Organic and Printed Electronics

Dr. Danick Briand – EPFL

Prof. Vivek Subramanian – EPFL

OPE course content and schedule

Dates	Lectures	Lecturers
20.02	**Introduction**	D. Briand
27.02	**Physics of printing I**	V. Subramanian
06.03	**Physics of printing II**	V. Subramanian
13.03	**Materials for large area electronics**	V. Subramanian
20.03	**Thin film transistors fundamentals**	V. Subramanian
27.03	**Thin film transistors devices & Circuits**	V. Subramanian
03.04	**Organic light emitting diodes**	V. Subramanian
10.04	**Solar cells**	V. Subramanian
17.04	**Flexible and printed sensors**	D. Briand
01.05	**Energy storage & Encapsulation**	D. Briand
08.05	**Integration & Smart Systems**	D. Briand
15.05	**Sustainable electronics**	D. Briand
22.05	**Case study**	D. Briand

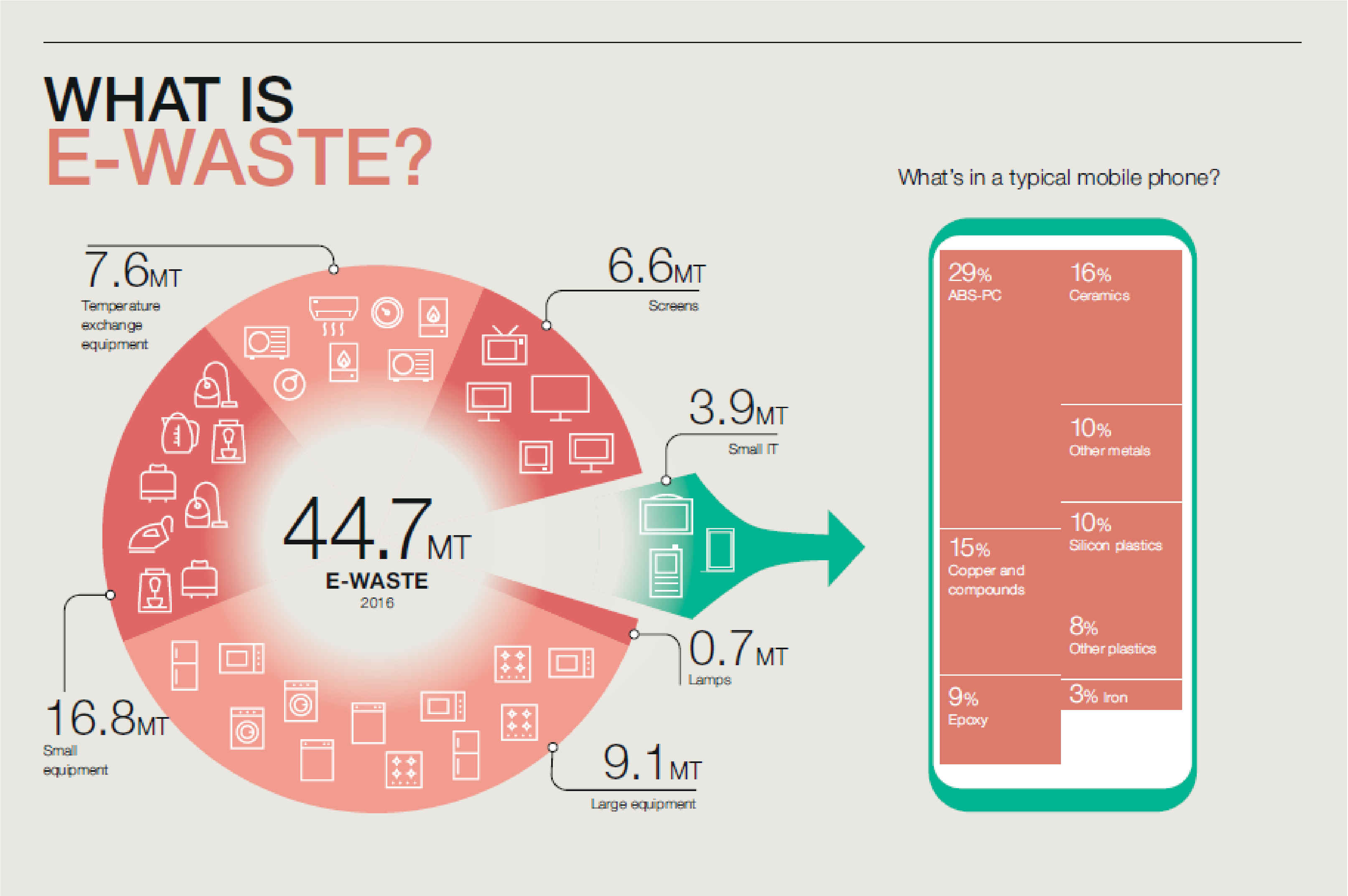
LESSON 11 – SUSTAINABLE ELECTRONICS

Dr. Danick Briand

Reference book 2nd Ed. on OPE: Chapter 13

Motivation: Need for Sustainable Electronics

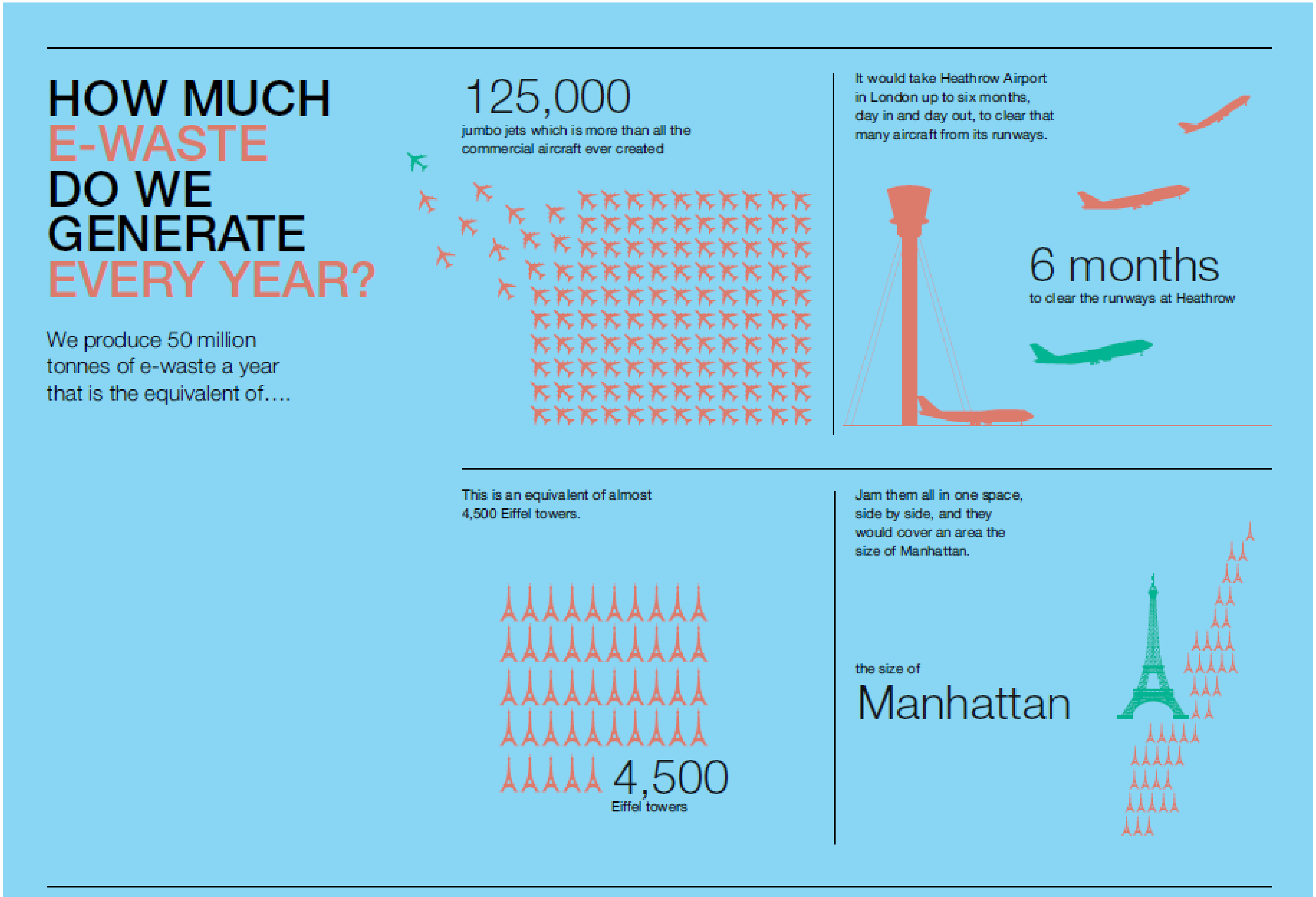
What is e-waste ?



A New Circular Vision for Electronics Time for a Global Reboot. Platform for Accelerating the Circular Economy (PACE), World Economic Forum, January 2019. https://go.nature.com/2IViK3m

Source: Global E-waste Monitor, 2017

How much e-waste do we generate ?



A New Circular Vision for Electronics Time for a Global Reboot. Platform for Accelerating the Circular Economy (PACE), World Economic Forum, January 2019. https://go.nature.com/2IViK3m

Source: E-waste Monitor, 2017

Context: E-WASTE

“A record 62 Mt of e-waste was produced in 2022, Up 82% from 2010; expected to rise to 82 Mt in 2030…

…less than one quarter (22.3%) was documented as having been properly collected and recycled in 2022”

The Global E-waste Monitor 2024

Swiss-ePrint - 25/09/2024 Dübendorf - Lina Kadura

Context: E-WASTE

Electronic devices are used almost in every sector of modern economy

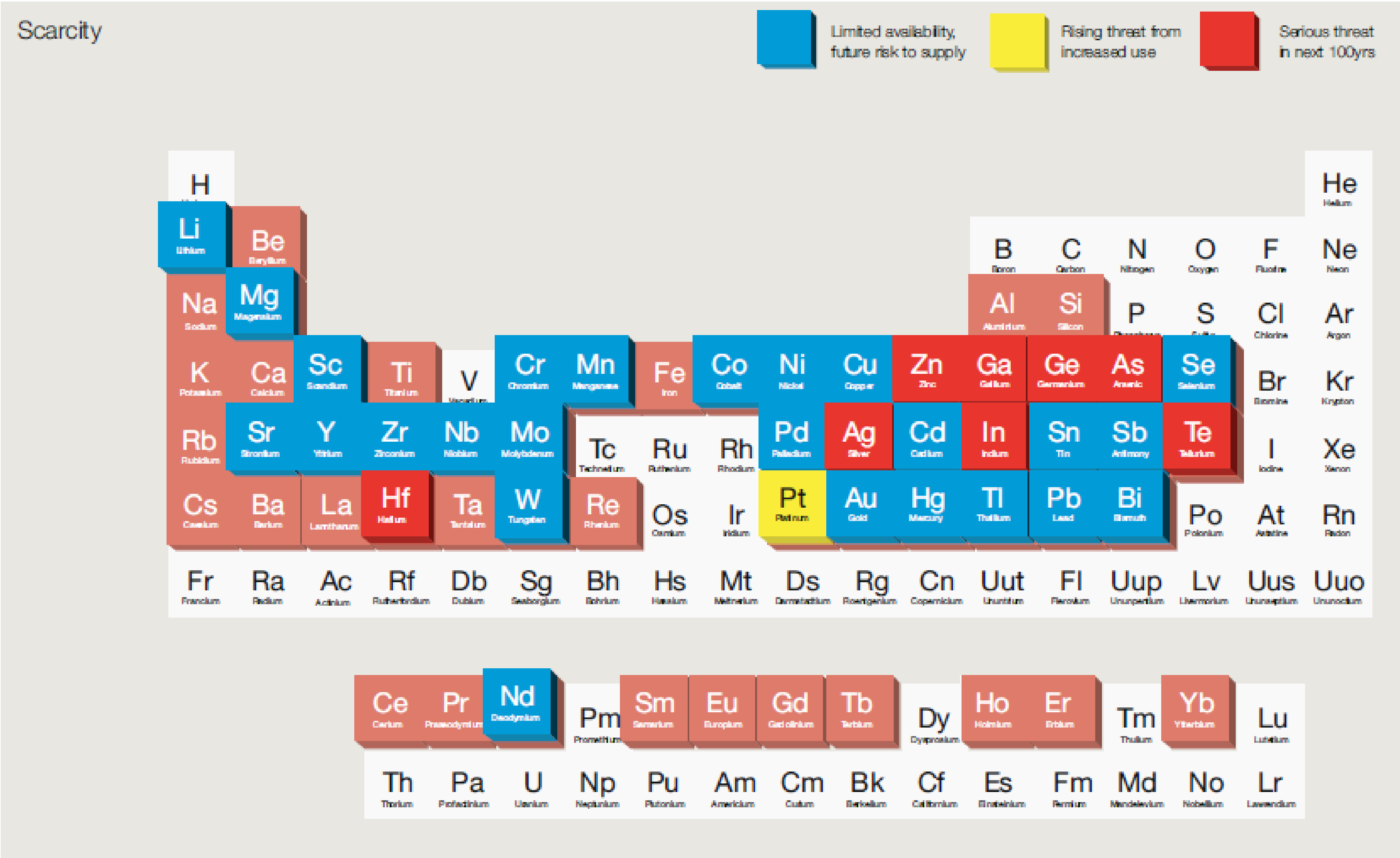
Conventional Printed Circuit Boards (C-PCBs) are the brain of all the electronics devices.

Their production involves **energy and resource intensive processes**, use of Critical Raw Materials, Precious Metals that are lost at End of Life, and highly polluting additives

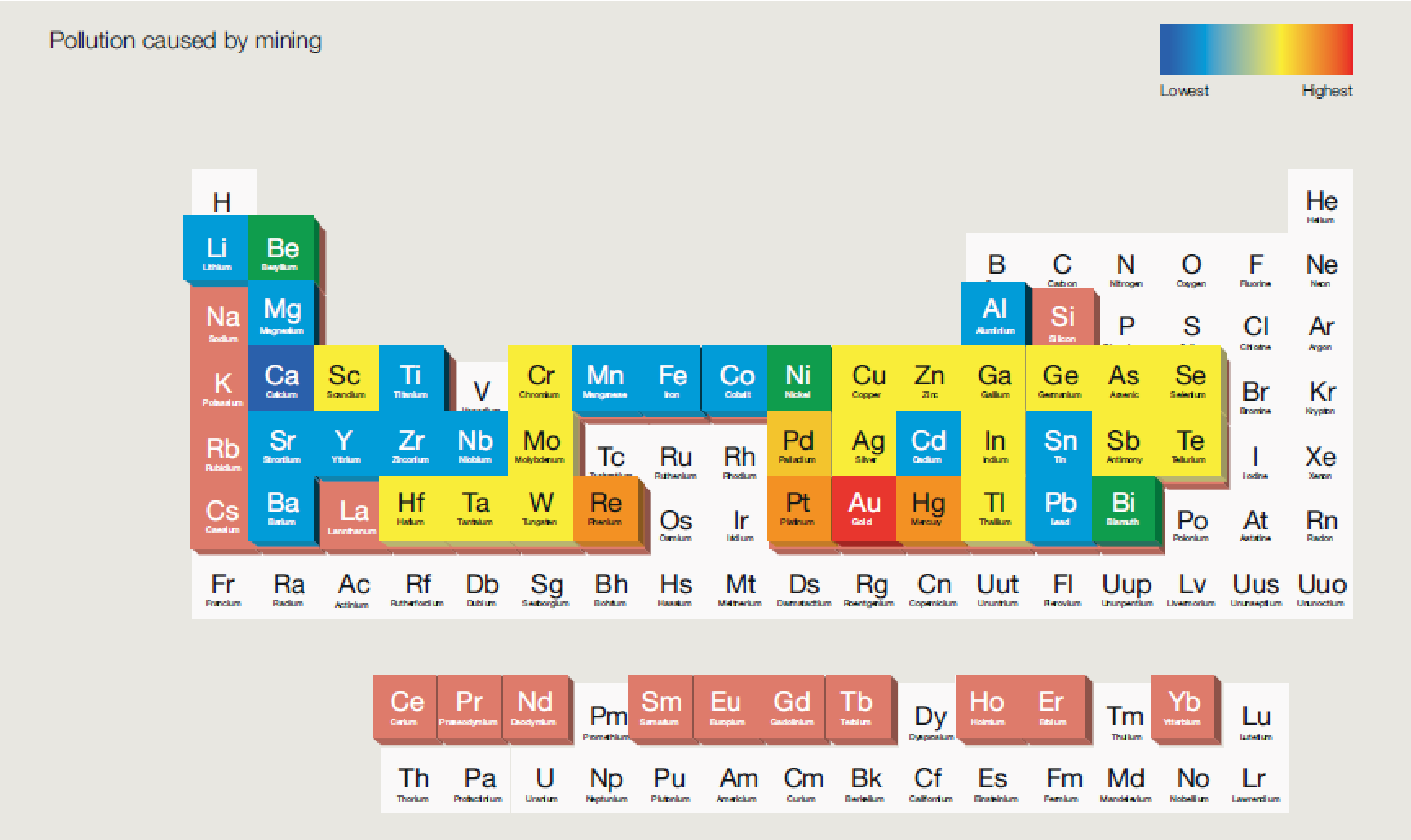
https://energyindustryreview.com/environment/an-opportunity-in-the-economy-e-waste/

Swiss-ePrint - 25/09/2024 Dübendorf - Lina Kadura

Ressources


Scarcity
Limited availability, future risk to supply
Rising threat from increased use
Serious threat in next 100yrs
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Tc
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Po
At
Rn
Fr
Ra
Ac
Rf
Db
Sg
Bh
Hs
Mt
Ds
Rg
Cn
Uut
Fl
Uup
Lv
Uus
Uuo
Ce
Pr
Nd
Pm
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Th
Pa
U
Np
Pu
Am
Cm
Bk
Cf
Es
Fm
Md
No
Lr

Ressources

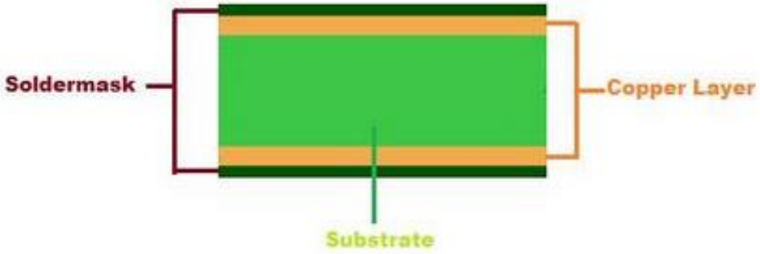


Pollution caused by mining
Lowest
Highest
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Ac Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv Uus Uuo
Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr

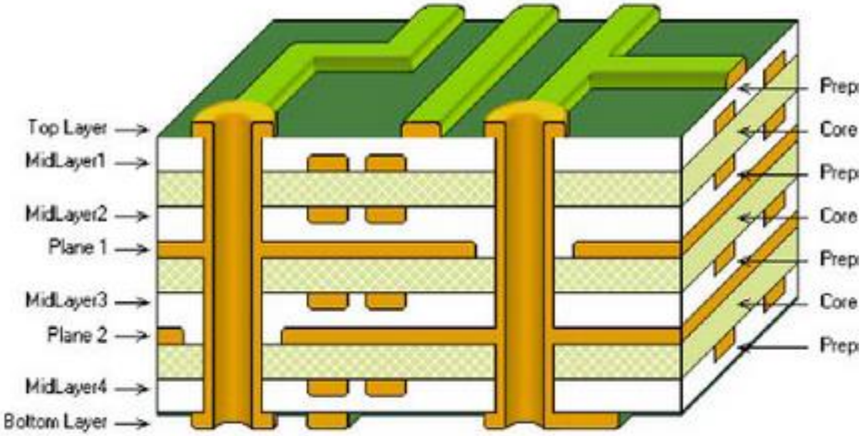
Printed Circuit Boards (PCBs) materials and fabrication

Single layer

Double layer



Multi layer

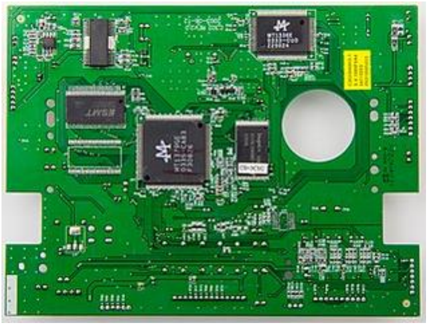


Copper plating + photopatterning & wet etching → substractive process

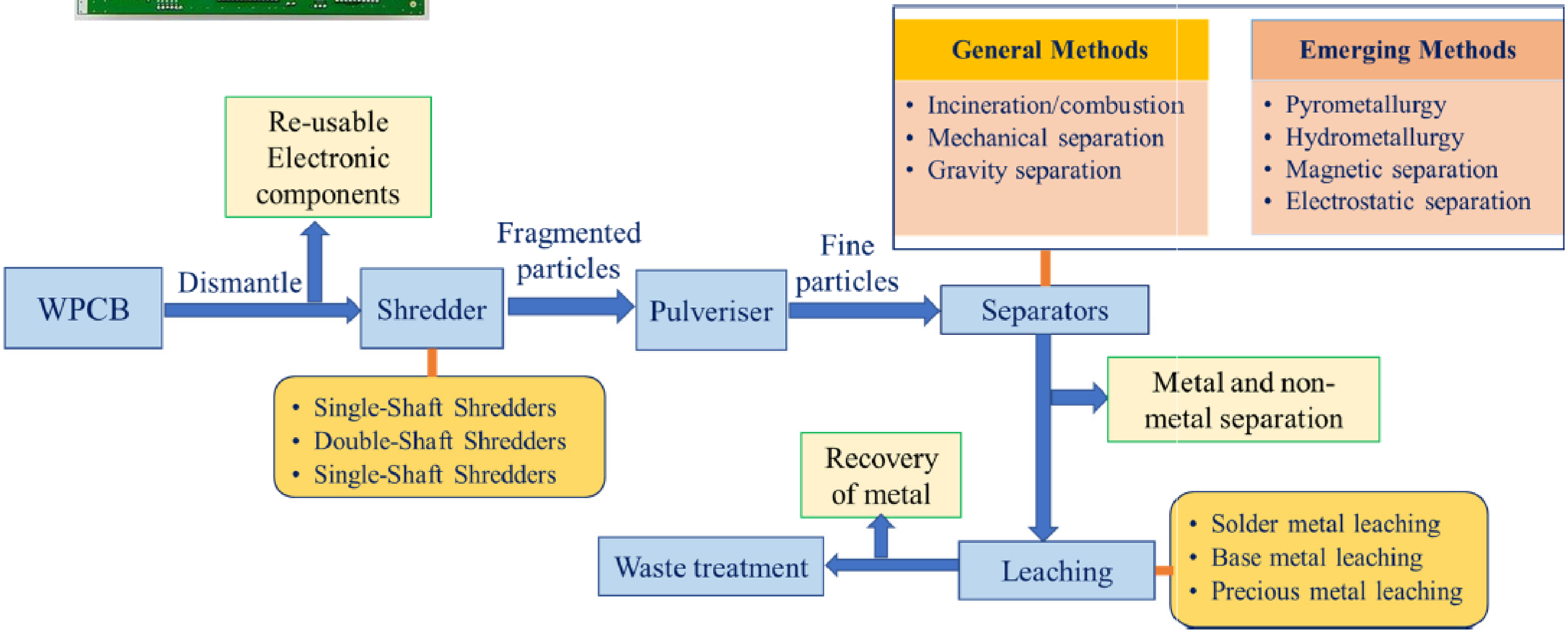
PCB components	Common materials
Substrate grades	
XXXPC, FR2	Phenolic-Cotton paper
FR3	Epoxy-Cotton paper
FR4, FR5, G10	Epoxy-Woven glass
FR6	Polyester-Mat glass
CEM-1, CEM-2	Epoxy-Cotton Paper / Woven Glass
CEM-3, CEM-4	Epoxy-woven glass/Mat glass
CRM-5, CRM-6	Polyester-woven glass/Mat glass
CRM-7, CRM-8	Polyester-Mat glass/glass veil
PI (Kapton), PTFE	Common flexible substrates that are hazardous when incinerated
Pyralux (flexible foil)	PI-fluoropolymer composite
Conformal coating to protect board from corrosion & environment effects	Acrylic, urethane, PU, epoxy, parylene etc. They can cause health safety concern after EOL of PCB
Connecting tracks	
Conductive metals	Cu, Sn
Wire coatings	PVC

M. Chakraborty, J. Kettle¨, R. Dahiya Electronic Waste Reduction Through Devices and Printed Circuit Boards Designed for Circularity

Standard PCB recycling (when they are!)



e-waste PCB with mounted electronic components
Source: Wikipedia



General scheme for WPCB recycling.

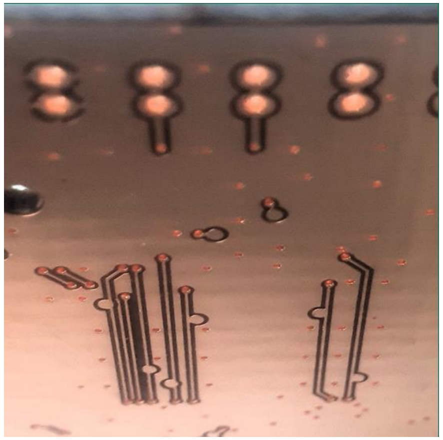
M. Chakraborty, J. Kettle , R. Dahiya Electronic Waste Reduction Through Devices and Printed Circuit Boards Designed for Circularity

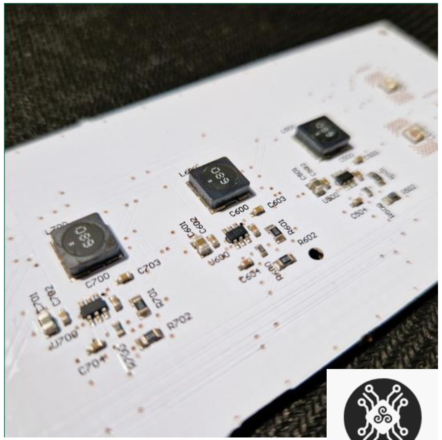
New PCBs materials allowing recycling

- **Fully recyclable and biodegradable PCB laminate – 60% lower carbon foot print**

Soluboard® is manufactured by impregnating natural fibres with a water-soluble polymer and a halogen-free flame retardant. The composite material is then consolidated and supplied to PCB fabricators as panels of copper clad laminate (CCL) available in a range of sizes.

Organic structure can be dissolved in hot water in controlled environment which enables to recover natural fiber, copper, and electronic components

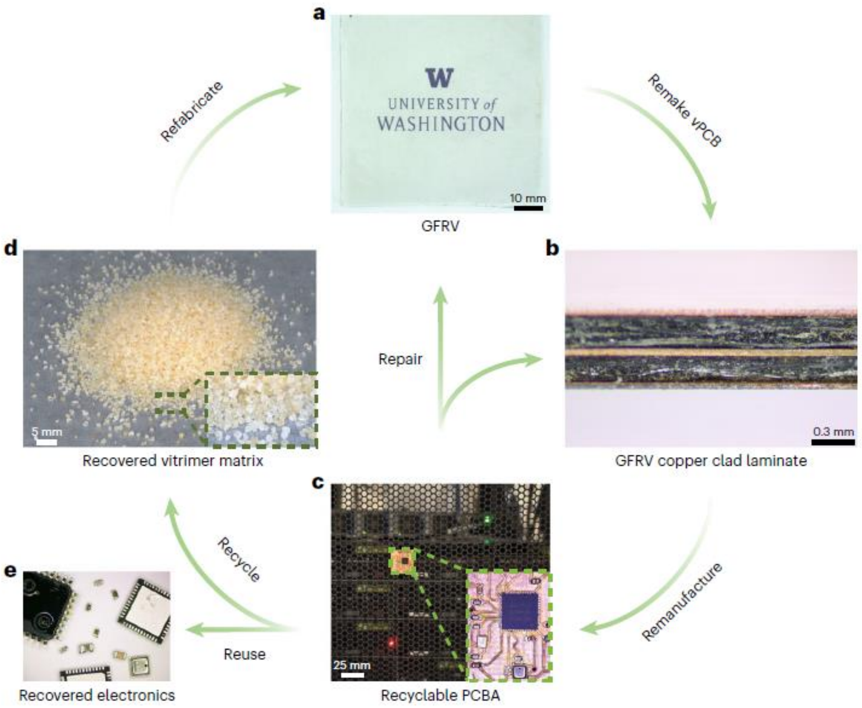




https://www.jivamaterials.com/

JIVA

- **Recyclable vitrimer-based PCBs**



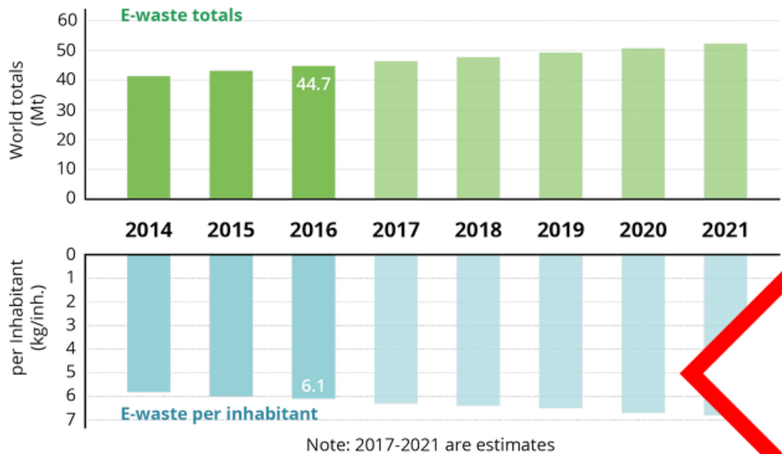
Non-destructive recycling process based on polymer swelling with small-molecule solvents. This recycling process achieves 98% polymer recovery, 100% fibre recovery and 91% solvent recovery to create new vPCBs without performance degradation.

LCA results show 47.9% improvement in global warming potential (GWP)

Zhang, Z., Biswal, A.K., Nandi, A. *et al.* Recyclable vitrimer-based printed circuit boards for sustainable electronics. *Nat Sustain* 7, 616–627 (2024).

E-waste concern

Unsustainable Materials + Unsustainable Processes



Predicted Global E-waste production, 2020:
51 Megatons

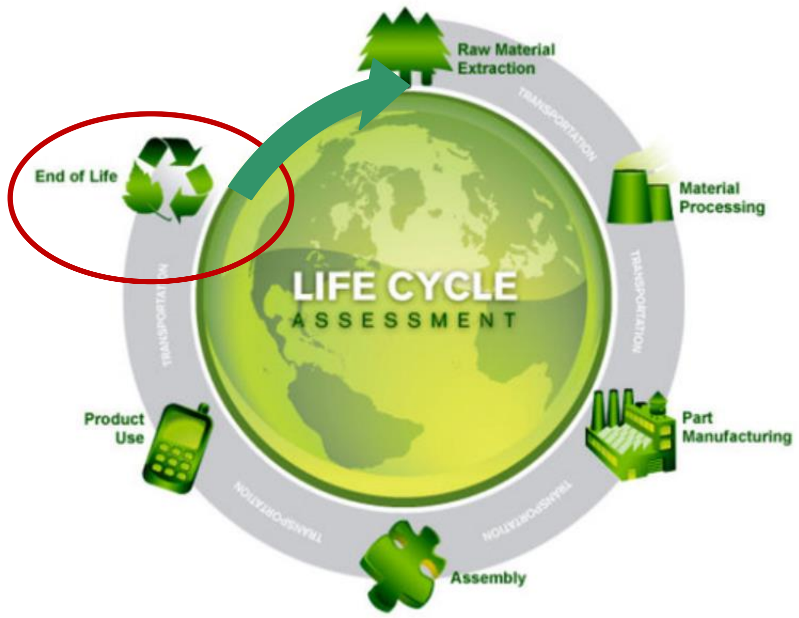
Toxic Chemicals
- Reagents
- Etchants

Material Waste
- Subtractive Processes
- Single-Use Equipment
- Waste Water

Energy Use
- Instrument Operation
- Envir. Control

Towards circular economy for sustainaible electronics

Reuse
Repair
Recycle



Towards more sustainable electronics from TNO-Holst Center

State-of-the-art	Re-usable	Resource usage	Circular	Renewable	Compostable
High volume Low cost Petrochemical Single use Only 20% recycled	2nd life Repair Upgrade Waste management on product level	Energy and materials consumption CO_2 emission	End-of-life Recycled mate Used in new products Waste management on component level	Biobased Building blocks from organic nature No fossil based materials	End-of-life Materials in waste stream No waste management

Sustainable & Green Electronics:

Towards Recyclability & Biodegradability

Objectives and content

Objectives

- Highlight the potential of organic and printed electronics for greener electronics

Content

- Introduction to sustainable electronics
- More sustainable materials and processes
- Environmental friendly devices and systems
- End of life: Disposability & recyclability

Three aspects to be considered in relation to Life Cycle Assessment

- Materials
  - Environmental friendly substrates: paper,bio-PET, biopolymers
  - Less toxic inks with greener solvents (i.e. water)
  - More abundant, environmental friendly, ultimately recyclable or biodegradable
- Manufacturing
  - Additive (no subtraction of materials as for lithography)
  - Lower temperature processes
  - Reduced infrastructure
  - Less severe control of the environment
- End of life
  - Potential to re-use, recycle parts or the whole system (circular economy)
  - Potential to environmentally friendly dispose the system (not harmful)
  - Compostable electronics (all parts biodegradables in compost)

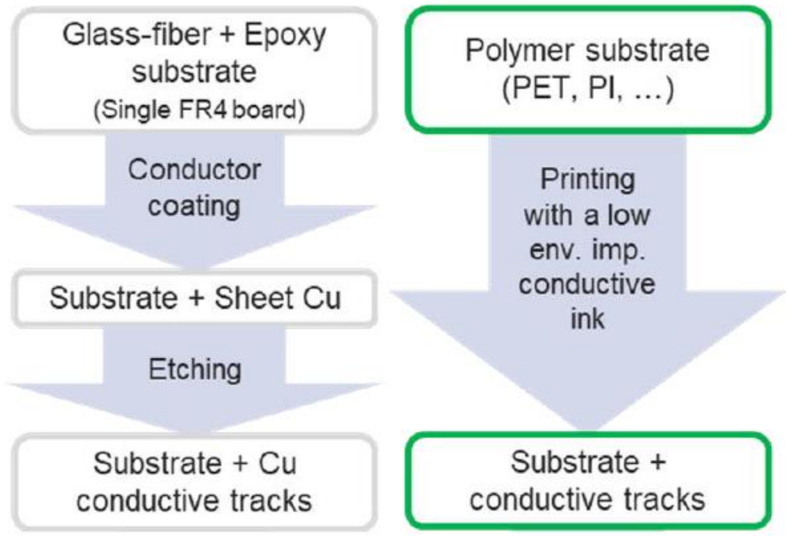
Printed Electronics for Printed Circuits Boards

Printed electronics:

→ Lower energy and resource efficient **additive processing techniques**

→ Compatible with the use of **low environmental impact materials**

C-PCB vs P-PCB



Environmental impact of P-PCB vs C-PCB ?

Swiss-ePrint - 25/09/2024 Dübendorf - Lina Kadura

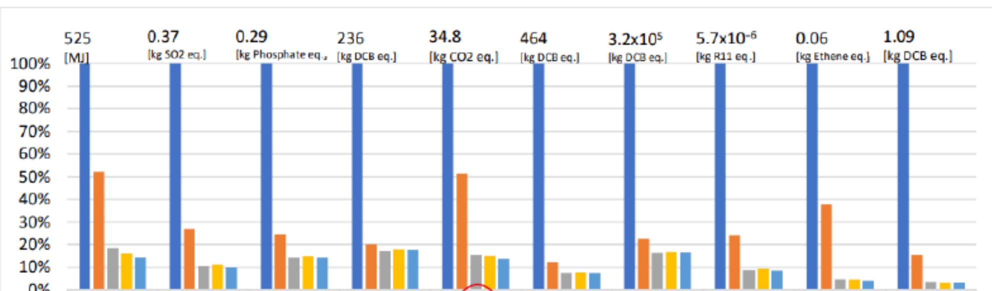
Preliminary LCA studies

Published in 2021

Article

Alternative Materials for Printed Circuit Board Production: An Environmental Perspective

Mohammad Naji Nassajfar [1,*], Ivan Deviatkin [1], Ville Leminen [2] and Mika Horttanainen [1]



	ADP Fossil	AP	EP	FAETP	GWP	HTP	MAETP	ODP	POCP	TETP
S1	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
S2	52%	27%	24%	20%	51%	12%	22%	24%	38%	15%
S3	18%	11%	14%	17%	15%	8%	16%	9%	5%	4%
S4	16%	11%	15%	18%	15%	8%	17%	9%	5%	3%
S5	14%	10%	14%	18%	14%	7%	17%	9%	4%	3%

Figure 2. Lifecycle comparison of five scenarios based on the impact categories of CML 2001—August 2016. Numbers on top of bars indicate the absolute value for S1 in each impact category.

Table 1. Scenarios for PCB production.

Scenario	Substrate	Conductive Material
S1	FR4	Etched-Copper
S2	FR4	Ag NPs
S3	PET	Ag NPs
S4	PLA60%–GF40%	Ag NPs
S5	Paper	Ag NPs

Swiss-ePrint - 25/09/2024 Dübendorf - Lina Kadura

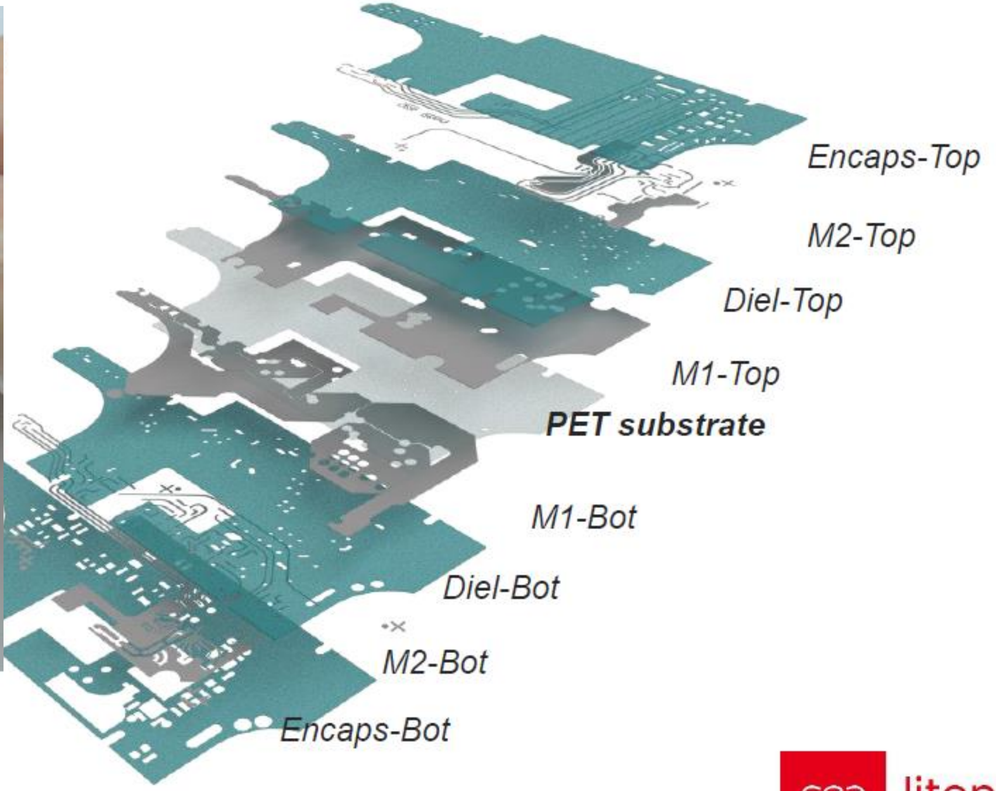
→ LCA studies show a **reduction of 50%** on GWP just by using **additive manufacturing**

→ It can reach up to **85% reduction** by replacing the **substrate with PET**

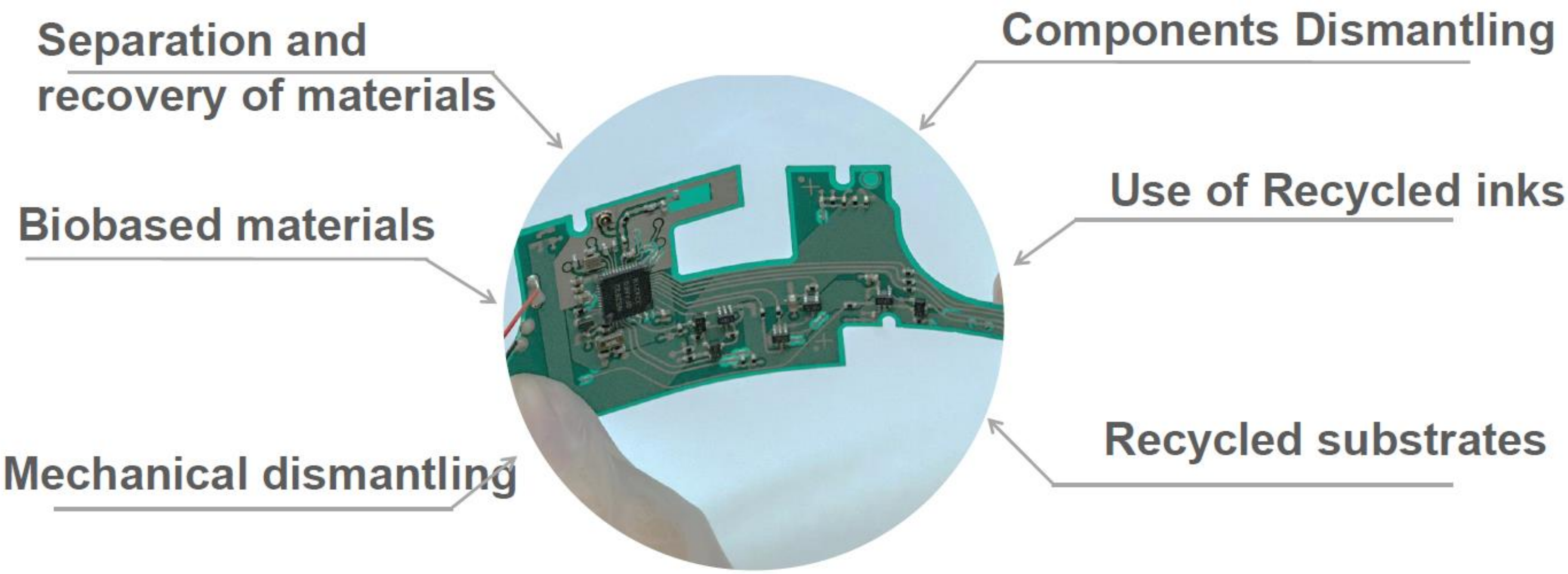
GWP: Global Warming Potential

Printed Electronics for Printed Circuits Boards

Screen printed silver tracks on PET substrate: 4 layers double side PCB



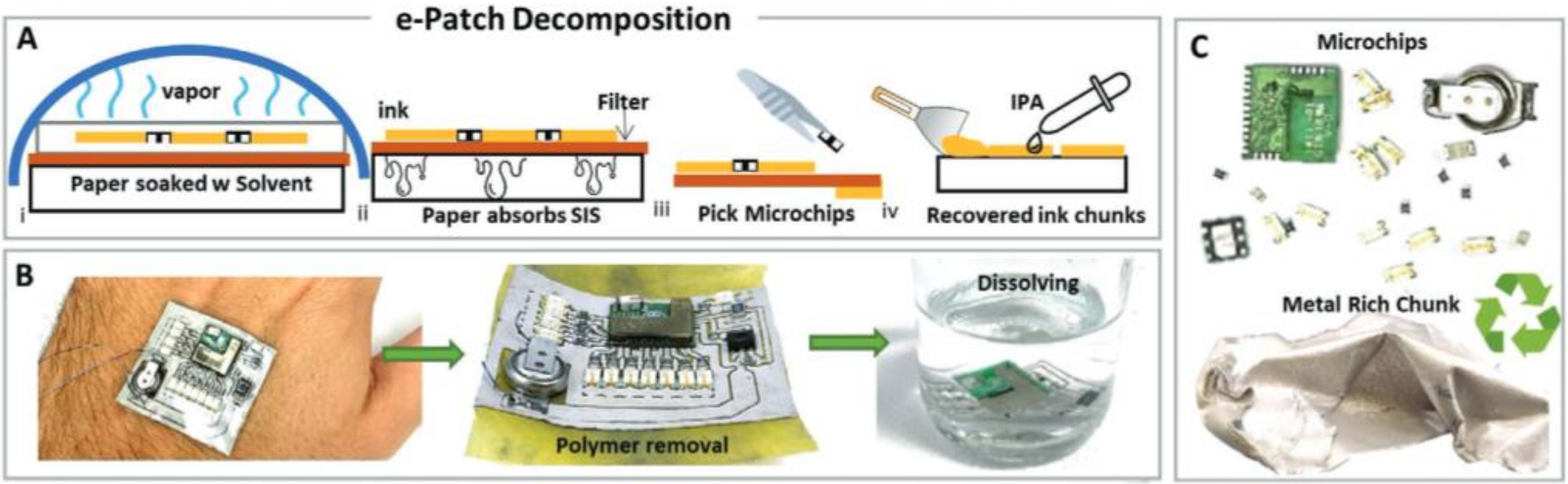
Next generations → Adding circularity



Swiss-ePrint - 25/09/2024 Dübendorf - Lina Kadura

Circular economy model

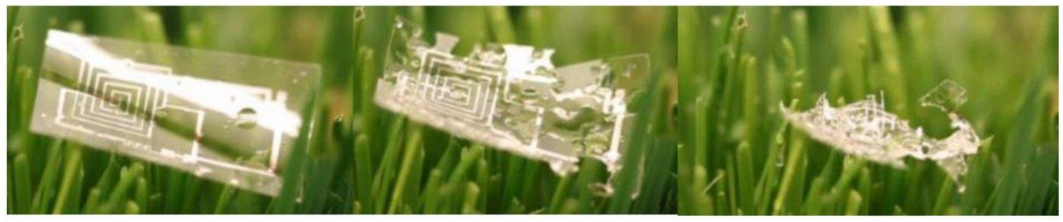
Dismantling concepts coming up to recover the different components from printed circuit boards:



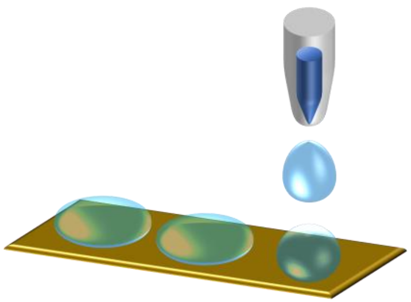
Two decomposition scenarios for a skin e-patch with the dissolution of the substrates and recovery of the metallic traces and microchips involving a printable biphasic liquid metal solder compatible with biopolymers.

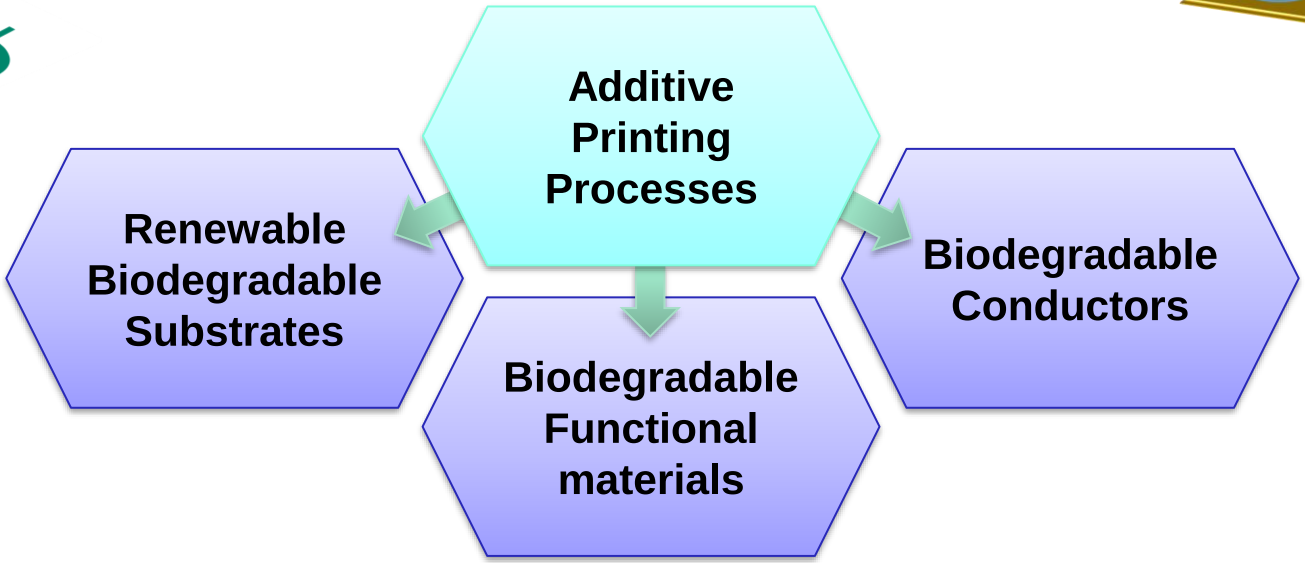
M. Tavakoli et al., 3R Electronics: Scalable Fabrication of Resilient, Repairable, and Recyclable Soft-Matter Electronics. *Adv. Mater.* (2022) 2203266.

Technology shift for more sustainable electronics

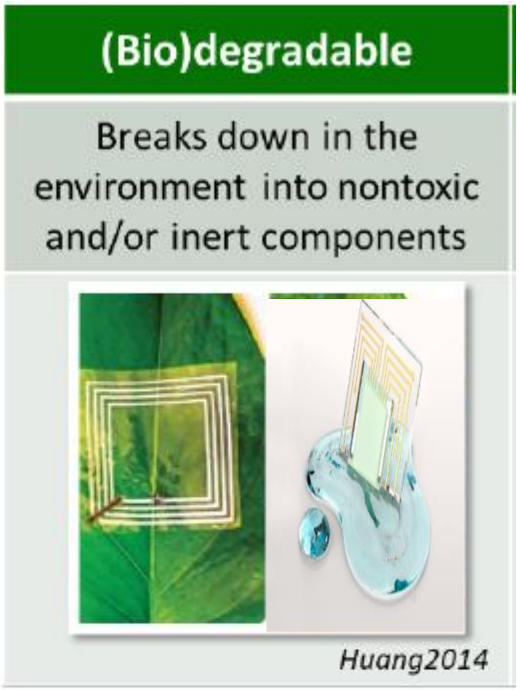


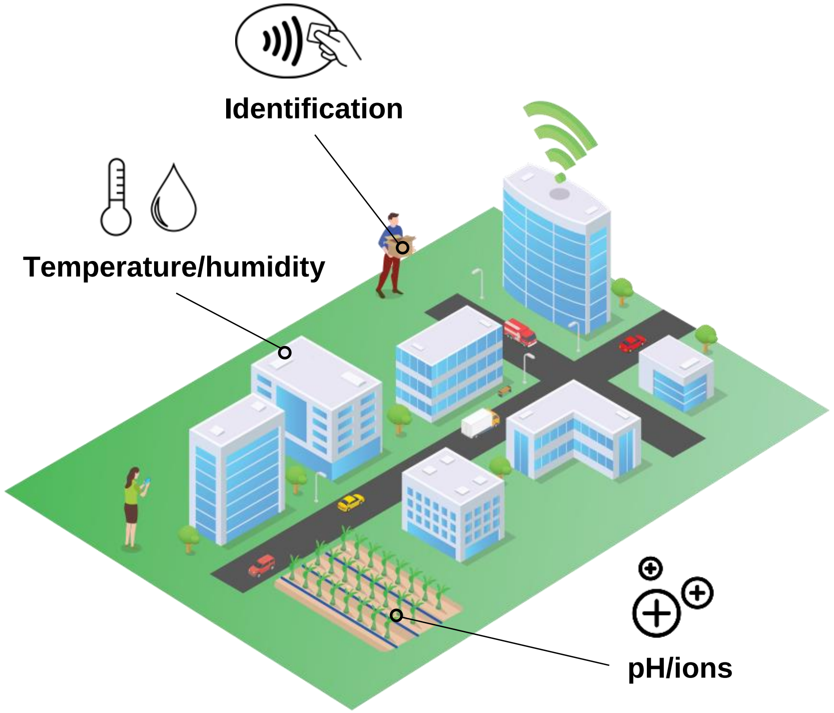
Recyclable / eco-resorbable printed electronics & microsystems





- **Ecoresorbable and Recyclable electronics:**



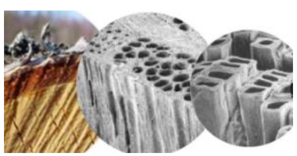


→ **Reduce toxic waste for disposable electronics**

Biodegradable functional materials

Transient electronics based on renewable and biodegradable functional materials

"Can degrade into smaller environmentally harmless substances"



Insulating

- **Enzyme degradation**

Polysaccharide
  - Starch
  - Cellulose

- **Hydrolitically degraded**
  - PLA
  - PHBH
  - PVA

Proteins/Lipids
- Animals (collagen, shellac)
- Plants (gluten)
- Silk (fibroin)

Electrically conductive

- **Metals:**
  - Magnesium (Mg)
  - Iron (Fe)
  - Zinc (Zn)
- **Carbon-based**
- **Conducting polymers:**
  - PEDOT
  - PPy
  - PANi

Challenges

- Limitation in terms of materials and inks available
- Materials inherently degradable in contact with humidity, temperature, solvents
  → Compatibility of liquid chemistry

  → Stability of electronic characteristics over time
- Reactivity of biodegradable metals (i.e. oxidation) → ink formulation and processing are problematic
- Temperature sensitive substrates, with generally a low glass transition temperature (Tg) → restrictions on inks curing and sintering processes
- Limited performances
- Reaching a true sustainability

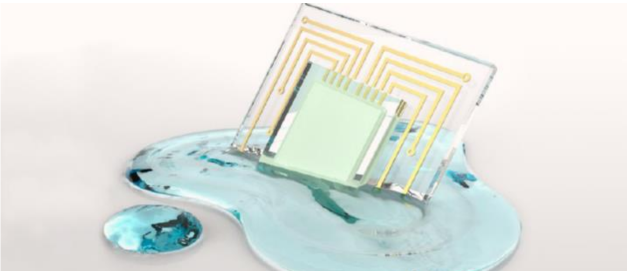
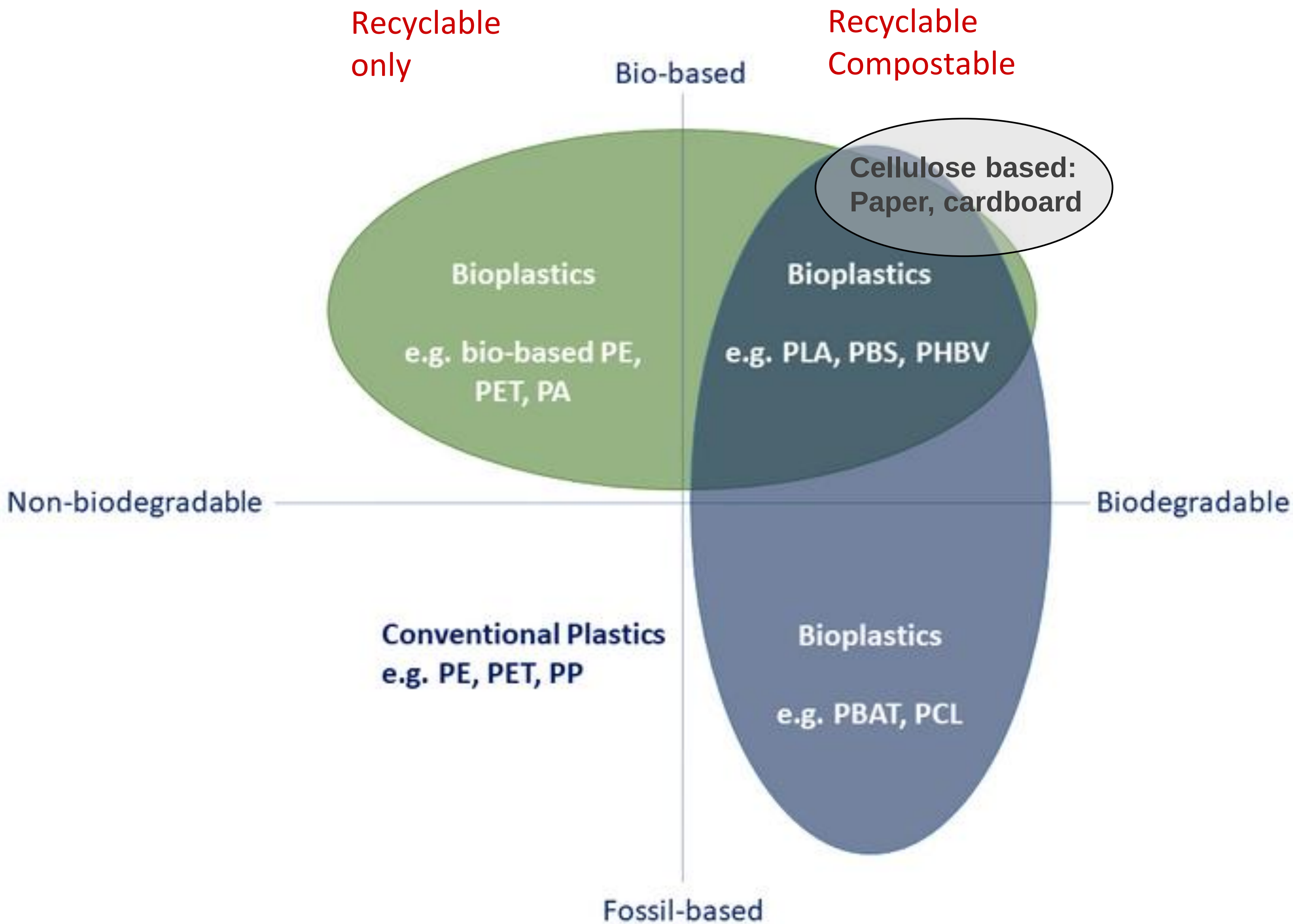


Image from Fu2016

Sustainable substrates



https://bioplasticseurope.eu/

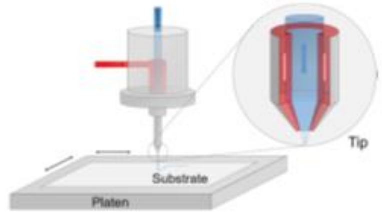
Additive manufacturing + Photonic sintering

Printing

Inkjet Printing (2D)

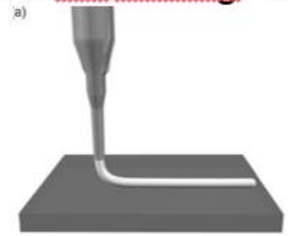
Circuitry and sensors

Aerosol Printing (2.5D)



Fine and conformal features

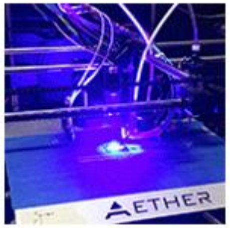
Direct Ink Writing - DIW (3D)



Structural and functional materials interconnections

Processing

Laser Sintering



Local rapid exposure

Flash Sintering

(Xe lamp)

Global rapid exposure

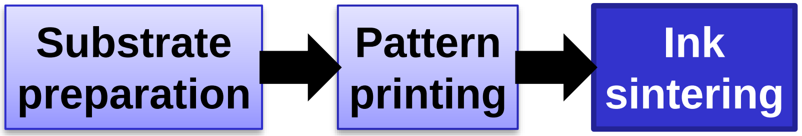
NIR / UV

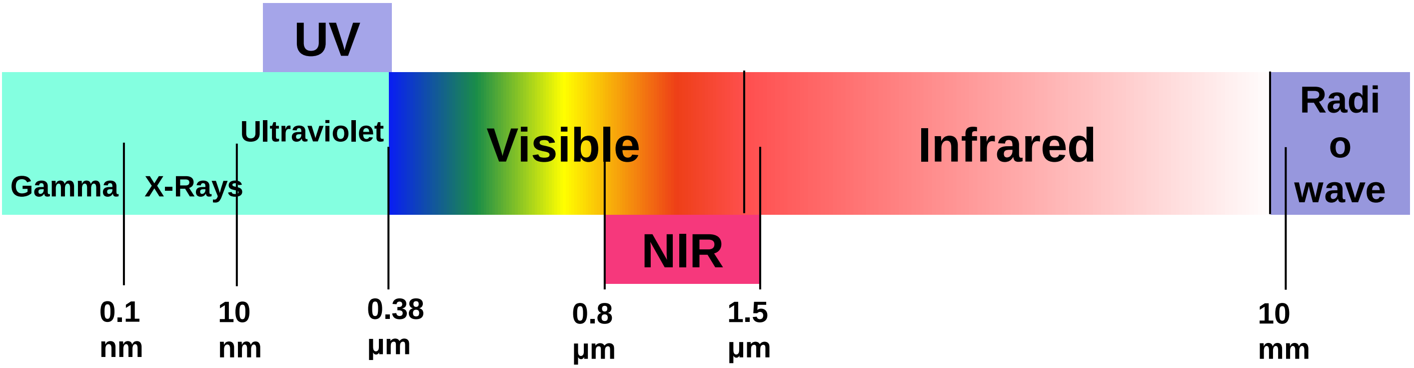
Integrated photonic exposure

- **Additive manufacturing for local deposition of materials**
- **Eco-friendly ink formulations**
- **Photonic sintering for processing on temperature sensitive materials**

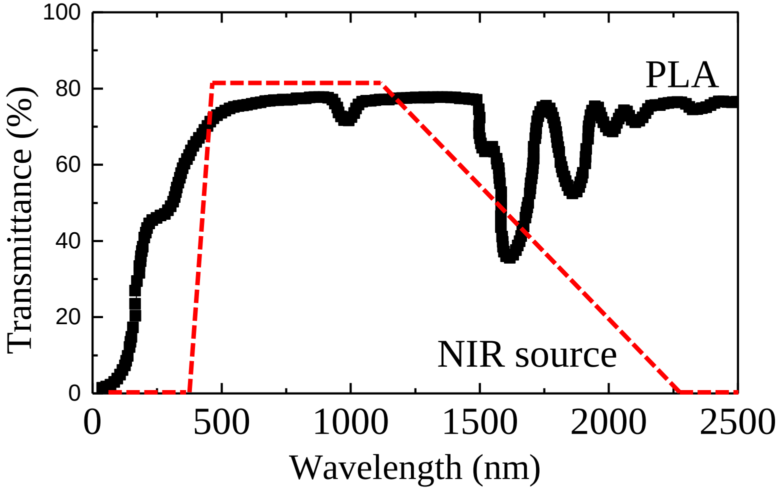
Dimatrix Droplet Watcher, Smith et al. (2017) Flex. Print. Electron., Lewis (2006) Adv. Func. Mater.

Photonic flash sintering





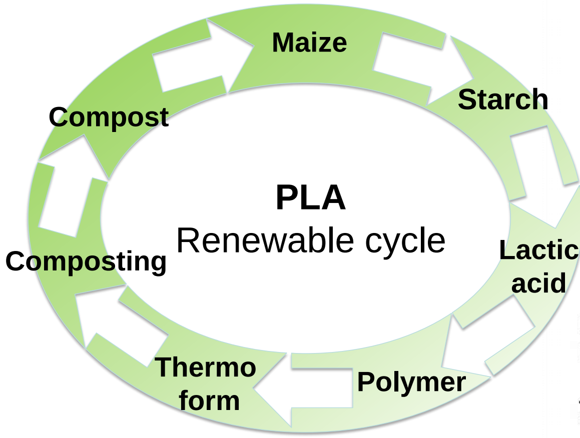
- **PulseForge 120 Novancentrix**
  - 200 – 1500 nm
  - Duration controlled by pulses (micro seconds)
  - Energy: 3000-5000 mJ/cm^2 (for this case)
- **Absorption of metal much higher than PLA**
- **PLA remains at low temperature**

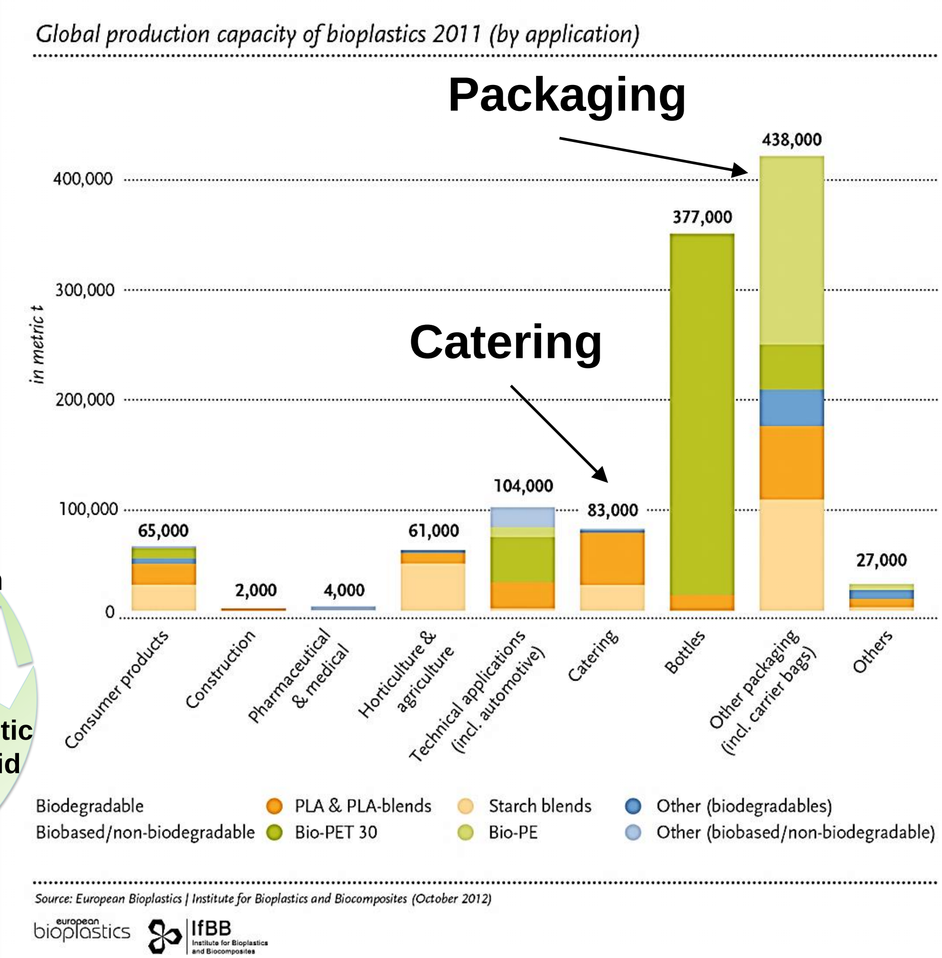


W. Mulbry et al. Bioresource Tech. 109 (2012), 93-97.
C. Aulin et al. Appl. Mater. Interfaces 2013, 5, 7352-7359.
A. Ulrici et al. Chem. Intelligent Lab. Sys. 122 (2013), 31-39.

Biopolymer: Polylactic acid – PLA

- Bio-
  - Compatible
  - Degradable
  - Compostable
- Food packaging solutions
- Renewable cycle





European Bioplastics

PLA-based printed sensors

- **On/In body measurements**
  - **Biomedical diagnostics / PoC …**
- **Smart packaging and environmental monitoring**
  - **Cold chain supply monitoring**
  - **i.e. temperature, humidity, bacteria...**

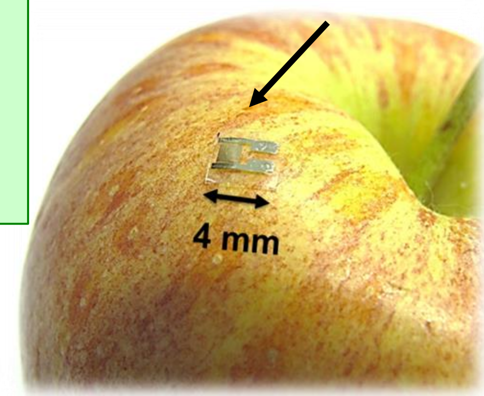
Georgia Tech.

Printing transducers on PLA
- **Capacitive**
- **Resistive**
- **Transistors**

Tg ~ 58°C !

Univ. of Illinois at Urbana Champaign.

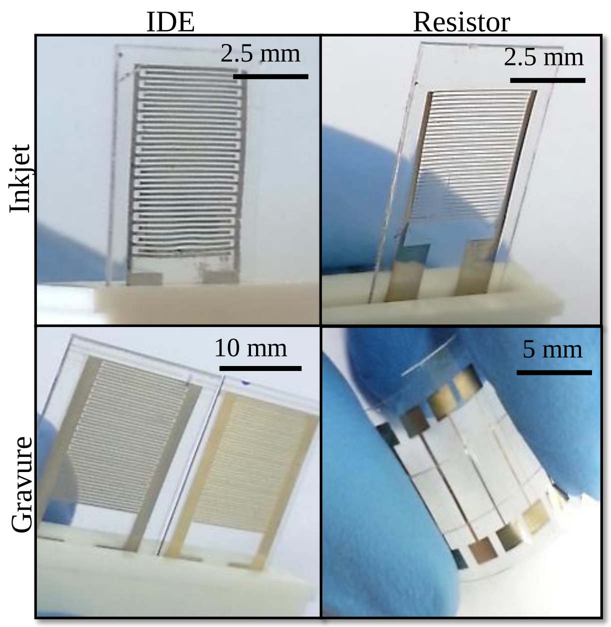
R.H. / T°C sensor

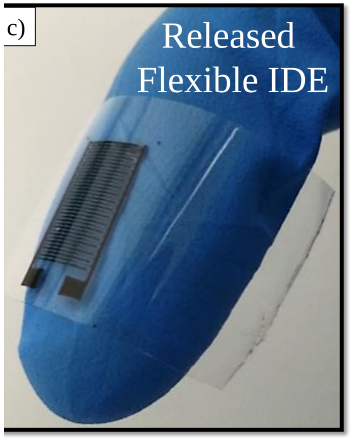


PLA-based printed sensors

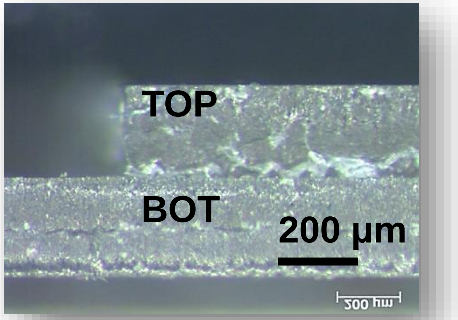
On biodegradable substrates low Tg (56°C) poly lactic acid (PLA) → detection of humidity and temperature for green packaging

- Printing of Au inks
- **Photonic sintering** for localised heat generation





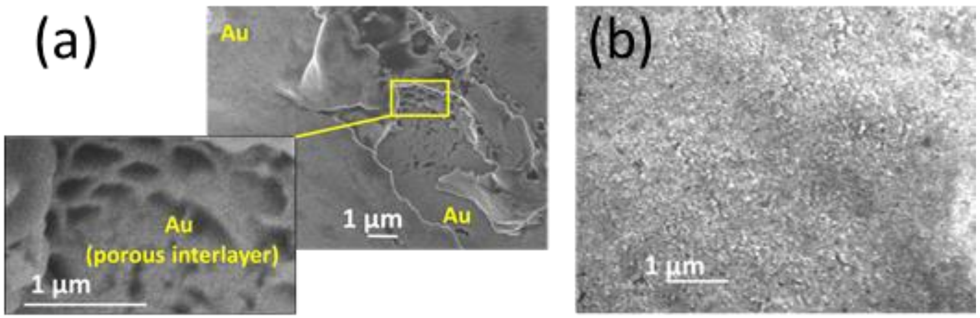
Encapsutation by lamination



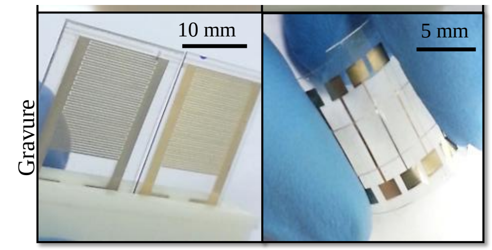
Photonic flash sintering

- On biodegradable substrates low Tg (56°C) poly lactic acid (PLA)

- Printing of Au inks+ Photonic sintering

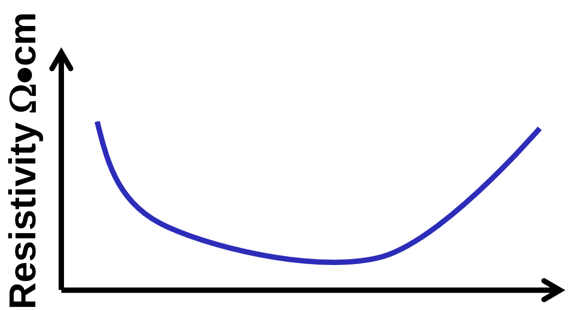


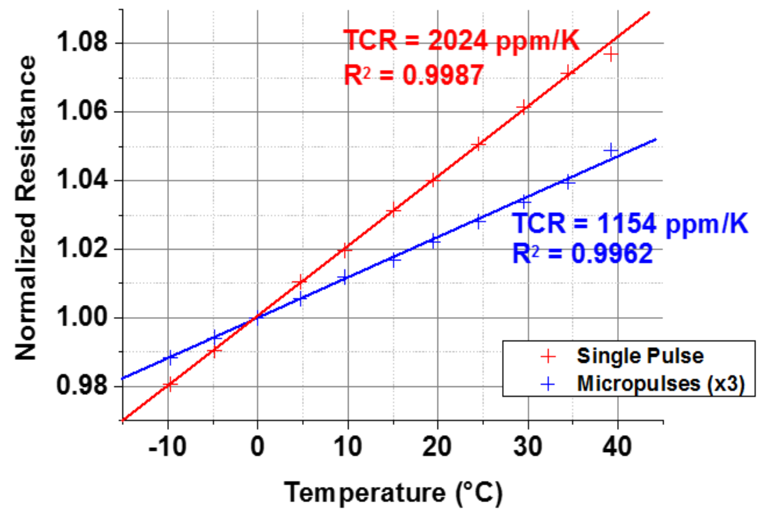
SEM pictures of gold sintered with (a) single pulse and (b) multipulse (x3) at 1.5 J/cm² energy



Gold patterns

- Multipulse preserve the film integrity





- Temperature coefficient of resistance (TCR) can be tuned by the pulse regime

Biocompatible gold RTD

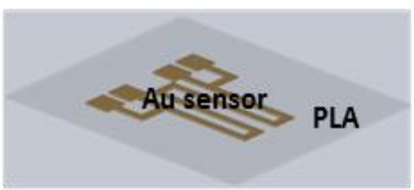
Inkjet and flash sintered gold NPs

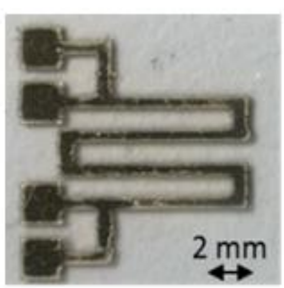
- 1.5 J/cm^2 using two different pulse regimes
- Single pulse: 55 Ω / TCR: 2024 ppm/K
- Three multipulses: 220 Ω / TCR: 1154 ppm/K

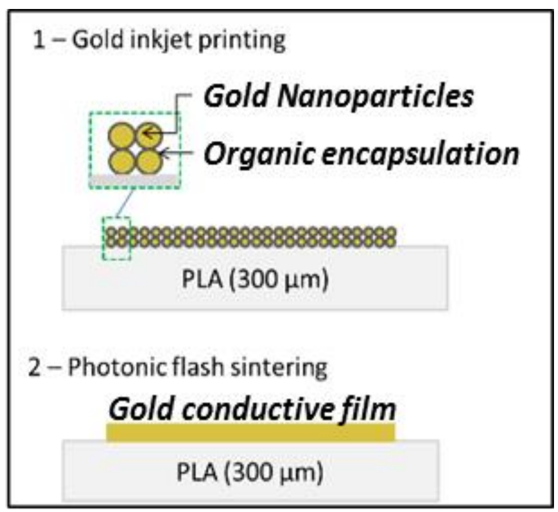
$$R(T) = R_0[1 + \alpha(T - T_0)]$$

TCR = α

- **Trade-off between the TCR value and the nominal resistance for optimal sensitivity of the temperature sensor**







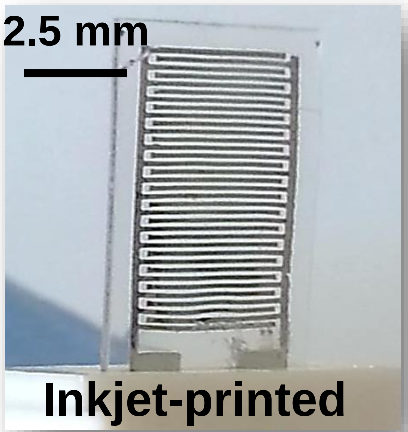
Line thickness and width:

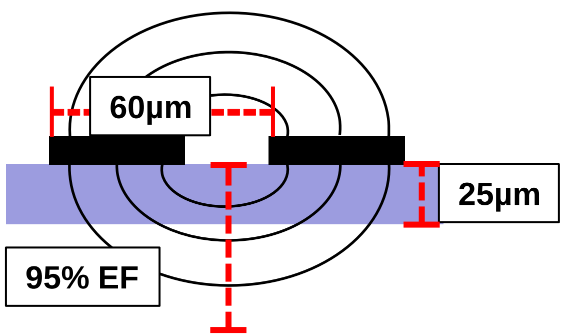
- Before sintering: 300 nm
- Single pulse: 530 nm
- Multipulse: 700 nm

- 60 µm linewidth

Printed capacitive humidity sensor on PLA

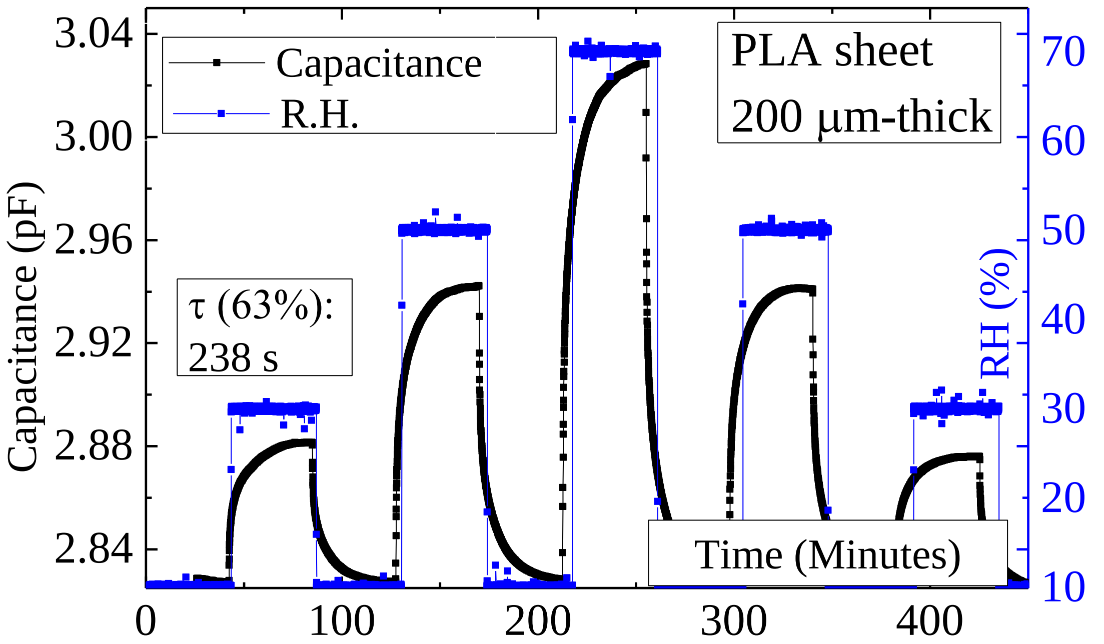
- PLA substrate as sensing layer with gold IDEs





cross-section

Response to humidity

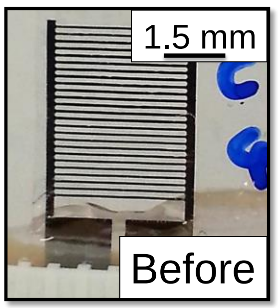


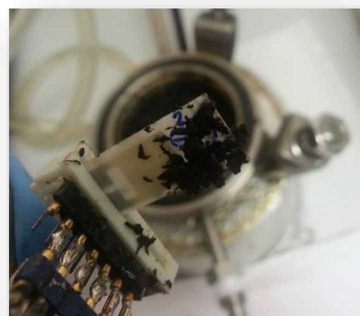
Climatic chamber at 25°C (steps of 1h)

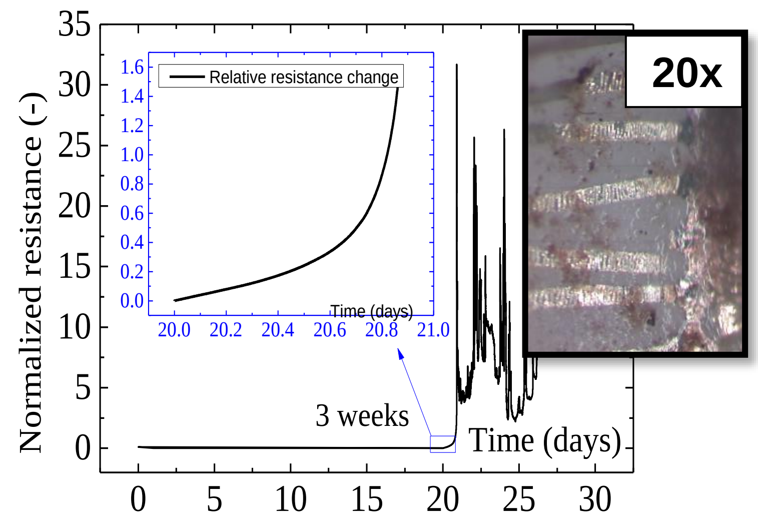
Biodegradation / Bioresorption

- Tests in controlled environment (Temperature, humidity, enzymes…)
- Biodegradability / resorption can be tuned by the nature and thickness of the encapsulant material(s), interfaces are critical

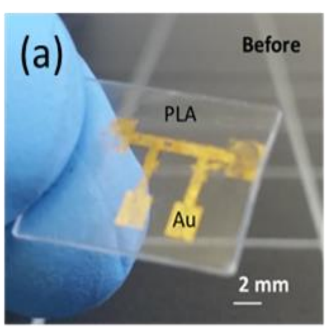
Au on PLA in Compost

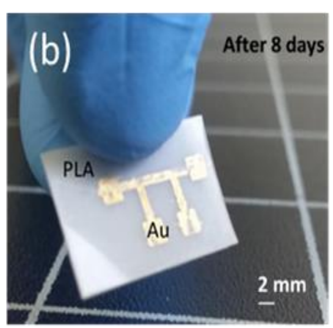






Au on PLA phosphate buffered saline (PBS) solution at 37°C

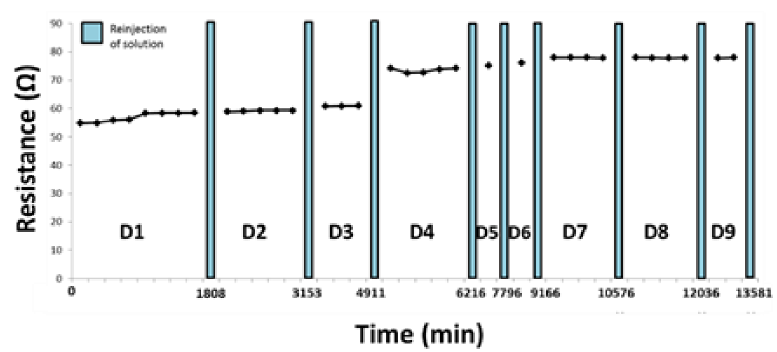




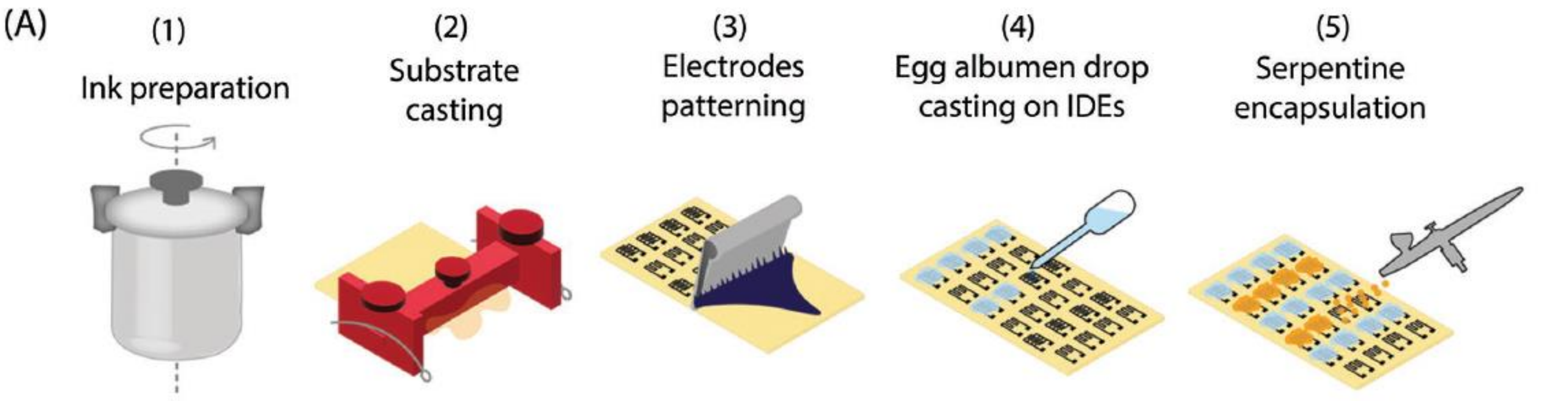
<u>After 8 days</u>

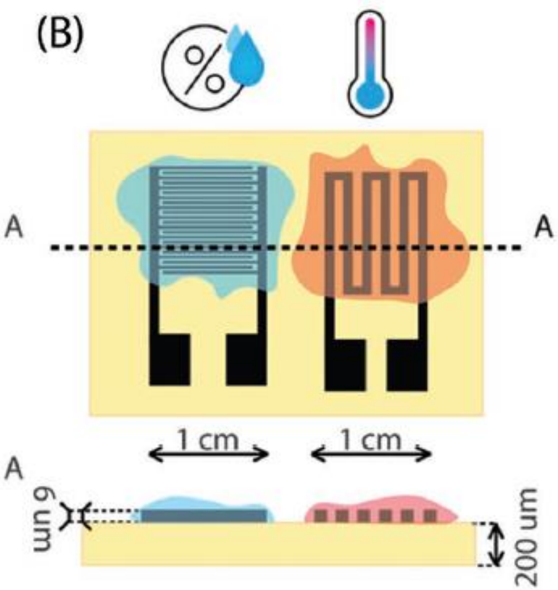
PLA whitening

Au delamination

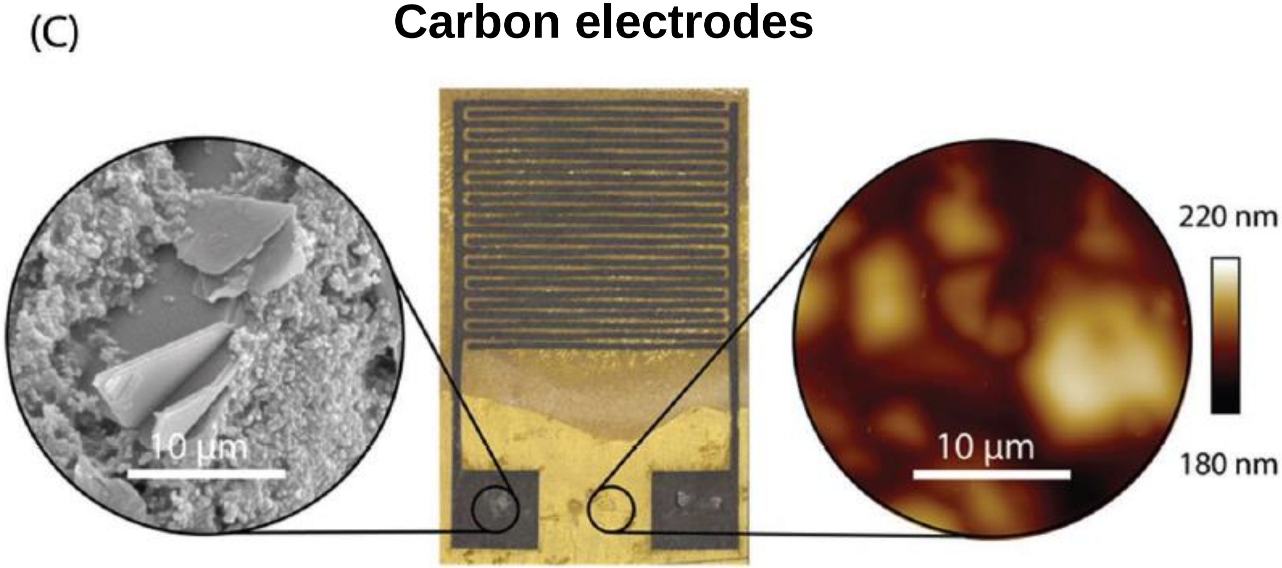


Implementing biodegradable carbon electrodes





Carbon electrodes

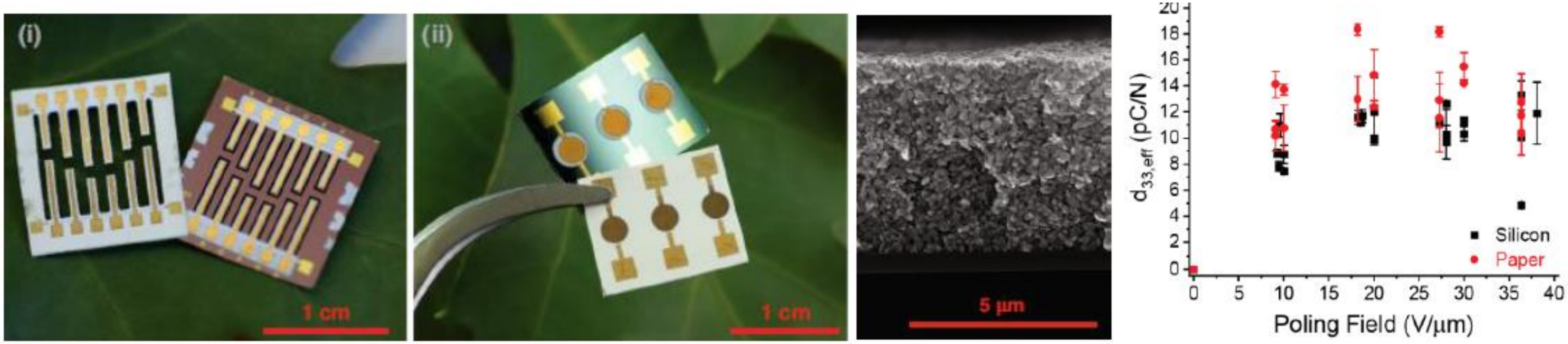


Substrate made of shellac, less sensitive to humidity compared to PLA, paper

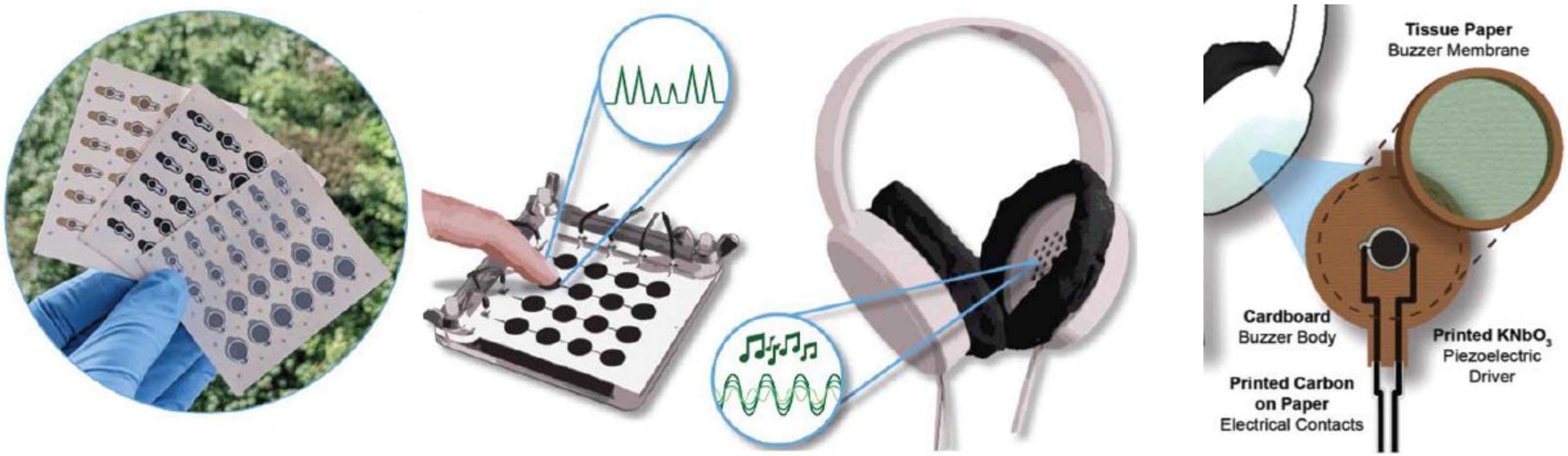
Adv. Mater. Technol. **2022**, 2201302

Eco-friendly piezotronics on paper

Screen printed KN particles ink on paper with low temperature poling



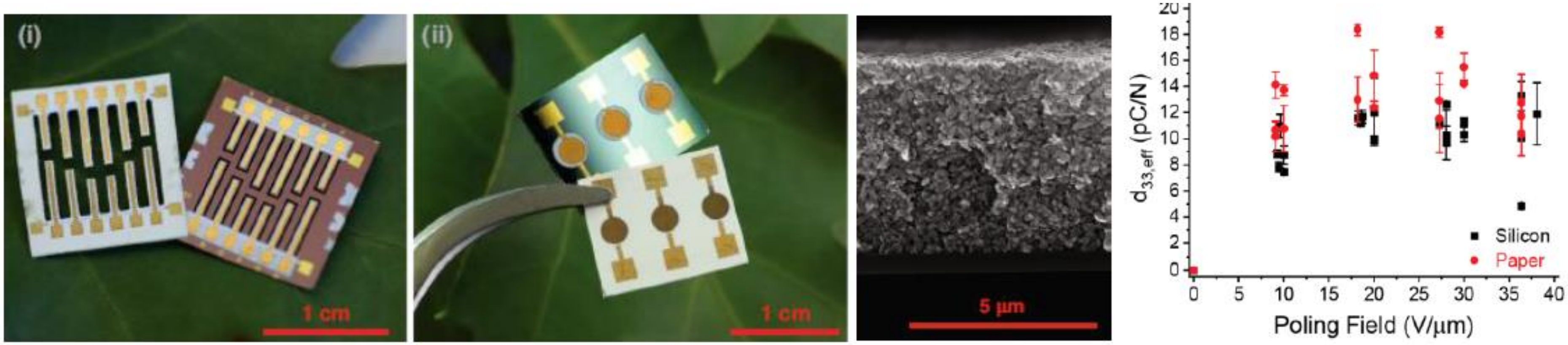
Piezoelectric sensors and actuators made of degradable materials



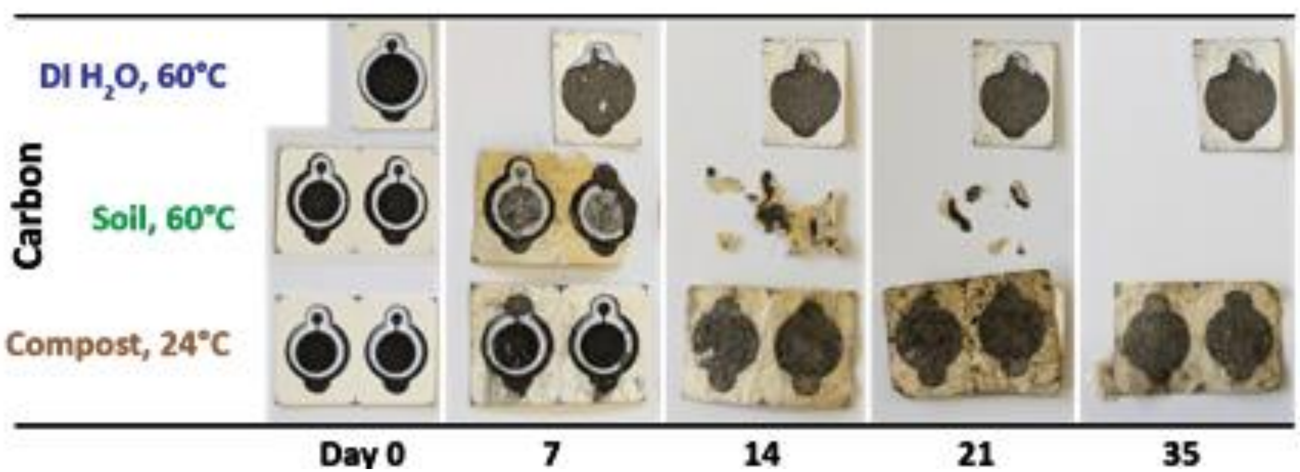
M. Monroe et al., Microsystems and Nanoengineering (2023)
M. Monroe et al., Adv. Materials Technologies (2024)

Eco-friendly piezotronics on paper

Screen printed KN particles ink on paper with low temperature poling



Piezoelectric sensors and actuators made of degradable materials



M. Monroe et al., Microsystems and Nanoengineering (2023)
M. Monroe et al., Adv. Materials Technologies (2024)

Printing of degradable metallic conductors

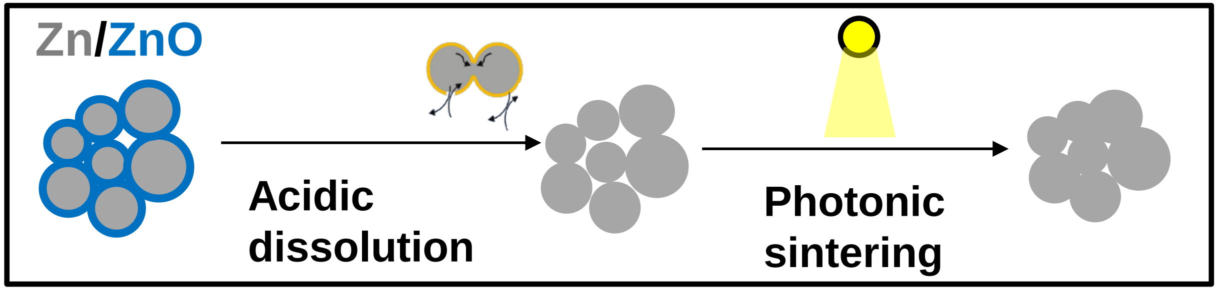
Zinc: lowest melting of the bioresorbable metals
reduction of zinc oxide passivation layer

	Thermal stability[141]	Active material	Solvent
Mg	T_m: 651 °C	Laser-synthesized NPs	N/A
Zn	T_m: 419.5 °C	Milled/wire-exploded NPs[89–91]	Alcohols
Fe	T_m: 1538 °C	Fe/Fe_2O_3 powder[248]	Dichloro-methane
W	T_m: 3410 °C	Wire-exploded NPs[249]	Methanol
Mo	T_m: 2167 °C	Wire-exploded NPs	N/A

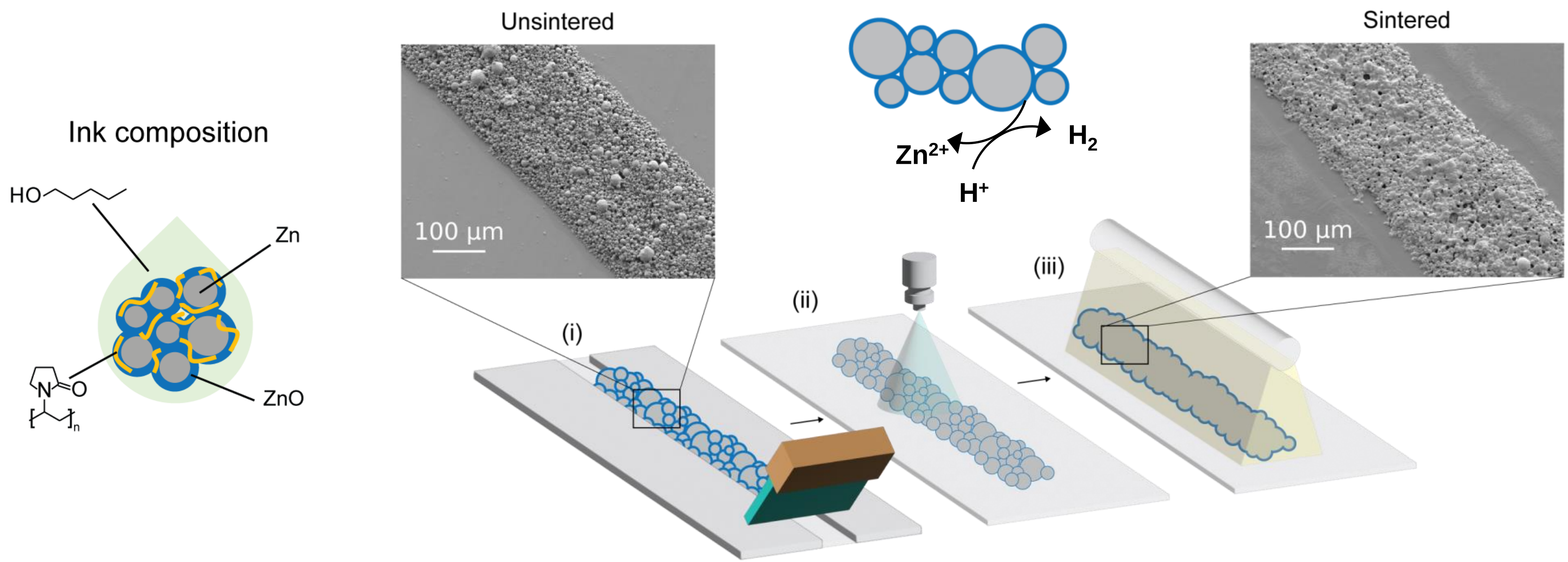
Yu2018

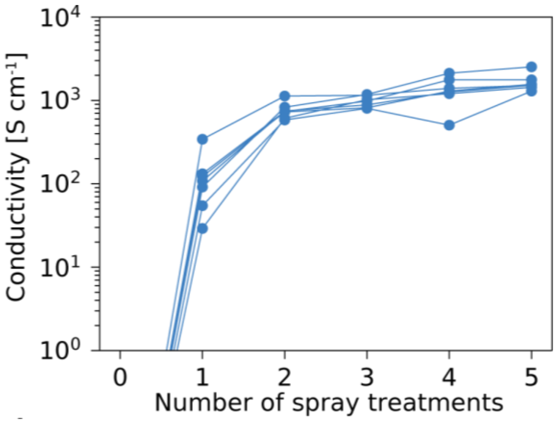
Zinc tracks

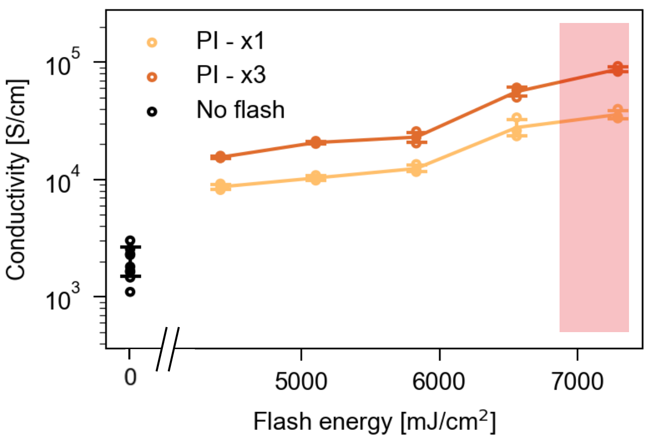
High-resolution printable Zn by combining chemical and photonic sintering (patent pending)

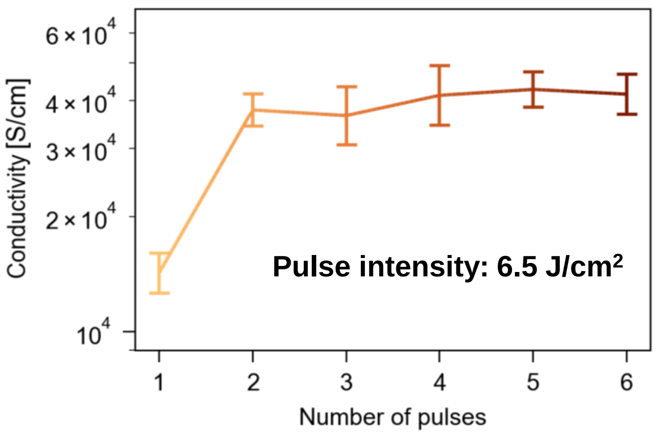


Hybrid sintering of printed zinc metallic ink



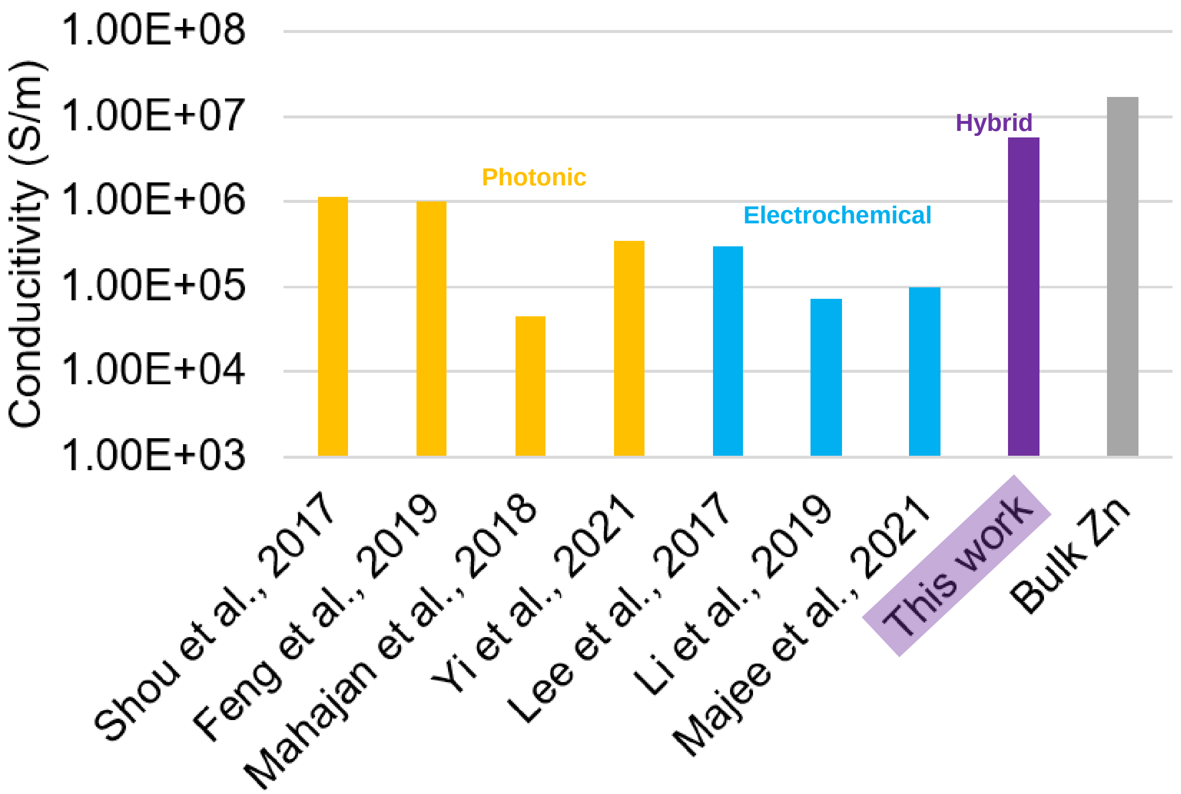






Fumeaux et al., npj Flex. Electron. (2023)

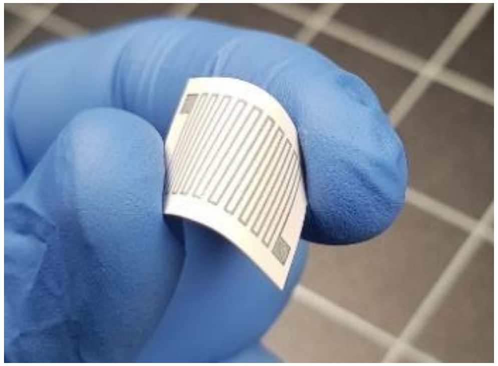
Hybrid sintering of printed zinc metallic ink

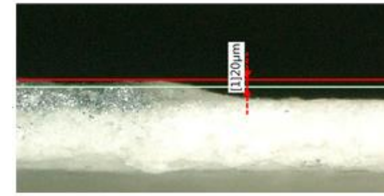


- **Highest electrical conductivity for printed transient metal**
- **Stability compatible with post-processing**
- **High long term stability**

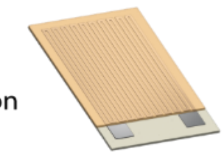
Fumeaux et al., npj Flex. Electron. (2023)

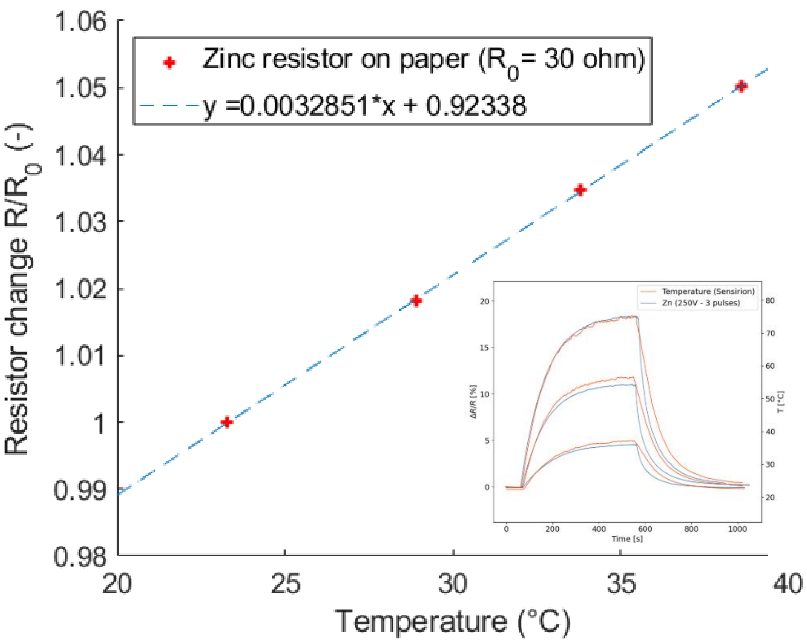
Ecoresorbable Zinc RTD on paper

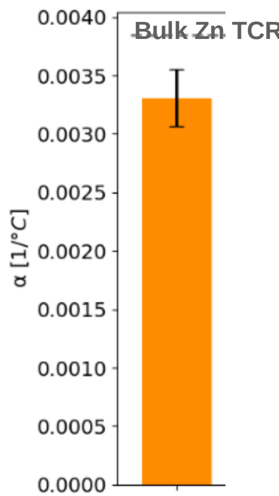


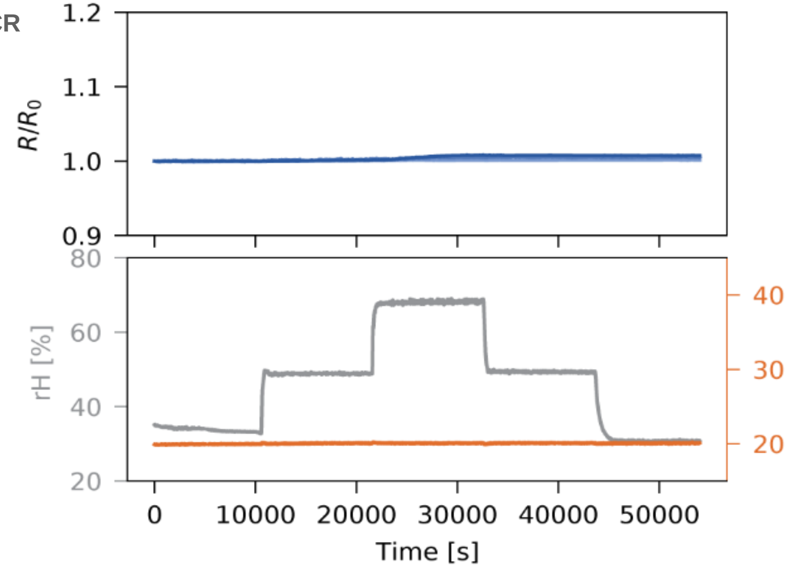


Beeswax encapsulation



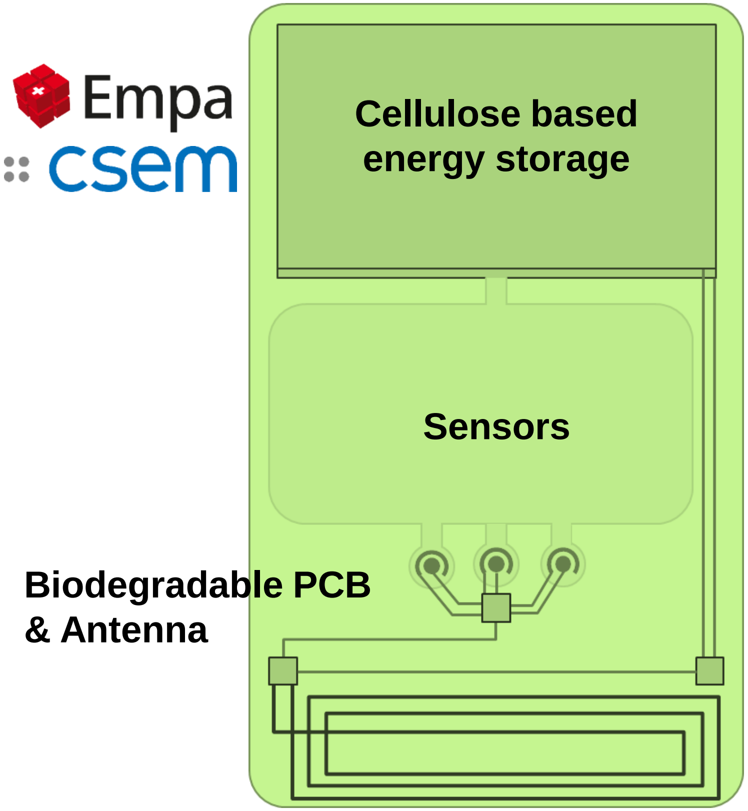






Towards biodegradable smart systems

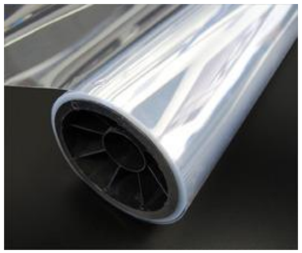
- **Green substrates: Cellulose / biopolymers**
- **No toxic electronic materials: Carbon and biodegradable metals**
- **Compostable electronics**
- **Added environmental value:**
  - Disposable systems
  - Green PCB and electronics
  - Green sensing: packaging, agriculture, environment, IoT
  - Green energy storage (batteries)
  - Bioresorbable implants
  - Edible electronics

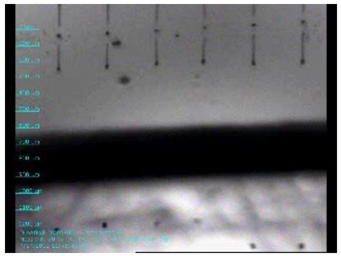


Concept

Fully printed and biodegradable smart systems

⇒ Printing on large area biopolymers/paper



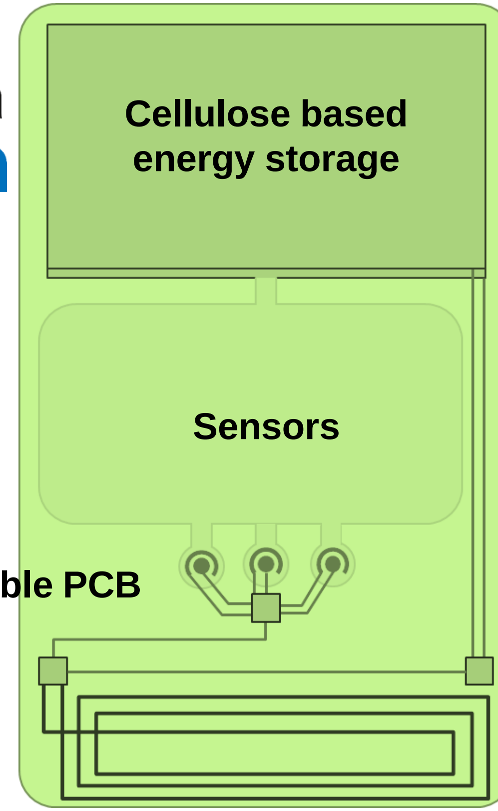


⇒ Biodegradable smart tags

- Biodegradable metals (Zn)
- Very thin silicon or chipless (no Si)
- Sensing capabilities
- Biodegradable battery
- RF read-out and communication

Green manufacturing and disposal

Empa
csem



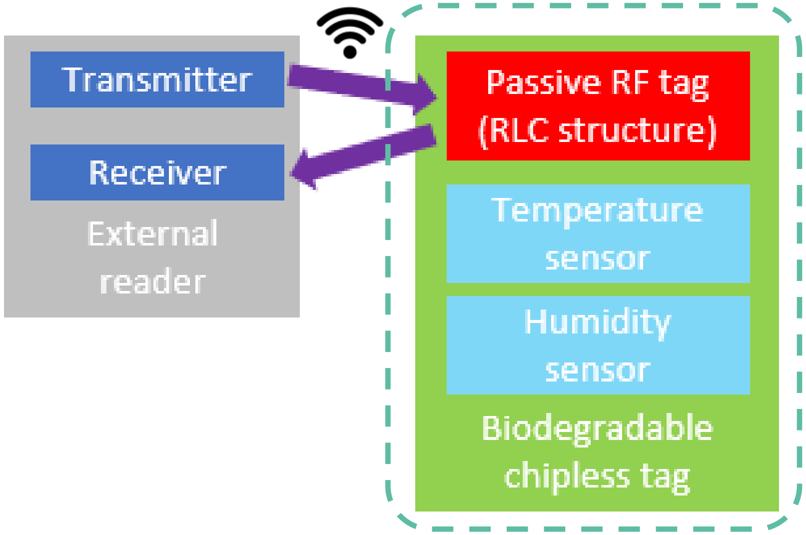
Biodegradable PCB & Antenna

SNF-Bridge
GreenSpack project

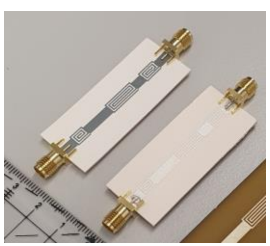
Eco-friendly degradable sensing tags

Environmental sensing tags:

- Biodegradable
- Fully printed
- T° and RH sensing
  - Continuous
  - stimuli-responsive
- Wireless & chipless (no Si components)



General concept



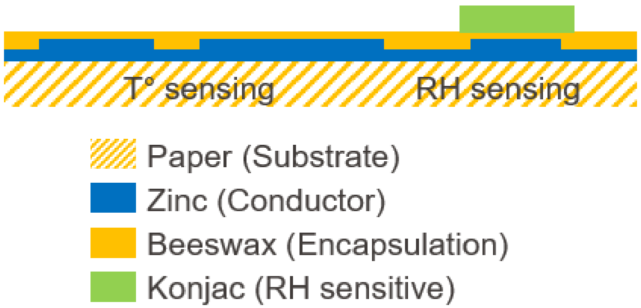
Biodegradable antenna on paper
ArjoWiggins: HD800 µm

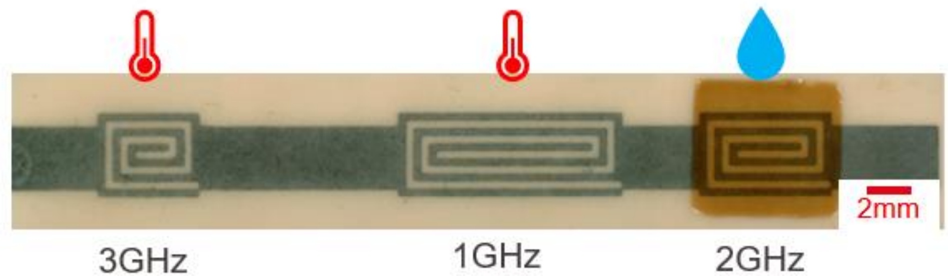
RLC RF Zinc resonators printed on paper

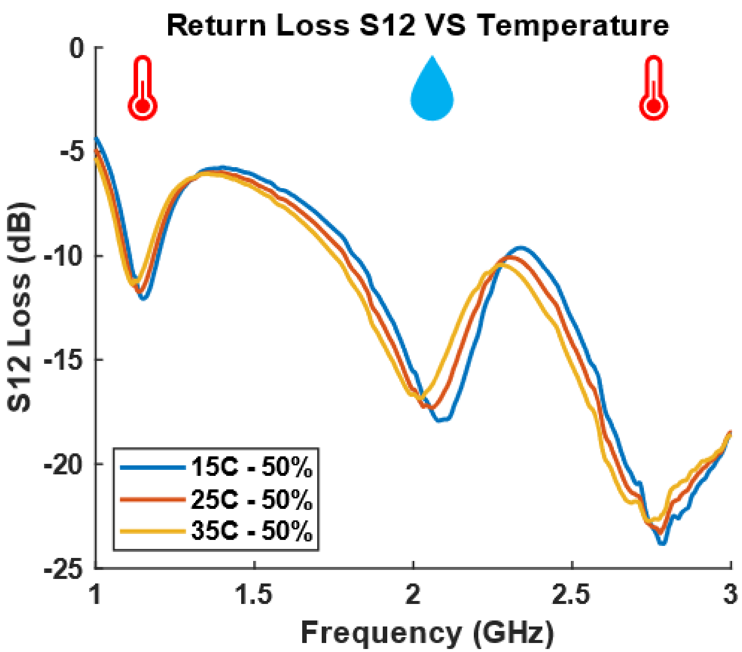
GREENsPACK – SNF Bridge

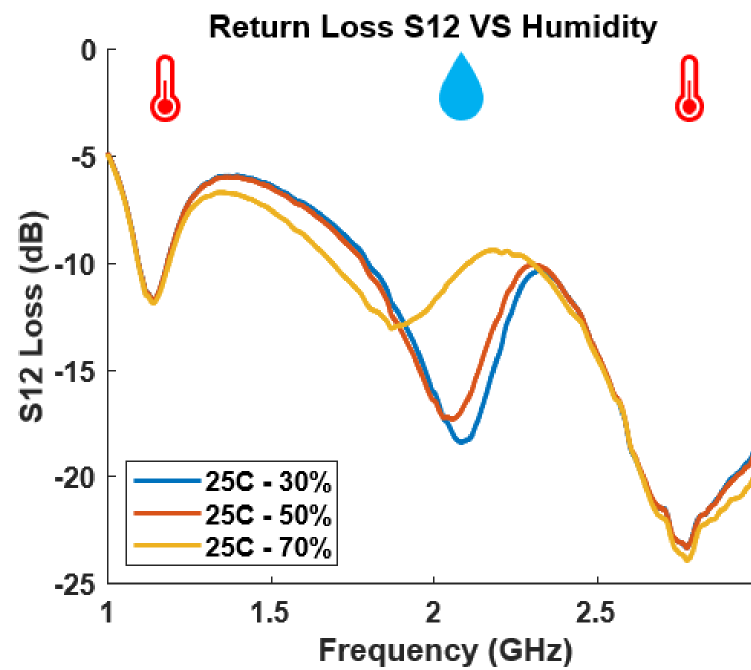
Eco-disposable chipless sensing tags

RF Zinc striplines printed on paper









Temperature increases losses ($TCR\ of\ zinc = 0.0038$)

Konjac absorbs water → $\Delta\varepsilon_r$
Encapsulated T° resonators do not change

Bourely et al., under publication

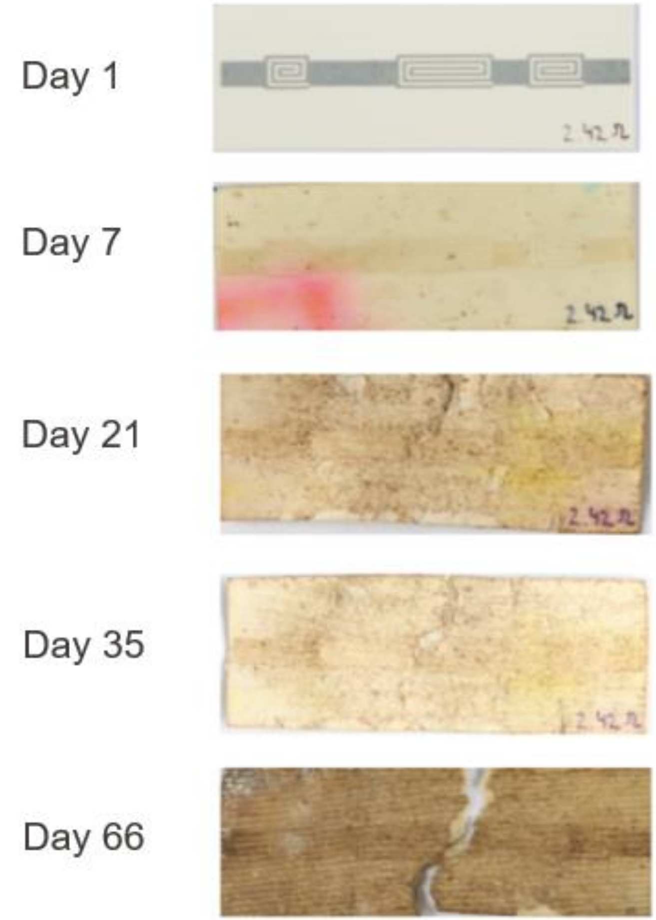
Biodegradation in compost

- According to ISO 20200

58°C in solid waste compost

Controlled pH and humidity

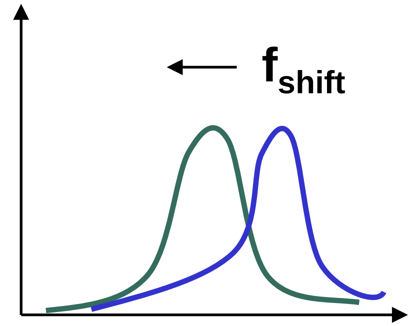
→ Degradation of the zinc after 1 week
→ Cellulose/beeswax degradation starting after 3 weeks

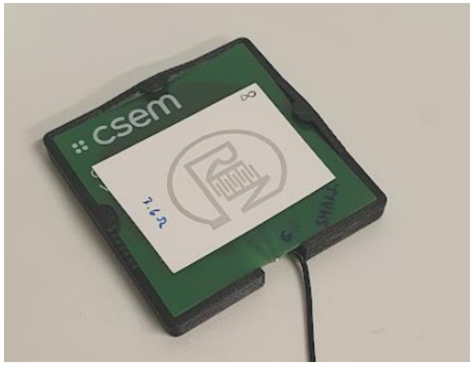


Temperature threshold chipless tag

$T > T_{threshold}$

T has crossed $T_{threshold}$

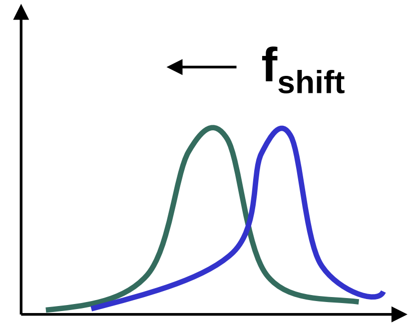


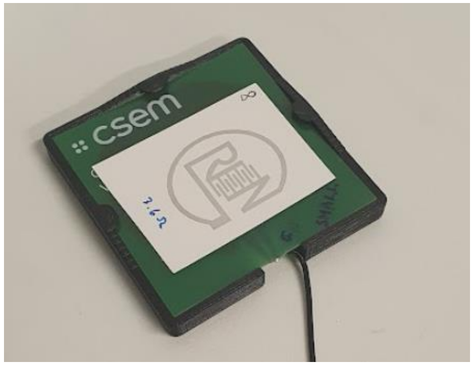


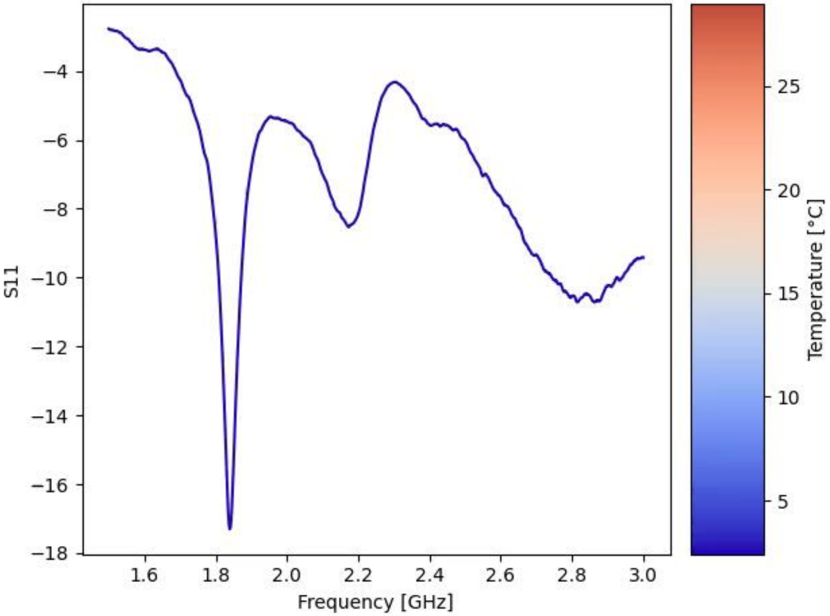
Temperature threshold chipless tag

$T > T_{threshold}$

T has crossed $T_{threshold}$

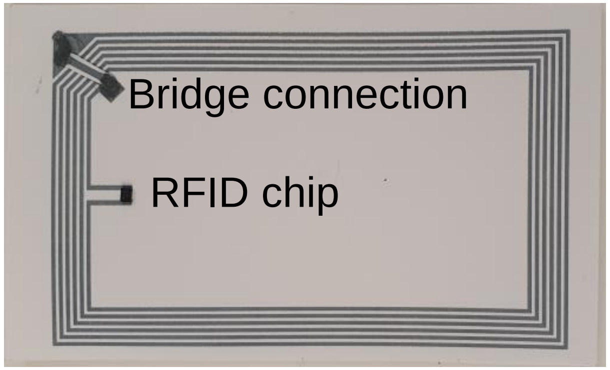


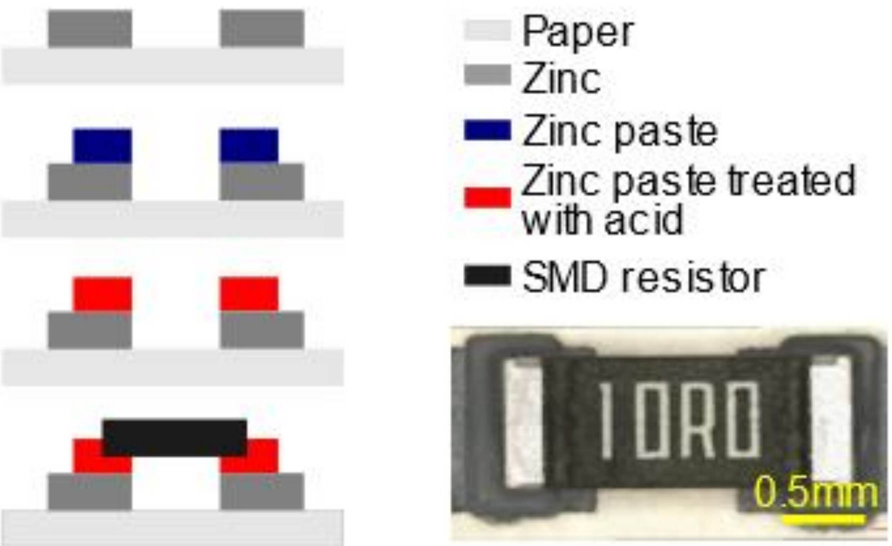




RFID tag fully made of degradable materials

- Screen printed Zinc antenna on paper
- RFID chip transfer using a Zinc electrically conductive adhesive





Presented at Eurosensors 2023 conference

End of Life

The status is that OPE components are mainly treated as:

- Electronic waste
- Garbage waste if environmental friendly (to be burnt or buried)
- Or electronics associated to other types of waste: white goods, textile, etc

Regulations and infrastructure still to be developed for their environmental friendly disposal:

- Circular economy model to recycle/ to reuse some or all parts (preferred but still complex)

- Composting or biomining for clean disposal and to recover some materials, require collection of high volume of OPE (but OPE products are heteroclite)

- **If not disposed properly**: micro-plastic generation, nanotoxicology, etc !!!

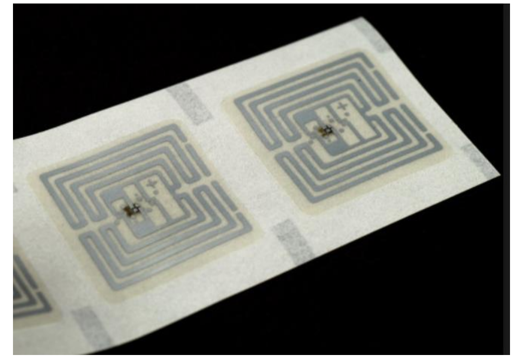
End of Life

Paper electronics: circuits, sensors

Sekitani & Someya
University of Tokyo

Stora Enso Smart packaging

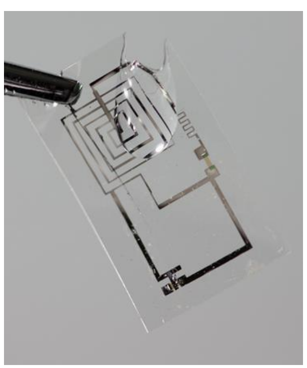
Circular economy model to be developed



- Paper recyclable

Paper RFID tag

Biodegradable transient electronics



John Rogers lab, USA

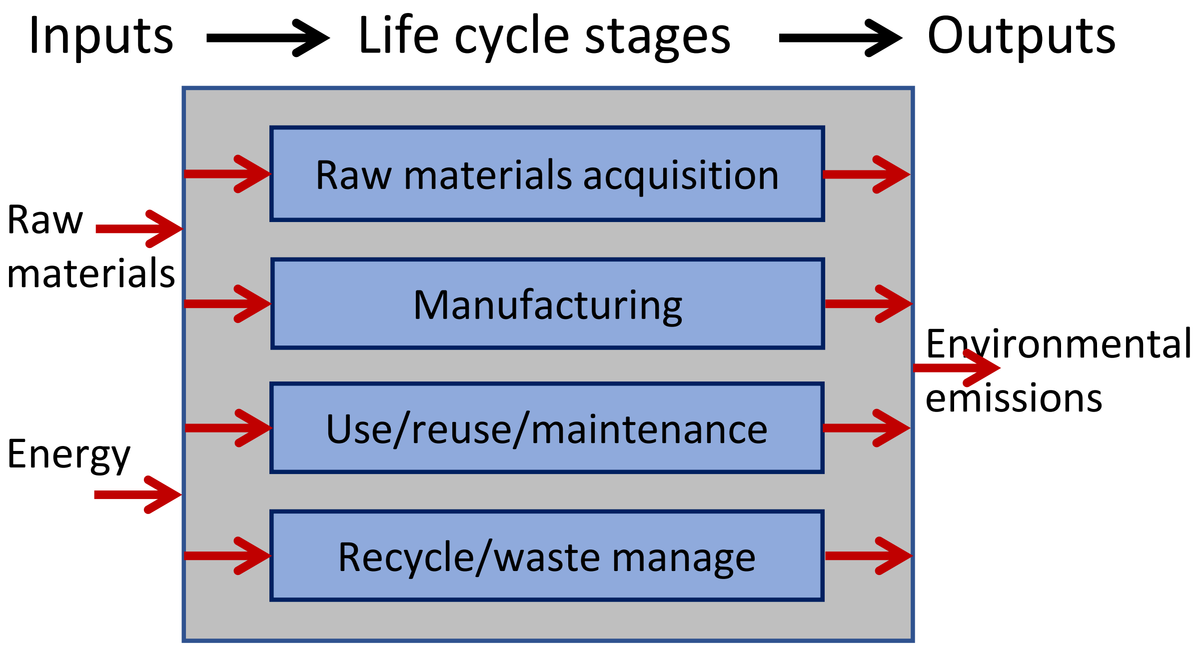
Salvatore G. A. et al. *Adv. Funct. Mater.* 2017, *27*, 1–10.

Collection of systems ?

Biodegradable silicon electronics demonstrated

Life Cycle Assessment Analysis (LCA)

Life cycle assessment to be established to determine the real and complete carbon foot print to be able to compare the greeniness of different technologies



LCA: Methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product.

An LCA study involves a thorough inventory of the energy and materials that are required across the industry value chain of the product and calculates the corresponding emissions to the environment. LCA thus assesses cumulative potential environmental impacts.

Conclusions

Additive manufacturing in combination with eco-friendly and renewable materials can lead to more sustainable electronics

Potential fields of application:

- Disposable IoT and systems
- PCB and electronics
- Smart packaging and agriculture
- Edible and implantable electronics
- Energy storage (i.e. batteries and supercapacitors)
- Edible and implantable electronics

The End of Life of FPE technologies needs to be addressed to fully exploit its eco-friendly potential

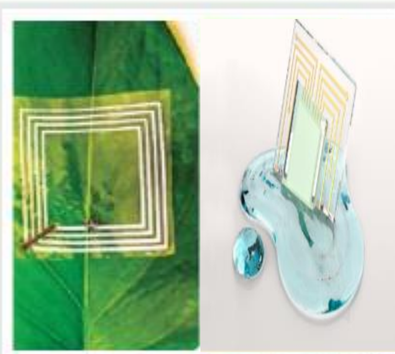
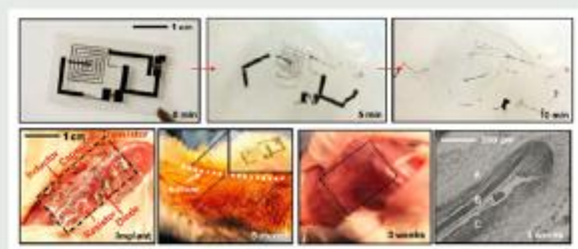
LCA to be performed to assess the environmental impact

Some questions

- How can OPE contribute to more sustainable electronics
- Challenges to produce sustainable electronics
- Materials and processes for greener electronics
- Some exemples of devices: materials, process, operation
- Potential strategies to reduce e-waste based on OPE technologies

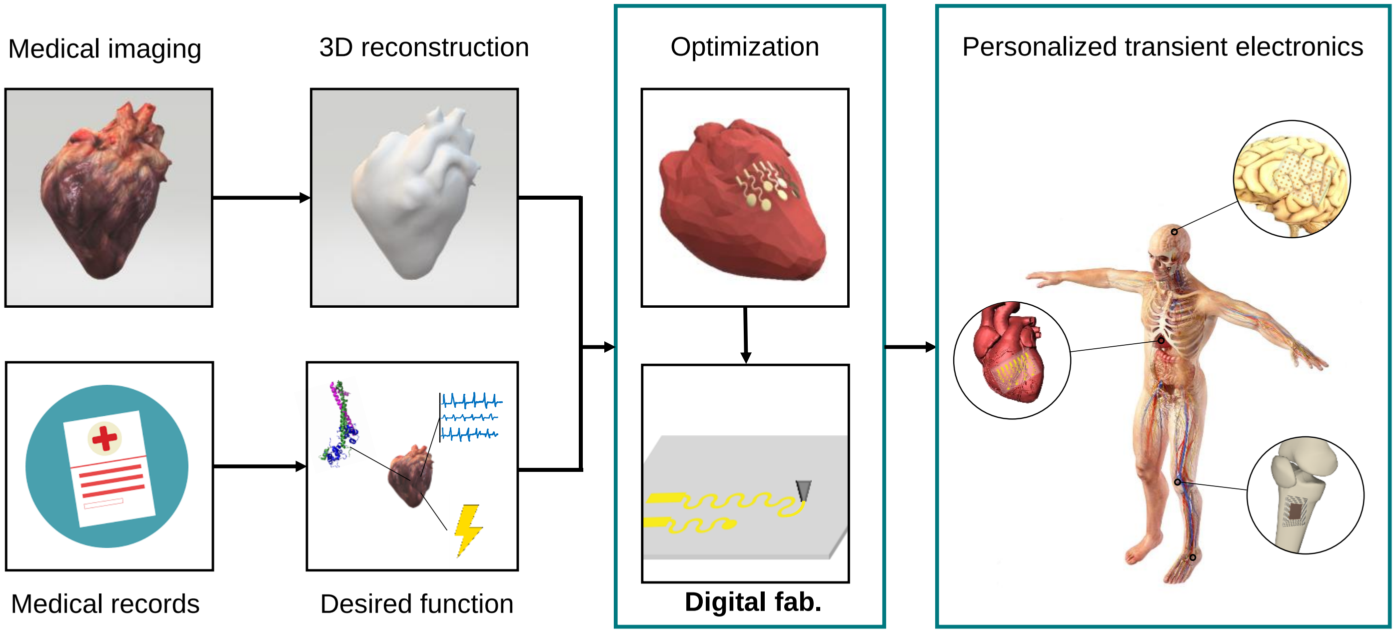
«Transient» materials & electronics

Devices that perform their function and degrade after a trigger/the desired period of time

Transient		Intransient
(Bio)degradable	**Bioresorbable**	**Biocompatible**
Breaks down in the environment into nontoxic and/or inert components	Safely implantable in humans *and* disappears after a period of time	Safely implantable in humans without causing them any long-term harm, but remains in place
 *Fu2016* *Huang2014*	 *Hwang2012*	 *Lei2017*

"Can degrade into smaller environmentally harmless substances"

Customized 3D bioresorbable implants



Electrodes, physical and (bio)chemical sensors for nerve /spinal cord, brain, gut, heart…