Innovations in Large-Area Electronics Conference

24 - 25 February 2022 Online

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10:00

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- 10.4 **Dr Claudia Delgado Simão, Fundació Eurecat**
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  3D/additive electronics: New methods for new applications?

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  Wireless and wearable humidity sensors with enhanced stability and sensitivity made with water-based hexagonal boron nitride inks
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  Tantalum/silicon multicomponent oxides as gate dielectrics for flexible electronics

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17.20 **Session 15** — Speaker Prize sponsored by Emerson & Renwick and Poster Prize sponsored by ARM & SiSTEM Technologies

1.3 Electronic Skins and the Next- Generation Wearables for Medical Applications

Professor Takao Someya, University of Tokyo

The human skin is a large-area, multi-point, multi-modal, stretchable sensor, which has inspired the development of electronic skin for robots that simultaneously detect pressure and thermal distribution. By improving its conformability, the application of electronic skin has expanded from robots to human bodies reaching a point where ultrathin semiconductor membrane can be directly laminated onto the skin. Such intimate and conformal integration of electronics with the human skin allows continuous monitoring of health conditions for a long time, enabling personalization of medical care. The ultimate goal of the electronic skin is to non-invasively measure human activities under natural conditions, enabling electronic skin and human skin to interactively reinforce each other. In this talk, I will review recent progress in stretchable thin-film electronics for applications to robotics and next-generation wearables and address issues and the future prospect of electronic skin.

Biography

Takao Someya was appointed dean of School of Engineering, the University of Tokyo in 2020, where he has been member of faculty since 1997 and professor since 2009. He also conducted research at Columbia University's Nanocenter and at Bell Labs.

He served on the board of directors of the Material Research Society 2009-2011. He is also Chief Scientist at RIKEN and Team Leader at its Center for Emergent Matter Science since 2015. His expertise is stretchable and organic electronics, developing the world's first stretchable electronic skin for robotic application. He was awarded the 16th Leo Esaki Prize in 2019.

SESSION 2: MANUFACTURING

2.1 Prof Matti Mäntysalo, Tampere University (Invited)

Prof. Matti Mäntysalo received the D.Sc. (Tech.) degree in electrical engineering from the Tampere University of Technology, Tampere, Finland, in 2008. From 2011 to 2012, he was a Visiting Scientist with the iPack Vinn Excellence Center, School of Information and Communication Technology, KTH Royal Institute of Technology, Stockholm, Sweden. He is currently a Professor of Electronics with Tampere University. His current research interests include printed electronics materials, fabrication processes, stretchable electronics, sensors, and the integration of printed electronics with silicon-based technology (hybrid systems). He has published over 100 papers. He is active in IEEE, IEC, and Organic Electronic Association. He was a recipient of the Academy Research Fellow Grant (2015-2020) from the Academy of Finland.

2.2 Dr Firat Güder, Imperial College London (Invited)

Dr Firat Güder is an associate professor in the Department of Bioengineering at Imperial College London. Firat and his team work in the interface of material science, electronics, chemistry and biology, focusing on the development of intelligent interfaces to connect complex chemical and biological systems with machines. Firat is passionate about solving problems concerning animal and human health, agriculture and food systems. In addition to his scholarly activities, he has also co-founded multiple startups to translate his research to address real world problems.

2.3 Ziam Ghaznavi, Emerson & Renwick

Process & Equipment Engineer at E&R Group. PhD student at the University of Texas at Austin

2.4 Dr Filip Granek, XTPL

Filip is the founder and the CEO of XTPL S.A. in Poland - a supplier of advanced technology of ultra-precise dispensing for the fabrication of the next generation electronics. He received his PhD degree from University of Freiburg (Germany) in 2009, and MSc in Electronics from Wroclaw University of Technology (Poland) in 2004. Prior to founding the XTPL in 2015, he was with ECN in the Netherlands and at Fraunhofer ISE in Germany working on R&D in the field of silicon solar cells. He authored over 70 academic publications and over 30 international patent applications in the fields of printed electronics, nanotechnology and photovoltaic solar cells.

2.5 Steve Haws, University of Cambridge

Steve graduated in chemistry from York University and joined GEC's Central Research Laboratory in London. Over 12 years he managed semiconductor R&D/pilot process facility while also researching new processes and devices initially in CMOS/SOS but mostly later in psi AMLCD. The culmination of this was a 1 year project that successfully delivered the largest full colour video psi AMLCD. After an MBA at Durham University a life in business beckoned but one that involved the technical and commercial development of the latest semiconductor and related technologies. He has managed the Ambient Cluster facility for 4 years and this covers all aspects of maintaining and developing an effective R&D platform including maintenance, H&S, training and baseline process development. Very interested in opportunities that further expand industry and external academic participation in the Ambient Cluster.

2.1 Printed Conformable Body-Worn Sensors and Systems for Health Monitoring

Prof Matti Mäntysalo, Tampere University (Invited)

Chronic diseases require a continuing medical care and limits the daily activities of patients. Digital health solutions, such as wearable electronics, enable transition from discrete monitoring to continuous monitoring. The current body-worn sensors and wearable electronic devices, however, are based on miniaturized form of conventional rigid electronics, which leads to bulky form factor and uncomfortable devices that will prevent the adoption of the technology. Unlike traditional electronics, printed intelligence enables fabrication of devices that are thin, flexible, and stretchable, i.e., skin conformable.

This presentation will focus on fabrication of printed conformable body-worn sensors and sensing systems including discussion related to rigid-stretchable interface. Sensor elements are fabricated on soft substrates using inkjet and screen-printing technologies. The performance of printed amplifiers is limited to low-frequencies, and therefore, Flexible Hybrid Electronics approach is used when computation power or high-frequency communication is needed. Reliability of stretchable-rigid interface is one of the key challenges in such cases, and a practical way to address is presented. In addition, pre-amplifiers can be fabricated by printing using organic semiconductors.

2.2 Fabrication of Wearable Sensors with Computerised Embroidery

Dr Firat Güder, Imperial College London (Invited)

The textile industry has advanced processes that allow computerized manufacturing of garments at large volumes with precise visual patterns. The industry, however, is not able to mass fabricate clothes with seamlessly integrated wearable sensors, using its precise methods of fabrication (such as computerized embroidery). This is due to the lack of mechanically robust conductive threads compatible with standard manufacturing methods used in industry. We developed a low-cost poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS)-modified cotton conductive thread (PECOTEX) that is compatible with computerized embroidery. Using PECOTEX and a domestic computerized embroidery machine, we produced a series of wearable electrical sensors including a facemask for monitoring breathing, a t-shirt for monitoring heart activity and textile-based gas sensors for monitoring ammonia as technology demonstrators. PECOTEX has the potential to enable mass manufacturing of new classes of low-cost wearable sensors integrated into everyday clothes.

2.3 R2R Nanofabrication Process for Nanoscale Cu Metal Mesh Transparent Conducting Electrodes

Ziam Ghaznavi, Emerson & Renwick

Authors: Ziam Ghaznavi (1), S.V. Sreenivasan (2), Ovadia Abed (2)
(1) Emerson & Renwick
(2) University of Texas

Transparent conducting electrodes (TCEs) are essential components in many optoelectronic technologies including light-emitting diodes, photovoltaics, and touch screen panels. Transparent conducting oxides, specifically indium-doped tin oxide (ITO), are currently the industry standard TCE material due to their high electrical conductance and optical transparency. However, conventional ITO electrodes are intrinsically brittle, require high-temperature vacuum processing and suffer from fluctuating material costs making them undesirable for future generation devices and incompatible for flexible devices. As a result, alternative TCEs have garnered significant research interest over the past few decades. Metal mesh-based electrodes offer a pragmatic solution to replace ITO for future flexible devices due to their highly tunable electrical and optical properties, low material cost, and inherent mechanical robustness. However, metal mesh TCEs require high-resolution, ultra-large area nanoscale patterning on flexible polymer substrates beyond the capabilities of optical lithography. Moreover, commercial metal mesh electrodes will depend upon high throughput, scalable roll-to-roll (R2R) processing in order to meet the cost needs of the projected markets.

In this work, nanoscale Cu metal mesh electrodes on flexible polycarbonate substrates and rigid quartz substrates are demonstrated using a novel R2R compatible fabrication process employing jet-and-flash nanoimprint lithography (J-FIL), linear ion source etching (LIS) and selective electroless Cu metallization (ECu) using a Pd seed layer. Process step verification details are provided including a morphological study of ECu deposition. Cu grain size is found to be independent of Pd seed layer thickness and plating time in solution, and resistivity of ECu deposited thin films was found to be about 8 times higher than bulk Cu at 13 μΩ cm. Rectangular cross-section trench patterns arranged in a square grid geometry embedded in UV cured imprint resist define the fabricated Cu metal meshes. Two trench dimensions were explored in this work: (i) height of 100 nm, linewidths of 300 nm and pitch of 3 μm, and (ii) height of 100 nm, linewidths of 500 nm and pitch of 5 μm. The flexible metal mesh samples achieved sheet resistances as low as 3.4 Ω/sq. and average transmittances of roughly 50% in the visible spectrum with significant potential for optimization. Comparison of measured spectral transmittance and simulations showed a reduction in broadband transmittance up to 40% due to the sputter-coated 3 nm thick Pd seed layer required to reliably catalyze the ECu reaction. The focus of the experimental work was to use existing J-FIL templates to establish the R2R compatible nanofabrication process. The optimum mesh design to maximize transmission while minimizing sheet resistance was not the focus of experiments. In order to further improve metal mesh TCE performance, a preliminary optimization strategy is proposed to identify optimum mesh geometry given a target application. Optimization results suggest a pitch to linewidth ratio of about 100 and maximize grid line aspect ratio for high transmittance while minimizing for sheet resistance. Simulation and process development insights incorporated in this thesis provide guidance for future research to further refine the proposed R2R compatible fabrication process for and design of flexible metal mesh TCEs.

2.4 Ultra-Precise Deposition: An Additive Manufacturing Process for Large-Area Electronics

Dr Filip Granek, XTPL

Authors: Aneta Wiatrowska (1), Karolina Fiączyk (1), Łukasz (1), Jolanta Gadzalińska (1), Mateusz Łysień (1), Ludovic Schneider (1), Filip Granek (1)
(1) XTPL

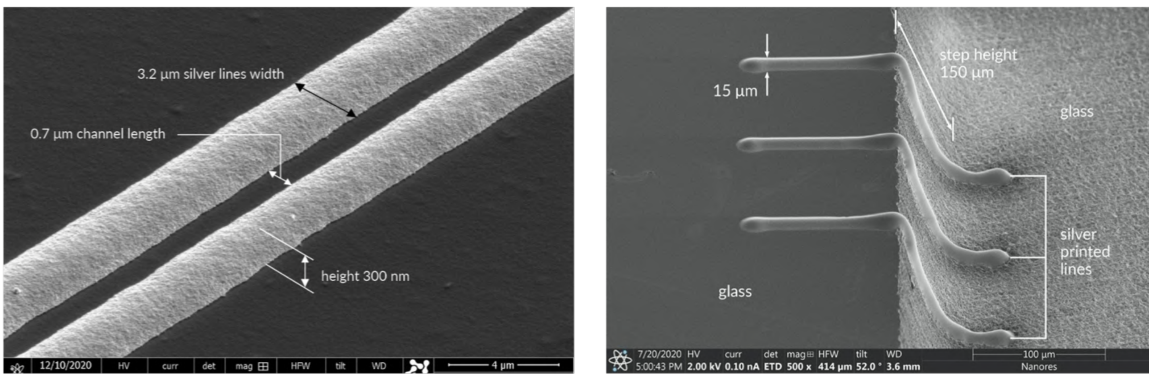
When thinking about fabrication of large-area electronics (LAE) systems, additive manufacturing seems to be an obvious choice: it typically offers high throughput and low cost. Yet, the current trend towards miniaturization of electronic components and devices requires not only efficiency, but also reliability and precision. In this contribution we will discuss how the Ultra-Precise Deposition (UPD) technology can address these seemingly contradictory requirements. In particular, we will focus on current challenges in LAE: integration in flexible hybrid electronics, lean manufacturing, and reliability of LAE systems.

UPD allows maskless deposition of micrometer-size conductive structures on complex substrates: highly-concentrated paste based on metallic nanoparticles (silver or copper) is directly extruded from a nozzle with diameter in the range from 0.5 to 10 µm. This gives the printed feature size from 1 to 10 µm with the electrical conductivity up to 40% of the bulk value. The process itself is governed by pressure, but the possibility to extrude such high-viscosity materials is possible thanks to the simultaneous optimization of the paste, parameters of the process, as well as the printing nozzle (both in terms of the geometry and material properties). The key advantage of using high-viscosity pastes is that regardless of the wetting properties of the substrates, the printed structures preserve their shape and closely map the substrate's topography. These features of UPD significantly simplify the design of metallization schemes in LAE systems.

In our presentation we will demonstrate how UPD can be used in a wide range of applications, including displays, lightning, and energy harvesting devices. To give a flavour of this versatility, we provide a couple of examples. In Figure 1a) we show an example set of silver lines printed on a PEN foil. The line width is 3.2 µm and the interline distance is 0.7 µm. It is important to notice that the lines are clearly separated: the interline distance is kept constant and there are no points of contact, which would result in a short circuit. In Figure 1b) we show a set of continuous silver lines with the width of 15 µm, printed on the steep vertical step with the height of 150 µm. Therefore, the step is ten times higher compared to the line width. Such interconnectors are a mechanically-robust alternative for standard wire bonding techniques. In Figure 2a) we show an empty micro-via with depth of 60 µm and diameter of 150 µm, which is then uniformly filled with a silver paste (85 wt.% of solid content), as shown in Figure 2b). Finally, in Figure 3 we demonstrate the capabilities of the UPD technology for mass production. The figure shows 7500 printed segments for transistors with the line width of 4 µm.

We will argue that UPD brings to the world of large-area electronics both the typical advantages of additive manufacturing, like high throughput and low cost, as well as reliability and precision, paving the way for a widespread use of printed electronics for microfabrication.

Fig 1



a) b)

Fig 2

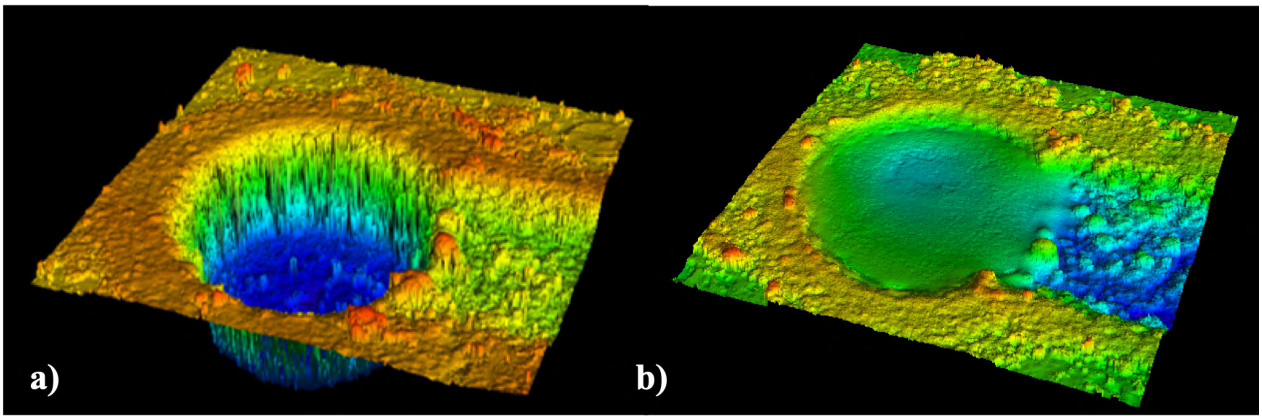
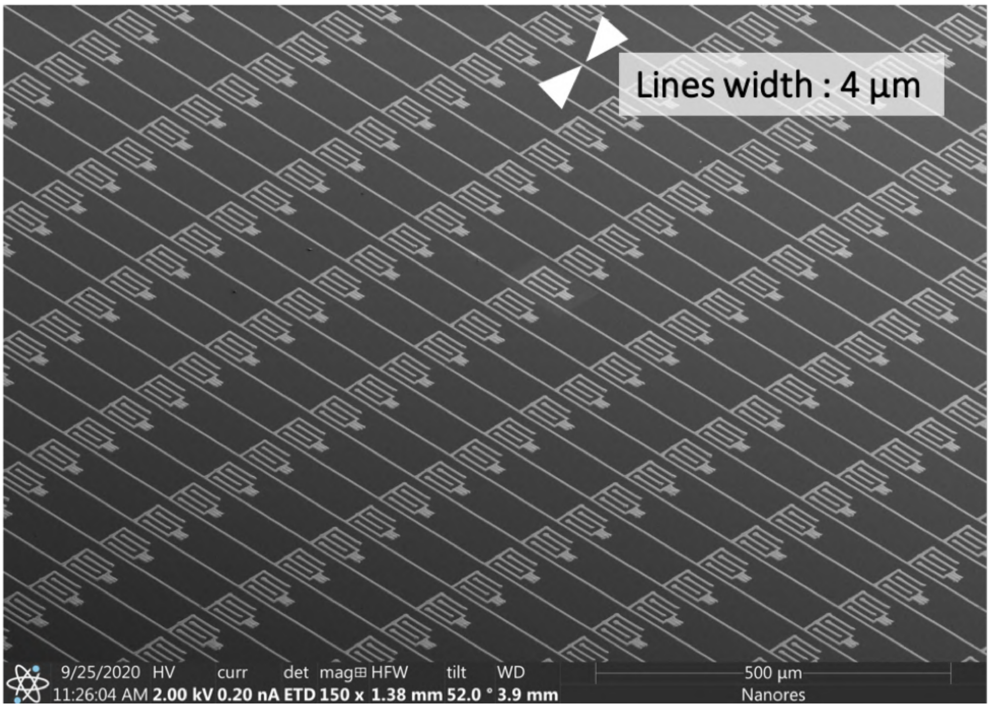

a)
b)

Fig 3


Lines width : 4 µm
9/25/2020 HV curr det mag HFW tilt WD
11:26:04 AM 2.00 kV 0.20 nA ETD 150 x 1.38 mm 52.0 ° 3.9 mm
500 µm
Nanores

2.5 Ambient Processing Cluster Tool

Steve Haws, University of Cambridge

Authors: Steve Haws (1), Henning Sirringhaus (1)
(1) University of Cambridge

In the development of various low temperature LAE materials and device technologies it can often be the case that some or all of the device stack are sensitive to O2 and H2O and requires processing up to encapsulation in a dry inert environment.

As part of the Henry Royce Institute hosted by the University of Cambridge we have set up a uniquely configured ambient processing cluster tool that comprises 11 interconnected process modules for a wide range of deposition methods, such as vacuum evaporation, atomic layer deposition, pulsed laser deposition as well as various printing techniques, which are all under a dry N2 or dry Ar ambient. Through a transfer system samples can be transferred under inert atmosphere between the individual glovebox modules. This enables complete processing finishing with encapsulation without exposure to ambient atmosphere.

The talk will describe the capabilities of the tool and illustrate them with results of various research projects in the areas of organic PV, organic LEDs, perovskite PV, battery materials, artificial photosynthesis and organic electronics.

SESSION 3: BIOELECTRONICS I

3.1 Ana Maiques, Neuroelectrics (Invited)
Ana Maiques is the CEO of Neuroelectrics. She was nominated by IESE as one of the most influential entrepreneurs under 40 in Spain in 2010. She received the EU Prize for Women Innovators from the European Commission EC in 2014. In 2015 & 2016, she was named one of the most inspiring women on the Inspiring Fifty list in Europe. Ana continues breaking the barriers of science and technology in an impactful way with Business Ethics.

3.2 Dr Anna Shirinskaya, Omini Labs (Invited)

3.3 Tomás Pinheiro, CENIMAT, i3N
Tomás Pinheiro received his integrated master's degree in Biomedical Engineering from Nova School of Science and Technology in 2018, with his master thesis developed at i3N|CENIMAT in the area of paper microfluidics and gold nanoparticles applied for plasmonic, colorimetric transduction targeting the development of new diagnostic tools for relevant health markers. Currently, he is a PhD student in the Nanotechnology and Nanoscience program, aiming at the study and application of Laser-induced Graphene for the development of electrochemical biosensors and their translation towards wearable biosensing systems for sweat biochemical monitorization. The main topics of his research consist of the study of laser-induced graphene in sustainable substrates, such as paper, as its application for the development of versatile electrochemical biosensors able to be applied into biosensing systems for diabetes management.

3.4 Prof Dr Jean Manca, Universiteit Hasselt
Prof. Dr. Jean Manca is full professor experimental Physics at Universiteit Hasselt (Belgium). From 2001 to 2014 he was group leader of the research group ONE2 ('Organic and Nanostructured Electronics & Energy Conversion') at the Institute of Materials Research (IMO-IMOMEC) of Universiteit Hasselt and IMEC (Belgium). Jean Manca was a co-founder of the spin-off company LUMOZA on large area printed electroluminescent displays. In 2015 he founded the cross-disciplinary research group "X-LAB" and started with the yearly X-FESTIVAL (www.x-festival.be). Activities of X-LAB involve the cross-disciplinary investigation of (bio-)photovoltaics, photosynthesis, bio-electricity, and the exploration of novel (bio-inspired) concepts/ materials for energy conversion, sensing and next generation electro-optical applications towards a creative and sustainable future on earth and in space.

SESSION 3: BIOELECTRONICS I

3.1 A New Era of Personalized Treatment, Neurotwin: Meet the Digital Copy of Your Brain

Ana Maiques, Neuroelectrics (Invited)

The successful implementation of deeptech could propel a big step forward in the treatment of neurological diseases. "Digital twins" is a term used in industry to describe the development of almost exact replicas of different products for monitoring purposes and add-ons testing. In this presentation we will introduce the concept of personalised hybrid brain models. Using neuroimaging data to build a model that recapitulates the networks and the dynamical landscape of the individual brain.

3.2 Multisensing Platform for Heart Failure Patient Monitoring

Dr Anna Shirinskaya, Omini Labs (Invited)

Talk abstract to be provided

3.3 Paper-based, Laser-Induced Graphene for Bioelectronic Applications and Electrochemical Sensor Production

Tomás Pinheiro, CENIMAT, i3N

Authors: Tomás Pinheiro (1), Sara Silvestre (1), João Coelho (1), Carolina Marques (1), Rodrigo Martins (1), M. Goreti F. Sales, Elvira Fortunato (1)
(1) CENIMAT, i3N, NOVA School of Science and Technology

Laser-Induced Graphene (LIG) has recently established itself as a very attractive material for the fabrication of electrodes for multiple applications, including bioelectronics [1]. Sparked by the discovery of graphene, a 2D material with outstanding electrical and mechanical properties, alternative synthesis techniques, that can complement traditional ones such as chemical vapor deposition (CVD) or wet-chemistry approaches, have been investigated, with LIG showing the possibility for less cumbersome production and patterning of graphenic structures. For LIG synthesis, a laser source, more commonly but not exclusively, a CO2 laser, is focused on a carbon-based, polymeric substrate, inducing a photothermal conversion of the carbon bonds to a 3D, porous graphenic structured film of sp2 hybridized carbon. (Figure 1).

Conventionally, a polyimide (PI) film is used for laser irradiation, allowing for a green, mask-free, one-step approach for both the synthesis of the material and fabrication of active structures. This decreases the burden of synthesis optimization, when compared to conventional techniques, while increasing the flexibility of patterning and fabrication of electronic elements, opening the applicability of LIG for a myriad of applications, ranging from energy harvesting and storage, mechanical actuation and sensing, electronics and more specifically, electrochemical sensor production [2]. Other natural, carbon-based polymers, such as cellulosic materials, can also be used for LIG synthesis, and by harnessing the potentialities of this laser processing technology, naturally sourced LIG, with tuneable compositions, morphologies and conductive properties can be produced and explored for bioelectronic applications. More specifically, common, widely available paper substrate can be successfully applied for the fabrication of LIG electrodes, bringing added value to these mundane substrates and increasing the efficiency, accessibility and flexibility of production for these active electronic elements.

Here, we present the adaptation of the laser irradiation process for LIG production toward the fabrication of paper-based, planar electrodes, targeting electrochemical sensor development [3]. Through an appropriate fire-retardant chemical pre-treatment, LIG was successfully synthesized from both chromatography and office paper substrates, being fully characterized in terms of morphological, chemical and conductive properties, showing sheet resistances as low as 56 Ω sq-1, comparable to LIG films produced from PI. Subsequently, it was successfully applied for patterning of planar electrodes, to produce on-chip, three-electrode electrochemical cells for electrochemical sensing purposes, which were fully characterized in terms of their electrochemical properties by cyclic voltammetry and electrochemical impedance spectroscopy. Electrochemical characterization indicated the applicability of these paper-based LIG cells for tracking of electrochemical reactions, showing an electrochemical active area more than doubling the geometric area, and charge transfer kinetics comparable to LIG electrodes produced from polyimide, with Heterogeneous Electron Transfer (HET) rate constant k0 as high as 7.15 x 10-4 cm s-1. These on-chip cells were subsequently applied for the development of bi-enzymatic glucose sensors, showing good analytical performance for these simple, on-chip glucometers (Figure 2). This paves the way for the development of more sustainable, accessible and alternative electronic devices and elements, with potential application for wearable bioelectronics and flexible electrochemical monitoring systems.

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SESSION 3: BIOELECTRONICS I

Fig 1

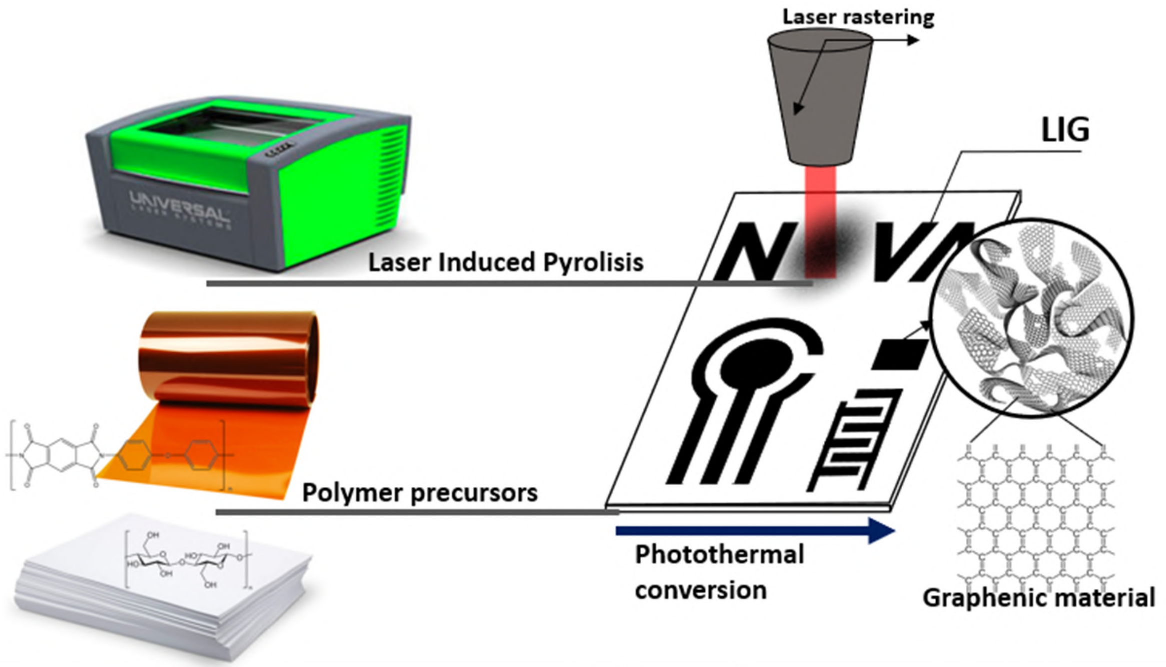

***Fig.1**. Principles for LIG production.*

Fig 2

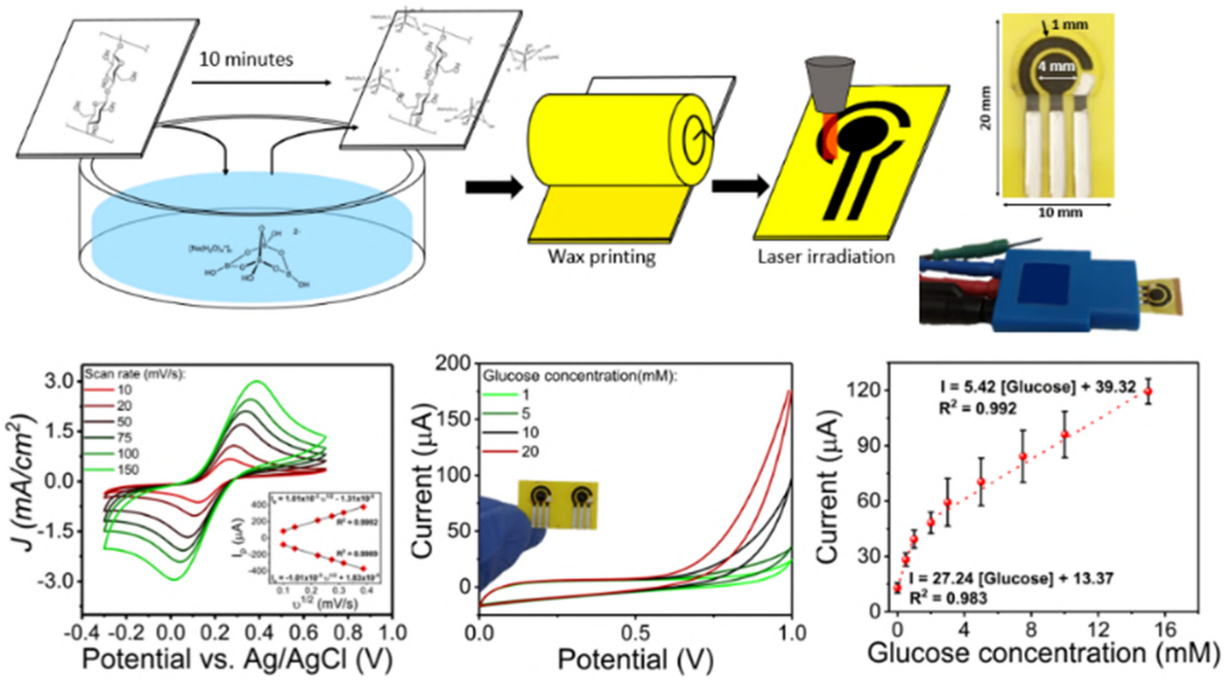

***Fig.2**. LIG on paper applied to electrochemical sensor production.*

3.4 Cable Bacteria : Electrifying 'Bad Guys' with Record Intrinsic Electrical Properties as Biological Electronic Materials

Prof Dr Jean Manca, Universiteit Hasselt

Authors: Jean Manca (1), Robin Bonné (1), Raghavendran Thiruvallur Eachembadi (1), Koen Wouters (1), Roland Valcke (1), Bart Cleuren (1)
(1) Universiteit Hasselt

Cable bacteria, a group of recently discovered filamentous electroactive bacteria, have developed a unique energy metabolism and parallel fibre structures demonstrating electron transport for conduction lengths up to 1 cm and with fibre conductivities exceeding 10 S/cm. Conduction measurements carried out in high vacuum excluded the possibility of ionic conduction, but the fundamental charge transport mechanisms remain unknown. The observed electron transport in cable bacteria over distances in the order of centimeters is unprecedented in the biological world.

Cable bacteria as 'champion living electrical wires' are of fundamental interest to better understand the underlying biological processes, but are also potentially interesting as alternative organic electronic materials for the emerging field of bioelectronics as e.g. biocompatible electrical connections and circuits, conductive composite materials, (nano-) sensors, transistors,...

In order to investigate the intrinsic electrical properties and underlying transport mechanisms, our approach is to study them with a range of solid state electrical characterisation techniques. These activities revealed an unique electrical network architecture and intrinsic electrical properties very similar to for instance organic semiconductors, situating them in the context of electrical functional materials between semiconductors and conductors.

These electrifying 'bad guy' microorganisms – which from various perspectives behave as they are not supposed to – are attracting growing interdisciplinary interest and in the long-term could open novel avenues in emerging domains such as bioelectronics, biodegradable electronics and electronic biological materials (e-biologics).

SiSTEM Technology

At SiSTEM Technology, we offer a wide range of leading edge process tools and ancillaries, automation and consumables to the microelectronics and other high technology industries. Amongst many others, below are a few of the companies we represent, and of particular interest to innoLAE attendees...

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Leading supplier of industrial inkjet printing systems for functional materials. The n.jet inkjet platform is used to produce printed circuit boards, semiconductor components, OLED & QLED displays, sensors, as well as high-precision optical 3D parts. Notion Systems relies on decades of expertise, bringing precise inkjet systems to clients, and scaling up digital printing processes from laboratory to industrial production.

osiris

Photolithography wet process tools used in industries such as semiconductors, micro-OLED, micro-electromechanical systems (MEMS), glass and optical components. Semi-automated and fully automated spin/spray coating, developing, baking or smart EBR. Also, wet cleaning, post CMP clean, etching and metal lift-off. Substrates up to 51" x 51".

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SESSION 4: PANEL DISCUSSION

4.1 Panel Discussion: Towards Next Generation Wearable Devices

Chaired by Dr Luigi Occhipinti, University of Cambridge

Panellists:

Dr Feras Alkhalil, Principal Scientist and Director of R&D, PragmatIC

Dr Claudia Delgado Simao, Senior Researcher, Eurecat - Centre Tecnologic de Catalunya

Dr Wim Christiaens, R&D Director, Quad Industries

Prof Danilo Mandic, Professor of Signal Processing, Imperial College London

SESSION 5: KEYNOTE

5.2 Electronic Skins and the Next- Generation Wearables for Medical Applications

Prof John Rogers, Northwestern University

Over the last decade, a convergence of new concepts in materials science, mechanical engineering, electrical engineering and advanced manufacturing has led to the emergence of diverse classes of 'biocompatible' electronic technologies with physical properties matched to soft biological tissues. This talk describes the key ideas and presents some of the most recent examples in skin-interfaced systems, including (1) wireless, battery-free devices that can continuously measure traditional vital signs and advanced metrics of health, with applications in monitoring the status of premature babies and in tracking the symptoms of COVID-19, and (2) microfluidics-enabled electronic platforms that can capture, manipulate and perform biomarker analysis on microliter volumes of sweat, with uses in athletic performance and worker safety.

Biography

Professor John A. Rogers obtained BA and BS degrees in chemistry and in physics from the University of Texas, Austin, in 1989. From MIT, he received SM degrees in physics and in chemistry in 1992 and the PhD degree in physical chemistry in 1995. From 1995 to 1997, Rogers was a Junior Fellow in the Harvard University Society of Fellows. He joined Bell Laboratories as a Member of Technical Staff in the Condensed Matter Physics Research Department in 1997, and served as Director of this department from the end of 2000 to 2002. He then spent thirteen years on the faculty at University of Illinois, most recently as the Swanlund Chair Professor and Director of the Seitz Materials Research Laboratory. In the Fall of 2016, he joined Northwestern University as the Louis Simpson and Kimberly Querrey Professor of Materials Science and Engineering, Biomedical Engineering and Medicine, with affiliate appointments in Mechanical Engineering, Electrical and Computer Engineering and Chemistry, where he is also Director of the recently endowed Querrey-Simpson Institute for Bioelectronics. His research has been recognized by many awards, including a MacArthur Fellowship (2009), the Lemelson-MIT Prize (2011), the Smithsonian Award for American Ingenuity (2013), the Benjamin Franklin Medal (2019) and a Guggenheim Fellowship (2021). He is a member of the National Academy of Engineering, the National Academy of Sciences, the National Academy of Medicine, the National Academy of Inventors and the American Academy of Arts and Sciences.

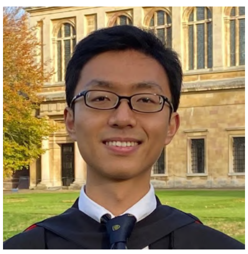
SESSION 6: NOVEL DEVICES & SYSTEMS I

6.1 Prof Oana Jurchescu, Wake Forest University (Invited)
Oana D. Jurchescu is a Baker Professor in the Physics Department at Wake Forest University (WFU) USA and a Fellow of the Royal Society of Chemistry (FRSC). She received her PhD in 2006 from University of Groningen, the Netherlands, and was a postdoctoral researcher at the National Institute of Standards and Technology in Gaithersburg, MD, USA, until 2009, when she joined the WFU as an Assistant professor. Her expertise is in charge transport in organic and organic/inorganic hybrid semiconductors, device physics and semiconductor processing. She won the National Science Foundation CAREER award, the ORAU Ralph E. Powe Junior Faculty Enhancement award, the WFU award for excellence in research, the WFU innovation award, the WFU prize for excellence in teaching and the WFU award for excellence in mentoring.

6.2 Prof Frederik Krebs, infinityPV (Invited)
Frederik C. Krebs has an extensive and prolific scientific track (1993-2017) with many hundreds of publications, patents, books and conferences contributions . In 2017 he left academia in pursuit of commercializing printed solar cell technology and today he holds the position of CEO at infinityPV. While no public measure of his scientific output is accessible, the focus that the absence of obligations for public communication grants, has increased the level of research that has been carried out and progressed the technology further than what would have been possible in a Danish academic environment.

6.3 Dr (Sam) Yun Fu Chan, CPI
Dr. (Sam) Yun Fu Chan (PhD in Chemistry, University of Reading) is a Principal Scientist at CPI. He has over 15 years of industrial experience and has extensive expertise in Optoelectronics such as OLEDs, LECs, OTFTs, Device Integration for display application, OPV and ALD Barrier Coating, as well as Laser processing and Lithium ion Battery. A post-doctoral researcher (University of Reading), he furthered development of novel electronically-conducting materials with potential applications as "molecular wires". As a Synthetic Inorganic Chemist for OLED-T Ltd, he invented novel electroluminescent OLED materials. He was also a Materials Chemist at Polymertronics Ltd where he scaled-up and optimised OLED devices used for the treatment of skin cancer.

6.4 Jeroen Hustings, Universiteit Hasselt
A passionate researcher, Jeroen is active at the UHasselt as a PhD student in the interdisciplinary research group X-LAB. Motivated to work on a cleaner and sustainable future, his work focuses on renewable energy. After having completed his master's degree in nuclear physics at the KU Leuven in 2018, he found his calling in the study of solar cell devices, in particular performing degradation and stabilization studies on dye-sensitized solar cells. He spends most of his days in the lab where he specializes in optical techniques to investigate the complex bleaching mechanisms of these devices.



6.5 Dr (Andy) Wenyu Wang, University of Cambridge
Dr Wenyu Wang, Andy is currently a research associate in the Department of Engineering in Cambridge University, his research focuses on biological and electronic material processing and analytics.

6.1 RAD-OFETs: Large-Area, Tissue-Equivalent, Radiation Dosimeters Based on Organic Transistors

Prof Oana Jurchescu, Wake Forest University (Invited)

Radiation therapy is an effective medical procedure for cancer treatment that relies on the fact that high-energy ionising radiation can destroy cancer cells. Nevertheless, the risks of malignancies induced by peripheral radiation in healthy tissues surrounding the target volumes represents a serious concern for all patients and doctors alike. Positioning of the patient, inhomogeneities in the target (muscles/bones/adipose tissue), and even minor movements (e.g. breathing), can alter the received dose and targeted volume, and thus affect the outcome of the procedure. Therefore, being able to measure radiation doses with high accuracy and in real time is a critical aspect of diagnostics and treatment. In this presentation I will introduce a new type of radiation dosimeter, the RAD-OFET (Radiation Detector based on Organic Field-Effect Transistor), which can validate in real time the dose being delivered and ensure that for nearby regions an acceptable level of low dose is being received.

The RAD-OFETs exploit trap generation/annihilation in organic semiconductors, are sensitive to doses relevant to many radiation treatment procedures and are robust when incorporated into conformal large-area electronic applications. Placement of the sensor directly onto the human body, coupled with the similarity in the Z-number between the electronically active layer and the human tissue, allows for direct measurement of the radiation dose, eliminating the need for extensive data processing faced by current technologies. The direct consequence is a greater precision and lower complexity in the medical equipment: their adoption in clinical settings will facilitate the application of therapeutic radiation with high precision, a process that will increase the effectiveness on treating cancerous tissue and minimise the impact on the surrounding healthy cells. These results uncover new opportunities for organic circuits that will improve the quality of healthcare through better, lower cost in vivo dose monitoring during radiation therapy.

6.2 Seeing Solar as it Rolls By

Prof Frederik Krebs, infinityPV (Invited)

The most scalable and fastest method to manufacture large surfaces is by using roll-to-roll processing methods. Functional films such as solar cells requires many technical developments in areas ranging from chemistry, through inks, application methods, quality control and post processing. To harvest the fruits of the vast potential that the roll-to-roll world offer one needs availability of materials, machines and testing. The bridge is the machines that can do it. This talk will focus on just that bridge between the desired end product and the scientific concepts that grants it.

6.3 Direct Printed Battery-on-Flexible Circuit Boards for Smart Device Applications (POETICS Project)

Dr (Sam) Yun Fu Chan, CPI

Authors: (Sam) Yun Fu Chan (1), Paolo Melgari (1), Robert Douglas (1), Andrew Graham (1), Aimee Wyatt (1), Jon Gowdy (1), Ian Manfren (1), Amponsah Kyeremateng(1), Brian Krejcarek(2)
(1) Centre for Process Innovation Ltd, United Kingdom
(2) Reelables Europe Limited

All data generating devices require a power source. In the field of asset tracking, the solutions on the market require extensive work or are very expensive to use and install. The simplest options are either barcode solutions which require manual scanning or RFID tracking by installing high power antennas in the warehouse ceiling or doorway to implement the data collection without using manual scanners. An alternative expensive method is active tracking devices using Bluetooth, WiFi, or carrier networks, and are heavily burdened by the cost structure and physical geometry of current battery technologies.1,2

CPI have been working with partners including Reelables in the Innovate UK POETICS project to develop a new approach to manufacture direct printed battery-on-flexible circuit boards for smart device applications. Reelables has invented a smart label to make tracking things at work completely automatic. It simply peels and sticks like a barcode label and coupling their unique software enable tracking of day-to-day items at any moment. This feasibility study investigated the innovative methodology in manufacturing process to form a battery directly alongside a wireless circuit on a thin plastic film in batch scale, transferring the key learnings to roll-to-roll process with an aim to reduce the manufacturing cost of the smart devices.

In this paper we summarise the novel process of thermal evaporation of a Lithium metal anode on copper current collector developed in-house at CPI. This was combined with the coating of a formulated cathodic battery slurry directly onto current collector on a dissimilar plastic substrate, direct printed battery pouch cells were assembled, and fully charged and tested. Working direct printed battery-on-flexible circuit boards of smart device demonstrator were produced and tested for functionality.

References
[1] D. Miorandi, S. Sicari, F. De Pellegrini, and I. Chlamtac, Ad Hoc Netw., 10(7), 1497 (2012).
[2] A. Raj, D. Steingart, J. Electrochem. Soc., 165, B3130 (2018)

Acknowledgement – The authors We acknowledge financial support from Innovate UK under grant No. 105735, POETICS

6.4 Photovoltaic Photographs - Blending 'The Power of Beauty' and 'The Beauty of Solar Power'

Jeroen Hustings, Universiteit Hasselt

Authors: Jean Manca (1), Jeroen Hustings (1), Kristof Vrancken (2), Rob Cornelissen (3), Roland Valcke (1), Nico Fransaert,
(1) Universiteit Hasselt
(2) LUCA School of Arts
(3) POM Limburg

In the field of photovoltaics (PV), an important trend and technological challenge is to increase the aesthetic and creative design aspects of solar cells towards more attractive and customized devices for integration in for instance architecture (e.g. Building Integrated Photovoltaics BIPV). Recent evolutions in this domain are mainly situated in the class of emerging PV such as organic solar cells (OPV), dye sensitized solar cells (DSSC) and perovskite solar cells. These solar cell technologies provide additional degrees of design freedom, as in principle they can be processed by printing and allow the realization of semi-transparent solar cells and the use of various colors. So far however, these activities have been limited to the realization of uniform photovoltaic films with no or little attention to patterned devices.

We present a novel technique that allows for the direct one-step transfer of an image into a DSSC device. This work demonstrates a DSSC fabrication procedure going one step beyond inkjet-printed anodes by integrating a photograph directly onto the photoactive layer through selective bleaching of the dye stained photoanode of a DSSC which results in a "photovoltaic photograph". The process in inspired by the ancient technique of anthotype photography. In this way, any image can be monochromatically displayed at high special resolution. The procedure proves to be inexpensive and easy to integrate into the existing production line without disturbing other processes. Proof-of-principle demonstrators have been prepared using both synthetic and natural dyes (e.g. anthocyanins), the latter being readily available, low cost and biocompatible. Since the technique consist of a one-step photoinduced patterning process, the production time is independent of solar cell size which is a unique benefit towards large-area PV devices. Current prototypes are on the scale of 10 by 10 cm, but can be upscaled to sizes compatible for BIPV applications.

Starting from this proof-of-principle demonstrator, within X-LAB we are further exploring in a cross-disciplinary manner how photographic processes could be combined with other PV technologies to enhance the aesthetic and creative possibilities of solar cells - blending 'the power of beauty' and 'the beauty of solar power'...

6.5 Conducting Fibre Printing Towards 3D Sensing Architectures and Bio-Interface Devices

Dr (Andy) Wenyu Wang, University of Cambridge

Fibrous structures and materials widely exist in nature and have played an important role in our daily life and industry. Thanks to the high aspect ratio, low bending stiffness, flexibility and transparency, fibres possess unique physical and optical properties that are usually inaccessible with conventional planer structures. Combining with functional materials and polymers, such as piezoelectric, conducting polymers and biocompatible materials, novel fibre-based devices and textiles could open up possibilities for emerging applications. Such prospects could range from transparent textile-based sensors to biointerfacing architectures. However, challenges largely remain with the current fibre fabrication techniques, in which the synthesised fibres are usually deposited to a surface substrate. Thus, the optomechanical properties of the planer substrates would largely compromise the advantageous properties of the fibres. Moreover, conventional fibre printing techniques usually suffer from inefficient functional material usage (e.g. blending functional material with passive polymer), and this could lead to an overall reduced performance in the final products.

Herein, we present two original fibre printing techniques, which are especially developed to efficiently print substrate-free functional fibres with different fibre dimensions and applications. First, the dynamic near-field electrospinning is developed to fabricate in situ poled piezoelectric nanofiber mesh, with high visible light transparency (> 97%) and air permissiveness. Such suspended nanofibre mesh harnesses the physical merits of spider web in its high acoustic sensing ability and broad active bandwidth. Combined with piezoelectric polymers, such spider-web inspired acoustic sensor has a broad sensitivity bandwidth covering 200–5000 Hz at hearing-safe sound pressure levels. Second, inflight fluidic fibre printing, which integrates conducting fibre production and fibre-to-circuit connection in a single step is developed to produce metallic (silver) or organic (PEDOT:PSS) fibres with 1-3 μm diameter. Using PEDOT:PSS fibres as a cell-interfaced impedimetric sensor and a moisture sensor, we show that even a single fibre component can achieve complex functions or outperform conventional film-based devices. The capability to design suspended fibres and networks of homo-, hetero-cross-junctions, paves the way to applications including flow-permissive devices, and 3D optoelectronic and sensor architectures. Overall, we demonstrate the versatility and scalability of novel fibre printing methods that could pave way for the next-generation fibre-based devices that could fully harness the potential of the physical merits of fibres and the functional performances of advanced materials.

SESSION 7: BIOELECTRONICS II

7.1 Dr Francesca Santoro, IIT (Invited)

Francesca Santoro received her Bachelor's and Master's degrees in Biomedical Engineering at the 'Federico II' University of Naples (Italy). She received a PhD in 2014 in Electrical Engineering and Information Technology in a joint partnership between the RWTH Aachen & the Forschungszentrum Juelich (Germany). In 2014, she joined the Chemistry Department at Stanford University (USA) and received a research fellowship in 2016 by the Heart Rhythm Society. She joined IIT in July 2017 and as Principal Investigator of the 'Tissue Electronics' lab. In 2018 she has been awarded the MIT Technology Review Under 35 Innovator ITALIA and EUROPE and the 'Premio Italia Giovane'. In 2019 she was included in the list of '100 women who are changing the world' and among the 50 Italians running as women of the year by the national newspaper 'La Repubblica'. She has been awarded an ERC Starting Grant in 2020. She is among the Inspiring Fifty Italy and is also the winner of the Falling Walls Science Breakthrough of the Year in Engineering and Technology in 2021. Since January 2022 she is Professor and head of the in Neuroelectronic Interface Lab (NEI) at RWTH Aachen and FZJ Juelich.

7.2 Dr Paschalis Gkoupidenis, Max Planck Institute for Polymer Research (Invited)

Paschalis Gkoupidenis has a BSc in Physics from the University of Ioannina (2005), an MSc in Microelectronics from the University of Athens (2007) and a PhD in Materials Science from NCSR "Demokritos", Athens, Greece (2014). During his PhD, his research focused on ionic transport mechanisms of organic electrolytes. In 2015 he started his postdoc at the Department of Bioelectronics (EMSE, France), where, he worked on the design and development of organic neuromorphic devices based on electrochemical concepts. In 2017, Gkoupidenis joined the Max Planck Institute for Polymer Research (MPIP, Mainz, Germany), and he is currently a Group Leader at the Department of Molecular Electronics. The research in his group focuses on the field of Organic Neuromorphic Electronics.

7.3 Liam Johnson, University of Manchester

Liam is a PhD candidate enrolled with Advanced Biomedical Materials Centre for Doctoral Training at the University of Manchester. His interests lie in the growing field of bioelectronics, where he has experience developing interfacing materials for both implantable and non-invasive devices which monitor the heart and brain. Currently he works within Manchester's Non-invasive Bioelectonic Systems lab developing flexible, skin-integrated sensing devices which monitor the body's vital signs and refine pre-clinical research. Here his research applies large area manufacturing techniques such as screen printing to develop cost-effective biosensors, and aims to explore novel materials which enable mechanically compliant form factors that better interface with dynamic biological surfaces.

7.4 Lawrence Coles, University of Cambridge

Lawrence Coles is a Sensor CDT PhD student working in the Bionic Systems group at the University of Cambridge, under the supervision of Dr. Christopher Proctor and Dr. Damiano Barone. His current project focuses on the development of minimally invasive neural implants for cortical recording. He also has a MEng in Electrical and Electronic Engineering from the University of Southampton.

7.5 Dr Leslie Askew, University of Surrey

The primary focus of our group is to develop an artificial retina from both synthetic carbon conjugated materials and naturally-occurring dyes.

SESSION 7: BIOELECTRONICS II

7.1 In Vitro Biomimetic Electronics

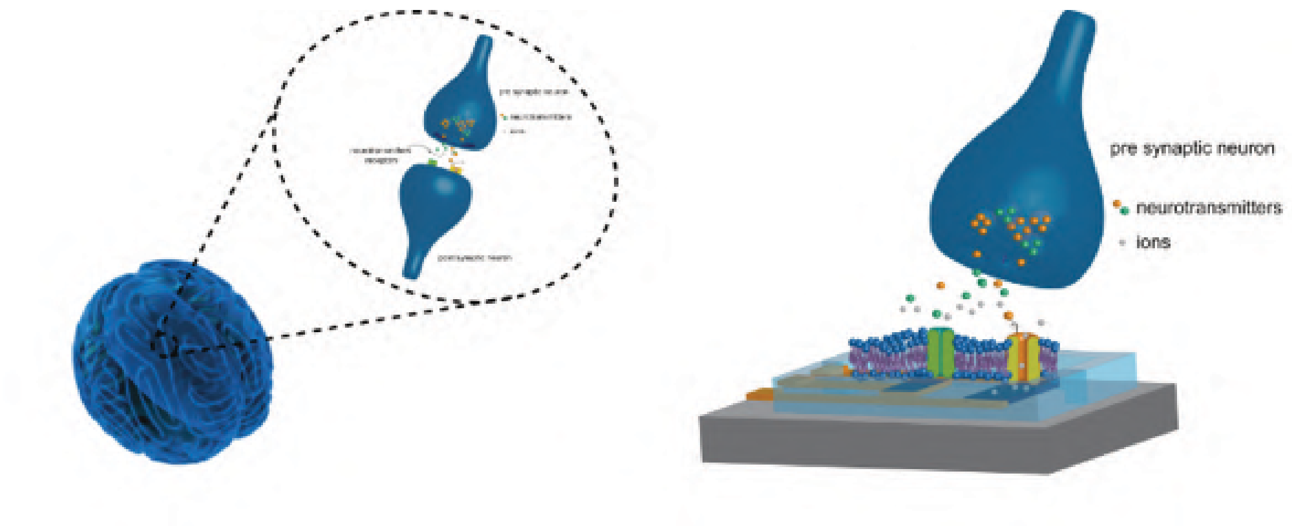
Dr Francesca Santoro, IIT (Invited) (1, 2, 3)

(1) IIT
(2)Faculty of Electrical Engineering and IT, RWTH Aachen
(3) Institute of Biological Information Processing – BioElectronics , IBI-3, Forschungszentrum Juelich

The interface between biological cells and non-biological materials has profound influences on cellular activities, chronic tissue responses, and ultimately the success of medical implants and bioelectronic devices. The optimal coupling between cells, i.e. neurons, and materials is mainly based on surface interaction, electrical communication and sensing.

In the last years, many efforts have been devoted to the engineering of materials to recapitulate both the environment (i.e. dimensionality, curvature, dynamicity) and the functionalities (i.e. long and short term plasticity) of the neuronal tissue to ensure a better integration of the bioelectronic platform and cells.

On the one hand, here we explore how the transition from planar to pseudo-3D nanopatterned inorganic and organic materials have introduced a new strategy of integrating bioelectronic platforms with biological cells under static and dynamic conditions.. On the other hand, we investigate how organic semiconductors can be exploited for recapitulating electrical neuronal functions such as long term and short term potentiation. In this way, both the topology and the material functionalities can be exploited for achieving in vitro biohybrid platforms for neuronal network interfacing.



7.2 Organic Neuromorphic Electronics: Bio-Inspired Functions and Sensorimotor Learning in Robotics

Dr Paschalis Gkoupidenis, Max Planck Institute for Polymer Research (Invited)

Artificial intelligence applications have demonstrated their enormous potential for complex processing over the last decade. However, they are mainly based on digital operating principles while being part of an analogue world. Moreover, they still lack the efficiency and computing capacity of biological systems. Neuromorphic electronics emulate the analogue information processing of biological nervous systems. Neuromorphic electronics based on organic materials have the ability to emulate efficiently and with fidelity a wide range of bio-inspired functions including synaptic plasticity, homeostasis and spatiotemporal phenomena. In this work we present a path planning robot that uses a small-scale, locally-trained organic neuromorphic circuit to navigate through a maze. The neuromorphic circuit responds and adapts to environmental stimuli directly, as it is integrated with the robot's sensorimotor system. The on-chip integration of sensorimotor signals together with the unconventional form factors of organic neuromorphic electronics paves the way toward stand-alone, brain-inspired computing circuitry in autonomous and intelligent systems. Novel platforms for rapid prototyping and education, at the intersection of materials science and robotics, are also expected to emerge.

7.3 Screen Printed, Non-Invasive Electrophysiology Probes for the Mouse Model

Liam Johnson, University of Manchester

Authors: Liam Johnson (1), Prof. David A. Bechtold (1), Dr. Alexander J. Casson (1)
(1) University of Manchester

Flexible, skin-compliant sensors are finding many uses in human healthcare for long-term monitoring of physiological parameters. Their emergence can be attributed to advances in large-area manufacturing, such as screen printing, which enable the incorporation of functional materials into soft, compliant substrates which readily interface with the human body. There is now a substantial opportunity for using similar flexible electronics approaches for interfacing with animals. Preclinical research utilising transgenic mouse models relies on electrophysiology monitoring, and has been instrumental in advancing our understanding of cardiovascular disease, muscular dystrophy, and neurological disorders. However, current monitoring tools for mice are rigid and unsuitable for conscious free-moving animals, or require invasive implantation which burden the animal. For example, the gold-standard for electrocardiogram (ECG) collection in free-moving mice requires surgical placement of a device weighing up to 20% the animal's body weight, and involves a 2-week recovery period.

This work investigates flexible, on-skin sensors for mice, which could refine experimental design by progressing a non-invasive alternative for recording electrophysiology in rodents. We designed three screen printed silver/silver-chloride ECG probes. Two were fabricated by printing Ag/AgCl onto a 25 μm thick polyethylene naphthalate (PEN) substrate, attached to mouse skin using either conductive electrophysiology paste or an adhesive polyurethane (PU) backing; while a third variation was printed on temporary tattoo paper (Fig. 1). Each design was electrically characterised, in which skin-contact impedance was modelled by recording the interface's frequency response when attached to depilated mouse skin. Subsequently, the ability of each design to record ECG signals from unconscious mice was assessed in comparison to gold-standard needle electrodes.

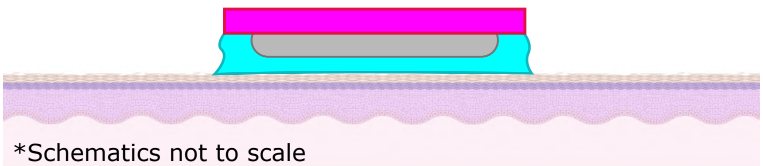
Impedance analysis found conductive paste electrodes had substantially lower skin-contact impedance at the lower frequencies relevant to electrophysiology. For instance, at 10 Hz paste interfaces averaged a contact impedance of 5.84±1.37 (std err.) kΩ, while PU backed and tattoo electrodes averaged 74.9±25.1 kΩ and 142±46.4 kΩ respectively. Models created using impedance sweep data suggest this is the result of a resistive connection facilitated by the paste, contrasting to the capacitive connection modelled in the other probes (Fig. 2). Analysis of ECG signals acquired from mice demonstrated that all designs were able to collect signals with discernible waveform features (P-Q-R-S-J), which are essential for advanced analysis (Fig. 3). Furthermore, comparing the signal-to-noise-ratio (SNR) of collected ECGs revealed PU backed electrodes were least noisy (37–39.2 dB), outperformed only by the needle electrode gold-standard (39.9–42.3 dB). Whereas the conductive paste (35.4–35.7 dB) and tattoo electrodes (34.4–35.7 dB) resulted in comparable levels of noise.

This data affirms that capacitively coupled electrodes offer a viable means of recording larger electrophysiological signals within mice, such as ECG. Although conductive paste provides better admittance via a resistive connection, its long-term utility is limited by poor physical attachment, leaving the probe vulnerable to dislodgment. In contrast, temporary tattoo probes offer highly conformal attachment to the mouse's skin, whilst introducing minimal somatosensory irritation to the animal. Future experiments should investigate material durability when attached to free-moving mice, and explore plausible solutions to challenges including fur regrowth and grooming behaviour.

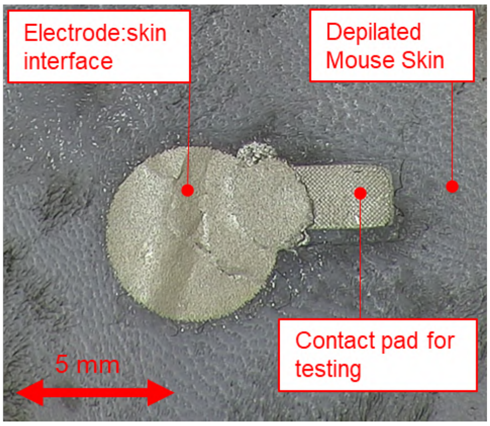
Figure 1. Screen Printed Ag/AgCl Electrodes Interfacing with Depilated Mouse Skin

A) Temporary Tattoo Electrode

Interface Schematic

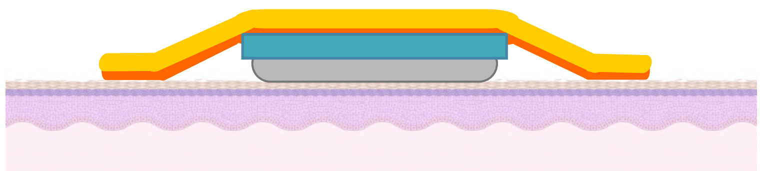


- Temporary tattoo paper substrate
- Printed silver/silver-chloride
- Temporary tattoo adhesive (polyvinyl acetate)

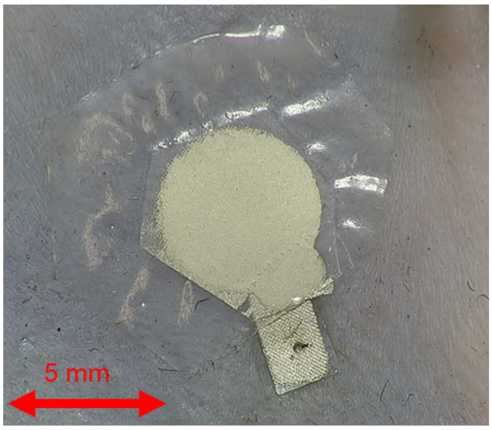


B) Adhesive Polyurethane (PU) Backed Electrode

Interface Schematic

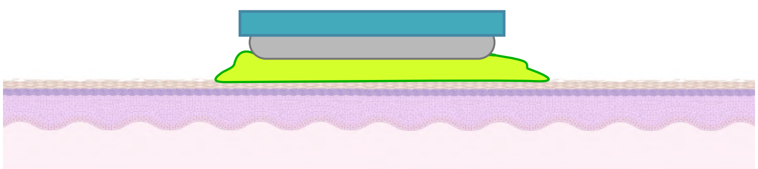


- Polyurethane film
- Biocompatible adhesive layer
- 25μm thick polyethylene naphthalate (PEN)
- Printed silver/silver-chloride



C) Conductive Paste Electrode

Interface Schematic



- 25μm thick polyethylene naphthalate (PEN)
- Printed silver/silver-chloride
- Conductive electrophysiology paste

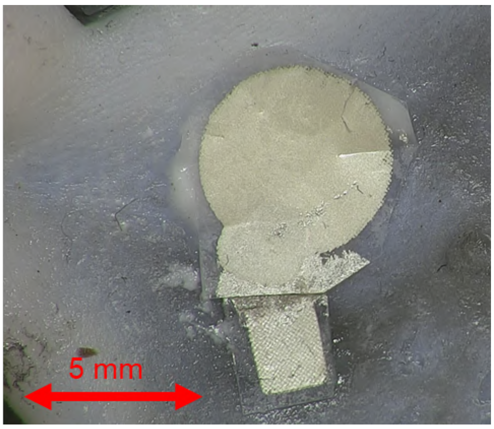
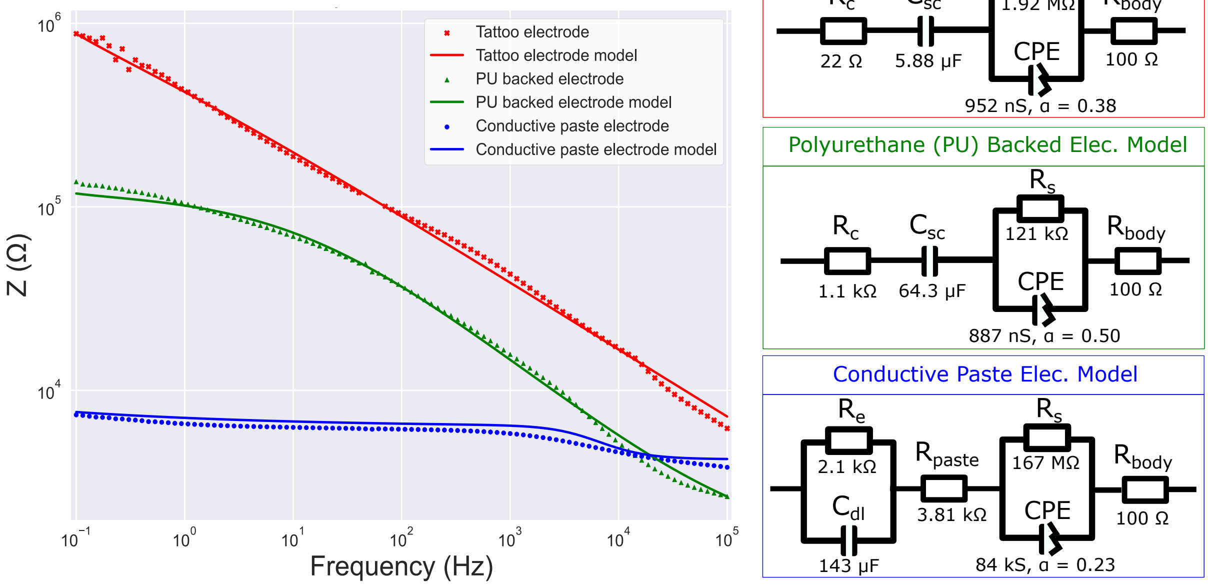
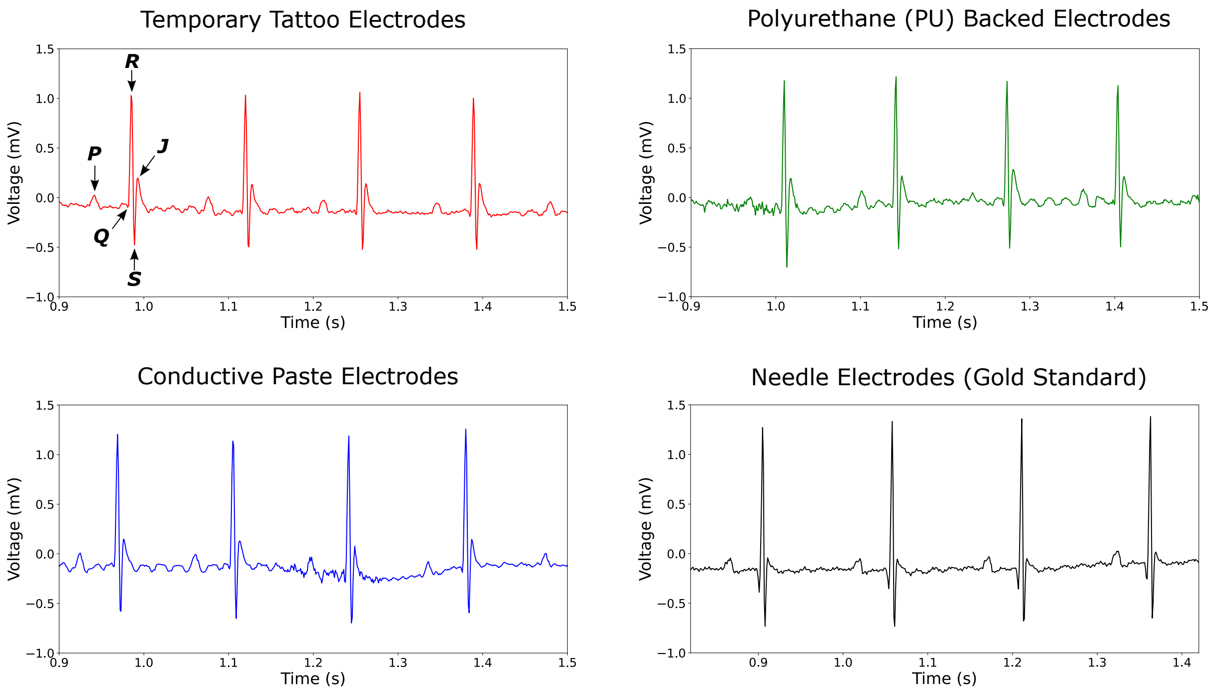


Figure 2. Electrical Characterisation and Modelling of Printed Electrodes on Mouse Skin



C_{sc}	= Electrode: skin capacitive coupling	R_e	= Faradaic charge transfer
CPE	= Constant phase element for skin surface capacitance	R_s	= Skin surface conductivity
C_{dl}	= Double layer capacitance at Ag/AgCl: paste interface	R_{paste}	= Conductive paste resistance
R_c	= Resistivity of the electrode connection	R_{body}	= Epidermal tissue resistance

Figure 3. Mouse Electrocardiograms Acquired Using Printed Interfaces



7.4 Large Area Bioelectronics with Shape Actuation for Minimally-Invasive Electrocorticography

Lawrence Coles, University of Cambridge

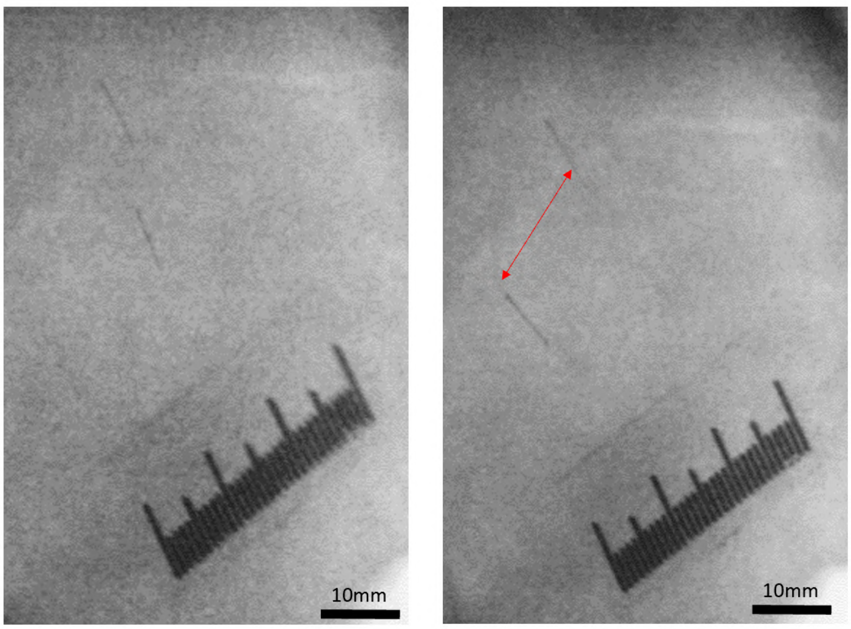
Authors: Lawrence Coles (1), Damiano Barone (1), Christopher Proctor (1)
(1) University of Cambridge

The development of innovative neural interface devices would allow for novel approaches to diagnose, monitor, and treat neurological conditions and impaired neural-mediated motor function. Electrocorticography (ECoG) is an implanted neural interface technique that has been developed to record brain activity using large area electronic arrays placed on the cortical surface and is used as a diagnostic tool in Epilepsy and Parkinson's monitoring, and brain-computer interfaces for prosthesis control. There has been extensive investigation into flexible ECoG devices, with a variety of substrate materials and electrode designs, however, the implantation of these devices is very invasive due to the size of craniotomy required.

This project aims to design flexible ECoG neural implants that can be implanted with minimally invasive surgical techniques, whilst still retaining the large area mapping and spatial resolution of existing ECoG technologies. We are currently developing a microfluidics-based soft-robotic ECoG design that would allow us to deploy a rolled thin-film ECoG with a small burr-hole craniotomy onto the cortical surface, before deploying the full large bioelectronic array onto the cortex using fluidic actuation. Soft-robotic technologies in implants is an emerging field, applying the use of soft-materials in actuators to allow the shape actuation of implant devices, whilst also allowing large bioelectronic arrays to mechanically match the surrounding soft environment of human tissue.

The ECoG designs were tested in human cadaveric models, demonstrating that soft-robotic technologies would be a feasible approach for delivering larger ECoG designs to the cortical surface with a burr-hole craniotomy. By reducing the invasiveness of flexible ECoG sensors, it allows for the reduction of both surgical risk and cost, increasing the availability of these sensors for clinical applications.

Figure 1. X-ray imaging of a the shape-changing ECoG devices implanted subdurally in a human cadaveric model. X-ray opaque markers track the fluidic driven expansion of the device from rolled to deployed post-implantation.



7.5 Interlayer Effects in Organic Semiconductor Layered Systems in Optoelectronic Prosthetic Prototype

Dr Leslie Askew, University of Surrey

Authors: Dr Leslie Askew (1), Dr Maxim Shkunov (1), Aimee Sweeney (1)
(1) University of Surrey

Photosensitive organic semiconductor materials designed as active layers in a bioelectronic device provide an effective means to stimulate cells, in our case with a particular focus on neuronal stimulation in retinal prosthetics. Yet the nature of the resulting charge transfer mechanism has implications for the efficacy of such a device. Here, we present a set of interlayers that can be used to control both the polarity at the active interface, and the optoelectronic transduction process between the active layer and the electrolyte, be it faradaic or capacitive. To this end, each of four thiophene-based materials developed to simulate the four human photoreceptors (1) was interfaced with a range of metal oxide interlayers that have favourable energy levels chosen to maximise charge at the working electrode. Our results demonstrate that the addition of interlayers can control the charge species at the working electrode and enhance photocurrent magnitude, both of which make the use of interlayers a critical component in the development of a full-colour retinal prosthetic solution.

(1) Shkunov, M., et al. (2021). "Pixelated full-colour small molecule semiconductor devices towards artificial retinas." Journal of Materials Chemistry C 9(18): 5858-5867.

SESSION 8: PANEL DISCUSSION

8.1 Panel Discussion: Power Sources for Flexible Hybrid Electronic Systems – Printed Batteries and Energy Harvesting

Chaired by Dr Simon Johnson, CPI

Panellists:

Prof Steve Beeby, RAEng Chair in Emerging Technologies, University of Southampton

Dr Pritesh Hiralal, Co-founder and CEO, Zinergy UK LTD

Dr Neil Chilton, Technical Director, Printed Electronics Limited

Paolo Melgari, Principal Scientist, CPI

9.2 PlasticARM: Challenges of TFT VLSI on a Flexible Substrate

John Biggs, arm

The projected market for the Internet of Things (IoT) is vast with some predicting an installed base of over 25Bn "things" by 2030 (Statista). However, this opportunity also presents some significant challenges to the silicon-based electronics industry, such as design cost, NRE and form factor, which can perhaps be more easily met by flexible ICs.

PlasticARM is a "blue sky" research project that is looking into the viability of building very cheap (disposable?) Arm-based microcontrollers using state of the art thin-film transistors on a flexible plastic substrate.

This presentation will draw on the experience of established VLSI design techniques that have been used in the silicon-based electronics industry for many years to outline the challenges and opportunities that may lie ahead in fully exploiting the cost benefits of thin-film flexible ICs.

By looking back at the developments in silicon ICs over the last few decades some interesting comparisons can be made with recent developments in thin-film flexible ICs that may allow future predictions to be made.

Biography

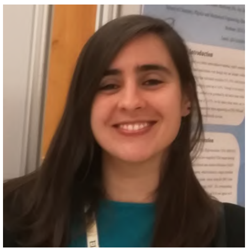
John Biggs has been involved with Arm developments since 1986 and co-founded Arm Ltd. in 1990. After a number of years working as a VLSI design engineer, he went on to form Arm's Design Methodology Group in 1995. John is a Distinguished Engineer at Arm and has been working in the research group since 2000. He has a keen interest in the development of advanced methodologies for the low-power deployment of synthesisable Arm IP. However, more recently John has been working on some exciting "blue-sky" research projects looking at novel applications of state of the art thin-film transistors on a flexible substrate.

John holds a BSc in Electronic and Electrical Engineering from the University of Manchester and is currently chair of the IEEE1801 (UPF) work group.

SESSION 10: NOVEL DEVICES & SYSTEMS II

10.1 Dr Wim Christiaens, Quad Industries (Invited)

Dr. Wim Christiaens is expert in the field of flexible and stretchable electronics development and manufacturing. He obtained his PhD in electronic engineering from Ghent University (Belgium) in 2009 for his work on the integration of passive and active components inside flexible circuit boards, and has further experience in business development and printed circuit board manufacturing. He joined Quad Industries in 2014 as R&D director to coordinate strategic innovations with a strong focus on exploring new technologies and applications in the field of (screen)printed electronics.



10.2 Dr Ana Rovisco, NOVA.iD.FCT

Ana Rovisco is currently a postdoctoral researcher at CENIMAT, where she is a researcher since 2013. She completed the PhD in Nanotechnologies and Nanosciences in December 2019 by NOVA School of Science and Technology, NOVA University Lisbon (at Department of Materials Science and i3N/CENIMAT) and the Integrated Master in Physics Engineering in December 2012 by the same University (at Department of Physics). Since 2014 she is also lab assistant of several courses related with nanofabrication and materials characterization in the same University (at Department of Materials Science). The main focus of her work is the synthesis (by solution processes), characterization and application (eg: FETs, energy harvesters and photocatalysis) of oxide nanostructures.

10.3 Dr Mahmoud Wagih, University of Southampton

Dr. Mahmoud Wagih received his BEng and PhD in electrical and electronic engineering from the University of Southampton in October 2018 and April 2021, respectively, receiving over 5 early career and best doctoral research awards. He is currently a Royal Academy of Engineering IC Research Fellow at the University of Southampton. His interests broadly cover applying novel antennas and microwave techniques to sensing, energy harvesting, wearables, and circular sustainable electronics.

10.4 Dr Claudia Delgado Simão, Fundació Eurecat

Dr. Claudia Delgado Simão is the leader of the Printed Sensors and Actuators research group at Fundació Eurecat, in Barcelona Spain. She obtained her MSc degree in Chemistry at Instituto Superior Técnico, Universidade Técnica de Lisboa (Portugal) in 2007 and her PhD in Materials Science in Universitat Autònoma de Barcelona (Spain) in 2011. Her research interests center on autonomous and low power sensor devices, to set new advancements in applications related to sustainable electronics, healthcare and energy devices, enabled by functional materials, surface engineering and printing technology. Her focus is in bridging science and business in her coordination of public and private funded research, development and innovation projects, and bring research results from concept to market.

10.5 Dr Matthew Dyson, IDTechEx

Matthew is a Senior Technology Analyst at IDTechEx, specializing in printed/organic/flexible/hybrid electronics. Matthew has a PhD in Physics from Imperial College, where he explored optoelectronic properties of organic semiconductors, followed by post-doctoral research at Eindhoven Technical University into organic photodetectors. This background has equipped him with a comprehensive understanding across the printed/organic/flexible electronics field.

SESSION 10: NOVEL DEVICES & SYSTEMS II

10.1 Flexible Printed Electronics: A World of Opportunities

Dr Wim Christiaens, Quad Industries (Invited)

This talk will provide insights into printed electronics, which is a platform technology to create electrical devices on various substrates. Printed circuit foils are already used since more than 20 years for the production of user interfaces (including membrane switches and capacitive touch) but the biggest opportunity in the field of printed electronics is that many new applications are emerging.

Quad Industries is a leading innovator in this field, and by means of highly accurate screen-printing techniques smart functionality is integrated on a wide range of materials such as flexible or even stretchable films, textiles and paper. Some of our recent developments and applications include in-mold electronics, printed heaters, force sensors and smart patches.

10.2 Sustainable Zinc-Based Nanostructures for Energy Harvesting Applications

Dr Ana Rovisco, NOVA.iD.FCT

Authors: Dr Ana Rovisco (1), Andreia dos Santos (2), Sofia Henriques Ferreira (1), Filipe Sabino (1), Rita Branquinho (1), Rui Igreja (1), Elvira Fortunato (1), Rodrigo Martins (1), Pedro Barquinha (1)
(1) NOVA.iD.FCT
(2) Alma Science

The current trend for smart, self-sustainable and multifunctional technology demands for the development of energy harvesters based on widely available and environmentally friendly materials. Most of these harvesters are based on piezoelectricity, triboelectricity, or both effects [1]. Amongst the variety of piezoelectric materials that have been explored so far, the growing concern with the use of sustainable materials makes zinc oxide (ZnO) and zinc-tin oxide (ZTO) nanostructures some of the most appealing for further developments. In order to produce robust energy harvesters, composites were fabricated by mixing zinc-based nanostructures with a micro-structured PDMS film [2-5]. Three zinc-based nanostructures were considered for these composites: ZnO nanowires, ZnO porous nanostructures and $ZnSnO_3$ nanowires [4,6,7-9]. All of these nanostructures were produced by seed-layer free hydrothermal routes at temperatures lower than 200 °C. ZnO nanowires and ZnO porous nanostructures were synthesized using microwave-assisted method, while the $ZnSnO_3$ nanowires were synthesized using a conventional oven. The approach of micro-structuration nanostructures@PDMS composites has a double effect of enhancing the piezoelectric effect of the nanostructures, and increasing the triboelectric effect of PDMS. This results in great performances, specially using $ZnSnO_3$ nanowires, leading to output voltage, current, and instantaneous power density up to 120 V, 13 µA and 2 $mW{\cdot}cm^{-2}$, respectively [2]. As proof of concept, a demonstration of lighting up multiple LEDs by directly connecting them to the fabricated harvester and other small electronic devices is shown [10]. This way, the great potential of these devices for wearables and portable electronics is demonstrated.

References:
[1] Lee, K. Y., Nano Energy 2015, 14, 139–160.
[2] Rovisco, A. et al., et al., ACS Appl. Mater. Interfaces 2020, 12, 18421–18430.
[3] dos Santos, A. et al., Chemosensors 2021, 9(2), 27.
[4] Ferreira, S.H. et al., In Nanopores; IntechOpen, 2021.
[5] dos Santos, A. et al., Adv. Electron. Mater. 2018, 4(9), 1.
[6] Coelho, D., Master Thesis, FCT-NOVA, 2019.
[7] Rovisco, A. et al., ACS Appl. Nano Mater. 2018, 1, 3986–3997.
[8] Rovisco, A. et al., Nanomaterials 2019, 9, 1002.
[9] Rovisco, A. et al., In Novel Nanomaterials; IntechOpen, 2020.
[10]https://www.youtube.com/watch?v=cliRqn7rqZs&fbclid=IwAR1c88Y10R8ylT4pfZ_9lZ2y72QlxkhTuqRaDXa6dp6EZoXkHZ4pz2QTMYo

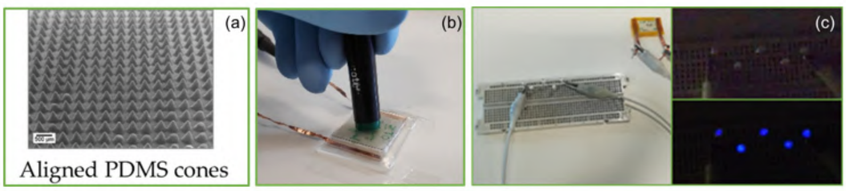


Figure 1. (a) SEM image of a micro-structured nanostructures@PDMS film. (b) Photograph of a nanogenerator. (c) Nanogenerator directly lighting up 5 LEDs by applying manual force.

10.3 Radio Frequency-Enabled "Green" Large Area Electronics: From Robust Sensors to Biodegradable Antennas

Dr Mahmoud Wagih, University of Southampton

Authors: Mahmoud Wagih (1), Junjie Shi (1), Menglong Li (1)
(1) University of Southampton

With the prevalence of RF-enabled technologies such as RFID, interest has grown in RF-based sensing and power transmission to enable sustainable large area electronics (LAE). This work presents RF-enabled sensing LAE through three examples. Firstly, we realise battery-free highly sensitive and robust passive sensors using RF LAE, demonstrating better compared to their counterparts on conventional PCBs. The integration of novel LAE sensing materials with RF circuits is then proposed to improve the sensor's performance and integration. We finally demonstrate biodegradable RF antennas with comparable performance to their metal-based counterparts, showing the potential for a "green" Internet of Things.

A flexible compact RFID dipole antenna on an organic polymer substrate was proposed as a reliable and battery-free ice detection sensor, as shown in Figure 1. Unlike reported sensors, the antenna was designed to have a higher gain and efficiency when loaded with an ice layer, as in Figure 1(b), improving its immunity to interference [1]. The scalability of the sensing approach was demonstrated through a 2.4 GHz ice sensor, exhibiting a linear response to the ice layer covering the antenna [2]. Despite their miniaturized form-factor and low-cost construction, both antennas outperform existing RF ice sensors which utilise costly RF laminates with complex geometries, restricting their integration in pervasive LAE IoT applications [2].

Integrating novel sensing materials with RF components can significantly improve their performance. A novel large-area positive temperature coefficient (PTC) thermistor based on a carbon-fibre/PDMS composite has been realized with a low-temperature resistance under 150 /square, shown in Figure 2. While PTC thermistors are non-linear and rarely used for sensing over a wide temperature range, we demonstrate that using an RF-based readout circuit, the thermistor's response can be detected over a 4x wider temperature range. By using the large-area thermistor composite as a substrate for a simple microwave resonator, the sensor's response exhibits high linearity up to 200oC. Battery-free temperature sensing has also been realized using thermistor-loaded flexible RFID tags.

Passive RF components such as metamaterials and retrodirective tags demonstrate the potential for chipless devices. To tackle the increasing electrical and electronic waste (WEEE) footprint of the IoT, biodegradable conductors can be used to realize RF LAE. An e-textile patch antenna, in Fig. 3, was realised with over 3 dBi gain based on an all-polymer biodegradable PEDOT:PSS conductor, with a total thickness under 30 µm. The microwave transmission properties of a PEDOT:PSS transmission line indicate the suitability of biodegradable transmission lines for high-speed application. Passive flexible components such as "metal-on-metal" RF capacitors have also been developed using non-metal all-polymer PEDOT:PSS electrodes, demonstrating that complete passive RF systems can realised using biodegradable conductors.

The three proposed examples demonstrate the potential for an RF-enabled large-area IoT, underpinned by robust RF sensors and biodegradable RF components. Future work and challenges in system-level integration of RF-enabled LAE will also be discussed.

References:
[1] Wagih and Shi. IEEE Sensors Journal 2021. DOI: 10.1109/JSEN.2021.3087326
[2] Wagih and Shi. Techrxiv 2021. DOI: 10.36227/techrxiv.14958174.v1
[3] Athauda and Karmakar. IEEE Microwave Magazine 2019 DOI: 10.1109/MMM.2019.2922118

SESSION 10: NOVEL DEVICES & SYSTEMS II

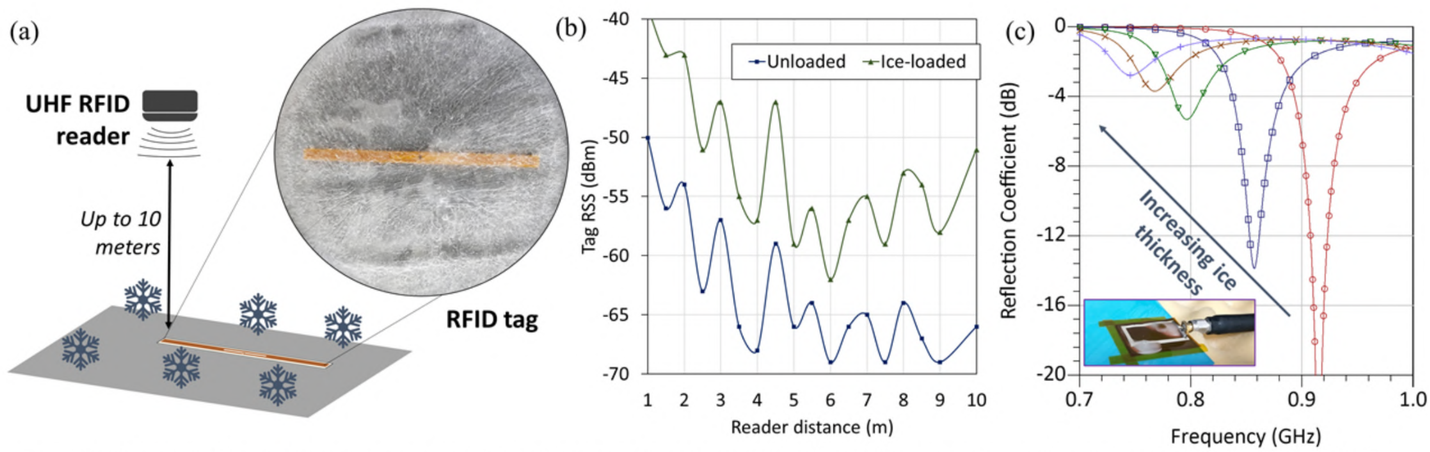


Figure 1. Robust large-area RF-enabled sensors for ice detection and monitoring in smart cities applications [1]: (a) illustration of the battery-free sensing system and a photograph of the ice-loaded RFID tag; (b) the measured sensor's performance showing at least 10 dB sensitivity; (c) the underlying operation principle where the ice "superstrate" shifts the resonant frequency; inset shows the dipole ice sensing antenna.

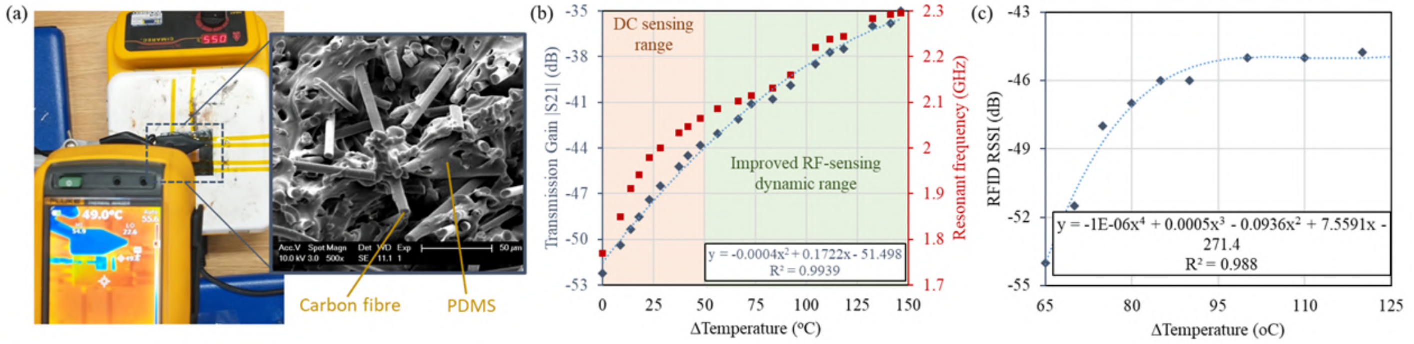


Figure 2. RF-enabled large-area thermistor: (a) Photograph showing the thermistor characterization setup and an SEM micrograph showing the material's formation; (b) measured RF sensor response showing high sensitivity and improved dynamic range over resistive measurements; (c) wireless interrogation of a battery-free RFID temperature sensor enabled by the large-area thermistor.

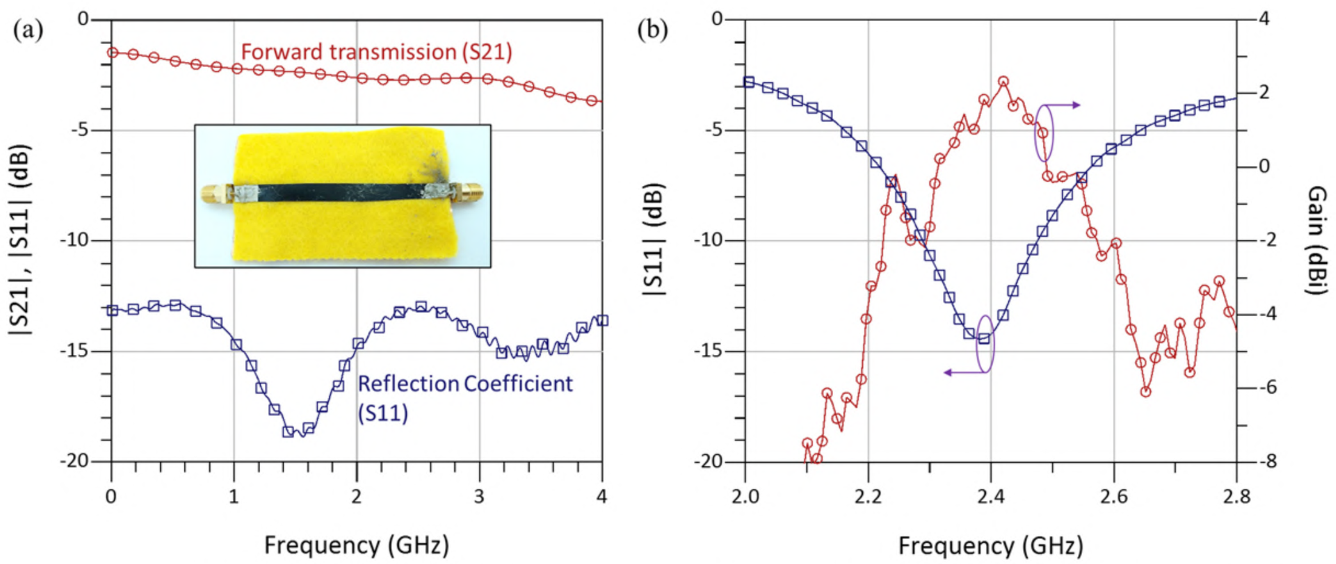


Figure 3. Biodegradable e-textile antennas and RF lines towards "green" chipless RF LAE: (a) A PEDOT:PSS printed transmission line for material characterisation and its measured transmission properties of the PEDOT:PSS line on a textile substrate; (b) The measured reflection coefficient and gain of a 2.4 GHz textile patch antenna using an all-polymer biodegradable radiating element.

10.4 Novel Fully Printed Piezoelectric Devices for Sustainable Electronics and Wearable Applications

Dr Claudia Delgado Simão, Fundació Eurecat

Authors: Dr Claudia Delgado Simão (1), Marc Alique (1), Paul Lacharmoise (1), David Otero (1)
(1) Fundació Eurecat

In this work, the latest advancements in fully printed piezoelectric devices will be presented. Our recent studies focus the development of fully printed piezoelectric devices for multifunctional single device platforms for wearable applications.[1] Mechanical movement produced by environmental phenomena or by the people in their everyday life can be recovered as energy thanks to piezoelectric devices.[1] This effect is a reversible process, thus, when an electric signal is applied to a piezoelectric material, the reorientation of charges causes a mechanical deformation that can be translated as a deflection of the material.[2] This duality allows piezoelectric materials to be used as sensors, actuators and energy harvesters.[3] A key point for the advance in wearable technology is the need for integration with soft and flexible devices, and since the growth of printing technologies the reality is getting closer every day.[4] Here we present a full fabrication methodology of a novel fully printed device and its demonstration of their multifunctionality and their robustness in response. This technological advancement represents a leap ahead in the possibilities for disruptive integration of these devices in wearables or objects. The evaluation of the relationship between the design and the response of the devices with different areas has been done to validate its operation as sensor, actuator and energy harvester. We pair there assays to compare the performance of the versatile device. The response of the device as actuator is presented. When the applied voltage of the AC source increases, the vibration amplitude of the device increases proportionally. The output voltage across the load resistors ranges from 47 kΩ to 1.9 MΩ with different accelerations (0.25, 0.5 and 0.75 G). As seen, a maximum output power of 1.6 μW is observed across the optimal load resistor of 1.12 MΩ. In summary, here we present a novel fabrication route of a fully printed piezoelectric device based on PVDF-TrFE copolymer, combining advantages of screen and inkjet printing techniques on flexible and stretchable substrates. All prepared devices show a robust performance working as a sensor, actuator or energy harvester. This versatile multitechnological approach paves the way for exploring novel applications in wearable applications.

REFERENCES

[1] a) M. Alique, C. Delgado Simao, A. Moya, and G. Murillo, "Fully-Printed Piezoelectric Devices for Flexible Electronics Applications," Adv. Mater. Technol., 2021. b) Marc Alique, Ana Moya David Otero, Marcos Duque, Martin Kreuzer, Paul Lacharmoise, Gonzalo Murillo, C. D. S. "Robust multifunctional fully printed device platform: sensing, actuation, energy harvesting and switching behavior in a single piezoelectric device design." Adv. Mater. Technol. submitted, admt.202101461 (2021).
[2] M. T. Chorsi et al., "Piezoelectric Biomaterials for Sensors and Actuators," Adv. Mater., vol. 31, no. 1, pp. 1–15, 2019, doi: 10.1002/adma.201802084.
[3] G. Murillo et al., "Electromechanical Nanogenerator–Cell Interaction Modulates Cell Activity," Adv. Mater., vol. 29, no. 24, pp. 1–7, 2017.
[4] F. Mokhtari et al., "Highly Stretchable Self-Powered Wearable Electrical Energy Generator and Sensors" Adv. Mater. Technol., vol 6, 2021

10.5 3D/Additive Electronics: New Methods for New Applications?

Dr Matthew Dyson, IDTechEx

Incorporating electronic functionality into new settings offers huge potential to add sensing, communication, energy harvesting, and other capabilities in both domestic and industrial contexts. However, at present, incorporating electronics generally involves finding space for the rigid rectangle of a PCB. Flexible electronics of course enables electronics to be added to a smooth object's surface or wrapped around a curve, but what about embedding electronics within the object itself?

Achieving this compelling ambition is the aim of 3D/additive electronics. Electronic functionality can either be added directly to the surface of a 3D object or integrated within the structure itself during additive manufacturing of both structural and electronic functionality.

3D/additive electronics has applications across multiple sectors and length scales, ranging from IC and sensor packaging to replacing wiring harnesses. Advantages include integrating electronics in previously challenging locations, reduced material consumption, and decoupling the existing inverse relationship between price and volume via digital manufacturing.

This talk will provide an overview of the emerging area of 3D/additive electronics, including discussion of innovative manufacturing methodologies, such as 5-axis printing of conductive inks and laser induced forward transfer, along with the advanced materials required. It will outline the current state of the market and assess the potential of current and future applications.

SESSION 11: HIGH PERFORMANCE MATERIALS I

11.1 Prof Dr Maria Antonietta Loi, University of Groningen (Invited)

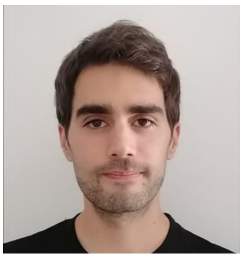
Maria Antonietta Loi studied physics at the University of Cagliari in Italy where she received the PhD in 2001. In the same year she joined the Linz Institute for Organic Solar cells, of the University of Linz, Austria as a postdoctoral fellow. Later she worked as researcher at the Institute for Nanostructured Materials of the Italian National Research Council in Bologna, Italy. In 2006 she became assistant professor and Rosalind Franklin Fellow at the Zernike Institute for Advanced Materials of the University of Groningen, The Netherlands. She is now full professor in the same institution and chair of the Photophysics and OptoElectronics group.

11.2 Dr Mario Lanza, KAUST (Invited)

Mario Lanza got a PhD in Electronic Engineering (with honors) in 2010 at Universitat Autonoma de Barcelona. In 2010-2011 he was NSFC postdoc at Peking University, and in 2012-2013 he was Marie Curie postdoc at Stanford University. In October 2013 he joined Soochow University as Associate Professor, and in March 2017 he was promoted to Full Professor. Since October 2020 he is an Associate Professor of Materials Science and Engineering at the King Abdullah University of Science and Technology (KAUST), in Saudi Arabia. Prof. Lanza leads a research group formed by 10-15 PhD students and postdocs, and they investigate how to improve electronic devices and circuits using 2D materials, with special emphasis on resistive switching applications.

11.3 Prof Cinzia Casiraghi, University of Manchester

Prof Cinzia Casiraghi graduated in Nuclear Engineering from Politecnico di Milano (Italy) and received her PhD in Electrical Engineering from the University of Cambridge (UK) in 2006. She was awarded with the Humboldt Fellowship and the prestigious Kovalevskaja Award (1.6M Euro) in 2008, which allowed her to establish an independent research group at the Physics Department of the Free University Berlin (Germany). In 2010 she joined the School of Chemistry, at the University of Manchester (UK), where she holds a Chair in nanoscience. She is recipient of the Leverhulme Award in Engineering (2016) and the Marlow Award (2014), given by the Royal Society of Chemistry in recognition of her meritorious contributions in the development of Raman spectroscopy for characterisation of carbon nanostructures. She authored and co-authored more than 70 peer reviewed articles, collecting more than 22k citations. Her current research work focuses on the development of 2D inks and their use in printed photodetectors, memories, thermoelectrics, sensors and biological applications.



11.4 Dr Jorge de Souto Martins, i3N/CENIMAT and CEMOP/UNINOVA, FCT-UNL

Jorge Martins is a postdoctoral researcher at CENIMAT. He completed his PhD in Nanotechnologies and Nanosciences in February 2021 by NOVA School of Science and Technology, NOVA University Lisbon, (at Department of Materials Science, CENIMAT/i3N) and the Integrated Master in Physics Engineering in December 2012 by the same University, Department of Physics. The main topic of his research is the improvement of oxide TFT technologies with focus on its investigation aided by TCAD simulation tools.

SESSION 11: HIGH PERFORMANCE MATERIALS I

11.1 Scalable, Template Driven Formation of Highly Crystalline Lead-Tin Halide Perovskite Films

Prof Dr Maria Antonietta Loi, University of Groningen (Invited)

Low bandgap lead-tin halide perovskites are predicted to be candidates to maximize the performance of single junction and tandem solar cells based on metal halide perovskites. In spite of the tremendous progress on lab-scale device efficiency, devices fabricated with scalable techniques fail to reach the same efficiencies, which hinder their potential industrialization. Herein we propose a method which involves a template of a two-dimensional (2D) perovskite deposited with a scalable technique (blade coating), and then is converted in-situ to form a highly crystalline three-dimensional (3D) lead-tin perovskite. These templated grown films are alloyed with stoichiometric ratio and are highly oriented with the (l00) planes aligning parallel to the substrate. The low surface/volume ratio of the obtained single-crystal-like films contribute to their enhanced stability in different environments. Finally, the converted films are demonstrated as active layer for solar cells, opening up the opportunity to develop this scalable technique for the growth of highly crystalline hybrid halide perovskites for photovoltaic devices.

SESSION 11: HIGH PERFORMANCE MATERIALS I

11.2 Integrated Circuits made of 2D Materials

Dr Mario Lanza, KAUST (Invited)

Two-dimensional layered materials (2D-LMs) materials have outstanding physical, chemical and thermal properties that make them attractive for the fabrication of solid-state micro/nano-electronic devices and circuits. However, synthesizing high-quality 2D-LMs at the wafer scale is difficult, and integrating them in semiconductor production lines brings associated multiple challenges. Nevertheless, in the past few years substantial progress has been achieved and leading companies like TSMC, Samsung and IMEC have started to work more intensively on the fabrication of devices using 2D-LMs. In this talk, I will discuss the state-of-the-art on micro/nano-electronic devices made (entirely or partially) of 2D-LMs, as well as their integration in CMOS chips. I will present the most sophisticated prototypes developed so far, with special emphasis on devices that employ hexagonal boron nitride, the only 2D-LM with an enough high band gap to be employed as dielectric. I will also discuss the main technological challenges to face in the next years and provide some recommendations on how to solve them.

11.3 Wireless and Wearable Humidity Sensors with Enhanced Stability and Sensitivity made with Water-based Hexagonal Boron Nitride Inks

Prof Cinzia Casiraghi, University of Manchester

Authors: Xiuju Song (1), Liming Chen (1), Wuliang Yin (1), Cinzia Casiraghi (1)
(1) University of Manchester

Two-dimensional (2D) materials show great promise in sensing applications due to their unique chemical and physical properties, high surface area-to-volume ratios and ultra-high surface sensitivity to the environment [1]. Graphene oxide (GO) and reduced GO (rGO) have been widely exploited for humidity sensing because their abundant oxygen bearing functional groups provide a highly hydrophilic surface, thus enabling the sensing of humidity by monitoring changes in resistance. However, resistive-based GO and rGO humidity sensors suffers from large hysteresis [2] and they can operate only in a small range of temperature, as the material has limited thermal stability. In addition, the resistive readout is also subjected to strong cross-sensitivity issues, as changes in humidity, strain, temperature, etc. will also all contribute to a change in resistance.

Amongst 2D materials, hexagonal boron nitride (h-BN) is well known for its excellent chemical and thermal stability. Herein, we prepared water-based h-BN inks [3] and exploited them as sensing element in impedance-based devices, by recording changes in resistance and capacitance as a function of the relative humidity (RH). We found a resistance sensitivity of 1.8×10^{10} Ohms/%RH in the RH range between 5% and 100% at 20°C. The maximum capacitance sensitivity is 0.75 pF/%RH in the RH range between 50% and 100%. We finally fabricated a wireless breathing sensing device able to record in real-time signals from different individuals in daily activities (e.g. watching TV, reading, running, deep breathing and swallowing). The breathing sensor can be used to monitor in real-time several common symptoms of COVID-19 and flu, including cough, fever, runny and stuffy nose, shortness of breath or difficulty breathing.

References

[1] Geim A. K., Novoselov K. S.,et al. Nat. Mater. 2007, 6, 183-191.
[2] Anichini C., Aliprandi A., Gali S. M. et al. ACS Appl. Mater. Interfaces 2020, 12, 44017.
[3] McManus D, Casiraghi C., et al, Nature Nanotechnol., 2017, 12, 343–350.
[4] Chen. L. Yin W. L., Casiraghi C., Song X., Nat. Commun. Under review

11.4 Tantalum/Silicon Multicomponent Oxides as Gate Dielectrics for Flexible Electronics

Dr Jorge de Souto Martins, i3N/CENIMAT and CEMOP/UNINOVA, FCT-UNL

Authors: Dr Jorge de Souto Martins (1), Pedro Barquinha (1), Asal Kiazadeh (1), Joana Pinto, (1) Ana Rovisco (1), Jonas Deuermeier, (1) Rodrigo Martins (1), Elvira Fortunato (1)
(1) i3N/CENIMAT and CEMOP/UNINOVA, FCT-UNL

The quick progress on amorphous oxide thin films in recent years led to their application in the display industry, for which materials such as indium-gallium-zinc oxide (IGZO) are an advantageous alternative to conventional Si technologies. Amorphous oxides are well suited for large area, transparent and flexible electronics [1] (or even paper electronics [2]), enabling disruptive electronic concepts for markets expected to provide high revenue and well-being, such as medical, security and item tracking. The substrates typically required for these applications impose low thermal budgets (T < 200 °C) that unavoidably result in poorer device performance. Furthermore, concepts involving full electronic systems on a single substrate often demand energy supply schemes such as RF harvesting or printed batteries, making low power electronics preferable. To tackle these issues, the employment of dielectrics with high dielectric permittivity (high-κ dielectrics) in thin-film transistors (TFTs) can reduce driving voltages and compensate for poorer semiconductor quality through higher charge density generation at the semiconductor per unit voltage. However, when compared to conventional dielectrics such as SiO_2, high-κ materials can have higher defect densities (aggravated by low thermal budgets) which may cause threshold voltage (V_{th}) instability, leakage, and scatter carriers in the channel.

In this work, to benefit from the advantages of both high-κ dielectrics and the reliable silicon dioxide, SiO_2 and Ta_2O_5($\varepsilon_r \approx 25$) were co-sputtered to form multicomponent and multilayered gate dielectric stacks for IGZO TFTs, under thermal budgets compatible with flexible substrates (T <=180 °C). The incorporation of the high-κ material in the gate dielectric was investigated and device characterization was performed in terms of static performance (Figure 1), reliability, and stability. Anomalous Vthshifts under positive gate bias stress were unexpectedly aggravated for higher SiO_2 contents (Figure 2), and the analysis of the stress and recovery processes (Figure 3) suggests the migration of ionic species in the dielectric material [3]. Regardless, incorporating SiO2 layers in the dielectric stack is shown to effectively balance the V_{th} shifts while also compensating for inherent disadvantages of the high-κ material. Optimized multilayered stacks present $\varepsilon_r \approx 13$ and result in stable and reliable devices, with field-effect mobility > 16 $cm^2V^{-1}s^{-1}$, subthreshold slope < 0.15 V/dec, On/Off ratio > 10^7, good insulation reliability and V_{th} shift of 1.3 V after 1 h of positive gate bias stress. This multicomponent/multilayered approach for a high capacitance gate dielectric is in line with the needs of large area, flexible and transparent electronics, with integration of these devices in a flexible X-ray sensing system being shown [4].

[1] A. Facchetti, et al., Transparent Electronics; John Wiley & Sons, Ltd, ISBN 9780470710609.
[2] R. Martins, et al., Appl. Mater. Today 2018, 12, 402–414
[3] K. Shiraishi et al., Thin Solid Films 2006, 508, 305–310
[4] J. Martins et al., Electron. Mater. 2021, 2(1), 1-16

SESSION 11: HIGH PERFORMANCE MATERIALS I

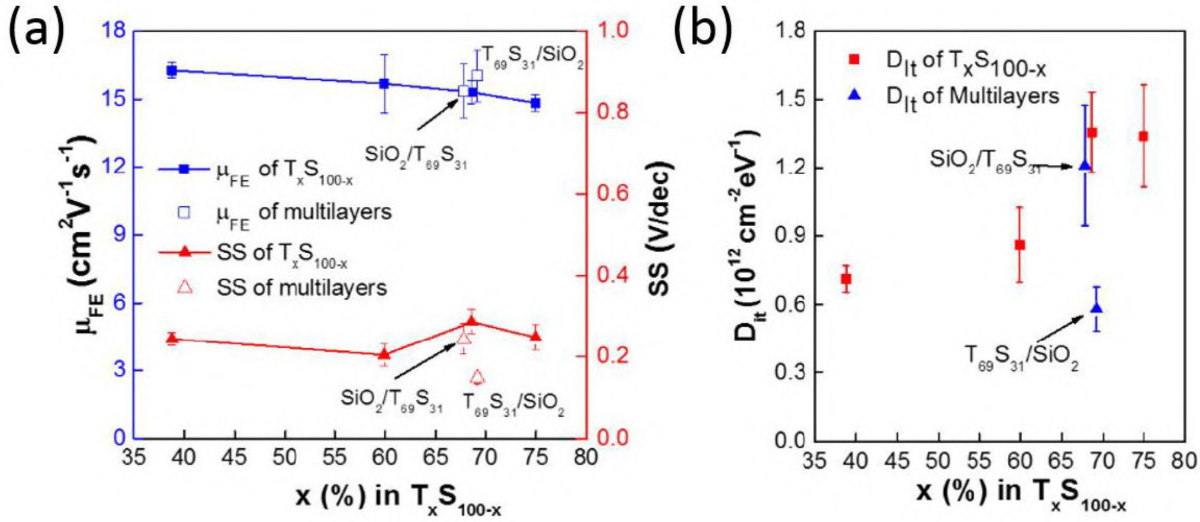


Figure 1 - (a) Field effect mobility and subthreshold slope and (b) trap density at the interface for TFTs employing the multicomponent and the multilayered dielectrics. Abbreviations: "T": T_2O_5, "S": SiO_2.

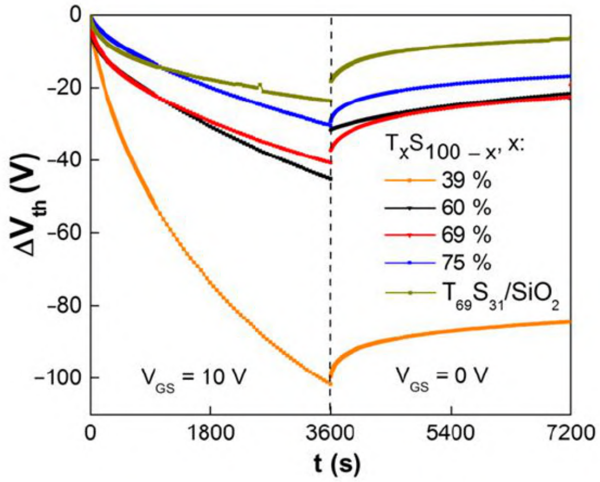


Figure 2 - V_{th} shift during positive gate bias stress (V_{GS} = 10 V) and recovery (V_{GS} = 0 V). Abbreviations: "T": T_2O_5, "S": SiO_2.

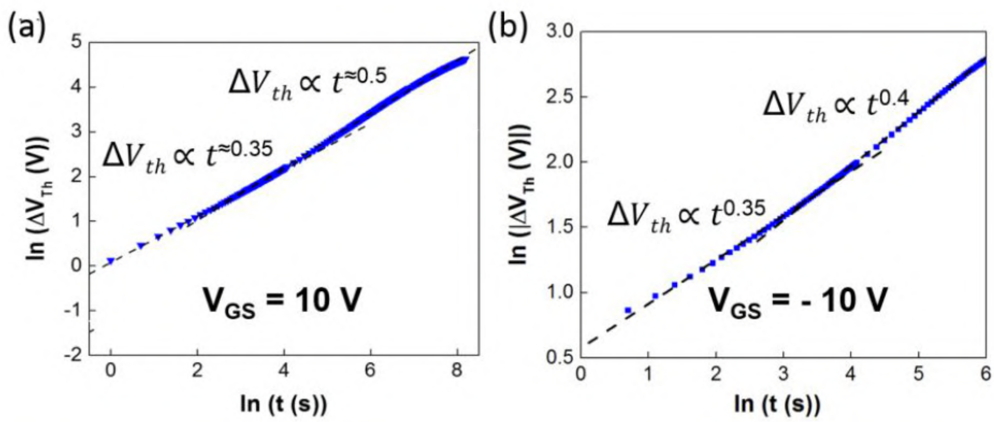


Figure 3 - V_{th} shift during (a) positive gate bias stress (V_{GS} = 10 V) and (b) positive gate bias stress (V_{GS} = – 10 V) of a previously stressed device, showing power law time dependencies for both processes.

12.2 Electronic Skins and the Next- Generation Wearables for Medical Applications

Dr Aaron Franklin, Duke University

For decades we've been hearing about the promise of printing electronics directly onto any surface. However, despite significant progress in the development of inks and printing processes, reports on fully, direct-write printed electronics continue to rely on excessive thermal treatments and/or fabrication processes that are external from the printer. In this talk, recent progress towards print-in-place electronics will be discussed; print-in-place involves loading a substrate into a printer, printing all needed layers, then removing the substrate with electronic devices immediately ready to test. A key component of these print-in-place transistors is the use of inks from various nanomaterials, including: 2D graphene and hexagonal boron nitride, 1D carbon nanotubes, and quasi-1D silver nanowires. Using an aerosol jet printer, functional 1D-2D thin-film transistors (TFTs) are printed without ever removing the substrate from the printer and using a maximum process temperature of 80 ºC with most processing at room temperature. To achieve this, significant advancements were made to minimize the intermixing of printed layers, drive down sintering temperature, and achieve sufficient thin-film electrical properties. Devices are demonstrated on various substrates, including paper. What's more, recent progress towards a completely recyclable printed transistor will be discussed, fabricated entirely using nanoscale carbon-based inks. These fully recyclable devices use an ink from crystalline nanocellulose designed to yield printed electrolyte dielectrics that allow for low-voltage nano-carbon TFTs that are fully recyclable. These demonstrations give evidence for an electronic future involving devices with fabrication and/or function that goes beyond what is possible with silicon-based technologies, including the potential for large-area recyclable electronics.

Biography

Dr Aaron Franklin received his Ph.D. in Electrical Engineering from Purdue University in 2008 and then spent six years on the research staff at the IBM T. J. Watson Research Center in Yorktown Heights, NY. In 2014, he joined the faculty at Duke University where his group has three primary research thrusts: 1) nanomaterials in high-performance nanoelectronic devices, 2) nanomaterial inks for low-cost printed electronics, and 3) harnessing nanomaterial sensitivity in biomedical sensing systems. He is most widely known for his work on low-dimensional nanoelectronics with specific emphasis on carbon nanotube (CNT) transistors, including device scaling, transport studies, and advanced integration approaches. Sponsored research in the Franklin lab includes projects involving high-performance transistors, printed electronics, thin-film transistors, and biomedical assays. In addition to leading a successful scientific research group, Dr. Franklin has been actively involved in the translation of inventions out of the lab, holding more than 50 issued patents and being engaged in two start-up companies.

SESSION 13: HIGH PERFORMANCE MATERIALS II

13.1 Dr Zhichao Weng, Paragraf & Queen Mary University of London (Invited)

Dr Zhichao Weng is a KTP (Knowledge Transfer Partnerships) Research Associate from Queen Mary University of London (QMU) working on-site in the industrial partner Paragraf Ltd, on the Innovate UK funded project about graphene light emitting devices. He obtained his PhD in condensed matter physics at QMU in 2019, on the project of investigating spintronics and magnetic field effect in OLEDs, with 3 publications on peer-reviewed journals as the first and corresponding author. Dr Weng then joined Prof. Sir Colin Humphreys research group as a postdoc researcher working on the Innovate UK funded project of replacing indium tin oxide with graphene in OLEDs. By the end of the one-year project, he successfully fabricated the ITO-replaceable graphene-based OLED.

13.2 Prof Barry Rand, Princeton University (Invited)

Barry Rand earned a BE in electrical engineering from The Cooper Union in 2001. Then he received MA and PhD degrees in electrical engineering from Princeton University, in 2003 and 2007, respectively. From 2007-2013, he was at imec, as a principal scientist, researching the understanding, optimization, and manufacturability of thin-film solar cells. Since 2013, he is in the Department of Electrical Engineering and Andlinger Center for Energy and the Environment at Princeton University, currently as an Associate Professor. Prof. Rand's research interests highlight the border between electrical engineering, materials science, chemistry, and applied physics, covering electronic and optoelectronic thin-films and devices.

13.3 Prof Vincenzo Pecunia, Simon Fraser University

Vincenzo Pecunia is an Associate Professor and the Head of the Pecunia Research Group – Sustainable Optoelectronics. His research covers environmentally-friendly, printable semiconductors, their photoelectronic properties, and their applications in optoelectronics and photovoltaics. Prior to establishing his own group, Vincenzo spent 6+ years at the Optoelectronics Group of the Cavendish Laboratory, University of Cambridge. Whilst there, he earned his PhD in Physics and worked as a Postdoctoral Research Associate. Drawing from his research experience, Vincenzo has authored the books 'Organic Narrowband Photodetectors' (Institute of Physics Publishing) and 'Organic & Amorphous-Metal-Oxide Flexible Analogue Electronics' (Cambridge University Press).

13.4 Arka Mukherjee, IISER Thiruvananthapuram

In 2013, I obtained my BSc degree from the University of Calcutta, and in 2015, I received my MSc degree in Applied Physics from the Central University of Jharkhand. I am now working on my PhD in physics at the Indian Institute of Science Education and Research (IISER) Thiruvananthapuram, Kerala, India. In my fifth year of the PhD programme I have experience fabricating FETs with a variety of device architectures involving various materials such as organic semiconductors, CNTs, TMDs, oxide materials, two and three-terminal memristor fabrication, synthesis of oxide semiconducting materials for transistors, and have also used probe microscopy (AFM and STM) to investigate bandgap, thickness, work function.

13.5 Sam Dale, IDTechEx

Sam Dale is a Technology Analyst at IDTechEx, specialising in advanced materials for electronics. Sam has research involvement in fields ranging from machine learning to medical imaging and has a master's in Chemical Engineering from Imperial College London. At IDTechEx he analyses companies and technologies in the electronics materials sector, assessing innovations from a technical and commercial perspective. IDTechEx offers independent market research and business intelligence on a wide range of emerging technologies to clients in over 80 countries. These emerging technologies include 5G/6G, printed/additive electronics, electric vehicles, sensors, and advanced materials.

SESSION 13: HIGH PERFORMANCE MATERIALS II

13.1 Mass-Producible Graphene Replacing Indium Tin-Oxide in OLEDs

Dr Zhichao Weng, Paragraf & Queen Mary University of London (Invited)

Organic Light-Emitting Diodes (OLEDs) have become the booming technology in the display industry, including TVs, smart phones, tablets, etc., and Indium tin oxide (ITO) is widely used for transparent electrode applications in OLEDs due to its high electrical conductivity and relatively straightforward deposition technology. However, Indium is one of nine rarest elements on Earth and there's limited availability of Indium in the Earth's crust, making the future OLED technology non-sustainable. Graphene, the fully carbon-based 2D material, is considered as a promising material for replacing ITO but for this to become possible, a low-cost and scalable fabrication method that produces graphene with comparable performance to ITO is required. By taking advantage of high-quality monolayer graphene directly deposited on a transparent substrate using a commercially available metal–organic chemical vapor deposition (MOCVD) system at Paragraf™, graphene-based organic light-emitting diodes (OLEDs) without the use of metal catalysts or a graphene transfer process are developed. The as-grown graphene is patterned using photolithography and its conductivity is enhanced by doping with nitric acid prior to deposition of the OLED stack. The electrical and optical performances of the as-fabricated graphene-based OLEDs are identical to the control devices with conventional ITO anodes. All the processes used in the fabrication of graphene-based OLEDs can be performed at wafer scale. This work demonstrates the potential for graphene to replace ITO as anodes in OLED devices in a technologically and commercially effective manner for the future display applications.

13.2 Can Metal Halide Perovskite Light Emitting Diodes Be Very Bright?

Prof Barry Rand, Princeton University

Hybrid inorganic-organic lead halide perovskites have captured significant interest in the thin film optoelectronics community due to their impressive optical and electrical properties. For light emitting diodes (LEDs), we are exploring their operation under very high current densities, for high-brightness applications, exploring whether they can operate at brightnesses akin to inorganic LEDs. We demonstrate high brightness, and show that Joule heating and voltage-induced electrochemical interface reactions present substantial challenges to these operating conditions for sustained periods of time.

13.3 High-Performance Colour-Selective Light Sensing with Solution-Processed Organic Semiconductors

Prof Vincenzo Pecunia, Simon Fraser University

The tunability of the light absorption properties of organic semiconductors makes them particularly attractive for filterless colour-selective light detection beyond the limitations of conventional, filter-based technologies (e.g., silicon-based) [1][2]. However, a key remaining challenge has been to realise high-performance colour-selective OPDs with facile, solution-based methods as well as simple and scalable device architectures [3]. In fact, overcoming this challenge is essential to deliver low-cost colour-selective OPDs and imagers thereof, which could have a disruptive impact in a wealth of application areas, such as colourimetry, computer vision, healthcare, and chemical analysis, as well as smart sensing for the Internet of Things [1].

To go beyond the limitations arising from fullerenes—a class of electron acceptors widely used in OPDs yet detrimental to colour selectivity due to their broad absorption tail—we first pursued a narrowband-absorption strategy based on solution-processable non-fullerene acceptors (NFAs) [4][5]. Specifically, we investigated bulk-heterojunction OPDs whose electron acceptors were either a benzodithiophene-based compound with narrowband absorption in the far-red range (solid-state spectral absorbance width of 132 nm) or a subphthalocyanine-based compound with narrowband absorption in the green range (solid-state spectral absorbance width of 80 nm) [4][5]. By tailoring the resultant solution-processed NFA-based photoactive layers, we achieved narrowband-absorption-type photodetection with cutting-edge performance. In self-powered mode, our NFA-based OPDs for the far-red range delivered the highest specific detectivity to date (1.4×10^{13} Jones) of all narrowband-absorption far-red-selective OPDs and concurrently achieved the narrowest spectral width (141 nm) of all solution-processed implementations [4]. Moreover, our green-selective NFA-based OPDs delivered a spectral width of 130 nm with an external quantum efficiency of up to 40%—i.e., the highest to date for green-selective solution-processed narrowband-absorption-type OPDs [5].

To overcome the limitations of conventional colour filter arrays, we additionally investigated the viability of a solution-processed vertically-stacked OPD architecture for the direct sensing of multiple colours within the same pixel. Specifically, we successfully demonstrated for the first time the solution-based integration of green-sensitive OPDs atop blue-sensitive OPDs [6]. The resultant device stack concurrently enabled the spectrally-selective detection of green and blue light, delivering high photoconversion efficiency and spectral selectivity, as well as a linear dynamic range spanning four orders of magnitude [6].

By illustrating the versatility of solution-processed materials and device architectures for high-performance colour-selective OPDs, these findings constitute an important step towards the realisation of the full potential of OPDs for low-cost colour sensors and imagers.

[1] V. Pecunia, Organic Narrowband Photodetectors: Materials, devices and applications, Institute of Physics Publishing, Bristol, UK, 2019.
[2] R. D. Jansen-van Vuuren, A. Armin, A. K. Pandey, P. L. Burn and P. Meredith, Adv. Mater., 28, 2016, 4766–4802.
[3] V. Pecunia, J. Phys. Mater., 2019, 2, 042001.
[4] K. Xia, Y. Li, Y. Wang, L. Portilla and V. Pecunia, Adv. Opt. Mater., 2020, 8, 1902056.
[5] Pecunia et al., in preparation.
[6] Pecunia et al., in preparation.

13.4 Oxide Films Ultralow Voltage Field-Effect Transistors of Nanometer-Thick Transparent Amorphous Indium-Gallium-Zinc

Arka Mukherjee, IISER Thiruvananthapuram

Authors: Arka Mukherjee, Bikas Chandra Das
(1) Indian Institute of Science Education and Research (IISER)

Design of solution processed transparent transistors with ultralow voltage operation and planar architecture can be a paradigm shift towards ultralow-power electronic circuit realization due to congeniality with the existing CMOS platform. We report a robust and solution-based device fabrication protocol to demonstrate near-steep-slope transparent oxide field-effect transistors (TO-FETs) with operating voltage at or below 0.5 V using nanometer-thick amorphous indium-gallium-zinc oxide (a-IGZO) channel and ultrathin anodized aluminum dielectric. Transmittance spectra confirm the excellent transparency (> 98 %) of a-IGZO thin film for the entire visible range. Hysteresis free transfer characteristics exhibit its operation as n-channel TO-FET with a low threshold voltage (~ 96 mV), near-thermionic subthreshold swing (SS) down to 85 mV/dec, and high current ON/OFF ratio ($>10^5$). The consistency of these TO-FET results of ultralow-power operation with near-steep-slope nature was demonstrated by enormously large specific capacitance values of ultrathin anodized alumina gate dielectrics as the forcing factor. Moreover, half-volt operation of the TO-FET is also demonstrated at room temperature flawlessly with hysteresis-free characteristics. Hence, these planar TO-FETs could be a potential technological breakthrough for the future of cost-effective and high-performance transparent ultralow-power applications, including quantum and neuromorphic computation field of research.

Figure (1) Transfer characteristics of solution-processed a-IGZO/Al_2O_3 thin-film FETs at V_D = 1.0 V with gate leakage test (dashed line) and plot (empty circles) for the devices with two different thicknesses of alumina anodized at 2.5 V. (2) Positive bias stress (PBS) stability test result by recording drain (I_D) and gate (I_G) current of 2.5 V anodized device over a period of about 70 minutes. (3) Recorded transfer curves at regular time intervals during PBS test. Inset shows shifting of curves over time passed by zooming into the encircled area.

Refecence:
Mukherjee, A., Ottapilakkal, V., Sagar, S. & Das, B. C. Ultralow-Voltage Field-Effect Transistors Using Nanometer-Thick Transparent Amorphous Indium–Gallium–Zinc Oxide Films. ACS Applied Nano Materials 4, 8050–8058 (2021).

Fig 1

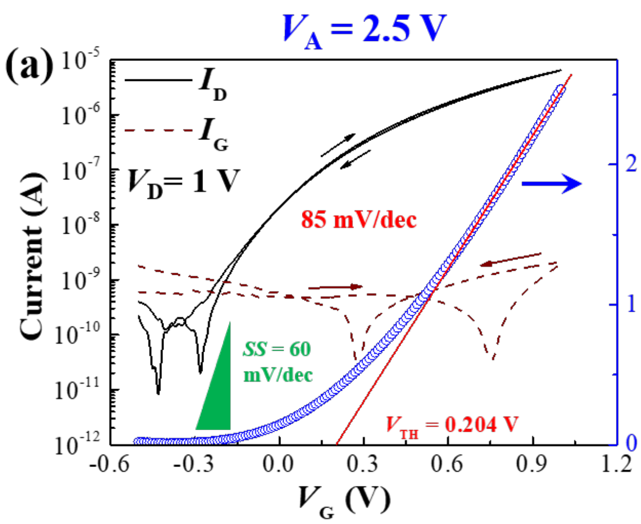


Fig 2

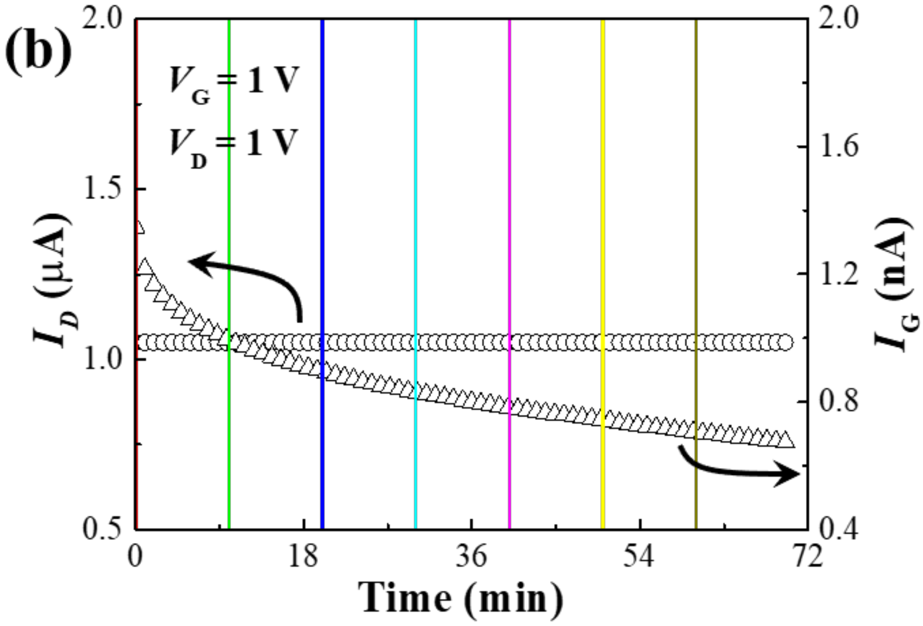
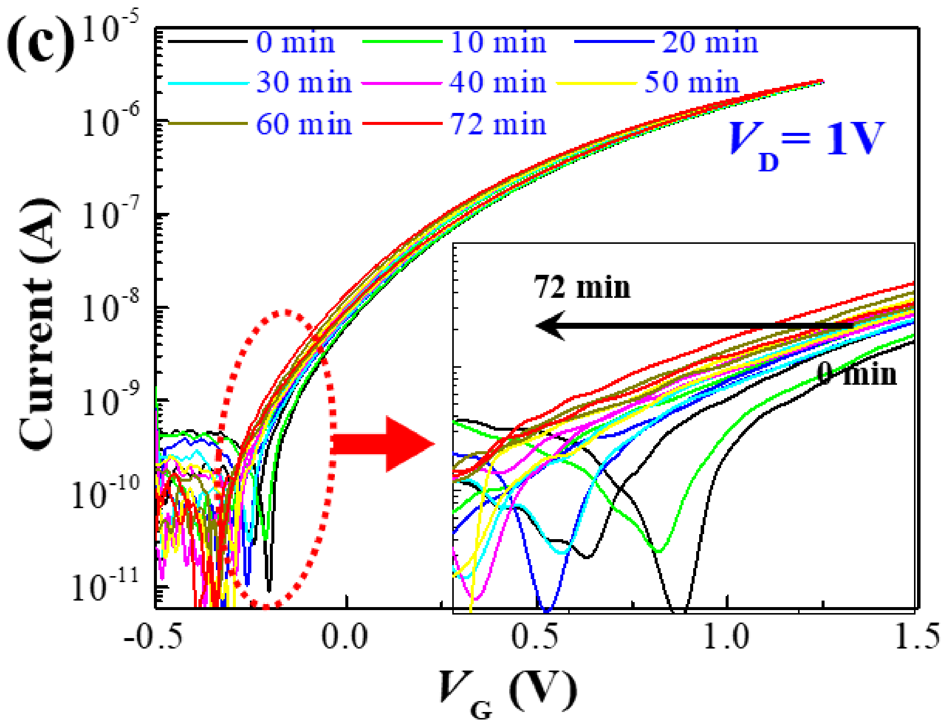

(b)
V_G = 1 V
V_D = 1 V
I_D (μA)
I_G (nA)
Time (min)
2.0
1.5
1.0
0.5
2.0
1.6
1.2
0.8
0.4
0
18
36
54
72

Fig 3


(c)
0 min
10 min
20 min
30 min
40 min
50 min
60 min
72 min
V_D= 1V
72 min
0 min
Current (A)
V_G (V)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
-0.5
0.0
0.5
1.0
1.5

13.5 Emerging Opportunities for Transparent Conductors

Sam Dale, IDTechEx

While transparent conductors are established components of touch sensitive displays, multiple technological transitions are enabling many new application opportunities. Flexible displays will become increasingly common in consumer devices, requiring flexible transparent conductors due to the brittle nature of ITO. Proliferating and higher frequency wireless communications will require more antennas, with transparent conductors enabling this functionality to be added to windows. The drive towards vehicle autonomy means more optical sensors in our cars which need to operate through surfaces unsullied by frost or condensation, creating demand for transparent heaters. Given the wide range of transparent conductive technologies such as metal mesh, silver nanowires, carbon nanotubes and conductive polymers, assessing the appropriate choice for these emerging applications can be challenging.

In this talk, the landscape of existing and emerging transparent conductive material technologies will be outlined. Emerging applications will be discussed, with attention given to the material technologies best suited to fill these niches. The remaining technological challenges to be met will be highlighted and forecast adoption roadmaps presented.

SESSION 14: APPLICATIONS & SUSTAINABILITY

14.1 Dr Russel Torah, University of Southampton (Invited)

Dr Russel Torah is a Principal Research Fellow in the Smart Electronic Materials and Systems (SEMS) Research group. His work is primarily focused on the development and fabrication of smart textiles. He has over 20 years experience of printed electronic sensor development and has been co-investigator on over £5m grant funded projects in e-textiles development for wearable, medical and creative applications. He is a co-founder and director of the Smart Fabric Inks Ltd spin-out company based on his research on smart textiles. He is currently the Principle Investigator for the WEARPLEX Horizon 2020 EU funded project: http://wearplex.soton.ac.uk/

14.2 Joshua Young, OE-A (PragmatiC) (Invited)

As Market Development Manager at PragmatIC Semiconductor, Josh leads activities for identifying and developing new use cases for flexible integrated circuits to create a more sustainable future and circular economy. With a degree in Electronic Engineering from the University of Huddersfield, he has over 6 years 'technical sales and business development experience, working with global high-tech semiconductor and electronics organisations bringing new technologies to market.

14.3 Kevin Rodrigues, CeNTI

Kevin Rodrigues has a Master degree in Chemical Analysis and Characterization Techniques and is Licentiate in Biochemistry from the University of Minho. Currently works as a researcher at CeNTI's Smart Materials team. During his training he acquired knowledge in the characterization and analysis of materials, developing more profound knowledge in the characterization of chemical formulations for fibre to rubber adhesion. Therefore, he acquired experience in fibre impregnation processes, chemical formulations characterization and morphologic and mechanical characterization of fibres and composites. During his professional experience, he acquired knowledge in printed electronic technologies for the development of sensors, actuators and devices in different substrates, acquiring also knowledge in the development of smart textiles and smart composites.

14.4 Dr Emanuel Carlos, UNINOVA

Emanuel Carlos finished his PhD in February 2021 in Nanotechnologies and Nanoscience's, NOVA University Lisbon. He has been working in solution-based metal oxide electronics since 2015, focusing on sustainable materials and technologies. His work involves the design, deposition, and characterization of solution-based metal oxide thin films, fabrication, and characterization of electronic devices. He is co-author of more than 15 peer-reviewed papers (h-index=10, 536 citations, October 2021) in high-impact journals and 2 book chapters in this area. He has been participating in national (Neuroxide) and international (i-Flexis, 1D-NEON, SuperSmart, DIGISMART, FOXES) research projects in the area, with academia and industry.

14.5 Cristina Furtado, CeNTI

Cristina Furtado has a master's degree in Physics Engineering from the Faculty of Sciences of the University of Porto and has been working as a researcher at CeNTI since 2020. Currently, she integrates the Smart Materials area, being focused on developments related to the printed electronics branch and project management. In this scope, the work that she has been developing is related to the production of printed devices for different applications, as sensing systems (temperature, humidity, strain, capacitive), electroluminescent devices and heating systems. She has been involved in several R&D projects, giving her the opportunity to acquire a solid knowledge regarding the design, integration, and production of printed systems, as well as the characterization techniques of these devices.

SESSION 14: APPLICATIONS & SUSTAINABILITY

14.1 WEARPLEX – Printed Wearable Multiplexed Electrodes Using Electrical Stimulation and Electrophysiological Recording Arrays

Dr Russel Torah, University of Southampton (Invited)

WEARPLEX is a multidisciplinary research and innovation action with the overall aim to integrate printed electronics with flexible and wearable textile-based biomedical multi-pad electrodes. It aims to answer the growing need for user-friendly electrodes for pervasive measurement of electrophysiological signals and application of electrical stimulation. It focuses on the development of the printable electronics and manufacturing processes for textile based multi-pad electrodes with integrated logic to facilitate the creation of new products for the healthcare and lifestyle markets.

14.2 From cradle to grave – How Flexible Electronics can Enable a more Sustainable Future

Joshua Young, OE-A (PragmatiC) (Invited)

Moore's law shows that the number of transistors in integrated circuits doubles every two years, following the demand for higher performance devices at any cost. Leading semiconductor manufacturers TSMC and Intel now have a greater carbon footprint than General Motors. We are therefore becoming increasingly aware of the extensive use of energy and resources required within semiconductor manufacturing and the overall impact on our environment. 74% of Apple's total carbon emissions today come from the electronics manufacturing of their products, and more than half of this is from the integrated circuits alone.

While flexible electronics can't provide the same level of complexity and performance, they do have the potential of having a significantly low carbon footprint to produce. Current developments and efforts in flexible integrated circuits create an opportunity to design electronics for sustainability and tackle use cases with 'good enough' performance that isn't possible with conventional semiconductor devices.

The most significant sustainability opportunities will be highlighted and compared across a device's lifecycle - with examples from manufacturing, the supply chain, in-market use cases, to end of life, supporting a path to a more sustainable future.

14.3 Printed Wind Sensors for Urban Wind Turbines

Kevin Rodrigues, CeNTI

Authors: Joana Diniz da Fonseca (1), Sarah Brito Bogas (1), Alexandre Fonseca (1), Miguel Peixoto (1), Kevin Rodrigues (1), Cristina Furtado (1), Daniela Campanhã (1)
(1) CeNTI

The exponential increase in energy consumption, associated with population growth, inevitably causes an increase in the demand for fossil fuels, responsible for several environmental problems. Thus, there has been a growing need to resort to renewable sources, capable of replacing currently existing sources and reducing the associated environmental issues. The wind is described as an alternative energy source with high potential and can be used in industrial, agricultural, or urban applications. A conventional turbine starts operation and produces energy with 10 km/h wind speeds and safely turns off at 90 km/h. For wind speed monitorization, commercial anemometers are used, however, it is quite expensive and susceptible to mechanical degradation. Thus, within the scope of the Baterias2030 project, a flexible and printed flow sensor is being developed.

This work aims the development of a wind flow sensor manufactured by screen printing techniques that meet the market needs, with flexible properties, and manufactured with methods capable of being scalable for industrial production. The developed sensor is a multilayer device based on the calorimetric measuring principle.

The sensing system consists of conductive Ag tracks and printed thermistors using homemade new PTC or NTC formulations based on polymeric solvents combined with conductive or semiconductive nanoparticles, depending on the thermistor typology. Each element presents similar temperature – electrical resistance performance, thus enabling a controlled utilization as sensing and active elements for thermal flow sensing.

For the experimental setup a wind tunnel was designed and to obtain the desired laminar flow the dimensions were adjusted to obtain the correct Reynolds Number (Re). Both flow velocity value and direction were successfully extracted, and the results were consistent with the commercial anemometer values.

The performance of the developed flow sensors proved that the proposed device has appropriate characteristics suitable for measuring wind flow in wind turbines in where robust devices with easy implementations are required. Furthermore, the fabrication methods involved offer the possibility for production at a large scale, with a reduction of the costs usually associated with the development of these devices.

This work was developed in the scope of Baterias2030 project (POCI-01-0247-FEDER-046109) which was co-financed by Portugal 2020, under the Operational Program for Competitiveness and Internationalization (COMPETE 2020) through the European Regional Development Fund (ERDF).

14.4 Printed Metal Oxides: A Demand for Sustainable Electronics

Dr Emanuel Carlos, UNINOVA

Authors: Dr Emanuel Carlos (1), Rita Branquinho (1), Jaakko Leppäniemi (2), Ari Alastalo (2), Jonas Deuermeier (1), Rodrigo Martins (1), Elvira Fortunato (1)
(1) UNINOVA
(2) VTT

Nowadays, the number of electronic devices that each person has is quite impressive and it tends to increase exponentially in the next 30 years. This will lead to a high quantity of electronic waste accumulation that will not be recycled and will most likely end in landfills of developing countries. To overcome this serious societal problem, it is necessary to rethink the production process of some electronic devices and to reconsider their life cycle assessment, more specifically their environmental footprint. Printed electronics can be a solution and its market is expected to have a compound annual growth rate of 21.5 % from $7.8 billion in 2020 to $20.7 billion by 2025. By adopting more sustainable materials and processes electronics waste is reduced, leading to the reduction of the carbon footprint, and paving the way for green electronics. Printed metal oxides fulfill these requirements and have been considered as key to surpass the high production costs, materials' waste and still allow large-area production. However, some challenges remain on printing efficient and stable eco-devices using a low thermal budget and high-throughput compatibility.

In this work, suitable processes and materials are developed to assure the upscale of metal oxide-based devices to printing industry levels.[1-3]These devices will lead to great societal impact since they can power up the speed and efficiency of lighter and thinner wearable applications, highly needed for the emergent IoT. To reach a real product in the near future these printed metal oxide devices should be combined with silicon integrated circuits, also called hybrid electronics. This will be crucial to achieve high performance and sustainability standards.

References
[1] Carlos E, Leppäniemi J, Sneck A, Alastalo A, Deuermeier J, Branquinho R, Martins R and Fortunato E 2020 Printed, Highly Stable Metal Oxide Thin-Film Transistors with Ultra-Thin High-κ Oxide Dielectric Adv. Electron. Mater. 61901071
[2] Carlos E, Deuermeier J, Branquinho R, Gaspar C, Martins R, Kiazadeh A and Fortunato E 2021 Design and synthesis of low temperature printed metal oxide memristors J. Mater. Chem. C 1 3777
[3] _Carlos E., Branquinho R., Jansson E., Leppäniemi J., Menezes J., Pereira R., Deuermeier _J., Alastalo A., Eiroma K., Hakola L., Fortunato E. and Martins R. _submitted 2021 Printed Zinc Tin Oxide Diodes: From Combustion Synthesis to Large-Scale Manufacturing _Flex. Print. Electron._

14.5 Printed Devices for the Future of Automotive Human-Machine-Interface

Cristina Furtado, CeNTI

Authors: Duarte Nuno Ferreira Dias (1), Daniela Campanhã (1), Vanessa Miranda (1), Felipe Afonso (1), Isaque Sá (1), Francisco Vieira (1)
(1) CeNTI

Nowadays, cars are increasingly customized, and manufacturers are progressively adapting interior features to distinguish between models and from other brands. Therefore, there are extensive opportunities for printed/ flexible electronics to add functionality to the cockpit while promoting an efficient manufacturing. Examples include more and higher performance displays, innovative control interfaces, and general improvement of the aesthetics with organic designs and integrated functionality. On the other hand, the combination of printed electronics and the automotive interior offers several advantages, such as low weight, low cost, and a higher innovation prospect.

In this way, deposition of functional inks after 3D structure manufacture also presents advantages since several functional inks can be used besides inks compatible with the injection moulding process, which allows the diversification of the automotive interior functionalities. This has encouraged R&D on the design and production of highly decorative and functional polymeric parts. The present work has been carried out within the scope of VINCI7D project, which intends to incorporate functional and interactive properties by printing directly onto 3D structures through robotic printing. Functional devices as lighting, sensing and haptic feedback systems are proposed to achieve an improved and distinctive human-machine-interface (HMI), without resorting to conventional devices or complex designs.

The main advantage of these functional 3D structures is the differentiation of the HMI, which can be specifically targeted for the final user's needs, providing an improved experience (mainly sensory) by anticipating and following the new market trends of automotive industry.

From printing directly on the injected piece, a clean design and a distinguished user´s experience are also achieved, being the main features the ventilation and temperature control through capacitive sensors with the respective values being displayed through a numeric electroluminescent display. Additionally, a capacitive slider is integrated for the selection of functions on the central display of the car, joined with an haptic feedback device to provide a sensory response to the user.

As for the materials used in the production of the proposed functional devices, conductive, electroluminescent, and dielectric inks were used for the above-mentioned developments, guaranteeing their compatibility for further application on the 3D substrates using printing technologies. In the end, the electroluminescent, piezoelectric, and capacitive device's performance were evaluated using control electronics according to the final application.

This work was developed in the framework of VINCI7D project (n.45102), which was co-financed by Portugal 2020, under the Operational Program for Competitiveness and Internationalization University of Manchester(COMPETE 2020) through the European Regional Development Fund (ERDF).

SESSION 15: POSTER & SPEAKER PRIZES

Speaker Prize

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Poster Prize

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SiSTEM Technology

SESSION 16: POSTERS

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16.1.1 Sheng Yong, University of Southampton

Sheng Yong is a research fellow in Smart Electronics and Material Group, the School of Electronics and Computer Science at the University of Southampton, UK. He received BEng degree in Electrical &Electronic Engineering in 2011 from the Imperial College London, his MSc degree in Microelectromechanical systems (MEMS) in 2012 and his PhD degree in fabrication and characterization of fabric supercapacitor in 2017 from the University of Southampton, UK. His current research focuses on functional material formulation for e-textile, at the same time, developing energy storage device for printed e-textiles, such as, supercapacitor, primary and secondary batteries, hybrid battery–supercapacitor energy storage device. Sheng can be reached by phone at +44 (0)23 8059 3119 or by email at sy1v16@soton.ac.uk.

16.1.2 Dimitrios Simatos, University of Cambridge

Dimitrios is a final year PhD student at the University of Cambridge, with degrees in Nanotechnology and Electrical Engineering.

16.1.3 Steve Haws, University of Cambridge

Steve graduated in chemistry from York University and joined GEC's Central Research Laboratory in London. Over 12 years he managed semiconductor R&D/pilot process facility while also researching new processes and devices initially in CMOS/SOS but mostly later in psi AMLCD. The culmination of this was a 1 year project that successfully delivered the largest full colour video psi AMLCD. After an MBA at Durham University a life in business beckoned but one that involved the technical and commercial development of the latest semiconductor and related technologies. He has managed the Ambient Cluster facility for 4 years and this covers all aspects of maintaining and developing an effective R&D platform including maintenance, H&S, training and baseline process development. Very interested in opportunities that further expand industry and external academic participation in the Ambient Cluster.

16.1.4 Miriam Seiti, KU Leuven

Miriam Seiti is a Ph.D candidate in Additive Manufacturing for bioelectronics and tissue engineering. Miriam's research focus is on the development of innovative 3D neuronal scaffolds and related additive manufacturing technology for multi-material / multi-functional printing. This includes the use of aerosol jet- and syringe extrusion- based printing technologies.

16.1.1 Flexible Supercapacitor in Textile for Wearable Electronics

Sheng Yong, University of Southampton

Authors: Sheng Yong (1), Stephen Beeby (1)
(1) University of Southampton

In order to meet our ever-increasing demand for energy whilst also addressing the concerns of climate change it is necessary to shift away from the burning of fossil fuels towards greener sources of energy generation. Consequentially, it is foreseen that solar power will contribute significantly to our future energy supply. Currently, most solar energy generation relies on silicon-based photovoltaic (PV) technologies. Whilst the cost of silicon PV has dropped significantly over the past decade, it still has some downsides. For example, the relatively high weight of silicon PV increases installation costs, limits potential applications, and presents environmental concerns associated with shipping and transportation. One technology that has the potential to overcome many of the limitations of silicon PV is organic PV (OPV). OPV devices are comparatively much lighter, are solution processable and can be fabricated with less energy intensive methods on both flexible and rigid substrates. OPV device efficiencies are also rapidly increasing and are now approaching 20% under AM1.5G conditions, bringing increased commercial interest. However, for the successful commercialisation of OPV to be realised, several stumbling blocks remain. One of the major outstanding challenges facing OPV is the difficulty in translating the high device performances achieved with small-scale laboratory manufacturing methods over to larger area, industrially compatible methods. In this work we study a polymer:non-fullerene OPV system and, through a range of advanced characterisation techniques, including the use of high-resolution multi-mapping methods, we attempt to unravel the reasons behind the differing performances of spin-coated, doctor-blade coated and slot-die coated devices. Further, we show that through careful optimisation of the slot-die coating process it is possible to drastically narrow the efficiency gap between the different coating methods and we explain the reasons behind the improved performance.

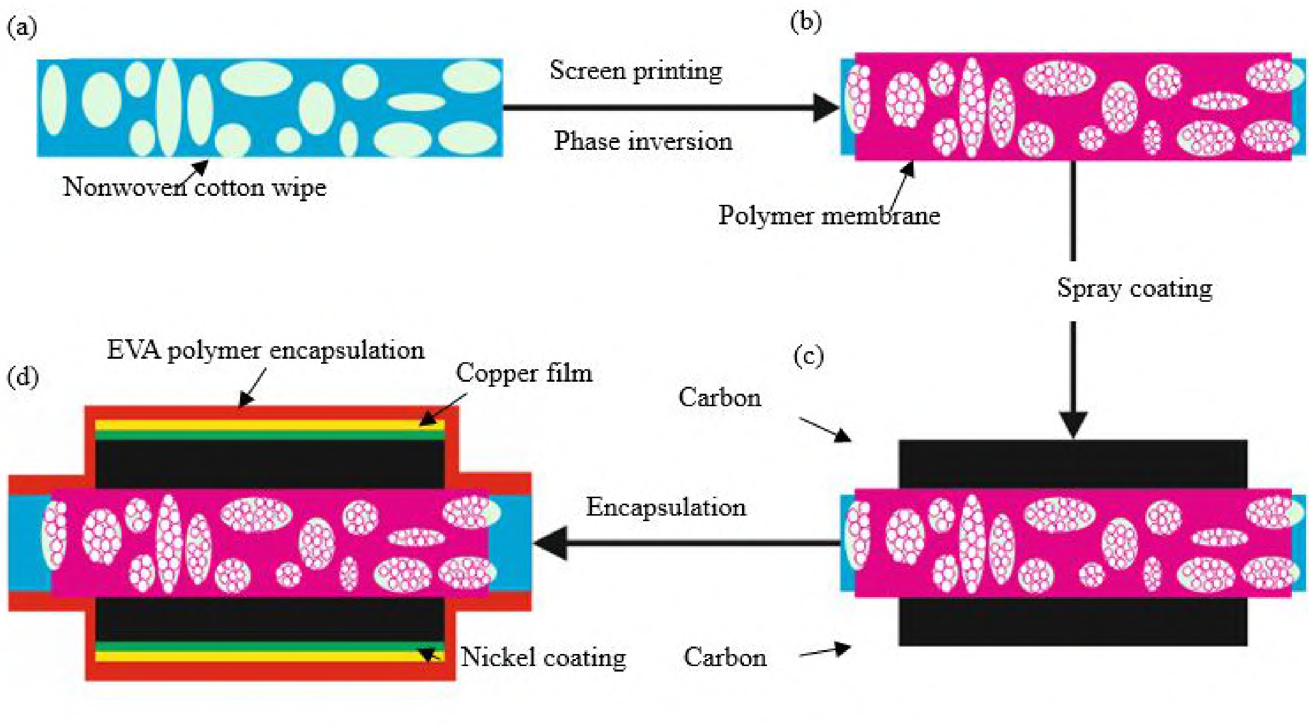


Fig. 1: Fabrication process of textile supercapacitor.

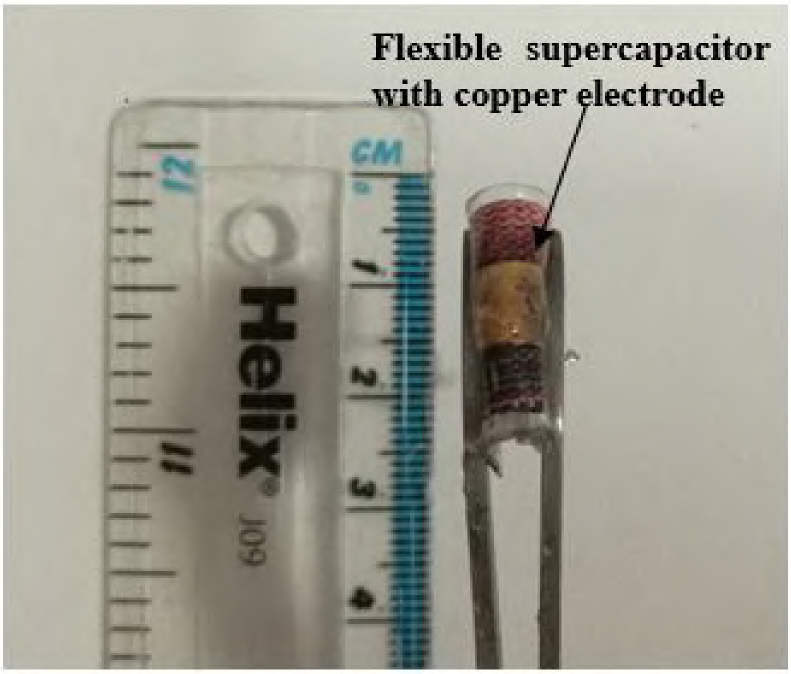


Fig. 2: Flexible supercapacitor under 180 degrees of bending conditions

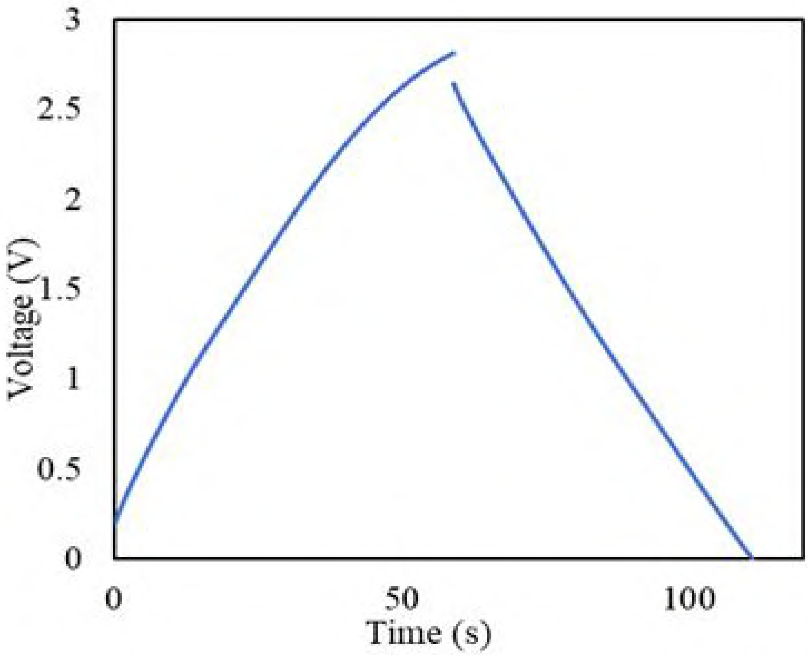


Fig. 3: Galvanostatic cycling tests (1 $mA.cm^{-2}$)

16.1.2 Effects of Processing-Induced Contamination on Organic Electronics Devices

Dimitrios Simatos, University of Cambridge

Organic (opto)electronics is a field of research that has enabled the creation of semiconductor devices made from a variety of aromatic compounds, such as conjugated polymers and small molecules. Owing to their softness, stretchability, low fabrication cost, and their ability to conduct both electrons and ions, these organic electronic devices have been applied in a broad range of applications from large-area flexible displays and electronics to bioelectronics, photovoltaics and thermoelectrics. Organic electronic devices can be solution processed and printed, and are often marketed as easy to fabricate and defect-tolerant, without requiring the scrutiny and cleanliness of their inorganic counterparts. There is some literature on how contaminants may affect the energy levels of organic materials, induce hysteresis, or about how fabrication- and storage-induced contamination affect a device's electrical stability. However, there are few experimental techniques available to monitor contaminants at device relevant levels, and the presence of contaminants during processing or their incorporation into the thin films is usually not monitored. It is surprising that not more attention is paid to this. In the field of biology it is well known, for example, that the same disposable plasticware used to fabricate organic electronics can contaminate biological experiments, by leaching contaminants that can affect growth of cell cultures and activate or inhibit various enzymes. Some of the leachables have plasticizing properties, just like molecular additives used for stabilization, which suggests that they can affect the polymer's free volume. In the past, mass spectrometry has been used to detect contaminants in aqueous solutions, whereas nuclear magnetic resonance (NMR) spectroscopy has been used to detect contaminants in thin films. In this work, we use NMR spectroscopy to detect and quantify contaminants in solutions and thin films, and trace their origin to the glovebox atmosphere and laboratory consumables commonly used during film processing, including disposable needles, plastic pipettes and plastic syringes. An in-depth understanding of the sources of contamination during organic electronic device fabrication allows us to establish clean fabrication protocols, and make contamination-free samples. We investigate how re-introducing the identified contaminants as additives in a controlled manner can affect the thin-film processing behavior and the electrical properties of organic electronic devices. Our study highlights the role of unintentional contaminants in organic electronic devices, and demonstrates that certain stringent processing conditions need to be met so as to avoid scientific misinterpretation, ensure device reproducibility, and facilitate performance stability.

16.1.3 Royce Ambient Cluster

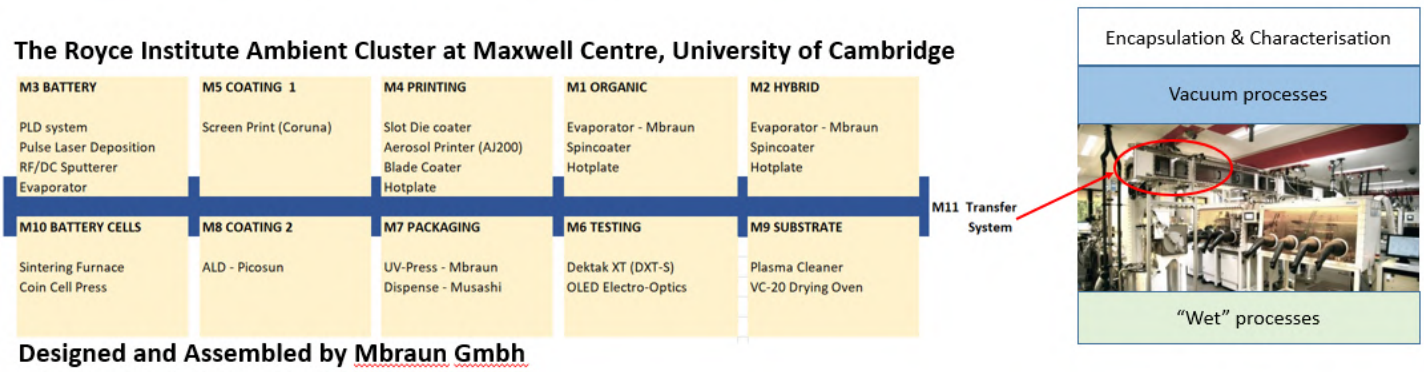
Steve Haws, University of Cambridge

Authors: Steve Haws (1), Henning Sirringhaus (1)
(1) University of Cambridge

In the development of various low temperature LAE materials and device technologies it can often be the case that some or all of the device stack are sensitive to O2 and H2O and requires processing up to encapsulation in a dry inert environment.

As part of the Henry Royce Institute hosted by the University of Cambridge we have set up a uniquely configured ambient processing cluster tool that comprises 11 interconnected process modules for a wide range of deposition methods, such as vacuum evaporation, atomic layer deposition, pulsed laser deposition as well as various printing techniques, which are all under a dry N2 or dry Ar ambient. Through a transfer system samples can be transferred under inert atmosphere between the individual glovebox modules. This enables complete processing finishing with encapsulation without exposure to ambient atmosphere.

The talk will describe the capabilities of the tool and illustrate them with results of various research projects in the areas of organic PV, organic LEDs, perovskite PV, battery materials, artificial photosynthesis and organic electronics.



16.1.4 Aerosol Jet® Printing on Non-Traditional Substrates: A Product-Process Development Flow

Miriam Seiti, KU Leuven

Authors: Miriam Seiti (1), Akash Verma (1), Eleonora Ferraris (1)
(1) KU Leuven

Aerosol Jet®Printing (AJ®P) is a relatively novel, direct-writing printing technique of functional materials for applications predominantly in the printing of electronics (PE) industry. Moreover, due to the ability to print biomaterials, the application spectrum stretches beyond electronics and reaches towards bioelectrical and tissue engineering. AJ®P can indeed print diverse functional materials, such as metal-based nanoparticle inks (silver, copper), conductive polymers (Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), Polyaniline (PANI)), biomaterials (collagen, gelatin), and dielectrics. The printing can be performed on mostly any substrate: rigid (FR4 board, glass), flexible (Indium tin oxide (ITO), poly(ethylene terephthalate) (PET), Kapton), and stretchable (Thermoplastic Urethane (TPU), silicone Polydimethylsiloxane (PDMS) foils) patterns. The class of substrates also includes metal sheets (Al foil), ceramic sheets, injection-moulded Acrylonitrile butadiene styrene (ABS), and fibre-based paper substrates. Besides, due to the exponential increase in the usage of Additive Manufacturing (AM) techniques, the portfolio of PE substrates has been extended to Fused Filament Fabricated (ABS, Polylactic acid (PLA)), and stereolithography-based resins. Along with rise in the usage of AJ®P, some substrates (glass, FR4, Al, …) have been more often used and exploited than others (plastics, paper,...) due to their ease of usage.

In this work, opportunities and challenges of some of the above-mentioned special substrates are investigated in terms of: i) ink-substrate interaction (by determining the surface energy of the substrates via the OWRK model, scotch tape adhesion, and wettability tests); ii) electrical properties (namely sheet resistance via 4-point method), and iii) ability to withstand thermal sintering (by visual inspection). Ink-substrate interaction measurements can indeed predict the behavior of a substrate with regards to an ink prior to actual printing, while sheet resistance measurements can support the theoretical design of printed patterns as from targeted applications. The ability to withstand thermal sintering is also a key parameter for substrates. Special substrates, like paper or ABS, are prone to structural modifications just above 100°C, thus demanding either low temperature sintering (<150°C) for long time (e.g. 1 hour), or the use of alternative inks and sintering methods (like photonic sintering, cold plasma sintering, UV sintering, etc.), hence laying new technological challenges and material science demands. The contribution of the surface roughness on the conductivity and wettability of printed patterns is also investigated. As a result, it is demonstrated that paper like and porous substrates with high surface roughness (2-3 µm) induce higher resistances compared to smoother papers (~500 nm). All analyses were performed using a silver nanoparticle ink (Novacentrix, USA), being the most standard commercial PE ink.

This work is a first step towards the generation of a numerical database as a decision-making tool prior to actual printing to support the development of printed applications, with respect to substrate pre-treatment, ink selection, pattern designs, fine tuning of print parameters, hence mitigating the product-process time, material loss and production cost at industrial level. This will ultimately allow to expand the use of special substrates to further novel industrial applications (e.g. printing on paper as a temperature indicator for smart packaging solutions).

SESSION 16.2: POSTERS - HIGH PERFORMANCE MATERIALS

16.2.1 Marcin Gwiazda, University of Manchester

Marcin Gwiazda graduated Master Degree in Materials Science and Engineering at the Warsaw University of Technology in Poland, specialized in Biomaterials in 2018. His master degree project was related to the fabrication and characterization of tissue engineering scaffolds in the application for the implant of the anterior cruciate ligament. In addition, he attended the international internship programs as a research fellow in Menzies Health Institute Queensland at Griffith University, Gold Coast, Australia and National Institute for Materials Science, International Centre for Materials Nanoarchitectonics in Tsukuba, Japan. Currently, he participates in the Central of Doctoral Training program (CDT) in Advanced Biomedical Materials. He is a PhD student under the supervision of Professor Michael Turner in the Organic Materials Innovation Centre (OMIC) at the University of Manchester. His research is based on the synthesis of the Conjugated Polymer Nanoparticles through the Suzuki-Miyaura cross-coupling polymerisation in the application for a photosensitive platform for future retina prosthesis.

16.2.2 Emilie Gerouville, University of Southampton

Emilie Gerouville holds a Bachelor's in Chemistry from the Université Libre de Bruxelles, where she started learning about material chemistry. To deepen her knowledge and broaden her scientific horizons, she participated in an international Master's in Chemistry. During these two years, she studied in Lille (France), Leipzig (Germany) and Krakow (Poland), where she prepared her Master's Thesis: studying carbon based nanoparticles using Raman spectroscopy. Emilie is currently preparing a PhD, in the Centre for Electronics Frontiers at the University of Southampton. She is working on using polyoxometalates (POMs) to create resistive memory devices.

16.2.3 Zixing Peng, University of Manchester

Zixing Peng received his BS and MS (2020) degrees at the school of Materials Science and Engineering, South China University of Technology. In 2021, he joined Prof. Cinzia Casiraghi group as a PhD candidate under the CSC scholarship. His research interest focuses on the design, preparation, and electrical performance investigation of two-dimensional based printed devices.

16.2.4 Dr Jack McGhee, University of Manchester

Dr Jack McGhee completed his master's in chemistry at Loughborough University in 2015. He then continued his studies at Loughborough University's Design School working with Dr Darren Southee and Peter Evans as part of the EPSRC grant "Sustainable Manufacturing of TCO Inks and Thin Films" into developing 2D and 3D printable inks using conductive metal oxides for passive electronics and sensor applications. His research included printed temperature and humidity sensors and methods for the rapid fabrication of printed metal oxide nanowires using laser-based post processing. After completion of his Ph.D., he joined the EPSRC grand challenge project SYMETA in Loughborough University's Wolfson School of Mechanical, Electrical and Manufacturing Engineering working with Prof. Yiannis Vardaxoglou, developing manufacturing methods for 3D printed meta-atoms, electromagnetics, and metamaterials. Following this position, he now performs research within Prof. Cinzia Casiraghi's group within the Department of Chemistry at Manchester University researching graphene-based printed temperature sensors.

16.2.1 Optimisation of the Synthesis of Conjugated Polymer Nanoparticles by Suzuki-Miyaura Polymerisation via Miniemulsion for Future Application in the Eye Retina Prosthesis

Marcin Gwiazda, University of Manchester

Authors: Marcin Gwiazda (1), Michael Turner (1), Simon Webb (1)
(1) University of Manchester

Nowadays, the increasing number of the global prevalence of different types of retinal diseases such as retinal pigmentosis and age-related macular degeneration (AMD) is an essential challenge for regenerative medicine. It was noted the significant growth of the total number of AMD cases in the UK from approximately 600,000 to 700,000 in 2020, which was especially observed for the older population. Moreover, the current trend of the ageing population requires appropriate effective systems of retina implants to restore vision. Consequently, the main aim of the planned research is to develop a novel approach to functional eye retinal prostheses based on the application of photosensitive conjugated polymer nanoparticles (CPNs) with the light absorption relating to the native photoreceptors rods and cones. It was demonstrated the initial results of the synthesis of the CPNs through the Suzuki-Miyaura cross-coupling polymerisation via miniemulsion for three types of the selected materials corresponding following receptors: poly(9,9-dioctylfluorene-alt-bithiophene) (PF8T2) for rods, poly (9,9-di-n-octylfluorenyl-2,7-diyl) (PFO) for blue S-cones, and poly(3-hexylthiophene-2,5-diyl) (P3HT) for green M-cones. According to the received results, it was conducted optimization process of the polymerisation to obtain CPNs with an average size below 100 nm, and an average molecular weight of more than 15 kDa. Furthermore, the obtained CPNs will be incorporated in the biocompatible aqueous inks and deposited with selected patterns by the ink-jet printing onto the flexible polymer substrate to deliver final soft organic electronic devices. The performance of these devices to detect incident visible light with high photosensitivity will be examined and the ability to transduce the optical input into an electrical signal to trigger retinal neurons and hence deliver an optical nerve response will be assessed. The high advantage of this approach is related to the application of the uniform photosensitive electrode with desirable patterns of the CPNs printed on an array to directly mimic the structure of the natural human retina and enable visions of different colours. The proposed system can significantly improve the biocompatibility with retina ganglion cells (RGCs) with relatively low stiffness in comparison to the current epi- and sub-retinal silicon photodiode retina prosthesis. In addition, the performed study could be potentially used in the future soft organic retina implant with NIR or UV absorbing chromophores, which allows obtaining the continuous hyperspectral imaging response of the detected light with different wavelengths of the visible region, and it can considerably enhance the neural stimulation to improve visual perception.

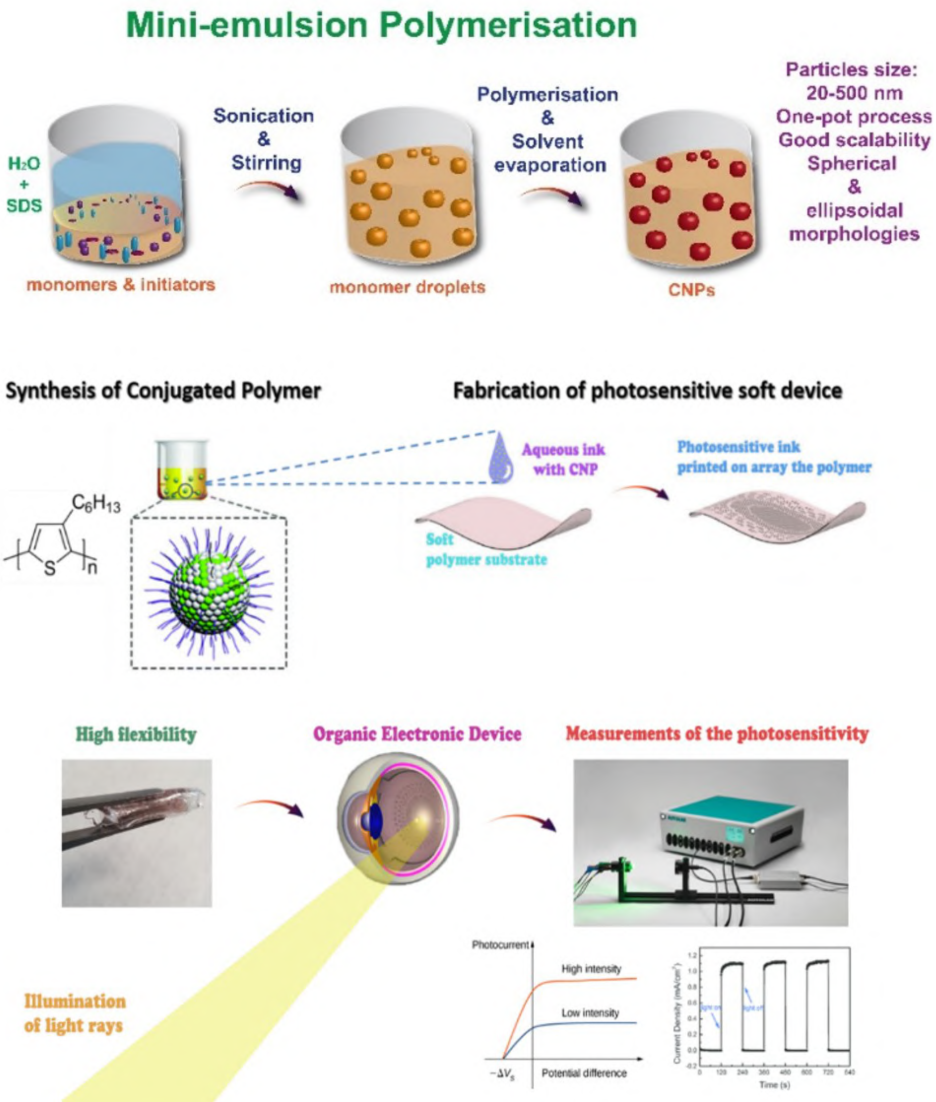
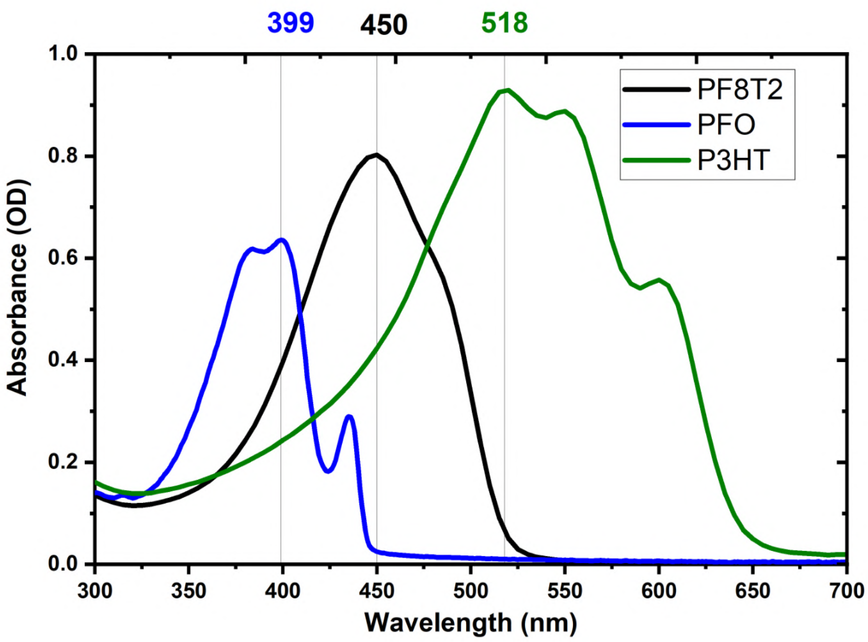

Mini-emulsion Polymerisation
H_2O + SDS
monomers & initiators
Sonication & Stirring
monomer droplets
Polymerisation & Solvent evaporation
CNPs
Particles size: 20-500 nm
One-pot process
Good scalability
Spherical & ellipsoidal morphologies
Synthesis of Conjugated Polymer
Fabrication of photosensitive soft device
Aqueous ink with CNP
Photosensitive ink printed on array the polymer
Soft polymer substrate
High flexibility
Organic Electronic Device
Measurements of the photosensitivity
Illumination of light rays
Photocurrent
High intensity
Low intensity
Potential difference

Fig 1


399
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518
PF8T2
PFO
P3HT
Absorbance (OD)
Wavelength (nm)
1.0
0.8
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0.4
0.2
0.0
300
350
400
450
500
550
600
650
700

Fig 2

16.2.2 Polyoxometalate-Based Nanoscale Electronic Devices

Emilie Gerouville, University of Southampton

Authors: Emilie Gerouville (1), Themis Prodromakis (1), Dimitra Georgiadou (1)
(1) University of Southampton

Polyoxometalates (POMs) are a class of inorganic, ionic (usually anionic), nanometer-sized metal oxide molecules. They present many attractive inherent properties, such as chemical stability in temperatures ranging from -150°C to 195°C, ease of processing using water-based solvents, structural diversity, facile functionalisation, and ability to exchange reversibly multiple electrons without much structural change (rich redox properties)[1]. Because POMs can accept electrons, they support oxygen vacancy migration. This attribute can be used to form/ disrupt conductive filaments between two electrodes, which is relevant to the operation of resistive memory devices. Therefore, POMs can be used to create molecular memristors[2]

Herein we demonstrate resistive switching behaviour at low voltages for a number of POM-based devices ($H_3PW_{12}O_{40}$ and $H_3PMo_{12}O_{40}$). We achieved this by spin-coating or drop casting these POMs solutions into a nanogap (∼10 nm) between coplanar Al and Au electrodes. These electrodes were patterned using adhesion lithography (a-lith), a low-cost, high-throughput and large-area fabrication technique, compatible with both rigid and flexible substrates[3].

Our preliminary results indicate that multi-state memory behaviour is within reach with these materials, while we also present molecular self-assembly approaches to better control the resistive switching at the nanoscale. Since only a few electrons are required to function, these devices hold promise for low power consumption and high speed operation. With molecular memories being increasingly studied owing to their potential to solve issues with traditional electronic devices, such as severe leakage current caused by the reduction in cell dimensions and inhomogeneous doping, POM-based memories research is very timely.

References:
Chen, X.; Zhou, Y.; Roy, V. A. L.; Han, S.-T., Evolutionary Metal Oxide Clusters for Novel Applications: Toward High-Density Data Storage in Nonvolatile Memories. Advanced Materials 2018, 30 (3), 1703950.
Busche, C.; Vilà-Nadal, L.; Yan, J.; Miras, H. N.; Long, D. L.; Georgiev, V. P.; Asenov, A.; Pedersen, R. H.; Gadegaard, N.; Mirza, M. M.; Paul, D. J.; Poblet, J. M.; Cronin, L., Design and fabrication of memory devices based on nanoscale polyoxometalate clusters. Nature 2014, 515 (7528), 545-549.
Semple, J.; Georgiadou, D. G.; Wyatt-Moon, G.; Yoon, M.; Seitkhan, A.; Yengel, E.; Rossbauer, S.; Bottacchi, F.; McLachlan, M. A.; Bradley, D. D. C.; Anthopoulos, T. D., Large-area plastic nanogap electronics enabled by adhesion lithography. npj Flexible Electronics 2018, 2 (1), 18.

16.2.3 Hysteresis Study in Fully Printed Heterostructures Made of 2D Materials

Zixing Peng, University of Manchester

Authors: Zixing Peng (1), Cinzia Casiraghi (1)
(1) University of Manchester

Two-dimensional (2D) crystals are a new class of materials exhibiting excellent electrical, optical, thermal and mechanical properties. Furthermore, they can be easily processed in solution and assembled into heterostructures by using simple and low-cost fabrication techniques such as ink-jet printing [1]. While several types of devices have been reported so far [2-4], hysteresis effects have been hardly studied and reported in the literature.

Here we investigate hysteresis in fully printed 3 layers heterostructures, composed by a bottom electrode, a semiconducting film and a top electrode. The inks were produced as described in Ref. 1. Silver or graphene were used as bottom electrode, while MoS_2 was used as middle layer. The effect of post-processing was also investigated under two different conditions: step-by-step annealing, i.e. annealing is performed after printing each layer of the heterostructure; and annealing of the whole device after complete fabrication. The printing direction, number of printed passes, etc were also investigated. The electrical characteristics have been measured by changing the sweep rate and using several cycles (up to 10). We found that devices made by using graphene as both bottom and top electrodes do not show significant hysteresis, in particular after step by step annealing; in contrast, the use of silver induces hysteresis effects, which are enhanced after step-by-step annealing, in agreement with literature [5].

References
[1] McManus, D., Vranic, S., Withers, F., Sanchez-Romaguera, V., Macucci, M., Yang, H., Sorrentino, R., Parvez, K., Son, S. K., Iannaccone, G., Kostarelos, K., Fiori, G., & Casiraghi, C. (2017). Water-based and biocompatible 2D crystal inks for all-inkjet-printed heterostructures. Nature Nanotechnology, 12(4), 343–350. https://doi.org/10.1038/nnano.2016.281
[2] Worsley, R., Pimpolari, L., McManus, D., Ge, N., Ionescu, R., Wittkopf, J. A., Alieva, A., Basso, G., Macucci, M., Iannaccone, G., Novoselov, K. S., Holder, H., Fiori, G., Casiraghi, C. (2018). All-2D material inkjet-printed capacitors: toward fully printed integrated circuits. ACS Nano, 13(1), 54-60. https://doi.org/10.1021/acsnano.8b06464
[3] Conti, S., Pimpolari, L., Calabrese, G., Worsley, R., Majee, S., Polyushkin, D. K., Paur, M., Pace, S., Keum, D. H., Fabbri, F., Iannaccone, G., Macucci, M., Coletti, C., Mueller, T., Casiraghi, C., & Fiori, G. (2020). Low-voltage 2D materials-based printed field-effect transistors for integrated digital and analog electronics on paper. Nature Communications, 11(1), 1-9. https://doi.org/10.1038/s41467-020-17297-z
[4] Pimpolari, L., Calabrese, G., Conti, S., Worsley, R., Majee, S., Polyushkin, D. K., Paur, M., Casiraghi, C., Mueller, T., Iannaccone, G., Macucci, M., & Fiori, G. (2021). 1/f Noise characterization of bilayer MoS_2 field-effect transistors on paper with inkjet-printed contacts and hBN dielectrics. Advanced Electronic Materials, 7(7), 2100283. https://doi.org/10.1002/aelm.202100283
[5] Feng, X., Li, Y., Wang, L., Chen, S., Yu, Z. G., Tan, W. C., Macadam, N., Hu, G., Huang, L., Chen, L., Gong, X., Chi, D., Hasan, T., Thean, A. V. W., Zhang, Y. W., & Ang, K. W. (2019). A fully printed flexible MoS_2 memristive artificial synapse with femtojoule switching energy. Advanced Electronic Materials, 5(12), 1900740. https://doi.org/10.1002/aelm.201900740

16.2.4 Seebeck Coefficient of Printed Graphene-Based Films

Dr Jack McGhee, University of Manchester

Authors: Jack McGhee, Khaled Parvez, Cinzia Casiraghi
(1) University of Manchester

Thermoelectric materials are able to convert heat into electricity or vice-versa. They are therefore very attractive as power can be generated from waste heat, hence helping in reducing CO_2 emission and providing a sustainable technology for power generation. The energy conversion is evaluated by the figure of merit ZT, which depends on the Seebeck Coefficient (SC), the electrical conductivity and the thermal conductivity of the material.

Solution processed graphene is very attractive in printed technologies due to its conductivity, biocompatibility, and ease integration into IoT devices. Furthermore, the surface chemistry and number and type of defects can be easily tuned during chemical exfoliation, hence providing a family of graphene-based inks with tuneable properties.

Here we investigate how the SC is related to the structure and surface chemistry of graphene produced by liquid phase exfoliation and electro-chemical exfoliation [1-2]. Graphene films are inkjet printed on paper and measured in a home-made setup under ambient conditions, between 14 ^{o}C and 80^{o}C. In the case of printed graphene films made by liquid-phase exfoliation, we found an average SC of 38.9 μV/K +/- 1.55 across the measured temperature range, while in the case of electrochemically exfoliated graphene, the SC strongly depends on the processing conditions used during exfoliation.

References
[1] McManus, D., Vranic, S., Withers, F., Sanchez-Romaguera, V., Macucci, M., Yang, H., Sorrentino, R., Parvez, K., Son, S. K., Iannaccone, G., Kostarelos, K., Fiori, G., & Casiraghi, C. (2017). Water-based and biocompatible 2D crystal inks for all-inkjet-printed heterostructures. Nature Nanotechnology, 12(4), 343–350. https://doi.org/10.1038/nnano.2016.281
[2] Parvez, K., Worsley, R., Alieva, A., Felten, A., & Casiraghi, C. (2019). Water-based and inkjet printable inks made by electrochemically exfoliated graphene. Carbon, 149, 213–221. https://doi.org/10.1016/j.carbon.2019.04.047

SESSION 16.3: POSTERS - NOVEL DEVICES & SYSTEMS

16.3.1 Woojo Kim, POSTECH

Woojo Kim received the B.S. degree in electrical engineering from Kyunghee University, Seoul, South Korea, in 2016, where he is currently pursuing the Ph. D. degree in convergence IT engineering. His current research interests include the design and fabrication of flexible and printed electronics circuits and systems.

16.3.2 Akash Verma, KU Leuven

Akash Verma is a Ph.D. researcher in Advanced Manufacturing Lab, KU Leuven. His focus of Ph.D. is Aerosol Jet Printing for printed electronics application like antennas and sensors. Along with it, he is exploring the fundamentals of Aerosol Jet Printing. He did his Masters in Micro and Nano Systems at TU Chemnitz with thesis focusing on stretchable electronics.

16.3.3 Diogo Garcia, Fundació Eurecat

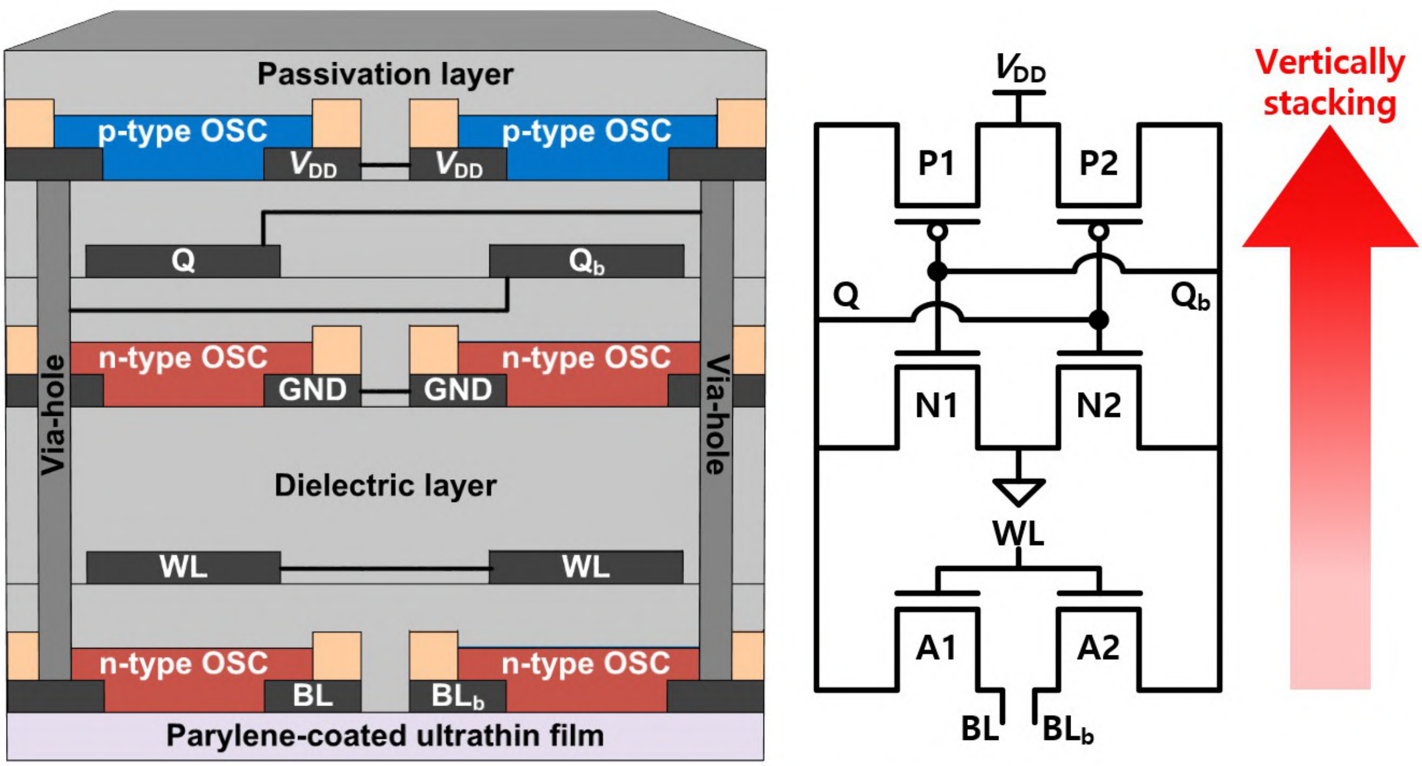
Diogo Garcia is a Materials Engineer currently based in the Printed Sensors and Actuators research group at Fundació Eurecat, in Barcelona (Spain). He obtained his MSc degree in Materials Engineering at NOVA School of Science and Technology|FCT NOVA, Universidade Nova de Lisboa (Portugal) in 2018 and published his MSc thesis results under the title "Large-Area Paper Batteries with Ag and Zn/Ag Screen-Printed Electrodes", a collaboration between Fundació Eurecat and FCT NOVA, in 2019. Since 2018, he is a Marie-Curie PhD fellow within the eSCALED Project (project ID 765376 — H2020-MSCA-ITN-2017) enrolled in the Université de Pau et des Pays de l'Adour (UPPA, France) and Université de Namur (Belgium) under a. His project focus on the development of functional catalytic CO_2/H^+ reduction electrochemical devices for artificial photosynthesis devices. During his PhD project, he has worked 12 months in UPPA, 3 months in a secondment in Collège de France (France), 11 months at Université de Namur and is currently at Fundació Eurecat. His research interests center on energy conversion/storage and electrochemical sensor devices based on functional materials and surface functionalization through printing technology. He aims to focus his research on user-centered design and technology development from basic principles and concepts to market.

16.3.1 Three-Dimensional, Flexible, and Printed Complementary Organic TFTs-Based Static Random-Access Memory

Woojo Kim, POSTECH

Authors: Woojo Kim (1), Sungjune Jung (1)
(1) POSTECH

For intelligent and wearable electronics of the future, printed organic memories should be provided for large-area, low-cost, and light-weight forms as well as high performance. Compared to dynamic random-access memory and nonvolatile memory, static random-access memory (SRAM) has more advantages in terms of fast speed access and storage, strong noise immunity, and low power consumption. SRAMs based on organic semiconductors (OSCs) have been investigated for use in flexible and wearable electronics. However, reported memories are difficult to apply in future intelligent electronics due to their low memory density, low static noise margin, and high operating voltage. Here, we propose a three-dimensional (3-D), flexible, and printed static random-access memory (SRAM) based on complementary organic thin-film transistors (TFTs). The 3-D SRAM exhibited the smallest area of 2.1 mm^2, the highest normalized static noise margin of 62%, and the maximum gain of 16.8 V/V compared to reported values of organic SRAM. The 3-D SRAM cell design enables us to match the strengths of transistors by modifying the dielectric thickness without changing the channel geometry. This high-performance complementary organic thin-film transistors-based SRAM shows its high application potential in large-scale and low-cost wearable intelligent electronics for data storage and processing.



<Proposed 3-D SRAM>

16.3.2 Design and Development of a RFID Assisted Flexible Printed Temperature Threshold Indicator

Akash Verma, KU Leuven

Authors: Akash Verma (1), Jarne Machiels (3), Raf Appeltans, Mieke Buntinx (2), Wim Deferme (2), Eleonora Ferraris (1)
(1) KU Leuven
(2) Hasselt Universiteit
(3) Tape Converters Holland BV

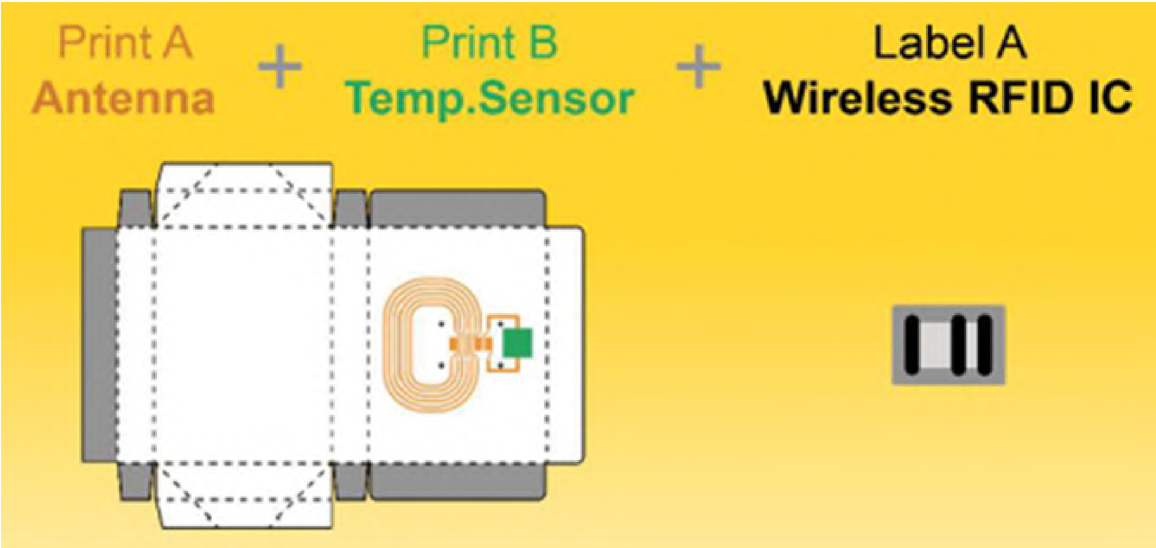
Smart (intelligent) packaging plays an important role in the frozen food industry supply chain process. Besides ensuring protection and containment of the product, it helps to monitor the quality of the product or detect damages, and enables to provide the real-time status of the whole package. A Temperature Threshold Indicator (TTI) label laminated on the package can be implemented as a detection system to communicate any cold chain breach of frozen food.

The TTI consists of a multi-layer system that changes its resistance on a trigger. This trigger will cause an irreversible resistance change of the printed circuit of around 3 orders of magnitude (from insulating to conducting), which can be detected with an electronic readout. An RFID thin-film chip pasted on the top of the label and a printed RFID antenna was used to read the change of resistance. As a case of a multi-layered system, the first deposited layer is a silver nanoparticle ink while the second layer is a polyaniline Emeraldine base. All the layers are printed by Aerosol Jet®Printing on a fibre-based paper substrate. Polyaniline Emeraldine base is a non-conducting polymer, which is blue in appearance. As a trigger for this work, an acetic acid drop is drop casted on the base layer, which turns the base into Polyaniline Emeraldine acid, which is conducting in nature and green in appearance.

In this work, an Aerosol Jet® Printer (AJ®300, Optomec Inc, USA) was used to print an antenna and interdigitated electrodes on fibre-based acid resistance paper substrate (Algo Baress) with silver ink (Metalon A221AE, Novacentrix Inc, USA) as layer 1. For layer 2, an in-house formulated polyaniline ink was deposited with AJP on the top of the interdigitated electrodes. Acid was casted as a later step on the top of Polyaniline Emeraldine base. The polyaniline ink was synthesized based on the selection of different solvents, the molecular weight of Emeraldine base, mixing technique, etc. The printing parameters were optimized for both inks and paper substrates. The paper substrate was chosen for its low-cost, lightweight, recyclability, flexibility, and common availability in the packaging industry.

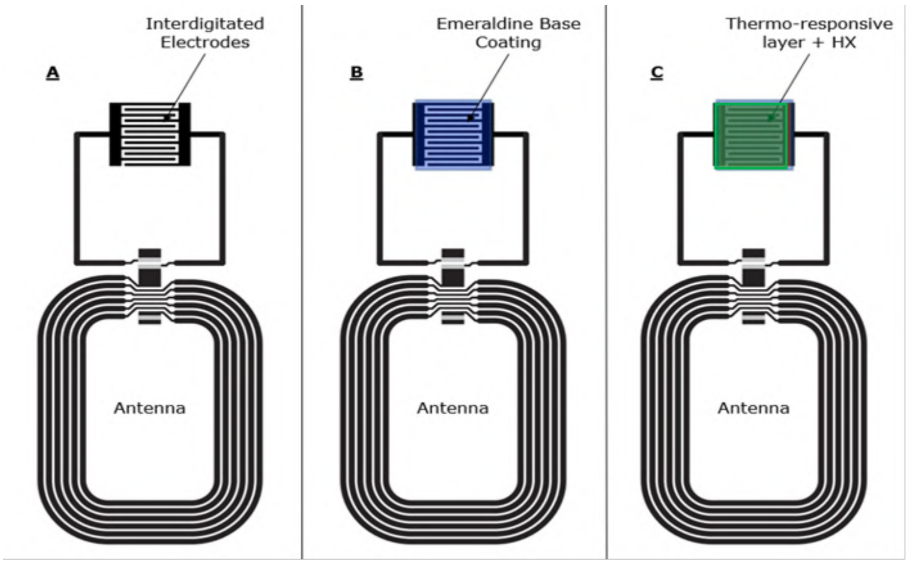
The TTI was successfully printed and validated. This work is one of the novel TTI applications printed using Aerosol Jet® Printing. Such work generates a large potential in the field of smart (intelligent) packaging and will be more cost-effective with high scalability (roll-to-roll printing). As a future work, a frozen acid thermo-responsive layer which releases acid with temperature change can be implemented along with the sensing label for real-life applications.

Fig 1



Components of a Temperature Threshold Indicator (TTI)

Fig 2



STEP 1
Printing of RFID antenna and Interdigitated electrodes with silver ink

STEP 2
Deposition of Emeraldine Polyaniline base over interdigitated electrodes

STEP 3
Acid is casted over polyaniline base turning into salt

Layer structure of a Temperature Threshold Indicator (TTI)

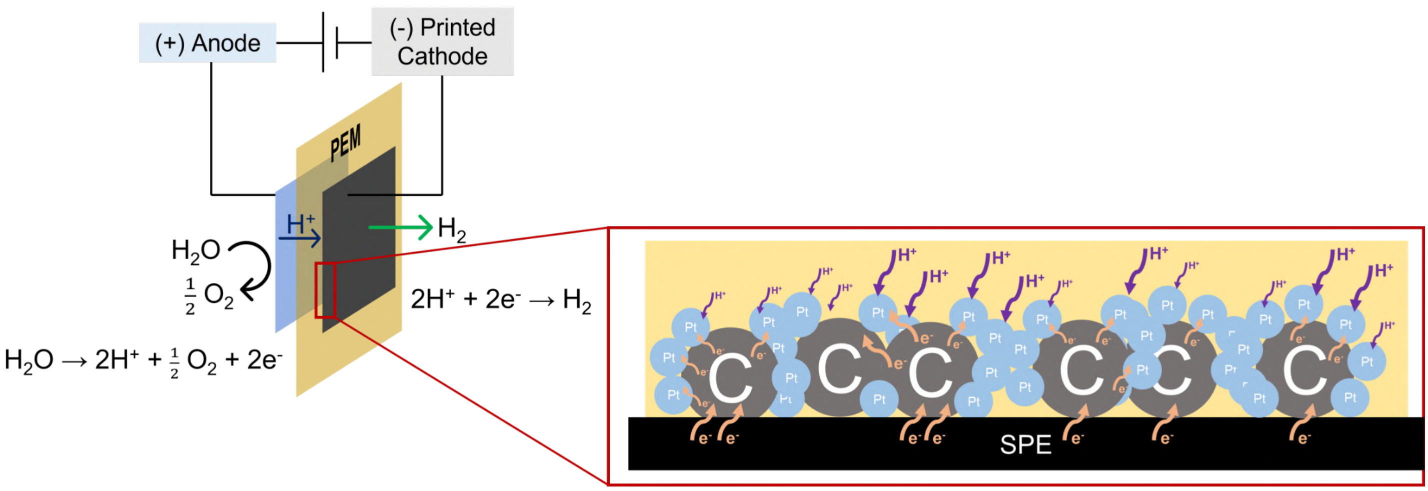
16.3.3 Preparation and Integration of Flexible Printed Electrodes for Lightweight and Thin Electrolyser Cells for Hydrogen Evolution

Diogo Garcia, Fundació Eurecat

Authors: Diogo Garcia (1), Paul Lacharmoise (1), Claudia Delgado Simao (1)
(1) Fundació Eurecat

Water electrolysis has the potential to store the electricity provided from renewable sources in chemical bonds, through water splitting, generating H2. Proton exchange membrane electrolyser cells (PEMEC) have the advantages of the simplicity and compact design of the device, performance at high current densities and great purity of H2 obtained, not requiring further purification steps. Moreover, PEM devices present fast response, which is suitable for the combination with intermittent and fluctuating power sources such as wind and solar. Expected to be the dominant technology by 2030, PEM water electrolysis is still the most expensive technology due to the high costs of the membrane electrode assembly (MEA) and fabrication processes employed. In this study, inspired by thin leaves in nature, we propose, for the first time, the use of screen-printed electrodes (SPEs) for water electrolysis, targeting a fully printed monolithic MEA for a lightweight, flexible, thin, large area and cost-effective electrolyser cell based in printed electronics.

SPEs with different designs and working areas provide sufficient electron conductivity to promote the hydrogen evolution reaction (HER) in neutral pH buffered solution at -1.6 V (vs Ag/AgCl). The stability of SPEs is assessed through the electrochemical performance and mechanical stability in different pH and temperatures. The electrochemical performance of bare and Pt-coated carbon-based SPEs with different designs is described by chronoamperometric tests in different electrolyser cell configurations: H-cell, flow cell, and proton exchange MEA.



16.5.1 Kevin Rodrigues, CeNTI

Kevin Rodrigues has a Master degree in Chemical Analysis and Characterization Techniques and is Licentiate in Biochemistry from the University of Minho. Currently works as a researcher at CeNTI's Smart Materials team. During his training he acquired knowledge in the characterization and analysis of materials, developing more profound knowledge in the characterization of chemical formulations for fibre to rubber adhesion. Therefore, he acquired experience in fibre impregnation processes, chemical formulations characterization and morphologic and mechanical characterization of fibres and composites. During his professional experience, he acquired knowledge in printed electronic technologies for the development of sensors, actuators and devices in different substrates, acquiring also knowledge in the development of smart textiles and smart composites.

16.5.2 Karolina Spalek, Zinergy UK

I am an applied chemist. As a scientist at Zinergy my R&D work focuses on the electrochemistry of ultra-thin flexible batteries. I previously participated in an Innovate UK project on biosensor wristbands for the elderly as well as an electrode wettability study in collaboration with the National Physical Laboratory. My latest project involves the development of thin power sources for cold chain logistics.

16.5.1 Printed Strain Gauges for 2nd Life Battery Pack State Monitoring

Kevin Rodrigues, CeNTI

Authors: Joana Diniz da Fonseca, Felipe Afonso, Miguel Evaristo, Sarah Brito Bogas, João Silva, Kevin Rodrigues, Cristina Furtado, José Silva
(1) CeNTI

With the growth of the 100% electric and hybrid car market in the next years, it is expectable that an increasing number of batteries that no longer meet the requirements of automotive applications will flood the market. Since typically these kinds of batteries retain around 90-70% of the initial charge capacity, the use on less demanding renewable energy storage applications instead of just recycling rises as an interesting possibility. Refurbishment, when viable, is potentially more economically attractive and more effective in reducing the environmental footprint of the EV battery life cycle.

In the reported work, new printed gauges were developed to monitor refurbished batteries. The gauges were specifically designed for "pouch" cells to sense faint deformations in the devices, resulting from internal pressure variations caused by chemical reactions during charging and discharging cycles. Any abrupt alteration in this process can be an early indication of thermal runaway reactions that need immediate answers, namely, turning off the damaged cell.

The developed devices consist of printed conductive silver associated with a force-sensitive layer, both applied to a thin flexible substrate by screen-printing. The developed sensor reads the gauge electrical resistance, which presents a significant variation for a small physical deformation. With the physical properties of the analysed surface, it is possible to measure the applied force and, by monitoring it over a long period, correlate it to the normal charging and discharging cycles.

The goal of these developments is to obtain a simple and affordable flexible sensor for integration in refurbished battery packs made of second-life EV battery cells for effective monitoring of the internal pressure of these devices.

This work was developed in the scope of Baterias2030 project (POCI-01-0247-FEDER-046109) which was co-financed by Portugal 2020, under the Operational Program for Competitiveness and Internationalization (COMPETE 2020) through the European Regional Development Fund (ERDF).

16.5.2 Thin Power Source for Cold Chain Logistics

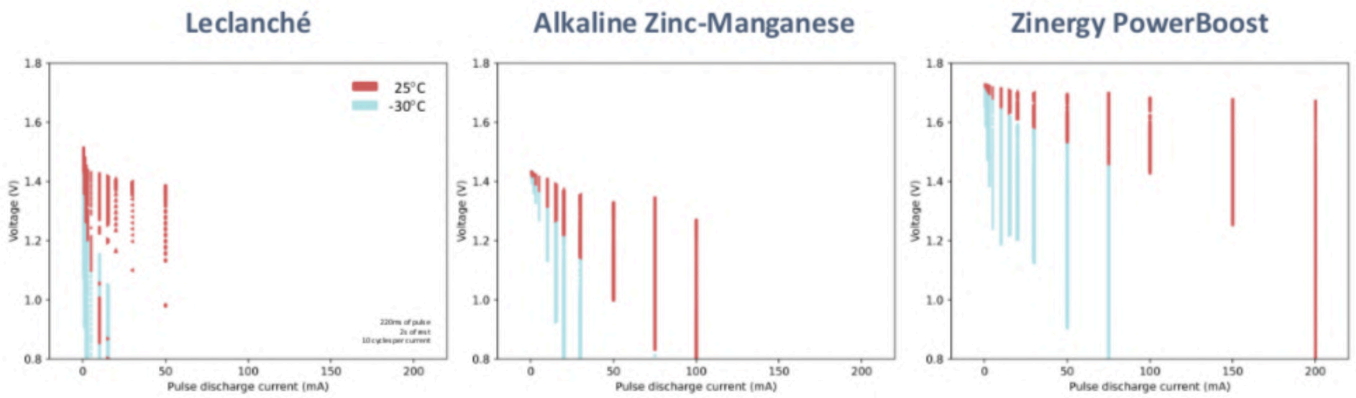
Karolina Spalek, Zinergy UK

Authors: Karolina Spalek (1), Dilek Ozgit Butler (1), Pritesh Hiralal Popat (1)
(1) Zinergy UK

Supply chain logistics is challenging, even more so when temperature sensitive products such as frozen foods and pharmaceuticals are handled due to their response to temperature fluctuations throughout their journey. Every single change in environmental parameters not only during transfer from one hub to another at ambient temperature but also unexpected delays for instance in customs and failure of cooling units during storage affects safety, lifetime, quality of goods and produces waste to a great degree. Losses associated with temperature excursions, disruptions and deficiencies in the cold food chain are approximately $35 billion annually in biopharma industry. On average, 25% of vaccines reaching their destination have degraded efficacy.[1]

IoT enabled monitoring is essential to tackle the challenges for more reliable logistics with minimum possible waste. Many communication technologies coupled with a power source have been proposed in thin label form to be placed on individual assets. However, those are mainly powered by lithium batteries posing safety risks. Here, we propose and demonstrate a safer zinc-based battery chemistry and product which is RoHS compliant and is superior to other zinc chemistries in terms of power capability and can operate competitively down to -30^{0}C.

The graphs below compare three types of Zinc-based battery chemistries. The most common and the oldest – the Leclanche type - consists of Zinc-Manganese electrodes with aqueous acidic electrolyte and a predominantly zinc chloride solution (shown in the left panel). The graph in the middle panel, shows the performance of an alkaline primary battery with the pulse current performance at room temperature (in red) and at -30 degrees Celsius (in light blue). The graph on the right shows our recently developed Zinergy PowerBoost with a high pulse current performance. Performance at room temperature and at -30 deg. C is shown and reaches currents of up to 150mA and 50mA, respectively. Our results show that our battery chemistry outperforms the alkaline battery chemistry in terms of the current by a factor of 2 and at least by a factor of 20 in the case of the Leclanche battery. In addition, when comparing the voltage values plotted on the y-axes, there is a major advantage brought on by Zinergy PowerBoost range proposed by us, with higher voltages oscillating between 1.7-1.75V and resulting in the possibility of sustaining higher currents.



[1] Sykes C. Time- and Temperature-Controlled Transport: Supply Chain Challenges and Solutions. P T. 2018;43(3):154-170.