LOUGHBOROUGH DESIGN SCHOOL

Energy Research Laboratory

Loughborough University

Printed & textile supercapacitors: Applications Design, integration and the journey from research to enterprise

Energy Harvesting 2016
11th May 2016
Ambassadors Bloomsbury Hotel, 12 Upper Woburn Place, London, WC1H 0HX

Dr. Darren Southee

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Design for Digital Fabrication Research Group
Energy Research Lab (Chemistry)
Loughborough University
UK
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Scope

Printed Electronics (Background)

Energy Sources & Printing

Energy Sources & Weaving

Applications Design - Opto-Physiological Wearable Sensor

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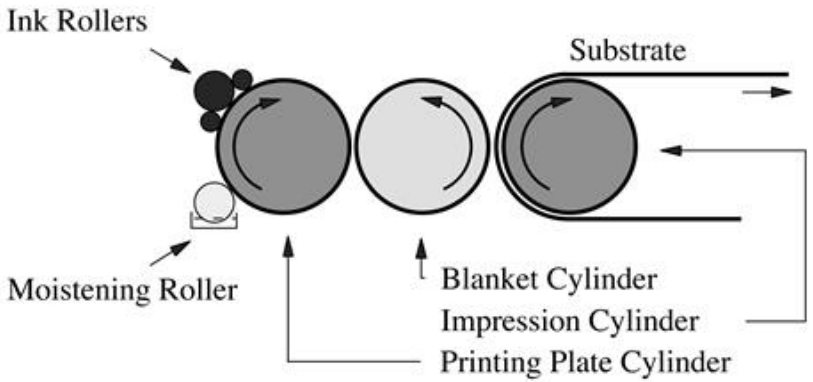
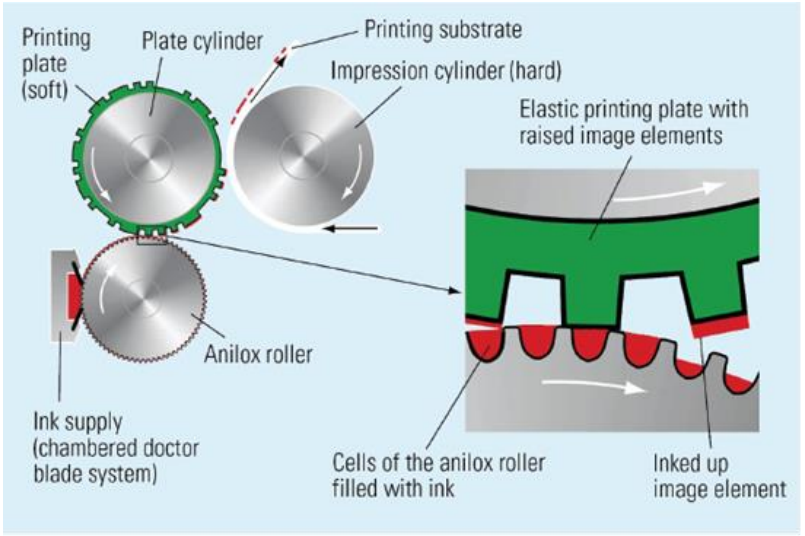
Printing Processes

The Offset Lithographic printing process



The Lithographic Printing Process

Flexographic (Flexo) printing



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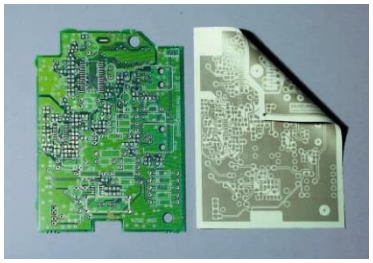
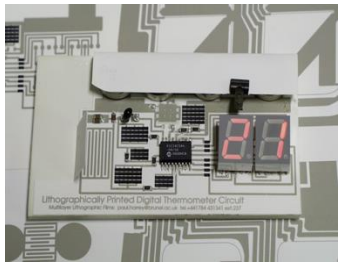
Heidelberg GTO46

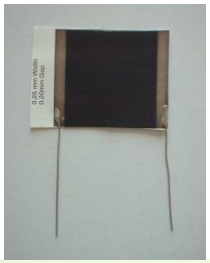
Screen printing
DEK 1202

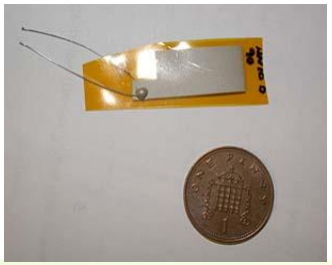
CLFs

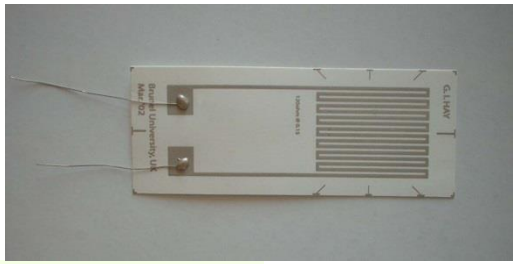




Printed interconnect utilising both SMT and printed passives components and ICs (1990s)







Printed transducers (temperature, humidity and strain) (2000s)

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Offset Lithography: We had joy, we had fun.....

ARJOWIGGINS

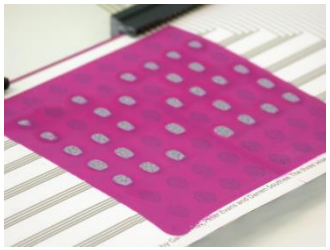
DuPont Teijin Films

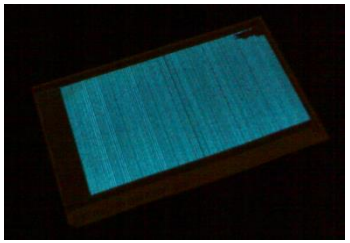
Hallmark

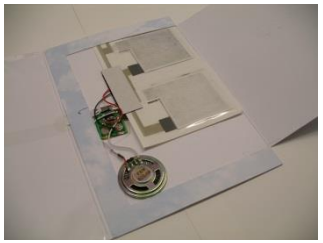
Parlex EUROPE

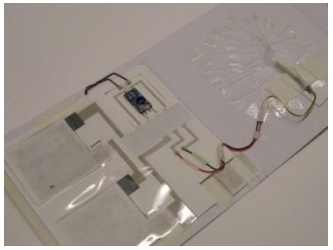
Integration of Printed Power Sources with Electronic Systems

(Grant no. 774611MM-CONWAY 10/2006 to 05/2008)









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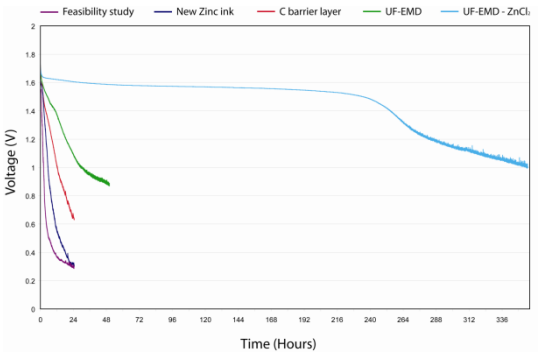
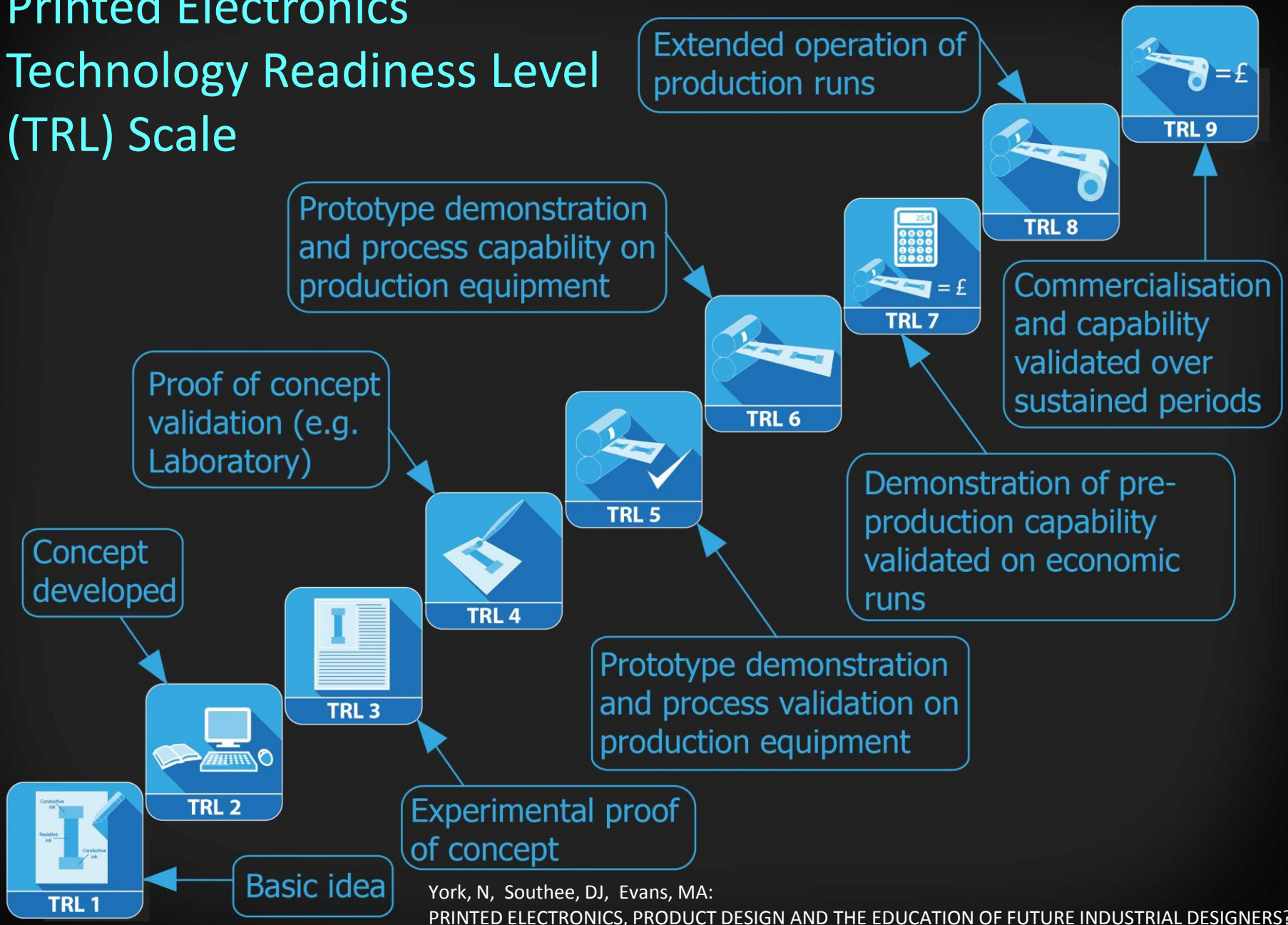
Powered a greeting card for a month….



Printed Electronics Technology Readiness Level (TRL) Scale



York, N, Southee, DJ, Evans, MA:
PRINTED ELECTRONICS, PRODUCT DESIGN AND THE EDUCATION OF FUTURE INDUSTRIAL DESIGNERS?
, **Great Expectations: Design Teaching, Research & Enterprise** , ISBN: **978-1-904670-62-9**

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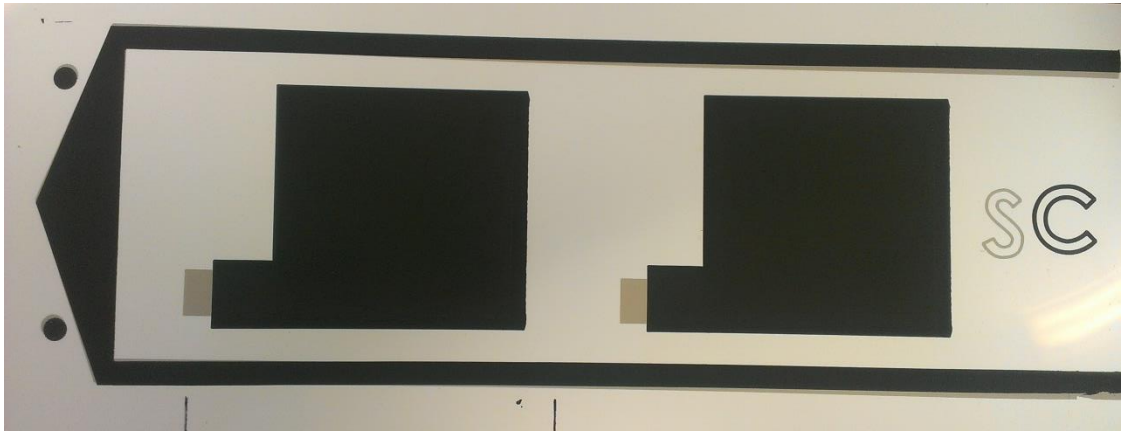
Integration of Rechargeable Printed Power Sources with Electronic Systems(Grant: SP/05/02/14 08/14 to 12/14)



GWENT GROUP
ADVANCED MATERIAL SYSTEMS

The aim of the EPSRC/IeMRC funded project:

- Explore the design and manufacture of rechargeable energy storage devices using mass produced printed electrodes

What we did:

- Characterised the original offset litho electrodes and the new flexo electrodes (Gwent inks)
- Construct a range of supercapacitors using various electrolytes

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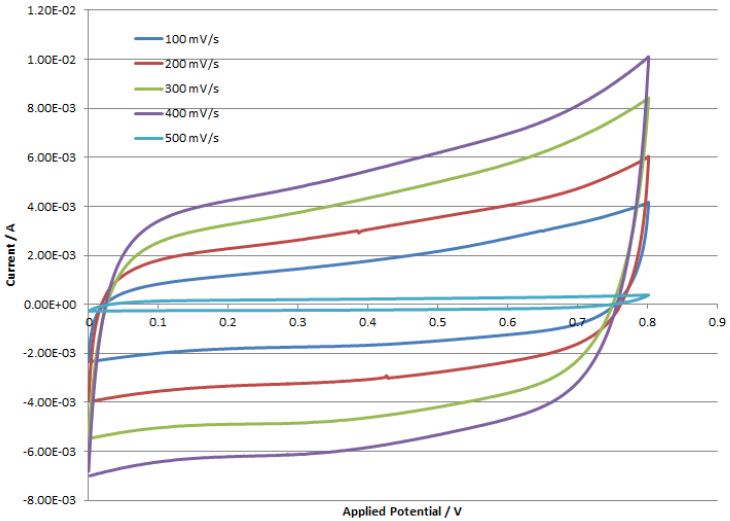
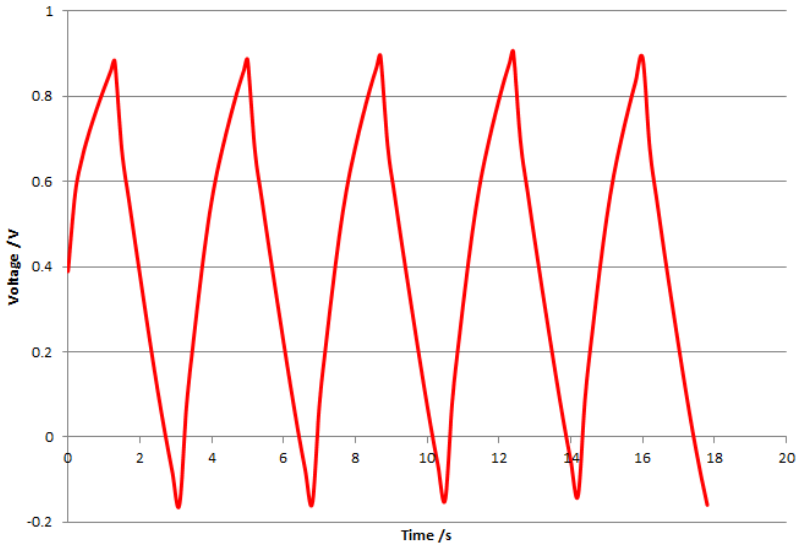
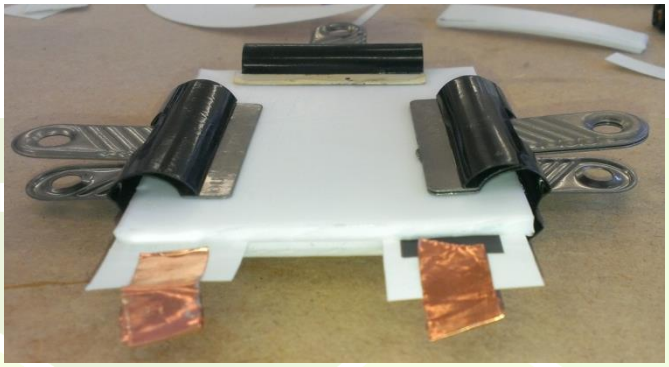
Offset Litho Electrodes in 6 M KOH – filter paper separator supercapacitor testing







	Device	Per cm^2
Capacitance	0.0137 F	0.000453 F/cm^2
Series Resistance	2.74 Ω	-
Energy	0.00438 J	0.000145 J/cm^2
Power	0.0584 W	0.00193 W/cm^2

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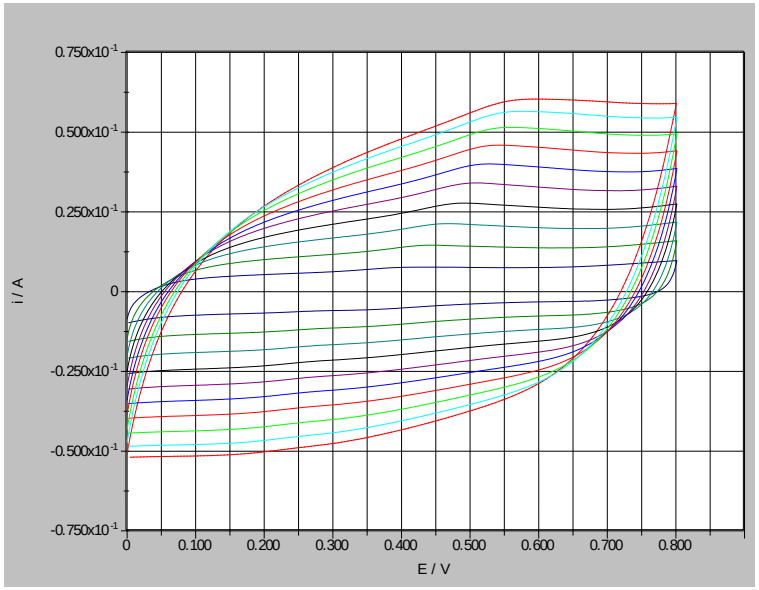
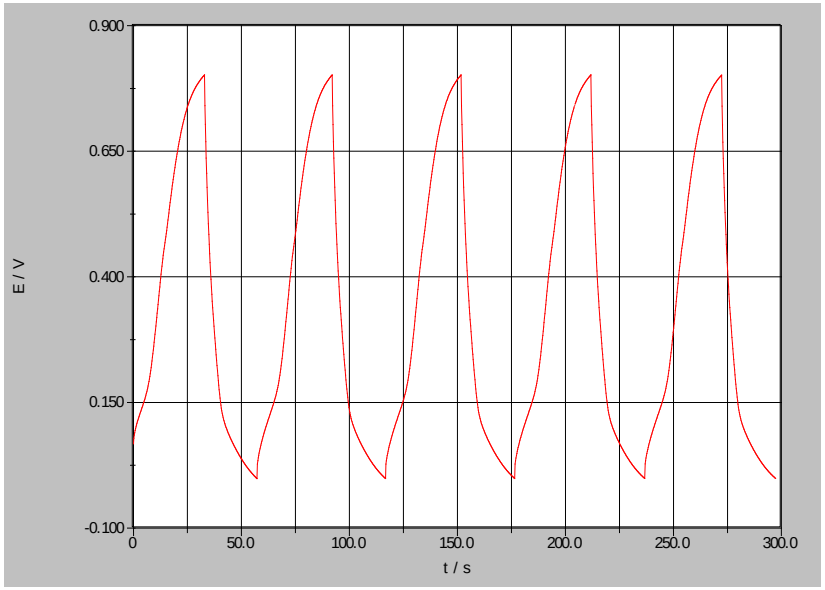
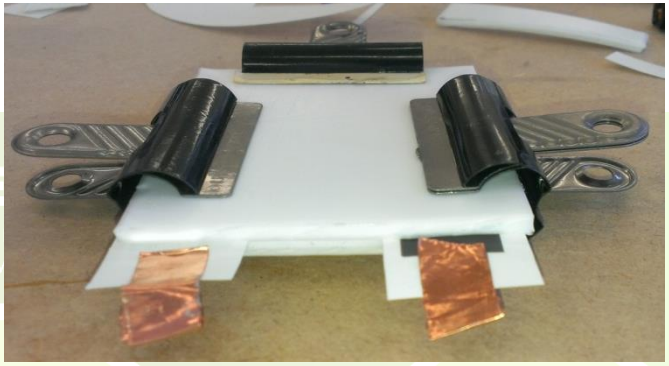
Flexo Electrode Testing in 6 M KOH, filter paper separator







	Device	Per cm^2
Capacitance	0.0500 F	0.00165 F/cm^2
Series Resistance	1.4 Ω	-
Energy	0.016 J	0.000529 J/cm^2
Power	0.114 W	0.00377 W/cm^2

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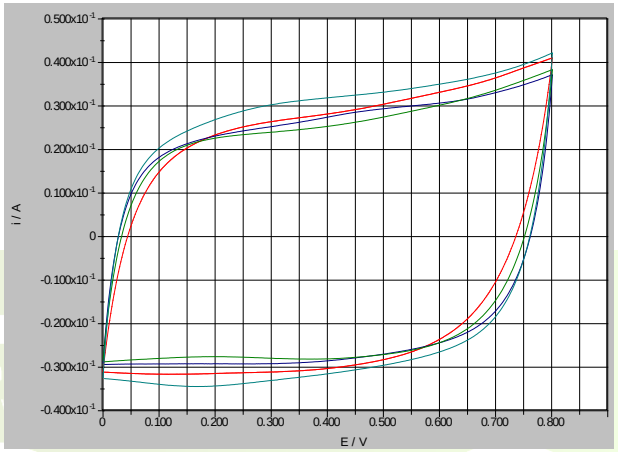
Solid state PVA-KOH supercapacitor

- **PVA gel**
- **Electrodes coated in the gel**
- **Two electrodes assembled**
- **No separator is required**



Reproducibility of 4 electrodes from batch 1
At 500 mV/s

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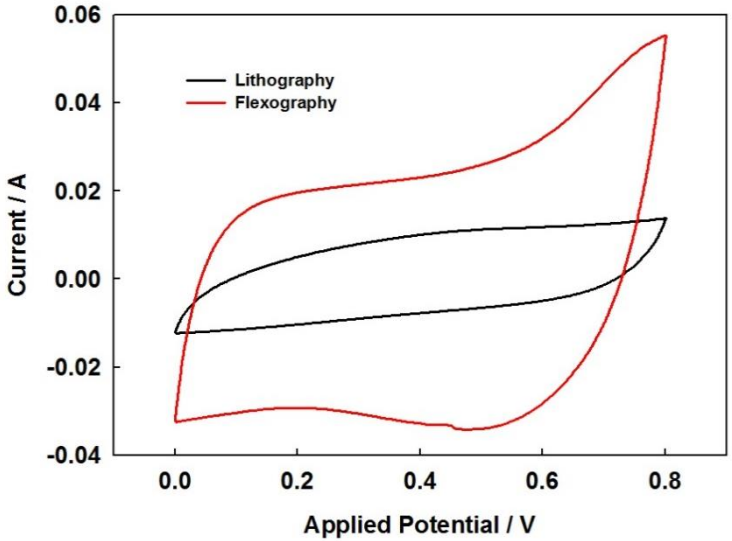
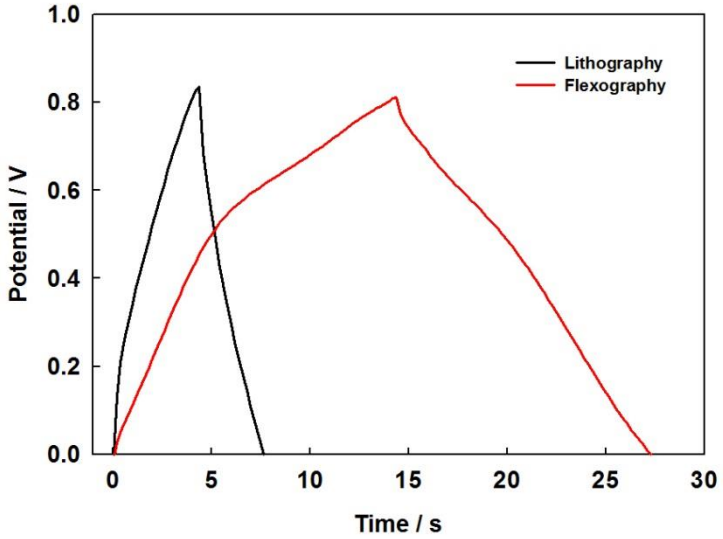
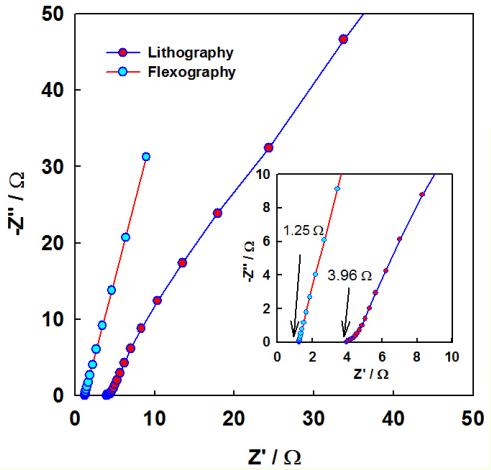
Comparison of the solid state supercapacitors: Litho vs. Flexo







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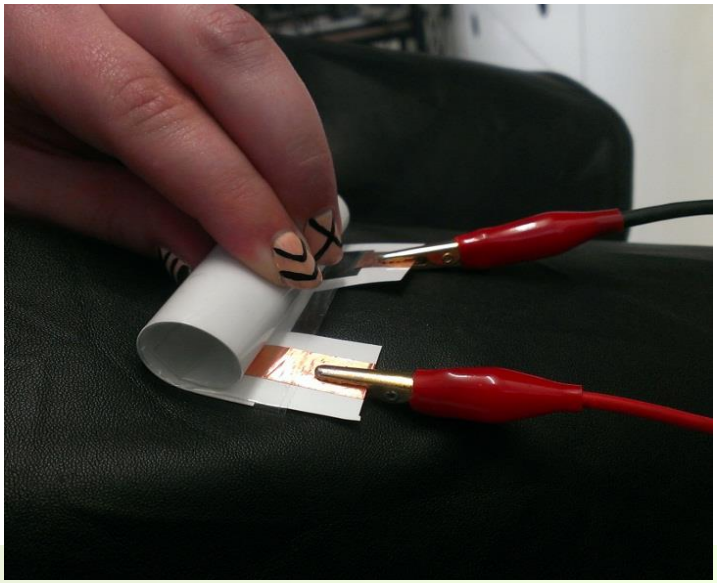
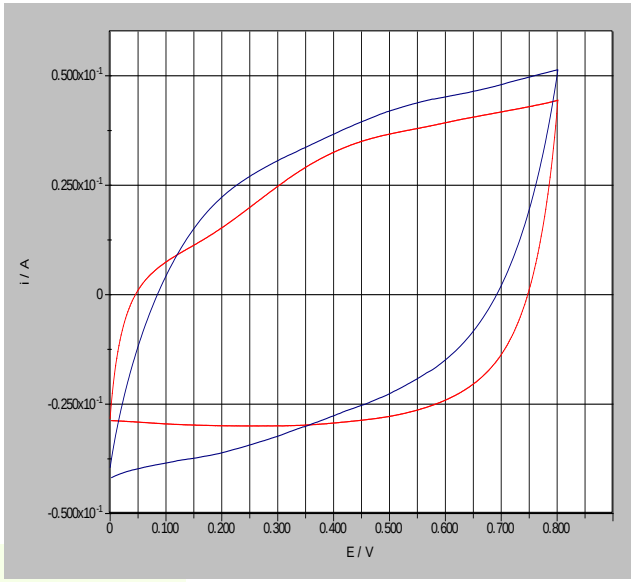
Flex - testing





Blue: before rolling
Red: after rolling

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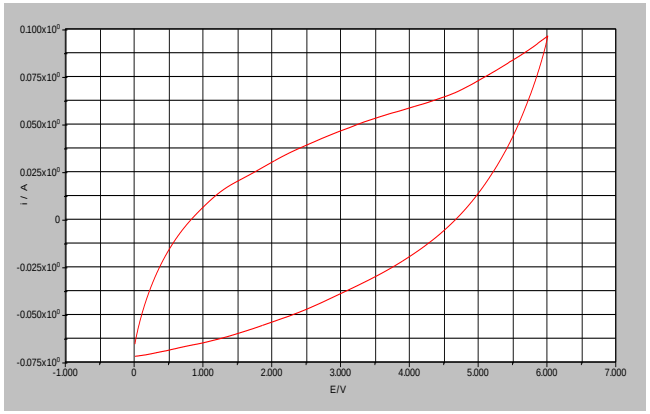
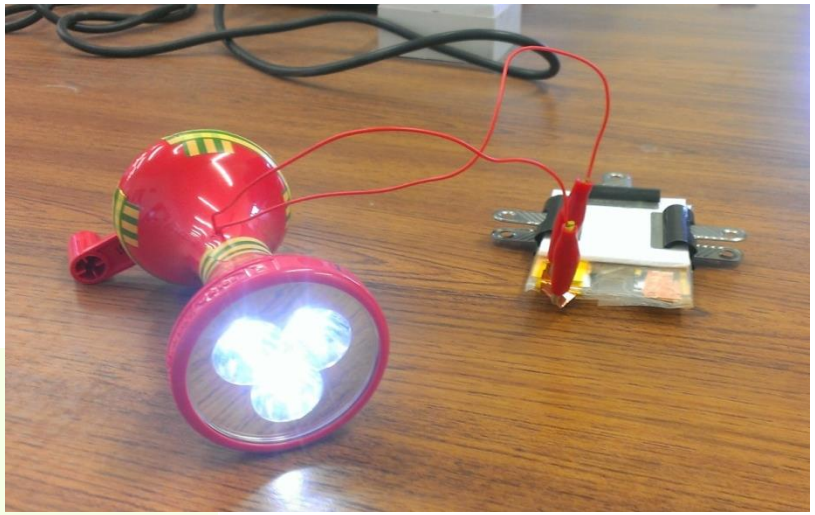
Developments

- Activated carbon layer/ionic liquids used as the electrolyte to give a larger voltage.
- Two of these supercapacitors were connected in series.
- With this combination, the supercapacitors can be charged to 6 V, and give a capacitance of around 0.5 F.



cyclic voltammetry at 100 mV/s



Demonstrator 2

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- Useful rechargeable power sources made from printed electrodes.
- Liquid electrolytes provide challenges.
- Solid-state supercapacitors incorporating printed electrodes have been fabricated, and characterised. There is evidence of commercial interest

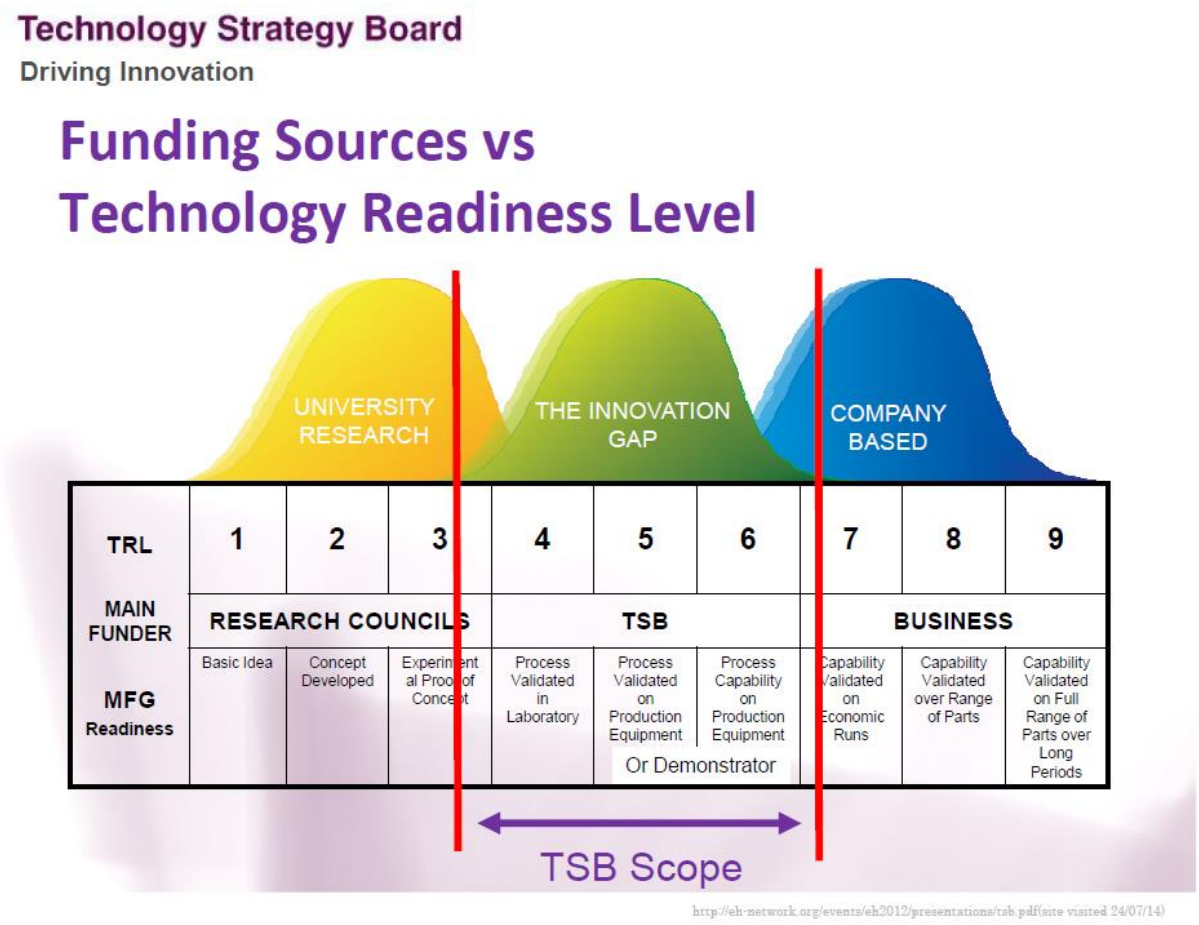
- **CONFERENCE**
  Invited to present at the IeMRC 9th Annual and Final Conference, held at Sir Denis Rooke, Holywell Park, Loughborough University on 17th February 2015
  http://www.lboro.ac.uk/microsites/research/iemrc/conference9.html

- **JOURNAL**
  Jagdeep S. Sagu, Nicola York, Darren Southee**, K. G. Upul Wijayantha**, *Printed Electrodes for Flexible, Light-weight Solid-state Supercapacitors – A Feasibility Study*, Circuit World, 2015, 42, 80-86. (DOI: http://dx.doi.org/10.1108/CW-01-2015-0004).

- **ENTERPRISE**
  Patent filed
  Project undertaken with industrial partner

so TRL 3/4 can just about be claimed with some elements of 5

Market survey is complete and suggests there is an appetite for the product(s).



TRL aspiration

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Development of Textiles for Electrical Energy Generation and Storage

Powerweave

NMP-2011-SME-5 : SME-targeted Collaborative Projects
NMP.2011.4.0-3 : Advanced textiles for the energy and environmental protection markets

SEVENTH FRAMEWORK PROGRAMME

Grant:	€4.0M
Timescale:	1 June 2012 – 30 Nov 2015 (42 Months)
Coordinator:	TWI Limited (UK)
R&D Partners:	EPFL (CH), Centexbel (BE), Brunel University(UK), CeNTI (Portugal), Cetemmsa (Spain)
Industry:	Ohmatex (DK), Bonar Technical Fabrics (BE), VdS Weaving (BE), Lindstrand Technologies (UK), Sefar (CH), Cyanine Technologies (IT), Peerless Plastic Coatings (UK)

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www.powerweave.eu

Lindstrand Technologies

TWI

EPFL École Polytechnique Fédérale de Lausanne

CENTI

BONAR Technical Fabrics

pieneta

CENTEXBEL

Peerless plastics & coatings ltd

Brunel University London

VdSWEAVING innovative partnerships

ohmatex smart textile technology

CETEMMSA Technological Centre

SEFAR

Airship – Lindstrand Technologies

A small scale mobile airship with electric propellers powered from the Powerweave gas envelope.

Agricultural fabric – Bonar Technical Fabrics

Greenhouse shading for southern European climates providing power for ventilation, pumping water and lighting in remote location.

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Develop a knitted or woven fabric that will generate power from sunlight or ambient lighting and store the energy within itself. **Aim to generate 10W/m^2 peak and to store 10Wh/m^2**.

Develop photovoltaic fibres, diameter 150µm. Generating **1.5mW/m**.

Develop rechargeable energy storage fibres, diameter 150µm. **Storing 2mWh/m**.

Design and develop reliable interface and interconnection methods combined in a fabric structure of the photovoltaic and the energy storage fibres.

Connect the fabric and demonstrate operation in large area PV/storage applications.

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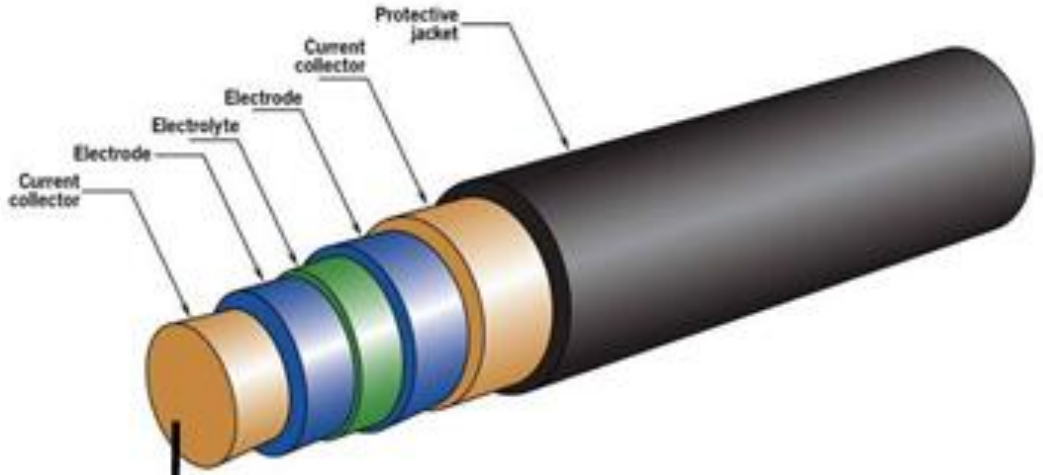
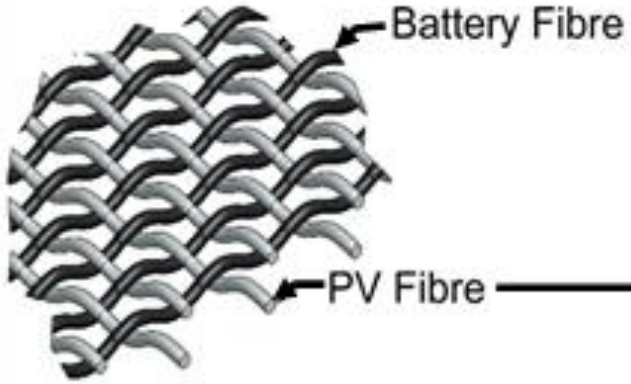
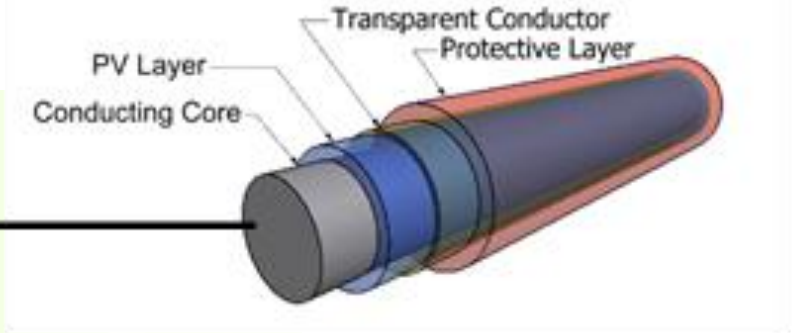
Powerweave project... objectives

Initial concept…

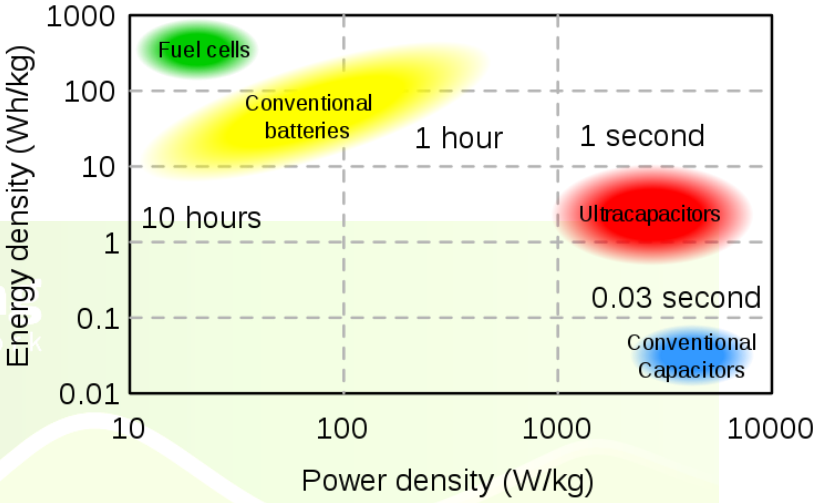


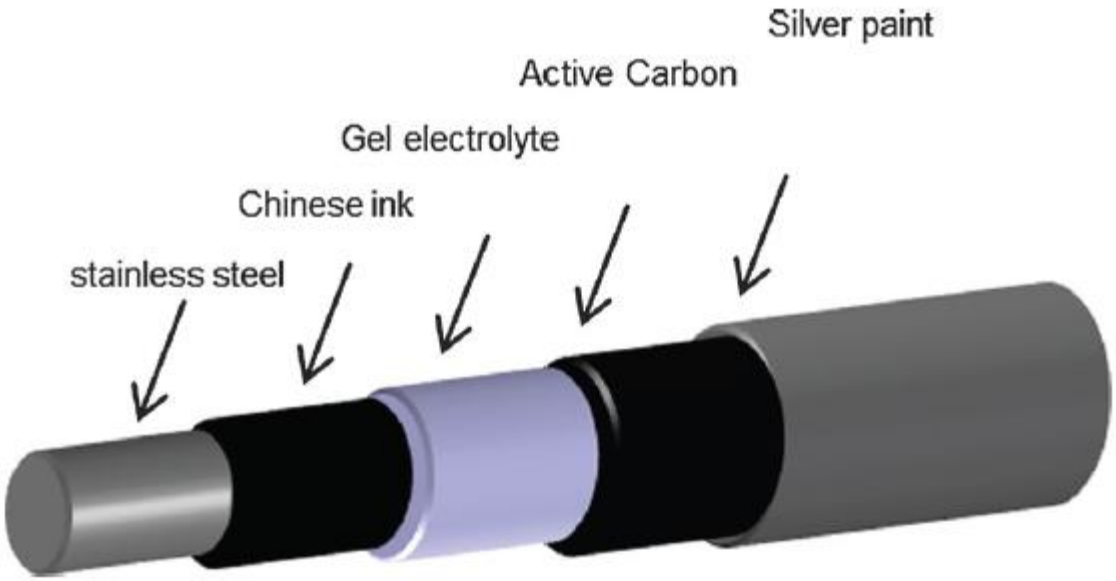


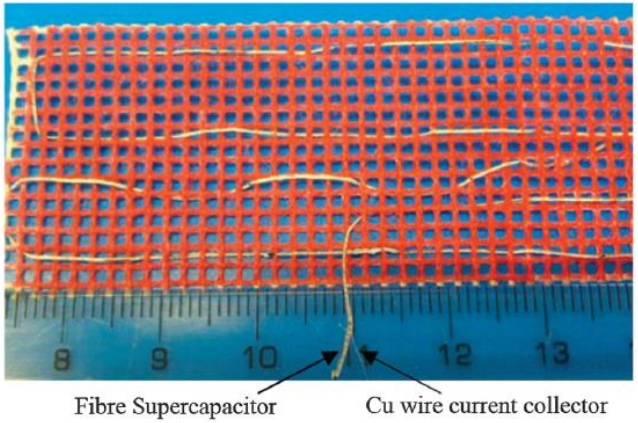


Choice between thin film Li-ion cells and supercapacitors:

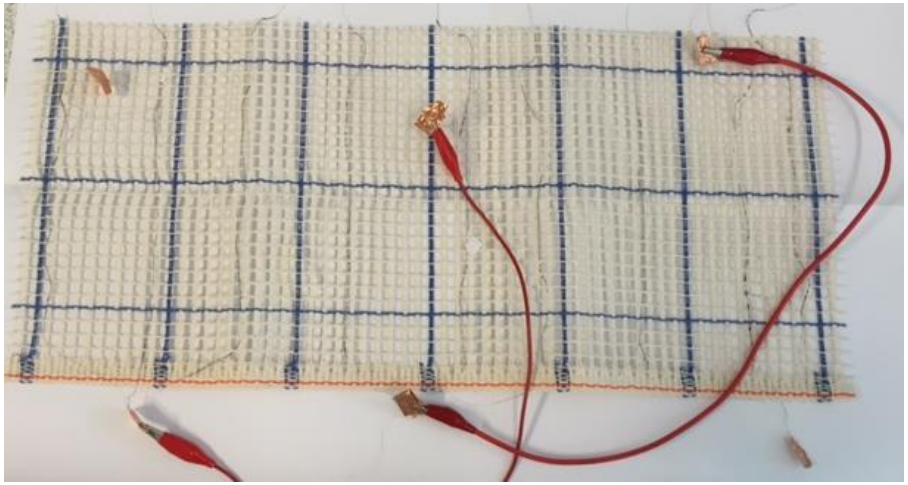
- Supercapacitors were chosen due to high power density, high lifetime and low internal resistance
- Supercapacitors can be constructed from commonly available, low cost materials
- Brunel University (and I) developed chemical structures suited to fibre format supercapacitors

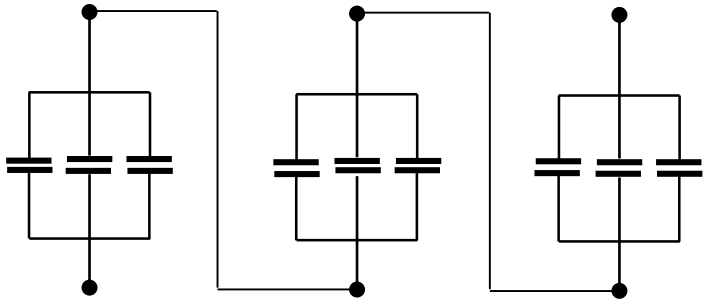






An energy storage device – a coaxial single fibre supercapacitor – was developed using a dip coating method and characterised using electrochemical methods. The specific capacitance per unit area and length were calculated to be 3.18 mF cm^{-2} and 0.1 mF cm^{-1}, respectively, for a 2.6 cm supercapacitor.





US 20150340169A1

(19) **United States**

(12) **Patent Application Publication**
QIU et al.

(10) **Pub. No.: US 2015/0340169 A1**

(43) **Pub. Date: Nov. 26, 2015**

(54) **SUPERCAPACITOR**

(71) Applicant: **BRUNEL UNIVERSITY**, Uxbridge Middlesex (GB)

(72) Inventors: **Fulian QIU**, Uxbridge, Middlesex (GB); **David Jonathan HARRISON**, Uxbridge, Middlesex (GB); **John Richard FYSON**, Uxbridge, Middlesex (GB); **Darren John SOUTHEE**, Shepshed, Leicester (GB)

(73) Assignee: **Brunel University**, Uxbridge, Middlesex (GB)

(21) Appl. No.: **14/761,480**

(22) PCT Filed: **Mar. 6, 2014**

(86) PCT No.: **PCT/GB2014/050657**

§ 371 (c)(1),
(2) Date: **Jul. 16, 2015**

(30) **Foreign Application Priority Data**

Mar. 6, 2013 (GB) 1304033.2

Publication Classification

(51) **Int. Cl.**

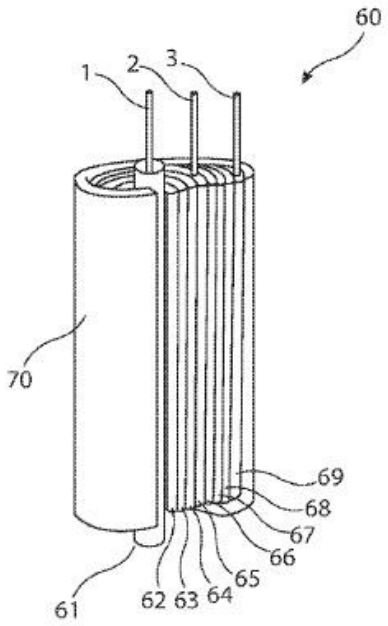
H01G 11/04	(2006.01)
H01G 11/86	(2006.01)
H01G 11/44	(2006.01)
H01G 11/34	(2006.01)
H01G 11/10	(2006.01)
H01G 11/38	(2006.01)

(52) **U.S. Cl.**

CPC ***H01G 11/04*** (2013.01); ***H01G 11/10*** (2013.01); ***H01G 11/38*** (2013.01); ***H01G 11/44*** (2013.01); ***H01G 11/34*** (2013.01); ***H01G 11/86*** (2013.01)

(57) **ABSTRACT**

A supercapacitor comprises a single core (preferably an electrically conducting fibre core) having sequential coaxial layers of: (i) a first electrode, (ii) a gelled electrolyte which functions as a separator for the supercapacitor, (iii) a second electrode, and (iv) a conductor for collecting current. A further supercapacitor layer can be provided. The supercapacitor fibre can be incorporated into fabric to form articles of clothing.



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ENTERPRISE

"Powerweave" Patent(s) published [PCT]:

700 metres of Energy Storage thread has been woven into a functional structure using industrial (production) machinery (Nov 2015) so TRL7 can be claimed?

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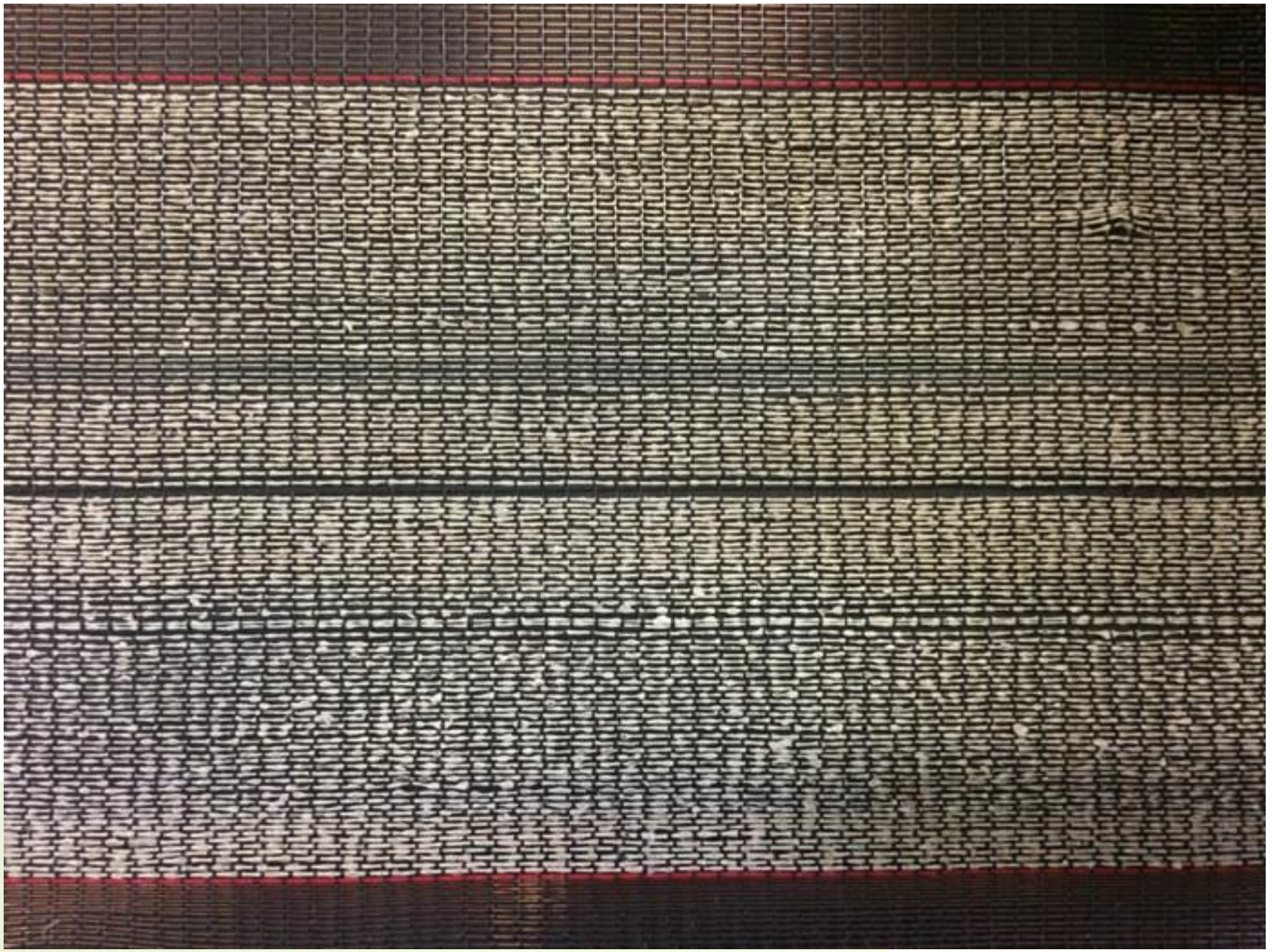
~2m x 1m



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- **JOURNAL**

Harrison, D, Qiu, F, Fyson, J, Xu, Y, Evans, P, **Southee, D** (2013) A coaxial single fibre supercapacitor for energy storage, *Phys. Chem. Chem. Phys*, 15, pp.12215-12219, Full text: http://pubs.rsc.org/en/Content/ArticleLanding/2013/CP/C3CP52036F. DOI: 10.1039/C3CP52036F.

- **ENTERPRISE**

“Powerweave” Patent(s) published [PCT] :

700 metres of Energy Storage thread has been woven into a functional structure using industrial (production) machinery .

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Wearable Opto-physiological Monitoring Sensor

Research, technologies and commercialisation

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Energy Harvesting

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www.eh-network.org

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Opto-Physiological Monitoring

Focuses on 3 aspects:

- Optimisation & characterisation of tissue illumination,
- light interaction in biological tissue, and
- effective capture of light trans-illuminating tissue.

Binary Heart

Opto-physiology and Photoplethysmography (PPG) are consolidated into Opto-physiological monitoring.

Opto-Physiological Monitoring - Issues

- The use of oversimplified PPG models to describe and implement the technology has limited its applicability
- The principles of current PPG is typically described as a blood filled cuvette, based on the Beer-Lambert law
- No scattering effects (μ_s, g) and the light sources are assumed to be monochromatic

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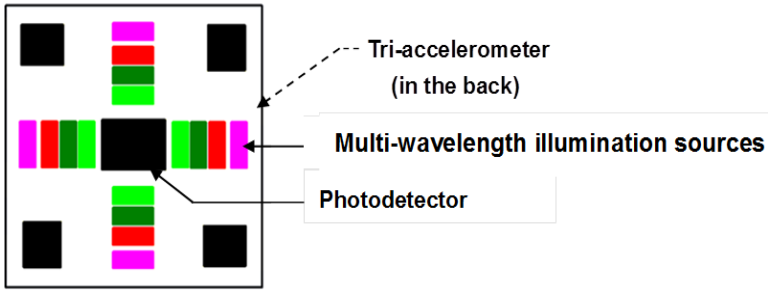

Novel sensor design

- Redundant illumination sources at multiple wavelengths
- Layout key IP feature, manage motion artefacts
- Additional sensor options e.g. accelerometer, temperature

Multiple versions built in house

- Tested on colleagues v's commercial product

Moving to bespoke electronics

- Gain full sensor control for performance optimisation

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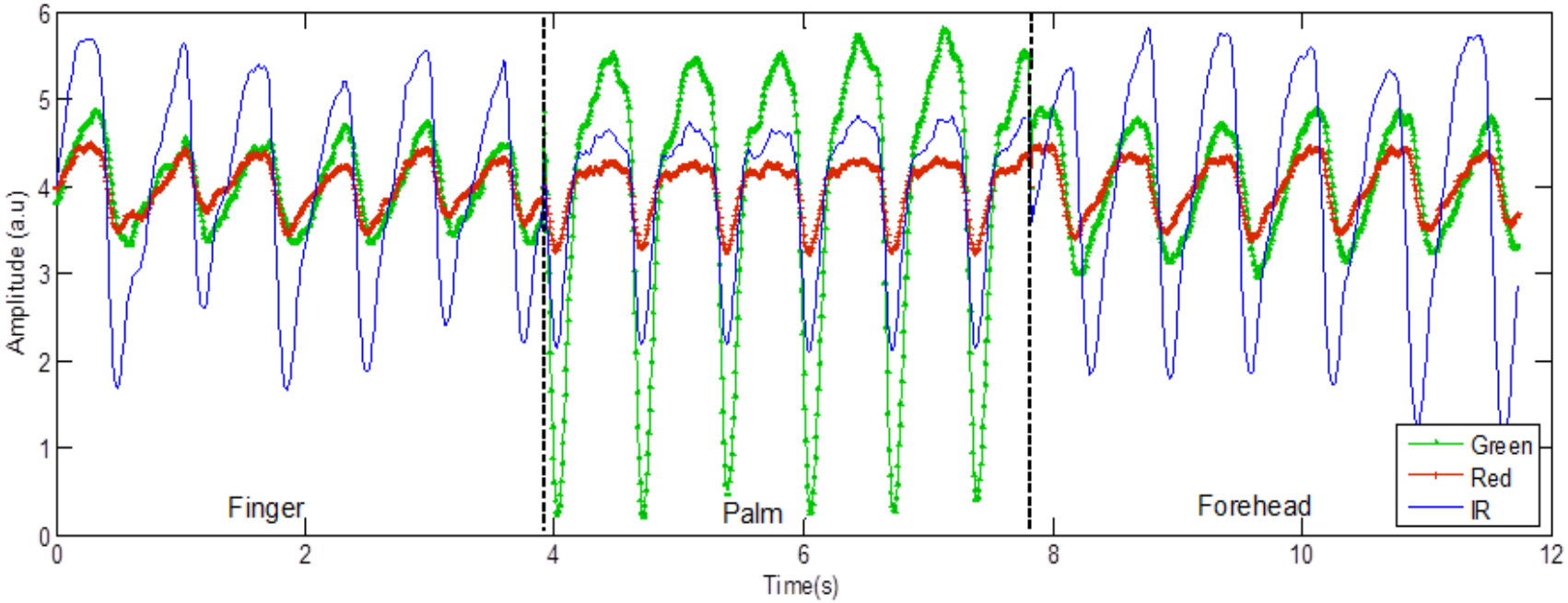
Wearable Sensor – Technology

PPG signals of heart rate monitored at different illumination wavelengths



Pulsatile waveforms gained from three measurement sites (e. g. finger, palm and forehead) under three wavelength illumination sources (e.g. green, red and IR).

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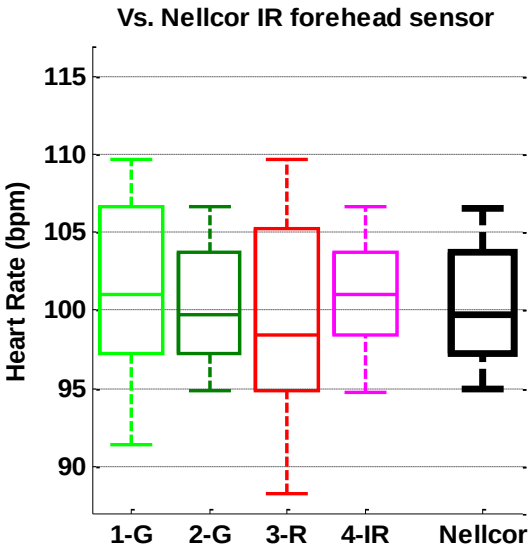
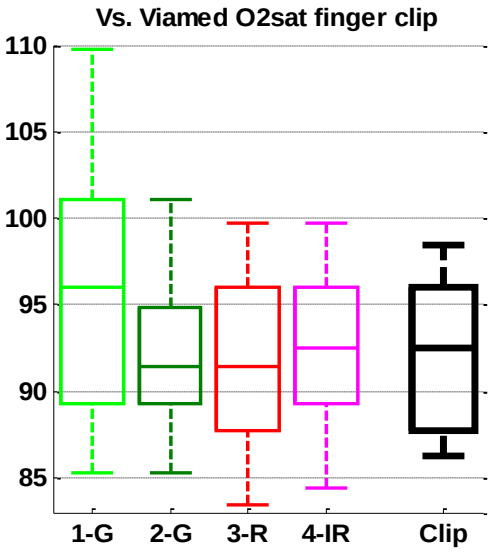
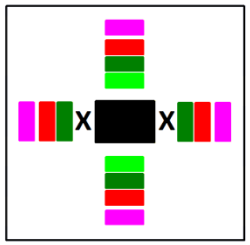
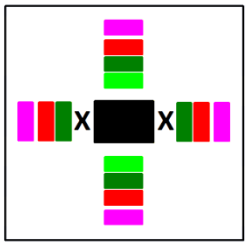
Wearable Sensor – Comparison Studies

Demonstrated equivalence with existing medical products









Alzahrani, A., Hu, S*., Azorin-Peris, V., "A Comparison Study of Physiological Monitoring with a Wearable Opto-Electronic Patch Sensor (OEPS) for Motion Reduction", *Biosensors*, 5, 288-307 (2015); doi:10.3390/bios5020288

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[Link to movie]

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Ready to go? TRL 5/6?

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Thank You