PROGRAM

Bad Honnef Physics School 2021

Exciting nanostructures: Characterizing advanced confined systems

18 - 23 July 2021, Physikzentrum Bad Honnef

Organized by Christian Klinke (University of Rostock) and Nikolai Gaponik (TU Dresden)

Sunday, 18 July 2021

17:00 – 21:00 *Registration*

18:30 DINNER / Informal get together

Monday, 19 July 2021

08:00 BREAKFAST

08:45 – 09:00 *Opening and welcome*
Prof. Christian Klinke and Prof. Nikolai Gaponik

09:00 – 10:15 *Nanocrystals: what was, what is and what might be*
Prof. Horst Weller (University of Hamburg)

10:15 – 10:45 COFFEE BREAK

10:45 – 12:00 *Can we synthesize colloidal quantum dots that are all the same size?*
Prof. David J. Norris (ETH Zurich)

12:00 **Conference Photo (in front of the Physikzentrum)**

12:15 LUNCH

14:30 – 15:45 *Computational-chemistry approaches to modelling nanostructures and their properties*
Dr. Jan-Ole Joswig (University of Dresden)

15:45 – 16:15 COFFEE BREAK

16:15 – 17:30 *Flash talks by the students*
Each talk has 2 min with 1 slide on their subject/poster

18:30 DINNER

Tuesday, 20 July 2021

08:00 BREAKFAST

09:00 – 10:15 *Two-dimensional nanostructures: Control the inorganic core and the surface chemistry*
Prof. Sandrine Ithurria (ESPCI Paris)

10:15 – 10:45 COFFEE BREAK

10:45 – 12:00 *Tutorial on the fabrication of electronic nano- and micro-devices*
Dr. Andres Castellanos (CSIC Instituto de Ciencia de los Materiales de Madrid)

12:15 LUNCH

14:30 – 15:45 *The history of doping in semiconductor nanocrystals*
Prof. David J. Norris (ETH Zurich)

15:45 – 16:15 COFFEE BREAK

16:15 – 17:30 *Electronic transport through nanostructures: example of two-dimensional materials*
Dr. Andres Castellanos (CSIC Instituto de Ciencia de los Materiales de Madrid)

18:30 DINNER

19:30 **Poster session 1**

Wednesday, 21 July 2021

08:00 BREAKFAST

09:00 – 10:15 *Optical spectroscopy of two-dimensional materials*
Prof. Tobias Korn (University of Rostock)

10:15 – 10:45 COFFEE BREAK

10:45 – 12:00 *Principles of nanocrystal assembly*
Prof. Nadja Bigall (Leibniz University Hannover)

12:15 LUNCH

14:00 – 18:00 Excursion & Café (hike in the vicinity, boat trip in case of rain)

18:30 DINNER (at the Physikzentrum)

19:30 – 21:00 Meet the Editor
Prof. Andrey L. Rogach (City University of Hong Kong and Associate Editor of *ACS Nano*)

Thursday, 22 July 2021

08:00 BREAKFAST

09:00 – 10:15 *Coordination chemistry at interfaces and the engineering of low-dimensional metal-organic nanosystems*
Prof. Johannes Barth (TU Munich)

10:15 – 10:45 COFFEE BREAK

10:45 – 12:00 *Testing without Touching: Time-Resolved Terahertz-Spectroscopy for Nanostructures*
Dr. Jannika Lauth (Leibniz University Hannover)

12:15 LUNCH

14:30 – 15:45 *X-ray methods for nanostructures*
Dr. Marcus Scheele (University of Tübingen)

15:45 – 16:15 COFFEE BREAK

16:15 – 17:30 *Charge and heat transport in nanocrystal arrays*
Prof. Dmitri Talapin (University of Chicago)

18:30 DINNER

19:30 **Poster session 2**

Friday, 23 July 2021

08:00 BREAKFAST

09:00 – 10:15 *Magnetooptics of colloidal nanocrystals*
Dr. Elena Shornikova (TU Dortmund)

10:15 – 10:45 COFFEE BREAK

10:45 – 12:00 *Lead Halide Perovskite Nanocrystals: From Discovery to Superfluorescent Superlattices*
Prof. Maksym Kovalenko (ETH Zurich)

12:00 – 12:15 *Poster awards and closing remarks*
Prof. Christian Klinke and Prof. Nikolai Gaponik

12:30 LUNCH

End of the physics school and Departure

Nanocrystals: what was, what is and what might be

Horst Weller

Institute of Physical Chemistry, University of Hamburg, Germany

The lecture will give insight to the principles of colloidal nanocrystal synthesis. It will show how research activities from different disciplines finally merged into what we now call nanoscience and summarize some historical milestones of the past 40 years.

Today, nanocrystals are used in several industrial applications like in the display and lighting marked. We will discuss several examples in materials and life sciences showing how long the way from academic research to an industrial application typically is. Against the background of how many pioneering results in nanoscience are still on the level of basic research, one can easily imagine the impact of nanoscience and nanotechnology for the next decades on our daily life.

Can we synthesize colloidal quantum dots that are all the same size?

David J. Norris

Optical Materials Engineering Laboratory, ETH Zurich, Switzerland

Nanometer-scale semiconductor particles, known as colloidal quantum dots, exhibit optical properties that are strongly dependent on their diameter. For example, this effect can be used to tune the wavelength range over which they absorb and fluoresce light. This phenomenon is useful for various applications including solar cells or light-emitting devices. However, during the synthesis of these particles, one inevitably obtains a distribution in particle sizes. This causes a broadening in their absorption and emission, which is detrimental for applications. In this lecture, we will discuss why real-world samples have a size distribution and the strategies that researchers have used to minimize it. We will describe the advantages and disadvantages of various synthetic approaches and then focus on the "hot-injection method." This latter synthetic methodology separates particle nucleation and growth, which has long been known as a strategy to obtain narrow size distributions. Ostwald ripening, and our ability to control its negative influences will also be discussed.

The history of doping in semiconductor nanocrystals

David J. Norris

Optical Materials Engineering Laboratory, ETH Zurich, Switzerland

Since the discovery of colloidal semiconductor quantum dots (nanocrystals) over 35 years ago, researchers have sought to incorporate intentional atomic impurities, or dopants, into these materials. This has been primarily motivated by three factors. First, researchers wished to study the impact of impurities on nanocrystals due to the critical role that dopants play in bulk semiconductor devices, such as the transistor. Second, impurities in nanocrystals should exhibit even more dramatic behavior than in bulk semiconductors because the dopants are confined to extremely small volumes. Finally, doping could in principle help address key problems in potential applications of nanocrystals (e.g., light-emitting diodes and solar cells). In particular, many applications utilize thin films of densely-packed nanocrystals. Electronically active impurities can provide extra electrical carriers, i.e. electrons or holes, to the particles and enhance the conductivity of these films. Due to these fundamental and technological motivations, nanocrystal doping has moved forward over the last thirty years. In this talk, we will review the progress and discuss some of the remaining challenges. In general, doping has followed the development of the broader field. Advances in nanocrystal synthesis have been exploited to understand the doping process (i.e. how impurities can be incorporated). Advances in optical and electrical characterization of nanocrystals have been utilized to understand the impact of impurities on their properties. During these efforts, interesting and important connections have also been made to related physical phenomena, such as charging, diffusion, and surface effects. Thus, researchers working on the "doping problem" have not only slowly developed a sub-class of nanocrystal materials that are important for future nanocrystal devices, but have contributed to a deeper understanding of nanocrystal behavior more broadly.

Computational-chemistry approaches to modelling nanostructures and their properties

Dr. Jan-Ole Joswig

Theoretische Chemie, Technische Universität Dresden, Germany

Modelling properties of nanostructures and their assemblies faces a number of severe problems. The main challenge is to deal with the fact that the systems are large, but finite. For this reason, the typical approach of imposing periodic-boundary conditions as in solid-state calculations cannot be applied.

In this lecture, we will review computational-chemistry approaches of modelling structural, electronic and optical properties of large, but finite systems, in particular of semiconductor and metal nanoparticles. The fundamental theories as well as their advantages and limits will be shortly discussed. This includes density-functional theory, molecular-dynamics and Monte-Carlo simulation approaches. Case studies will be presented dealing with modelling excitations in cadmium-chalcogenide nanoparticles, core-shell nanoparticles, and quasi-two-dimensional systems. Furthermore, the aggregation of nanoparticles to form assemblies will be part of the lecture.

Two-dimensional nanostructures: Control the inorganic core and the surface chemistry

Sandrine Ithurria

Laboratory of Physics and Material Studies, ESPCI Paris PSL, Paris, France

Nanocrystals due to their high surface to volume ratio need to be thought as an ensemble comprising an inorganic core and its surrounding shell of ligands.
In this lecture I will give some examples of synthetic method leading to the growth 1D nanowires and rods and to the growth of 2D objects such as nanosheets and nanoplatelets. I will show that most anisotropic growth can be sort over four class of mechanism: lattice induced anisotropy, ligand induced anisotropy, lattice defect induced growth and self-assembly of preformed nanocrystal. The lecture will mostly focus on wurtzite and zinc blende 2D nanoparticles. I will discuss, the different opportunities to control the inorganic core of these particles.

In the last part of the presentation, the focus will be on the surface chemistry of these 2D nanoparticles. Indeed, for nanosheets whose only confinement direction is the thickness, a modification of the latter, even on a single atomic plane can greatly modify the optical properties.

Tutorial on the fabrication of electronic nano- and micro-devices

Andres Castellanos-Gomez

Instituto de Ciencia de Materiales de Madrid ICMM-CSIC, Madrid, Spain

This lecture is intended to provide an overview of the different alternatives for the fabrication of nano and microdevices to the students. I will review the main methods employed to fabricate electronic devices out of nanomaterials. The different strategies will be critically discussed pointing their cost, complexity, technical requirements and strengths and weaknesses.

Electronic transport through nanostructures: example of two-dimensional materials

Andres Castellanos-Gomez

Instituto de Ciencia de Materiales de Madrid ICMM-CSIC, Madrid, Spain

In this lecture, I will describe the main approaches to handle and characterize electronic devices based on nanomaterials. I will focus on electronic devices based on 2D materials as an example but generalizing for other nanomaterials based devices. The different experimental tools/setups required to test the electronic transport through these nano-scale devices will be discussed focusing on the tips and tricks needed to perform low-noise electron transport measurements.

Optical spectroscopy of two-dimensional materials –
from basic concepts to seminal experiments and recent advances

Tobias Korn

Institute of Physics, University of Rostock, Germany

A surprising property of many two-dimensional materials is their remarkably strong interaction with light. This is important for basic tasks such as finding atomically thin flakes of a material under the optical microscope, but also plays a key role in understanding their electronic structure and provides access to beautiful many-body physics in complex van der Waals heterostructures. In this lecture, we will briefly discuss the basics of spectroscopy techniques such as photoluminescence, absorption and Raman scattering by revisiting some seminal experiments performed on various two-dimensional materials. Then, we will take a look at more recent results obtained with optical spectroscopy on van der Waals heterostructures.

Lead Halide Perovskite Nanocrystals: From Discovery to Superfluorescent Superlattices

Maksym V. Kovalenko

ETH Zürich, Department of Chemistry and Applied Biosciences, CH-8093, Zurich, Switzerland
Empa-Swiss Federal Laboratories for Materials Science and Technology, CH-8600, Dübendorf, Switzerland

We will discuss the discovery and recent developments of colloidal lead halide perovskite nanocrystals (LHP NCs, NCs, A=Cs^+, FA^+, FA=formamidinium; X=Cl, Br, I). LHP NCs exhibit spectrally narrow (<100 meV) fluorescence, tunable over the entire visible spectral region of 400-800 nm. Owing to their high oscillator strength, slow dephasing (long coherence times of up to 80 ps), minimal inhomogeneous broadening of emission lines, and a bright triplet exciton character with orthogonal dipole orientation, these NCs make for a highly versatile platform for creating controlled, aggregated states exhibiting collective phenomena. Long-range ordered superlattices (SLs) with the simple cubic packing of cubic perovskite NCs exhibit sharp red-shifted lines in their emission spectra and superfluorescence (a fast collective emission resulting from coherent multi-NCs excited states). We now present perovskite-type ABO3 binary and ternary NC SLs by a shape-directed co-assembly of $CsPbBr_3$ nanocubes (occupying B- and/or O-sites) with spherical dielectric Fe_3O_4 or $NaGdF_4$ NCs (A-sites) and truncated-cuboid PbS NCs (B-site). Such ABO_3 SLs, as well as other newly obtained SL structures (binary NaCl- and AlB_2-types, columnar assemblies with disks etc.), exhibit a high degree of orientational ordering of $CsPbBr_3$ nanocubes. These mesostructures exhibit superfluorescence as well, characterized, at high excitation density, by emission pulses with ultrafast (22 ps) radiative decay and Burnham-Chiao ringing behaviour with a strongly accelerated build-up time.

Coordination chemistry at interfaces and the engineering of low-dimensional metal-organic nanosystems

Johannes V. Barth

Physik Department E20, Technische Universität München, D-85748 Garching, Germany

The judicious use of metal-ligand interactions providing a versatile strategy to control transition and other metal centers in unique environments. Interfacial coordination chemistry using solid supports as anchoring or even construction platforms emphasizes the full involvement of the surface atomic lattice in the metal-ligand interactions and coordination spheres. Individual functional molecules and their metal-directed assembly are characterized by scanning tunneling microscopy and spectroscopy, as well as complementary x-ray spectroscopy studies and computational modeling. The atomistic insight gained is used to systematically steer the formation of nanoarchitectures with special structural features and novel physicochemical properties. We explore the presented coordinatively unsaturated sites in terms of their electronic nature, magnetic characteristics and chemical reactivity. Furthermore surface-mounted rotator modules as well as switchable complexes have been fabricated, with intriguing dynamic phenomena that were monitored and analyzed. The described approach constitutes a new domain in coordination chemistry, wherein the special environments provide a unique setting for metal centers, and the nanoscale control yields distinct and tunable functionalities.

Testing without Touching:

Time-Resolved Terahertz-Spectroscopy for Nanostructures

Dr. Jannika Lauth

Institute of Physical Chemistry and Electrochemistry,
Leibniz University Hannover, Hannover, Germany

Pump-probe (time-resolved) spectroscopic methods are excellent techniques for characterizing and understanding the photophysics and charge carrier dynamics of nanostructures. In this lecture, I will present an introduction to time-resolved terahertz spectroscopy (TRTS) and its use as all-optical method for non-contact photoconductivity measurements as well as for gaining information about bound excitons and free charges in nanostructures.

Principles of nanocrystal assembly

Prof. Nadja Bigall (Leibniz University Hannover)

Institute of Physical Chemistry and Electrochemistry, Leibniz University Hannover, Hannover, Germany

Colloidal synthesis nowadays gives us the opportunity to obtain a large range of nanocrystals with atomic shape and size precision. However, not for all applications the nanoparticles are needed in solution, which means assembly strategies have to be developed. When assembling nanoparticles into larger entities, interparticle interactions are likely to occur altering the original nanoscopic properties. This can reach an extent, where new physical properties are observed which can only be accessed by the special type of assembly applied. Therefore, careful structure-property investigations need to be conducted. The types, shapes and facetations of the nanocrystals, their interparticle distance or connection as well as the surface chemistry are factors which need to be considered. This lecture will discuss selected assembly techniques for templated and non-templated assembly, ordered and non-ordered assembly as well as assembly to macroscopic or microscopic objects.

X-ray methods for nanostructures

Marcus Scheele

Institute of Physical and Theoretical Chemistry, University of Tübingen, 72076 Tübingen, Germany

By design, most nanostructures are too small to be imaged with visible light, such that electromagnetic radiation of higher energy is needed. Apart from electron beam-based techniques, such as transmission electron miocroscopy, methods based on photons from the X-ray regime of the electromagnetic spectrum are ideal for this purpose. While wide-angle X-ray powder diffraction is fairly routinely applied in research of nanomaterials, small-angle X-ray scattering in transmission or grazing incidence geometry provide additional structural information. Advances in the brilliance and coherence of synchrotron light sources have enabled the design of highly specialized experiments based on these standard techniques, such as simultaneous wide- and small-angle X-ray scattering, scattering at liquid interfaces or diffraction experiments with nanofocussed X-ray beams.

In this tutorial, I will summarize the basics of routine X-ray scattering techniques for elucidating the structure of nanomaterials, provide an overview of the benefits and advantages of several novel scattering experiments for nanomaterial research that have evolved at the world's leading synchrotron facilities and showcase some practical examples.

Magnetooptics of colloidal nanocrystals

Elena V. Shornikova

Experimental Physics 2, TU Dortmund University, Dortmund, Germany

This lecture will give an overview of various approaches, which can be used to address spins of charge carriers and excitons in colloidal nanocrystals. First, I will introduce spectrally- and time-resolved polarized photoluminescence, and fluorescence line narrowing, which are simple but powerful techniques. They provide important information about exciton fine structure, exciton and trion (charged exciton) recombination times, g-factors and spin dynamics. Also, some exotic parameters, such as nanocrystal orientation in ensemble or charge transfer rates between nanocrystals, can be deduced from these experiments. Next, I will present several magnetooptical methods, which are widely used to study spin properties of epitaxial structures and transition metal dichalcogenides but are not popular in colloidal community so far. These methods include pump-probe Faraday rotation, Raman spin-flip, and optically detected magnetic resonance. In the end, I will describe spin phenomena, which are related to surface properties of colloidal nanocrystals: exchange interaction with surface spins, exciton recombination assisted by surface spins, and magnetic polaron formation.

Charge and heat transport in nanocrystal arrays

Dmitri V. Talapin

Department of Chemistry, James Franck Institute, and Pritzker School of Molecular Engineering, University of Chicago, Chicago, USA

The rise of colloidal nanomaterials has introduced exciting opportunities for design of electronic materials from precisely engineered nanoscale building blocks. Potentially, this approach can combine the advantages of crystalline inorganic semiconductors with size-tunable electronic structure and inexpensive solution-based device fabrication. Along these lines, colloidal semiconductor quantum dots (QDs) are widely explored as the functional elements in printable electronics (field-effect transistors, memory devices, etc), light emitting devices, photodetectors and solar cells. All the above applications rely on efficient charge transport in nanocrystal arrays. Somewhat underappreciated, thermal transport in nanocrystal layers is also very important for efficient and stable operation of nanocrystal devices. In the recent years significant progress has been achieved in understanding charge and heat transport through nanocrystal films. New chemical approaches have been developed to improve electronic transport. I will review the fundamentals of transport in disordered semiconductors and granular materials. The transport in nanocrystal solids is directly related to the nanocrystal surface chemistry. I will review our work on conductive inorganic surface ligands and conclude with a discussion of the remaining issues and unsolved problems in the field.