PROJECT FULLFLEX: A MULTIFUNCTIONAL FLEXIBLE ELECTRONIC LABEL

Jean-Christophe P. Gabriel

Printed and Flexible Electronics Congress 2017

21st-22nd Feb 2017
London, UK
London Heathrow Marriott Hotel

Abstract: We will present a CEA joint effort that delivered a multifunctional label prototype that integrates flexibles: (i) photovoltaic cells; (ii) a nanoparticle based Li-battery; (iii) a battery management system; (iv) a tension regulator; (v) a temperature sensor; (vi) a light sensor; (vii) a silver nanowire based transparent capacitive touch sensor; (viii) four LEDs; (ix) an electronic motherboard integrating a micro-controller.

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CEA/DRF/DPNS
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DE LA RECHERCHE À L'INDUSTRIE

NanoSciences
Programme transversal

PROJECT FULLFLEX:

A MULTIFUNCTIONAL FLEXIBLE ELECTRONIC LABEL

Dr. Jean-Christophe P. Gabriel

Dep. Director Nanoscience & **ChimTronic** Programs

Printed & Flexible Electronics Congress

February 21st, 2017

www.cea.fr

CEA Key Figures (2015)

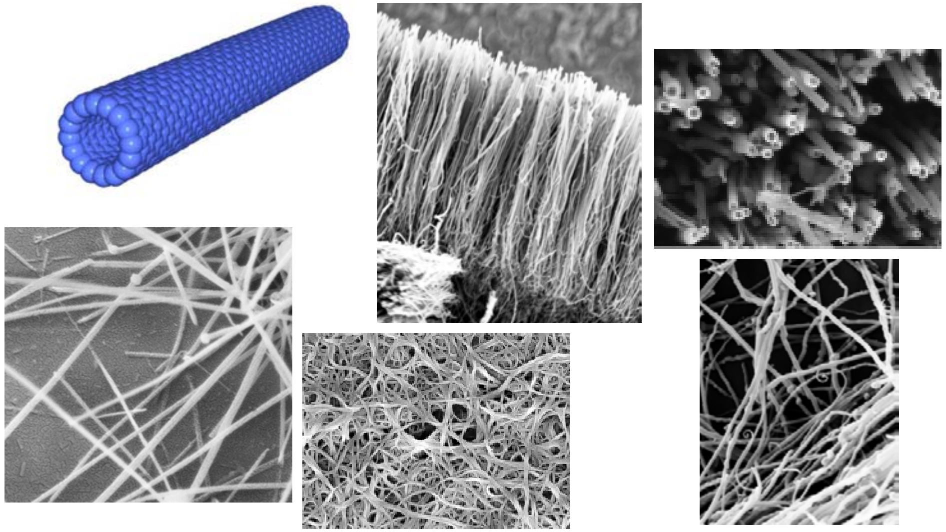
- ~17800 collaborators (~16000 staff members)
- Budget : € 4.1 BN, including € 2,8 BN in subsidies

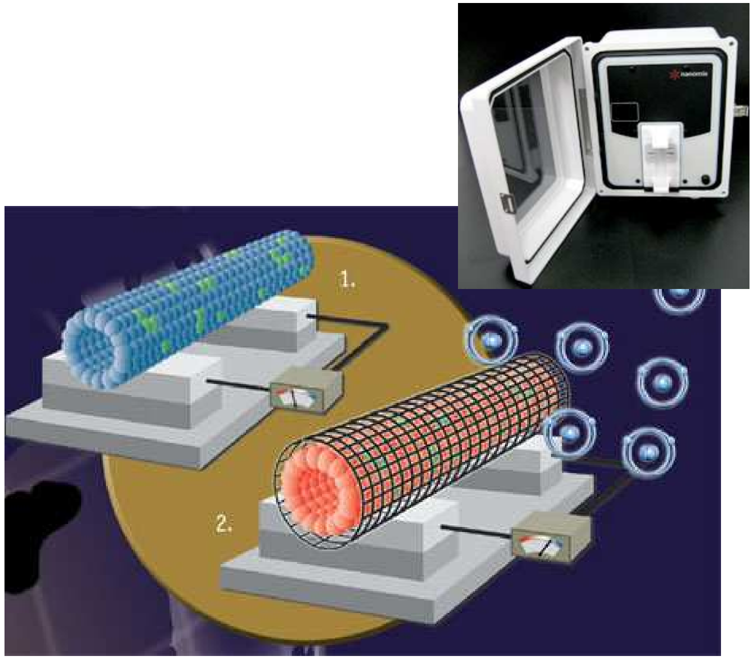
4 900	Scientific publications (in 2014 ISI base; IF = 4,5)
85	ERC grants
1 150	PhD students
5 840	Patent families in portfolio
735	Delivered priority patents deposited
850 M€	Revenues (460M€ ind. Rev.): Research vs Industry
187	CEA's Spin-off since 1972 (124 since 2000)
1st	Reuters' Ranking of Innovative Research Institutions
51	Joint research groups (including CNRS)

CAN A LOT BE DONE FROM NEW PARADIGMS? THE EXAMPLE OF CNTS

- 2001-2007 @ Nanomix (nano.com): CNT integration – Chemical sensors

nanomix





Molecular Wires for Molecular Sensing

- First commercial sensors in 2005: H_2 sensor on Si wafers
- Printed NT sensors deployed in West Africa during Ebola crisis in 2015.
- $36M raised over 15 years!!!

Nature **413**, 504-508, **2001**, ***Phys. Rev. Lett.*** **91**(21) 218301, **2003**, ***Adv. Mater.***, **16**(22) 2049-2052**, 2004**, ***J. Phys. Chem. B****. 110*(42); 21014-21020, **2006; *Proc. Nat. Acad. Sciences*** **103**(4), 921–926, **2006**, **. *J. Phys. Chem. B****. 110*(42); 21014-21020, **2006;** C. R. Physique, *11*(5-6), 362-374, **2010**; *Appl. Phys. Lett.* **103**, 051907, **2013** + ~50 patent applications

CEA NANOSCIENCES SEEDING PROGRAM: 1M€/Y

- Leverage effect (period 2008-2013, 98 projects, budget 7M€) : **170%**
- Direct income: **7M€** (32 projets: ANR, FP7,…)
- Indirect incomes: **5M€** (15 projets: ANR, FP7, ERC,…)
- Overall awarded money (with partners) **: 78M€**

260 articles de journaux sur 2009-2016 (4806 citations)

31% of articles (80) in top 10% *(according to ESI Physics criteria)*

6% of articles (16) in top 1%

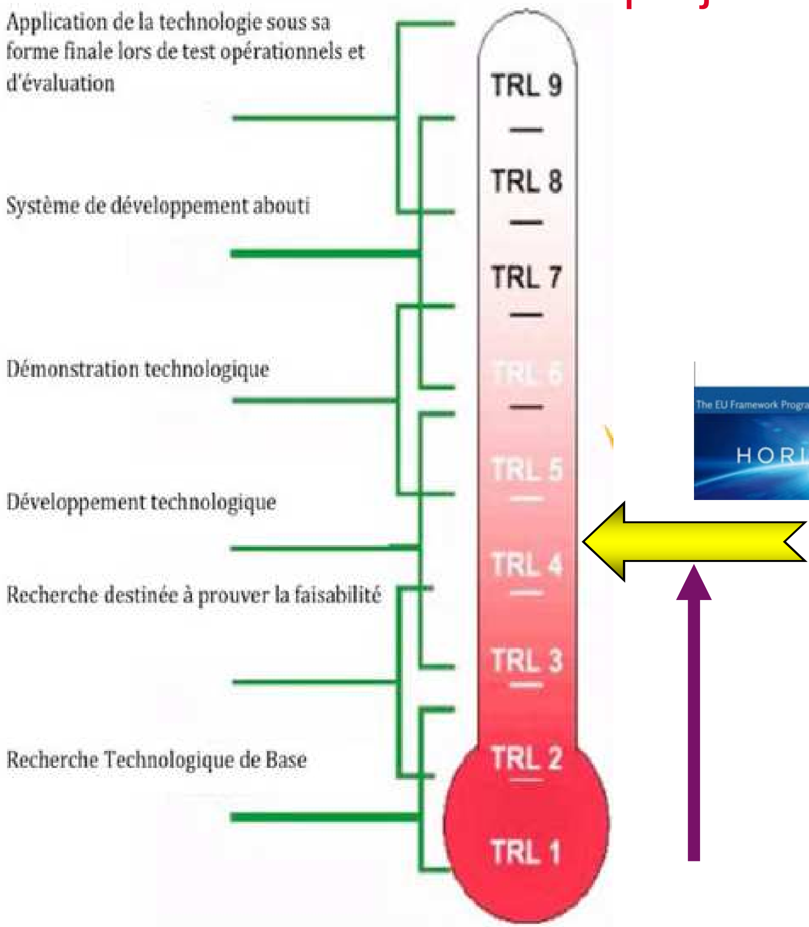
- **4 start-up** benefited directly from results initiated with program
- **29 patents** (2008-2013)

FULLFLEX PROTOTYPE CHALLENGE?

Objectif: go beyond germination!

Build a prototype Integrating technological components developped within Nanoscience & ChimTronic seed projects

- Reach higher TRL



FULLFLEX PROTOTYPE CHALLENGE?

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- Reach higher TRL
- Development of new technologies of flexible interconnects
- => A new prototype for CEA's Showroom

FULLFLEX PROTOTYPE CHALLENGE?

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Build a prototype Integrating technological components developped within Nanoscience & ChimTronic seed projects

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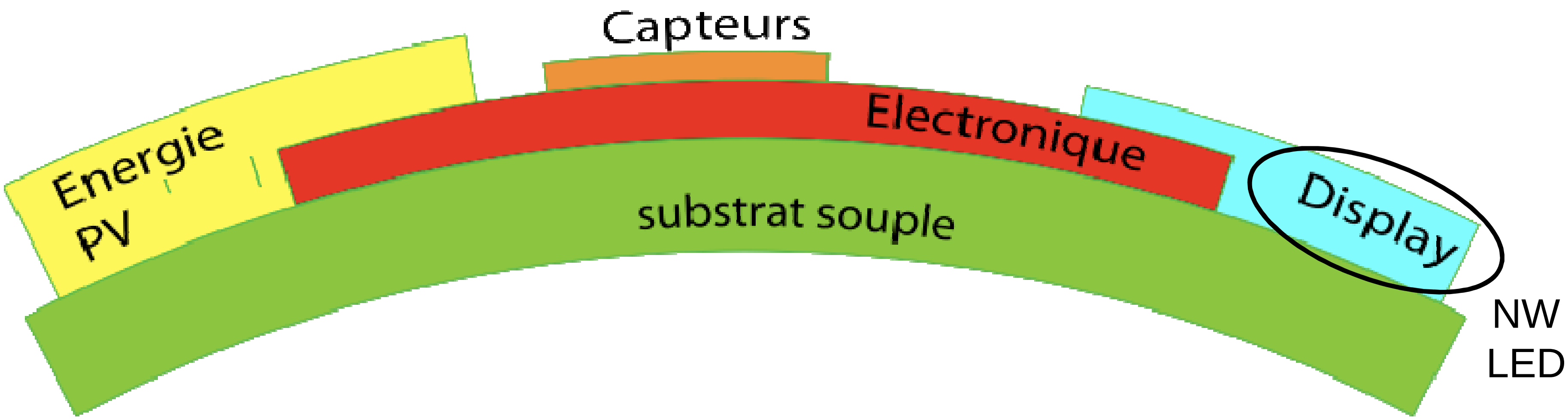
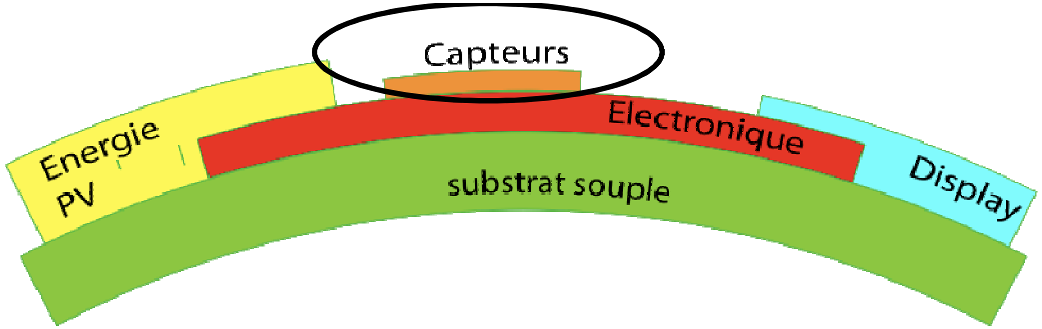
Initial Concept: a flexible autonomous, multifunctions label



FULLFLEX: WHAT TEAM?

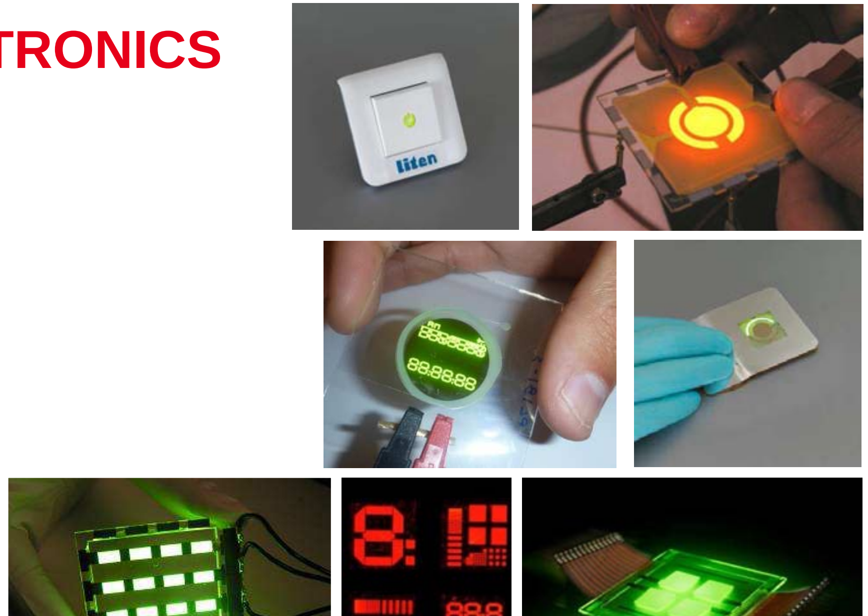
Component	Investigators	Affiliation
Battery (Si NP)	Marc BRESTAZ	DRT/LITEN/DEHT/LCPB
	Séverine JOUANNEAU	DRT/LITEN/DEHT/LCPB
	Willy PORCHER	DRT/LITEN/DEHT/LCPB
	Axelle QUINSAC (NTE)	DSM/IRAMIS/SPAM/EDNA
	Yann LECONTE	DSM/IRAMIS/SPAM/EDNA/LFP
	Nathalie HERLIN	DSM/IRAMIS/SPAM/EDNA
PV organic	Rémi DE BETTIGNIES	DRT/LITEN/DTS/LMPV
	Nicolas GAUTHIER	DSM/INAC/SCIB/RICC
	Marinella MAZZANTI	DSM/INAC/SCIB/RICC
	Daniel IMBERT	DSM/INAC/SCIB/RICC
	Renaud DEMADRILLE	DSM/INAC/SPRAM/LEMOH
	Amélie REVAUX	DRT/LITEN/DTNM/LCSN
LED (NW)	Benoit AMSTATT + François LEVY & Alexandre LAGRANGE	DRT/LETI/DOPT/SCOOP/LCE
	Joël EYMERY + Benjamin GREVIN	DSM/INAC
Transparente Electrode (CNTs or NW)	Eléonore MOREAU	DRT/LITEN/DTNM/LCRE
	Jean-Pierre SIMONATO + Caroline CELLE	DRT/LITEN/DTNM/LCRE
	Benjamin GREVIN + Renaud DEMADRILLE	DSM/INAC DSM/INAC
Printed Electronics	Abdelkader ALIANE	DRT/LITEN/DTNM/LCEI
	Romain COPPARD	DRT/LITEN/DTNM/LCEI
System /integration	Jean-François MAINGUET	DRT/LETI/DSIS/SIPP
	Tristan HAUTSON	DRT/LETI/DSIS/SIPP
	Pascale RIVIER	DRT/LETI/DSIS/SIPP
Pilotage	Jean-Christophe GABRIEL	DSM/DIR/DPNS
	Norbert DANIELE	DRT/LETI/DSIS/SIPP
	Tiana DELHOME	DRT/LETI/DSIS/SIPP



Printed Temperature Sensors

Abdelkader Aliane

PRINTED ORGANIC ELECTRONICS @CEA/LITEN



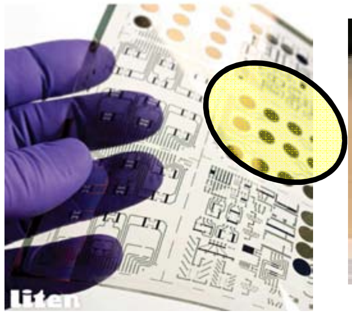
PLED (Polymer Light-Emitting Diodes)

- HMI, signage
- Devices, systems
- Single digit, matrix
- Logos
- **cf Talk Tony Maindron (OLED)**

Antennas

Sensors

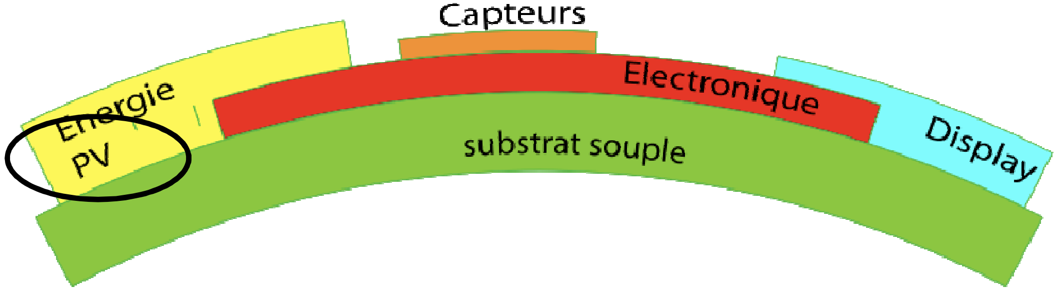
- Temperature (Resistors)
- Capacitive
- Pressure sensitive



Large Surface Printing Platform (PICTIC):

- 50 researchers and technicians
- €9 million in investment
- 600 sq. m of clean rooms
- Slot-die, gravure, flexography process equipment
- Industrial partnerships, startup (ISORG)

DE LA RECHERCHE À L'INDUSTRIE



Photovoltaic flexible modules

Renaud DEMADRILLE – DRF / INAC / LEMOH
Solenn Berson – DRT/INES/SMPV

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Bulk-heterojunction solar cells (BHJ) : Concept

Heeger et al.*Science*, 1992, 258, 1474.

- 2 Interpenetrated percolating networks
- Optimal phase segregation (10-20nm)

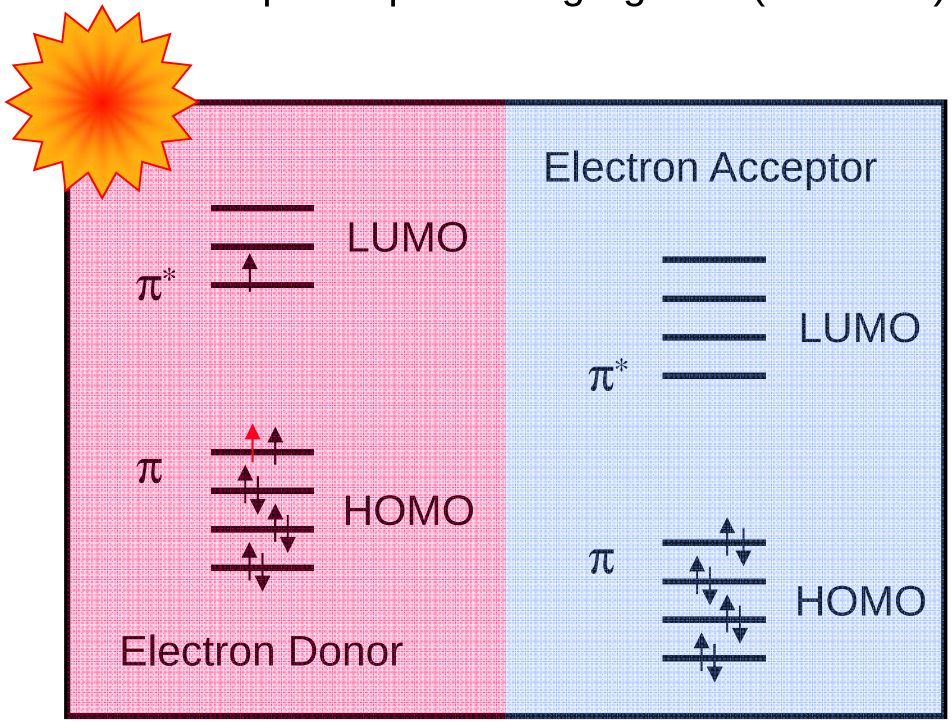


Photo-induced charge transfer

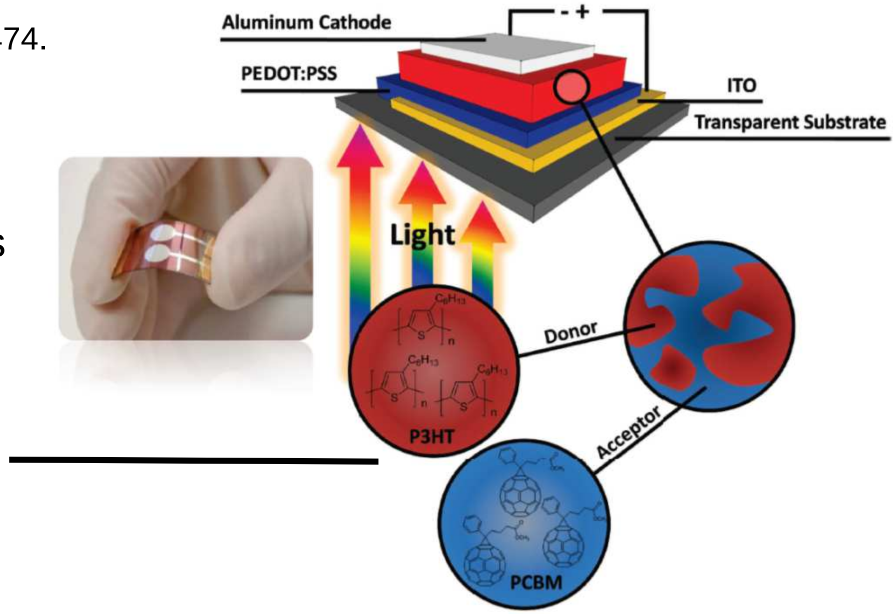
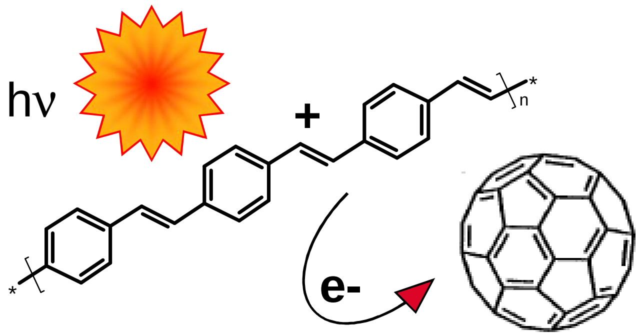
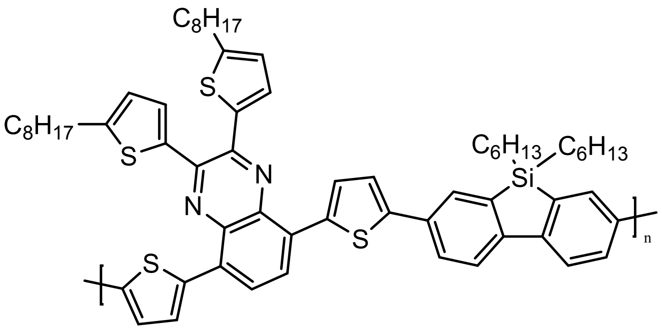


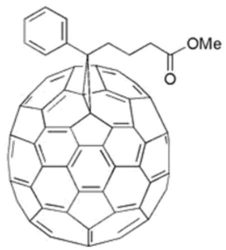
Photo-induced charge transfer < 10^{-12} s

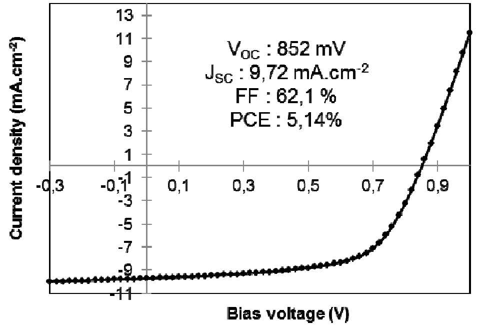


Innovative materials and fabrication of flexible modules

Development of new materials for use in the active layer



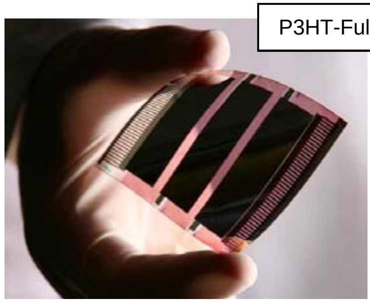




Polymer Chem., **2016**, 7, 4160

Laboratoire des Modules Photovoltaïques Organiques (LMPO) – S. Berson (DRT-INES)

Development of OPV modules by printing techniques (ink-jet)
First examples with P3HT



P3HT-Fullerene

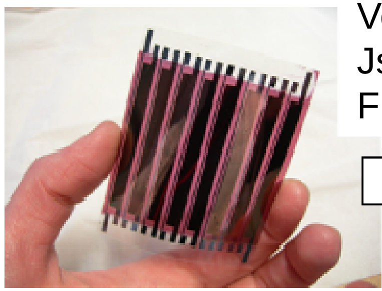
S = 11,04 cm²

PCE = 2,9%
Voc = 1,61 V
Jsc = 3 mA/cm²
FF= 60 %

Printed modules : S.Berson, R. De Bettignies, DRT-INES

P = 30mW

Cf talk Solenn Berson



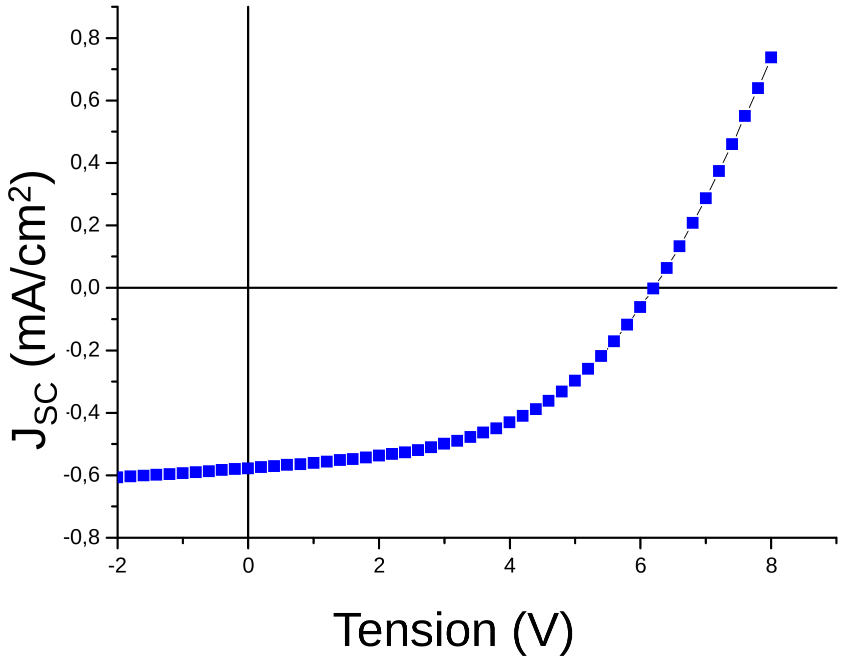
PCE = 2,1%
Voc = 4,9 V
Jsc = 1.1 mA/cm²
FF= 40 %

P3HT-Fullerene

Compatible with Li Ion batteries
Vmin = 3.7V

PV DEVELOPED FOR THE LABEL

All Interconnects: conducting adhesive



Voc= 6.2 V
Jsc= 0.577 mA/cm²
FF= 48.2 %
PCE= 1.73 %
Vmax = 4.1V
Imax = 35.8 mA

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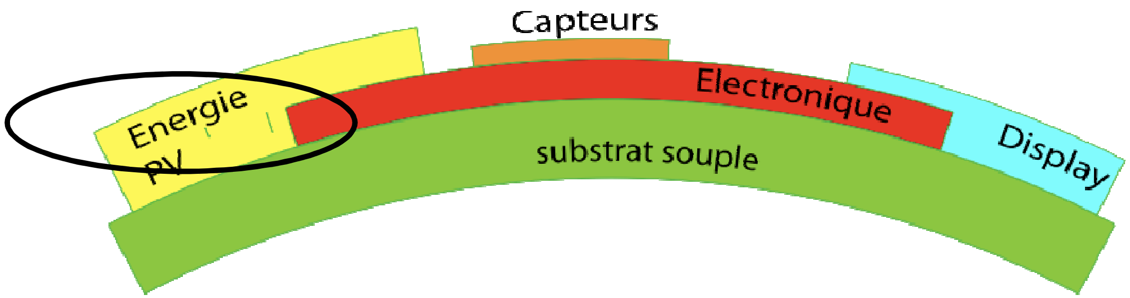
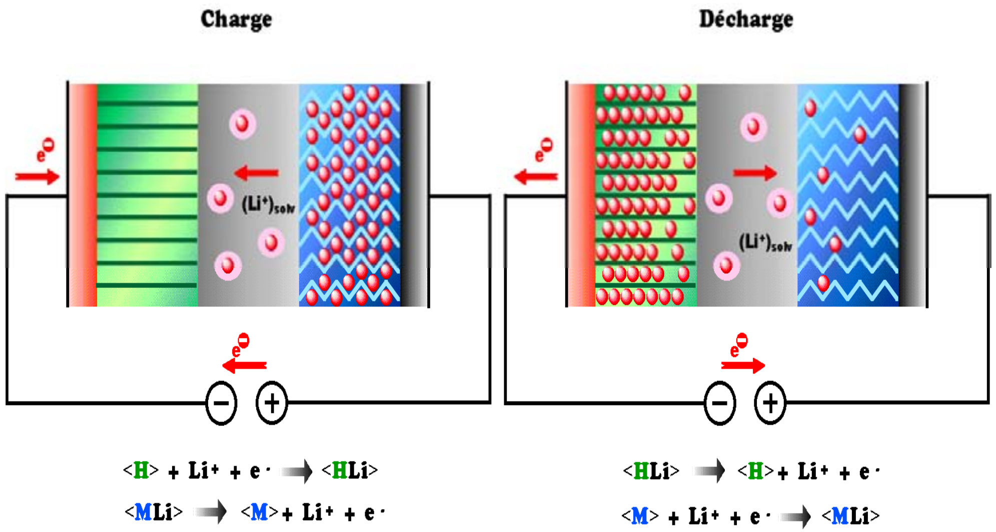


Silicium NP based battery

Nathalie Herlin, Séverine Jouanneau,

Willy Porcher



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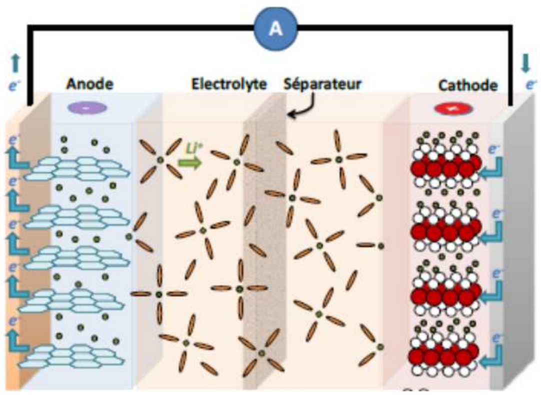
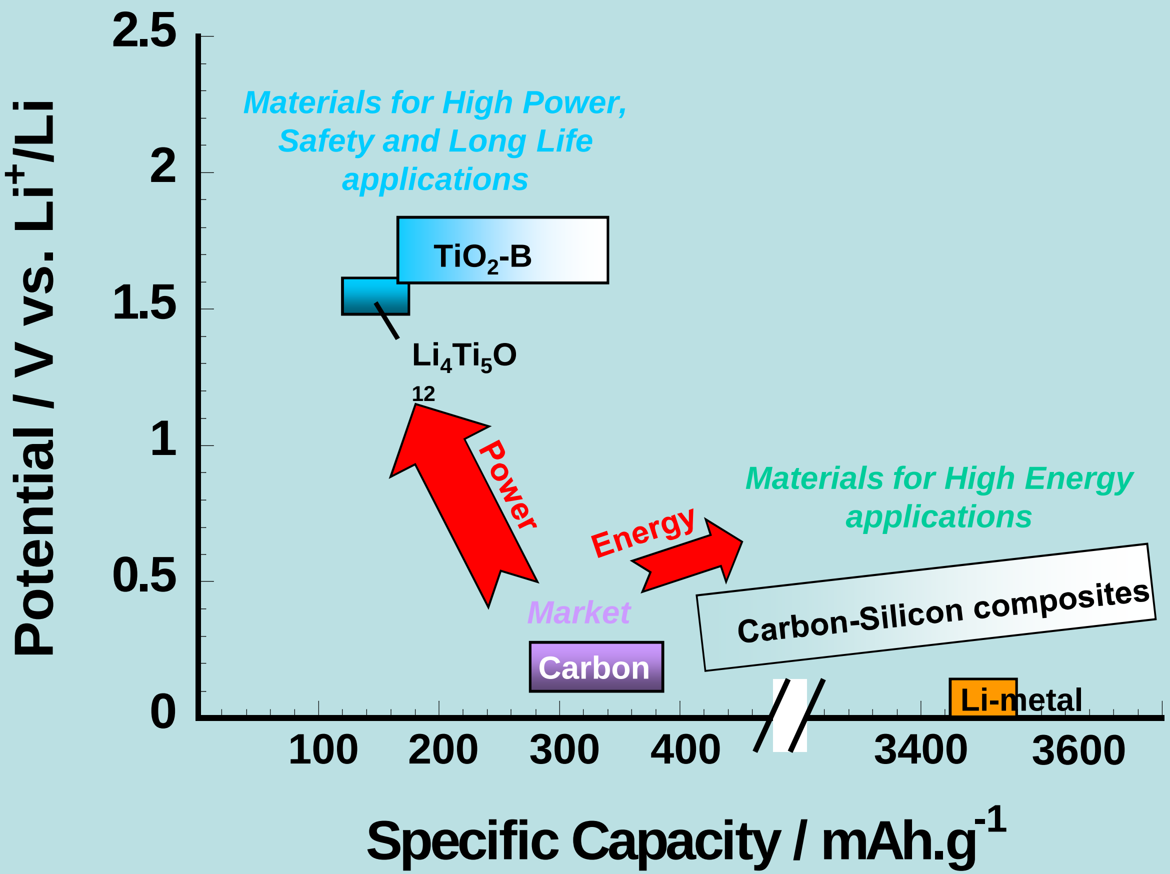
FLEXIBLE SI NP BASED LI BATTERY

Batteries lithium-ion



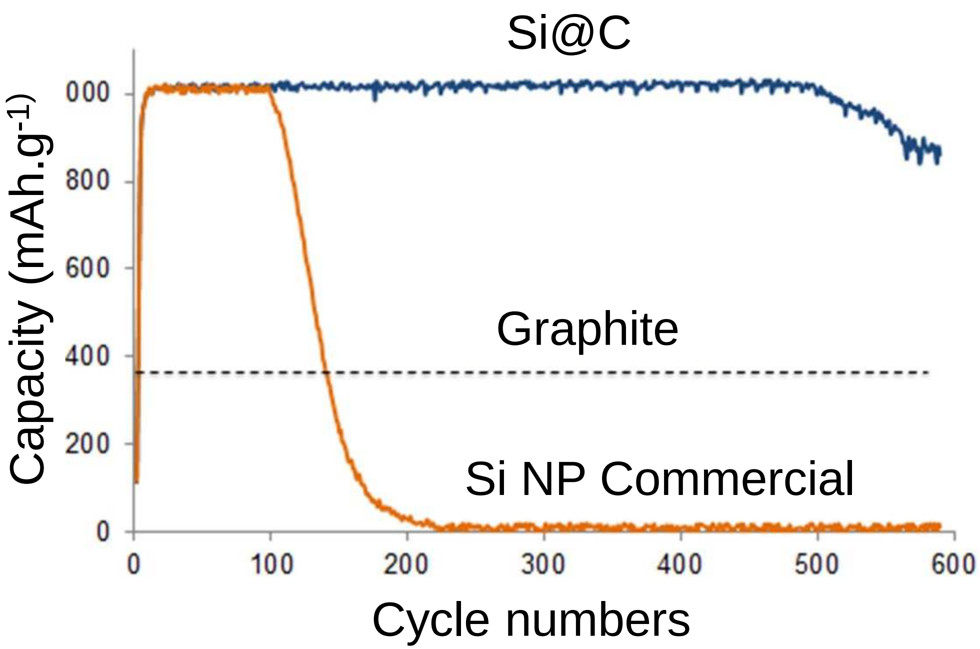


AVANTAGE :
Max = 3578 mAh/g (Si → Li3,75Si) = 10x graphite

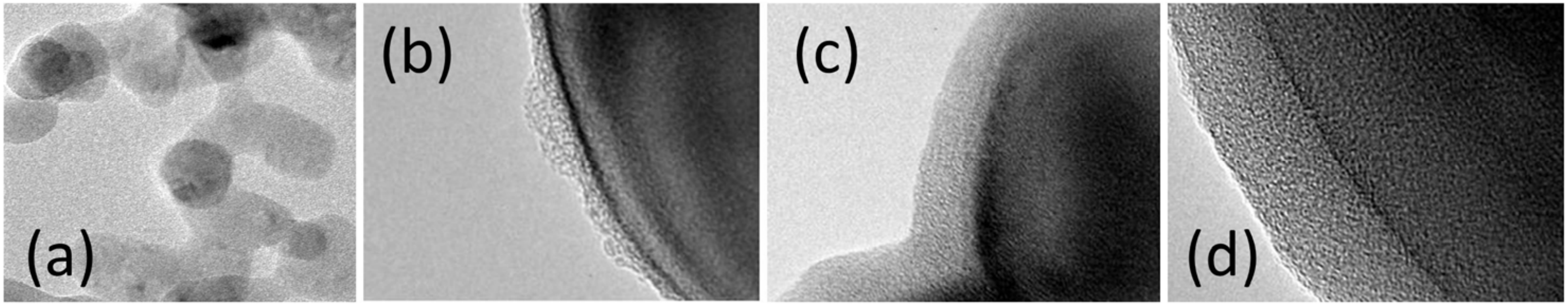
DISAVANTAGE: V_{inc} = +280%

=> NP Si

NP Si & Si@C in SACLAY: LASER PYROLYSIS

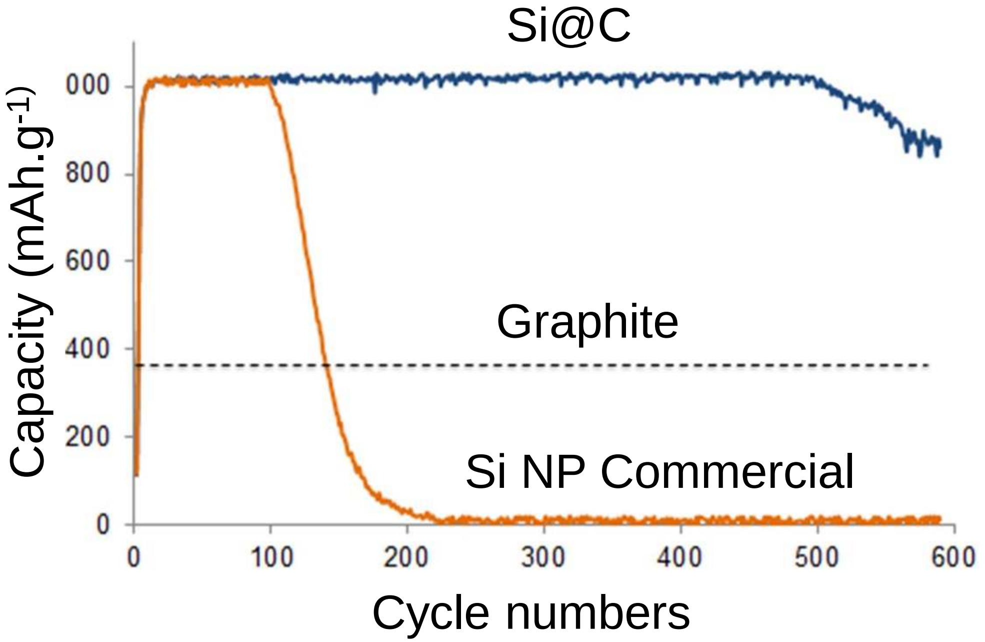


- Core-shell amorphous silicon-carbon nanoparticles for high performance anodes in lithium ion batteries
- *Journal of Power Sources* **328** (2016) 527-535
- Patent: US9205399 (2015), US20150299861 US20150303462
- 1 startup (Nanomakers)



NP Si@C: Amorphous C layer = 3nm 10 nm 15 nm

NP Si & Si@C in SACLAY: LASER PYROLYSIS



- Core-shell amorphous silicon-carbon nanoparticles for high performance anodes in lithium ion batteries
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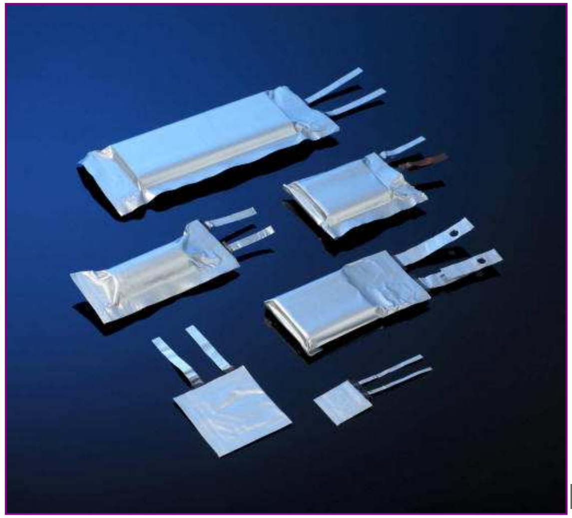
Overall
Positive Electrode: NMC ($LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$)
Ref. Element: 3Ah for 3x3 cm x 5 mm cell
Power < 3W
Surface capacity: 3 mAh/cm^{-2}
Voltage : 3,5 V

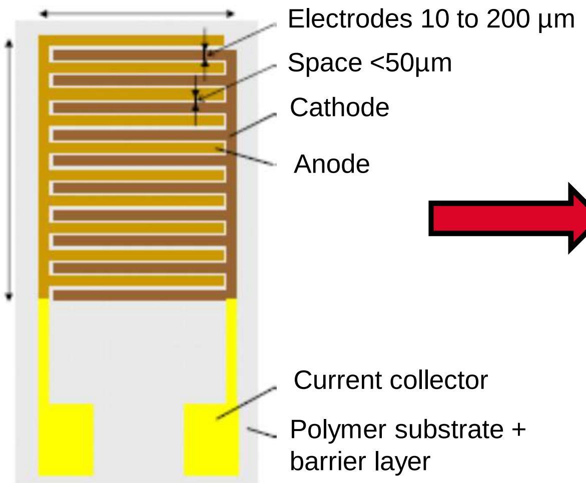


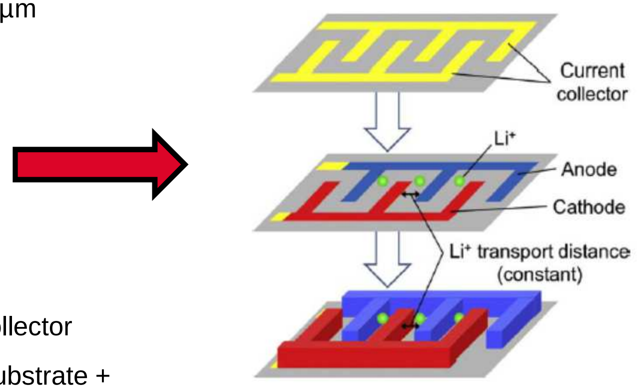
NEW DESIGN: ENABLES DIGITAL PRINTING BATTERIES

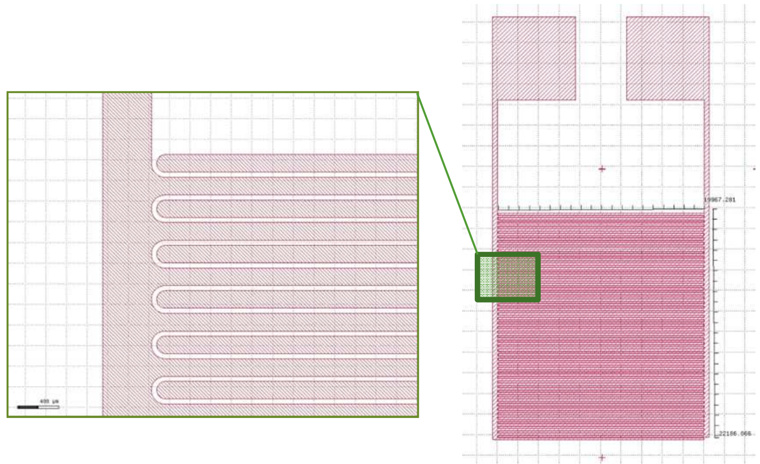
To simplify or solve several technological barriers, another battery architecture is possible: the interdigitated planar design

- **The interdigitated concept reverses at 90 ° stacked architecture**
  - ✓ Architectured current collectors on the same plane
  - ✓ Electrodes printed side by side on respective collectors
  - ✓ Separator printed between the electrodes printed on the entire surface
  - ✓ Gellified electrolyte
- **Constraints of the concept:**
  - ✓ High printing resolution(10µm +/- 1µm)

- Dimensions:
  - Width of lines : 200µm
  - Distance between lines : <100µm (target 50µm) → electrolyte compartment
- Solid electrolyte configuration
- No densification







Patent BF3007206

=> Thomas Yohann

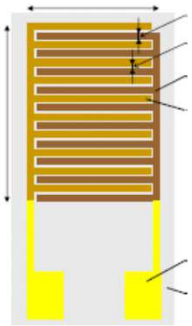
DIGITAL PRINTING BATTERIES @ LITEN

Current collectors
Electrodes
Electrolyte

Flexible and fully printed multi materials

Non stacked configuration

simplification of interfaces (more flexibility with reduced mechanical constrains)



Interdigitated design

Nano inks

High resolution

Width of lines : 200µm
Distance between lines : <100µm (target 50µm) → electrolyte compartment

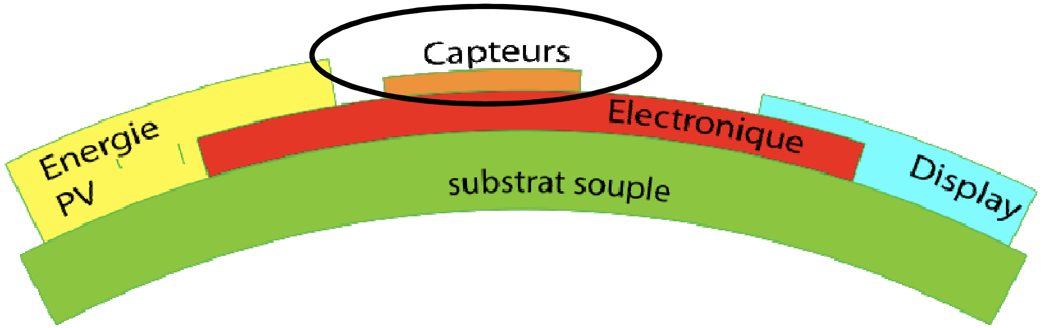
Non contact printing technique

Ink-jet

Aerosol jet printing

- More flexibility
  - Design
  - Interfaces
- Versatility of shapes

DE LA RECHERCHE À L'INDUSTRIE



Transparent Electrode

+

Capacitive Sensors

JEAN-PIERRE SIMONATO

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NEW TECHNOLOGIES = NEW NEEDS

A NEW NEED FOR FLEXIBLE TRANSPARENT ELECTRODES




TCOs (ITO) have serious limitations

- × ***Indium is a major critical raw material***
- × ***High cost process (capex, material)***
- × ***Brittleness***

Alternatives ?

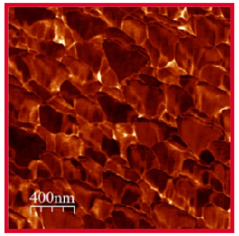
- ✓ ***Conductivity / Transparency***
- ✓ ***Flexibility / stretchability***
- ✓ ***Low cost (material / process)***

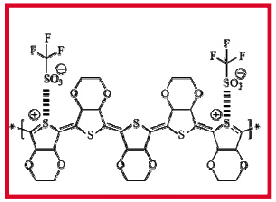
SUBSTITUTION of ITO by Nanomaterials

DE LA RECHERCHE À L'INDUSTRIE

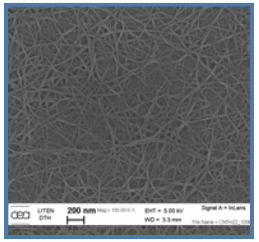
POTENTIAL ALTERNATIVES

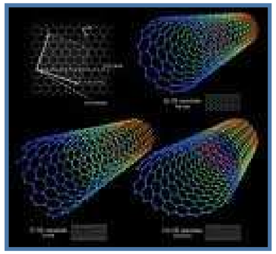
- **Conducting polymers**



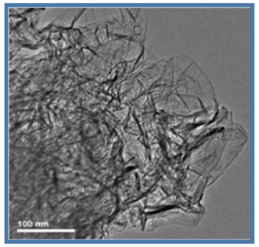


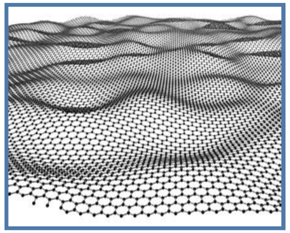
- **Carbon Nanotubes**



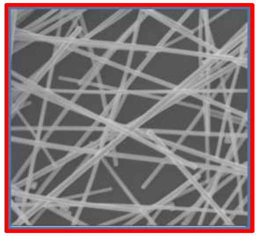


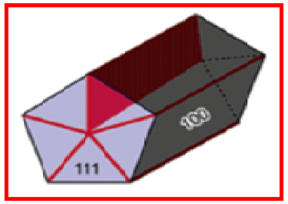
- **Graphene**





- **Metallic nanowires**





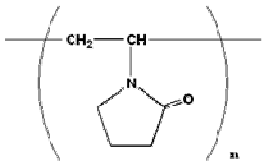
POTENTIAL ALTERNATIVES

➢ **Conducting polymers**	***J. Mater. Chem. C,*** 2014 ***Chemical Science***, 2015 ***Chemistry of Materials***, 2016
➢ **Carbon Nanotubes**	***Nano Letters,*** 2003 ***Carbon,*** 2012 ***Carbon***, 2014
➢ **Graphene**	***Applied Physics Letters***, 2014 ***Ultramicroscopy***, 2015
➢ **Metallic nanowires**	***Nanoscale,*** 2015 ***Small,*** 2016 ***Nano Research***, 2012, 2014 ***Nanotechnology***, 2013 x 2 ***Nano Letters,*** 2016

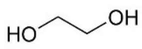
Ag NW SYNTHESIS: COMPLICATED?

$AgNO_3$

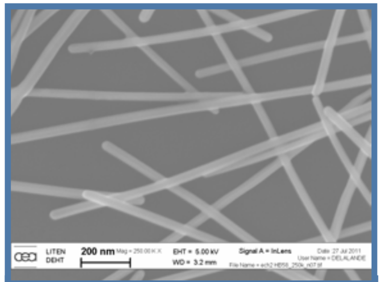
PVP



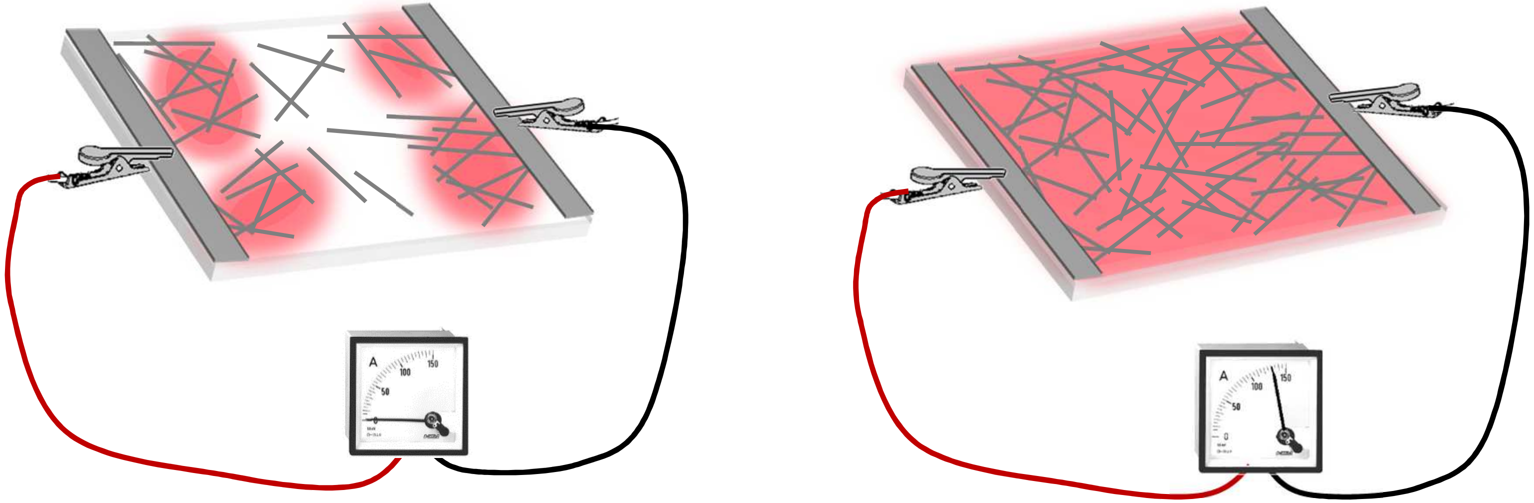
Ethylene Glycol



NaCl



PERCOLATIVE RANDOM NETWORKS OF AG NANOWIRES



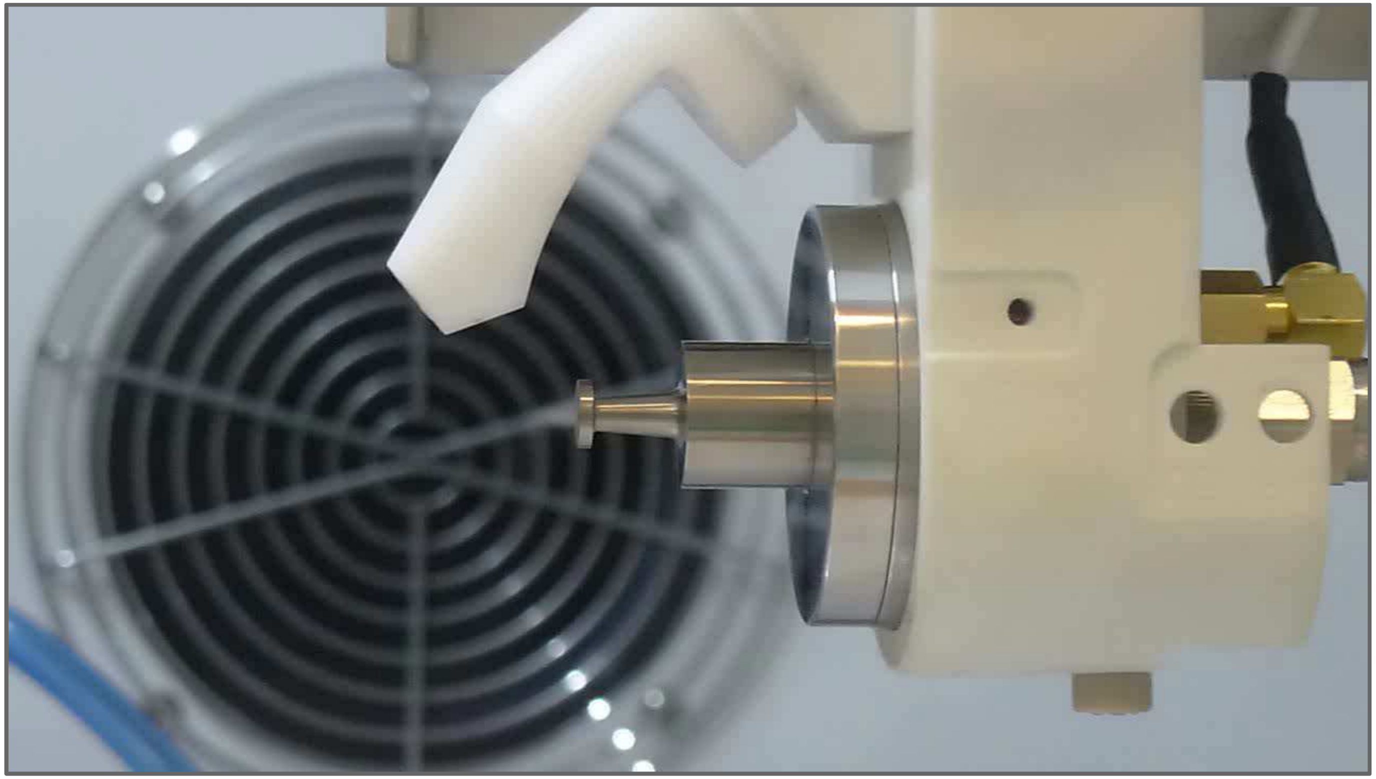

CEA
BREVET D'INVENTION

DECISION DE DELIVRANCE

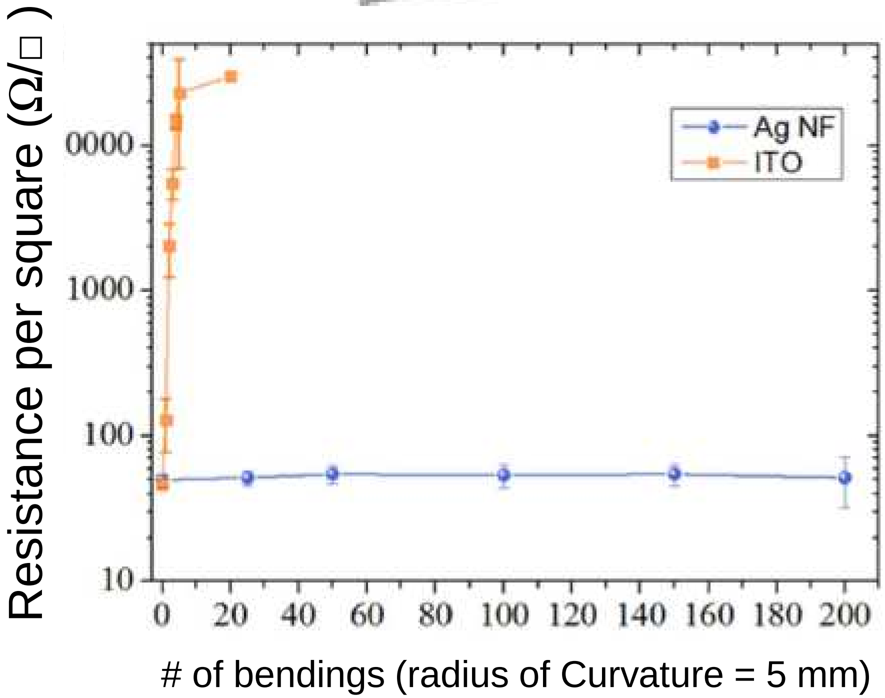
Percolation

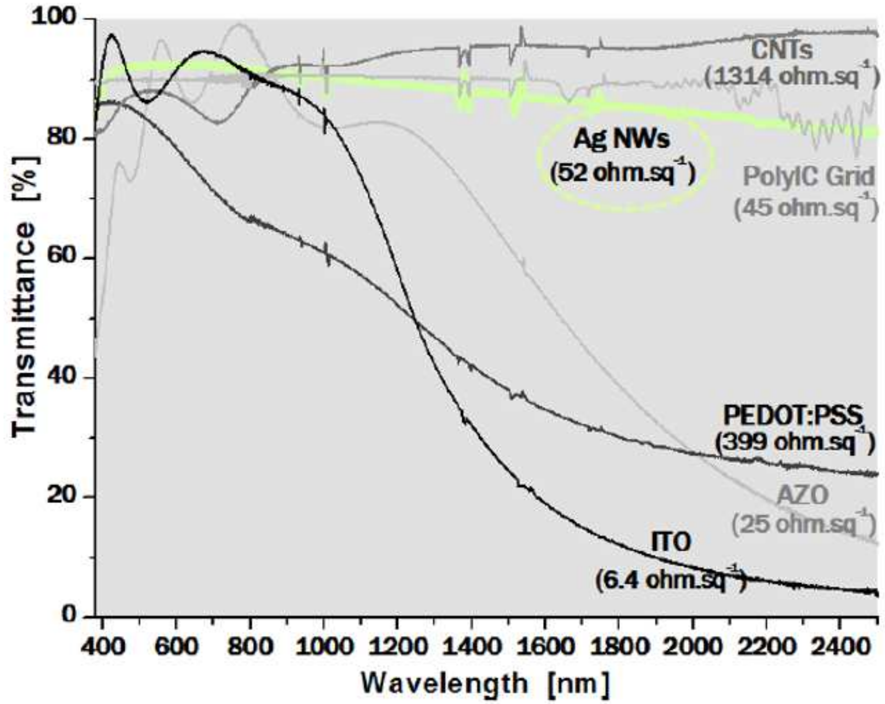
~ 15 PATENTS

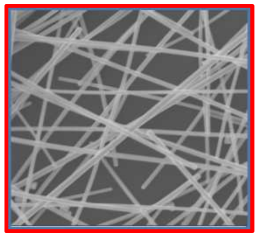
SPRAY-COATING, A METHOD OF CHOICE

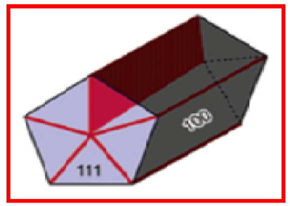


PERFORMANCES?



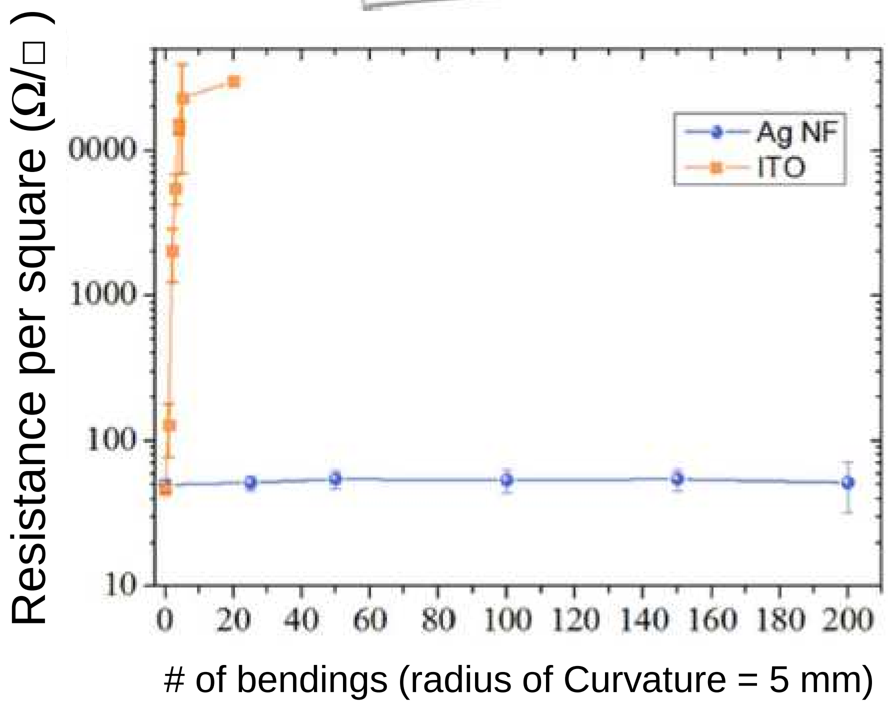


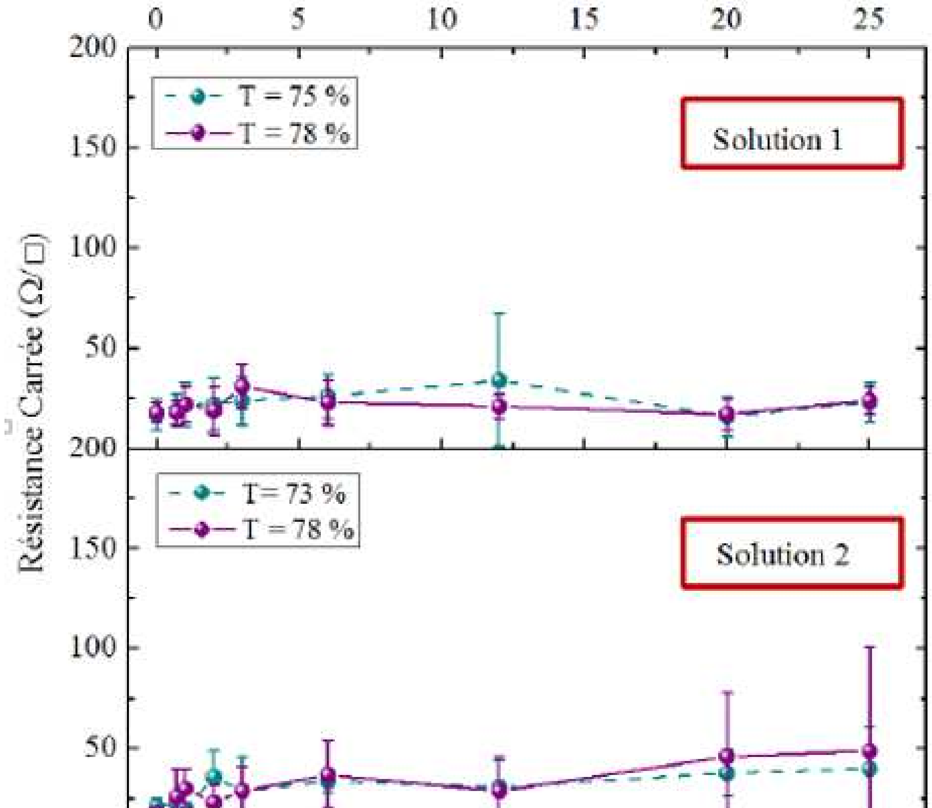


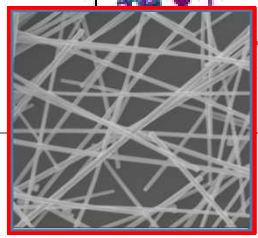


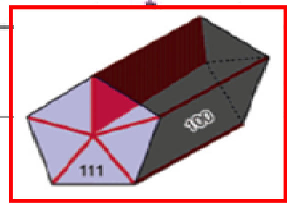
Nanoscale, 2015 ***Nano Research***, 2012, 2014 ***Nanotechnology***, 2013 x 2 ***Nano Letters,*** 2016

PERFORMANCES?









Nanoscale, 2015 ***Nano Research***, 2012, 2014 ***Nanotechnology***, 2013 x 2 ***Nano Letters,*** 2016

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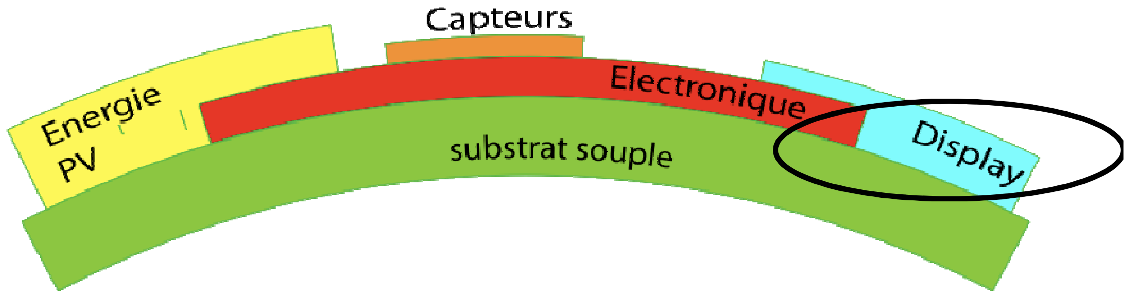
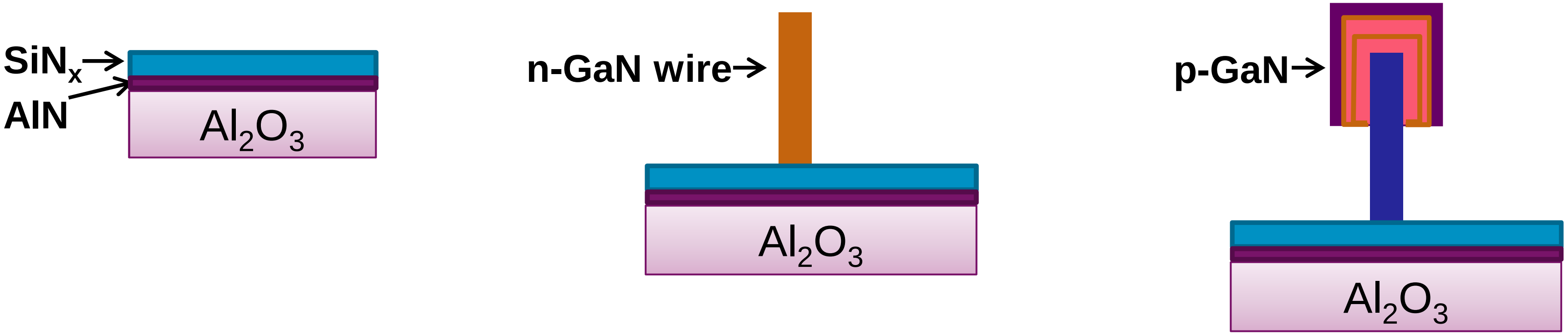


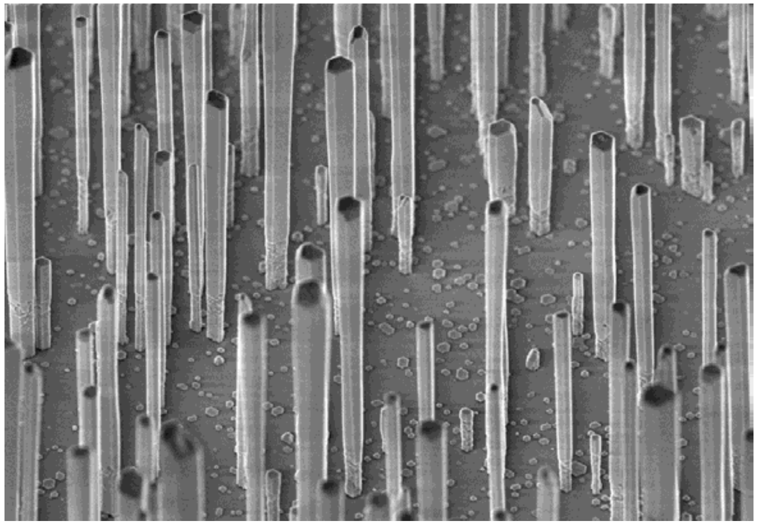
Nanowire based LED

JOËL EYMERY, FRANÇOIS LEVY

NITRIDE NW BY CATALYST-FREE MOVPE

1. Nitridation under NH_3 and SiN deposition
2. Wire growth under Silane injection and low V/III ratio
3. InGaN QW growth and p-GaN capping layer





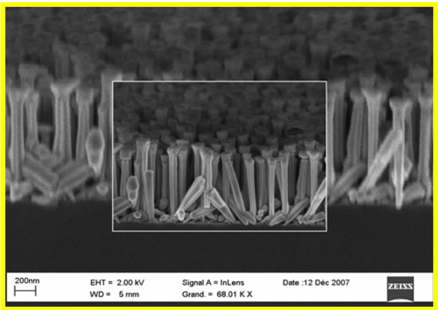
Nanowire morphology

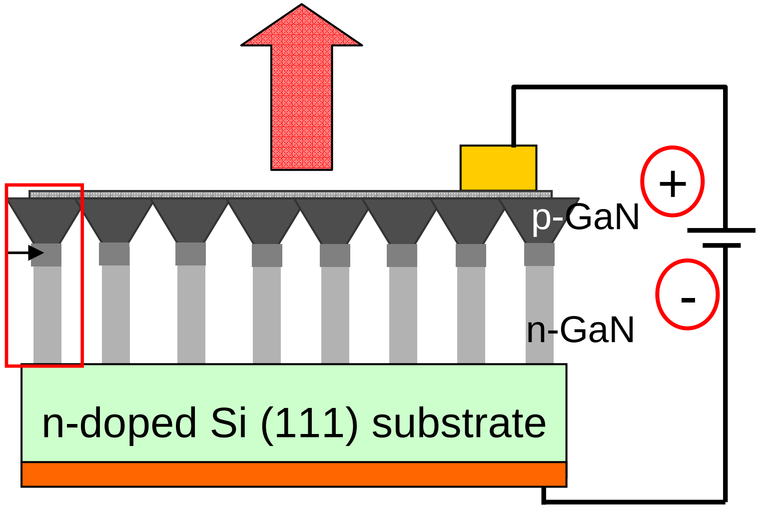
- **Diameter** : 500 nm – 2 µm
- **Height** : 10 – 30 µm
- **Density :** 10^7 cm^{-2}

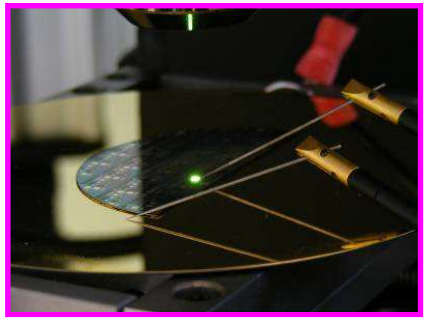
Spontaneous growth – big surface available for process optimization

MOCVD growth by C. Durand, J. Eymery (CEA-Grenoble)

Koester et al., Nanotechnology 21, 015602 (2010)



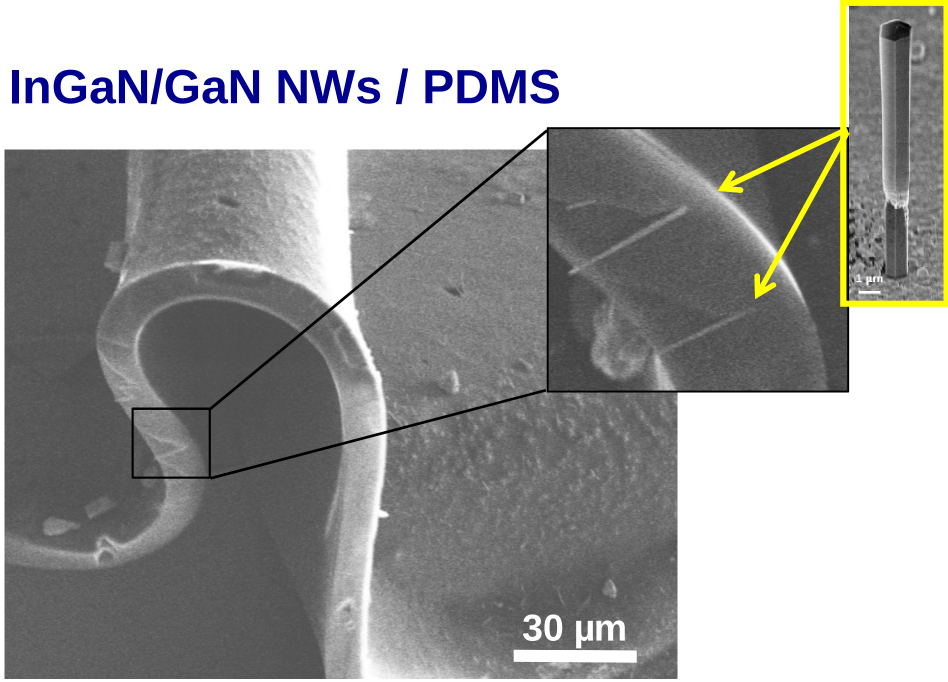


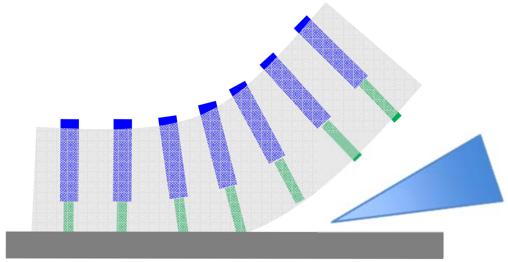


A-L Bavencove et al., Nanotechnology 22 (2011) 345705
Submicrometre resolved optical characterization of green nanowire-based light emitting diodes

GaN NW BASED LEDS ON FLEXIBLE SUBSTRATES

InGaN/GaN NWs / PDMS

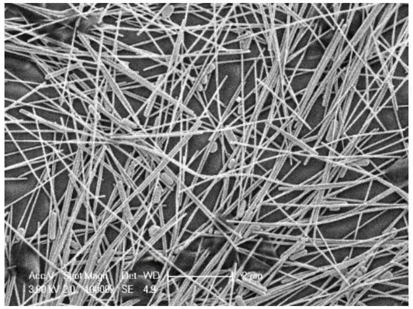




- GaN nanowires embedded into PDMS
- Mechanical lift-off of the composite film
- Back-side metallization and mounting on PET substrate

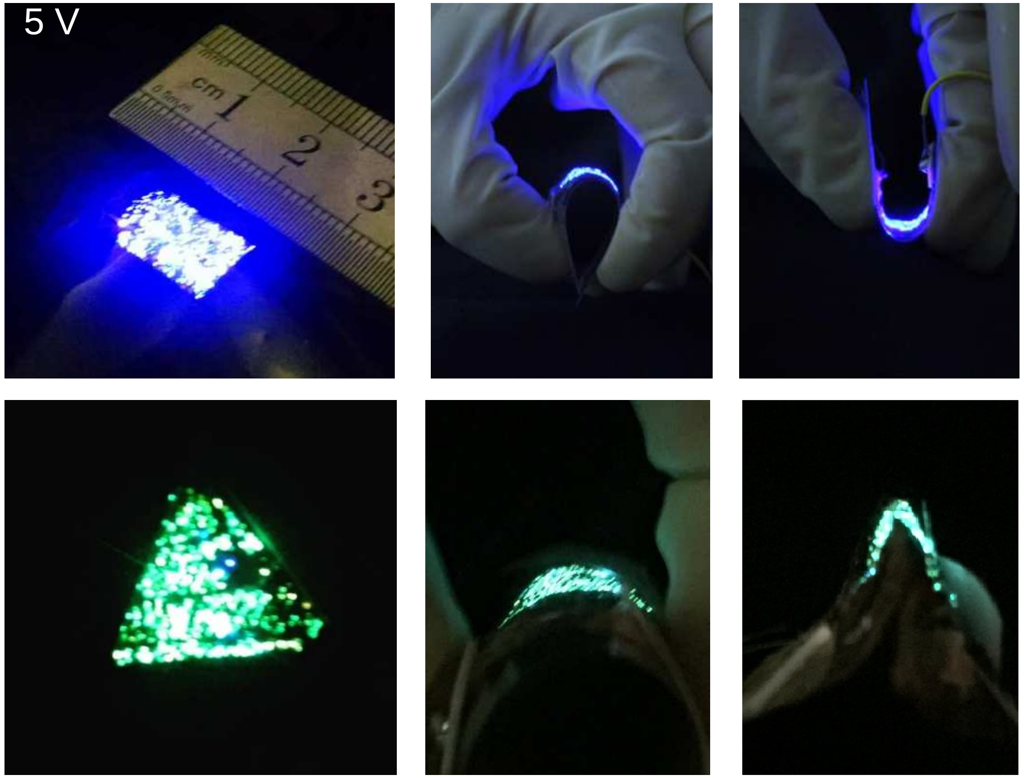
Main challenge – transparent flexible contact

- Thin TCO layers
- Graphene and/or graphene µ-flakes
- **Silver nanowire mesh**



V. Neplokh, et al, Nanosc Res Lett 2015

FLEXIBLE LEDS



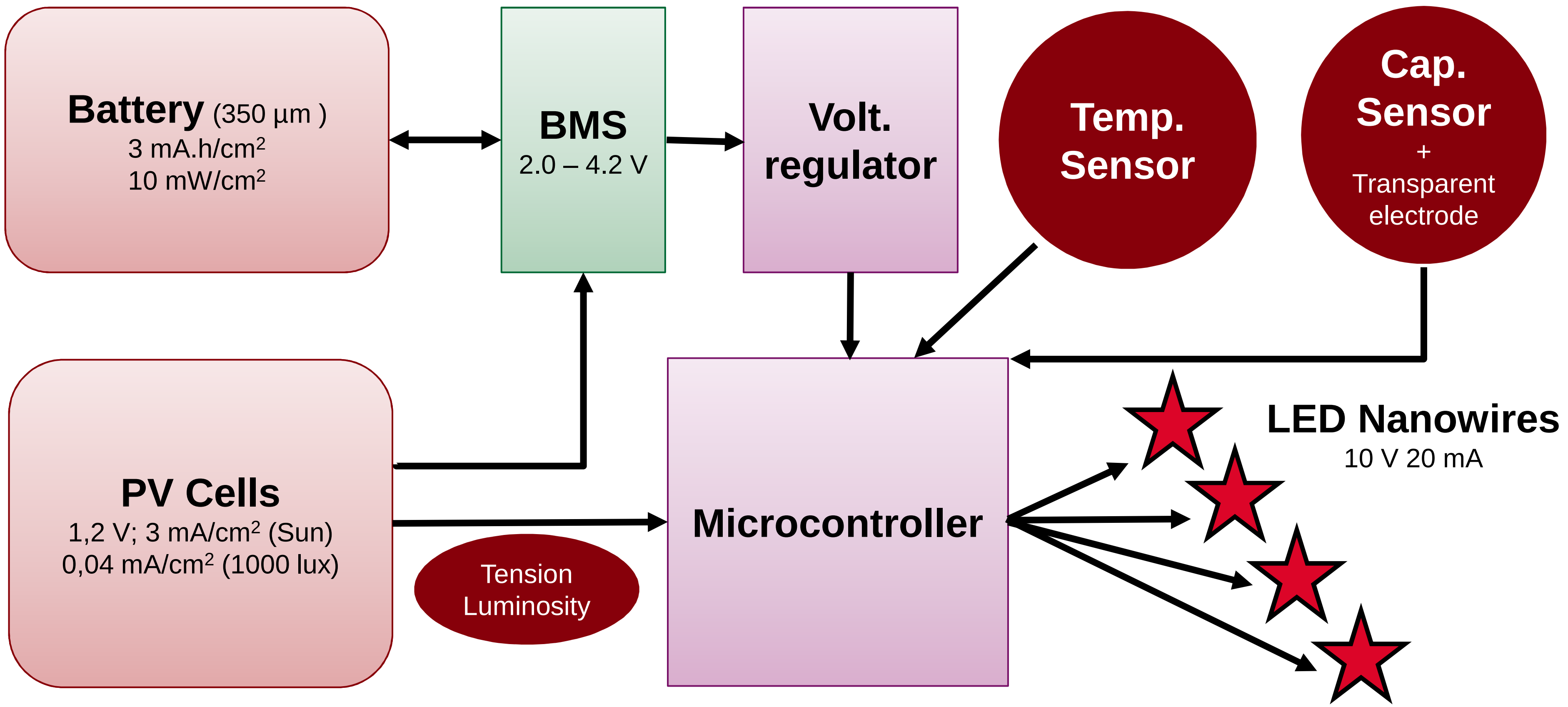
Blue LED

Green LED

- Large area flexible LEDs (active area of several cm^2)
- No I-V or EL degradation after 10 bending cycles (**$R_{bending}$ ≈ 0.3 cm**)
- Further improvement of emission homogeneity with organized NW arrays is under investigation

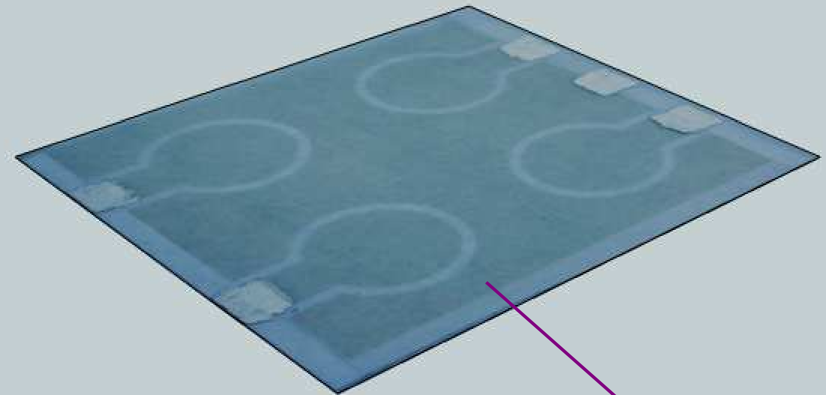
D. Xing et al, NanoLetters, 2015
La Recherche 2016 Award

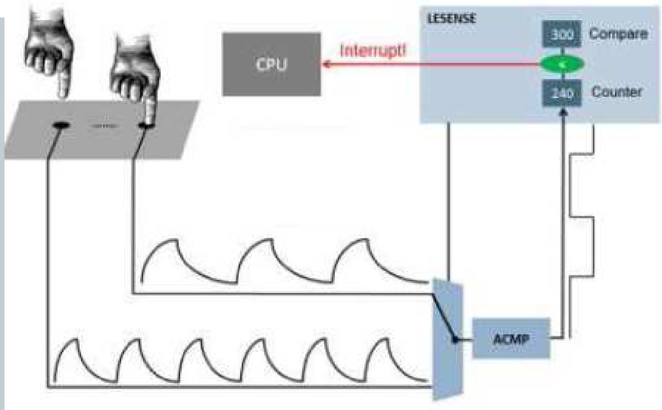
SPECIFICATIONS/PERFORMANCES & INTEGRATION

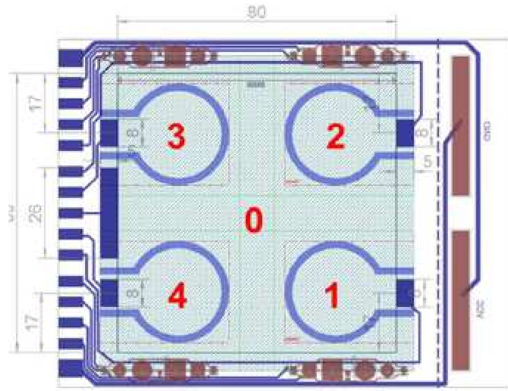


Three Sensors: Light, temperature, capacitive

OVERALL ASSEMBLY?

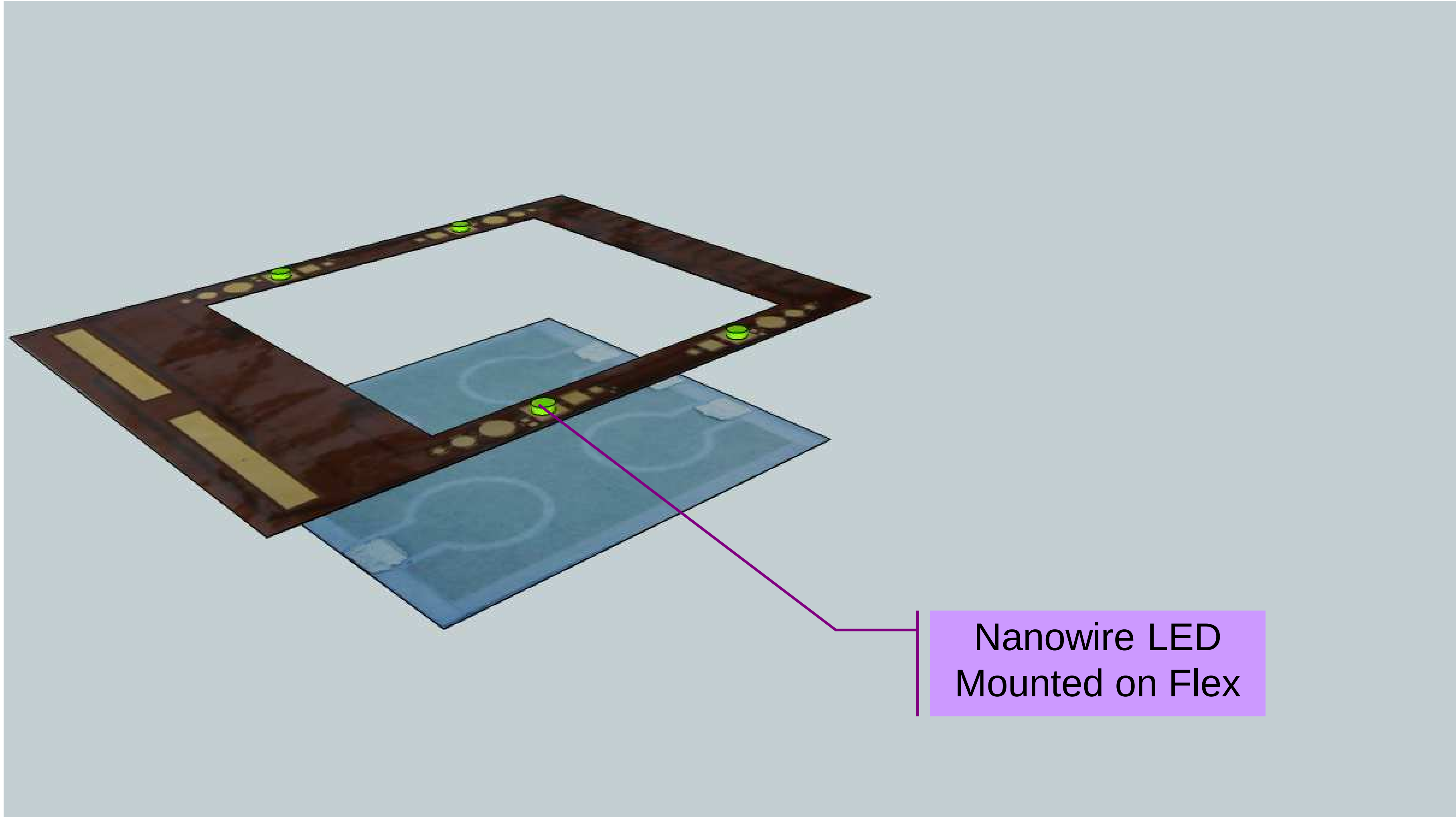




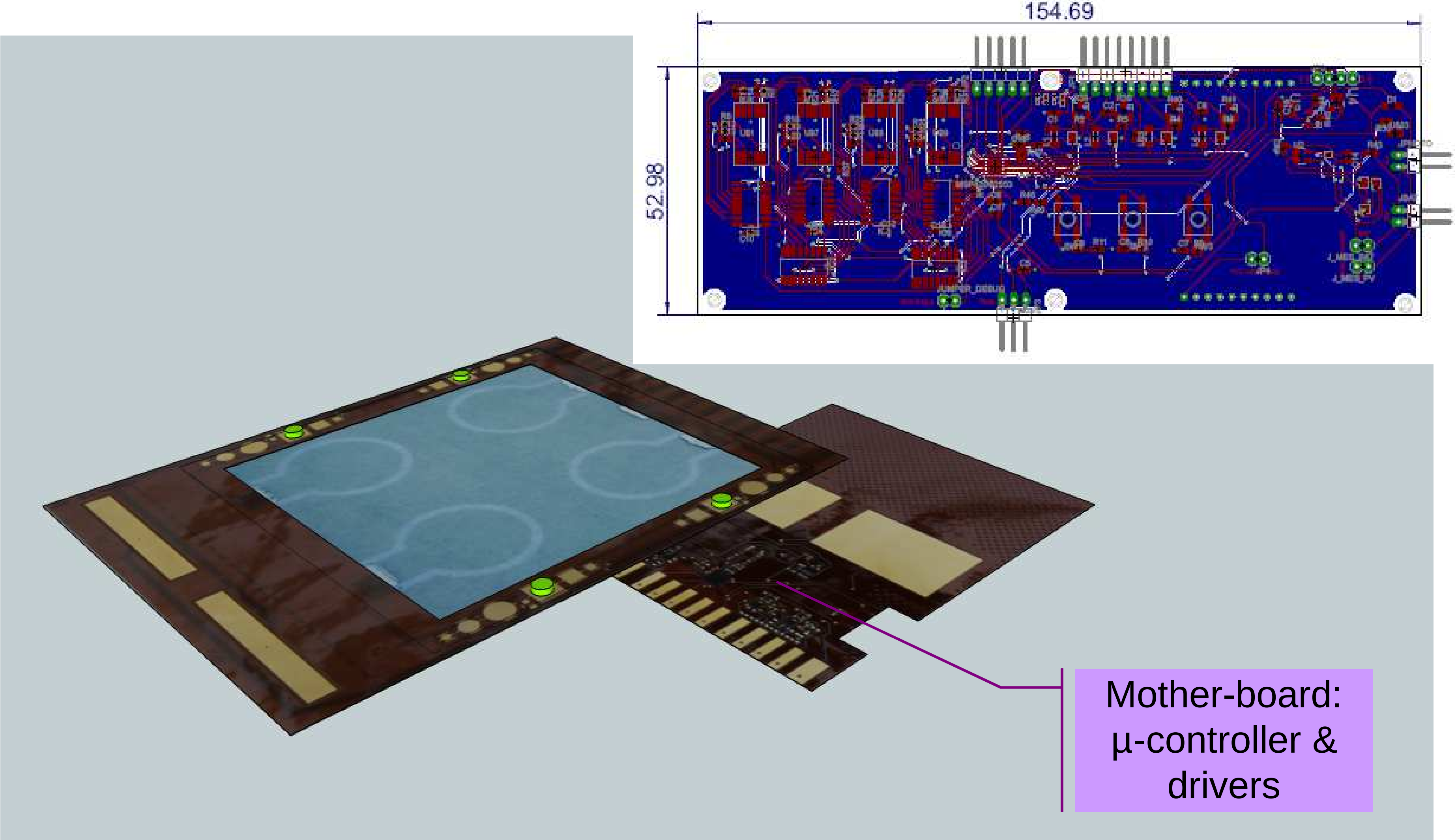


Silver Nanowires
Transparent electrode

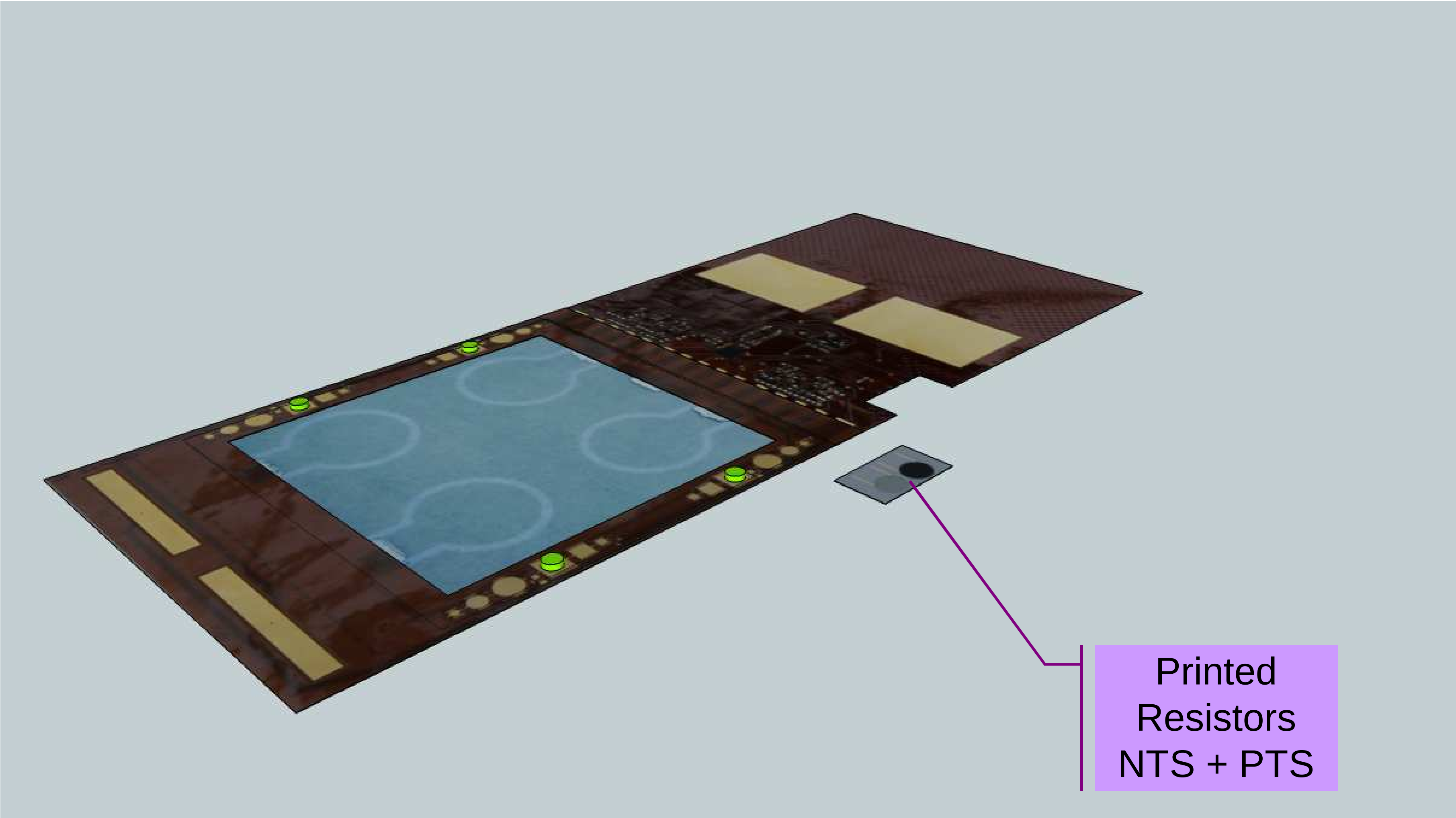
ASSEMBLY



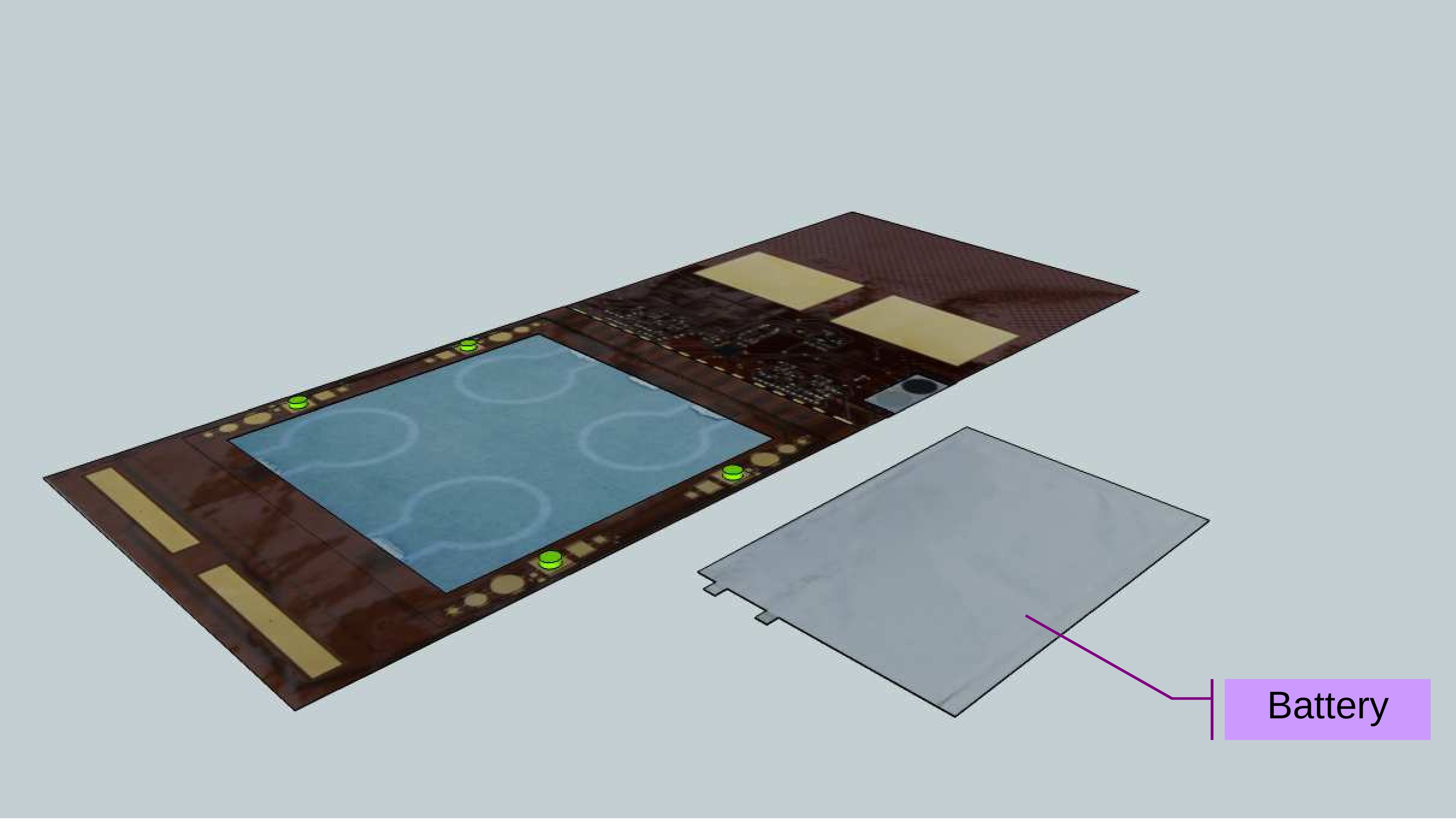
Flexible electronic mother board



ASSEMBLY



ASSEMBLAGE



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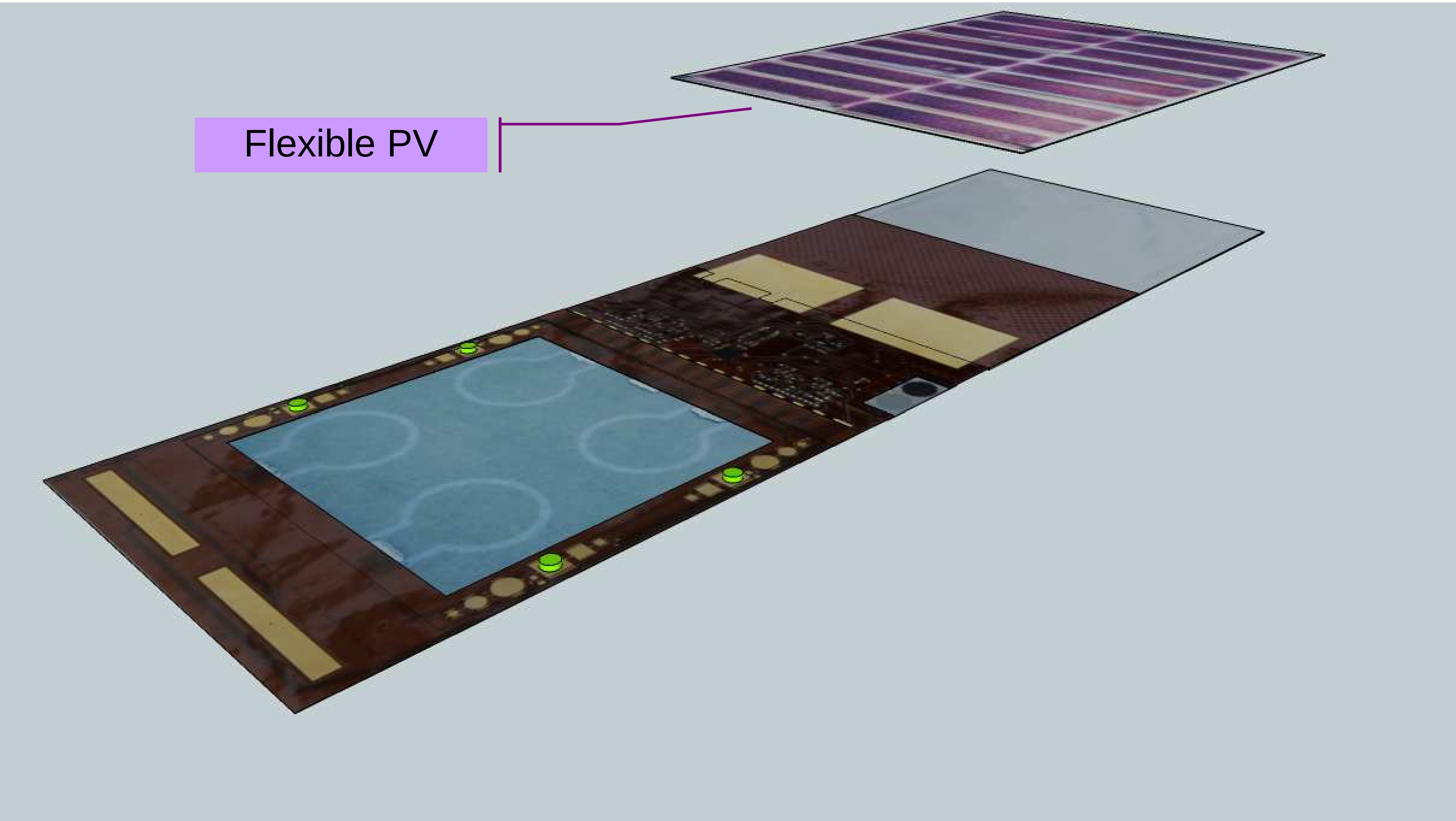
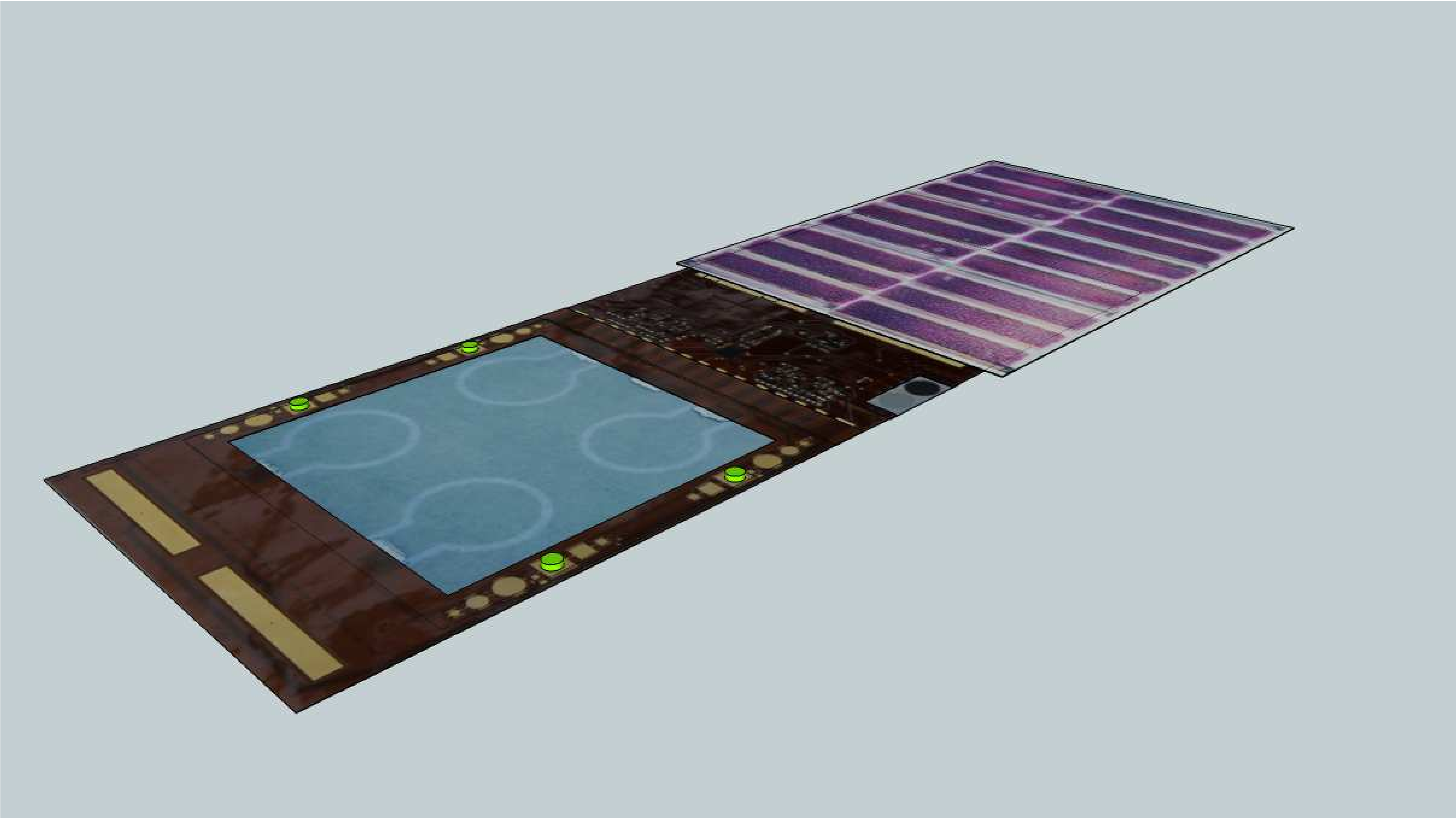
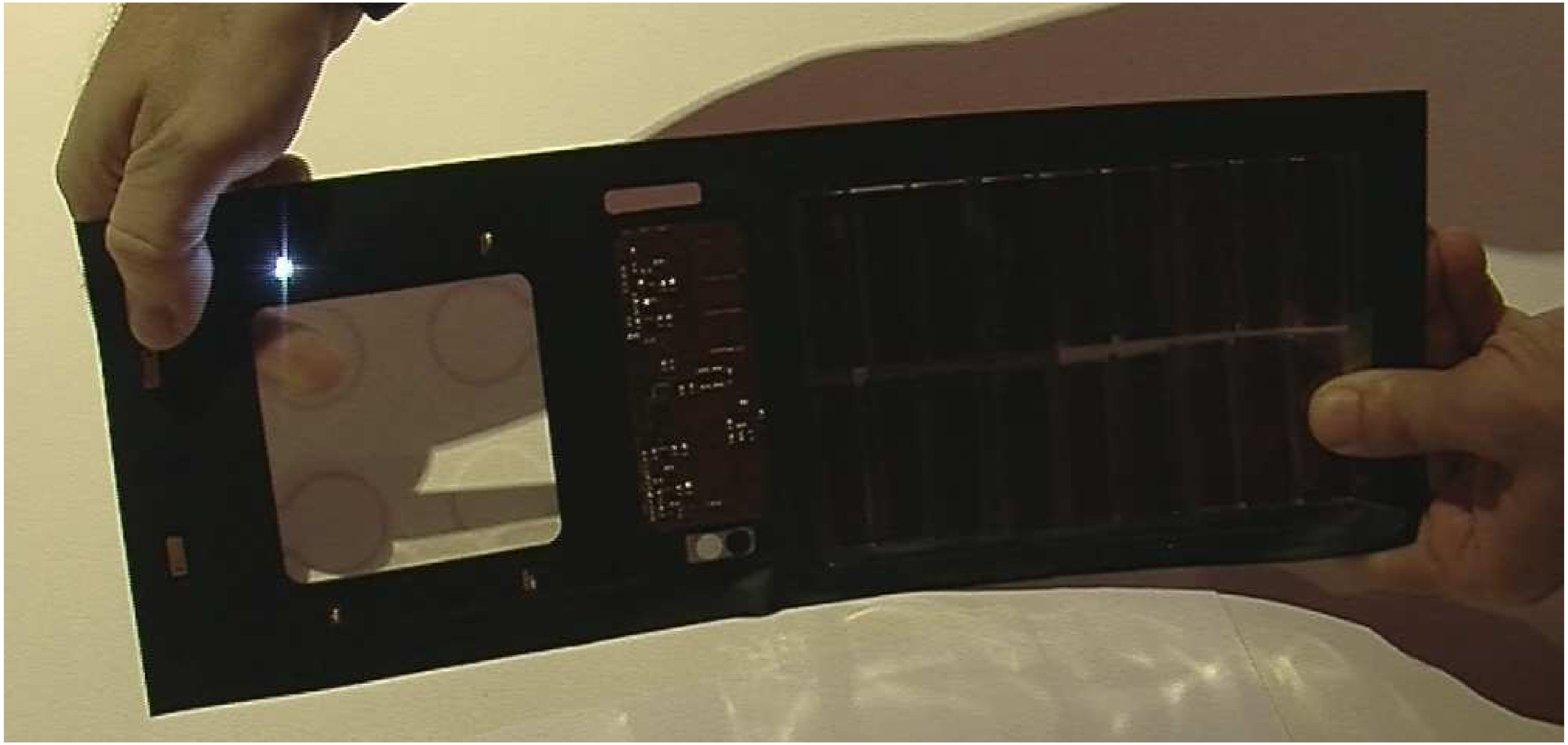


ASSEMBLY



Assembled Flexible Multi-functional Label

ASSEMBLED FLEXIBLE MULTI-FUNCTIONAL LABEL



- Capacitive mode (movie)
- Temperature alarm mode (movie)
- Light mode (movie)

CONCLUSIONS

- ✓ **1 year project, successfull**
- ✓ **Deadline met**
- ✓ **4 CEA's new techno. integrated**

Since then:

- ✓ **3 startups, 20 patents, numerous H2020 projects + industrial contracts**

More info:

jean-christophe.gabriel@cea.fr

QUESTIONS?

FULLFLEX: WHAT TEAM?

Component	Investigators	Affiliation
Battery (Si NP)	Marc BRESTAZ	DRT/LITEN/DEHT/LCPB
	Séverine JOUANNEAU	DRT/LITEN/DEHT/LCPB
	Willy PORCHER	DRT/LITEN/DEHT/LCPB
	Axelle QUINSAC (NTE)	DSM/IRAMIS/SPAM/EDNA
	Yann LECONTE	DSM/IRAMIS/SPAM/EDNA/LFP
	Nathalie HERLIN	DSM/IRAMIS/SPAM/EDNA
PV organic	Rémi DE BETTIGNIES	DRT/LITEN/DTS/LMPV
	Nicolas GAUTHIER	DSM/INAC/SCIB/RICC
	Marinella MAZZANTI	DSM/INAC/SCIB/RICC
	Daniel IMBERT	DSM/INAC/SCIB/RICC
	Renaud DEMADRILLE	DSM/INAC/SPRAM/LEMOH
	Amélie REVAUX	DRT/LITEN/DTNM/LCSN
LED (NW)	Benoit AMSTATT + François LEVY & Alexandre LAGRANGE	DRT/LETI/DOPT/SCOOP/LCE
	Joël EYMERY + Benjamin GREVIN	DSM/INAC
Transparente Electrode (CNTs or NW)	Eléonore MOREAU	DRT/LITEN/DTNM/LCRE
	Jean-Pierre SIMONATO + Caroline CELLE	DRT/LITEN/DTNM/LCRE
	Benjamin GREVIN + Renaud DEMADRILLE	DSM/INAC DSM/INAC
Printed Electronics	Abdelkader ALIANE	DRT/LITEN/DTNM/LCEI
	Romain COPPARD	DRT/LITEN/DTNM/LCEI
System /integration	Jean-François MAINGUET	DRT/LETI/DSIS/SIPP
	Tristan HAUTSON	DRT/LETI/DSIS/SIPP
	Pascale RIVIER	DRT/LETI/DSIS/SIPP
Pilotage	Jean-Christophe GABRIEL	DSM/DIR/DPNS
	Norbert DANIELE	DRT/LETI/DSIS/SIPP
	Tiana DELHOME	DRT/LETI/DSIS/SIPP