Printed electronics for radio-frequency: an overview

IMEP-LaHC Webinar, RFM team
05/27/2020

DELFAUT Camille
WAWRZYNIAK Maxime

Context

Radio-Frequencies devices ➔ Up to 22 billions of connected object & 1 trillion sensors in 2025

Source : Keysight Technologies

Communications

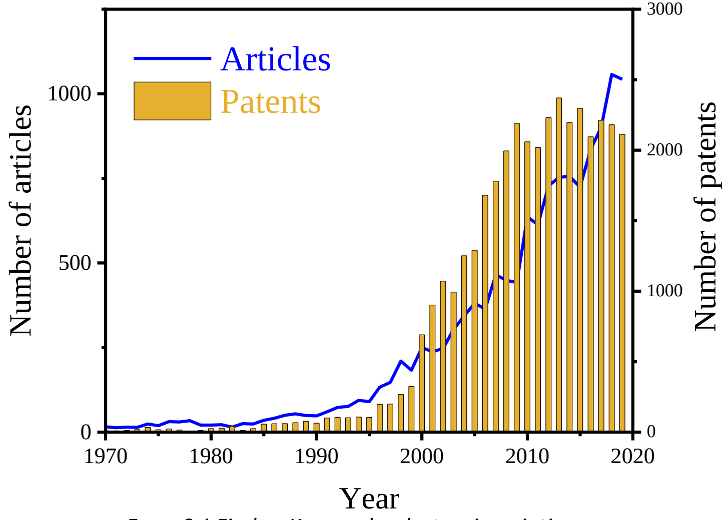
IoT

Smart building

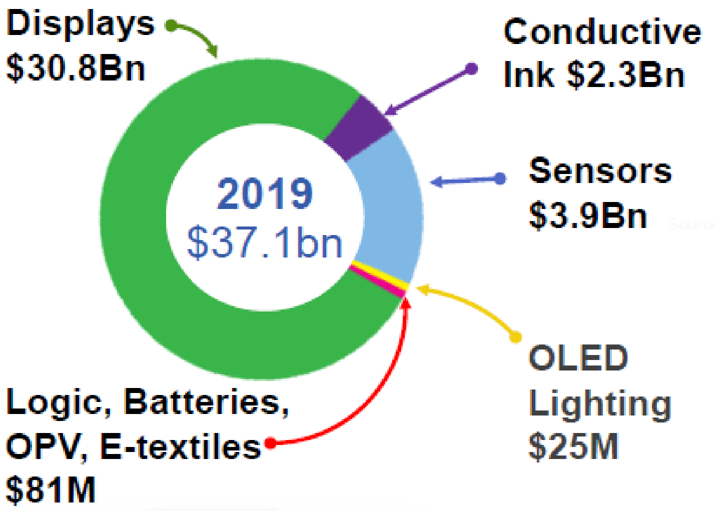
Smart security

Printed radio-frequencies devices is an answer for innovative applications

Interest for printing electronics



From Sci-Finder. Keywords: electronic, printing.



IdTechEx. *Printed, Organic and Flexible Electronics 2020-2030 : Forecast, Technologies, Markets* ; 2020

Growing interest for printed electronics

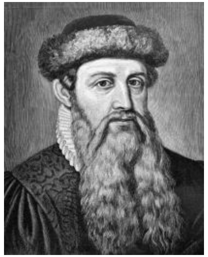
Parallel evolution from innovative and flexible applications

Market forecast : more than **$74 bn** in 2030 !

Printed electronics : definition

Printed

➔ Refers to printing processes



- Invented by Gutenberg in 1454
- Evolution of process
- Well-known today

Electronics

- Start with transistor in 1947
- Moore's Law & More than Moore
- Design limited on solid substrate

	Conventional Electronics	Printed Electronics
Materials	Silicon, Ceramic, Glass	Organic semiconductors, Polymers, Specialty inks
Manufacturing technique	Photolithography, Micromachining, Ablation	Printing processes on plastic, textile, paper, foil
Product Feature	Rigid, Brittle, Miniaturized	Flexible, Robust, Large Area

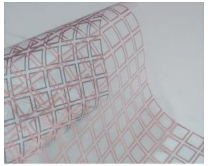
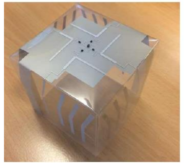
Printing methods to create electrical devices on various substrates using functional inks

Plan

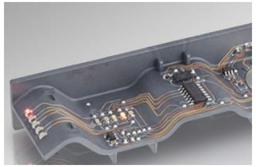
- ❑ Materials & Process in Printed RF devices



- ❑ Printed Radio-frequency devices : storyboard at IMEP-LaHC


- ❑ Conclusions & Perspectives



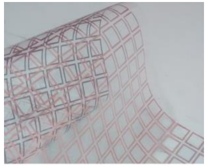
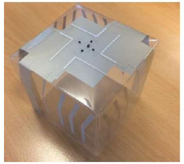

IMEP-LAHC

Plan

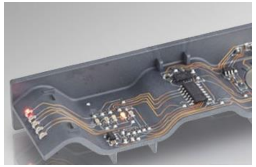
- Materials & Process in Printed RF devices



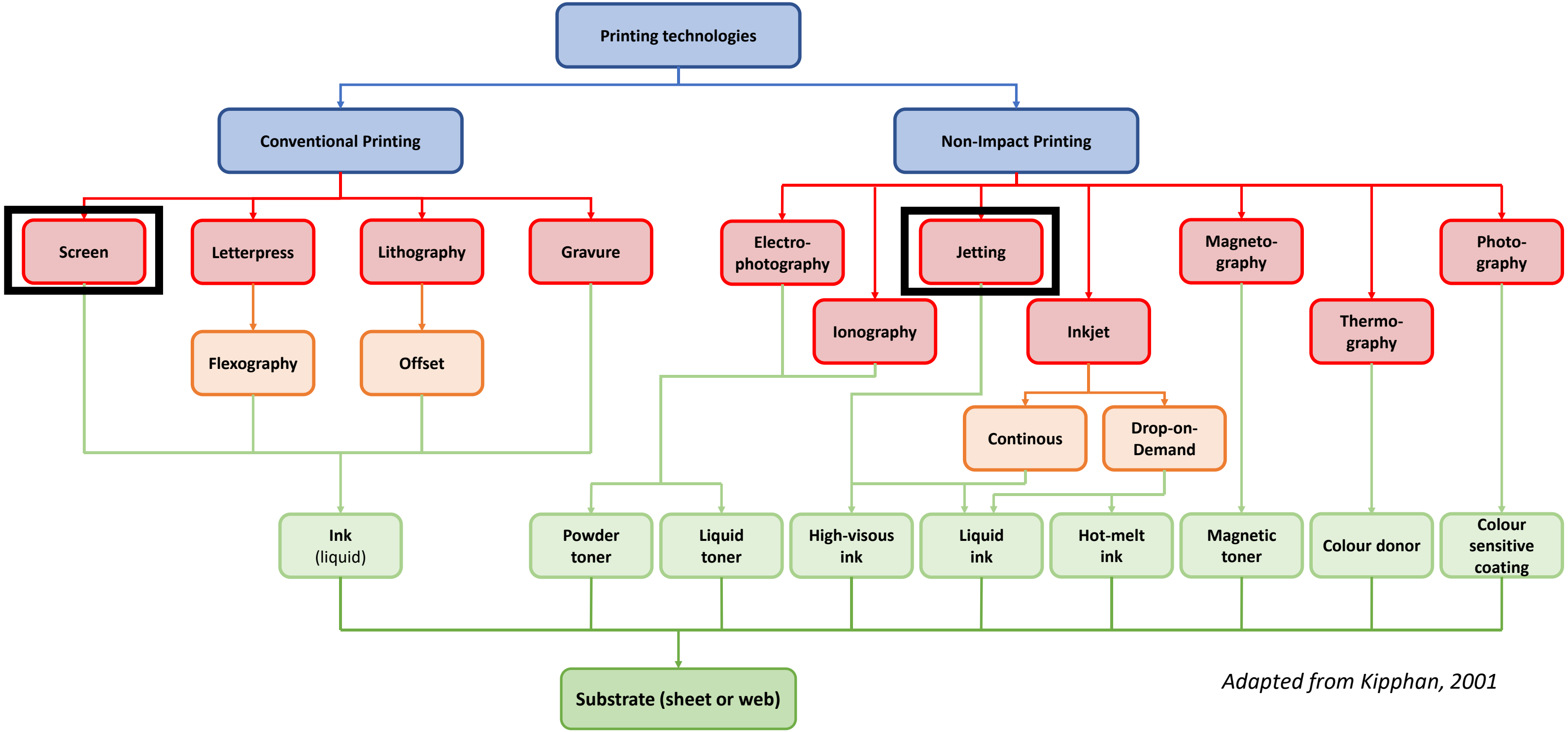
- Printed Radio-frequency devices : storyboard at IMEP-LaHC


- Conclusions & Perspectives



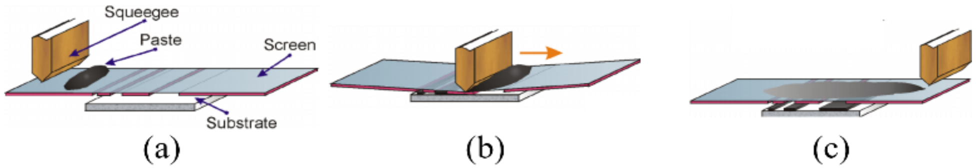

Printing processes



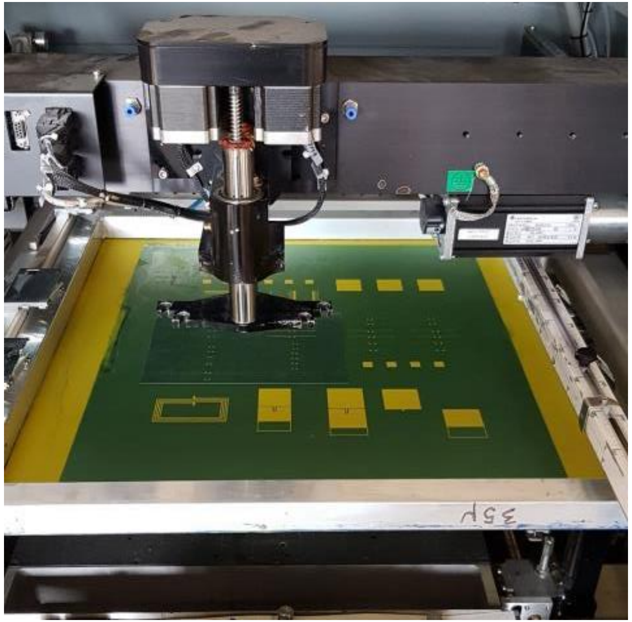
Adapted from Kipphan, 2001

Various printing process for differents applications: only screen-printing & jetting presented

Screen-printing



(a) : Deposition of ink on screen-frame
(b) : Printing of the design
(c) : End of printing & preparation for a new print



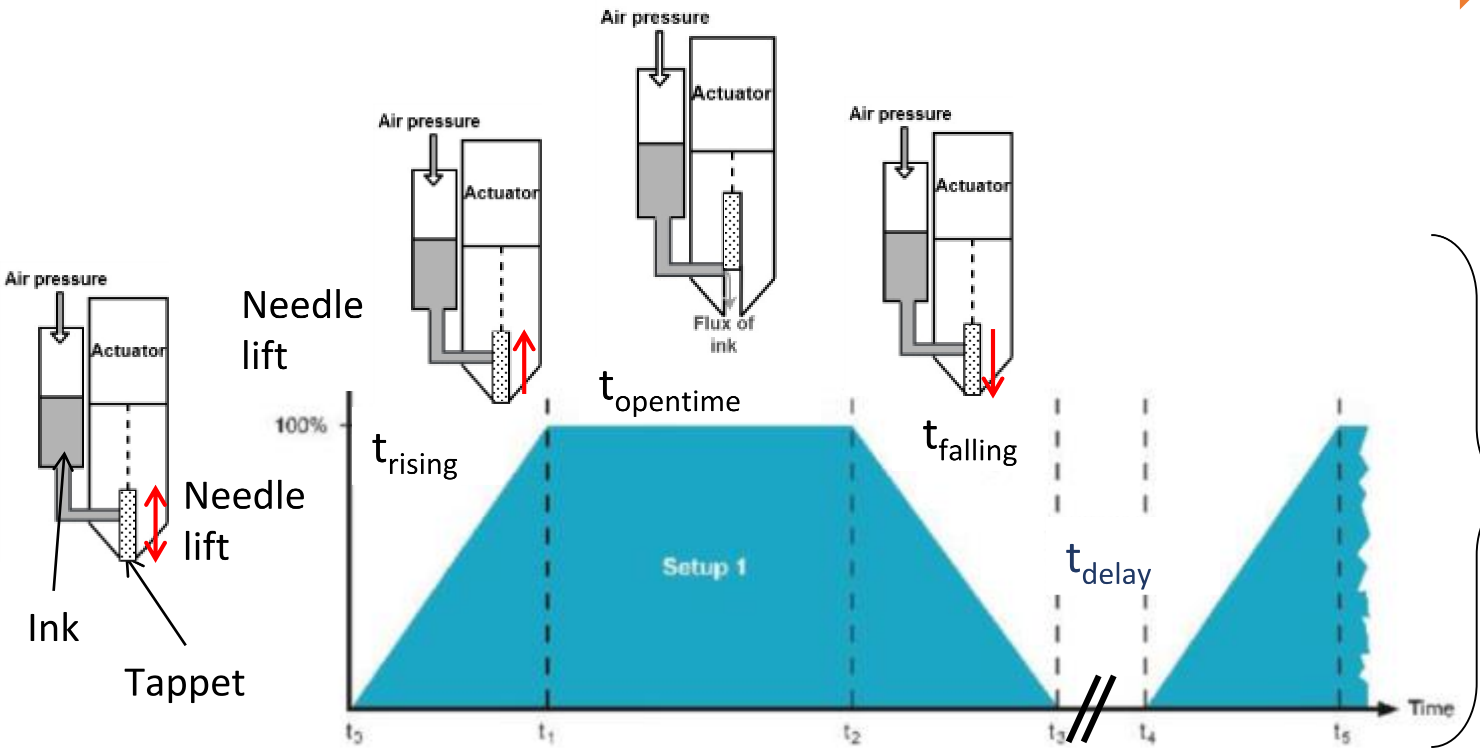
Used screen-frame:

- $\varnothing_{Thread}$ = 34 µm
- 120 thread.cm
- Snap-off : 1mm
- Layer thickness ∈ [2-100] µm
- Layer width ≥ 50 µm

Printing techniques with industrial interest & high fidelity

Jetting process

V_{print} is the linear or angular movement of the printing device



t_{delay} (ms)

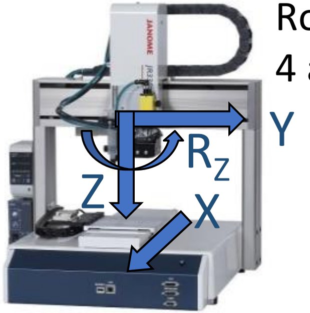
35 19.2 9

v_{print}=35 mm/s

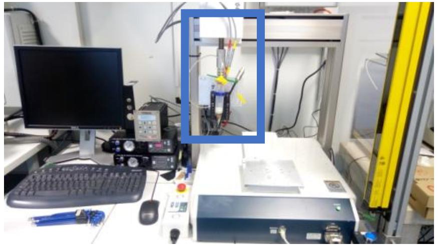
Jetting process: in MINT chaire

1st set up:
2D and 3D
(not all shapes)

+

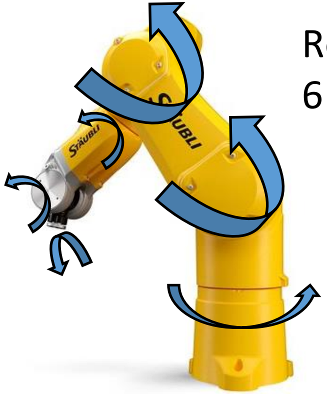


Robot Janome
4 axes



Vermes jetting device

+



Robot Staubli
6 axes

Allow to print easily on 3D shape

2^{d} set up:
2D and 3D

Jetting process: in MINT chaire

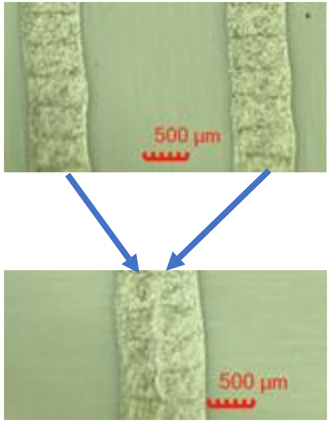
High viscous silver ink (2.87 ±0.14 ×10^6 S/m) required for jetting device

No overlapping

Thickness (µm)	Width (µm)
25 ±1	689 ±23

Overlapping of 2 lines

Thickness (µm)	Width (µm)
42 ±6	973 ±16



Advantages

- 2D and 3D substrate
- No chemical treatment
- Short process
- Fast commissioning

Challenges

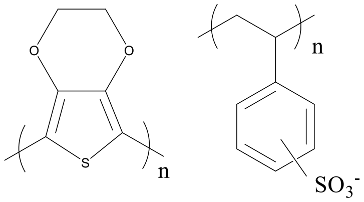
- Roughness substrate
- Environment dependency on the ink behaviour (particularly temperature)

Functional inks

≠ inks: - Semiconductor - Dielectric - **Conductive**

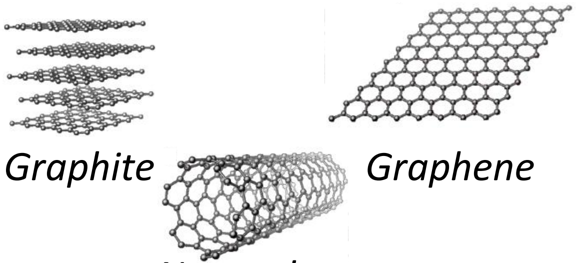
≠ conductive inks:

Conductive polymers



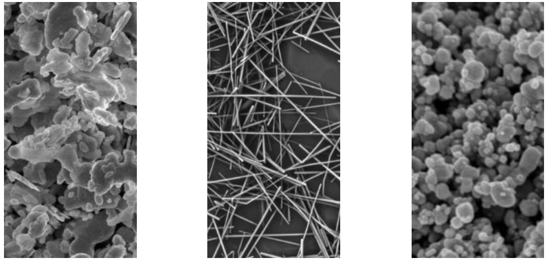
PEDOT:PSS

Carbon particles



Nanotubes

Silver particles



Flakes *Nanowires* *Nanoparticles*

Material	Sheet resistance ($\Omega.sq^{-1}$)
PEDOT:PSS	190-900
Carbon particles	30-10000
Silver particles	<0.03

$$\sigma = f(conductive\ material)$$

Silver particles selected

Require post-treatment

Ink post-treatment

Several ink post-treatment:

Sintering [1], [2]**:** coalescence of particules into a solid by thermal energy (T > 300°C)

Annealing[1]**:** same as sintering but at lower temperature (~90°C). Particules are in contact

Curing[1]**:** chemical modifications by polymerisation of the ink (UV curing is mainly used)

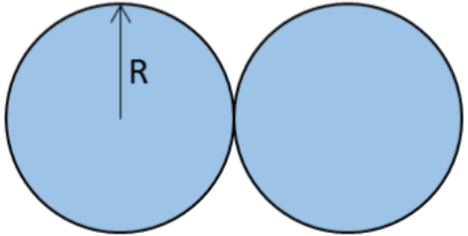
(1) D. Sette, PhD thesis, Université Grenoble Alpes, 2014

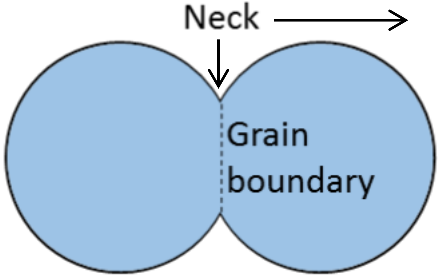
(2) H. Atkinson, Metallurgica, vol. 36, no. 3, pp. 469–491, 1988.

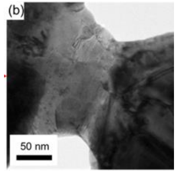
Ink post-treatment

Nanoparticles (NP) coalescence depending on the temperature (from annealing to sintering):

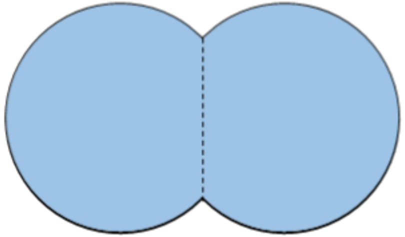
Adapted from (1)

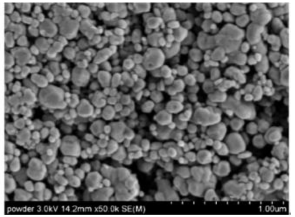




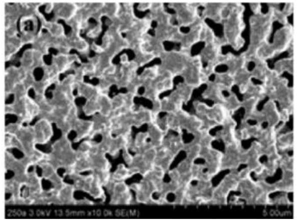


(2)

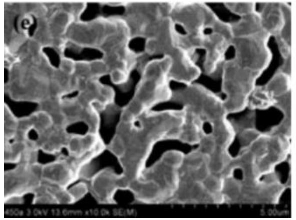



(3)

Silver NP


(3)

Silver NP at 250°C
Resistivity: 7.14 µΩcm


(3)

Silver NP at 450°C
Resistivity: 4.11 µΩcm

For both our thesis, **annealing** used because of low substrates glass temperature

(1) D. Sette, PhD thesis, Université Grenoble Alpes, 2014
(2) Yeom, Jeyun, et al, 2019
(3) PARK, Keunju, SEO, Dongseok, et LEE, Jongkook., 2008

Annealing processes

Thermal curing

+ Easy to implement
+ Cheap equipment
+ Conductivity

- High temperature for substrate
- Time ≈ 30 min

Ohmic curing

+ Time ≈ 1 min
+ Easy to implement
+ Cheap equipment

- High temperature localized
- Only on line shape

Infrared curing

+ Time ≈ 5 min
+ Conductivity

- High temperature localized
- Expensive equipment

Photonic curing

+ Time ≈ 5 min
+ Conductivity

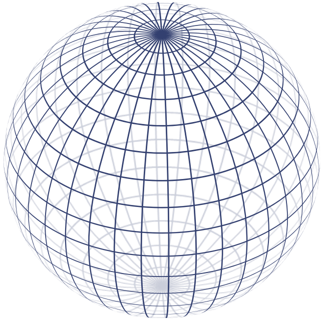
- High temperature localized
- Very expensive equipment

For both our thesis, **thermal annealing** privilegied

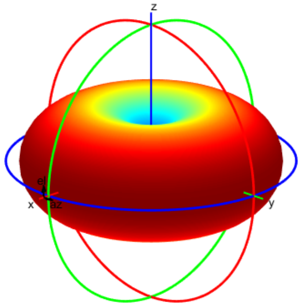
Antennas

IEEE Standards: Interface between both guided and free-space media

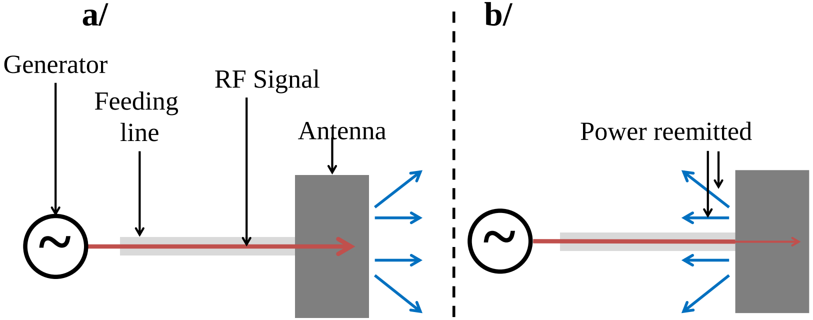
⬄ interface between an electrical power and an electromagnetic signal



Isotropic radiation for an ideal antenna

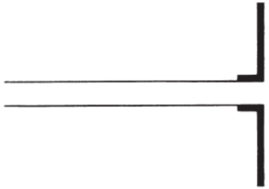


Radiation pattern for a dipole antenna

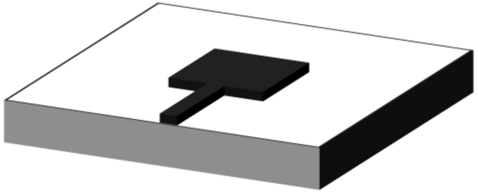


Adaptation of an antenna

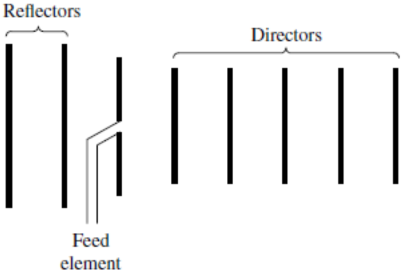
Dipole Antennas



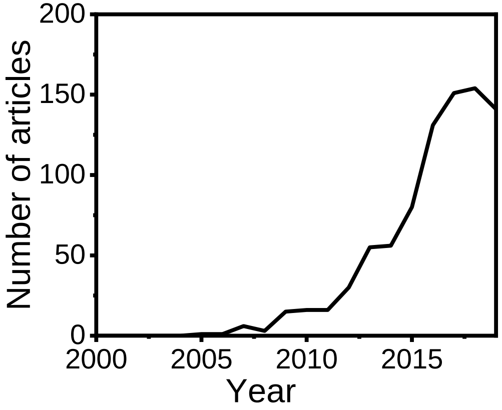
Microstrip Antennas



Array Antennas

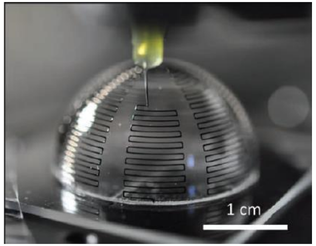
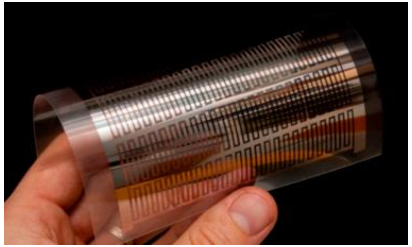


Printed radio-frequency devices



From IEEE Xplore. Keywords: Antenna, printing

- Interest started in 2010
- More than 150 paper in 2019
- Still a niche in RF field
- Differents printed RF devices

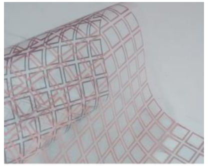
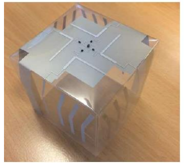
Antennas	Frequency Selective Surface (FSS)	Sensors	Transmission lines
			
J. J. Adams *et al. Adv. Mater.* **2011**, *23*, 1335	Huang *et al.*, Sci Rep **6,** 38197 (2016)	P. Dzik *et al.*, ACS Appl. Mater. Interfaces, 2015,7,16177–16190	J. M. Lopez-Villegas *IMS* 2019

Plan

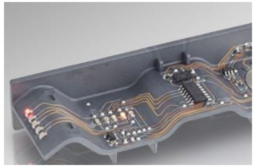
- Materials & Process in Printed RF devices



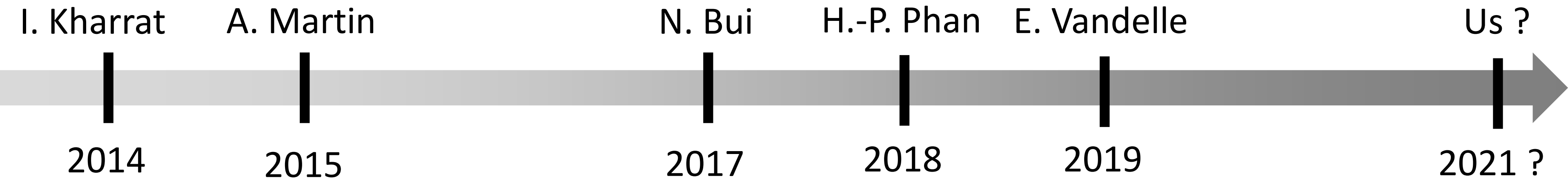
- Printed Radio-frequency devices : storyboard at IMEP-LaHC


- Conclusions & Perspectives




Storyboard at IMEP-LaHC



Storyboard at IMEP-LaHC

I. Kharrat — 2014
A. Martin — 2015
N. Bui — 2017
H.-P. Phan — 2018
E. Vandelle — 2019
Us ? — 2021 ?

Conception of printed device for energy harvesting

- Printed antennas for energy harvesting on paper board by flexography
- Printed antenna on polyester flexible by screen printing

Double monopole
2.45 GHz and 4.9 GHz

Rectenna monopole
2.45 GHz

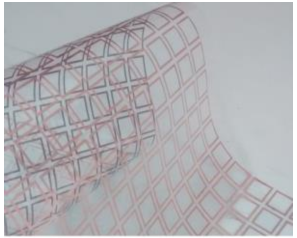
- Study of the folded impact on RF properties
- Study of the substrate curvature impact on RF properties

Storyboard at IMEP-LaHC

I. Kharrat — 2014
A. Martin — 2015
N. Bui — 2017
H.-P. Phan — 2018
E. Vandelle — 2019
Us ? — 2021 ?

Printed devices for filtering electromagnetic waves

- Printed Frequency Selective Surfaces for filtering by screen-printing
- Printed Frequency Selective Surfaces for transmission improvement by screen-printing



↗ of transmission 3 GHz

Tri-band Wifi rejected 0.97GHz, 2.25GHz and 3.14 GHz

- New setup fabricated for anechoic chamber
- Study of printed patterns for FSS

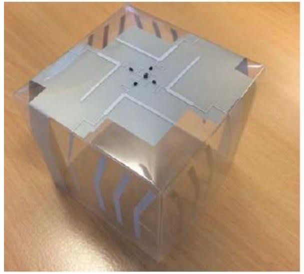
Storyboard at IMEP-LaHC

I. Kharrat	A. Martin	N. Bui	H.-P. Phan	E. Vandelle	Us ?
2014	2015	2017	2018	2019	2021 ?

Printed flexible antenna for energy harvesting

- Printed & Foldable dipole & coplanar antennas for energy harvesting
- Printed on Polymeric substrate (PET) by screen-printing

Coplanar antennas, without and with folding



Rectifier foldable antenna

- Diversity of printed rectenna printed on PET substrable
- Median harvested power [13-121]nW

Storyboard at IMEP-LaHC

I. Kharrat	A. Martin	N. Bui	H.-P. Phan	E. Vandelle	Us ?
2014	2015	2017	2018	2019	2021 ?

Design of 2D and 3D antennas on flexible substrate

- Printed & Foldable antenna for packaging & home-networking devices
- Printed on paper substrate by screen-printing

Wideband antenna with connector

Binded wideband antenna

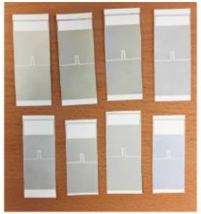
- RF characterization of ≠ paper substrates
- Influence of bending effects on RF properties dependent of :
  - Bending location
  - Bending angle

Storyboard at IMEP-LaHC

I. Kharrat — 2014
A. Martin — 2015
N. Bui — 2017
H.-P. Phan — 2018
E. Vandelle — 2019
Us ? — 2021 ?

Energy harvesting and wireless power transmission

- 3D energy harvesting structure
- Folded antenna for miniaturisation on paper by screen-printing



- Comparison antenna printed/antenna copper
- 3D structure for maximisation of energy harvesting

Wi-Fi antennas at 2.45 GHz with air gap

Left : before assembly   Center : copper tape assembly   Right : silver ink assembly

Storyboard at IMEP-LaHC

I. Kharrat — 2014
A. Martin — 2015
N. Bui — 2017
H.-P. Phan — 2018
E. Vandelle — 2019
Us ? — 2021 ?

MINT Project:
3D printed electronic for Molded Interconnected Devices (MID) dedicated to internet of Things applications

E-Transparent (E-T.) Project:
Development of innovative and transparent Radio-Frequency devices based on nanocelluloses-silver nanowires hybrid system

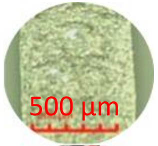
Projet MINT

How can we integrate easily RF devices on 2D or 3D plastic part?

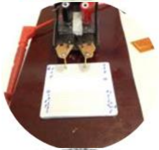
Process characterisation → **Innovative printed devices**

Properties and limitations:

- Geometric

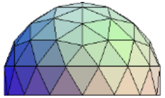


- Electric



- Electromagnetic

- Antenna
- FSS



- Energy harvesting

Innovative printed devices reliable and robust

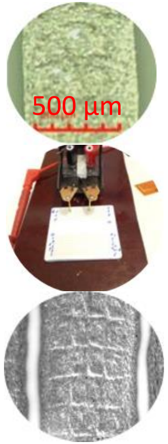
Projet MINT

How can we integrate easily RF devices on 2D or 3D plastic part?

Process characterisation

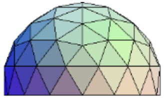
Properties and limitations:

- Geometric
- Electric
- Electromagnetic



Innovative printed devices

In this presentation

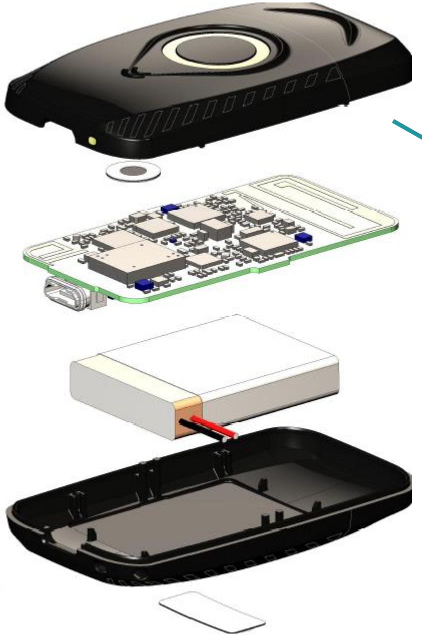
- Antenna → **LoRa antenna**
- FSS 
- Energy harvesting

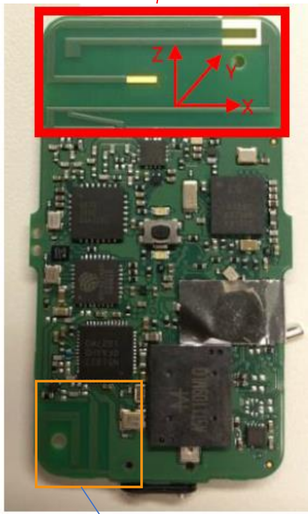
Innovative printed devices reliable and robust

Projet MINT: application

LoRa and GPS antenna
Resonant frequencies:

- 0.868 GHz LoRa
- 1.575 GHz GPS





WiFi antenna

Miniaturisation

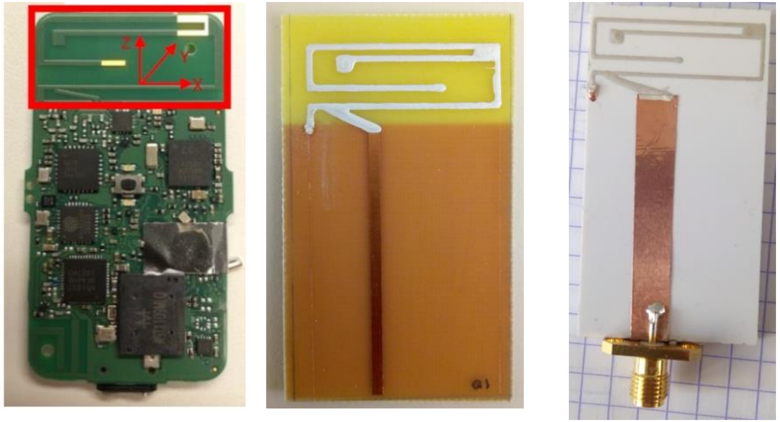
LoRa antenna Improvement

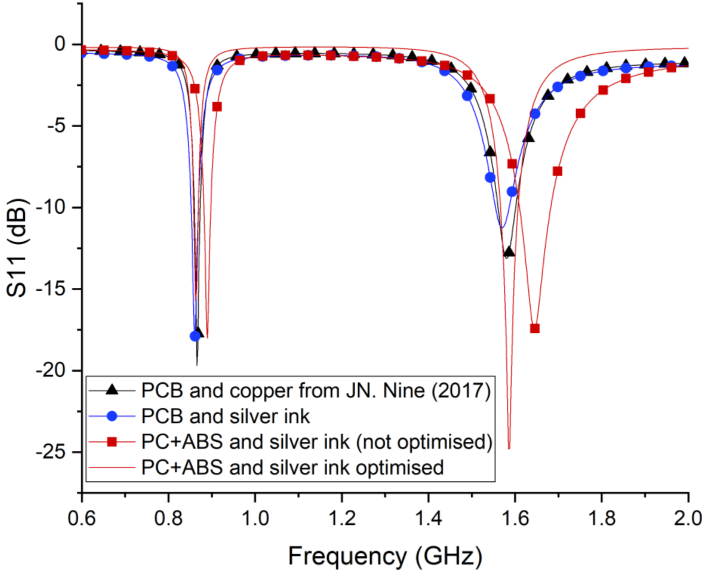
Deporting LoRa antenna on plastic case

Cost reductions

WiFi antenna improvement

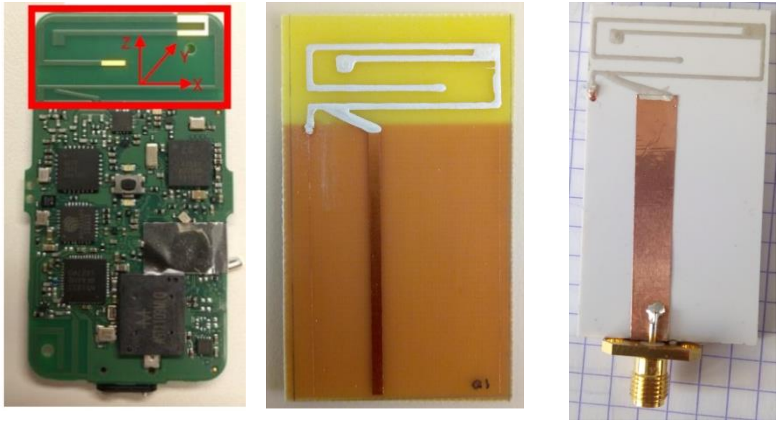
Projet MINT: application



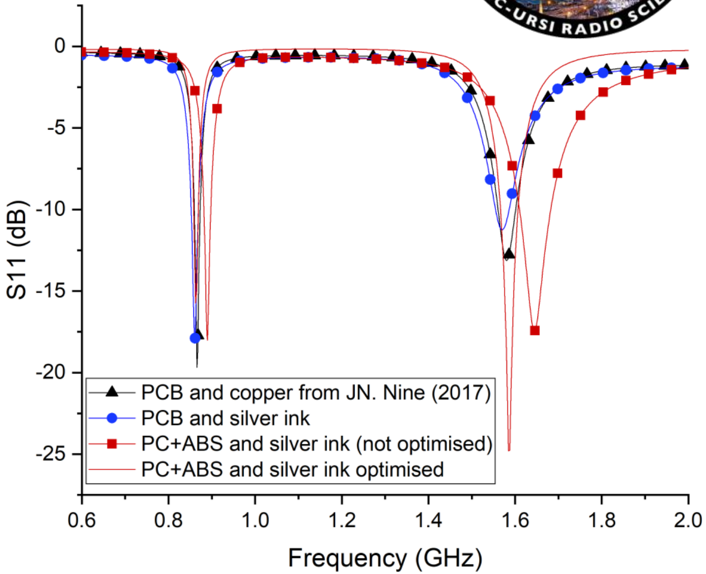


	Traditional antenna	Printed antenna on PCB	Printed antenna on plastic
Substrate	FR4	FR4	PC
Conductive track	Copper	Microsilver ink	Microsilver ink

Projet MINT: application



	Traditional antenna	Printed antenna on PCB	Printed antenna on plastic
Substrate	FR4	FR4	PC
Conductive track	Copper	Microsilver ink	Microsilver ink



Validation of jetting process to move antenna on the case without loss of adaptation

Projet MINT

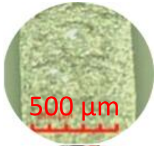
How can we integrate easily RF devices on 2D or 3D plastic part?

Process characterisation → Innovative printed devices

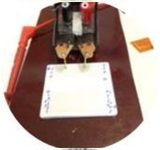
Process characterisation

Properties and limitations:

- Geometric ✓



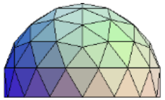
- Electric ✓



- Electromagnetic — In progress

Innovative printed devices

- Antenna ✓
- FSS — In progress



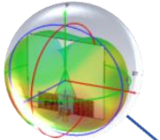
- Energy harvesting

Innovative printed devices reliable and robust

E-T. Project: Introduction

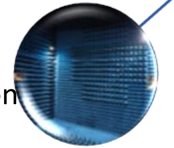
Design for Transparent Antenna

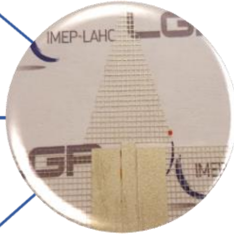
Simulation



Substrate Characterization

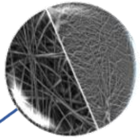
Antennas Characterization





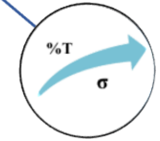
IMEP-LAHC

Formulation of Transparent & Conductive ink



Hybrid system AgNW/CNF_t

Printing & Charaterization



Optimization of opto-electrical properties

LGP2

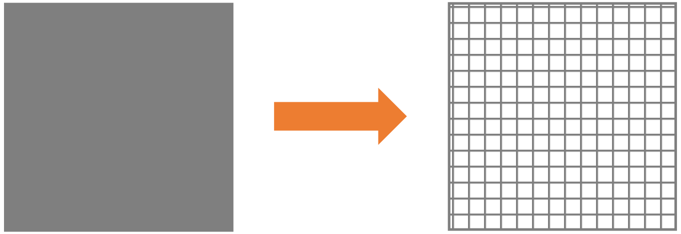
Transparent Radio-Frequencies Devices

E-T. Project: RF approach

Goal : Develop transparent printing antennas by meshing without affecting properties

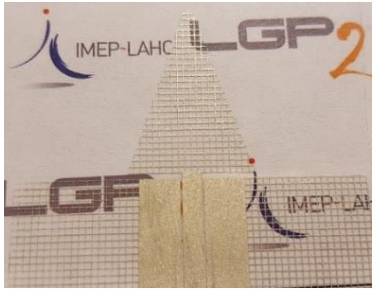
➔ **Removing metalic part to let light pass through**

➔ Introduced in 1991 by Ito and Wu[(1)]



Full pattern *Meshed pattern*

In this project, 2 **models** of antenna

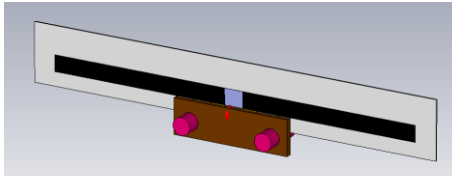


CPW Antenna @ 3.6 GHz

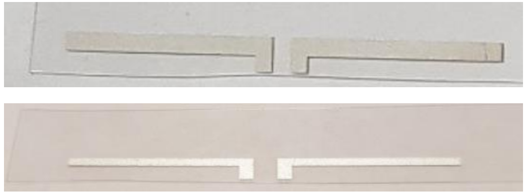
Dipole antenna @ 2.45 GHz

(1) Ito and Wu,*ICAP 91 (IEE)* 133–136, 1991

E-T. Project: Meshed results

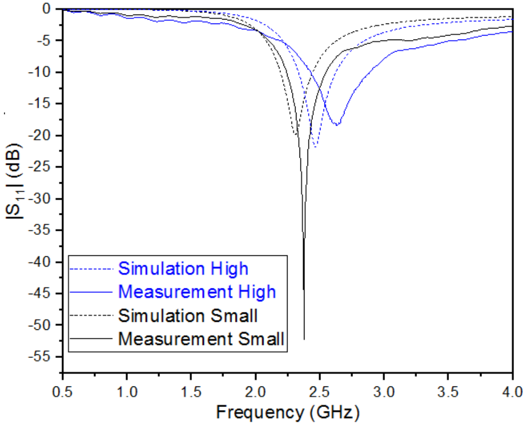


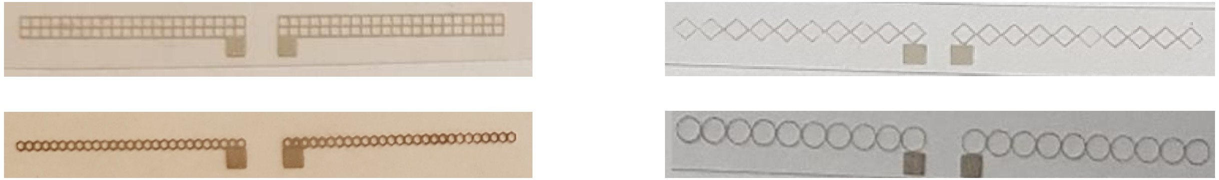
Printing antenna



Reference Antenna , no meshed

Reference printed antenna & miniaturized model





Square and Honeycomb ➔ Good results vs simulations
Diamond & Circle ➔ Experimental <<<< Simulations
High transparency (%T > 78%) and conservation of RF properties

EuMW 2019
UNIVERSALITY THROUGH MICROWAVES

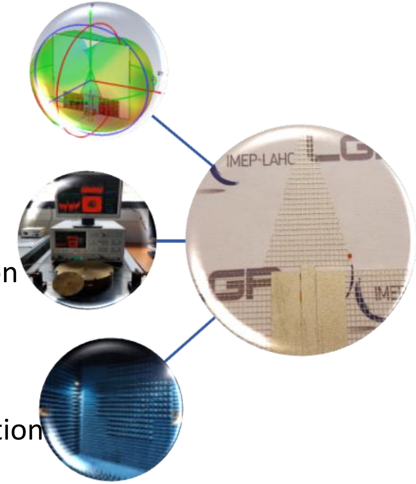
E-T. Project: Introduction

Design for Transparent Antenna

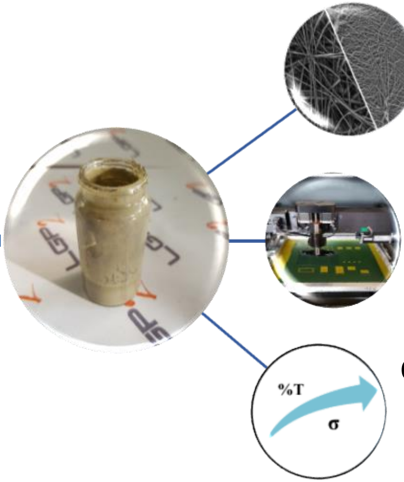
Simulation

Substrate Characterization

Antennas Characterization



Formulation of Transparent & Conductive ink



Hybrid system $AgNW/CNF_t$

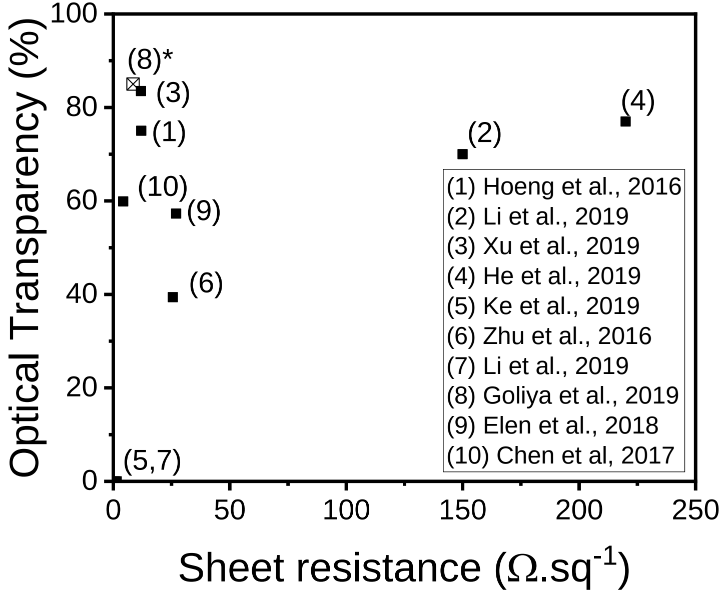
Printing & Charaterization

Optimization of opto-electrical properties

Transparent Radio-Frequencies Devices

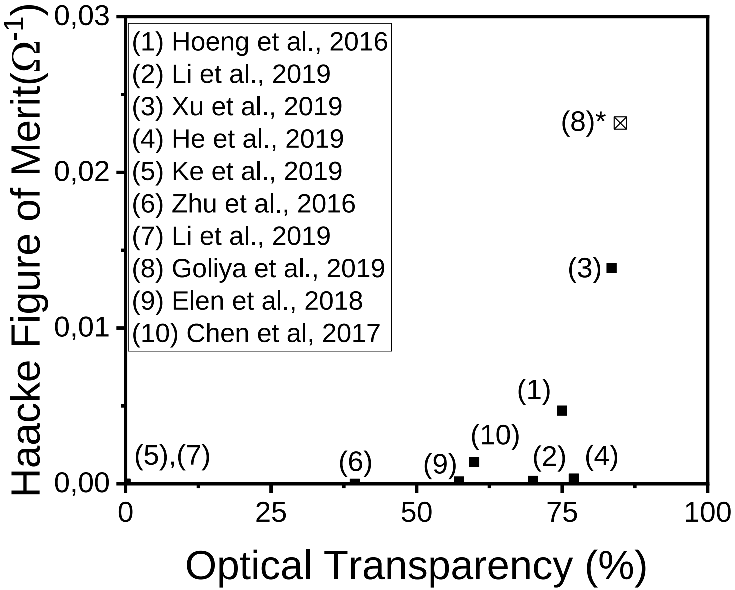
Transparent inks: a review

Goal : Development of **transparent** and **conductive** (<2 Ω.sq^{-1}) ink for **RF applications** by **screen-printing**



Haacke's law

$$FoM = \frac{T^{10}}{R_S}$$



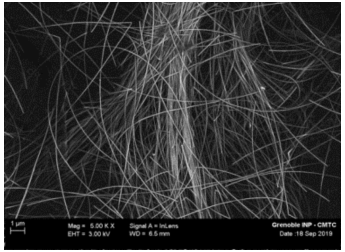
Few references for the development of conductive & transparent ink for screen-printing

E-T. Project: Raw materials

Conductive material

Silver Nanowires (AgNW)
1%wt in isopropanol
Ratio L/Φ ≈ 660

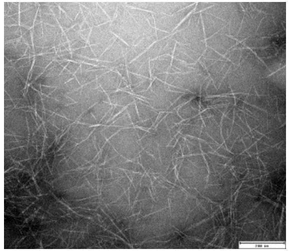
High conductivity
Transparency & conductivity

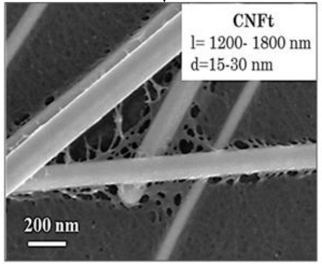


Nanocellulose

Cellulose NanoFibrils (CNF)
TEMPO-oxidizated ➔ CNFt

4 roles :
- Transparent matrix
- Adapted Rheological
- Adhesion Promoter
- Dispersing Agent





CNFt-AgNW film
Hoeng et al., *J. Mater. Chem. C* **2016**, *4* (46), 10945–10954.

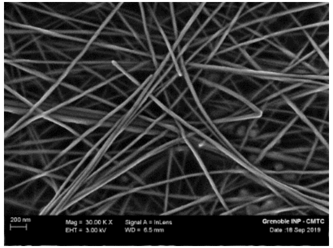
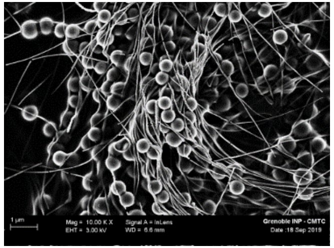
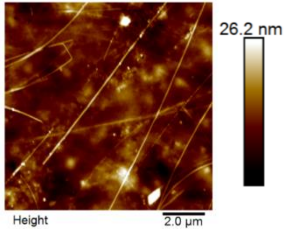
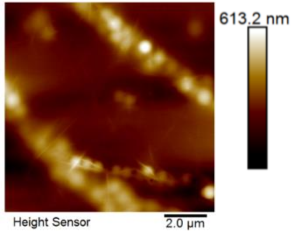
+

Additive material (S.NP)

Ø : 500 nm
Spherical particle

2 Presumed roles :
↗ Dispersion of AgNW ⇔ VdW interactions
↘ Percolation threshold

E-T. Project: Improvement of σ

	Optimum system based on CNF_t/AgNW	**Addition of S.NP (additive material)**
FEG-SEM		
AFM *Tapping mode*		
%T @550 nm	81 ± 6	73 ± 1
R_S ($\Omega.sq^{-1}$)	48 ± 10	8 ± 1

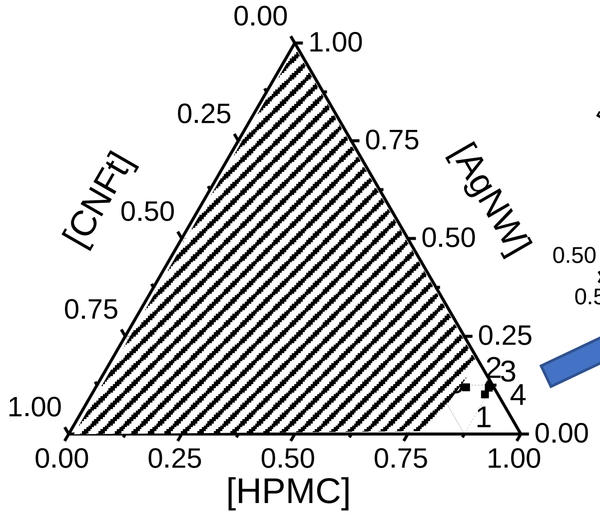
HYP : Improvement of conductivity due to organization inside AgNW Network

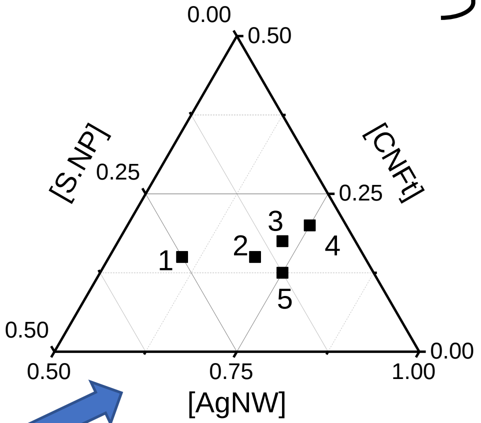
- ↘ R_s for a same ratio of conductive material
- Low Impact on %T (- 8%)

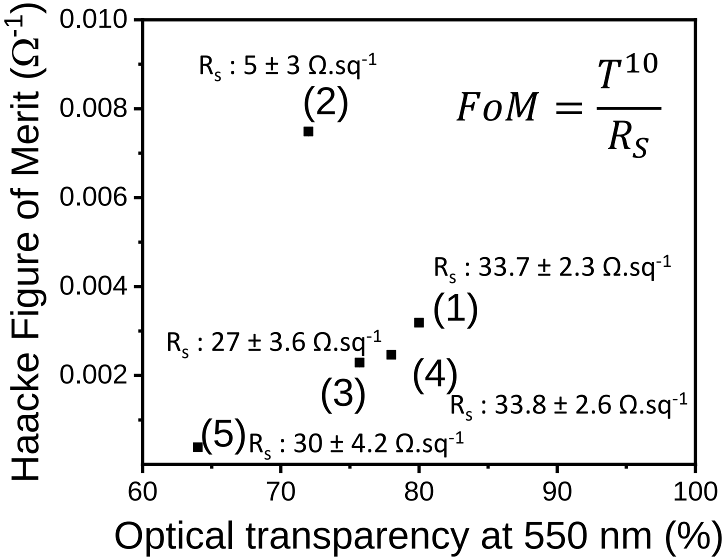
E-T. Projet : Transparent ink

Formulation with 5%wt of solid content, described as
- 87% of HPMC
- 13% AgNW/CNF_t/S.NP

Influence of [S.NP] on σ investigated
➔ Design of Experiments (DoE)

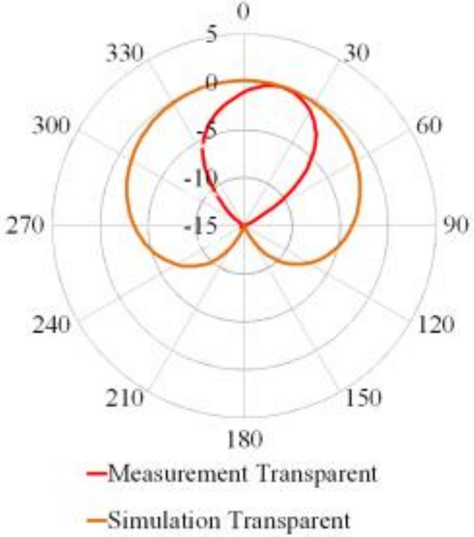






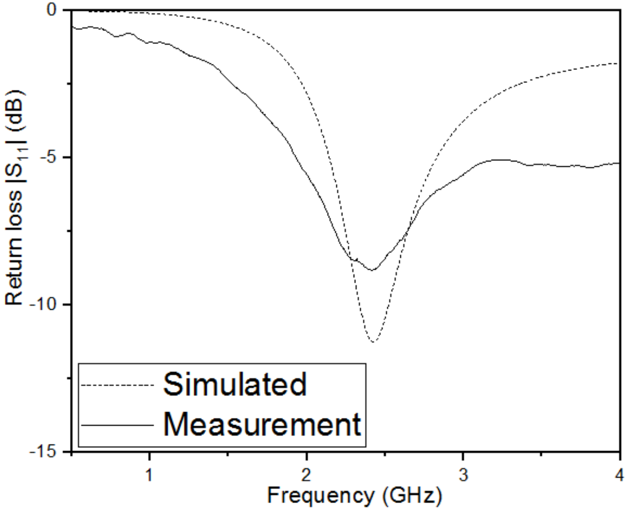
Formula (2) is the best trade-off between transparency and conductivity

E-T. Project : Transparent antennas



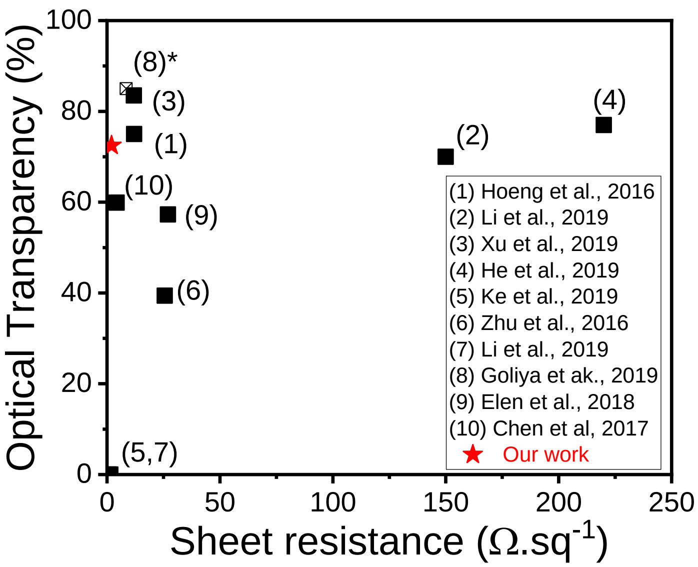
Measured gain : 0.02 dBi

Simulated gain : 0.29 dBi



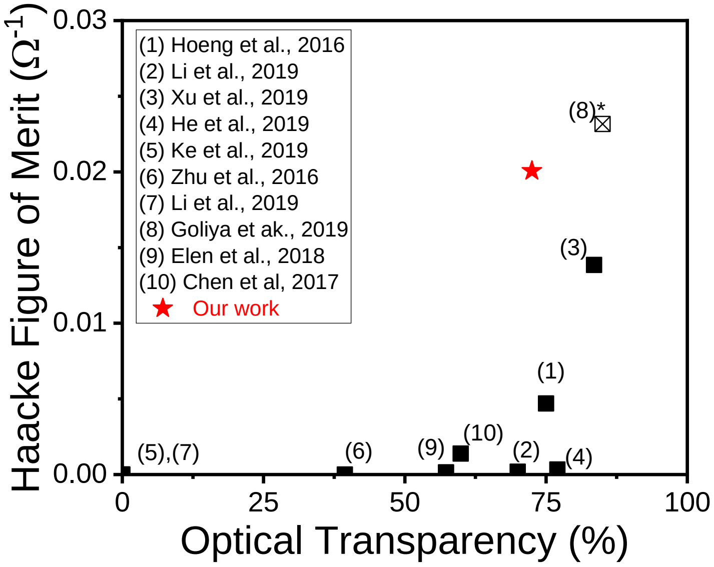
Proof of concept validated
Measured gain in agreement with simulation

E-T. Project : Conclusions



Haacke's law

$$FoM = \frac{T^{10}}{R_S}$$



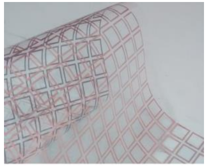
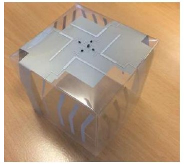
- Investigation on the type of bound between S.NP & AgNW to continue
  ➔ New formulation with other oxydes & diameter to understand this phenomena
- Influence of the [S.NP] with new grade of binding agent offer new horizons of formulations

Plan

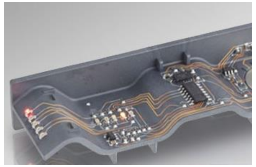
- Materials & Process in Printed RF devices



- Printed Radio-frequency devices : storyboard at IMEP-LaHC


- Conclusions & Perspectives




Conclusions

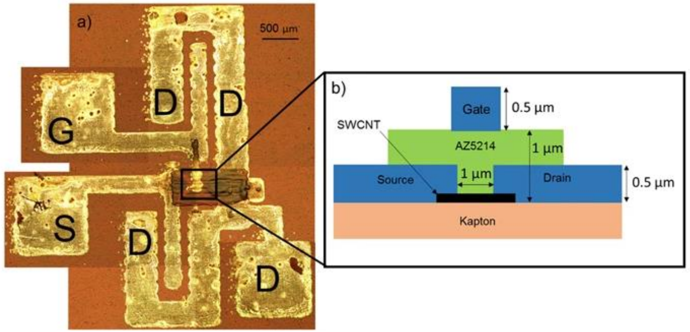
- Printed electronics is an innovative solution for flexible applications
- Various processes depending for various outputs parameters
- Conductive inks properties as a function of raw material
- Silver inks privilegied
- Post-treatment mandatory to improve σ
- Process applied to RF devices with ↗ interest
- Long story of printing RF research at IMEP-LaHC with 2 current PhD :
  - MINT Project: 3D solutions for RF
  - E-T. Project: Transparent solutions for RF

Perspectives

- Innovative ways for IoT, smart packaging & smart building applications
- Improvement of 3D printing processes
- Enhancement of trade-off transparency/conductivity

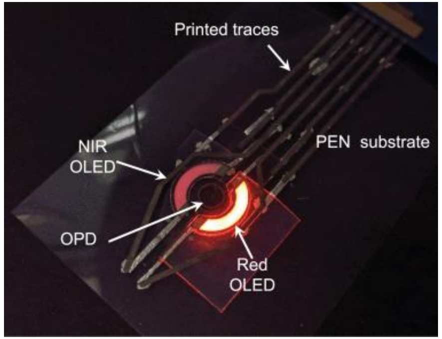
- Printing processes can also be available for other teams at IMEP-LaHC:

Inkjet Transistors



Grubb *et al.*, *Sci Rep* **7**, 1–8 (2017).

Optoelectronic sensors



Khan, Y. *et al. IEEE Access* **7**, 128114–128124 (2019).

IMEP-LAHC

Thank you for attention