Washable and wearable electronic textiles enabled by two-dimensional materials

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Wearable 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

Bio-compatibility and environmental stability required

Textile for wearable electronics

Textile is the ideal substrate!
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

Ultrasonic, shear mixing

Graphene ink

Shear forces enable exfoliation

F. Torrisi et al. ACS Nano (2012)
Microfluidic exfoliation of GNP - SEM

Single layer graphene flakes yield ~ 40%

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


Metal Oxides  Metal chalcogenides  Boron Nitride
Application:

Inkjet printed large area electronics
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 characteristics

- \( L = 50 \, \mu m \), \( W = 580 \, \mu m \)
- Mobility (hole) \( \sim 150 \pm 18 \, cm^2 V^{-1} s^{-1} \)
- ON/OFF ratio \( \sim 2.5 \)
- Power consumption < 10 \( \mu W \)
- Room temperature operation

Graphene Printing on Flexible Substrates

- **Printed electronics over large area**
  

- **Bio-compatible**
  
  F. Fabbro *et al*. ACS Nano (2016)

  Tested also with *skin cells* and *myocardial cells*
Inkjet printing on polyester 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

H₂SO₄ + H₃PO₄ + KMnO₄ stirred at 50°C

Graphene oxide

Rinsing in ice bath with H₂O₂ + HCl

Negatively charged graphene oxide ink
Inkjet-printed graphene-based electronic textiles

Negatively charged graphene oxide ink

Ink-jet printing

(a) Cotton fabric
(b) Graphene-cotton fabric

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

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

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

Smart electronic textiles:
Inkjet printed circuits on textiles
Inkjet printing a wearable field-effect transistor on textile

Drain Voltage (V)
Gate Voltage (V)
Drain Current (μA)

\[ V_{ds} = 1 \text{ V} \]

Gate Voltage (V)
Drain Voltage (V)

-2 V
0 V
2 V

Mobility ~ 105 cm²V⁻¹s⁻¹
ON/OFF ~ 2.5
Power consumption < 10 uW
Operation in ambient condition

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: $\Delta \mu \sim 10\%$ at 4% strain

Ink-jet printed 2d material FET on textiles
Design of printed integrated circuits in textiles

Truly smart textiles
- Sense data
- Manage the data

OR gate

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

MVTR > 1500 g/m²/day
Graphene/h-BN heterostructure textile capacitor

Polyurethane along edges
BNF as dielectric layer
HGFs as electrodes

$\varepsilon_r \sim 2.4$

Capacitance $\sim 50$ 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
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Printing 2D Materials

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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
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