ANNUAL REPORT No. 2
May 2016– April 2017

We are very pleased to present the second annual report of the WAFT Collaboration. This has been another successful year of both building-up capabilities and new research. Some of the key research highlights of the second year were the development of modelling frameworks for interdigitated electrode gas sensors and the ongoing development of a flexible substrate manufacturing process, as well as the development of a new optoelectronic metrology tool.

Key findings of 2016-2017:

- Development of graphene nanoelectrode know-how for scaling phase change memories and deploying this on flexible substrates.
- Refinement of sensor technologies using percolation sensors and the development of new manufacturing processes for flexible manufacturing of sensors, based on the discovery of a novel self-assembly process, JINA.
- Development of models for optimization of device parameters across a range of devices, and the development of a library of refractive indexes for in-situ metrology during deposition.
- Establishing CVD processes for Chalcogenides and Emerging Materials.

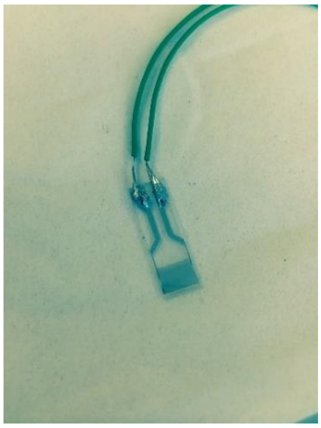
Quick look at 2016-2017

- We expanded the Industrial Advisory Board with increased number of Industrial Partners from 15 to 18 and provided project updates to 28 WAFT industrial collaborators and EPSRC portfolio representatives.
- 9 research investigators, 15 postdoctoral associates, 14 doctoral researchers, 2 undergraduate researchers, 3 laboratory technicians contributed to the 11 WAFT research strands.
- 83 journal articles, conference proceedings and science posters made up the WAFT publication list in April 2017.
- John Yarwood Memorial Medal was awarded to Martin Castell for meritorious contributions to surface science.
- Moritz Riede was elected co-chair of the Global Young Academy for 2017-18.
- The WAFT project has been extended to April 2020 at no cost by EPSRC (EP/M015173/1).

Project Highlights for 2016-17

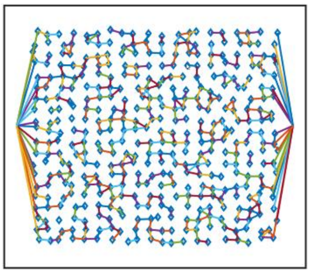
Interdigitated Electrodes for Sensing Applications

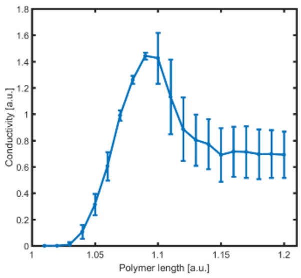
Gas sensors that use interdigitated electrodes (developed by Martin Castell's group and in collaboration with dstl) was integrated with models developed in David Wright's research team. A modelling framework was created in order to understand how the percolation network could grow across the interdigitated electrodes.



Interdigitated electrode (photo courtesy of Krishnan Murugappan)

Modelling Flexible and Wearable Electronics





We use modelling to optimize devices, i.e. reduce variability from one device to another.

Model of 20 by 20 percolation network connected to electrodes and conductivity of the fabricated sensor vs polymer length (illustration courtesy of Arseny Alexeev)

To create processes for flexible substrate manufacturing of such sensors, we are combining that with aspects related to self-assembly to translate this technology onto flexible substrates (Harish Bhaskaran's lab). Thus, natural integration between work packages in the project have now started to happen, so-much-so, that our annual report cannot be split into work packages (a metric of success!).

Metrology

As our capabilities to both model and create devices has grown, so has our requirement for advanced metrology. An example of this is to be able to probe at RF frequencies both the optical and electronic response of advanced materials.

Probe station to measure both the electrical and optical characteristics of flexible and wearable optoelectronic devices (photo courtesy of Nathan Youngblood)

In order to significantly expand on work done earlier by the Exeter-Oxford collaboration and to create a tool that can be used more widely, we have built a test set-up with integrated optics to be able to do this across a wide array of materials ranging from phase change materials to organic materials. As we continue to add features to the set-up we welcome our partners to work with us to help with any of metrology needs that are unique and not known. In general, we can show how materials respond electronically to optical pulses or optically to electronic pulses at microscopic scales. We can do this at a range of bandwidths from DC to GHz frequencies.

Publication Highlight

Joint publication between Wright & Bhaskaran in Advanced Electronic Materials:
G. Rodriguez-Hernandez, P. Hosseini, C. Rios, C.D. Wright, H. Bhaskaran, "Mixed-Mode Electro-Optical Operation of Ge2Sb2Te5 Nanoscale Crossbar Devices", Adv. Electron. Mater. 2017, Vol. 17000079, DOI: 10.1002/aelm.201700079

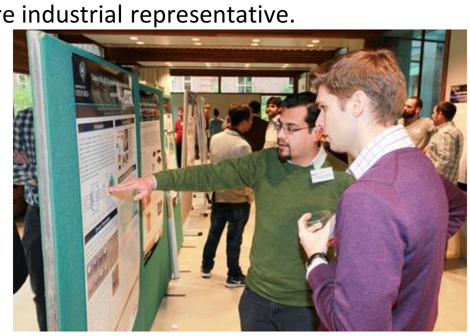
Funding Highlights

- Martin Castell: EPSRC iCASE with Dstl
- Martin Castell: Newton Fund, British Council Funding to extend percolation gas sensing work for land mine detection in Colombia
- Harish Bhaskaran, Dan Hewak: Innovate UK grant award with Bodle Technologies Ltd and M-Solv Ltd ("UltraSRD")
- Arseny Alexeev: EPSRC Impact Acceleration Award "Tunable Dielectric Materials Enabled by Phase-Change Materials" – extension of the WAFT project into the metamaterials research theme.

Annual WAFT Scientific and IAB meeting

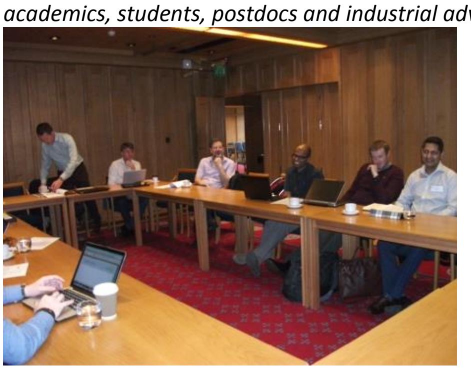
Our 2nd annual meeting was held in Somerville College, Oxford over two days in October 2016. It was an extremely well attended event with 54 total attendees over half of which were industrial representative.

WAFT Annual Meeting welcomed 54 attendees on 20 October 2017



13 research posters enabled vibrant discussions of academics, students, postdocs and industrial advisors

Historic Somerville College was the venue



Discussions at the IAB meeting on 21 October 2017

WAFT Industrial Partners:

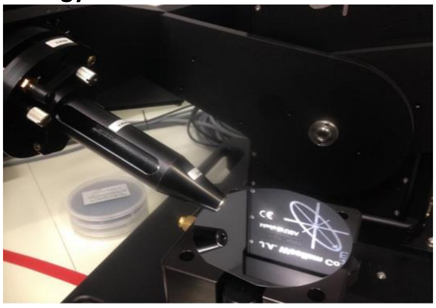
Defence Science & Tech Lab (Detection), BASF AG, CreaPhys GmbH, Kurt J Lesker Co Ltd, Asylum Research (USA), Sharp Laboratories of Europe Ltd, Centre for Process Innovation Ltd, Fraunhofer FEP, IBM Research – Zurich, CSEM SA, Oxford Instruments, Asylum Research (UK), Bodle Technologies Ltd, Oxford PV, Heliatek GmbH, PragmatIC Ltd, Eckersley O'Callaghan, Plasma App Ltd.

Dissemination Highlights

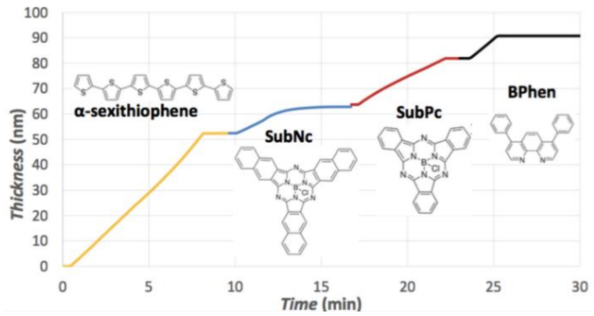
- WAFT project website – revamping in progress, keep a watch at www.waftcollaboration.org
- Hazel E. Assender: Roll-to-roll manufacture of all-evaporated organic circuits for flexible electronics, Printed and Flexible Electronics Congress (February 2017).
- Harish Bhaskaran's TEDx talk at TEDx Eton (March 2017).
- Arseny Alexeev's talk at MRS 2017 in Phoenix.

Research Progress

Metrology



Ex situ characterization and in situ monitoring (photo courtesy of Sameer Vajjala Kesava)



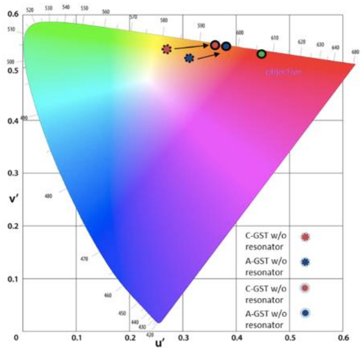
In-situ film thickness measurements: utilizing the ellipsometer for an organic solar cell as the model system, Sameer Kesava has successfully demonstrated real-time monitoring of thickness of each layer sequentially deposited in a multilayer stack (see picture above right). The equipment has now been used by both Bhaskaran's Group and Bodle Technologies Ltd.

Nathan Youngblood and Ghazi Sarwat are in the process of building a custom probe station which has the ability to measure both the electrical and optical characteristics of flexible and wearable optoelectronic devices. Unique to this probe station is the ability to couple a laser or LED source to the optical path and probe a device's response to various wavelengths of light. Additionally, a motorized linear stage can be computer controlled to automatically measure the electrical properties of flexible devices under stress. This will be useful to determine the robustness of flexible electronics after multiple bending or stretching cycles. We are open to helping our industrial partners to measure other devices or materials using this capability.

Devices

Phase Change Meta-Display

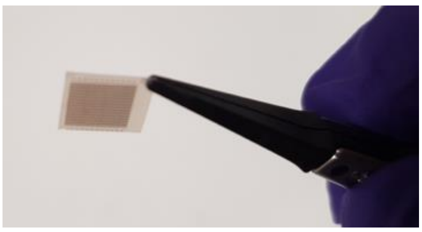
Bhaskaran's and Wright's teams are developing new functionalities for phase change materials such as the exploitation of ultra-thin phase-change layers to deliver an entirely new form of non-volatile optoelectronic display along with the combination of phase-change materials with metamaterial structures to provide tuneable/adaptable meta-devices, such as perfect absorbers and reflectarrays. The aim is to control the purity of the colour spectrum produced by phase-change pixels. Reflectance spectra were simulated using COMSOL Multiphysics, and photometric and colorimetric calculations and optimisations of various phase-change meta-display configurations using Matlab and Livelink for Matlab



Photometric and colorimetric calculations (illustration courtesy of Santiago Garcia Cuevas Carillo)

Phase Change Memory

An essential aspect of wearable and flexible technologies is the memory (data storage) element. Bhaskaran's team have also demonstrated phase change memory devices on a flexible substrate. They used graphene nano-gap electrodes to realise very efficient PCM devices. This project is ongoing, so keep an eye out.



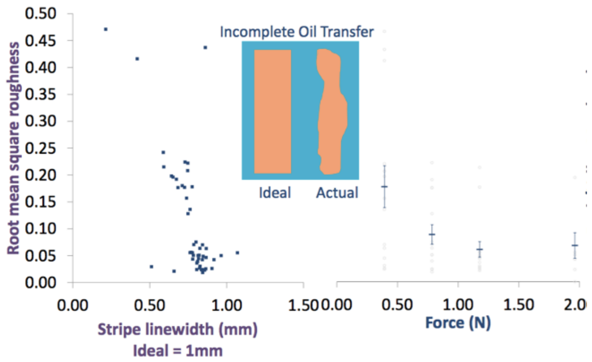
Phase change memory device on flexible substrate (photo courtesy of Ghazi Sarwat)

Martin Castell's team successfully synthesised a percolation network of gold nanoparticles with conducting polymers and have performed preliminary gas sensing experiments to show that these percolation sensors are more sensitive then thin film sensors. They have also investigated electropolymerising different conducting polymers to build up a library of a wide range of conducting polymers that can be potentially used for gas sensors.

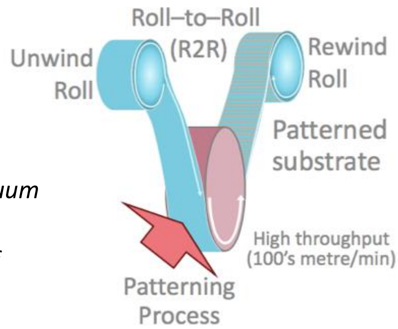
Dan Hewak's team is developing a thermo-electric module, complementing the organic photovoltaics as a secondary energy source. Flexibility requirements limit the choice of the substrate material. They successfully deposited BiSbTe and BiTe thin films by RF sputtering on polyimide at temperatures below 200^{o}C. The group also demonstrated p-type and n-type Ga:La:S thin films for potential applications in thermoelectric devices.

David Wright's team supported the development of organic thin film percolation sensors by creating semi-analytical model to predict sensors properties and performance and helping to analyse experimental results. This was presented in the research highlights of this report. In addition they have worked closely with Southampton on supporting development of flexible thermoelectric devices for energy harvesting. Gino Hrkac's team is supporting the development of new materials using atomistic simulations to design thermoelectric materials with enhanced properties. Bhaskar Choubey's team aims to establish rule-based strategies for thin film device manufacturing and identify system circuit configurations for coping with variability for truly wearable.

Thin film deposition of the various materials options will be designed and implemented on Hazel Assender's roll-to-roll vacuum webcoating facility. The facility itself has made much progress in the use of patterned substrates, and while promising progress has been made, more research is required to create better defined lines and patterns.



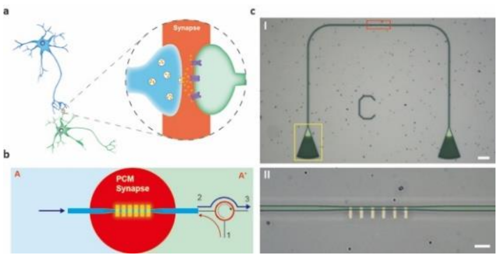
Depositing patterns of aluminium using a vacuum roll-to-roll technique (illustration courtesy of Thomas Cosnahan)



Impact of the WAFT Project in 2017

- The findings of the WAFT collaboration contributed to some non-academic outputs specifically towards developing tools and techniques to commercialize displays, especially through the involvement of Bodle Technologies Limited.
- A materials list was compiled by Southampton which has been circulated to industrial partners keen to take up any materials deposition on their chips for further integration. This could lead to breakthroughs in disruptive optoelectronic devices.

New emerging science



Optical synapse structure (illustration courtesy of Zengguang Cheng)

Optical Synapse based on Phase-Change Material

Neuromorphic computing has superior ability in processing complex tasks with extremely low power consumption comparing with conventional computing based on Von Neumann architecture. Brain-inspired solid state devices mimicking the functionalities of neuron synapse is the first and essential step to realize the neuromorphic computing. Motivated by the speed and energy-efficiency of photonic platform, optical synapse has many advantages that are superior to electrical synapse. Above mentioned studies on the optical applications of phase change materials including nanopixels and integrated photonic memory have paved a new direction of these 'out of fashion' materials. Herein, we report a first ever on-chip photonic synapse with plasticity based on PCMs. This work is done synergistically in WAFT leveraging funding from the ChAMP Partnership (EP/M015130/1) and Bhaskaran's Manufacturing Fellowship (EP/J018694/1).