \text{ GHz}$.

Acoustically-induced quasi-energy spectrum



- Upper-branch polaritons in GaAs parametrically driven by a bulk LA-wave of $\nu_{ac}=7.6 \text{ GHz}$ and $I_{ac}=0.1 \text{ W/cm}^2$. $D_x = 9.6 \text{ eV}$ and $v_s = v_s^{\text{LA}} = 4.25 \times 10^5 \text{ cm/s}$.



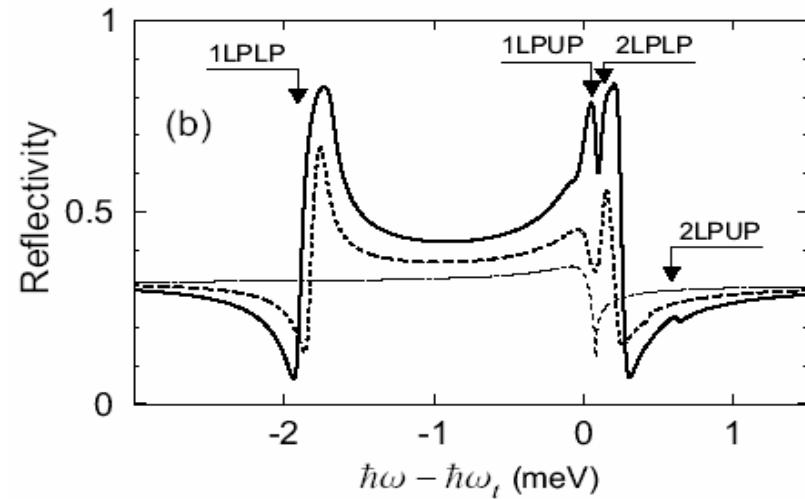
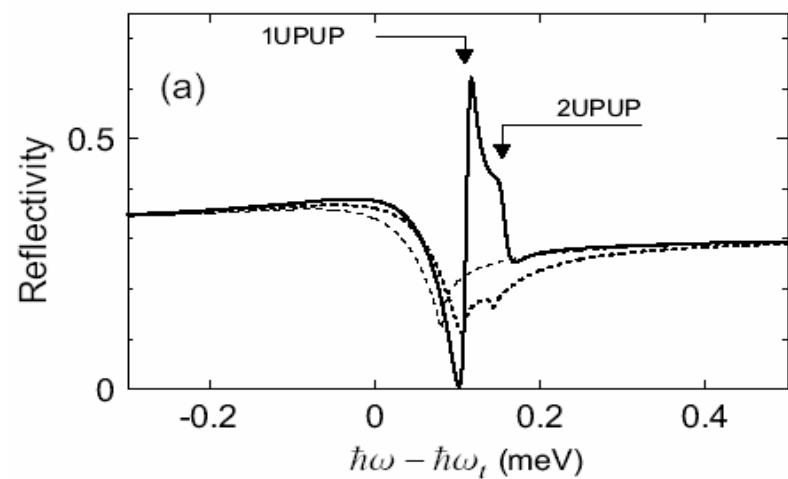
- Polaritons in bulk GaAs driven by a SAW of $I_{\text{SAW}} = 1.13 \times 10^{-2} \text{ mW/mm}$ ($I_{ac}=10 \text{ W/cm}^2$), $\nu_{ac}=25.3 \text{ GHz}$ and $v_s = v_s^{\text{SAW}} = 2.87 \times 10^5 \text{ cm/s}$.

Polariton-mediated optical response of an acoustically driven bulk semiconductor (GaAs)

- Macroscopic equations:

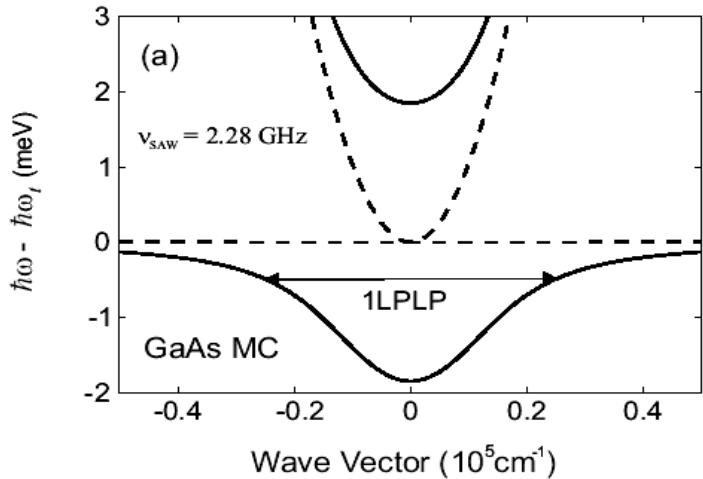
$$\left[\frac{\varepsilon_b}{c^2} \frac{\partial^2}{\partial t^2} - \Delta \right] \mathbf{E}(\mathbf{r}, t) = - \frac{4\pi}{c^2} \frac{\partial^2}{\partial t^2} \mathbf{P}(\mathbf{r}, t) ,$$

$$\left[\frac{\partial^2}{\partial t^2} + 2\gamma^x \frac{\partial}{\partial t} + \omega_t^2 - \frac{\hbar\omega_t}{M_x} \Delta - 4 \frac{m_k^x}{\hbar} \omega_t \cos(\Omega_{\mathbf{k}}^{ac} t - \mathbf{k}\mathbf{r}) \right] \mathbf{P}(\mathbf{r}, t) = \frac{\varepsilon_b \Omega_e^2}{4\pi} \mathbf{E}(\mathbf{r}, t) .$$



- Bulk LA-wave of $\nu_{ac}=7.6$ GHz, $\hbar\gamma^x = 10$ μ eV, $I_{ac}=0.1$ W/cm² (dotted line) and 0.5 W/cm² (solid line).
- SAW of $\nu_{ac}=25.3$ GHz, $\hbar\gamma^x = 30$ μ eV, $I_{SAW}=1.13 \times 10^{-2}$ mW/mm (bold dashed line) and $I_{SAW}=5.66 \times 10^{-2}$ mW/mm (solid line).

Acoustically-driven MC polaritons



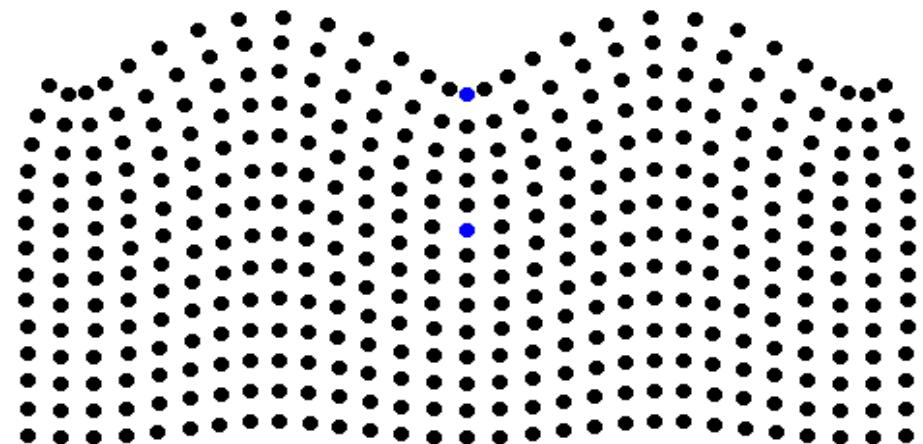
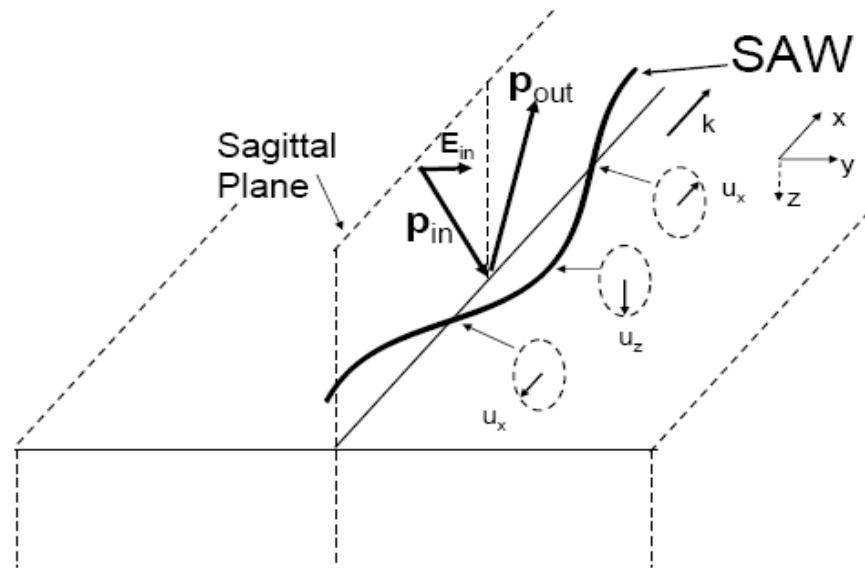
- The MC polariton dispersion :

$$\frac{c^2 p_{\parallel}^2}{\varepsilon_b} + \omega_0^2 = \omega^2 + \frac{\omega^2 (\Omega_x^{MC})^2}{\omega_t^2 + \hbar \omega_t p_{\parallel}^2 / M_x - \omega^2},$$

- the cavity eigenfrequency $\omega_0 = (2\pi c)/(L_z \sqrt{\varepsilon_b})$,
- the MC Rabi frequency Ω_x^{MC} , $\hbar \Omega_x^{MC} = 3.7 \text{ meV}$.

- Well-controlled in-plane wave interaction in microcavities ;
- Compatibility of semiconductor microcavities with the SAW technique ;
- The possibility to realise one-dimensional geometry for resonant, SAW-mediated interaction of two counter-propagating MC polaritons ;
- Effective suppression of γ^x , due to the motional narrowing .

Surface acoustic wave



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$$m_{\mathbf{k}}^x = I_{ac}^{1/2} \frac{|u_x|}{(|u_x|^2 + |u_z|^2)^{1/2}} |m_{x-ac}^{DP} + i\gamma_{saw} m_{x-ac}^{PE}|$$

SAW of $v_{saw} = 24$ GHz in GaAs QWs has been reported (I. V. Kukushkin et al., 2004)

The quasi-energy spectrum of acoustically-driven MC polaritons

- The initial Hamiltonian :

$$\begin{aligned}
 H = & \sum_{\mathbf{p}_{\parallel}} \left[\hbar \omega_{\mathbf{p}_{\parallel}}^X B_{\mathbf{p}_{\parallel}}^{\dagger} B_{\mathbf{p}_{\parallel}} + \hbar \omega_{\mathbf{p}_{\parallel}}^{\text{MC}} \alpha_{\mathbf{p}_{\parallel}}^{\dagger} \alpha_{\mathbf{p}_{\parallel}} \right. \\
 & + i\hbar \frac{\Omega_x^{\text{MC}}}{2} (\alpha_{\mathbf{p}_{\parallel}}^{\dagger} B_{\mathbf{p}_{\parallel}} - B_{\mathbf{p}_{\parallel}}^{\dagger} \alpha_{\mathbf{p}_{\parallel}}) \\
 + & im_k^x \left(B_{\mathbf{p}_{\parallel}}^{\dagger} B_{\mathbf{p}_{\parallel}-\mathbf{k}} e^{-i\Omega_k^{\text{act}} t} - B_{\mathbf{p}_{\parallel}-\mathbf{k}}^{\dagger} B_{\mathbf{p}_{\parallel}} e^{i\Omega_k^{\text{act}} t} \right) \Big] , \\
 \rightarrow \hbar \omega_{\mathbf{p}_{\parallel}}^X &= \hbar \omega_t + (\hbar^2 p_{\parallel}^2)/(2M_x) , \\
 \rightarrow \hbar \omega_{\mathbf{p}_{\parallel}}^{\text{MC}} &= \hbar \sqrt{\omega_0^2 + c^2 p_{\parallel}^2 / \varepsilon_b} , \\
 \rightarrow m_k^x &= m_{x-\text{ac}}(\mathbf{k}) \sqrt{N_0^{\text{ph}}} \quad \text{and} \quad N_0^{\text{ph}} \propto I_{\text{ac}} .
 \end{aligned}$$

- Removal of the time dependence :

$$\begin{aligned}
 S = \exp \left[it \sum_{\mathbf{p}_{\parallel}} (\mathbf{v}_s \cdot \mathbf{p}_{\parallel}) \left(B_{\mathbf{p}_{\parallel}}^{\dagger} B_{\mathbf{p}_{\parallel}} + \alpha_{\mathbf{p}_{\parallel}}^{\dagger} \alpha_{\mathbf{p}_{\parallel}} \right) \right] , \\
 B_{\mathbf{p}_{\parallel}} \rightarrow S B_{\mathbf{p}_{\parallel}} S^{\dagger} = B_{\mathbf{p}_{\parallel}} e^{-i(\mathbf{v}_s \cdot \mathbf{p}_{\parallel})t} , \\
 \alpha_{\mathbf{p}_{\parallel}} \rightarrow S \alpha_{\mathbf{p}_{\parallel}} S^{\dagger} = \alpha_{\mathbf{p}_{\parallel}} e^{-i(\mathbf{v}_s \cdot \mathbf{p}_{\parallel})t} .
 \end{aligned}$$

• The quasi-energy spectrum

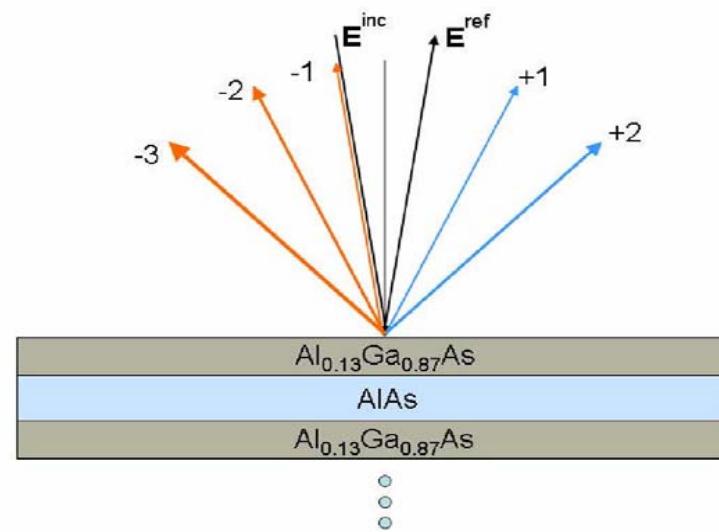
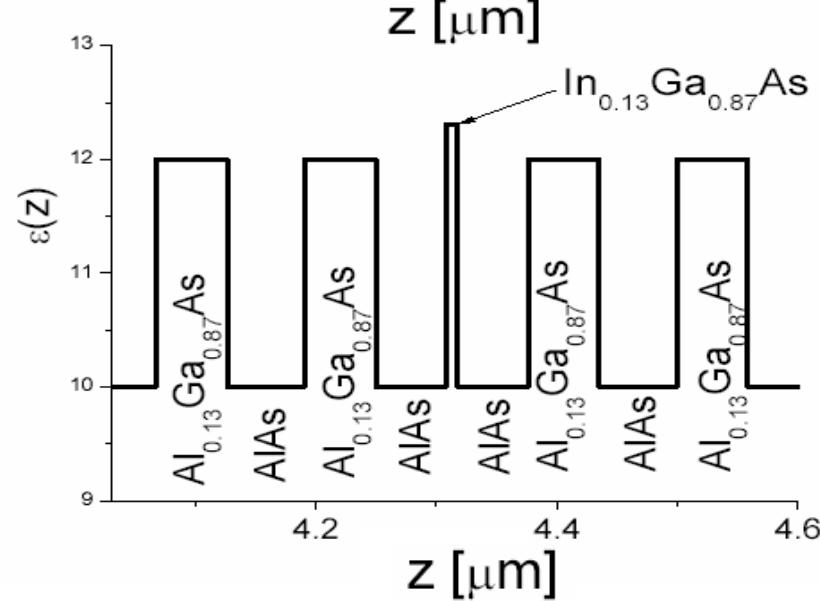
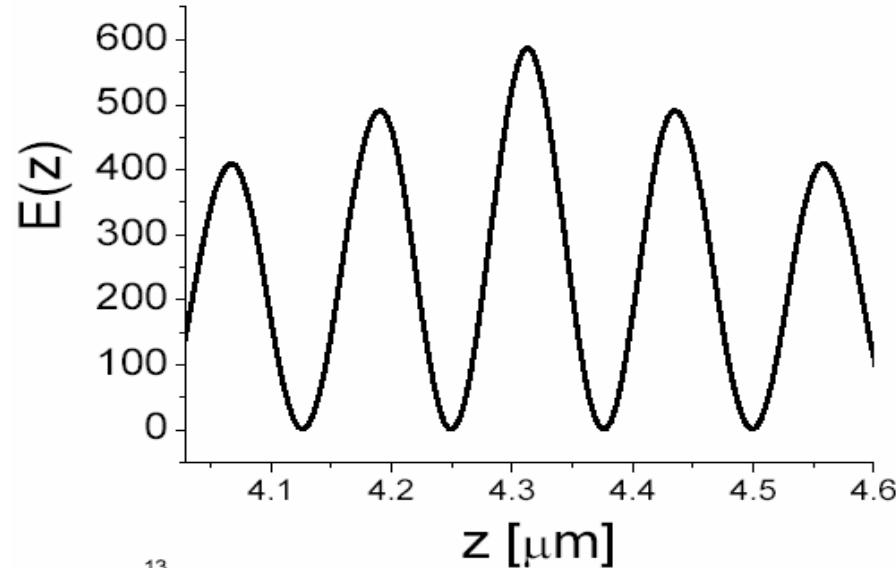
$$\begin{aligned}
 \omega^2 = & (\tilde{\omega}_{\mathbf{p}_{\parallel}}^X)^2 - \frac{(\omega \Omega_x^{\text{MC}})^2}{\omega^2 - (\tilde{\omega}_{\mathbf{p}_{\parallel}}^{\text{MC}})^2} \\
 & - \frac{4\omega_t^2 |m_k^x|^2}{\omega^2 - (\tilde{\omega}_{\mathbf{p}_{\parallel}+\mathbf{k}}^X)^2 - \frac{(\omega \Omega_x^{\text{MC}})^2}{\omega^2 - (\tilde{\omega}_{\mathbf{p}_{\parallel}+\mathbf{k}}^{\text{MC}})^2} - M_{\mathbf{p}_{\parallel}+2\mathbf{k}}} \\
 & - \frac{4\omega_t^2 |m_k^X|^2}{\omega^2 - (\tilde{\omega}_{\mathbf{p}_{\parallel}-\mathbf{k}}^X)^2 - \frac{(\omega \Omega_x^{\text{MC}})^2}{\omega^2 - (\tilde{\omega}_{\mathbf{p}_{\parallel}-\mathbf{k}}^{\text{MC}})^2} - M_{\mathbf{p}_{\parallel}-2\mathbf{k}}} = 0 ,
 \end{aligned}$$

$$\rightarrow \hbar \tilde{\omega}_{\mathbf{p}_{\parallel} \pm n\mathbf{k}}^{X,\text{MC}} = \hbar \omega_{\mathbf{p}_{\parallel} \pm n\mathbf{k}}^{X,\text{MC}} \mp n\hbar \Omega_k^{\text{act}} = \hbar \omega_{\mathbf{p}_{\parallel} \pm n\mathbf{k}}^{X,\text{MC}} \mp n\hbar (\mathbf{v}_s \cdot \mathbf{k}) ,$$

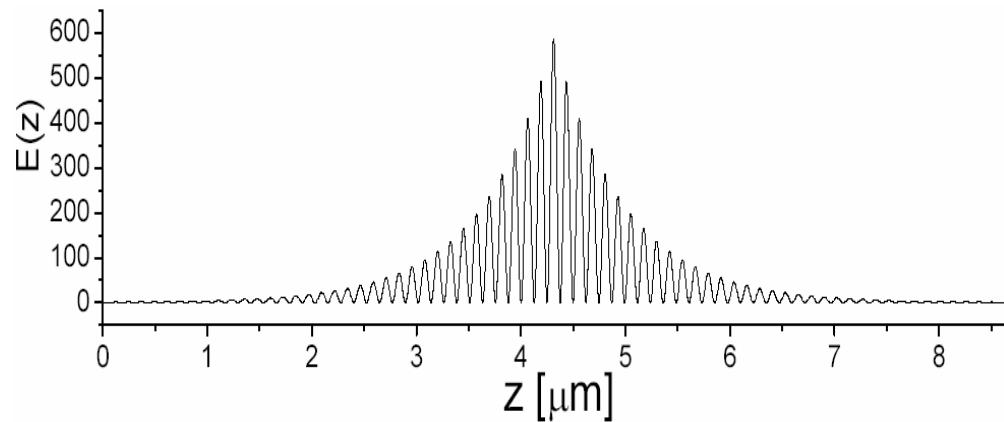
$$\rightarrow M_{\mathbf{p}_{\parallel} \pm n\mathbf{k}} = \frac{4\omega_t^2 |m_k^x|^2}{\omega^2 - (\tilde{\omega}_{\mathbf{p}_{\parallel} \pm n\mathbf{k}}^X)^2 - \frac{(\omega \Omega_x^{\text{MC}})^2}{\omega^2 - (\tilde{\omega}_{\mathbf{p}_{\parallel} \pm n\mathbf{k}}^{\text{MC}})^2} - M_{\mathbf{p}_{\parallel} \pm (n+1)\mathbf{k}}} .$$

Bragg spectroscopy of SAW-driven MC polaritons

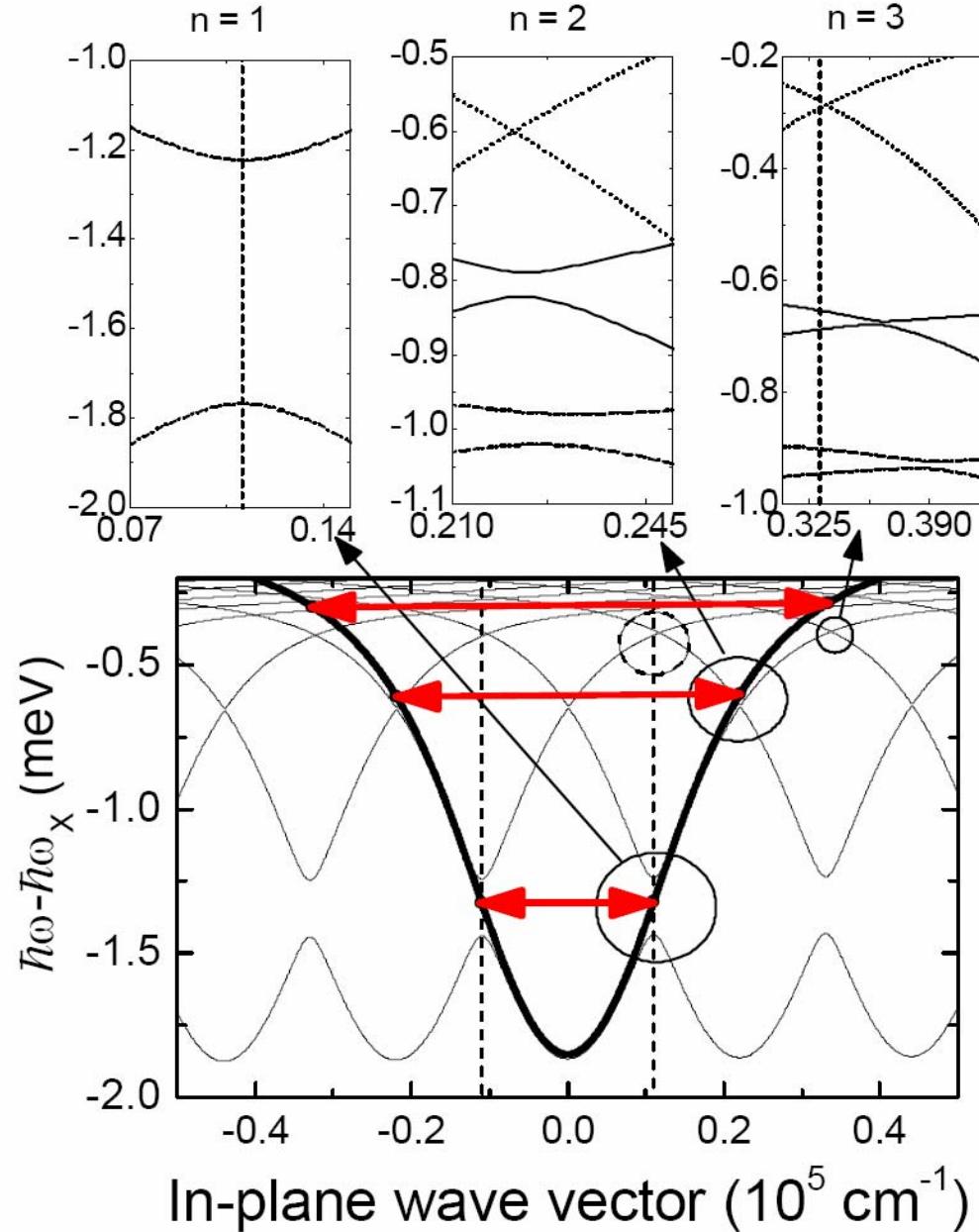
[K. Cho, K. Okumoto, N. Nikolaev and A.L. Ivanov, Phys. Rev. Lett. **94**, 226406 (2005)]



$$\sin \Theta_B = \lambda_{\text{opt}} / (2 \Lambda_{\text{ac}})$$



Quasi-energy spectrum of SAW-driven MC polaritons



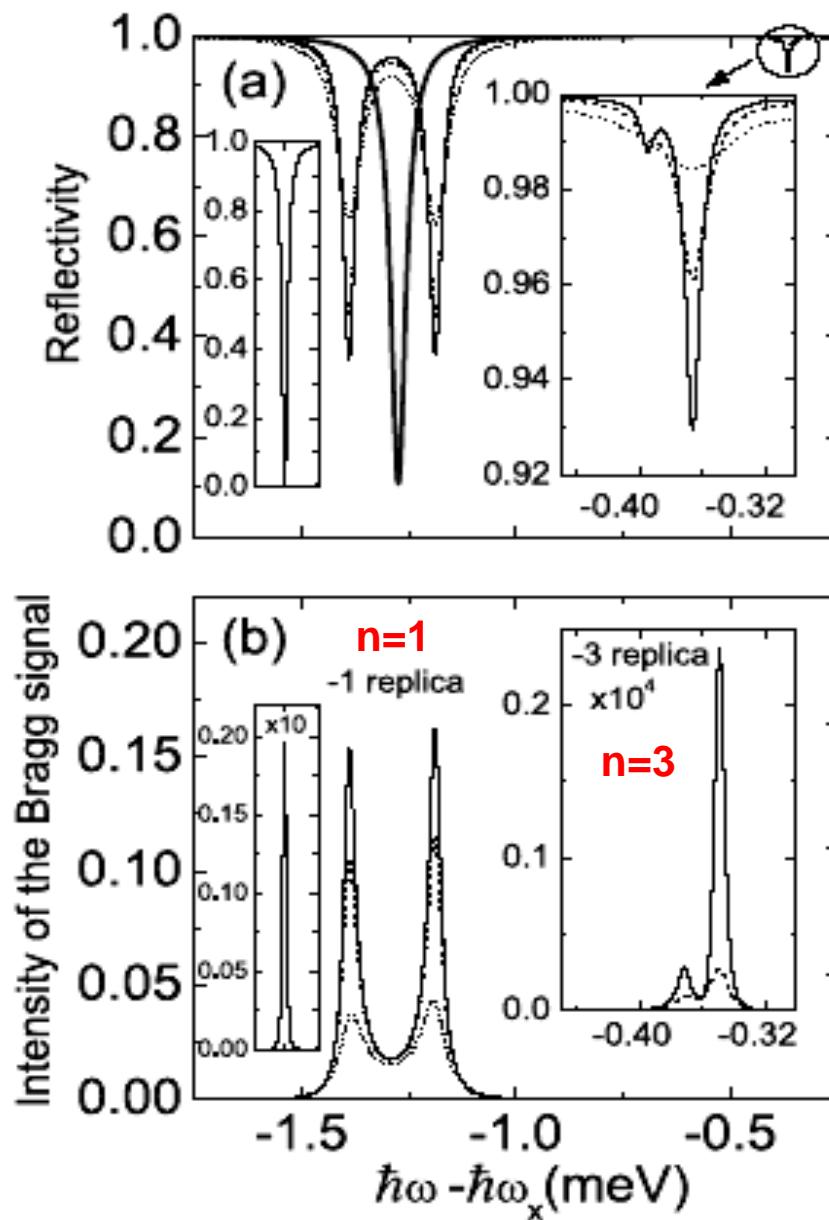
$$I_{\text{ac}} = 100 \text{ W/cm}^2$$

$$\begin{aligned} \delta\varepsilon_{x-\text{ac}}^{\text{MC}} &= 4\pi\chi_{\gamma-\text{ac}}^{\text{MC}(2)}(\omega)I_{\text{ac}}^{1/2} \\ &= \varepsilon_b \left(\frac{\Omega_x^{\text{MC}}}{\omega_T - \omega} \right)^2 \frac{m_{x-\text{ac}}^{\text{DP}} I_{\text{ac}}^{1/2}}{\omega_T} \end{aligned}$$

$$\begin{aligned} \ell_{\gamma-x-\text{ac}} &\simeq \frac{4\pi v_{\text{pol}}^{\text{MC}}(k/2)}{\Delta_{\text{ac}}^{\text{MC}}(I_{\text{ac}}, k/2)} \\ &\propto \frac{1}{I_{\text{ac}}^{1/2}} \sim 10 - 100 \mu\text{m} . \end{aligned}$$

$$I_{\text{ac}} = 10 \text{ W/cm}^2$$

Bragg spectroscopy of SAW-driven MC polaritons



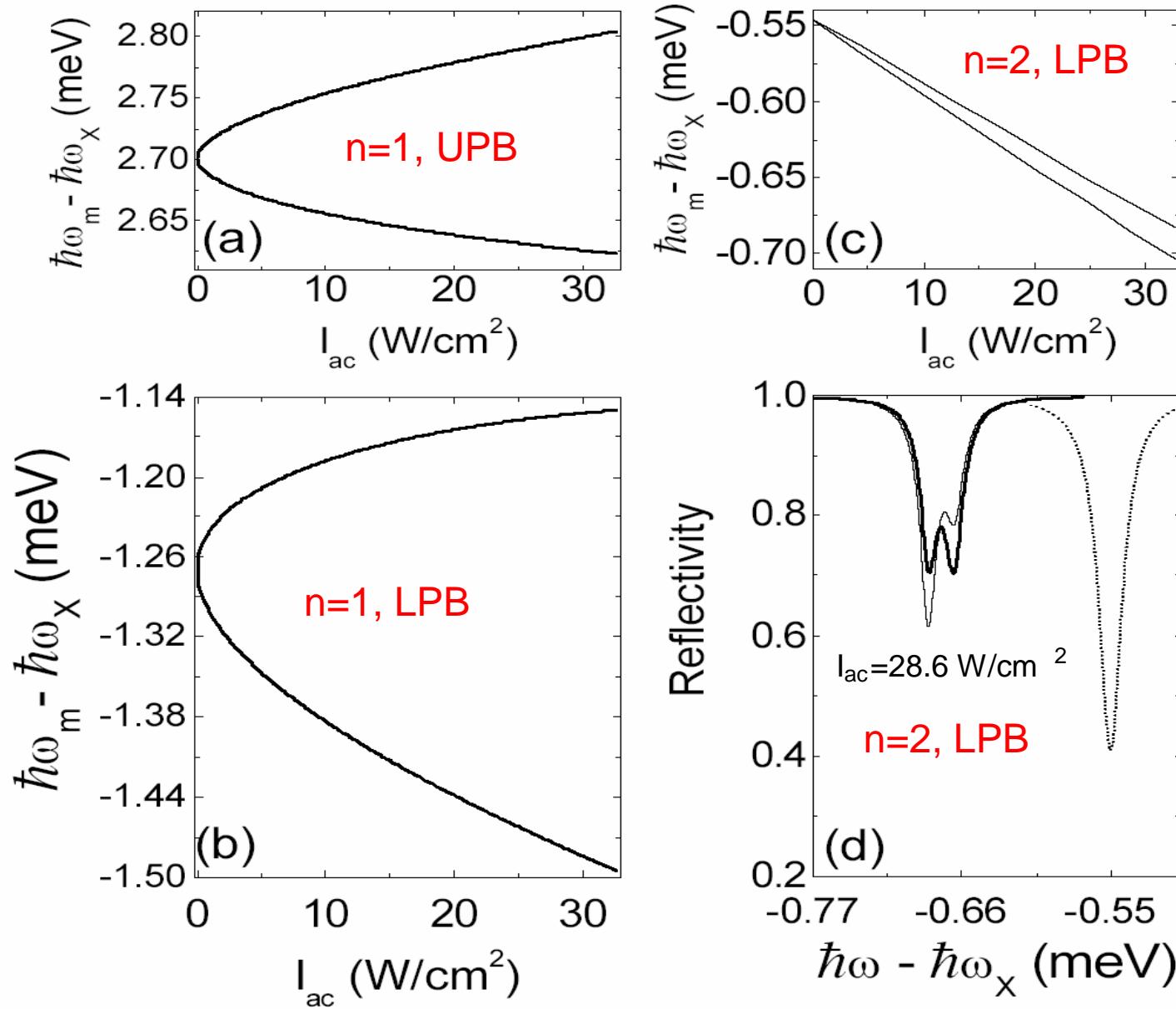
The Bragg angle is 8.22 $^{\circ}$

$$I_{ac} = 10 \text{ W/cm}^2$$

The excitonic damping is

5 micro-eV (solid lines),
10 micro-eV (dashed lines),
30 micro-eV (dotted lines)

Bragg spectroscopy of SAW-driven MC polaritons



Recent observation of the resonant acousto-optic effect in GaAs microcavities

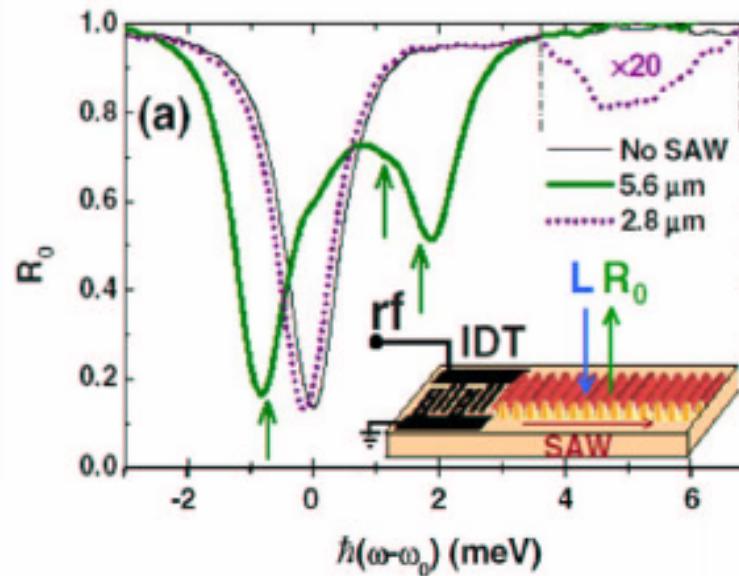
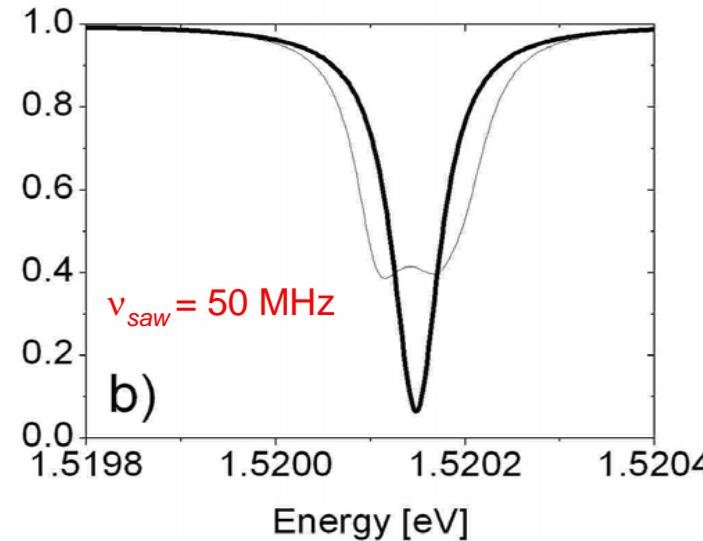
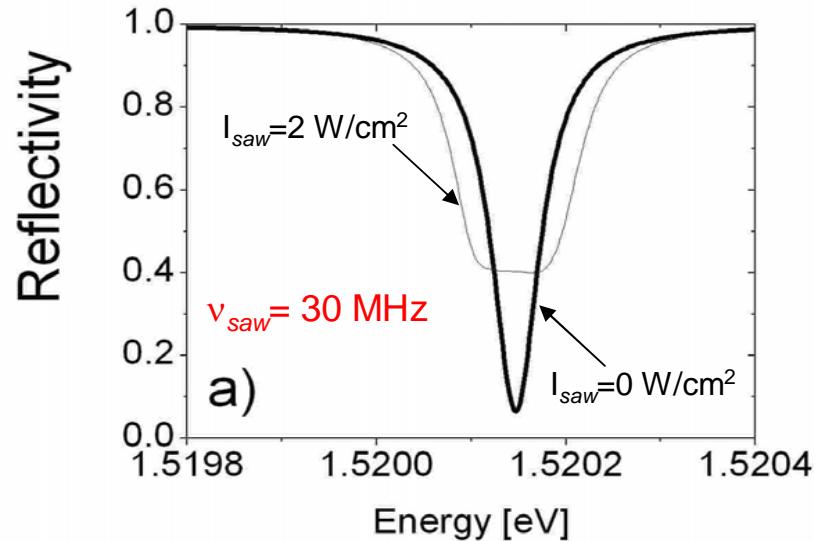


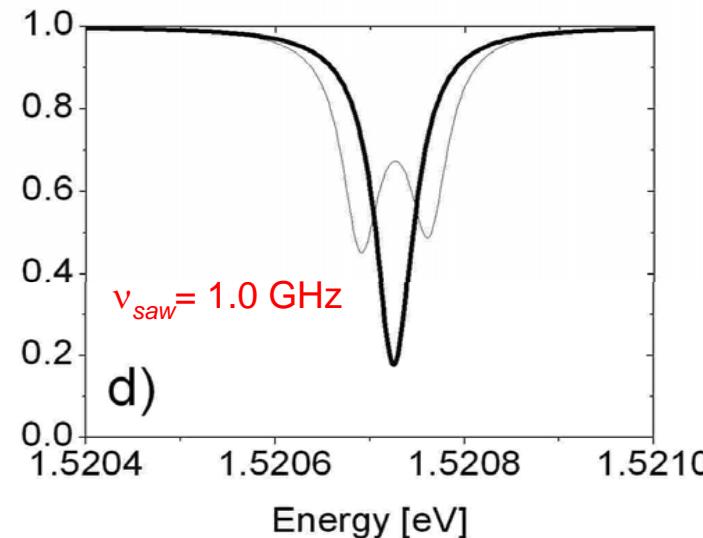
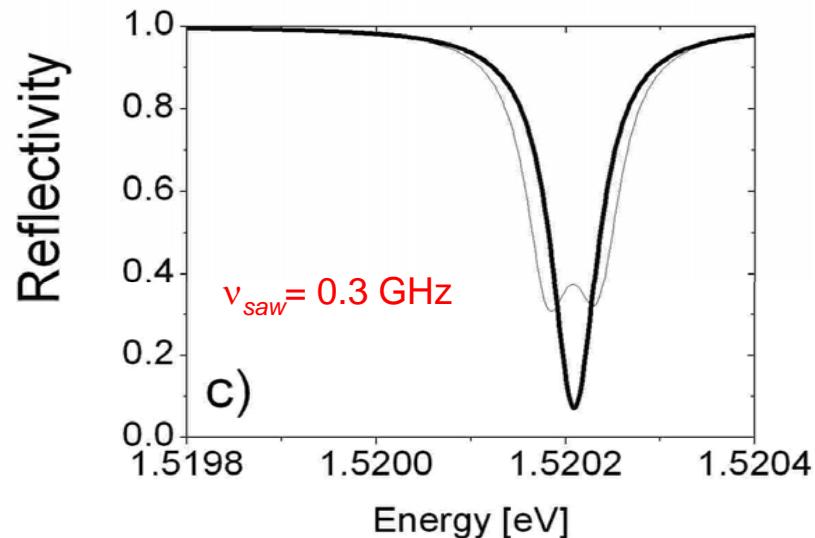
Figure 1: Observation of the acousto-optic Stark effect in GaAs-based microcavities with very large negative detuning between the cavity photon mode and the exciton transition. [M. M. de Lima, R. Hey, P. V. Santos, and A. Cantarero, Phys. Rev. Lett. 94, 126805 (2005)].

[see also M. M. de Lima, M. van der Poel, P. V. Santos, and J. M. Hvam, 2006]

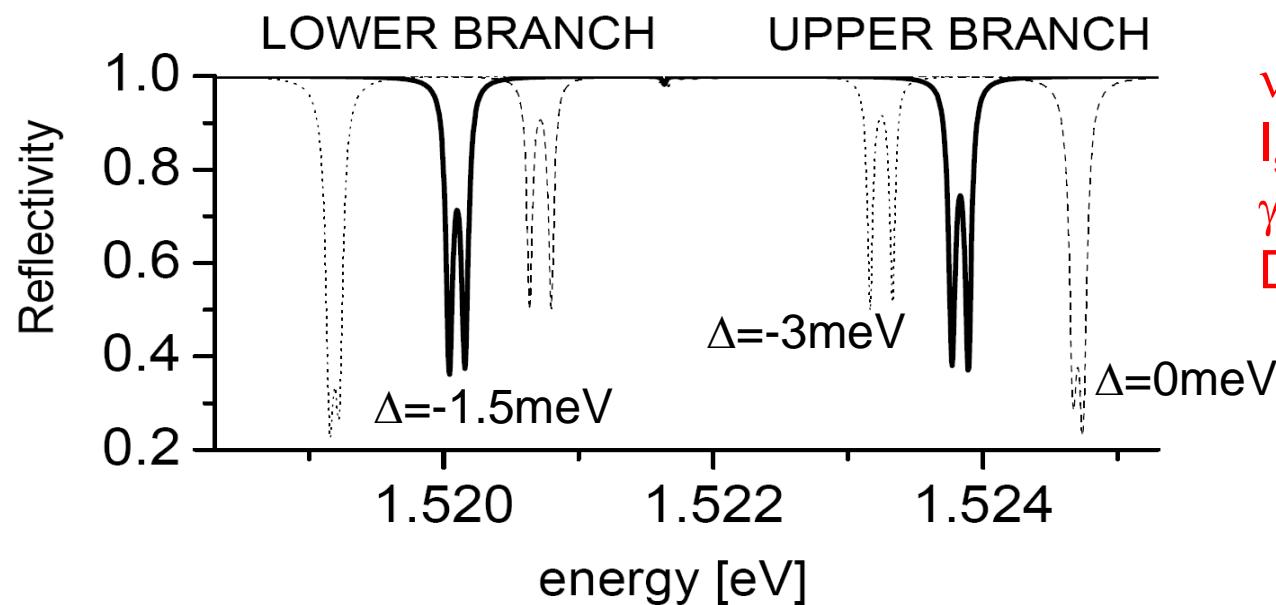
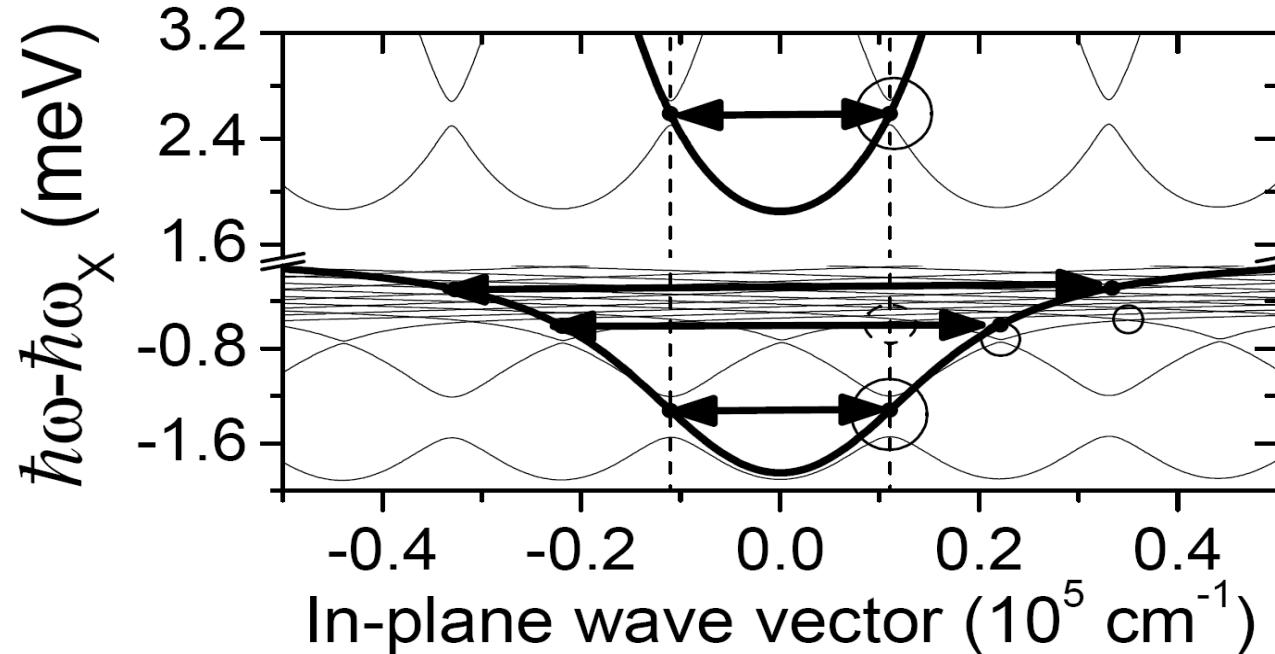
Bragg spectroscopy of SAW-driven MC polaritons (a low-frequency surface acoustic wave)



MC detuning = 0 meV,
 $\gamma_x = 15 \mu\text{eV}$,
 $I_{\text{saw}} = 2 \text{ W/cm}^2$.



SAW-driven upper- and lower-branch MC polaritons



$v_{\text{saw}} = 1.0 \text{ GHz}$,
 $I_{\text{saw}} = 10 \text{ W/cm}^2$,
 $\gamma_x = 15 \mu\text{eV}$,
DBR – 35 layers

Towards room-temperature resonant acousto-optics

- GaAs-based microcavities :

$$\Omega_x^{MC} \simeq 3 - 4 \text{ meV},$$

$$\epsilon_x^{\text{bulk}} = 4.2 \text{ meV},$$

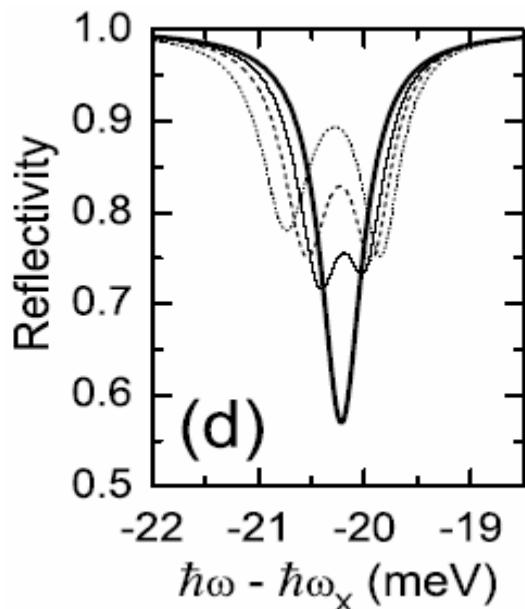
$$\epsilon_x^{\text{QW}} \simeq 10 - 12 \text{ meV}.$$

- ZnSe-based microcavities :

$$\Omega_x^{MC} \simeq 44 \text{ meV},$$

$$\epsilon_x^{\text{QW}} \simeq 40 \text{ meV},$$

$$T = 300 \text{ K} \rightarrow \hbar\gamma_{\text{QW}}^x \simeq 10 \text{ meV}.$$



- CdTe-based microcavities :

$$T = 300 \text{ K} \rightarrow \varphi^{\text{MC}} \hbar\gamma_{\text{QW}}^x \simeq 1 \text{ meV} \text{ (Le Si Dang).}$$

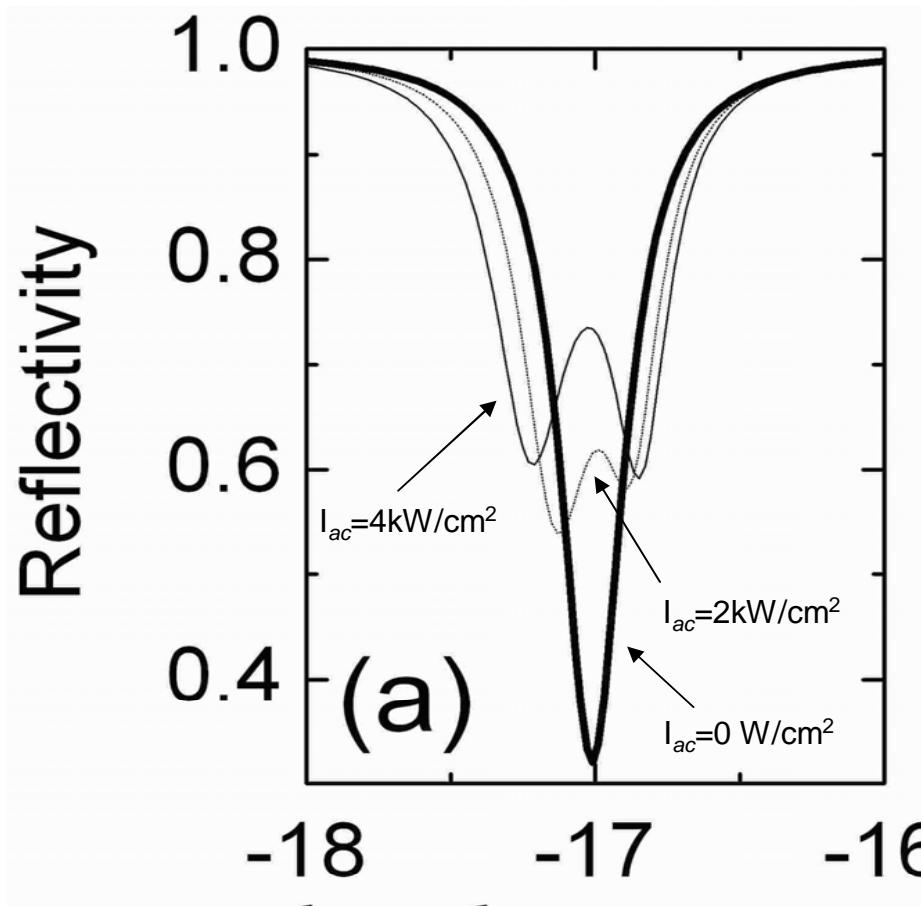
- GaN-based microcavities .

$\hbar\gamma_x = 1 \text{ meV}$, $\hbar\Omega_x^{\text{MC}} = 20 \text{ meV}$ and MC detuning $\delta^{\text{MC}} = -17 \text{ meV}$
1 kW/cm² (thin line), 2 kW/cm² (dashed line), and 4 kW/cm² (dotted line).

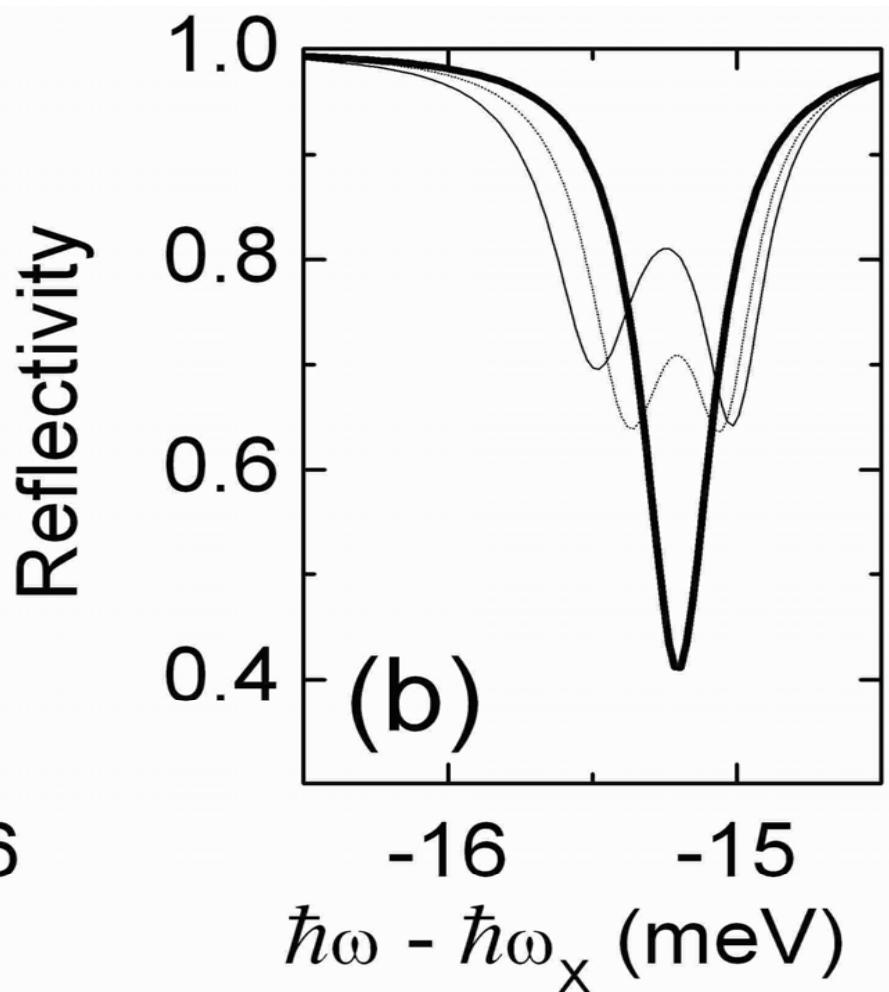
Bragg spectroscopy of SAW-driven MC polaritons

High temperatures: $\gamma_x = 1$ meV;

Microcavity Rabi splitting: 10 meV.



MC detuning = -17meV



MC detuning = -15meV

Acoustic versus optical pumping

- Low acoustic pump intensities $I_{\text{ac}} \sim 10^{-8} - 10^{-6} I_{\text{opt}}$:

$$N_0^{\text{x}} = \frac{1}{V} \langle B_{\mathbf{k}}^\dagger \rangle \langle B_{\mathbf{k}} \rangle = \frac{I_{\text{opt}}}{\hbar \omega_{\mathbf{k}}} \frac{\sqrt{\varepsilon_b}}{c} \frac{\Omega_{\text{c}}^2}{4(\omega_t - \omega_{\mathbf{k}})^2},$$

$$N_0^{\text{ph}} = \frac{1}{V} \langle c_{\mathbf{k}}^\dagger \rangle \langle c_{\mathbf{k}} \rangle = \frac{I_{\text{ac}}}{\hbar \Omega_{\mathbf{k}}^{\text{ac}}} \frac{1}{v_s}.$$

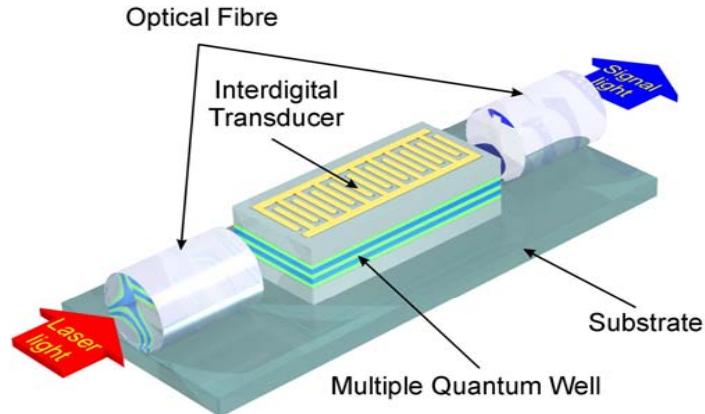
$$\rightarrow v_{\text{pol}} \sim c/\sqrt{\varepsilon_b} \gg v_s;$$

$$\rightarrow E^{\text{X}} = \hbar \omega_t \gg \hbar \Omega^{\text{ac}}.$$

- An acoustically pumped intrinsic semiconductor remains in its ground electronic state:

$$\text{for } I_{\text{SAW}} = 40 \text{ W/cm}^2 \rightarrow N_0^{\text{ph}} \simeq 0.9 \times 10^{20} \text{ cm}^{-3}.$$

Resonant acousto-optics: device applications



- A general “formula” of the resonant acousto-optics :
A. L. Ivanov and P. B. Littlewood, Patent “Acoustically induced Stark effect for optical modulation and switching (GB 0121448.5, filed on 04 September 2001) :
 - Modulators ;
 - Tunable optical filters ;
 - Optical beam splitters .
- The nonresonant acousto-optic nonlinearities :
the interaction length is large, $\ell_{\gamma-\text{ac}} \sim 10 \text{ cm}$,
For the resonant acousto-optics : $\ell_{\gamma-\text{ac}} \sim 10 \mu\text{m}$;
- A MC-based resonant acousto-optic element :
switching on/off times on a sub-nanosecond time scale ;
- Room temperature resonant acousto-optics of MC polaritons :
ZnSe-, CdTe- and GaN-based microcavities .

Conclusions

- Resonant acousto-optics of photon-dressed excitons:
 - a) giant, resonantly-enhanced acousto-optical nonlinearities,
 - b) acoustically-induced optical band gaps in the polariton spectrum,
 - c) nontrivial Bragg spectroscopy of SAW-driven polaritons.
- Resonant acousto-optics of microcavity polaritons:
 - a) compatibility of semiconductor MCs with the SAW technique,
 - b) 1D geometry for the SAW-mediated interaction of MC polaritons,
 - c) the SAW frequency of 1-3 GHz, the SAW intensity 1-100 W/cm,
 - d) the interaction length of 10-100 micrometers.
- Device applications of resonant acousto-optics.

Review papers: (a) A. L. Ivanov, phys. stat. sol. (a) **202**, 2657 (2005).
(b) in the book *Problems of Condensed Matter Physics* (Oxford University Press, 2006), Editors A. L. Ivanov and G. S. Tikhodeev.