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*WINTER COLLEGE ON
SPECTROSCOPY AND APPLICATIONS*

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"Ultrafast Processes in Semiconductors"

presented by:

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These are preliminary lecture notes, intended only for distribution to participants.

Ultrafast Processes in Semiconductors

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1. Elementary excitations in semiconductors
2. Ultrafast time scales
3. Experimental techniques
4. Coherent optical polarizations
5. Coherent generation of carriers
6. Carrier thermalization and cooling
7. Ultrafast optoelectronics

Literature

Textbooks and Monographies :

N.W. Ashcroft, N.D. Mermin: Solid State Physics, Holt Saunders, New York 1976

K. Seeger : Semiconductor Physics, Springer Verlag, Berlin 1985

B.K. Ridley : Quantum Processes in Semiconductors, Clarendon Press, Oxford 1993

H. Haug, S.W. Koch : Quantum theory of the optical and electronic properties of semiconductors, World Scientific, Singapore 1993

S.M. Sze : Physics of Semiconductor Devices, Wiley, New York 1981

W. Kaiser (Ed.) : Ultrashort Laser Pulses - Generation and Application, 2nd ed., Springer Verlag, Berlin 1993

J. Shah : Ultrafast Spectroscopy of Semiconductors and Semiconductor Nanostructures, Springer Verlag, Berlin 1996

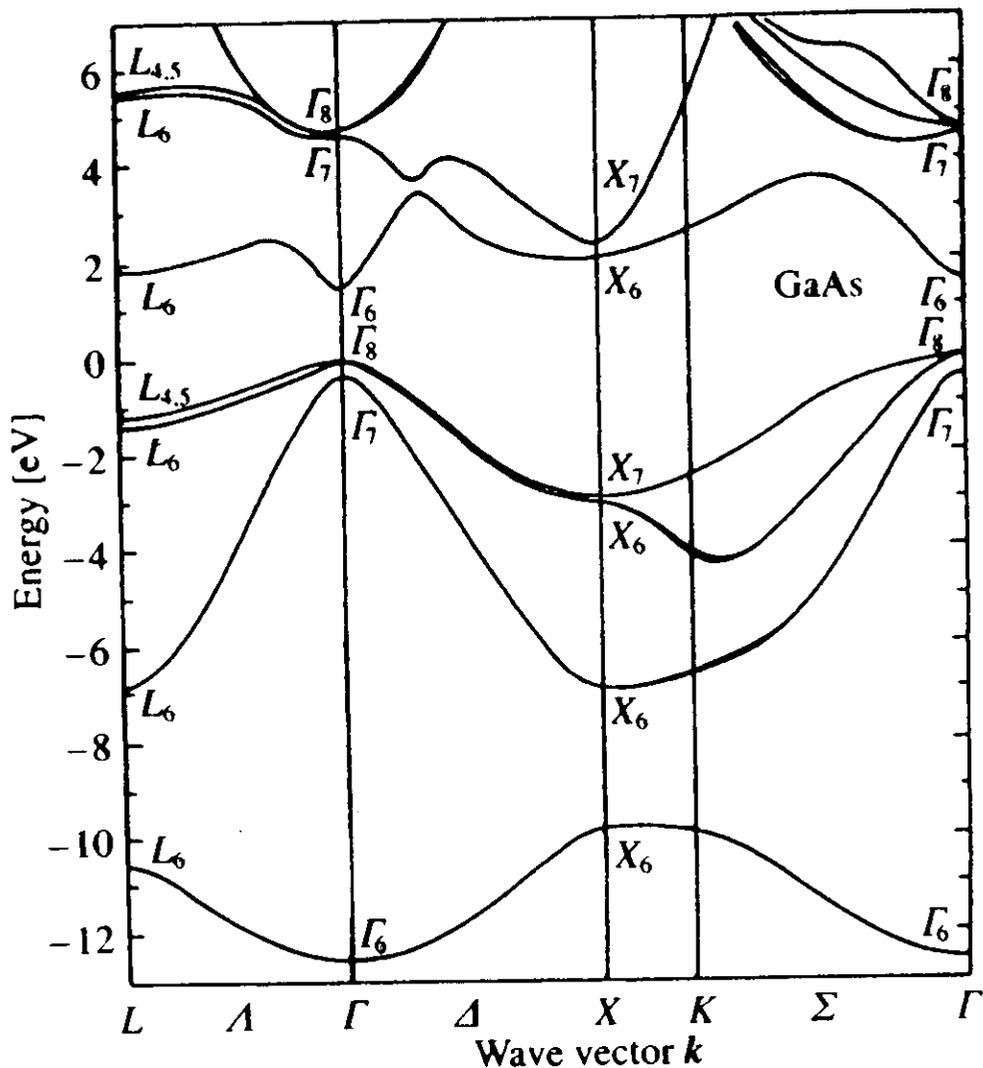
J. Shah (Ed.) : Hot Carriers in Semiconductor Nanostructures, Academic Press, San Diego 1992

T. Elsaesser, J.G. Fujimoto, D.A. Wiersma, W. Zinth (Eds.) : Ultrafast Phenomena XI, Springer Verlag, Berlin 1998

Journals :

Physical Review Letters, Physical Review B, Applied Physics Letters, Electronics Letters

Electronic Bandstructure of Bulk GaAs



Fundamental bandgap Γ_6 - Γ_8 : $E_G = 1.42$ eV at 300 K
 $E_G = 1.517$ eV at 10 K

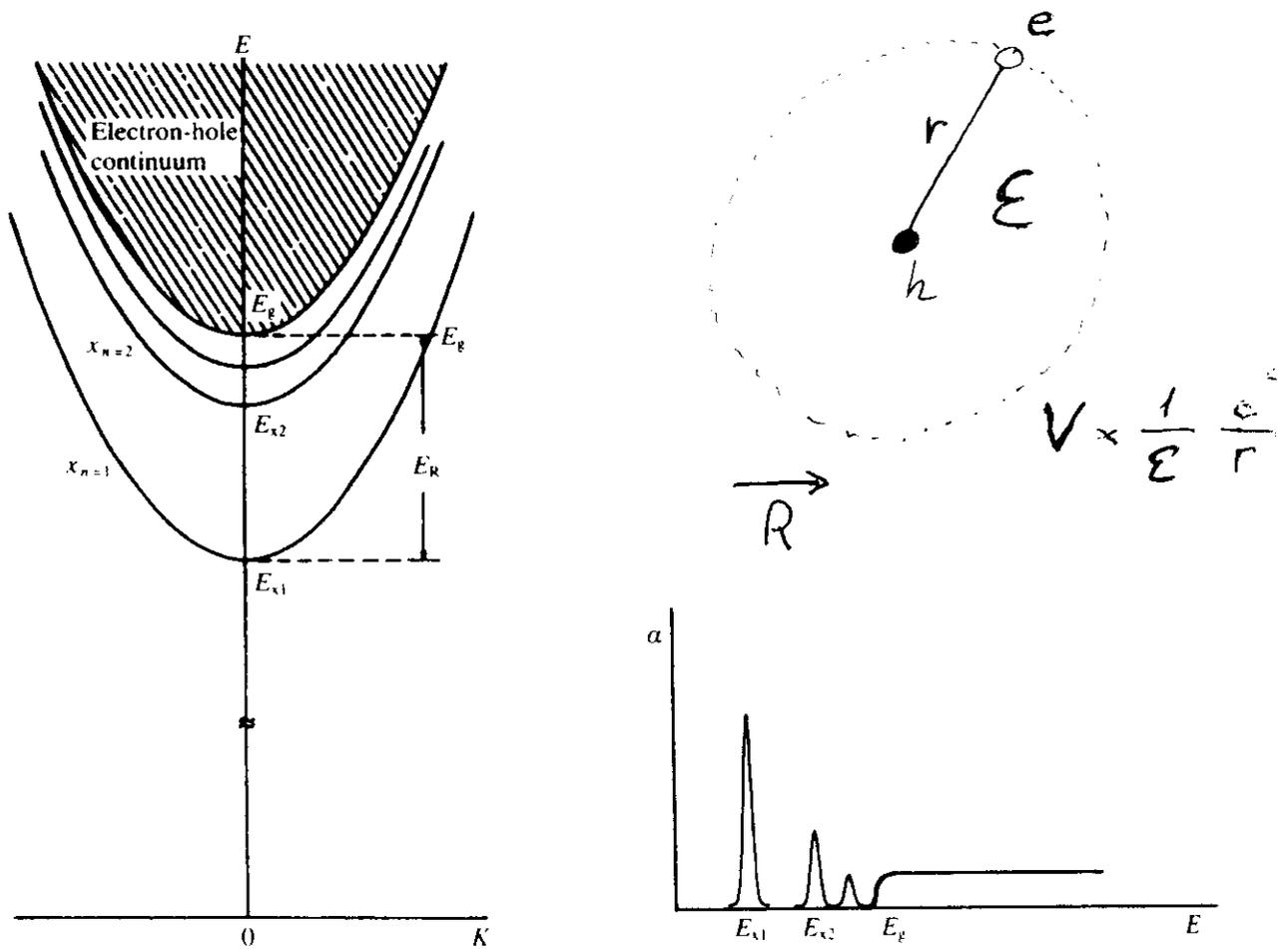
Quasi-continuous band-to-band absorption of free carriers:

$$\alpha(\omega) = \alpha_0 \frac{\hbar\omega}{E_0} \left[\frac{\hbar\omega - E_G}{E_0} \right]^{1/2} \theta(\hbar\omega - E_G) \times [1 - f_e - f_h]$$

$$E_0 = \frac{\hbar^2}{2m_r a_0^2}, \quad a_0 = \frac{\hbar^2 \epsilon_0}{e^2 m_r}, \quad E_0 \propto \frac{e^2}{\epsilon_0} \frac{1}{a_0}$$

Excitonic Transitions in Bulk GaAs

Coulomb interaction of electron and hole leads to formation of Wannier excitons



Total exciton energy:

$$E_{total,n} = E_G - E_{b,n} + \frac{\hbar^2 K^2}{2M}, E_{b,n} = \frac{E_0}{n^2}$$

Excitonic absorption (Elliott formula):

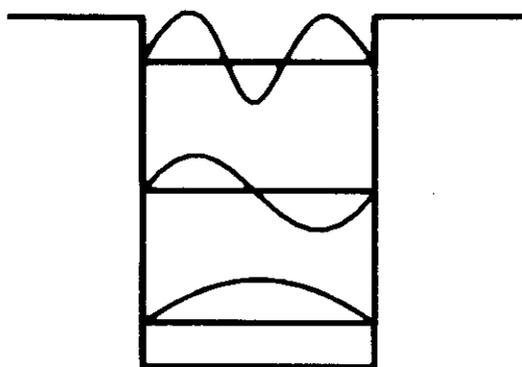
$$\alpha(\omega) = \alpha_0 \frac{\hbar\omega}{E_0} \left[\sum_{n=1}^{\infty} \frac{4\pi}{n^3} \delta(\Delta + 1/n^2) + \theta(\Delta) \frac{\pi e^{\pi\sqrt{\Delta}}}{\sinh(\pi/\sqrt{\Delta})} \right]; \Delta = \frac{\hbar\omega - E_G}{E_0}$$

Quasi-two-dimensional semiconductor nano-structures

quantum wells

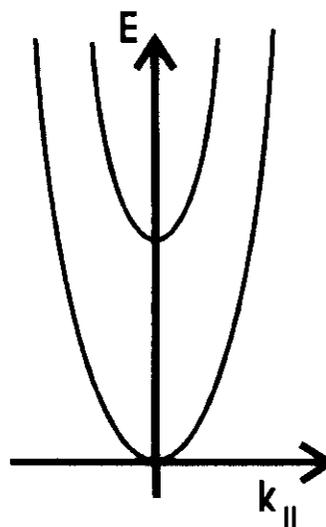


z



confined electron waves

subbands



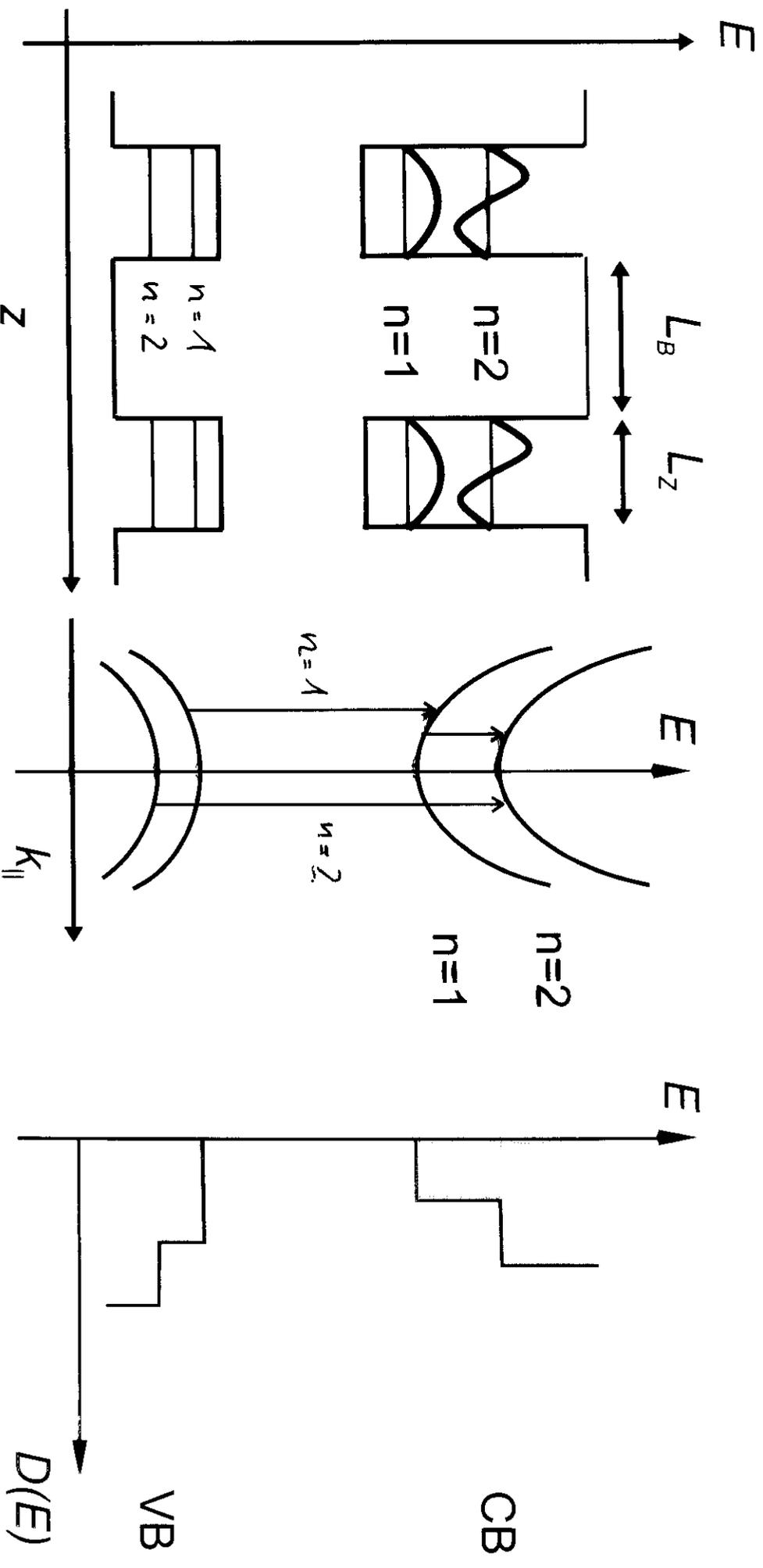
free motion
parallel to layers

Inter-subband

Intra-subband

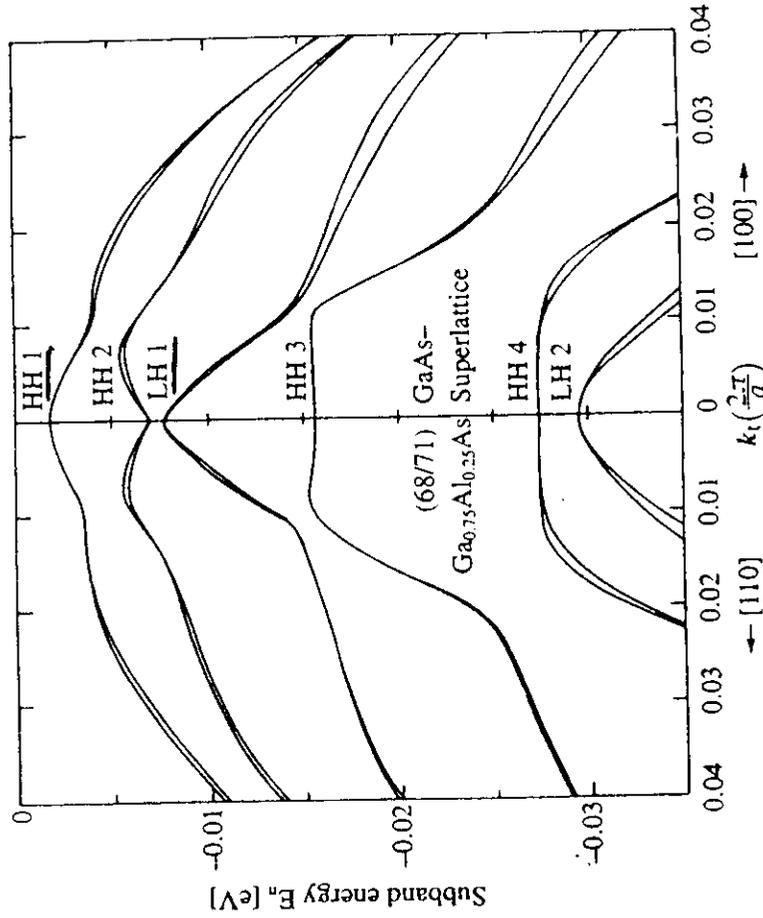
scattering processes

Band-to-band absorption in quasi-two-dimensional semiconductors

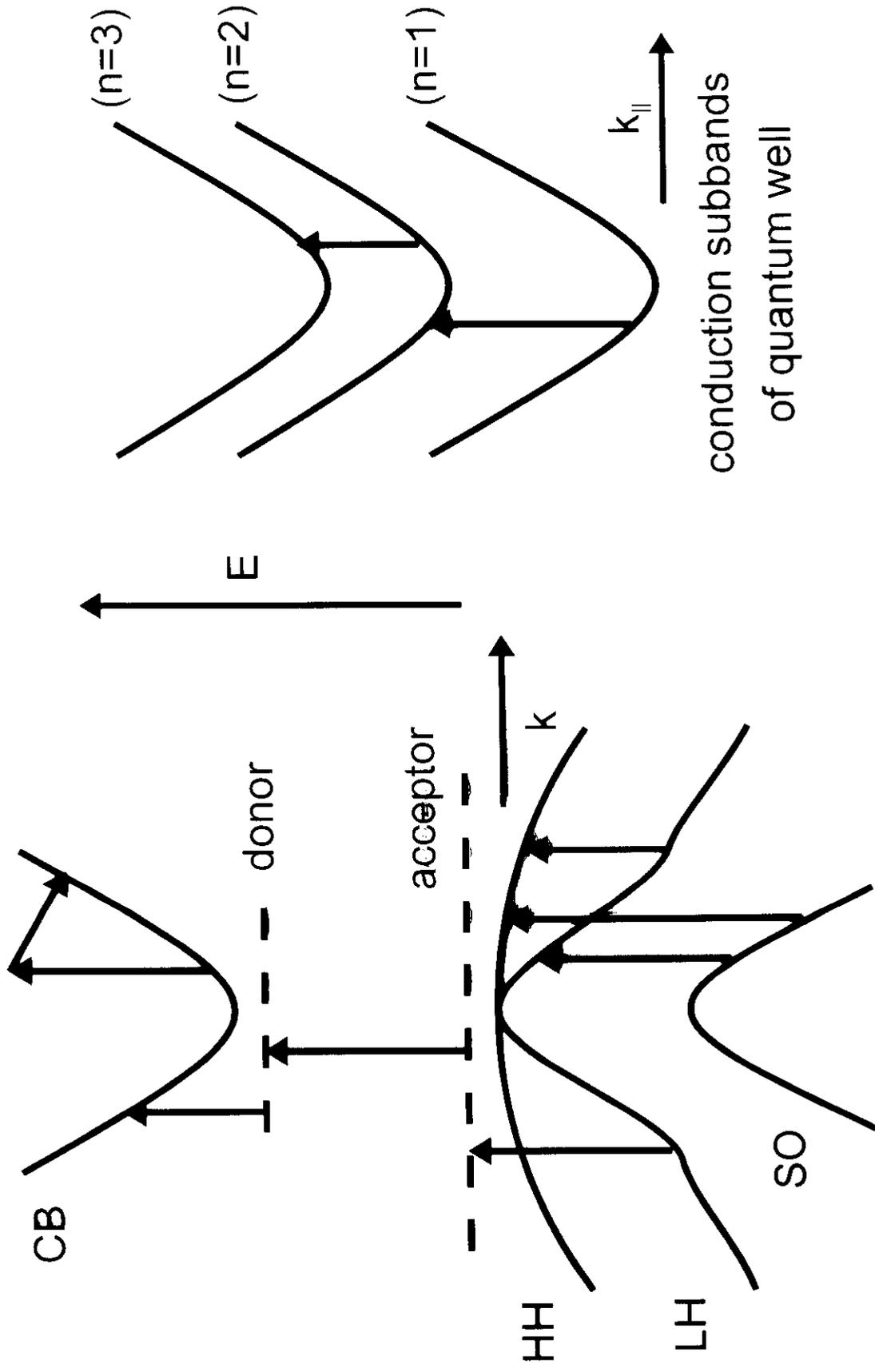


Excitons: $E_{B,n} = E_0 / (n - 1/2)^2$

Valence band structure of quasi-two-dimensional semiconductors



Below-Bandgap Excitations



band structure of bulk semiconductor

Coupling of Elementary Excitations

Electronic excitations: Coulomb interaction leads to

- ♦ Carrier-carrier scattering (e-e, e-h, h-h) via Coulomb interaction
- ♦ Exciton-carrier scattering
- ♦ Exciton-exciton interaction

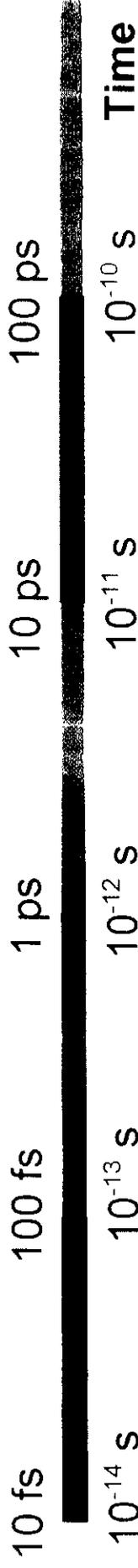
Electronic excitation - lattice:

- ♦ Carrier-LO phonon via polar-optical interaction
- ♦ Carrier-optical phonon via optical deformation potential
- ♦ Carrier-longitudinal acoustic phonon (piezoelectric scattering)
- ♦ Carrier-acoustic phonon via acoustic deformation potential
- ♦ Carrier-ionized impurity scattering via Coulomb interaction
- ♦ Carrier-neutral impurity scattering via dipole interaction and/or wavefunction mixing
- ♦ Carrier-defect (lattice imperfection) scattering

Scattering leads to phase and population (energy) relaxation

Ultrafast Processes in Semiconductors

Coherent Regime $\vec{P} = \chi : \vec{E}$ Thermalization of carriers Cooling Recombination
Impurity Trapping



Phase relaxation
of interband
excitation

Intra/inter-subband scattering

Coulomb Scattering
Optical Phonon Scattering

Acoustic Phonon Scattering

Ultrafast Processes, Optoelectronics, and Communication Technology

Ultrafast Processes in Semiconductors Optical Communication Technology Electronic Communication Techn.

Coherent Polarizations Optoelectronics

Carrier dynamics

Microwave

Digital electronics

100THz

1THz

10GHz

100MHz

10^{-14} s

10^{-13} s

10^{-12} s

10^{-11} s

10^{-10} s

10^{-9}

10^{-8} s

Ultrashort optical pulses

Optical/optoelectronic modulation techniques

Ultrafast Phenomena in Condensed Matter

Direct experimental study of the dynamics of elementary excitations

Time window 10^{-14} - 10^{-12} s

- ◆ *Microscopic interaction mechanisms*

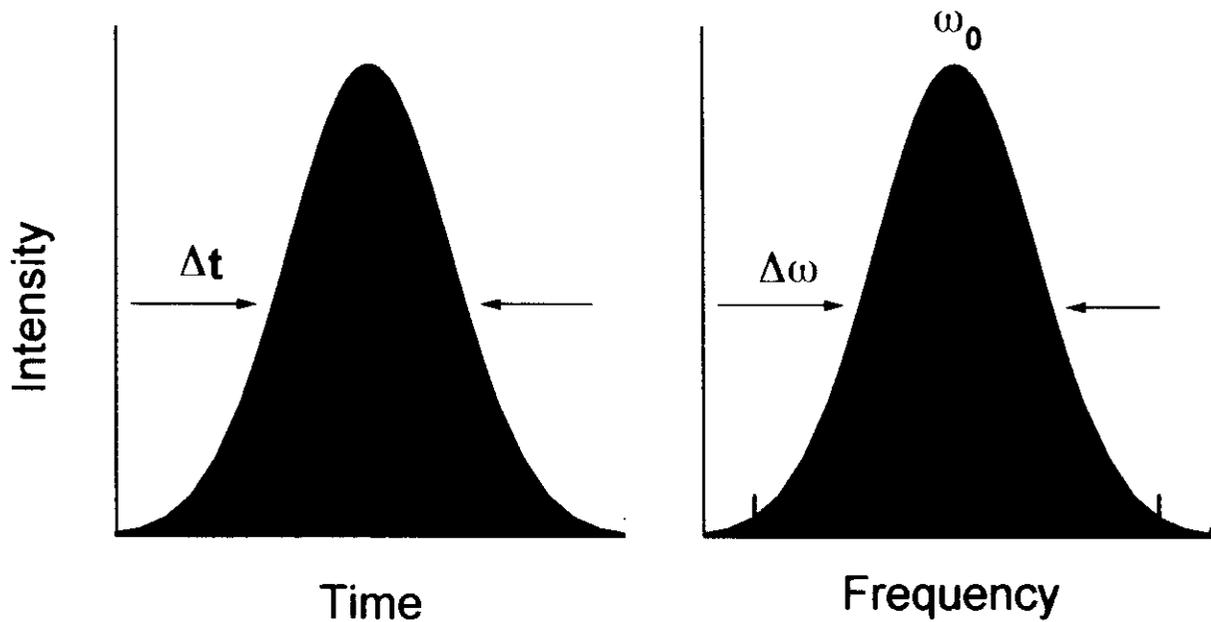
Femtosecond technology is relevant for

- ◆ *Metrology in physics, chemistry, biology*
- ◆ *optoelectronics/optical communications*
- ◆ *(material processing)*

Control of ultrafast processes by tailored optical excitation

- ◆ *Photochemistry, excitons in semiconductors*

Ultrashort Pulses



Optical Wavepackets

Time-bandwidth product : $\Delta t \times \Delta\omega = \text{const.}$

Gain bandwidth of the active medium :

$$\Delta t = 50 \text{ fs} \quad \Delta\omega = 5.53 \times 10^{13} \text{ Hz}$$

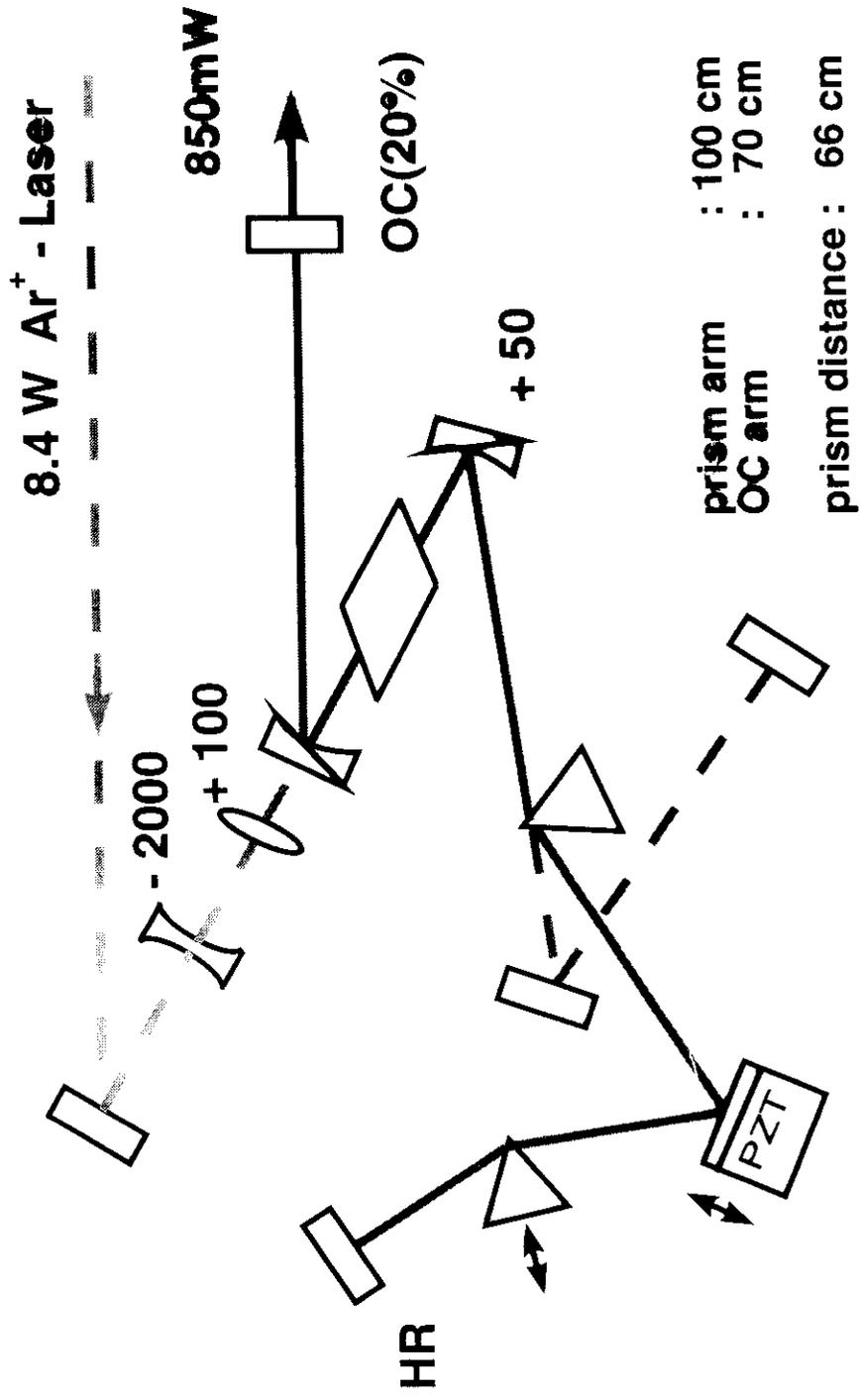
$(\Delta\omega/\omega_0) = 0.1$ for ω_0 in the visible spectral range

Mode synchronization :

Phase locking of longitudinal resonator modes

Dispersion control within the laser resonator

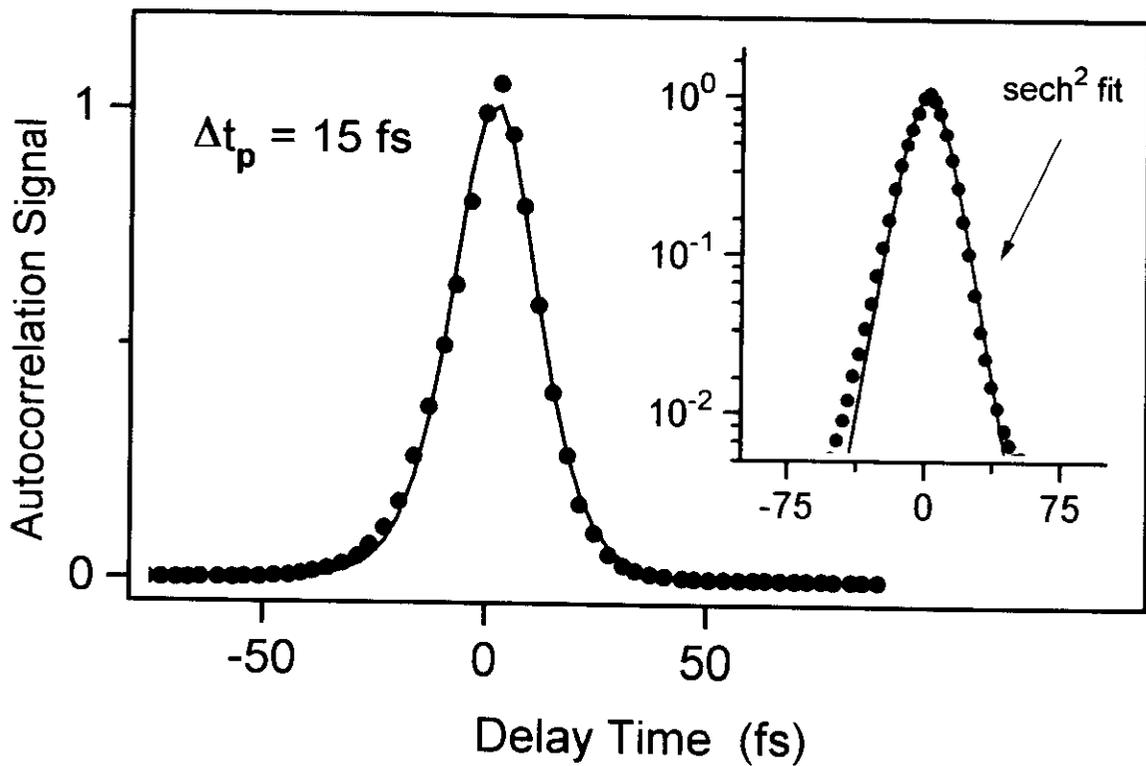
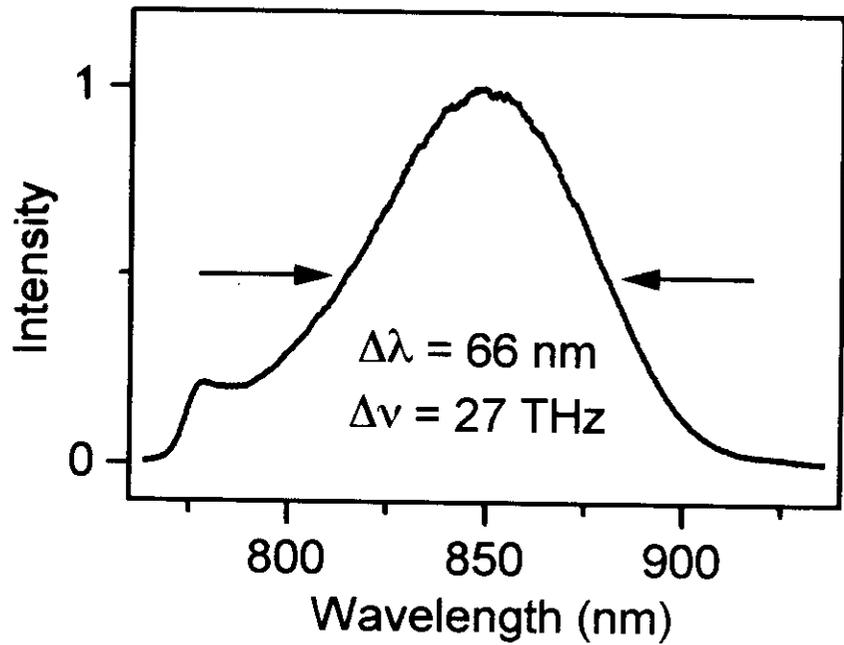
Schematic of the Ti:sapphire oscillator



Mode-locked Ti:sapphire laser

$P = 850 \text{ mW}$

$\Delta\nu\Delta t_p = 0.41$



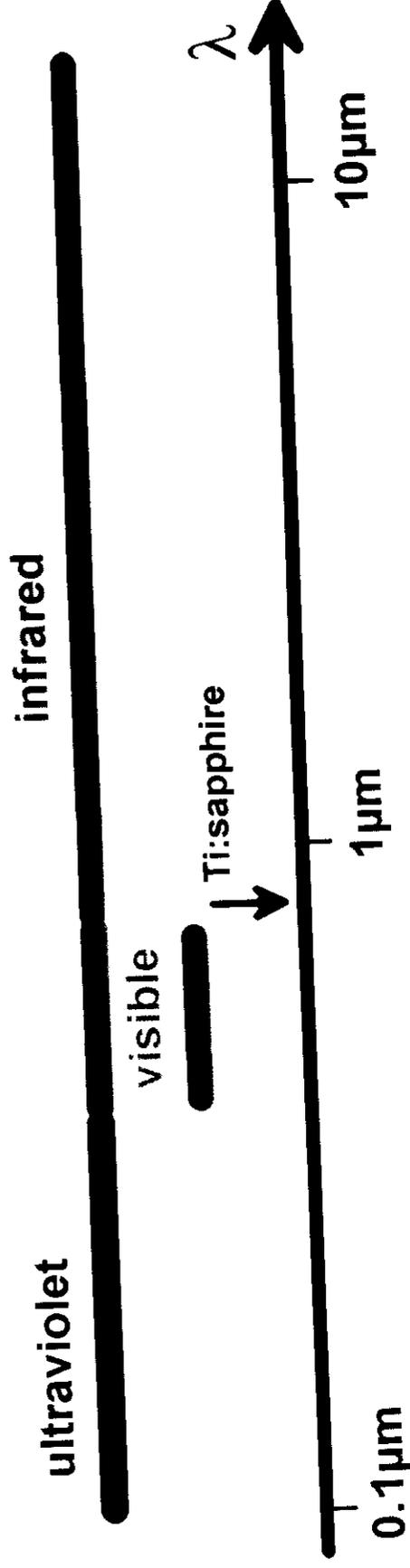
Amplification and Frequency Conversion of Ultrashort Pulses

Amplification: up to energies of mJ/pulse at kHz repetition rates
Regenerative amplification, multipass amplifiers

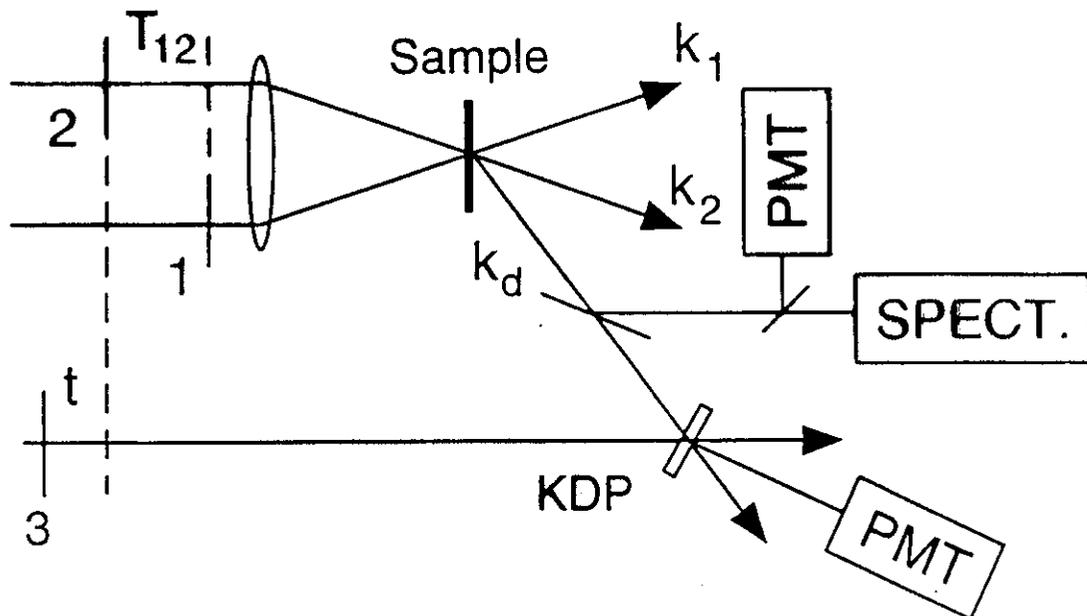
Nonlinear frequency conversion:

- ◆ Harmonic generation in nonlinear crystals (2nd order nonlinearities)
- ◆ Parametric frequency mixing (2nd order nonlinearities)
- ◆ White light continua by self-phase-modulation (3rd order nonlinearities)

State of the art: shortest pulse 4.5 fs, tuning range of ~100 fs pulses:



Degenerate Four-Wave-Mixing (FWM) Using Femtosecond Pulses



Nonlinear third-order polarization :

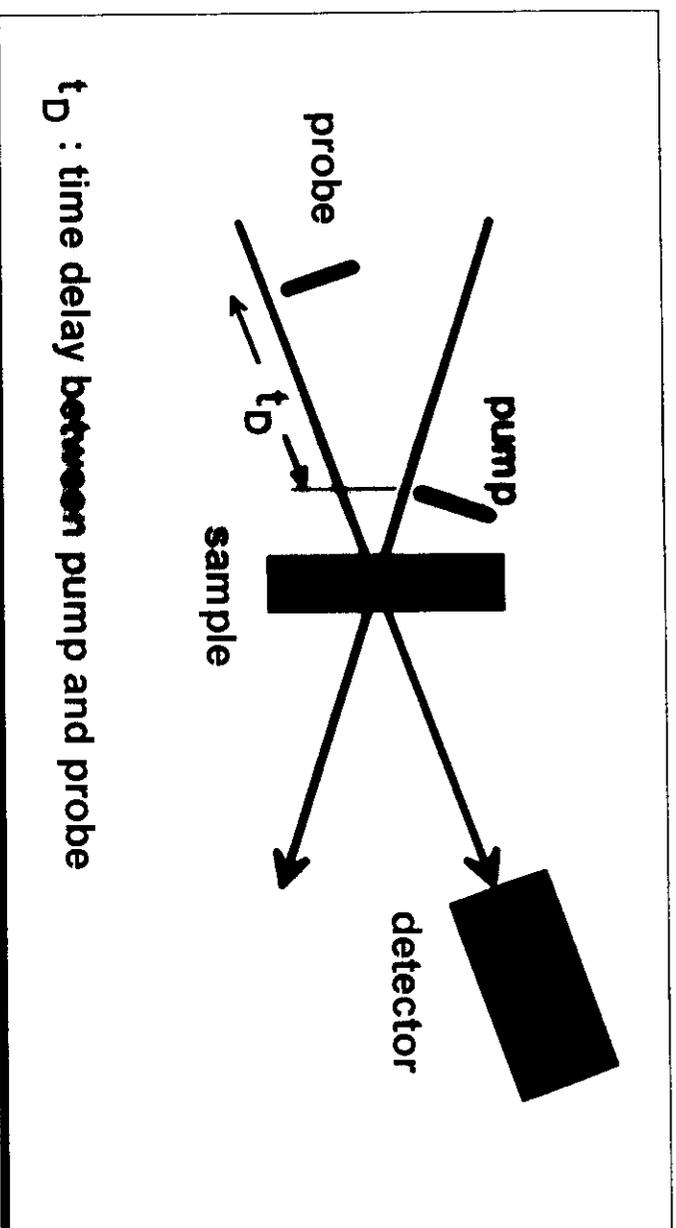
$$\mathbf{P}^{(3)}(\omega_1, \omega_2, \omega_3) = \chi^{(3)}: \mathbf{E}_1(\omega_1) \mathbf{E}_2(\omega_2) \mathbf{E}_3(\omega_3)$$

$$\omega_1 = \omega_2 = \omega_3 = \omega \quad \text{degenerate FWM}$$

$$\text{Diffracted intensity : } I_{FWM}(\omega, t) \propto |\mathbf{P}^{(3)}(\omega, t)|^2$$

$$\text{Phase-matching : } \mathbf{k}_d = 2\mathbf{k}_2 - \mathbf{k}_1, \quad 2\mathbf{k}_1 - \mathbf{k}_2$$

Pump and Probe Technique



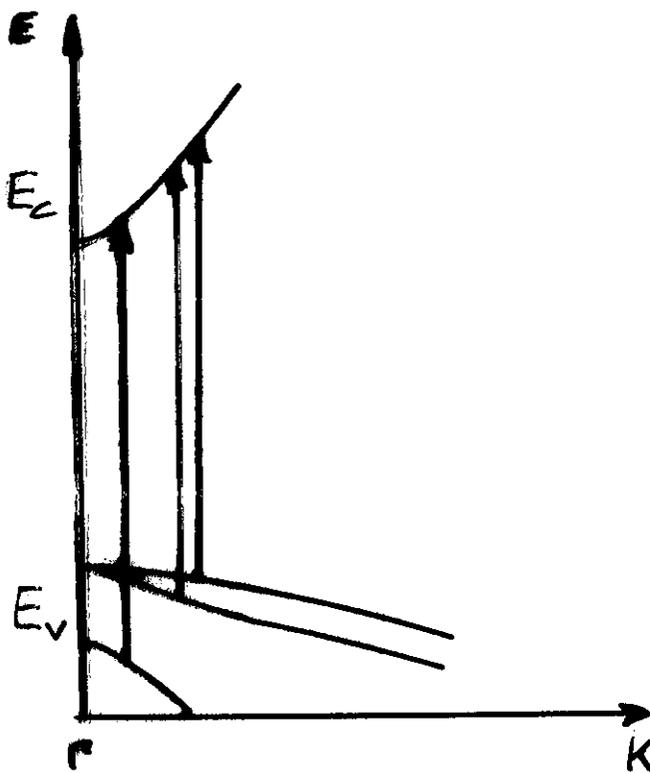
t_D : time delay **between** pump and probe

Pump pulse generates change of stationary optical properties (e.g., transmission, reflectivity)

Probe pulse monitors this change **as** a function of time delay t_D

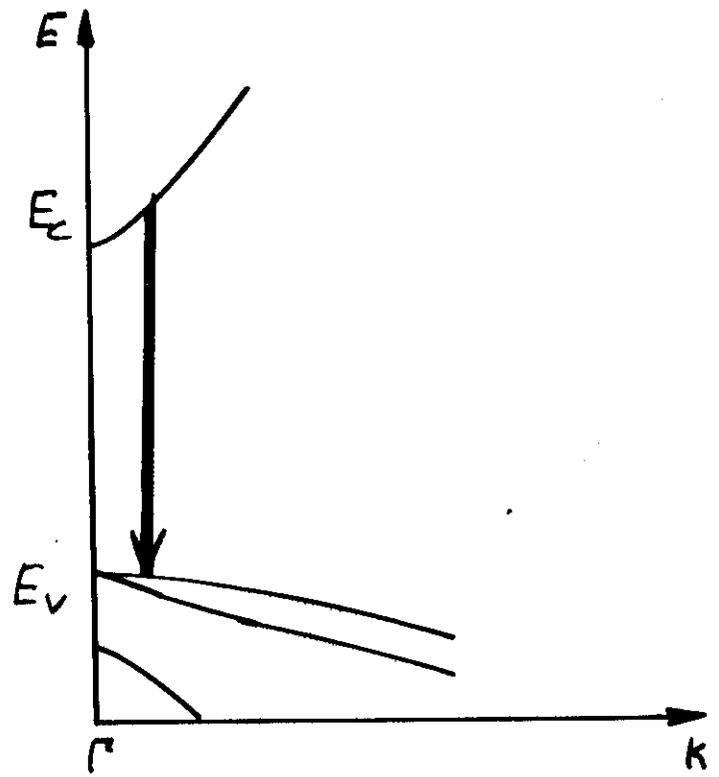
Time resolution is determined by **pulse** durations and dispersion in the sample

Time-resolved Probing of Hot Carrier Distributions



Nonlinear Absorption

$$\Delta\alpha(E) = -\alpha_0(E)[f_e(E_c) + f_h(E_v)]$$

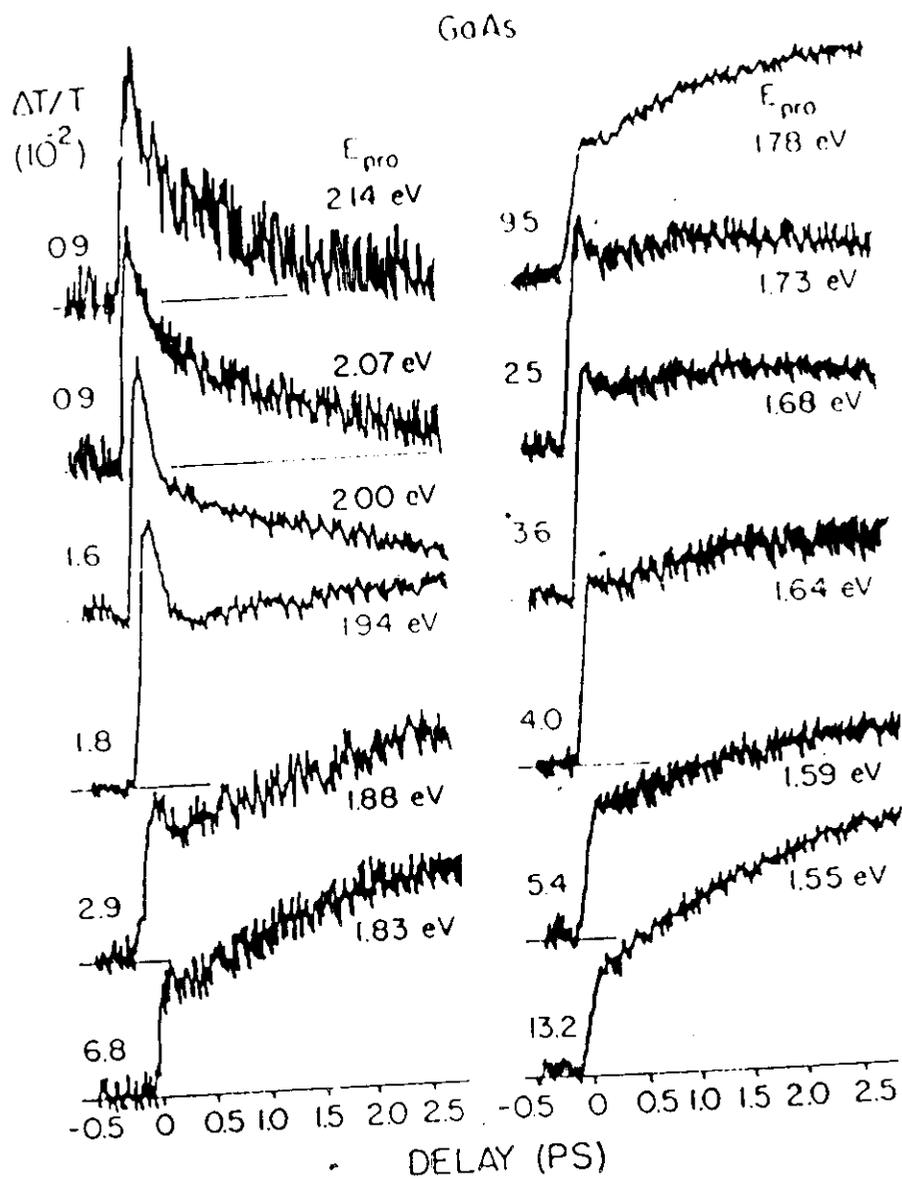


Luminescence

$$I_L(E) \propto \alpha_0(E)f_e(E_c)f_h(E_v)$$

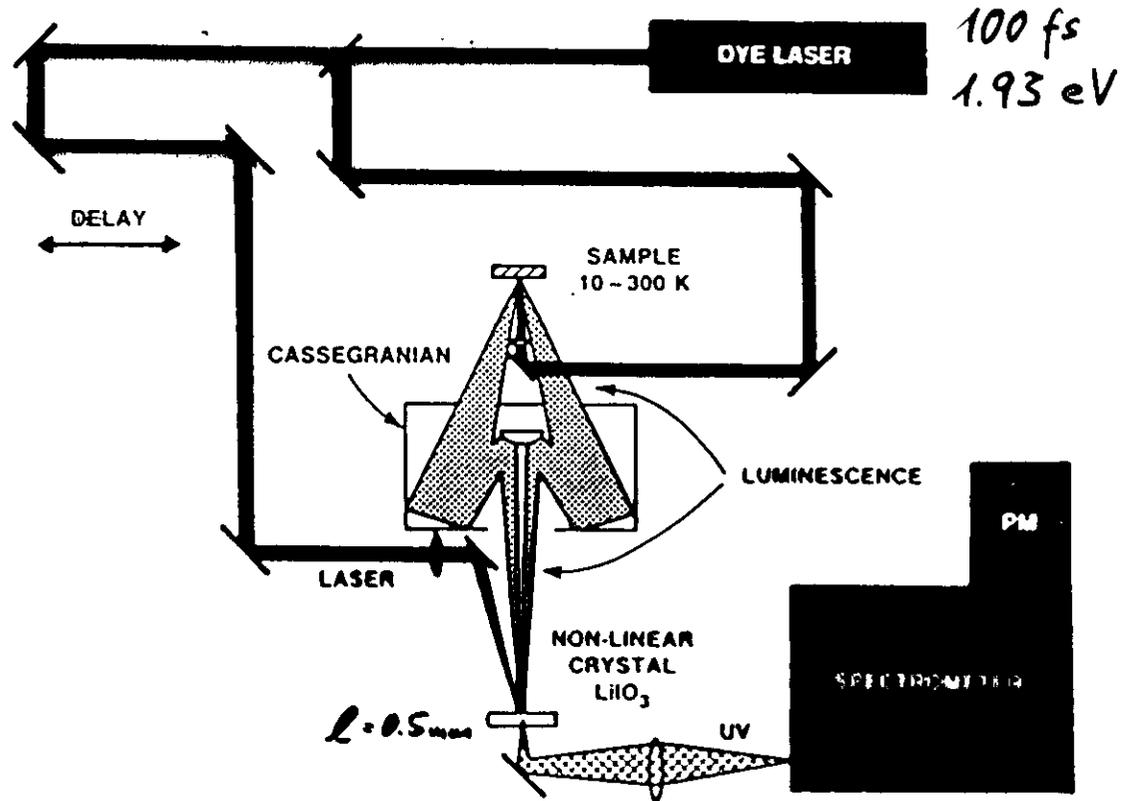
**Recombination of
electron and hole
at the same k**

W. Z. Liu, R. W. Schoenlein, J. G. Fujimoto, E. P. Ippen
IEEE J. Quant. Electron. QE-24 (1988)



Absorption

Femtosecond Luminescence Up-Conversion



Luminescence intensity : $I_L \propto \alpha_0(E) f_e(E_e') f_h(E_h')$

GaAs : $E < 1.7 \text{ eV}$: mainly electron \rightarrow heavy-hole recombination

Samples :

GaAs layer ($d = 0.6 \mu\text{m}$) clad by $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$

InP layer ($d = 2 \mu\text{m}$) grown on InP

Coherent Optical Polarizations

Experimental techniques:

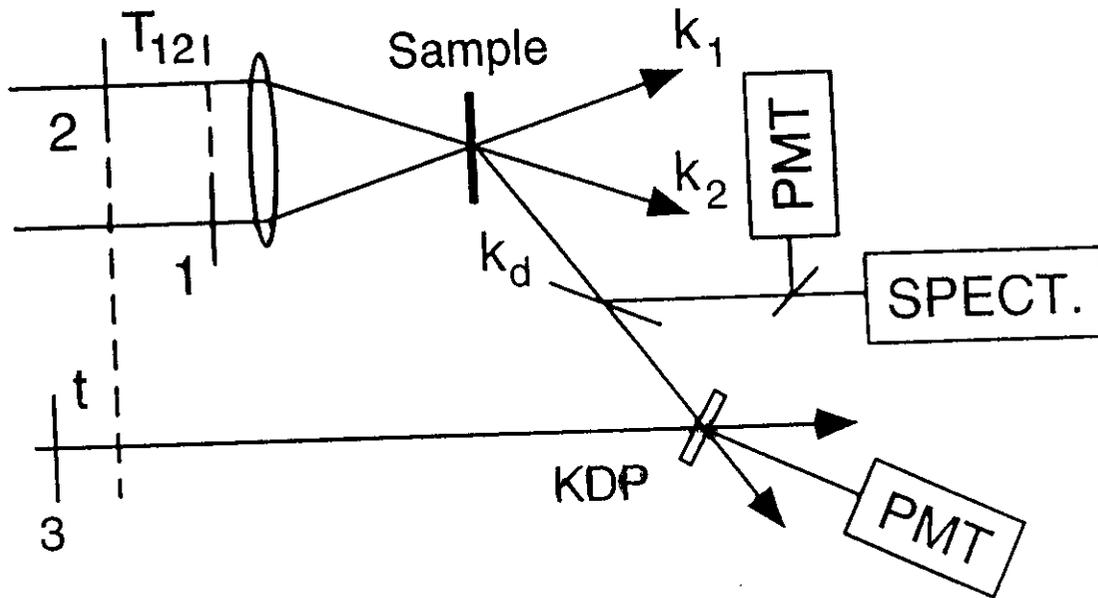
- ◆ Spectrally and time-resolved degenerate four-wave-mixing
- ◆ Pump-probe experiments on a 20 fs time scale

Coherent dynamics of excitons:

- ◆ Resonant enhancement of third order nonlinearities
- ◆ Quantum beats versus polarization interference
 - ◆ Interaction effects
- Quantum beats of continuum states

Coherent dynamics of intersubband polarizations

Degenerate Four-Wave-Mixing (FWM) Using Femtosecond Pulses



Nonlinear third-order polarization :

$$\mathbf{P}^{(3)}(\omega_1, \omega_2, \omega_3) = \chi^{(3)}: \mathbf{E}_1(\omega_1) \mathbf{E}_2(\omega_2) \mathbf{E}_3(\omega_3)$$

$$\omega_1 = \omega_2 = \omega_3 = \omega \quad \text{degenerate FWM}$$

$$\text{Diffracted intensity : } I_{FWM}(\omega, t) \propto |\mathbf{P}^{(3)}(\omega, t)|^2$$

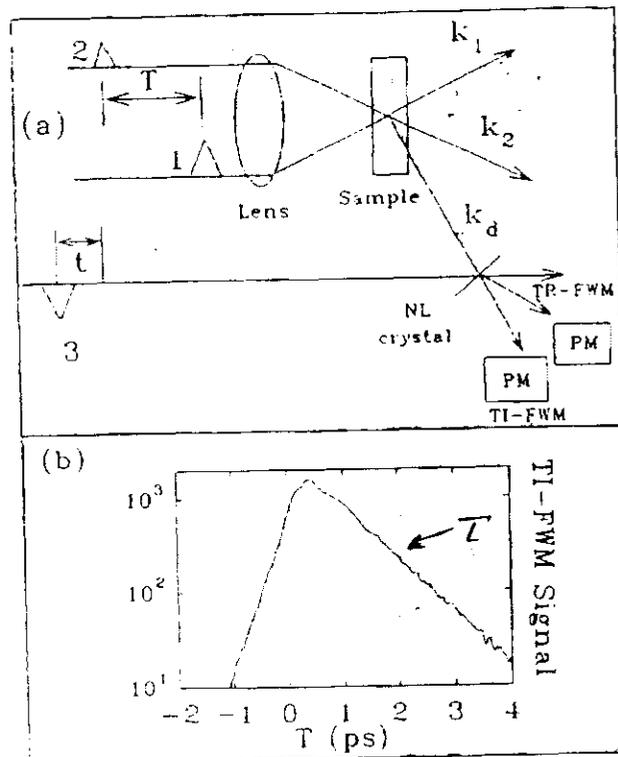
$$\text{Phase-matching : } \mathbf{k}_d = 2\mathbf{k}_2 - \mathbf{k}_1, \quad 2\mathbf{k}_1 - \mathbf{k}_2$$

Coherent Dynamics of Excitons

D.S. Kim et al., Phys. Rev. Lett. 69, 2725 (1992)

D.S. Kim et al., Phys. Rev. Lett. 68, 1006 (1992)

Time integrated FWM signal from a GaAs/AlGaAs multiple quantum well sample ($d=17\text{nm}$, 10 periods)



$$\bar{T} = \frac{T_2}{2}$$

T_2 : dephasing time

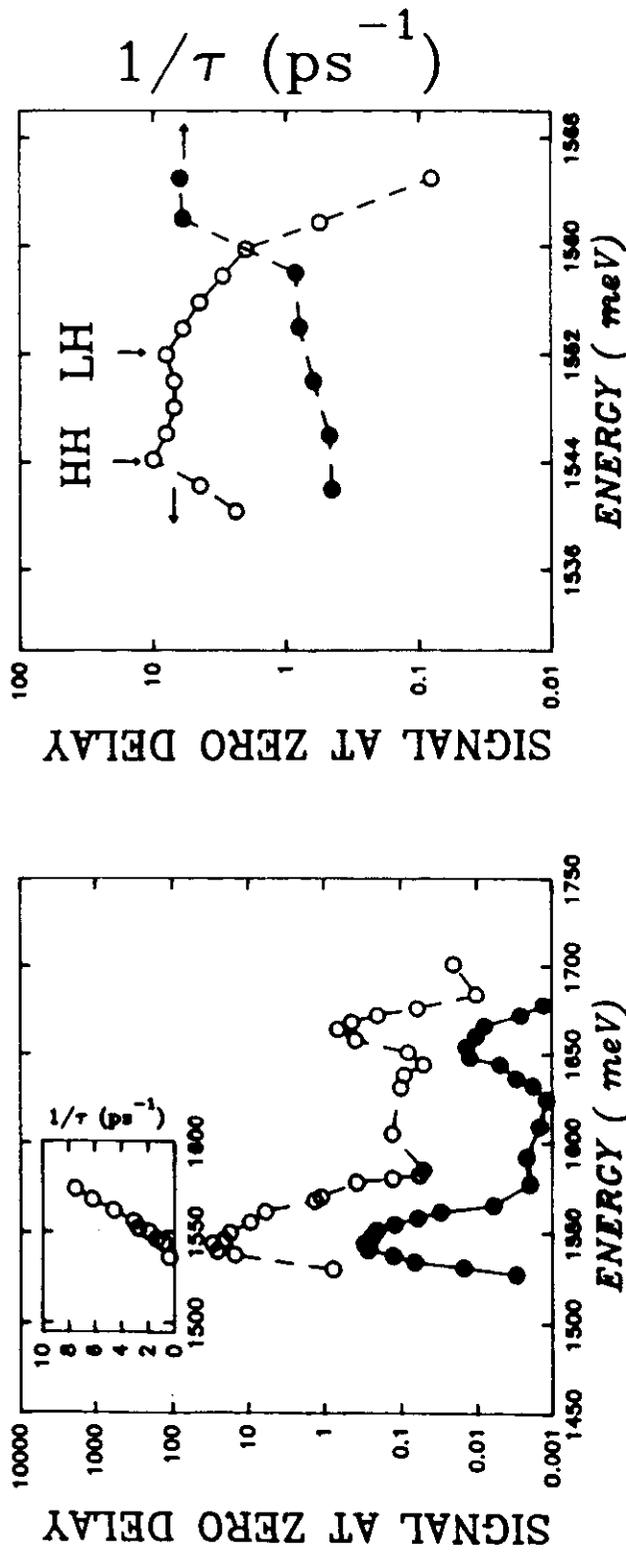
Decay times about 1 ps

Excitonic linewidth 0.7 meV, Stokes shift $< 0.1\text{meV}$

homogeneous broadening: free induction decay

Coherent Dynamics of Excitons II

D.S. Kim et al., *Phys. Rev. Lett.* 68, 1006 (1992)

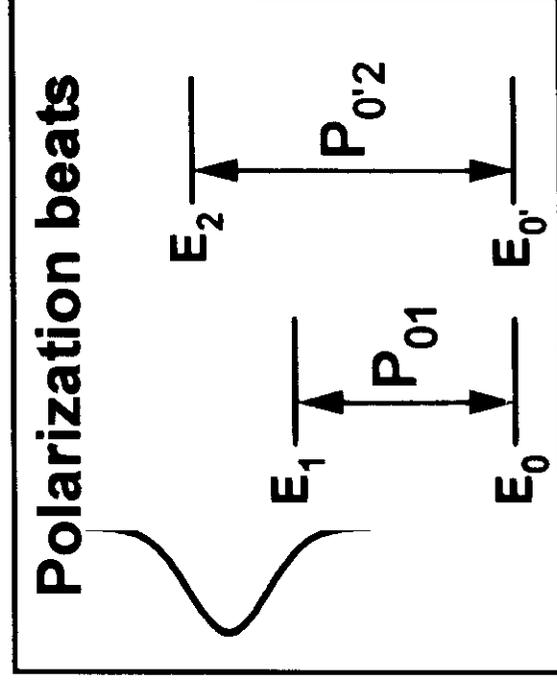


Time integrated FWM signal from a GaAs/AlGaAs multiple quantum well sample ($d=10\text{nm}$, 65 periods)

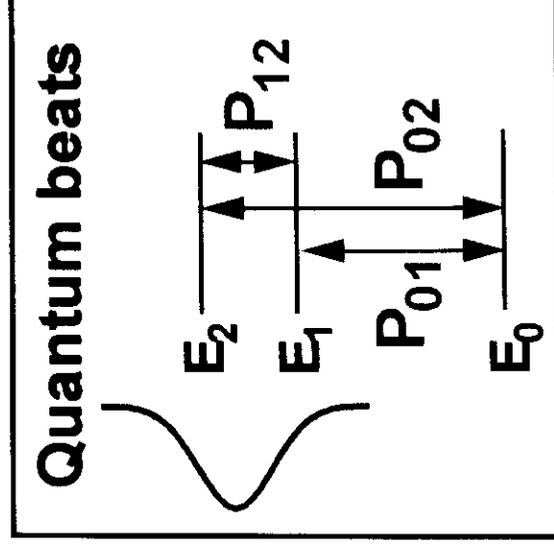
Resonant enhancement of FWM signals at the excitons

Coherent Spectroscopy of Excitons

- Excitons:
- large dephasing times ($T_2 \sim \text{ps}$)
 - discrete levels
 - large oscillator strength



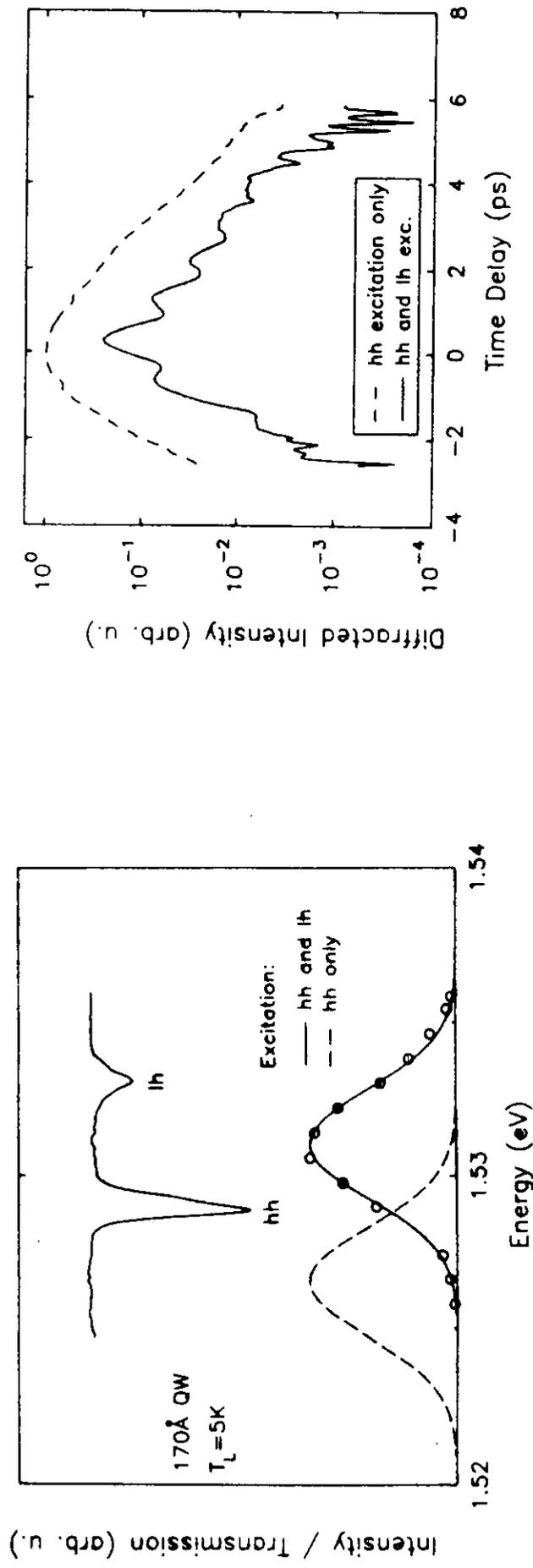
(Koch et al.)



2D: HH-, LH-excitons (Leo et al.)
magneto-excitons (Bar-Ad et al.)

Coherent Dynamics of Excitons III : Quantum Beats

K. Leo et al., *Appl. Phys. Lett.* 57, 19 (1990)

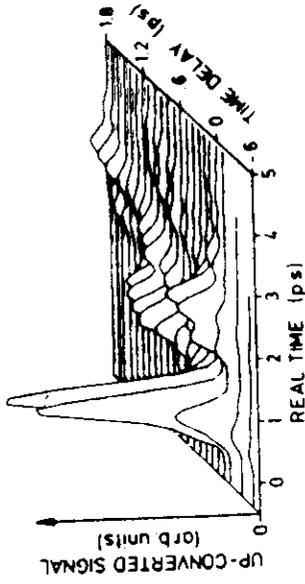


Time integrated FWM signal from a GaAs/AlGaAs multiple quantum well sample (d=17nm, 10 periods)

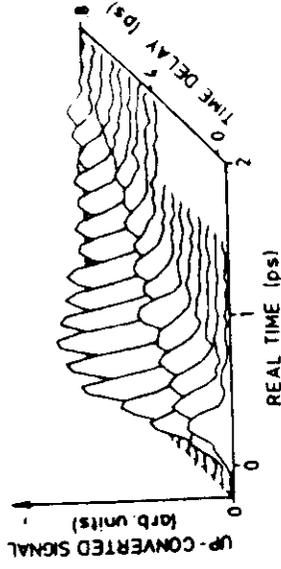
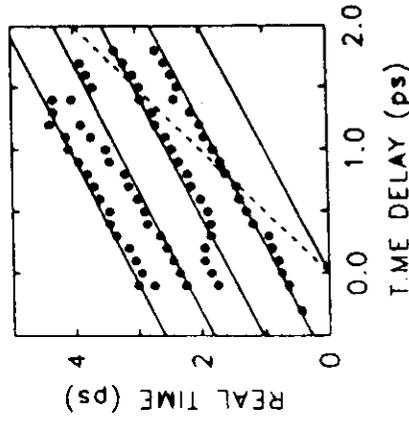
Heavy-light hole quantum beats of excitons

Coherent Dynamics of Excitons IV : Quantum Beats versus Polarization Interference

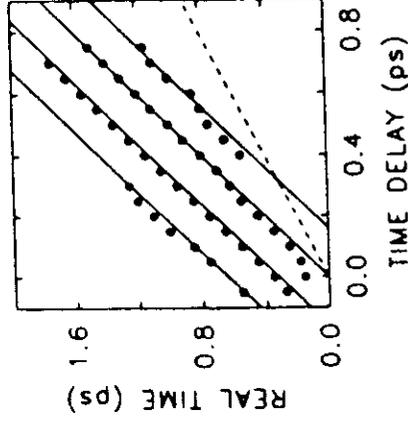
M. Koch et al., Phys. Rev. Lett. 69, 3631 (1992)



QB:
maxima
for
 $t = \tau + nT_B$

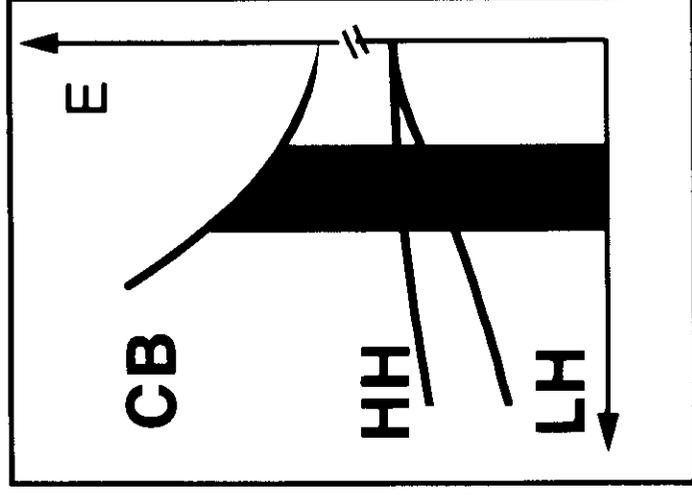


PI:
maxima
for
 $t = 2\tau \pm nT_B$



Time-resolved FWM signals from GaAs/AlGaAs multiple quantum well samples: ($d_1=8\text{nm}$, $d_2=9\text{nm}$, 2 x 40 periods)
($d=15\text{nm}$, 40 periods)

Coherent Spectroscopy of Free Carriers

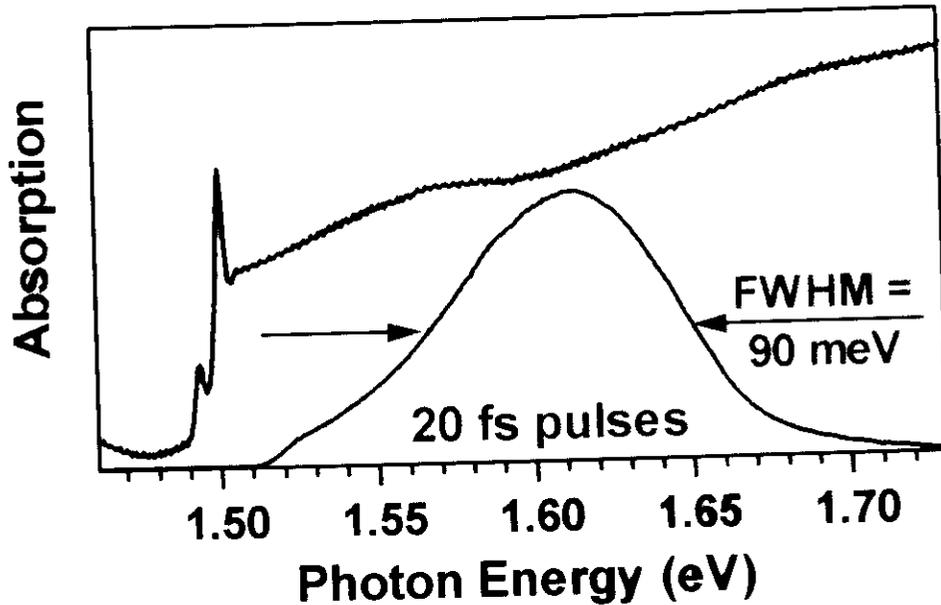


Band-to-band continuum:

- **ultrashort dephasing times ($T_2 < 100$ fs)**
Becker et al., Phys. Rev.Lett. 61, 1647 (1988)
Leitenstorfer et al., Phys. Rev. B 49, 16372 (1994)
Daunois et al., J. Appl. Phys. 77, 429 (1995)
- **inhomogeneously broadened systems**

time resolution: < 30 fs

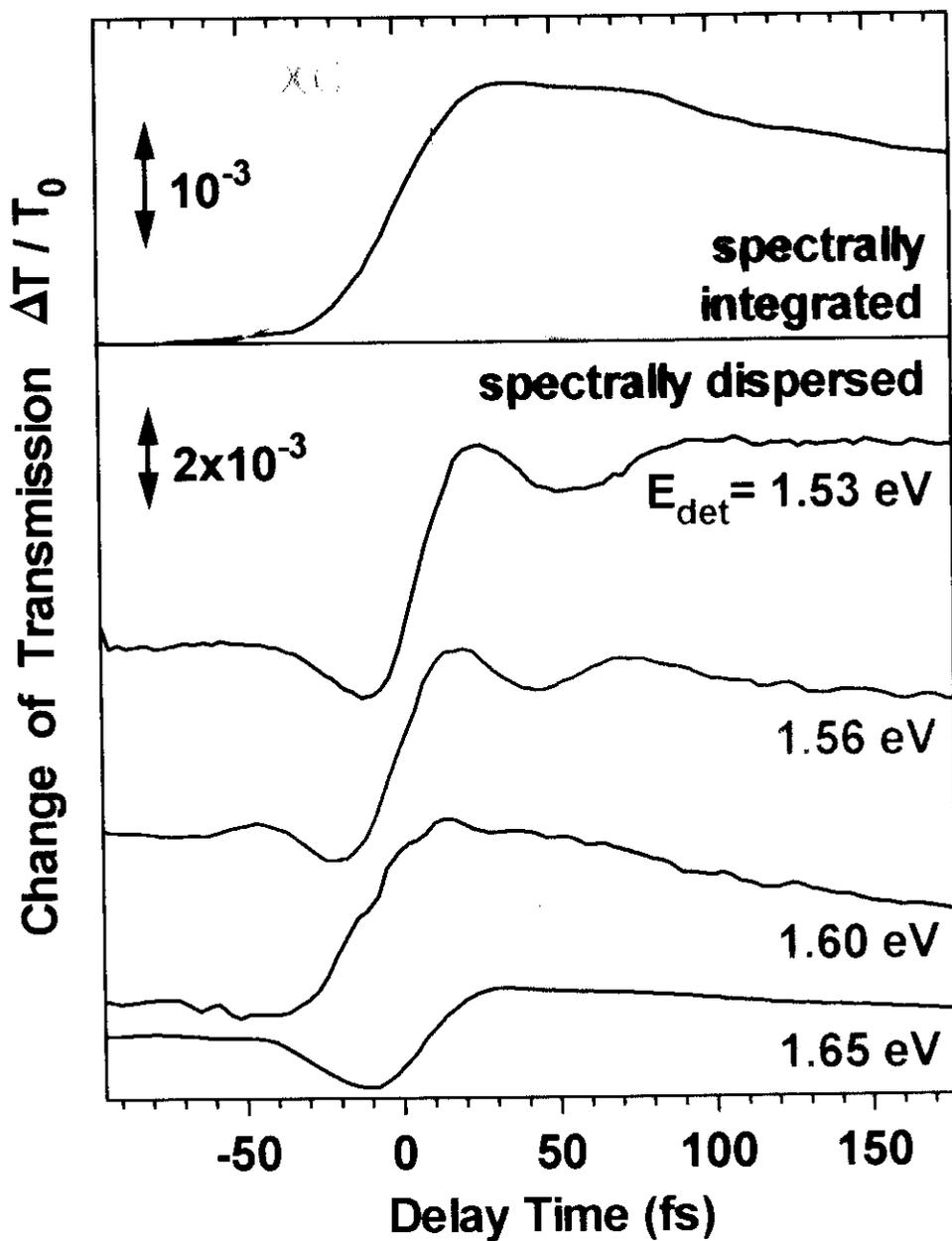
Experimental



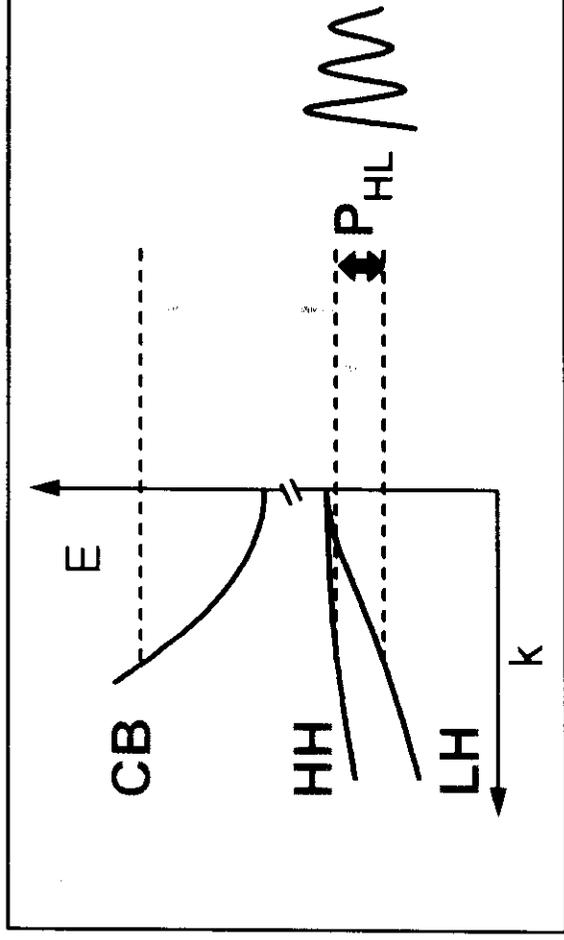
- no overlap with excitonic absorption lines
- parallel linear polarization of pump/ probe
- excitation density = $4 \cdot 10^{14}$ - $4 \cdot 10^{15}$ - $4 \cdot 10^{16} \text{ cm}^{-3}$
- 0.5 μm GaAs (clad between $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$)
 - undoped: $N_D < 1 \cdot 10^{15} \text{ cm}^{-3}$
 - n-doped: $N_D = 1 \cdot 10^{16}, 2 \cdot 10^{16}, 9 \cdot 10^{16} \text{ cm}^{-3}$
 - p-doped: $N_A = 3 \cdot 10^{16} \text{ cm}^{-3}$

Transient Interband Absorption of Intrinsic Sample

$n_{\text{ex}} \approx 4 \cdot 10^{15} \text{ cm}^{-3}$, parallel linear

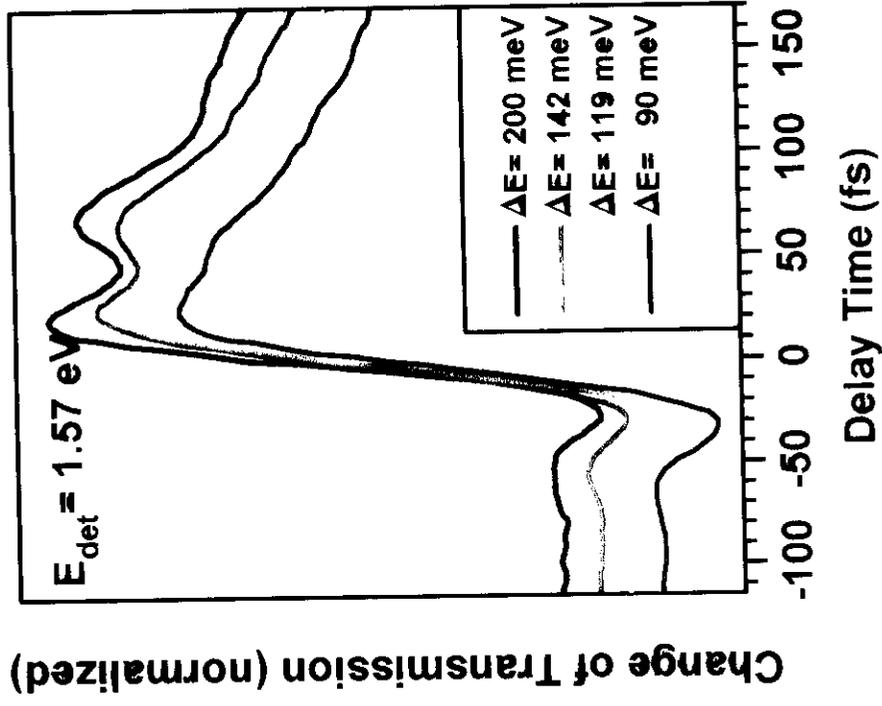


Quantum Beats in Bulk GaAs



- $\nu_{osc} = P_{HL} / \hbar$
- Coherent polarization P_{HL} oscillating with $\nu_{osc} = (E_{LH} - E_{HH}) / \hbar$.
- Oscillations of P_{HL} are transferred to pump-probe signal via $P^{(3)}$.

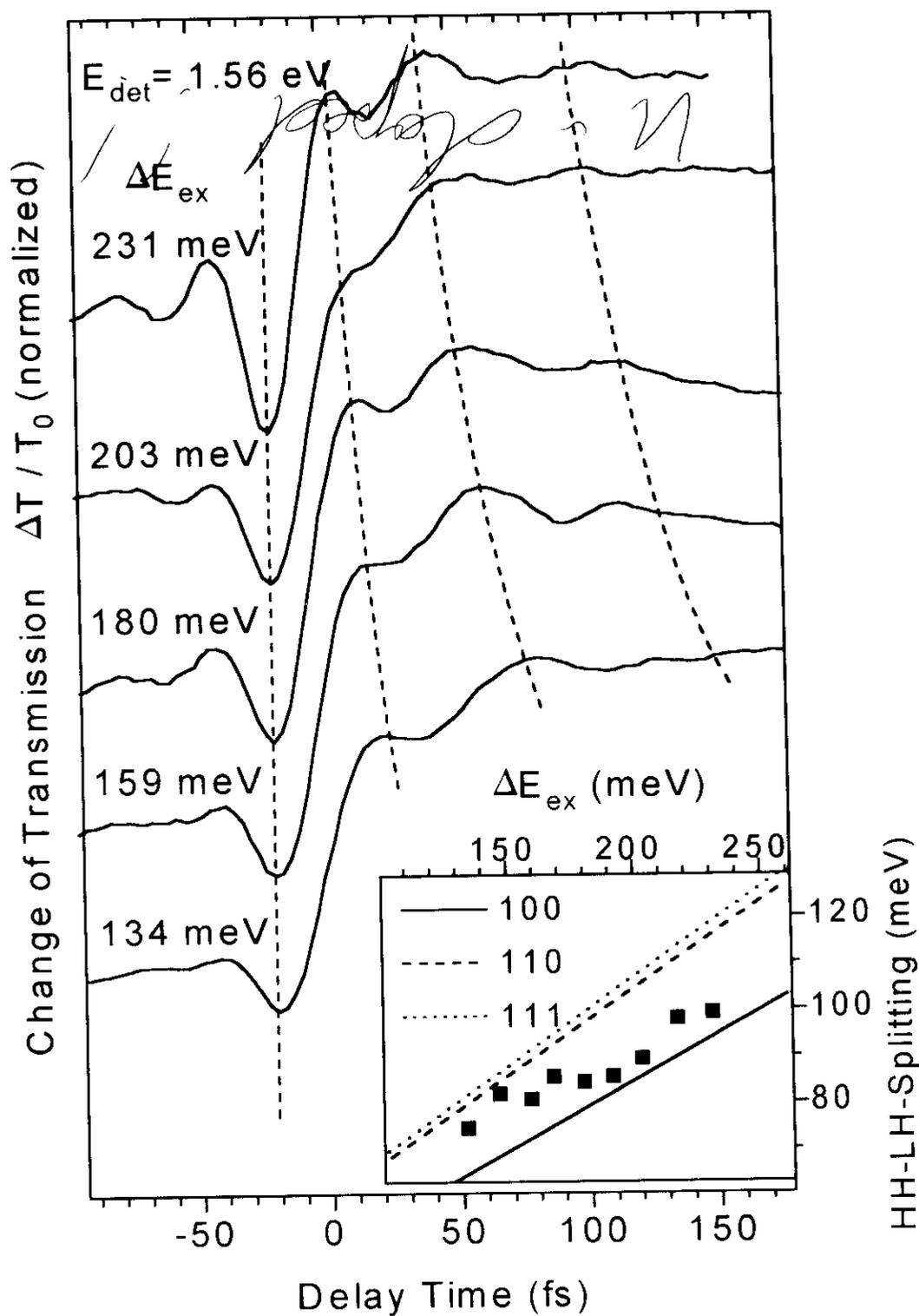
Reduction of Bandwidth before Interaction with Sample



Vanishing of coherent polarization P_{HL}

Heavy-Light Hole Quantum Beats

$$\text{Excess Energy } \Delta E_{\text{ex}} = E_{\text{pulse}} - E_{\text{gap}}(T_L)$$

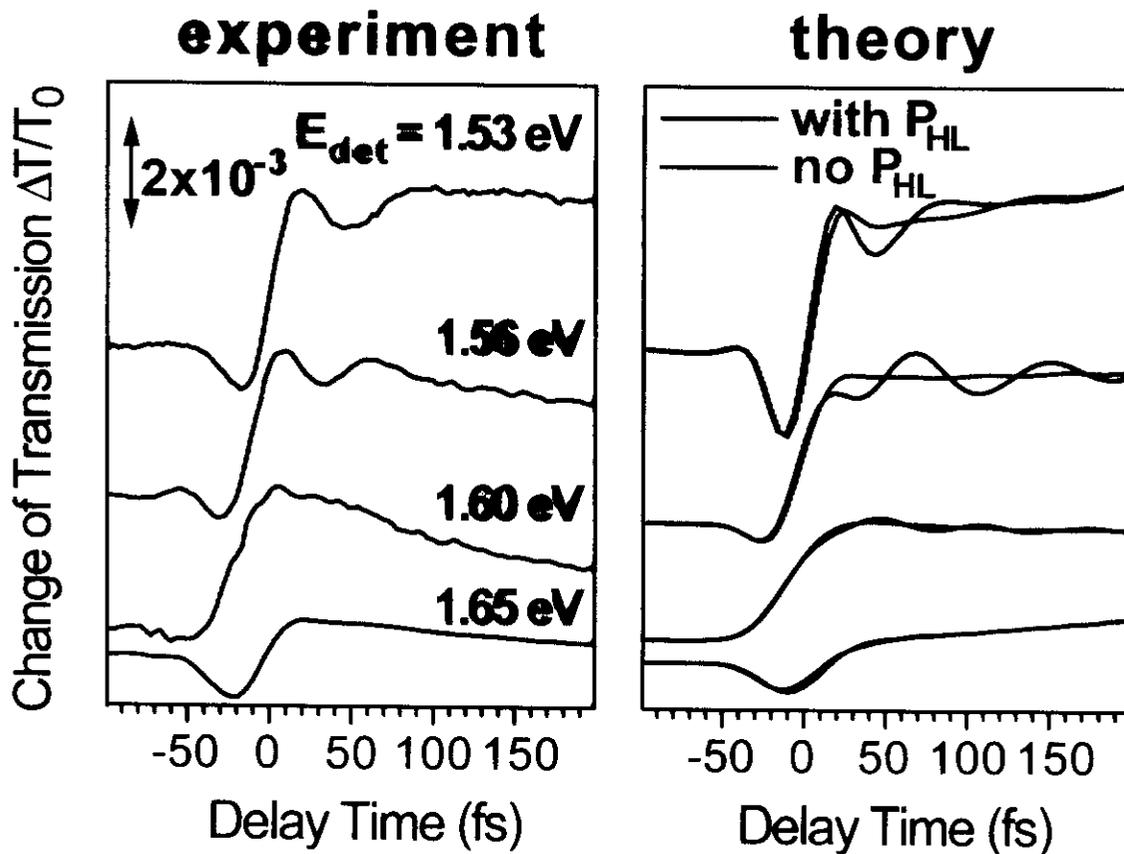


Theoretical Simulations

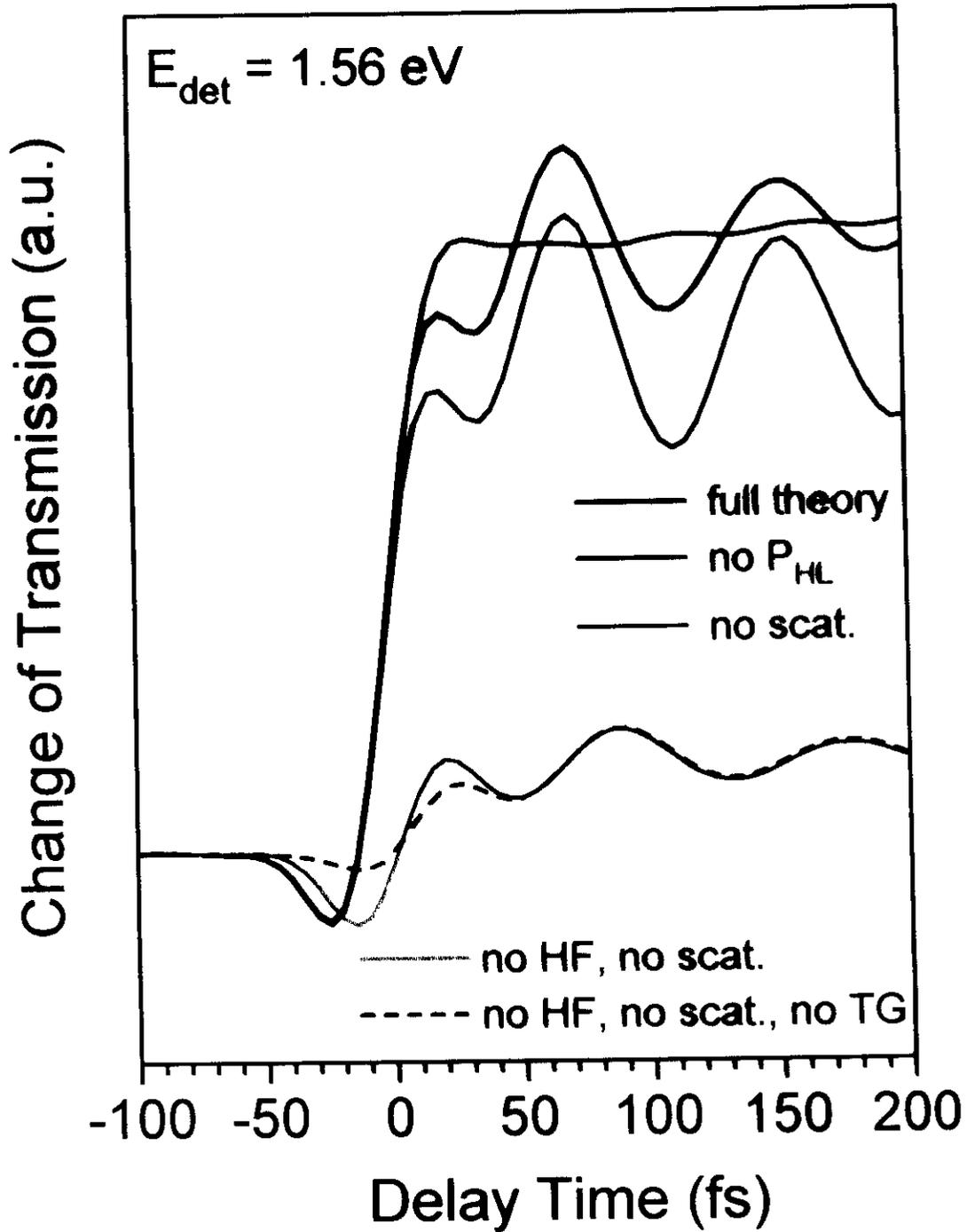
SBE: isotropic 3-band model
basic variables: $f_e, f_{hh}, f_{hl}, P_{CL}, P_{CH}, P_{HL}$

with: Coulomb correlations (static screening)
carrier-carrier scattering
carrier-LO-phonon scattering

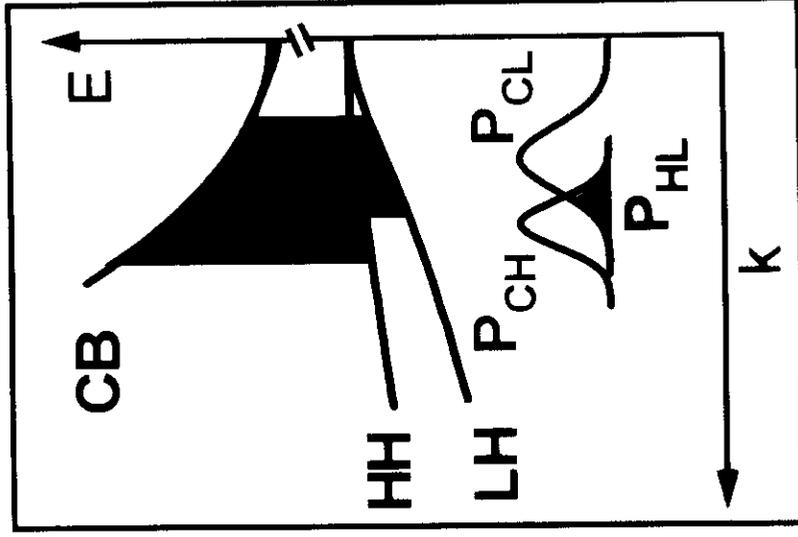
pump-probe geometry: spatial Fourier decomposition



Theoretical Simulations



Inhomogeneous Broadening



CB dispersion reduces:

overlap of excited HH-/ LH-transitions

⇒ range of frequencies in P_{HL}

⇒ damping of quantum beats

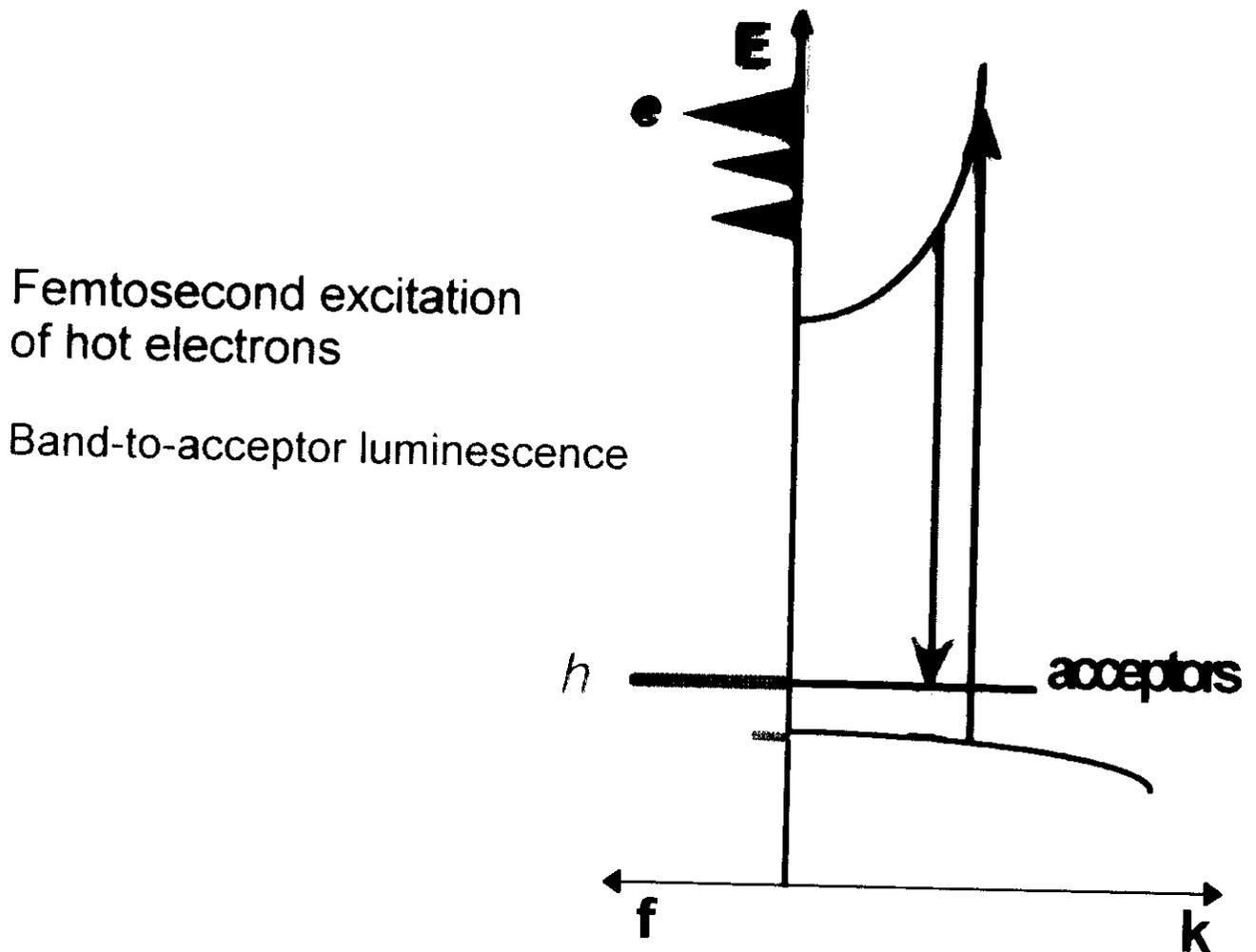
Conclusions

Spectrally and temporally resolved pump-probe experiments using 20 fs pulses

- Quantum beats in the band-to-band continuum of bulk GaAs
- Impulsively excited coherent polarization between heavy and light hole states gives rise to quantum beats
- Beat frequency is determined by heavy-light hole energy splitting
- Dephasing by carrier-carrier and LO phonon scattering and by inhomogeneous broadening within the optically coupled continuum states
- Heavy-light hole beats contribute to nonlinear response for band-edge excitation

M. Joschko et al., PRL 78, 737 (1997)

Coherent Femtosecond Carrier Generation in GaAs



Coherent coupling of laser pulse and material influences carrier generation process and initial distribution functions

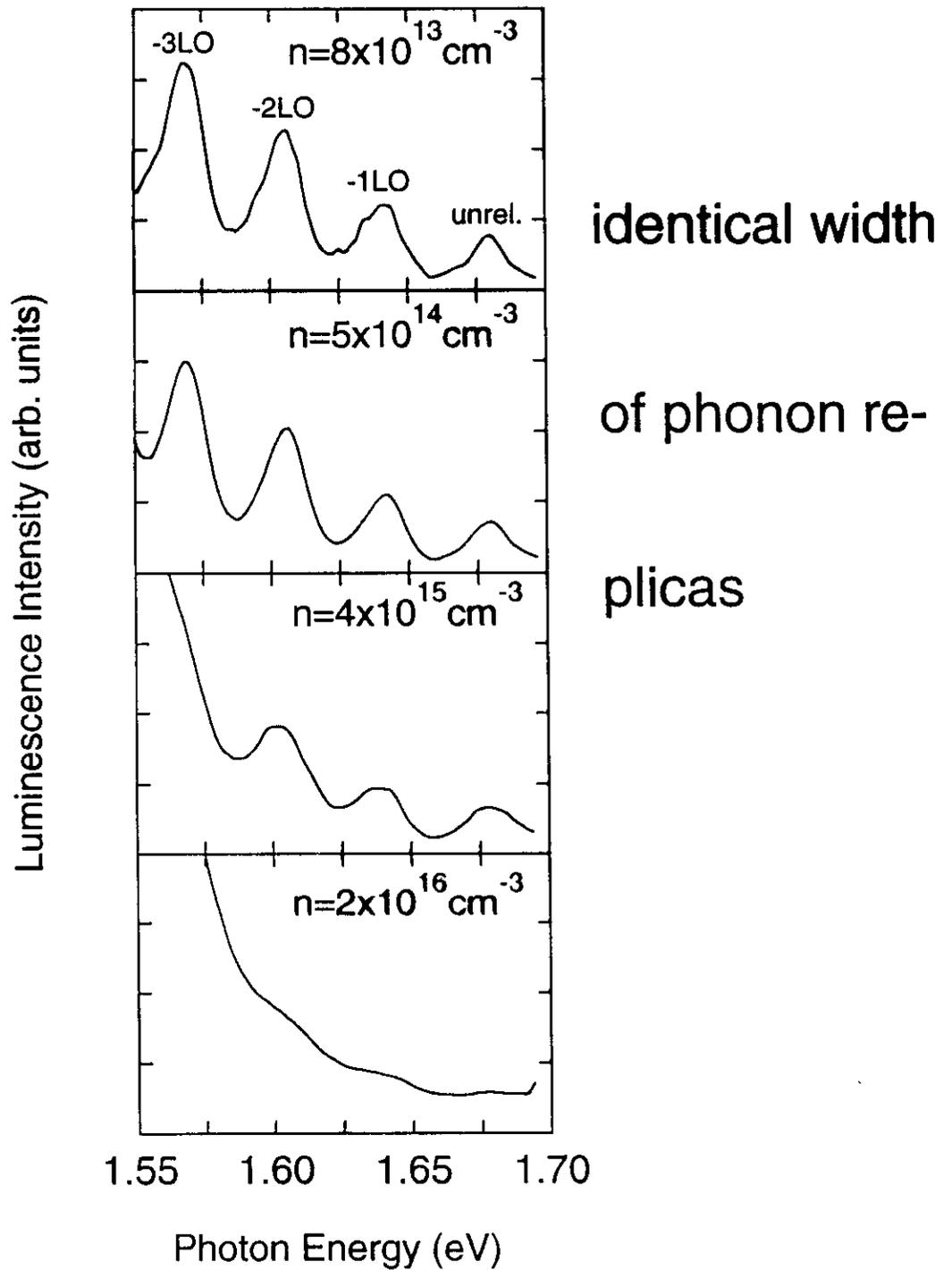
Direct observation of non-equilibrium electron distribution

Experiment: Time-integrated band-to-acceptor luminescence in p-type GaAs after femtosecond excitation

Luminescence spectra of p-type GaAs

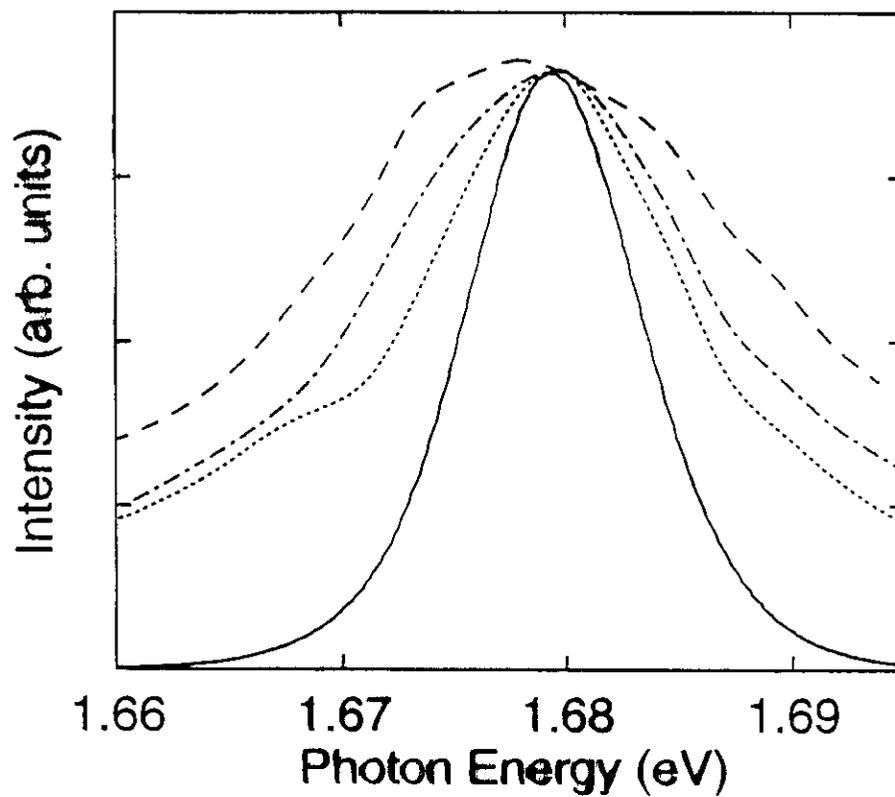
Acceptor concentration $3 \times 10^{16} \text{ cm}^{-3}$

150 fs excitation pulses (1.75 eV)



Phys. Rev. Lett. 73, 1687 (1994)

First Luminescence Peak

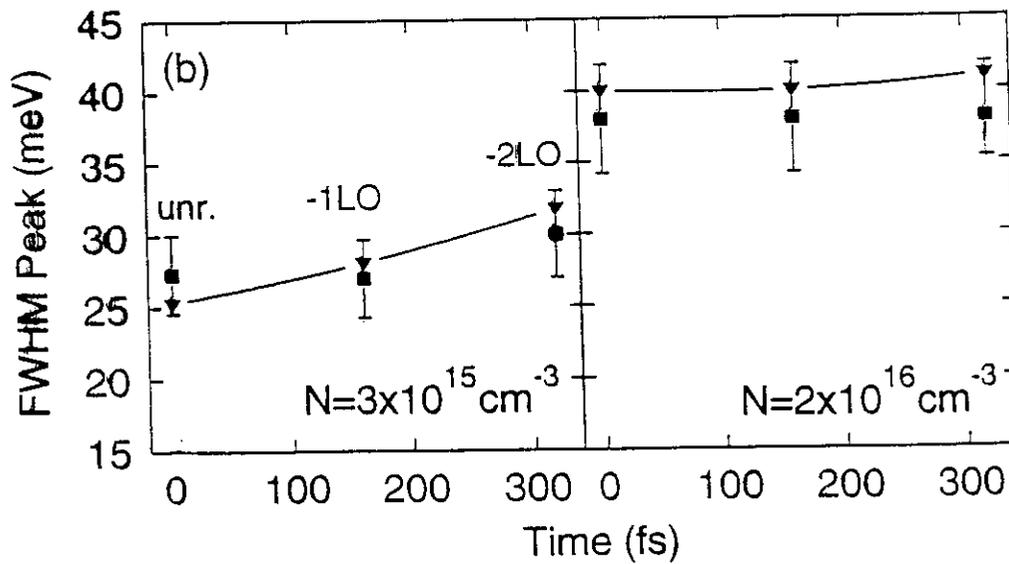
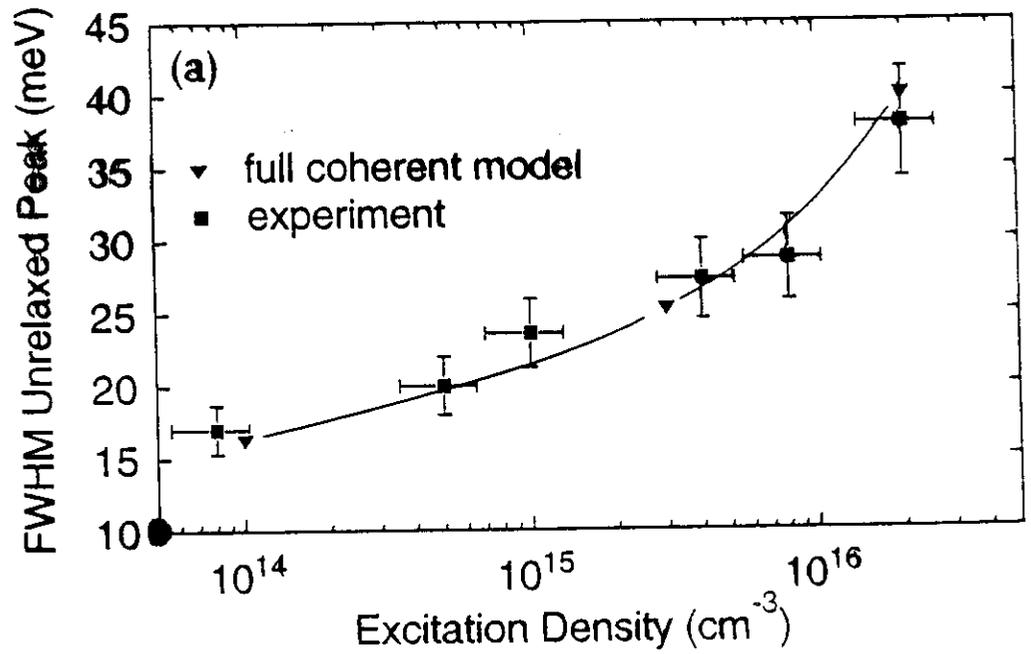


$$N = 8 \times 10^{13} \text{ cm}^{-3}$$

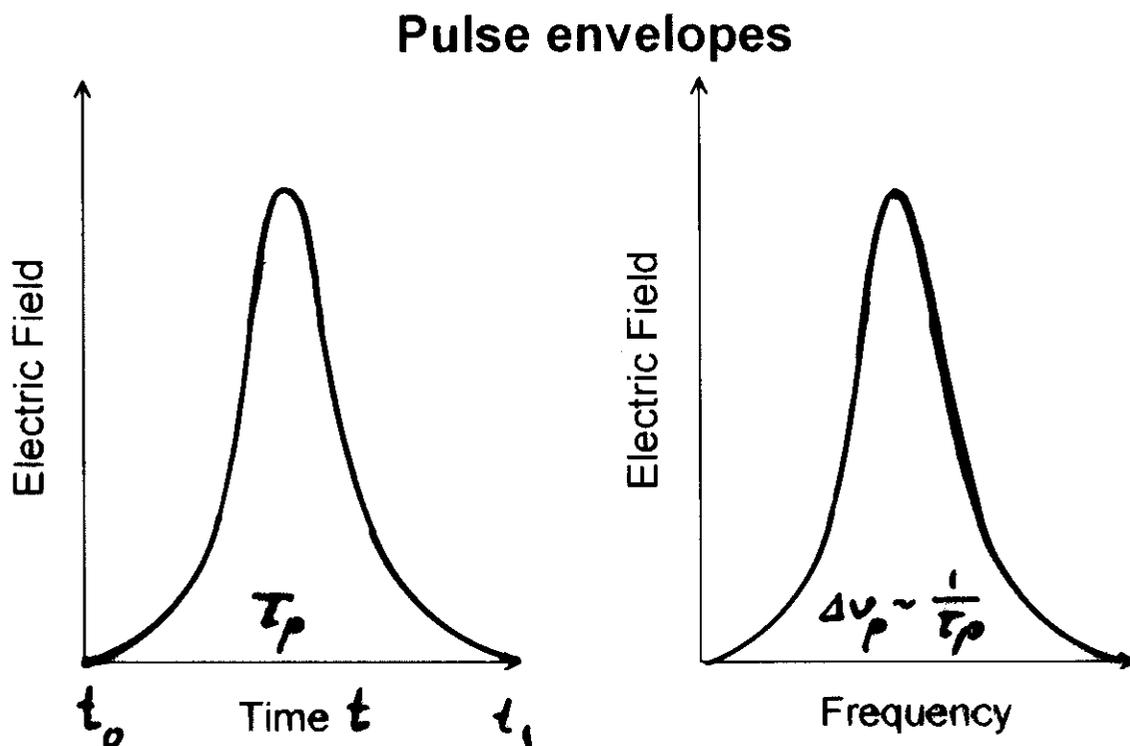
$$N = 5 \times 10^{14} \text{ cm}^{-3}$$

$$N = 4 \times 10^{15} \text{ cm}^{-3}$$

Spectral Width of the Luminescence Peaks



Shape of the Initial Electron Distribution



Momentary width of the electron generation rate:

$$\Delta E_{\text{mom}} \sim 1/(t-t_0)$$

Ideal system: no dephasing during excitation

Coherent recombination of electrons in off-resonant states

$t > t_1$: electron distribution follows power spectrum

Real system: strong dephasing during excitation

Broadening of initial electron distribution

Theoretical Model

Generalized Monte Carlo solution of the semiconductor Bloch equations:

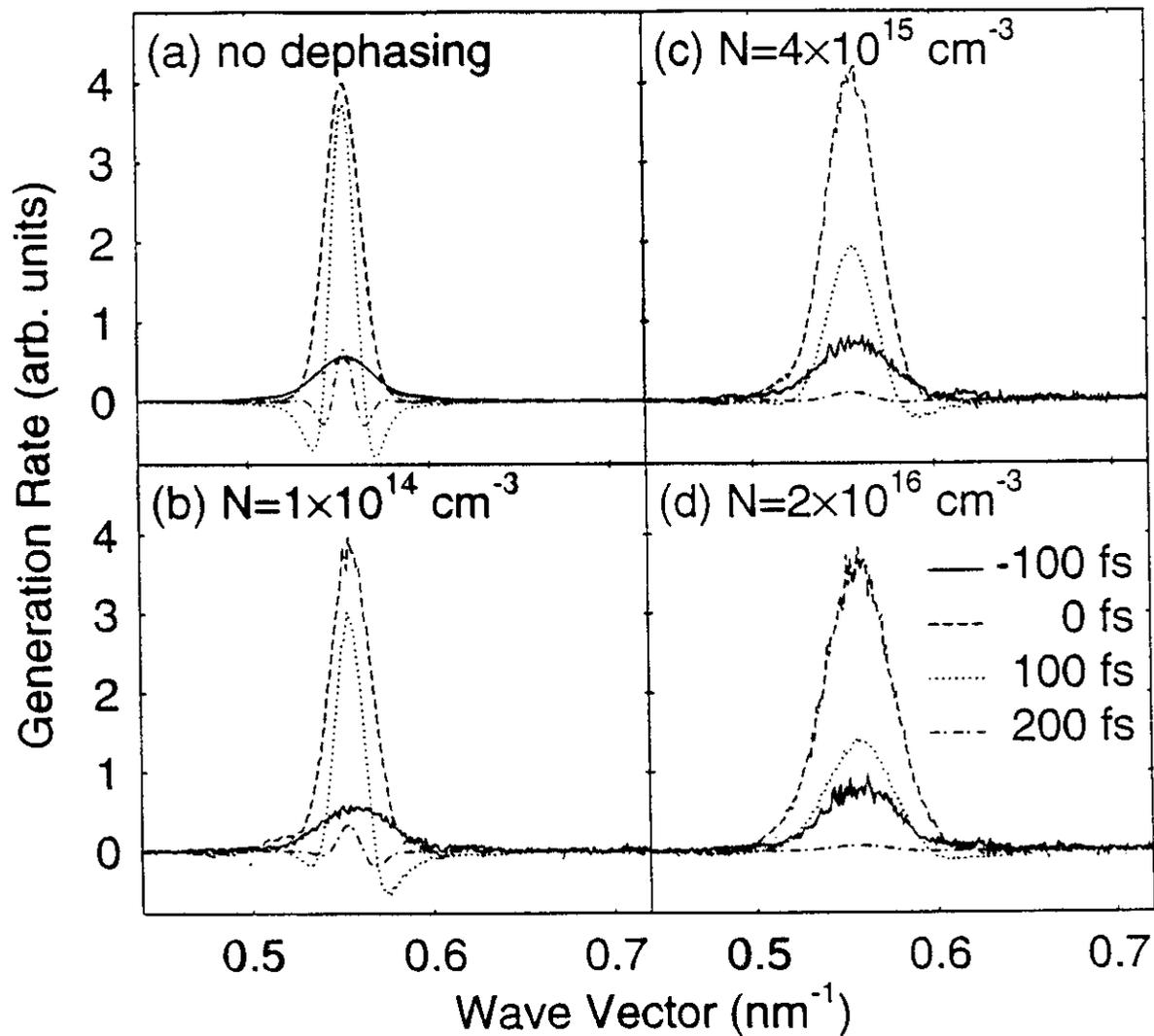
Simulation of both coherent and incoherent dynamics
(Interband Polarization, distribution functions)

Luminescence spectra calculated from distribution functions

Ref:

F.Rossi, S. Haas, T. Kuhn, PRL 72,152 (1994)

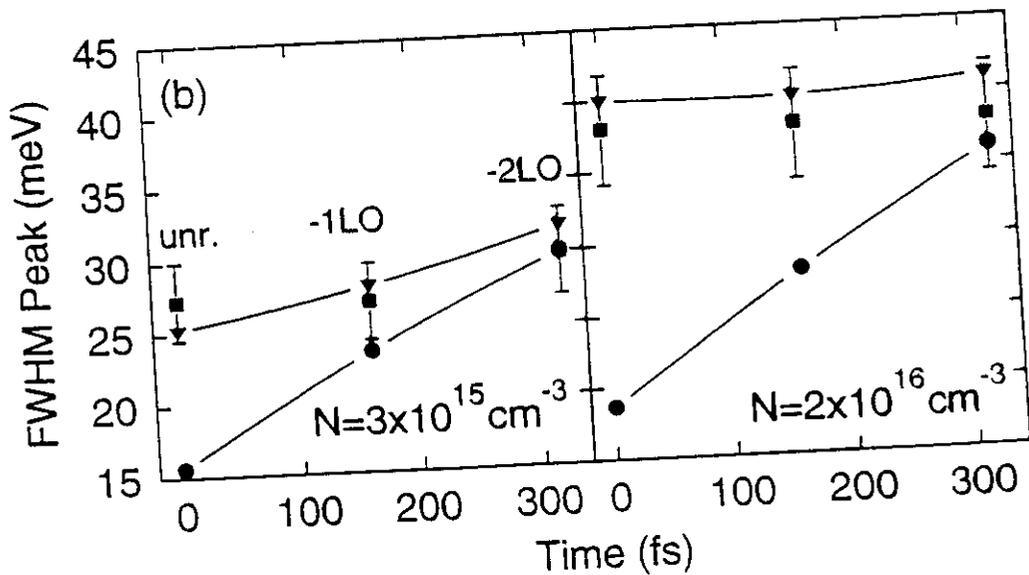
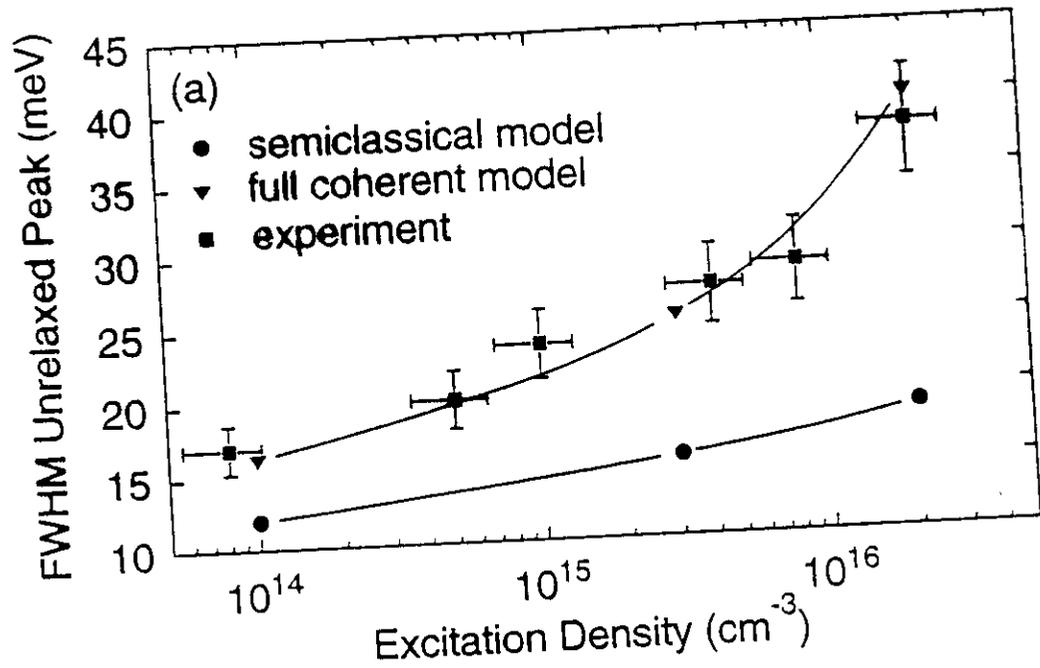
Calculated Carrier Generation Rates



**Main broadening mechanism :
Dephasing by carrier-carrier collisions**

Spectral Width of the Luminescence Peaks:

Theory and Experiment



Conclusions

Band-to-acceptor luminescence of p-type GaAs after femtosecond excitation :

- Luminescence peak from directly populated conduction band states shows larger spectral width than excitation pulse
- Identical spectral width of successively generated phonon replicas

Dephasing during excitation process determines spectral profiles.

Dominant mechanism : carrier-carrier scattering (important : hole-hole scattering)

Broadening due to carrier redistribution much less important

Theoretical calculations: generalized Monte-Carlo solution of the semiconductor Bloch equations

- quantitative agreement with experimental results

6. Carrier thermalization and cooling

Thermalization: Optically generated nonequilibrium distribution of **carriers** undergoes relaxation into a quasi-equilibrium, i.e. **hot Fermi distribution**.
Main scattering processes: **Coulomb** (carrier-carrier) scattering and **carrier-optical phonon** scattering.

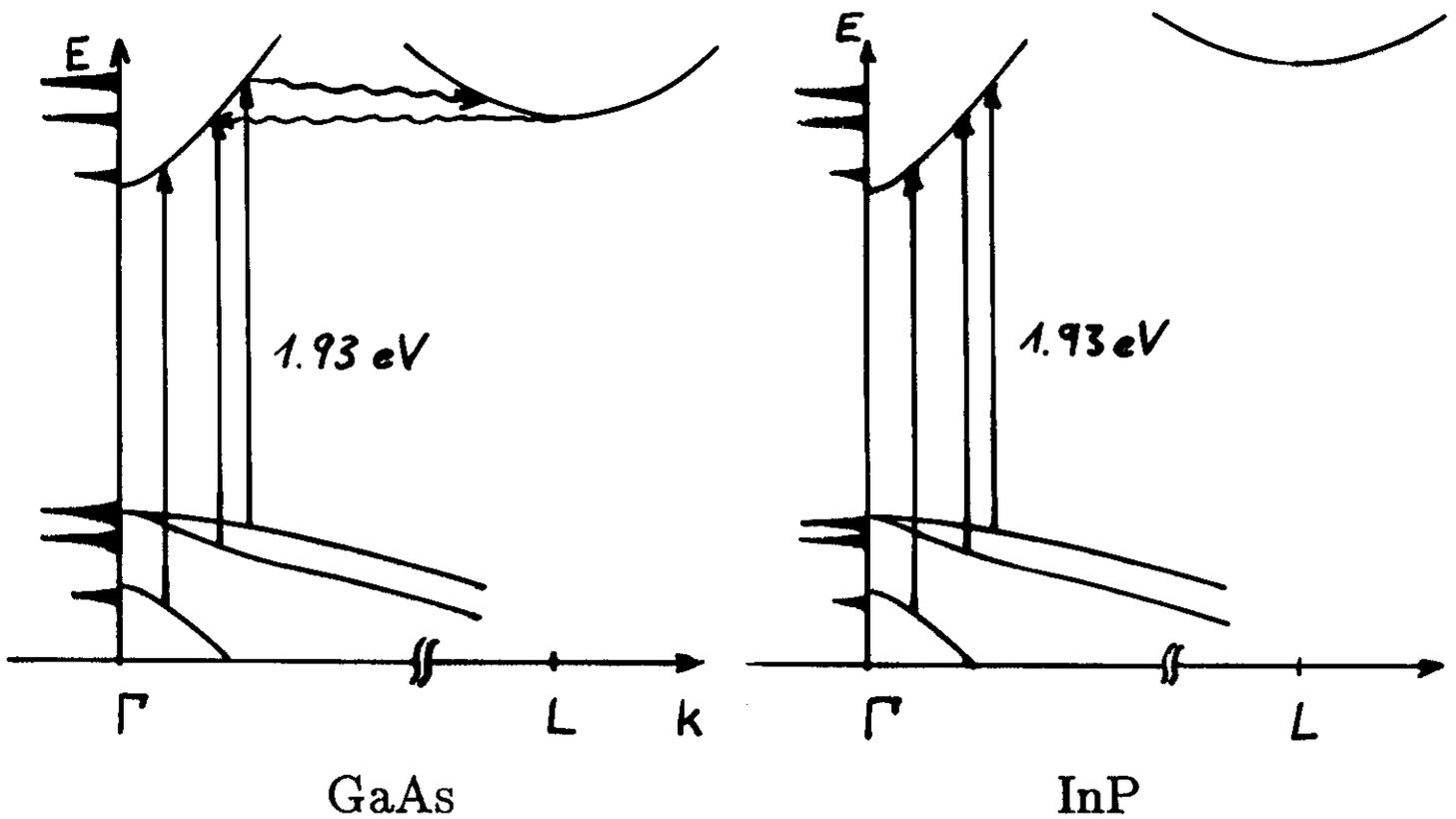
Cooling: Transfer of **excess energy** from a hot quasi-equilibrium distribution of carriers to the lattice.

Main scattering processes: Carrier-phonon scattering (both optical and acoustic phonons)

Examples:

- ♦ Thermalization of photoexcited electron-hole plasma in bulk GaAs
- ♦ Thermalization of holes in bulk p-type germanium
- ♦ Thermalization and cooling of an electron plasma after inter-subband excitation of quasi-two-dimensional quantum wells

Thermalization of Photoexcited Electron-Hole Plasma



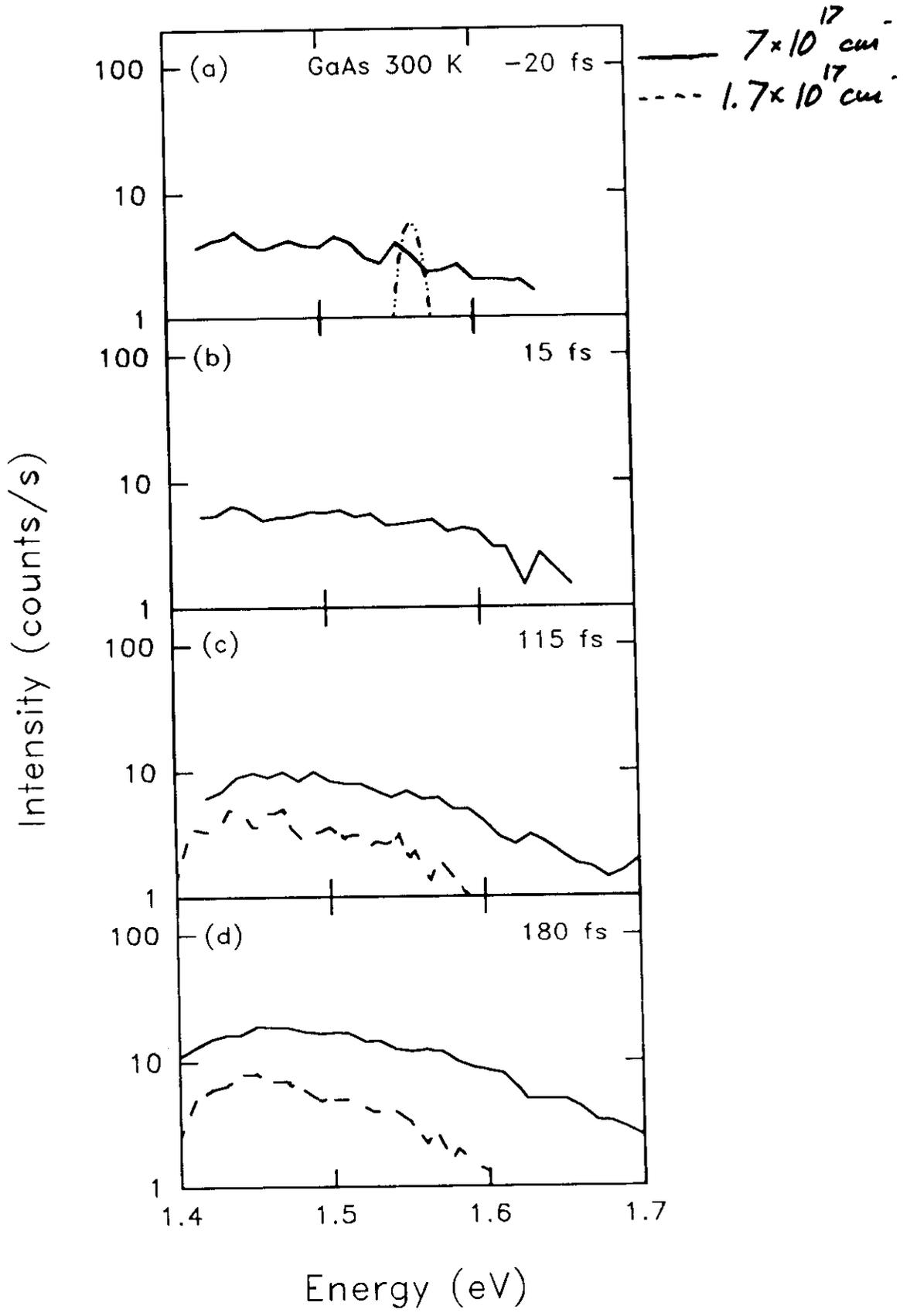
Inter-valley scattering

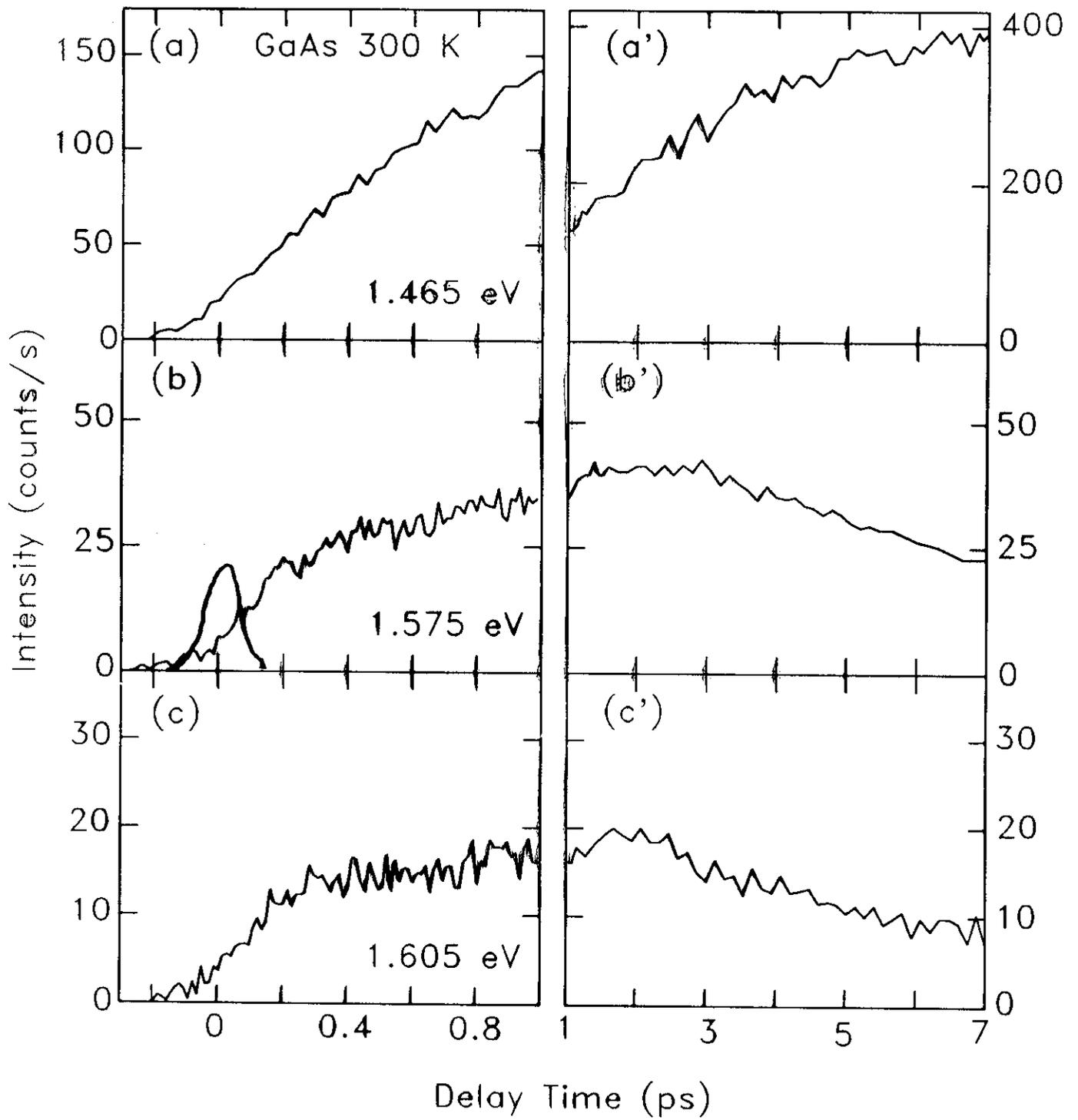
no inter-valley scattering

initial nonequilibrium distribution

carrier-carrier
carrier-LO-phonon
scattering

hot Fermi distribution





$$N = 7 \times 10^{17} \text{ cm}^{-3}$$

Ensemble Monte Carlo Simulations

2 models of carrier-carrier interaction :

1) Time dependent static screening of the Coulomb interaction potential

$$V(r) = \frac{e^2}{4\pi\epsilon r} \exp(-r/\lambda_S)$$

Inverse screening length $\beta = 1/\lambda_S$:

$$\beta^2 = \frac{ne^2}{\epsilon} \frac{1}{N} \sum_i \frac{1}{2E_i}$$

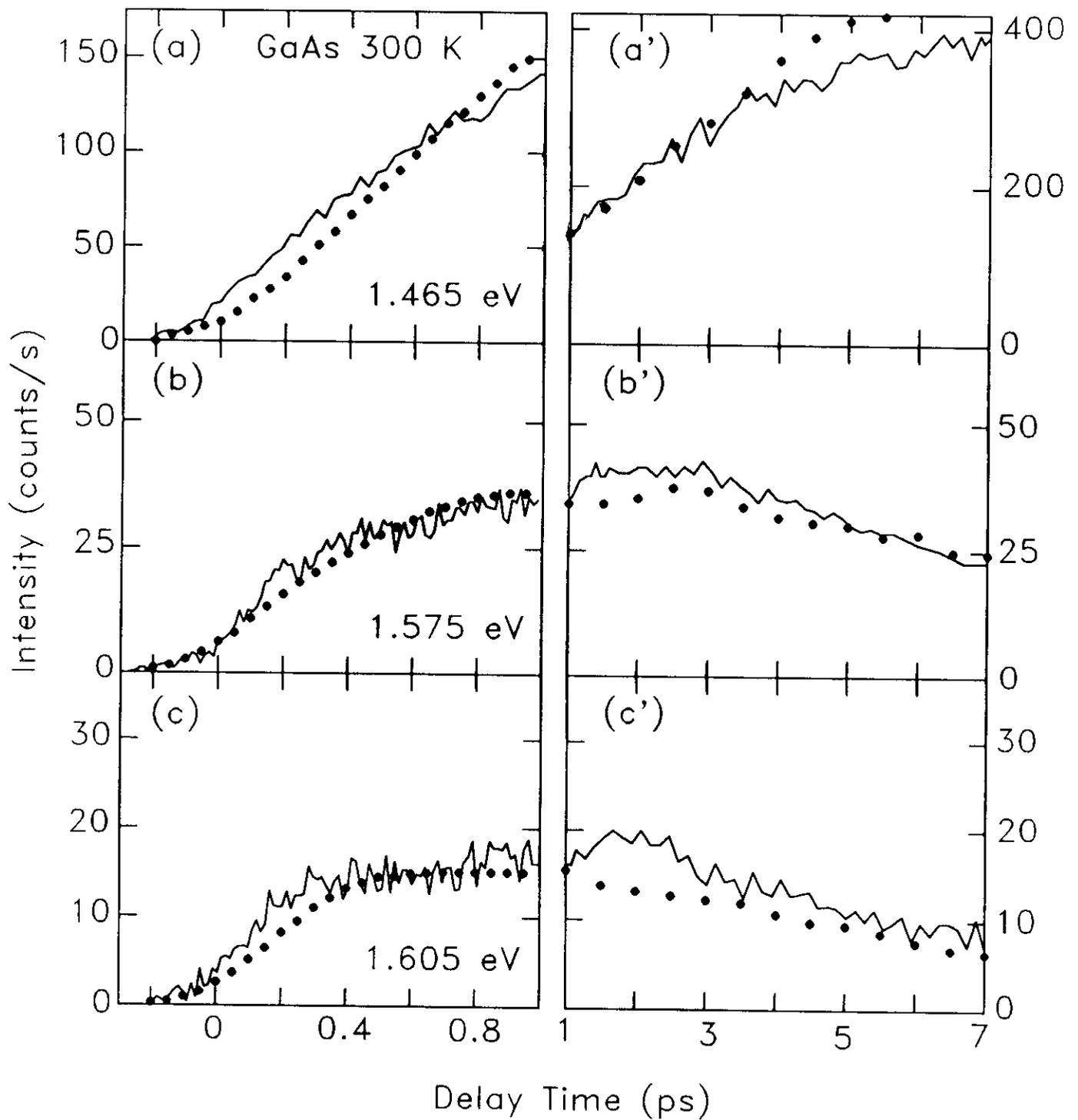
β updated every 10 fs

Scattering rates calculated from Fermi's golden rule

2) Molecular dynamics model

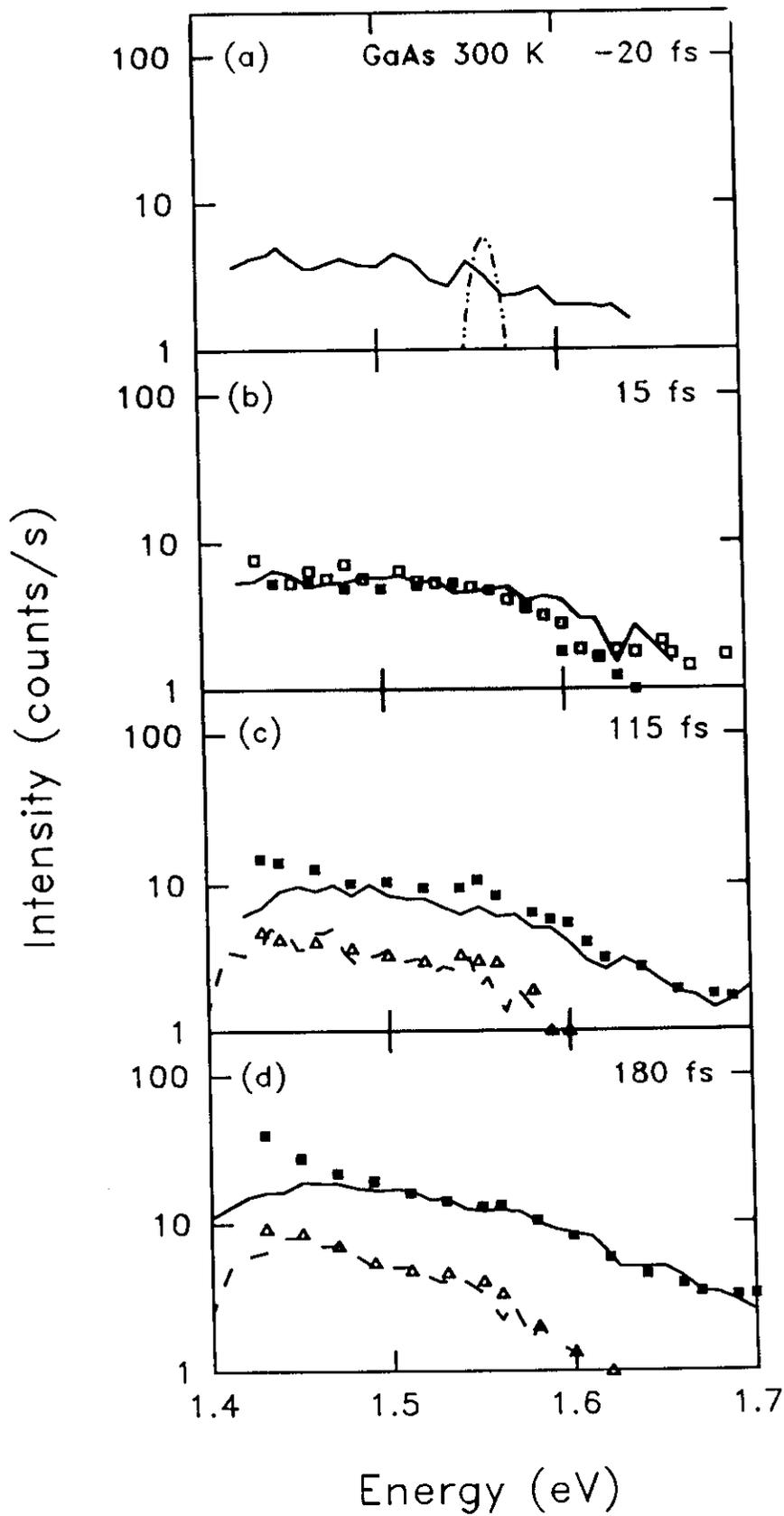
Calculation of real space trajectories

Carriers interact via bare Coulomb potential



$$N = 7 \times 10^{17} \text{ cm}^{-3}$$

• theory: static screening



Δ, \blacksquare static screening

\square molecular dynamics

Conclusions

Thermalization of electron-hole plasma in GaAs and InP at 300 K

Femtosecond luminescence up-conversion in LiIO₃
Time resolution 100 fs

Redistribution of electrons **and** holes over a wide energy range within 100 fs (carrier density 10^{17} cm⁻³ - 7×10^{17} cm⁻³)

Main mechanism : carrier-carrier scattering

Monte-Carlo simulations :

Carrier-carrier scattering rates higher than predicted for time dependent static screening of the interaction potential

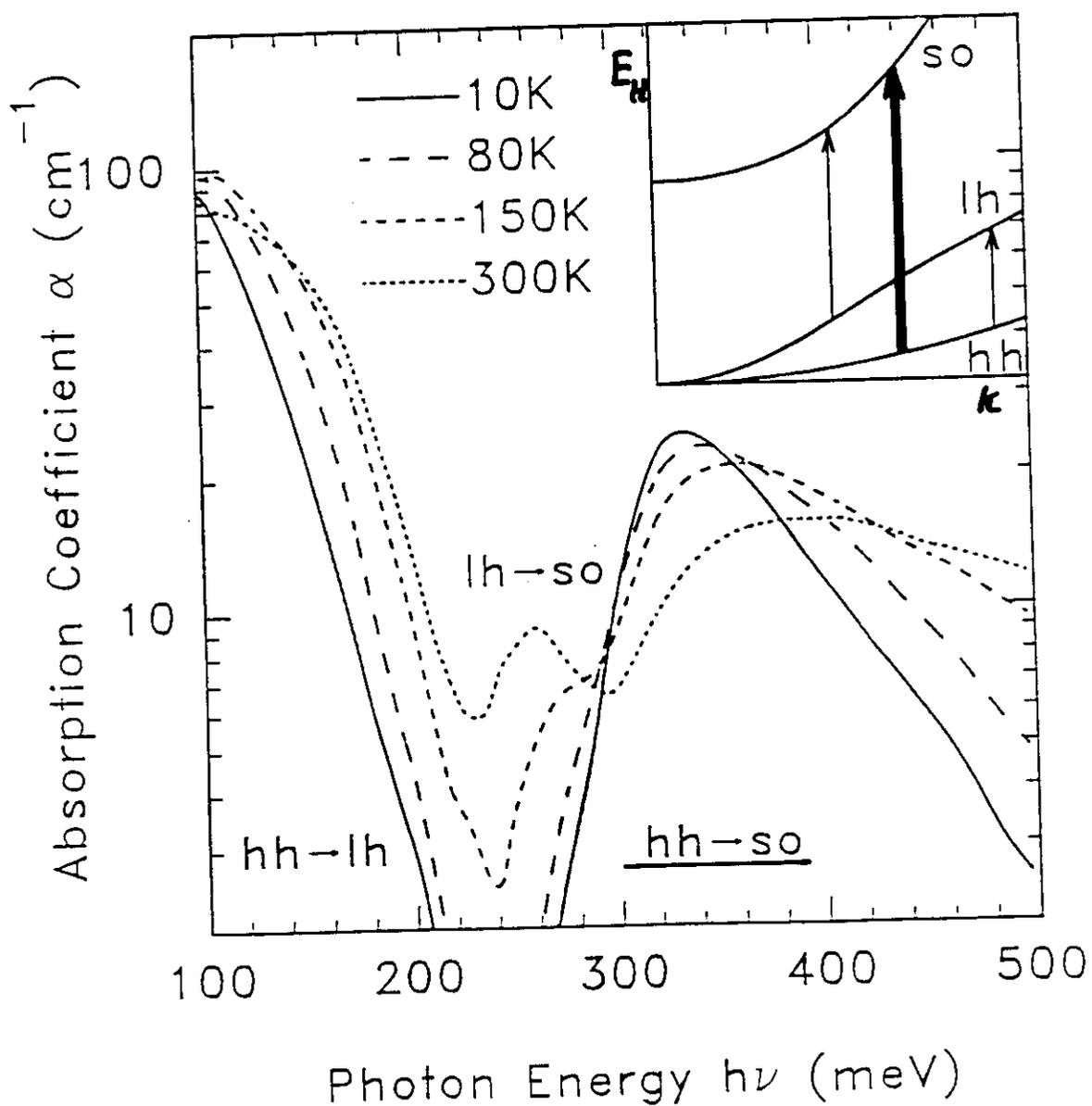
Molecular dynamics calculation gives enhanced scattering rates (dynamical screening), in good agreement with experimental results

Carrier cooling by emission of LO phonons on a time scale of 10 ps

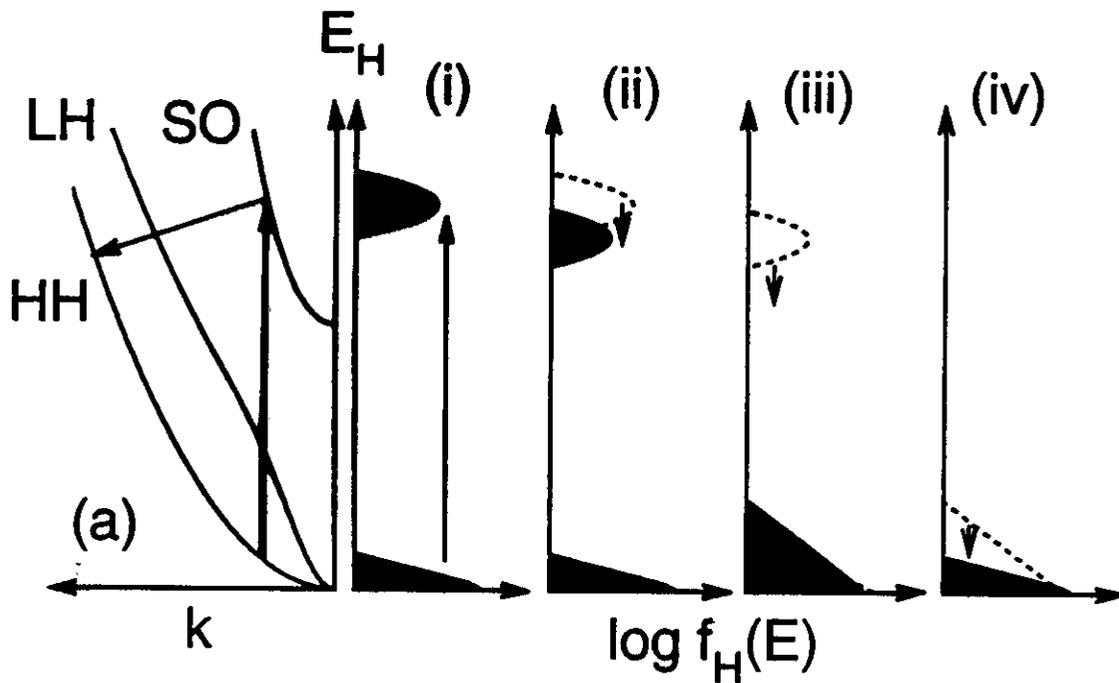
Inter-valence band absorption in p-type germanium

Spectra determined by :

- k -dependent dipole matrix elements
- hole distribution functions



Subpicosecond Scattering Dynamics of Photoexcited Holes



Inter-valence band scattering ($so \rightarrow lh, hh$)

$\tau_{iv} \leq 150$ fs *emission of optical phonons*

Thermalization of heavy holes : two time scales:

● **Hot carriers** $\tau_{therm} \simeq 700$ fs

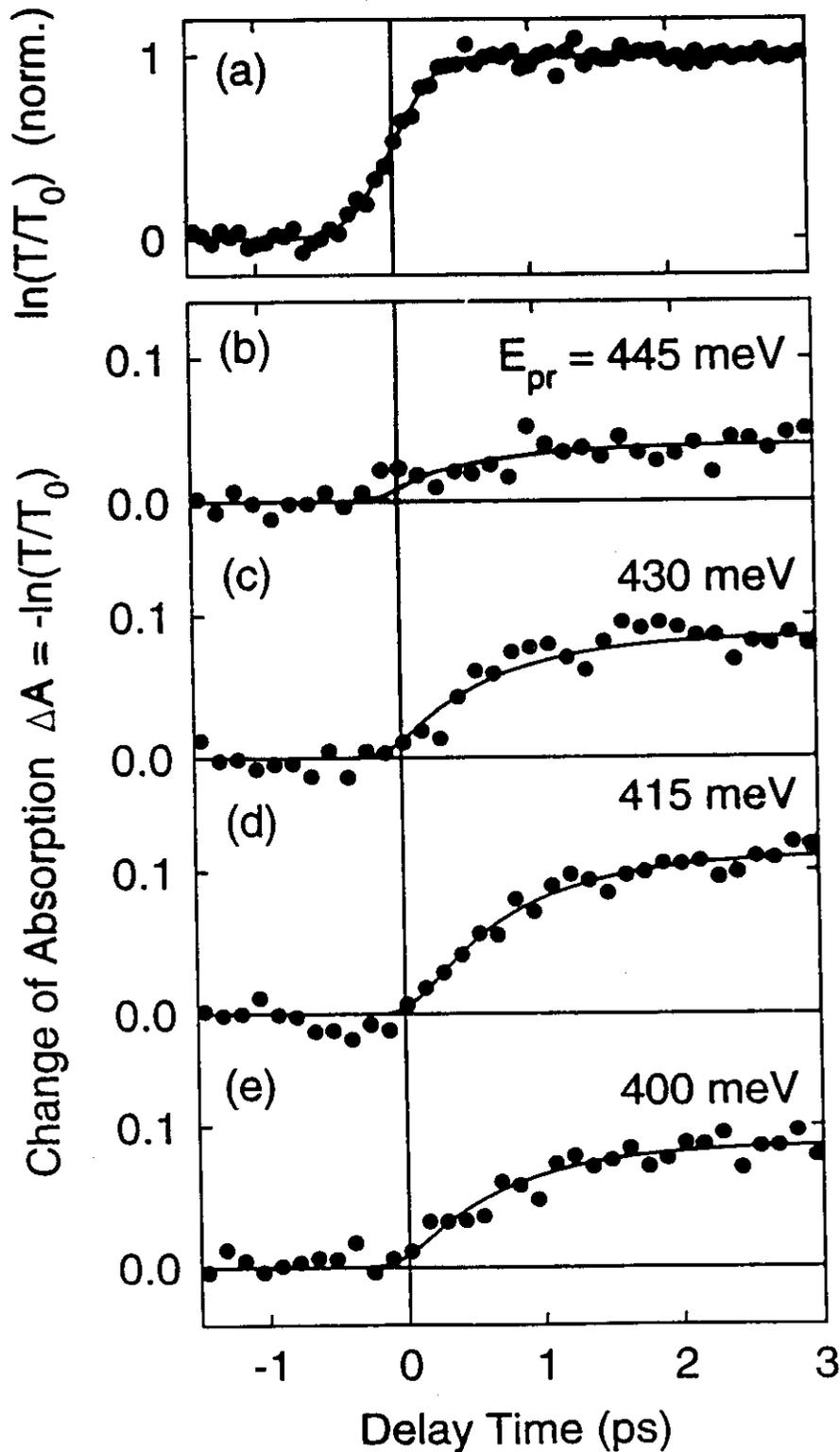
● **Cold (unexcited) carriers** $\tau_{therm} \leq 150$ fs

Carrier-carrier collisions, dynamical screening of Coulomb interaction

Optical deformation potential

Subpicosecond Dynamics of Inter-Valence Band Absorption

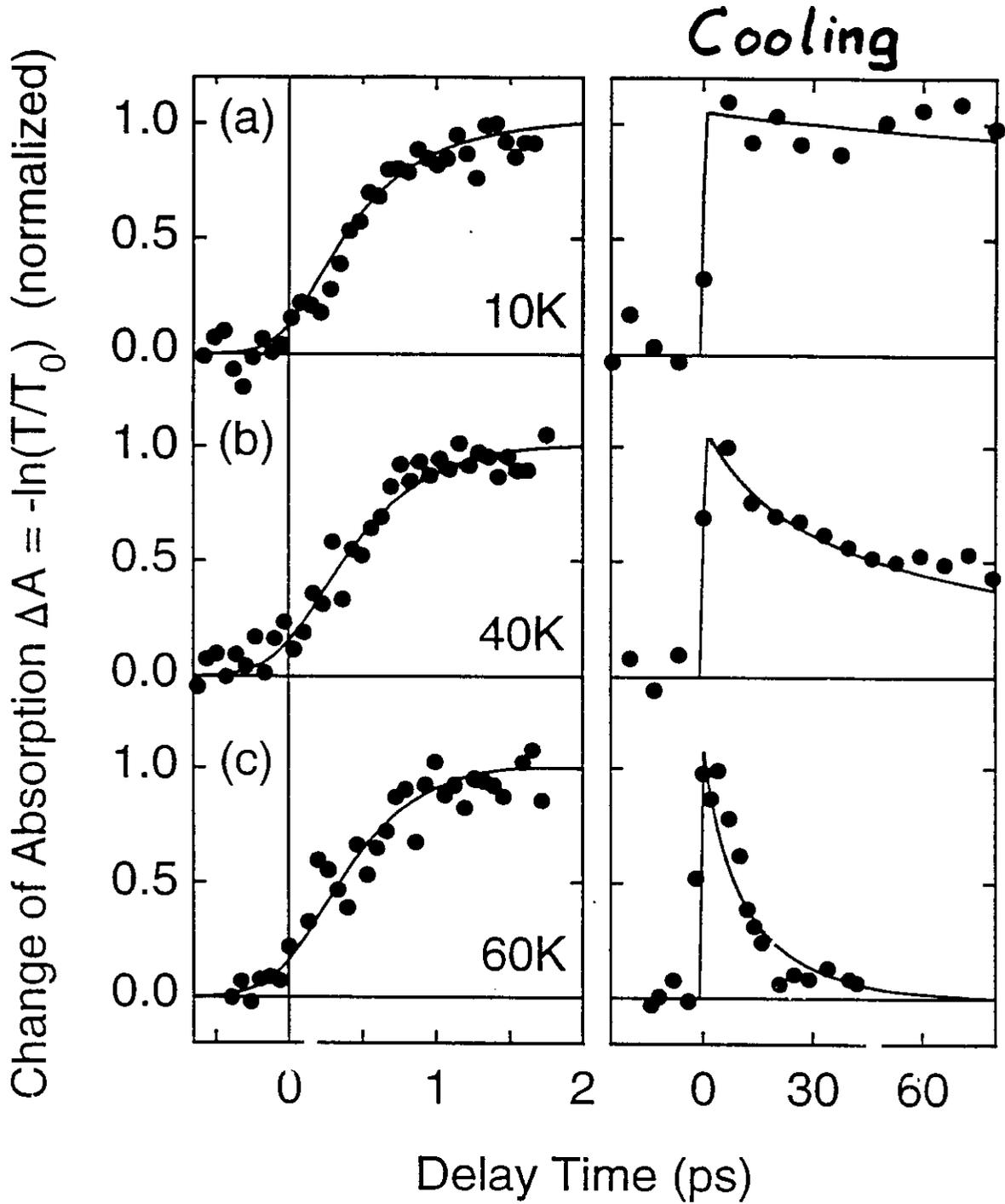
$$E_{ex} + E_{pr}, E_{ex} = 435 \text{ meV}, T_L = 10 \text{ K}$$



$\tau_{Rise} \approx 700 \text{ fs}$

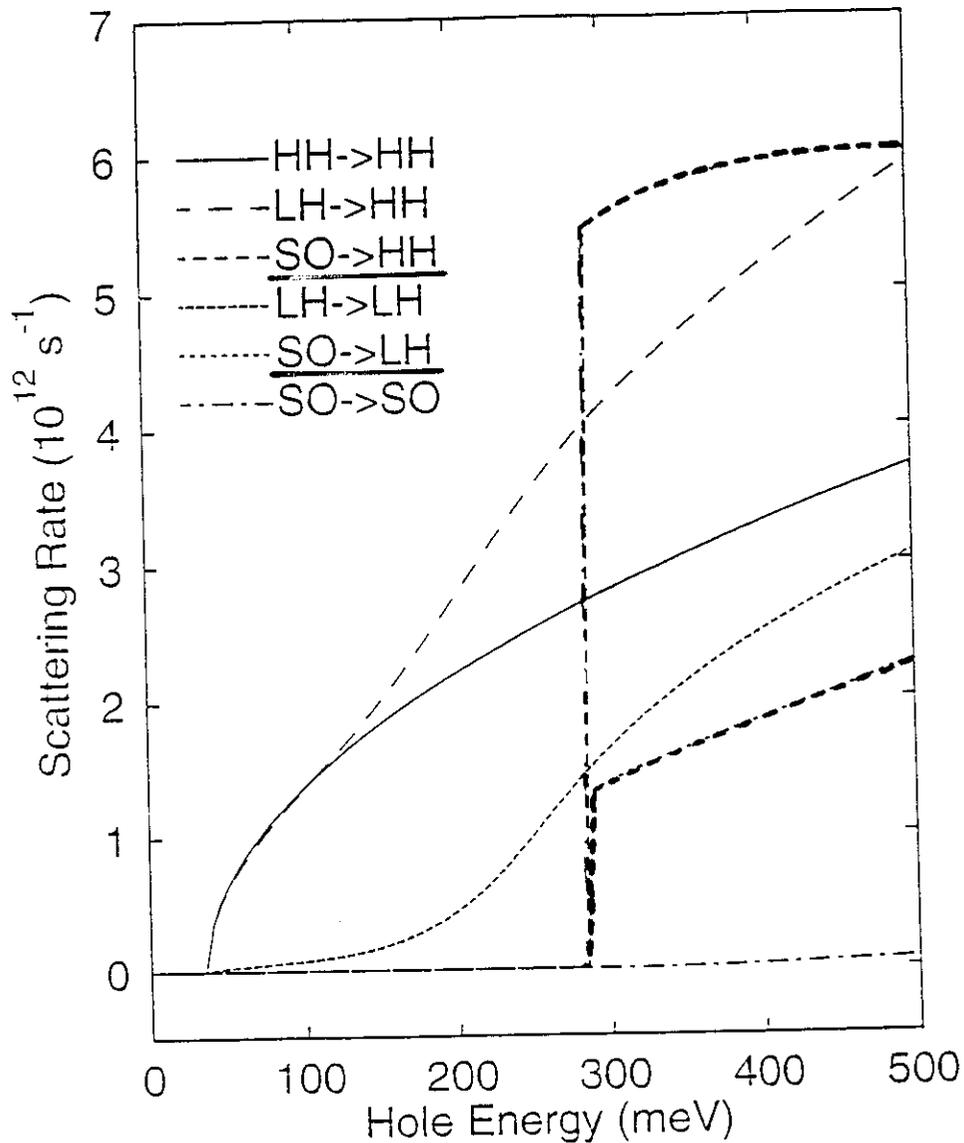
Time Evolution of Inter-Valence Band Absorption

$$E_{ex} = E_{pr} = 390 \text{ meV}$$



no hole burning

Scattering of holes with optical phonons via the optical deformation potential



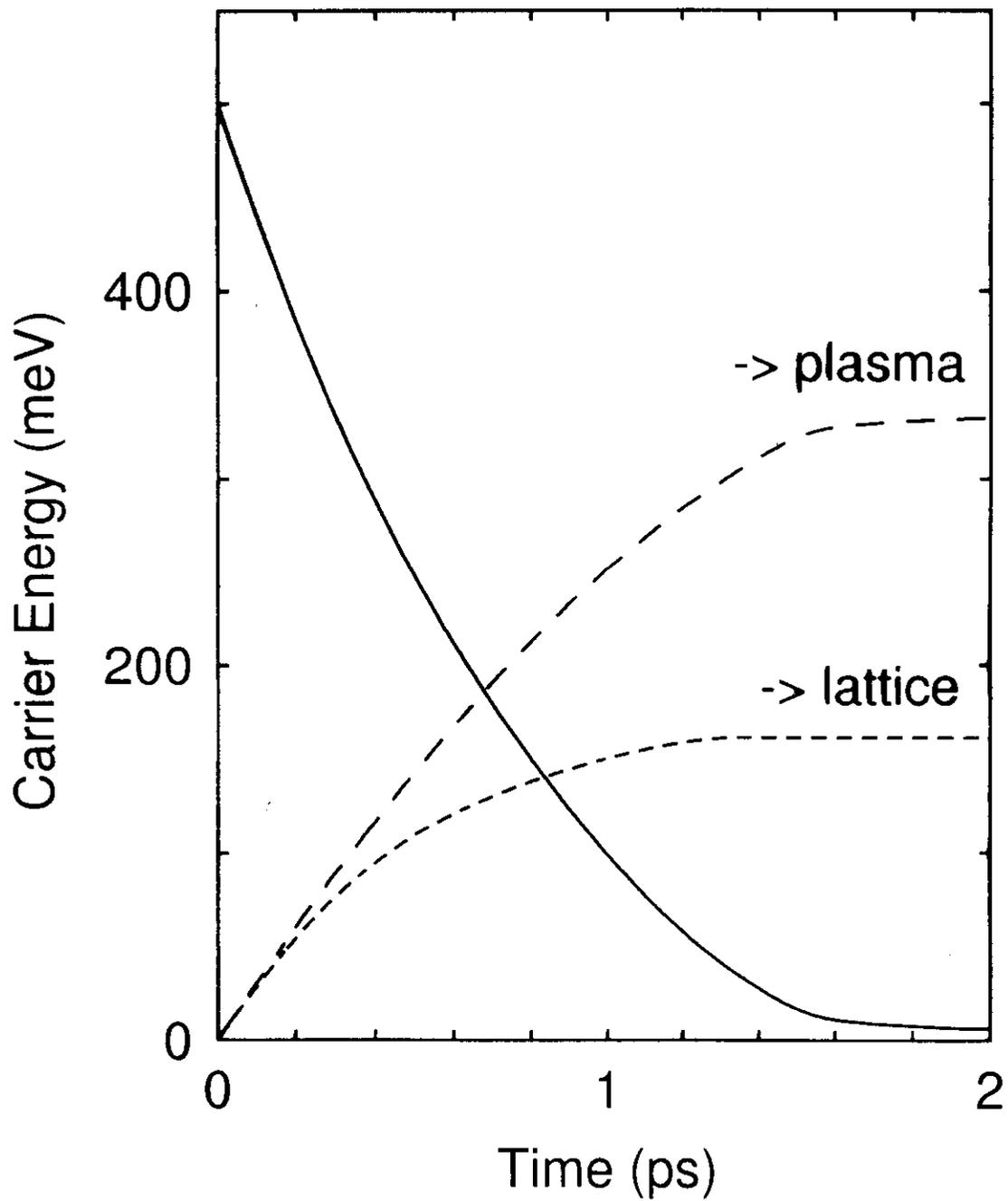
Coupling constant $D_0=6.3 \times 10^8 \text{ eV/cm}$

Estimated split-off (SO) lifetime 120 fs

Time-dependent Energy Loss: Theory

Hole-hole scattering via dynamically screened Coulomb potential

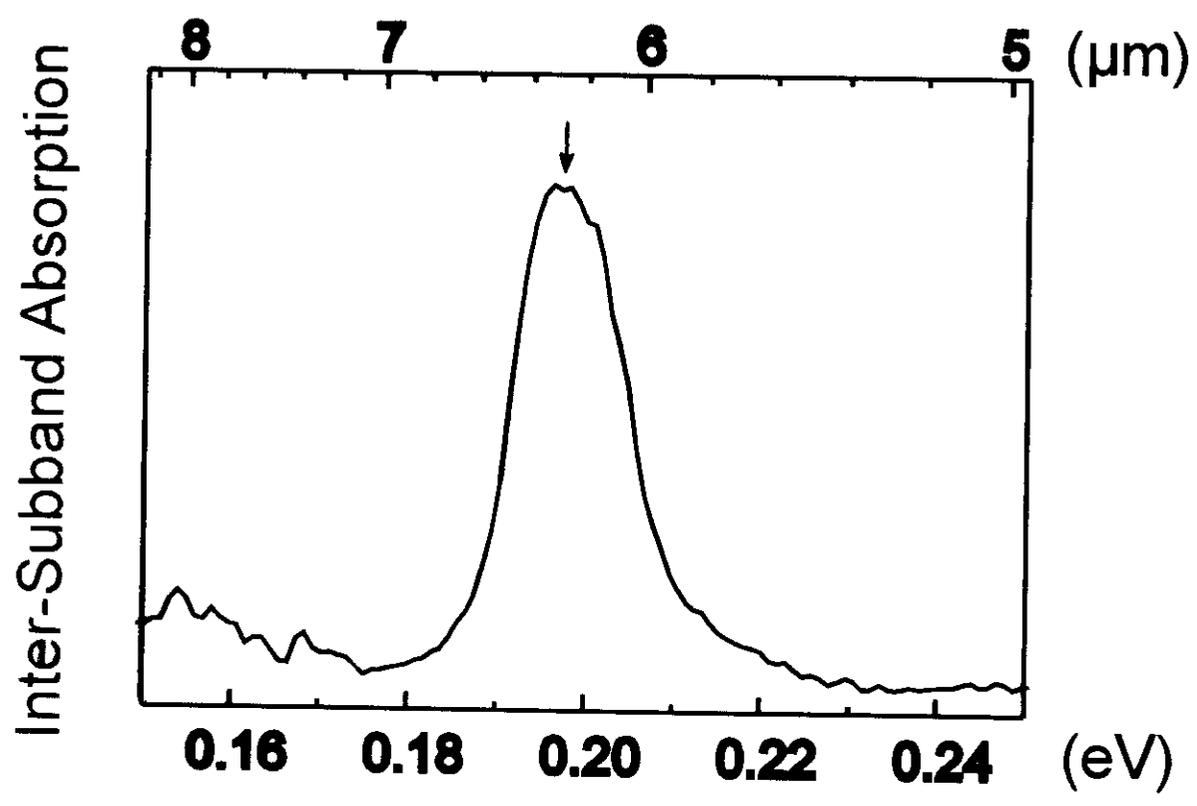
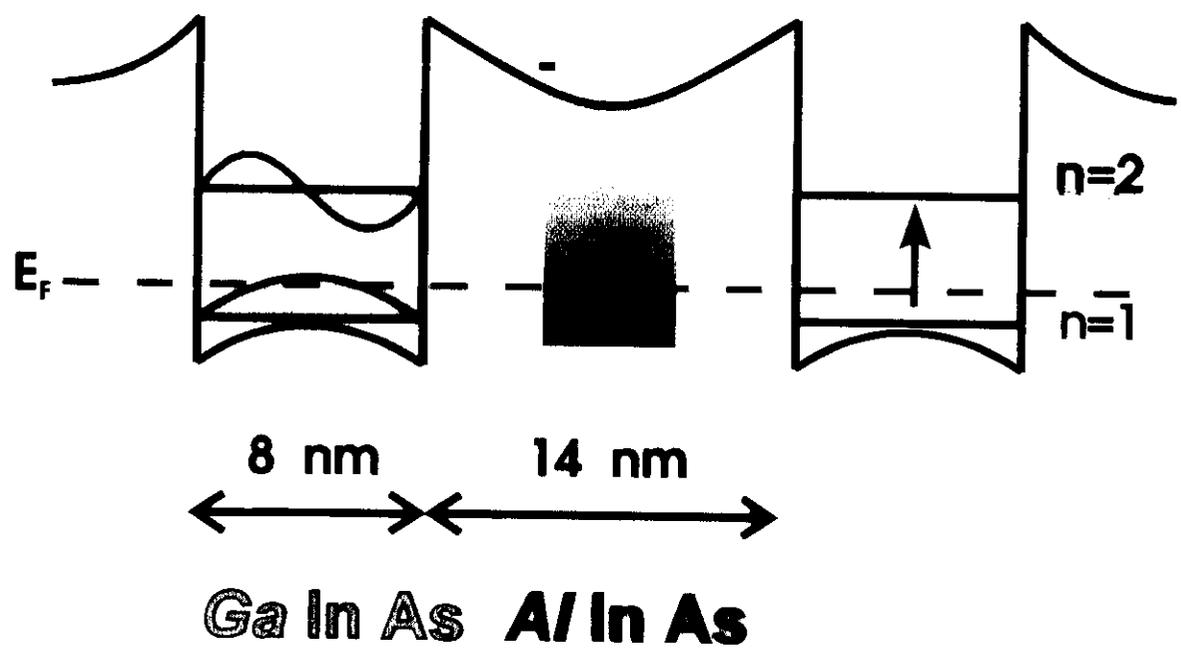
Hole-optical phonon scattering via deformation potential



Summary

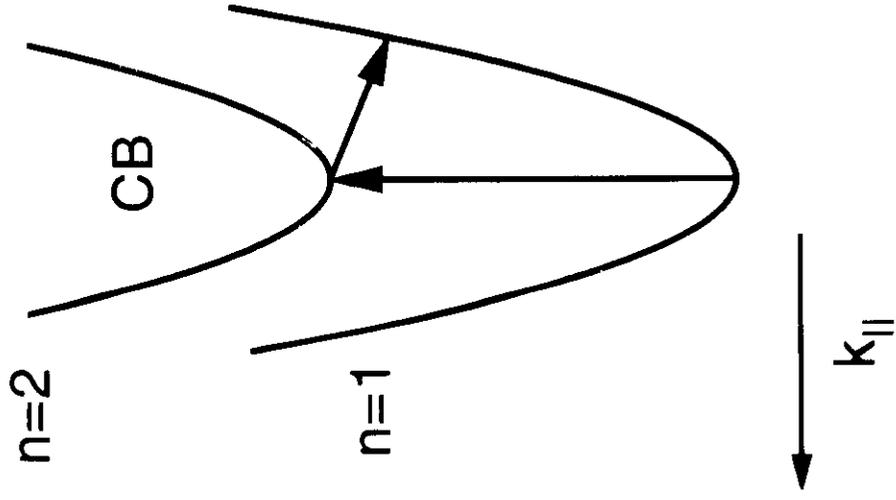
- Relaxation of holes in p-type Germanium photoexcited to the split-off band by femtosecond pulses in the mid-infrared directly monitored via the transient inter-valence band absorption
- Two thermalization processes:
 1. Excited carriers:
 - inter-valence band scattering within 100 fs
 - thermalization on a time scale of 700 fs, predominantly by inelastic scattering with unexcited holes
 2. Unexcited holes:
 - equilibration in the regime below 100 fs
- Model calculations:
 - Dynamic screening of the Coulomb interaction among the holes
 - Excitation of HH to LH inter-valence band transitions

GaInAs/AlInAs Quantum Wells

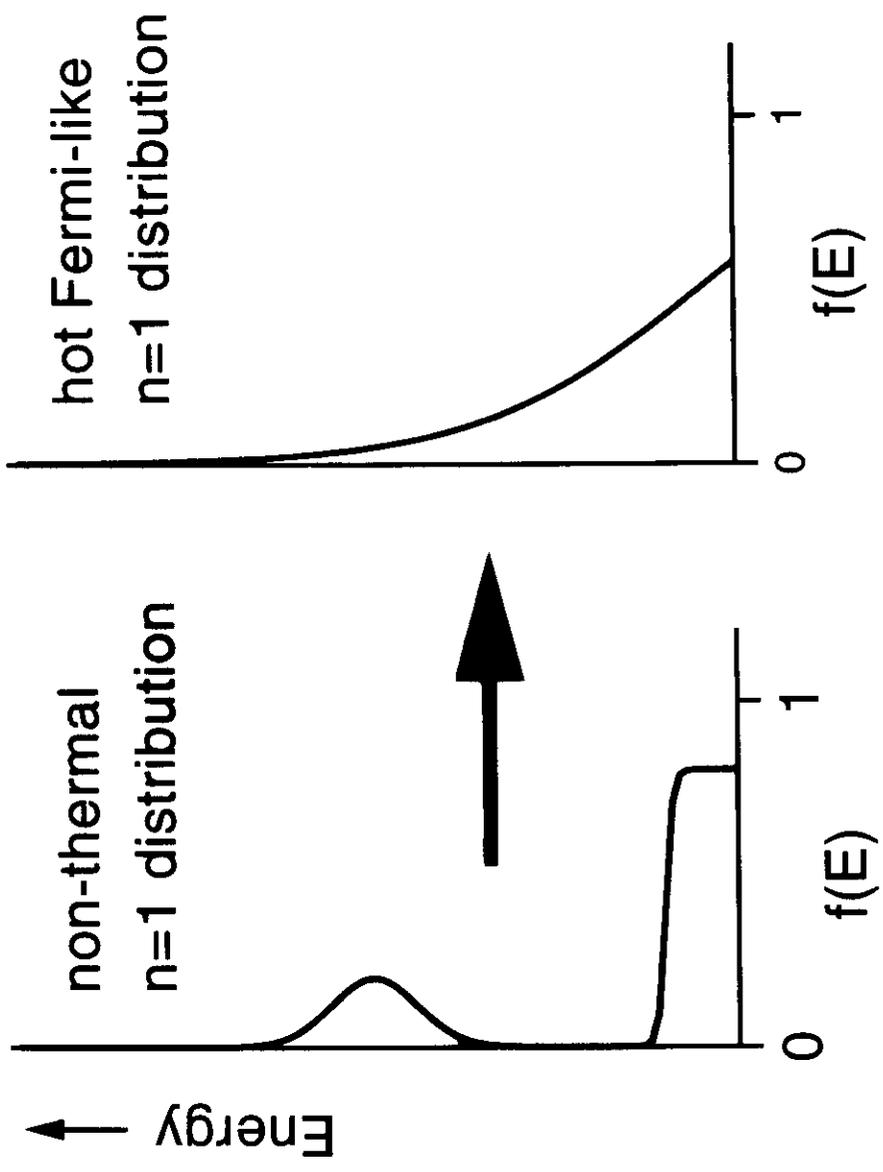


Nonequilibrium Dynamics

($n=2$) lifetime

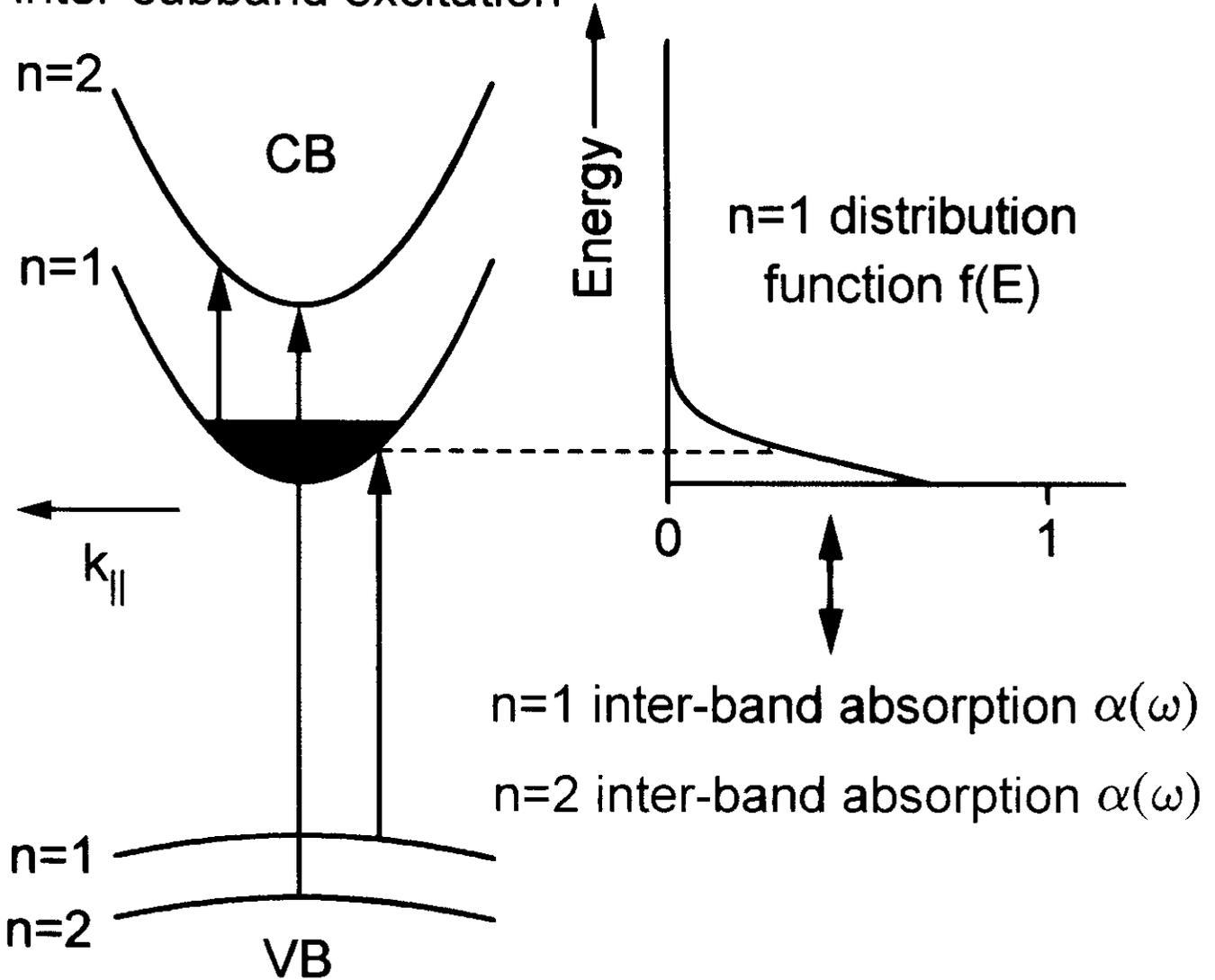


Thermalization ($n=1$) distribution



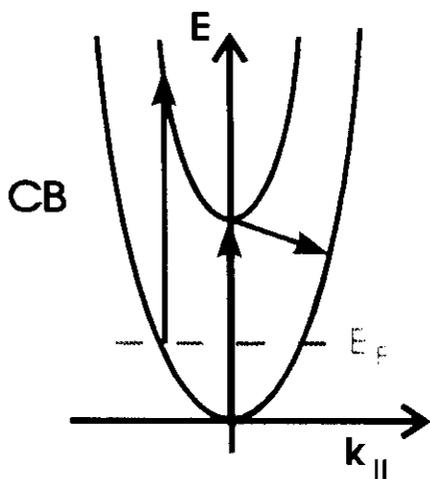
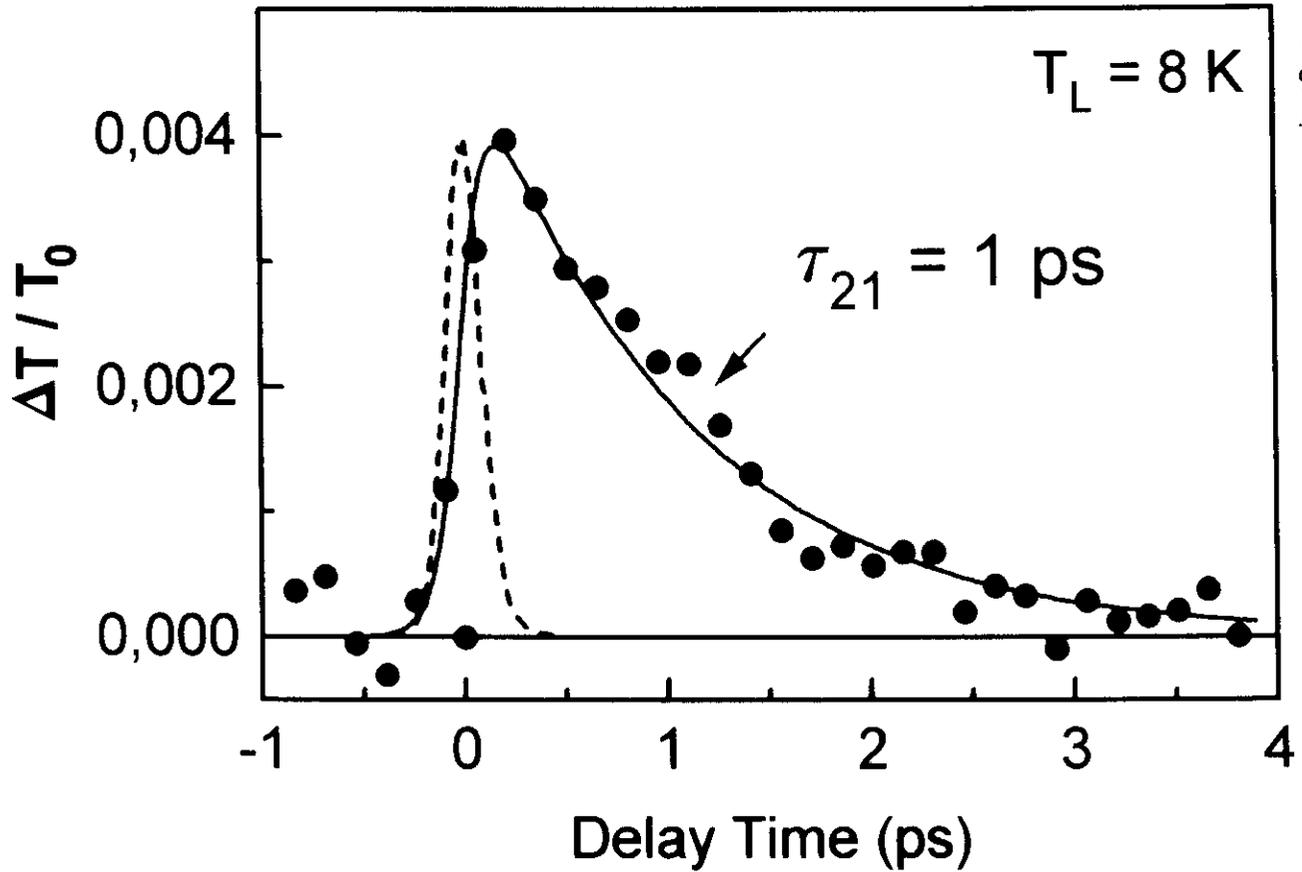
Experimental Concept

inter-subband excitation



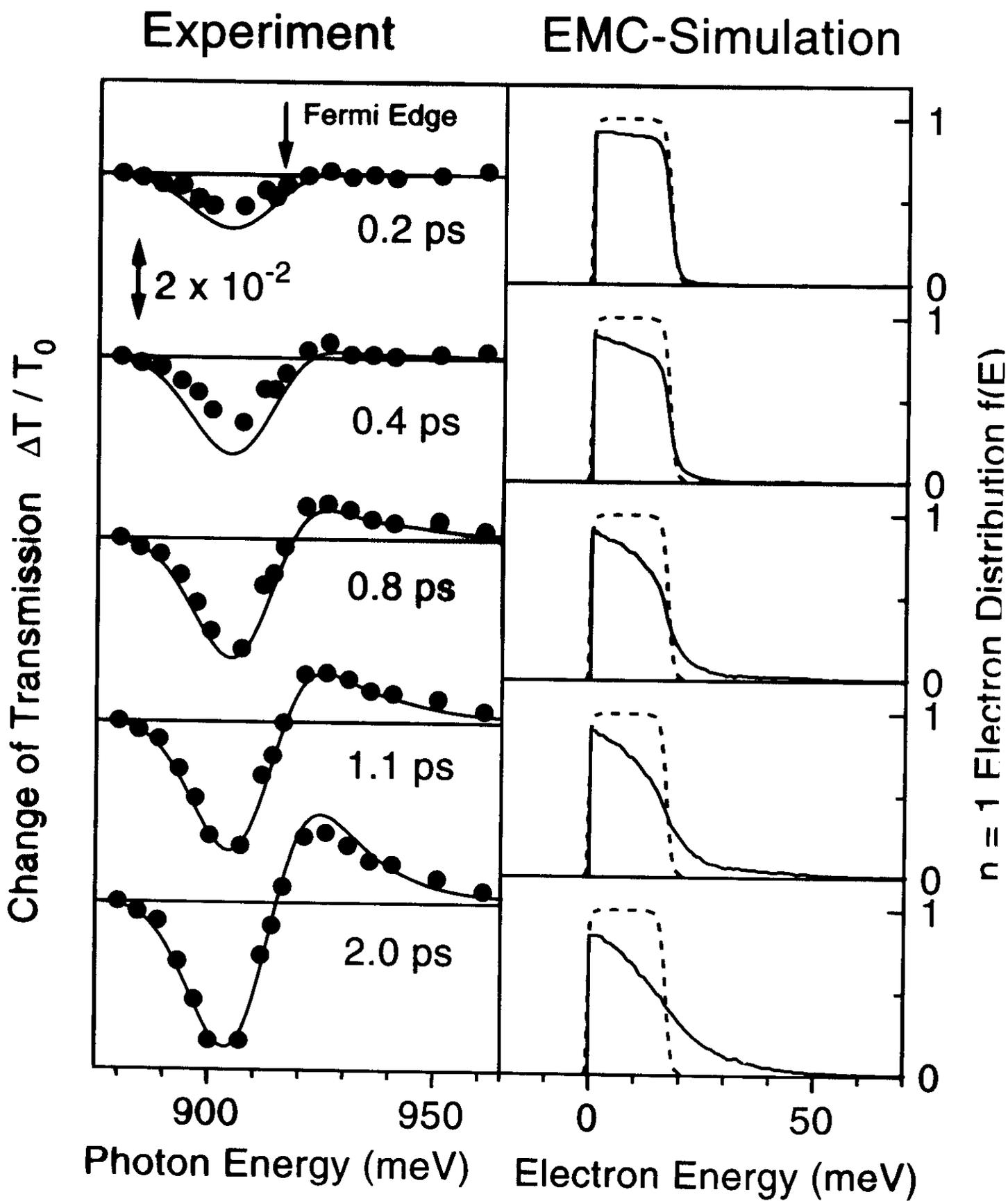
redistribution of an existing electron plasma
exclusively electron dynamics (no holes)

Transient ($n=2$) Population

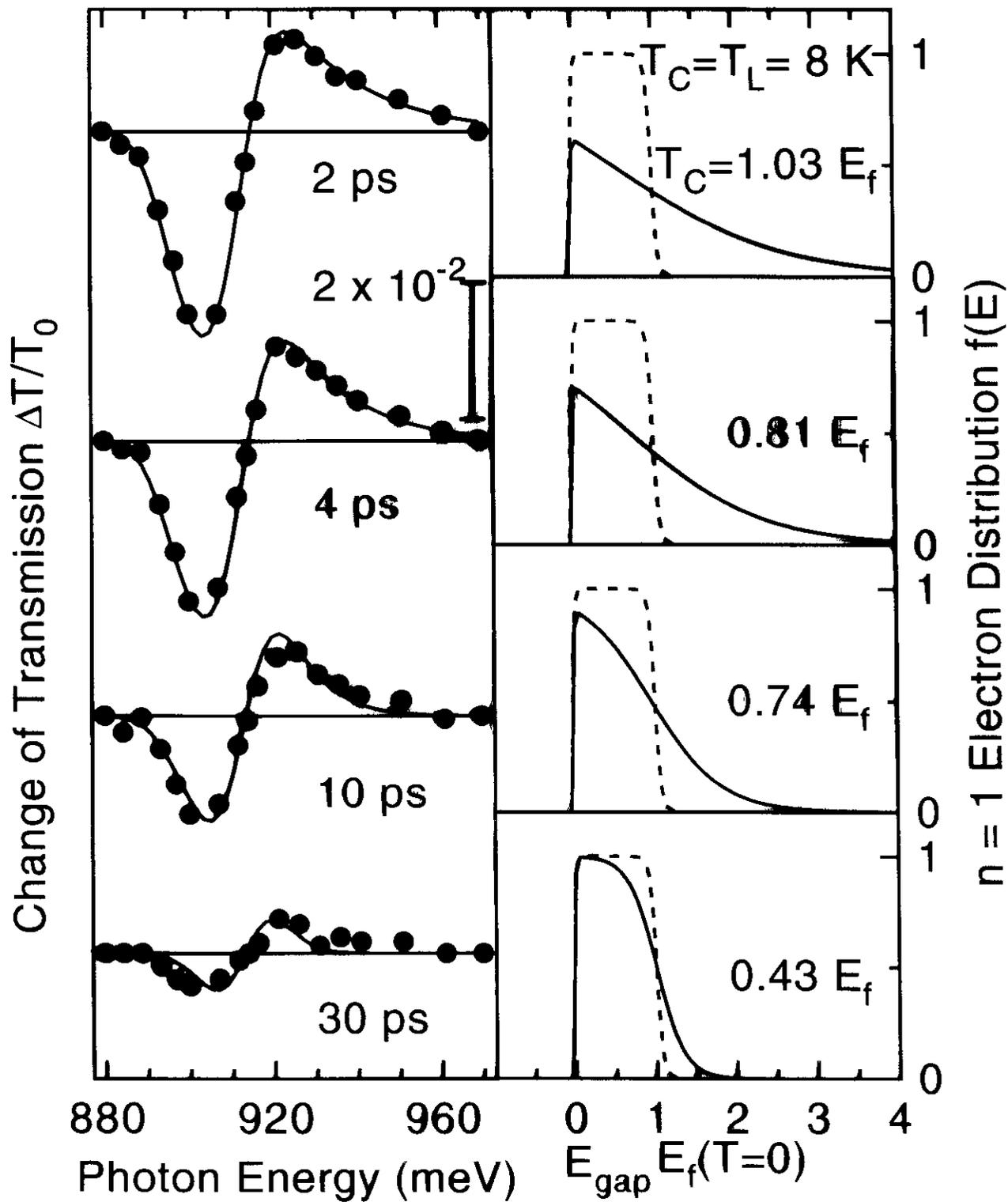


Ensemble Monte Carlo Simulation :
 $n=2$ depopulation by emission of confined and interface LO phonons

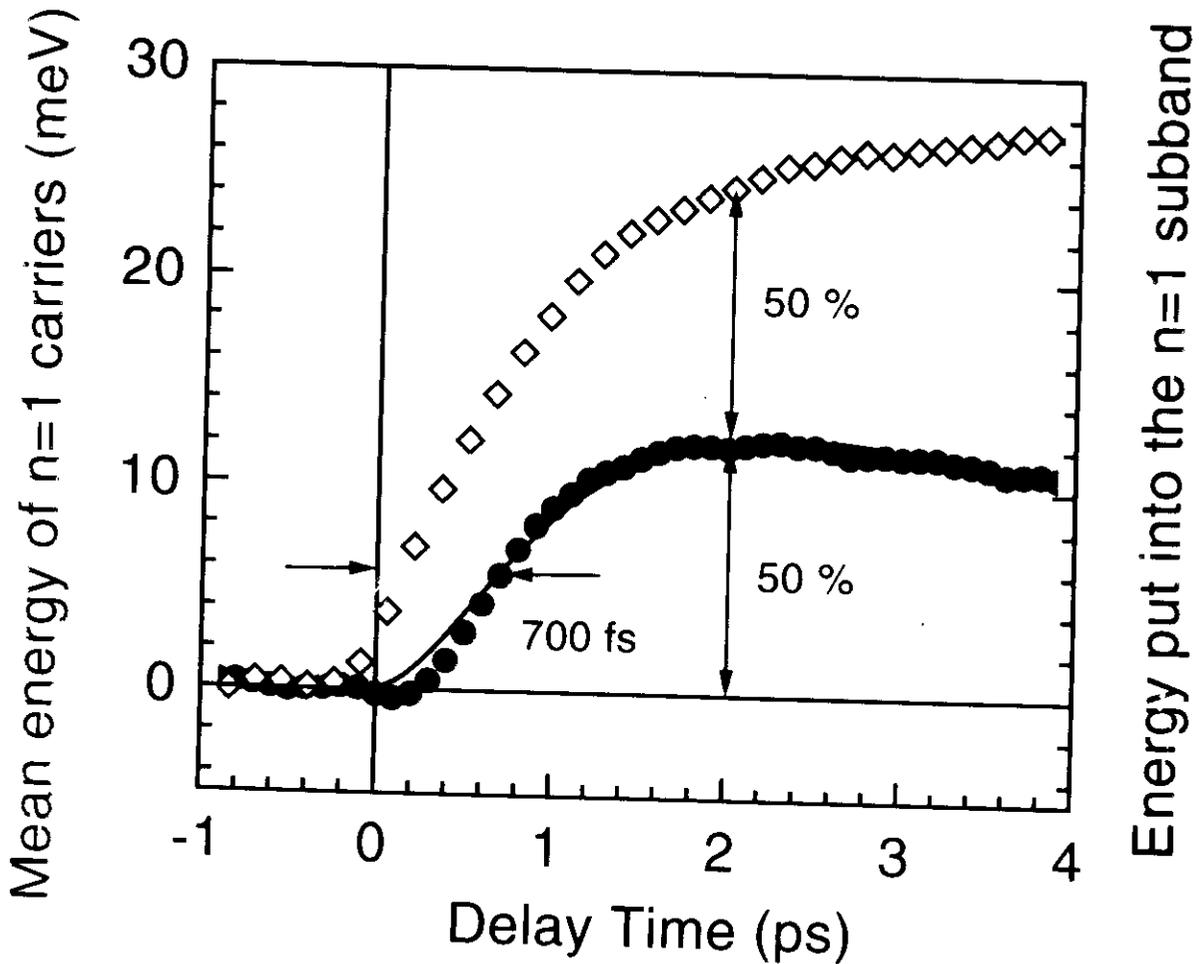
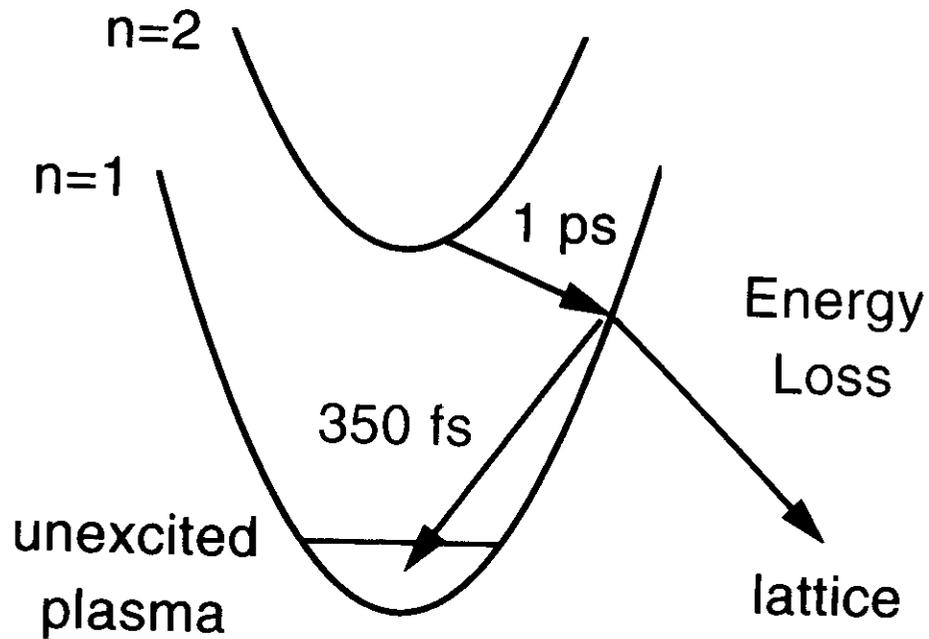
PRL 77, 3657 (1996)



Transient n=1 Absorption Spectra



Energy relaxation of $n=1$ carriers after inter-subband relaxation



Conclusions

Ultrafast dynamics of intersubband excitations of an electron plasma in GaInAs/AlInAs quantum wells

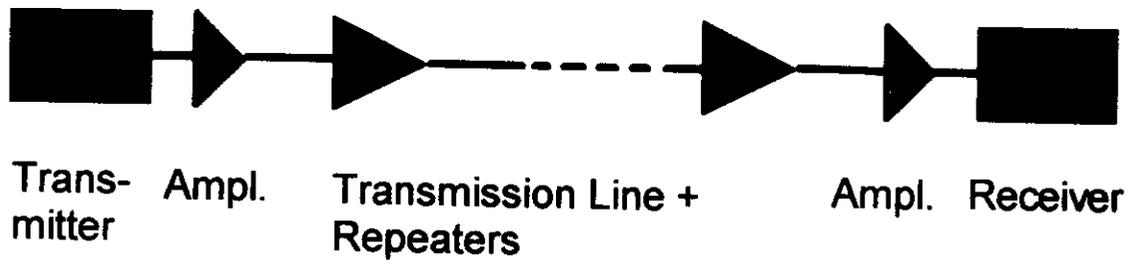
- └ Resonant excitation in the mid-infrared
- └ Decay of coherent intersubband polarizations on a time scale of 300 to 600 fs
 - Main dephasing mechanism: electron-electron scattering
 - Both homogeneous and inhomogeneous components of line broadening
- └ Lifetime of electrons in the ($n=2$) subband 1 ps
 - Backscattering to ($n=1$) subband by LO phonon emission
- └ Nonequilibrium electron distributions in the ($n=1$) subband for about 1 ps
 - Slow thermalization by electron-electron scattering
- └ Electron cooling on a 50 ps time scale by phonon emission

S. Lutgen et al., PRL 77, 3657 (1996); PRB 54, R17343 (1996)

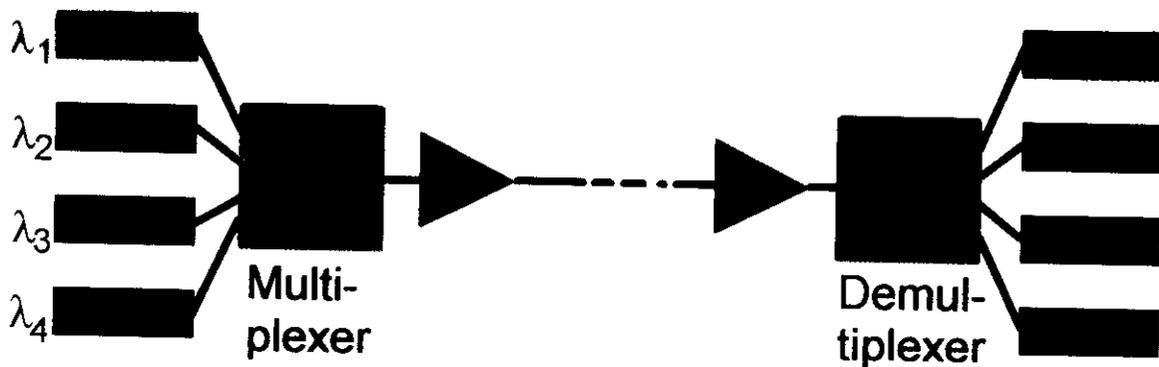
R. Kaindl et al., PRL 80, 3575 (1998)

Optical Communication Systems

Single channel system: λ_0



Multiple channel system (Wavelength Division Multiplexing) $\lambda_1, \lambda_2, \dots, \lambda_N$



Transmission rates (intercontinental, AT&T): 5Gbit/s

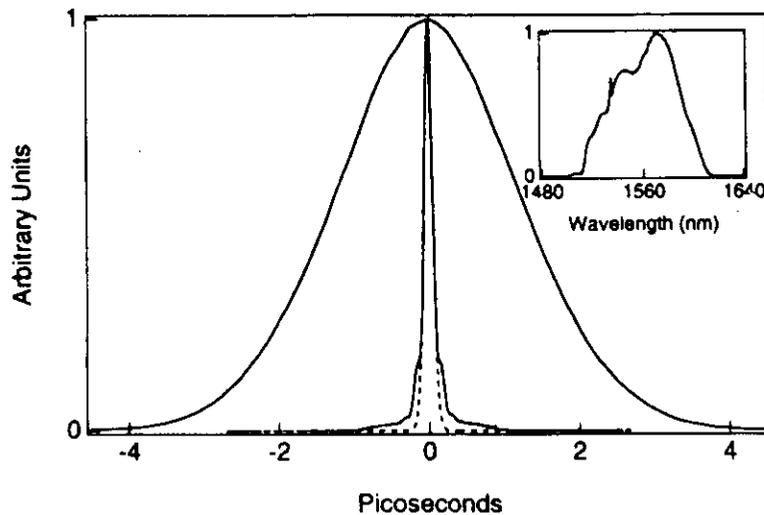
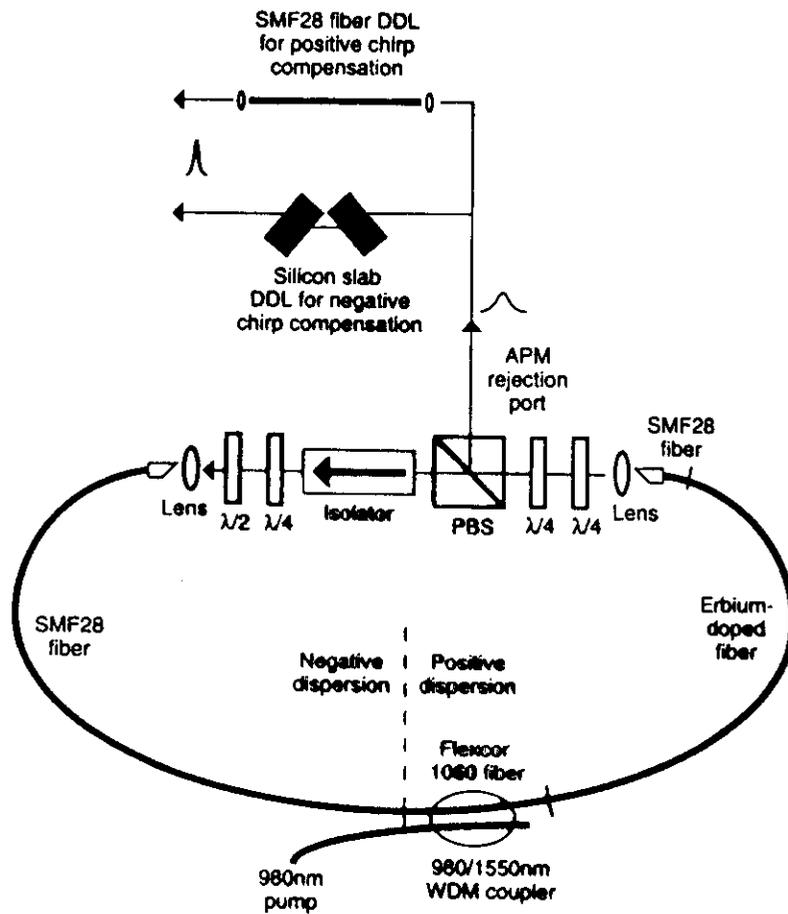
Future systems: Tbit/s

- ◆ Reduction of pulse duration and increase of repetition rates (TDM)
- ◆ Multiple channel systems with large overall transmission bandwidth (WDM)

Application of ultrafast technology

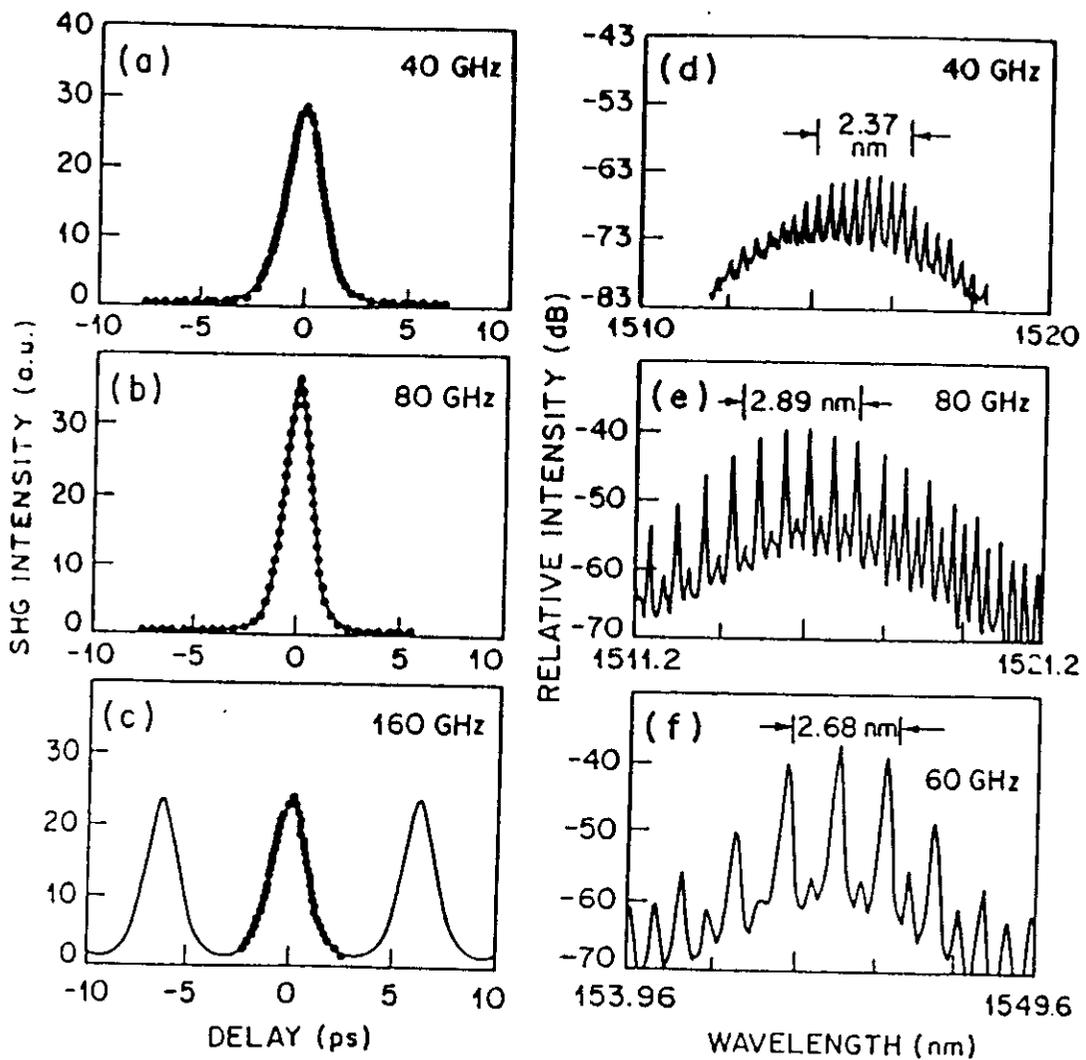
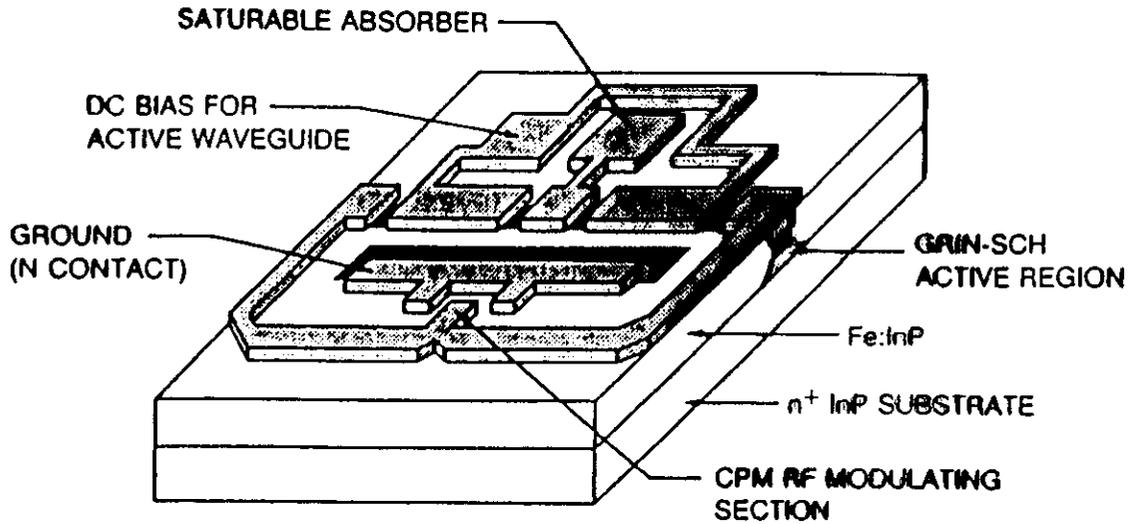
Additive Pulse Modelocked Er-doped Fiber Ring Laser

(K. Tamura, C.R. Doerr, L.E. Nelson, H.A. Haus, E.P. Ippen, *Optics Letters* 19, 46 (1994))



Monolithic semiconductor CPM laser

M.C. Wu et al., Appl. Phys. Lett. 57, 759 (1990)
Y.K. Chen et al, Appl. Phys. Lett. 58, 1253 (1991)



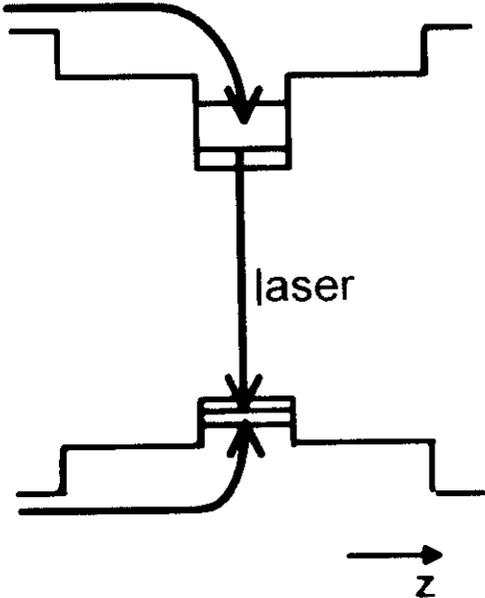
Application of Ultrafast Technology in Semiconductor Devices

◆ Carrier dynamics in semiconductor devices

Quantum Well Laser

Population inversion in quantum wells by
diffusion (10-500ps)
capture (0.5-10ps)
intersubband relaxation (200fs-10ps)
thermalization (50fs-2ps)

Nonlinear dynamics of laser emission

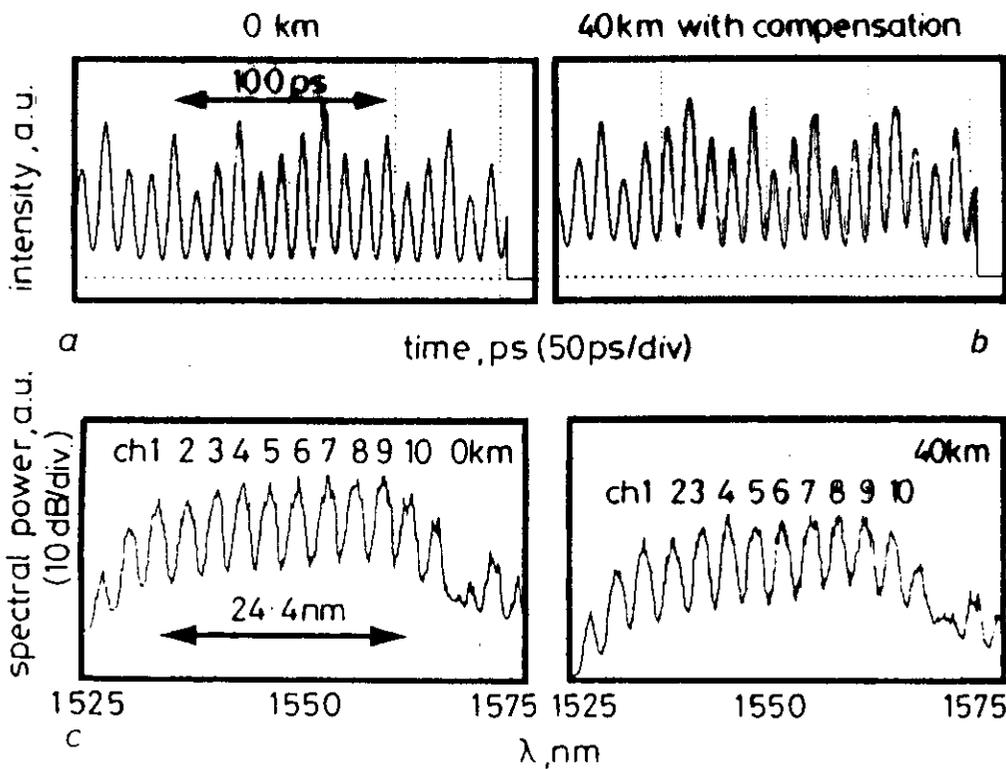
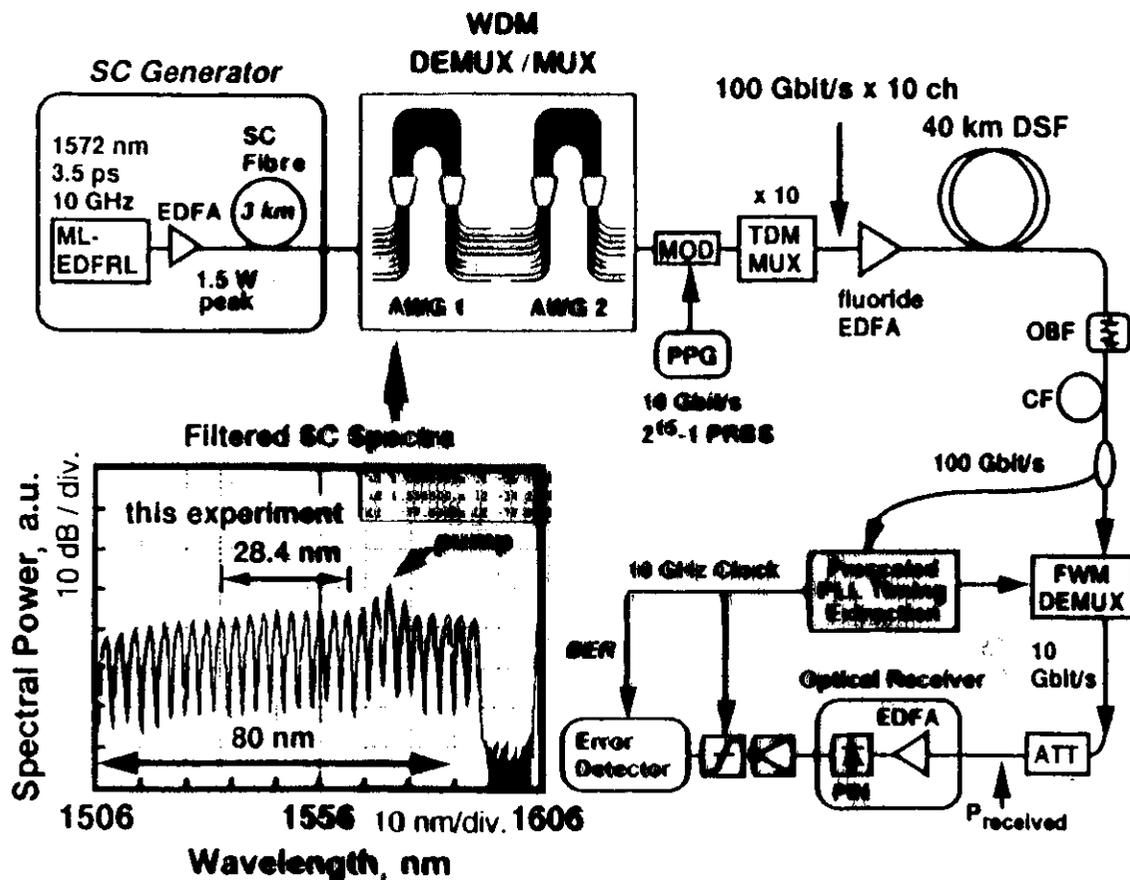


◆ Modelocking of semiconductor lasers

◆ Shaping and propagation of ultrashort pulses, e.g., in fiber networks

1 Tbit/s optical time division/wavelength division multiplexing transmission using a single supercontinuum WDM source

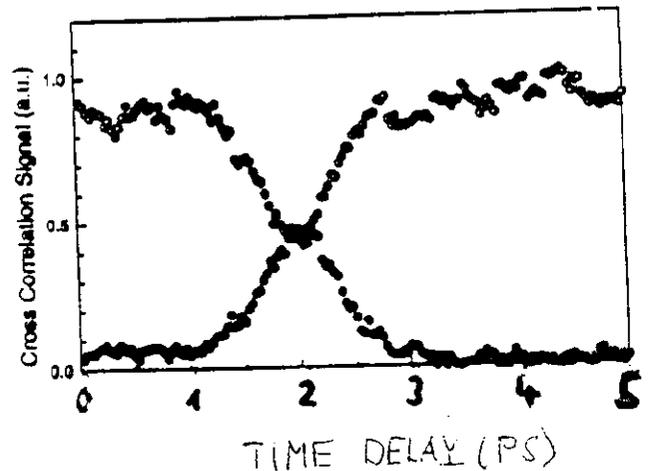
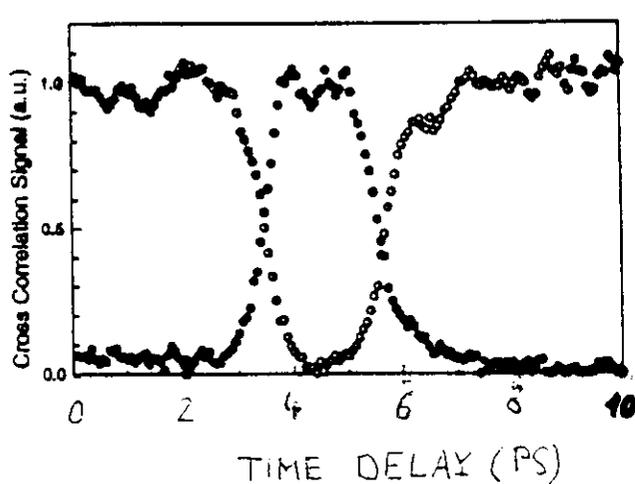
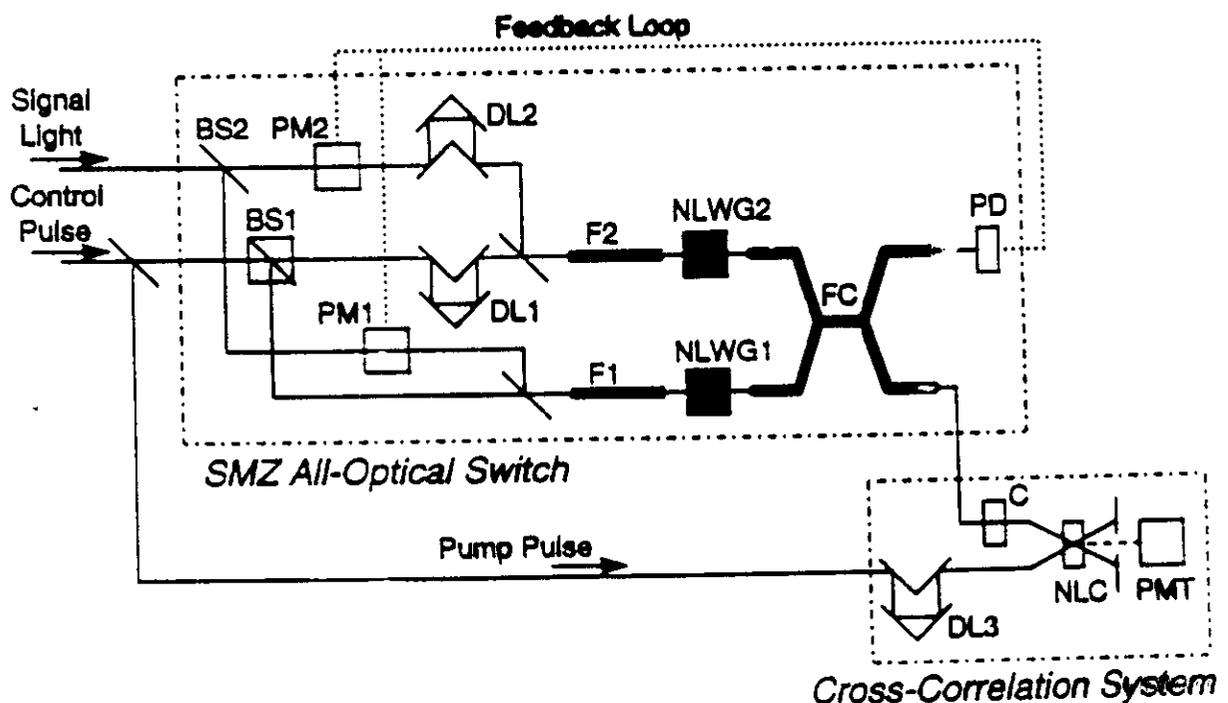
(T. Morioka et al., *Electronics Letters* 32, 906 (9th May 1996))



Subpicosecond switching with a symmetric Mach-Zehnder all-optical switch

(S. Nakamura, K. Tajima, and Y. Sugimoto, CLEO'96, Paper CMB1)

- ♦ Symmetric Mach-Zehnder interferometer
- ♦ Switching by photoinduced nonlinear change of refractive index (bandfilling, i.e. incoherent mechanism)



$\lambda = 870 \text{ nm}$

(GaAs/AlGaAs)