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# Organic Polymer Electronics – A Special Issue in Honor of Prof. Olle Inganäs

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Olle Inganäs (Image Credit: Magnus Bergström; reproduced with permission from the Knut and Alice Wallenberg Foundation)

Conjugated polymers (CPs) were first reported to exhibit high electrical conductivity upon heavy doping in 1977. For this discovery, Alan Heeger, Alan MacDiarmid, and Hideki Shirakawa were awarded the Nobel Prize in Chemistry in 2000. Since the initial publications, there has been tremendous research and development to make conjugated polymers useful and to expand the scope of available materials and properties. Professor Olle Inganäs has long been a tall figure in the development of conjugated polymers and the expansion of organic polymer electronics to include many diverse areas such as bioelectronics, electromechanical machines, solar cells, light-emitting diodes, energy storage, and printed electronics.

Here, we assemble a collection of articles in honor of Professor Inganäs to celebrate his 35 years of pioneering work, where he has contributed over 525 papers, focused on studies of conducting polymers throughout the areas of polymer physics, electrochemistry, electronics, and optics. His current interests include energy conversion and energy storage with organic photovoltaic devices and organic supercabatteries, as well as the use of biopolymers as organizers of electronic polymers.

Olle initiated his research career with the ambition to do biophysics and found inspiration in photosynthesis and novel organic electronic materials after the initial discovery of CPs. To emphasize his interdisciplinary ambition, he changed the name of his research division to Biomolecular and Organic Electronics in the year 2000, which reflected the combination of two fields: bioelectronics and organic electronics.

In the field of organic electronics, he carried out fundamental studies on thermochromism, charge transport, and electrochromic properties of conducting polymers (such as poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS), polypyrrole, and polythiophene). An area that further developed, based on these studies, was organic light-emitting diodes (OLEDs), where Olle made seminal work including new materials for OLEDs, covering the full visible spectrum and extending into the infrared and ultraviolet, and the first tunable white OLEDs, as well as the first nano-OLEDs in the 1990s.

His most productive field throughout the years has, however, been organic photovoltaics (OPVs), covering optimization of active materials, device engineering, modeling, and device physics. Olle was the first to employ a low-bandgap alternating polyfluorene to enhance the photocurrent of OPVs (2003) and extended the spectral coverage to long wavelengths. In the last three decades, he made many innovations in device engineering significantly contributing to the increase in photoconversion efficiency. Olle was also the first to employ PEDOT:PSS as a hole-transporting layer into polythiophene/C-60 photodiodes (1998) and to use aqueous solution-processed poly(ethylene oxide) as an electron-transporting layer to replace vacuum-deposited lithium fluoride (2007). PEDOT:PSS was introduced as an anode and a cathode, respectively, to replace ITO for printing large-area flexible OPVs (2002, 2006). Double efficiency was achieved in lateral reflective tandem OPVs via folded devices (2007 and 2008). Vacuum-free inverted semitransparent OPVs were realized (2009, 2012), which not only pave the way to large-scale printing of OPV modules, but also extend the installation of OPV panels to windows and facades of buildings.

Olle was the first to develop optical models of the OPV using the transfer matrix model (TMM) of multilayer OPV devices (1999). Furthermore, based on classical drift–diffusion models for electrons and holes, he also developed a model combining optical and electrical processes in OPVs in 2005.

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**Anna Herland** is an Associate Professor in Biohybrid Systems at KTH Royal Institute of Technology, and at Karolinska Institutet (Sweden). She received her Ph.D. in organic bioelectronics from Linköping Universitet (Sweden) under Olle Inganäs and did postdoc fellowships at Karolinska Institutet in stem cell engineering under Ana Texieira and at Harvard University (USA) in tissue engineering under Donald Ingber. Her current research focuses on creating microphysiological models of tissue, especially the central nervous system. She develops human primary and stem-cell-derived systems combined with microfluidics, and uses organic electronics or bioelectronics stimuli and read-outs for real-time assessment of biological functions.

**Fengling Zhang** is a Professor in the Department of Physics, Chemistry and Biology at Linköping University, Sweden. She specializes in device engineering and physics of organic photovoltaic devices. Her current research activities include polymer-based electrochromics, supercapacitors, thermoelectrics and integrated photocapacitors. She received her Ph.D. degree in solid-state physics from Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, and carried out postdoctoral research under Prof. Yasuhiko Shirota at Osaka University and Prof. Olle Inganäs at Linköping University.

**Qibing Pei** is Professor of Materials Science and Engineering and Professor of Mechanical Engineering at the University of California, Los Angeles. He specializes in synthetic polymers and composites for electronic, electromechanical, and photonic applications. His current research activities focus on stretchable electronics, nano-structured polymer composites, dielectric elastomers and bistable electroactive polymers for muscle-like actuation, and electrocaloric polymer cooling. He received his Ph.D. degree from the Institute of Chemistry, Chinese Academy of Sciences, carried out postdoctoral research under Olle Inganäs at Linköping University, and worked at UNIAX Corporation (now DuPont Display) and SRI International, Menlo Park, California.

Another important contribution was his first identification of the existence of charge-transfer states (CTS) and the origin of the open-circuit voltage, which was done by studying the photoluminescence and electroluminescence of polymer/fullerene bulk heterojunctions (BHJs) in OPVs (2009). Olle was the first to quantify the internal quantum efficiencies of charge generation in OPVs by investigating the device performance combined with optical modeling (2012). These studies have resulted in the emergence of nonfullerene acceptors, which minimize the exciton dissociation leading to increased power conversion efficiencies.

In addition to his heavy contributions in the field of organic energy conversion, Olle recently, made noteworthy contribution to energy storage, by illustrating that lignins, a green byproduct from the pulp industry, can form a structural composite with conducting polymers to store electric charge.

In the field of bioelectronics, his initial steps toward bioinspired electronic applications were taken in the 1990s, when he contributed to utilizing the effect of ionic intercalation into polypyrrole to achieve electromechanical actuation. This phenomenon was later combined with microfabrication to develop the first organic electronic micromuscle. In parallel to this work, Olle explored the conducting polymer PEDOT and its ion/electron transduction capabilities to demonstrate supercapacitors, electrochemical transistors, and displays. This work eventually enabled a true bioelectronic interfaces in the form of neural and enzymatic contacts.

Olle extended his activities to biosensing by developing water-soluble conjugated poly- and oligoelectrolytes, enabling optical probes for protein folding in vitro and protein diseases in vivo, as well as DNA chips. In a recent contribution, he demonstrated electronic interfacing of the lipid membranes and ion channels of cells using PEDOT in an electrochemical transistor.

This special issue contains a collection of reviews and original research papers from 13 groups, with a diverse range of research topics in which Olle made important initial contributions, ranging from organic solar cells to bioelectronics.

Andersson and co-workers (article number 1807275) review all-organic polymer solar cells. Zou and co-workers (article number 1806616) present a *Communication* studying flexible nonfullerene solar cells. Zhang, and co-workers (article number 1900690) present a *Progress Report* on the limitations and perspectives of triplet-based materials for organic solar cells. Gao, and co-workers (article number 1900326) present a *Progress Report* on the structural and functional diversity in lead-free perovskite materials. Berggren, Crispin, and co-workers (article number 1805813) present a *Progress Report* on ion–electron coupled functionality in conjugated polymers. Scheblykin and co-workers (article number 1805671) present a review of emerging polarization-microscopy methods for assessing organization and excitation energy transfer in single molecules, and beyond. Müller, Hamedi, and co-workers (article number 1807286) briefly review fiber-based organic electronics ranging from the molecular scale to the mega-scale. Malliaras, Herland and co-workers (article number 1806712) present an overview of biologic functions addressed using organic electronic devices. Bazan, Nilsson, and co-workers (article number 1806701) present a *Progress Report* on conjugated oligoelectrolytes for biosensing and therapeutics. Jaeger, and co-workers (article number 1808210) review conjugated-polymer actuators and devices. Kemerink and co-workers (article number 1806004) present a *Progress Report* on photogenerated charge transport in organic electronic materials. Wang and co-workers (article number 1807019) review donor–acceptor terpolymers for high-efficiency solar cells. Lastly, Pei and co-workers (article number 1807516) present a *Communication* studying stretchable organometal-halide-perovskite quantum-dot light-emitting diodes.

Beside academic ambitions, Olle has contributed to several startup companies including "Micromuscle", developing tools for single-cell manipulation using polymer micromuscles; "BioChromix", developing luminescence biodetection; "Epishine", developing large-scale semitransparent OPVs; and "Ligna Energy" developing wood-based energy-storage devices.

As a concluding remark, we quote Prof. Inganäs on the prospective outlook for the exciting field of organic electronics: "The most important aspect of organic electronic materials is found in energy conversion and storage... The energy payback time for OPV is weeks, rather than the years necessary for silicon. This is the only affordable route to avoid filling the atmosphere with even more carbon dioxide from fossil fuels."