



**NANOMICROFAB**  
ADVANCED LAB

Advanced technologies and applications for GaN and printable electronics: two cases of excellence at El. Eng Dept of Rome Tor Vergata



## NanoMicroFab@DIE-UNIROMA2 Prof. Andrea Reale



CHOSE - Centre for Hybrid and Organic Solar Energy  
Electronic Engineering Dept. - University of Rome «Tor Vergata»



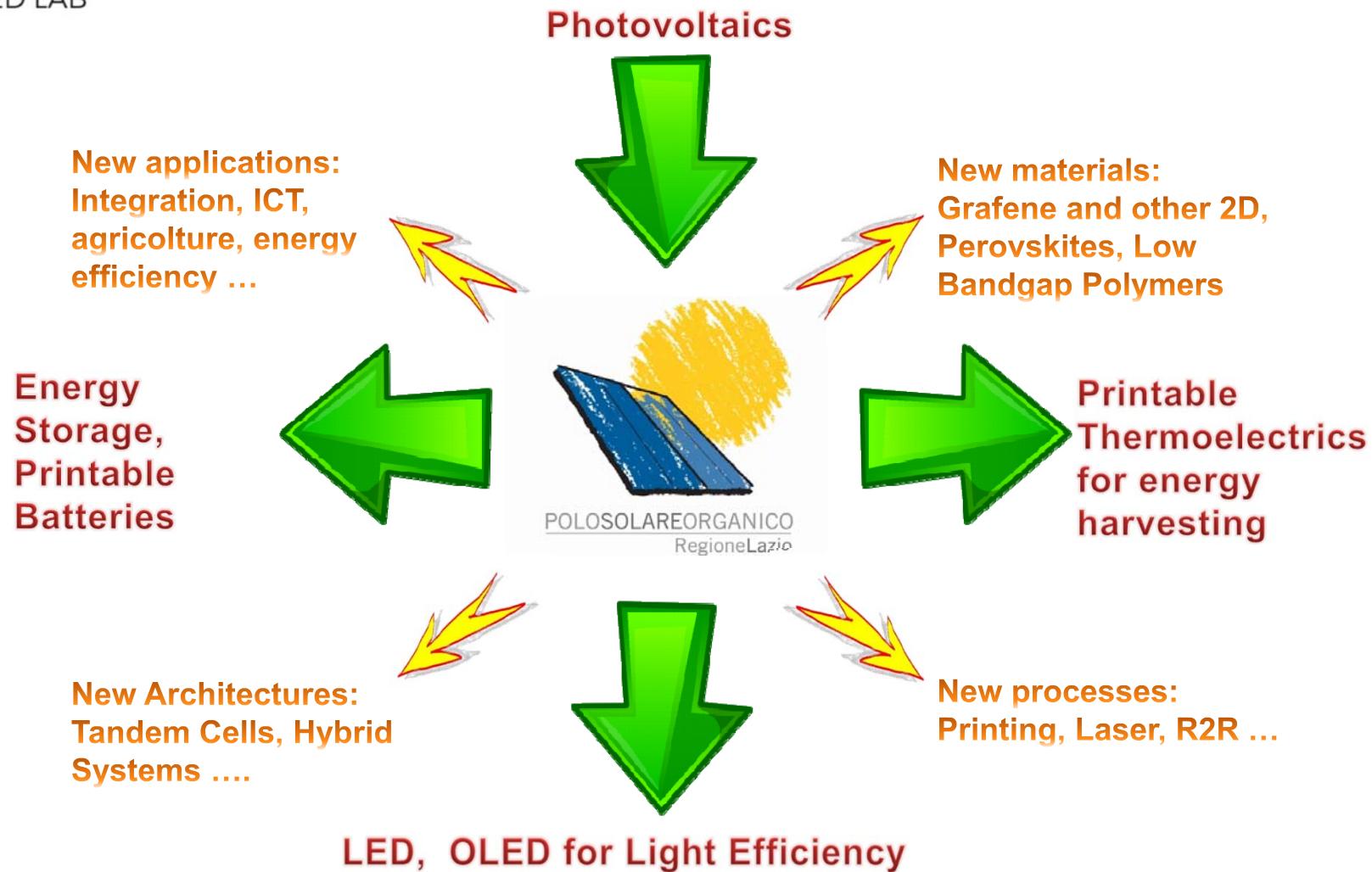
[reale@uniroma2.it](mailto:reale@uniroma2.it)

- With the collaboration of
- A. Di Carlo, T. Brown, F. Brunetti, A. Auf der Maur, C. Di Natale, E. Martinelli, E. Limiti, W.Ciccognani, S.Colangeli



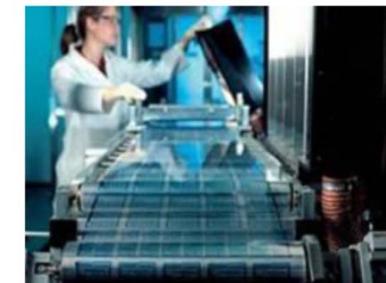
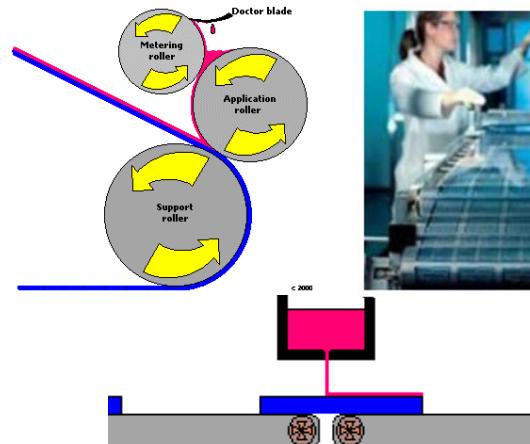
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## Printable Electronics: Energy

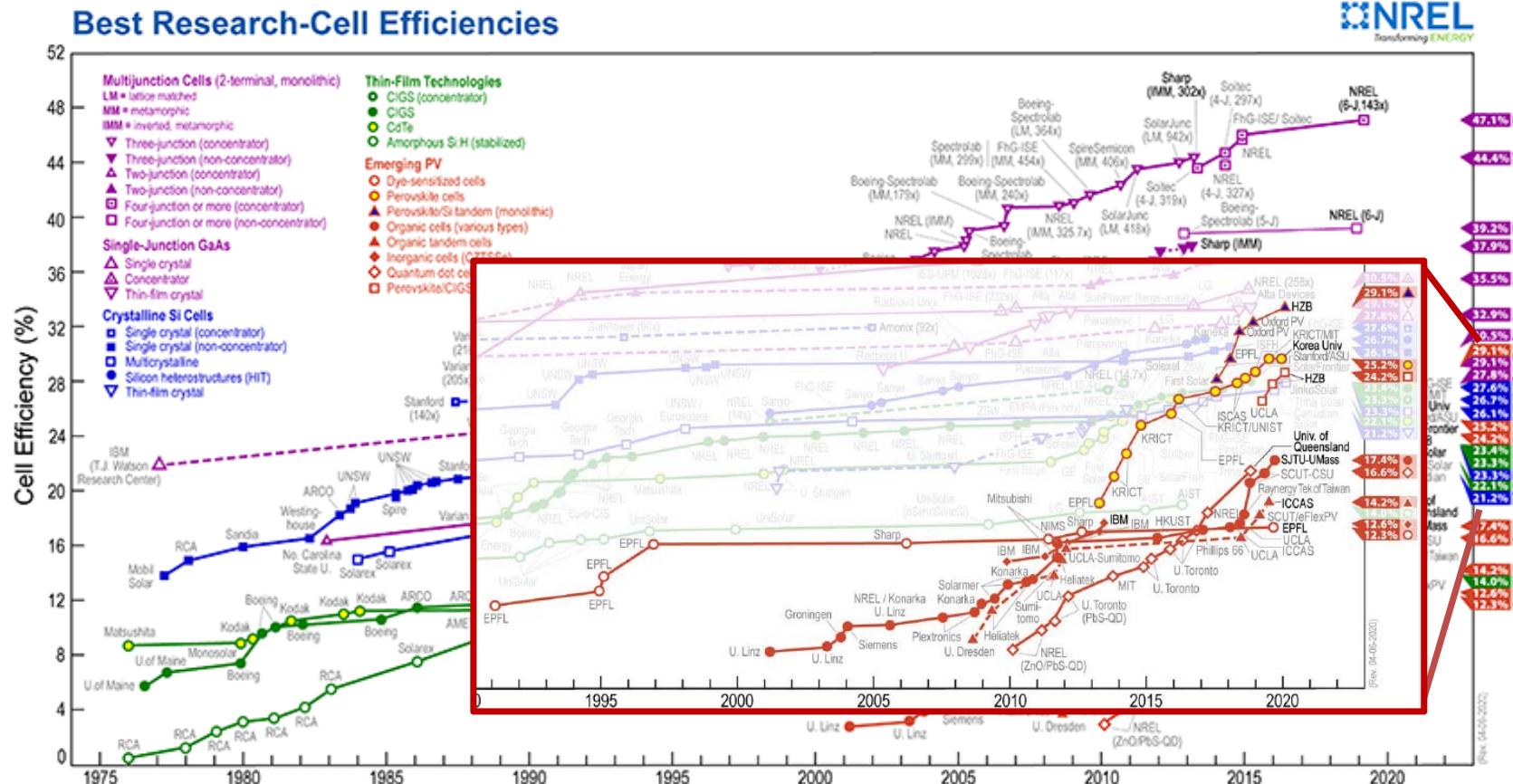


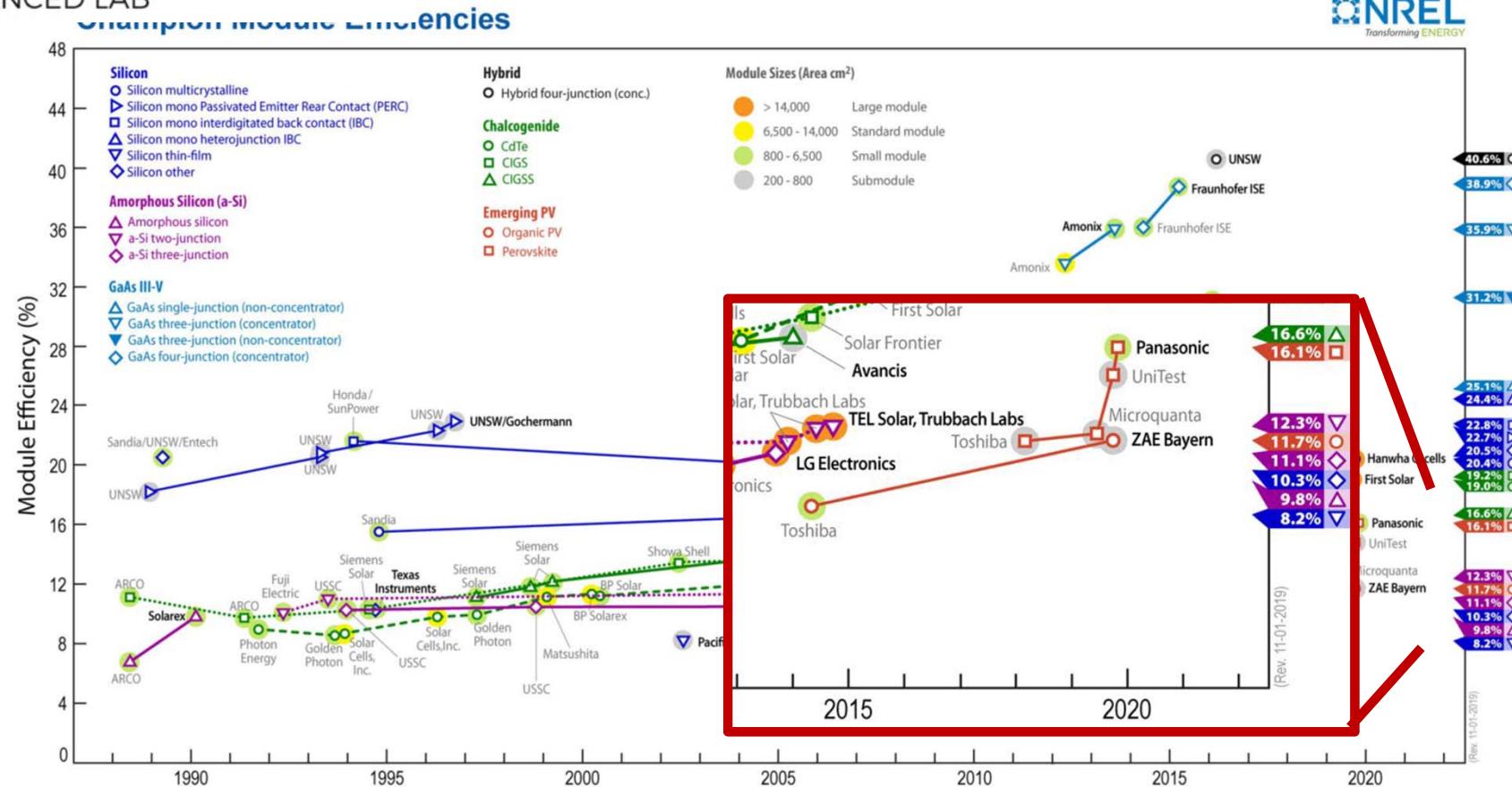


## Conventional Electronics → Printable Electronics



Conventional processing	Additive/printing processing
Subtractive batch processes (photolithography and wet/dry etching for layer definitions)	Additive continuous processes (printing, laser processing etc.) for layer definitions
Controlled (e.g., a vacuum environment)	Ambient temperature and pressure conditions
Fixed, long production runs of 'same product'	Flexible, short production runs - 'flexible' product functionality



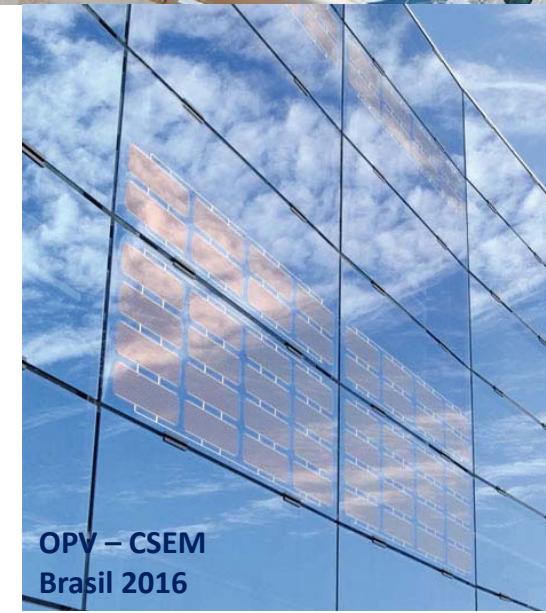
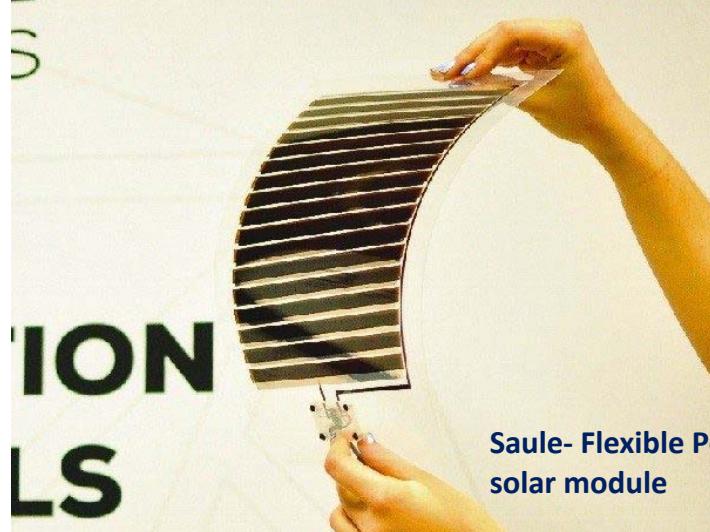


When scaling up the efficiencies are reduced and few technologies survive!



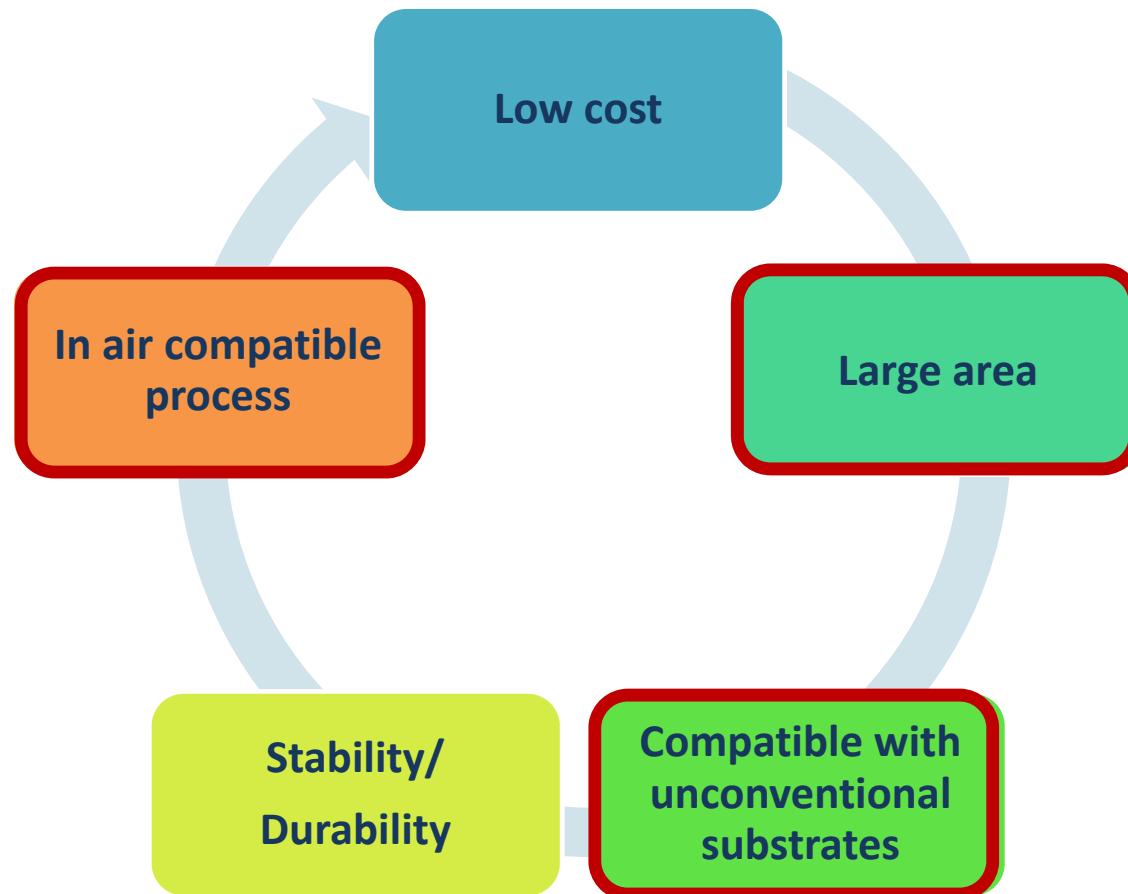
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## Solution processed Photovoltaic





## What do we need for Printable Photovoltaics?



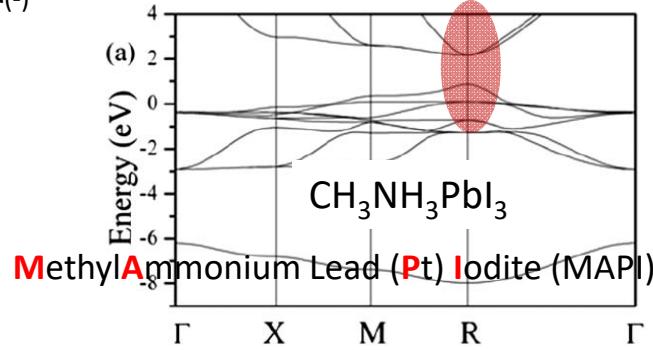


# Organometal trihalide Perovskite

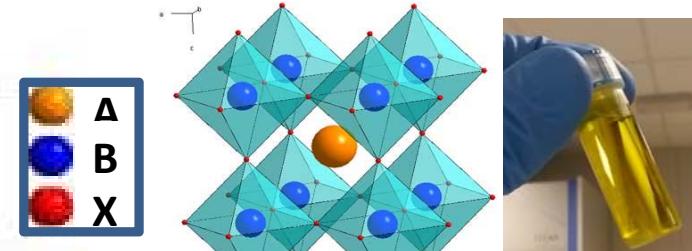
## Methylammonium lead halide perovskite

A=CH<sub>3</sub>NH<sub>3</sub><sup>(+)</sup>; NH<sub>2</sub>CHNH<sub>2</sub><sup>(+)</sup>; Cs    B= Pb<sup>(2+)</sup>

X= I<sup>(-)</sup>, Cl<sup>(-)</sup>, Br<sup>(-)</sup>



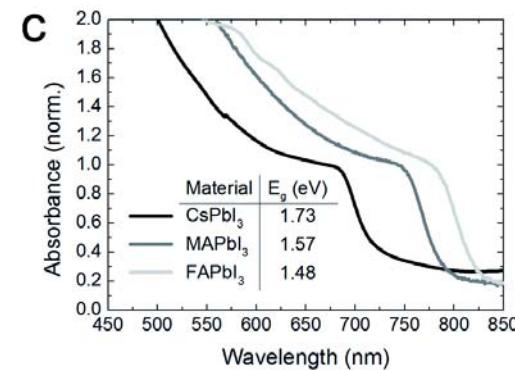
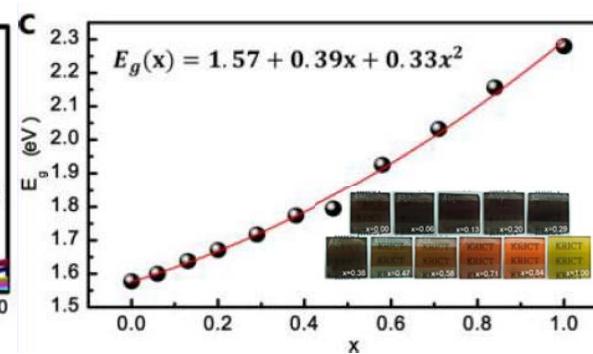
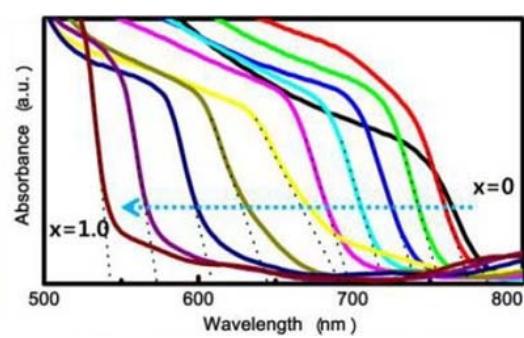
Direct band gap of 1.51 eV for CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub>



Solution process

Good hole and electron conductor, Diffusion length from 100 nm to 1 μm

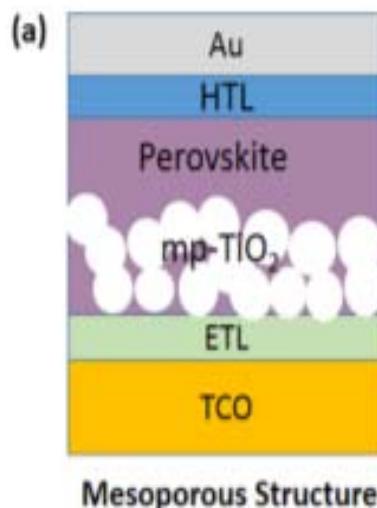
By the insertion of Br atoms (x) on the perovskite crystalline structure, or using a different organic molecule the energy gap can be varied.



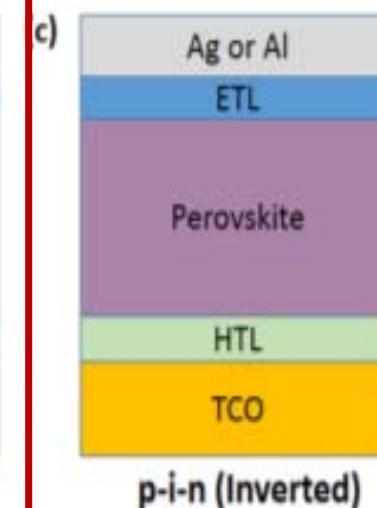


## Messtructured vs Planar Perovskite Solar cells

Messtructured  
(DSC like)



Planar  
(OPV like)



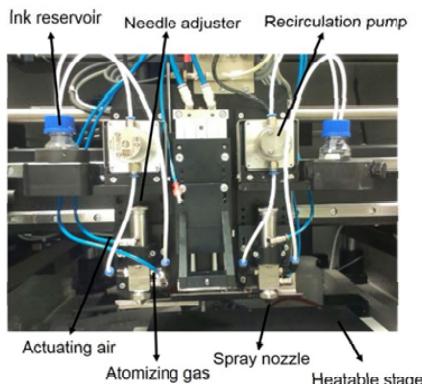
ITO/SnO<sub>2</sub>/PSK/Spiro-OMeTAD/Au

- ↳ Easier perovskite growth
- ↳ Better charge transport

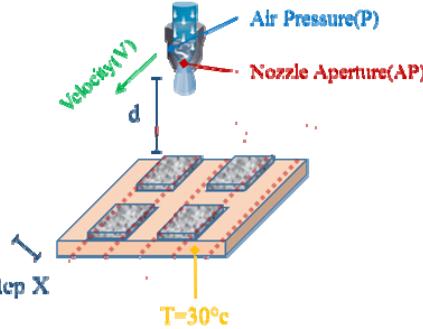
- ↳ Less production step
- ↳ No sintering step



## Higher repeatability and large scale



- Production on a large area
- Possibility of using substrates without any constraints in term of dimensions and geometry
- Deposition in the air
- Using non-toxic solvents
- Process Automation



Nozzle Aperture(AP): Nozzle opening radius

d : Distance between Spray nozzle and substrate

Air Pressure(P) : Air pressure Inside the nozzle

Velocity(V) : speed of nozzle X Y movements

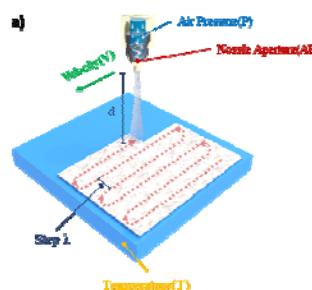
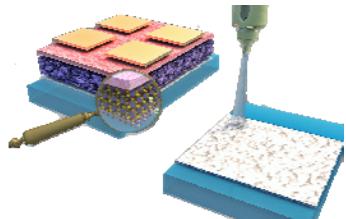
T=30°C : Substrate temperature

Step X : It depends on the path design

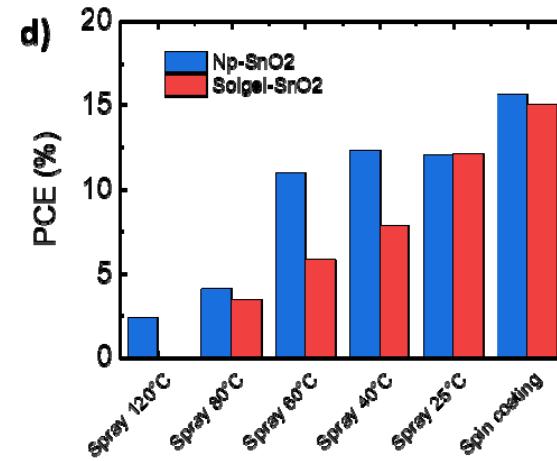
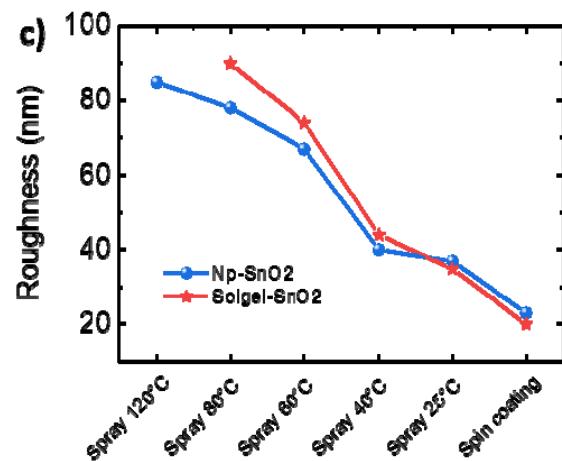
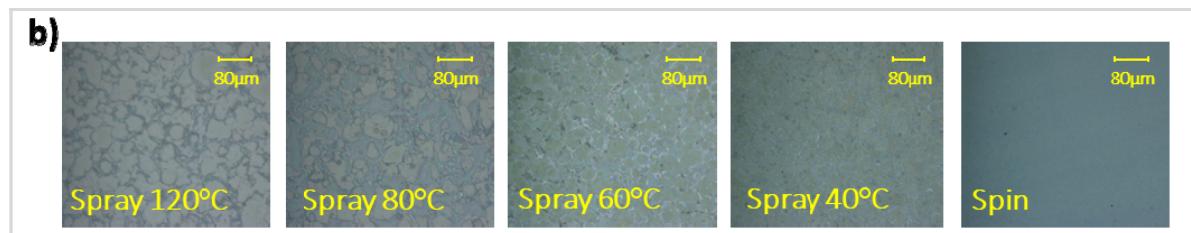
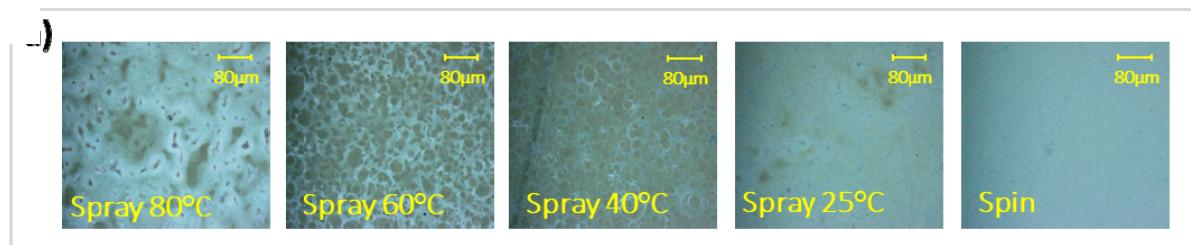
Flow rate (FR): Flow rate of solution

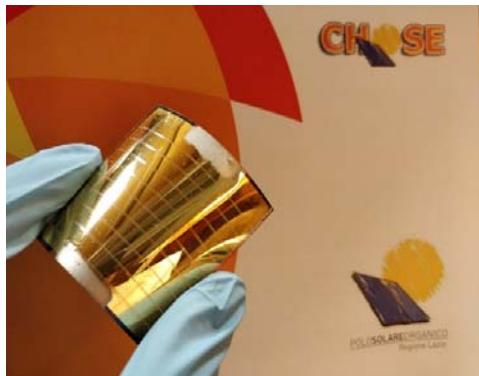


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## SnO<sub>2</sub> deposition via spray coating



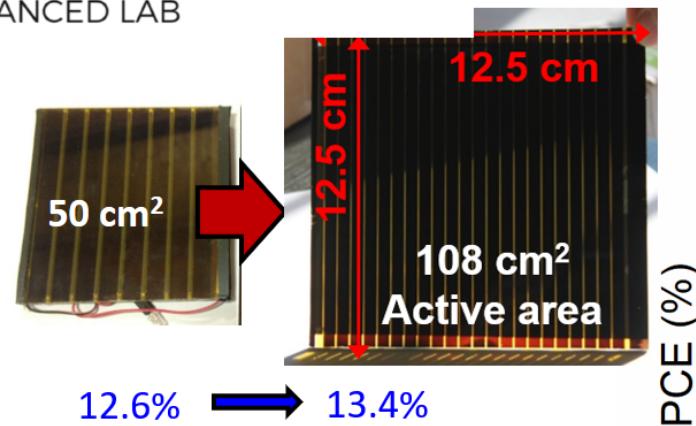


<i>Flex Module</i>	<i>PCE</i> (%)	<i>V<sub>oc</sub></i> (mV)	<i>J<sub>sc</sub></i> (mA/cm <sup>2</sup> strip <sup>-1</sup> ) <sup>a</sup>	<i>FF</i> (%)	<i>Active Area</i> (cm <sup>2</sup> )
Np-SnO <sub>2</sub> Spray Rev Scan	8.9	7.74	17.56	52.4	18.5
Np-SnO <sub>2</sub> Spray For Scan	8.3	7.52	18.06	48.9	18.5
Np-SnO <sub>2</sub> Spin Rev Scan	7.5	7.54	18.3	43.5	18.5
Np-SnO <sub>2</sub> Spin For Scan	5.3	6.8	18.3	38.4	18.5

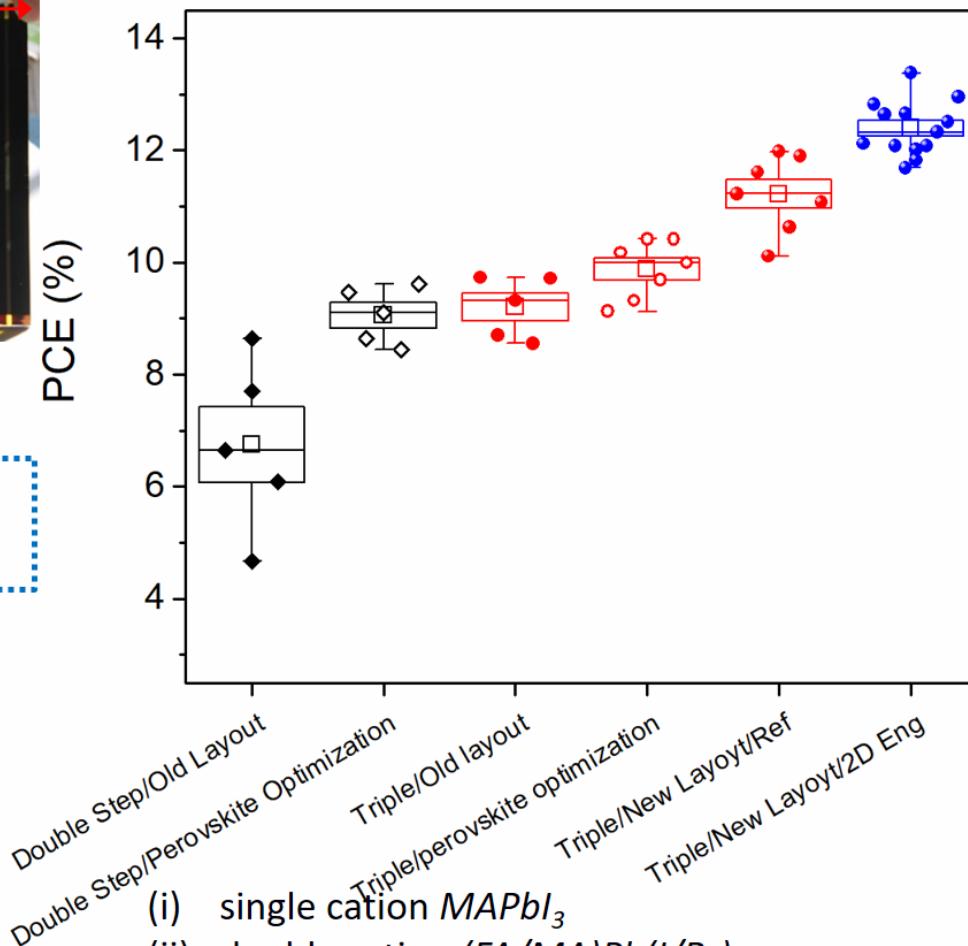
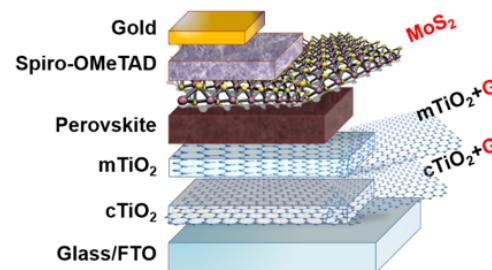
<sup>a</sup> Current density ( J<sub>sc</sub>) of a single strip



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Triple Cation  
**2D Engineering**

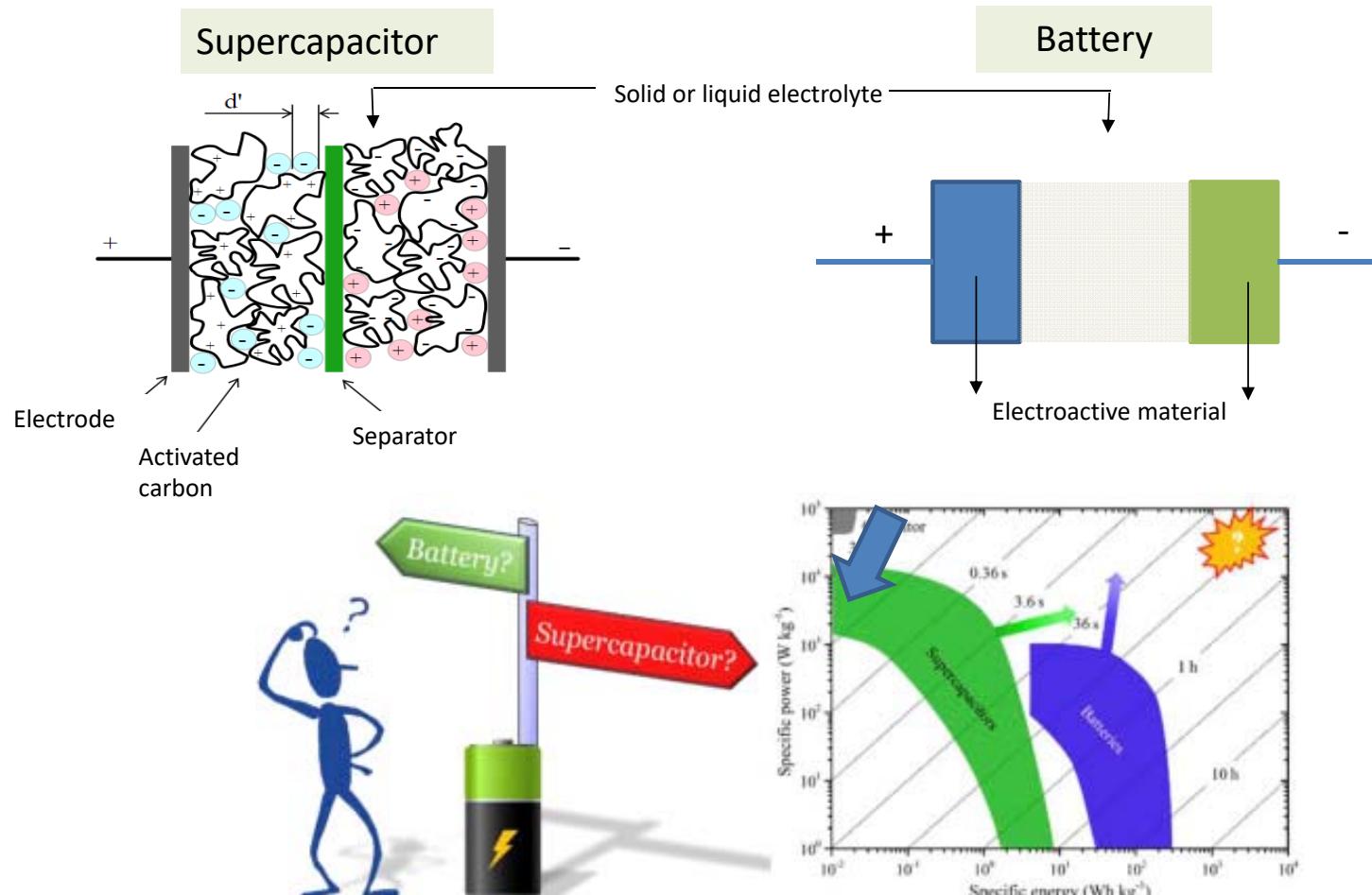




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## Printed Energy storage system

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### MATERIALS:

Non toxic and widely available materials



SUBSTRATE  
PAPER



<https://www.heraeus.com>  
HIGH CONDUCTIVE  
PEDOT:PSS



HYDROPROPOXYL  
CELLULOSE (HPC)



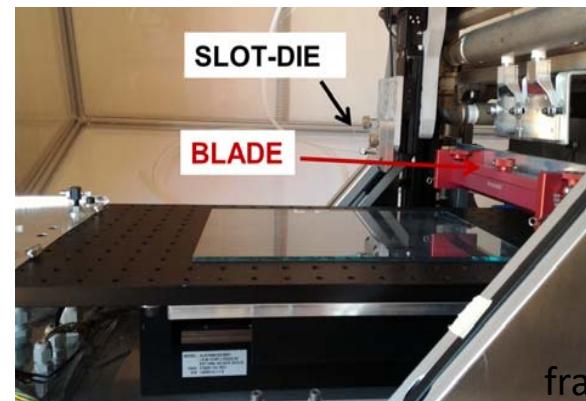
NANODIAMONDS  
(DND)



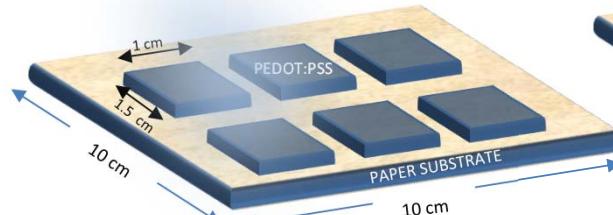
SODIUM SULPHATE  
(Na<sub>2</sub>SO<sub>4</sub>)

### PRINTING TECHNOLOGIES:

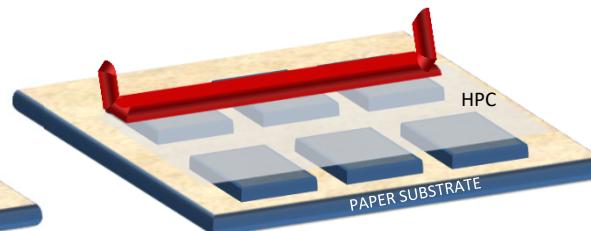
Low energy and low cost processes



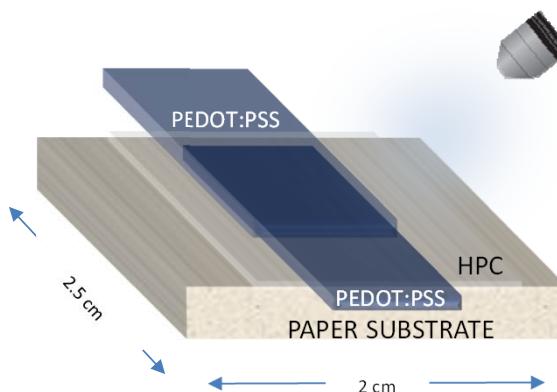
francesca.brunetti@uniroma2.it



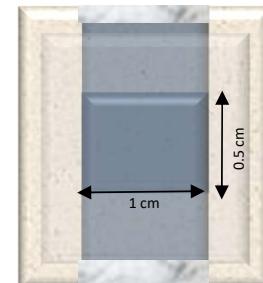
**1. Spray coating:**  
**PEDOT:PSS Bottom electrode**



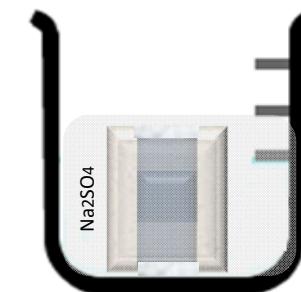
**2. Blade coating:**  
**5% HPC in H<sub>2</sub>O + 1% DND separator**



**4. Spray coating:**  
**PEDOT:PSS Top electrode**



**5. Dry device:**  
**Top View final device**

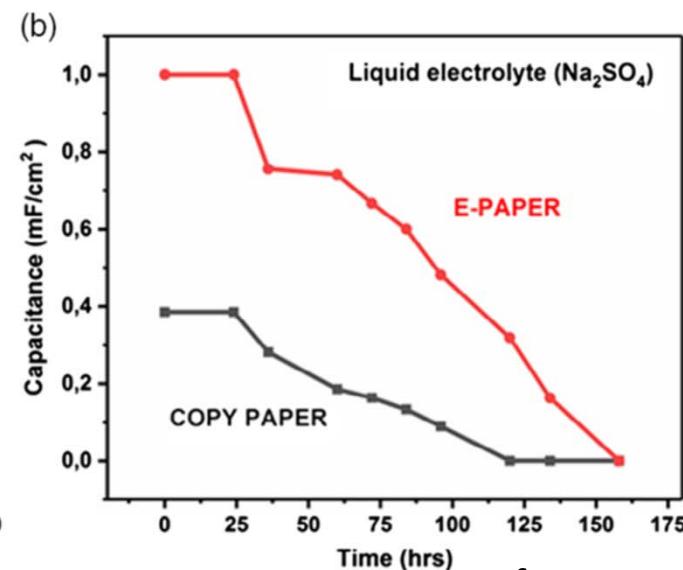
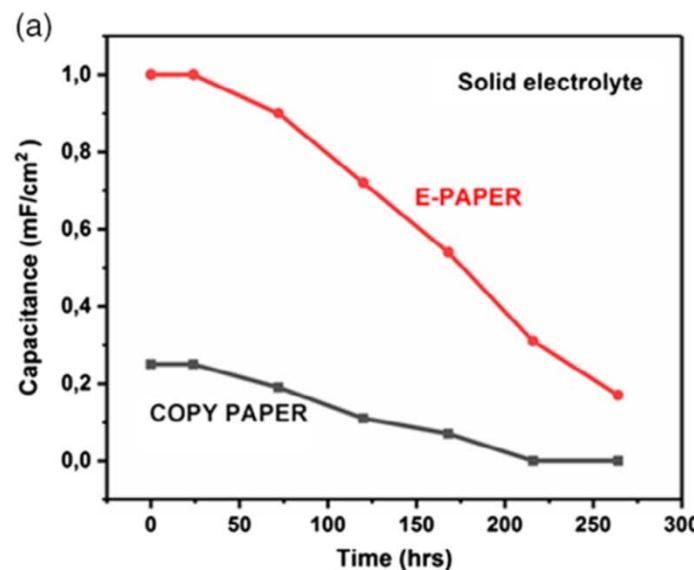
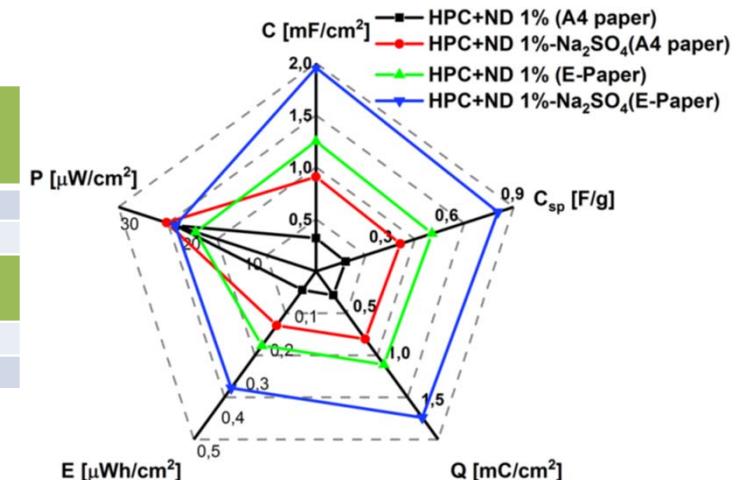


**6. Wet device:**  
**Sodium Sulphate Electrolyte**

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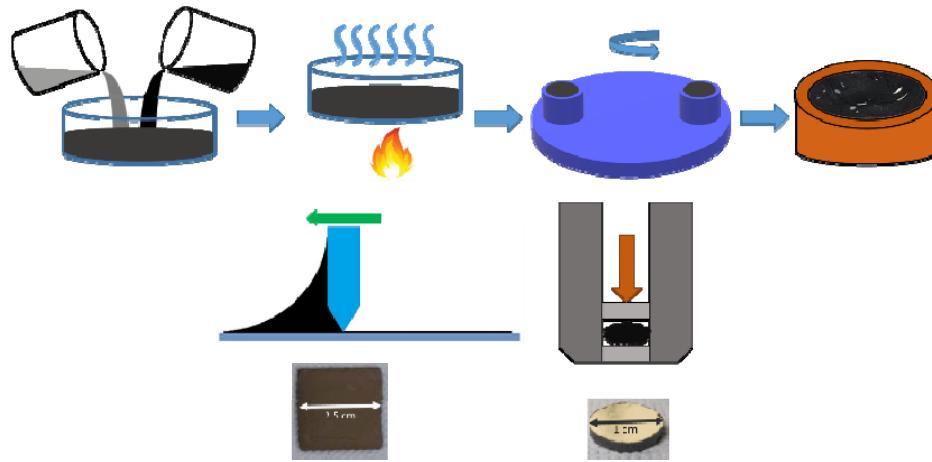
HPC+ ND 1% SOLID ELECTROLYTE	C (mF cm <sup>-2</sup> )	C <sub>sp</sub> (F/g)	Q (mC cm <sup>-2</sup> )	E (μWh cm <sup>-2</sup> )	P (μW cm <sup>-2</sup> )
Copy paper	319.14	0.13	255.31	0.056	22.69
E-paper	1248.09	0.52	998.47	0.221	19.48
HPC+ ND 1% +Na <sub>2</sub> SO <sub>4</sub>	C (mF cm <sup>-2</sup> )	C <sub>sp</sub> (F/g)	Q (mC cm <sup>-2</sup> )	E (μWh cm <sup>-2</sup> )	P (μW cm <sup>-2</sup> )
Copy paper	907.37	0.38	725.89	0.161	24.19
E-paper	1957.29	0.82	1565.83	0.347	22.77





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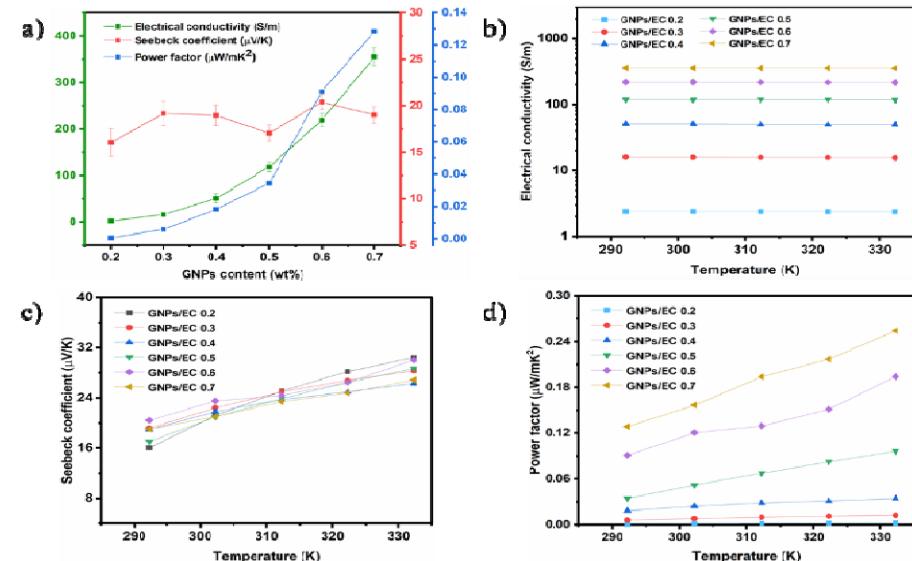
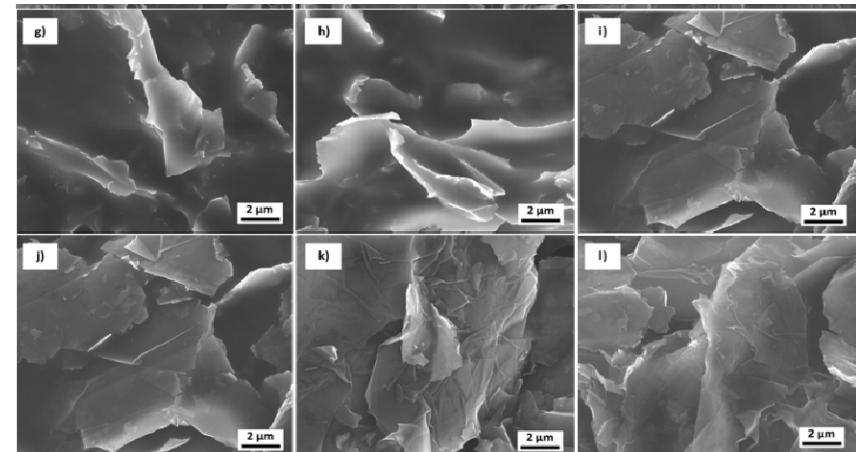
## Printable Electronics: Thermoelectric Devices



## Graphene NanoPlatelets / EthylCellulose composite

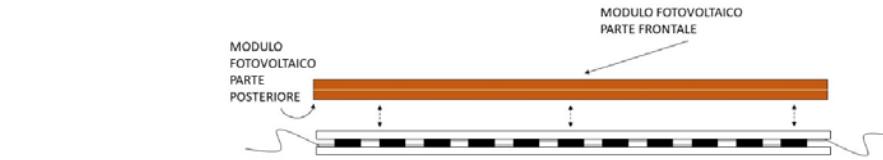
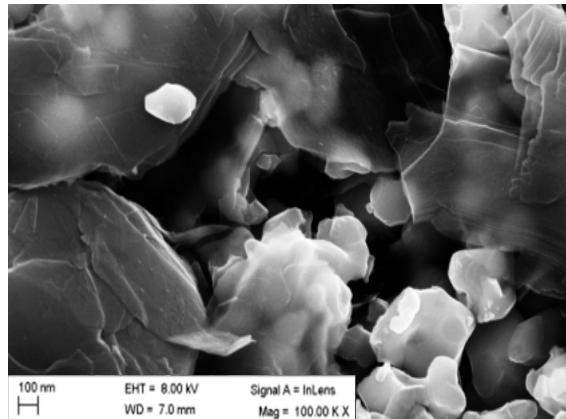
mixing of EC and GNPs solutions, followed by the heating, and evaporating of the solvents to make it into a paste and then using planetary ball milling to mix it properly.

Fabrication of a thick layer and a 3D form (pellet) from the paste.





- $ZT > 0.01$ 
  - $ZT = 0.008$  con sistema G-EC
- conducibilità elettrica  $> 10^3 \text{ S/m}$ 
  - $1200 \text{ S/m}$  con sistema G-EC-TiO<sub>2</sub>
- conducibilità termica  $< 5 \text{ W m}^{-1} \text{ K}^{-1}$ 
  - $0.15 \text{ W m}^{-1} \text{ K}^{-1}$  con sistema G-EC
- Coeff. Seebeck superiori a  $100 \mu\text{V/K}$ ,
  - $200 \mu\text{V/K}$  con P3HT (doped, 77kDa)
- power factor maggiore di  $0.1 \text{ mW cm}^{-1} \text{ K}^{-2}$ .
  - $0.1 \text{ mW cm}^{-1} \text{ K}^{-2}$  con P3HT (doped) + CNTF

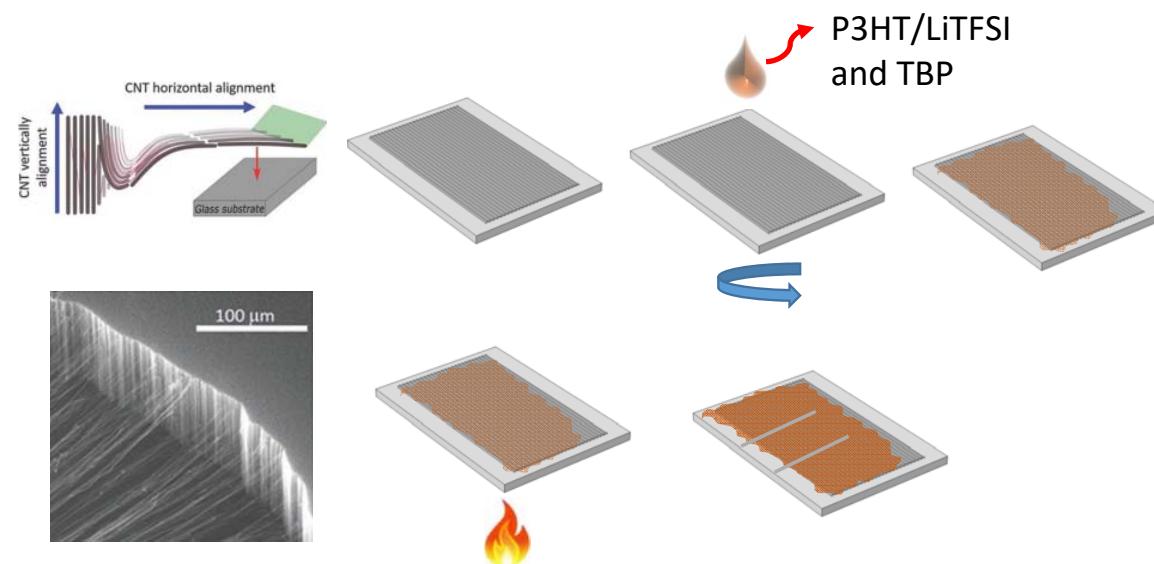




Ottimizzazione P3HT - poly (3-hexylthiophene)

1) Doping: Li-TFSI (agente drogante) + TBP (agente disperdente)

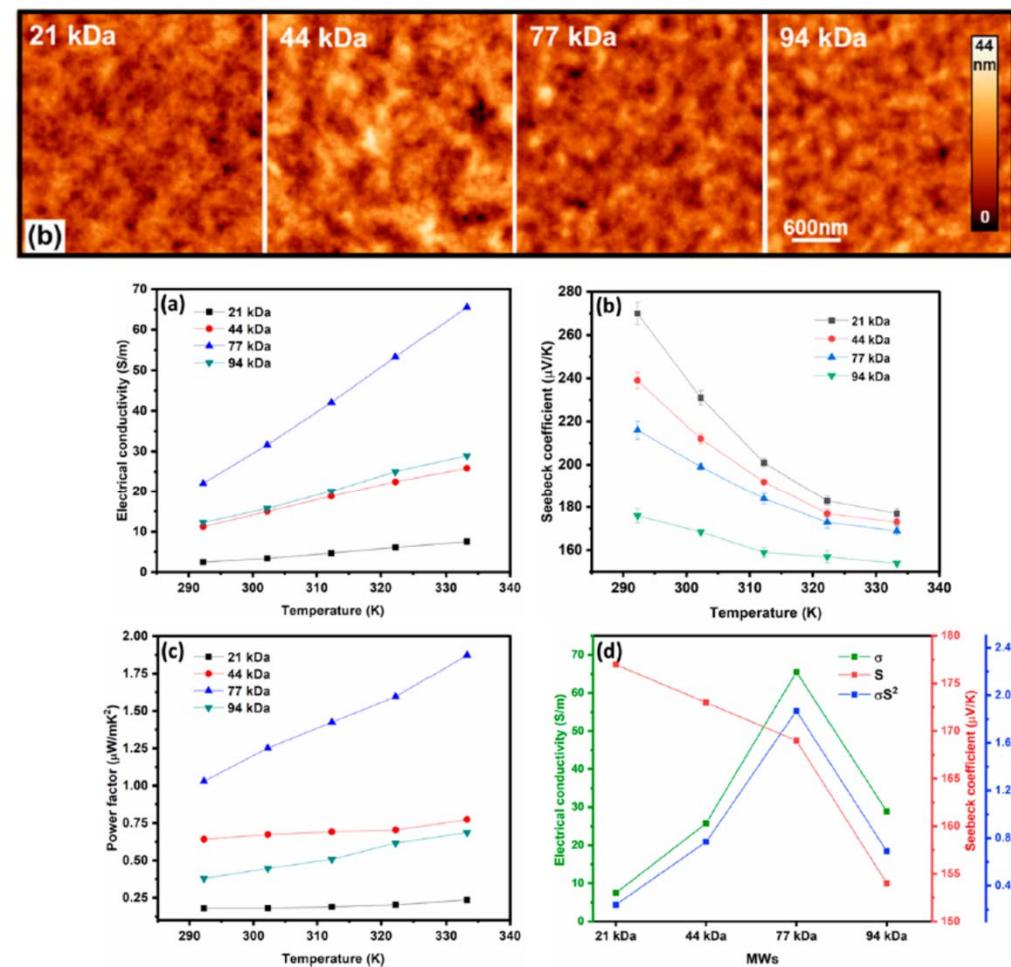
Filler conduttori: SWCNT - carbon nanotube forest –  
collab Prof. Vomiero, Lulea Univ (Svezia)



<https://dx.doi.org/10.1021/acsomega.0c02663>

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2) Ruolo MW P3HT - Doping: Li-TFSI+TBP



Materials **2020**, *13*, 1404; doi:10.3390/ma13061404



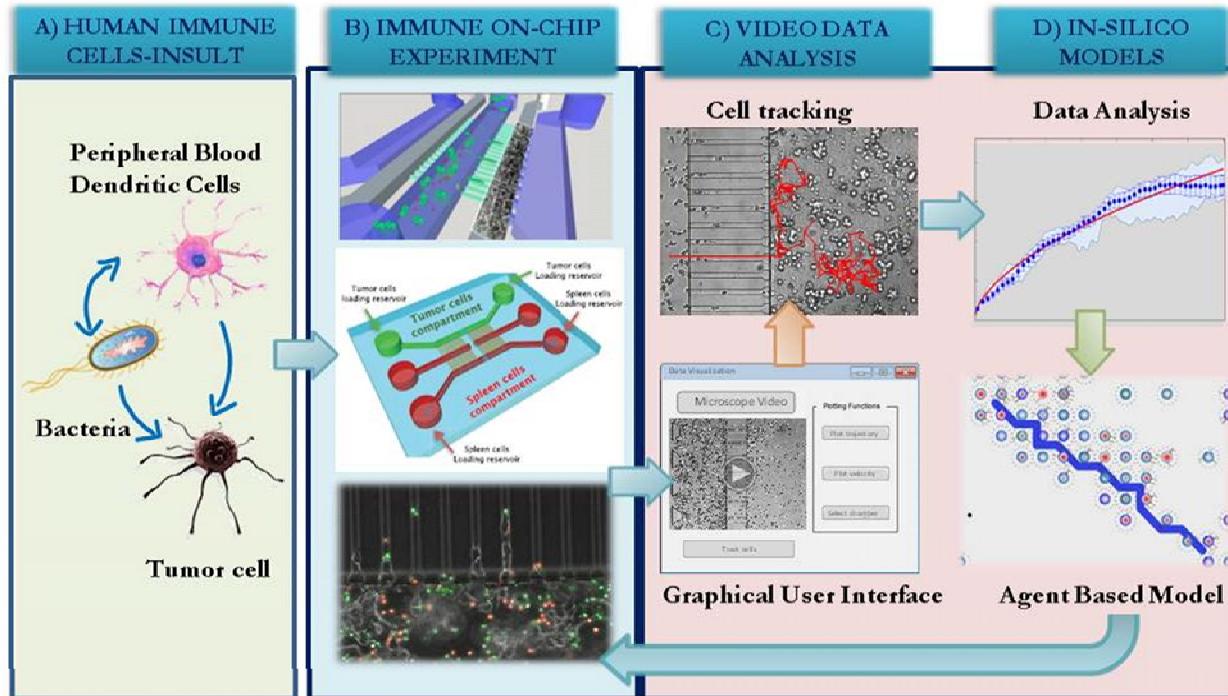
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## Printable Electronics: Bio-Electronics

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# From organ-on-chip to ORGAN-on SILICO



- Lab-on-chip fabrication and testing.
- Sensor and biosensor integration in lab on chip.
- Machine learning and image analysis

Parlato et al., Sci Rep 2017

Biselli et al., Sci Rep 2017

Nguyen et al. Cell Report 2018

Di Giuseppe et al, IEEE trans. Biomedical Engineering, 2019

Mencattini et al., Frontiers in Pharmacology 2019

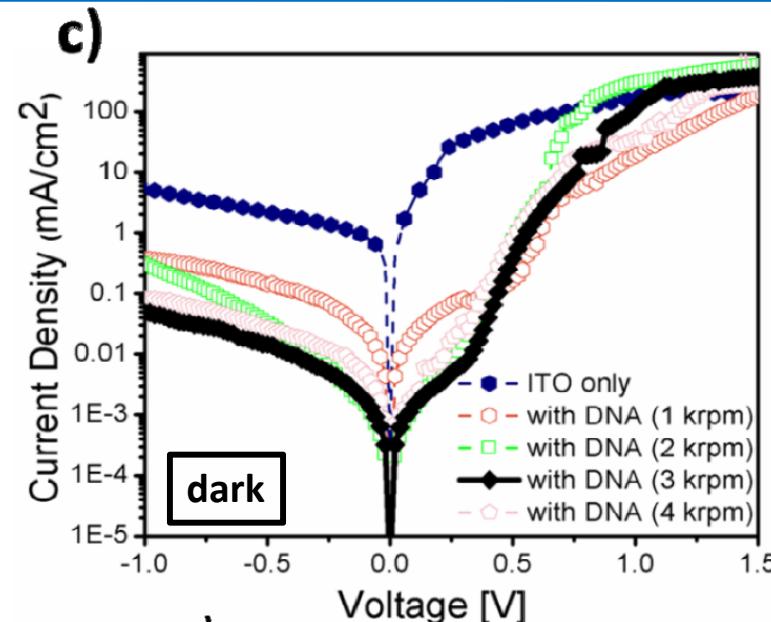
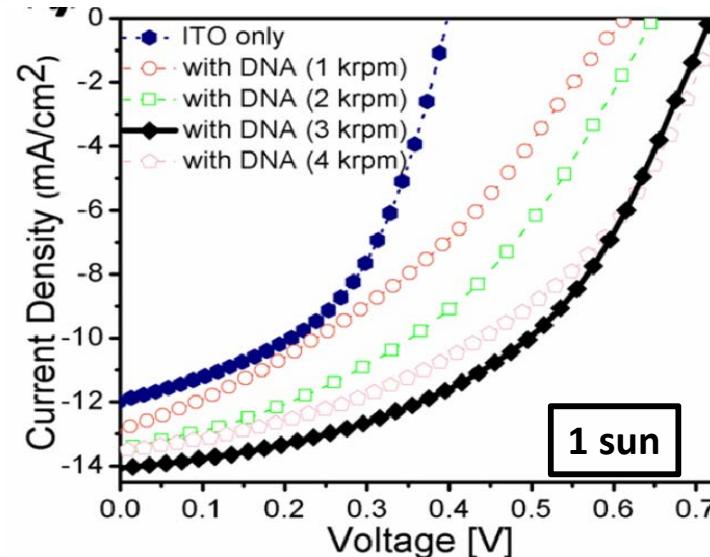
Comes et al. Sci Rep 2019

[martinelli@ing.uniroma2.it](mailto:martinelli@ing.uniroma2.it)

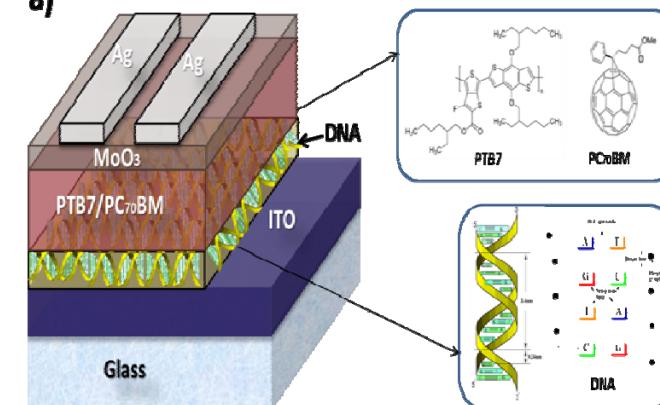


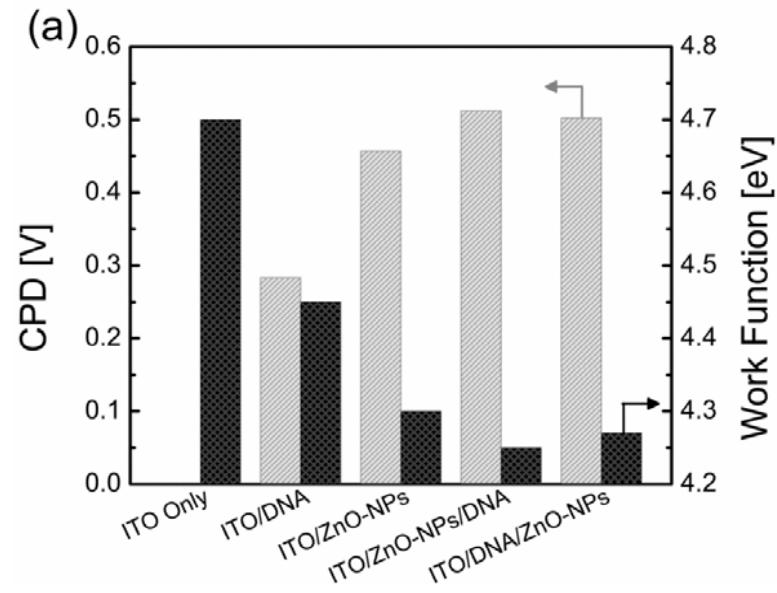
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# Solar cells with DNA electron-extracting layers

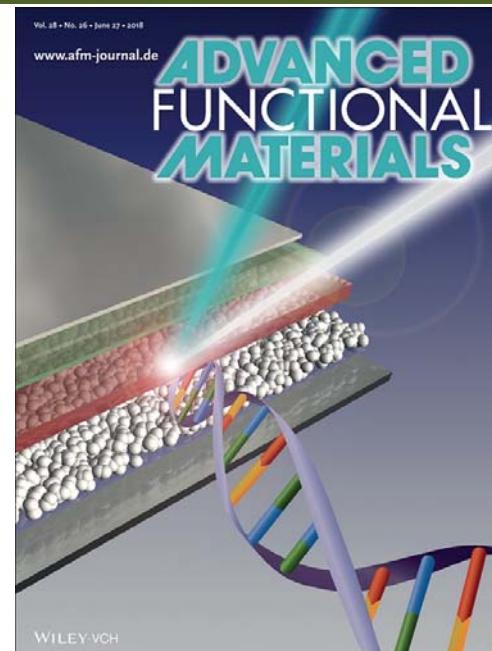


- **Insertion of DNA between photoactive layer & ITO leads to remarkable improvement in :**
  - **PV plot (Fig. b): Efficiency from 2% to 5%**
  - **On/off ratios dark (Fig. c) by a factor 125**
  - **DNA Thickness optimization for performance**





Via femtosec transient absorption spectroscopy DNA can “imprint” a different long range order to the photoactive polymer blend



- Significant lowering of the work function with DNA
- Larger DOS available
- Higher tunneling currents with DNA overlayers

J. Dagar et al, Nanoscale. 9, 19031 (2017)

F. Toschi et al, Adv. Funct. Mat. 1707126 (2018)

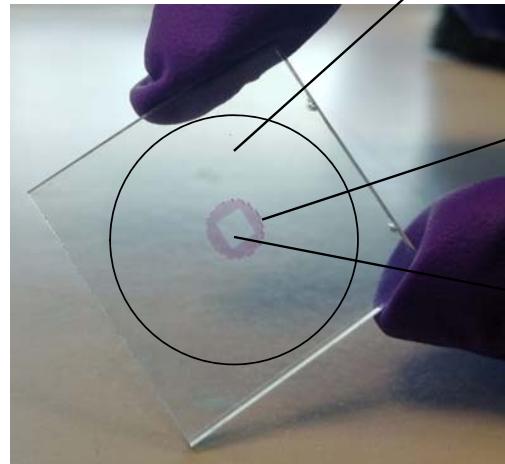
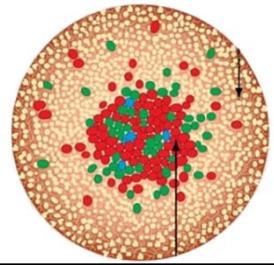
[thomas.brown@uniroma2.it](mailto:thomas.brown@uniroma2.it)



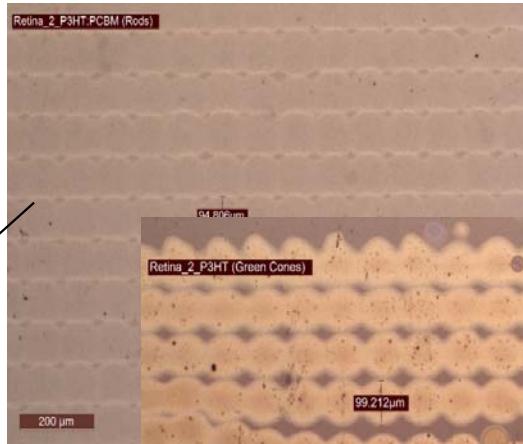
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# Photoresponsive polymers to mimic retina by ink-jet

$\varnothing 10\mu\text{m}$   
Photoreceptor  
(real retina)



P3HT:PCBM (rods)



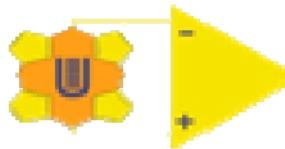
$\varnothing 100\mu\text{m}$   
ROUND "pixel"  
(artificial retina)  
3 types of polymer

P3HT  
(green cones)



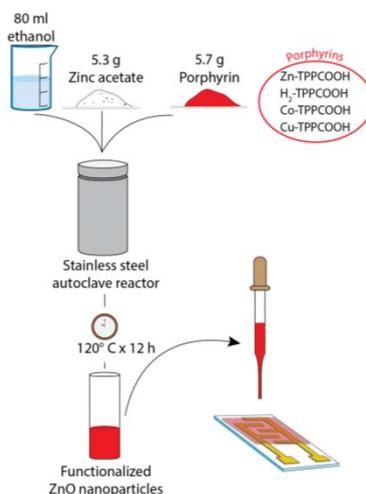
PFO (blue cones)

[thomas.brown@uniroma2.it](mailto:thomas.brown@uniroma2.it)

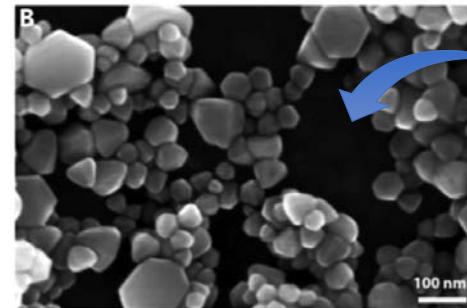
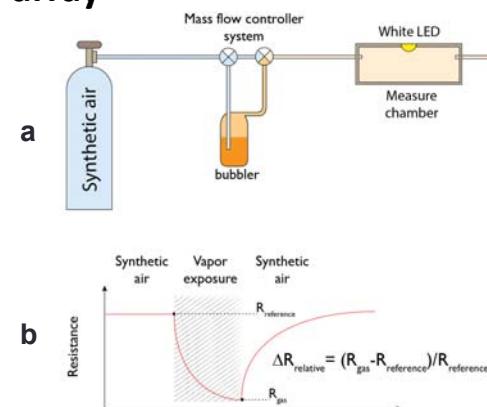


sensorsgroup.uniroma2.it  
dinatale@uniroma2.it

## Sensors based on organically capped nanoparticles



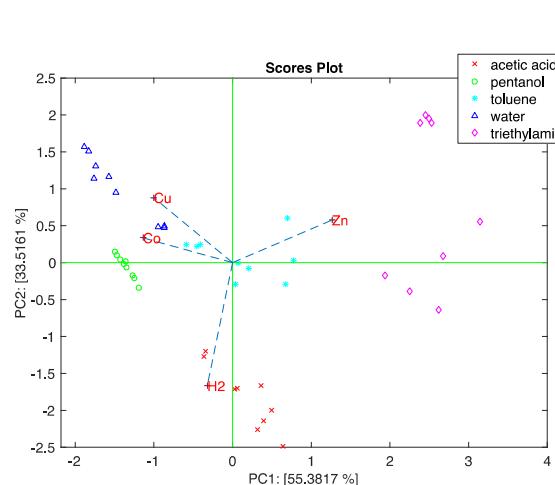
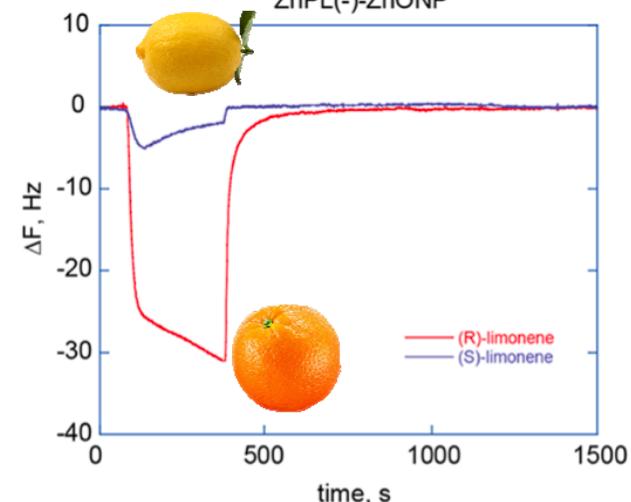
### Porphyrins capped ZnO nanoparticles sensor array



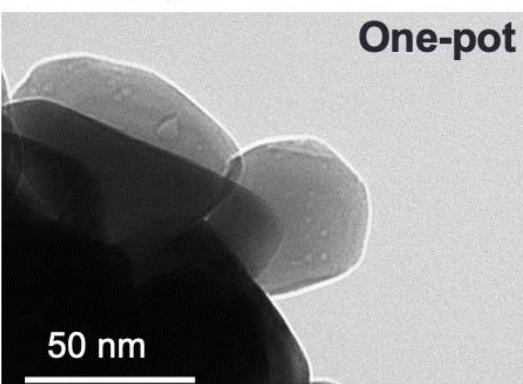
### Chiral recognition with propyhrins capped ZnO nanoparticles



(C) ZnPL(-)-ZnONP



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Sivalingam et al. J Phys Chem 2012  
Magna et al. Anal Chim Acta 2014  
Paolesse et al. Chemical Reviews 2017

Stefanelli et al. ACS Appl Mat Interf 2019



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## Advanced GaN Characterization



## Available instrumentation

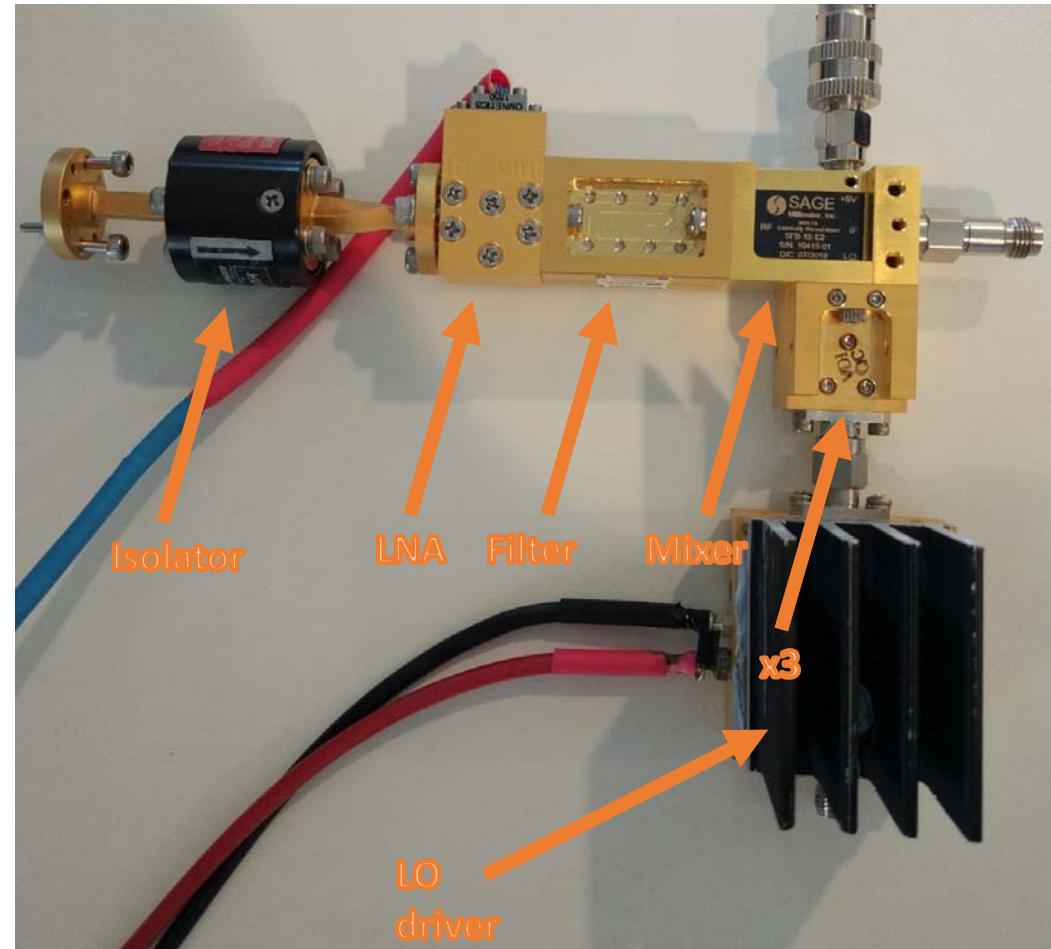
- At present measurement capabilities are:
  - scattering parameters up to 125 GHz
  - noise measurements up to 40 GHz
  - power measurements up to 40 GHz.





## Purposely acquired

- Down conversion section of the V-band noise figure measurement test-bench.
- Not shown in the picture are an electro mechanical WR-15 switch and a WR-15 noise-source.
- W-Band Noise characterization extension is under way, following the same approach.

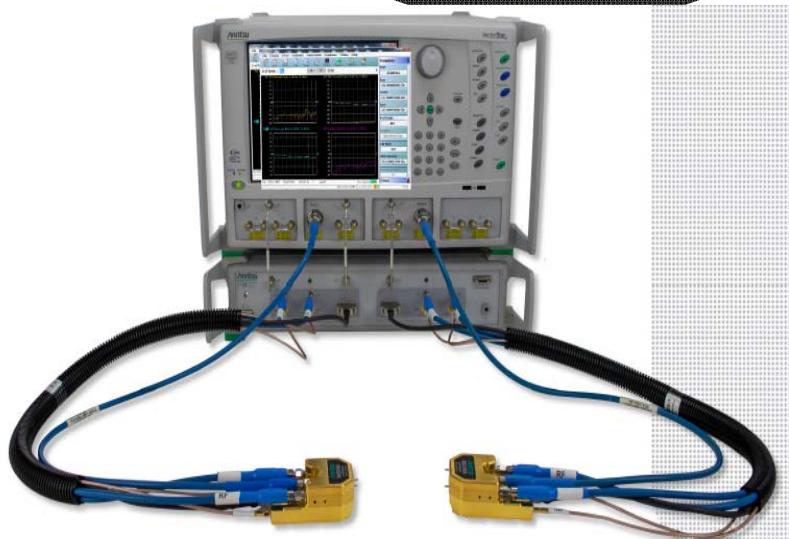




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## Advanced GaN Characterization

VNA  
DC to 220GHz



Ongoing  
acquisition

VNA frequency upgrade extending the  
characterization frequency up to  
220GHz in a SINGLE SWEEP from DC !

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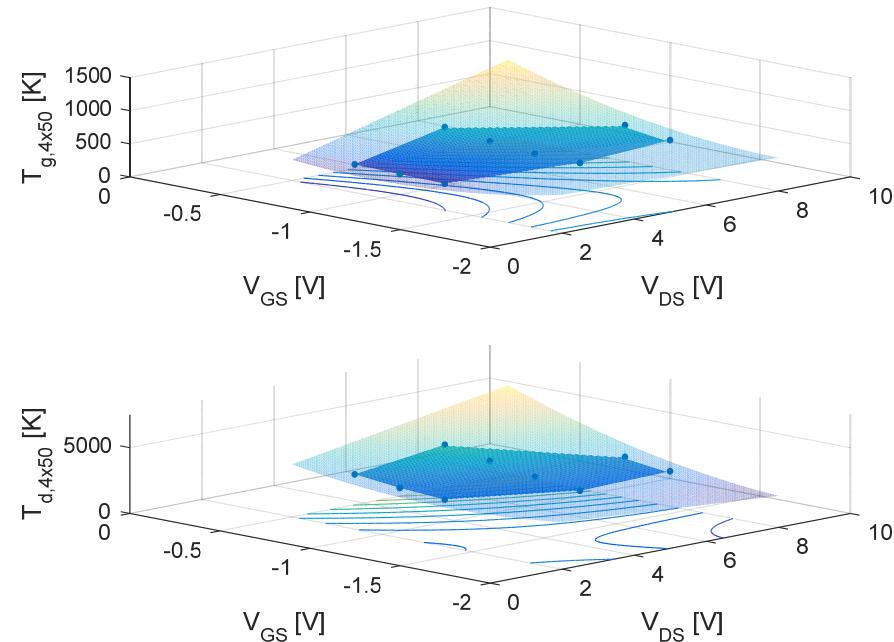


## High-frequency modeling

The team has a long experience in characterization and modeling of active devices for microwave and millimeter-wave applications.

Present frequency limitations are at 125 GHz and 40 GHz for small-signal and noise measurements, respectively. Extrapolations are used to extend model ranges.

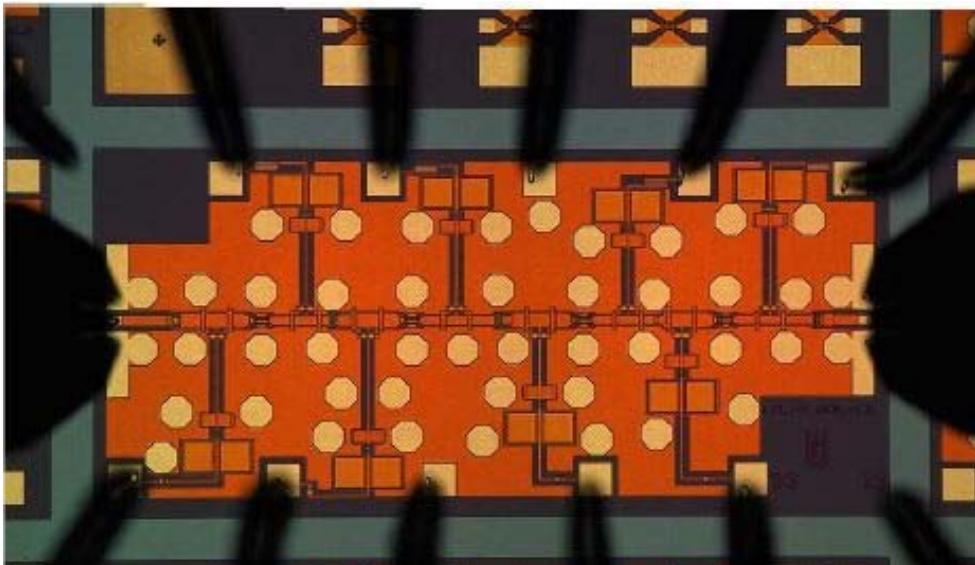
The newly acquired measurement equipment will allow direct model extraction/validation up to 2200 GHz and 110 GHz for small-signal and noise measurements, respectively.



Example of noise temperature extraction vs operating point: gate and drain noise temperatures of a 4x50  $\mu\text{m}$  GaN device.



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D-Band 125-155 GHz LNA  
with NF  $\approx$  5.0 dB

## Advanced GaN/GaAs Design

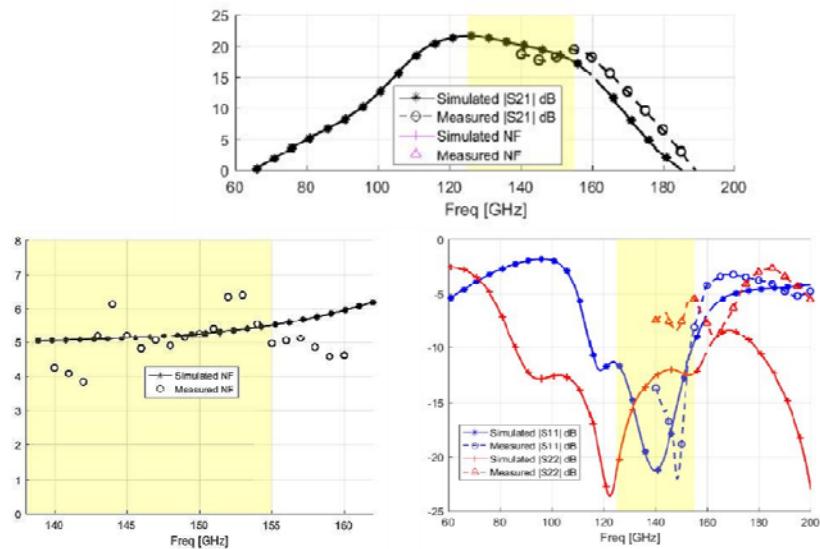
- OMMIC D004IH **40** nm GaAs process
- Four-stage, single ended *COPLANAR*
- MMIC Size: 2.0 x 1.0 mm<sup>2</sup>
- Gain 17dB - NF 5 dB TYP.

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# Advanced GaN/GaAs Design



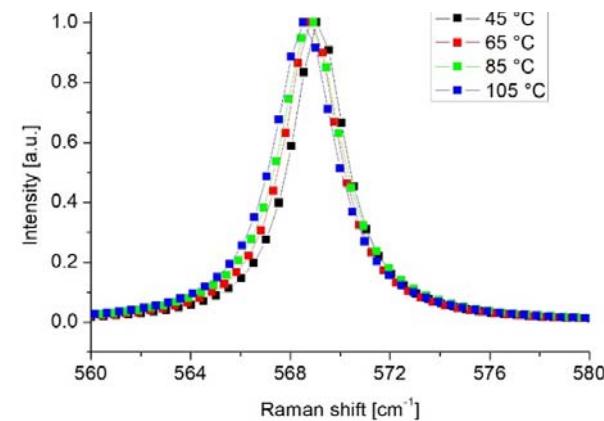
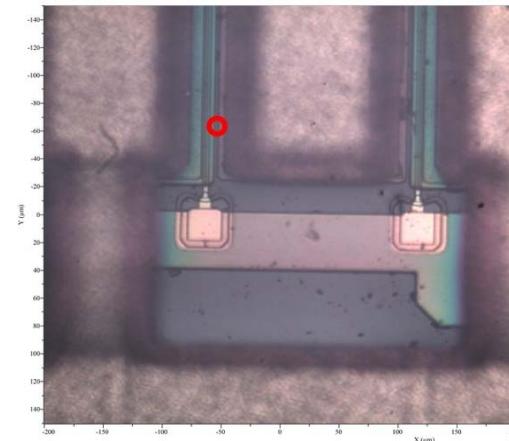
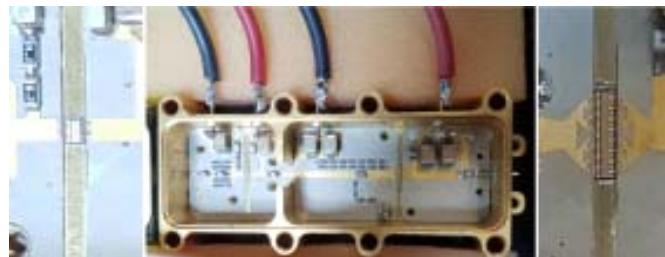
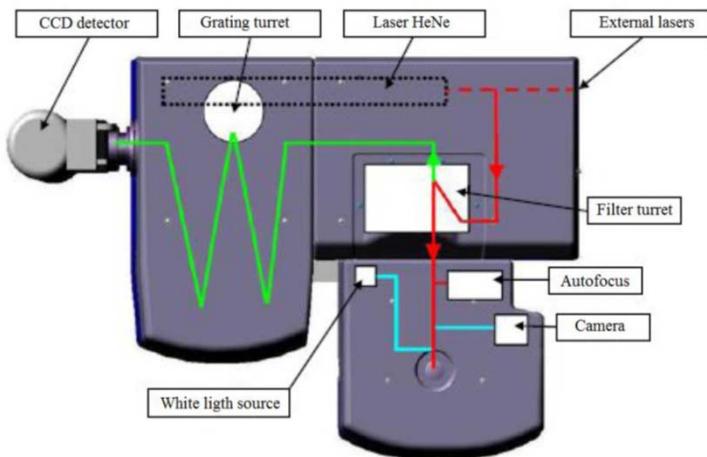
D-Band 125-155 GHz LNA  
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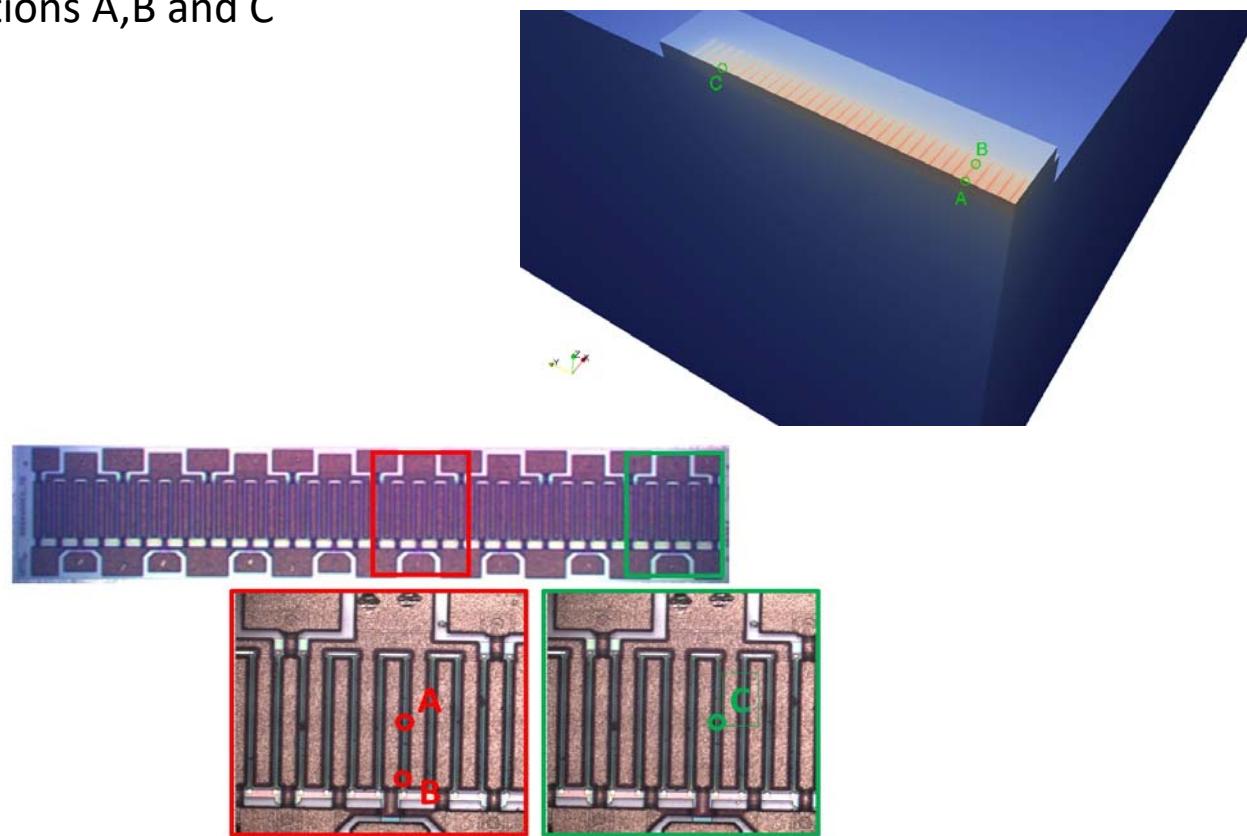


## Raman Thermography – Confocal Microscope





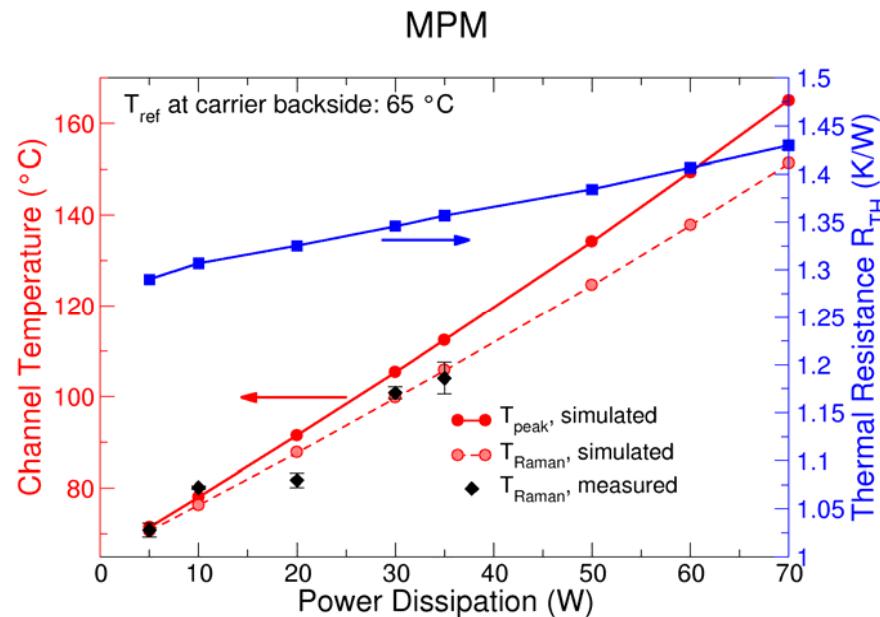
- Temperature has been extracted from measurements & simulations in positions A,B and C



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## Thermal Analysis on GaN Power Bar

- Position A: comparison with experimental values



- The estimated Raman temperature is consistent with the measured values
- The peak channel temperature from the 2D simulation leads to  $R_{\text{TH}}$  of 1.3 – 1.4 K/W for 0-50 W



## Acknowledgments



Thanks for your  
attention

Thanks to A. Di Carlo, T. Brown, F. Brunetti, A. Auf der Maur, C. Di Natale, E. Martinelli, E. Limiti, W.Ciccognani, S.Colangeli