The Power of Femtosecond Time-Resolved Ellipsometry – a Review

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ELI Ultrafast Science Workshop 12.02.2026, European XFEL

The SPIRIT of science

TECHNISCHE UNIVERSITÄT ILMENAU

Thanks to all who were involved in development of TSE method and physical understanding of processes: (alphabetically)

J. Andreasson, C. Armenta, E. Baron, C. Cobet, C. Emminger, **S. Espinoza**, D. Franta, Y. Gutierrez, **O. Herrfurth**, K. Hingerl, A. Horn, M. Kloz, J. Leveillee, M. Olbrich, T. Pflug, **M. Rebarz**, **S. Richter**, E. Runge, A. Schleife, N. Stiehm, Y. Slimi, C. Sturm, S. Vazquez-Miranda. S. Zollner, M. Zahradník

The SPIRIT of science
TECHNISCHE UNIVERSITÄT
ILMENAU

eli beamlines
Dolní Břežany, Czech Republic

UNIVERSITÄT LEIPZIG

Semiconductor Physics Group

JKU
JOHANNES KEPLER
UNIVERSITÄT LINZ

NM STATE UNIVERSITY
Las Cruces, New Mexico, USA

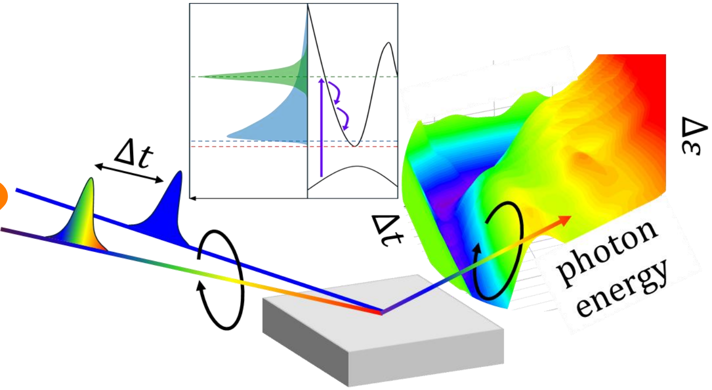
Ellipsometry and Polariton Physics Group

UC | Eunice EUROPEAN UNIVERSITY

UASLP
Universidad Autónoma
de San Luis Potosí

MUNI Masaryk University

Why ultrafast dynamics – why ultrafast ellipsometry?



(photo-induced) dynamics of

- in solid state and complex heterostructures
- excited charge carriers and vibrational modes (phonons), complex quasi-particles
- chemical reactions (example: photo-electrochemical water splitting)
- phase-changes, memristive switching (ferroelectric, magnetic, multiferroic)
- solid-liquid interfaces
- in interaction with fundamental theory: understanding of band structures, transition and recombination dynamics, electronic alignment, band-bending, …
- interaction of defects

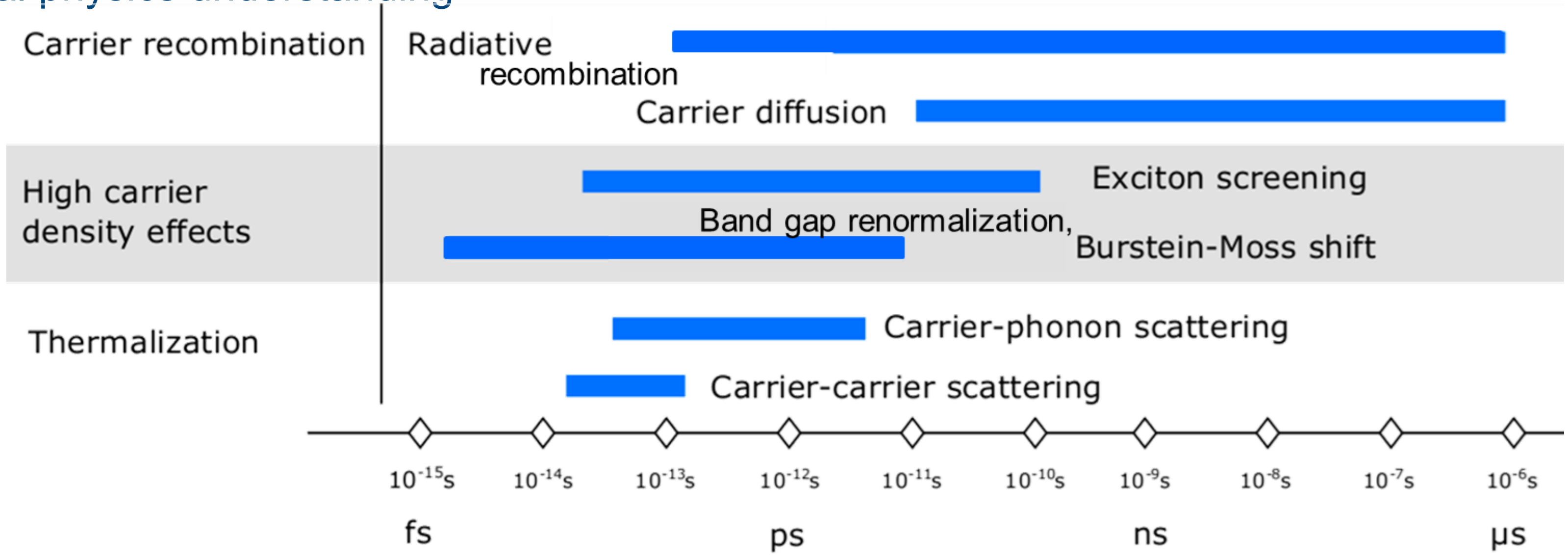
for understanding and improving of:

- fundamental physics
- applications – ultra-fast devices
- lasing, lightning and optical data transport and processing
- opto-electro-magnetic coupling and switching
- solar energy harvesting
- electronic transport

Ellipsometry: measures **complex optical response** → Kramers-Kronig consistent data – related to complex dielectric function

Ultrafast processes

fundamental physics understanding



Carrier recombination

Radiative recombination

Carrier diffusion

High carrier density effects

Exciton screening

Band gap renormalization, Burstein-Moss shift

Thermalization

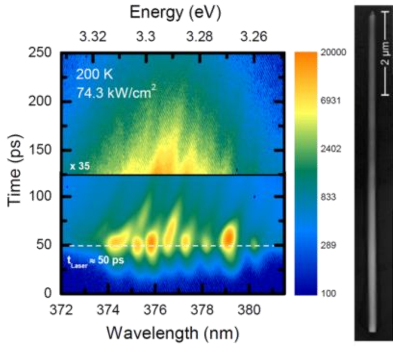
Carrier-phonon scattering

Carrier-carrier scattering

10^{-15}s 10^{-14}s 10^{-13}s 10^{-12}s 10^{-11}s 10^{-10}s 10^{-9}s 10^{-8}s 10^{-7}s 10^{-6}s

fs ps ns µs

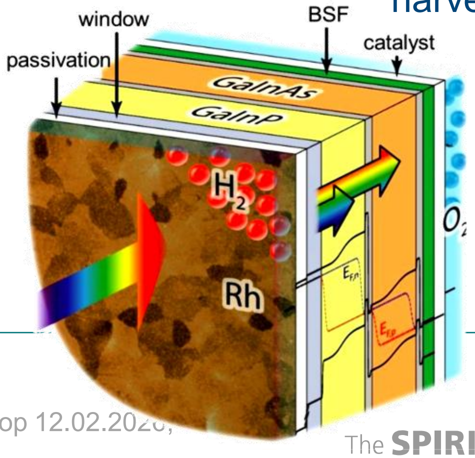
performance of opto-electronic devices, e.g.:



dynamics of lasing modes

*M. Wille, RSG et al.: Nanotechnology **27** (2016) 225702*

light-to-current conversion efficiency in light-harvesting applications



III-V semiconductors

GaP as one of the basic materials

*ACS Energy Lett. **3** (2018) 1795*

*Sol. RRL **8** (2024) 2301047*

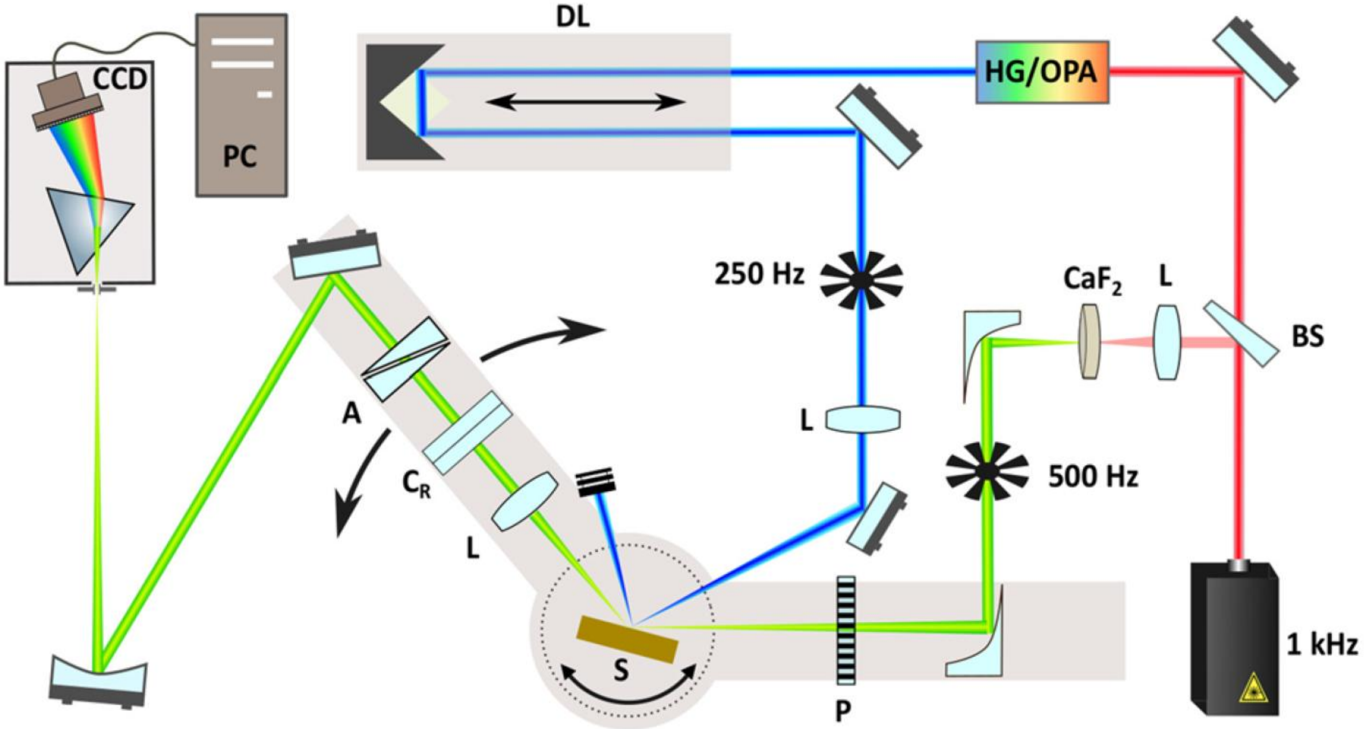
Review of Scientific Instruments

ARTICLE

Steffen Richter, Mateusz Rebarz, Oliver Herrfurth, Shirly Espinoza, Rüdiger Schmidt-Grund, and Jakob Andreasson
Rev. Sci. Instrum. ***92****, 033104 (2021)*

Broadband femtosecond spectroscopic ellipsometry

EP



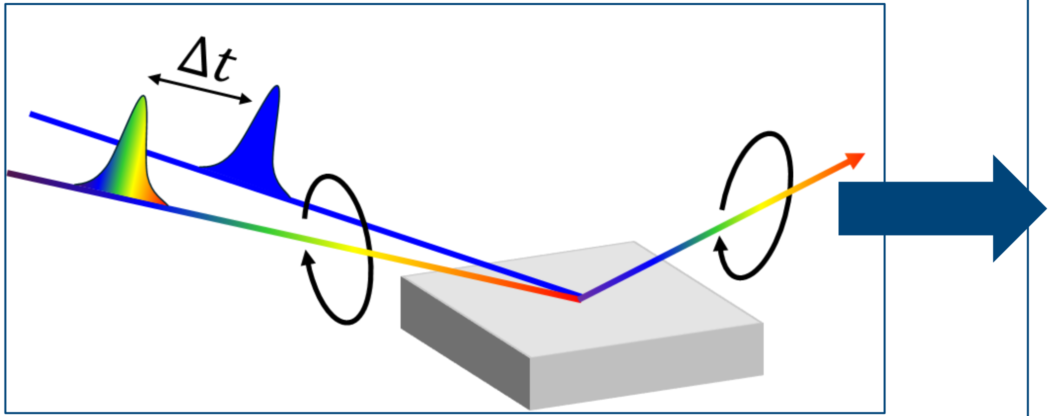
setup build up and located **@ ELI beamlines** facility in Dolní Břežany (Prague), Czech Republic

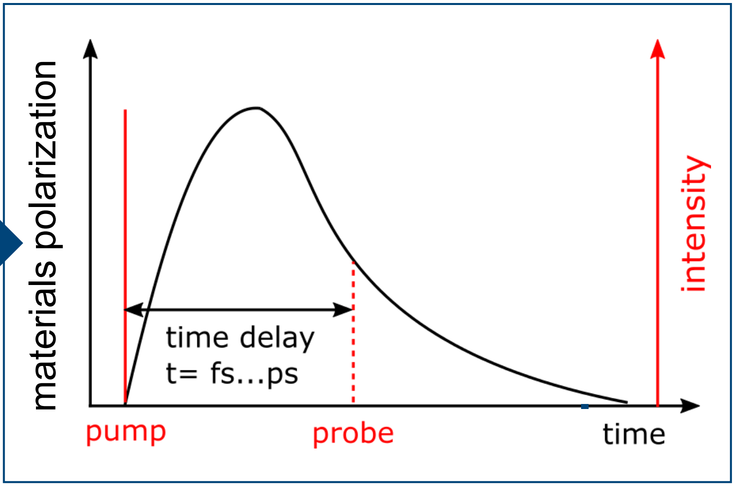
Method

principle

main work in method development and implementation:
Steffen Richter, Mateusz Rebarz, Oliver Herrfurth
but indeed, many others contributed

combine classic ellipsometry with classic pump-probe techniques





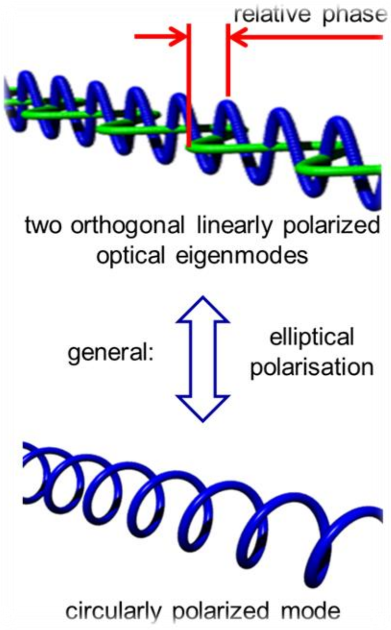
(pseudo-) dielectric function as response function –
depends on history,
e.g. by polarization / free charge carriers due to laser excitation by dynamics of $\chi(\tau)$

$$\Rightarrow \vec{P}(t) = \varepsilon_0 \int_0^\infty \chi(\tau)\vec{E}(t-\tau)\,\mathrm{d}\tau \qquad \chi(\omega) = \int_0^\infty \mathrm{e}^{\imath\omega\tau}\chi(\tau)\mathrm{d}\tau$$

Method

Ellipsometry

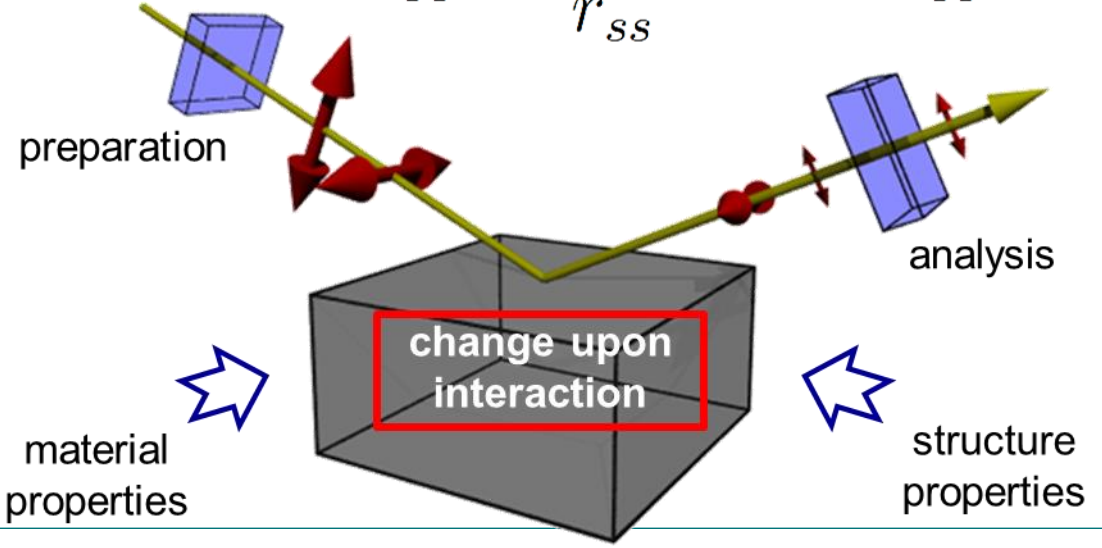
non-destructive optical method for investigation of structural and electronic properties of almost any materials and structures

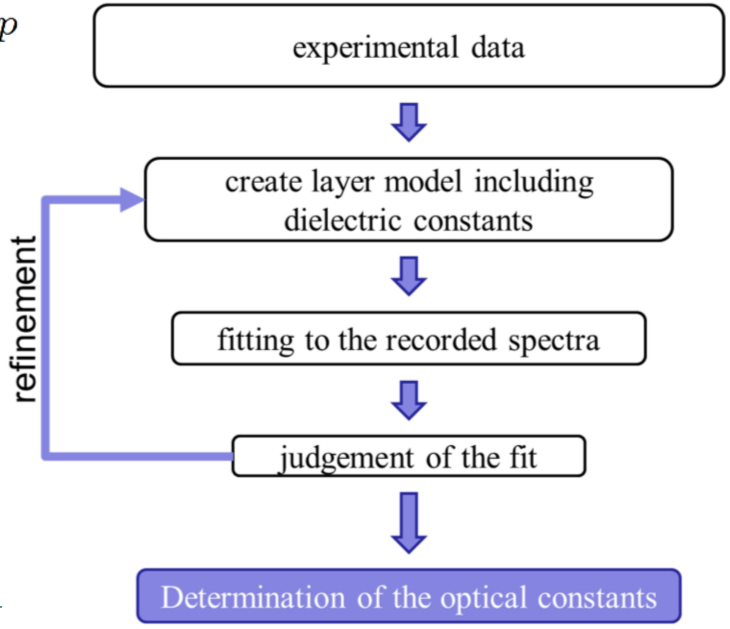


investigation of the **change of the polarization state** of light upon interaction with a sample

→ **amplitude and phase!**

$$\tilde{\rho}_{pp} = \frac{\tilde{r}_{pp}}{\tilde{r}_{ss}} = \tan\Psi_{pp} \cdot e^{i\Delta_{pp}}$$





experimental data

create layer model including dielectric constants

fitting to the recorded spectra

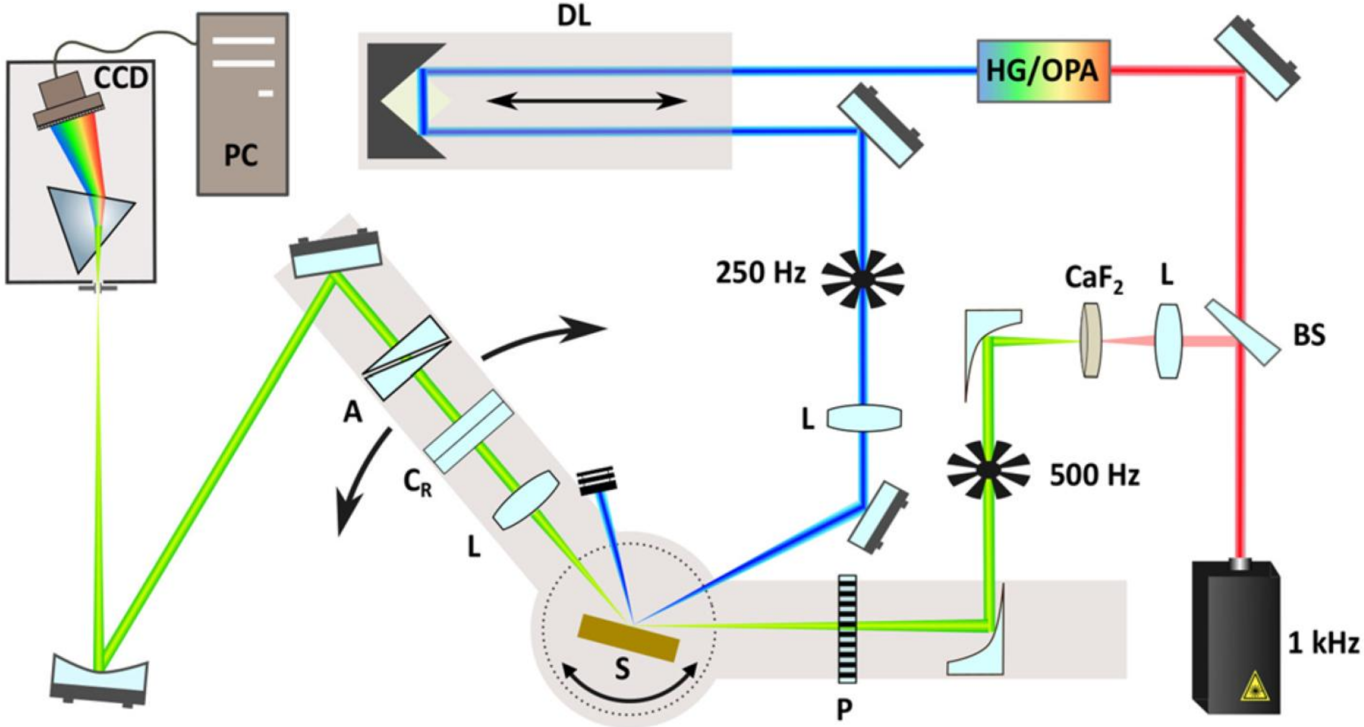
judgement of the fit

Determination of the optical constants

Review of Scientific Instruments ARTICLE

Steffen Richter, Mateusz Rebarz, Oliver Herrfurth, Shirly Espinoza, Rüdiger Schmidt-Grund, and Jakob Andreasson
Rev. Sci. Instrum. ***92****, 033104 (2021)*

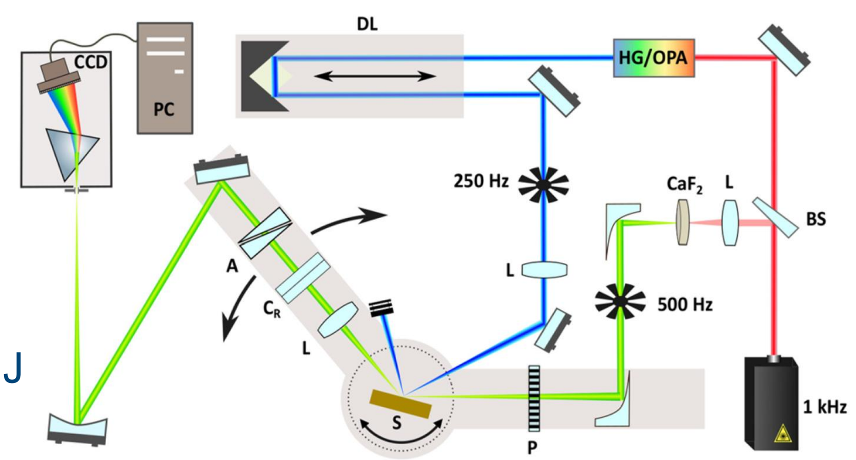
Broadband femtosecond spectroscopic ellipsometry



Steffen, Mateusz, Oliver

Method

Setup



Laser (1kHz amplified Ti:Sapph – 800nm):
Femtopower 20fs, 4mJ; Coherent Astrella 35fs, 6mJ

SHG, THG, OPA

Super-continuum white-light: CaF$_2$ – self-phase modulation

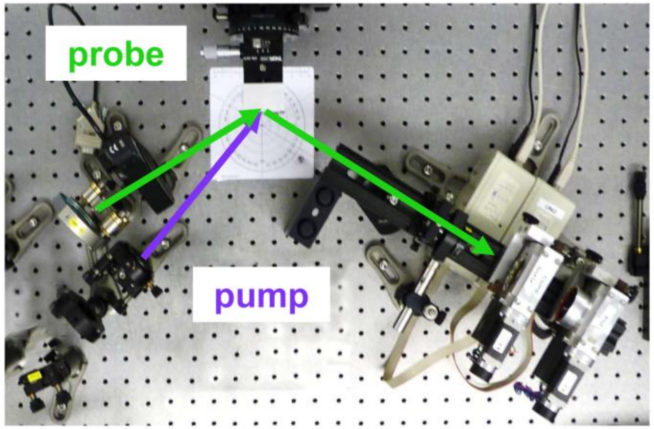
1m delay line (6ns); resolution 500 nm (3fs)

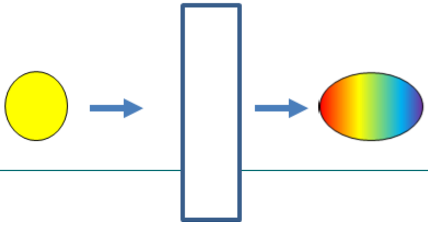
Ellipsometer: PSC$_R$A-configuration, rotating polarizer

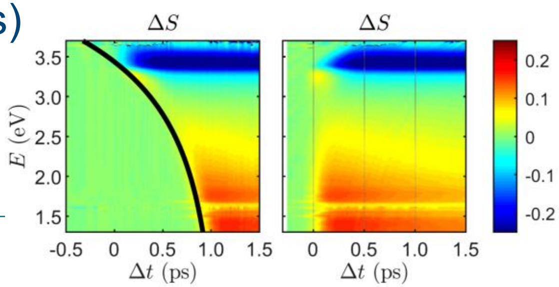
Detection: prism-spectrometer

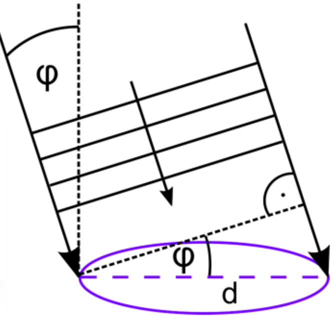
Polarization optics: ahead the sample (reflective optics, thin polarizer (group velocity dispersion – chirp))

Total time resolution ~ 80fs
(~ 20fs laser, non-colinear pump and probe ~ 60fs, non-correctable chirp and other smaller effects)









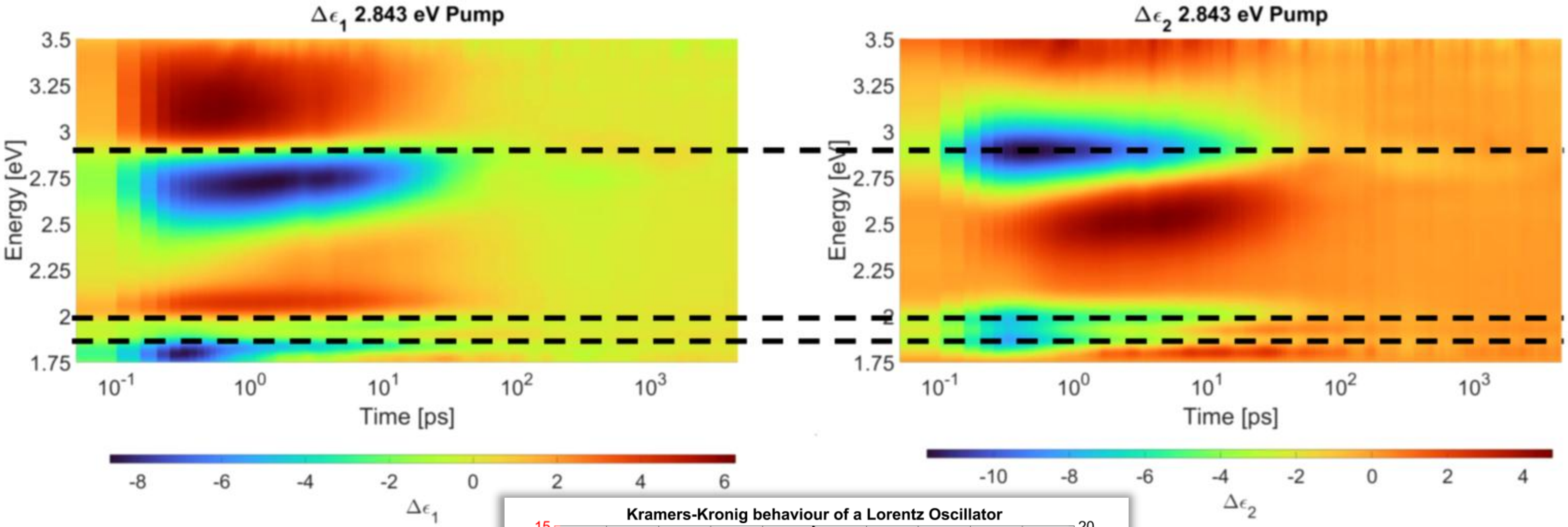
Richter, et al., Rev. Sci. Instrum. ***92****, 033104 (2021)*

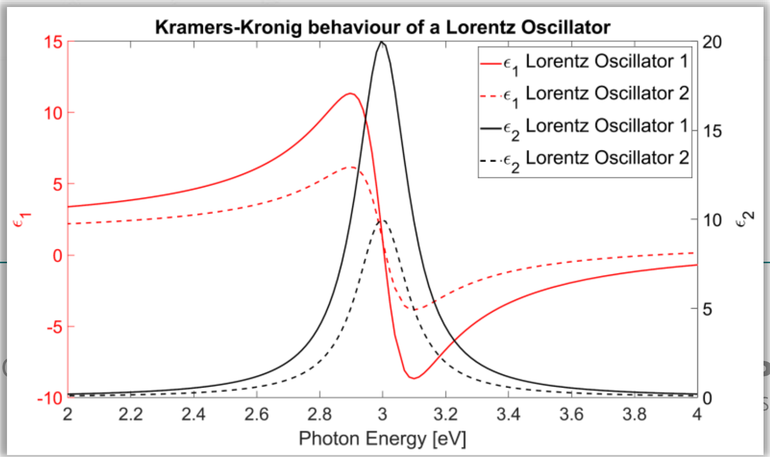
TSE Data – Textbook KK

example:

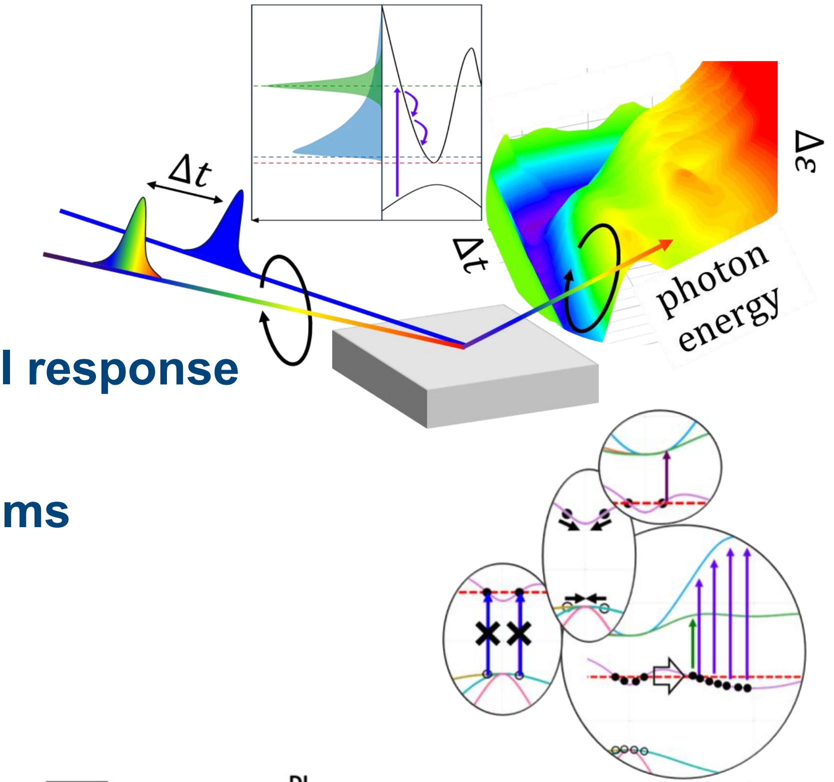
→ discrete two-level system-like excitations – Lorentzian

→ nice feature: data reflect textbook-like Kramers-Kronig relations

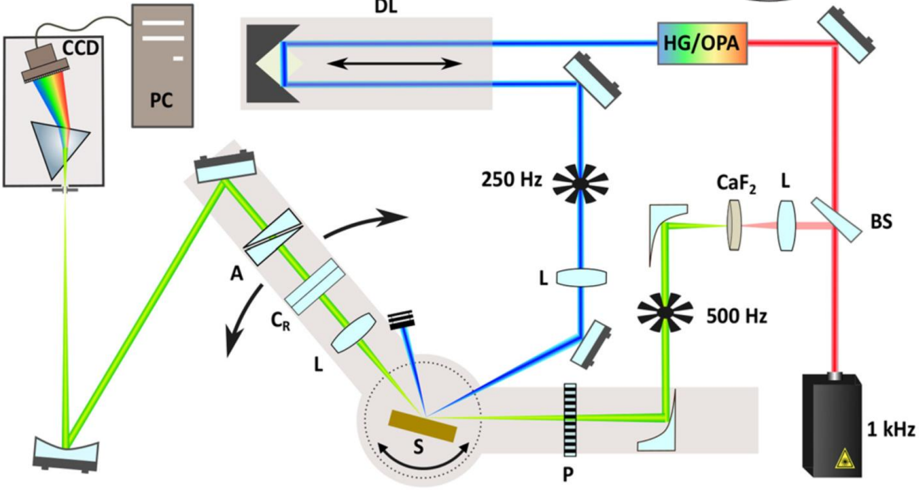




Pump-probe fs-TSE



- **method recently developed by us**
- **time evolution of the <u>full</u> complex optical response**
  → complex dielectric function
- **already applied to several material systems**
  - intra-band transitions (VB-VB and CB-CB)
  - hot-phonon scattering
  - ballistic carrier propagation
  - transient birefringence changes
  - coherent acoustic phonon oscillations
  - spectral weight transfer
  - insulator-to-metal transition
  - chemical reactions
  - …



What has been done so far?

and several other not published yet

Semiconductors

2D-Materials

Chemical Reactions (solid-liquid interface)

Phase Transitions

Fundamental Theory, Data-Theory

Time-resolved pump–probe spectroscopic ellipsometry of cubic GaN. I. Determination of the dielectric function

Time-resolved pump-probe spectroscopic ellipsometry of cubic GaN II: Absorption edge shift with gain and temperature effects

Transient dielectric function and carrier related processes in doped cubic GaN determined by femtosecond pump–probe spectroscopic ellipsometry

Transient dielectric functions of Ge, Si, and InP from femtosecond pump-probe ellipsometry

Femtosecond Pump-Probe Ellipsometry of Highly Doped InGaAs Quantum Wells Analyzed with Singular Value Decomposition

Band-filling and relaxation effects in the transient dielectric function of Ge

Subpicosecond Spectroscopic Ellipsometry of the Photoinduced Phase Transition in VO_2 Thin Films

Coherent Acoustic Phonon Oscillations and Transient Critical Point Parameters of Ge from Femtosecond Pump–Probe Ellipsometry

Ultrafast Exciton and Charge Carrier Dynamics in Monolayer MoS_2 Measured with Time-Resolved Spectroscopic Ellipsometry

Ultrafast dynamics of hot charge carriers in an oxide semiconductor probed by femtosecond spectroscopic ellipsometry

Time-resolved spectroscopic ellipsometry in solid-state thin films of thio-diketopyrrolopyrrole-based organic semiconductor

Photoinduced insulator-to-metal transition and coherent acoustic phonon propagation in $LaCoO_3$ thin films explored by femtosecond pump-probe ellipsometry

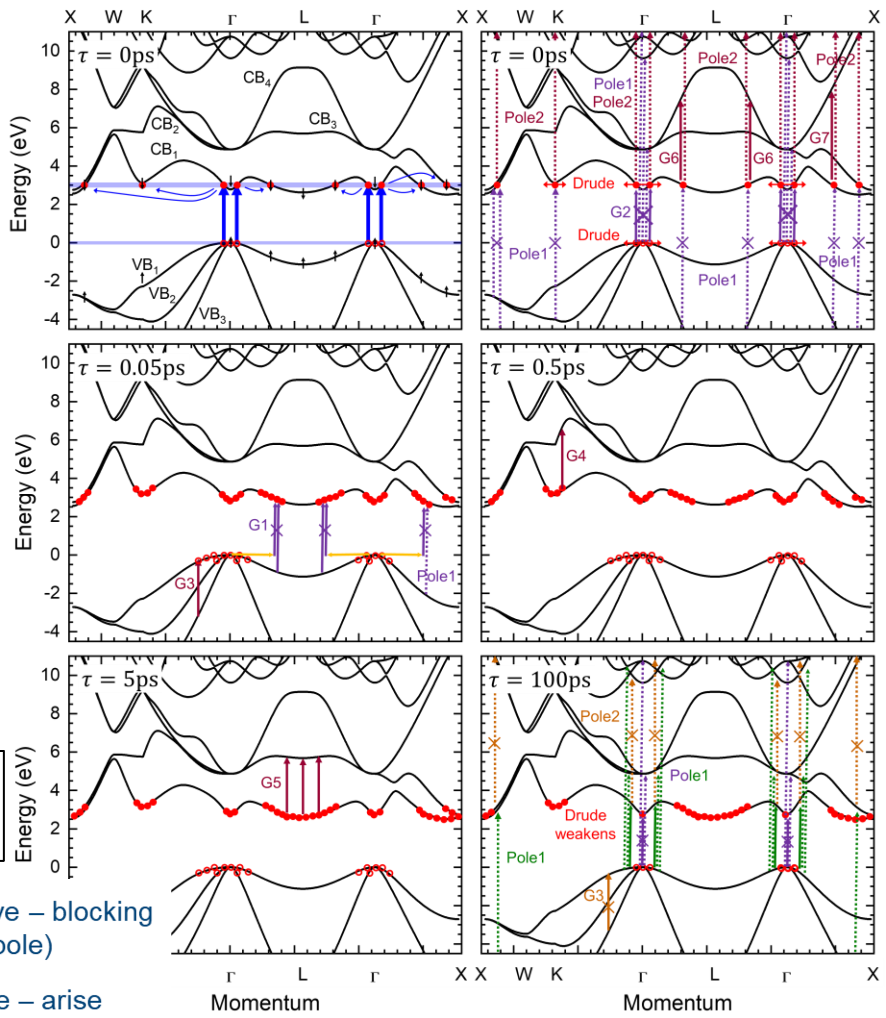
Optical transitions between entangled electron–phonon states in silicon

In-Situ and Time-Resolved Ellipsometry for Probing Surface Terminations and Reaction Kinetics via Exciton Resonances

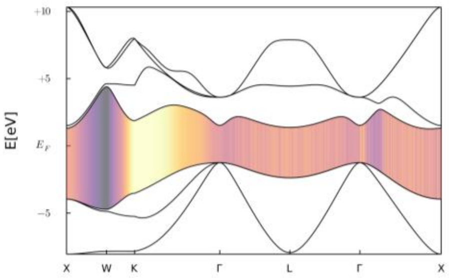
Semiconductors

- carrier excitation, scattering, relaxation, recombination
- band-filling, band gap renormalization
- interaction with lattice
- lifetimes, scattering times, relaxation times
- carrier trapping

identification of processes:
only due to Kramers-Kronig
only by ellipsometry!



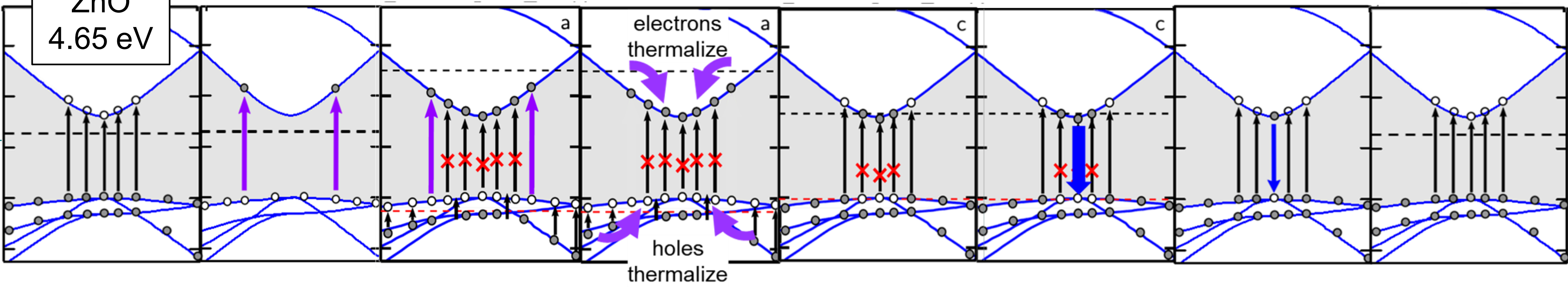
GaP
3.1 eV



↑↑ negative – blocking (TcL / pole)

↑↑ positive – arise (TcL / pole)

ZnO
4.65 eV

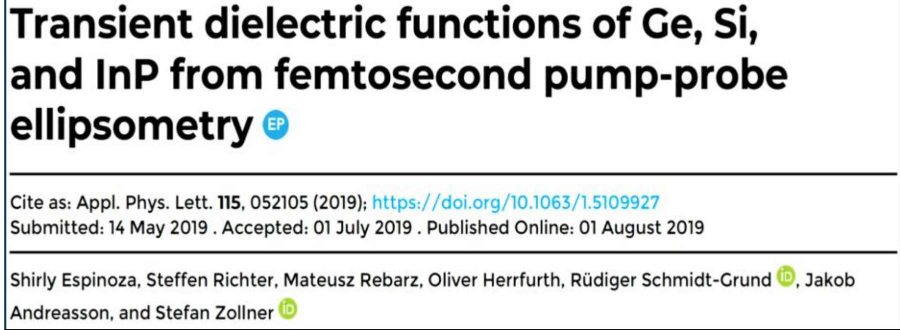


Carlos, Shirly

Semiconductors

Classic IV-IV and III-V

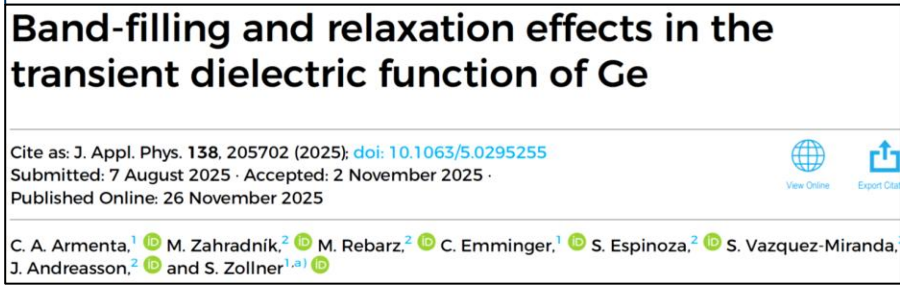
Band-Filling, Intervalley-Scattering, Intra-Band Transitions, Band-Renormalization



Transient dielectric functions of Ge, Si, and InP from femtosecond pump-probe ellipsometry

Cite as: Appl. Phys. Lett. **115**, 052105 (2019); https://doi.org/10.1063/1.5109927
Submitted: 14 May 2019 . Accepted: 01 July 2019 . Published Online: 01 August 2019

Shirly Espinoza, Steffen Richter, Mateusz Rebarz, Oliver Herrfurth, Rüdiger Schmidt-Grund, Jakob Andreasson, and Stefan Zollner



Band-filling and relaxation effects in the transient dielectric function of Ge

Cite as: J. Appl. Phys. **138**, 205702 (2025); doi: 10.1063/5.0295255
Submitted: 7 August 2025 · Accepted: 2 November 2025 ·
Published Online: 26 November 2025

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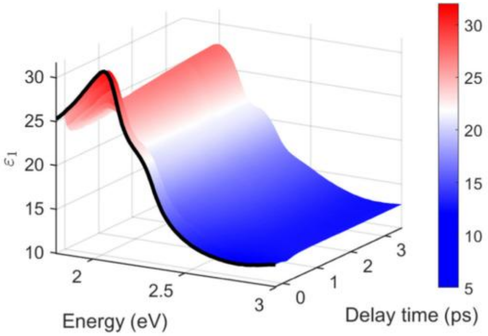
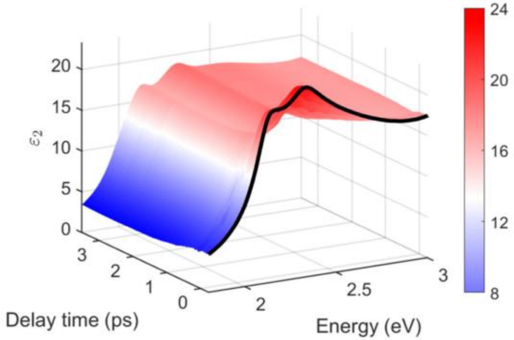
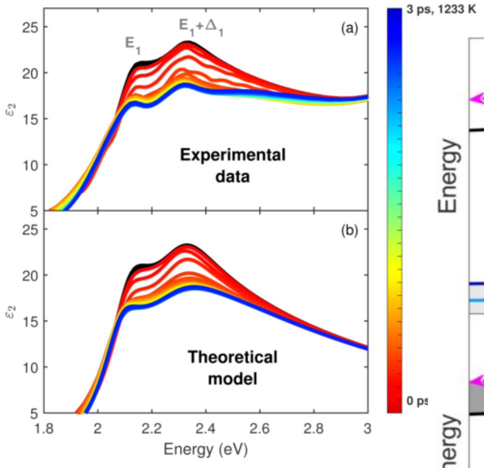
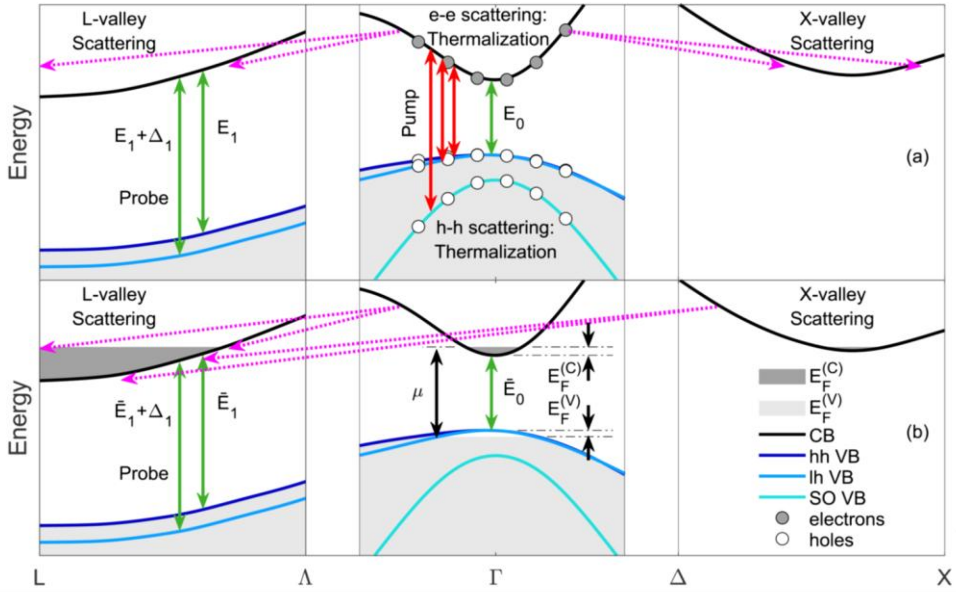
C. A. Armenta,[1] M. Zahradník,[2] M. Rebarz,[2] C. Emminger,[1] S. Espinoza,[2] S. Vazquez-Miranda,
J. Andreasson,[2] and S. Zollner[1,a)]







Ge

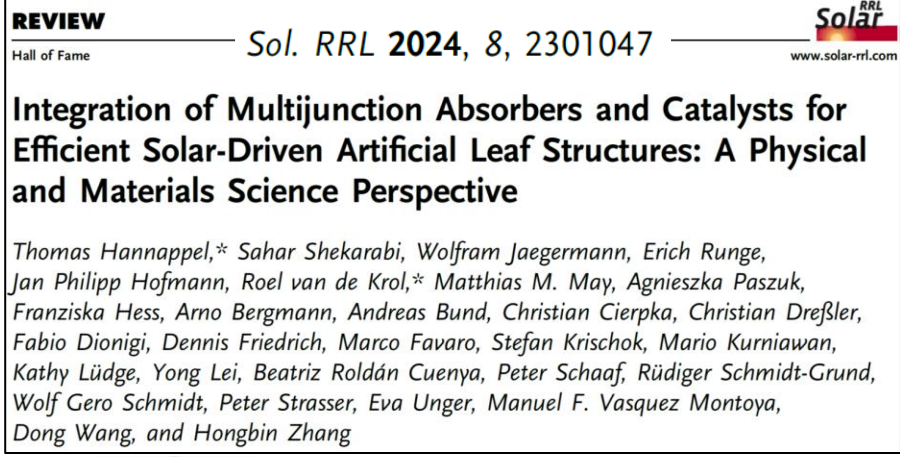


Noah

Semiconductors

Classic IV-IV and III-V

Band-Filling, Intervalley-Scattering, Intra-Band Transitions, Band-Renormalization



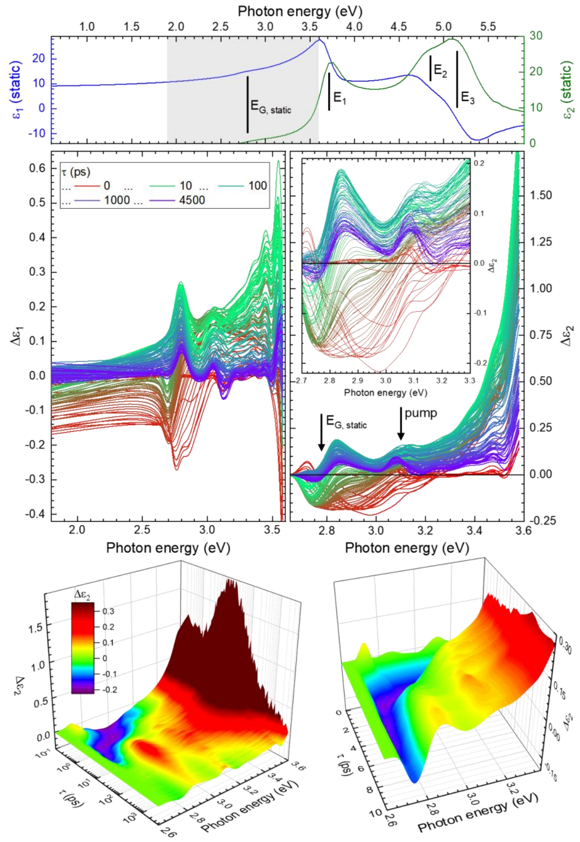
REVIEW
Hall of Fame

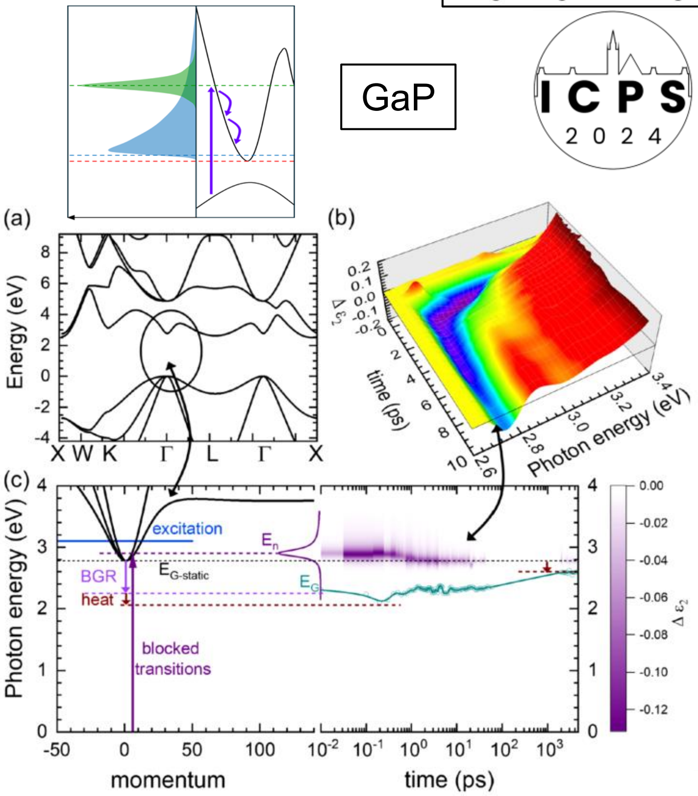
Sol. RRL **2024**, *8*, 2301047

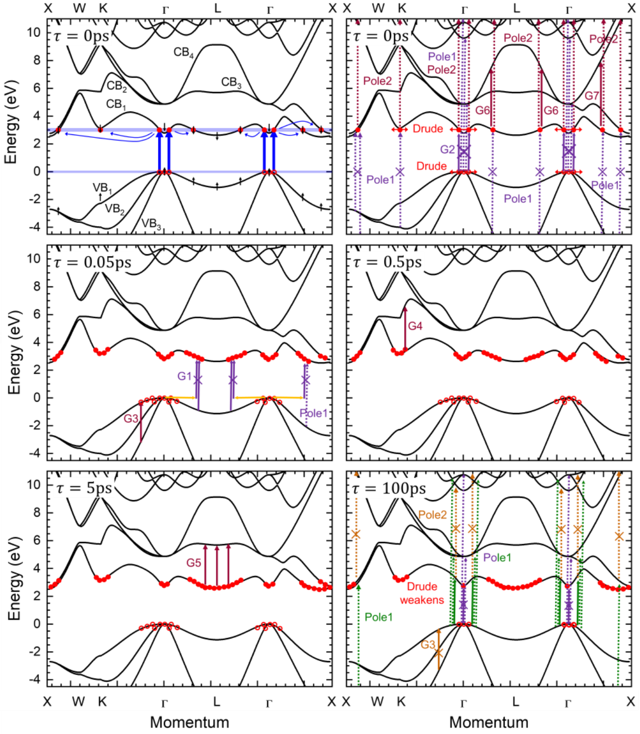
www.solar-rrl.com

Integration of Multijunction Absorbers and Catalysts for Efficient Solar-Driven Artificial Leaf Structures: A Physical and Materials Science Perspective

Thomas Hannappel, Sahar Shekarabi, Wolfram Jaegermann, Erich Runge, Jan Philipp Hofmann, Roel van de Krol,* Matthias M. May, Agnieszka Paszuk, Franziska Hess, Arno Bergmann, Andreas Bund, Christian Cierpka, Christian Dreßler, Fabio Dionigi, Dennis Friedrich, Marco Favaro, Stefan Krischok, Mario Kurniawan, Kathy Lüdge, Yong Lei, Beatriz Roldán Cuenya, Peter Schaaf, Rüdiger Schmidt-Grund, Wolf Gero Schmidt, Peter Strasser, Eva Unger, Manuel F. Vasquez Montoya, Dong Wang, and Hongbin Zhang*



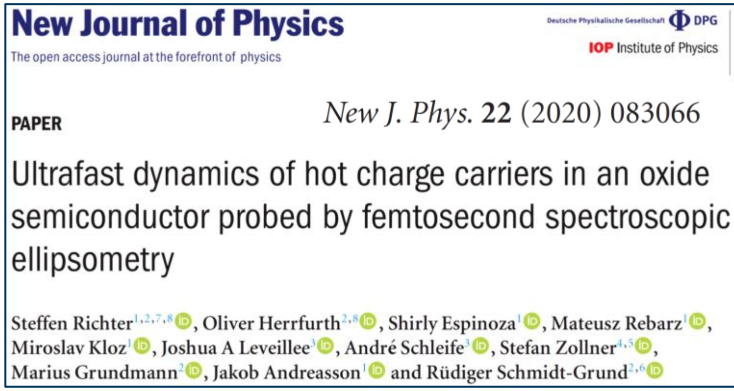




Steffen, Oliver

Semiconductors

ZnO: Hot Phonons


New Journal of Physics
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Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics

PAPER

New J. Phys. **22** (2020) 083066

Ultrafast dynamics of hot charge carriers in an oxide semiconductor probed by femtosecond spectroscopic ellipsometry

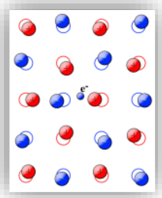
Steffen Richter[1,2,7,8], Oliver Herrfurth[2,8], Shirly Espinoza[1], Mateusz Rebarz[1], Miroslav Kloz[1], Joshua A Leveillee[3], André Schleife[3], Stefan Zollner[4,5], Marius Grundmann[2], Jakob Andreasson[1] and Rüdiger Schmidt-Grund[2,6]

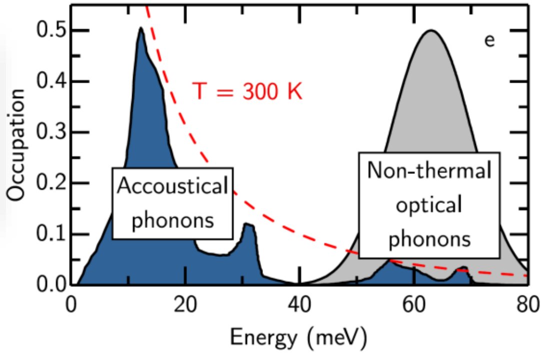
formation of hot-electron–hot-phonon states (hot exciton-phonon complexes)

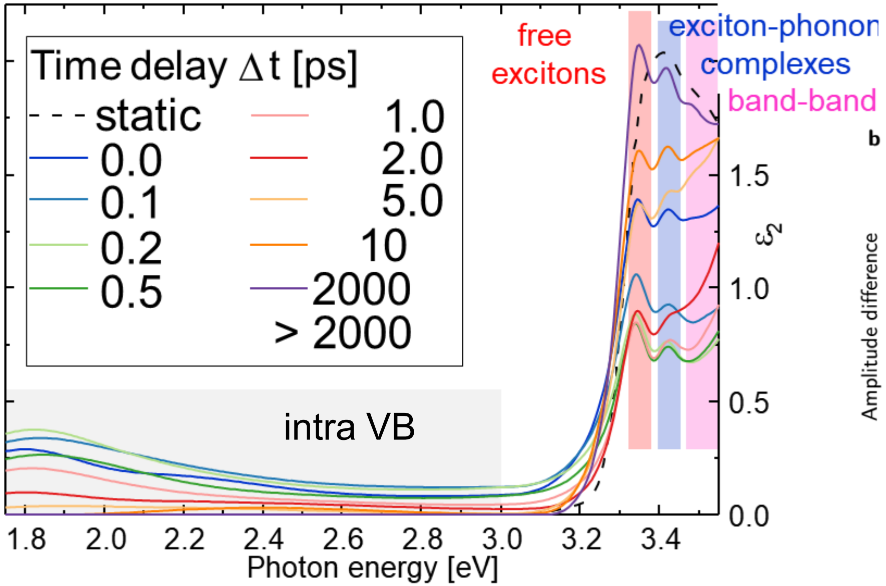
electron thermalization slowed down by hot-phonon effect:

- electron-phonon scattering: creation of hot phonons
- in turn hot electrons created by phonon decay
- exciton-phonon binding energy increases

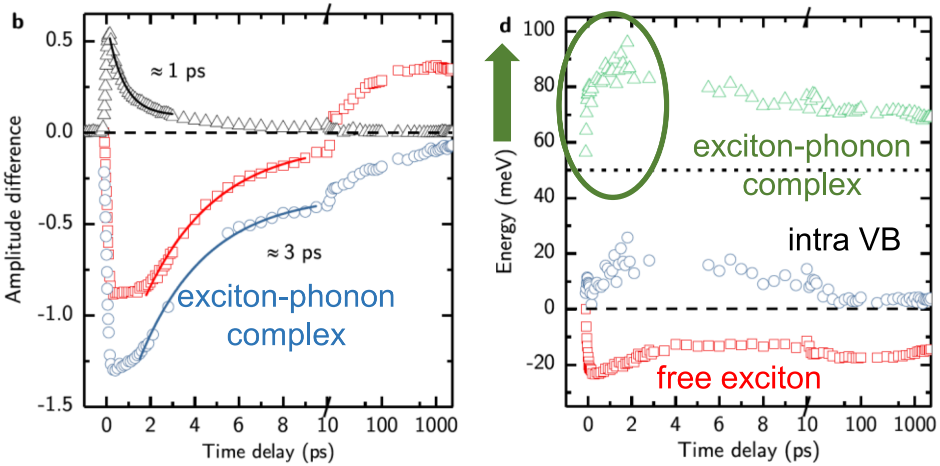
high-energy exciton-phonon complex (exciton-polaron)







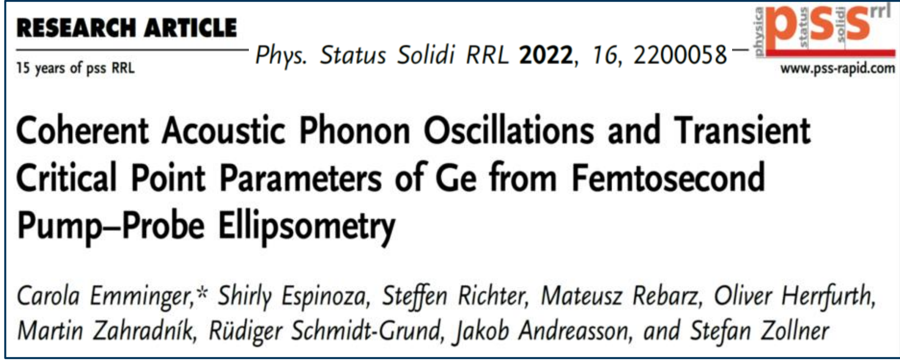
ZnO



Carola

Semiconductors

Phonon-Oscillations


RESEARCH ARTICLE
15 years of pss RRL
Phys. Status Solidi RRL **2022**, *16*, 2200058
www.pss-rapid.com

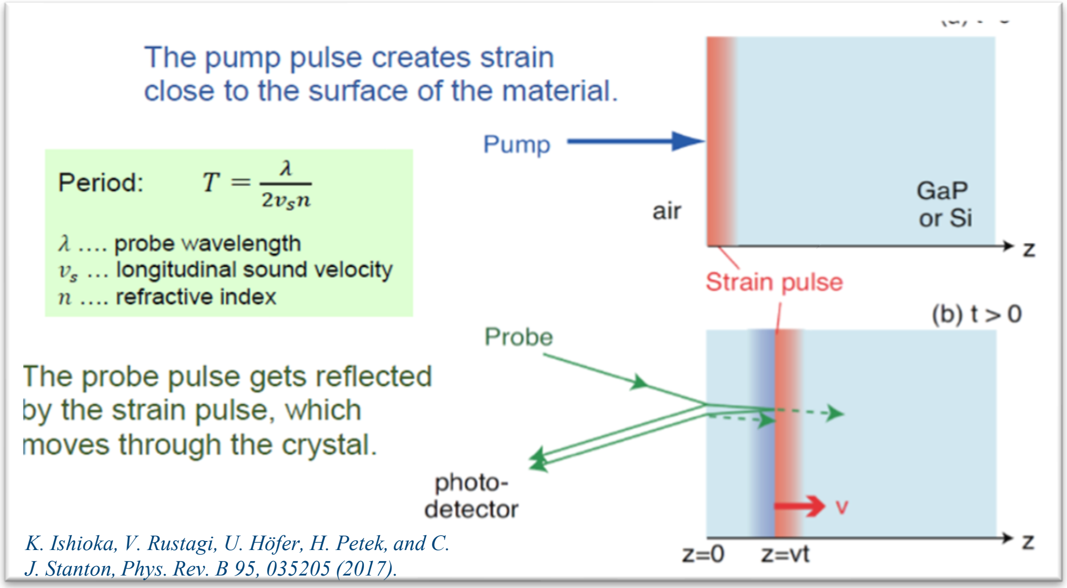
Coherent Acoustic Phonon Oscillations and Transient Critical Point Parameters of Ge from Femtosecond Pump–Probe Ellipsometry

Carola Emminger, Shirly Espinoza, Steffen Richter, Mateusz Rebarz, Oliver Herrfurth, Martin Zahradník, Rüdiger Schmidt-Grund, Jakob Andreasson, and Stefan Zollner*

pump pulse causes propagating strain wave
interference of probe light

oscillations in transient critical point energies in Ge:

$$\Delta E(t) = -\Delta E_{\mathrm{a}} \cos\left(\frac{2\pi t}{T} - \delta\right) e^{-\frac{t}{\tau_{\mathrm{a}}}} - \Delta E_{\mathrm{b}} e^{-\frac{t}{\tau_b}} \qquad T \approx \frac{\lambda}{2nv_{\mathrm{s}}}$$



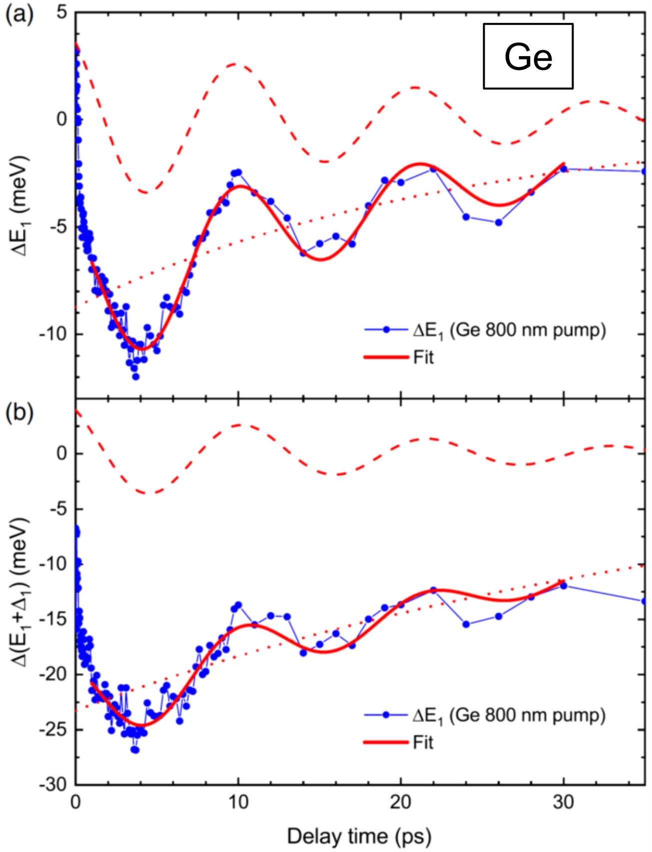
The pump pulse creates strain close to the surface of the material.

Period: $T = \frac{\lambda}{2v_s n}$

λ …. probe wavelength
v_s … longitudinal sound velocity
n …. refractive index

The probe pulse gets reflected by the strain pulse, which moves through the crystal.

K. Ishioka, V. Rustagi, U. Höfer, H. Petek, and C. J. Stanton, Phys. Rev. B 95, 035205 (2017).



Yael

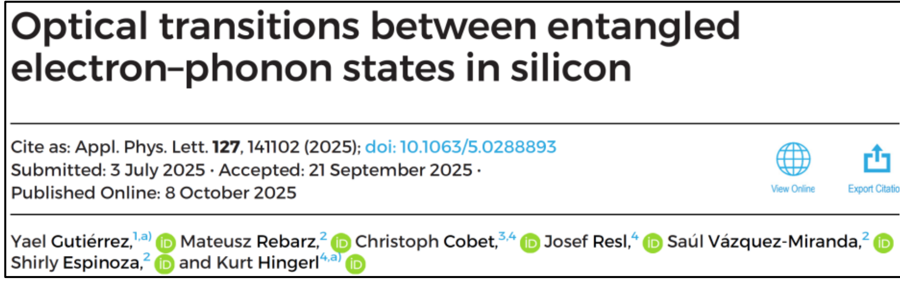
Semiconductors

Entangled Phonons

two-photon absorption

electronic excitation relaxes

- → generation of coherent longitudinal optical phonons along X
- → optical transitions of entangled electron–phonon states along K
- → transient, strongly correlated electron–phonon state (< 300 fs)
- → coherence time: electronic transition energies modulated by quantized phonon contributions

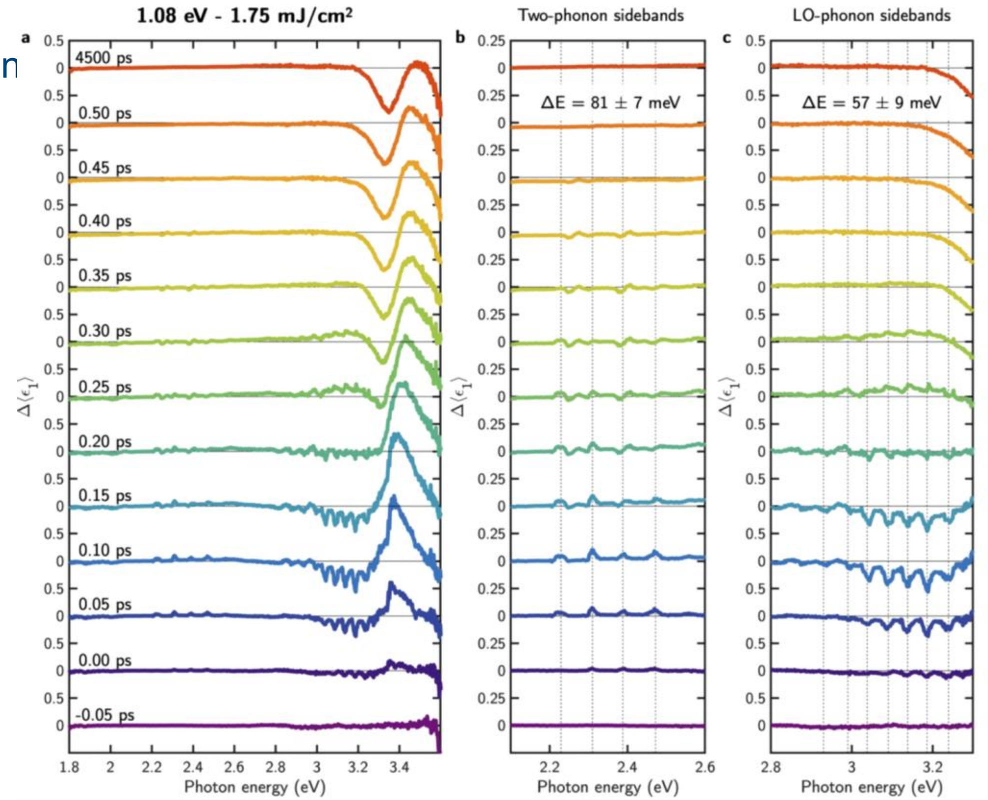


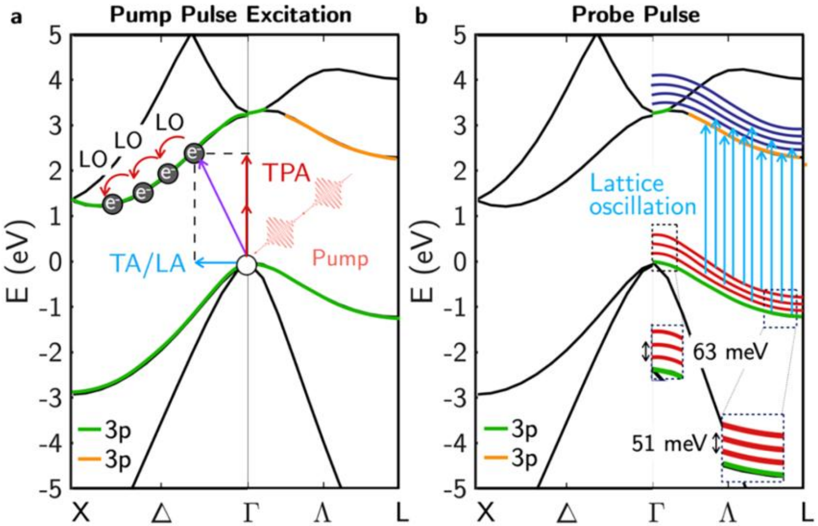
Optical transitions between entangled electron–phonon states in silicon

Cite as: Appl. Phys. Lett. **127**, 141102 (2025); doi: 10.1063/5.0288893
Submitted: 3 July 2025 · Accepted: 21 September 2025 ·
Published Online: 8 October 2025

Yael Gutiérrez,[1,a)] Mateusz Rebarz,[2] Christoph Cobet,[3,4] Josef Resl,[4] Saúl Vázquez-Miranda,[2] Shirly Espinoza,[2] and Kurt Hingerl[4,a)]

Si



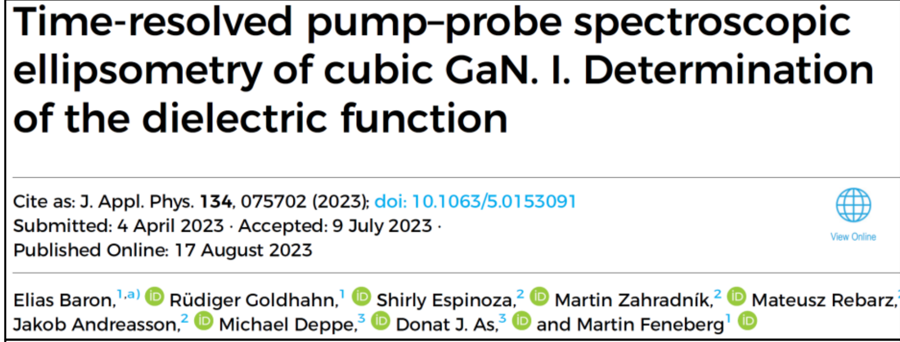


Elias

Semiconductors

Nitrides – GaN

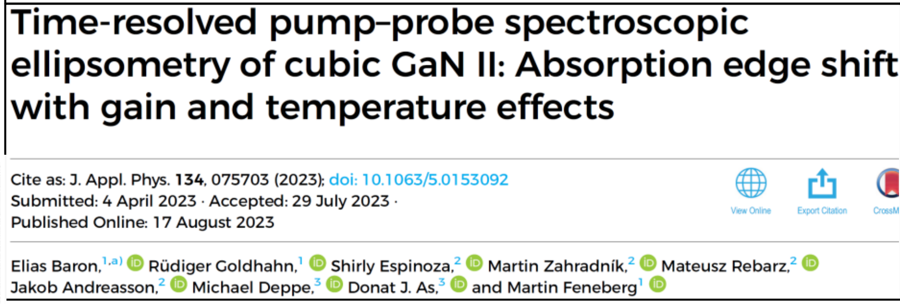
Theory and Advanced Modelling



Time-resolved pump–probe spectroscopic ellipsometry of cubic GaN. I. Determination of the dielectric function

Cite as: J. Appl. Phys. **134**, 075702 (2023); doi: 10.1063/5.0153091
Submitted: 4 April 2023 · Accepted: 9 July 2023 ·
Published Online: 17 August 2023

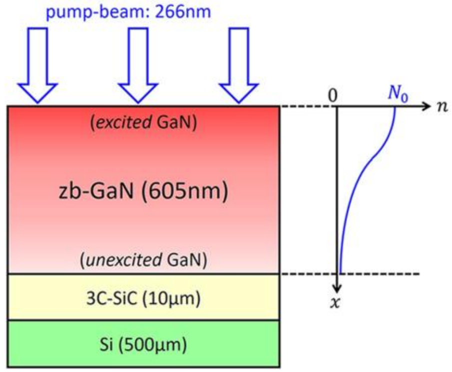
Elias Baron,[1,a)] Rüdiger Goldhahn,[1] Shirly Espinoza,[2] Martin Zahradník,[2] Mateusz Rebarz,
Jakob Andreasson,[2] Michael Deppe,[3] Donat J. As,[3] and Martin Feneberg[1]

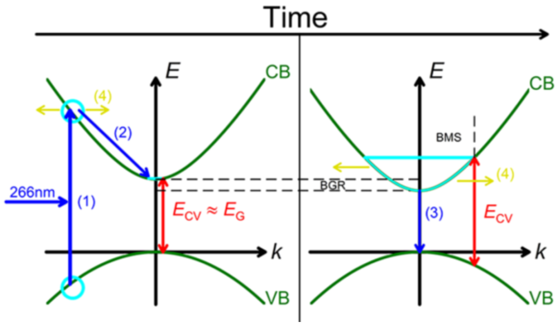


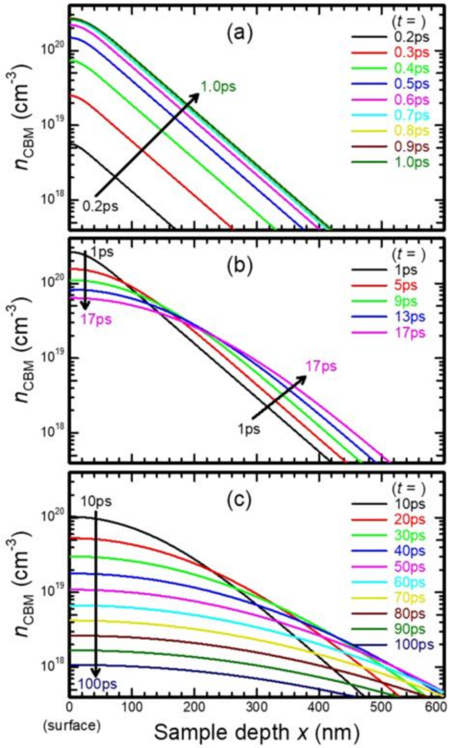
Time-resolved pump–probe spectroscopic ellipsometry of cubic GaN II: Absorption edge shift with gain and temperature effects

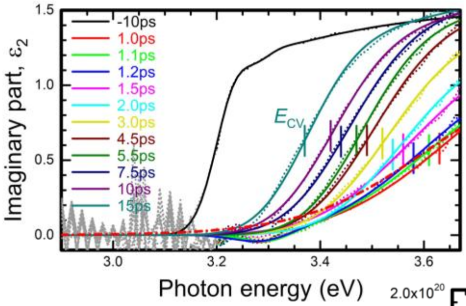
Cite as: J. Appl. Phys. **134**, 075703 (2023); doi: 10.1063/5.0153092
Submitted: 4 April 2023 · Accepted: 29 July 2023 ·
Published Online: 17 August 2023

Elias Baron,[1,a)] Rüdiger Goldhahn,[1] Shirly Espinoza,[2] Martin Zahradník,[2] Mateusz Rebarz,[2]
Jakob Andreasson,[2] Michael Deppe,[3] Donat J. As,[3] and Martin Feneberg[1]

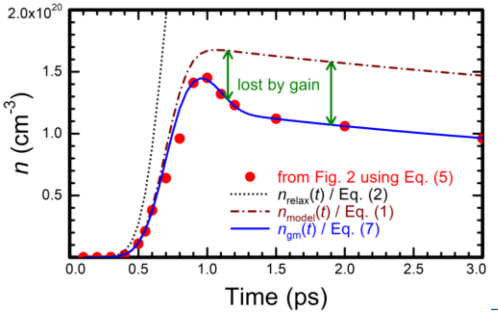








h-GaN



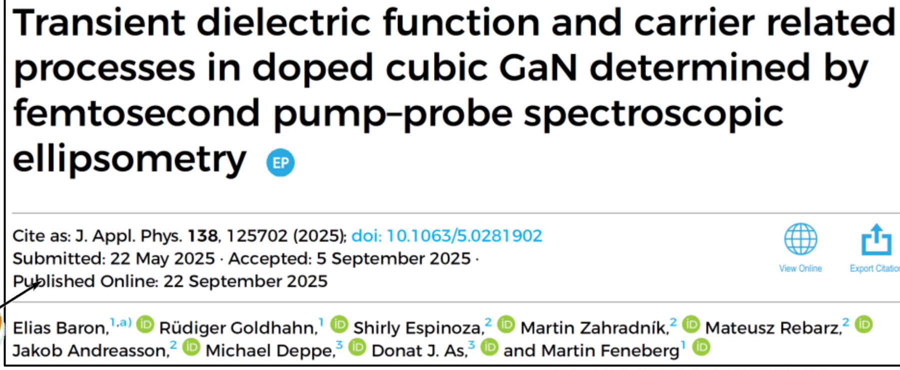
Elias, Younes, Malte, Max

Semiconductors

Nitrides – Cubic ScN, GaN

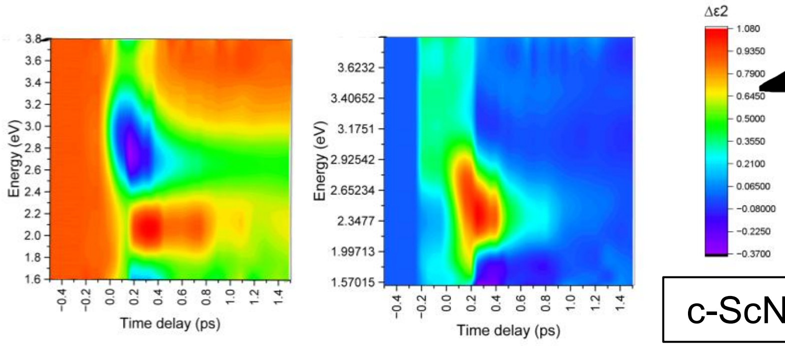
Theory and Advanced Modelling

ICSE-10

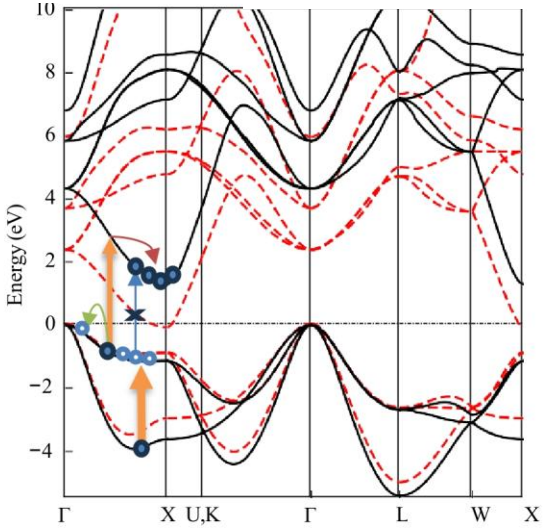

Transient dielectric function and carrier related processes in doped cubic GaN determined by femtosecond pump-probe spectroscopic ellipsometry

Cite as: J. Appl. Phys. 138, 125702 (2025); doi: 10.1063/5.0281902
Submitted: 22 May 2025 · Accepted: 5 September 2025 ·
Published Online: 22 September 2025

Elias Baron,[1,a)] Rüdiger Goldhahn,[1] Shirly Espinoza,[2] Martin Zahradník,[2] Mateusz Rebarz,[2] Jakob Andreasson,[2] Michael Deppe,[3] Donat J. As,[3] and Martin Feneberg[1]

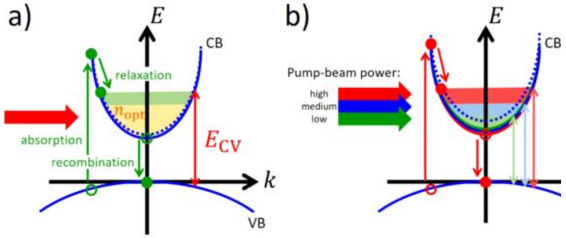


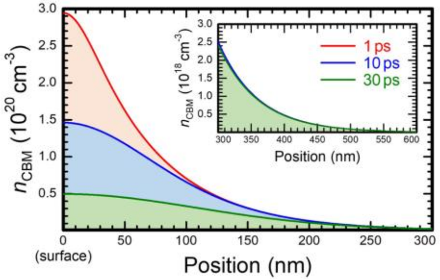
c-ScN

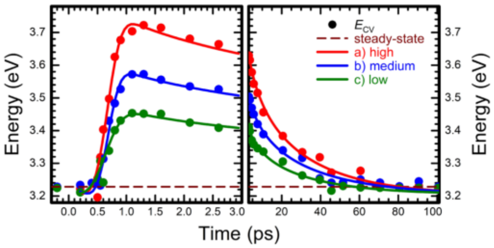


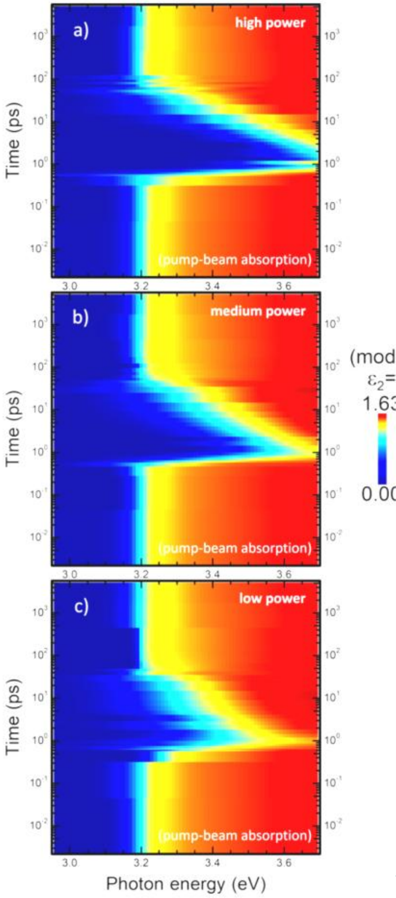
band structure calculated by QSGˆW (quasiparticle self-consistent GW method that incorporates vertex corrections (ladder diagrams) in the screened interaction W by solving a Bethe-Salpeter equation) **confirmed**

c-GaN





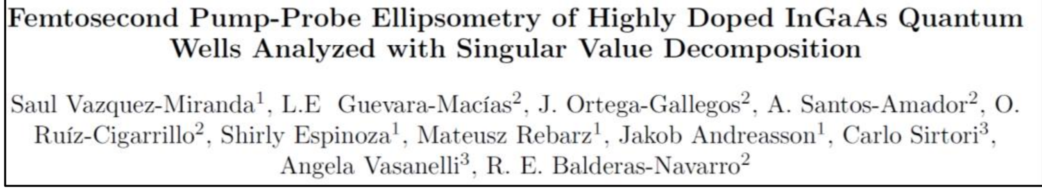




Saul

Semiconductors

Quantum Wells

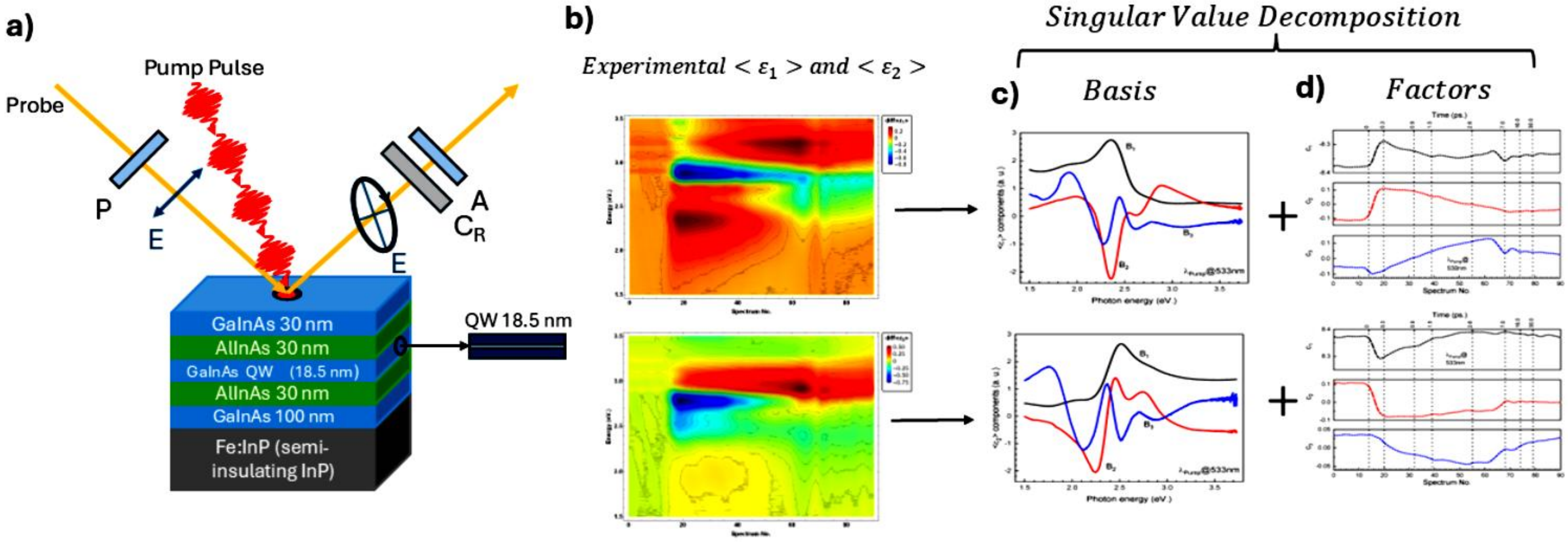


Femtosecond Pump-Probe Ellipsometry of Highly Doped InGaAs Quantum Wells Analyzed with Singular Value Decomposition

Saul Vazquez-Miranda[1], L.E Guevara-Macías[2], J. Ortega-Gallegos[2], A. Santos-Amador[2], O. Ruíz-Cigarrillo[2], Shirly Espinoza[1], Mateusz Rebarz[1], Jakob Andreasson[1], Carlo Sirtori[3], Angela Vasanelli[3], R. E. Balderas-Navarro[2]

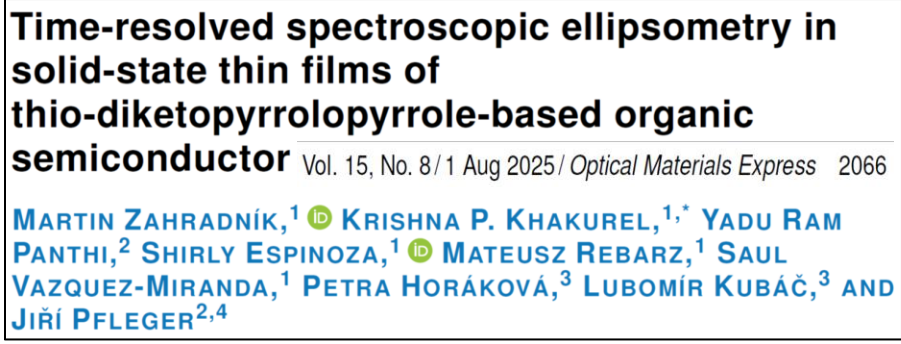
ICSE-10

Advanced Modelling – Singular Value Decomposition



Martin

Organic Semiconductors

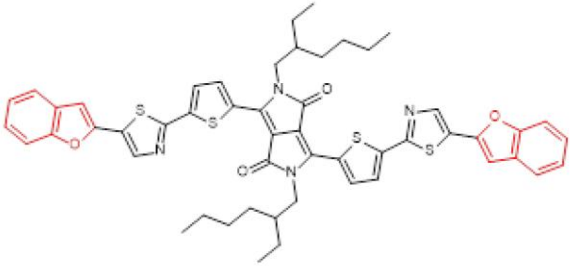


Time-resolved spectroscopic ellipsometry in solid-state thin films of thio-diketopyrrolopyrrole-based organic semiconductor

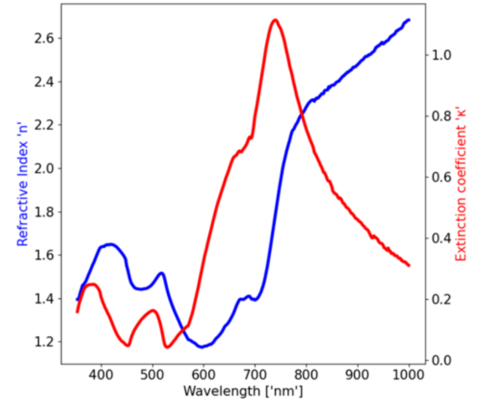
Vol. 15, No. 8 / 1 Aug 2025 / *Optical Materials Express* 2066

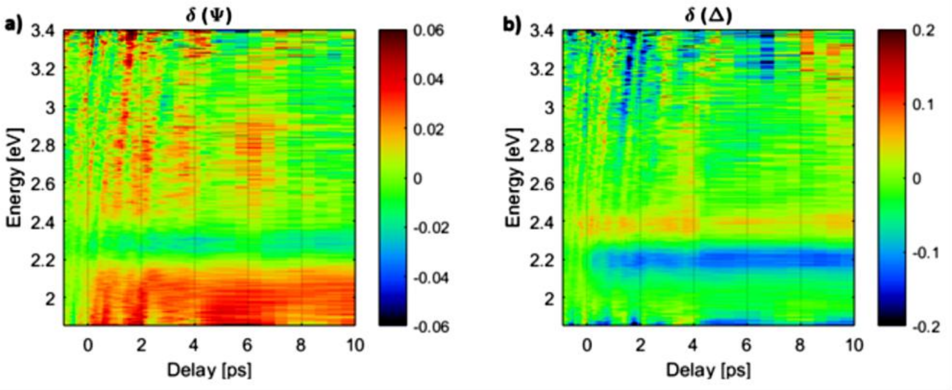
MARTIN ZAHRADNÍK,[1] KRISHNA P. KHAKUREL,[1,*] YADU RAM PANTHI,[2] SHIRLY ESPINOZA,[1] MATEUSZ REBARZ,[1] SAUL VAZQUEZ-MIRANDA,[1] PETRA HORÁKOVÁ,[3] LUBOMÍR KUBÁČ,[3] AND JIŘÍ PFLEGER[2,4]

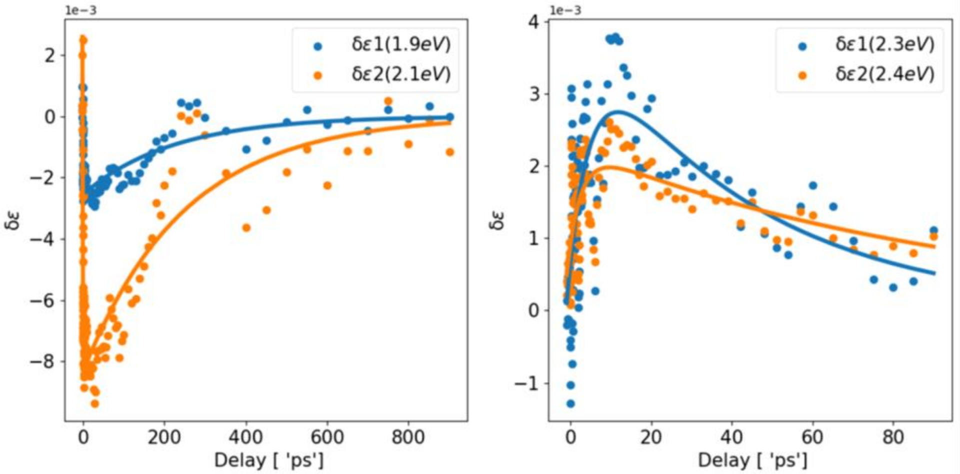
problem radiation damage
TSE advantageous for opaque substrates



TDPP







Luis, Saul

Chemical Reactions

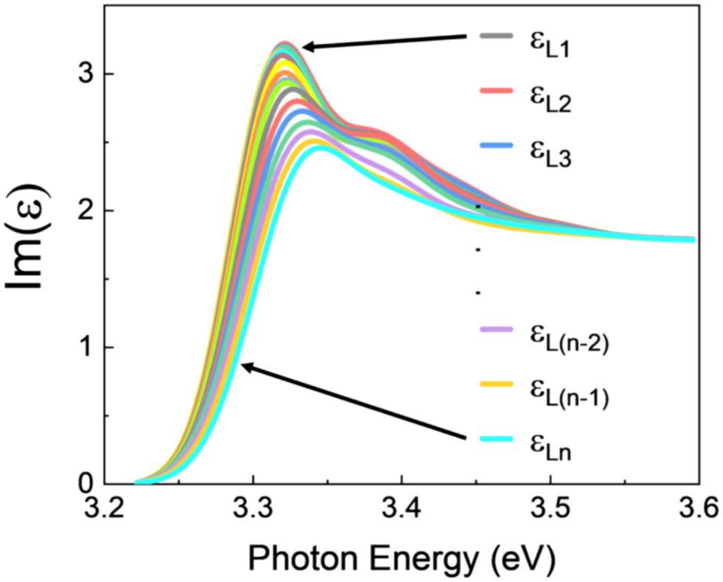
ZnO – CO_2 Reduction

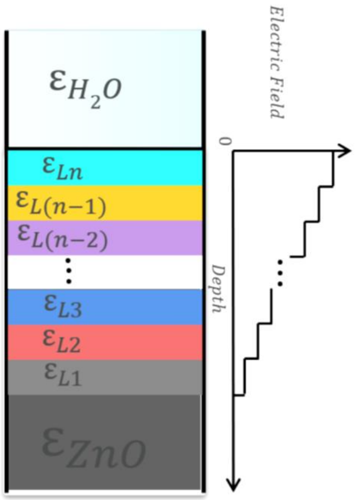
In-Situ and Time-Resolved Ellipsometry for Probing Surface Terminations and Reaction Kinetics via Exciton Resonances

Christoph Cobet[1], Luis Rosillo Orozco[1], Saul Vazquez-Miranda[2], Kurt Hingerl[1]

ICSE-10

observed via surface band-bending and exciton screening due to electric fields

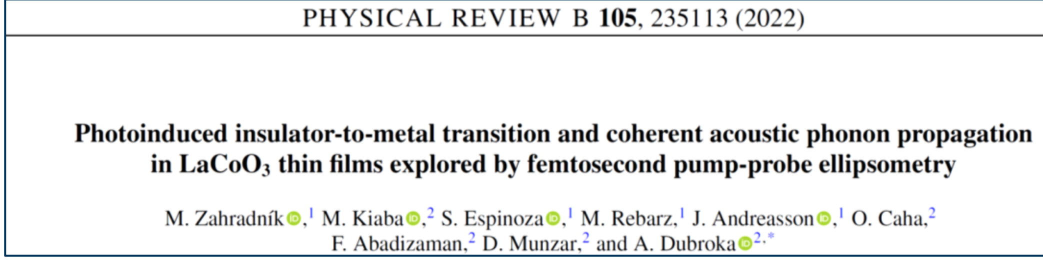




Martin

Magnetic Materials

photoinduced insulator-to-metal transition



PHYSICAL REVIEW B **105**, 235113 (2022)

Photoinduced insulator-to-metal transition and coherent acoustic phonon propagation in $LaCoO_3$ thin films explored by femtosecond pump-probe ellipsometry

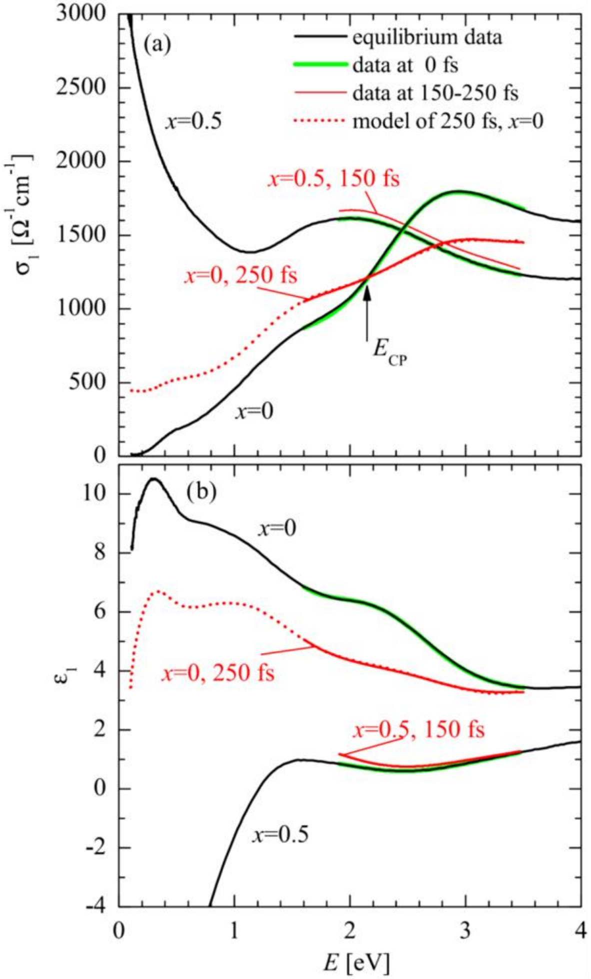
M. Zahradník,[1] M. Kiaba,[2] S. Espinoza,[1] M. Rebarz,[1] J. Andreasson,[1] O. Caha,[2] F. Abadizaman,[2] D. Munzar,[2] and A. Dubroka[2,*]

- within the first 200 fs after the pump: transfer of spectral weight from high energies above 2.1 eV to lower energies
  → insulator-to-metal transition

$LaCoO_3$

band gap: 0.2 eV
inter-band transitions:
$t_{2g} \rightarrow t_{2g}$ (0.4 eV) – Co,
$t_{2g} \rightarrow e_g$ (1.5 eV) – Co,
O 2p → Co e_g (3 eV)

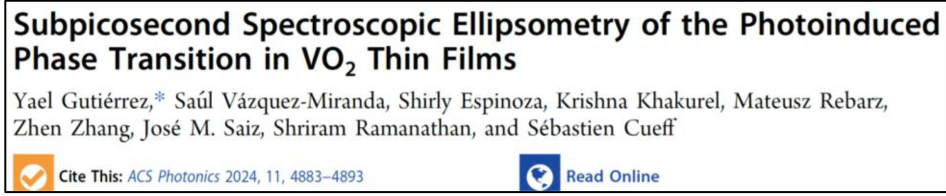
- corresponds to about 0.13 electron per Co ion
- within the next 200 ps: photoinduced metallic state relaxes back
- between 1 and 30 ps: propagation of acoustic strain pulse, velocity of 5.6 ± 0.2 nm/ps



Yael, Saul

Correlated-Electron Materials

photoinduced insulator-to-metal transition

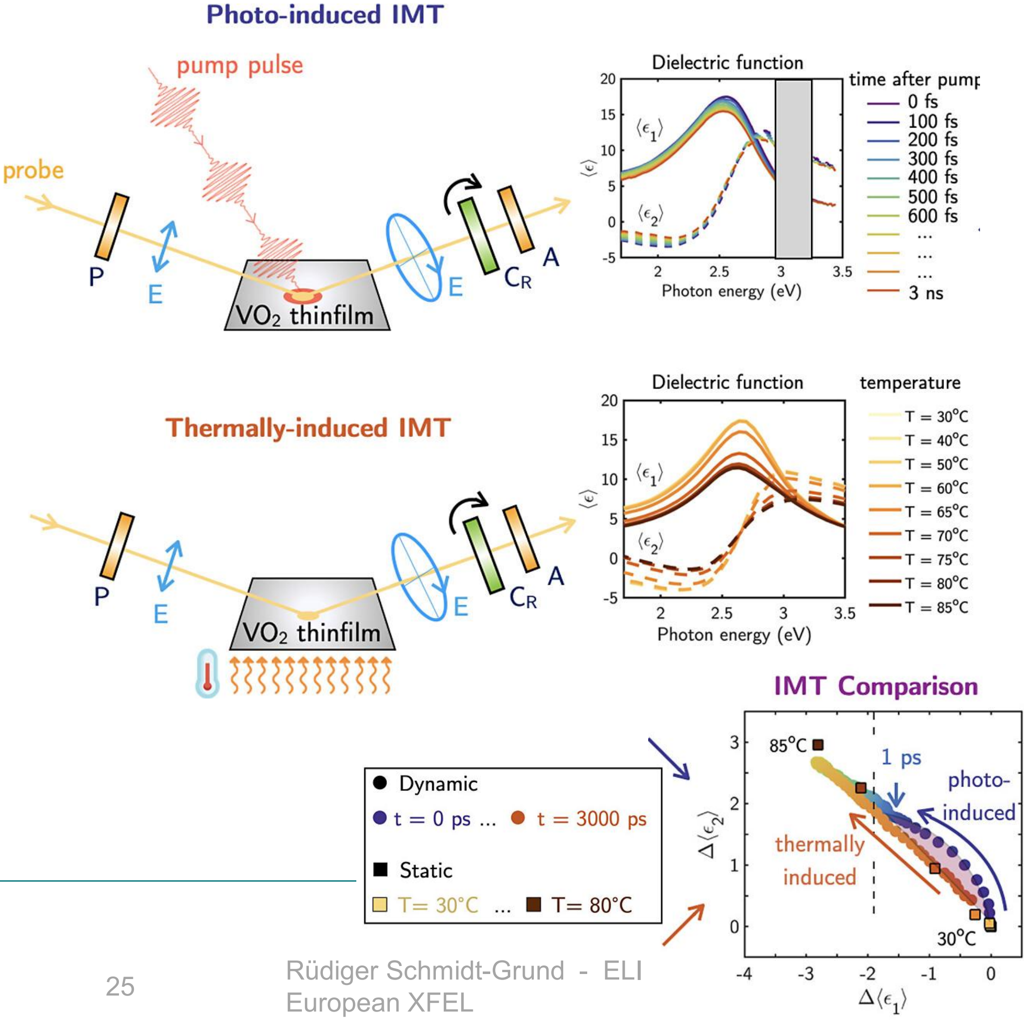

Subpicosecond Spectroscopic Ellipsometry of the Photoinduced Phase Transition in VO_2 Thin Films

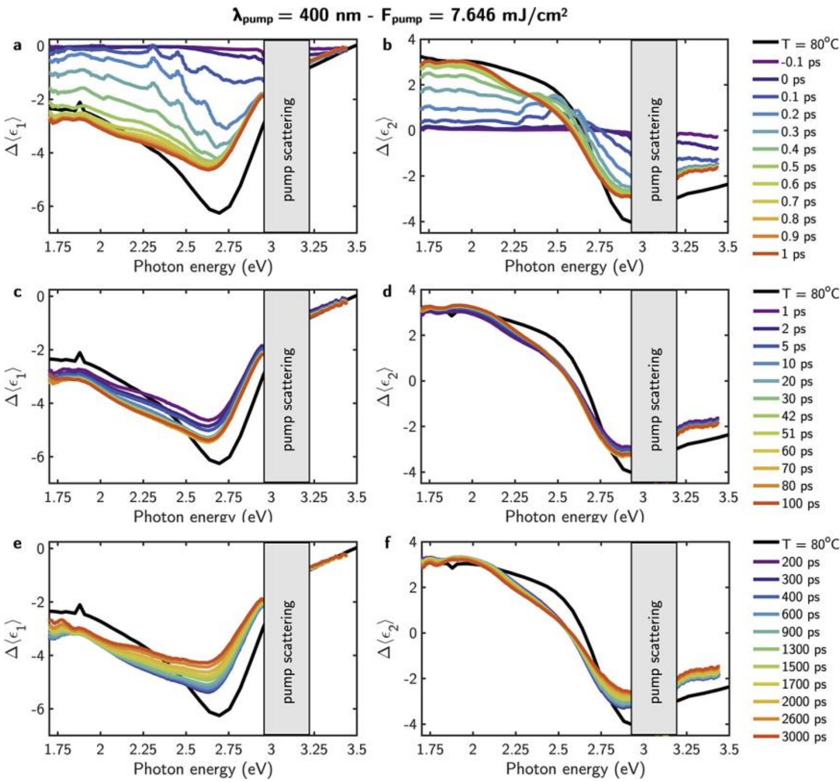
Yael Gutiérrez,* Saúl Vázquez-Miranda, Shirly Espinoza, Krishna Khakurel, Mateusz Rebarz, Zhen Zhang, José M. Saiz, Shriram Ramanathan, and Sébastien Cueff

Cite This: *ACS Photonics* 2024, 11, 4883−4893

Read Online

VO_2





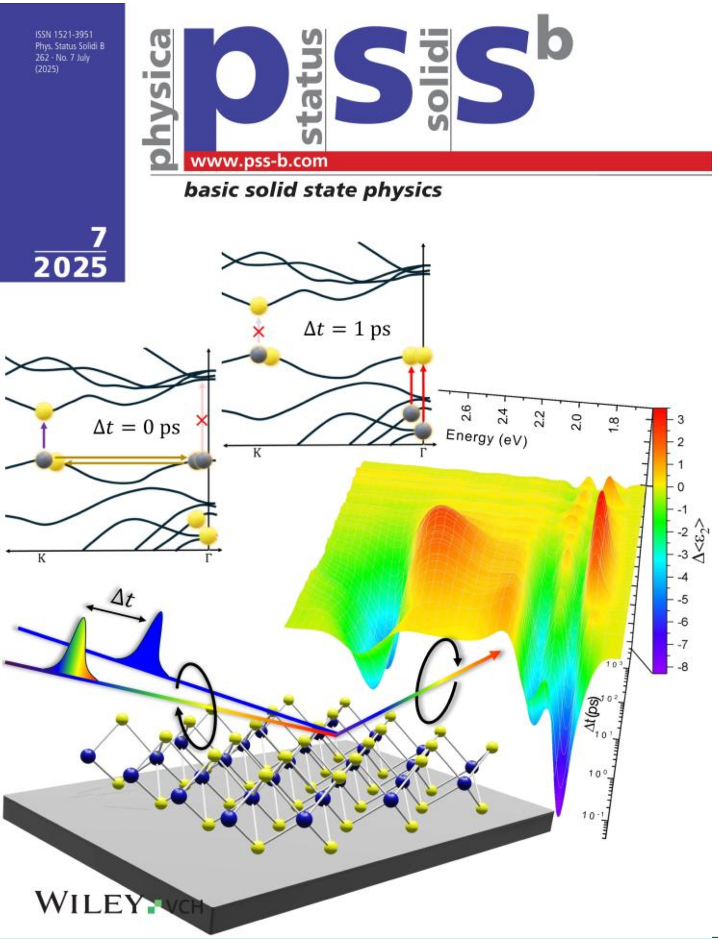
Lucas, Jakob

2D-Materials

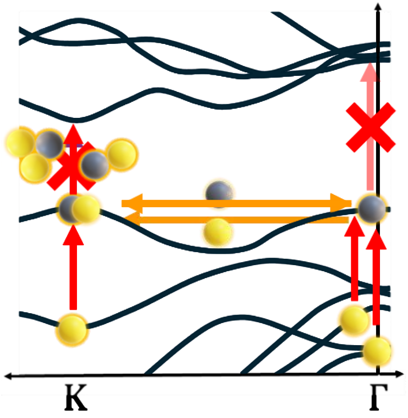
Exciton Screening, Trions, Intervalley-Scattering, Intra-Band Transitions, Band-Renormalization

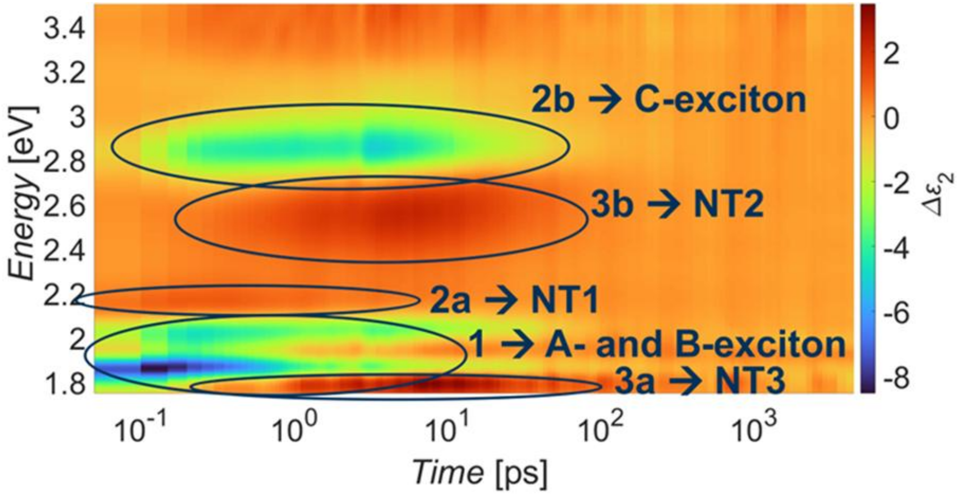
Ultrafast Exciton and Charge Carrier Dynamics in Monolayer MoS_2 Measured with Time-Resolved Spectroscopic Ellipsometry *Phys. Status Solidi B* **2025**, *262*, 2400547

*Lucas Krätschmer, Younes Slimi, Lukas Trefflich, Shirley Espinoza, Mateusz Rebarz, Saul Vazquez-Miranda, Jakob Seyfarth, Theo Pflug, Markus Olbrich, Noah Stiehm, Bernd Hähnlein, Chris Sturm, Alexander Horn, Jakob Andreasson, Marius Grundmann, Stefan Krischok, and Rüdiger Schmidt-Grund**



monolayer MoS_2





Elias, Jakob, Noah, Saul

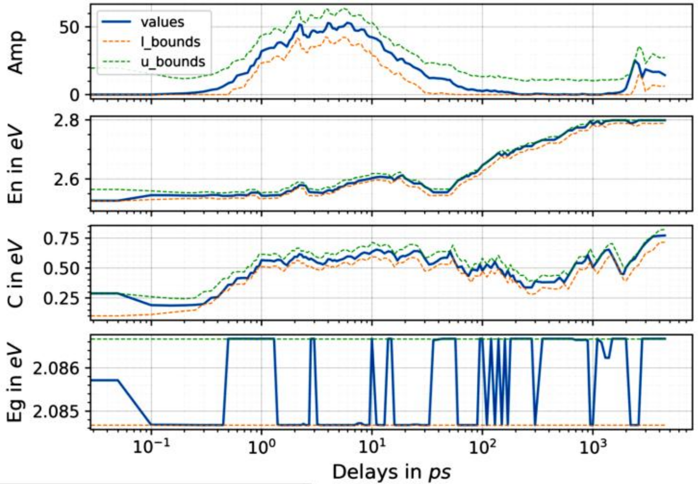
Modeling

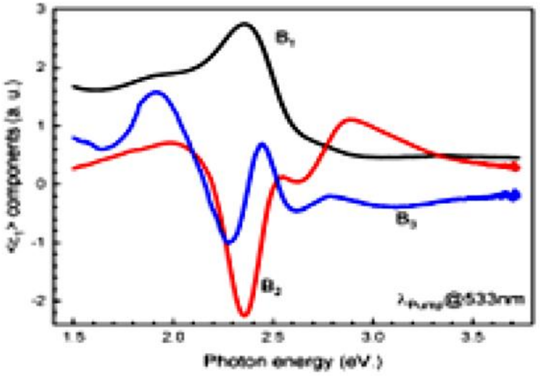
huge amount of data – subjective influence of researcher

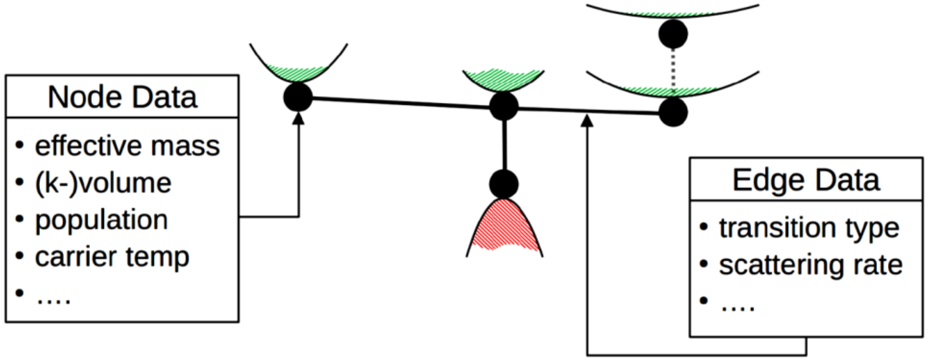
automated fitting, considering of temporal interconnection of processes

different approaches:

- automated line-function analysis with temporally smooth and confined parameter evolution – Jakob Seyfarth (Ilmenau)
- dynamic mode decomposition / singular value decomposition – Saul Vazquez-Miranda (ELI, San Luis Potosí), Noah Stiehm (Ilmenau)
- explicitly modelling spatial and energy-momentum charge carrier dynamics by fundamental theory – Elias Baron (Magdeburg)
- graph model for carrier dynamics – Noah Stiehm (Ilmenau)







Node Data

- effective mass
- (k-)volume
- population
- carrier temp
- ….

Edge Data

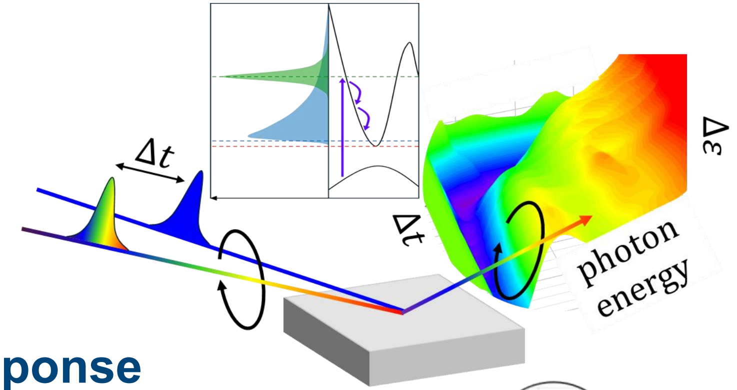
- transition type
- scattering rate
- ….

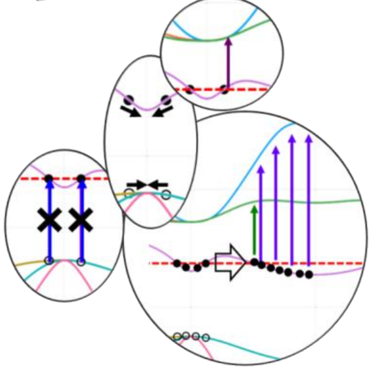
Summary

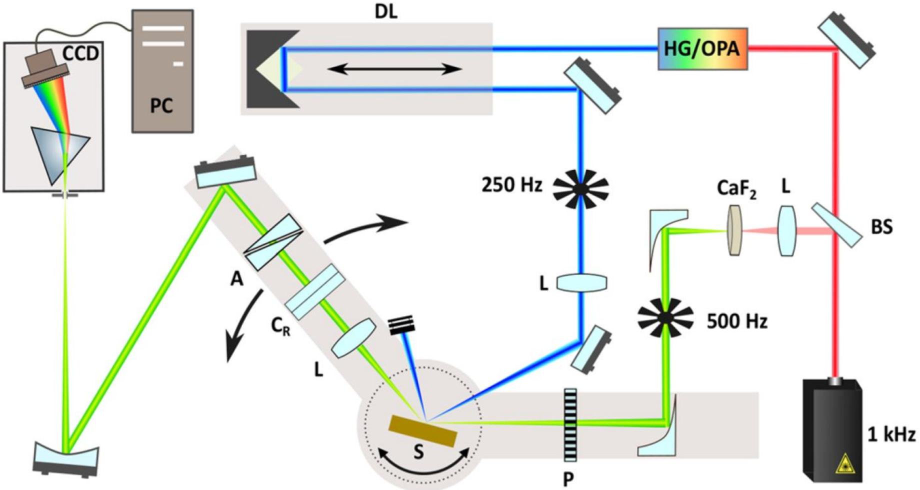
Pump-probe fs-TSE

- **method recently developed by us**
- **time evolution of the full complex optical response**
  → complex dielectric function
- **already applied to several material systems**
  - intra-band transitions (VB-VB and CB-CB)
  - hot-phonon scattering
  - ballistic carrier propagation
  - transient birefringence changes
  - coherent acoustic phonon oscillations
  - spectral weight transfer
  - insulator-to-metal transition
  - chemical reactions

materials so far:
Si, Ge, InP, GaP, ZnO, GaN, ScN, Rubi, VO_2, Te, MoS_2, LaSrCoO, organics







Thank You for Attention!

and thanks to all who were involved in development of TSE method and physical understanding of processes: (alphabetically)

J. Andreasson, C. Armenta, E. Baron, C. Cobet, C. Emminger, S. Espinoza, D. Franta, Y. Gutierrez, O. Herrfurth, K. Hingerl, A. Horn, M. Kloz, J. Leveillee, M. Olbrich, T. Pflug, M. Rebarz, S. Richter, E. Runge, A. Schleife, N. Stiehm, Y. Slimi, C. Sturm, S. Vazquez-Miranda. S. Zollner, M. Zahradník

CMD Mini-colloquium at

OePG-CMD-JOINTMEETING 2026

75th Annual Meeting of the Austrian Physical Society

32nd Meeting of the Condensed Matter Division of the European Physical Society

20-25 September 2026, University of Graz, Graz Center of Physics, Graz, Austria

M16: Advances in Ultrafast Time-Resolved Ellipsometry

Organizers: Shirly Espinoza, Rüdiger Schmidt-Grund

ruediger.schmidt-grund@tu-ilmenau.de | www.tu-ilmenau.de

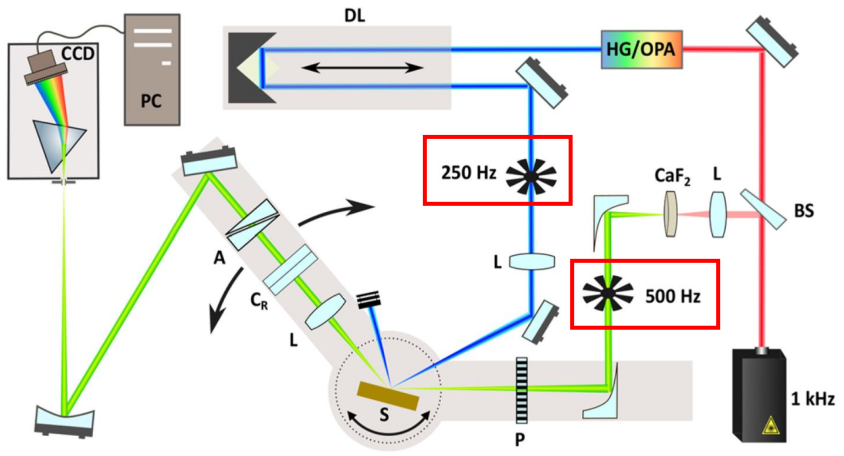
Steffen, Mateusz, Oliver

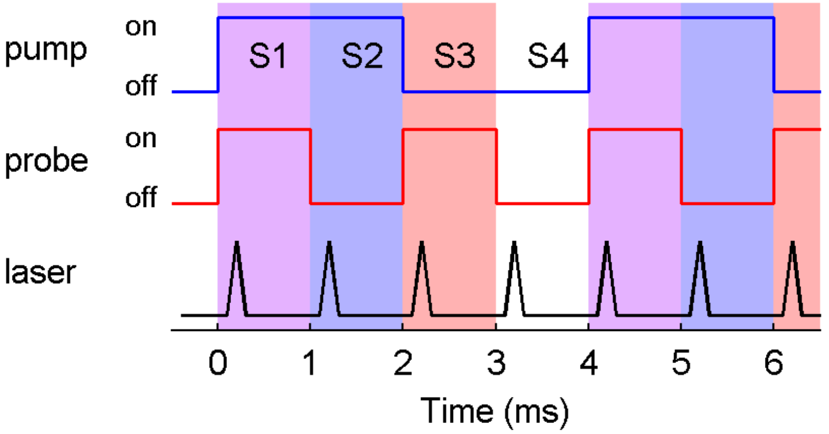
Method

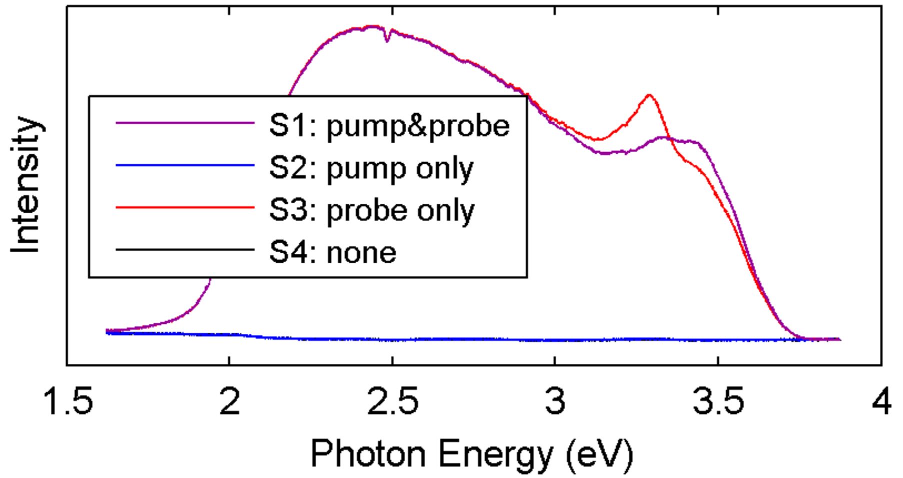
Data acquisition

Two-chopper scheme

→ Reflectance difference spectra







Measurement strategy:

Scan delay line for each different compensator angles

Standard: polarizer and analyser fixed

36 compensator angles, 270 delay time steps, 4000 pulses accumulation for each = 12h

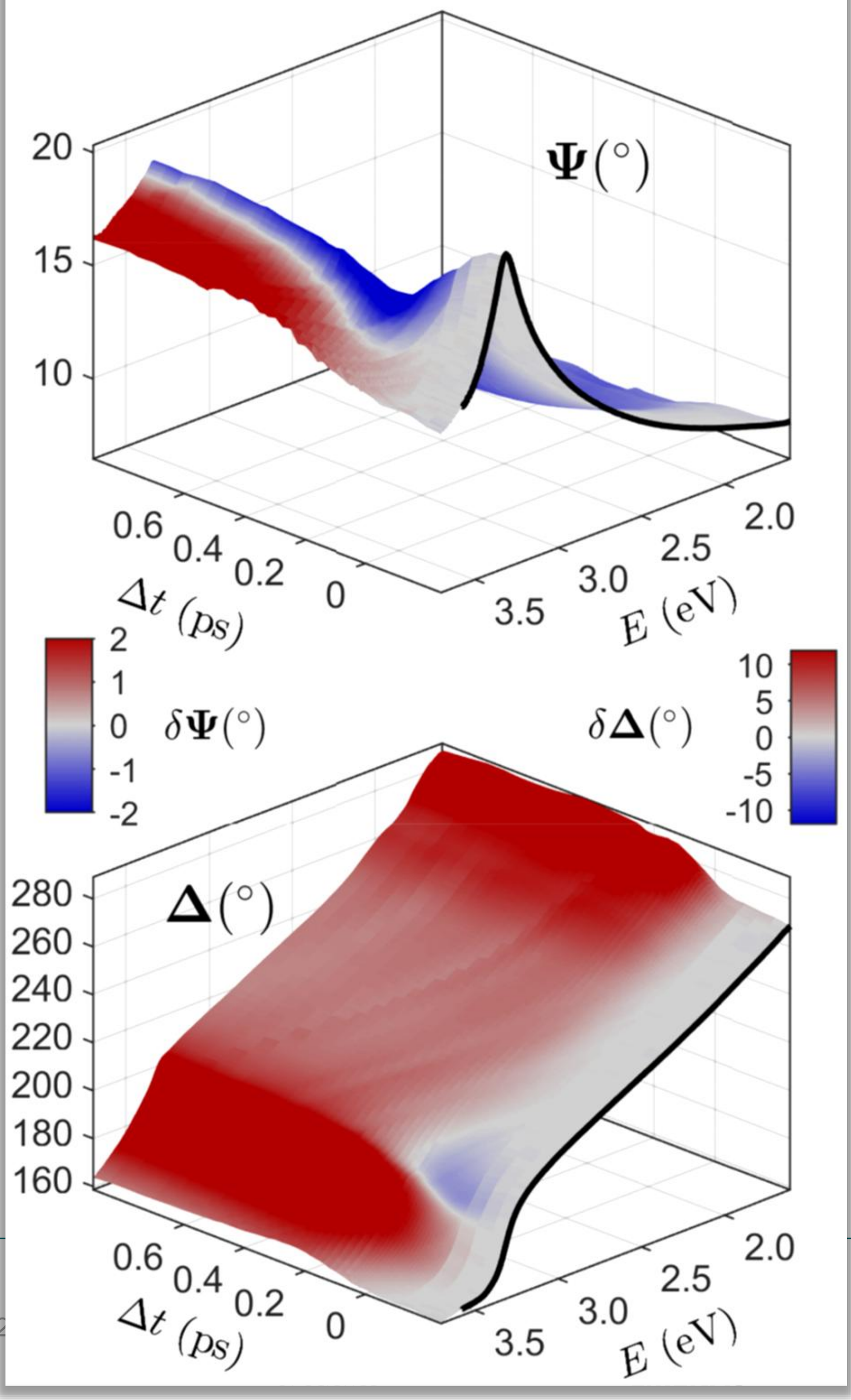
Richter, et al., Rev. Sci. Instrum. ***92****, 033104 (2021),* *New J. Phys.* ***22****, 083066 (2020)*

Method

Data acquisition

Data reduction

final transient spectra, example c-ZnO thin film on SiO_2 excited with $400\ \mathrm{nm}$



Richter, et al., Rev. Sci. Instrum. ***92****, 033104 (2021), New J. Phys.* ***22****, 083066 (2020)*

Method

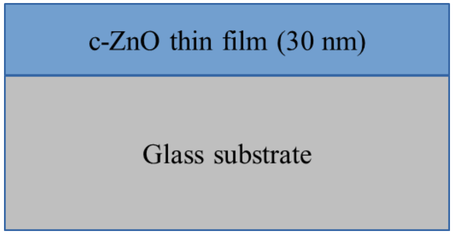
Data analysis

we model data for each $\Delta t = \tau$ to obtain the complex DF $\varepsilon(\tau)$

we model either $\varepsilon(\tau)$ or $\Delta\varepsilon(\tau) = \varepsilon(\tau) - \varepsilon(\tau = 0)$ or analyse the pseudo-DF $< \varepsilon(\tau) >$

1. step: numeric modelling by b-spline function

choose layer model according to situation

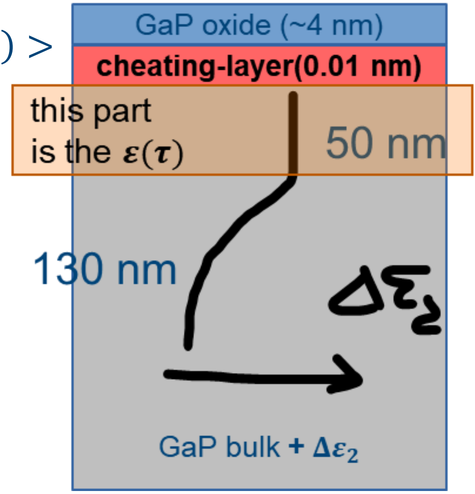


transparent substrate – minimum reflection
penetration depth ≈ thickness – homogeneous excitation
effectively optically isotropic response

2. step: model this using lineshape functions

(Gauss, CPM0, Tauc-Lorentz, Drude, Pole)

$\Delta\varepsilon_2$: negative and positive contributions



penetration depth of exciting laser roughly 150 nm
→ only in this range material is excited

at photon energies below excitation laser energy,
GaP-absorption coefficient is lower resp. zero

→ deeper penetration of probe light

→ probe light experiences gradient of excited DF

obviously: assuming homogeneous bulk model
cannot describe situation → negative total ε_2-values

⇒ thus introducing a gradient

Carola, Lucas, Mateusz, Noah, Oliver, Shirly, Stefan, Steffen

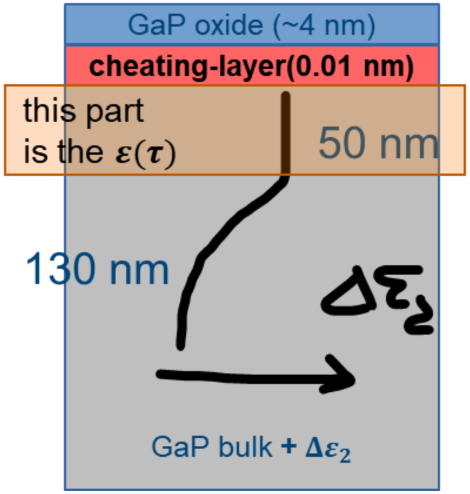
Method

Data analysis

Data reduction: final transient spectra

we model data for each $\Delta t = \tau$ to obtain the complex DF $\varepsilon(\tau)$

we model either $\varepsilon(\tau)$ or $\Delta\varepsilon(\tau) = \varepsilon(\tau) - \varepsilon(\tau = 0)$ or analyse the pseudo-DF $< \varepsilon(\tau) >$


GaP oxide (~4 nm)

cheating-layer(0.01 nm)

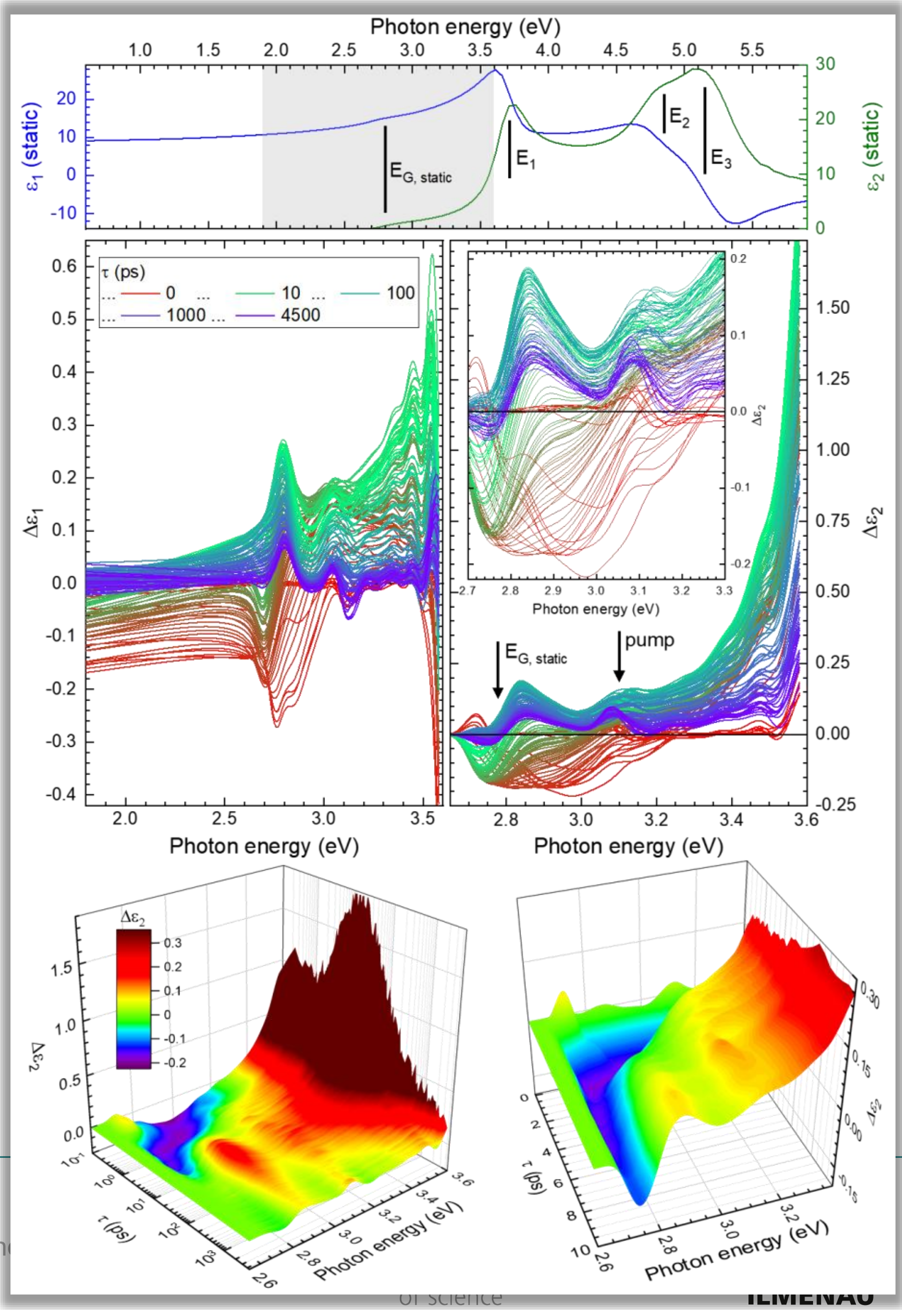
this part is the $\boldsymbol{\varepsilon(\tau)}$

50 nm

130 nm

$\Delta\varepsilon_2$

GaP bulk + $\boldsymbol{\Delta\varepsilon_2}$



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Method

Data analysis

line-shape modelling using parametrized functions (e.g. Tauc-Lorentz)