Wearable and Flexible Technologies

Enabled by Advanced Thin-Film Manufacture and Metrology

Newsletter, January 2020

Funded by:

EPSRC

Engineering and Physical Sciences Research Council

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WAFT ACADEMIC PARTNERS

University of Oxford

University of Exeter

University of Southampton

With International Academic Partners:

Penn — University of Pennsylvania

Westfälische Wilhelms-Universität Münster

FOREWORD

I am delighted to enclose this newsletter during the final few months of the EPSRC WAFT programme.

As you will see, several aspects of our research have come together coherently around the concept of manufacturing, and the research areas that have emerged as a result are exciting and enabling. From exciting new ammonia sensors to flexible memories, several of our device concepts are finding real-world interest amongst innovative companies in the UK and also from outside.

I am grateful to the extraordinary number of early career researchers (both Doctoral students and Postdoctoral colleagues), as well as our enthusiastic industrial partners, all of whom have worked seamlessly and closely to further knowledge in this emerging and exciting new manufacturing research area.

I hope a glimpse into our activities this year will pique your curiosity to find out more - please contact us at waft@materials.ox.ac.uk if you are interested in any of our research areas.

Professor Harish Bhaskaran
Principal Investigator of WAFT and Professor of Applied Nanomaterials, University of Oxford

The WAFT Collaboration has continued to succeed with both building-up capabilities and research. We have research highlights to share from Metrology, Nanomanufacturing, Scale Up and R2R Processing, Flexible Electronic Devices, In situ Optical Monitoring and Process Control and Phase-Change Meta-Displays. We review the Annual WAFT Meeting and feature an insight into the successful industry partnership with Dr Feras Alkhalil at PragmatIC.

The WAFT Project aims to accelerate the development of wearable and flexible technologies by integrating device components using advanced functional materials along with scalable, cost-effective and reliable manufacturing techniques.

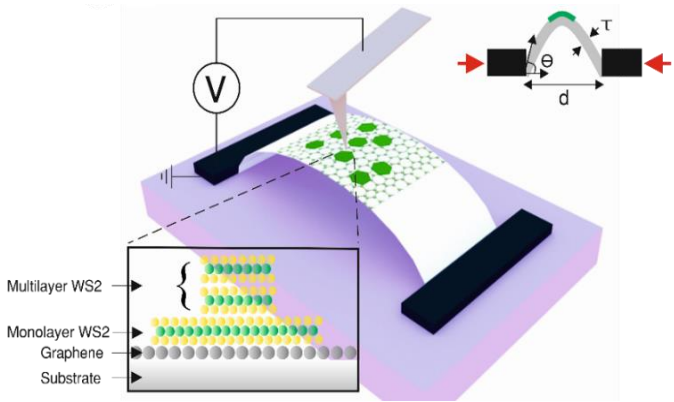
- ✓ Develop scalable roll-to-roll technologies suitable for cost-effective deposition of functional phase-change photovoltaic, organic sensor.
- ✓ Minimize waste in the deposition of thin-films in case of expensive or environmentally sensitive elements used in functional materials.
- ✓ Develop new appropaches for effective in-situ monitoring of key film parameters, in particular film thickness, to guarantee designed-for functional material properties at the manufacturing stage.

METROLOGY

STRESS AND STRAIN METROLOGY AT THE NANOSCALE

Ghazi Sawat

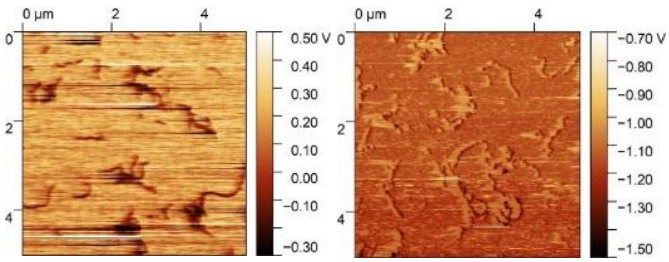
Syed Ghazi *et al. Nanoletters, 18 2018*



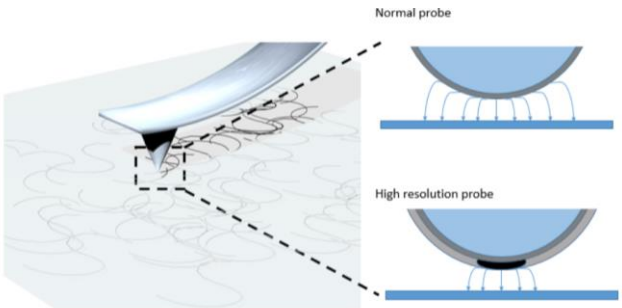
METROLOGY USING MASS MANUFACTURABLE PROBES

Eugene Soh

High resolution conductive AFM measurements enabled by phase change material coated probes.



Regular tip High res tip

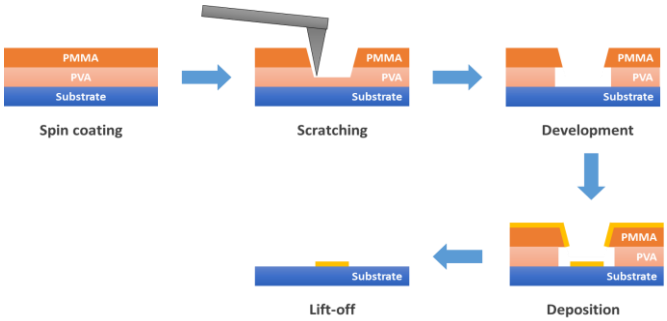


NANOMANUFACTURING

BILAYER LITHOGRAPHY

Yu Shu

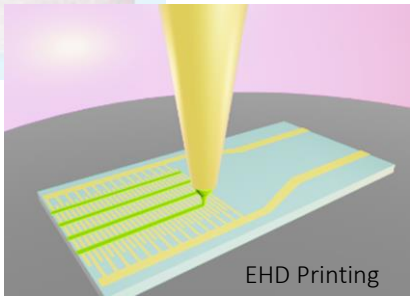
A flexible way to control the mechanical force to avoid under-cutting and over-cutting. The approach is friendly to flexible substrates, because only water gets involved in the fabrication process.



AMMONIA GAS SENSOR PRINTED ON FLEXIBLE SUBSTRATES

Nipho Mkhize & Krish Murugappan

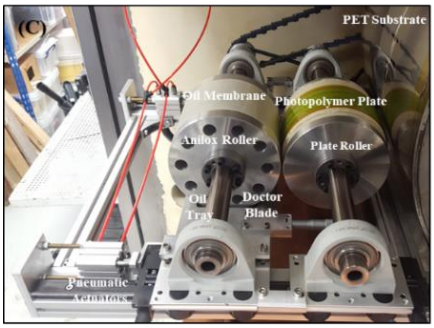
Printed conducting polymer based chemiresistors approach detection of 1.6ppm for ammonia gas.

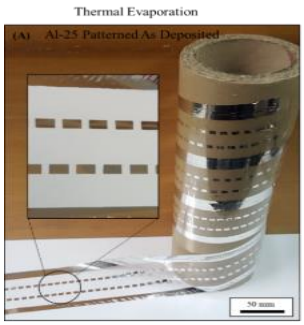


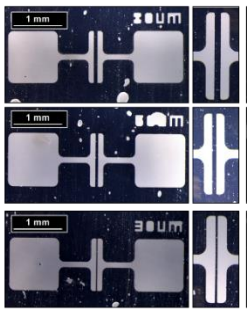
IN-LINE PATTERENED METALLIZATION

Bryan Stuart and Gemma Francis

High-throughput ≥25m/min roll-to-roll deposition of electrode materials for flexible devices. Applied various devices in WAFT: OTFTs, thermoelectrics sensors, metamaterials. Route to high-resolution (potentially EBL resolution), using surface modification, has been identified and patented.



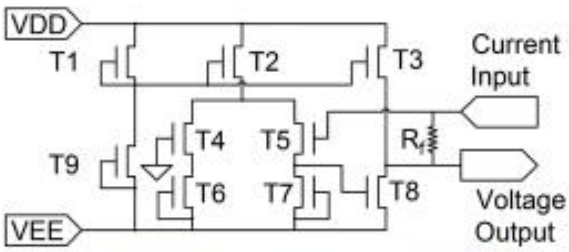


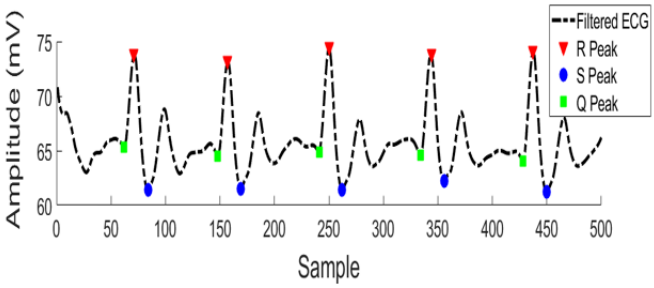


OTFT-BASED SENSOR CIRCUITS

Kai Zhang

Circuits based on OTFTs manufactured by high-throughput R2R evaporation process coupled to flexible sensors for biomedical chemicals and ECG measurement.

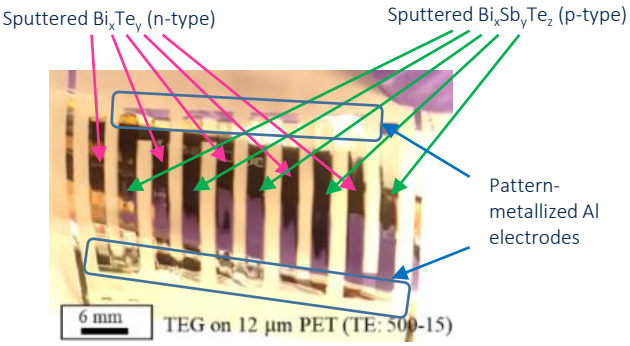




THERMOELECTRIC GENERATORS (TEGS)

Vincent Tobin & Xudong Tao

Deposition of thin film TEGs on polymer substrates which, in array, would produce enough power to run e.g. OTFT sensor circuit.



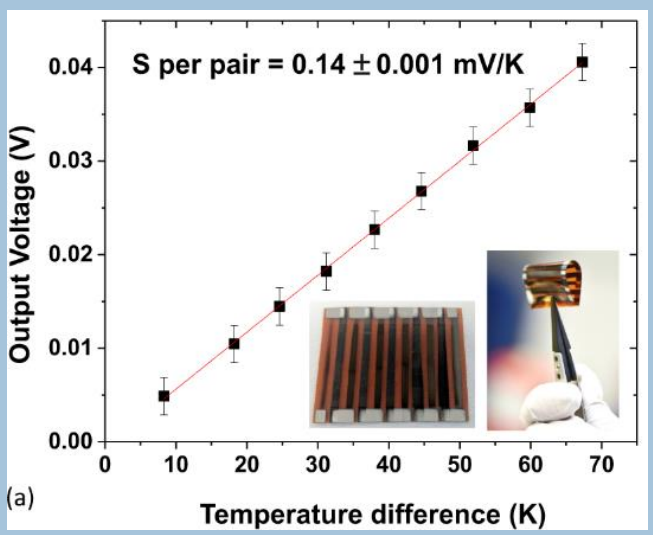


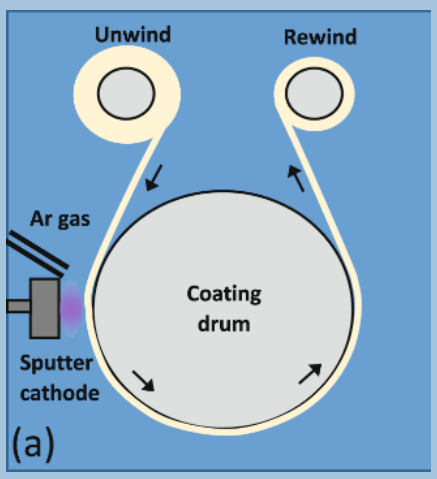


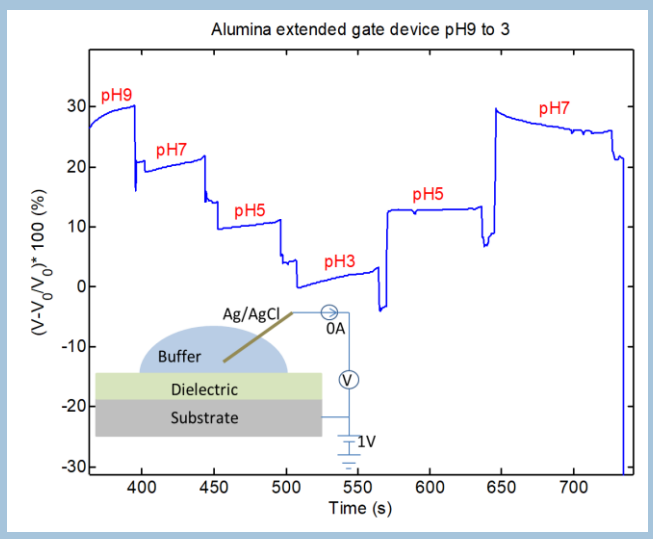

HIGH-THROUGHPUT PHYSICAL VAPOUR DEPOSiTION FLEXIBLE THERMOELECTRIC GENERATORS

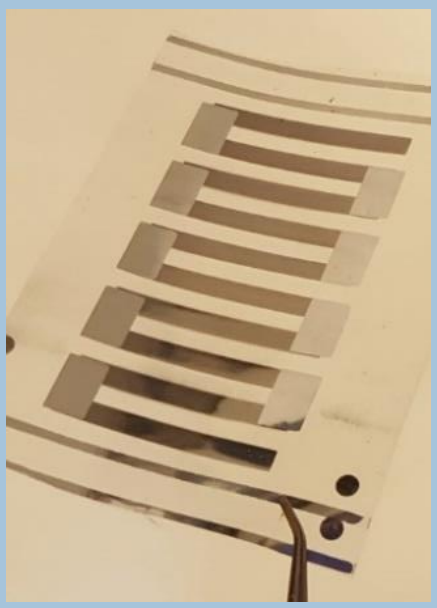
Dr Katrina Morgan, Dr Ioannis Zeimpekis, Prof Dan Hewak, Chris Craig, Dr Zhuo Feng, Prof Hazel Assender and Plasma App

K. A. Morgan et. al. Scientific Reports 4393 (2019)
K. A. Morgan et. al. Thermoelectric Cells for Wearable and Flexible Technology, Technical Report: WAFT consortium (2018)









ChAMP/WAFT COLLABORATION FUNDS

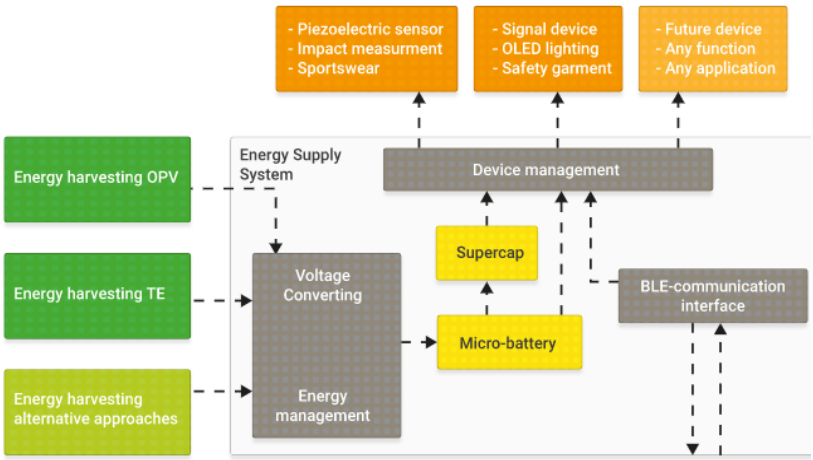
With University of Southampton and University of Oxford (Prof. Assender)

"Inline patterning of thermoelectric devices onto flexible substrates: a solution to large area manufacturing of wearable electronics", £18,350

"Scalable Flexible Ion sensors for Wearable Electrolyte Monitoring", £23,500

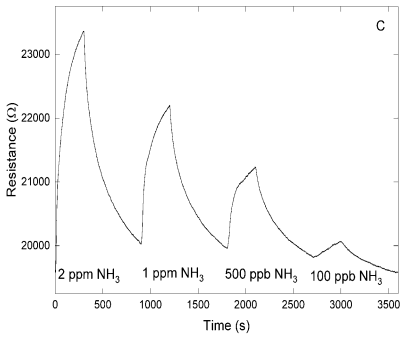
Smart2Go

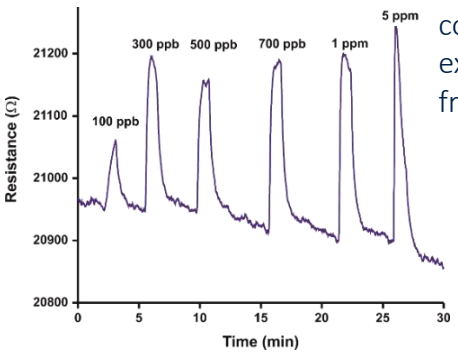
Flexible thermoelectric **results from WAFT fed into project** funded from the **European Union's Horizon 2020** research and innovation programme under grant agreement No. 825143, project Smart2Go (€4 million)



CHEMIRESISTIVE VAPOUR SENSORS BASED ON PERCOLATION NETWORKS

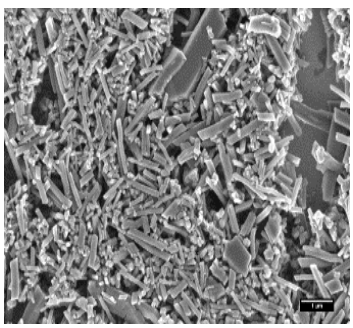
Merel Lefferts, Ben Armitage, Fubiao Gu, Krish Murugappan and Martin Castell





By using a percolation network of conductive polymers a significantly higher sensitivity can be achieved compared to more traditional conductive polymer thin film based sensors. Using a percolation network of polypyrrole we've achieved sensitivities as low as 9 ppb ammonia.

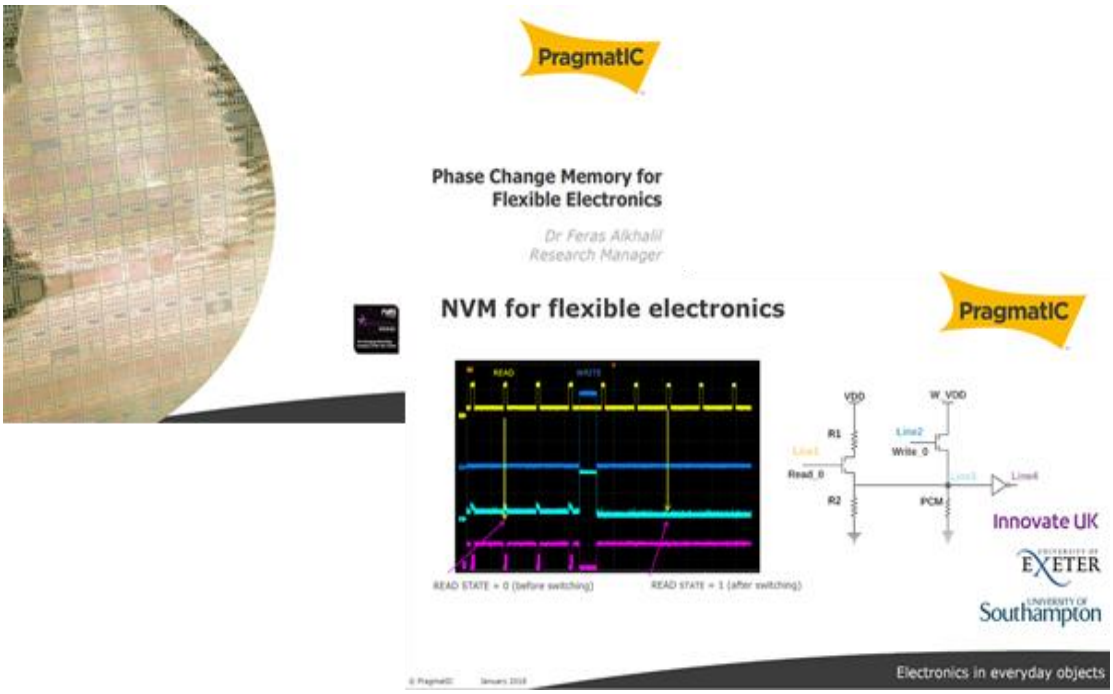
Using the same percolation principle high sensitivities analyte materials can also be achieved using different conductive polymers or for example the metal-organic-frameworks shown here.



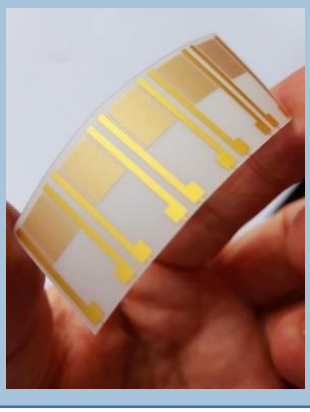
FLEXIBLE MEMORY DEVICES

University of Exeter (Prof Wright, Dr Au), University of Southampton (Prof Hewak) and PragmatIC (Dr Feras Alkhalil, Dr Catherine Ramsdale)

Development of non-volatile memories for flexible electronics applications. Led also to Innovate UK grant and follow-on PhD studentship funded by PragmatIC (starting 2020).



Highly sensitive vapour sensors were also successfully created on flexible substrates.



A small integrated device, capable of measuring the signal of four chemiresistive sensors, as well as temperature and humidity sensors was developed. This demonstrator uses Bluetooth to communicate with a mobile phone, eliminating large laboratory setups and ensuring portability, as well as allowing our sensors to be used in an electronic-nose type setup.

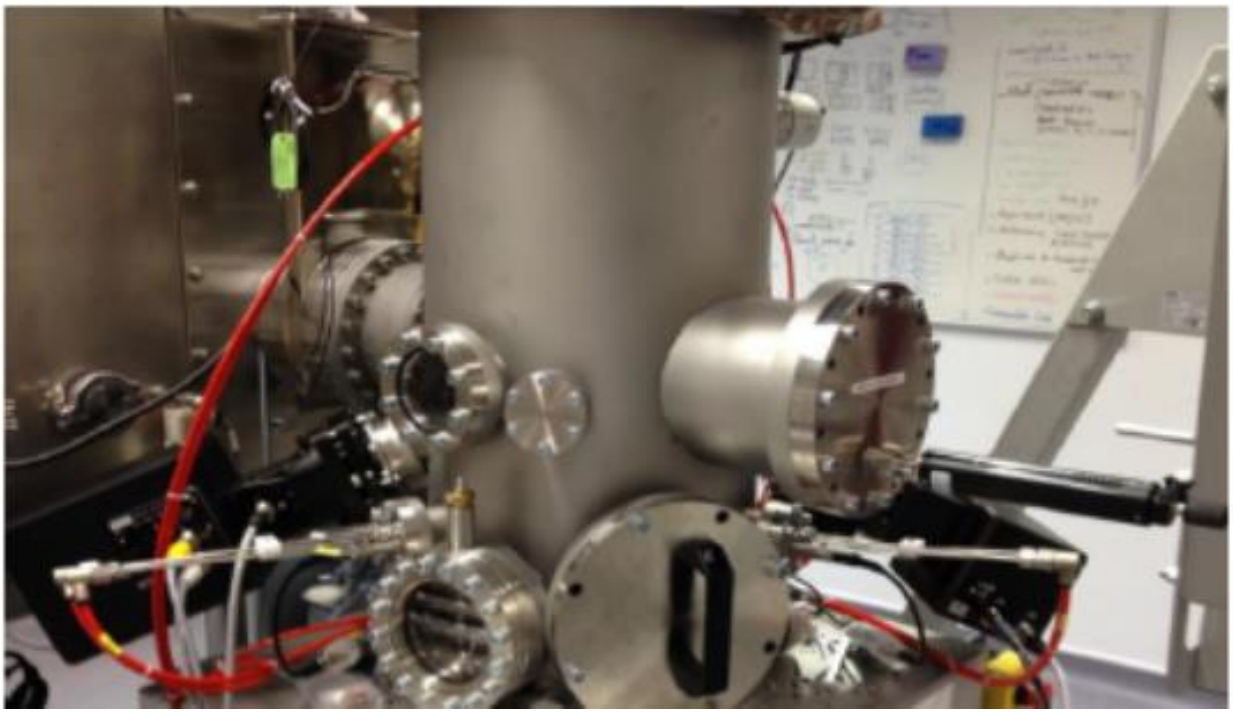





Sameer Kesava, Arnas Volcokas, Moritz Riede, David Wright, Emanuele Gemo, Carlota Ruiz de Galarreta

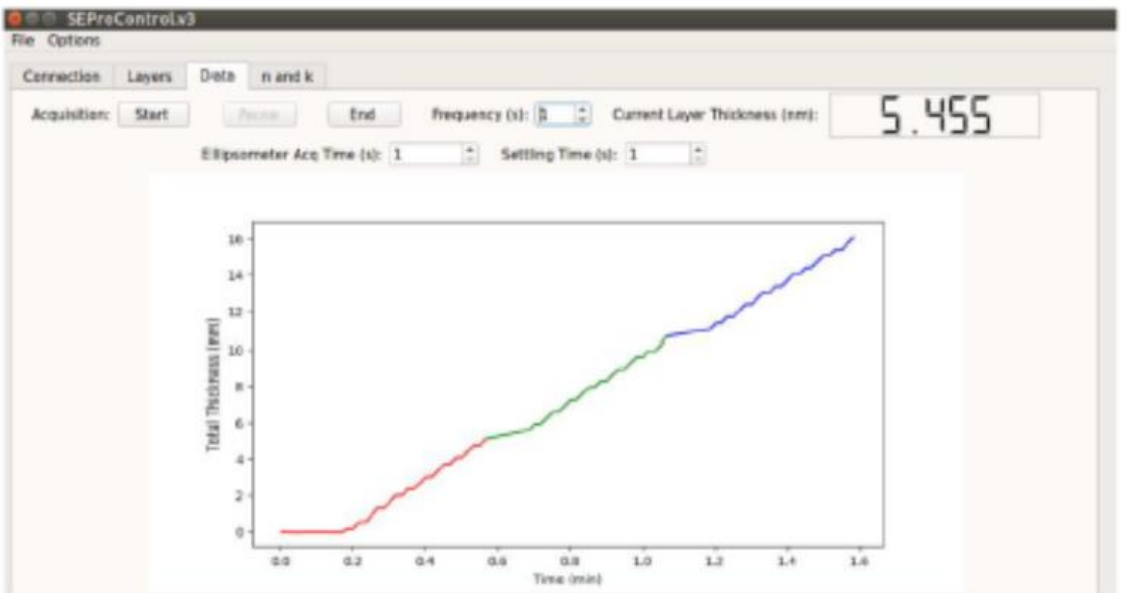
IN SITU MONITORING USING SPECTROSCOPIC ELLIPSOMETRY

Vacuum deposition system for organic semiconductors with in situ monitoring using a spectroscopic ellipsometer.



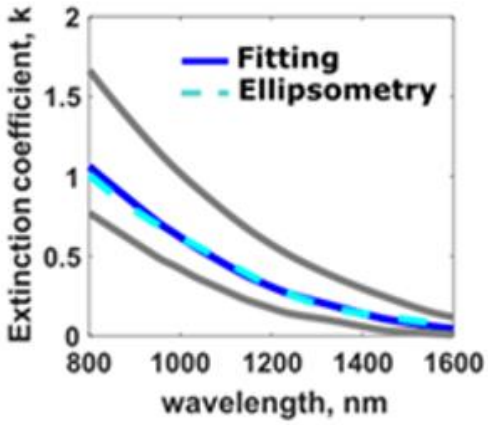
PROCESS CONTROL SOFTWARE

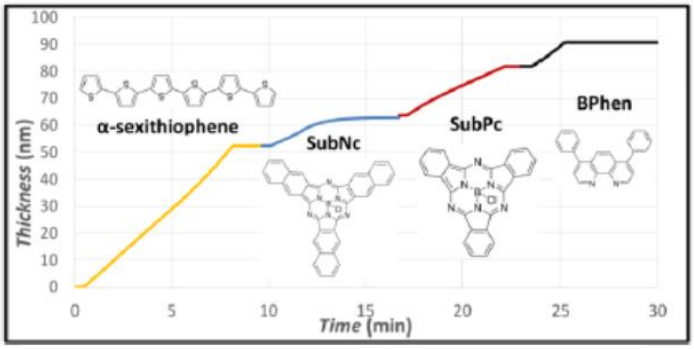
Process control software for monitoring thickness and optical properties of the thin films during deposition.

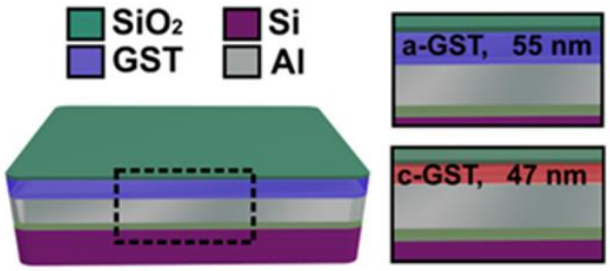


MONITORING OF MULTIPLE LAYER DEPOSITION

Using an organic solar cell, with a power conversion efficiency of ~6%, as a model system, methodology for monitoring thickness of multiple layers developed.

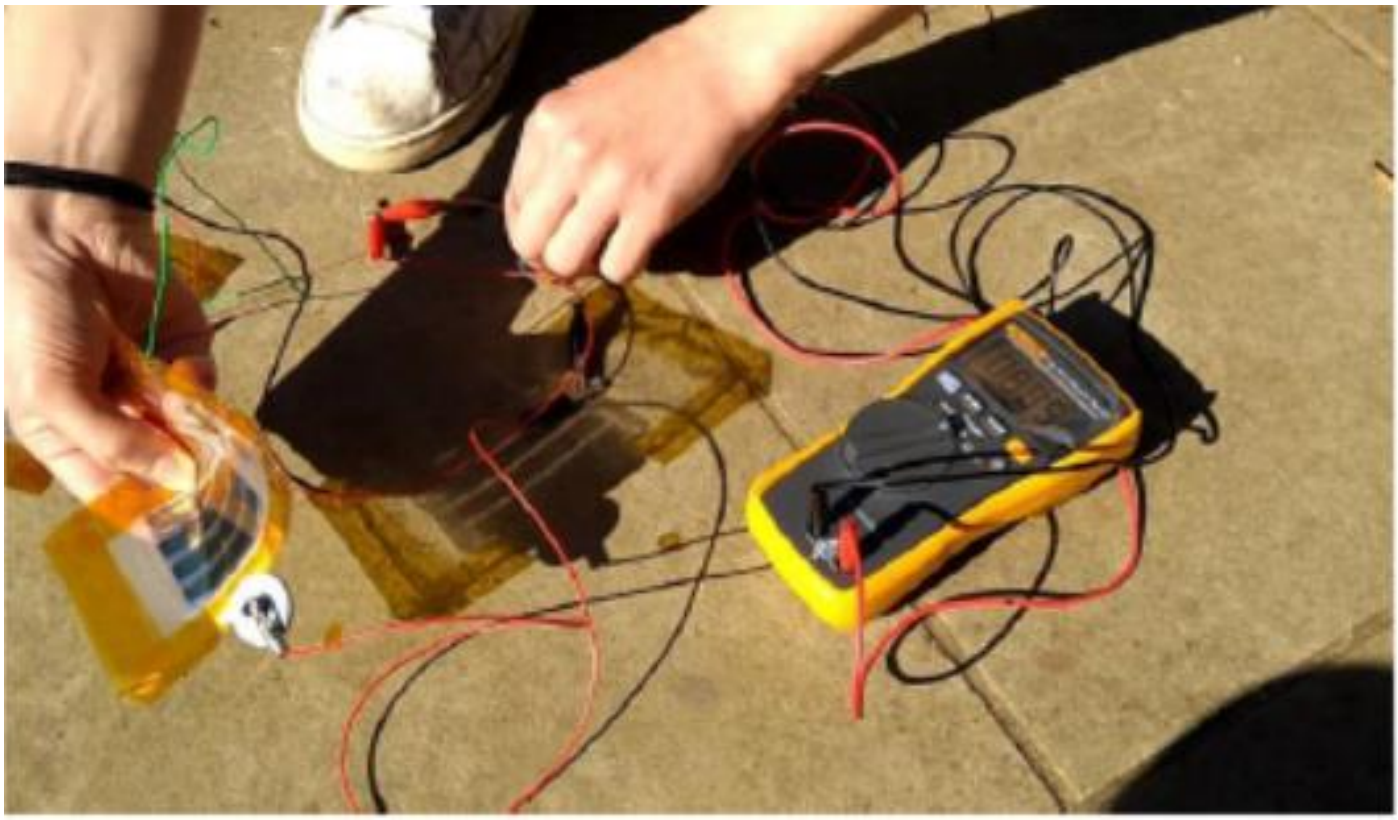






POWERING OF LOW-POWER ELECTRONICS

Demonstrating the powering of low-power electronics, a temperature sensor in this case, using a flexible organic solar cell.



NON-VOLATILE OPTOELECTRONIC DISPLAYS ENABLED BY COMBINATION OF PHASE-CHANGE MATERIALS AND OPTICAL METASURFACE CONCEPTS.

Santiago Carrillo, Liam Trimby, Peiman Hosseini, Harish Bhaskaran and David Wright

CMY pixel development using subtractive colour in metal-insulator-metal gap-plasmon structures.

University of Exeter in collaboration with University of Oxford and Bodle Technologies Ltd.

S GC Carrillo et al., Adv Opt Mater 2019 (DOI: 10.1002/adom.201801782)

Patent filed: Wright CD and Carrillo SG-C, A phase-change metamaterial display, WO/2019/038559 (2019)

BODLE

BEGBROKE SCIENCE PARK
6 FEBRUARY 2019

Collaborators came together to share cutting edge research and ideas.

ANNUAL WAFT MEETING, 20 AUGUST 2019, OXFORD

The annual WAFT meeting at Wolfson College, Oxford held on 20 August 2019 brought over 30 participants together consisting of academic and industrial partners.

We had the privilege of attending two invited talks given by Professor Cliff Jones and Dr Seongdong Lim. Cliff gave a comprehensive summary of his work on the use of liquid crystals for adaptive contact lenses; while Seongdong talked about his work on micro/nanostructured flexible sensors.

Industrial collaborators, which include CPI, PragmatIC, Plasma App, KJ Lesker and M-Solv, also shared with us their state of the art equipment and technologies.

Moreover, the co-investigators had the opportunity to give an overview of their research and contributions to the WAFT project.

Flash presentations about novel nanomanufacturing techniques and gas sensing applications on flexible substrates preceded the lively discussions during the poster session. Students also had the chance to interact with the industry collaborators. The day concluded with a dinner at Wolfson College.

Flash presentations before poster session which encouraged further discussions between academics, students and industrial collaborators.

Cliff Jones (above) gives his talk on the use of liquid crystals for adaptive contact lenses.

Seongdong Lim (above) describes his work on micro/nanostructured flexible sensors.

Poster session

PRAGMATIC'S DR FERAS ALKHALIL PROVIDES INSIGHT INTO COLLABORATING WITH WAFT

DR FERAS ALKHALIL, PRINCIPAL SCIENTIST & RESEARCH MANAGER

About PragmatIC:
PragmatIC is a world leader in ultra-low-cost flexible electronics, enabling the potential for trillions of smart objects that can engage with consumers and their environments. PragmatIC's unique technology platform delivers flexible integrated circuits (FlexICs) that are thinner than a human hair and can be easily embedded into everyday objects. PragmatIC's solutions provide the opportunity to add new functionality, as well as extending proven applications such as RFID and NFC into mass market use cases previously prohibited by the cost of traditional silicon Ics.

You learnt about WAFT after the grant was underway. How easy was it to get involved?
PragmatIC engaged with the consortium after WAFT's official kick off. Introduction to the consortium was straightforward after an email exchange with the consortium's PI Prof Harish Bhaskaran, at the University of Oxford,.

Did you learn of something on WAFT that was definitely not on your radar before, but you realized was an opportunity too good to pass?
Yes, involvement in the consortium showcased the leading phase change material expertise in the UK, from material discovery and development all the way to manufacturing of novel devices and systems. This led us to explore and successfully demonstrate phase change material set as a Non Volatile Memory (NVM) element in our Flexible Integrated Circuits (FlexICs) platform.

Academic collaborations tend not to emphasize industry-industry connection making. Did you make any connections to other industrial partners at WAFT that were unexpected but productive?
WAFT was unique in this sense, from the early stages, there was a clear focus on application led research with deliverables targeting scale up and manufacturability of the materials and technologies developed. This approach successfully brought together and engaged various industrial stakeholders across the wearable and flexible electronics supply chain. This provided valuable exposure, through regular discussions, to UK and European industrial partners and will lead to future collaborations.

Do you have advice for industrial firms wanting to get involved with this consortium in future?
There is great value in engaging with WAFT and future consortiums, it provides an opportunity to gain insight into cutting edge research, interact directly with leading experts and establish connections with academic industrial partners.

For PragmatIC, engagement with WAFT has been greatly beneficial leading to a joint development program with two WAFT academic partners, an Innovate UK project (successfully completed in 2018) and an industrial PhD studentship project (starting January 2020).

WAFT INDUSTRIAL PARTNERS

IBM Research - Zurich

Sharp Laboratories of Europe

Defence Science & Tech Lab (Detection)

Centre for Process Innovation

IAB CHAIR REPORT

It has been a privilege to serve as the Chair of the Industrial Advisory Board for this programme. Although Dstl is an agency of the MOD, it is considered an industrial partner by EPSRC and I had existing links with one of the WAFT work strands - Dstl was funding DPhil research in Prof Martin Castell's Group on Percolation Threshold Sensors for the detection of explosives.

It has been very encouraging to see a broad range of low TRL work on flexible technologies at the frontiers of science linked with research to de-risk manufacturing and commercial exploitation. A broad range of industry partners were represented on the technical advisory board, which has grown as the programme has progressed and more links have been developed, from 15 partners initially to over 32 industrial attendees at the last WAFT event. Particular highlights have been:

1) PragmatIC entered the consortium when the WAFT programme was well underway, because they identified expertise in flexible memories within the organization. They were specifically interested in using novel low temperature phase change materials. They were immediately put in touch with the entire consortium and were able to work out a project agreed with Exeter and Southampton with a bespoke agreement for these partners, within the context of WAFT. Although many of the results have been confidential, there is significant interest in follow-up work to explore commercialization.

2) In a very interesting development, two new industrial partners joined forces with Oxford to come together with existing industrial partners to take forward a project on smart windows. One was EOC, a large architectural engineering firm and the other was PlasmaApp, a small thin film deposition company based in Harwell who were brought to the consortium through Bodle Technologies. Using the combined expertise of Oxford, EOC and PlasmaApp, they explored the use of energy-saving active smart glazing for use on flexible substrates to apply on existing windows. The way they were embedded into the consortium was once again seamless and existing processes to create a bespoke agreement worked very well. This is particularly exciting as it is an area with significant greenhouse gas emission reduction potential.

From a personal perspective, I have been very pleased with the interactions between WAFT and Dstl in the area of wearables for detection of hazardous chemicals.

I have greatly enjoyed being the chair of this IAB, and it has been particularly encouraging to see the enthusiasm of doctoral students and postdoctoral researchers, several of whom have gone on to form their own research groups. I look forward to continue to work with the members of the WAFT consortium in the future, as WAFT transitions into further exploitation-focussed research and development.

Dr Matthew Brookes,
DSTL FELLOW, COUNTER-TERRORISM AND SECURITY DIVISION

THE FUTURE OF WAFT

The IAB or anyone interested in finding out how this effort can continue to be supported after the end of WAFT should contact:

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