# HL 5: Quantum Dots and Wires: Single Photon Sources

Time: Monday 9:30–12:15 Location: H15

**Invited Talk** HL 5.1 Mon 9:30 H15

**Quantum optics with quantum dots in photonic wires** — •Jean-Michel Gerard — Institute for Nanosciences and Cryogenics, Grenoble, France

Over the last 20 years, quantum dots have been fruitfully combined with optical microcavities to perform quantum optics experiments and to develop quantum light sources for QIPC. In this talk, I will show that the very basic photonic wire geometry opens an attractive alternative avenue in this context [1]. I will noticeably introduce the Photonic Trumpet (PT) [2], formed by a high-index single-mode waveguide and a conical tapering. Nearly perfect single-mode emission, low-divergence Gaussian radiation pattern, linear polarization control, efficient wavelength tuning based on strain effects, and high efficiency single photon emission (> 0.75 photon per pulse) are reported for a single quantum dot embedded in a PT. The PT also appears as a very promising platform to explore the unique optical properties of one-dimensional atoms[3] and hybrid optomechanical systems where the interaction between the two-level quantum system and mechanical modes is mediated by strain [4]. Work done with J. Claudon, J Bleuse, M Munsch, P Stepanov and with the groups of JP Poizat, O Arcizet, A Auffèves, M Richard (CNRS I. Néel Grenoble) and N Gregersen (DTU), who are gratefully acknowledged. [1] For a review see J Claudon et al Chem Phys Chem 14, 1393 (2013); [3] M. Munsch et al, PRL 110, 177402 and 239902(E) (2013) ; P Stepanov et al APL 106, 041112 (2015) : [4] D. Valente et al, New J. Phys 14, 083029 (2012); Phys Rev A 86, 022333 (2012) [5] I. Yeo et al, Nat. Nano. 9, 106 (2014)

HL 5.2 Mon 10:00 H15

**Phase super-resolution with N00N-states generated by on demand single-photon sources** — •M. Müller, H. Vural, S. L. Portalupi, and P. Michler — Institut für Halbleiteroptik und Funktionelle Grenzflächen, Allmandring 3, 70569 Stuttgart, Germany

Quantum metrology is a promising scientific field taking advantage of the probably most fundamental aspect of quantum mechanics, namely entanglement. Enhanced optical phase sensing for instance, which utilizes multi-photon entangled states has attracted a lot of attention in the community. Up to now, so called path-entangled N00N states have been generated by light sources possessing probabilistic photon statistics, e. g., parametric-down conversion. Here we present the experimental generation of two-photon N00N states with a single quantum emitter making use of the radiative biexciton-exciton cascade in a single semiconductor quantum dot. A resonant and coherent two-photon excitation process ensures the deterministic preparation of the quantum dot states. The subsequently emitted single-photons possess a reasonable indistinguishability for the production of the excitonic and biexcitonic two-photon N00N states. Phase super-resolution, i. e., a reduced de-Broglie wavelength of the photonic wave packet, expressed by pronounced oscillations with twice the single photon frequency, is observed. Theoretical calculations are in excellent agreement with the experimental results, allowing for a complete description of the system. Prospects and limitations related to optical phase measurements with a precision beating the standard quantum limit involving quantum dot single-photon sources will be discussed.

HL 5.3 Mon 10:15 H15

**Semiconductor source of single photons frequency matched to Rb** — •Jan-Philipp Jahn[1], Lucas Béguin[1], Mathieu Munsch[1], Andreas Kuhlmann[1], Martina Renggli[1], Yongheng Huo[2], Fei Ding[3], Rinaldo Trotta[2], Oliver G. Schmidt[3], Armando Rastelli[2], Philipp Treutlein[1], and Richard J. Warburton[1] — [1]Department of Physics, University of Basel, Switzerland — [2]Johannes Kepler University Linz, Austria — [3]IFW Dresden, Germany

Semiconductor quantum dots are excellent single-photon sources, providing triggered single-photon emission at a high rate and high spectral purity. Independently, atomic ensembles have emerged as one of the best quantum memories for single photons, providing high efficiency storage and long memory lifetimes. In this project, we combine these two physical systems to exploit the best features from both worlds. We have characterized a new type of self-assembled GaAs/AlGaAs quantum dots that emits lifetime-limited ($\Delta\nu \sim 1.42$GHz) single-photons at a wavelength compatible with Rb atoms [1]. Fine tuning of the photon frequency to address the Rb D2-line is achieved via strain. To overcome the inherent bandwidth mismatch between the two disparate systems we excite the QD in the Rayleigh scattering regime. This allows a temporal shaping of the QD photons in pulsed resonant excitation, a prerequisite to achieve high storage efficiencies. Furthermore we performed pulsed Hong-Ou-Mandel measurements to directly quantify the indistinguishability, which constitutes a key aspect for quantum information networks. [1] Jahn et.al. arXiv:1508.06461

HL 5.4 Mon 10:30 H15

**An electrically driven cavity-enhanced source of indistinguishable photons with 61% overall efficiency** — •Tobias Heindel[1], Alexander Schlehahn[1], Alexander Thoma[1], Pierce Munnelly[1], Martin Kamp[2], Sven Höfling[2,3], Christian Schneider[2], and Stephan Reitzenstein[1] — [1]Institut für Festkörperphysik, Technische Universität Berlin, Berlin, Germany — [2]Technische Physik, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany — [3]SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews, United Kingdom

Single semiconductor quantum dots (QDs) integrated into photonic microstructures are promising candidates for the realization of high-fidelity and high-speed quantum-light sources [1]. Besides a high single-photon flux and vanishing multi-photon emission probabilities, the photon-indistinguishability is a crucial attribute for quantum information processing schemes.

In this work, we report on state-of-the-art electrically triggered sources of single and indistinguishable photons. Exploiting the Purcell-effect and the highly-directional emission of electrically contacted QD micropillar cavities operated at excitation repetition rates up to 1.2 GHz, we extract cavity-enhanced single-photon emission with record-high efficiencies of $(61 \pm 11)\,\%$. Moreover, two-photon interference experiments reveal a photon-indistinguishability of $(41.1 \pm 9.5)\,\%$ under pulsed current injection at 487 MHz.

[1] G.-C. Shan et al., Front. Phys. 9, 170 (2014)

**30 min. Coffee Break**

HL 5.5 Mon 11:15 H15

**Single-photon emission at a rate of 143 MHz from deterministic quantum-dot microlenses triggered by a mode-locked VECSEL** — •Alexander Schlehahn[1], Mahmoud Gaafar[2], Max Vaupel[2], Manuel Gschrey[1], Peter Schnauber[1], Jan-Hindrik Schulze[1], Sven Rodt[1], André Strittmatter[1], Wolfgang Stolz[2], Arash Rahimi-Iman[2], Tobias Heindel[1], Martin Koch[2], and Stephan Reitzenstein[1] — [1]Institut für Festkörperphysik, Technische Universität Berlin, 10623 Berlin, Germany — [2]Department of Physics and Material Sciences Center, Philipps-Universität Marburg, 35032 Marburg, Germany

We report on the realization of an ultra-bright quantum-dot (QD) based single-photon source. The source consists of a deterministic QD microlens and is excited by a mode-locked vertical-external-cavity surface-emitting laser (ML-VECSEL). The frequency-doubled ML-VECSEL operates at a wavelength of 508 nm and features pulse widths of 4.2 ps at a repetition rate of 494 MHz, being about 6 times faster than conventional Ti:sapphire lasers. This unique and compact combination allows us to achieve single-photon fluxes of $(143 \pm 16)$ MHz collected by the first lens of the setup, corresponding to a photon-extraction efficiency of $(29 \pm 3)\%$ with $g^{(2)}(0)$ below 0.03 [1]. Beyond this proof of principle under non-resonant excitation, our concept is perfectly suited for the application of resonant excitation schemes using wavelength-tunable ML-VECSELs and spectrally matched QDs to generate indistinguishable single photons at high rates.

[1] A. Schlehahn et al., Appl. Phys. Lett. 107, 041105 (2015)

HL 5.6 Mon 11:30 H15

**Enhanced in-situ cathodoluminescence lithography for the deterministic fabrication of quantum light sources** — •Arsenty Kaganskiy, Manuel Gschrey, Alexander Schlehahn, Jan-Hindrik Schulze, Ronny Schmidt, Tobias Heindel, Sven Rodt, André Strittmatter, and Stephan Reitzenstein — Institut für Festkörperphysik, Technische Universität Berlin, Hardenbergstraße 36, D-10623

Future nanophotonic devices will rely on the development of sources for indistinguishable single photons and entangled photon pairs based on self-assembled quantum dots (QDs). Preselected QDs with the mentioned properties need to be deterministically embedded into photonic structures to enhance their photon extraction efficiency. In order to meet this requirement we developed a deterministic technology platform named enhanced in-situ cathodoluminescence lithography (eCLL) [1]. By using marker structures the eCLL technique allows for a detailed spectral pre-characterization of QD properties such as emission energy, fine-structure splitting (FSS) and decay time of excitonic complexes before integrating the QDs with high alignment accuracy into, e.g., microlenses. In this way, QDs with small FSS can be selected and integrated into microlenses in order to realize efficient sources of polarization entangled photon pairs. Moreover, the eCLL technique allows for a direct comparison of the QD properties before and after the processing. For instance we observed a two-fold shortening of the decay time that could be related to a moderate Purcell effect.

[1] A. Kaganskiy et al., Rev. Sci. Instrum. 86 (2015), 073903.

HL 5.7 Mon 11:45 H15

**Efficient single-photon sources based on deterministic quantum-dot microlenses with backside gold mirrors** — •Sarah Fischbach[1], Esra Yarar Tauscher[1], Peter Schauber[1], Ronny Schmidt[1], Jan-Hindrik Schulze[1], Alexander Thoma[1], Alexander Schlehahn[1], Benjamin Wohlfeil[2], Sven Burger[2], André Strittmatter[3], Tobias Heindel[1], Sven Rodt[1], and Stephan Reitzenstein[1] — [1]Institut für Festkörperphysik, Technische Universität Berlin, Germany — [2]Zuse-Institut Berlin (ZIB), Germany — [3]Institut für Experimentelle Physik, Otto-von-Guericke-Universität Magdeburg, Germany

By utilizing single semiconductor quantum dots (QDs) advances in creating single-photon sources (SPSs) have been made, enabling close to ideal single-photon emission in terms of $g^{(2)}(0)$ as well as the photon-indistinguishability. Applications in the field of quantum communications, however, require highest photon extraction efficiencies at precisely defined emission wavelengths at the same time. Here, we report on a novel approach to realize high fidelity SPSs by combining a single QD, deterministically integrated within a monolithic microlens, with a backside gold mirror. FEM-simulations are carried out to determine the optimum device geometry. The mirror is realized via a flip-chip process with thermo-compression gold bonding, while microlenses are patterned by in situ three-dimensional electron-beam lithography at cryogenic temperatures. In that way, bright QDs with preselected spectral features can be chosen to optimize their photon extraction efficiency.

HL 5.8 Mon 12:00 H15

**Exploring dephasing in deterministic quantum-dot microlenses by Hong-Ou-Mandel interferometry** — •Alexander Thoma[1], Peter Schnauber[1], Manuel Gschrey[1], Marc Seifried[1], Janik Wolters[1], Jan-Hindrik Schulze[1], André Strittmatter[1], Sven Rodt[1], Alexander Carmele[2], Andreas Knorr[2], Tobias Heindel[1], and Stephan Reitzenstein[1] — [1]Institut für Festkörperphysik, TU Berlin, Berlin, Germany — [2]Institut für Theoretische Physik, TU Berlin, Berlin, Germany

Bright quantum light sources based on single semiconductor quantum dots (QDs) integrated into photonic microstructures are key building blocks for the realization of advanced quantum computation schemes. Further advancement beyond proof-of-principle studies towards applications in quantum information technology will rely on deterministic device processing and profound knowledge of the underlying mechanism affecting their quantum optical properties. In this work we probe time-dependent dephasing processes in deterministic QD-microlenses [1]. In particular, we explore the photon-indistinguishability as a function of the time $\delta$t elapsed between consecutive photon emission events to gain experimental access to the underlying decoherence processes at a ns time-scale. Gradually increasing $\delta$t from 2 ns to 12 ns results in a plateau-like behaviour at low $\delta$t with visibilities close to unity, while the visibility decreases for larger $\delta$t ($>$ 8 ns). Our experimental observations are theoretically described by a non-Markovian noise process in agreement with fluctuating charge carriers in the QD's vicinity.

[1] A. Thoma et. al, arXiv:1507.05900 (2015)