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Cover image: A darkfield image of a droplet of 50%v methoxypropanol/50%v water including polystyrene spheres which is partway through the drying process.

Welcome and Message from the Chair

Welcome to this year's Group Newsletter. Firstly, thank you to everyone who has given their time to the Group this year and all those who have contributed items for the Newsletter. I would like to extend a special thanks to Roy Gray who has taken over as editor, as well as our Hon. Secretary, Emma Talbot, and Treasurer, Leszek Majewski, for their support over the course of the year.

Our annual meeting on the "Science of Inkjet and Printed Drops" was held at the Institute of Physics in November and continues to be well attended. We were again at the Institute of Physics in January for our annual student conference on the theme of "Printing for the Future", with a programme of wide-ranging talks on printed electronics, 3D printing and drop deposition. This year we are also pleased to be co-sponsoring the IS&T's Printing for Fabrication (NIP32) conference, which is being held in the UK for the first time and there is still time to register before the conference starts on the 12th September. The International Symposium on Technologies for Digital Photo Fulfillment (TDPF) is also being held in conjunction with NIP so please do come along and join us in Manchester.

I am pleased to report that we awarded a Research Student Conference Fund award to Tom Mitchell-Williams this year. Tom will be presenting his work at the 2016 Applied Superconductivity Conference in Denver, Colorado in September. I would also like to draw your attention to the new Early Career Researchers' Fund which has been set up to provide financial support for early career researchers to attend international meetings.

Finally we have two more Group events planned for the coming months. Our one day meeting on "Advances in Printed Sensors" is being held at the Institute of Physics in early November and we will be heading to Cambridge for our 2017 student conference in January. As always, details of Group events may be found on our website <http://pgs.iop.org> as they become available. Our Group pages on LinkedIn and Facebook are also regularly updated, as is our Twitter feed. We are always open to ideas for new meetings and events; please feel free to get in touch with myself or another member of the committee. I look forward to seeing you at future events.

Anna Fricker

Chair, Printing and Graphics Science Group
September 2016

Committee Membership 2015-2016

Chair

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Dr Davide Deganello

University of Swansea

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Mr Roy Gray

Dr Alan Hodgson

Alan Hodgson Consulting Ltd.

Prof. Ian Hutchings

University of Cambridge

Mr Trevor Lambourne

University of Leeds

Dr Ehab Saleh

University of Nottingham

Reports from Recent Group Events

Science of Inkjet and Printed Drops

10 November 2015

Institute of Physics, London, UK

This one-day meeting was the eighth in a series of annual events organized by the Group which started with meetings on 'Dynamics of printed drops' in 2008 and 2009. Since 2010 the scope has been extended to include all aspects of the formation, behaviour and deposition of liquid jets and drops. The six invited speakers covered a range of topics, with a strong focus on applications of inkjet printing for functional purposes. The meeting was well attended, attracting 50 delegates with a good representation from both industry and academia. The extended lunch break provided time for networking and also discussion of the 15 posters, whose subjects included both modelling and experimental studies of drop impact and subsequent behaviour, internal flows within drops on surfaces, inkjet-based hybrid fabrication processes (inkjet plus AFM scratching, inkjet plus laser), inkjet-printed conductive materials and issues of printability for Newtonian and non-Newtonian fluids.

Reinhard Baumann from TU Chemnitz started the meeting with a wide-ranging review of the current global print market, and then focused on developments in the printing of conductive materials, with a drive to move from silver to copper to reduce cost, and the use of novel sintering approaches (including photonic sintering) for nano-particle inks. The printing of semiconducting materials and the use of these together with insulators and conductors for printing thin-film transistors in high volumes faces challenges in achieving good yields and in the development and use of appropriate device architectures, which he discussed.

Steve Yeates from the University of Manchester described work with a commercial electrohydrodynamic jet printer (SIJ) to produce very fine features with droplet sizes $<1 \mu\text{m}$ (sub-femtolitre volumes). Lines narrower than $3 \mu\text{m}$ and complex patterns can be printed, and Steve's group has used the technique to investigate the printing of aligned polymer brushes by printing an initiator molecule and then growing the brushes by dipping the substrate into monomer solution. Brush heights were 100-500 nm, with potential applications in the biomedical field, in switchable adhesion (mimicking the gecko foot) and in sensors. By careful control of formulation, features as small as 250 nm have been directly printed. [Further details at Submicron Patterning of Polymer Brushes: An Unexpected Discovery from Inkjet Printing of Polyelectrolyte Macroinitiators, Adam V. S. Parry, Alexander J. Straub, Eva M. Villar-Alvarez, Takdanai Phuengphol, Jonathan E. R. Nicoll, Xavier Lim W. K., Lianne M. Jordan, Katie L. Moore, Pablo Taboada, Stephen G. Yeates, and Steve Edmondson

J. Am. Chem. Soc., 2016, 138 (29), pp 9009–9012, DOI: 10.1021/jacs.6b02952]

Alan Hodgson (Alan Hodgson Consulting Ltd.), long-time member of the Group Committee and former Chairman, gave a fascinating talk on the role of inkjet in security printing, for documents ranging from passports and other high-security applications to packaging and brand protection for consumer goods. Inkjet printing has several valuable features, including the use of low-viscosity inks which readily penetrate an absorbent substrate (rendering removal of the print more difficult for a forger), and the ease of use of small volumes of expensive and complex inks (which may produce unusual visual effects or have special overt or covert properties). Inkjet is used in conjunction with other more conventional printing processes and this can lead to challenges (such as problems printing on to paper after intaglio printing which has effectively calendered the surface, or on to a previously printed substrate with regions of differing wettability). But there are also novel possibilities, such as using changes in wettability to modulate the width or intensity of an inkjet-printed line on a fine scale. Challenges exist in increasing printing speeds and achieving acceptable drying times and smear resistance, but inkjet clearly has important and growing value in the field.

Cristina Rodriguez-Rivero from the Inkjet Research Centre at the University of Cambridge described an experimental investigation of aerodynamic effects in industrial inkjet printing, in which she had used high-resolution high-speed imaging to study the flow of air and ink drops between a commercial drop-on-demand printhead (with 1000 nozzles in two rows) and a substrate moving beneath it at up to 1 m/s. By using laser optics and particle image velocimetry (PIV) she demonstrated how the complex pattern of airflow became established and evolved, how it was affected by the ejection of the drops, and how the drops themselves, together with the smaller satellite drops, were affected by the airflow. The research provides answers to some puzzling observations of artefacts in single-pass printing with large stand-off distances, and provides a potential method for studying and optimising printer design. [Further details at Aerodynamic Effects in Industrial Inkjet Printing, Rodriguez-Rivero, Cristina; Castrejón-Pita, José Rafael; Hutchings, Ian M., Journal of Imaging Science and Technology, Volume 59, Number 4, July 2015, pp. 40401-1-40401-10(10) DOI: 10.2352/J.ImagingSci.Technol.2015.59.4.040401]

Adam Brunton from M-Solv Ltd., Kidlington, talked about his company's work in large-area electronics printing, including the manufacture of capacitive touch-screen sensors and cell interconnects for thin-film photovoltaics (PV). A hybrid process involving inkjet printing and laser scribing gives good reproducibility and yield, and can reliably produce conductive lines with 25 µm width and separation. Lasers can also be used for local sintering of nanoparticle conductive inks, giving good final properties in the track. He highlighted electromigration problems in the use of silver for conductors; copper is more resistant to this mode of degradation

and responds well to laser sintering. A promising method for PV cell interconnects which is simpler than the current process, less capital intensive and suited to roll-to-roll production, is to fill laser-cut trenches with UV-curable insulator, and a metallic nanoparticle conductive ink.

The final talk was from **Louise Evans** from the Centre for Process Innovation (CPI), Sedgefield, part of the UK High Value Manufacturing Catapult. She reviewed several recent and current projects using inkjet for functional printing. In digital high resolution printing of large areas, issues had been identified in the printing of silver conductive lines, and had been addressed in various ways. These included creating channels in a hydrophobic polymer layer by photolithography or by laser ablation, followed by inkjet deposition of the conductor. these methods could achieve line widths down to 5 μm , and give much higher yields than simple inkjet printing on to an unpatterned substrate. Inkjet printing was being used for fiducial marks to improve pattern alignment in lithographic printing on polymer films, and could also be a valuable and robust process for printing variable QR codes. Another droplet-based method being used for conductive tracks down to 10 μm wide was the aerosol jet, which can handle more viscous fluids (up to 1000 mPa s) than conventional drop-on-demand inkjet printing.

Ian Hutchings, University of Cambridge
Meeting organizer

Printing for the Future

19 January 2016

Institute of Physics, London, UK

The 2015 student conference, with the theme of printing for the future, was held at the Institute of Physics. The 15 talks covered topics from the evaporation behaviour of printed drops to 3D printing, indicating the range and depth of work going on in this area.

Conference Program

Session 1

- Jonathan Waite, Robocasting with Integrated Fusion: 3D printing in multiple material classes, University of Cambridge
- Seong Hyun Park, Biosensors based on organic field-effect transistors (OFETs), University of Manchester
- Ezra Feilden, 3D Printing Strong, Tough Ceramic Composites, Imperial College London
- Emmanouil Papastavrou, Incorporating self-assembly into additive manufacturing techniques for applications in hard tissue engineering, Nottingham Trent University
- Miles Morgan, Extensional flow and properties of polymer solutions for printing, Swansea University
- Tom Mitchell-Williams, Inkjet printed multifilamentary YBCO/PrBCO coated conductors, University of Cambridge

Session 2

- Mohammad Nazmul Karim, Inkjet Printing of Highly Conductive Graphene-based Composite Inks for Electronic Textiles Application, University of Manchester
- Shaila Afroj, Inkjet Printing of Flexible PCB with Silver Nanoparticle Inks, University of Manchester
- Beth Kazmierski, Inkjet Printing onto Patterned Substrates, Durham University
- R.I. Tomova, Inkjet printing and inkjet infiltration of functional coatings for SOFCs fabrication, University of Cambridge
- Anthony Lewis, Inkjet Printing of TiO₂ compact layers for application in 3rd generation photovoltaics, Swansea University

Session 3

- Richard C. T. Howe, Graphene inks for industrial-scale flexo printing, University of Cambridge
- Ashley S. Johns, Inkjet printing of high-molecular-weight polymers via emulsions, Durham University

- Matt Everett, The Effects of Mesh Ruling and Particle Size for EL Phosphors, Swansea University
- Guohua Hu, Low temperature processable, functional inks of TMDs for inkjet printing, University of Cambridge

Our first speaker of the morning was **Jonathan Waite** from the University of Cambridge. Jonathan used robocasting to deposit a ceramic and metal composite paste and then fused it via laser melting. The system enables the use of fine powders and materials with different melting temperatures.

Ezra Feilden from Imperial College London continued the topic of 3D printing in her talk about incorporating silicon carbide fibres or aluminium oxide platelets with printed ceramic composites. Ezra printed successive layers with different orientations to improve the mechanical properties of the composite.

Next came **Seong Hyun Park** from the University of Manchester who is looking to fabricate solution-processable OFETS which can operate at voltages below 1V. Success would enable the use of flexible OFETs for biosensors.

We then returned to the topic of additive manufacturing with a talk by **Emmanouil Papastavrou** from Nottingham Trent University who uses an ice templating technique to create synthetic bone substitutes. Emmanouil is investigating methods of controlling the pore microstructure by varying the freezing temperature or the rate of deposition.

Miles Morgan from Swansea University then spoke about his work on the use of flexography to create low cost electronic devices. Miles is interested in Boger fluids and is looking at different PVA/PAM blends and their effect on print uniformity.

The final speaker before lunch was **Tom Mitchell-Williams** from the University of Cambridge who uses inkjet printing to create patterned substrates for low cost multifilamentary coated conductors. These are formed by depositing successive layers of a high temperature superconductor (YBCO) over CeO₂ tracks printed on a substrate.

The first afternoon session continued along the theme of inkjet printing and opened with a talk by **Mohammad Nazmul Karim** from the University of Manchester. Mohammad is using inkjet printing to deposit graphene inks on cotton for electronic textiles applications. The substrate is treated prior to printing to maintain functionality after washing.

Also from Manchester, **Shaila Afroj** described her project to create printed circuit boards using silver nanoparticle inks. Their intended use; to detect cracks in pipelines requires a flexible substrate. Shaila is using inkjet printing to print lines of 100 μm width on a polyethylene naphthalate (PEN) substrate.

At Durham University **Beth Kazmierski** investigated the effect of patterning on the evaporation of printed drops. Beth used particle tracking velocimetry to follow the movement of silica particles in an organic solvent as the solvent evaporates from square cells.

Rumen Tomov from the University of Cambridge then spoke about the use of drop on demand inkjet printing for fabrication of solid oxide fuel cells. He has printed 5-10 layers of a ceramic particle suspension to create a gas-tight electrolyte layer around 5 -10 μm thick.

The last speaker of this session was **Anthony Lewis** from Swansea University who is investigating inkjet printing of TiO_2 for photovoltaics. Anthony's present focus is the creation of a uniform and stable printed layer and he is using XRD, FEG-SEM and interferometry to examine the printed substrate.

Our final session of the day began with a talk by **Richard Howe** from the University of Cambridge who spoke about developing graphene inks for flexography. Richard used a solvent mixture and binder system to develop an ink that is more conductive than carbon ink and can be printed onto paper and polymer substrates.

Ashley Johns from the University of Durham investigated inkjet printing of high molecular weight polymers. He used a polymer inside the dispersed phase of a surfactant stabilised emulsion to examine the system's evaporation behaviour.

Matt Everett from Swansea University then spoke about the effect of mesh ruling on electroluminescent images. The 25 μm phosphor particles were deposited via screen printing and Matt then looked at the thickness and roughness of the resulting layers and how that affected images.

The final speaker of the day was **Guohua Hu** from the University of Cambridge who has deposited transition-metal dichalcogenides (TMDs) onto silicon wafers, glass and PET substrates via inkjet printing. Guohua used contact angle measurements to investigate the drying behaviour of these inks and the uniformity of the printed layer.

The day ended with the presentation of two prizes for the best student presentations. These were awarded to Ashley Johns Beth and Kazmierski from the University of Durham. See under Awards section but abstracts are below.

Anna Fricker

Abstracts

Inkjet printing of high-molecular-weight polymers via emulsions

Ashley S. Johns, and Colin D. Bain*

Department of Chemistry, Durham University, South Road, Durham, DH1 3LE, United Kingdom

High-molecular-weight polymers are difficult to print in high concentrations using ink-jet methodology because they introduce non-Newtonian behaviour to

formulations. Fluid viscoelastic properties can significantly delay drop breakoff and prevent detachment entirely. We show that oil-in-water emulsions provide a means to overcome the limitations of ink-jet printing polymer solutions. Here, polymer is dissolved into the discontinuous phase and shielded from extensional flow during jetting by two mechanisms. First, the interfacial tension of the oil-water interface opposes deformation of the spherical emulsion droplets by shear forces. Second, the surface excess of a surfactant stabiliser is reduced as the dispersed phase drop is deformed, triggering a rise in interfacial tension. Extensional strain then occurs primarily in the continuous, and polymer-free, aqueous phase.

We have demonstrated this principle using a model ink containing 3.8 wt% polystyrene, prepared by emulsification of a 9.5 wt% polystyrene solution in methylbenzoate with a 14.8 mM sodium dodecylsulphate solution using an ultrasonic horn. The initial Mn of the polystyrene was 550 kDa and the polydispersity was 1.06, though the horn causes some scission of the polymer chains. The discontinuous phase made up 40 wt% of the final formulation. The printed deposits are continuous in structure, with a domed topography.

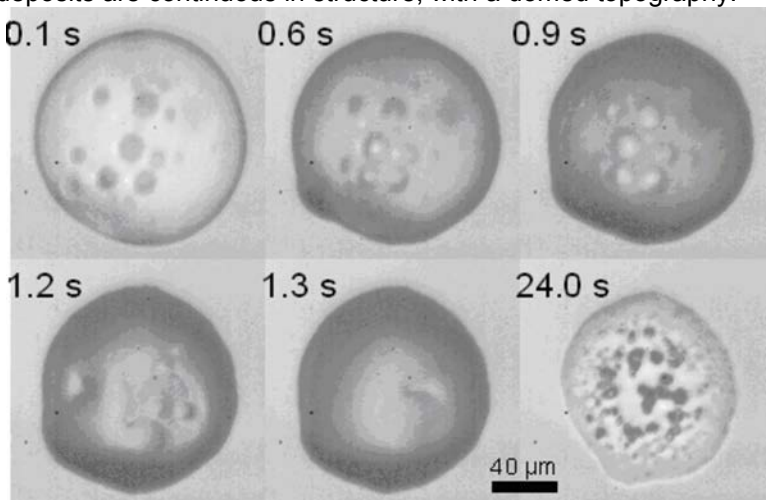


Figure 1. The drying process observed for an emulsion containing a 9.5 wt% solution of polystyrene in methylbenzoate (40 wt%) and 14.8 mM sodium dodecylsulphate solution as ink-jet printed from a nozzle of orifice diameter 50 μm . The nozzle was actuated with a symmetrical bipolar waveform of amplitude 100 V.

Inkjet Printing onto Patterned Substrates-

Beth Kazmierski, Prof. Colin Bain, Dr Lisong Yang. Durham University

It is a well-known phenomenon that drops containing particulate suspensions or solutes do not dry to give even deposits. Enhanced evaporation at the contact

line leads to ring-like deposits being left behind; often referred to as the coffee-ring effect.^{1,2} The coffee-ring effect is undesirable in inkjet printing as it reduces the quality of printed images. There have been reports of ways in which coffee-ring stains can be hindered or reduced using techniques such as the introduction of Marangoni flows or particle fixing.^{3,4} To date all literature has been focused on free-standing drops which are not contained in any way, for some applications is necessary to print drops into wells so they are surrounded by 'walls' on all sides. It is possible that the presence of walls around a droplet alters the evaporation flux across the droplet, this would change the flows present during drying and the profile of the deposits left behind.

Drops have been printed into self-contained square wells and the drying has been imaged. The flows present during the drying of single component drops and binary solvent mixtures have been tracked using particle tracking velocimetry (PTV) and the progression of the drying films characterised through interferometry.

(1) Deegan, R. D.; Bakajin, O.; Dupont, T. F.; Huber, G.; Nagel, S. R.; Witten, T. A. *Nature* 1997, 389, 827.

(2) Deegan, R. D.; Bakajin, O.; Dupont, T. F.; Huber, G.; Nagel, S. R.; Witten, T. A. *Physical Review E* 2000, 62, 756.

(3) Talbot, E. L.; Yang, L.; Berson, A.; Bain, C. D. *ACS Applied Materials & Interfaces* 2014, 6, 9572.

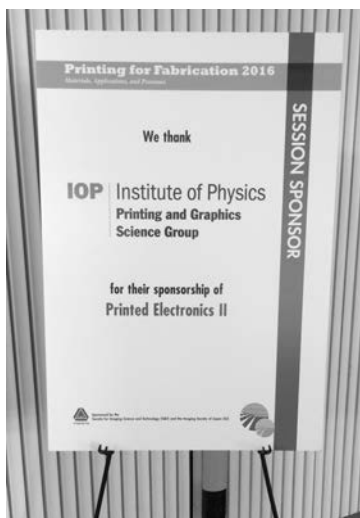
(4) Talbot, E.; Berson, A.; Bain, C. In *NIP & Digital Fabrication Conference; Society for Imaging Science and Technology: 2012; Vol. 2012, p 420.*

Printing for Fabrication

12-16 September 2016

Manchester, UK

It is too soon for any reports from the meeting. The Group sponsored the Printed Electronics meeting and here are some photos from the event.



Forthcoming Group Events

Technologies for Digital Photo Fulfilment

15-16 September 2016

Manchester, UK

Advances in Photovoltaics

30 September 2016

Institute of Physics, London, UK

Organised by the IOP Ion and Plasma Surface Interactions Group and co-sponsored by the PGS Group

<https://www.iopconferences.org/iop/872/home>

This one day meeting provides a forum to help assess the current state of the art in solar cells. It brings together a list of distinguished invited speakers whose expertise covers the range of photovoltaic technologies.

The conference programme and registration details are available at the link above.

24th Colour and Imaging Conference (CIC24)

7-11 November 2016

San Diego, USA

Advances in Printed Sensors

8 November 2016

Institute of Physics, London, UK

PGS Student Conference

Thurs 12th Jan 2017

**University of Cambridge - Institute for Manufacturing Seminar room 3 17
Charles Babbage Rd., Cambridge, CB3 0FS**

<https://www.eventbrite.co.uk/e/iop-pgs-conference-printing-for-the-future-2017-tickets-27580318475>

Organised jointly by the PGS Group and the Knowledge Transfer Network

IS&T Archiving 2017 Conference

15-18 May 2017

Riga, Latvia

Organised by the Society for Imaging Science and Technology and co-sponsored by the PGS Group

<http://www.imaging.org/ist/conferences/archiving/>

The IS&T Archiving Conference is an annual event aimed at the imaging science and the cultural heritage communities. The conference brings together imaging scientists and technicians with those working in the cultural heritage community (curators, archivists, librarians, etc.), government, industry, and academia to discuss the latest research and issues relating to the digital preservation and stewardship of hardcopy, audio and video.

There is still time to submit a paper for this conference. The deadline is the **1st November 2016**, please visit the website for further information.

Other Events of Potential Interest

IARIGAI 42nd Annual Conference

24-27 August 2016

Toronto, Canada

<http://iarigaitoronto.com>

12th Colour Conference

8-9 September 2016

Turin, Italy

<http://www.gruppodelcolore.it>

Plastic Electronics Conference

25-27 October 2016

Grenoble, France

<http://www.semiconeuropa.org/node/2981>

Printed Electronics USA 2016

16-17 November 2016

Santa Clara, California, USA

<http://www.idtechex.com/printed-electronics-usa>

RPS Good Picture 2016: Facets of Imaging

10 December 2016

London, UK

<http://www.rps.org/special-interest-groups/imaging-science/about/good-picture-2016-facets-of-imaging>

Electronic Imaging 2017

29 January - 2 February 2017

Burlingame, California, USA

http://www.imaging.org/site/IST/Conferences/EI_2017/IST/Conferences/EI_2017/Symposium_Overview.aspx

Large-area, Organic & Printed Electronics Convention (LOPEC)

29-30 March 2017

Munich, Germany

<http://www.lopec.com/>

Printed Electronics Europe 2017

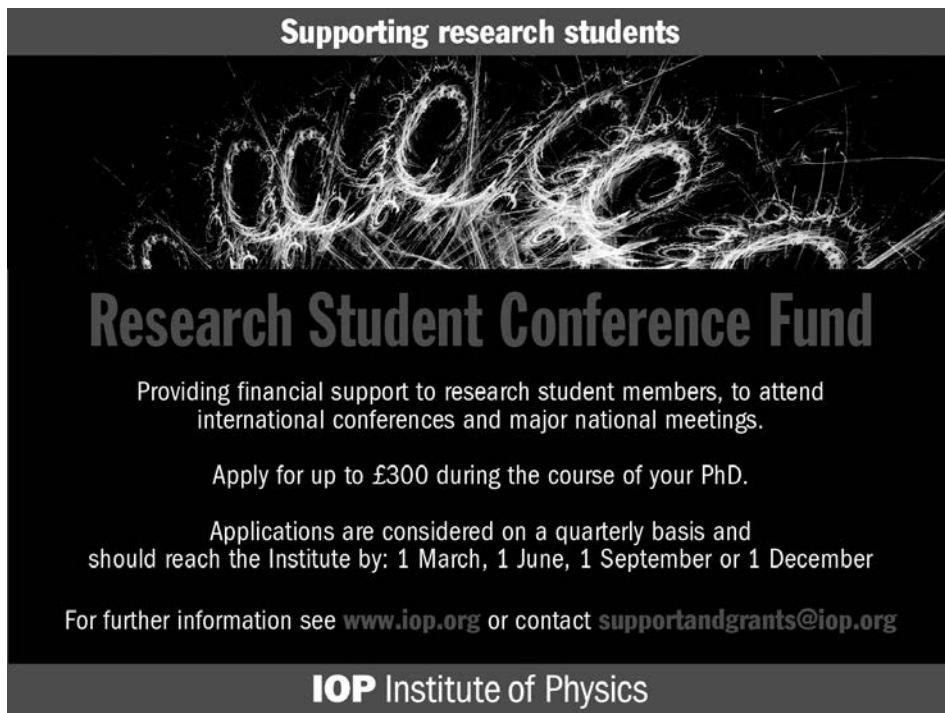
10-11 May 2017

Berlin, Germany

<http://www.idtechex.com/printed-electronics-europe/europe.asp>

Awards

Research Student Conference Fund

A dark banner with a white, glowing, abstract pattern resembling a network or a complex structure. The text is white and centered.

Supporting research students

Research Student Conference Fund

Providing financial support to research student members, to attend international conferences and major national meetings.

Apply for up to £300 during the course of your PhD.

Applications are considered on a quarterly basis and should reach the Institute by: 1 March, 1 June, 1 September or 1 December

For further information see www.iop.org or contact supportandgrants@iop.org

IOP Institute of Physics

Early Career Researchers Fund for Group Members

The Institute of Physics provides financial support to early career researchers to attend international meetings and visit international facilities. It supports and champions careers for physicists in industry and academia by providing opportunities for them to broaden their professional development and maximise their potential, particularly in their early career.

More information www.iop.org/about/grants/early-career/page_67022.html

PGS Group Awards

The PGS Group award two student presentation prizes each year. These prizes are open to all research students currently undertaking work at a university in the UK or Ireland, leading to a PhD or Masters degree, who present their work at the annual Printing and Graphic Science Group Student Conference. The Group awards two prizes of £50 for the best Student Presentations.

All presentations given at the Conference are considered for the year's prizes. For information on the next conference please see our group calendar. The 2015 Student Presentation Prizes were awarded as follows.

Beth Kazmierski, Durham University

Inkjet Patterning onto Patterned Substrates



Ashley Johns, Durham University

Inkjet Printing of High-Molecular-Weight Polymers via Emulsions



Other Information

PGS Group on LinkedIn, Facebook and Twitter

The Group has pages on the LinkedIn, Facebook and Twitter social networking sites which are regularly updated with news items and details of upcoming events. We look forward to seeing you there.

LinkedIn

<http://goo.gl/B0mds>

We can be found by searching for the 'Printing and Graphics Science' group on LinkedIn or by following the link above. You will need to be a member of LinkedIn to view the page.

Facebook

<http://goo.gl/vX0kC>

We can be found by searching for the 'Printing and Graphic Science Group' on Facebook or by following the link above. There is no need to be a Facebook member to view the page.

Twitter

https://twitter.com/PGS_IOP

The PGS Group is now on Twitter @PGS_IOP.

This newsletter is also available on the web and in larger print sizes

The contents of this newsletter do not necessarily represent the views or policies of the Institute of Physics, except where explicitly stated.

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