PROJECT FULLFLEX: A MULTIFUNCTIONAL FLEXIBLE ELECTRONIC LABEL
Jean-Christophe P. Gabriel

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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.

Jean-Christophe P. Gabriel
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PROJECT FULLFLEX:

A MULTIFUNCTIONAL FLEXIBLE ELECTRONIC LABEL

Dr. Jean-Christophe P. Gabriel
Dep. Director Nanoscience & ChimTronic Programs

Printed & Flexible Electronics Congress
February 21st, 2017
- ~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

Molecular Wires for Molecular Sensing

- First commercial sensors in 2005: H₂ sensor on Si wafers
- Printed NT sensors deployed in West Africa during Ebola crisis in 2015.
- $36M raised over 15 years!!!

_C. R. Physique, 11(5-6), 362-374, 2010; Appl. Phys. Lett. 103, 051907, 2013 + ~50 patent applications

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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)  

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Objectif: go beyond germination!

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

- Reach higher TRL

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FULLFLEX PROTOTYPE CHALLENGE?

Objectif: go beyond germination!

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

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

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Objectif: go beyond germination!

Build a prototype integrating technological components developed within Nanoscience & ChimTronic seed projects

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Initial Concept: a flexible autonomous, multifunctions label
## Component Investigators Affiliation

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Printed Temperature Sensors

Abdelkader Aliane
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)
Photovoltaic flexible modules

Renaud DEMADRILLE – DRF / INAC / LEMOH
Solen Berson – DRT/INES/SMPV
Bulk-heterojunction solar cells (BHJ) : Concept


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

Photo-induced charge transfer $< 10^{-12}$ s
Innovative materials and fabrication of flexible modules

Development of new materials for use in the active layer

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

Polymer Chem., 2016, 7, 4160

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All Interconnects: conducting adhesive

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

Nathalie Herlin, Séverine Jouanneau, Willy Porcher

Charge

$\text{H}^- + \text{Li}^+ + e^- \rightarrow <\text{HLi}>$

$<\text{MLi}> \rightarrow <\text{M}> + \text{Li}^+ + e^-$

Décharge

$<\text{HLi}> \rightarrow <\text{H}> + \text{Li}^+ + e^-$

$<\text{M}> + \text{Li}^+ + e^- \rightarrow <\text{MLi}>$
Batteries lithium-ion

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

DISAVANTAGE: $V_{inc} = +280\%$

=> NP Si
Core-shell amorphous silicon-carbon nanoparticles for high performance anodes in lithium ion batteries

*Journal of Power Sources* **328** (2016) 527-535


1 startup (Nanomakers)
• Core-shell amorphous silicon-carbon nanoparticles for high performance anodes in lithium ion batteries
• *Journal of Power Sources* **328** (2016) 527-535
• 1 startup (Nanomakers)

**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
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**

=> Thomas Yohann

**Patent BF3007206**

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Non stacked configuration

Flexible and fully printed multi materials

Non contact printing technique

Interdigitated design

Nano inks

High resolution

Current collectors
Electrodes
Electrolyte

- More flexibility
- Design
- Interfaces
- Versatility of shapes

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

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Transparent Electrode
+
Capacitive Sensors

JEAN-PIERRE SIMONATO
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)
- Britleness

Alternatives

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

SUBSTITUTION of ITO by Nanomaterials
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POTENTIAL ALTERNATIVES

- Conducting polymers
  - *Chemical Science*, 2015
  - *Chemistry of Materials*, 2016

- Carbon Nanotubes
  - *Nano Letters*, 2003
  - *Carbon*, 2012
  - *Carbon*, 2014

- Graphene
  - *Ultramicroscopy*, 2015

- Metallic nanowires
  - *Nanoscale*, 2015
  - *Small*, 2016
  - *Nanotechnology*, 2013 x 2
  - *Nano Letters*, 2016
Ag NW SYNTHESIS: COMPLICATED?

\[
\begin{align*}
\text{AgNO}_3 & \\
PVP & \\
\text{Ethylene Glycol} & \\
\text{NaCl} & 
\end{align*}
\]
PERFORMANCES?

Resistance per square ($\Omega/\square$)

# of bendings (radius of Curvature = 5 mm)

![Graph of Resistance per square vs. # of bendings](image)

![Graph of Transmittance vs. Wavelength](image)

PERFORMANCES?

Resistance per square ($\Omega/\square$)

# of bendings (radius of Curvature = 5 mm)

Nanowire based LED

JOËL EYMERY, FRANÇOIS LEVY
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
Submicrometre resolved optical characterization of green nanowire-based light emitting diodes

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

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Main challenge – transparent flexible contact
• Thin TCO layers
• Graphene and/or graphene μ-flakes
• Silver nanowire mesh

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

InGaN/GaN NWs / PDMS
• Large area flexible LEDs (active area of several $\text{cm}^2$)
• No I-V or EL degradation after 10 bending cycles ($R_{\text{bending}} \approx 0.3 \text{ cm}$)
• Further improvement of emission homogeneity with organized NW arrays is under investigation

D. Xing et al, NanoLetters, 2015
La Recherche 2016 Award
**Battery** (350 µm)
- 3 mA.h/cm²
- 10 mW/cm²

**PV Cells**
- 1.2 V; 3 mA/cm² (Sun)
- 0.04 mA/cm² (1000 lux)

**BMS**
- 2.0 – 4.2 V

**Volt. regulator**

**Temp. Sensor**

**Cap. Sensor**
- Transparent electrode

**LED Nanowires**
- 10 V 20 mA

**Microcontroller**

**Three Sensors**: Light, temperature, capacitive

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OVERALL ASSEMBLY?

Silver Nanowires
Transparent electrode

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Nanowire LED Mounted on Flex
Flexible electronic mother board

Mother-board: μ-controller & drivers
Battery
Assembled Flexible Multi-functional Label
• Capacitive mode (movie)
• Temperature alarm mode (movie)
• Light mode (movie)
1 year project, successful
Deadline met
4 CEA’s new techno. integrated

Since then:
3 startups, 20 patents, numerous H2020 projects + industrial contracts

More info:
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