Wearable and flexible technologies enabled by advanced thin-film manufacture and metrology

ANNUAL REPORT No. 1
May 2015 – April 2016

WAFT Project (2015-2019)

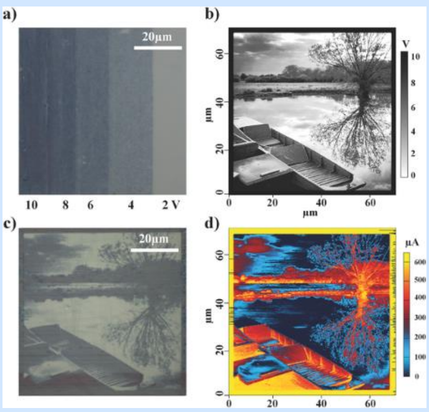
We aim to accelerate the development of wearable and flexible technologies by integrating device component development using advanced functional materials along with scalable, cost-effective and reliable manufacturing techniques.

Most research across the world for new device materials remained, for the time being, focused at laboratory scale, and there is a window of opportunity to develop a manufacturing lead in this area.

Featured equipment of the 1st year:

Woollam RC2 spectroscopic ellipsometer to measure advanced samples and nanostructures

Featured success of the 1st year:



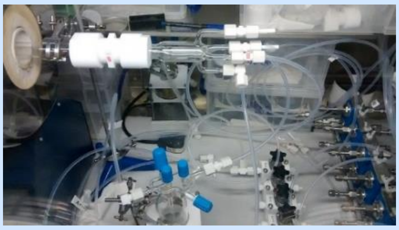
In 2016, the team of Harish Bhaskaran (Principal Investigator) developed the highest resolution display with pixels approaching 50 nm and showed the ability to render greyscale images for the very first time using brand new solid-state ultra-thin display technology.

Highlights for 2015-2016

In 2016 we have achieved a number of distinct technical milestones:

- Best elliptical spectroscope in the worldwide market (first in the UK), has now been installed for in situ metrology. The Woollam RC2 is the first spectroscopic ellipsometer with two rotating compensators allowing very sensitive measurements of film thickness, optical constants, composition, surface and interface roughness.
- Understanding the failure mechanisms in GST nanodisplays.
- Using a different chalcogenide material to produce grey scale for the very first time with very high resolution: 50 nm, a 40% improvement over previous work.
- Ability to differentiate the percolation region for interdigitated electrodes with a range of gaps for sensor applications.
- Understanding thermal and electrical properties of selected thin films and Ga:La:S feasibility in thermoelectric devices.

Featured method of the 1st year:



CVD Gas and Precursor Delivery for 2D thin film deposition

WAFT Facts 2015-2016

Complex, multidisciplinary project team from 5 university departments of 3 UK universities.

Widening Industrial Advisory Board with increased number of Industrial Partners from 7 to 15.

9 research investigators, 8 postdoctoral associates, 10 doctoral researchers, 1 undergraduate researcher, 3 laboratory technicians started project work across 11 research strands.

1 spin-out company, 1 iCase studenship, 2 other EPSRC grants are closely related to the WAFT Collaboration and with an EU grant project, research cooperation has been utilised.

25 journal articles and conference proceedings published

The WAFT research is supported by a £3.1 million, 4 year EPSRC project grant (EP/M015173/1) awarded to the University of Oxford (Lead), University of Exeter and University of Southampton.

Creativity and Innovation:

During the first year each component team generated high quality ideas in materials selection, research tool development and testing which they need to transform into realized innovation. The next year will add focus on large-scale and atomic scale modelling, integration, design for manufacturing and reliability improvements. The scale-up and development of roll-to-roll processes will start, aiming integrated device fabrication on large scale flexible substrates.

International collaborations:

WAFT PART-NERS	Academic/ University		Industry/ Private	
	in 2015	in 2016	in 2015	in 2016
UK	3	3	5	8
EU	1	1	2	6
USA	1	1		1
Total	5	5	7	15

Collaboration:

The first WAFT Scientific Meeting combined with the Industrial Advisory Board meeting in October 2015 helped to introduce the project to the 35-member academic and industrial audience.

Figure 1 The PI introducing the project to the IAB and the other members of the project at the introductory meeting in October 2015.

This included a successful poster session for students and postdocs to interact with industrial partners and with each other.

Figure 2 Dr Bernd Gotsmann and Harish Bhaskaran enjoying punting on the Cherwell as part of the IAB Meeting

WAFT Project Management Board Meetings were held in April, August, October 2015 and in February 2016.

WAFT Industrial Advisors:

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

Figure 3 Discussions at the closed-door IAB Meeting

WAFT Academic Partners:

University of Oxford, University of Exeter, University of Southampton

International Academic Partners:

- Karlsruhe Institute of Technology (Institute of Nanotechnology),
- University of Pennsylvania (Mechanical Engineering)

Dissemination:

- WAFT project logo was created
- WAFT project website: www.waftcollaboration.org
- The WAFT investigators and researchers demonstrated evidence of recognition and influence in the research community on an international scale.

Publication highlights:

- C. Ríos, P. Hosseini, R. A. Taylor, and H. Bhaskaran, "Color Depth Modulation and Resolution in Phase-Change Material Nanodisplays." Advanced Materials, (2016), 1-7., DOI: 10.1002/adma.201506238, WILEY-VCH Verlag GmbH & Co.
- S. G.-C. Carrillo, G. R. Nash, H. Hayat, M. J. Cryan, M. Klemm, H. Bhaskaran and C. D. Wright, "The design of practicable phase-change metadevices for near-infrared absorber and modulator applications." (2016), Optical Society of America
- C. Ríos, "Growth and nucleation dominated phase-change materials for nano-optoelectronics and display technology." INC11 Best Poster Award – Europe (2015)
- M. J. Lefferts and M. R. Castell, "Vapour sensing of explosive materials." Analytical Methods vol. 7 Issue 21, (Sept. 2015), 9005-9017., DOI: 10.1039/c5ay02262b, Royal Society of Chemistry
- P. Hosseini; H. Bhaskaran, "Colour performance and stack optimisation in phase change material based nano-displays." SPIE 9520, Integrated Photonics: Materials, Devices, and Applications III, (2015), 95200m., (June 1, 2015), DOI: 10.1117/12.2178658 (2015), SPIE Digital Library

Research Progress:

WP1. Metrology and Process Control for Waste Reduction

S1.1. In-situ Metrology Solutions for Thin Film Manufacturing

Co-Investigator: Moritz Riede,
PDRA: Sameer Vajjala Kesava.

Figure 4 Moritz trying to set the parameters right for the PV measurement

Moritz and Sameer procured and installed advanced metrology tools: the Woollam R2 spectroscopic ellipsometer and reflectometer. It was integrated to the upgraded vacuum chamber for in situ monitoring of thin film deposition.
Sameer visited Fraunhofer FEP (Germany) to gain understanding of roll-to-roll production of thin film technologies and metrology tools.

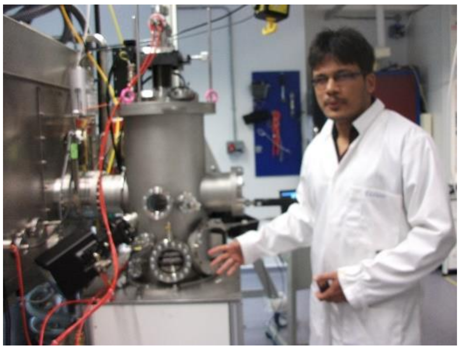


Figure 5 Sameer operating the vacuum deposition tool

S1.2 Ex-situ Metrology and Characterization

Principal Investigator: Harish Bhaskaran
PDRA: will start in July 2016
Undergraduate researcher: Jeremy Miles
Industrial Mentor: Asylum Research.

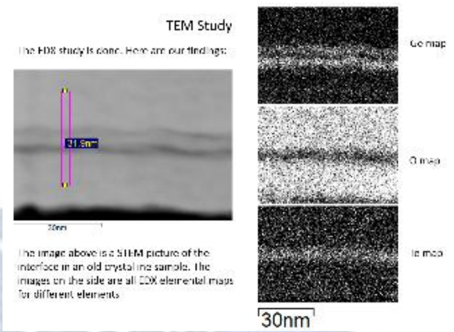


Figure 6 STEM imaging showing potential segregation of Ge

Harish and Jeremy worked on cross sectioning of components and carrying out electron microscopy to indicate aspects such as interfacial failures: delamination, electromigration, oxidation. Jeremy used electron microscopy and aberration corrected TEM and observed that Ge segregating to the interface is the failure mechanism.

S1.3. Waste Reduction

Co-Investigator: Moritz Riede
PDRA: Sameer Vajjala Kesava

Monitoring of material usage for each deposition was started, building broader database for material usage. The relationship between material usage, processing conditions and device performance should be obtained to improve process control and mechanical design.

WP2. Flexible and Functional Components

2.1. Flexible Display

Principal Investigator: Harish Bhaskaran
PDRA: will start in July 2016
PDRA: Zengguang Cheng,
PhD students: Carlos Ríos, Gerardo Rodriguez and Ghazi Sarwat;
Undergrad. researcher: Jeremy Miles.
Academic visitor: Peiman Hosseini (Bodle Technologies),
Industrial Mentor: Sharp

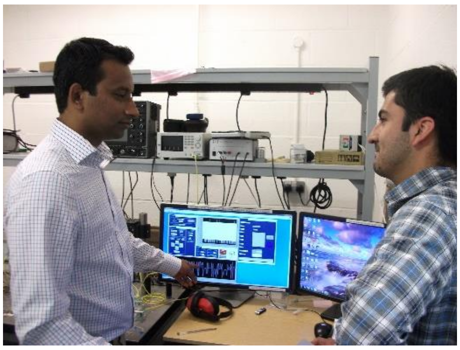


Figure 7 Harish and Carlos being forced to appear to be engrossed in conversation

50 nm pixels! – Harish's team started with their word record smallest display pixels demonstrated for potential application in projection-based displays as required for wearables. They developed transparent–electrode-based display in phase change materials with functional layer under 7 nm.

The focus was changed to enable grey scale with very high resolution: 50 nm pixels.

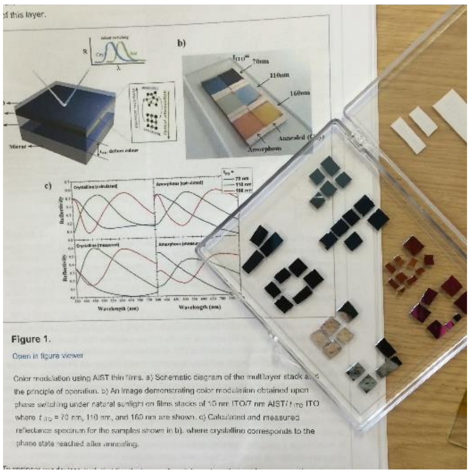


Figure 8 Some of the colourful samples from the latest result using new chalcogenides.

S2.2. Sensors

Co-Investigator: Martin R Castell,
PDRA: Krishnan Murugappan,
PhD student: Merel Lefferts

Figure 9 Krish working with various chips in Castell's Laboratory

Martin's team work on electrochemical sensors based on organic thin films, which yet lack the necessary sensitivity and selectivity. His postdoc Krishnan is developing an electrical percolation network of conducting organic lattices and becoming able to differentiate the percolation region for interdigitated electrodes with a range of gaps.

Figure 10 A PEDOT interdigitated electrode device connected to wires and ready for test

The task is the electrochemical polymerisation of PEDOT on interdigitated electrodes to create a percolation network followed by extensive characterisation.

S2.3. Thermoelectric Energy Harvesting Module

Co-Investigator: Dan Hewak
Senior research fellow:
Kevin Huang Chung-Che,
PDRA: Katrina Morgan, PhD students:
Nikos Aspiotis, Ghadah Alzaidy

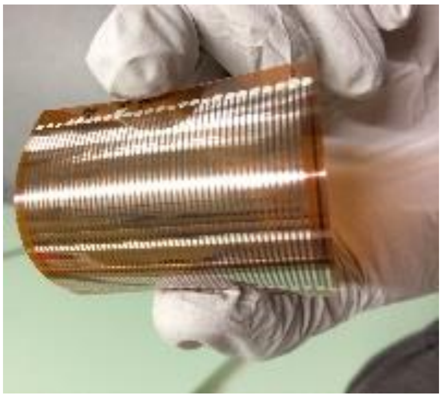


Figure 11 Flexible Thermoelectric Device in Hewak's Laboratory. Photo courtesy of Jin Yao

Dan's team is developing a thermo-electric module, complementing the organic photovoltaics as a secondary energy source. Flexibility limits the substrate material choice. The team successfully deposited BiSbTe and BiTe thin films by RF sputtering on polyimide at temperature below 200°C. Demonstrated p-type and n-type Ga:La:S thin films and reported on feasibility in thermoelectric devices.

S2.4. Organic Photovoltaic Energy Harvesting Module

Co-Investigator: Moritz Riede,
PDRA: Sameer Vajjala Kesava.

With active layers of only hundreds of nm, and processing on thin plastic films, organic photovoltaics are highly compatible with wearable and flexible electronics. Moritz's team needs to tailor OPV modules to the voltage requirements of other components as needed for integrated wearables. The challenge is the integration of 6-8 layers of advanced OPV modules. Sameer began cataloguing of module design based on voltage and power requirements of functional devices, and developing CAD layouts of various device geometries.

Figure 12 A CreaPhys Vacuum deposition Tool in Riede's Lab

WP3. Integration, Modelling and Reliablilty

S3.1. Modelling - large-scale as well as atomic scale of variations

Co-Investigators: C. David Wright, Gino Hrkac.
PDRA: Arseny Alexeev, PhD student: Santiago Garcia-Cuevas Carillo

Reliability of thin film processes is poorly understood, thus David's team needs to identify design guidelines to obtain acceptable performance for functional wearables. Santiago visited Oxford in Nov-Dec 2015 and studied the design of phase change devices. Gino is looking at atomistic simulations of materials and behaviour, concentrating first on the thermoelectric devices.

S3.2. Design for Manufacturing and Reliablilty Modelling

Co-I: Bhaskar Choubey
PDRA: will start in May 2017
Industrial Mentors: Sharp, Kurt J Lesker

Bhaskar'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 systems.

They will also study the lifetime failure of functional devices. Discussions started with Harish's display, Moritz's solar cell and Martin's sensor development specialists to see when they will reach a certain maturity with their devices for the engineering team to pick up the devices for testing and modelling their variability and reliability.

WP4. Scale-up via Roll-to-Roll Manufacturing

S4.1. Roll-to-Roll Process Development

Co-Investigator: Hazel E. Assender
Lab Technicians: Richard Turner, Clara Barker

Hazel started discussions with WP1 and WP2 researchers about upscaling issues of roll-to-roll manufacturing of ultrathin films of highly functional materials.

Figure 13 Assender's Roll-to-Roll Deposition Tool in Begbroke Science Park

S4.2. Device Fabrication using Roll-to-Roll on Flexible Substrates

Co-Investigator: Hazel E. Assender
Lab Technicians: Richard Turner, Clara Barker

Thin film deposition of the various materials options will be designed and implemented on Oxford's roll-to-roll vacuum webcoating facility.

Richard and Clara enhanced the webcoating equipment in Begbroke for optimal device layers depositions. It is suitable for evaporation of metals and organic materials, polymer deposition and sputtering. The ultimate aim is to investigate integration of multiple layer structures within a manufacturing facility to build test devices in a roll-to-roll manufacturing environment.

Facilities at CPI for roll-to-roll ALD deposition will be used for barrier and, if appropriate, device active layers.

Figure 14 Various rolls inside the R2R tool

Focus areas for 2016-2017:

- Test and improve the devices provided in display, sensor, photovotaic and thermoelectric harvesting development.
- Study compatibility of functional devices with flexible substrates.
- Intensify in situ and ex situ metrology support.
- Utilise the large-scale and intensive atomic scale modelling support.
- Collaborate effectively with industrial advisors through regular face-to-face meetings and focused research mentoring.