Washable and wearable electronic textiles enabled by two-dimensional materials

Felice Torrisi

Department of Chemistry, Imperial College London, UK

UNIVERSITY OF CAMBRIDGE

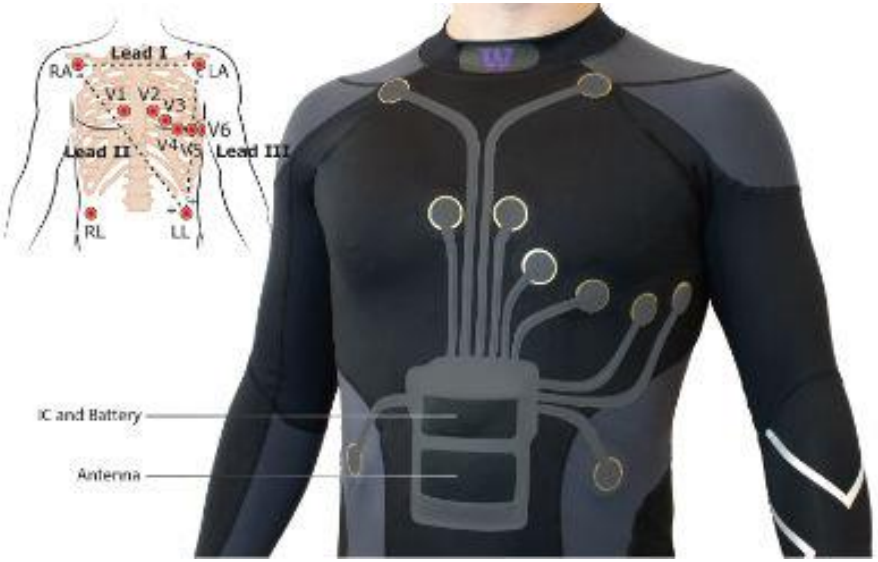
Imperial College London

Wearable electronic requirements

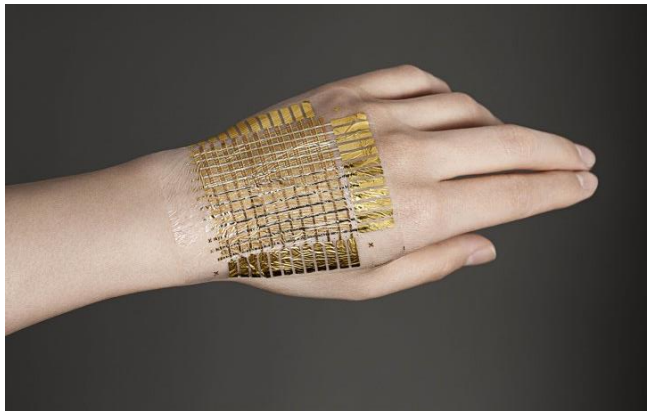
Werable electronic requirements:

- Highly stretchable (i.e. human skin elongation > 30%)
- Low-power
- Conformable
- Breathable
- Easy to integrate with clothes. (i.e. weavable)
- Washable (i.e. water resistant)

Electronic clothes and Body Area Networks



Electronic-skin

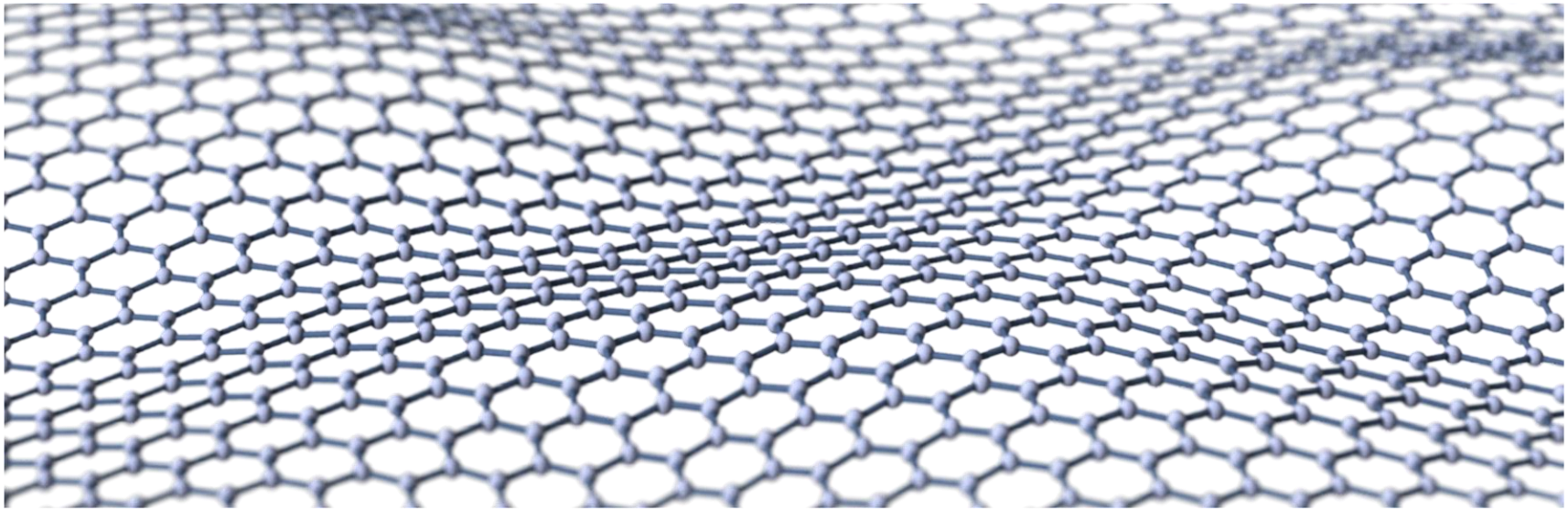


Kaltenbrunner *et. al.* Nature (2013)

Bio-compatibility and environmental stability required

Textile for wearable electronics

Graphene properties



Transparent

- Optical transmittance (across visible) : 97.7%

Conducting

- Doped graphene: sheet resistance~ 30 Ω/sq

Stretchable and conformable

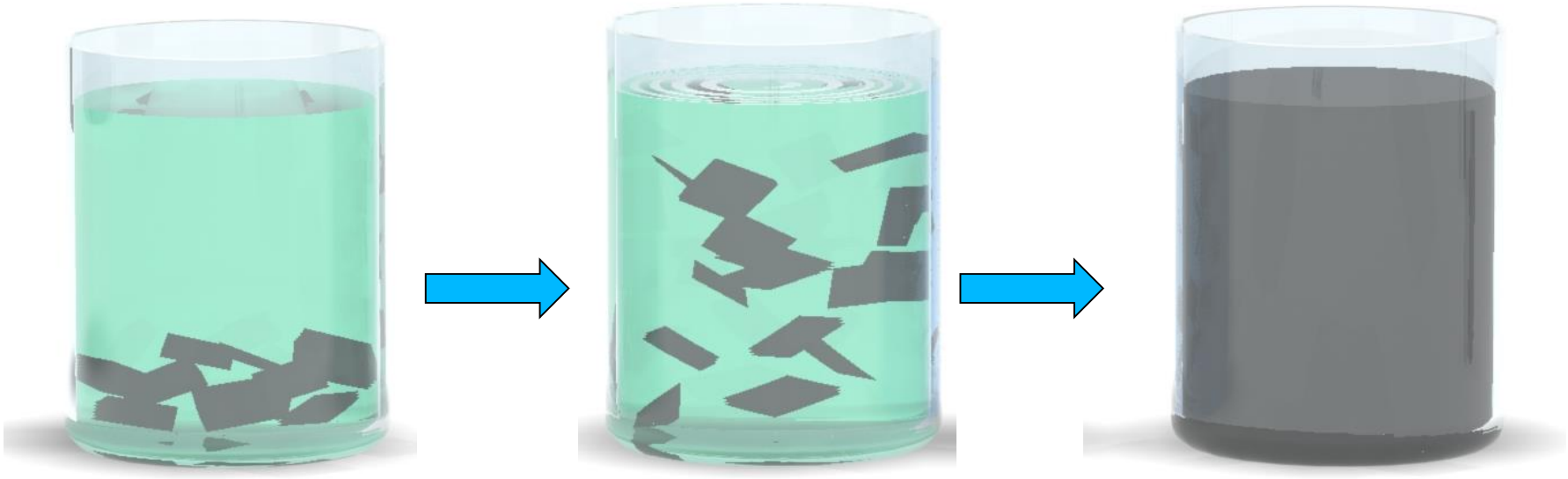
- Can withstand up to ~ 25% strain

Environmentally stable and bio-compatible

- Compatible with skin, myocardial and neuronal cells

Liquid Phase Exfoliation

Solvent



Natural/synthetic Graphite

Graphene ink

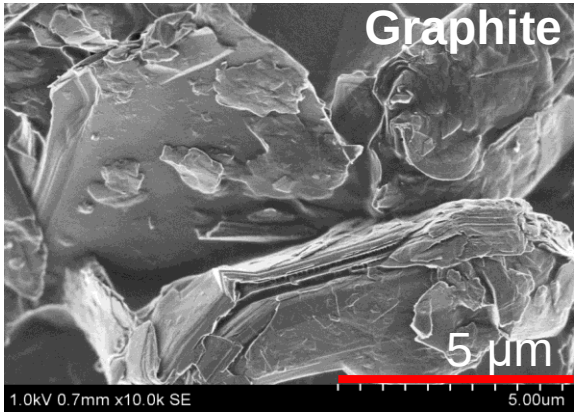
Ultrasonic, shear mixing

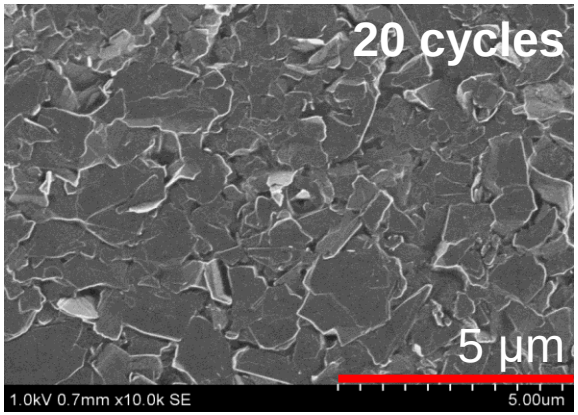
Shear forces enable exfoliation

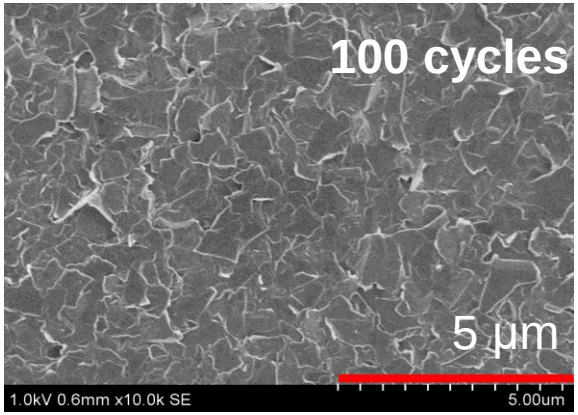
F. Torrisi *et al*. ACS Nano (2012)
T. Hasan, F. Torrisi *et al.* Phys. Stat. Sol. B (2010)
Y. Hernandez *et al*., Nature nanotechnol. (2008)

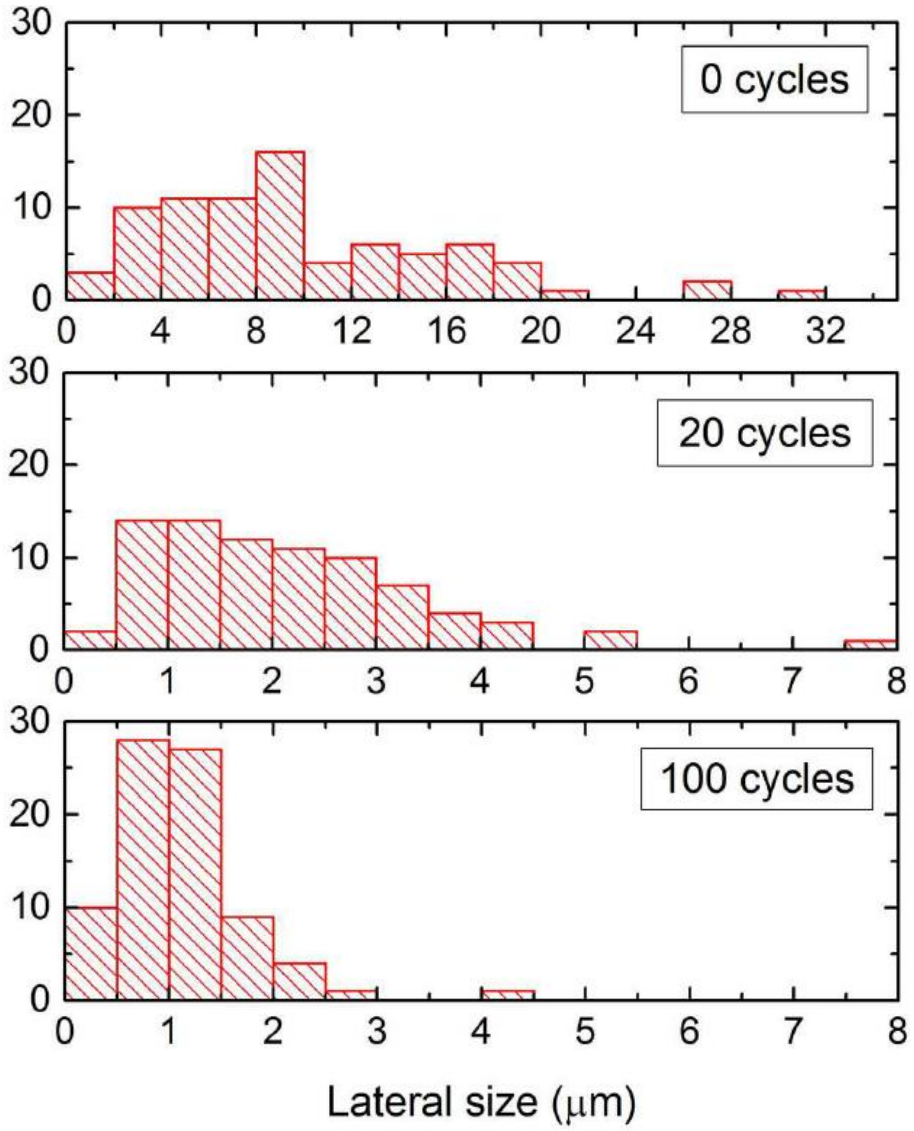
F. Torrisi *et al*. Nature nanotechnol. (2014)

Microfluidic exfoliation of GNP - SEM





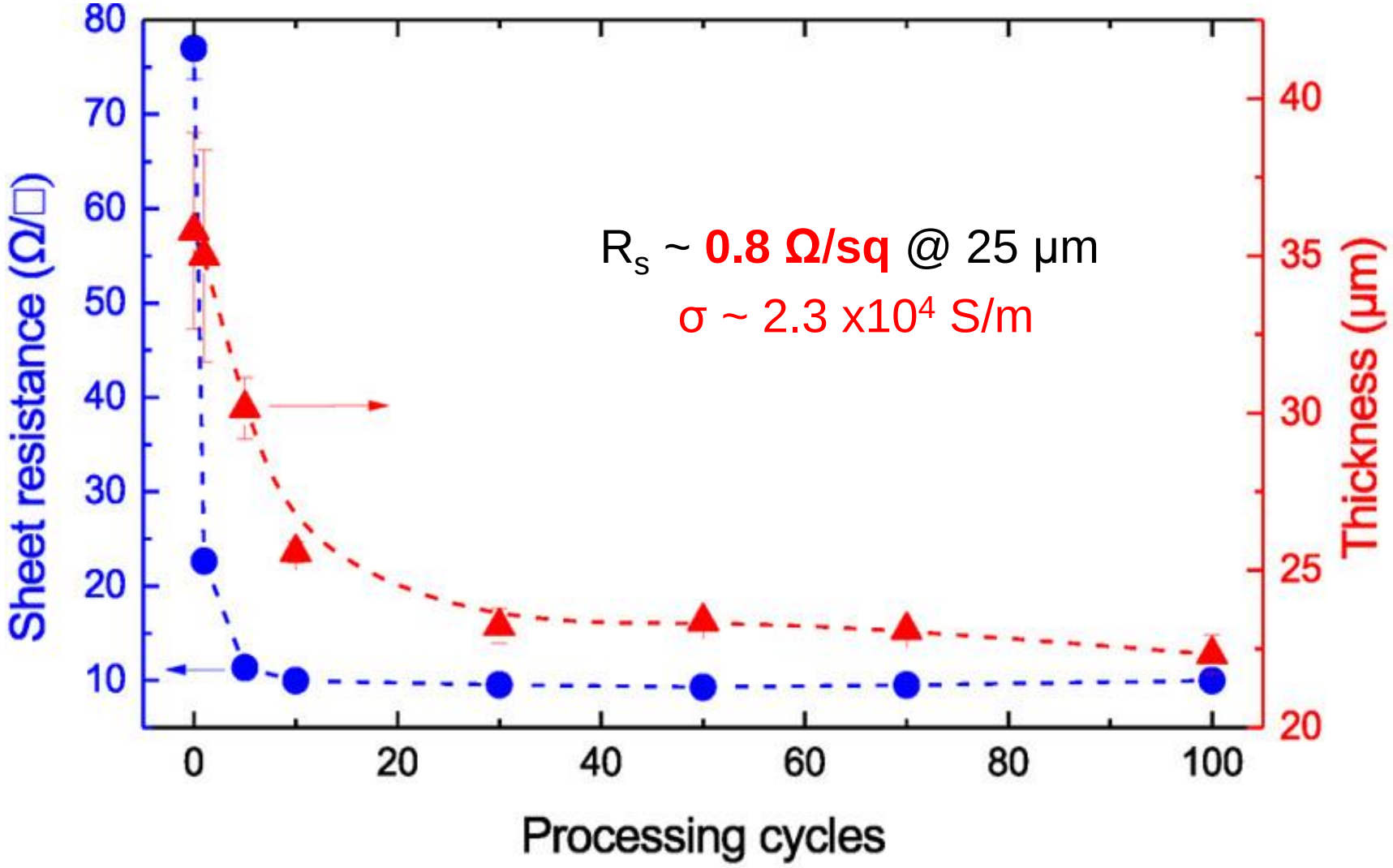




Single layer graphene flakes yield ~ 40%

P. Karagiannidis *et al.* ACS Nano, 11, 3 (2017)

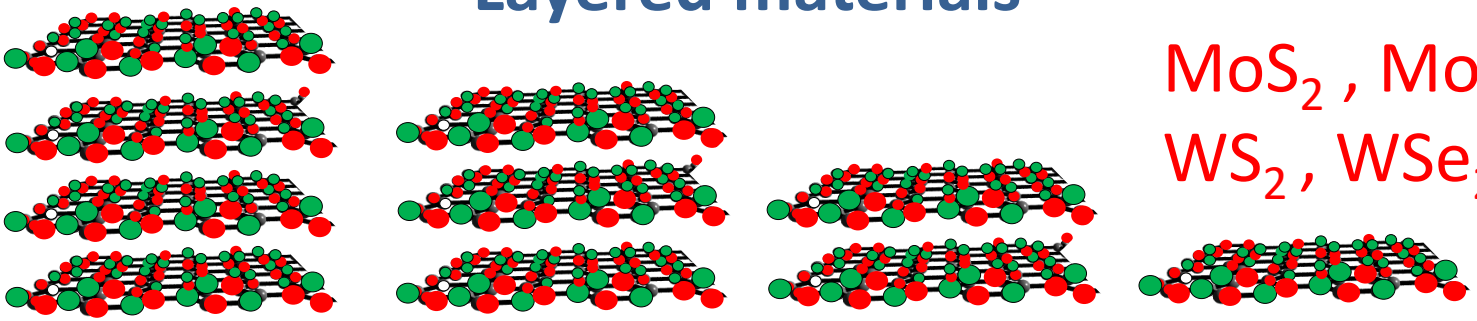
Conductivity of graphene ink vs exfoliation



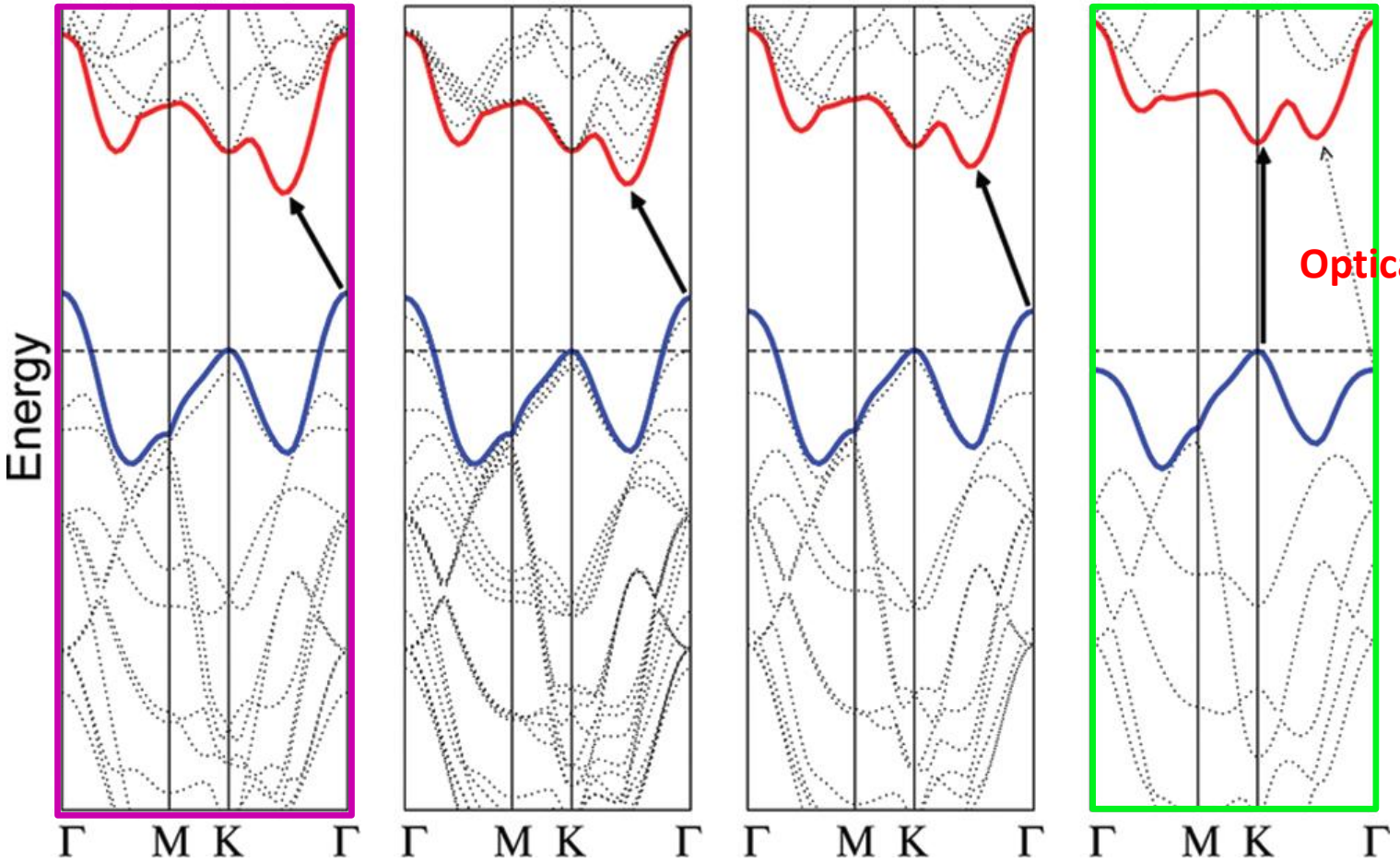
Conductivity of graphene inks is controlled by the exfoliation via the aspect ratio of the flakes

Karagiannidis et al. ACS Nano 2017

Layered materials



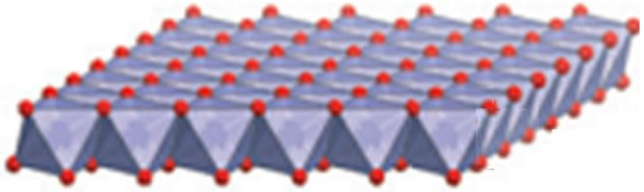
MoS_2 , $MoSe_2$
WS_2 , WSe_2 etc.



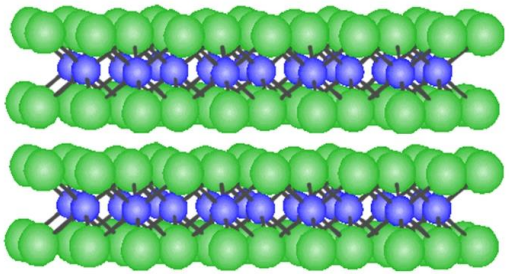
Optically active

Graphene inks production rate

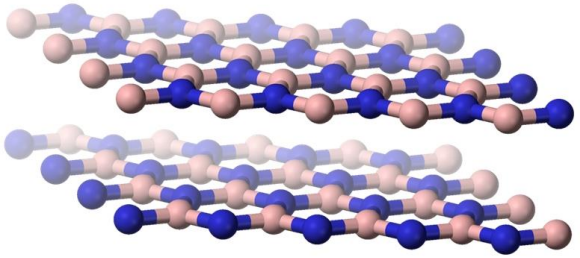
Paton *et al.* Nature Mater. (2014)



Metal Oxides



Metal chalcogenides



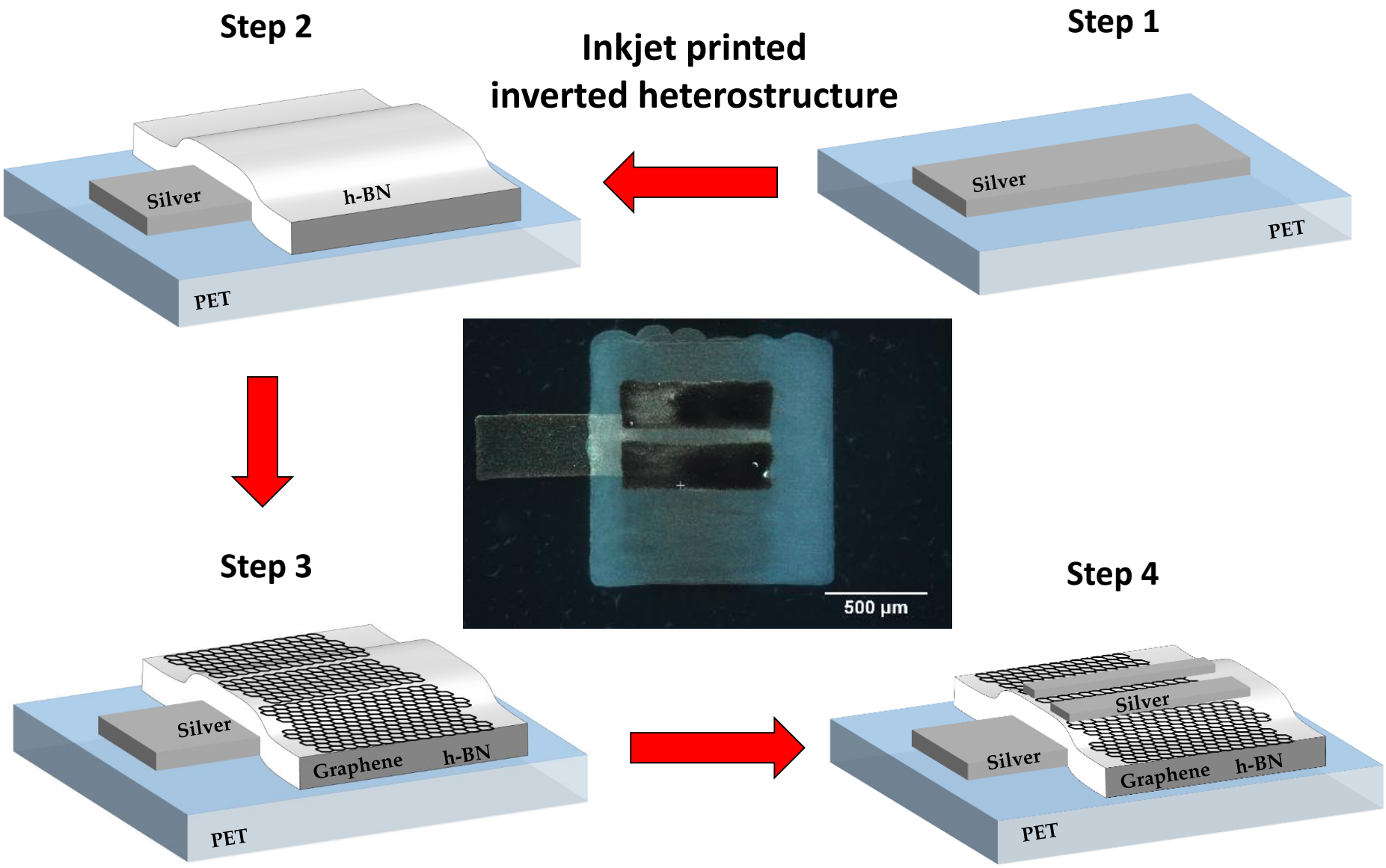
Boron Nitride

Application:

Inkjet printed large area electronics

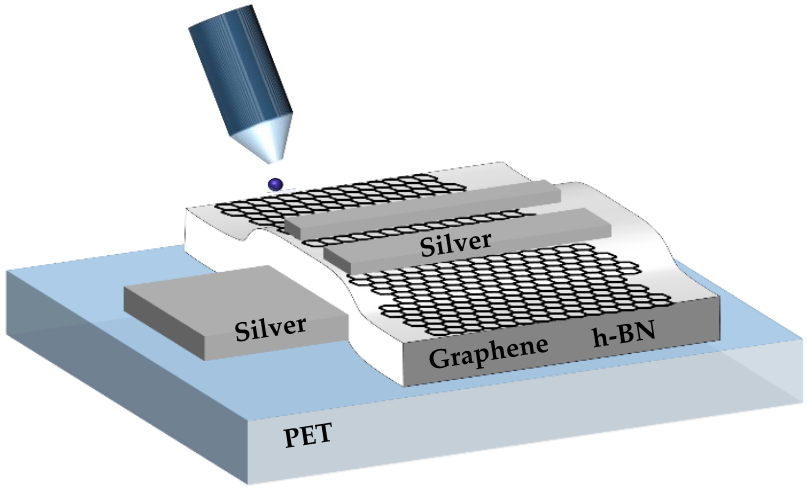

100
75
UNIVERSITY OF
CAMBRIDGE

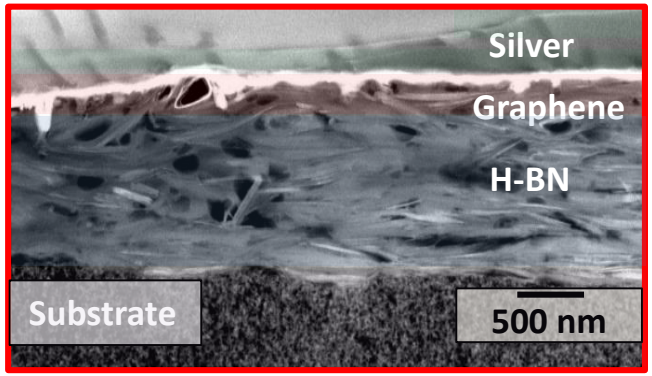
All ink-jet printed graphene/h-BN field effect transistors



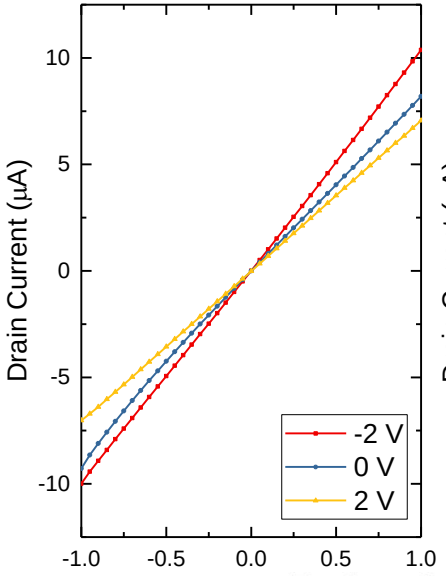
T. Carey *et al*. Nature Comms (2017), DOI: 10.1038/s41467-017-01210-2

Graphene/h-BN field effect transistors: I-V characterisatics

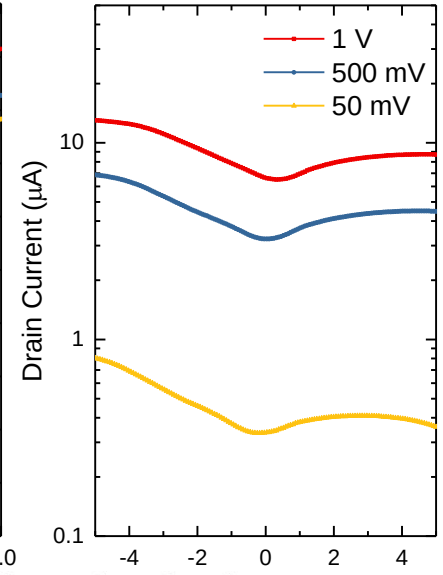


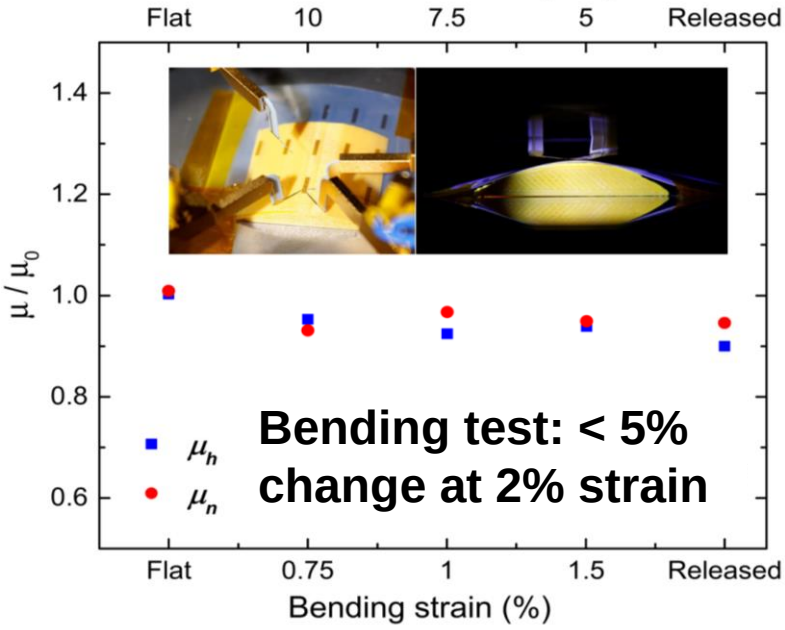


Output Characteristic



Transfer Characteristic





L= 50 μm, W= 580 μm

Mobility (hole) ~ 150 ± 18 $cm^2V^{-1}s^{-1}$

ON/OFF ratio ~ 2.5

Power consumption < 10 uW

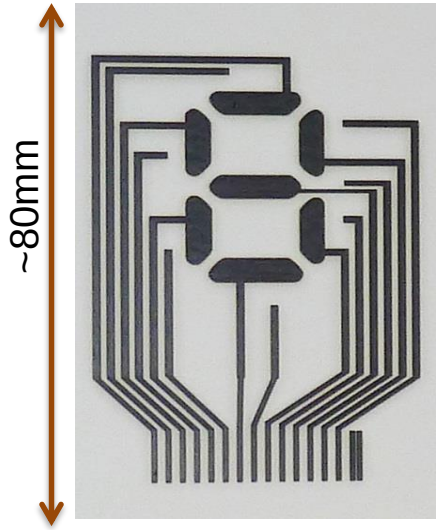
Room temperature operation

T. Carey *et al*. Nature Comms (2017)

Graphene Printing on Flexible Substrates

- **Printed electronics over large area**

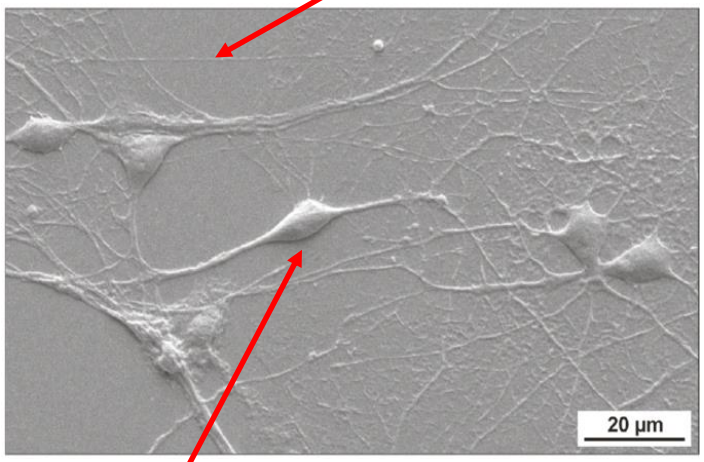
F. Torrisi *et al*. ACS Nano (2012)
F. Torrisi *et al.* Nature Nanotech. (2014)
P. Karagiannidis *et al.* ACS Nano (2017)

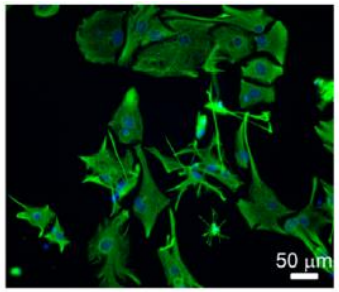


- **Bio-compatible**

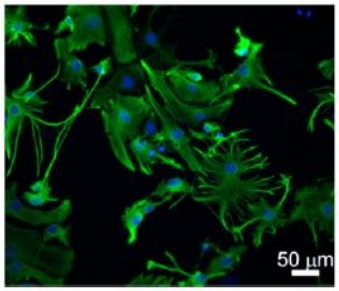
F. Fabbro *et al*. ACS Nano (2016)
McManus *et al.* Nature Nanotech. (2016)

Tested also with skin cells and myocardial cells





Control



Graphene substrate

Inkjet printing on textiles

Inkjet printing on polyerster or cotton fabric

Washable
Flexible

→

Design of an adhesion process of graphene ink on fabric

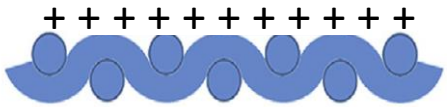
Engineering adhesion of graphene flakes on cotton

Positively charge induction on cotton

Cotton fabric

3-chloro-2-hydroxypropyltrimethylammonium chloride (CHPTAC) + NaOH

Cationic modification



Positively charged cotton fabric

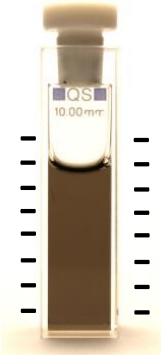
Negatively charged graphene

Graphene dispersion

H_2SO_4 + H_3PO_4 + $KMnO_4$ stirred at 50°C

Graphene oxide

Rinsing in ice bath with H_2O_2 + HCl

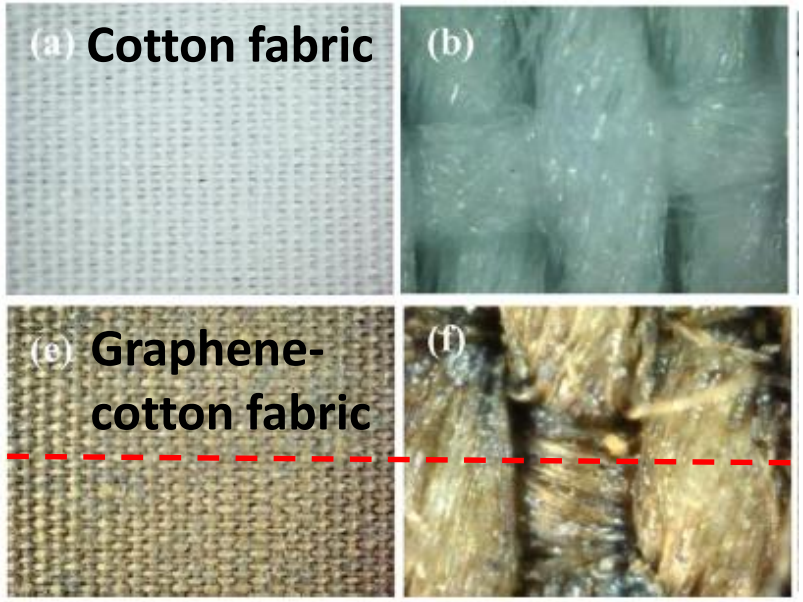


Negatively charged graphene oxide ink

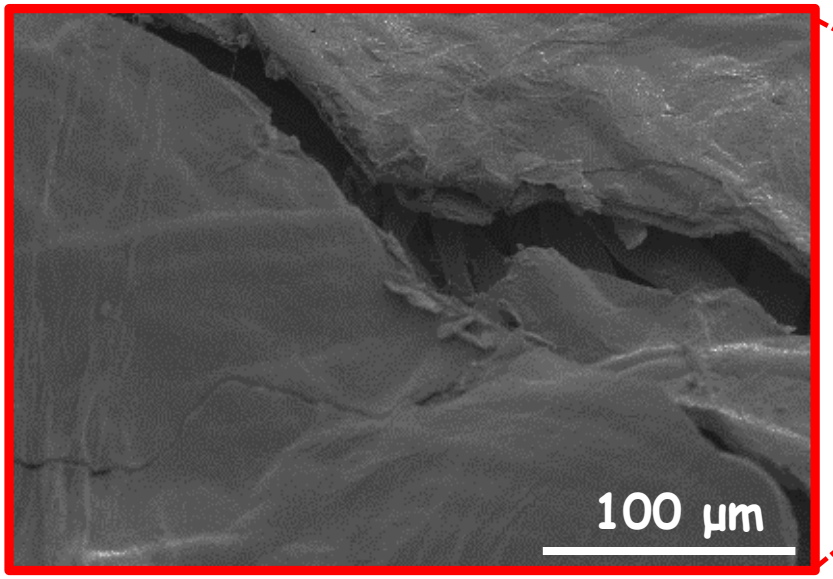
Inkjet-printed graphene-based electronic textiles

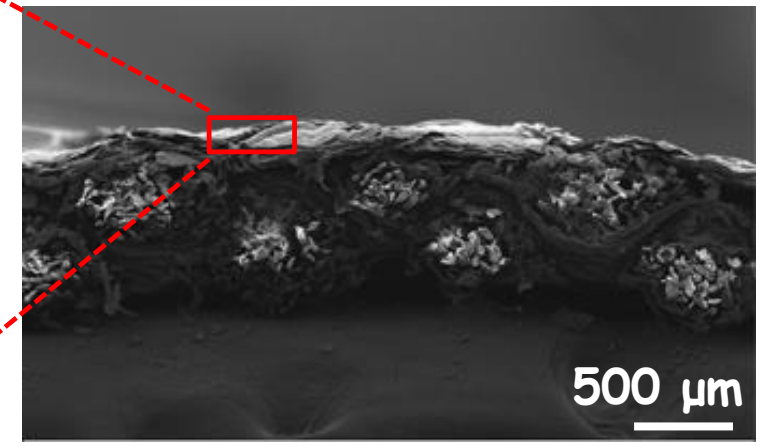
Negatively charged graphene oxide ink

Ink-jet printing



Hot press reduction @ 120°C



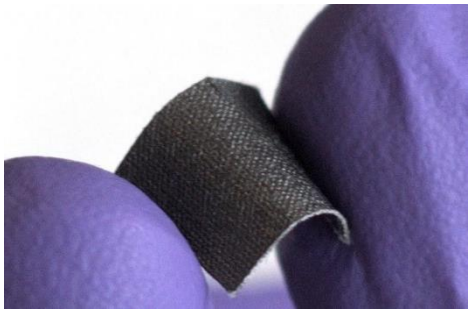


Graphene-cotton fabric

J. Ren et al., Carbon, 111,622 (2017)

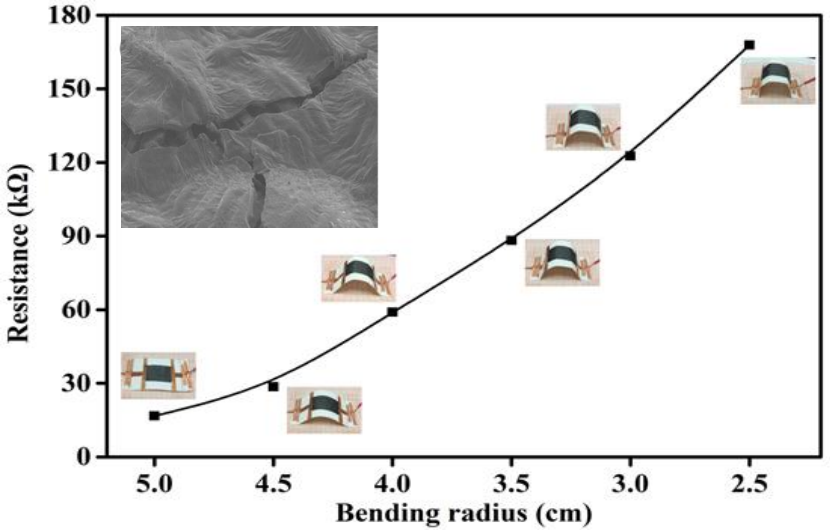
Electronic textiles:
Graphene-cotton motion sensor

Graphene-cotton motion sensor fabric

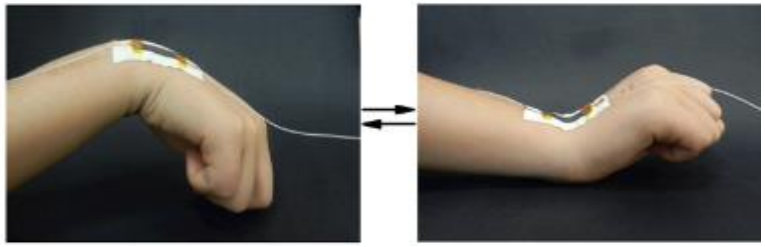


Graphene-cotton motion sensor

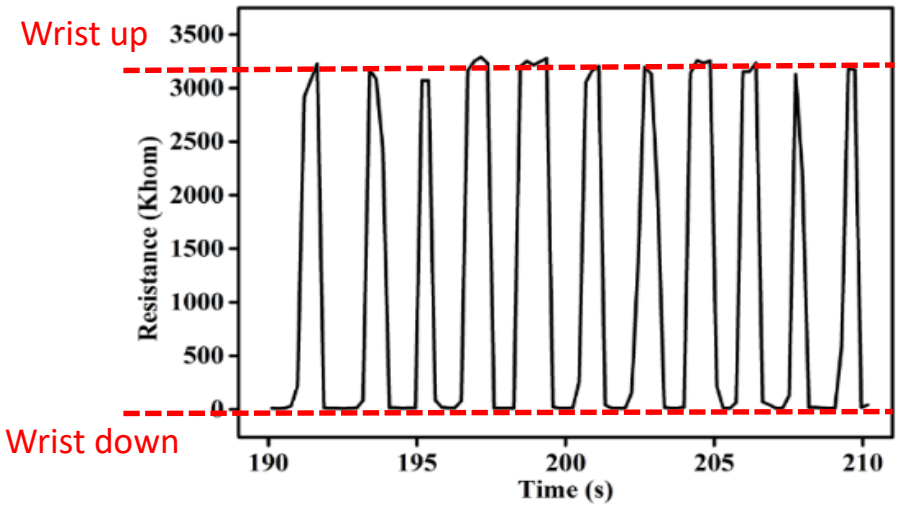
Designed and manufactured to be highly sensitive to strain and compression (gauge factor > 1500)



Linear relationship used to monitor the motion of the wrist in a wearable wristband

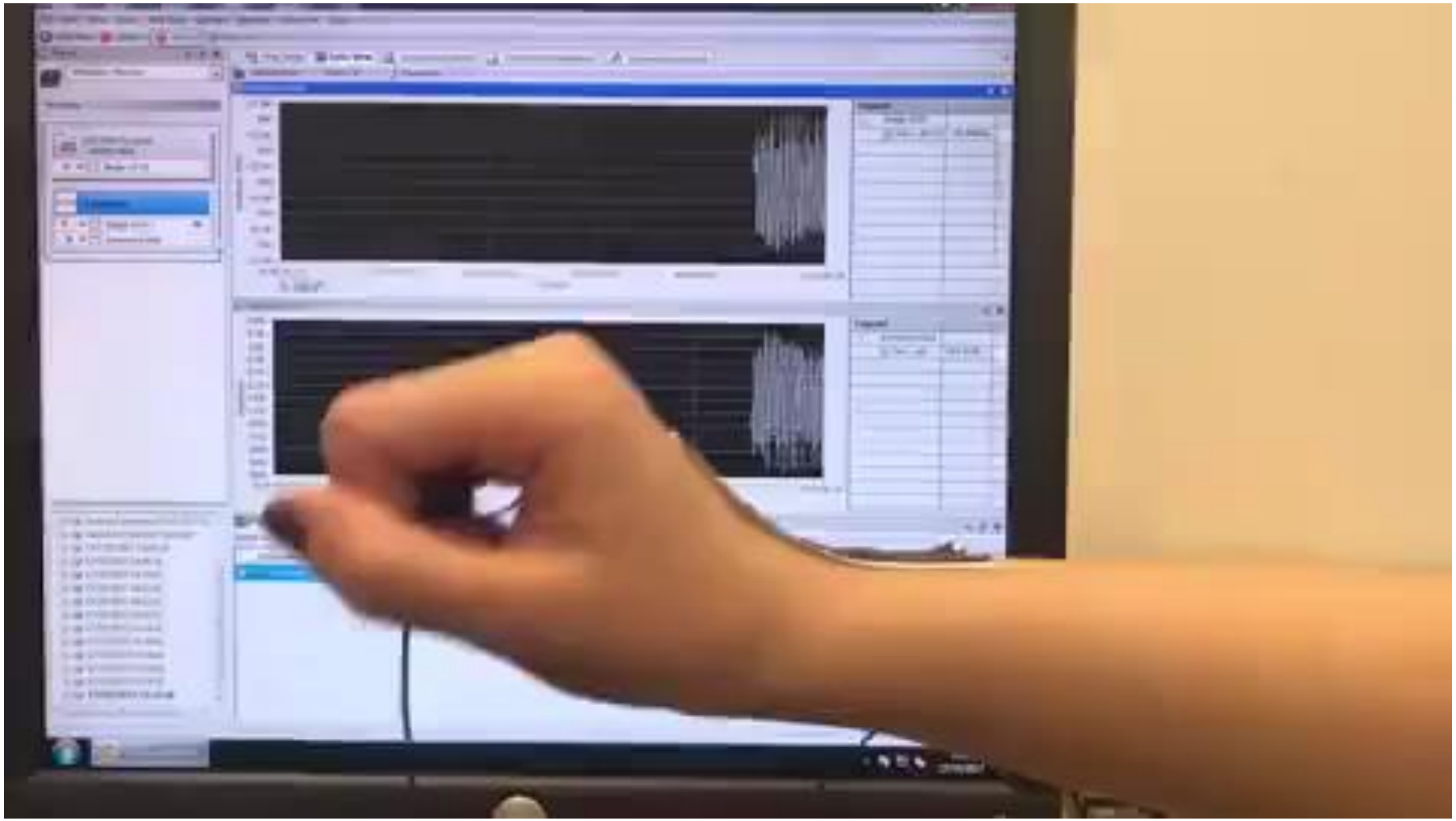


Pressure or motion sensors



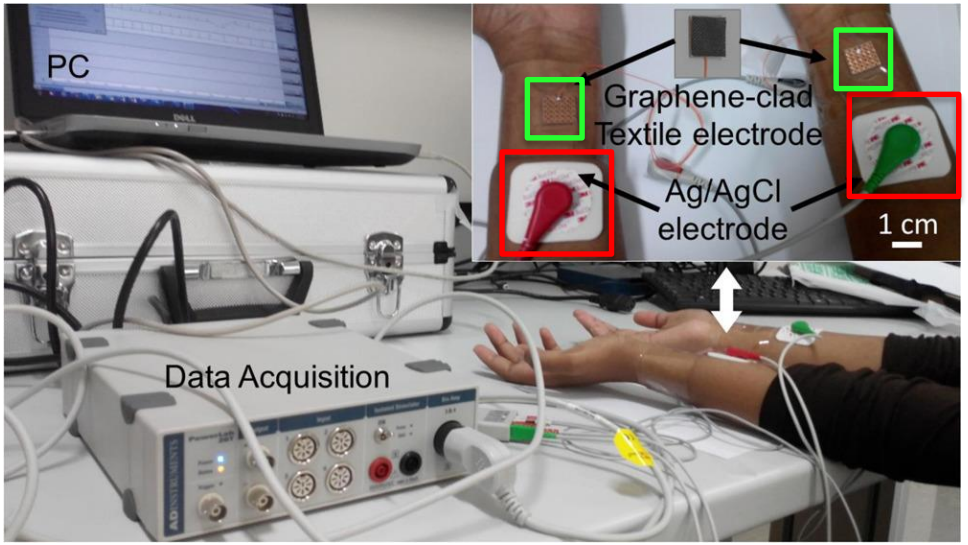
J. Ren et al., Carbon, 111,622 (2017)

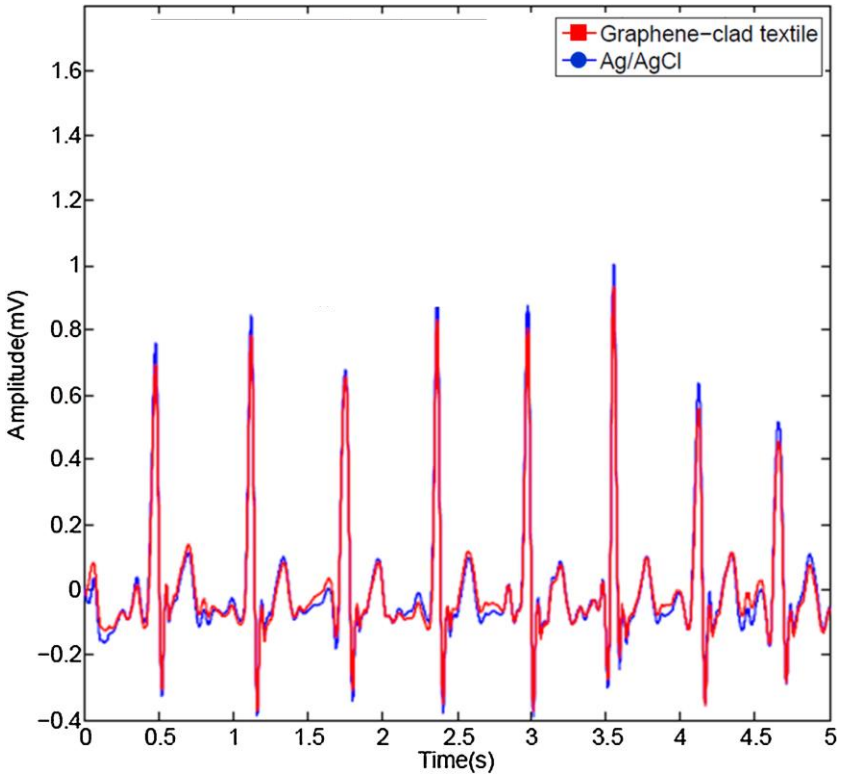
Graphene-cotton motion sensor fabric



Stable for more than 20 washing cycles!!

Graphene-cotton fabric for ECG electrodes





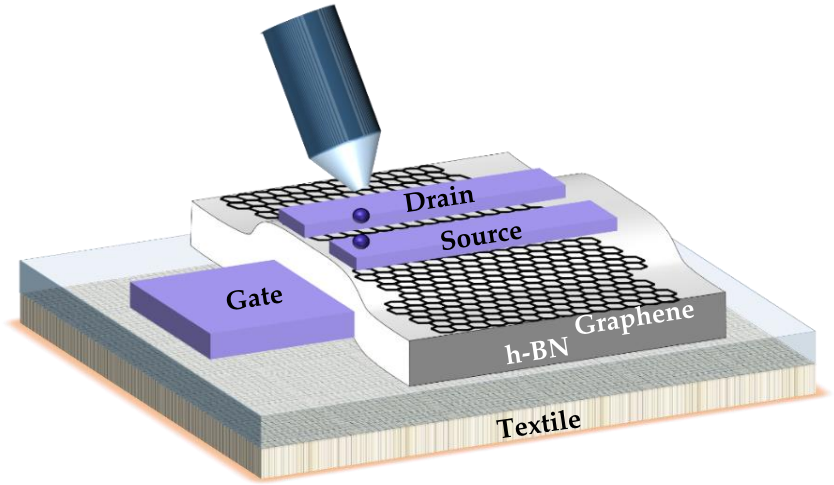
In collaboration with MRC | Epidemiology Unit

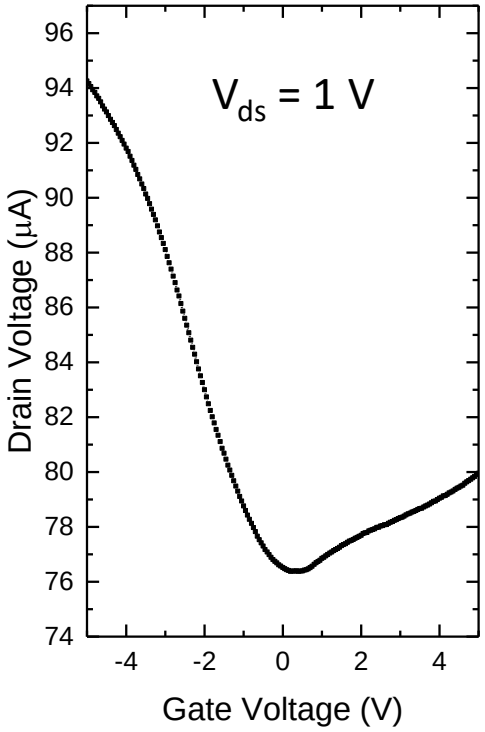
- **Stable ECG signal (5000 cycles)**
- **Stretchable**
- **Bio-compatible**
- **Washable**
- **Power consumption < 10 uW**
- **Operation in ambient conditions**

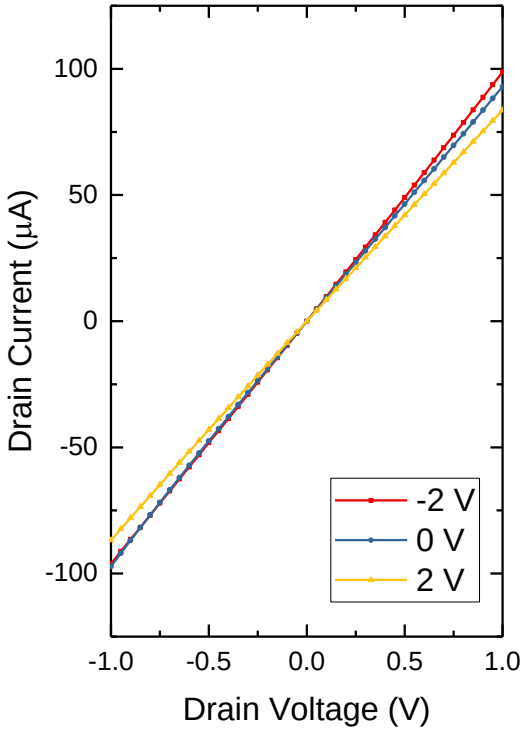
M. Yapici *et al.* Sensors and Actuators B (2015)

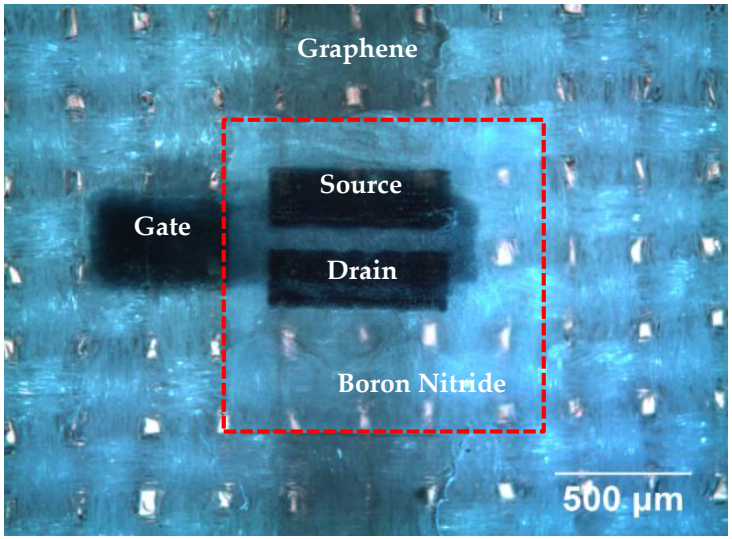
Smart electronic textiles:
Inkjet printed circuits on textiles

Inkjet printing a wearable field-effect transistor on textile







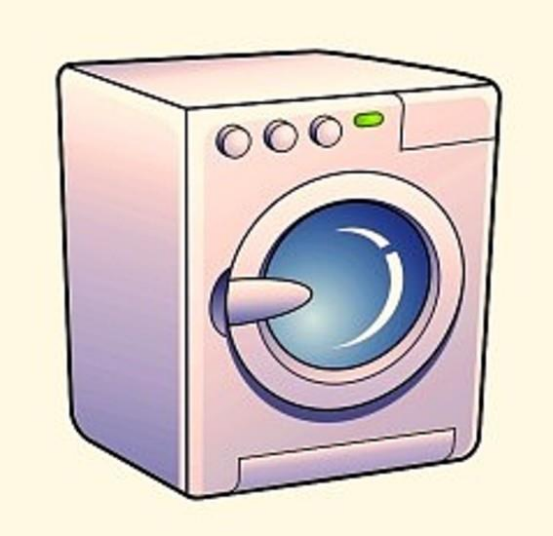


Mobility~ 105 $cm^2V^{-1}s^{-1}$
ON/OFF ~ 2.5
Power consumption < 10 uW
Operation in ambient condition

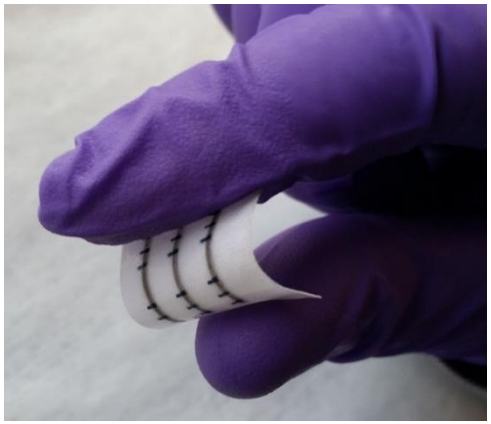
T. Carey *et al*. Nature Comms (2017)

Graphene field effect transistor on textile: washing, bending

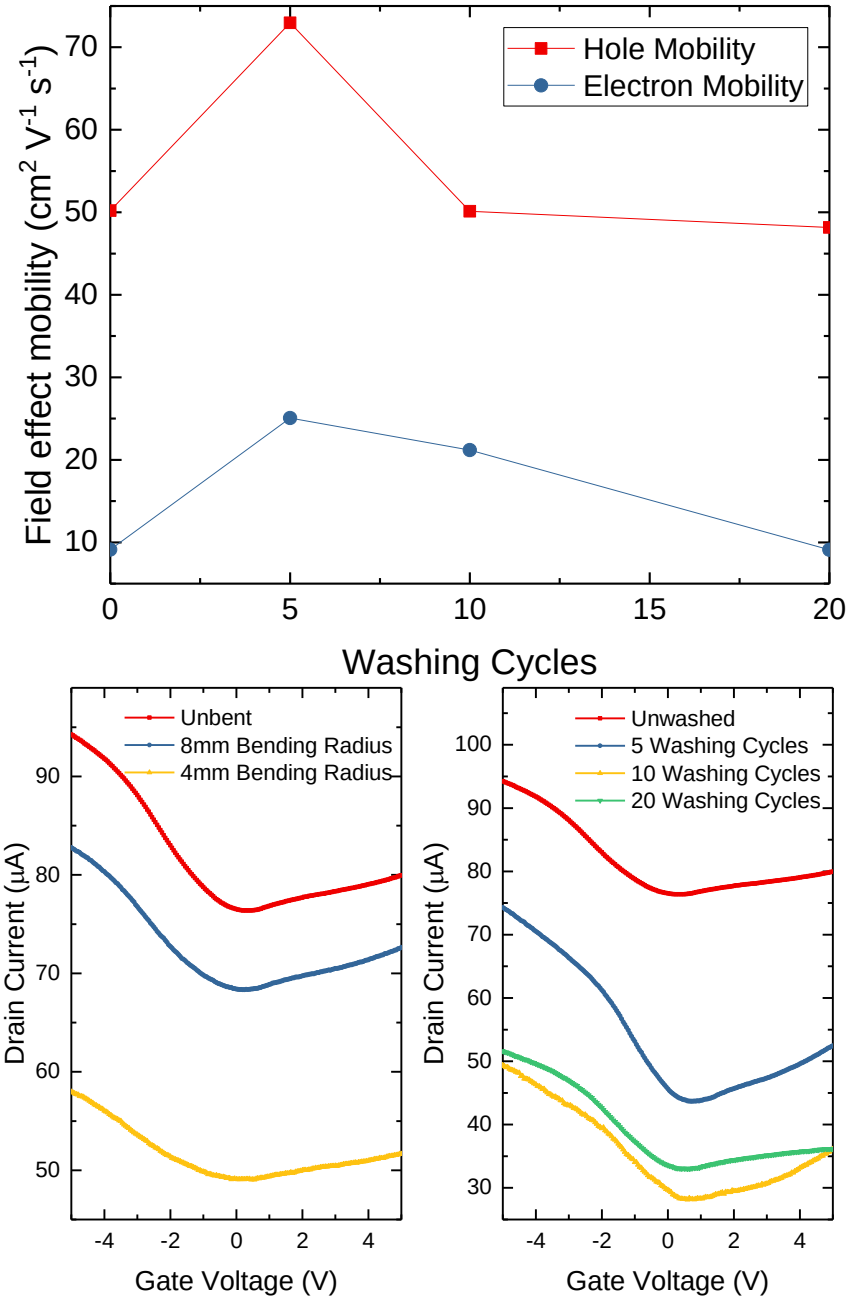
Washing test (ISO 9001):
30 min, 60°C, washing powder (cholates)



Washable > 20 washing cycles
Bending test: Δμ ~ 10% at 4% strain

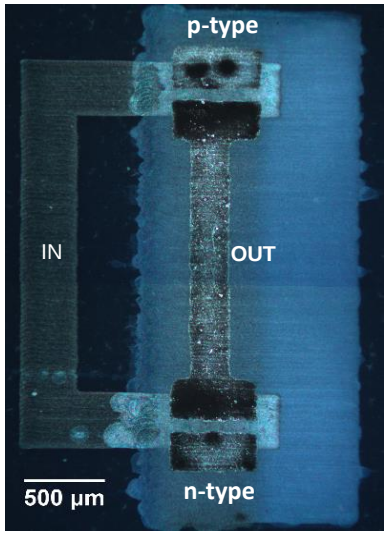


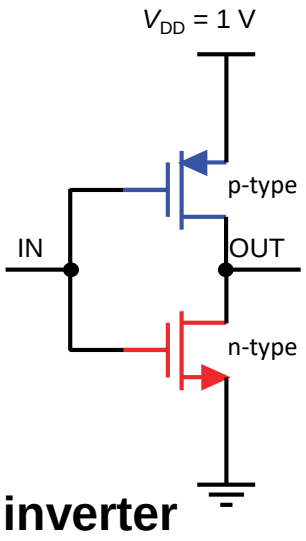
T. Carey et al., Nature comms (2017)



Ink-jet printed 2d material FET on textiles

Design of printed integrated circuits in textiles

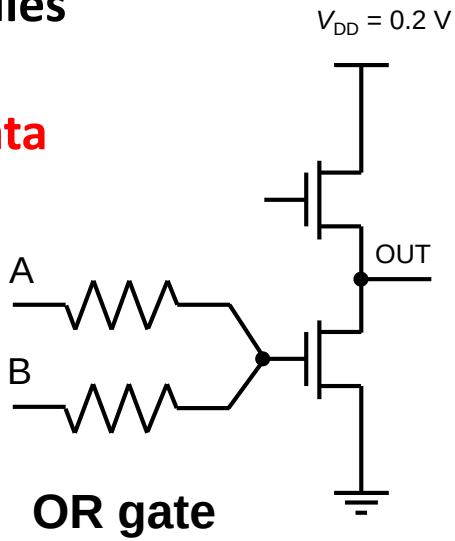




inverter

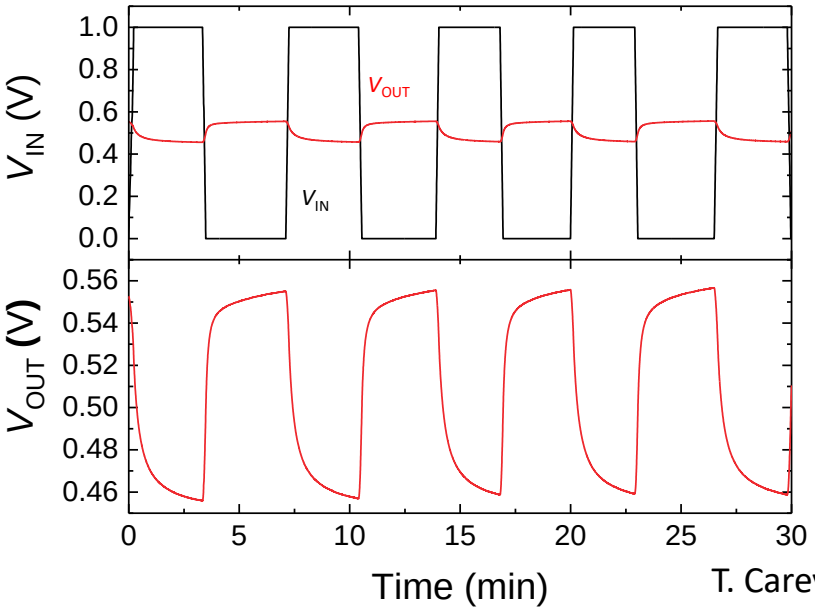
Truly smart textiles

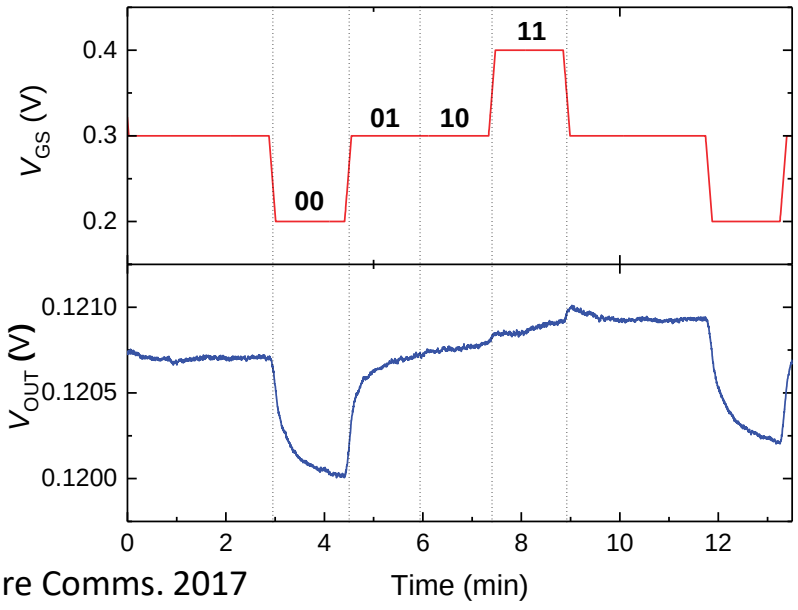
- **Sense data**
- **Manage the data**



OR gate

A	B	OUT
0	0	0
0	1	1
1	0	1
1	1	1





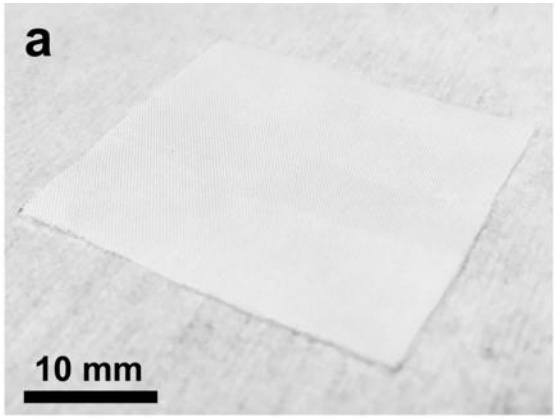
T. Carey et al. Nature Comms. 2017

Charge storage textiles:
Textile-based capacitors

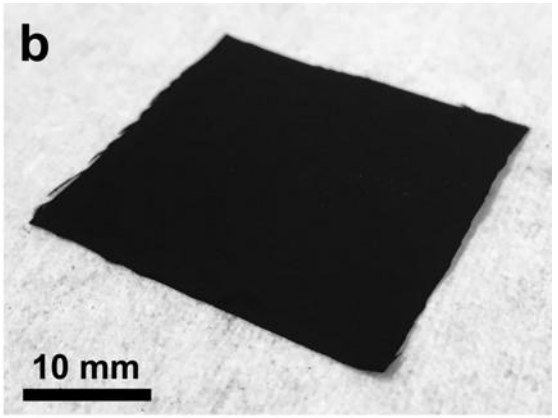
Graphene and h-BN polyester fabrics

Dip and dry process

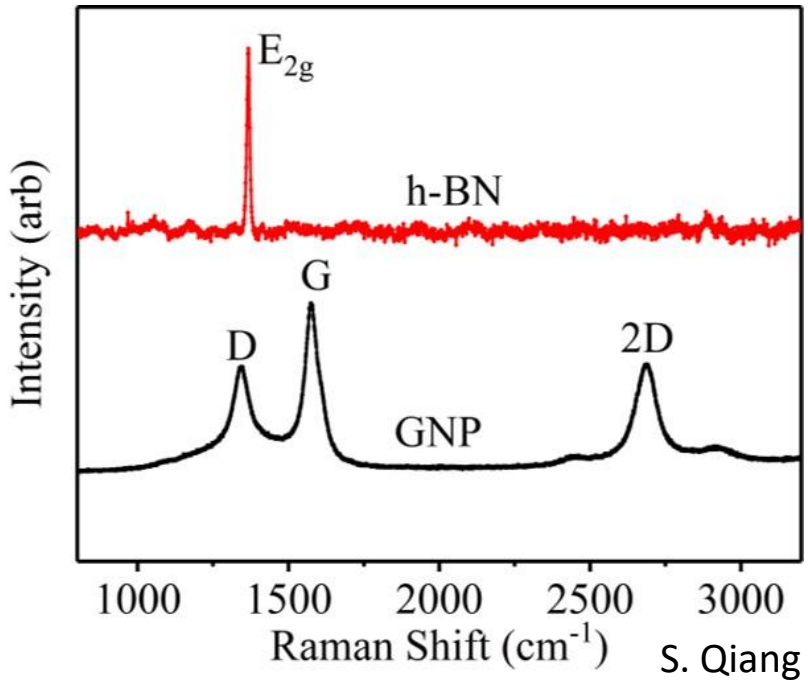
Gr-Eth ink **h-BN/CMC ink**

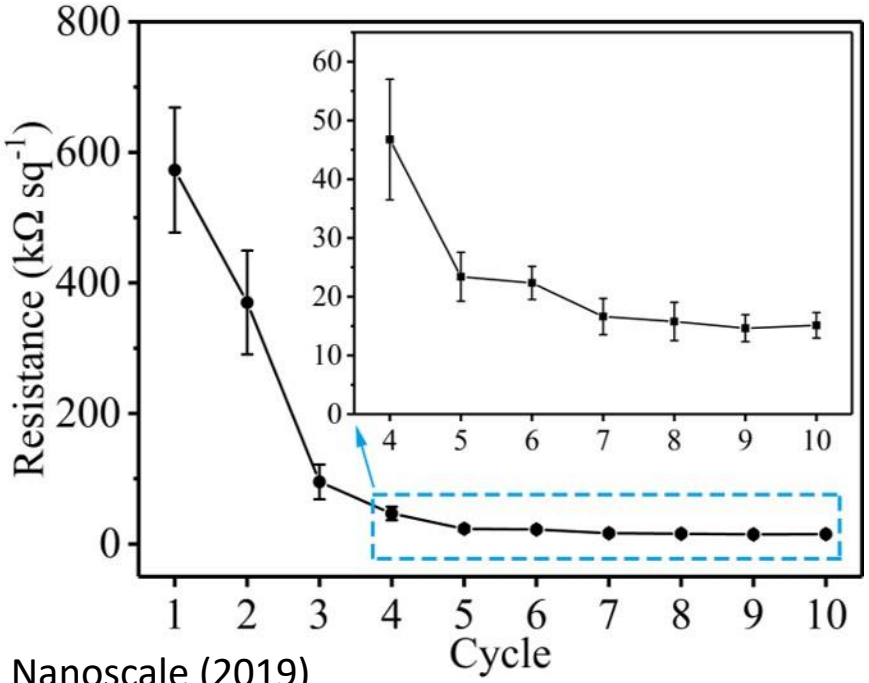


h-BN/polyester fabric



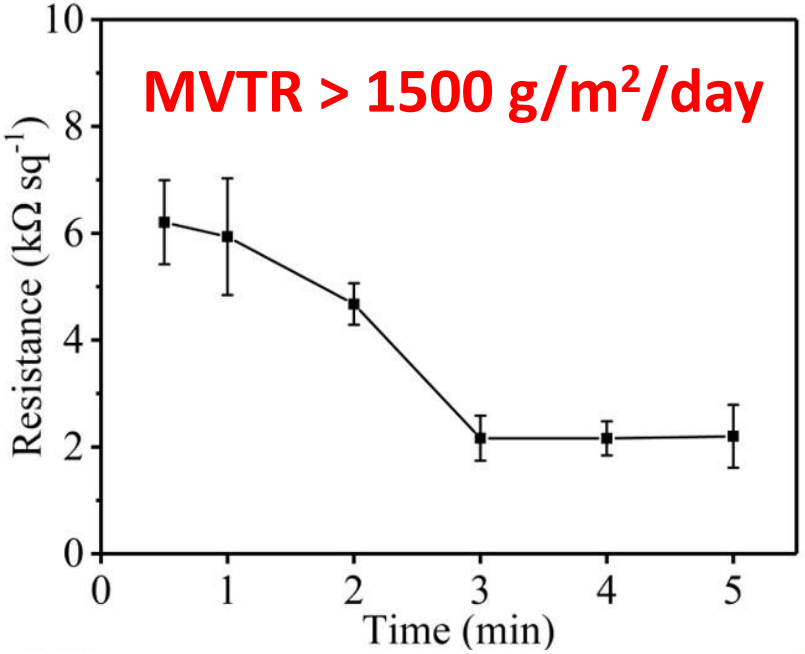
graphene/polyester fabric



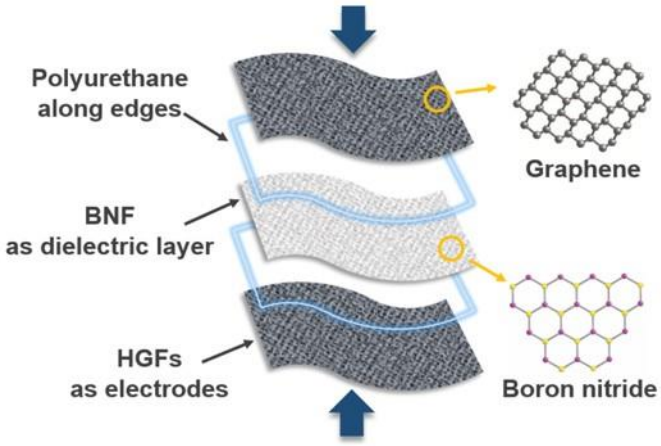


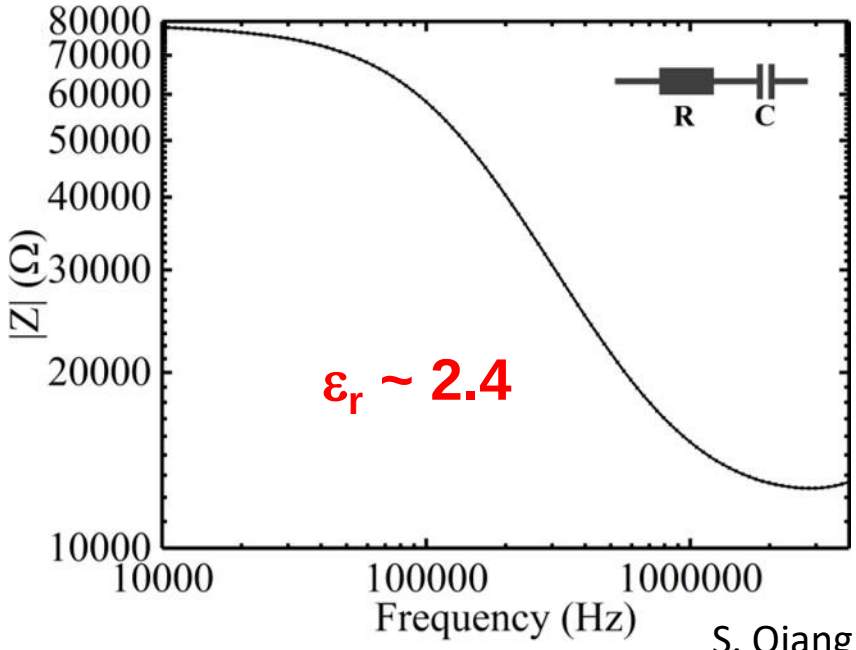
S. Qiang *et al*. Nanoscale (2019)

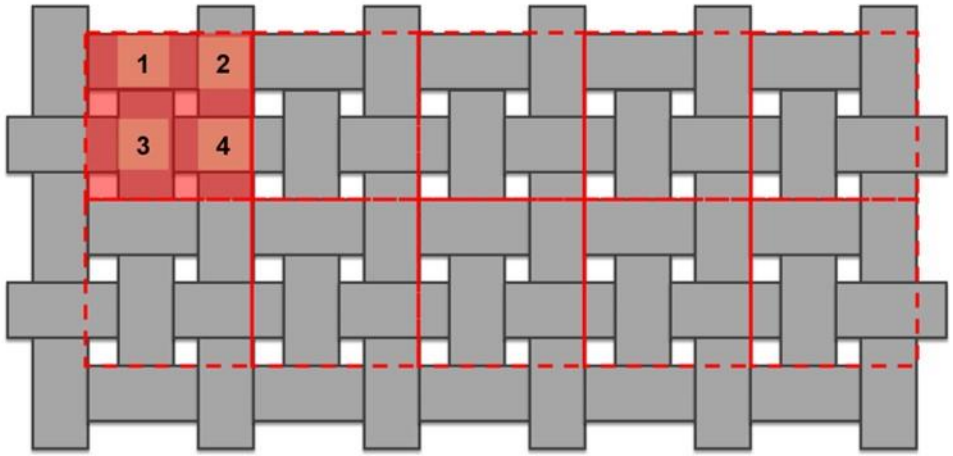
Superhydrophobic behaviour of the graphene-cotton fabric



Graphene/h-BN heterostructure textile capacitor





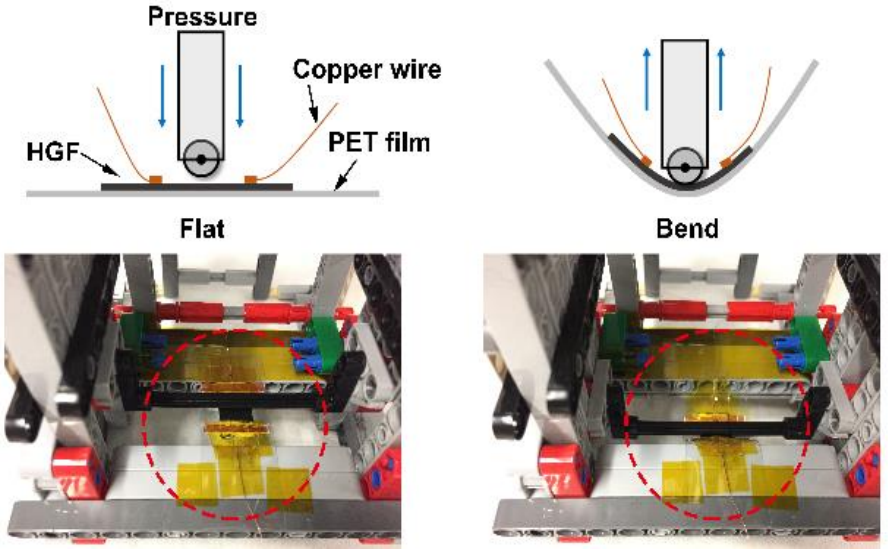


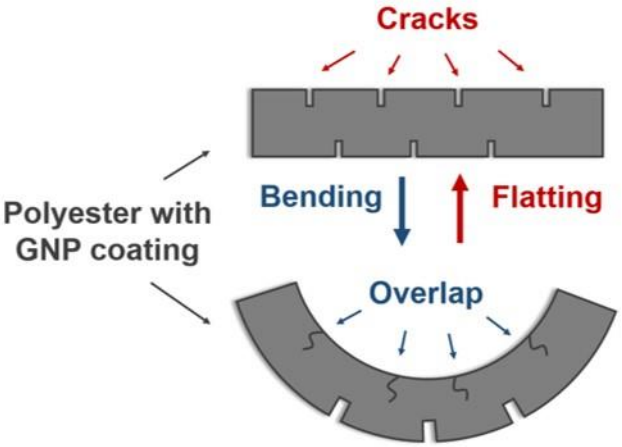
Capacitance ~ 50 nF/cm^{-2}

S. Qiang *et al*. Nanoscale (2019)

Graphene/h-BN heterostructure capacitor

One-point bending test





S. Qiang *et al*. Nanoscale (2019)

Conclusions

- **2D material inks as a viable platform for electronic textiles**
- **Chemically modified graphene and cotton fabric for inkjet printed graphene-based washable electronic textiles**
- **Suitable as electrodes and heaters on fabric**
- **Paves the way to fibre-based optoelectronics and sensors**

Thanks to

University of Cambridge

T. Carey

S. Cacovich

A. Arbab

H. Lee

G. Divitini

C. Ducati

A. C. Ferrari

J. M. Kim

L. Occhipinti

Nanjing University

F. wang

Jiangnan University

J. Ren

S. Qiang

C. Wang

Y. Yin

X. Ji

Politecnico di Torino

E. Piatti

R. Gonnelli

Politecnico di Milano

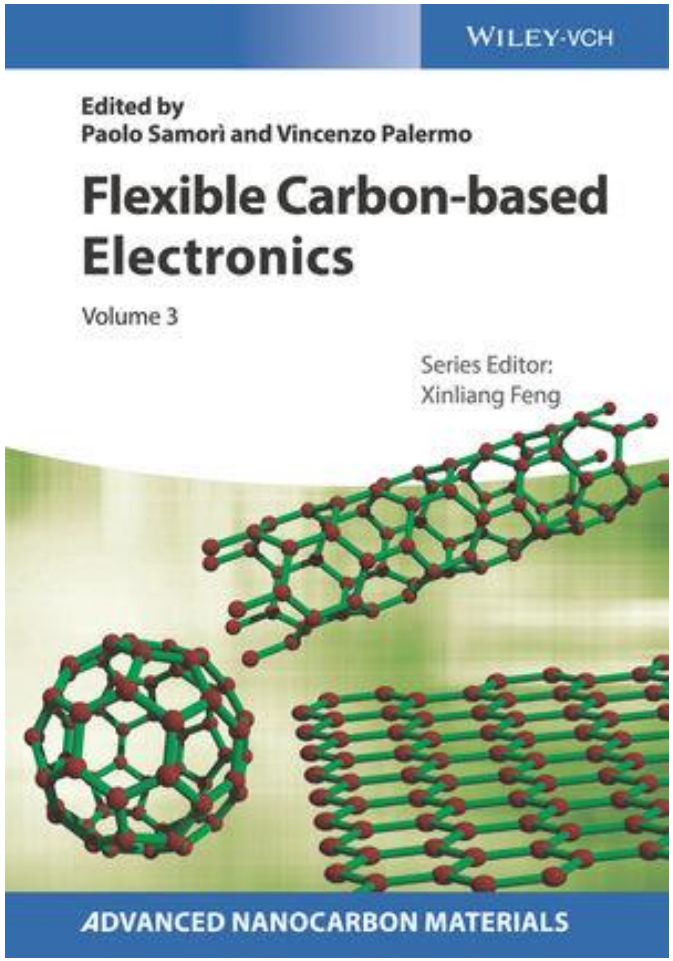
A. Mansouri

R. Sordan

Acknowledgements

GRAPHENE FLAGSHIP

Printing 2D materials



6

Printing 2D Materials

Felice Torrisi and Tian Carey

University of Cambridge, Cambridge Graphene Centre, Cambridge CB3 0FA, UK

6.1 Introduction

Ever-evolving advances in materials synthesis, solution processing, and device design have fueled many of the developments in the field of printed electronics. This technique has progressed from printing text and graphics [1] to a tool for rapid manufacturing [2], being now a well-established technique to print thin-film transistors (TFTs) [3–5], light-emitting diodes [6, 7], photodetectors [8, 9], photovoltaic cells [10, 11], sensors [12, 13], and photonic devices [14, 15]. New device integration processes combining flexible and

Washable and wearable electronic textiles enabled by two-dimensional materials

Felice Torrisi

Department of Engineering, University of Cambridge, UK
(now Department of Chemistry, Imperial College London, UK)

UNIVERSITY OF CAMBRIDGE

Imperial College London