



**IV Riunione IU.NET, Perugia 21-22 Settembre 2017**

# **Circuits on Cellulose Enabling LAE and Distributed Sensing**

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# IoT: solution or problem ?



# Electronic Waste

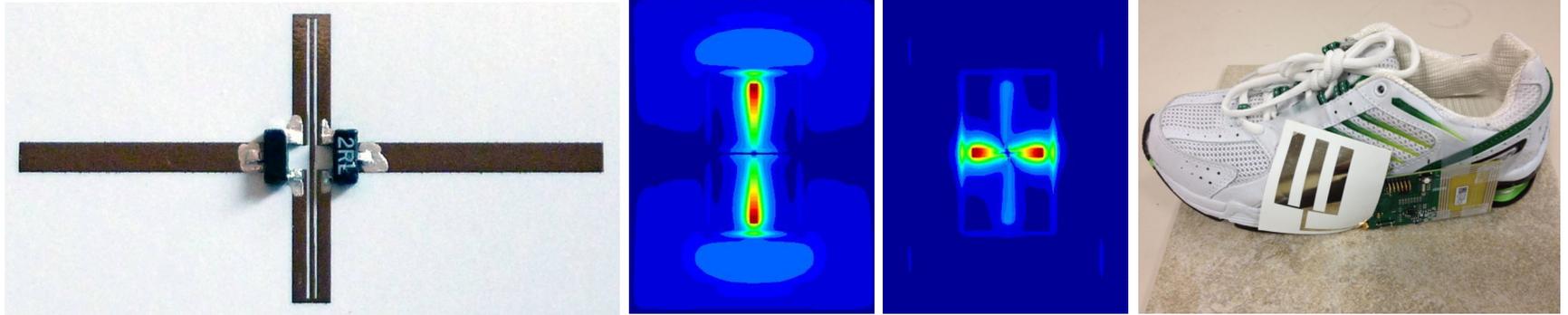
**50 million**  
metric tons per year



**9 Cheops Pyramids !**

# Circuits on Cellulose

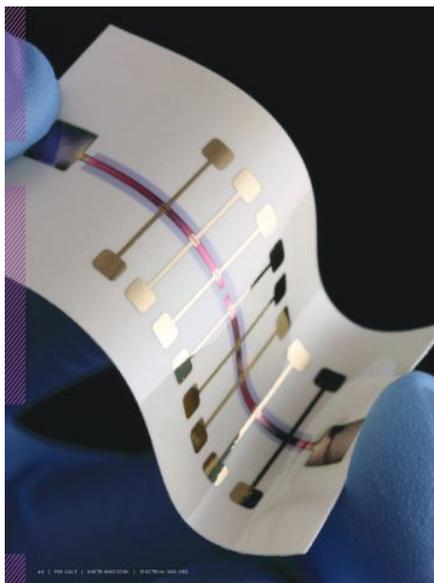
Georgia Institute of Technology (USA) + University of Perugia (IT)



**Environment  
Saving**

**Cost  
Reduction**

**Novel  
Applications**



University of Cincinnati (USA)

**LAE**

**Distributed  
Sensing**

# Surely you're joking ...



**Paper Bridge  
(cardboard tube)**

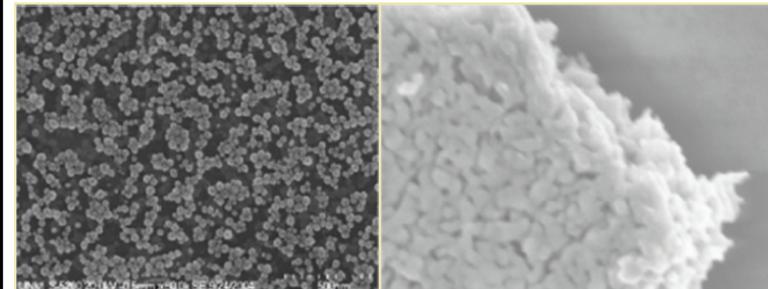
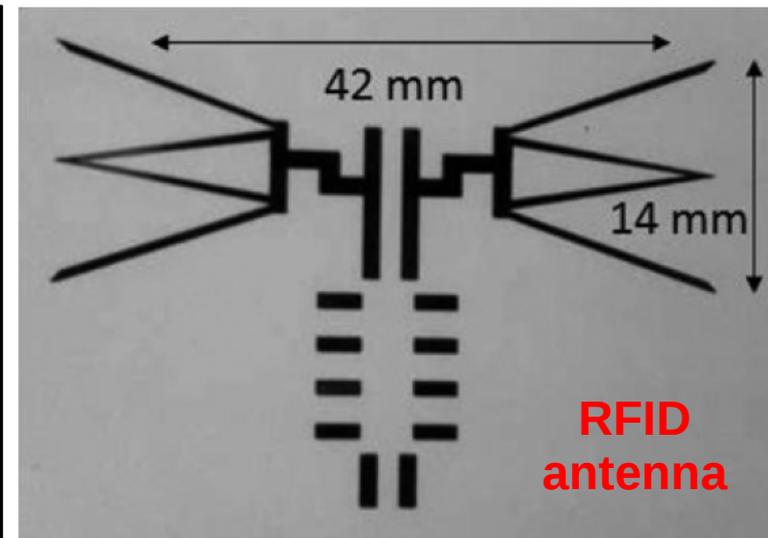
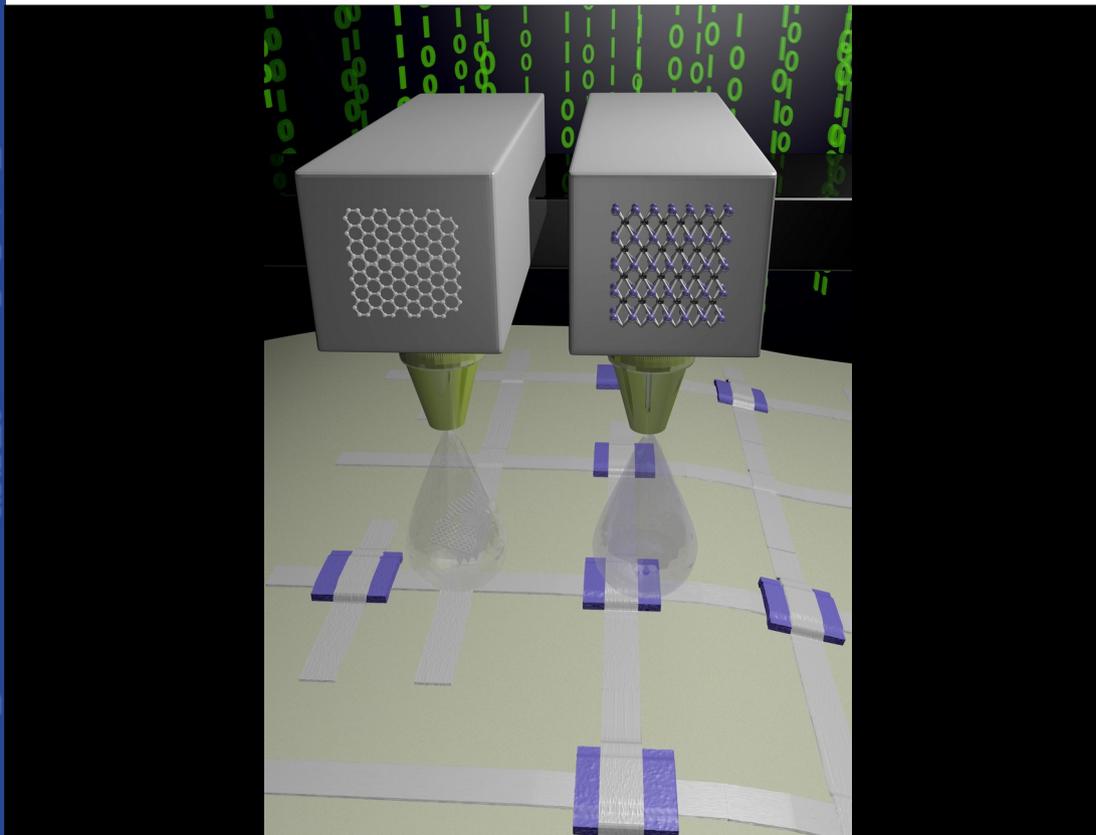
**Shigeru Ban**



## **Cellulose (paper) is:**

- ✓ the most common natural polymer
- ✓ practically inexpensive
- ✓ recyclable
- ✓ biodegradable

# Technology: inkjet printing (1/3)



University of Pisa &  
University of Manchester



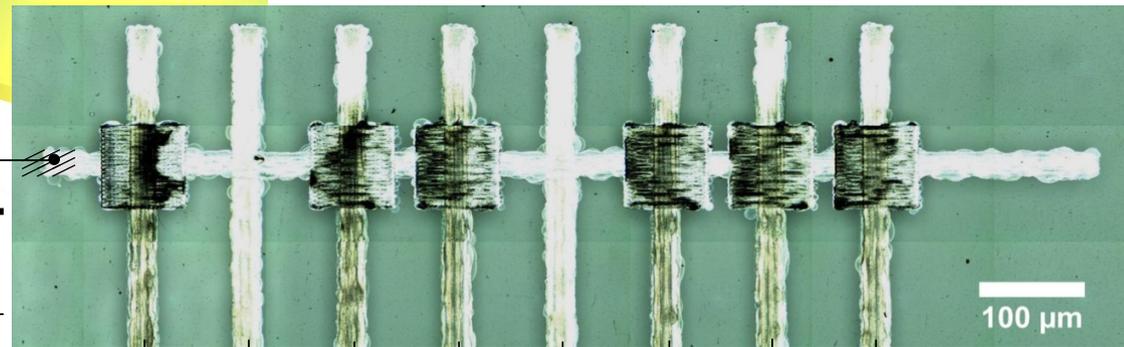
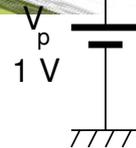
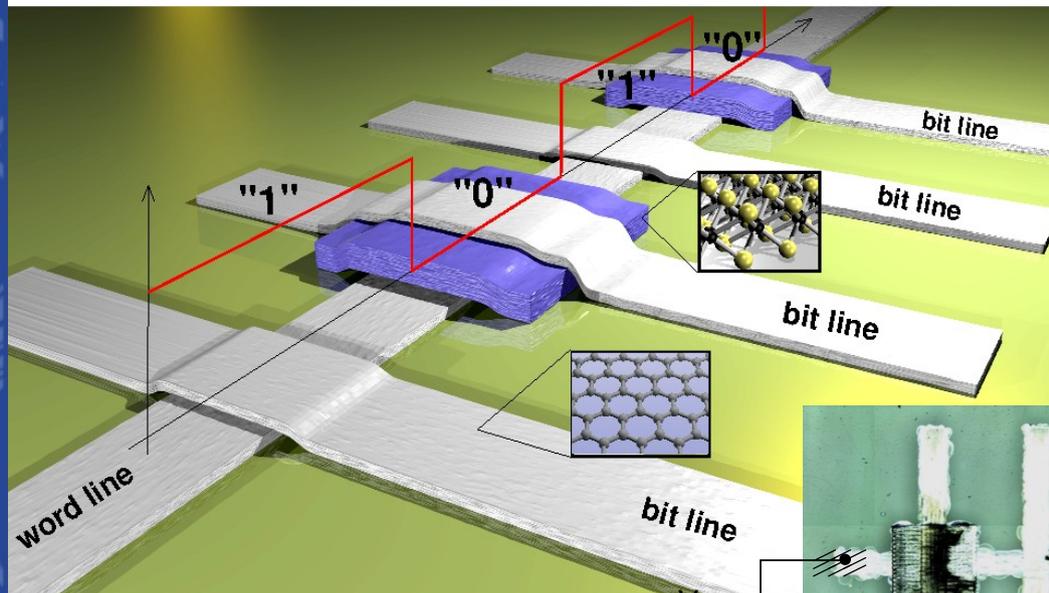
MANCHESTER  
1824

University of Perugia &  
Georgia Institute of Technology

After G. Orecchini *et al.*, in  
IET Microwave Antennas and  
Propagation, N. 8, Aug. 2011.

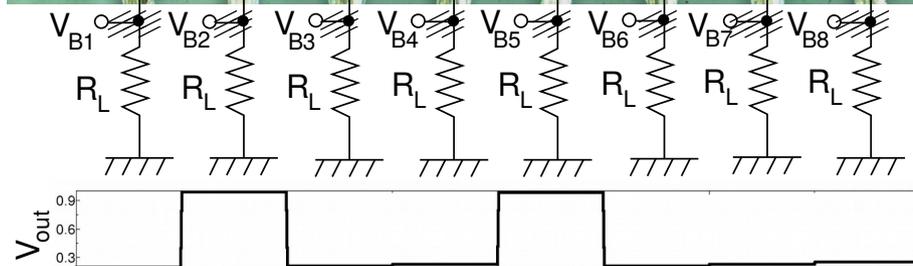
**IET Premium (Best Paper)  
Award, Year 2013**

# Technology: inkjet printing (2/3)

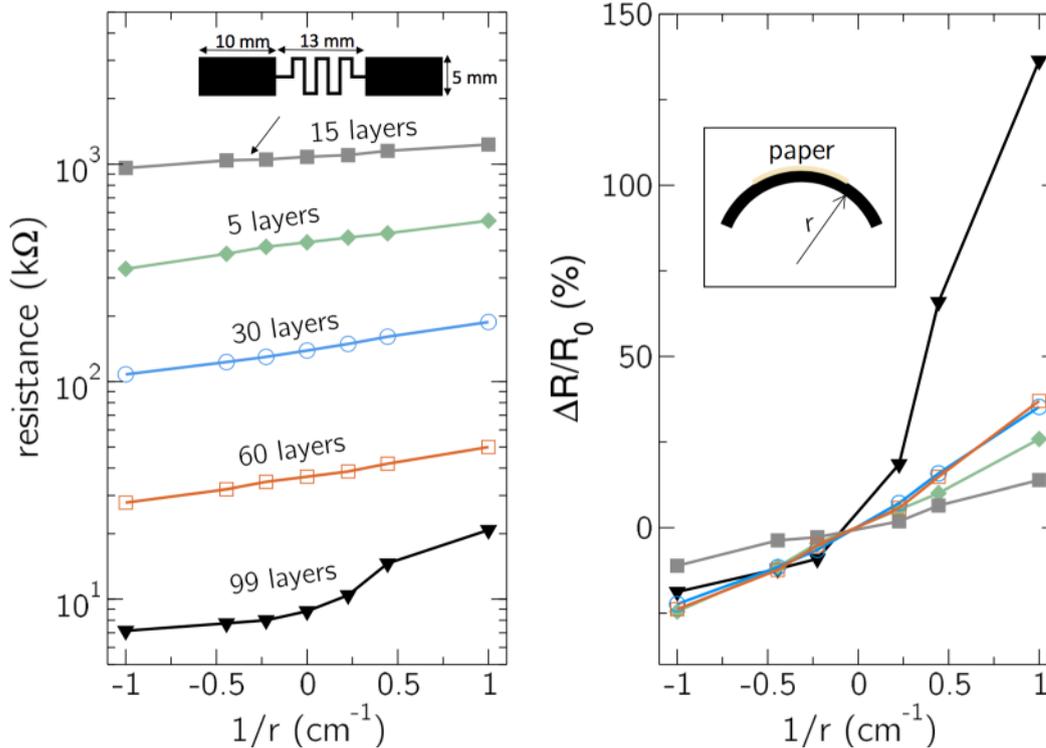


After D. McManus *et al.* in Nature Nanotechnology, 2017

✓ memory device  
proof of concept



# Technology: inkjet printing (3/3)

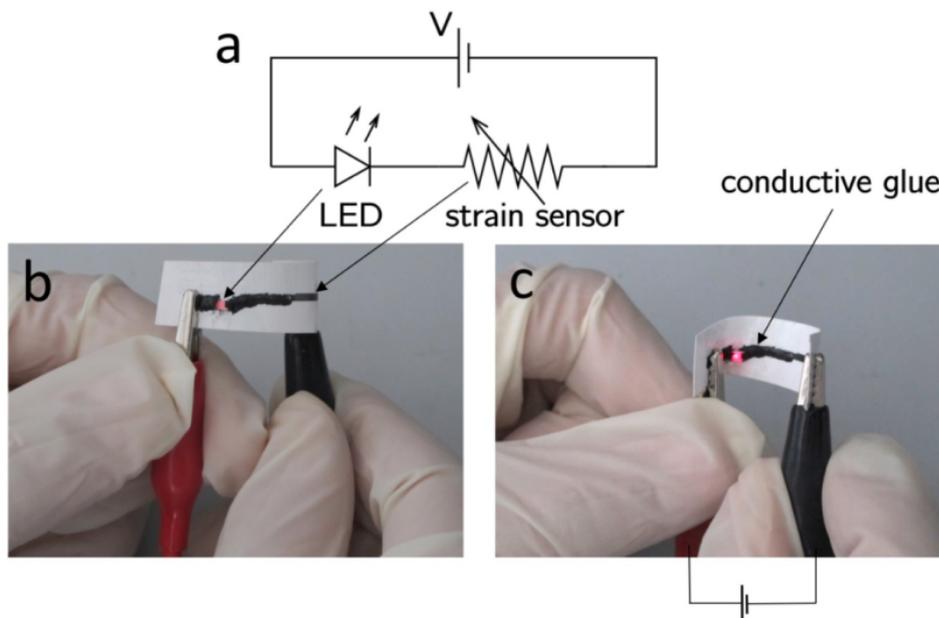


available at:

<http://arxiv.org/abs/1708.09829>

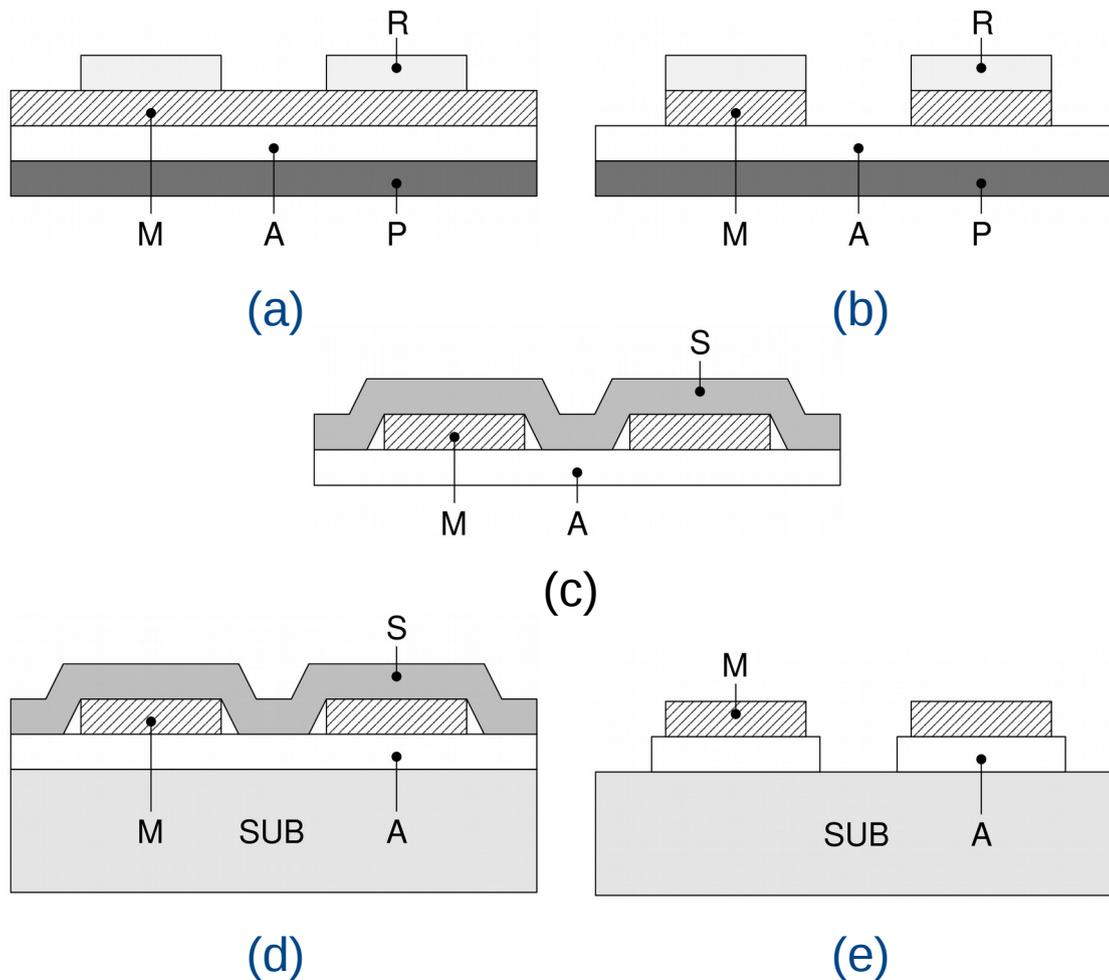


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✓ strain gauge on paper: proof of concept

# Technology: copper laminate

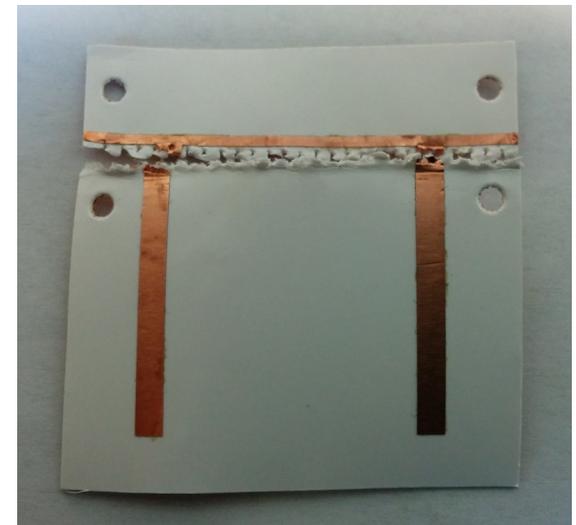
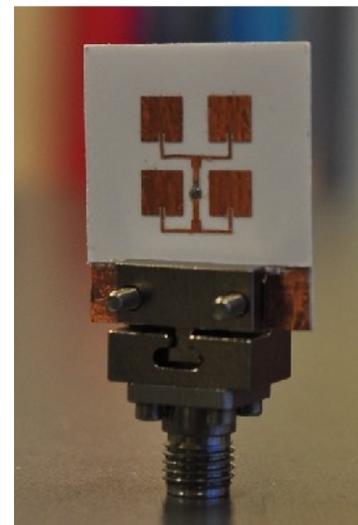
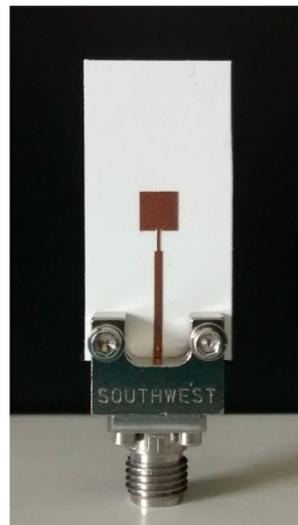
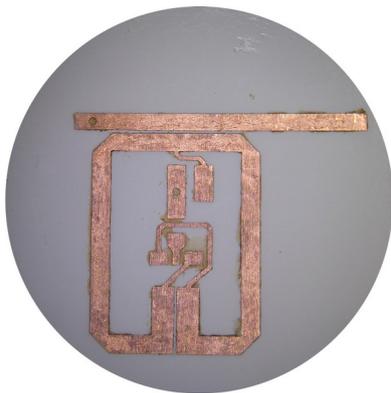
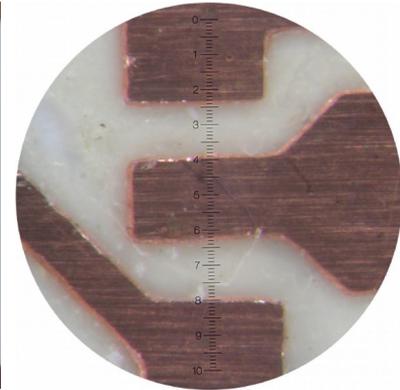
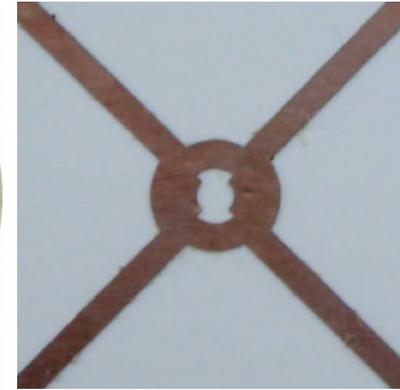
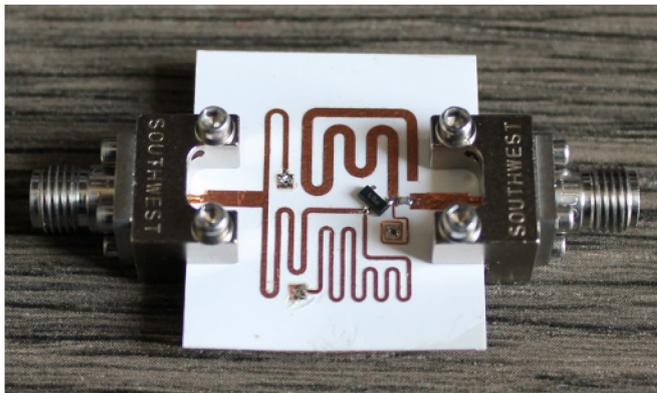
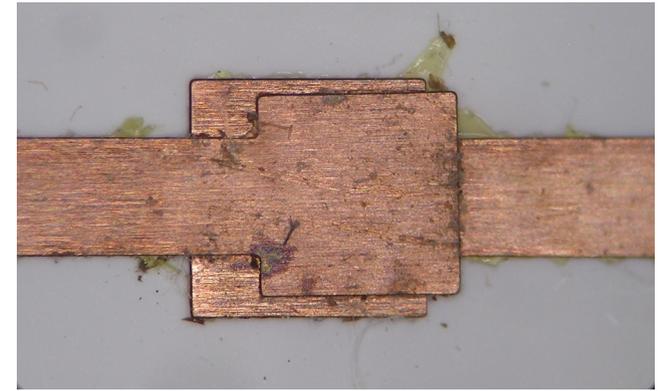
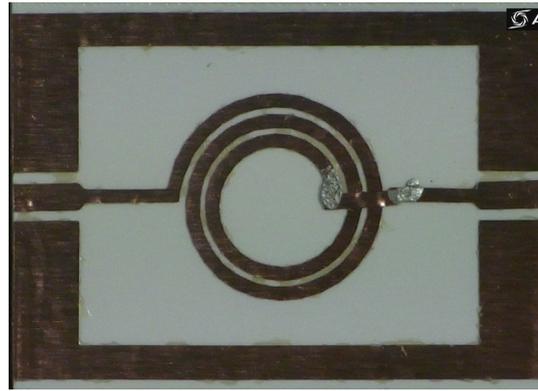
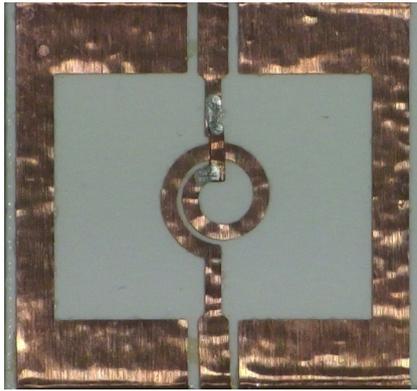


After **F. Alimenti et al.**, in *IEEE Microwave and Wireless Component Letters*, Dec. 2012.

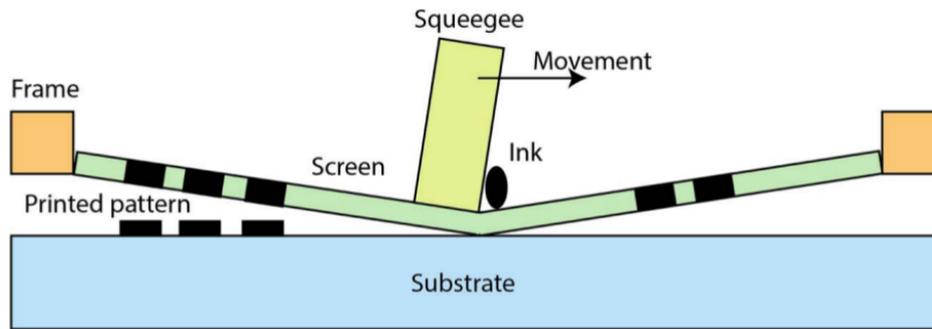


- ✓ The adhesive copper tape is **etched by photo-lithography**.
- ✓ Layout **transferred** to the host substrate **via sacrificial layer**.
- ✓ **The circuit can be stuck on demand !**

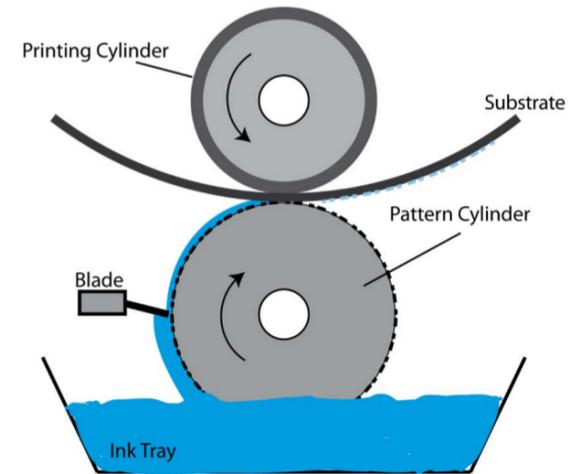
# RF circuits on cellulose



# Large-Area Electronics

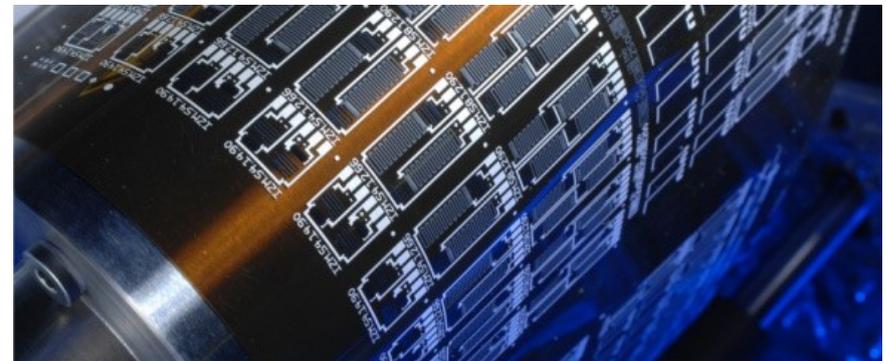
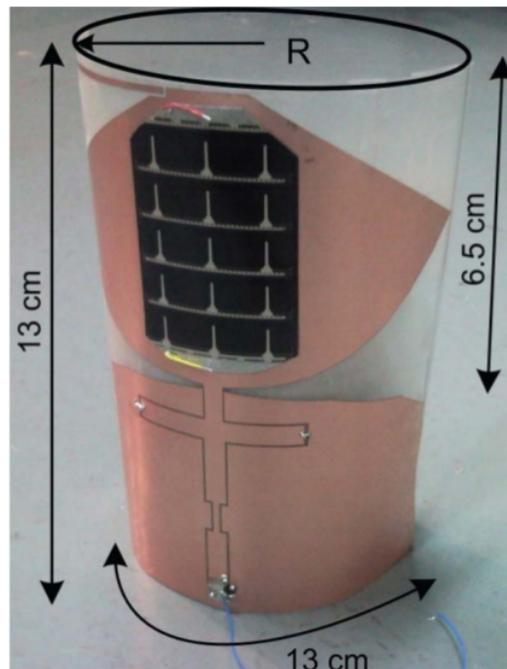


✓ screen printing



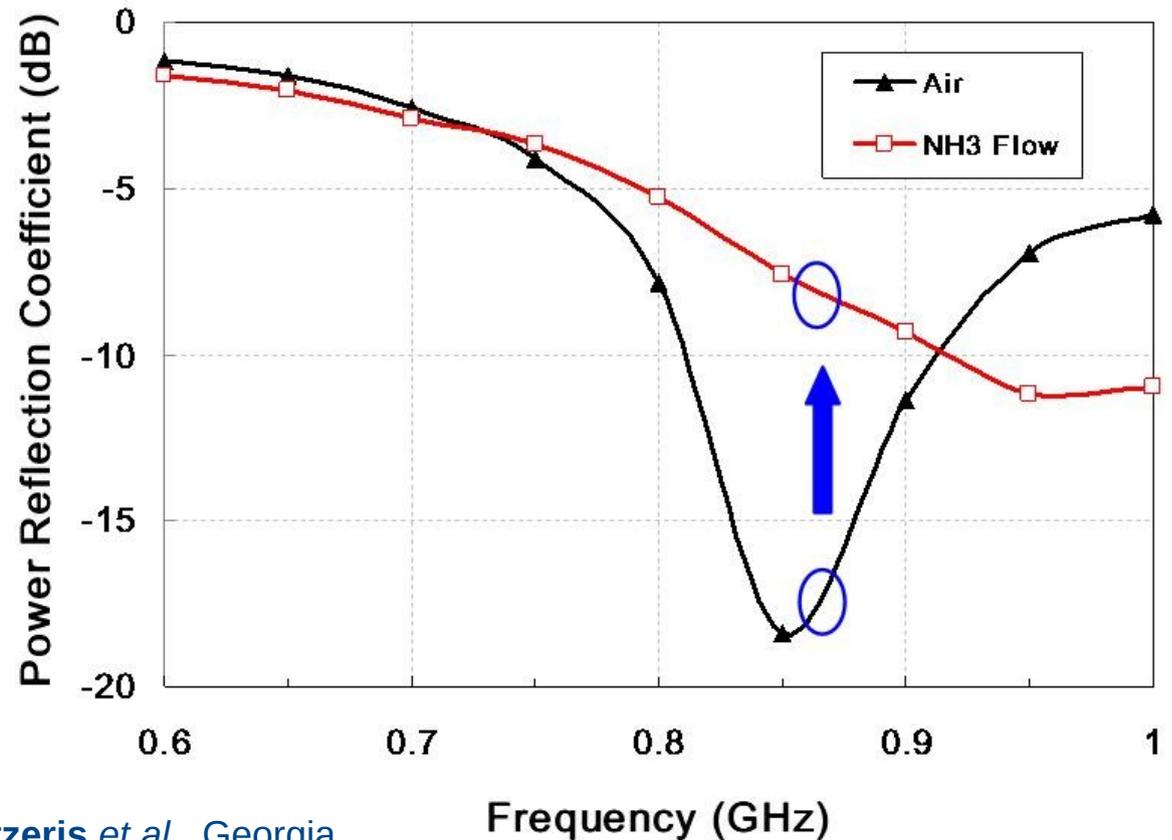
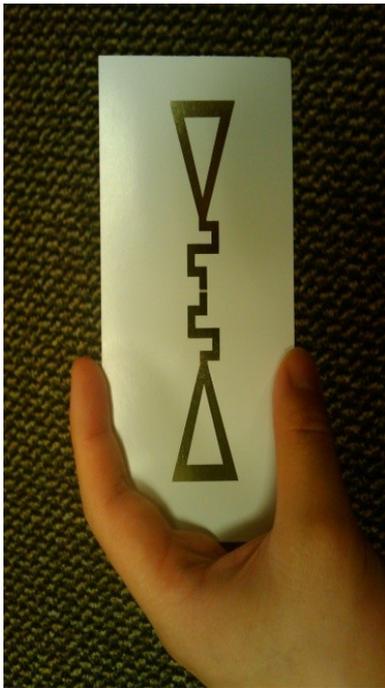
✓ gravure printing

After A. Collado et al., in IEEE Trans. Circ. Syst. I, Aug. 2013.



- ✓ Organic electronics
- ✓ PV cells
- ✓ LAE on cellulose ?

# Gas sensor



Cooperation with Prof. M. Tentzeris *et al.*, Georgia Institute of Technology, Atlanta (GA), USA

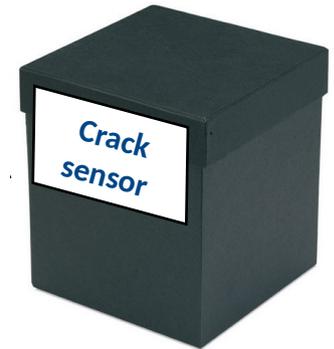
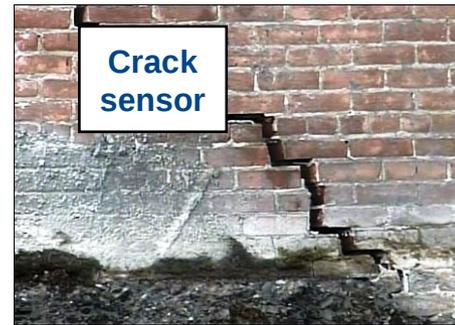
- ✓ **RFID chip-less tag**: antenna on cellulose loaded with a CNT layer.
- ✓ The **CNT** layer acts as a resistor sensitive to the **NH<sub>3</sub>** concentration.
- ✓ **The impedance changes are detected as a variation of the backscattered power level.**

# Crack sensor

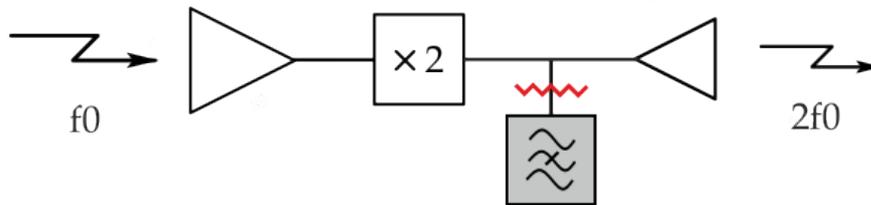
Sensor suitable for:

- ✓ Structural health monitoring
- ✓ Electronic sealing
- ✓ Supply chain monitoring

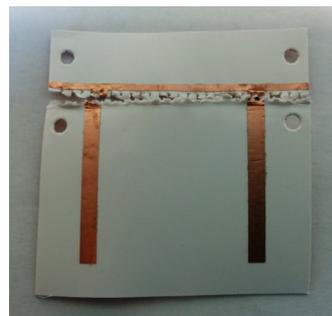
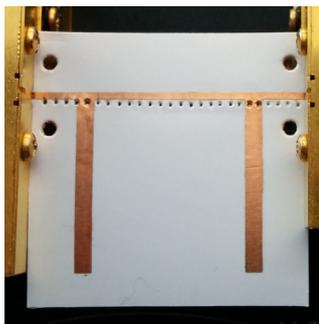
After V. Palazzi *et al.*, Wireless Power Transfer Journal, Cambridge University Press, Nov. 2015.



$f_0 = 1.04 \text{ GHz}$



Band-Stop Filter (BSF)

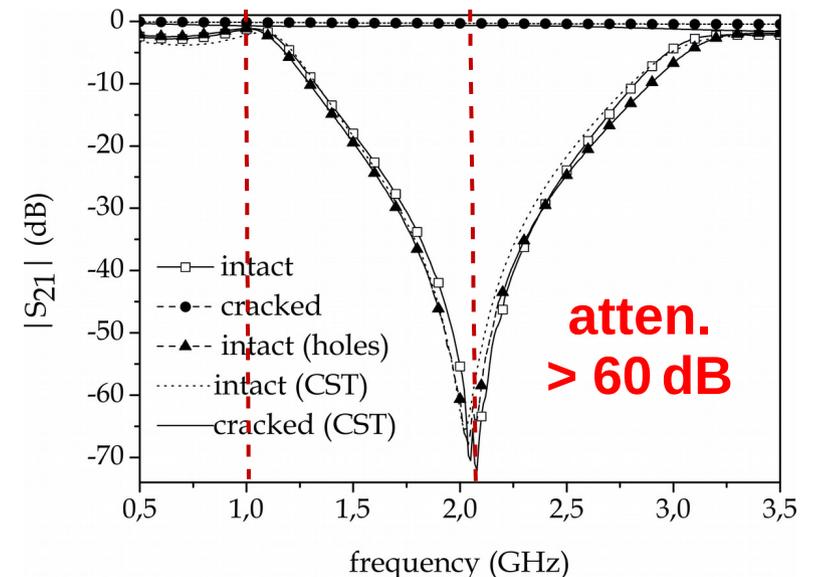


26 mm

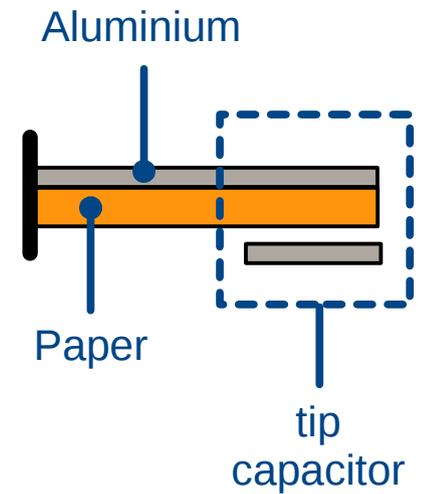
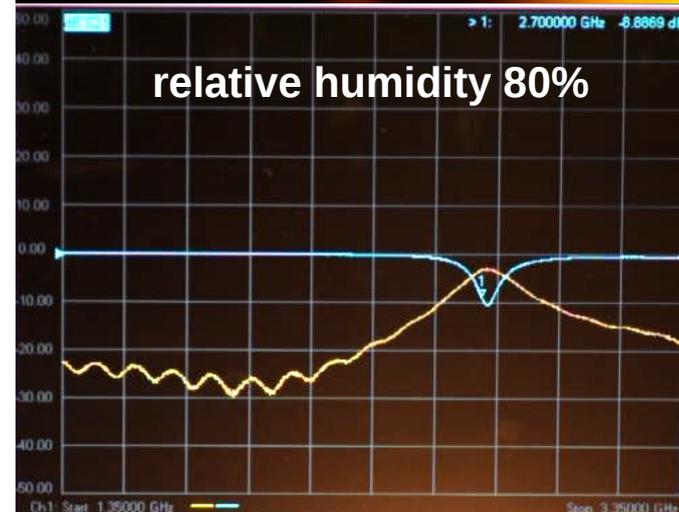
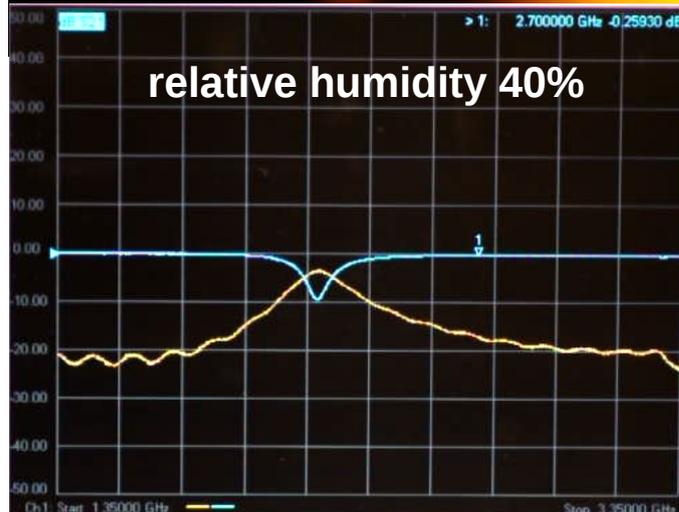
Disposable  
(cellulose-based)

## Operation principle

- ✓ Intact:  $2f_0$  short-circuited by the band-stop filter.
- ✓ Cracked:  $2f_0$  can reach the antenna ---> alarm !



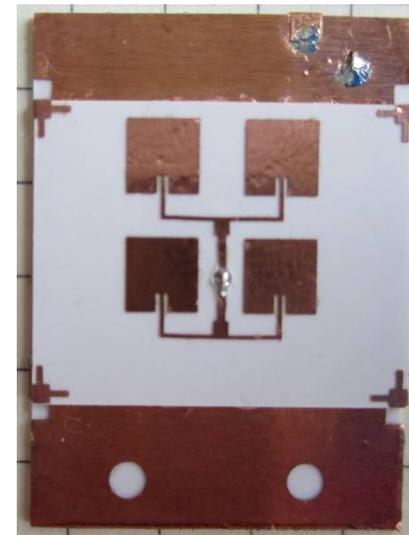
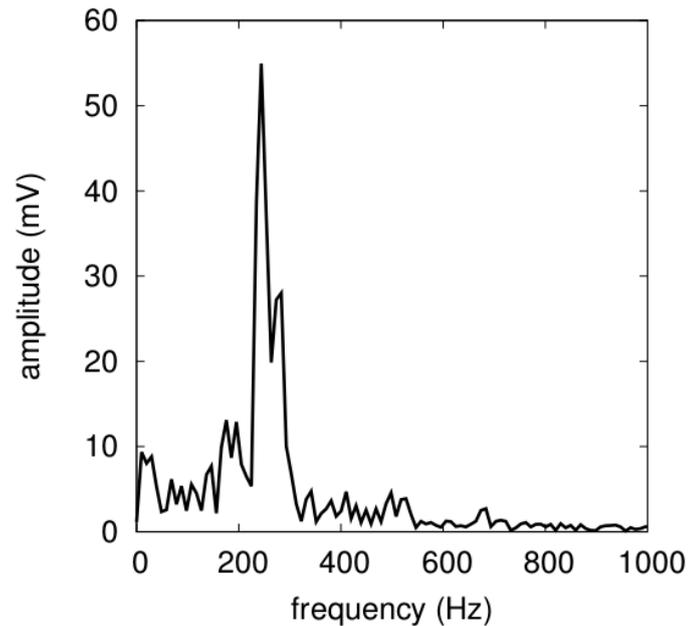
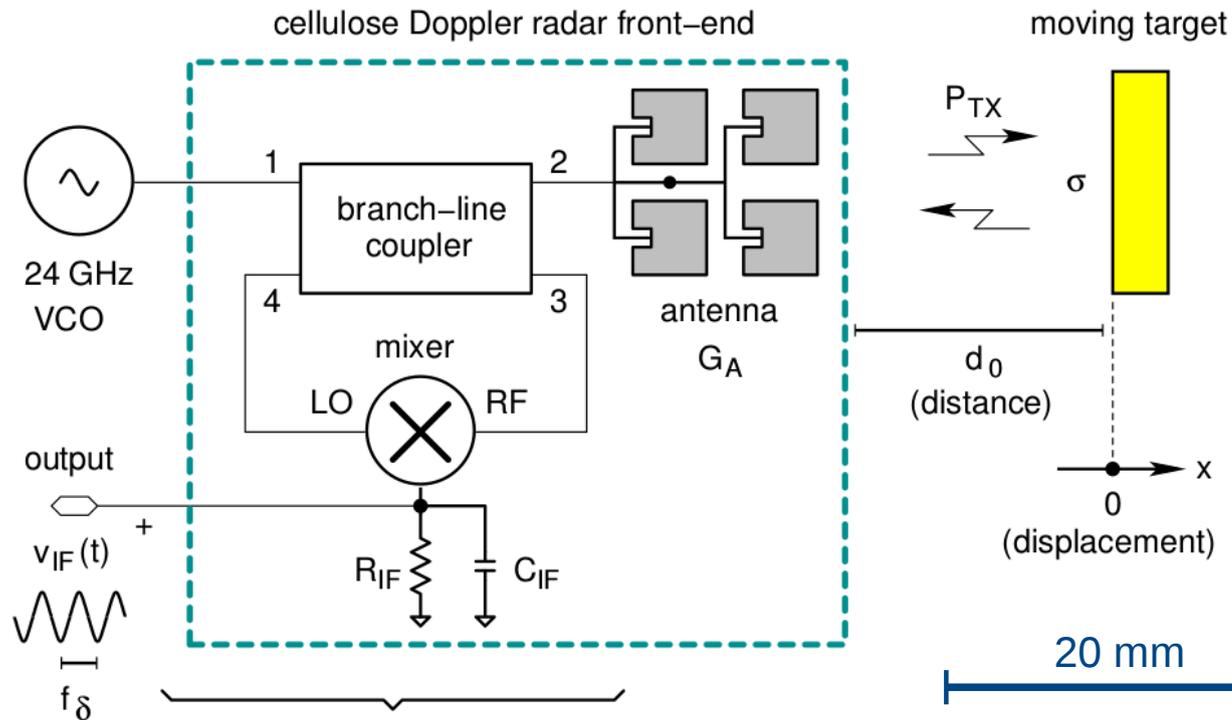
# Cellulose micro machines ?



✓ **Sensor structure: bi-material strip !**

- ✓ **MEMS on cellulose are feasible !**
- ✓ **Humidity sensor on paper**

# 24-GHz Doppler sensor on cellulose



# Future research lines

## Circuit technology

- ✓ micro-via fabrication & multi-layer
- ✓ combine ink-jet printing & copper laminate
- ✓ micro-fluidic devices (sensors, memories, etc.) !

## RF building-blocks & IoT applications

- ✓ microwave oscillators on paper
- ✓ zero-power wireless sensors concepts (harmonic radar, backscattering radio, chipless RFID, etc.)
- ✓ combine PV cells on cellulose with RF circuits for autonomous IoT sensor nodes !

## LAE & distributed sensing

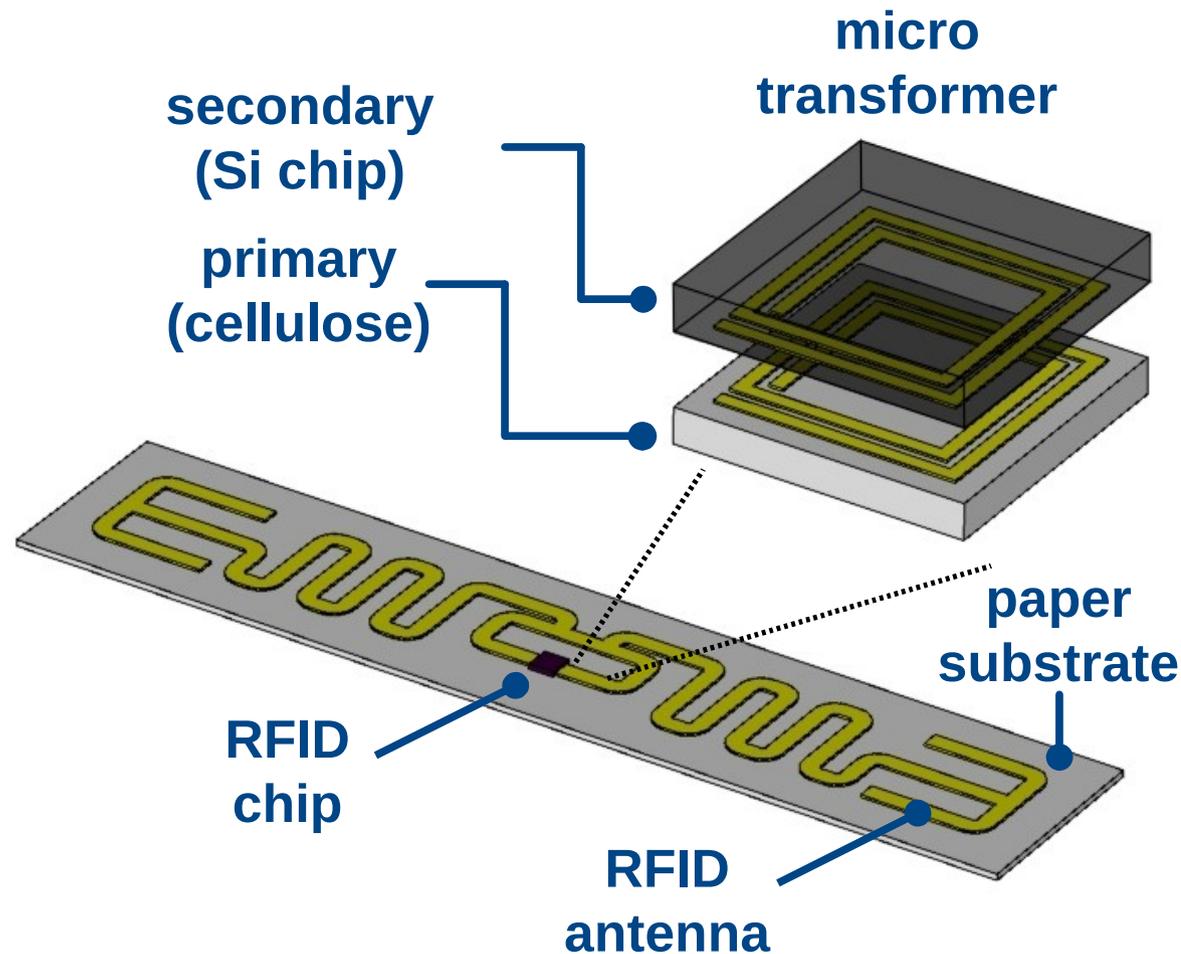
- ✓ electronic wall paper ?

# Conclusion



**Mother Nature already exploits Large Area  
Devices & Distributed Sensing on Cellulose**

# Si to cellulose interface



**Circuits on cellulose can be interfaced with CMOS chips !**

After F. Alimenti *et al.*, in IEEE MTT Transactions, Mar. 2011.

- ✓ interface achieved via **magnetic coupling**.
- ✓ place and glue: **no galvanic contacts !**