HL 13: Focus Session: Single Particle Sources for Electronic Devices II (Joint session of HL and TT, organized by HL)

Organizers: Rolf Haug (Universität Hannover) and Janine Splettstößer (Chalmers University)

Time: Monday 14:45–18:45 Location: H10

Invited Talk HL 13.1 Mon 14:45 H10

Energy- and time-resolved detection of hot single-electron wave packets — •Masaya Kataoka — National Physical Laboratory, Hampton Road, Teddington, Middlesex TW11 0LW, UK

On-demand semiconductor single-electron sources such as mesoscopic capacitors [1] have enabled an electronic analogy of quantum optics experiments. In further development of this field, the presence of a Fermi sea can present a challenge, causing decoherence due to electron-electron interactions [2]. One solution would be to set electron paths in an intrinsic region, where the conduction-band electrons are absent.

We demonstrate long-range electron transport along depleted edges of a two-dimensional system. A stream of hot electrons are emitted from a quantum-dot pump at ~100 meV above the Fermi energy. Due to a strong magnetic field applied, these electrons travel along the edge defined by shallow etching of the surface, while the background Fermi sea along the edge is depleted by a surface gate that covers the edge.

The transport of the hot-electron wave packets is investigated with energy- and time-resolved detectors [3]. We discuss the measurements of arrival-time distribution measurements with time resolution of < 5 ps, the measurements of edge-state velocity [4], a method to extend LO-phonon scattering length to > 0.5 mm, and how the timing of two-electron emission can be tuned by the shape of pump drive signal.

[1] G. Fève et al., Science 316, 1169 (2007).
[2] V. Freulon et al., Nat. Commun. 6, 6854 (2015).
[3] J. D. Fletcher et al., Phys. Rev. Lett. 111, 216807 (2013).
[4] M. Kataoka et al., arXiv:1512.02906v1.

HL 13.2 Mon 15:15 H10

Dopant controlled single electron pumping through a metallic quantum dot in silicon — •Tobias Wenz[1], Frank Hohls[1], Xavier Jehl[2], Sylvain Barraud[3], Girts Barinovs[4], Jevgeny Klochan[4], and Vyacheslavs Kashcheyevs[4] — [1]Physikalisch-Technische Bundesanstalt (PTB), 38116 Braunschweig, Germany — [2]University Grenoble Alpes and CEA-INAC, F-38000 Grenoble, France — [3]University Grenoble Alpes and CEA-Leti-Minatec, F-38000 Grenoble, France — [4]Faculty of Physics and Mathematics, University of Latvia, LV 1002 Riga, Latvia

Single electron pumps produce a quantized current by transferring an integer number of electrons n each cycle with a high frequency f, so that the current is $I = nef$ [1], where e is the electron charge, enabling a redefinition of the ampere by fixing the value of e. Commonly, single electron pumps utilize gate-defined quantum dots to create a quantized current. In this work, we investigate a silicon nanowire produced from an industrial CMOS process and take advantage of single phosphorus dopants located in both barriers of a gate-defined quantum dot. Due to their strongly localized potential wells, single dopants have large charging energies and sharp resonances that strongly influence the coupling of the main quantum dot to source and drain. By modulating the gates with suitable RF signals to switch the coupling on and off a quantized current can be generated. The operation principle can be modeled using simple assumptions and allows the study of dynamic effects in a coupled single dopant/metallic quantum dot system.

[1] Kaestner and Kashcheyevs, Rep. Prog. Phys. **78**, 103901 (2015)

Invited Talk HL 13.3 Mon 15:30 H10

The reabsorption effect with single-electron sources — •Géraldine Haack[1] and Michael Moskalets[2] — [1]University of Geneva, Switzerland — [2]University of Kharkiv, Ukraine

In the past years, ground-breaking experiments have been realised in quantum transport in generating single-electronic states [1]. Their controlled emission enables the investigation of fundamental quantum mechanical properties such as the coherence of these single-electron states [2], useful for quantum information purposes, and the realization of fermionic analogues of quantum optics experiments such as the Hanbury-Brown and Twiss and Hong-Ou-Mandel experiments [3].

In this talk, we show that the heat current enables us to gain crucial information about the shape of the single-particle states compared to the charge current. To this end, we investigate the reabsorption effect with two single-electron sources coupled in series [4]. While the charge current nullifies, we show that the energy carried by electron-hole pairs is enhanced by a factor 2. This can be explained by the time symmetry of the single-electron state. We finally discuss the validity of the Joule-Lenz law and the fluctuation-dissipation relation, when cavities emit electron-hole pairs and particles of the same kind.

[1] G. Fève et al., Science 316, 1169 (2007); N. Maire et al. , Appl. Phys. Lett. 92, 082112 (2008); J. Dubois et al., Nature 502, 659 (2013). [2] G. Haack, Phys. Rev. B 84, 081303 (2011); G. Haack et al., Phys. Rev. B 87, 201302 (2013). [3] E. Bocquillon et al., Phys. Rev. Lett. 108, 196803 (2012); E. Bocquillon et al., Science 339, 1054 (2013). [4] M. Moskalets et al., Phys. Rev. B 87, 125429 (2013).

HL 13.4 Mon 16:00 H10

Maxwell's demon in the quantum regime — •Gernot Schaller — TU Berlin, Institut für Theoretische Physik

Feedback control can be a useful tool to change the Full Counting Statistics of charges being transferred through a microscopic device. It can be used to suppress fluctuations of the current or to revert its direction e.g., against a potential gradient. The latter case is particularly interesting from a thermodynamic perspective. For an implicit modeling of the controller, this leads to an apparent violation of the second law that may be interpreted as a modification due to a Maxwell-type demon. In contrast, when the control becomes autonomous, i.e., when the controller is included in the thermodynamic description, these apparent paradoxes can be nicely resolved. I will illustrate this viewpoint for electronic transport through quantum dots. Interestingly, these concepts from stochastic thermodynamics can be generalized to true quantum systems, where the evolution of degenerate populations and coherences in the system energy eigenbasis is coupled.

30 min. Coffee break

Invited Talk HL 13.5 Mon 16:45 H10

Electronic states in a driven quantum contact — •Mihajlo Vanevic[1], Julien Gabelli[2], Wolfgang Belzig[3], and Bertrand Reulet[4] — [1]Department of Physics, University of Belgrade, Serbia — [2]Laboratoire de Physique des Solides, Univ. Paris-Sud, France — [3]Fachbereich Physik, Universität Konstanz, Germany — [4]Département de physique, Université de Sherbrooke, Canada

Minimal excitations in a voltage-driven quantum conductor are electrons excited above the Fermi level. Generation of these minimal excitation states requires carefully tailored Lorentzian voltage pulses carrying an integer number of charge quanta. However, a general time-dependent voltage excites both electrons and electron-hole pairs whose number and probability of creation depend on the shape and the amplitude of the drive. We have studied the many-body electronic state created by a general voltage drive and expressed it manifestly in terms of single-electron and electron-hole quasiparticle excitations. We have confirmed our theoretical predictions by probing the constituent quasiparticle states in a Hong-Ou-Mandel-type experiment on a tunnel junction. The knowledge of the many-body state opens a way of engineering the required time profile or energy distribution of single-electron and electron-hole excitations. Harmonic drive with ac amplitude smaller than dc voltage offset can be used to create single-electron states with a small admixture of electron-hole pairs.

HL 13.6 Mon 17:15 H10

Lissajous Rocking Ratchet: Realization in a Semiconductor Quantum Dot — •Sergey Platonov[1,2], Bernd Kästner[3], Hans W. Schumacher[3], Sigmund Kohler[4], and Stefan Ludwig[1,2] — [1]Center for NanoScience & Fakultät für Physik, LMU-Munich, 80539 München, Germany — [2]Paul-Drude-Institut für Festkörperphysik, Hausvogteiplatz 5-7 10117 Berlin, Germany — [3]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [4]Instituto de Ciencia de Materiales de Madrid, CSIC, 28049 Madrid, Spain

Symmetries are a very important concept of physics - the most famous one being the CPT symmetry. Breaking symmetries often gives rise to interesting effects and, in particular, breaking the time-reversal symmetry is a requirement for many applications such as information processing. Here we present such a concept based on a quantum dot (QD) electrostatically defined in a AlGaAs/GaAs heterostructure. We break time-reversal symmetry by periodically modulating its barriers such that a single electron tunneling current occurs. The current direction can be controlled by introducing a phase difference between the two periodic signals. We show that our QD resembles a Lissajous rocking ratchet. A consistent theoretical model based on scattering matrix formalism describes our experimental findings. Similar devices could be realized in a large variety of systems, for instance in nanomechanical or superconducting circuits. Possible applications include noise management, filtering and signal routing.

HL 13.7 Mon 17:30 H10

A charge-driven feedback loop in the resonance fluorescence of a single quantum dot — •Benjamin Merkel[1], Annika Kurzmann[1], Jan-Hindrik Schulze[2], André Strittmatter[2], Martin Geller[1], and Axel Lorke[1] — [1]Faculty of Physics and CENIDE, University of Duisburg-Essen, Lotharstr. 1, 47057 Duisburg, Germany — [2]Technische Universität Berlin, Institut für Festkörperphysik, Hardenbergstrasse 36, 10623 Berlin, Germany

Generating photons with transform-limited linewidths from semiconductor quantum dots (QDs) is challenging. Charge and spin noise from the environment cause spectral fluctuations of the resonance, limiting the generation of highly coherent photons.

In our micro-patterned samples we observe an electro-optical feedback mechanism by which the QD resonance frequency follows the excitation, leading to an optical bistability of the fluorescence signal. This feedback loop can be used to stabilize the resonance and reduce the noise of the emitted photons. We investigate the effect on InGaAs/GaAs QDs by time-resolved measurements of the fluorescence under two-colour excitation and also in a magnetic field. Experiments show a purely electrical origin of the feedback which lies in the formation of a hole gas at a valence band discontinuity close to the dot. The accumulated positive charge leads to a Stark shift of the dot's resonance frequencies. The hole gas is fed by carriers that are generated by resonant excitation of excitons in the dot and that tunnel into the hole gas states at the AlGaAs/GaAs interface. We are able to quantitatively reproduce the feedback dynamics by a numerical rate-equation model.

HL 13.8 Mon 17:45 H10

Exact duality for open system time-evolution and surprises in the heat current relaxation of an interacting quantum dot — •Roman Saptsov[1,2], Jens Schulenborg[3], Federica Haupt[4], Janine Splettstoesser[3], and Maarten Wegewijs[1,2,5] — [1]Institute for Theory of Statistical Physics, RWTH Aachen University, Aachen, Germany — [2]JARA - FIT — [3]Chalmers University of Thechnology, Götenborg, Sweden — [4]JARA Institute for Quantum Information, RWTH Aachen, Aachen, Germany — [5]Peter Grünberg Institut, FZ-Jülich, Jülich, Germany

Recent progress in nanoelectronics has brought the experimental detection and manipulation of few-electron heat currents in nanodevices within reach. However, a straightforward theoretical calculation of the heat-current relaxation – already for the simplest model of an Anderson quantum dot – exhibits a surprising behavior. More precisely, the contribution to the heat-current relaxation arising from the decay of the repulsive Coulomb interaction energy exhibits signatures of electron-electron attraction, and is governed by an interaction-independent decay rate [1]. The surprising behavior of the interaction-induced dissipation mode can only be understood with the help of a new duality relating the nonunitary evolution of an open quantum system to that of dual model with inverted energies [1]. Deriving from the fermion-parity superselection postulate, this duality applies to a large class of open systems, allowing for new general insights beyond the quantum-dot heat-current problem presented here.

[1] J.Schulenborg, R. B. Saptsov, F. Haupt, J. Splettstoesser, M.R. Wegewijs, arXiv: 1508.06145

HL 13.9 Mon 18:00 H10

Energy harvester with coupled quantum dots — •Holger Thierschmann[1,2], Rafael Sánchez[3], Börn Sothmann[4], Fabian Arnold[1], Christian Heyn[5], Wolfgang Hansen[5], Hartmut Buhmann[1], and Laurens W. Molenkamp[1] — [1]Experimentelle Physik 3, Universität Würzburg, Germany — [2]Kavli Institute of Nanoscience, Faculty of Applied Sciences, Delft University of Technology, The Netherlands — [3]Instituto de Cienca de Materiales de Madrid, CISC, Spain — [4]Département de Physique Theoretique, Univeristé de Genève, Switzerland — [5]Institute of Applied Physics, University of Hamburg, Germany

Multi-terminal thermoelectrics recieve an increasing attention because they allow for ways to separate heat and charge flow, thus pointing out a new route towards highly efficient thermoelectric devices. Here we present experiments on a three-terminal energy harvester with Coulomb coupled quantum dots (QD) following a recent proposal [1]. Energy is extracted from a hot electron reservoir via occupation fluctuations of a connected QD and is converted into a directed charge current in a conductor circuit which consists of another QD and two reservoirs at a lower temperature. Heat flow is mediated only through Coulomb interaction of the dots. The key ingredient of our device is an asymmetry in tunnel-coupling of the cold reservoirs and the QD which leads to rectification of charge fluctuations. Controlling this asymmetry with gate electrodes enables us to manipulate the direction of the resulting current even without changing the direction of heat flow. [1] R.Sánchez and M. Büttiker Phys. Rev. B 83 085428 (2011)

Invited Talk HL 13.10 Mon 18:15 H10

Clocked single-electron transfer: quantized currents and electron pair partitioning — •Frank Hohls — Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany

The clocked transfer of single electrons or electron pairs has applications both in metrology as quantized current source and in basic physics as building block for electron quantum optics. In the future redefinition of the International System of Units (SI), expected for 2018, the unit of the electrical current will be derived from a clock frequency f and the elementary charge e, $I = nef$. A promising realization is the non-adiabatic tunable-barrier pump which allows to transfer a highly quantized number of electrons n even at GHz driving frequency [1]. We will present latest results on accuracy verification of the resulting current quantization. For a pump driven at 545 MHz we find an agreement with $I = ef$ within the measurement uncertainty of 0.2 ppm [2]. Interestingly, the same type of electron pump also allows the controlled emission of electrons and electron pairs into a one-dimensional ballistic conductor formed at the edge of a quantum Hall system, opening the route to electron quantum optics experiments. We have examined the partitioning of such electrons at an electronic beam splitter using correlation measurements which validate high fidelity pair splitting and additionally reveal interesting correlation effects for the partitioning of electron pairs [3].

[1] B. Kaestner & V. Kashcheyevs, Rep. Prog. Phys. **78**, 103901 (2015).

[2] F. Stein *et al.*, Appl. Phys. Lett. **107**, 103501 (2015).

[3] N. Ubbelohde *et al.*, Nature Nanotechnol. **10**, 46 (2015).