HL 17: THz and MIR physics in semiconductors

Time: Tuesday 9:30–12:45 Location: POT 251

HL 17.1 Tue 9:30 POT 251

Terahertz-induced anomalous currents after optical excitation of excitons in quantum wells — •Cong Ngo[1], Shekhar Priyadarshi[2], Huynh Thanh Duc[3], Mark Bieler[2], and Torsten Meier[1] — [1]Department of Physics, Paderborn University, Warburger Strasse 100, D-33098 Paderborn, Germany — [2]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany — [3]Institute of Applied Mechanics and Informatics, VAST, 1 Mac Dinh Chi, District 1, Ho Chi Minh City, Vietnam

We study transient anomalous currents in GaAs quantum wells by solving the multi-band semiconductor Bloch equations in the length gauge, including excitonic effects and carrier longitudinal-optical and acoustic phonons scattering process. The band structure is obtained by diagonalizing a 14-band $\mathbf{k}\cdot\mathbf{p}$ model within the envelope function approximation. To solve the random phase problem originating from the numerical diagonalization of the band structure model, we apply a smoothing gauge transformation [1]. Our numerical results show quite strong anomalous currents appear for optical excitation near the excitonic resonances and simultaneous Terahertz excitation. The current transients oscillate with a frequency corresponding to the inverse of the energy difference between the 1s and 2s exciton states. The numerical results including excitons are in good agreement with experiments [2].

[1] L. H. Thong, C. Ngo, H. T. Duc, X. Song, and T. Meier, *Phys. Rev. B* **103**, 085201 (2021).

[2] S. Priyadarshi, K. Pierz, and M. Bieler, *Phys. Rev. Lett.* **115**, 257401 (2015).

HL 17.2 Tue 9:45 POT 251

Generation of THz vortex beams and interferometric determination of their topological charge — •Samuel W. Pinnock, Seulki Roh, Tobias Biesner, Artem V. Pronin, and Martin Dressel — 1. Physikalisches Institut, Universität Stuttgart, 70569 Stuttgart, Germany

We developed and demonstrated the efficacy of 3D printed spiral phase plates for the generation of vortex THz beams with orbital angular momenta $\ell = \pm 1$ and $\ell = \pm 2$. The vortex beam generation was confirmed by means of frequency-domain transmission spectroscopy. The topological charge of the vortex beams was determined via phase-sensitive Mach-Zehnder interferometry, which enabled the superposition of a vortex beam with ℓ and its conjugate beam with $-\ell$. The resulting interference patterns were found to be consistent with the expected intensity distributions for a given ℓ, which provides strong confirmation of the spatial phase structure of the generated vortex beams in the THz regime. Such THz vortex beams could be used in spectroscopic studies of optical transitions with $\Delta\ell \neq 0$ in different condensed-matter systems, including semiconductors and topological materials.

HL 17.3 Tue 10:00 POT 251

Ultrafast Terahertz-Wave Emission from Photoconductive Antenna Arrays and Spin Emitters — •Osama Hatem[1], Thales V. A. G. de Oliveira[2], Susanne C. Kehr[1], and Lukas M. Eng[1,3] — [1]Institute of Applied Physics, Technische Universität Dresden, 01062 Dresden, Germany — [2]Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany — [3]ct.qmat: Würzburg-Dresden Cluster of Excellence - EXC 2147, Technische Universität Dresden, Dresden, Germany

For long time, terahertz (THz) radiation (0.1 THz to 10 THz) was little used in science and technology owing to the lack of efficient terahertz sources and detectors. However, recent advances in laser technology and semiconductors industry sparked the interest in exploring this spectral range further. Recently, THz radiation has shown great importance in a wide range of potential applications including THz time-domain spectroscopy and imaging [1-2].

In this work, we report the emission of THz waves from GaAs photoconductive antenna arrays and Fe/Pt spin emitters upon excitation with femtosecond laser pulses at 800 nm. THz waves with bandwidth of 0.1- 5 THz and SNR > 500 below 1 THz were measured. Moreover, detection of THz waves by electro-optic sampling was investigated using ZnTe, GaP, and GaSe crystals of varying thickness. The results are of great significance for THz nanoscopy and imaging applications.

[1] M. Schall et al., Int. J. Infrared Millim. Waves 20, 595-604 (1999). [2] O. Hatem, J. Opt. Soc. Am. B 36, 1144-1149 (2019).

HL 17.4 Tue 10:15 POT 251

Characterization of semiconductors and their properties using terahertz TDS and the Drude-Lorentz model — •Joshua Hennig[1,2], Jens Klier[1], Stefan Duran[1], Kuei-Shen Hsu[3], Antje Hirsch[4], Christian Röder[3], Jan Beyer[3], Franziska Beyer[4], Georg von Freymann[1,2], and Daniel Molter[1] — [1]Center for Materials Characterization and Testing, Fraunhofer ITWM, Kaiserslautern — [2]Department of Physics and Research Center Optimas, Technische Universität Kaiserslautern (TUK), Kaiserslautern — [3]Institut für Angewandte Physik, TU Bergakademie Freiberg, Freiberg — [4]Department of Crystal Growth, Fraunhofer IISB, Freiberg

Semiconductors play an important role in our modern world enabling many of the technological advancements. Therefore, it is of vital interest for an ever-growing industry as well as scientifically to find techniques to characterize optical and electrical properties such as the refractive index as well as the resistivity of these materials. Here, first steps in such characterizations using terahertz time-domain spectroscopy, a nondestructive technology proven to be capable of these challenging tasks, are shown. First, measurements performed on silicon, one of the most commonly used semiconductors, are evaluated to show the measurement principle and confirm the Drude-Lorentz model to be suitable to describe the charge carrier behavior. Next, samples of silicon carbide, an important semiconductor material with applications e.g. in power electronics are examined. The knowledge of these important semiconductor properties can be helpful in quality checks in the production process and any future work with those materials.

HL 17.5 Tue 10:30 POT 251

Interband cascade infrared photodetectors based on Ga-free InAs/InAsSb superlattice absorbers — •Andreas Bader[1], Florian Rothmayr[2], Nabeel Khan[2], Fauzia Jabeen[1], Johannes Koeth[2], Sven Höfling[1], and Fabian Hartmann[1] — [1]Technische Physik, Physikalisches Institut and Würzburg-Dresden Cluster of Excellence ct.qmat, Am Hubland, D-97074 Würzburg, Germany — [2]nanoplus Nanosystems and Technologies GmbH, Oberer Kirschberg 4, D-97218 Gerbrunn, Germany

We present results on interband cascade infrared photodetectors (ICIP) based on Ga-free InAs/InAsSb superlattice (SL) absorbers. An alternative extraction path of photogenerated carriers is required when substituting the more standard InAs/Ga(In)Sb SL absorbers for Ga-free SLs. The device operates in the photovoltaic mode in the mid infrared spectral range with cut-off wavelengths between around 6.5 um at 100 K and 9 um at RT. At elevated temperatures, features of negative-differential-conductance (NDC) emerge. Under illumination, these NDC features can supply gain in the device leading to a peak responsivity of 0.45 A/W at room temperature. At 300 K the zero-bias detectivity D* of the presented device is around 1*10^8 Jones which compares well to similar ICIPs based on InAs/GaSb SL absorbers.

HL 17.6 Tue 10:45 POT 251

Assessment of epitaxially grown p-doped InAs on undoped GaSb exhibiting terahertz emission — •Cyril Salang[1], Dean Von Johari Narag[1], Rommel Jagus[1], Gerald Angelo Catindig[2], Mae Agatha Tumanguil[1], Alexander De Los Reyes[2], Ivan Cedrick Verona[2], Hannah Bardolaza[2], Armando Somintac[2], Elmer Estacio[2], and Arnel Salvador[2] — [1]Materials Science and Engineering Program, University of the Philippines Diliman, Philippines — [2]National Institute of Physics, University of the Philippines Diliman, Philippines

A p-InAs/undoped-GaSb thin film was grown via molecular beam epitaxy. The 260 Å p-InAs was grown on 260 nm undoped InAs over 10 periods of InGaAs(3 nm)/GaAs(3 nm) superlattice to minimize the surface roughness prior to the p-InAs growth. Three periods of 20-nm undoped GaAs/260-nm undoped InAs served as a buffer with growth interruption applied on the first 2 mins of deposition of each GaAs and InAs layer. X-ray diffraction shows a peak at $2\theta \sim 61^o$ corresponding to InAs. The sample's resistance was measured to be 43 Ω. The terahertz (THz) emission was evaluated using 1.55 μm femtosecond laser excitation in reflection geometry. The current sample emits at ∼20 times lower THz intensity compared to that of a previously investigated 1±0.4 μm p-InAs/n-GaSb sample possibly due to the lesser thickness leading to a lower photo-Dember response, and differing crystal qualities from the different growth processes. Nonetheless, exploring growth techniques for producing thin InAs films is desired to realize photoconductive antennas for transmission geometry.

30 min. break

HL 17.7 Tue 11:30 POT 251

Coherent State Steering in Condensed Matter Systems with Strong Light-Matter Engineering — •Michael Spencer, Joanna Urban, Maxamillian Frenzel, and Sebastian Maehrlein — Department of Physical Chemistry, Fritz Haber Institute of the Max Planck Society, Faradayweg 4-6, 14195 Berlin, Germany

Physical properties of materials are derived largely from their chemical constituents, structural arrangement, and local properties such as temperature and dielectric environment. Next-generation materials science is increasingly focused on manipulation of structural properties in order to access material properties on-demand, in search of emergent, enhanced, or even hidden states of matter. One such method to transiently modify crystalline materials is the application of intense terahertz (THz) laser pulses. These pulses allow for resonant and selective excitation of infrared-active vibrational modes (phonons) of a crystal, allowing for coherent and ultrafast modulation of condensed-matter system properties. With the introduction of an electromagnetic cavity, the subsequent enhancement of this light-matter interaction between the intense THz radiation and the phonons will provide expanded control over excited-state steering, allowing access to exotic, transient states of matter. I will present our steps towards first realizations of such strongly-coupled light-matter interactions of phonons in crystalline materials within the THz frequency range. In addition, I will discuss our novel measurement techniques for the detection of strong light-matter interactions, where we utilize the unique technical capabilities of terahertz time-domain spectroscopy.

HL 17.8 Tue 11:45 POT 251

Terahertz cyclotron emission from HgTe QWs — •S. Gebert[1,2], C. Consejo[1], S. Ruffenach[1], J. Torres[2], B. Jouault[1], and F. Teppe[1] — [1]Laboratoire Charles Coulomb (L2C), UMR 5221 CNRS, Université de Montpellier, F-34095 Montpellier, France — [2]Institut d'Electronique et des Systèmes (IES), UMR 5214 CNRS, Université de Montpellier, F-34095 Montpellier, France

Motivated by the emergence of graphene, several concepts for Landau-level (LL) lasers, tunable by a magnetic field over the whole terahertz (THz) frequency range, have been proposed. One hoped in particular was, that the non-equidistance of the LLs from Dirac fermions could efficiently suppress the non-radiative Auger recombination, which typically prevails over the radiative recombination. However, despite this non-equidistance an unfavorable non-radiative process still persists in Landau-quantized graphene, and no cyclotron emission from Dirac fermions has yet been reported. To eliminate this last non-radiative process, it is sufficient to slightly modify the dispersion of the Landau levels, e.g. by opening a small gap in the linear band structure. A proven example of such gapped graphene-like materials are HgTe quantum wells (QWs) close to the topological phase transition. We here experimentally demonstrate spontaneous Landau emission from Dirac fermions in such HgTe QWs, where the emission is tunable between 0.5 THz and 3 THz by both the magnetic field and the carrier concentration [1].

[1] S. Gebert et al., Nat. Photon. (accepted); preprint is avaliable at doi.org/10.21203/rs.3.rs-1630601/v1

HL 17.9 Tue 12:00 POT 251

Coherent phonon dynamics in quasi-2D perovskites probed by THz-induced Kerr effect — •Joanna M. Urban[1], Marie Cherasse[1,2], Maximilian Frenzel[1], Michael Spencer[1], Gaelle Trippe-Allard[3], Emmanuelle Deleporte[3], Luca Perfetti[2], Martin Wolf[1], and Sebastian F. Maehrlein[1] — [1]FHI of the Max Planck Society, Faradayweg 4-6, 14195 Berlin, Germany — [2]LSI, Palaiseau, France — [3]Université Paris-Saclay, LuMIn, Gif-sur-Yvette, France

2D hybrid organic-inorganic perovskites (HOIP) are self-assembled multiple quantum well structures, formed by metal halide octahedral layers alternating with large organic spacer cations. They combine the intriguing properties of the 3D HOIP polar, anharmonic lattice with optoelectronic properties arising due to low dimensionality. We study a family of 2D HOIPs in the Ruddlesden-Popper phase $(PEA)_2(MA)_{n-1}Pb_nI_{3n+1}$ (n=1,2,3). Using intense, close to single-cycle THz fields we excite coherent optical phonons and probe the lattice dynamics via THz-induced Kerr effect (TKE). Strikingly, we observe long-lived coherent phonon oscillations at room temperature. Comparison with static Raman spectroscopy results as well as the measured fluence and temperature dependence confirm that the observed features in the 0.5-3 THz range correspond to Raman-active modes of the inorganic sublattice, excited via a nonlinear driving process. The nontrivial azimuthal angle dependence of the TKE signal can be explained considering the crystal structure and the symmetry of the Raman modes using the $\chi^{(3)}$ nonlinear susceptibility tensor formalism.

HL 17.10 Tue 12:15 POT 251

Optically excited charge-carrier dynamics in the antiferromagnetic semiconductor MnTe — •Changqing Zhu[1], Patrick Pilch[1], Anneke Reinold[1], Gunther Springholz[2], Mirko Cinchetti[1], and Zhe Wang[1] — [1]TU Dortmund University, Germany — [2]Johannes Kepler University of Linz, Austria

Room-temperature antiferromagnetic semiconductors are very interesting for possible spintronic applications. With a long-range antiferromagnetic order (T_N = 307 K) at room temperature, the hexagonal α-MnTe is a relevant candidate for those applications. Here we report on time-resolved measurements of ultrafast dynamics of optically excited charge carriers in α-MnTe thin film, by optical pump - optical probe and optical pump - THz probe spectroscopic techniques at room temperature. In contrast to a phononic oscillation mode at 5.3 THz as observed by 2.4 eV pump [1], our studies with an 1.5 eV pump pulse cannot reveal the optical phonon mode but rather low-energy acoustic phonon-like behavior at high pump fluence. Moreover, nonlinear dependence on pump fluence is observed both in our optical and terahertz probes, for a pump fluence above ~ 2.0 mJ/cm^2. This indicates a different physical mechanism than in the previous studies. The observed relaxation processes can be associated to electron-hole recombination and electron-phonon scattering.

[1] D. Bossini et al. Phys. Rev. B 104, 224424 (2021).

HL 17.11 Tue 12:30 POT 251

Time-resolved nanospectroscopy on Si-doped GaAs-InGaAs core-shell nanowires — •Andrei Luferau[1,2], Maximilian Obst[2], Susanne Kehr[2], Lukas Eng[2], Stephan Winnerl[1], Alexej Pashkin[1], Emmanouil Dimakis[1], and Manfred Helm[1] — [1]Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany — [2]Institute of Applied Physics, Technische Universität Dresden, Dresden, Germany

High-quality epitaxial nanowires (NWs) based on III-V semiconductors offer the possibility to fabricate ultrafast optical devices due to their direct bandgap and the high electron mobility. Contactless investigation of photoexcited carriers within single NWs is enabled by optical-pump THz-probe scanning near-filed optical microscopy (SNOM) experiment. Here we report on first THz-pump MIR-probe SNOM studies on Si-doped GaAs-InGaAs core-shell NWs utilizing THz radiation from the free-electron laser FELBE. The experiment was carried out with SNOM setup from Neaspec equipped with nanoFTIR module, where a broadband MIR source (5-15μm) serves as a probe. Upon intraband THz-pump (25μm) we observed a red shift of amplitude and phase of the NW plasma resonance, while control interband optical pumping (780nm) induced a blue shift of the resonance, and in both cases an exponential decay with a time constant of 4-5ps is seen. We attribute the blue shift to the contribution of photogenerated carriers. The red shift is assigned to the heating of the electrons in the conduction band and the subsequent increase of the effective mass in the nonparabolic Γ-valley due to high peak electric fields of THz pulses.