Material fusion

Balancing their scientific and administrative contributions at the Collaborative Research Centre 951, Spokesman and Vice-Spokesman **Professor Drs Fritz Henneberger** and **Norbert Koch** are making great leaps in creating hybrid inorganic/organic systems

FH: FRITZ HENNEBERGER

NK: NORBERT KOCH

Could you introduce the Collaborative Research Centre 951 (CRC 951) Hybrid Inorganic/Organic Systems for Opto-Electronics (HIOS) project?

FH: The mission of HIOS is the merger of completely different materials – inorganic semiconductors, conjugated organic molecules and metal nanostructures – into joint functional units. Hybridising the chemical and physical properties of the structure's constituents potentially enables the CRC 951 to create superior optoelectronic functionalities to those achieved by any of the individual material classes alone. HIOS also aims to elucidate the still poorly understood chemical, electronic and photonic interactions arising from the different components.

Why is the creation of HIOS with high levels of optoelectronic functions increasingly important in modern society?

NK: Our information-based society continues to demand a concentration of optoelectronic functions, such as data processing, with increasingly higher capabilities in smaller and smaller volumes. Established materials have been pushed close to their intrinsic limits, but hybrid materials combining the strengths of their constituents offer the possibility to overcome currently existing restrictions.

What are the advantages and disadvantages of the range of materials used to create HIOS?

FH: Inorganic semiconductors are well-established optoelectronic materials that allow structural control on the atomic scale. Thin films and large crystals can be grown with the highest purity levels, atomically smooth interfaces, high charge carrier mobility and efficient electrical charge injection. However, their optical absorption cross-section is significantly smaller than that of conjugated organic molecules.

Conjugated organic materials exhibit strong light-matter coupling and highly flexible tunability of electrical and optical properties. Moreover, they feature self-assembly from the molecular level to macroscopic crystalline phases, and have tremendous structural and morphological variability. However, charge carrier mobility is notoriously low and limits the operation frequency and bandwidth of devices. Efficient injection of charge carriers into organic materials also remains a challenge.

Metal nanostructures are capable of confining and guiding light at subwavelength dimensions via plasmonic excitations, which is mandatory for HIOS functions on the molecular level. Additionally, high local optical fields as well as increased far-field scattering can be achieved by the metal nanostructures. However, the efficient processing of the received energy and the minimisation of its dissipation are still problematic characteristics of these structures. Moreover, appropriate geometries and schemes ensuring strong and controllable interaction between plasmonic fields and the optical dipoles of suitable co-materials are yet to be developed.

Is staying at the forefront of cutting-edge technology necessary for the CRC 951-HIOS to achieve its objectives?

NK: State-of-the-art research infrastructure is paramount in order to fabricate well-defined HIOS specimens and analyse their properties. For example, for the growth of hybrid structures in an all-ultra high vacuum (UHV) regime, a molecular-beam epitaxy (MBE)-tandem apparatus is available at the CRC 951. For structural characterisation, techniques in real space (such as transmission electron or scanning tunnel microscopy, which can reach atomic resolution), are combined with scattering methods in k-space. Advanced photoemission techniques, eg. two-photon excitation, provide information on the electronic and interface structure.

What has the CRC 951-HIOS achieved since its formation, and what still remains to be achieved?

FH: HIOS has achieved progress towards energy level alignment at hybrid interfaces, which is of particular importance as this determines whether the hybrid structure is useful for light-emitting or photovoltaic applications. It became clear that the doping level of the inorganic semiconductor represents an extra degree of freedom for engineering this alignment. Huge work-function changes in the eV range are realised at low energy transfer to the adjacent organic molecules. A new theoretical approach had to be implemented to adequately describe these findings. The next step is translating these findings into practical devices and demonstrating their functionality.

Potential applications of HIOS

High brightness directional light emitters and lasers – excitation in an inorganic semiconductor, realised by optical or electric pumping, is transferred with high efficiency to a conjugated organic material and followed by photon emission. Metal nanostructures arranged close to the conjugated organic light emitter enhance this energy transfer. Such HIOS may be capable of white light emission or coherent narrow-band lasing.

Efficient nanoscale light absorbers and converters to electrical energy – these exploit the wide absorption energy range of conjugated organic materials and their high absorption cross-sections. Subsequent charge separation at the interface between the conjugated organic materials and an inorganic semiconductor may result in unprecedented light-to-current conversion efficiency.

Nanoscale non-linear optical switches – these small switches can be used for processing data with an ultrafast response time and very low power consumption. Novel hybrid excitation states of conjugated organic materials and inorganic semiconductors might lead to a breakthrough.

Modernising optoelectronics

The Collaborative Research Centre 951 HIOS project in Berlin is a cross-disciplinary venture that aims to merge inorganic semiconductors, conjugated organic materials and metal nanostructures. The resulting hybrid structures will have optoelectronic functionalities superior to any of the individual material classes alone

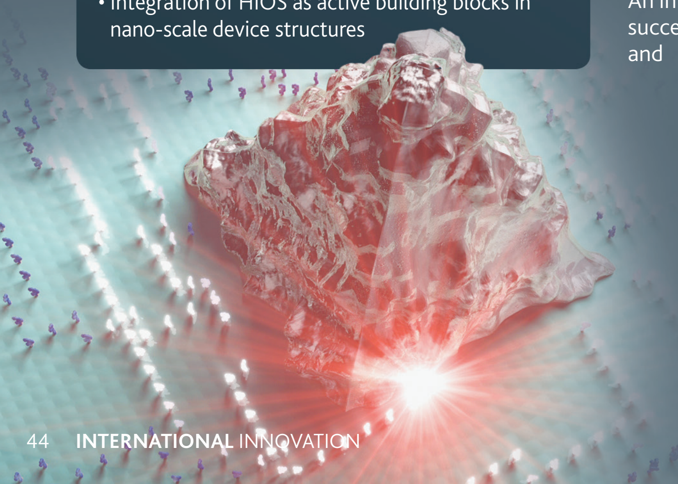
RECENT DECADES HAVE seen great progress in electronics. Using light, semiconductors and electricity, scientists have created devices that fundamentally changed our lives, including LEDs, transistors and solar cells. Efforts have typically been focused on creating devices which are smaller, faster and brighter, and information processing is built on mechanically crunching through a fixed set of strictly defined rules. However, many problems in our globalised world are too complex to be tackled by this method and these concepts will soon reach their limit.

Modern IT needs a radically different approach. Fortunately, nature provides the very tools required. Molecules that communicate by electric charges or light, but are much smaller than the building blocks of conventional semiconductor devices, can be found in a range of natural states.

However, there are challenges associated with exploiting these molecules for technical applications. Alone they have very little value – to control, for example, their light emission efficiently they must be placed in an environment where electrical signals can simulate them. Conventional semiconductors are well suited to this task. Joining these two worlds – soft organic molecules and hard inorganic semiconductors – is at the core of the Collaborative Research Centre 951 Hybrid Inorganic/Organic Systems for Opto-Electronics (CRC 951-HIOS) project in Berlin.

Milestones of optoelectronic objectives

- Identification of the mechanisms that govern the assembly of conjugated organic materials on inorganic semiconductors or metal nanostructures
- Development of tools for characterisation of structure and morphology of HIOS
- Development of rational methods to control the formation of high-quality HIOS
- Understanding and controlling the electronic and plasmonic structure and hybridisation in HIOS
- Understanding and tailoring the specific interactions in HIOS that give rise to energy and charge transfer and separation, as well as exciton hybridisation across interfaces
- Optimisation of the hybrid material properties relevant for device function
- Development of novel concepts for opto-electronic devices exploiting the superior features of HIOS
- Integration of HIOS as active building blocks in nano-scale device structures



THE COLLABORATIVE RESEARCH CENTRE 951

The CRC 951-HIOS project is developing novel hybrid materials composed of inorganic semiconductors, conjugated organic molecules and metal nanostructures. HIOS aims to improve, and perhaps create entirely new, optoelectronic properties by combining the advantages of these individual materials.

Firstly, HIOS needs to fully elucidate the fundamental interactions taking place in these systems. Based on this understanding, HIOS will adapt these interactions to develop materials which perform optoelectronic functions unachievable by any of the individual components alone.

An interdisciplinary approach is vital to succeed in this goal, as Spokesperson and Vice-Spokesman Professor Drs Fritz Henneberger and Norbert Koch elaborate: "Due to the manifold possible material combinations, the field of HIOS is tremendously wide. Bringing together specialists with complementary expertise in an interdisciplinary forum is therefore essential". Previously, the three material classes under study by HIOS were developed in separate research spheres, with sparse communication occuring between them. The CRC 951 is well positioned to change this paradigm and provides an environment that is highly conducive to collaboration. Structured interactions between principal investigators, with diverse knowledge and expertise, will enable the proper mobilisation of resources and the sharing of new concepts and techniques. The CRC 951 also provides training for students and researchers to ensure they develop a broad knowledge base at the early stages of their career, and HIOS Young Researcher Workshops enable PhD students and postdocs to discuss their own research with experts from varied backgrounds.

A TRICKY CONCEPT

Heterostructures made from different materials have revolutionised electronic and optical technologies. At the heart of HIOS is the idea that each material has its own specific chemical and electrical properties, and that there are advantages, but also drawbacks, of using each material. The HIOS project is able to exploit the benefits and compensate for the deficits when combining the materials.

A major difficulty in joining the materials lies in the fact that molecules often break when they are brought into contact with semiconductors, causing them to lose their beneficial properties. Therefore, the materials must be chosen and modified with care to retain their internal structure and to ensure they can perform their intended function. It is also important that the organic molecules are arranged on the inorganic surface in a regular array, so they can collectively fulfil their function, such as emitting or absorbing light.

But the complexity does not end there. HIOS must then find a way of allowing charge carriers to pass from one side of the system to the other – a suitable molecular interlayer must be used as a mediator to enable the molecules to emit light. HIOS takes this concept one step further: The project will amplify the intensity of this light emission by orders of magnitude, incorporating metal nanoparticles to build light-driven circuits on the same length scale as conventional electronic circuits.

HIOS offers great potential for achieving novel optoelectronic function by hybridising different quantum states. However, before that can be realised, there are challenges to overcome and knowledge gaps to address. In light of this, the core scientific mission of

HIOS institutions

University institutions

- Humboldt University of Berlin: Department of Physics, Department of Chemistry and Integrative Research Institute for the Sciences
- Technical University of Berlin: Department of Theoretical Physics
- University of Potsdam: Institute of Physics and Astronomy

Non-university institutions

- Helmholtz Centre Berlin for Materials and Energy : Division Functional Materials
- Fritz Haber Institute of the Max Planck Society: Theory Department and Department of Physical Chemistry
- Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy: Division C: Nonlinear Processes in Condensed Matter
- Paul-Drude-Institute for Solid State electronics: Department of Semiconductor Spectroscopy and Department of Epitaxy

the project is to elucidate the chemistry and physics underlying HIOS formation. Beyond making significant contributions to the basic science of this new class of heterostructures, HIOS will also generate innovative applications for future communication and information applications.

MULTIFUNCTIONAL MATERIALS

The fundamental obstacle to progress is the lack of knowledge of HIOS – their structure, properties and interactions – and of systematic approaches to tackle the crucial aspects of HIOS from a unified perspective. The CRC 951 is integrating projects and encouraging collaboration between expert scientists in different disciplines to overcome these barriers.

Thus far, HIOS has gained knowledge that will allow for the development of methods for the robust fabrication of these heterostructures and control of their optoelectronic properties. By merging these dissimilar materials, many fundamental optoelectronic functions will be possible: light absorption and emission, energy transport, optical switching and plasmonic emission and amplification – all in (or scalable to) meso- and nanoscopic dimensions.

Looking ahead, the CRC 951 believes inorganic-organic hybrids will play a major role in the development of advanced functional nanomaterials. The novel functionality of these materials will solve many existing and future problems; for example, data processing in the optical domain will improve on electronic circuitry, both in terms of speed and bandwidth. This is currently very difficult, as the optical properties of existing materials do not scale appropriately. HIOS is able to provide an alternative route through the hybrid exciton states of inorganic semiconductors and conjugated organic materials. Yet applications are not limited to information processing, they will be widespread, reaching into many fields including optics, mechanics and medicine.

INTELLIGENCE

HYBRID INORGANIC / ORGANIC SYSTEMS (HIOS) FOR OPTO-ELECTRONICS

OBJECTIVES

The project aims to merge inorganic semiconductors, conjugated organic materials and metal nanostructures. The resulting hybrid structures will have optoelectronic functionalities superior to any of the individual material classes alone. In addition, significant contributions to the basic science of this new class of heterostructures will be made.

MANAGING BOARD

Professor Dr Fritz Henneberger (Spokesman)

Professor Dr Norbert Koch (Vice-Spokesman)

Dr Maurizio Roczen (Managing Director)

PARTNERS

Humboldt University of Berlin • Technical University of Berlin • University of Potsdam • Helmholtz Centre Berlin for Materials and Energy • Fritz Haber Institute of the Max Planck Society • Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy • Paul-Drude-Institute for Solid State electronics

FUNDING

German Research Foundation (DFG)

CONTACT

Professor Dr Fritz Henneberger
Spokesman

Humboldt-Universität zu Berlin
Institut für Physik
Newtonstraße 15
12489 Berlin
Berlin
Germany

T +49 (0) 302093 7670
E sfb951@physik.hu-berlin.de

www.physik.hu-berlin.de/sfb951

FRITZ HENNEBERGER has been Full Professor of the Humboldt University of Berlin since 1993. He was Director of the Physics Department between 1993-94 and 2002-06 and is Director of the Humboldt Centre of Modern Optics since 2010. He has contributed to numerous Priority programmes of the DFG.

NORBERT KOCH has been Full Professor of the Humboldt University of Berlin since 2009. Prior to this he was Head of the Emmy Noether Independent Junior Research Group from 2004-09. He received the Karl-Scheel-Preis on his work 'Conjugated organic materials and their functional interfaces'.