Electronic Textile Challenges: Supplying Power and Manufacturing

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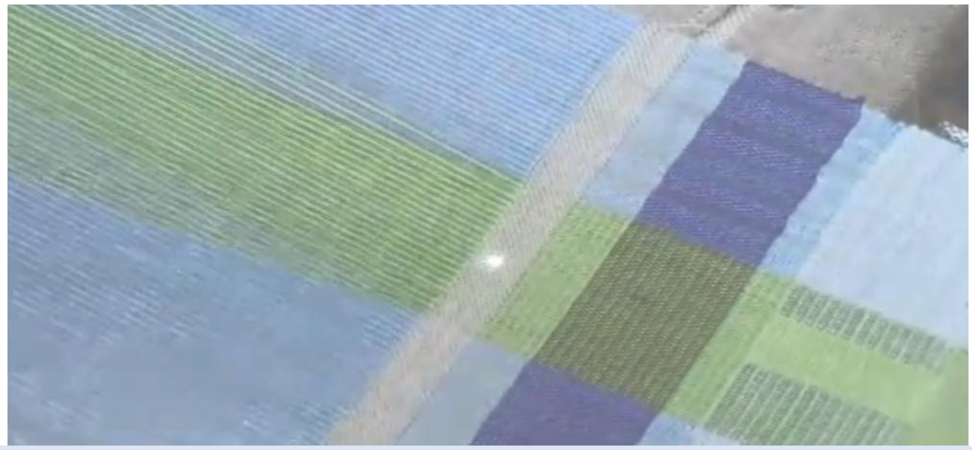
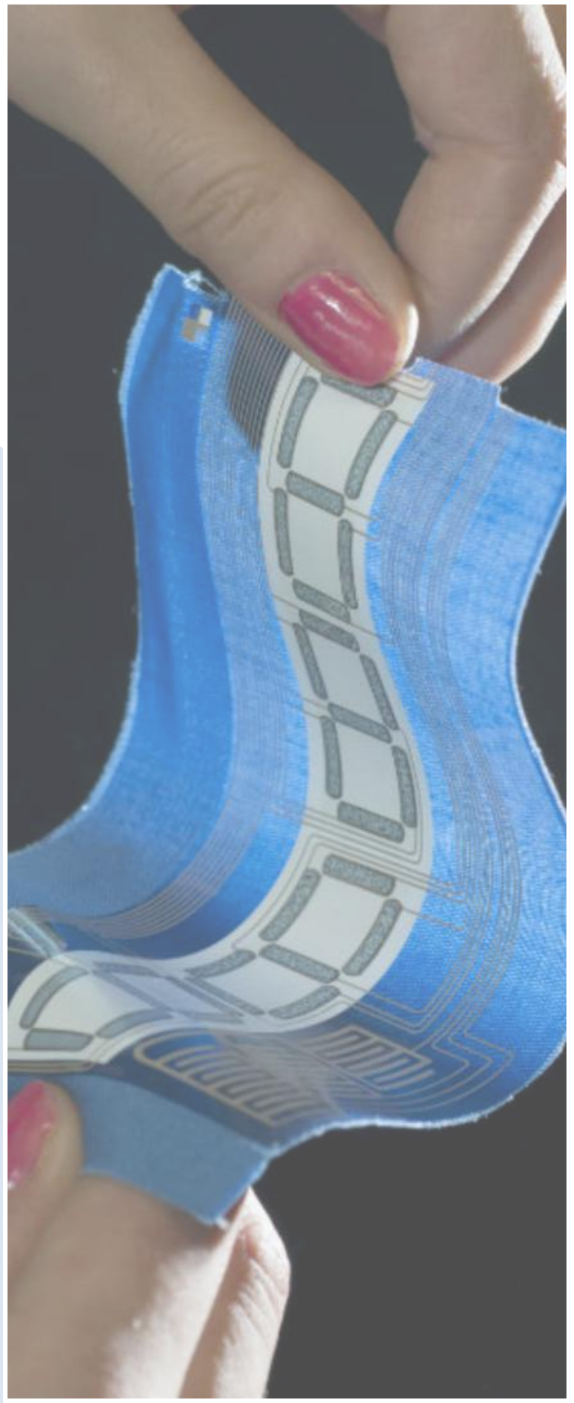
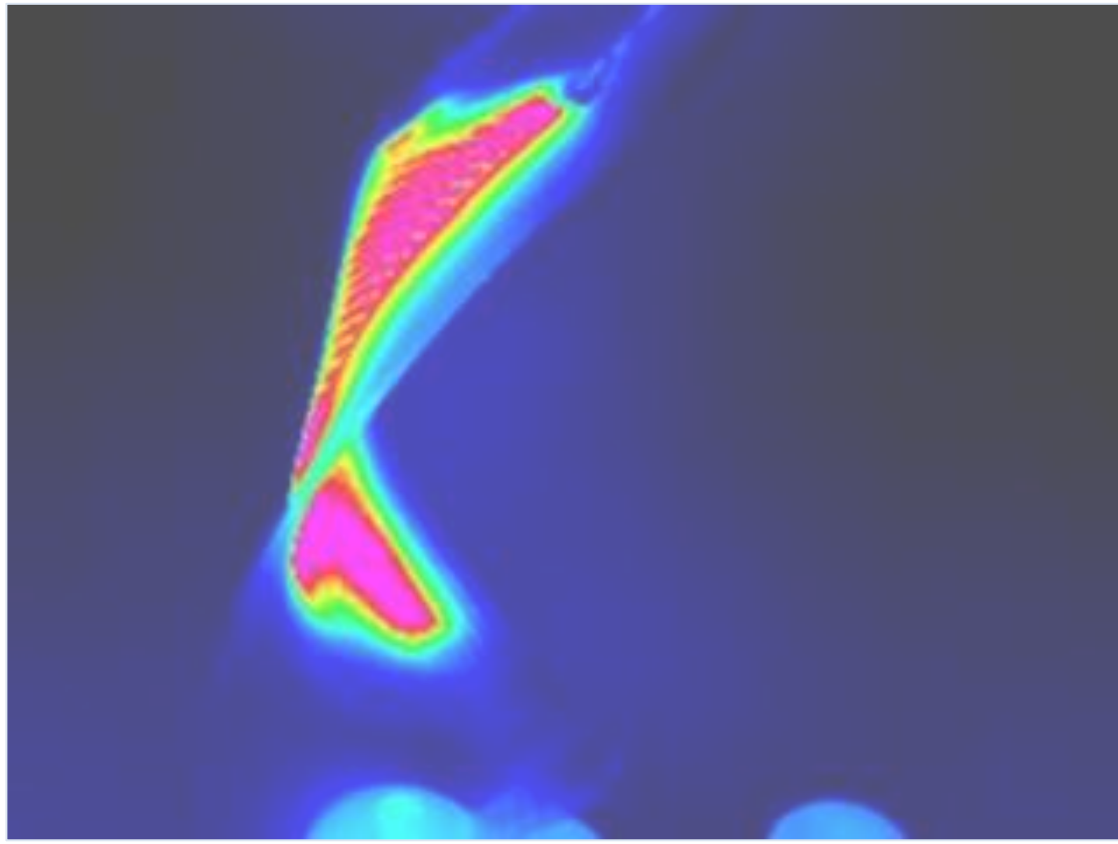
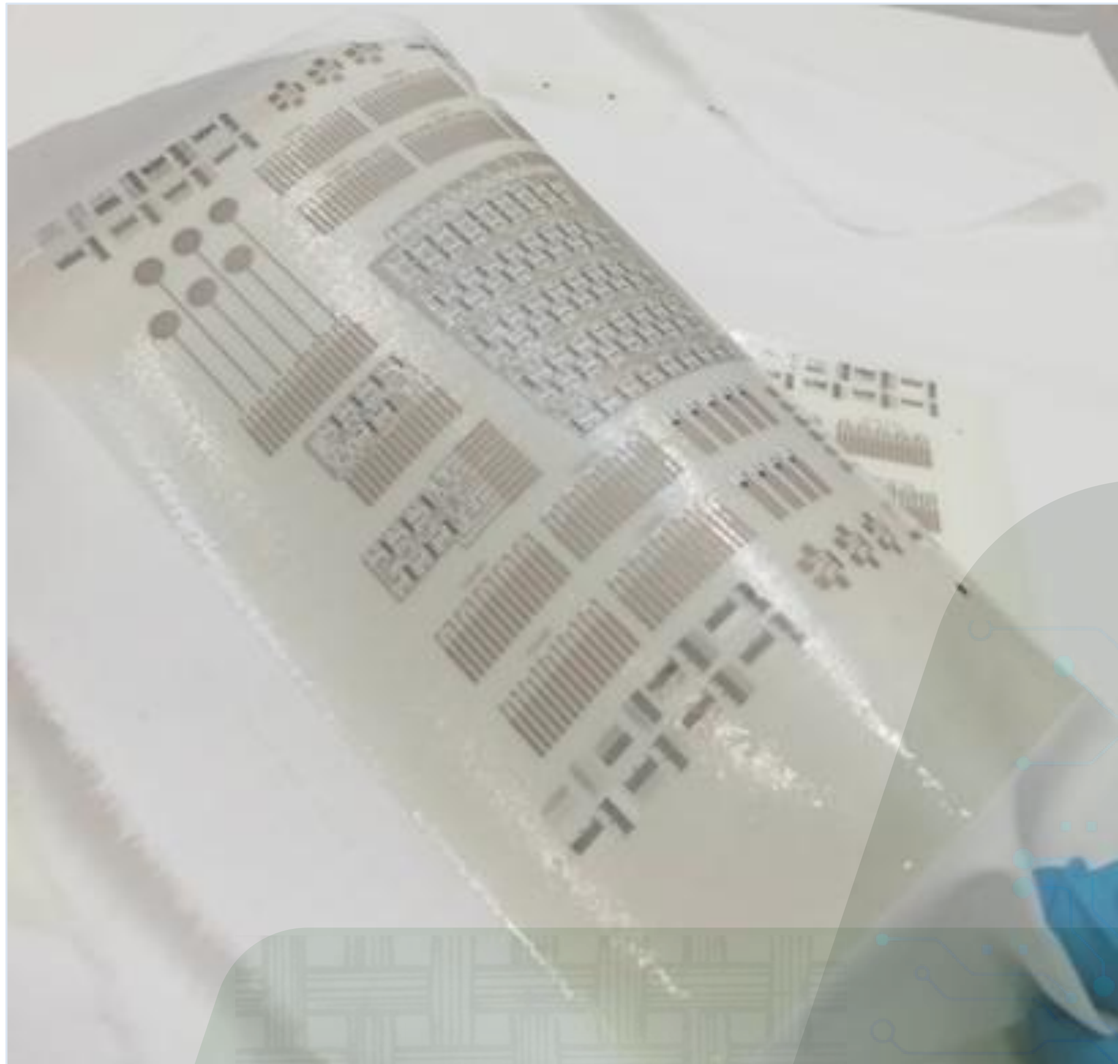
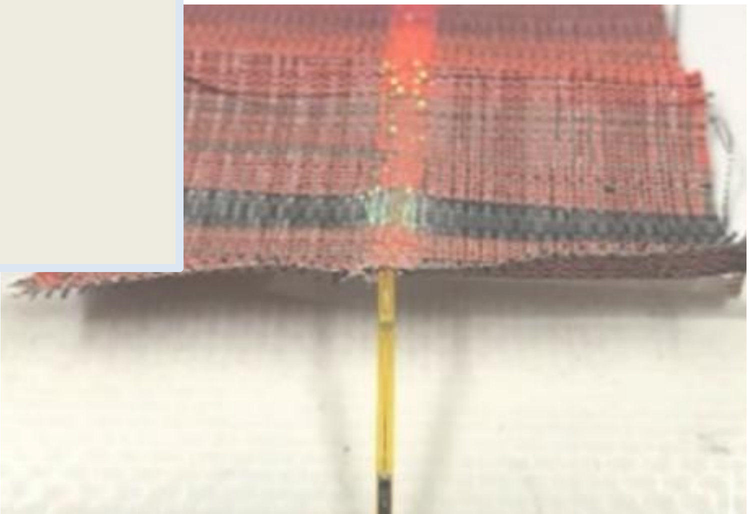
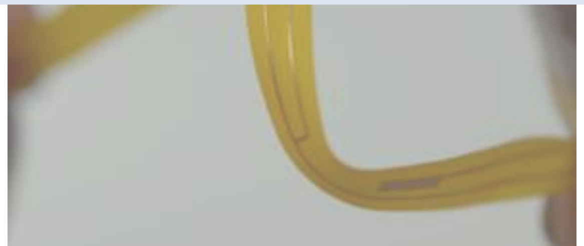




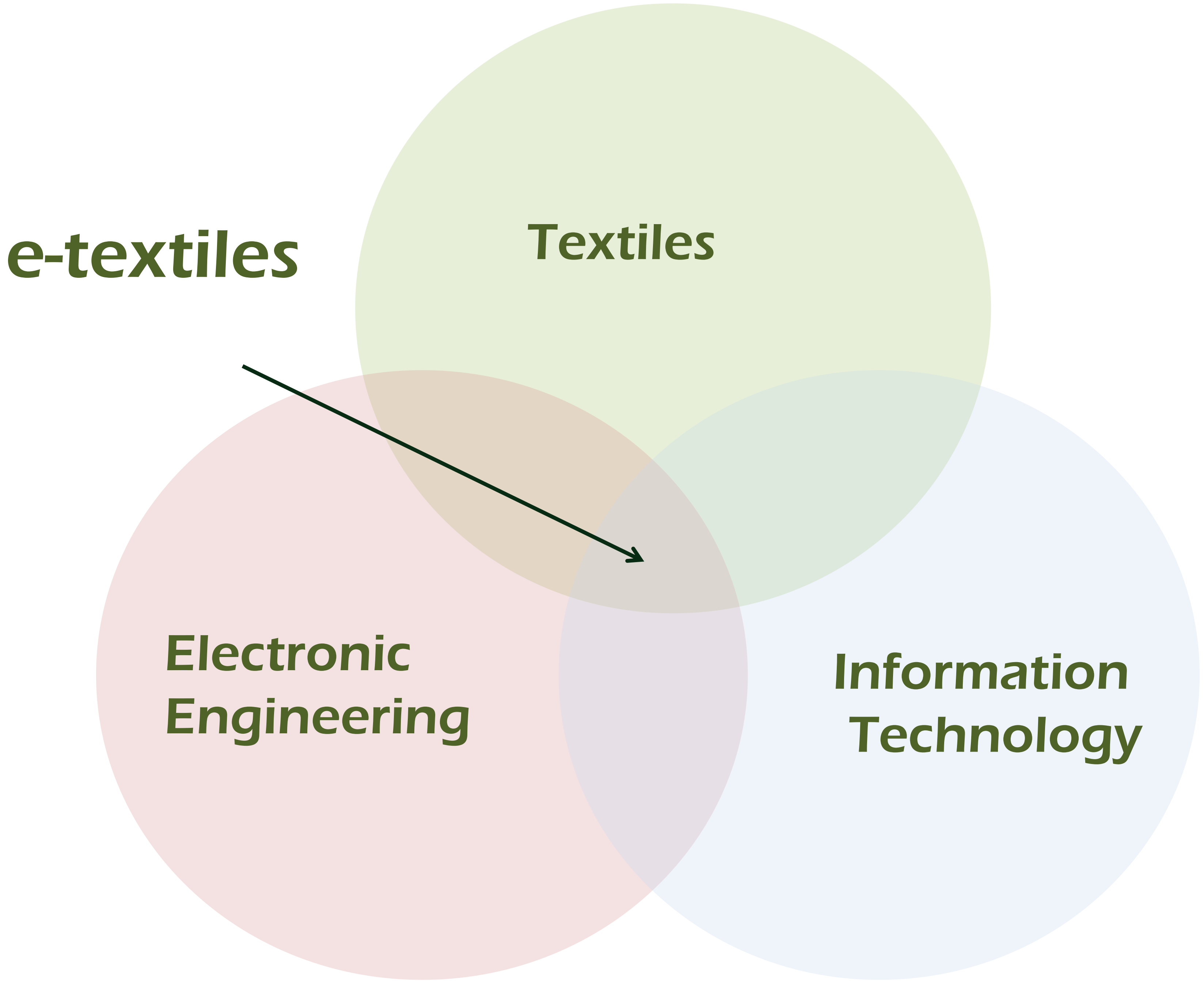
Outline

- What are e-textiles?
- Manufacturing approaches
- Supplying power:
  - Energy harvesting and wireless power
  - Energy Storage
- Example Applications

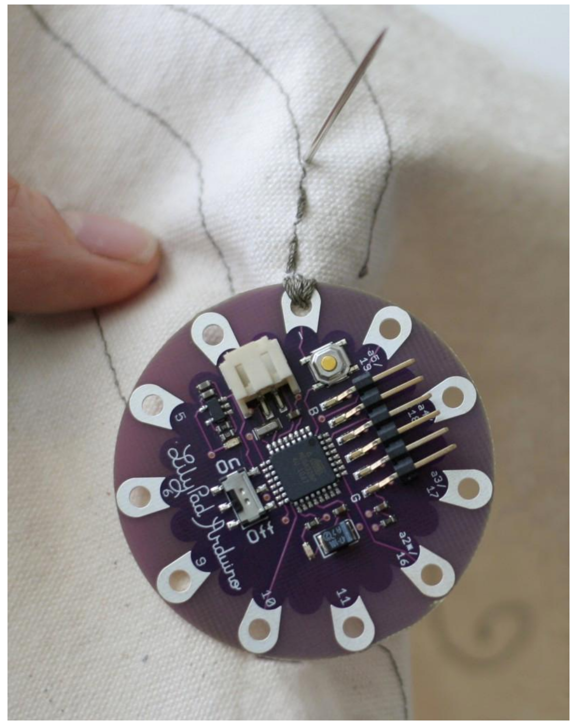





Electronic Textiles



Also known as "Smart Fabrics", commonly associated with wearables but applications wherever textiles are found.



Vision

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Developing reliable, cost-effective, ubiquitous platform technologies:

- **Scalable** manufacturing methods using solution processing and flexible electronics.
- **Wirelessly enabled** e-textile systems for power, comms and sensing. Minimise wires)
- **Battery free** self-powered e-textile systems (energy harvesting)
- New techniques for **storing energy** within a textile

Practical, robust, and sustainable e-textiles

"Wearable" tech **hidden** in clothing

Clothing appears and feels "**normal**"

Autonomy with **minimal user-intervention**

Printed e-textiles

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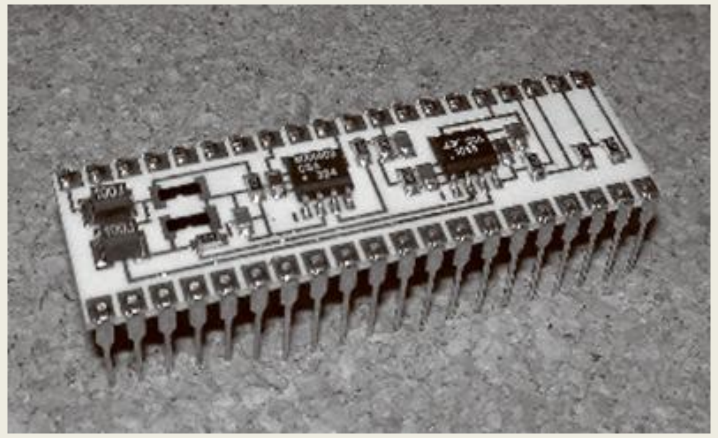
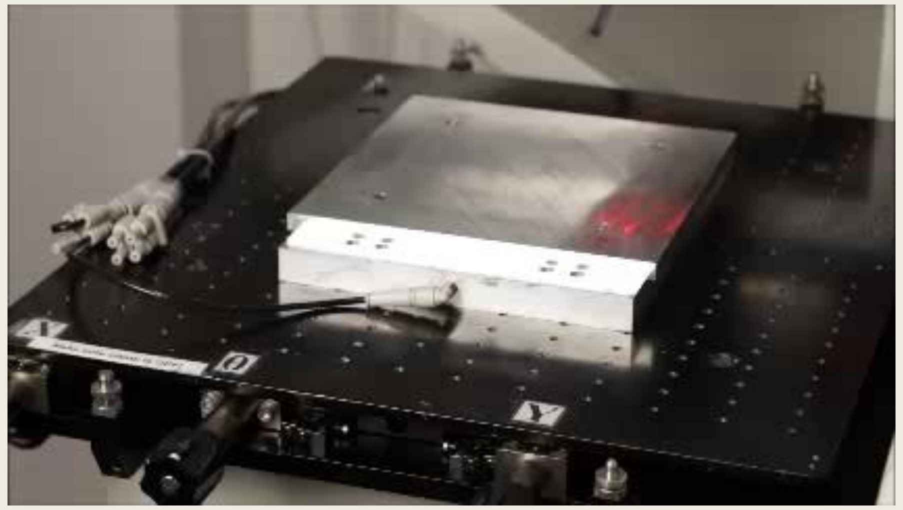
Solution processing



Printing/coating are **low-cost *additive* manufacturing processes** suitable for **roll-to-roll manufacturing** and are familiar to the textiles industry.

- **Screen printing** – (flat and rotary-based processes), good for thicker layers (>10 mm).
- **Inkjet printing** – digital printing directly from the design, thin films with low-viscosity inks.
- **Dispenser printing** – ink printed through a syringe direct from design, good range of ink viscosities but slow.
- **Spray coating** – good for large areas and relatively thin layers, high-resolution patterning is difficult.



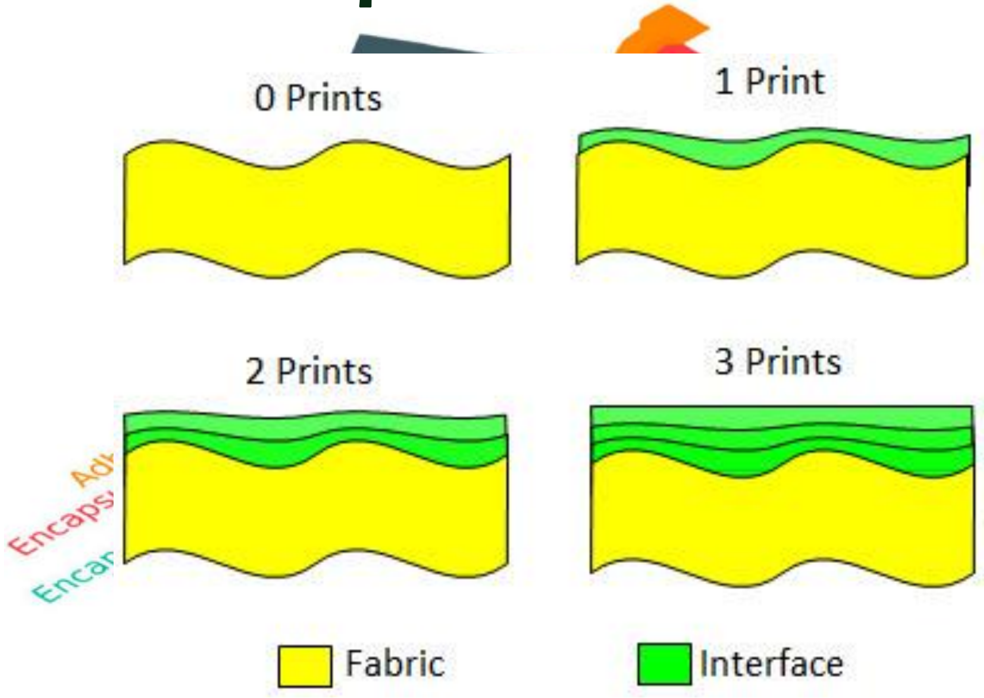
Printed e-textiles

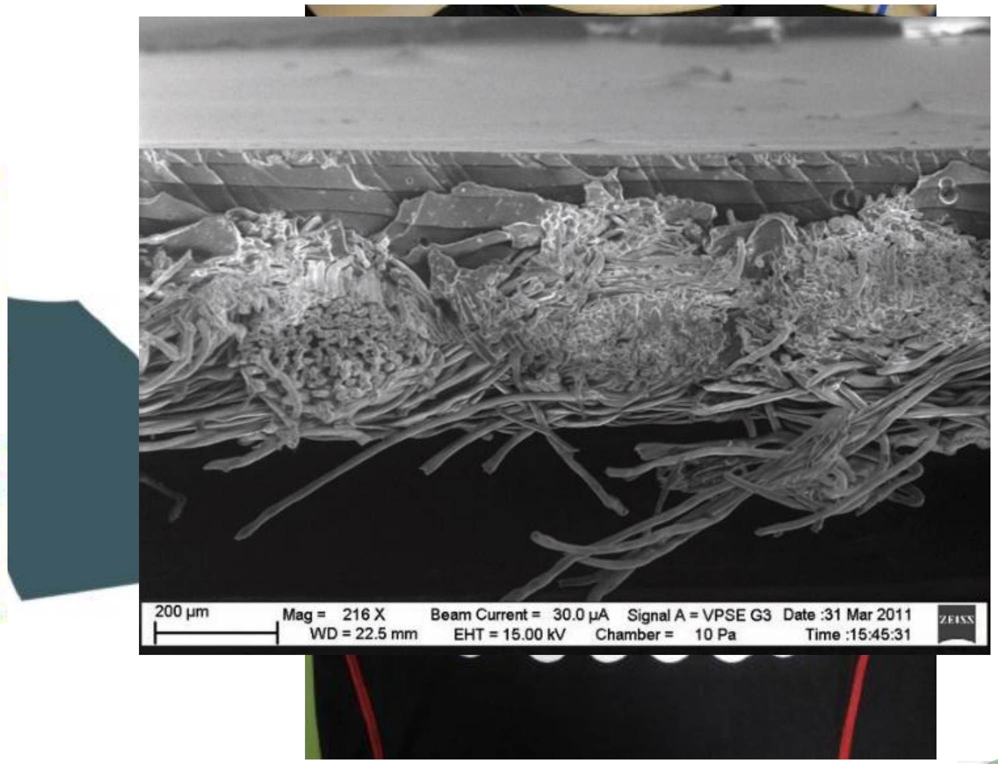
Textile-compatible inks must be:
- Low temperature/UV curable.
- Flexible, potentially stretchable.
- Co-compatible (e.g. surface energy).
- Robust.

Passive	Basic functional	Advanced functional
Interface layer	Conductive	Piezoresistive
Encapsulation layer	Dielectric	Piezoelectric
Structural	Skin electrodes	Electroluminescent
Sacrificial		Semiconducting

Printing on textiles is challenging

Surface planarisation

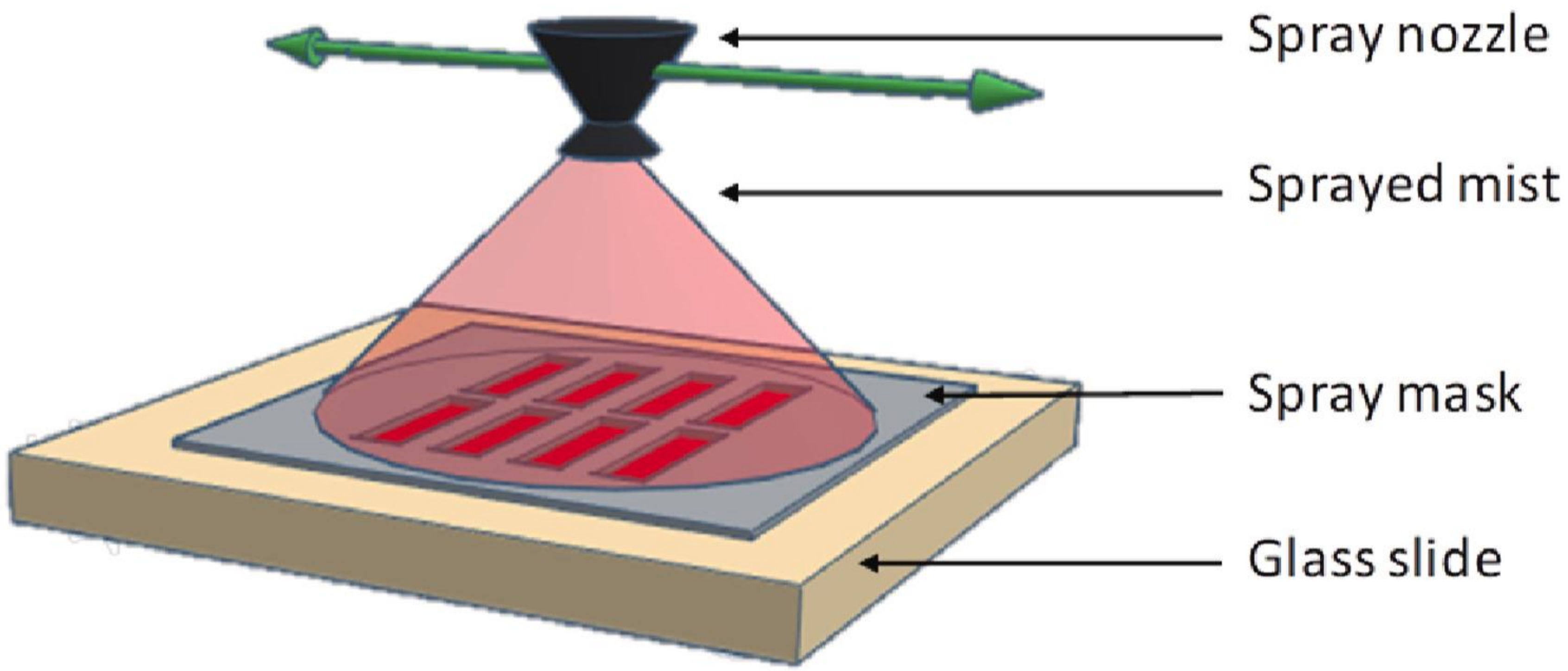




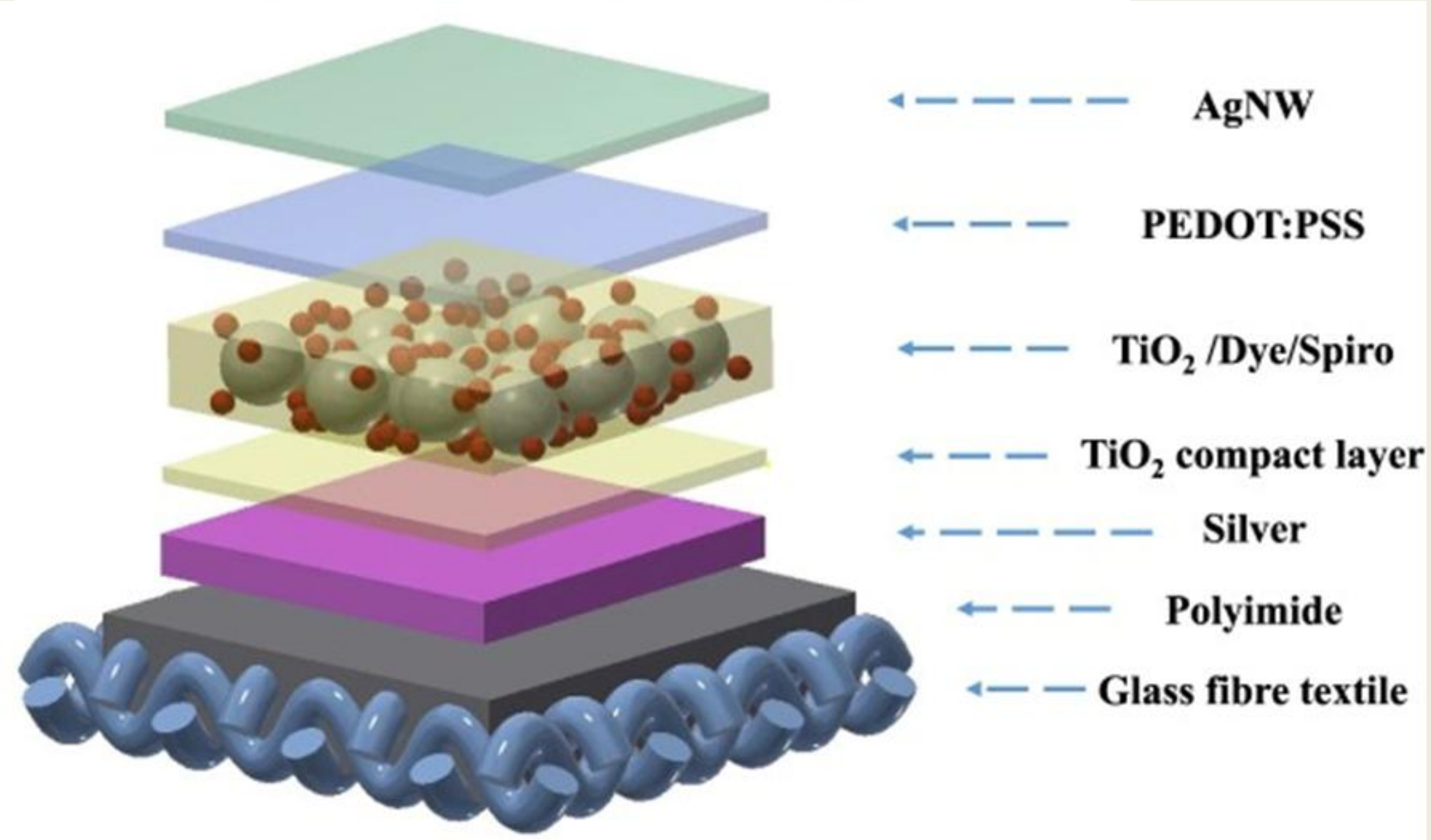
Conductive transfers: printed interconnected on a polymer film and thermally bonded to the textile.

Printing directly on the fabric

Spray Coating



Pneumatic spray coating is suitable for large areas and depositing thin films. Low-resolution patterning is possible through shadow masking.



Organic solar cells: device thickness <1 μm, efficiency 1.2% achieved.

Dye sensitised solar cells: efficiency 4% and stable long term operation.

Example - printed e-textiles

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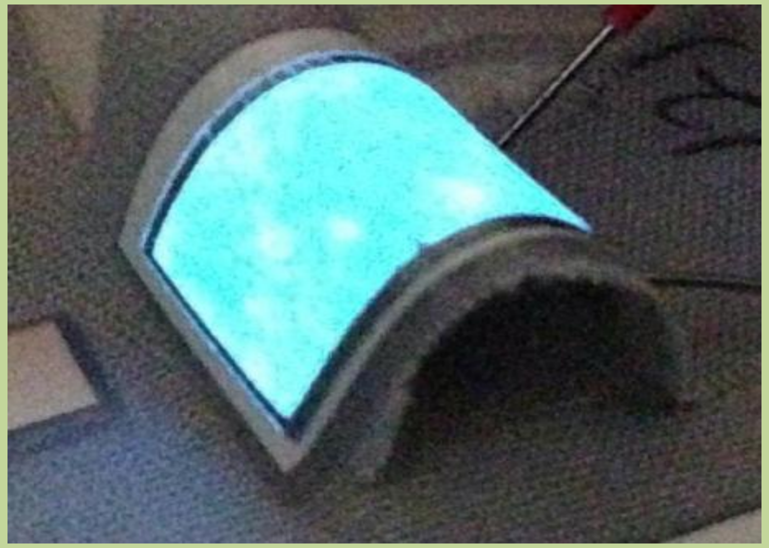
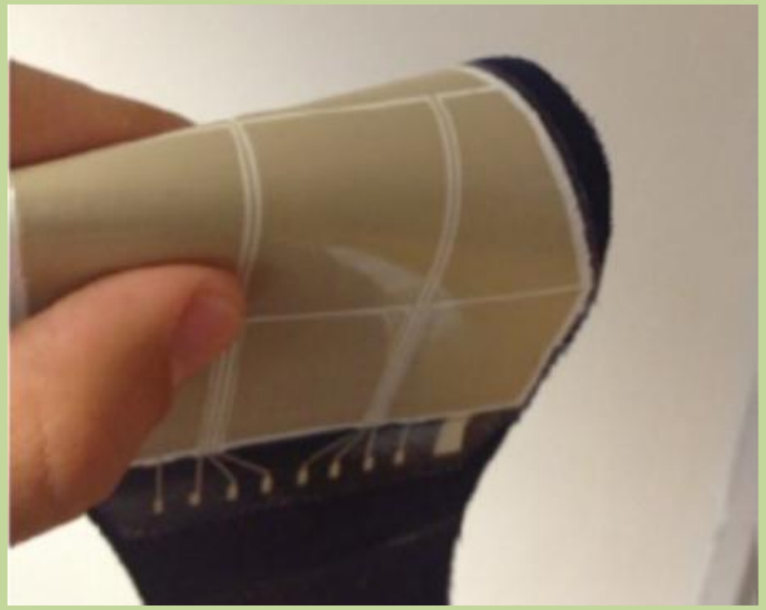
Printed heater

Light emitting films

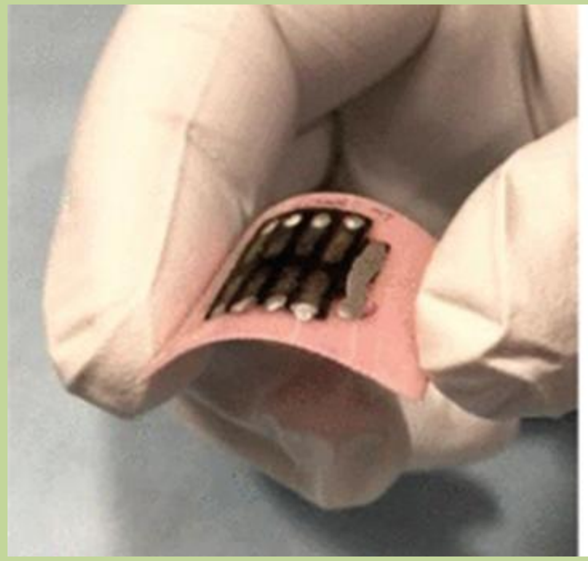


Skin electrodes

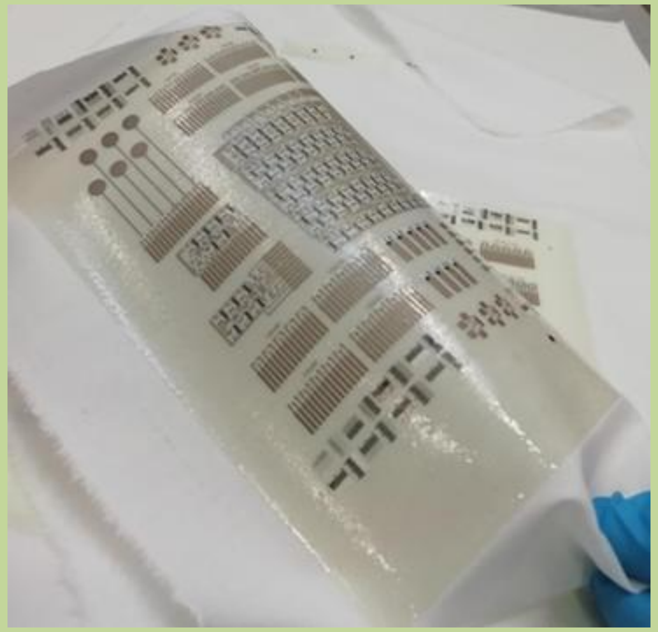
Printed piezoelectric



Textile solar cells

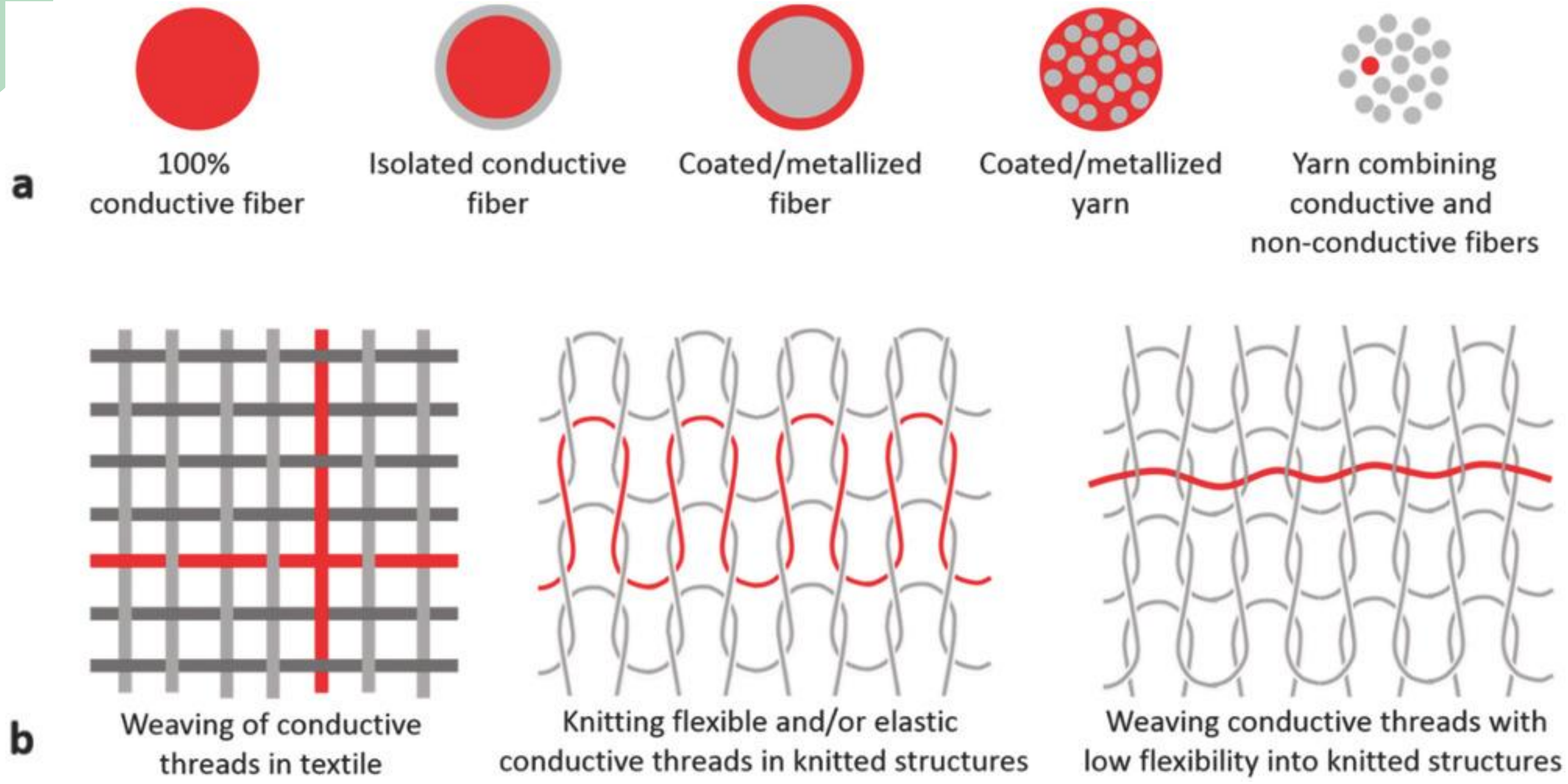


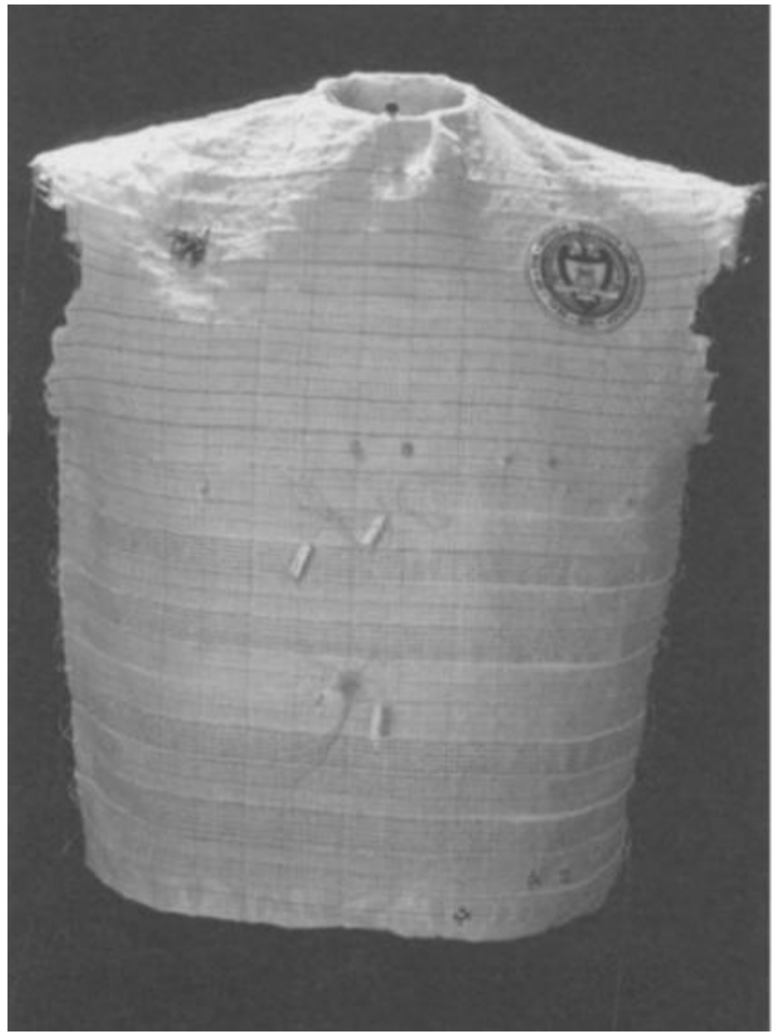
OECTs on textile



Carbon antenna

Woven/knitted textile circuits





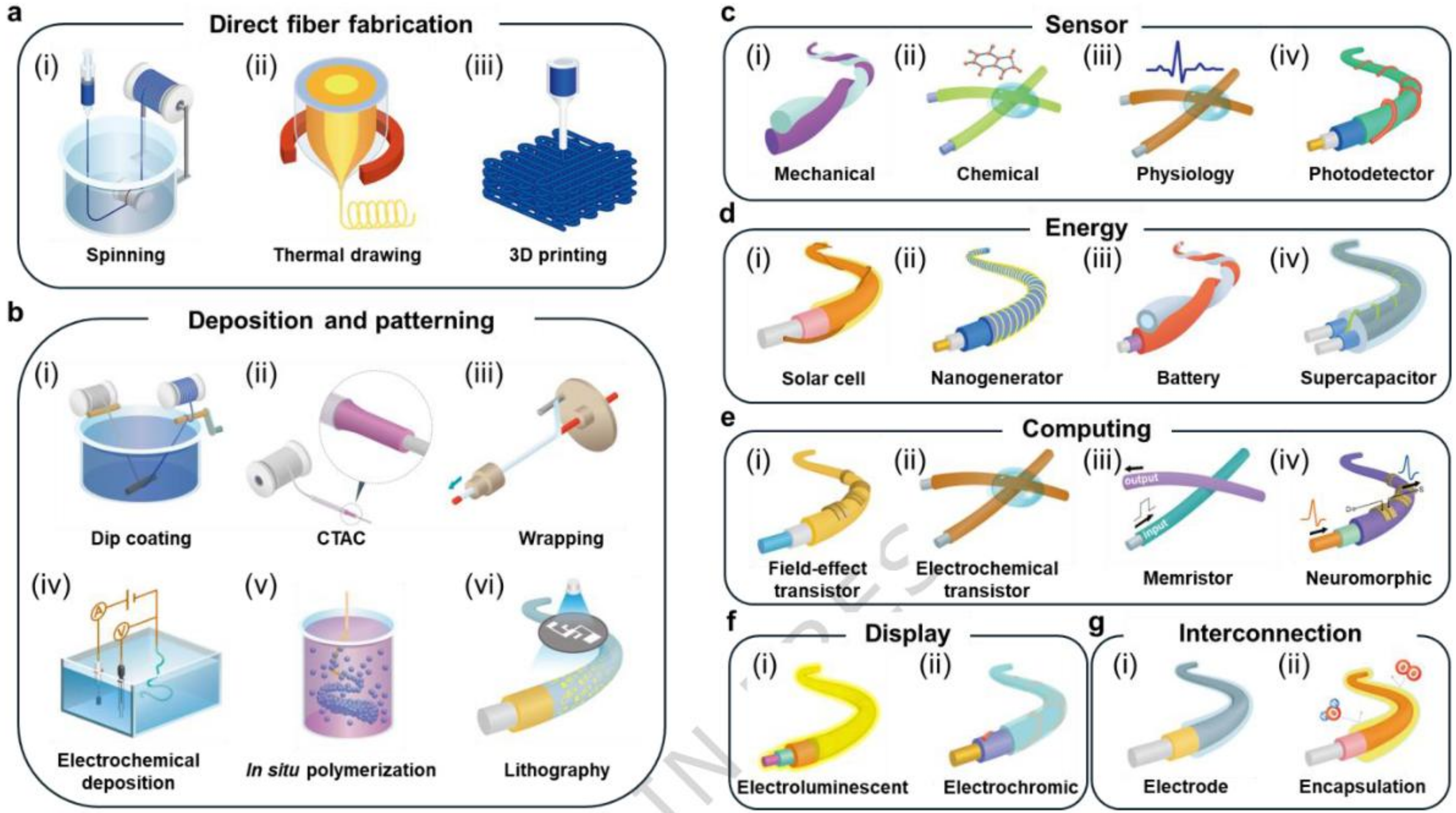
Georgia Tech
Wearable Motherboard (1999)

Coated yarns **offer a much wider range of functionality**

S. de Mulatier, M. Nasreldin, R. Delattre, M. Ramuz, T. Djenizian, *Adv. Mater. Technol.* 2018, 3, 1700320.
https://doi.org/10.1002/admt.201700320

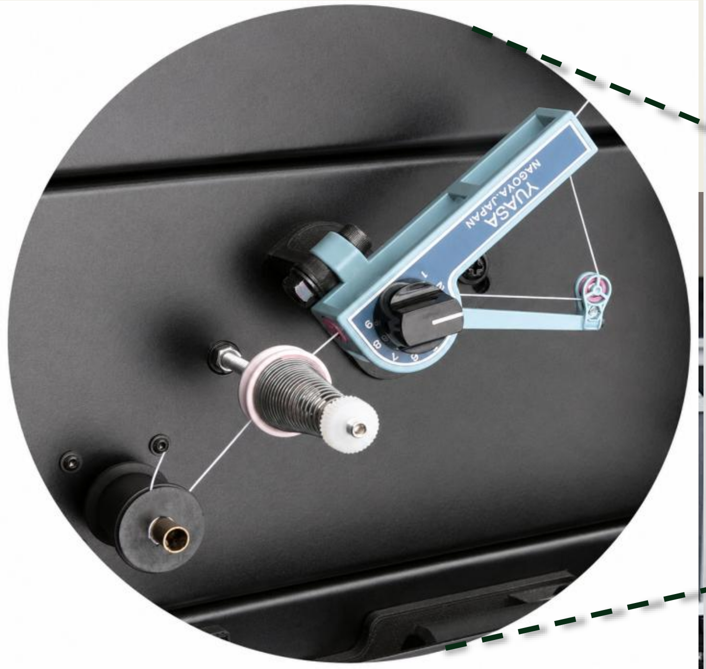
Adding functionality through coated fibers/yarns

Coated yarns offer a much wider range of functionality – building up layers. Inks can be applied to coat yarns

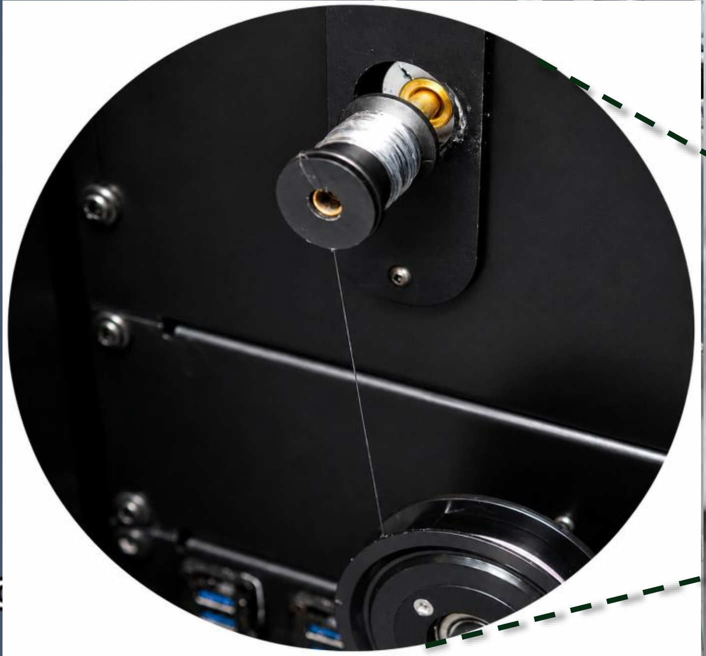


Won, J., Lee, G., Kim, DH. *et al.* One-dimensional (1-D) fiber-based electronics: from building blocks to integrated wearable systems. *npj Flex Electron* (2026). https://doi.org/10.1038/s41528-026-00612-

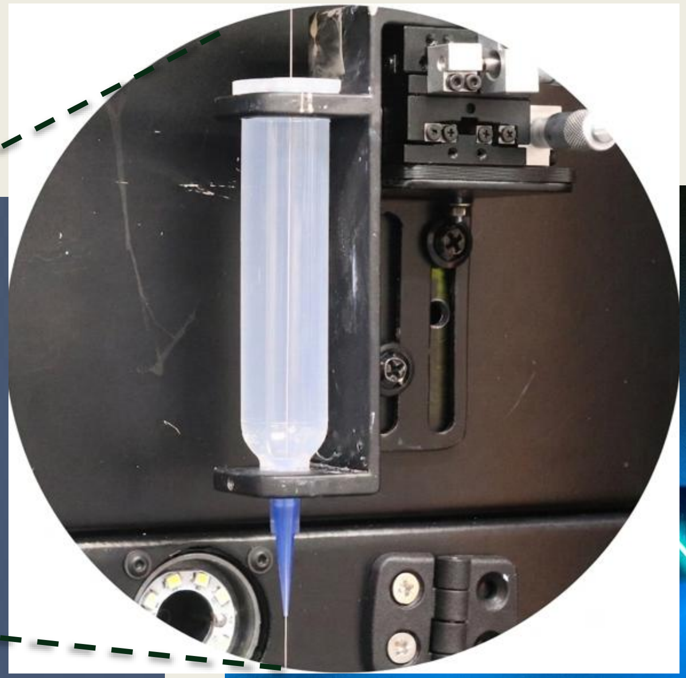
Solution processes coated yarns



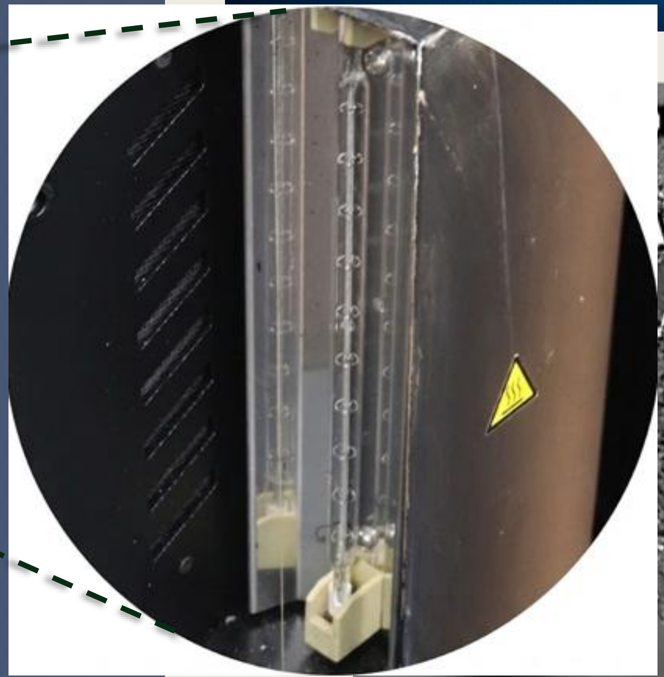
Yarn spool and tensioner



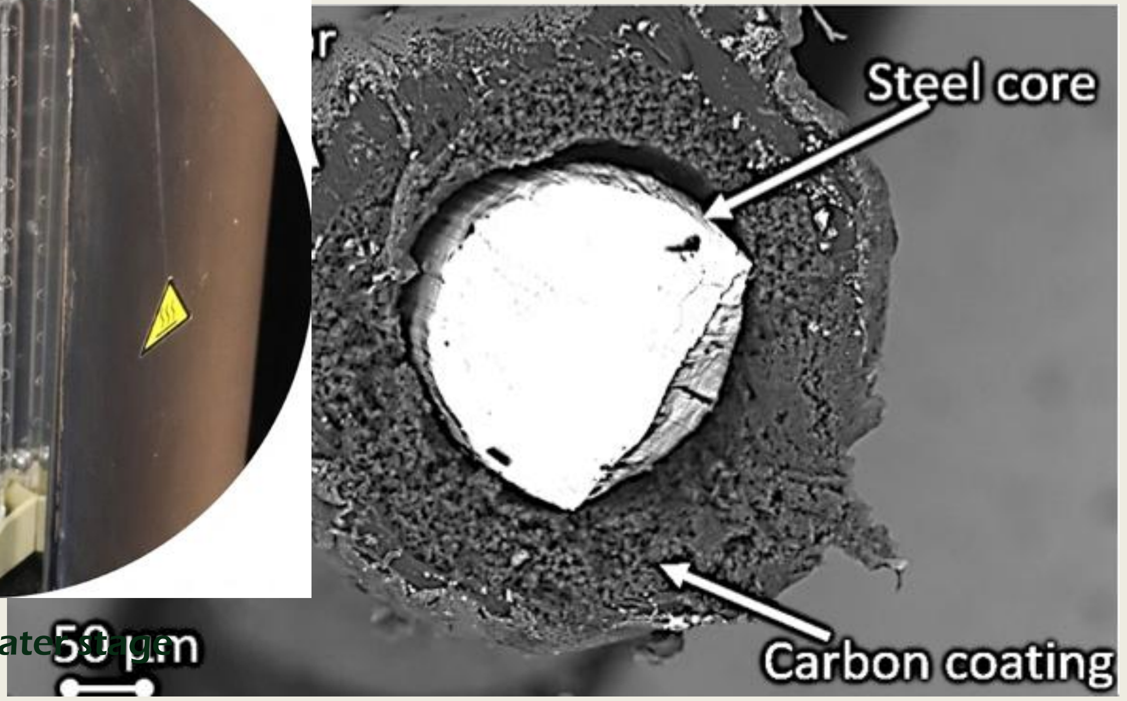
Motorised collecting spool
(control fiber speed)



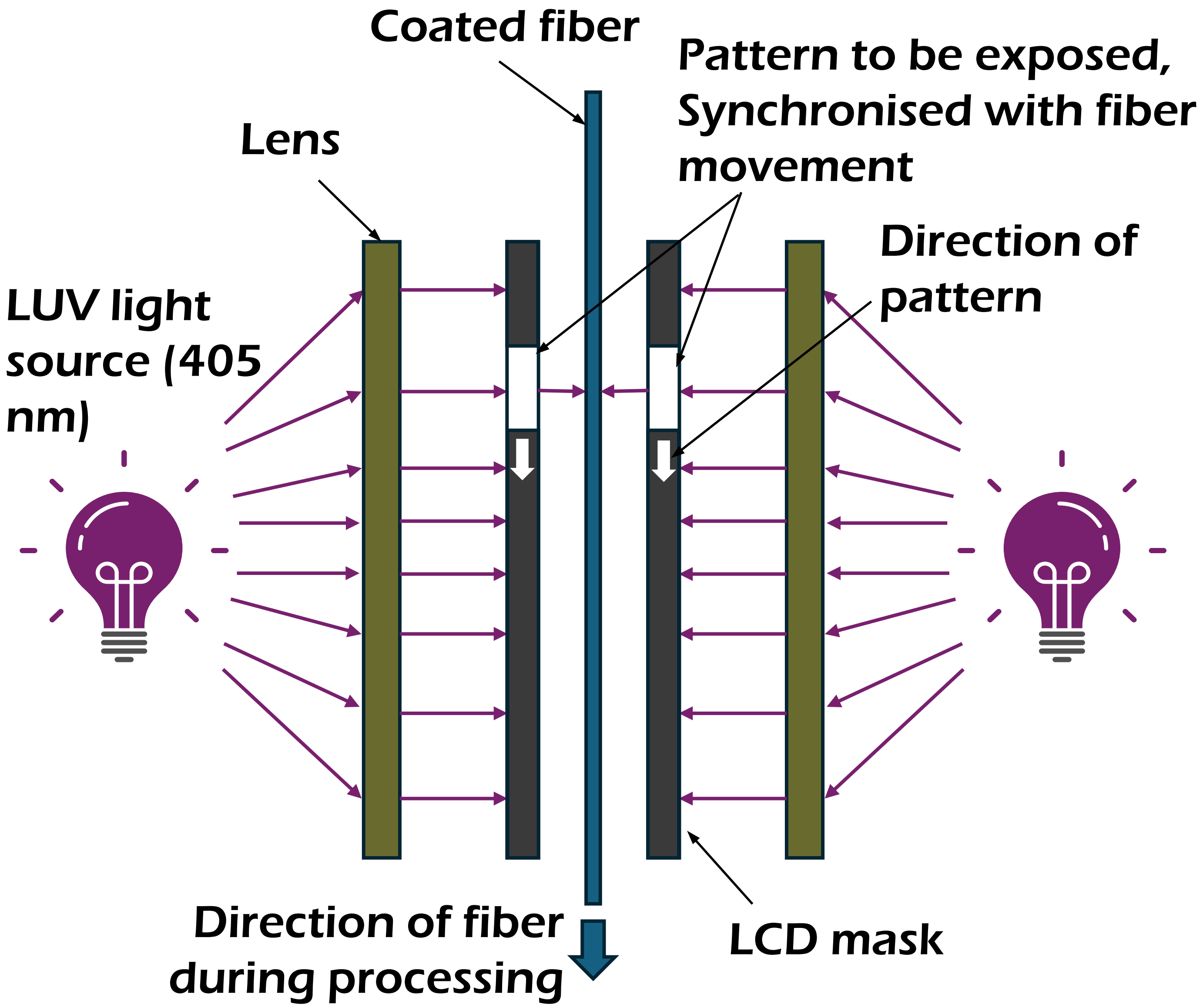
Coating syringe, tapered nozzle, and
inspection cameras

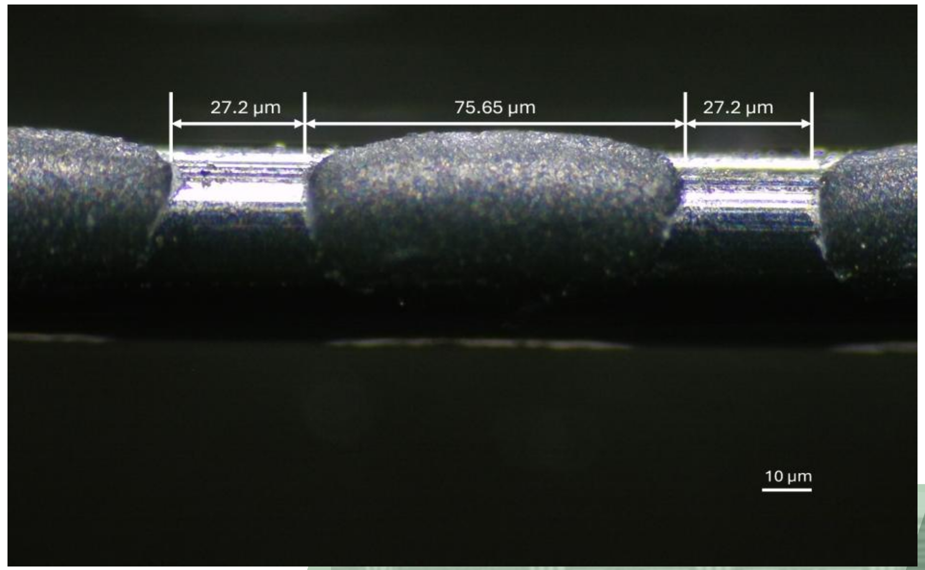


Infrared heater stage



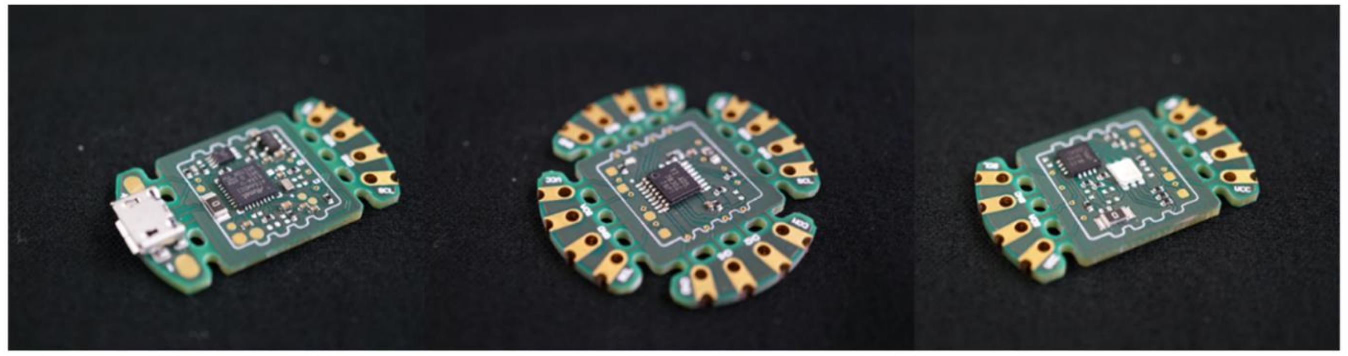
Yarn coating system





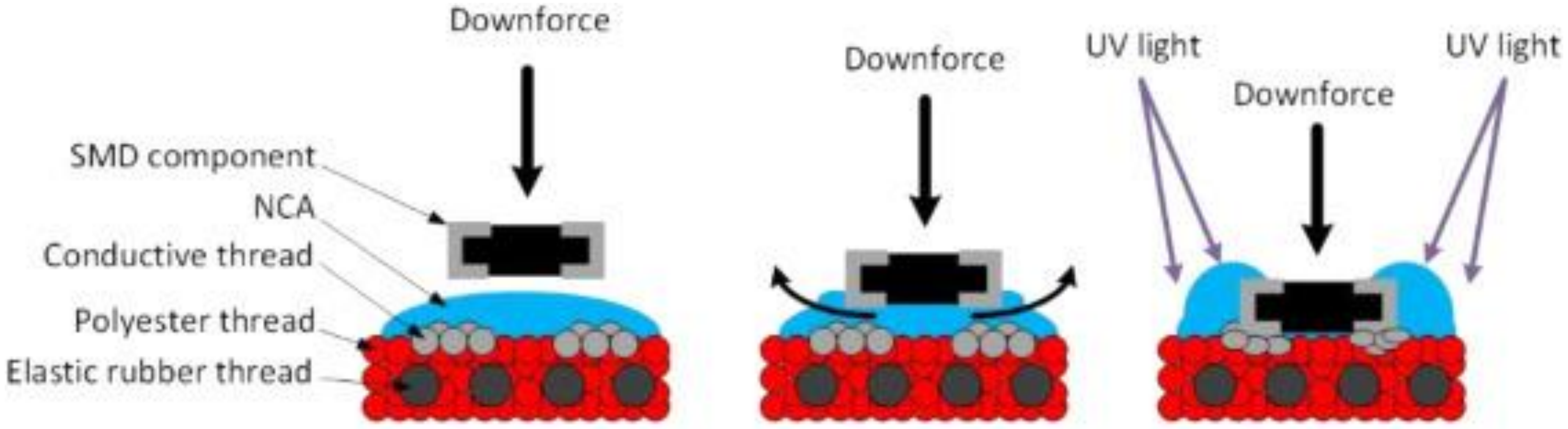
UK Patent Application No. 2620287.9
Applicant: University of Southampton
Title: Method and System for Processing a Yarn

Adding electronic circuits

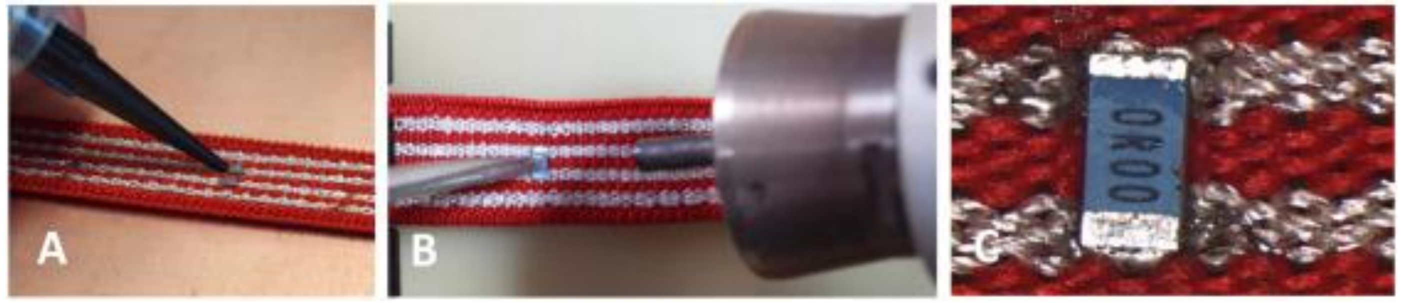


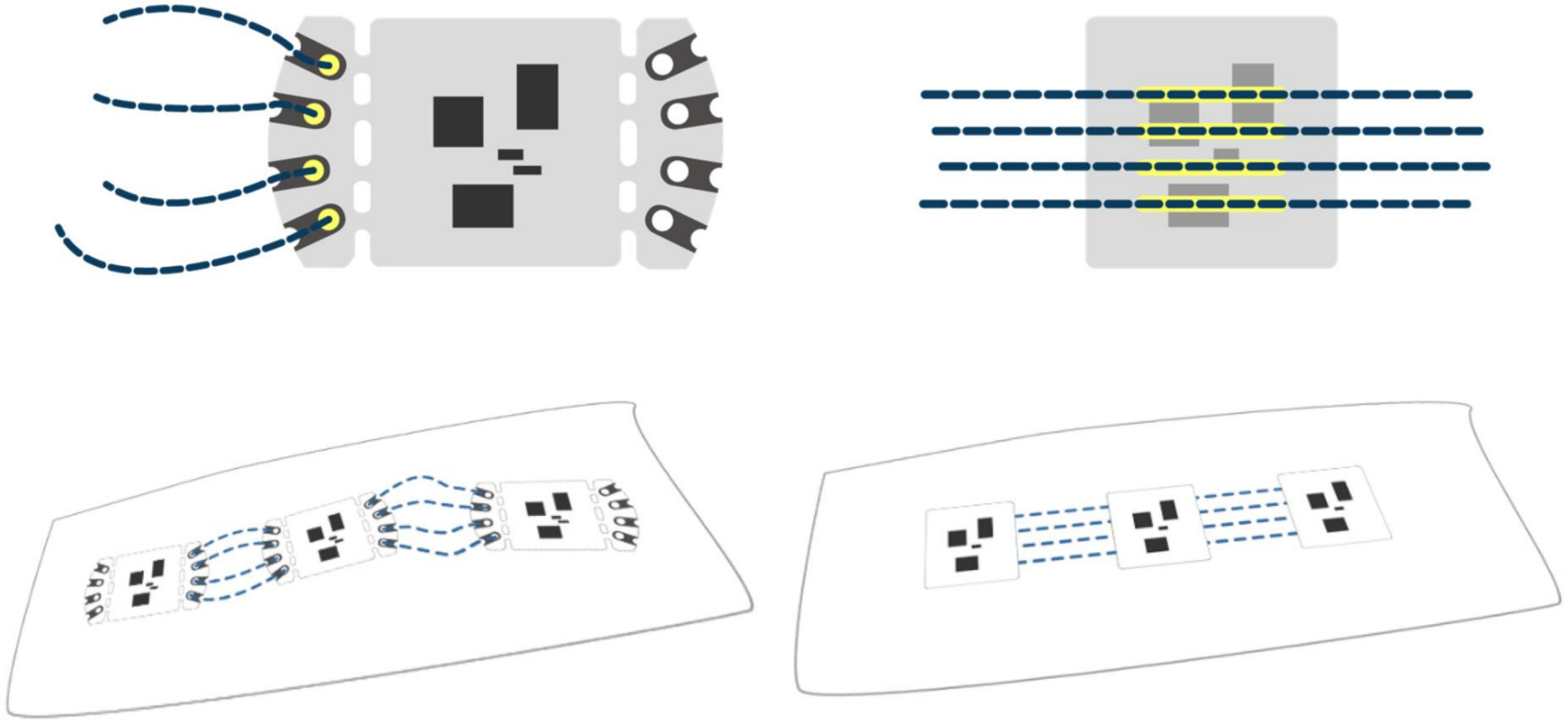
Bespoke rigid boards designed for textiles

Example bonding process – UV curing adhesive



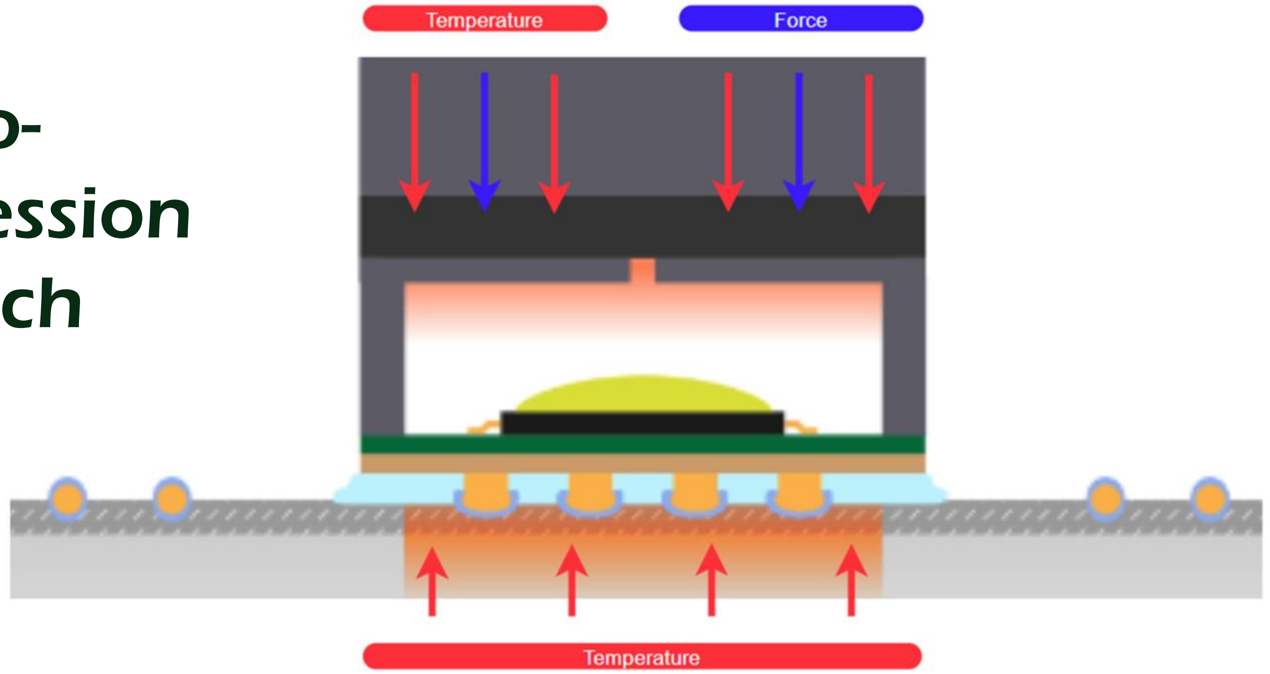
Soldering approach





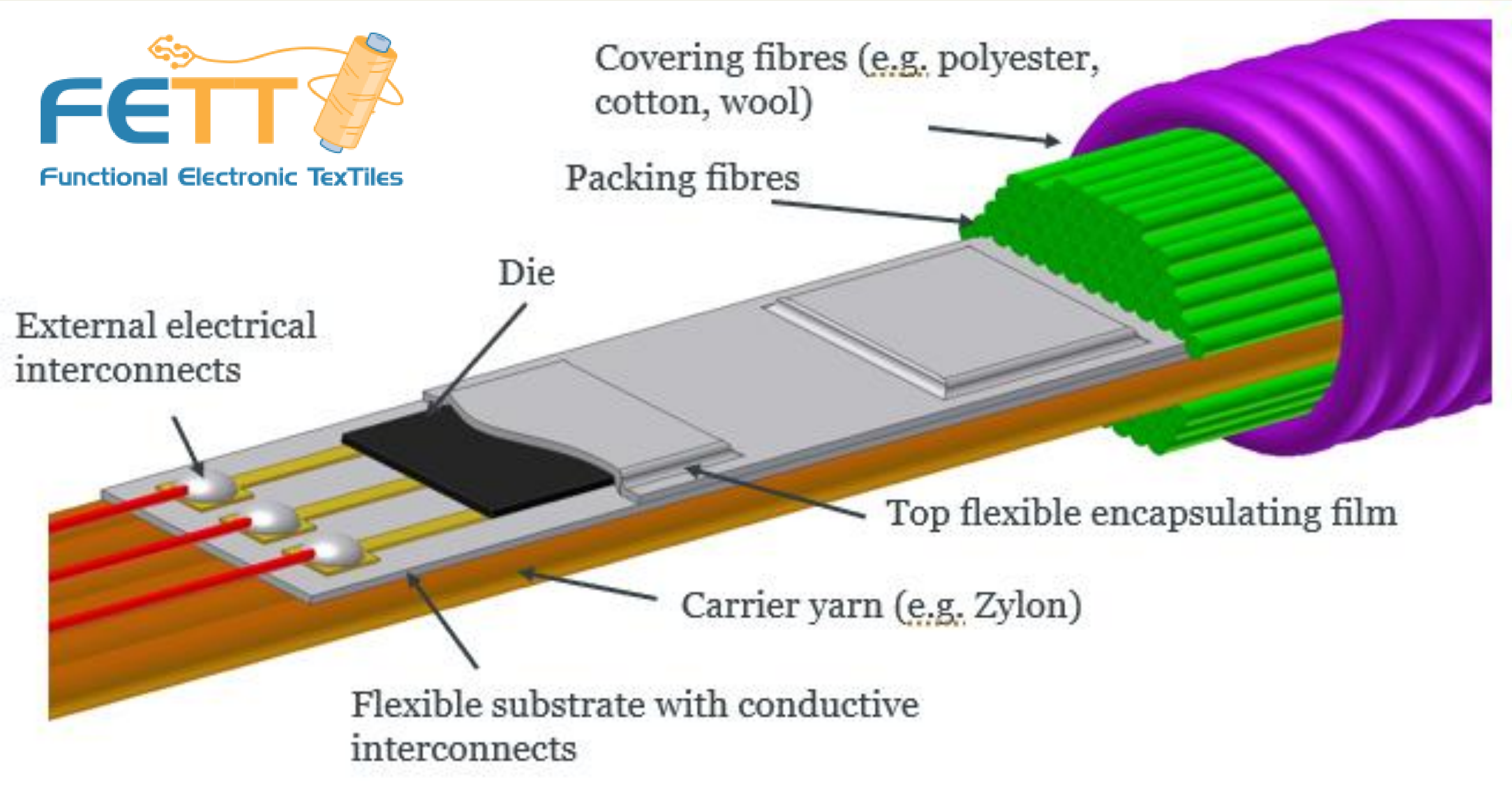
Two connection strategies: manual (left), automated non-conductive adhesive bonding technology, developed at the Fraunhofer IZM (right)

Thermo-compression approach



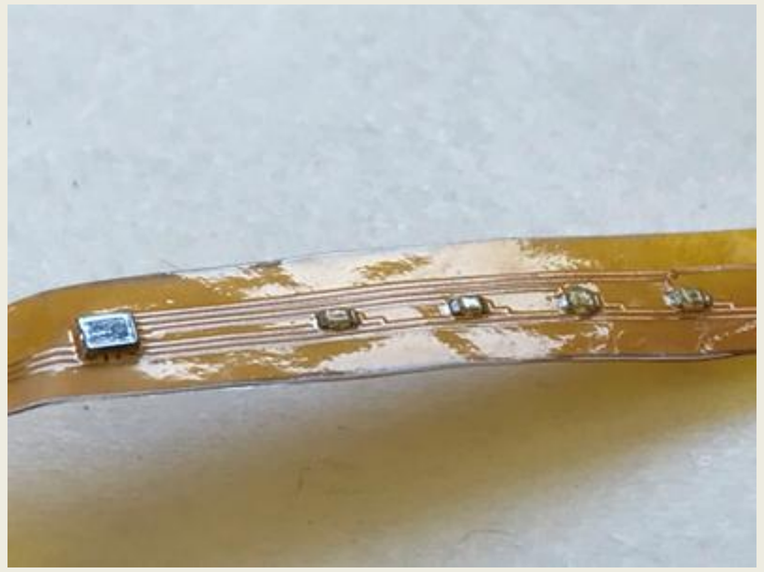
Garbacz, K.; Stagun, L.; Rotzler, S.; Semenec, M.; von Krshiwoblozki, M. Modular E-Textile Toolkit for Prototyping and Manufacturing. *Proceedings* **2021**, *68*, 5. https://doi.org/10.3390/proceedings2021068005

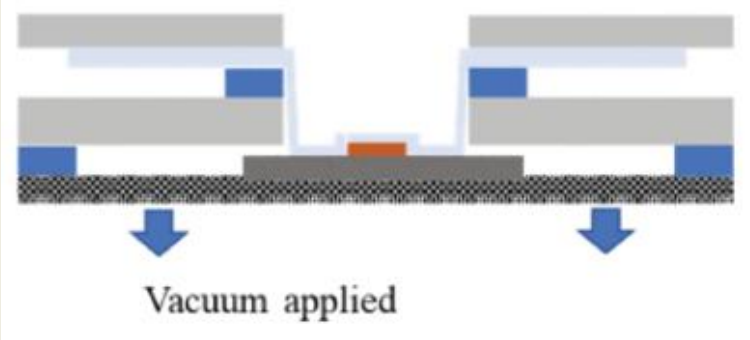
Integrating flexible circuits



Variety of integration approaches.

Vacuum packaging process.



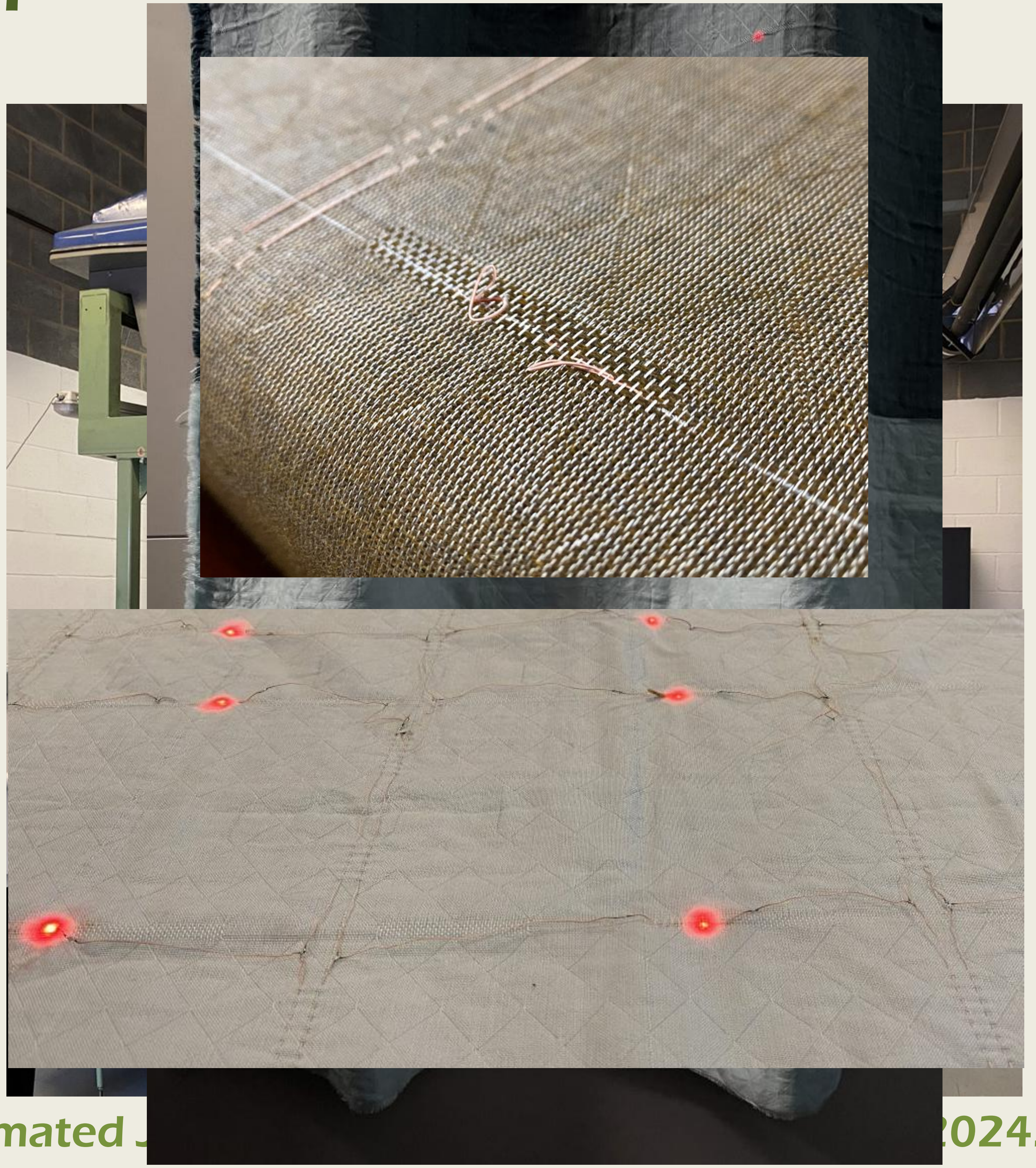


Challenges include circuit fabrication, electrical connections, integration within the yarn, manufacturability and reliability.

A. Komolafe, R. Torah, Y. Wei, H. Nunes-Matos, M. Li, D. Hardy, T. Dias, M. Tudor, S. Beeby, Integrating Flexible Filament Circuits for E-Textile Applications. *Adv. Mater. Technol.* 2019, 4, 1900176. https://doi.org/10.1002/admt.201900176

Weaving Flexible Circuits

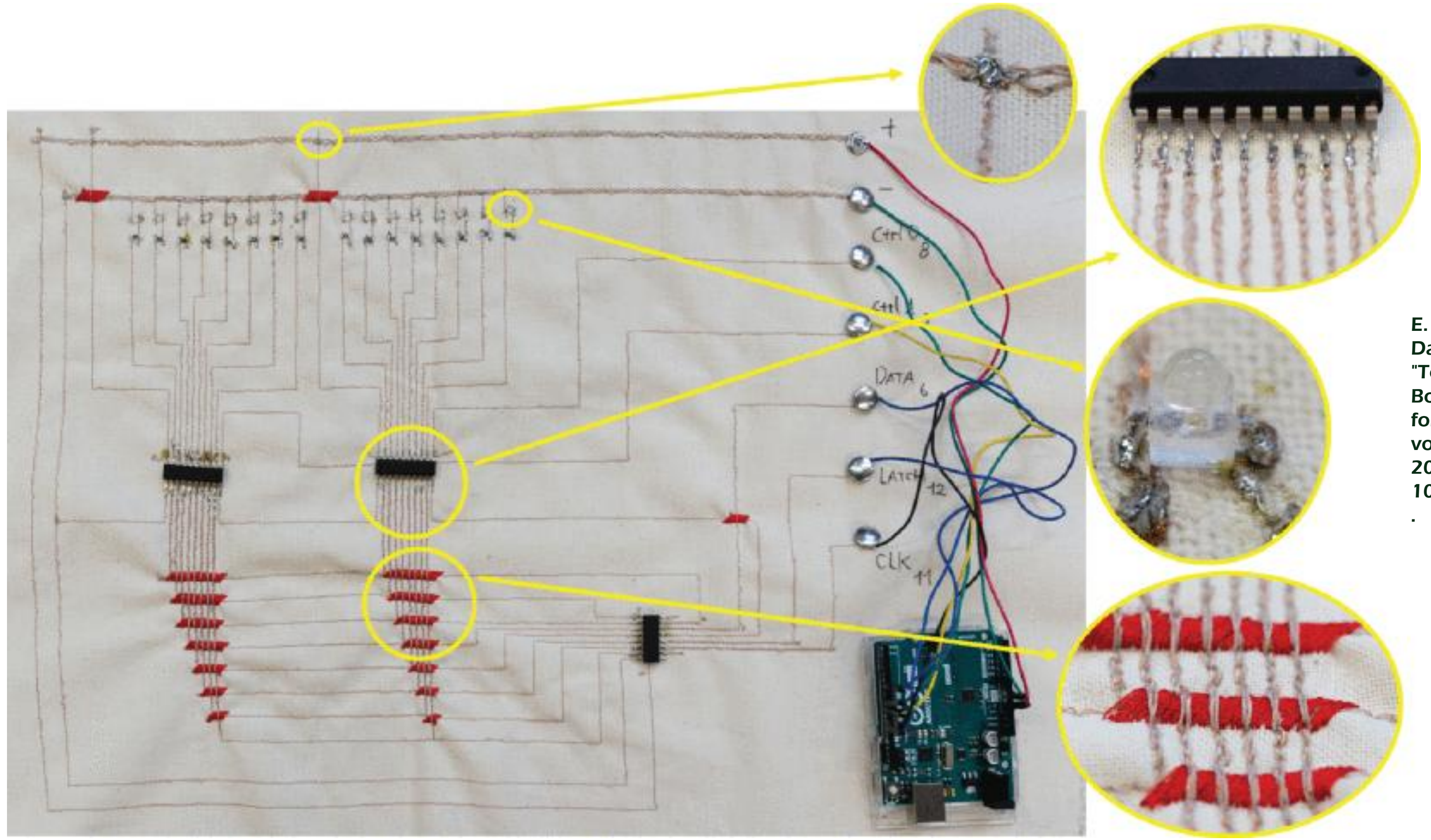
Towards mass production – Jacquard weaving loom



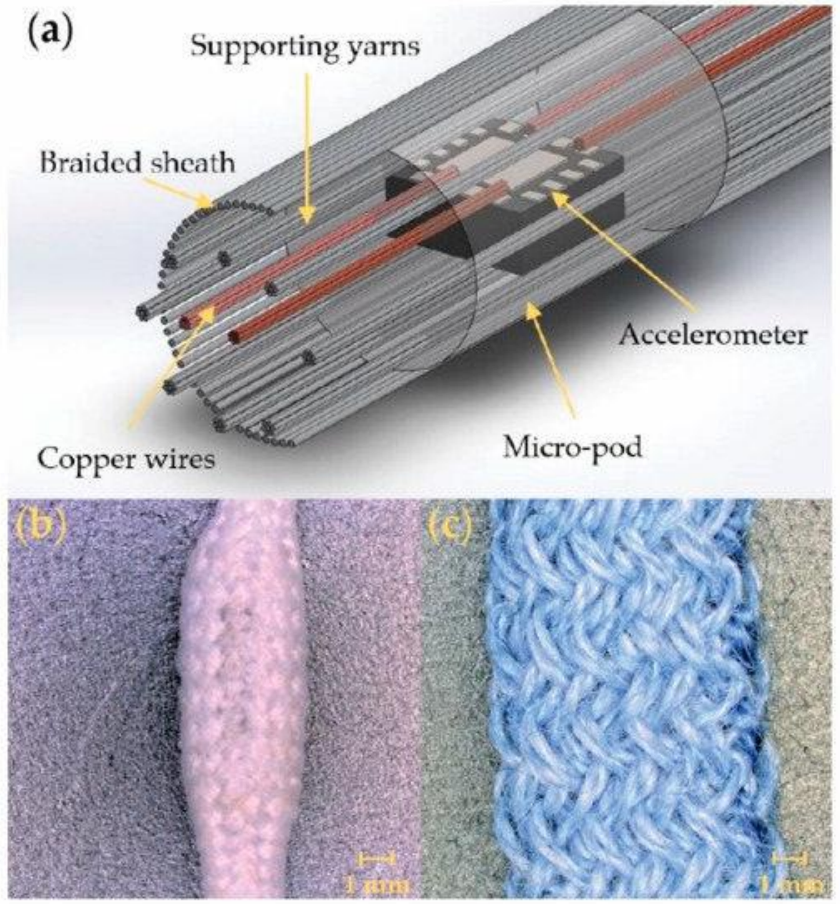
Automated J … 2024.

Other flexible circuit techniques

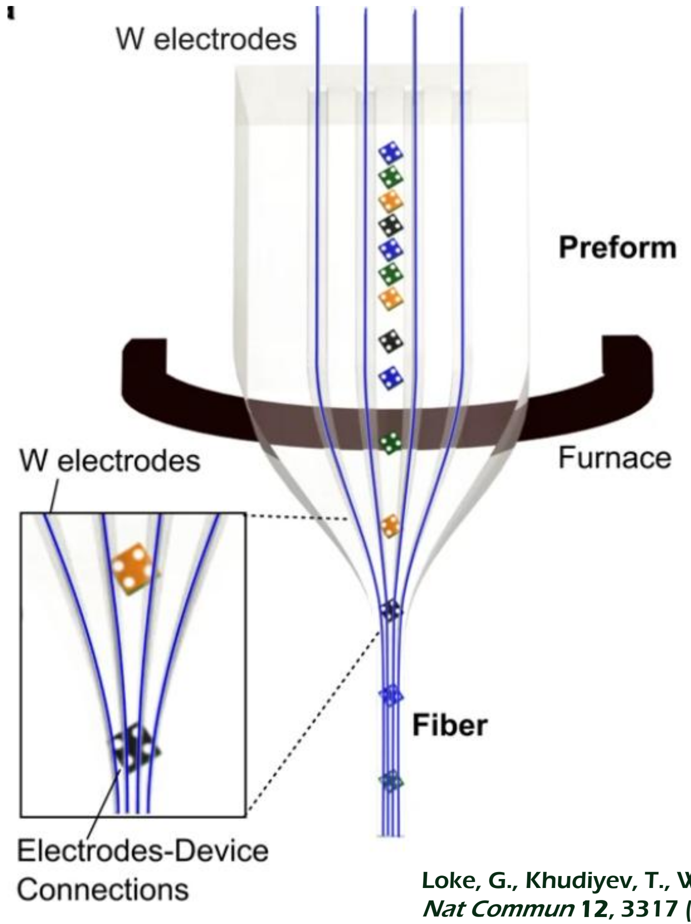
Wicaksono, I., Tucker, C.I., Sun, T. *et al.* A tailored, electronic textile conformable suit for large-scale spatiotemporal physiological sensing in vivo. *npj Flex Electron* 4, 5 (2020). https://doi.org/10.1038/s41528-020-0068-y

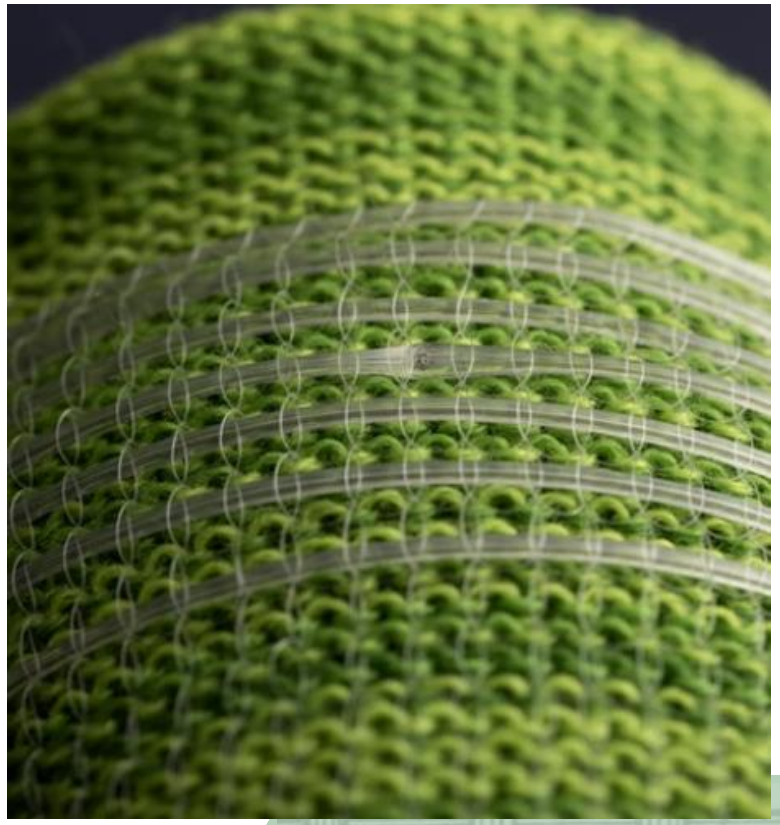


E. Ismar, X. Tao, F. Rault, F. Dassonville and C. Cochrane, "Towards Embroidered Circuit Board From Conductive Yarns for E-Textiles," in *IEEE Access*, vol. 8, pp. 155329-155336, 2020, doi: 10.1109/ACCESS.2020.3018759 .



Rahemtulla, Z., Hughes-Riley, T., & Dias, T. (2021). Vibration-Sensing Electronic Yarns for the Monitoring of Hand Transmitted Vibrations. *Sensors, 21*(8), 2780. https://doi.org/10.3390/s21082780





Loke, G., Khudiyev, T., Wang, B. *et al.* Digital electronics in fibres enable fabric-based machine-learning inference. *Nat Commun* 12, 3317 (2021). https://doi.org/10.1038/s41467-021-23628-5

Research challenges: batteries and wires

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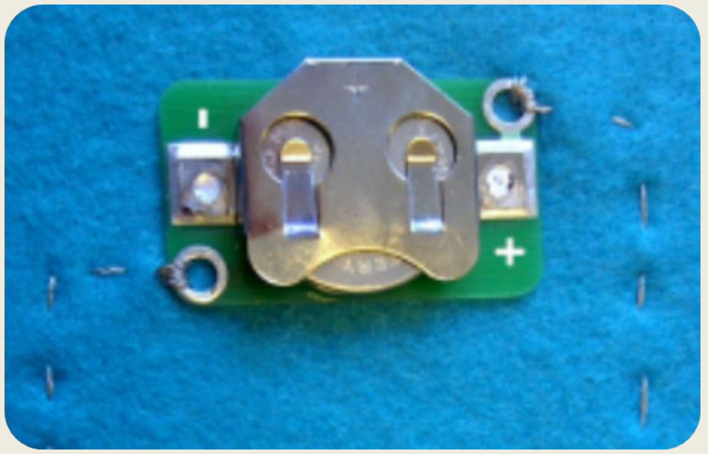
Dragonfly Golf, $5k+
Sensors have to be removed for washing

E-textile power supplies rely on conventional rigid **batteries**. These are incompatible with the feel of the textile, cannot be washed and negate imperceptible electronics.



Teslasuit, $10k+
Can't be washed

The requirements for reliability make existing commercial solutions expensive, with bulky wires and sensors, only suitable for niche applications.

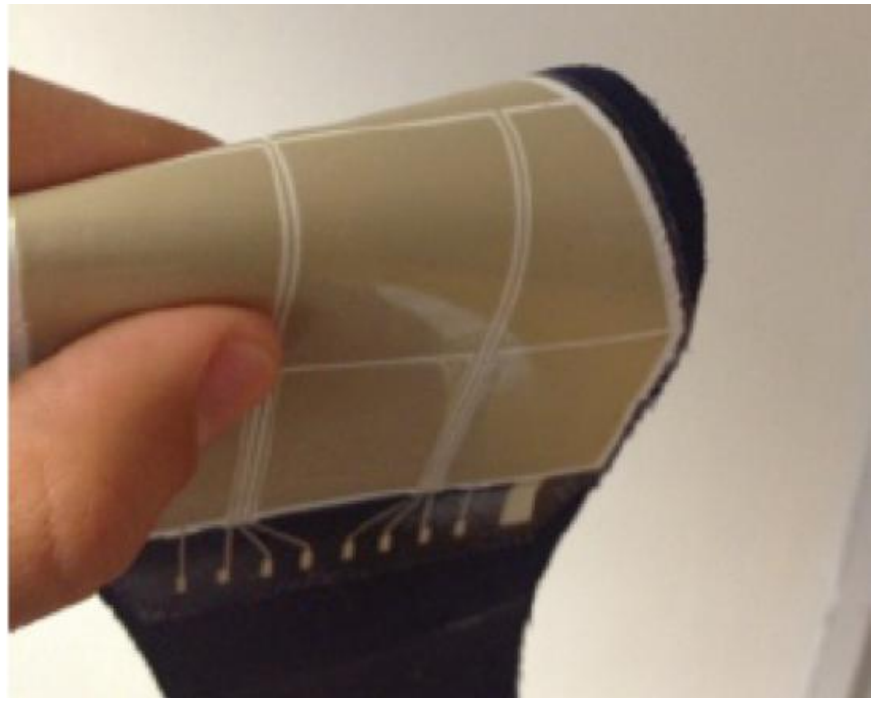
Power supplies not shown

Capturing mechanical energy

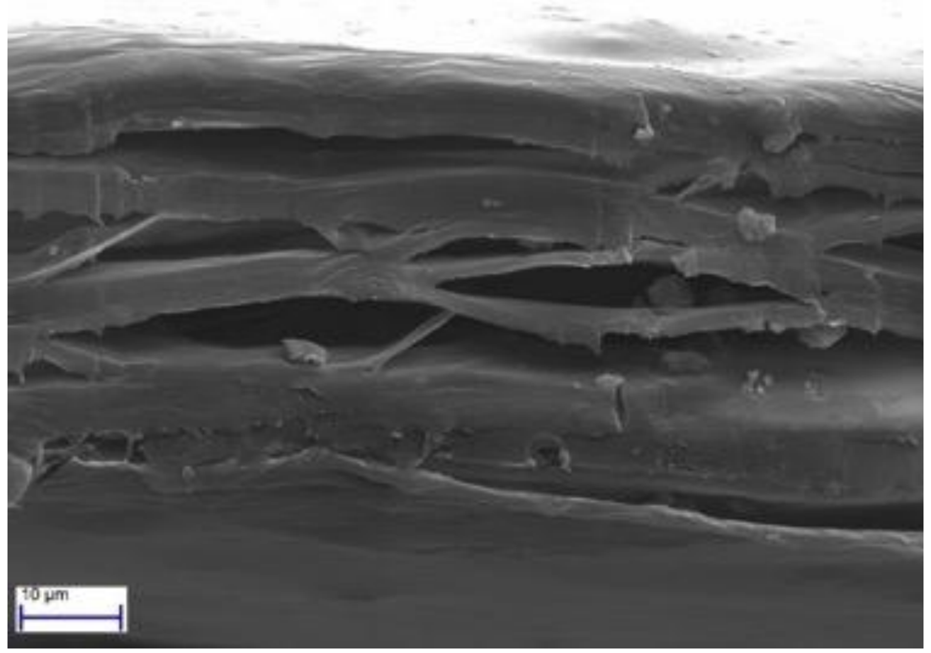
Transducers that convert movement or forces into electrical energy:

- Flexible printable piezoelectric material compatible with textiles.
- Ferroelectret materials – soft compliant materials (foams) that appear piezoelectric.
- Triboelectric effect - convert kinetic energy into electricity based on contact electrification and the electrostatic induction effect.

Challenge: Implementing in a garment



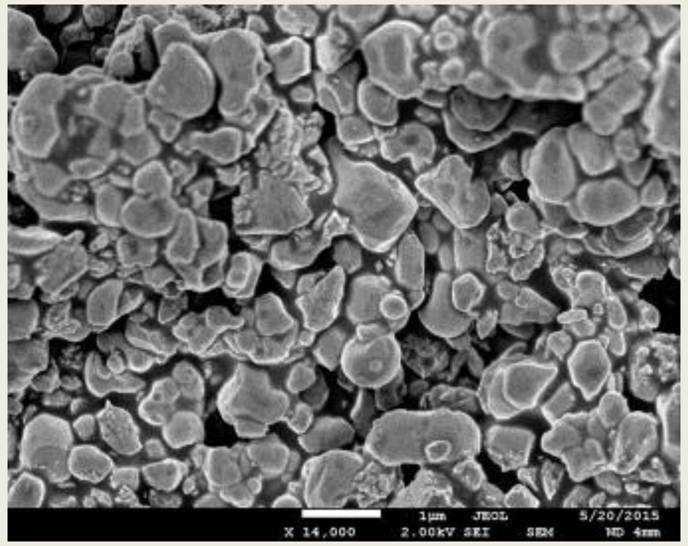
Flexible piezoelectric film

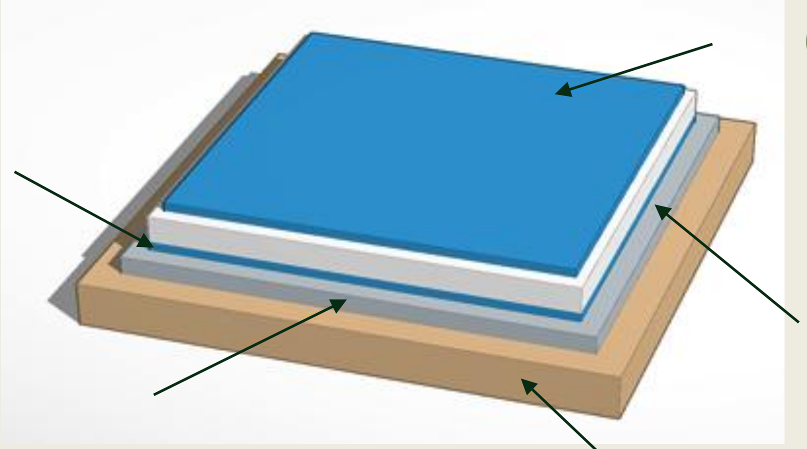


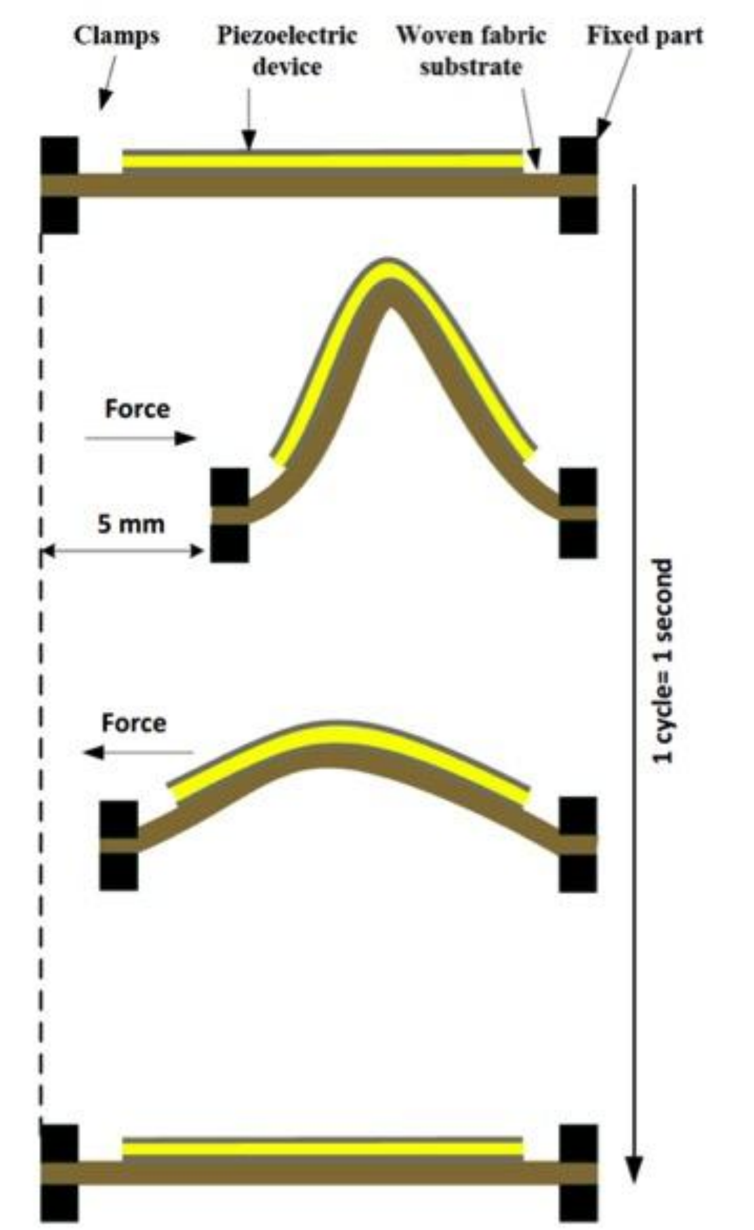
Polypropylene (PP) ferroelectret (Emfit Ltd)

Screen printed piezoelectric film

- **Flexible polymer PZT based screen printable ink, freestanding d_{33} coefficient 98 pC/N (PVDF ~ 30pC/N).**
- **38 and 14 mJ energy generated per compression and bending action**
- ***Textile compliance limits power.***



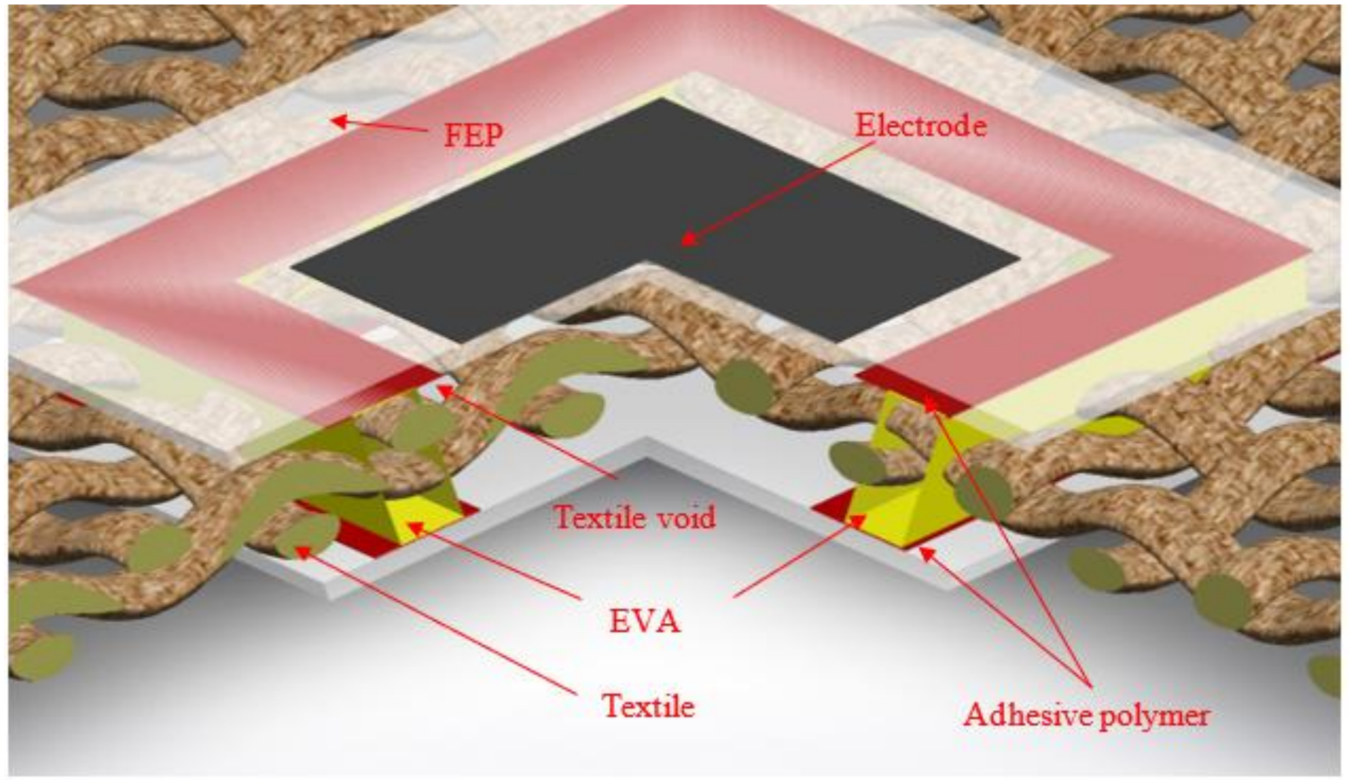


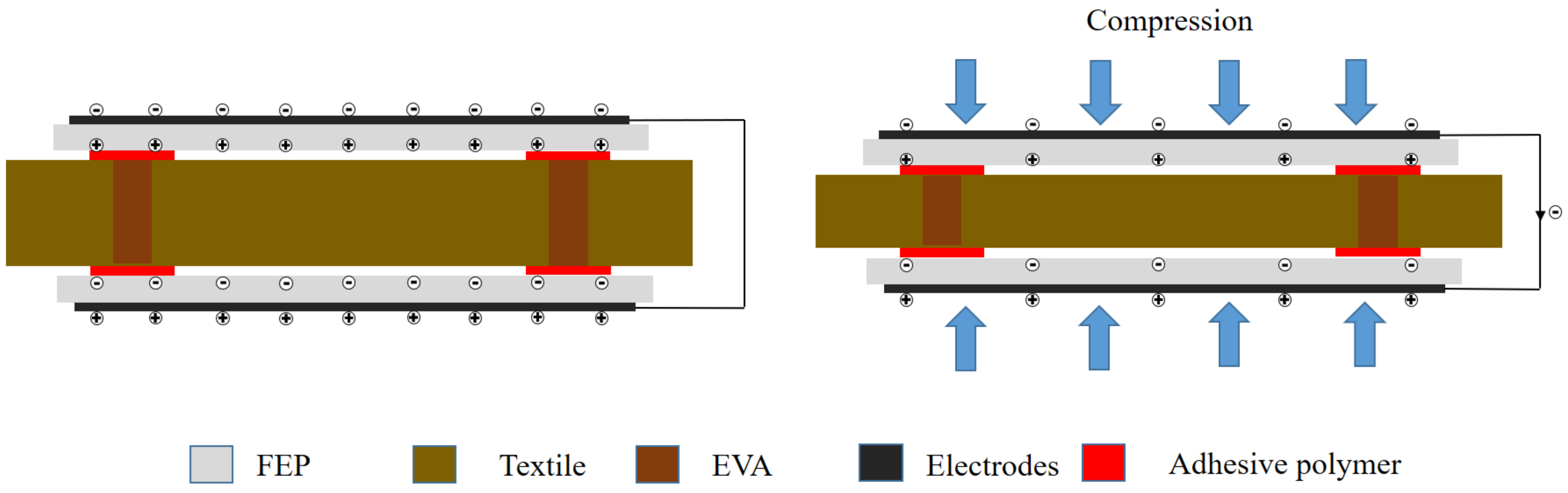


Flexible piezoelectric nano-composite films for kinetic energy harvesting from textiles (2017) Nano Energy 33, 146–56

Textile Ferroelectret

- Ferroelectret energy harvesting – based on charged fluorinated ethylene propylene (FEP) sheets bonded to a textile.
- Textile acts as a soft mechanical spring element.
- Charge generated with applied forces, d_{33} of >1200 pC N^{-1} for silk.
- Best for compressive forces – **location?**





The effect of fabric properties on the performance of a textile based ferroelectret generator toward human body energy harvesting, Smart Materials and Structures, DOI 10.1088/1361-665X/ac56b8

Triboelectrics: Self-Powered Sensing & Energy Harvester

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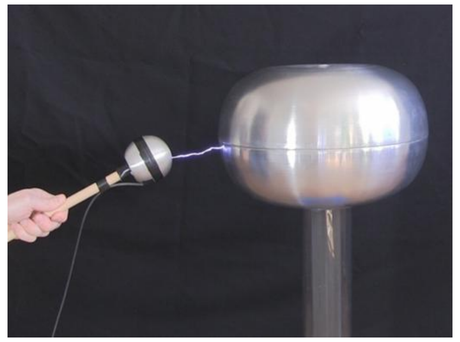
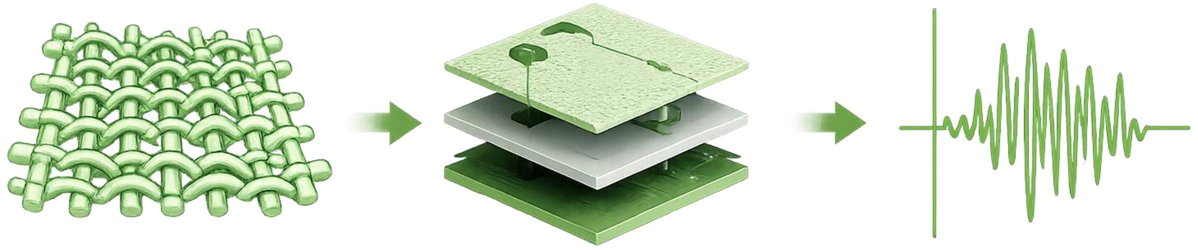
Triboelectric TENGs convert everyday **mechanical motion** into **electrical signals** and **usable energy** using textile native, flexible and scalable architectures



Self Powered Textile Sensing

Textile Structure → T-TENGs based sensors Electrical Signal



Key Focus

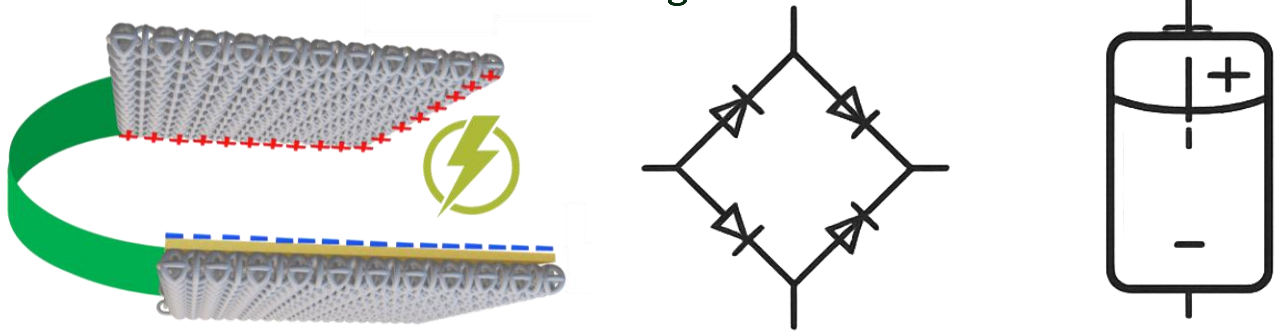
T-TENGs sensor design & fabrication, high sensitivity, reliability, durability and self powered operations

One Textile Platform
Multiple Functions

SENSE • HARVEST • INTEGRATE

Energy Harvesting

Energy Harvesting Power Management Energy Storage



Key Focus

Efficient energy harvesting under real human motion and integrate into power management & storage device.

Applications

Motion sensing

Event detection

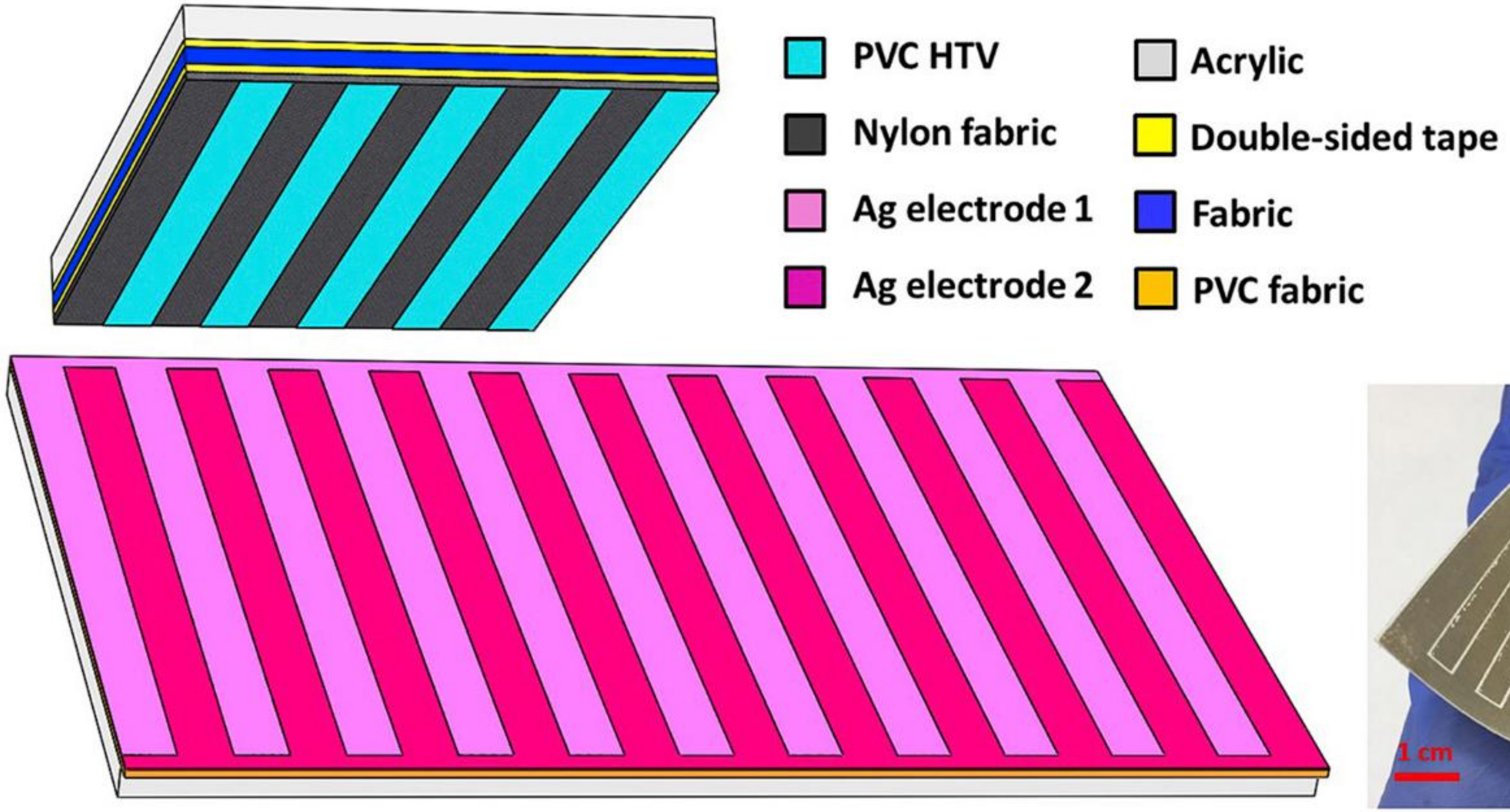
Touch/Pressure sensing

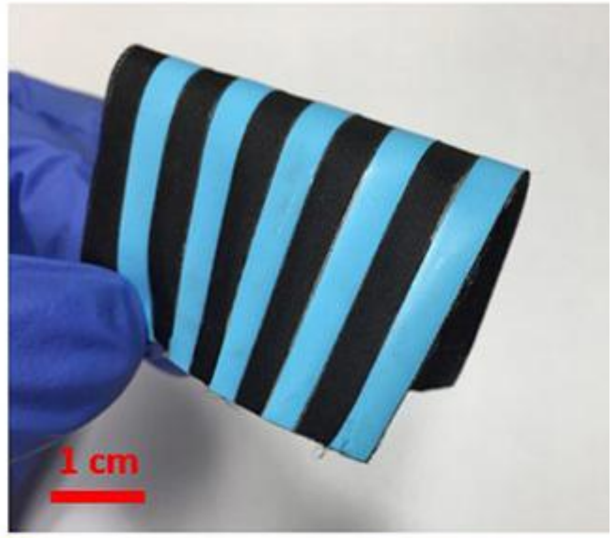
Vibrational/speech sensing

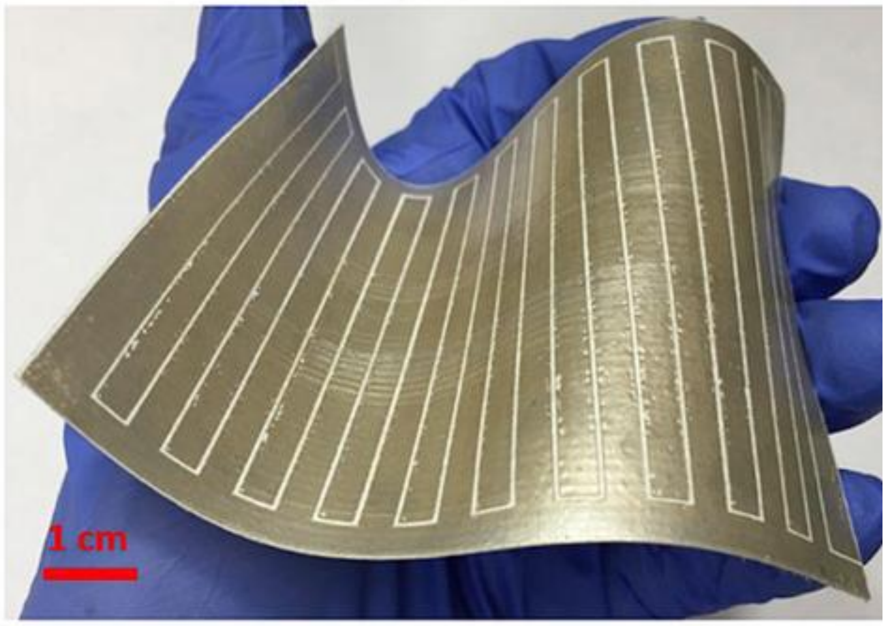
Energy Harvesting

Textile-based TENGs

Investigated textile TENG (T-TENG) structure with alternate grated strips of positive and negative triboelectric material operating in freestanding triboelectric-layer mode.

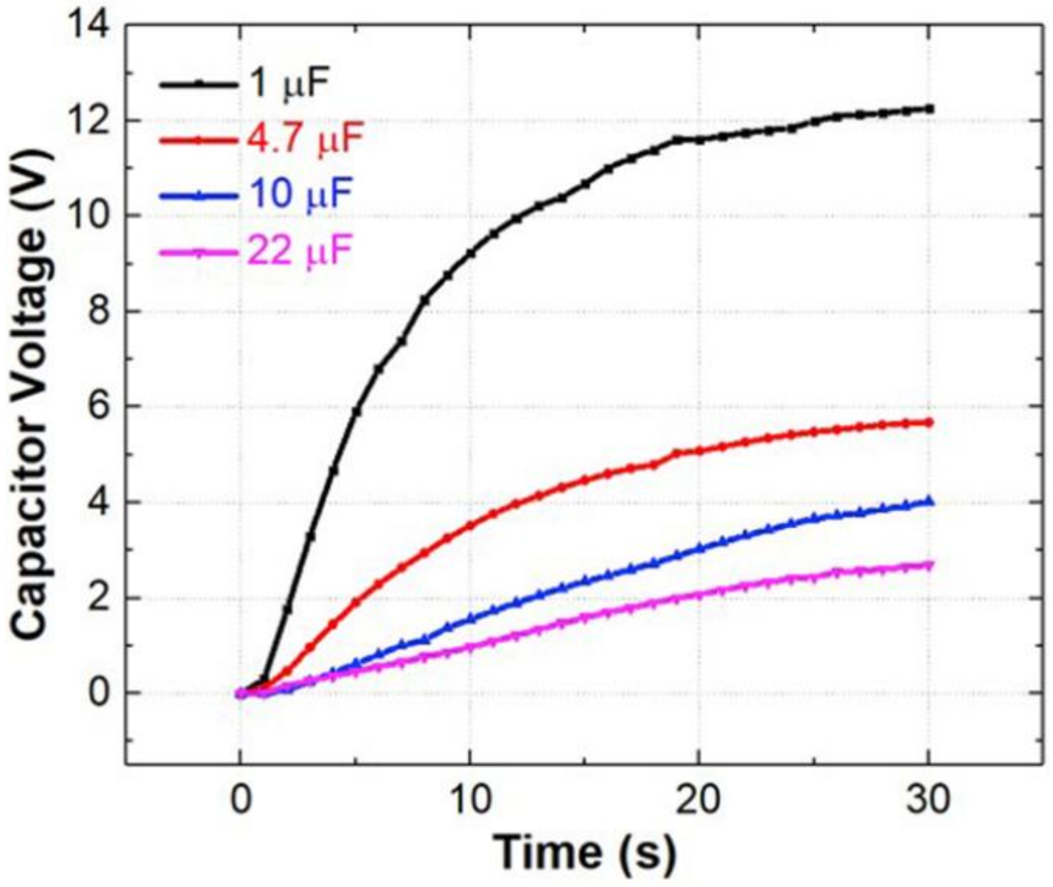






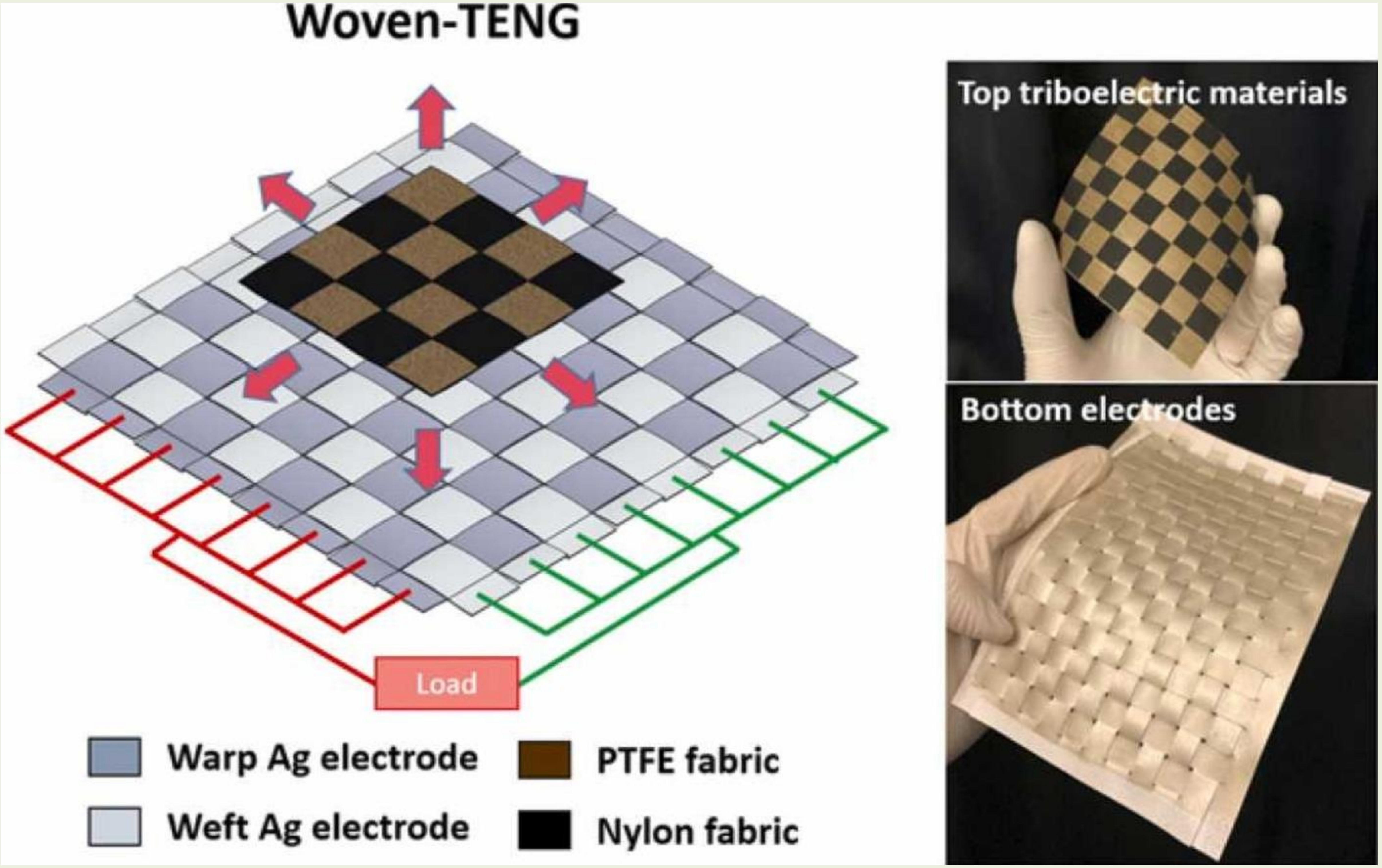
Paosangthong et al "Textile-based triboelectric nanogenerator with alternating positive and negative freestanding grating structure," Nano Energy, 66, 2019.

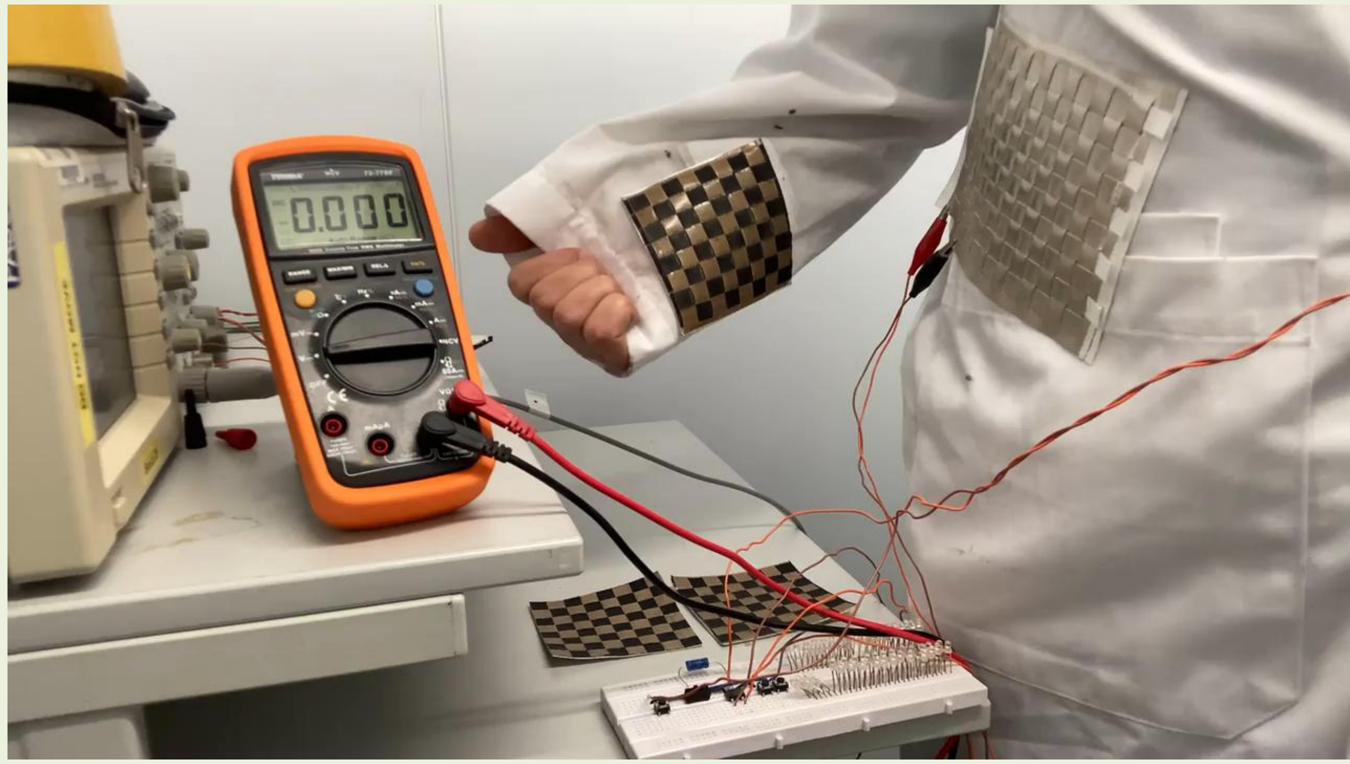
T-TENG in Action



Max charging power = 39.0 μW

Omnidirectional T-TENG





Textile TENGs: Contact separation mode Energy Harvester

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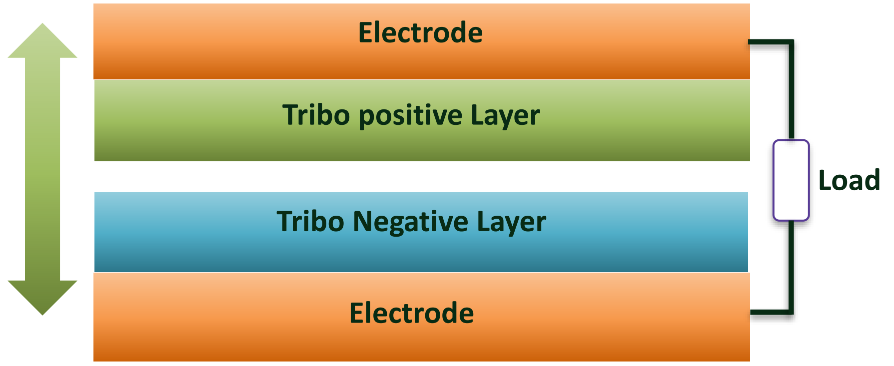
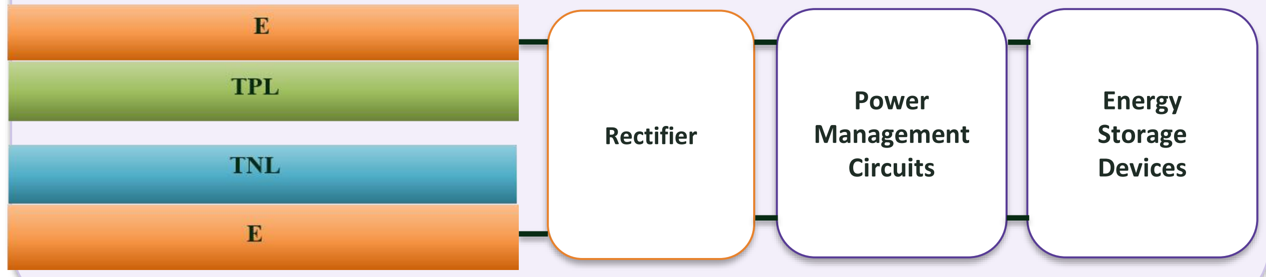
Textile TENGs Device Acrchiture



Textile TENGs System Acrchiture



Current Challenges

High internal impedance

Poor load transfer

Motion dependent output

Limited usable energy

Our Approach

Textile acrchiture optimisation

Internal impedance reduction and load matching

Inbuilt energy storage integration

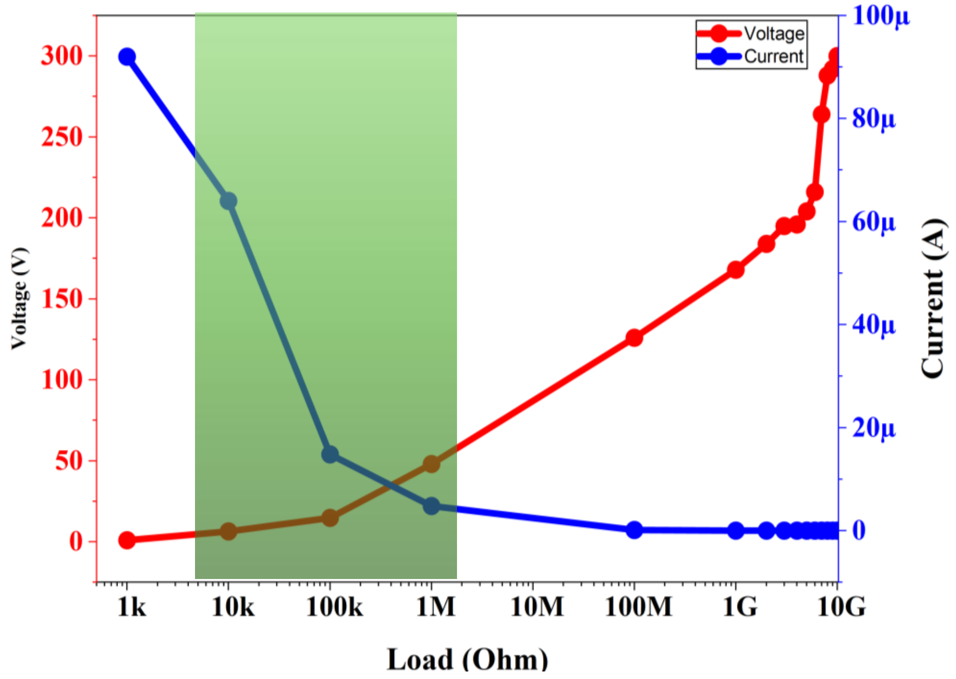
Our Approach

1. Dual-mode textile TENGs

- Contact-separation: Combining impulsive and sustained contact to generate a more continuous electrical output
- Textile-native switching architectures for impedance matching and improved energy transfer to practical loads

2. Hybrid energy management

- TENG + supercapacitor: Harvest, store and deliver energy within a single textile platform.
- Low-power power-management circuits matched to high-impedance TENGs for efficient energy transfer.



Load matching → identify maximum-power operating region

Application Pathways

➢ **Footwear / insoles**
Pressure + gait sensing + event sensing + energy harvesting

➢ **Socks**
Distributed sensing across a large, conformable textile area
Foot motion + contact/event detection

➢ **Sleeves / gloves**
Bending + stretching + gesture / interaction sensing

Wide-Range Pressure Sensing with Textile TENGs

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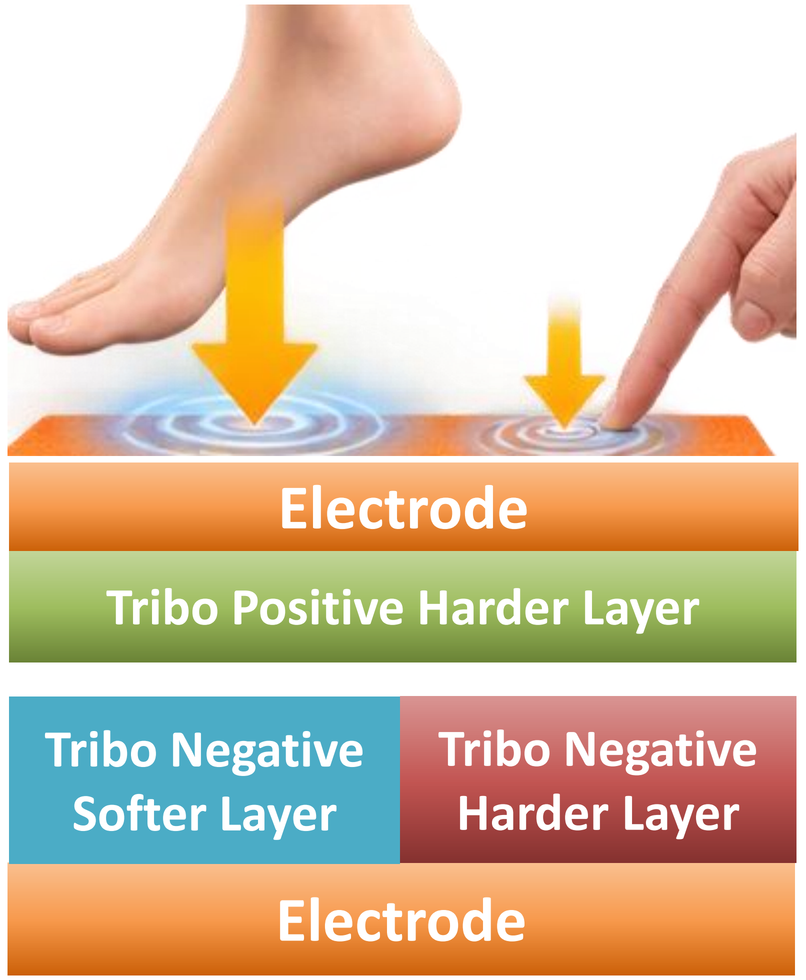
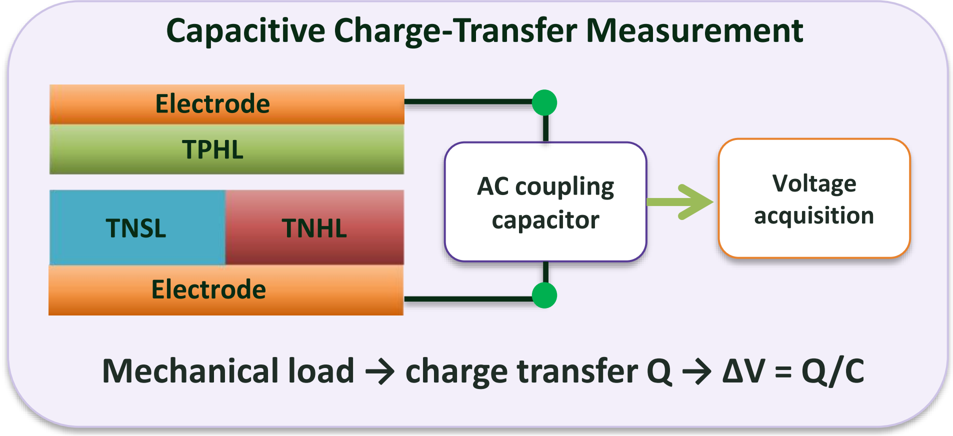
Can **mechanically heterogeneous triboelectric interfaces** extend the **usable pressure range of a textile TENG** by providing different deformation and contact regimes under low and high mechanical loads?

Textile TENGs Pressure Sensor Acrchiture



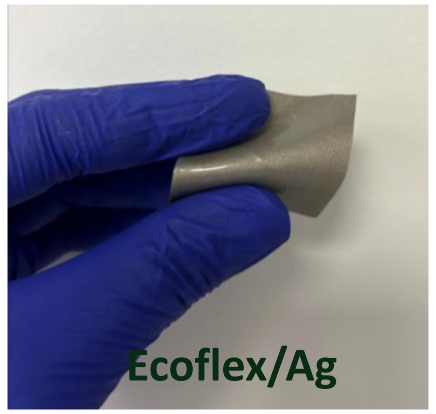


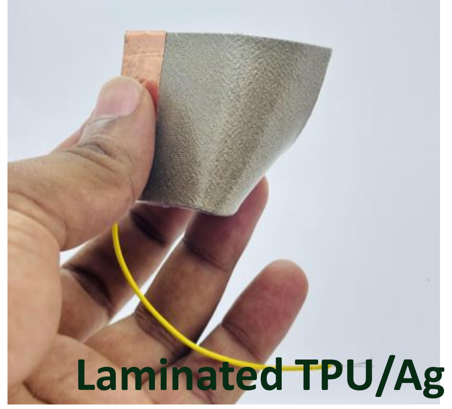
Current Challenges

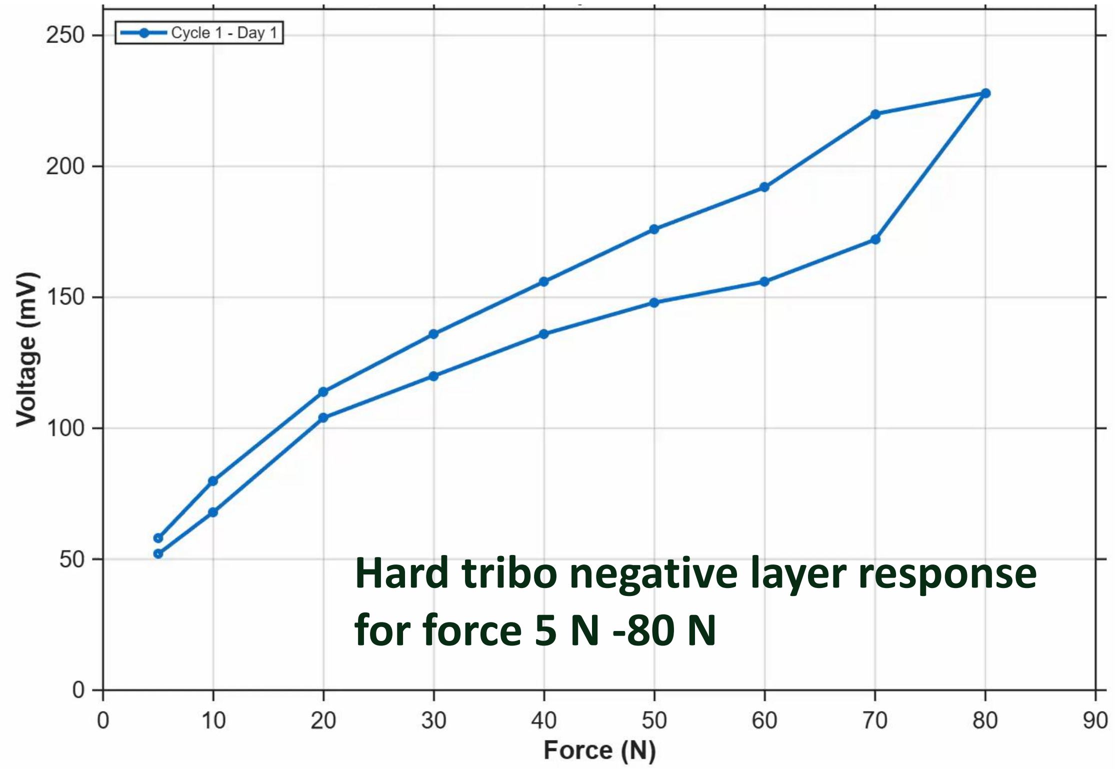
- T-TENG response depends on **pressure, deformation, frequency, loading rate and environment.**
- **Voc / Isc** alone do not quantify charge transfer or energy delivered to a load.
- Single mechanical architectures can exhibit limited usable pressure range.
- Need a defined electrical measurement pathway for reproducible, application-relevant sensing.

Our Approach

Soft tribo negative layer: compliant deformation for low-pressure sensitivity.
Hard tribo negative layer: progressive engagement for the higher-pressure regime.
Combined architecture: extends the usable sensing range by activating different mechanical regimes under increasing load.







Applications Pathways

Smart footwear / insoles
Foot-pressure mapping, Gait & activity monitoring, Step/event detection and Human–machine interaction

Wearable pressure interfaces
Touch/contact detection, Grip/force monitoring
Assistive & rehabilitation interfaces

Textile TENGs for Acoustic Sensing and Speech-Vibration Reconstruction

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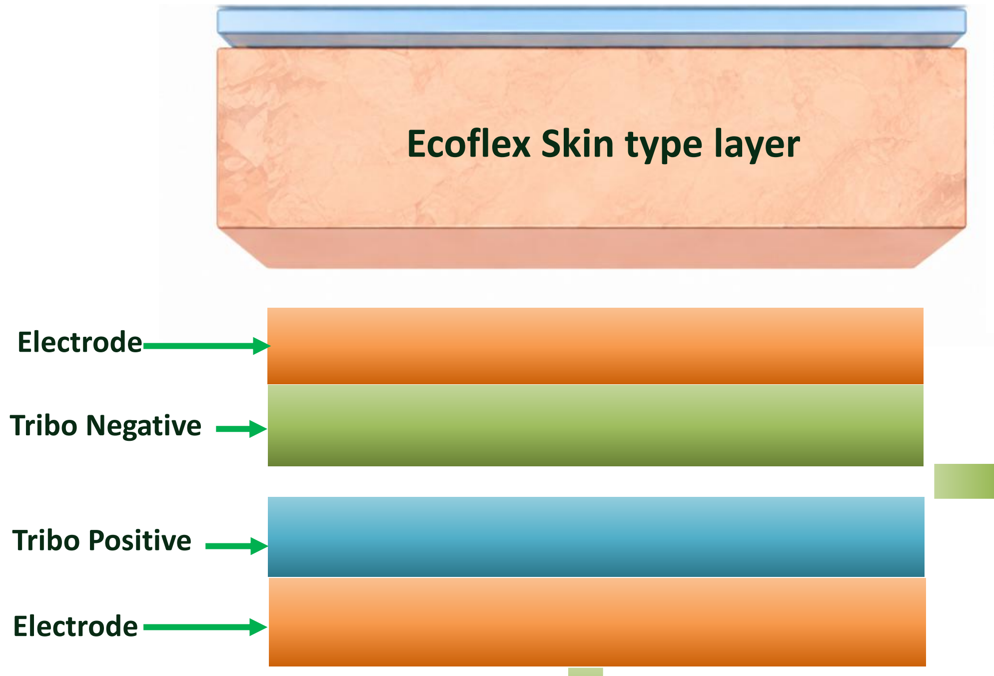
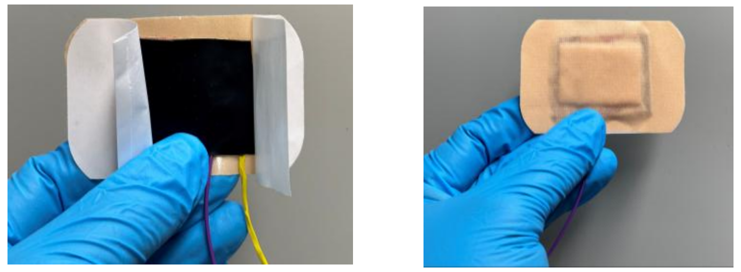
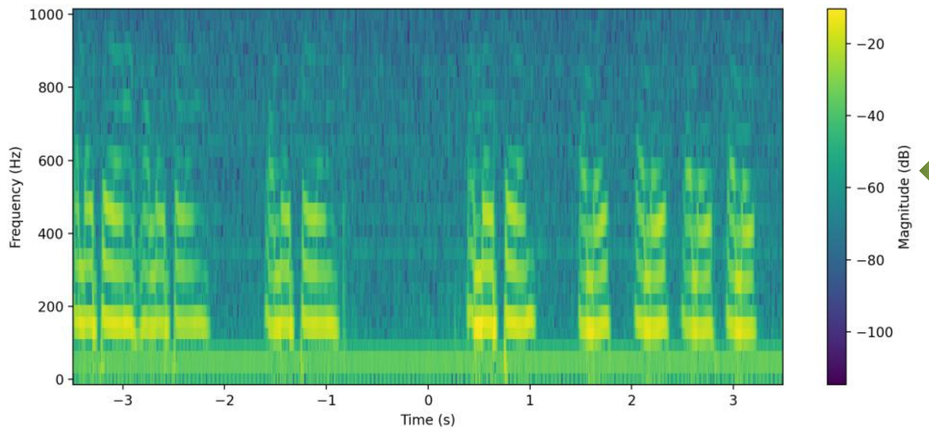
Acoustic Source (Speaker)



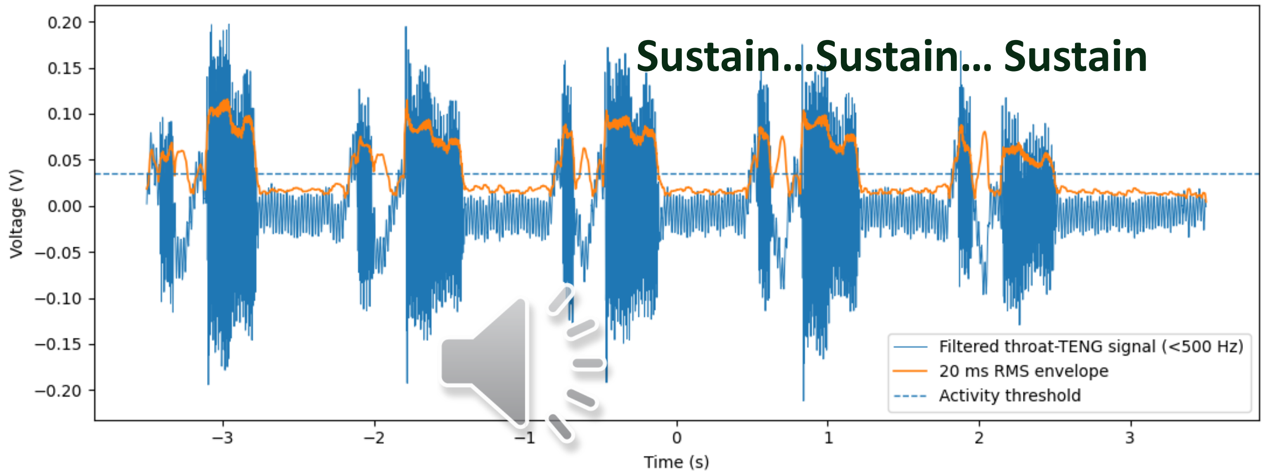


Our Approach: Wireless Self-Powered Neck Acoustic Interface

Textile TENG neck bandage → wireless RF/inductive signal transfer → external low-power electronics for speech and assistive sensing



4 Audio Reconstruction (Waveform Recovery)



3 Signal Processing (Feature Extraction)

FFT/PSD/ Spectrogram/SNR/ THD

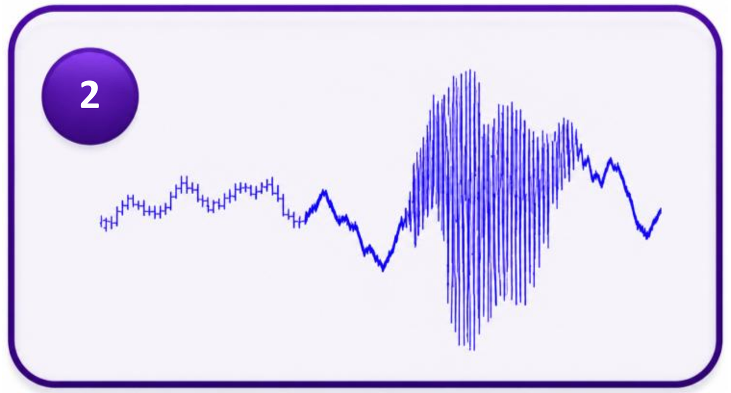
Applications Pathways

1. **Assistive communication for speech impairment**
Throat vibration sensing → speech intent → digital / visual / haptic communication

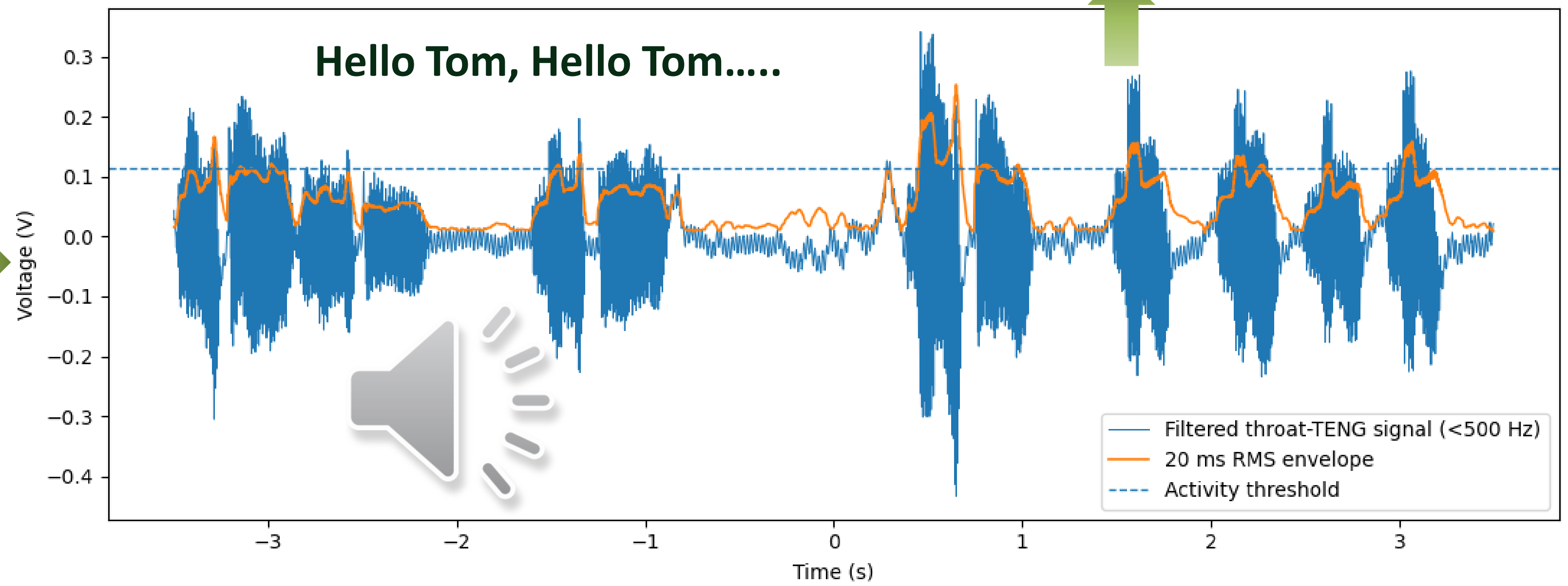
2. **Silent / low-audibility speech interfaces**
Throat vibration → speech features → commands / communication.

3. **Wearable physiological monitoring**
Body vibration → physiological events → continuous monitoring
Detect swallowing, coughing, muscle movement breathing-related and vocal activity

Electrical Signal (AC Voltage)



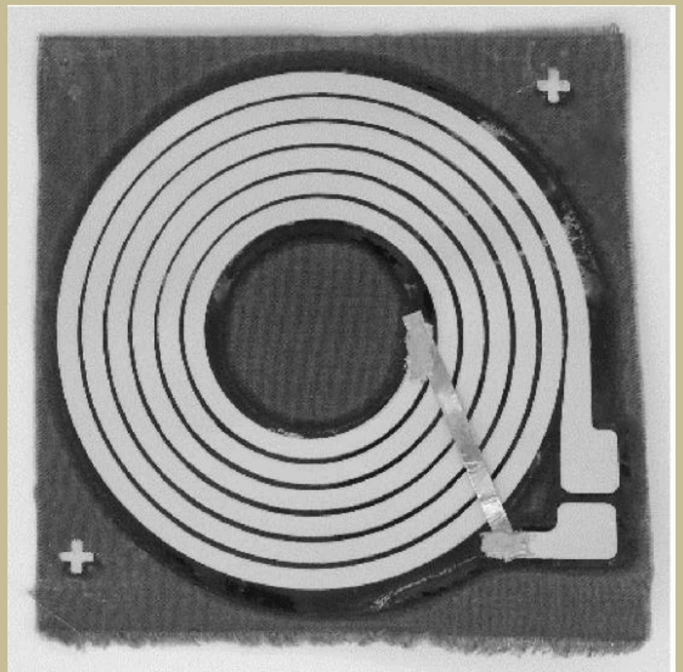
Signal Acquisition (Raw Signal Capture)



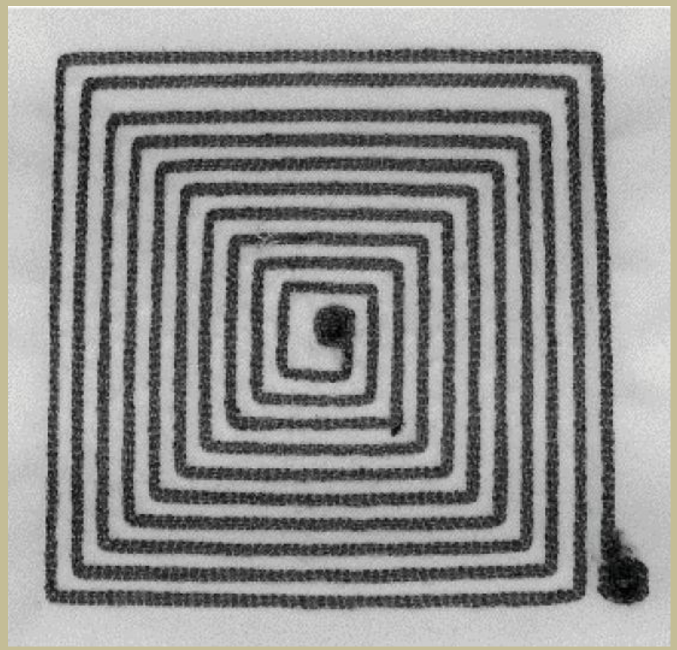
Supplying power *wirelessly*

Wireless power transfer: Resonant inductive

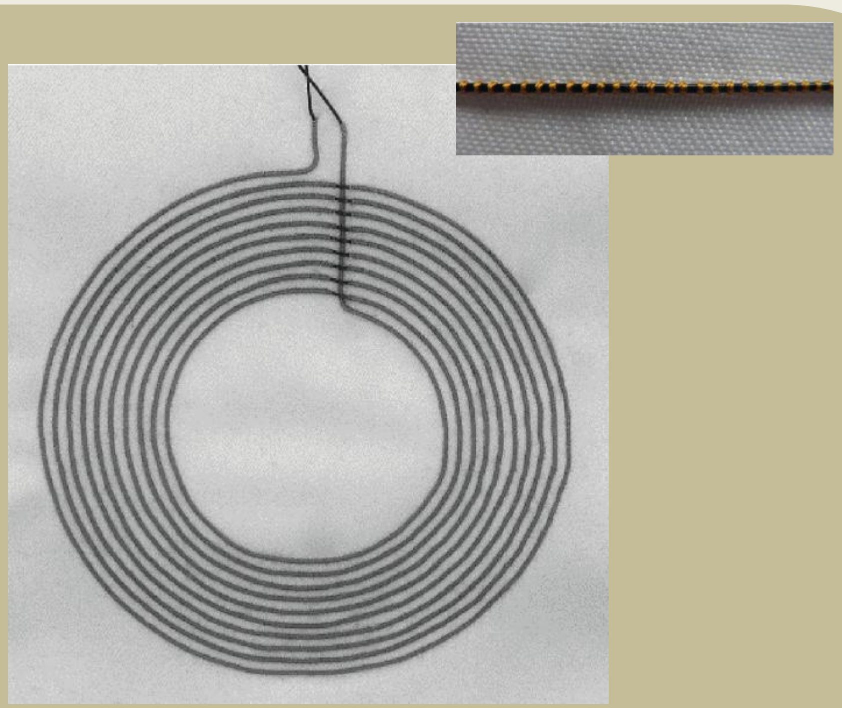
Coils tuned to exhibit matched resonant frequencies to efficiently transfer energy. Fabricating coils on textiles compromise coil properties (e.g. flexible, low temp. processing, rough surface). A variety of coil fabrication methods have been investigated and coil properties measured.



Screen printed silver: Low resistance, low inductance, low Q factor, expensive to fabricate, stiff fabric.

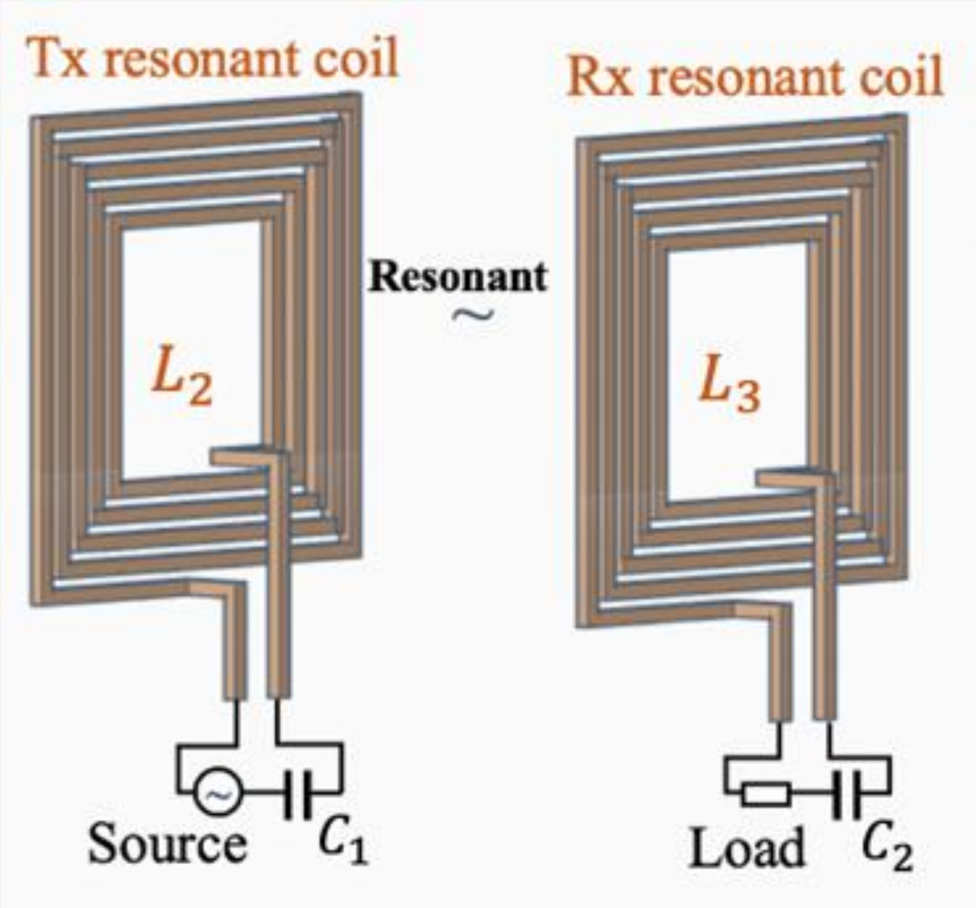


Embroidered conductive thread: High resistance, low inductance, very low Q factor, expensive thread, flexible fabric but 'lumpy'.

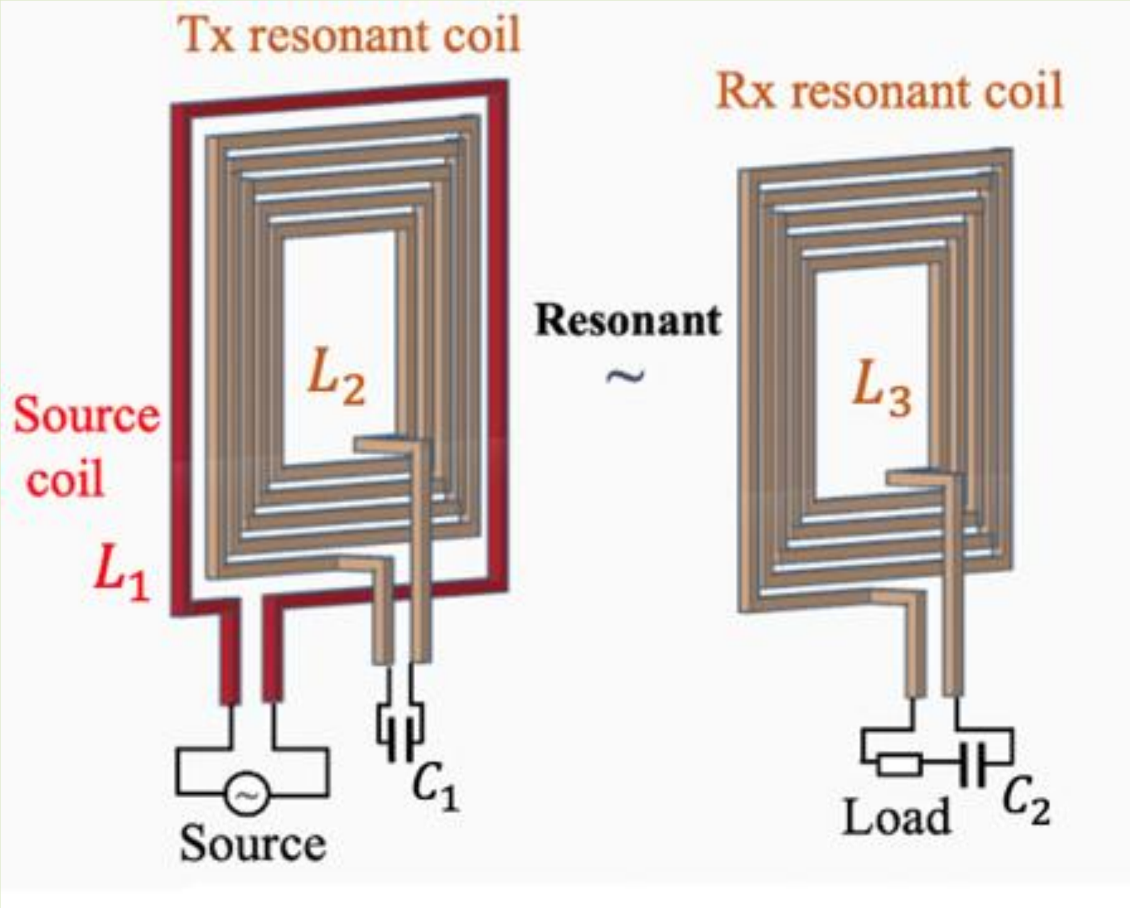


Couched copper Litz wire: High inductance, low resistance, high Q factor, low-cost automated manufacture, flexible fabric and minimum impact on fabric properties.

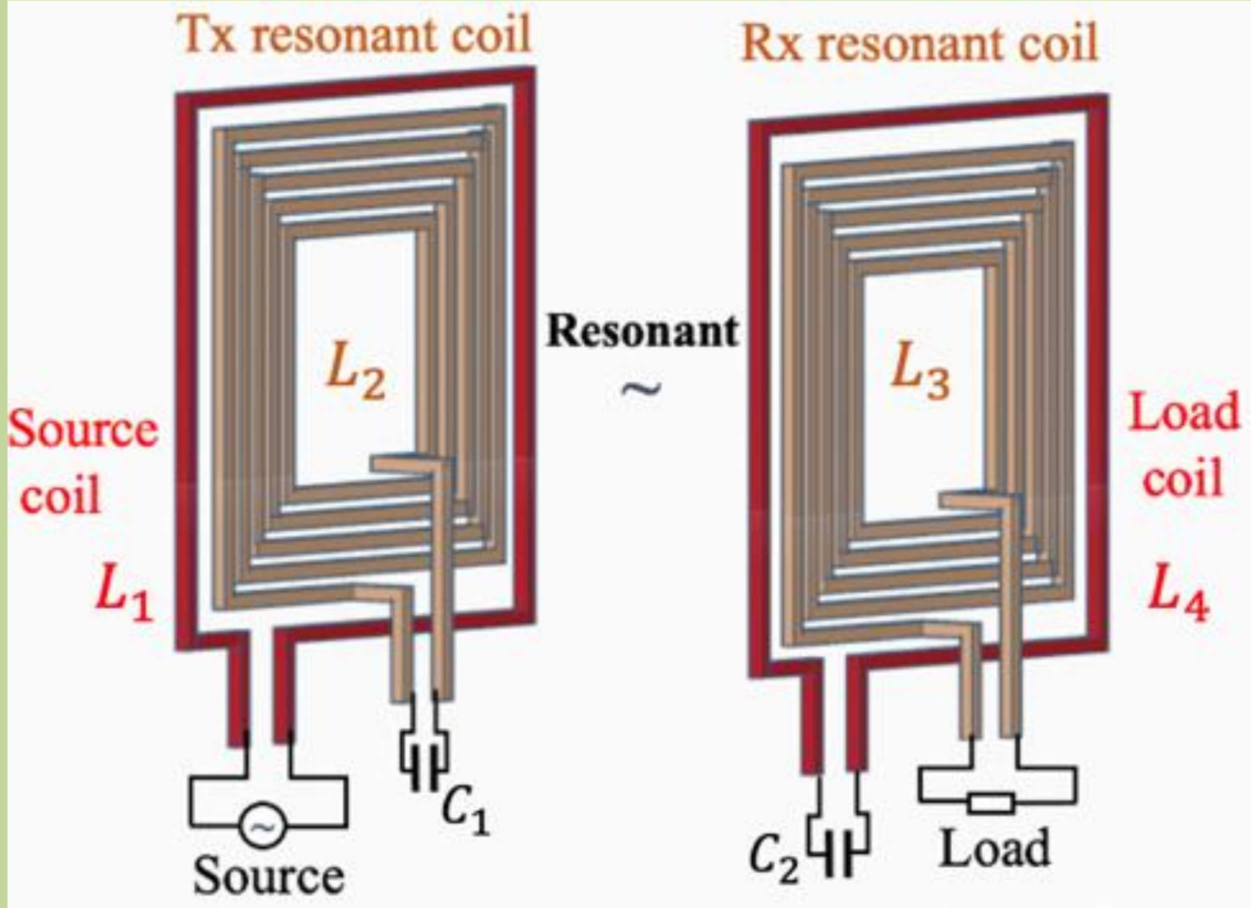
2, 3 and 4 coil systems



2-coil system

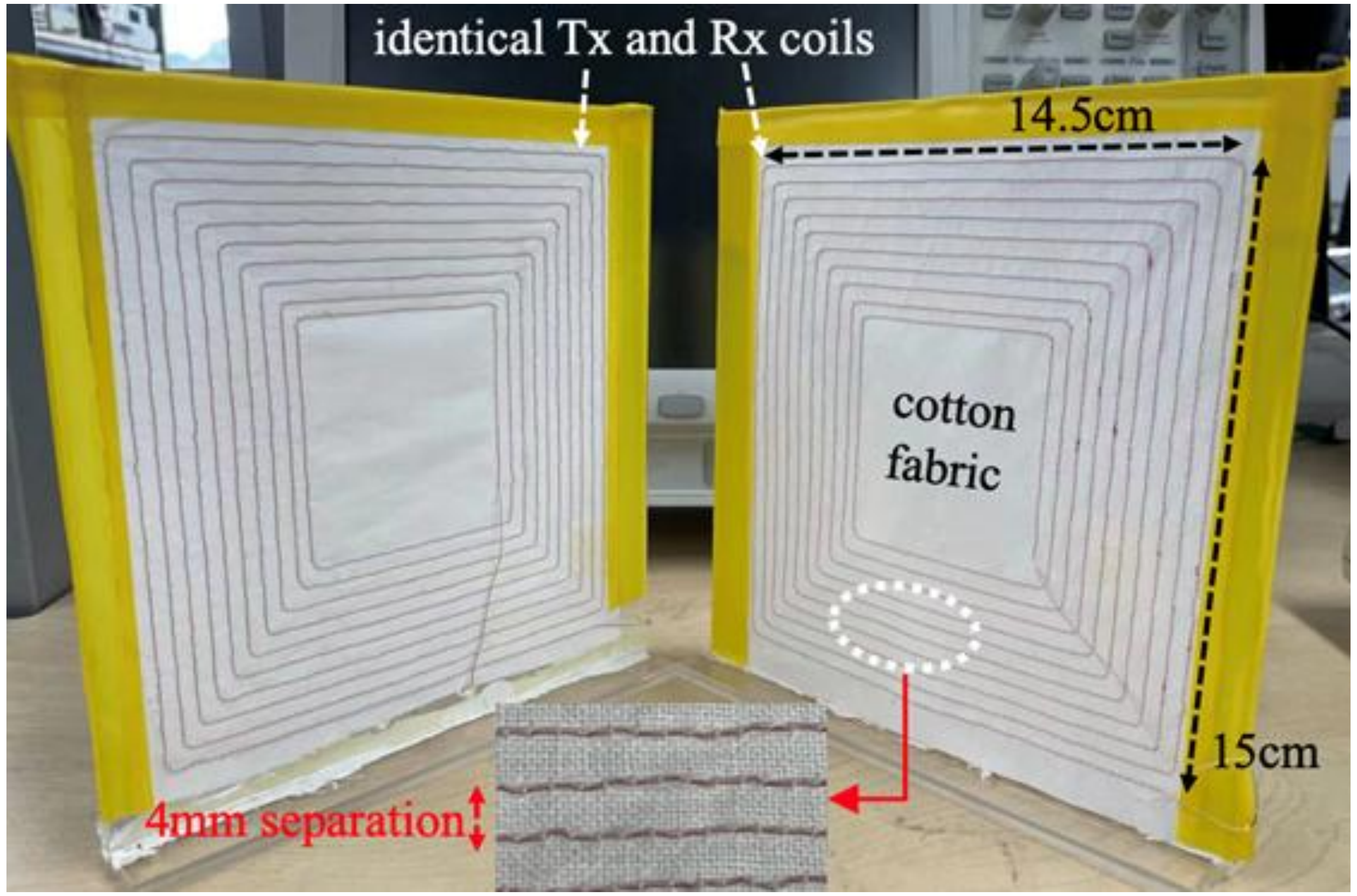


3-coil system

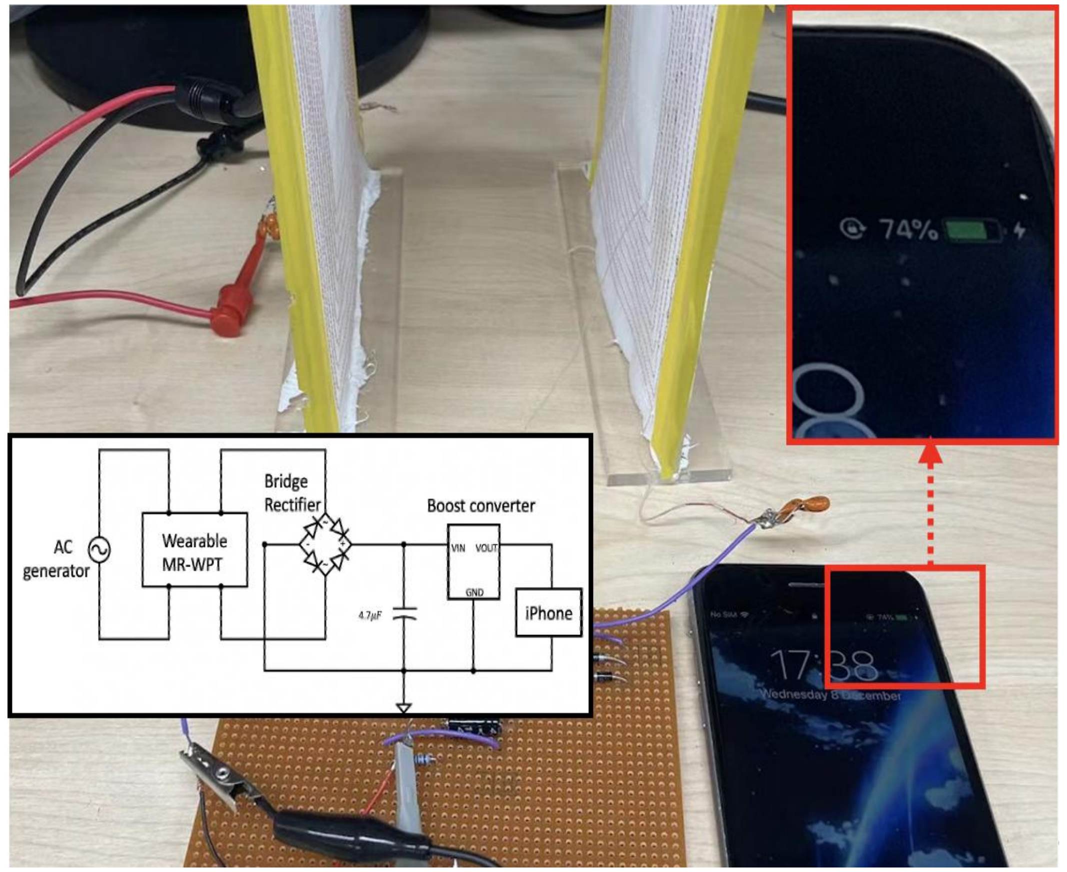


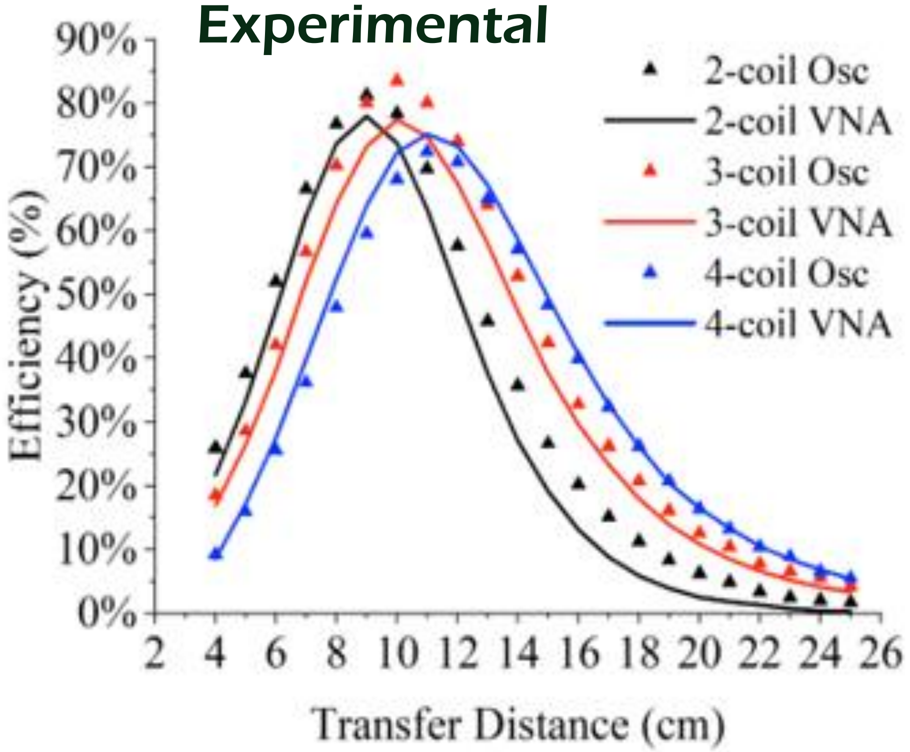
4-coil system

Textile coil system results

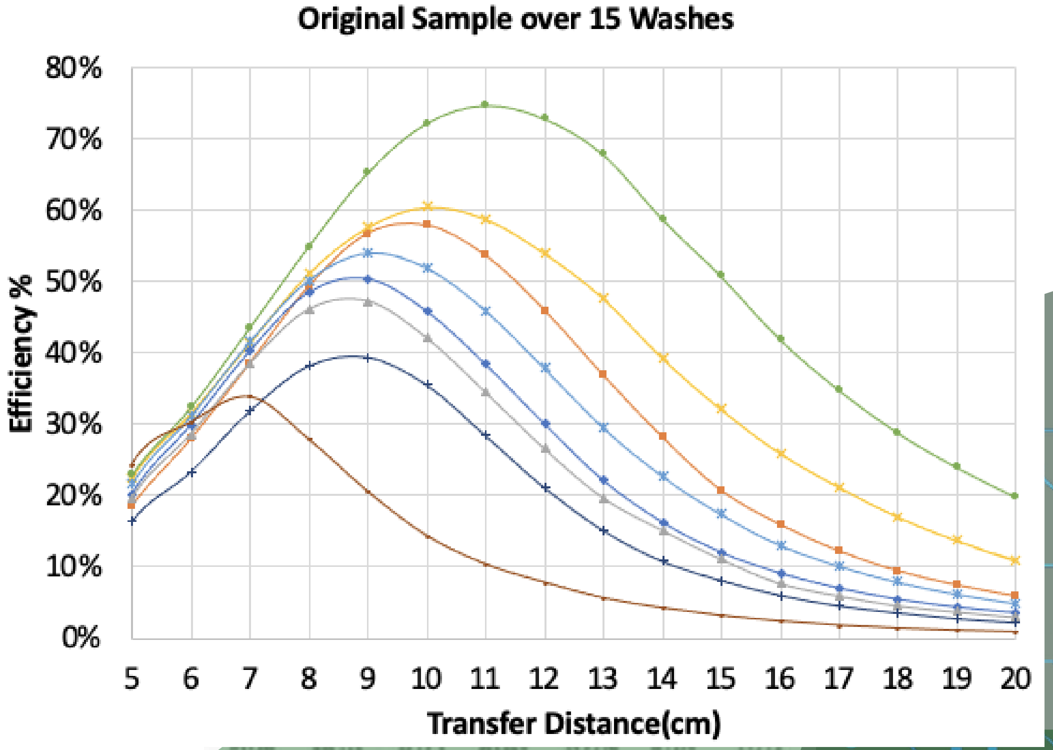


Fabricated coils tuned to 6.78 MHz





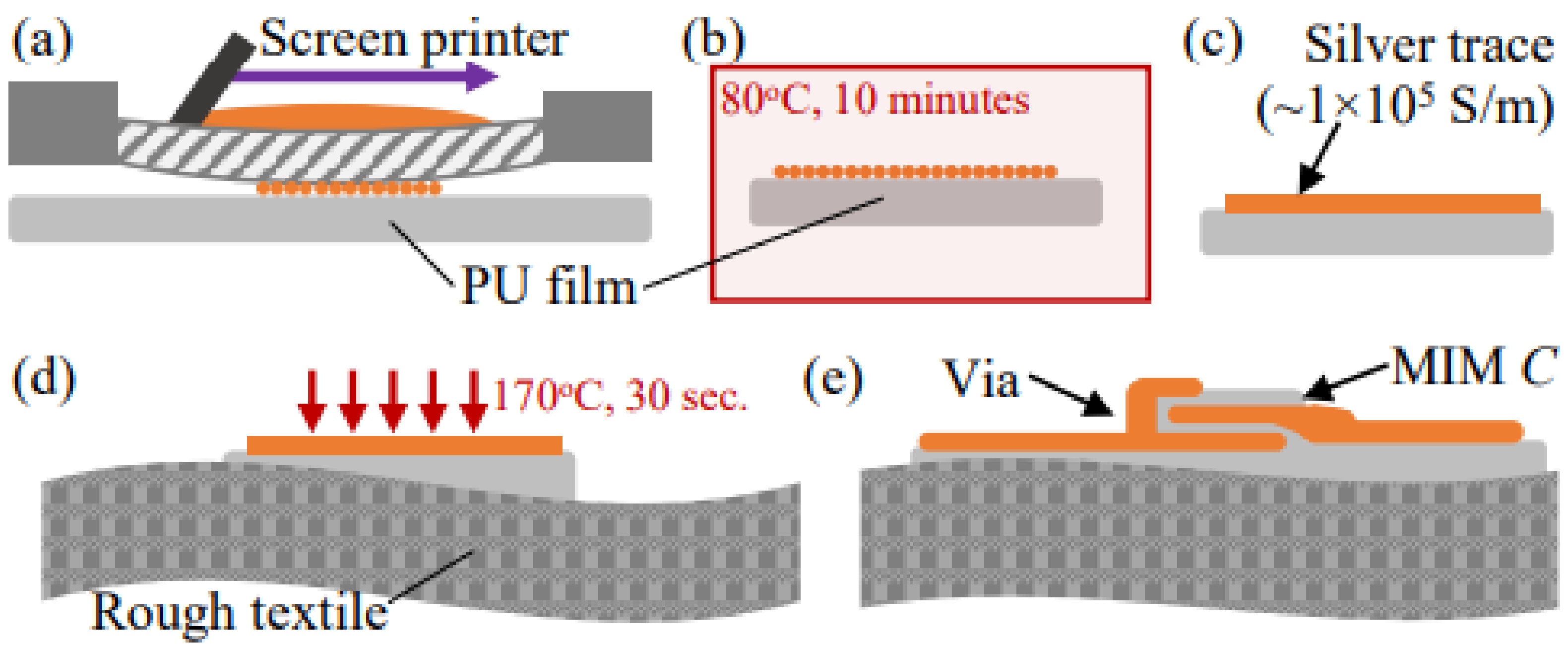
Wash testing



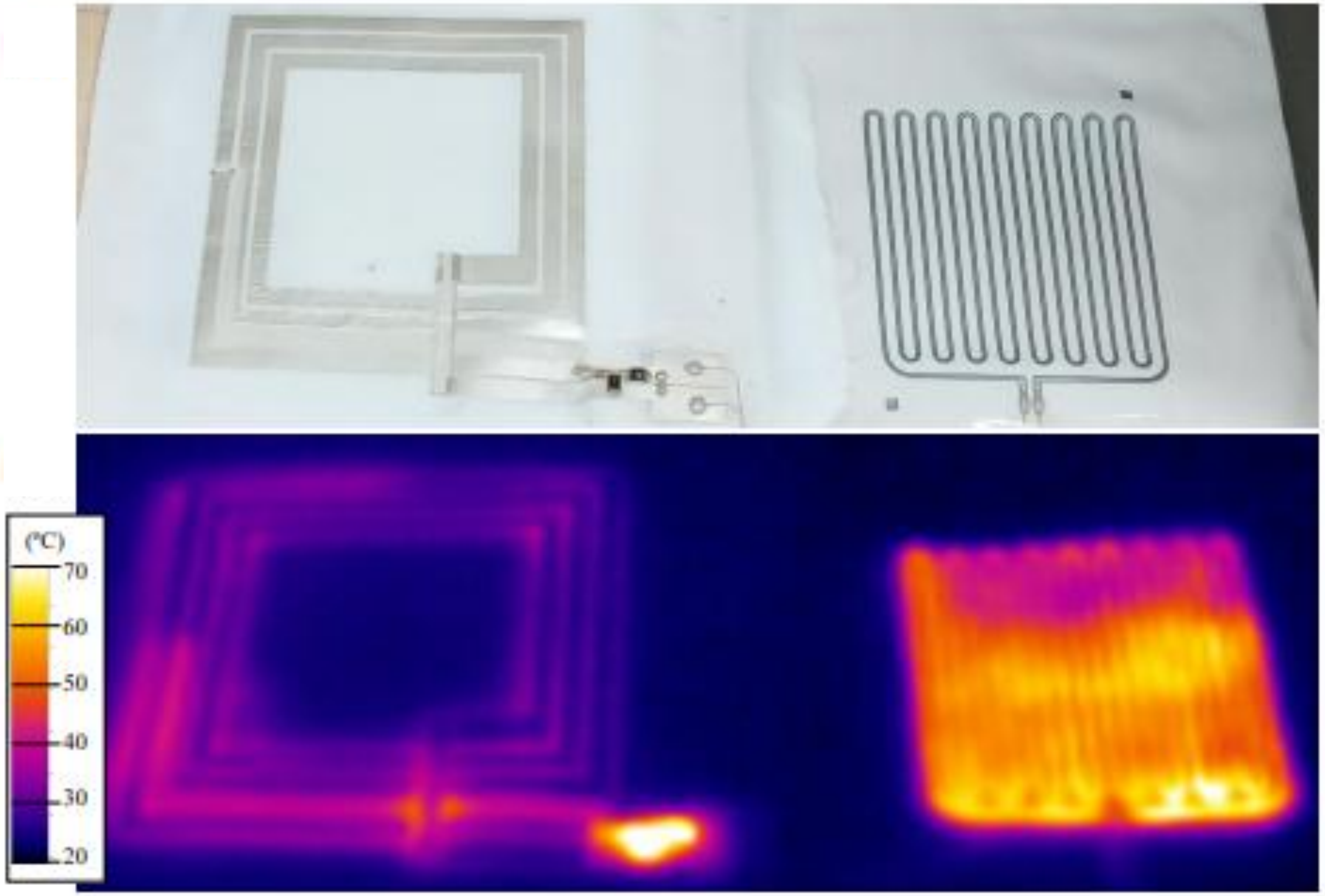
Efficiency vs. transfer distance

Inductive WPT – Joule heater application

Fabrication process – screen print onto a smooth 75 µm thick polyurethane (PU) film, heat-pressed onto the fabric. Metal-insulator-metal (MIM) tuning capacitors integrated within the coil.



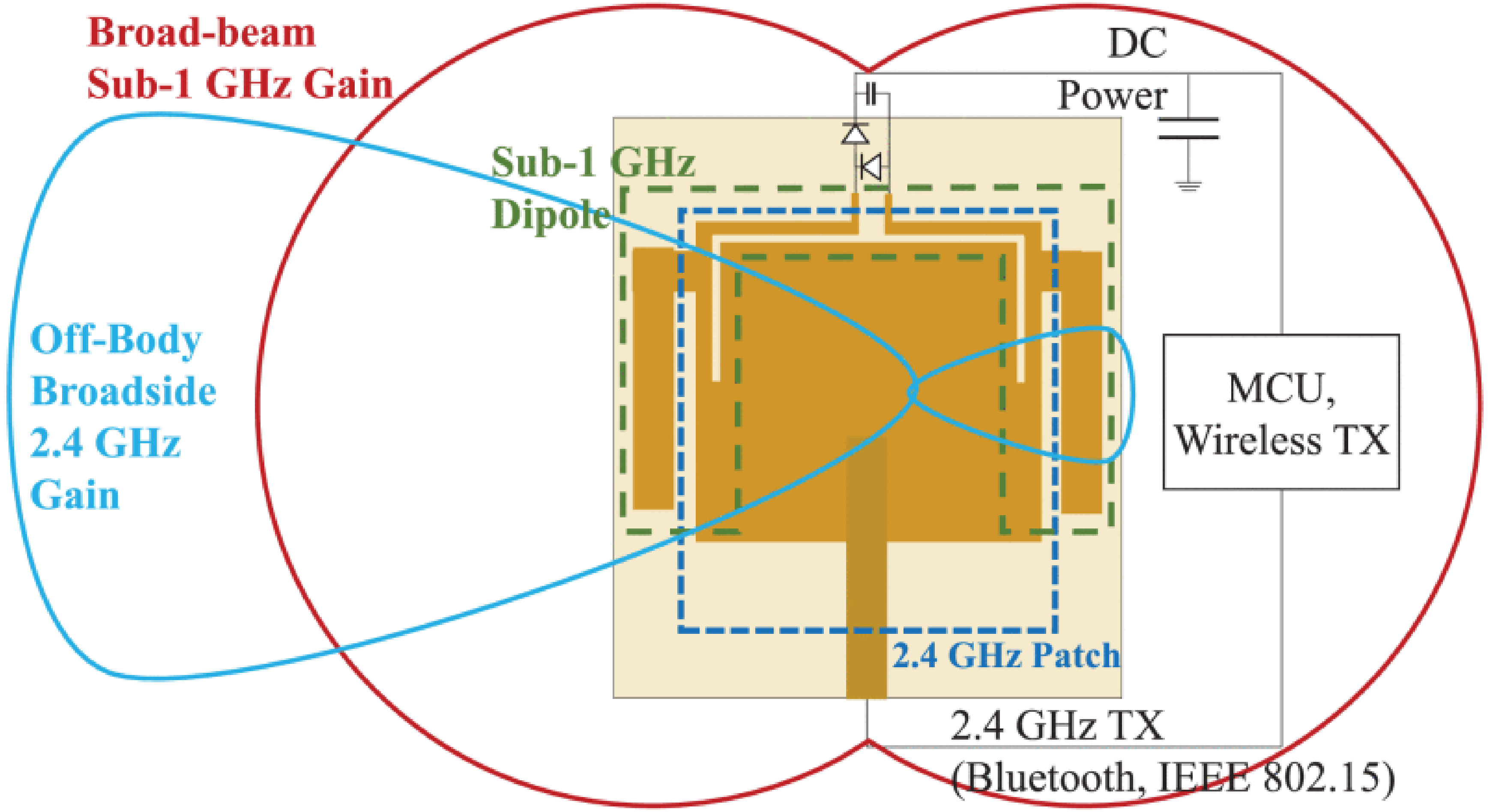
1–15 W DC power with >50% DC-DC efficiency:
Heater designed to approach the optimum current draw of the rectifier to maximise RF-DC conversion efficiency.



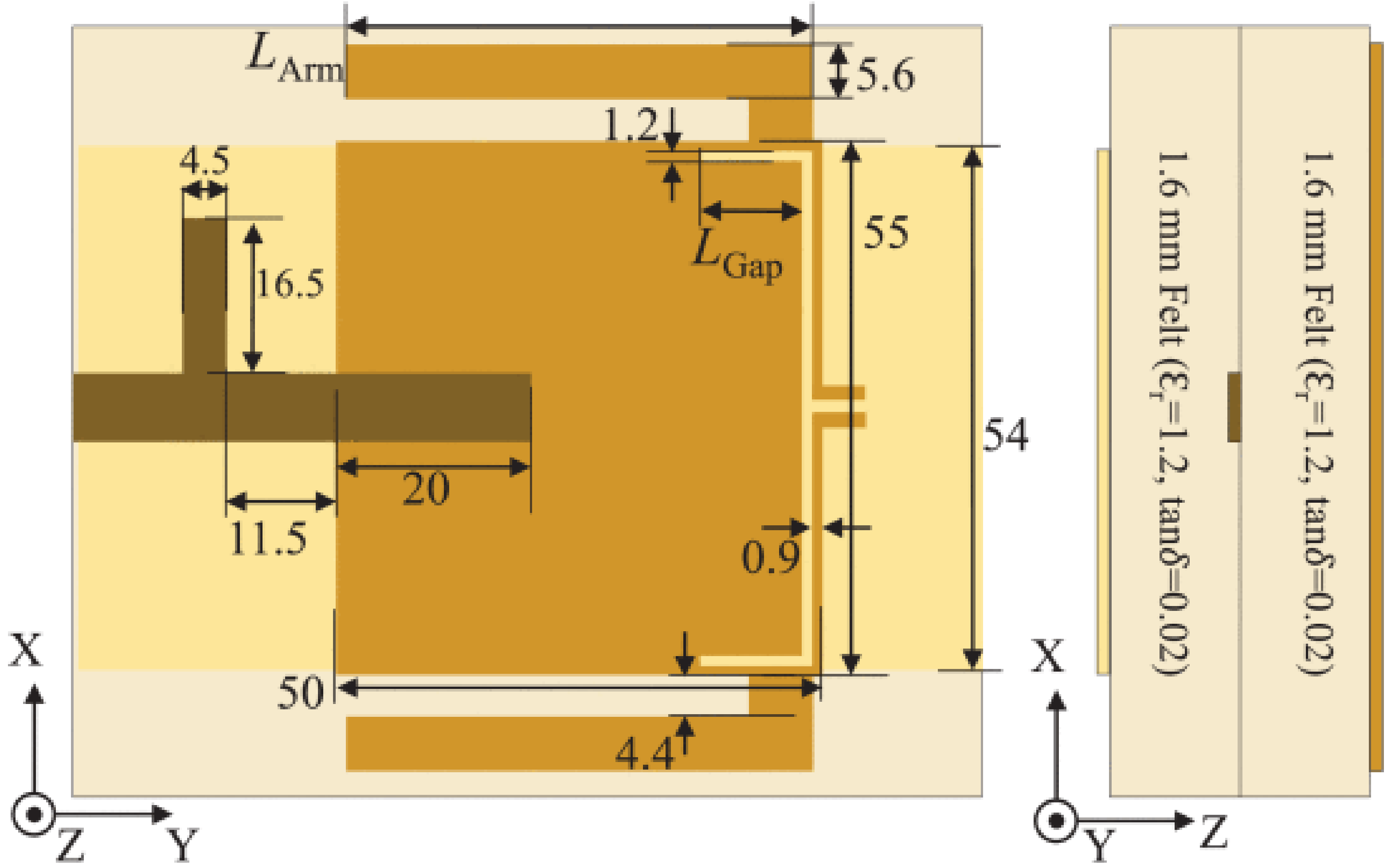
Constant 60°C heater temperature.

Dual-band/dual-mode textile antenna

..... for wearable Simultaneous Wireless Information and Power Transfer (SWIPT)



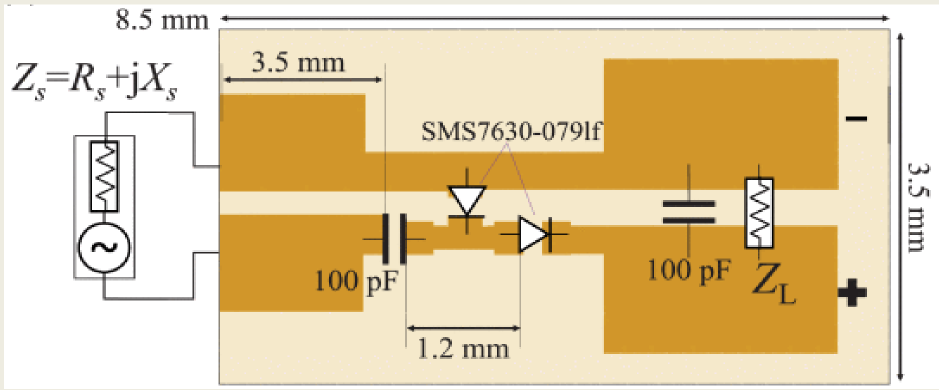
Sub-1 GHz WPT and 2.4 GHz communications, with omnidirectional and broadside and radiation patterns. Mutual coupling needs to be minimized.

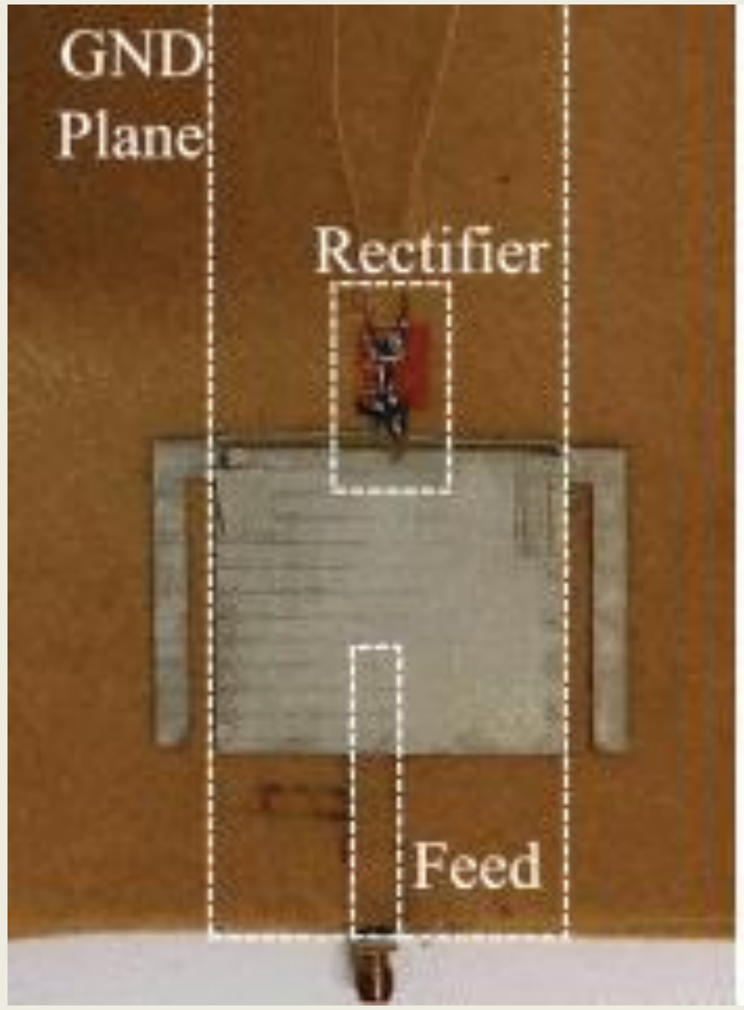


3 layer (2 textiles) structure with proximity-coupled microstrip feed and minimised ground plane. Dipole dimensions designed to match rectifier impedance.

SWIPT antenna fabrication

The antenna was fabricated using adhesive-backed conductive fabric. Sheet resistance was <50 mΩ /square, and does not change after hand-washing and drying and it is **breathable**. However, copper on Kapton required for voltage double rectifier



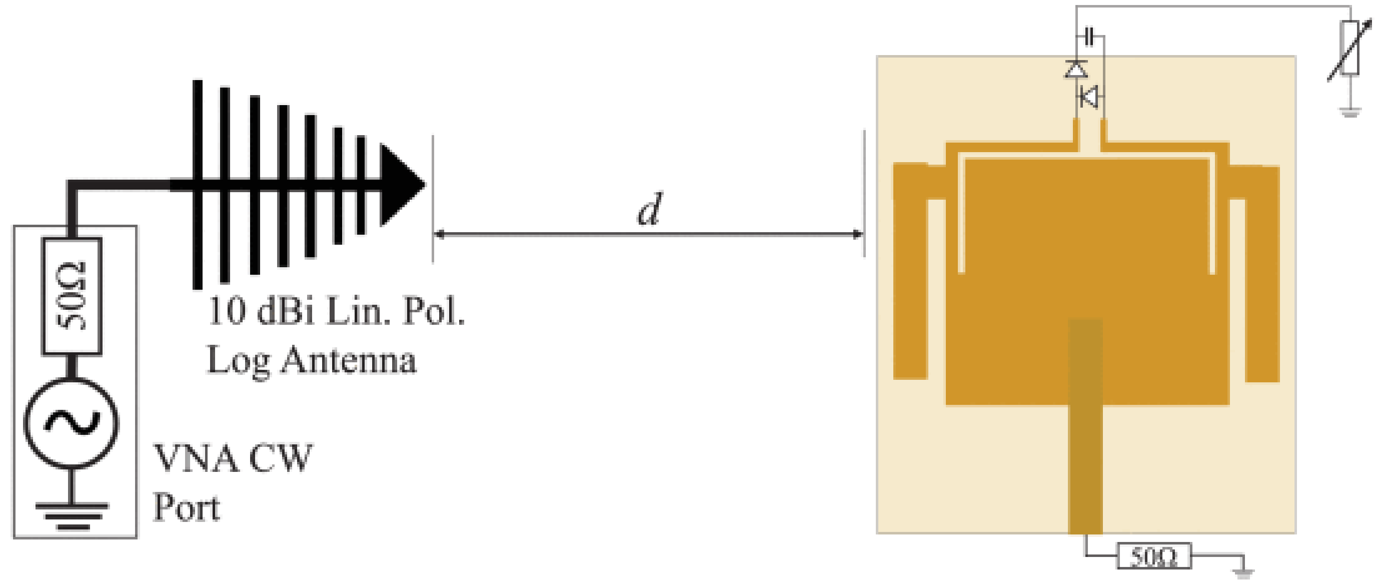


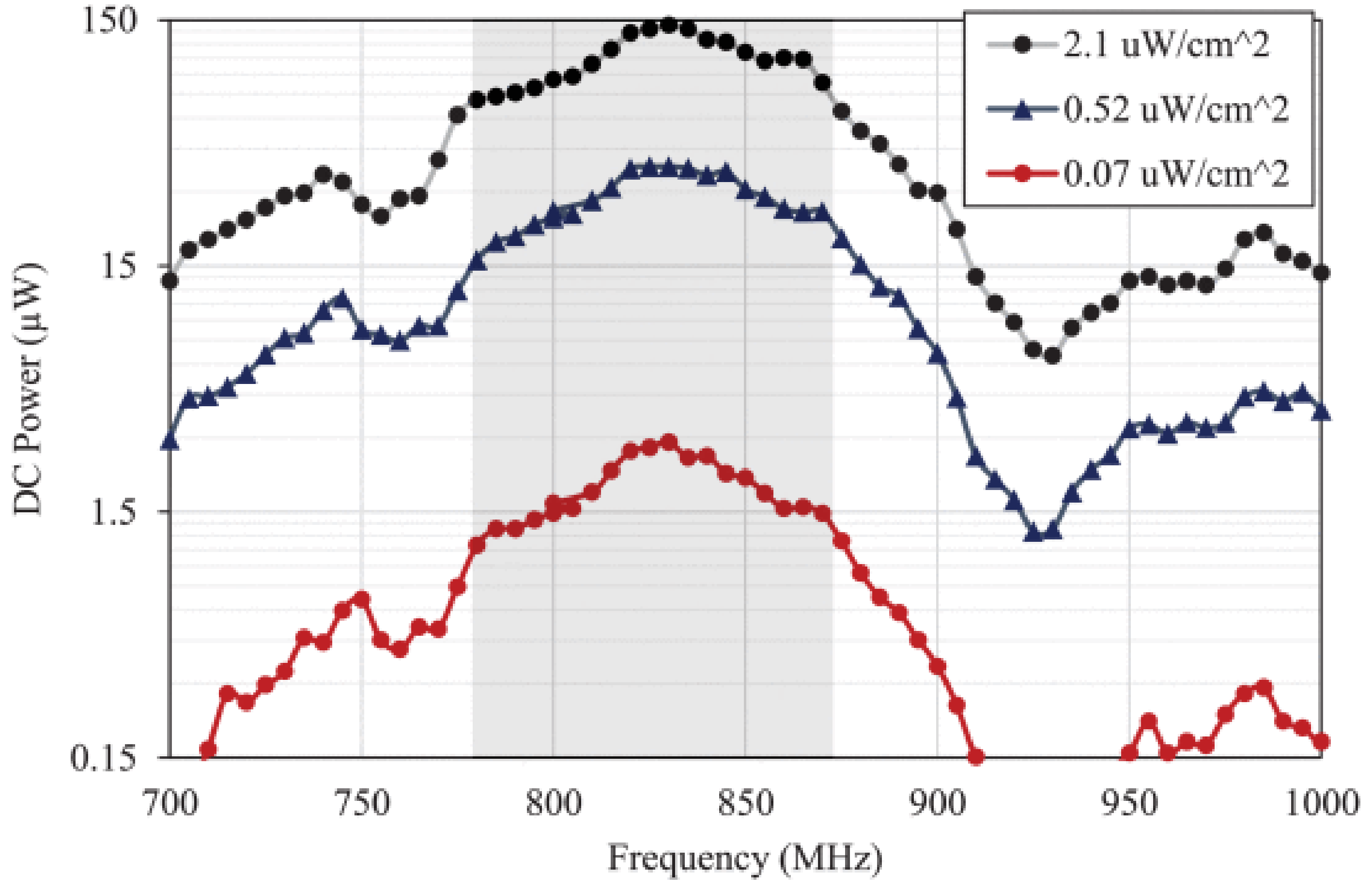
Felt fabric

Antenna

Rectifier

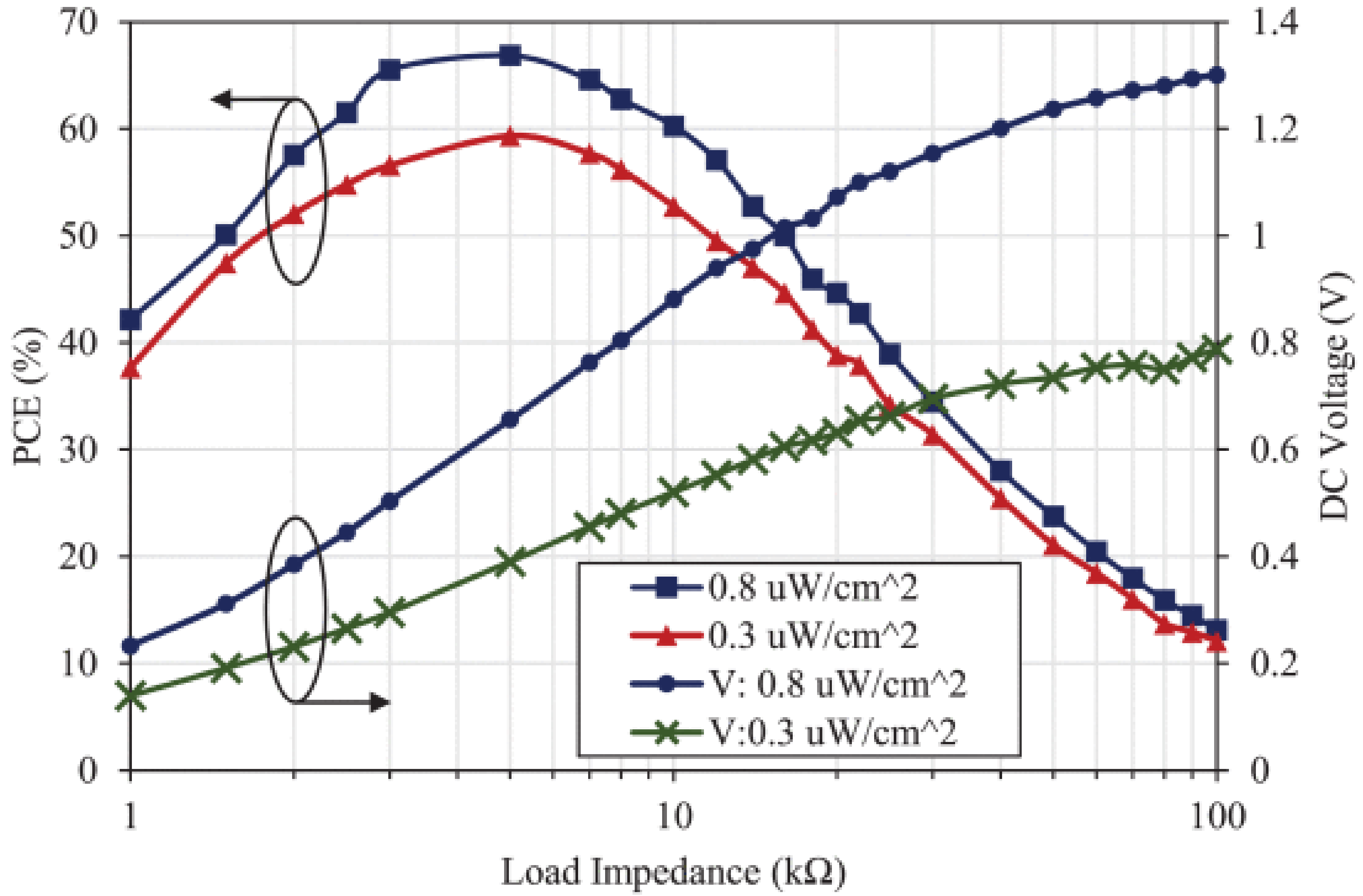
SWIPT antenna perfromance





Measured dc power harvested by the rectenna at varying frequencies for a 20 kΩ load.

Operating bandwidth 785–875 MHz

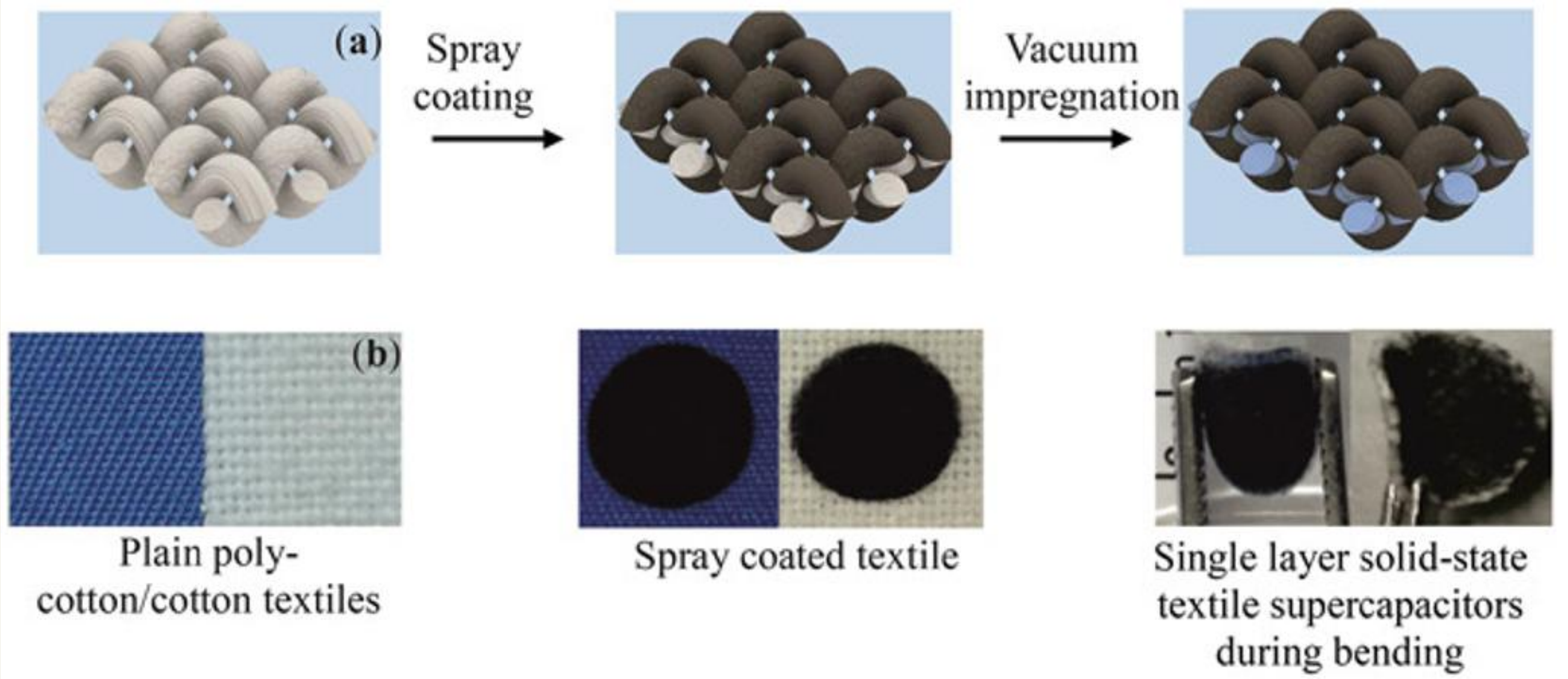


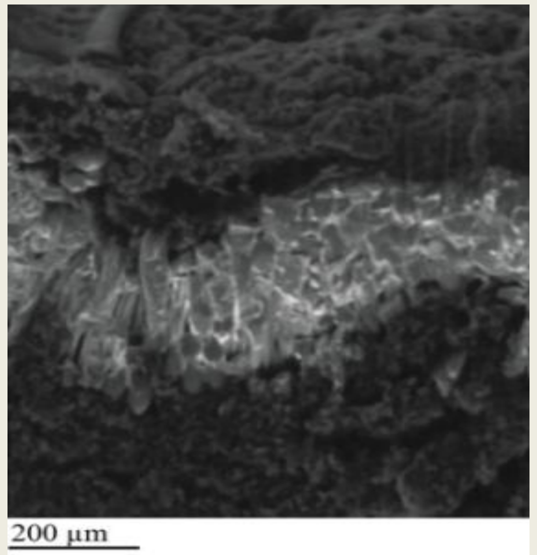
Efficiency and DC voltage vs load. Optimum load (5 kΩ) invariant with incident power.

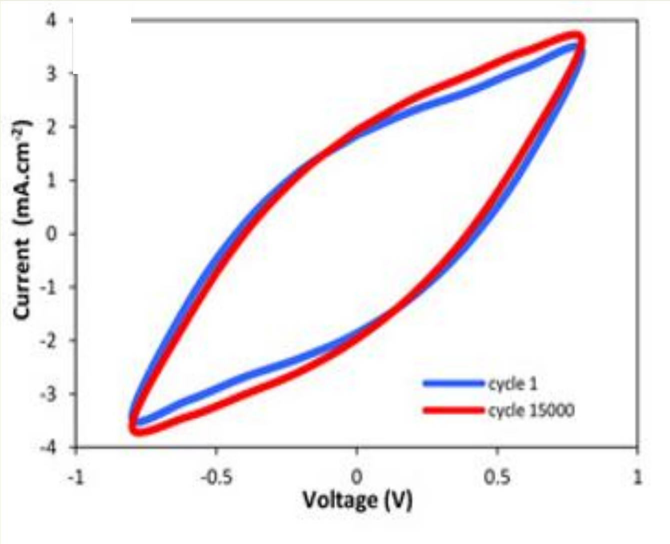
The rectenna achieves a **best-in-class RF to dc efficiency of 62% from 0.8 µW/cm²**. This antenna is the first dual-band, dual-mode antenna demonstrated on textiles for SWIPT applications.

Energy Storage

Textile supercapacitor

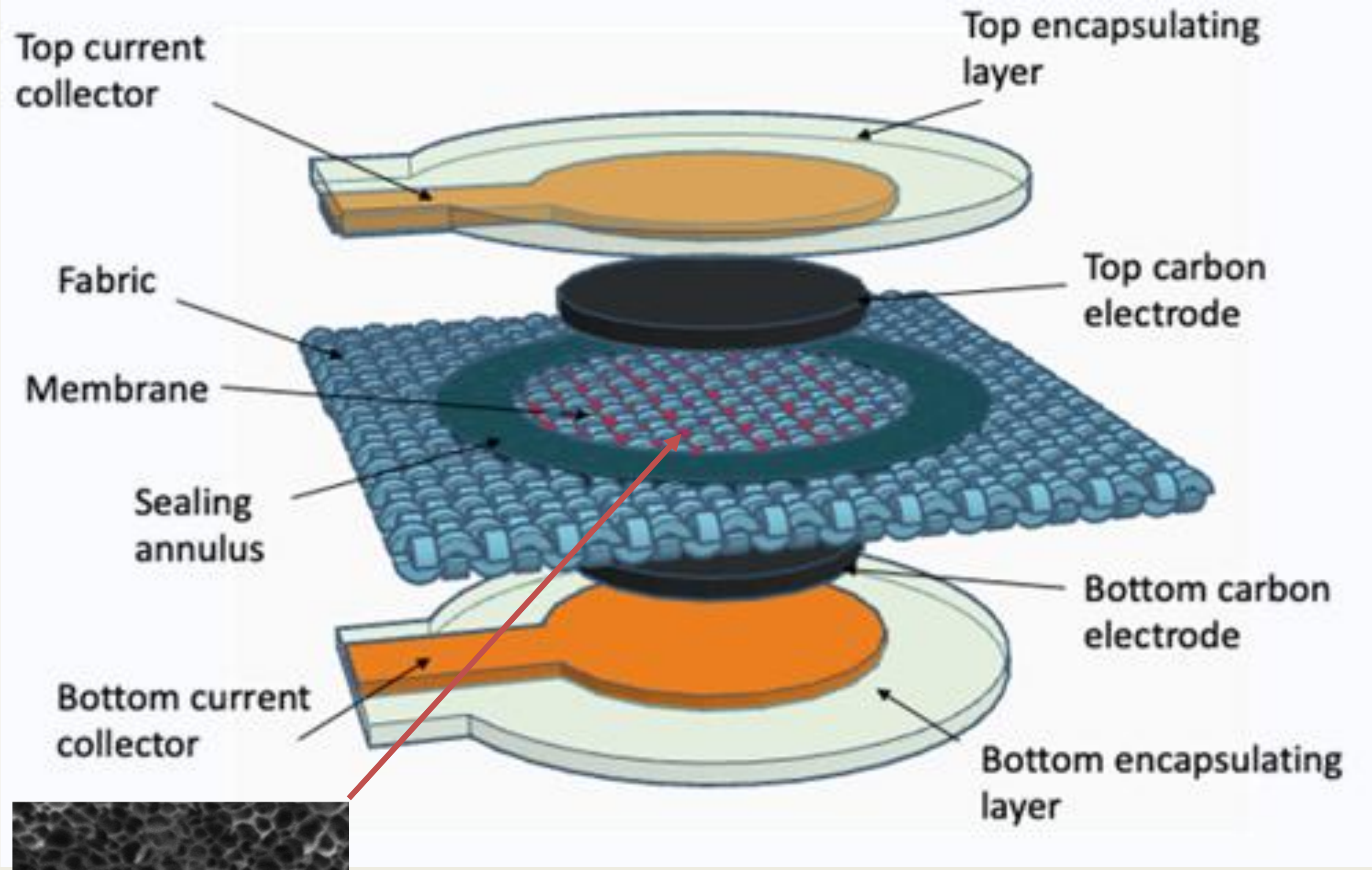


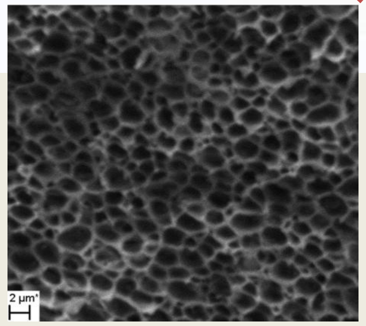




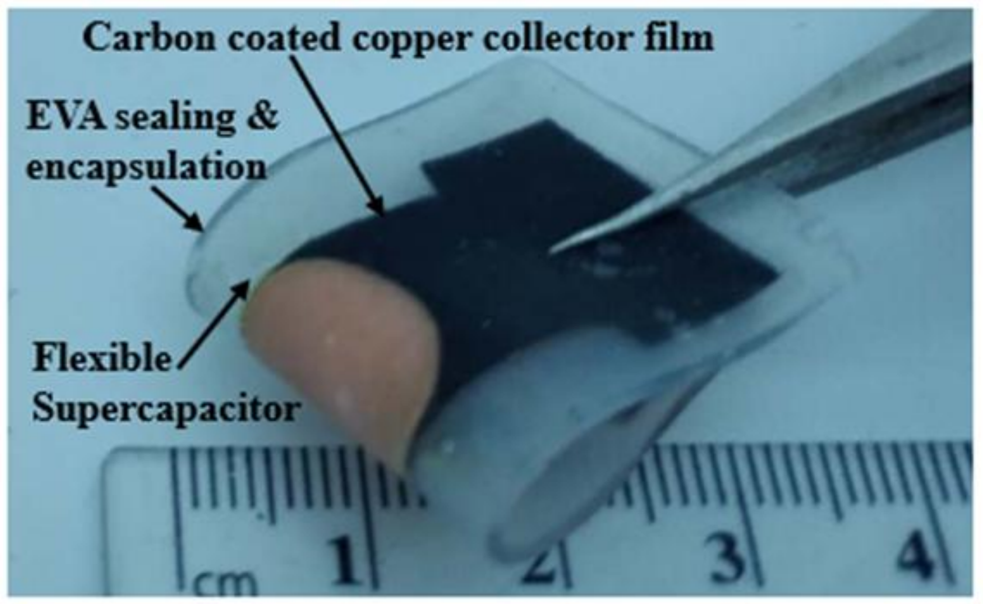
+ Demonstrated good performance from low-cost materials.
- Not a standalone device and fabrication method not suitable for all textiles.

Porous polymer membrane



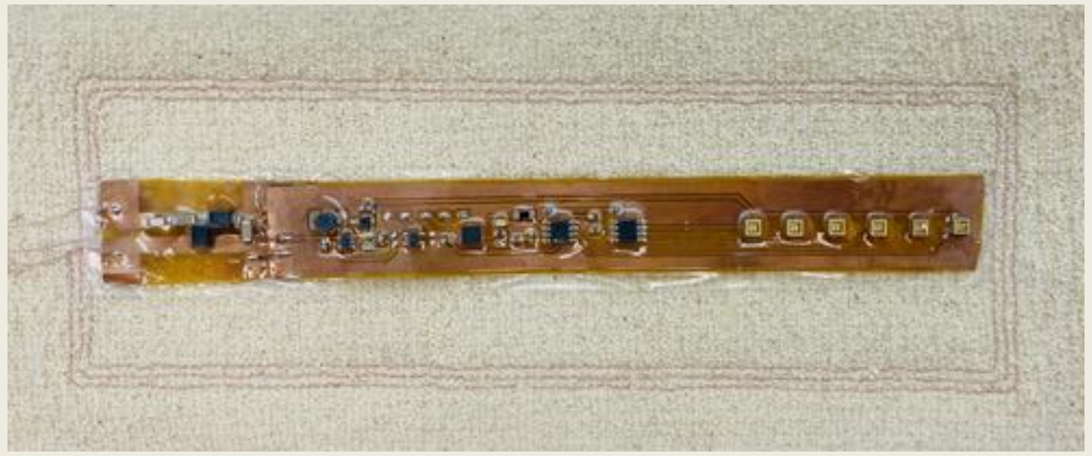


The membrane acts as a robust, electrically insulating separator suitable for all textiles.



E-textile applications

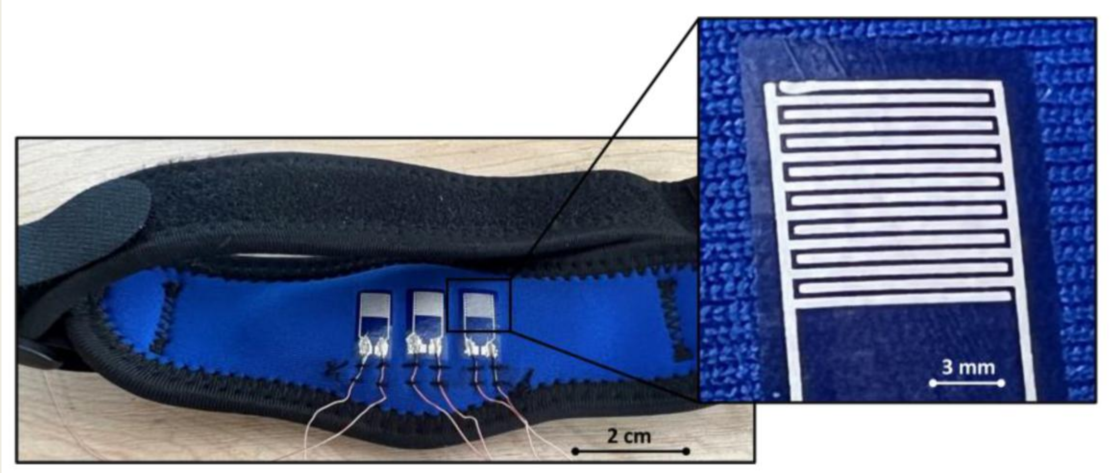
Smart wound healing bandage

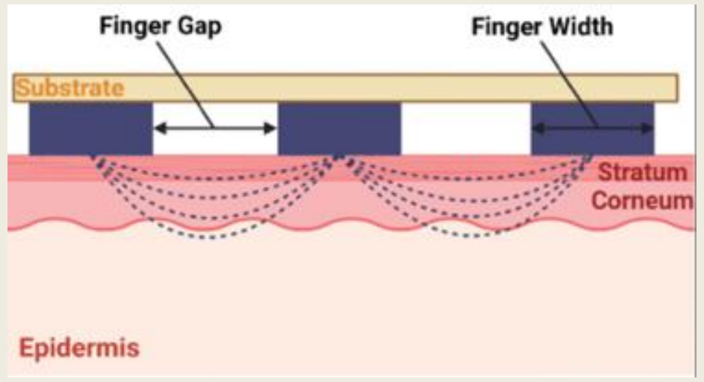


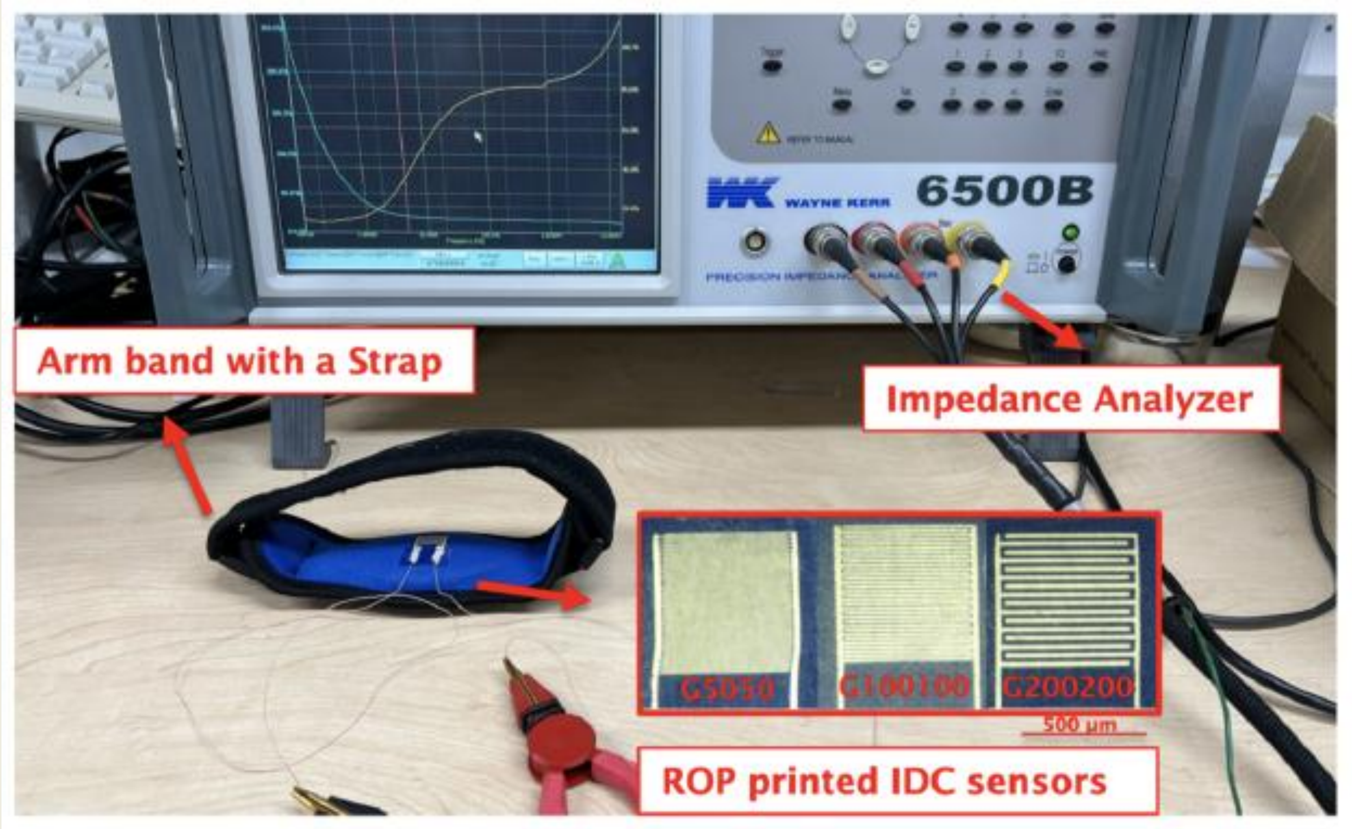
Inductive powered

UVC LEDs affect cell growth irrespective of the applied light intensity with very low light intensity of 10 μW enough to cause immediate cell apoptosis and disrupt cell growth

Skin sensor for Atopic Dermatitis (AD)







Sensor geometries investigated and encapsulation materials investigated to optimise sensitivity and robustness

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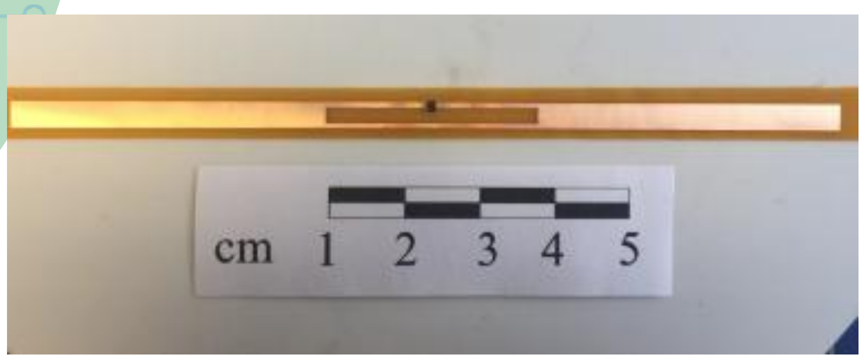
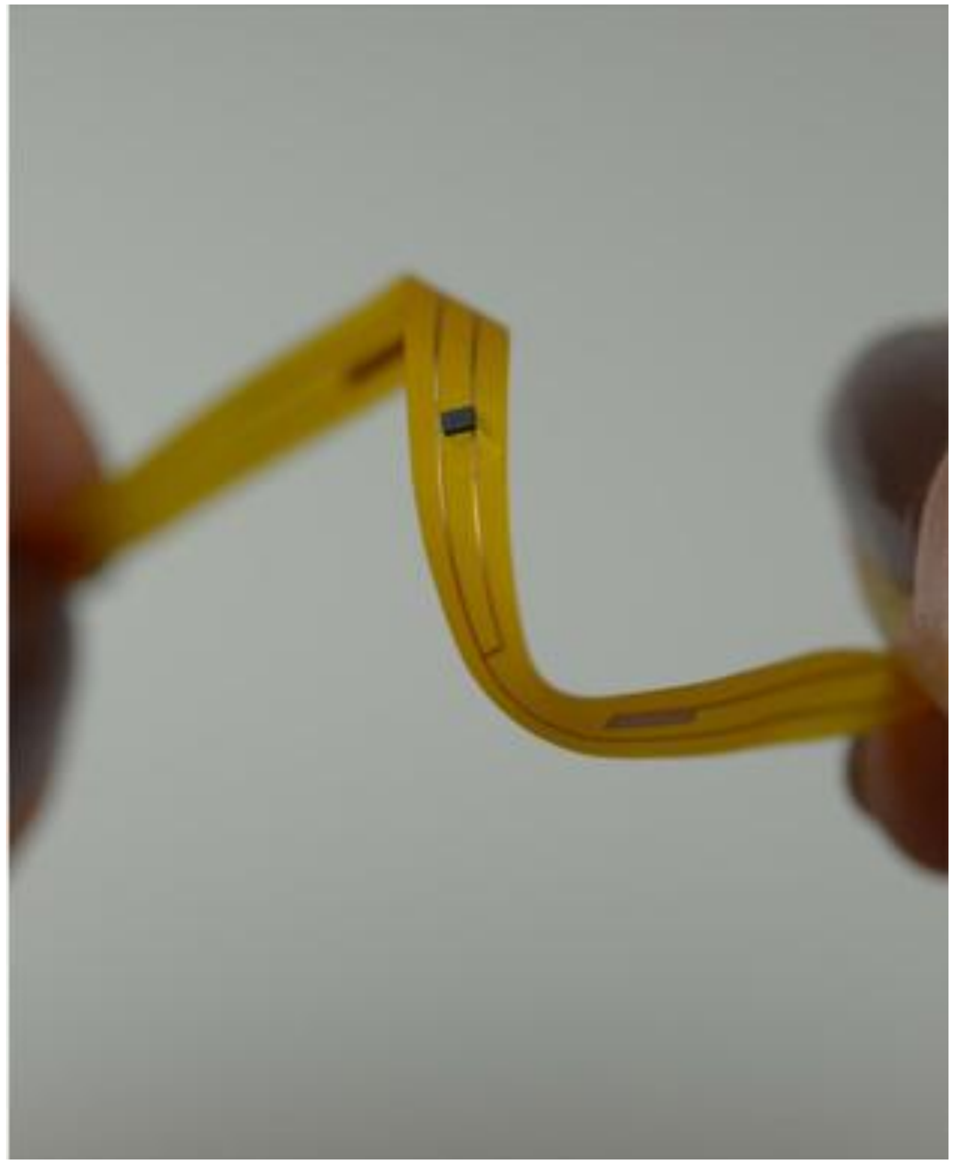
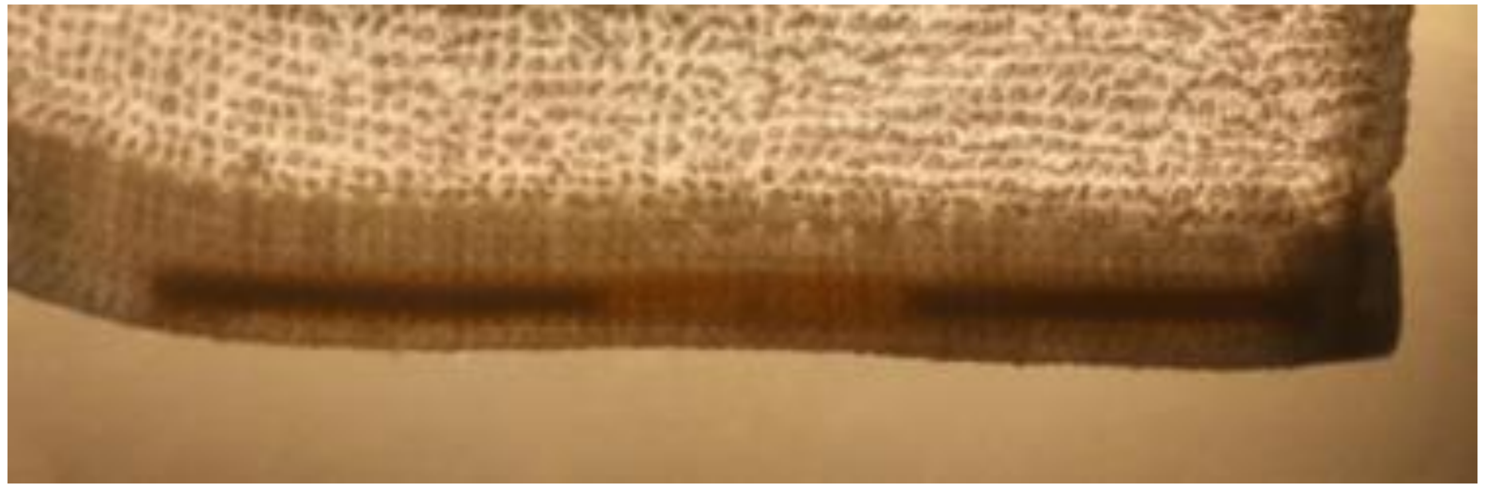
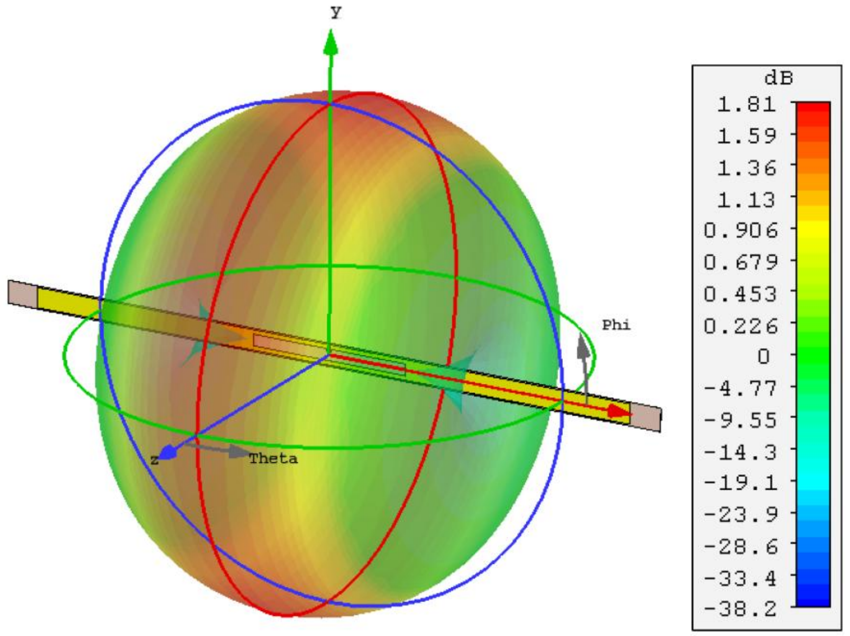
Reliable flexible RFID tag





Flexible filament circuits technology ideal for RFID antenna @ 915 MHz





Simulated peak gain of 1.81 dBi, operating range >10 m.

RFID technology enables wireless e-textile sensors.

Non-invasive electromagnetic sensors – respiration monitoring

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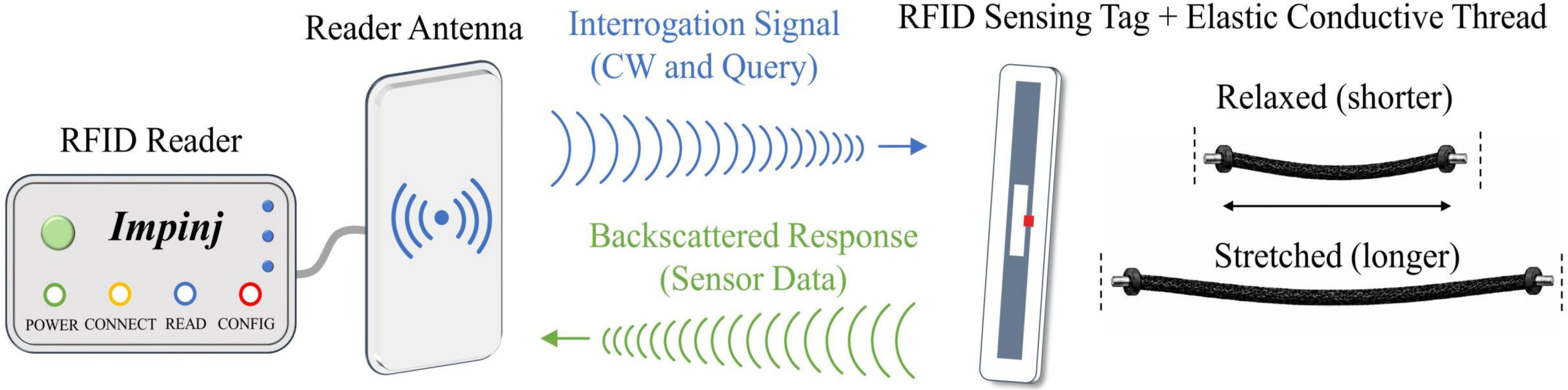
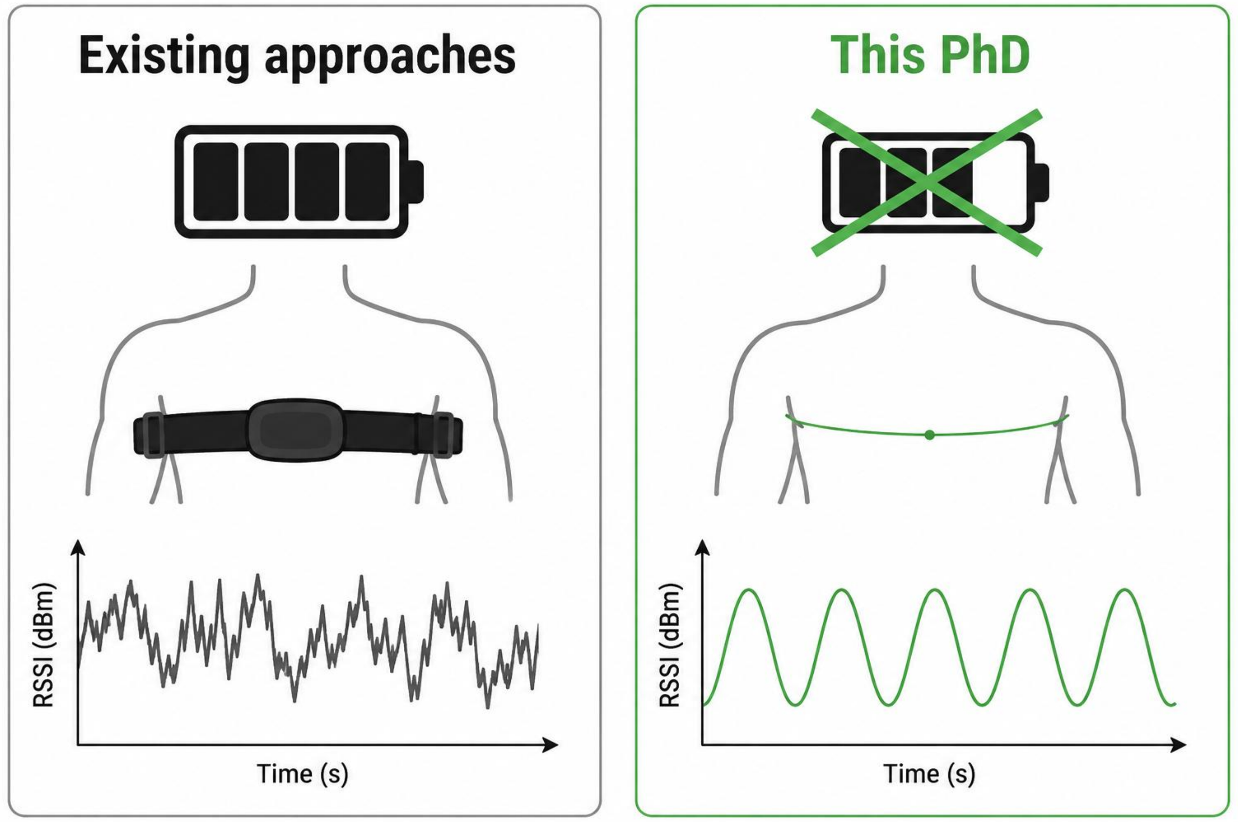
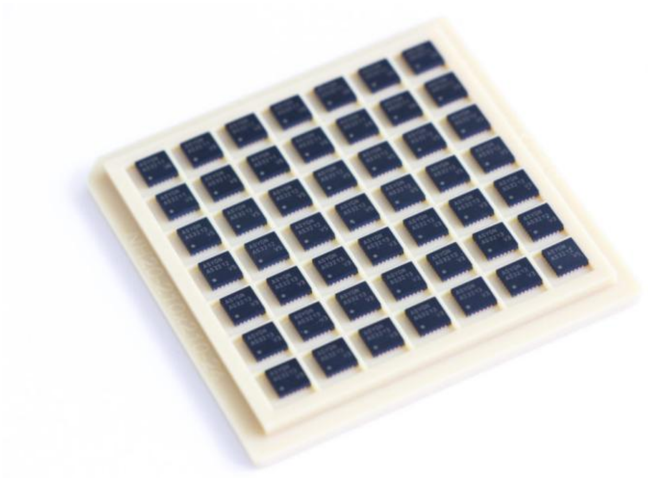
Measuring breathing wirelessly – no battery, no wires, no charging





The Technology Gap

- Previous RFID-based respiratory sensing relies on RSSI — unreliable due to multipath, orientation sensitivity, and reader variability
- No commercially available fully-passive RFID chip has previously been applied to continuous resistive strain sensing for respiration
- No published work characterises the AS3212.6 for this application



The AS3212.6 is the first fully-passive UHF RFID chip with a built-in Wheatstone bridge interface. This PhD is the first to characterise and apply it to respiratory monitoring.

Battery-Free Wearable Respiratory Monitoring Using Passive UHF RFID

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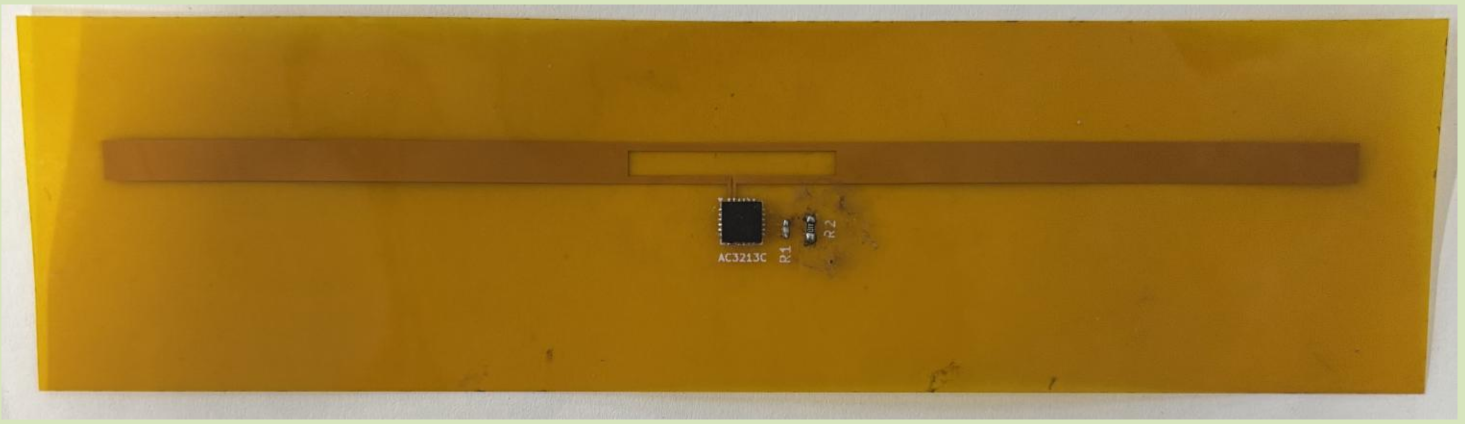
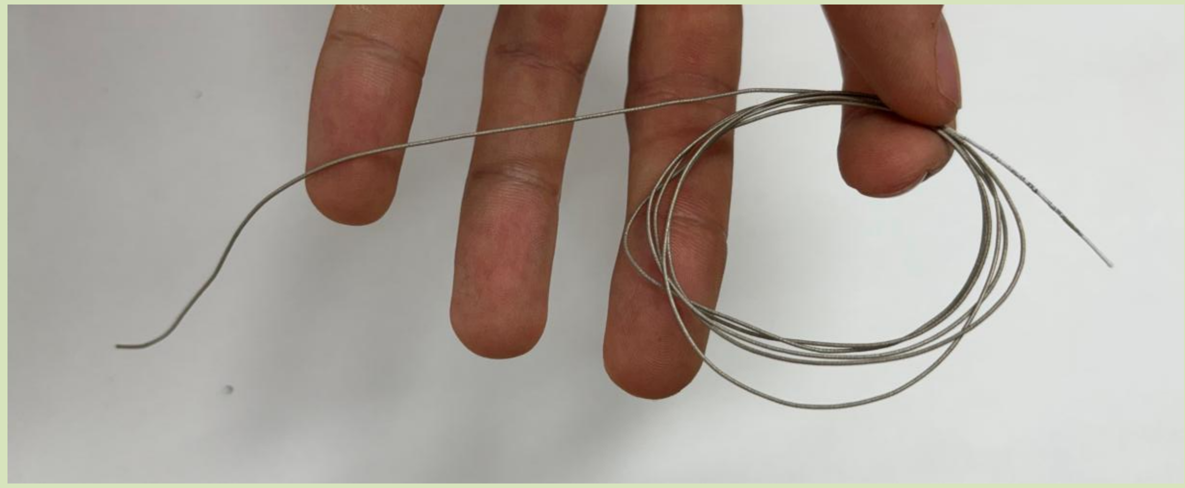
The chip and circuit



AS3212.6 — fully passive, 10-bit ADC, half-bridge configuration, EPC Gen2 compliant.

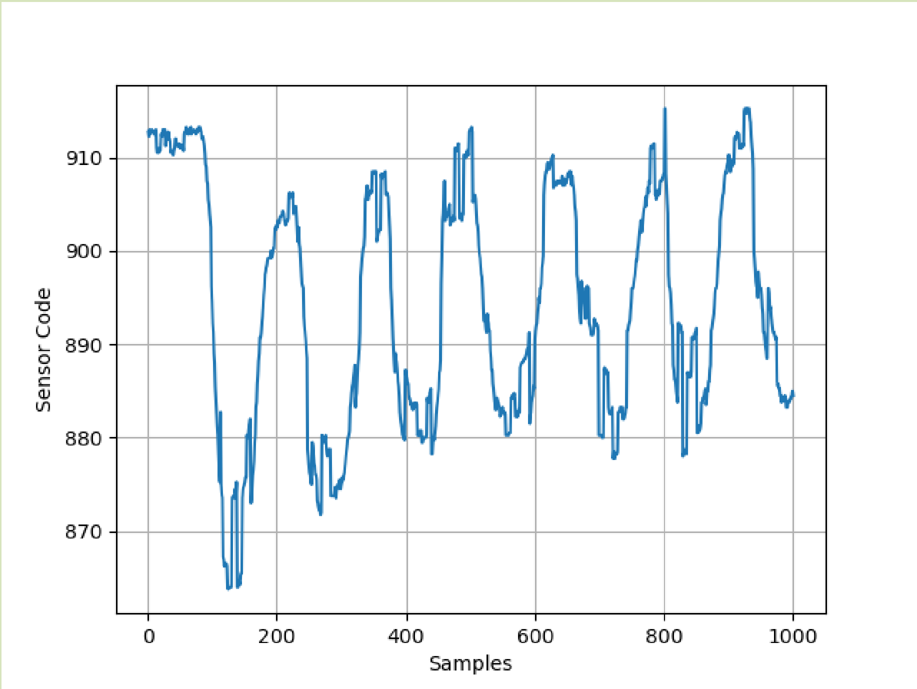
The sensing element



Silver-only conductive elastic thread

The key result

Wireless battery-free detection of cyclic resistance oscillations at breathing-relevant frequencies



Future Work

1. On-body chest strap integration and wearable testing
2. Clinical validation against reference respiratory system
3. Full mathematical model — temperature dependence, full-bridge configuration
4. Multi-sensor array for distributed sensing

Sustainability

Underpinned by a focus on sustainability, not properly considered to date in e-textiles.

E-Textile solutions must be robust, reliable, reusable and repairable. Design for disassembly must be considered; batteries and wires minimised.

C-FLEET
CENTRE FOR FLEXIBLE ELECTRONICS AND E-TEXTILES

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SEVENTH FRAMEWORK PROGRAMME

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THANK YOU FOR YOUR ATTENTION!