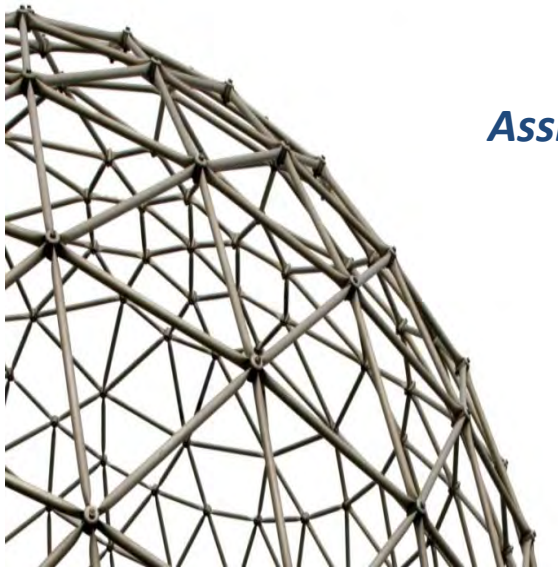
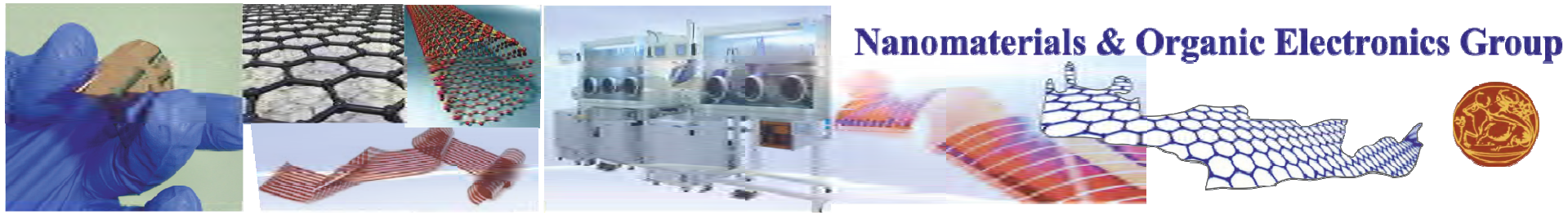
Advanced Laser Processes for Photovoltaic Energy Production

Dr. Konstantinos Petridis

Assistant Professor, Dept. of Electronic Engineering and
Center of Advanced Materials & Photonics
c.petridischania@gmail.com



http://nano.teicrete.gr/



TEI of Crete
Technological Educational Institute of Crete

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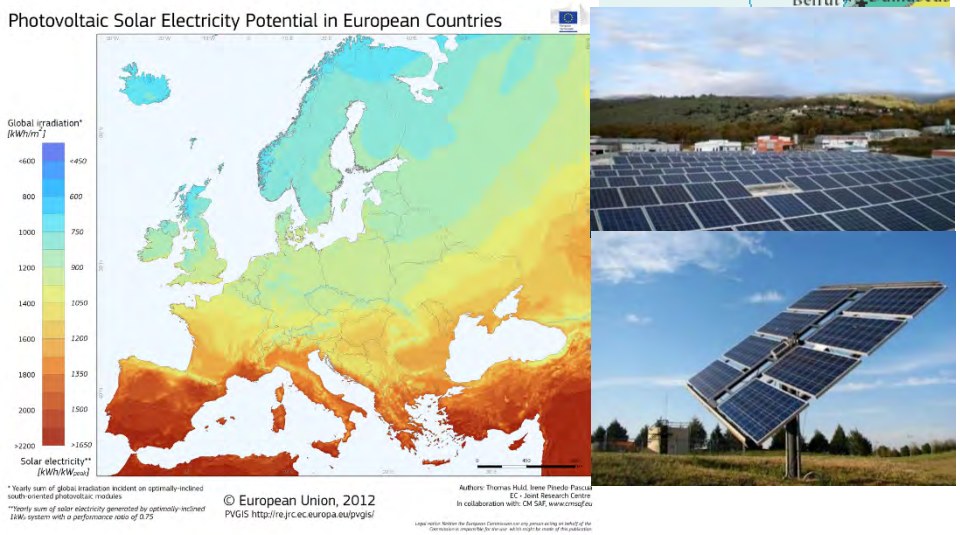

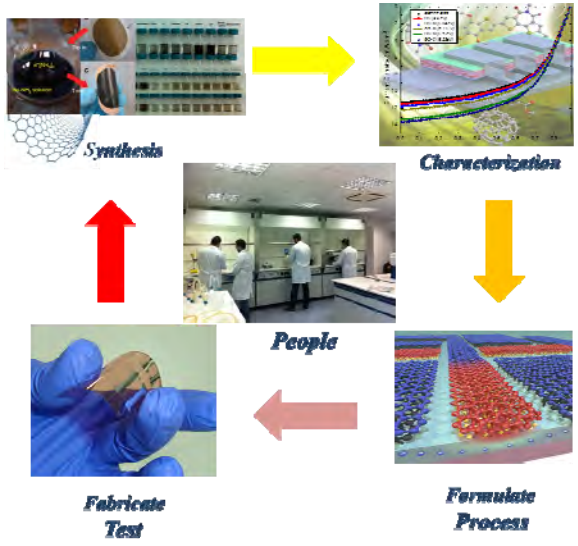

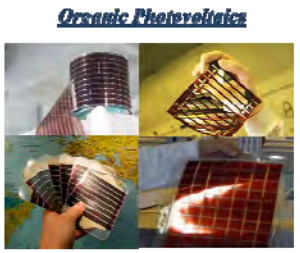

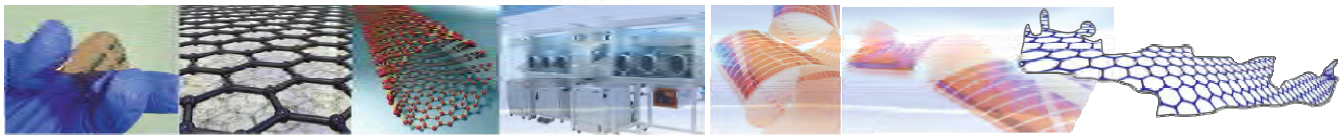

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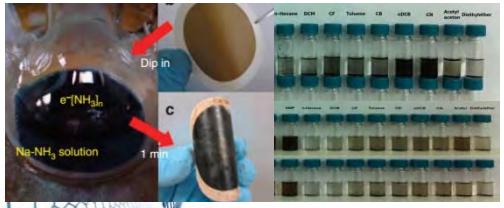
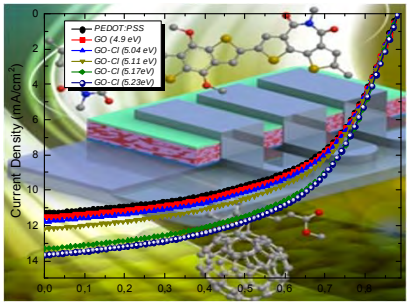
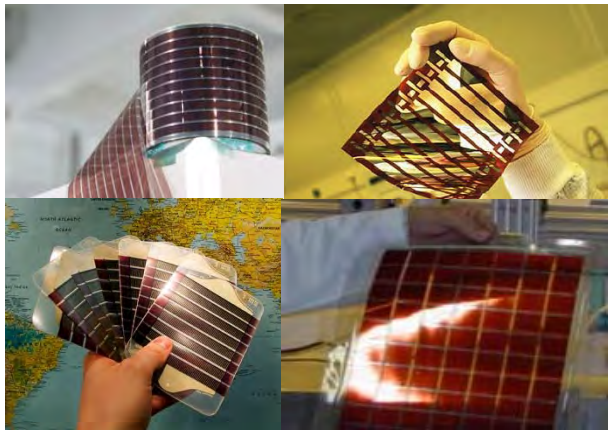


Synthesis



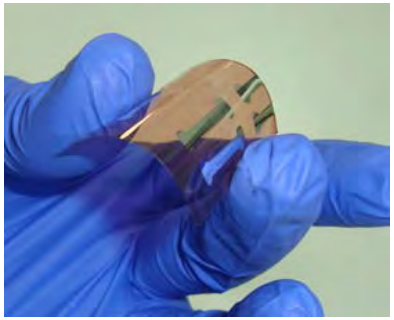
Characterization

Organic & Hybrid Photovoltaics

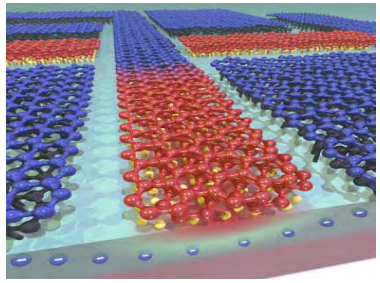


People

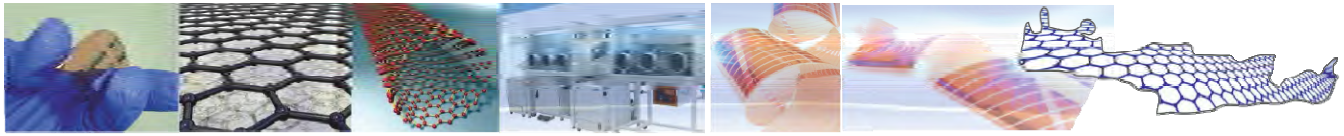
Flexible electronics



Fabricate
Test



Formulate
Process



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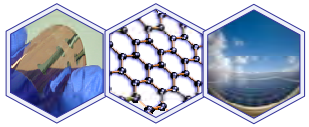
Outline



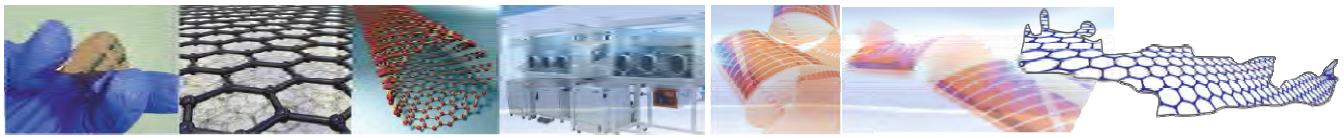
- Introduction to Organic Photovoltaics
  - Status of OPVs
  - Why OPVs / Applications of OPVs
  - Working principle
  - Device Architectures
  - Approaches to improve OPV performance (efficiency and stability)

- Laser Processes in OPVs
  - Why Lasers?
  - Photothermal Processes
  - Photochemical Processes

- Photothermal Processes exploited in nano group
  - Reduction of Graphene Oxide Films: Towards free ITO OPVs
  - Laser ablation method for NPs production
  - Graphene-based OPVs

- Photochemical Processes exploited in nano group
  - Laser Induced Doping
  - Laser Production of metal NPs
  - Laser Induced Decoration

- A brief review of our group: Research & Educational Activities



PV Technologies

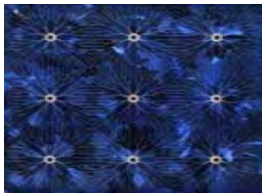
First Generation

crystalline silicon (mono & multi)

This will be the PV-backbone technology and leader of the BIPV sector.

module efficiency:

13% ····· **20%**



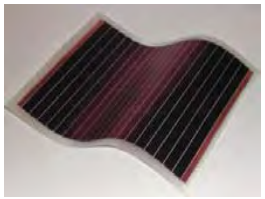
Second Generation

thin film: a-Si, CdTe, CIGS

Viable competitor in BIPV and roll-to-roll process for flexible substrates.

module efficiency:

9% ····· **15%**



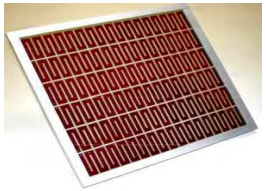
Disruptive/ New Generation

Organic and Perovskite Solar Cells

Initially niche market oriented, but breakthroughs could push field towards mass power generation.

module efficiency:

5% ····· **20+%**



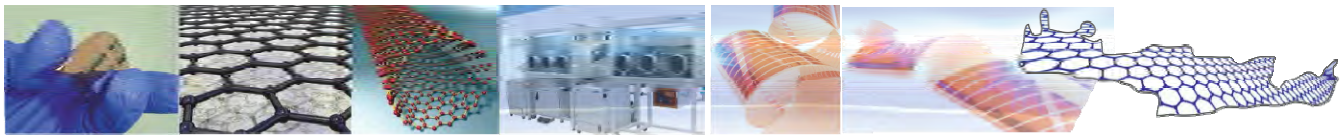
Hybrid Tandem Solar Cells

2000 $0.30/kWh

2010

2020

2030 $0.05/kWh



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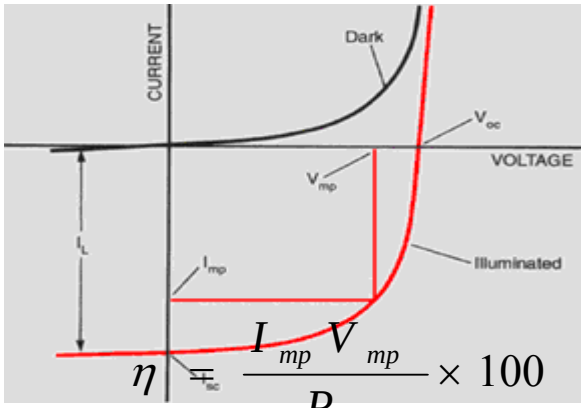
Cell efficiency

< Power conversion efficiency (η) >



I_{SC} : Short-circuit current

→ Current value when V = 0

V_{OC} : Open-circuit voltage

→ Voltage value when I = 0

P : Power output of the cell

$$P = IV$$

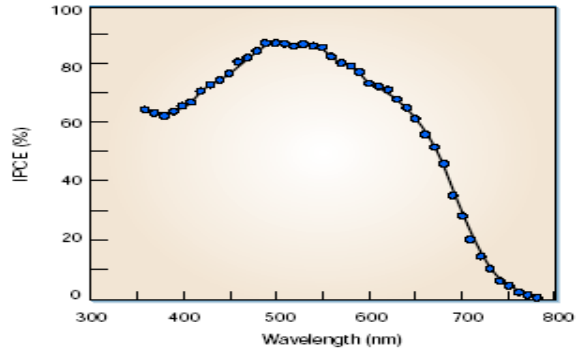
F.F : Fill factor

$$FF = \frac{I_{mp} V_{mp}}{I_{sc} V_{oc}}$$

$$\eta = \frac{I_{sc} V_{oc} FF}{P_S} \times 100$$

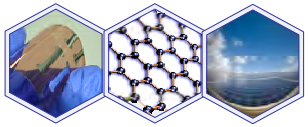
Under **AM 1.5G** simulated solar illumination

< Incident-photon-to-current conversion efficiency (IPCE) >



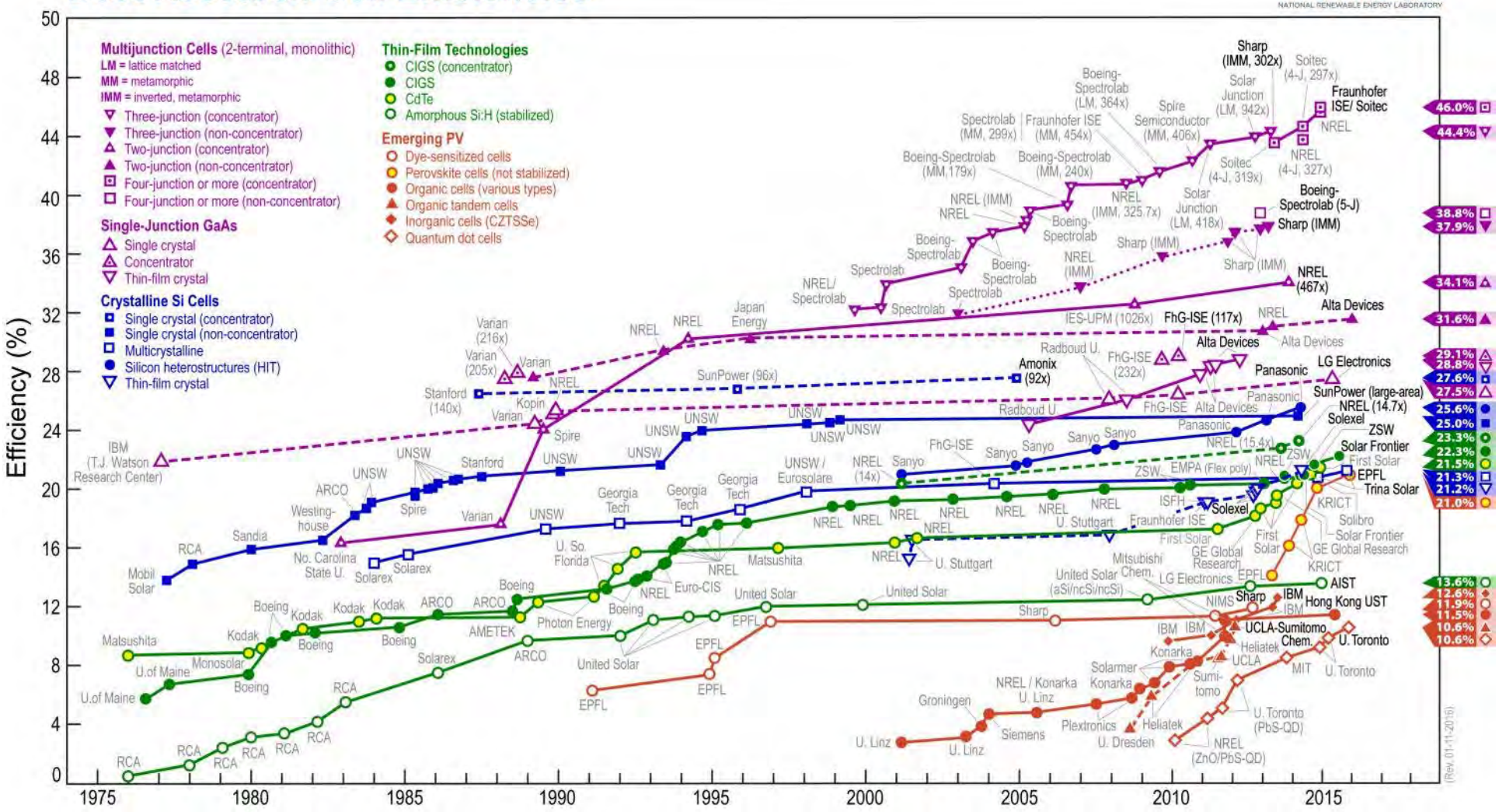
$$IPCE = \frac{\text{no. of electrons through the external circuit}}{\text{no. of photons incident}}$$

$$= \frac{[1240\, eV\, nm][photocurrent\ density\ (\mu A\, cm^{-2})]}{[wavelength\ (nm)][irradiance\ (mW\, cm^{-2})]}$$



Best Research-Cell Efficiencies

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



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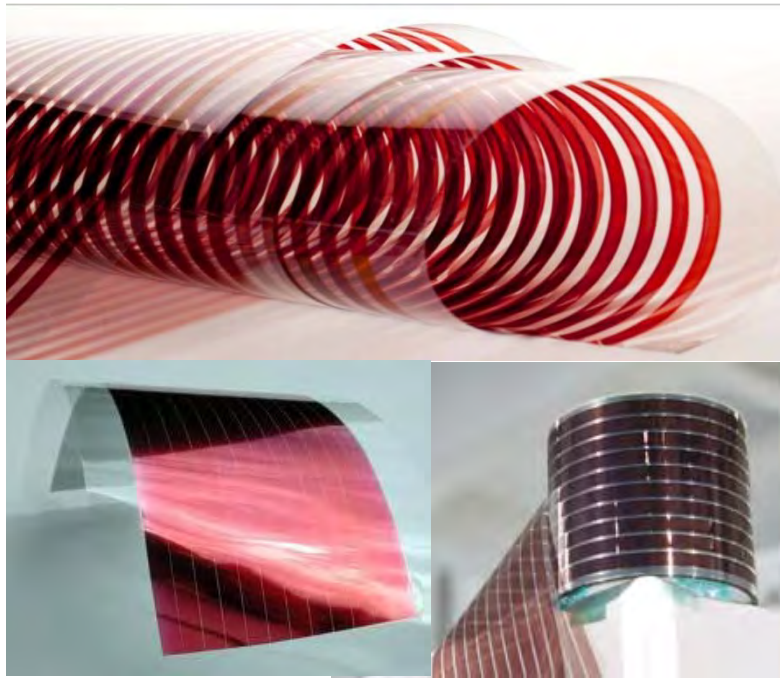
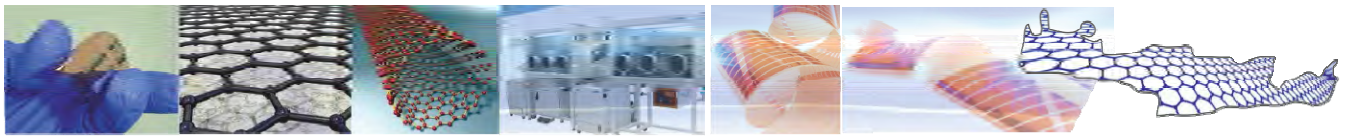
Why OPVs ?

- ✓ Processed easily over large area
  - -spin-coating
  - -doctor blade techniques (wet-processing)
  - -evaporation through a mask (dry processing)
  - -printing
- ✓ Low cost of fabrication
  - ✓ Poly and TF-Si costs around 500-1000 $/m^2
  - ✓ Plastic-PV expected below 50 $/m^2
- ✓ Light weight technology
- ✓ Mechanical flexibility and transparency
- ✓ Band gap of organic materials can be easily tuned chemically by incorporating different functional groups



- OPVs shows a promising technological development - efficiencies at 10% level.
- The usage of roll to roll printing technologies guarantees a favorable cost structure
- The PV market demands low cost flexible solutions



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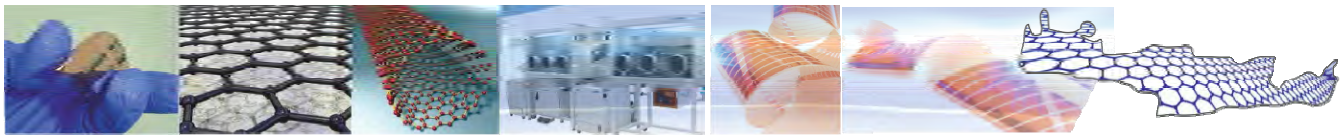
What is special about OPVs applications?

➔ Light weight

NEUBER's

ecoTraveler™



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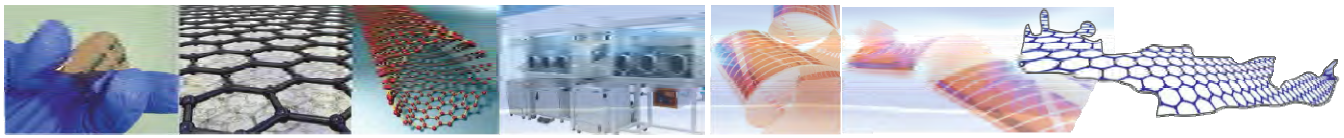
What is special about OPVs applications?

➔ Flexible



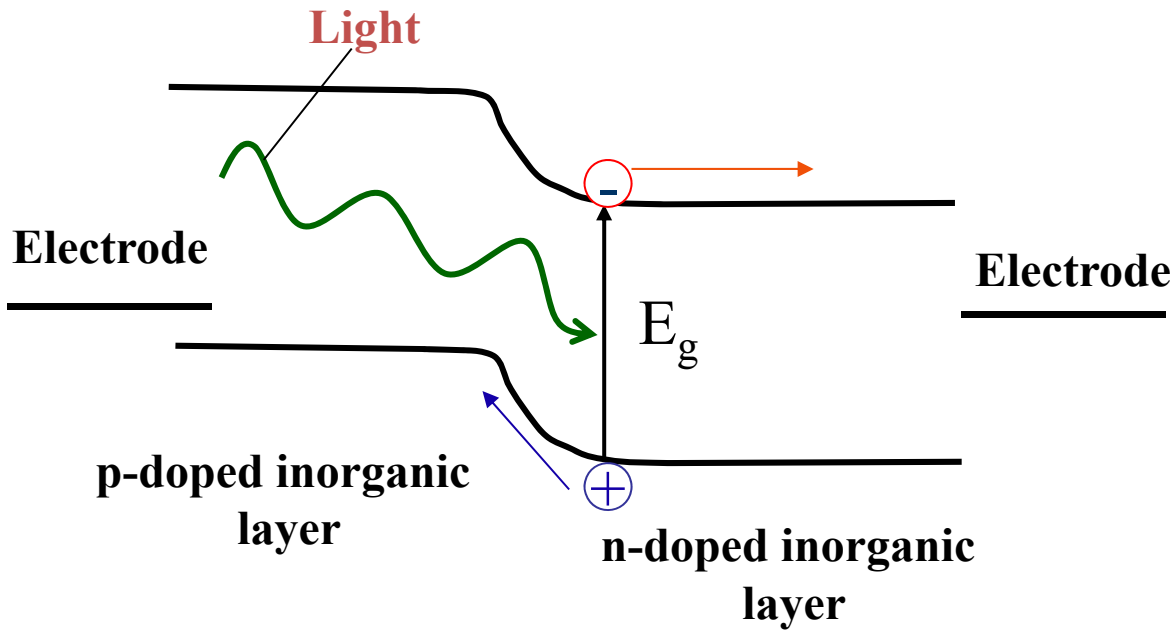
Inorganic vs Organic

Theory of Inorganic Semiconductors

p-n junction :

- Light creates electron-hole pairs throughout semiconductor
- p and n layers provide selective contacts
- Free charge carriers
- Mobility of charges is relatively high

- Band gap enables photogeneration
- n and p type doping ⇒ asymmetric electrodes

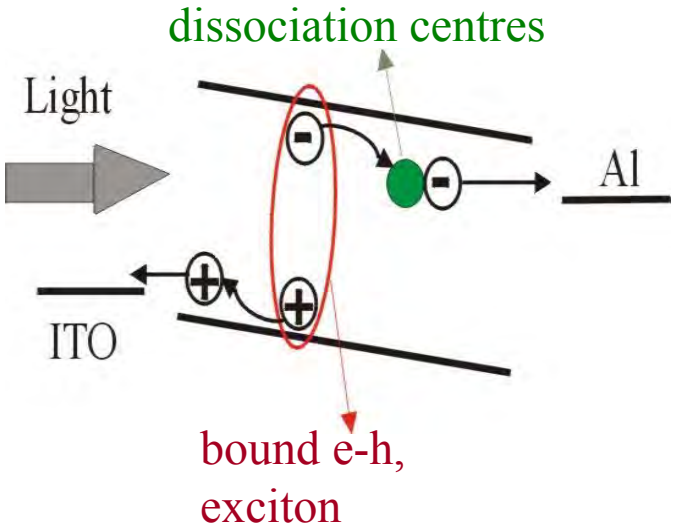


Inorganic vs Organic

Theory of Organic Semiconductors

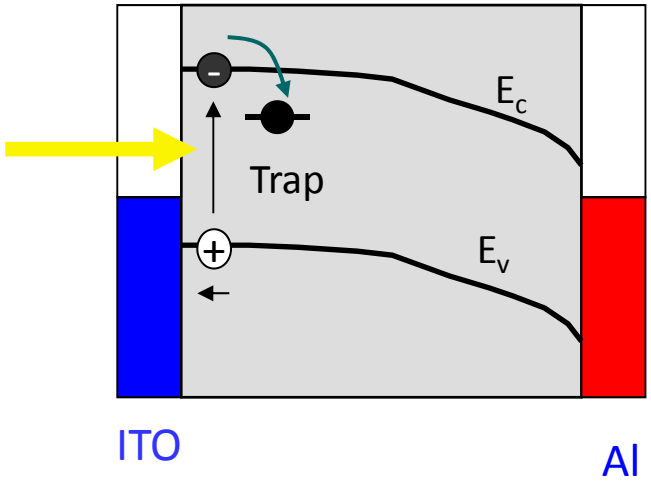
Conjugated Polymers:

- Light creates bound e-h pairs, excitons (0.4eV)
- Mobility of charges is relatively low



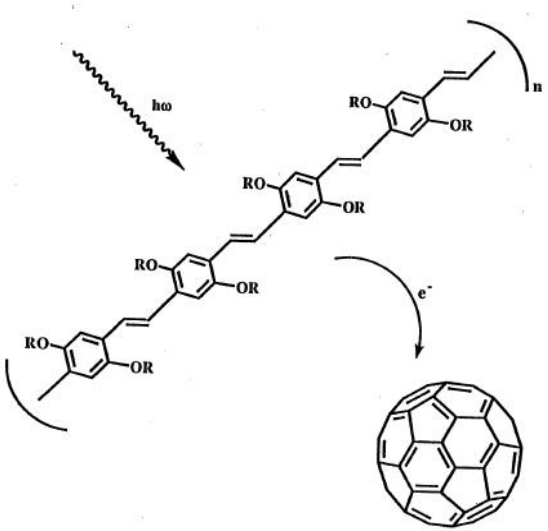
In a single-layer polymer photovoltaic device, excitons may be dissociated at:

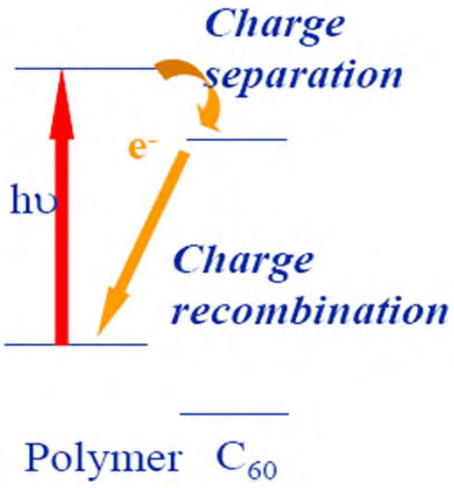
- *strong internal electric fields found at polymer/metal interfaces.*
- *dissociation centres, such as oxygen acting as e^- traps.*



Road to Bulk Heterojunction concept in OPVs

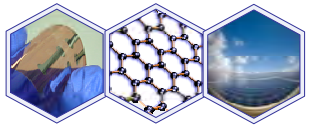
Conjugated Polymer and Fullerenes



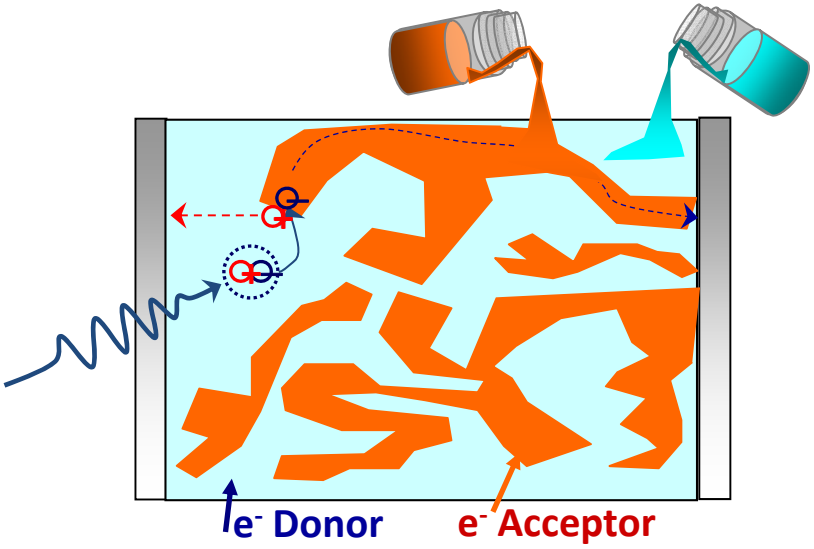


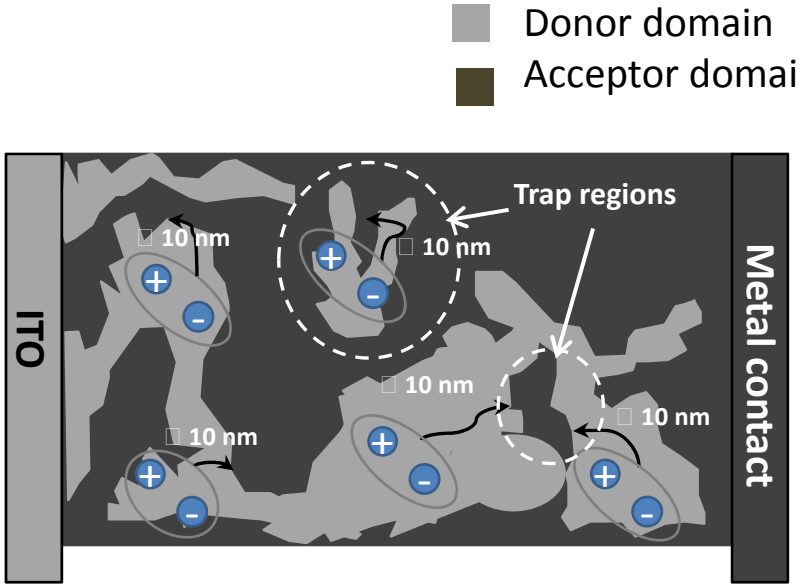
Ultrafast Photoinduced Charge Separation (fs) in the interface
Slow Charge Recombination (µs)

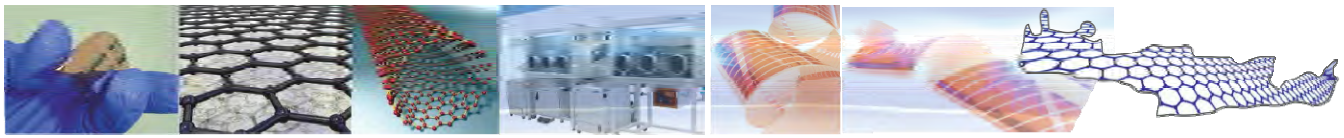
Blended Devices - Bulk Heterojunction Concept



- Mix hole and electron acceptor materials with offset energy levels together → bicontinuous nanoscale mixture of D-A materials
- Both D and A materials must be very soluble in the same solvent
- Length scale of blend ~ exciton diffusion length (10-20nm)
- Exciton dissociation at interfaces; Electrons transferred to e^- acceptor, while h^+ to the polymer
- Percolation limit for both materials has to be reached.
- The blend morphology has to enable charge-carrier transport in the two different phases in order to minimize acceptor recombination







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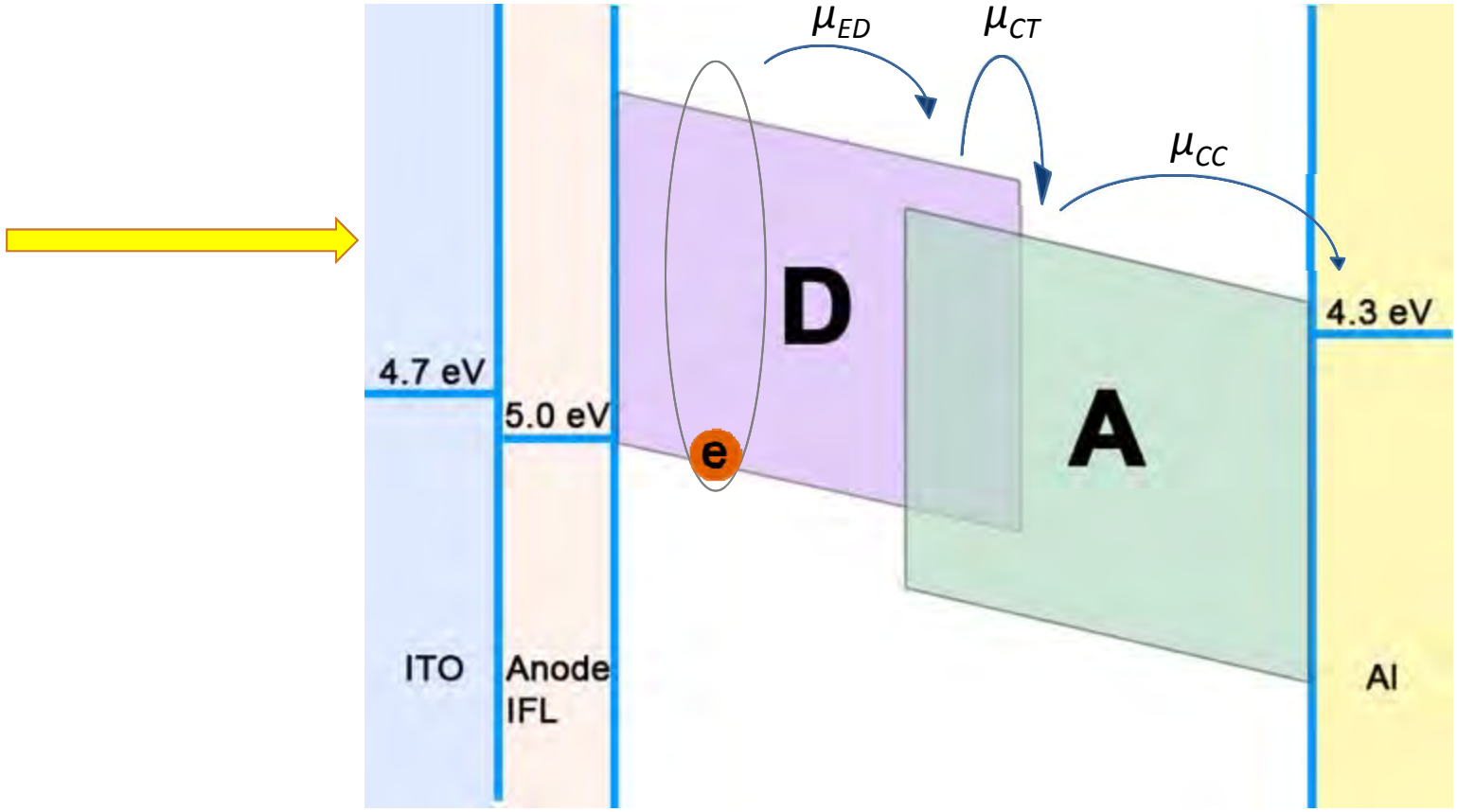
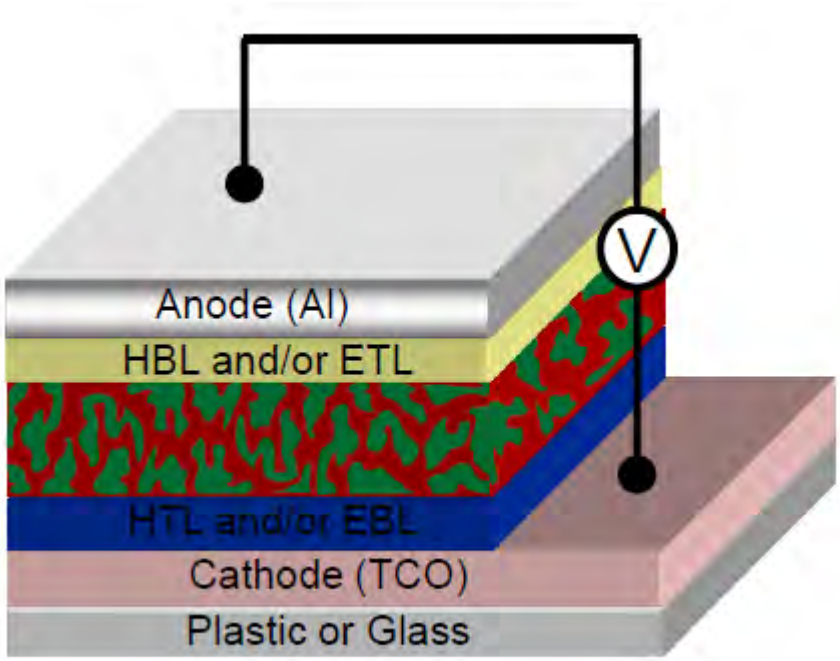
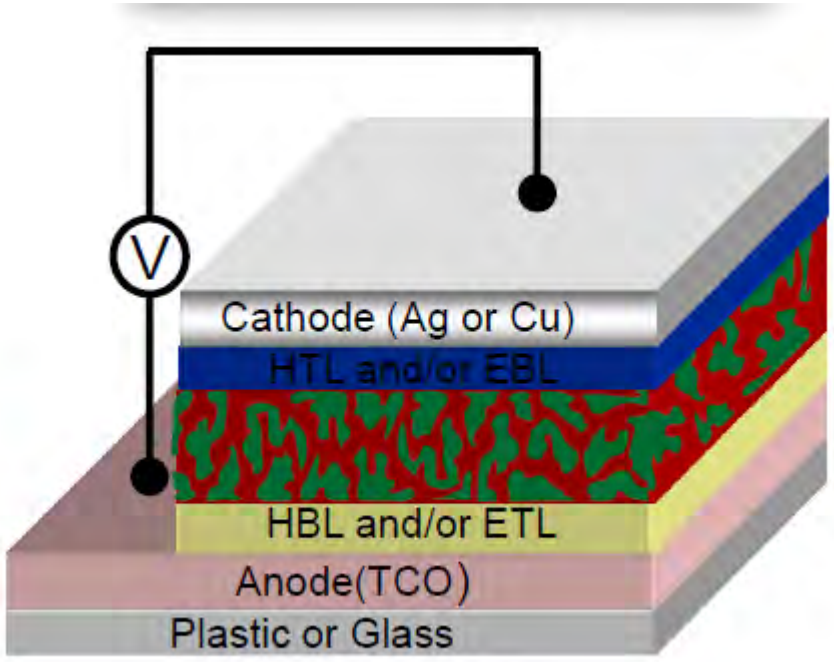
OPV device operation principle



Device structures



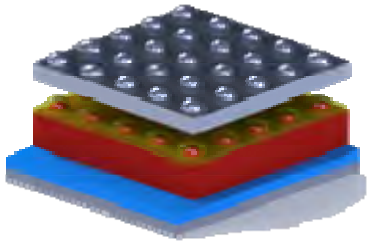
Normal stack



Inverted stack

How to improve OPV performance - Research Activities

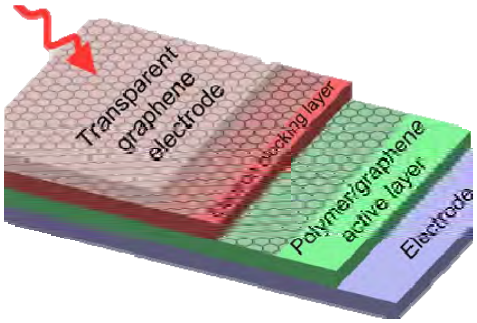
Photon Management



Plasmonics

Metallic nanostructures enable light manipulation at the nanoscale. Photonic and plasmonic enhancement of photocurrent

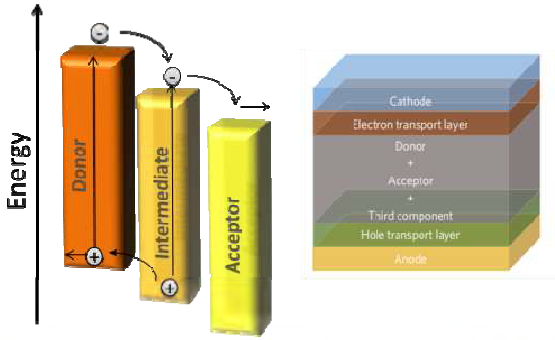
Novel materials



Solution processable graphene and 2D based materials

As electrode, interfacial layer, electron acceptors, and additive materials, compatible with r2r

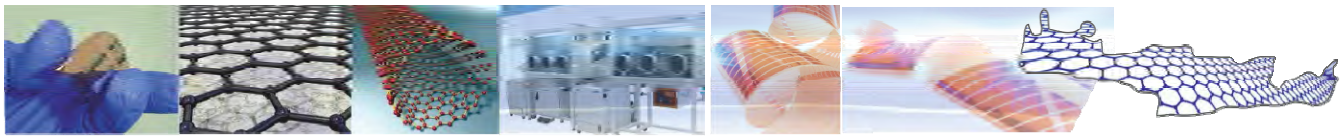
Device Engineering



Ternary organic-inorganic hybrids etc.

Ternary devices to enhance light harvesting; Optimize electron/hole transport

Enhancing OPV Performance and Stability through Integrated Material, Interfacial, and Device Engineering



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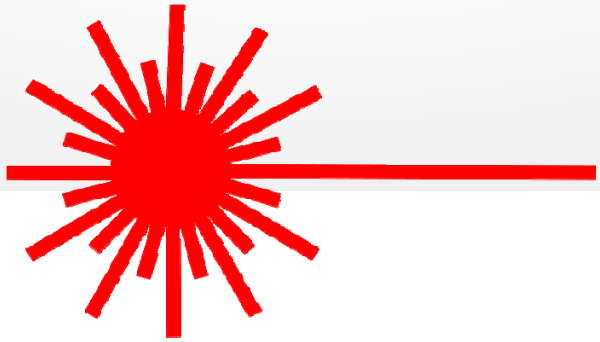
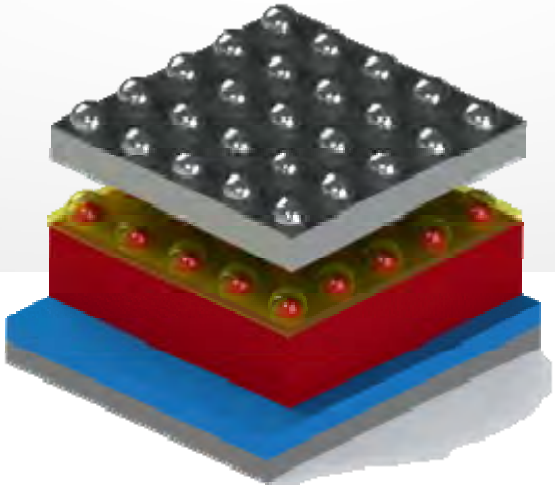
Utilize the Laser Tool

Lasers represents an interesting fabrication tool in the field of OPVs. Lasers based photochemical & photothermal processes are fast, precise, fully automated, localized, facile and fully controllable



Photon Management

Metallic nanostructures enable light manipulation at the nanoscale. Photonic and plasmonic enhancement of photocurrent



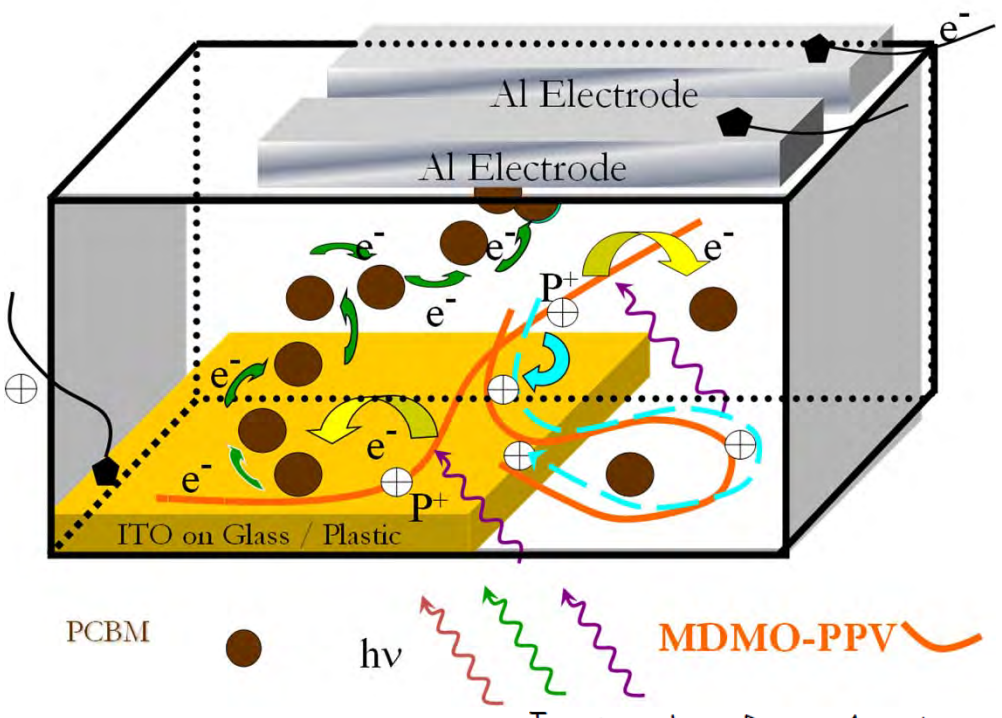
Photon Management

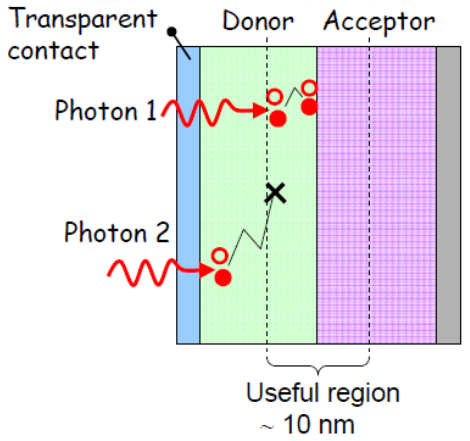
Key problems towards high efficient OPVs

- ✓ Exciton binding energy ~200-500meV
- ✓ Exciton diffusion length l ~ 10 nm
- ✓ l << layer thickness
- ✓ Tradeoff between light absorption length and exciton diffusion length.

Decrease layer thickness:
Light absorption ↓
Charge collection ↑

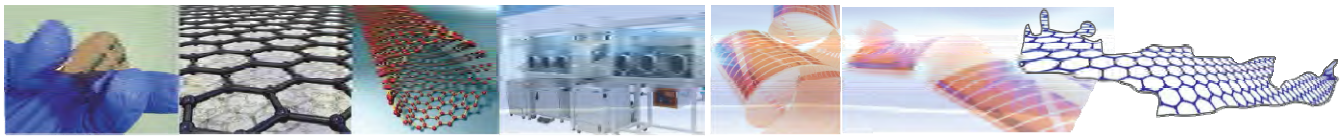
Increase layer thickness:
Light absorption ↑
Charge collection ↓





Solution: **Light trapping by plasmonic structures**

Improving the light absorption by plasmonic effects, enabling to thin down OPVs without sacrificing efficiency, leading to lower material utilization and a cost benefit



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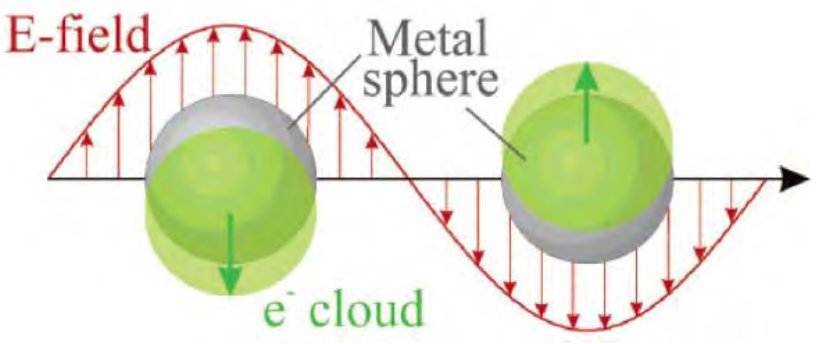
What is a Plasmon ?



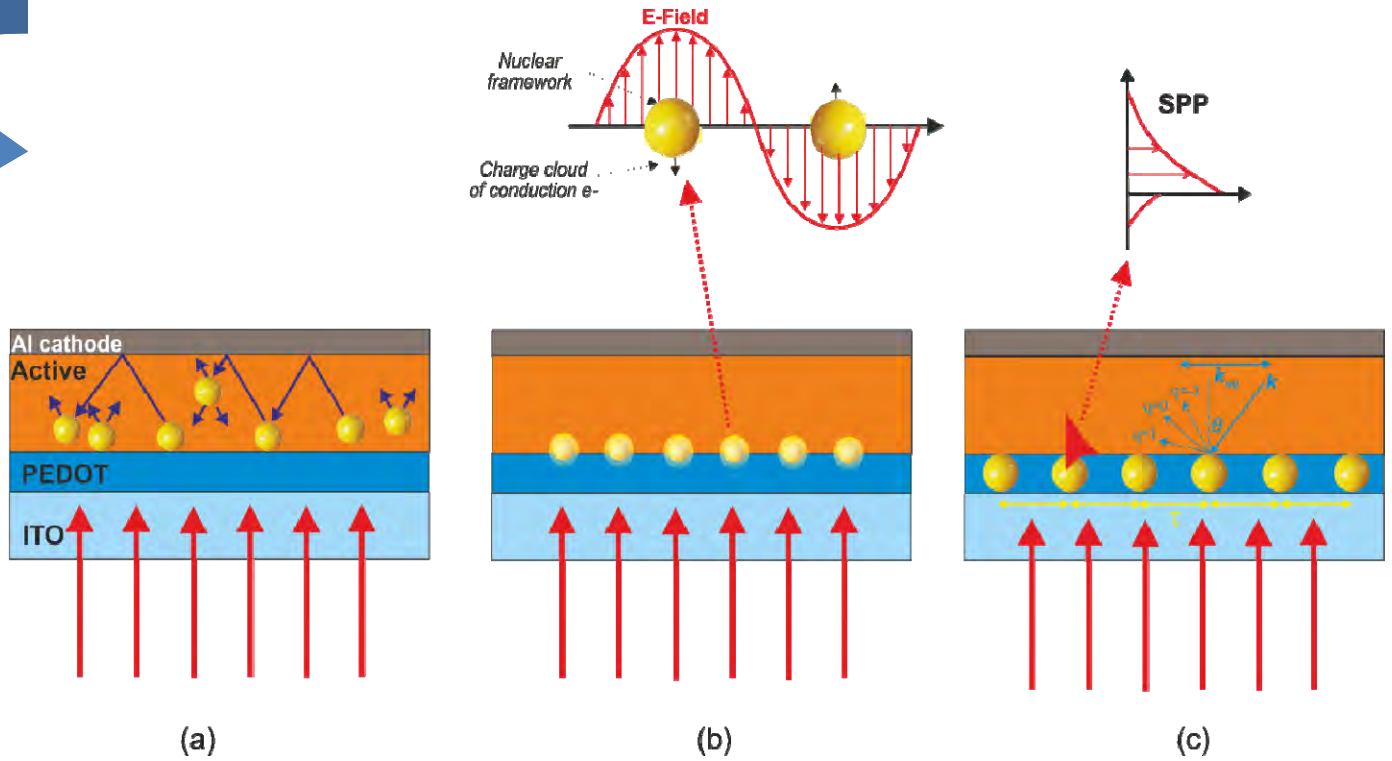
➔A plasmon is a density wave in an electron gas. It is analogous to a sound wave, which is a density wave in a gas consisting of molecules.

➔Plasmons exist mainly in metals, where electrons are weakly bound to the atoms and free to roam. The electrons in a metal can wobble like a piece of jelly, pulled back by the attraction of the positive metal ions that they leave behind. The free electron gas model provides a good approximation (also known as jellium model).

➔In contrast to the single electron wave function that we encountered already, a plasmon is a collective wave where billions of electrons oscillate in sync.

Light Harvesting: Combining Photovoltaics with Plasmonics

Increasing Cell Efficiency: How ???

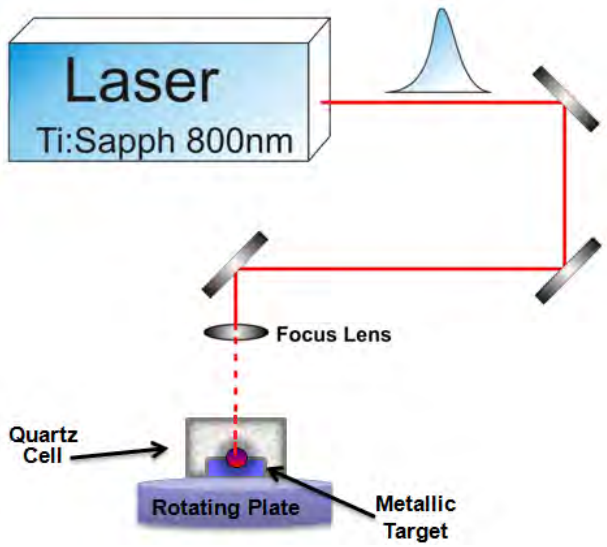


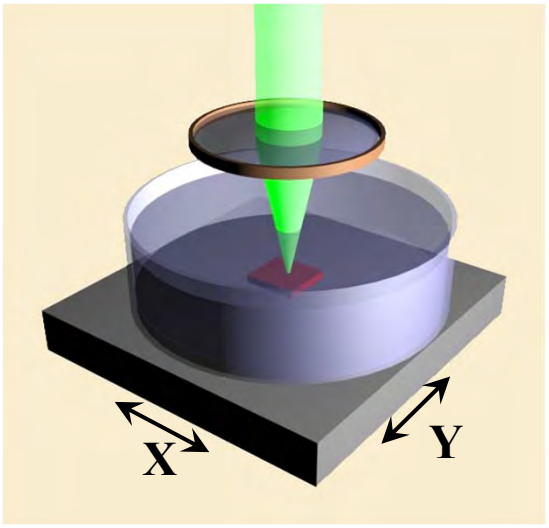
(a) scattering from large diameter (>50 nm) metal NPs into high angles inside the photoactive layer, (b) LSPRs induced by small diameter (5-20 nm) metal particles (c) Excitation of SPPs at the NPs/photoactive layer interfaces ensures the coupling of incident light to photonic modes propagating in the semiconductor layer plane.

E. Stratakis, E. Kymakis, **Materials Today** (2013), 16, 133-146

Laser-assisted synthesis of metallic NPs

Our Approach: Ablation in liquid by ultrashort laser pulses

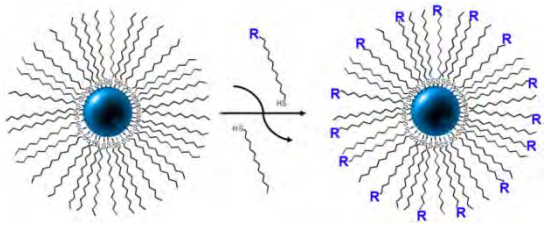




Ti-Sapphire laser, 100 femtosecond pulses at 800 nm wavelength

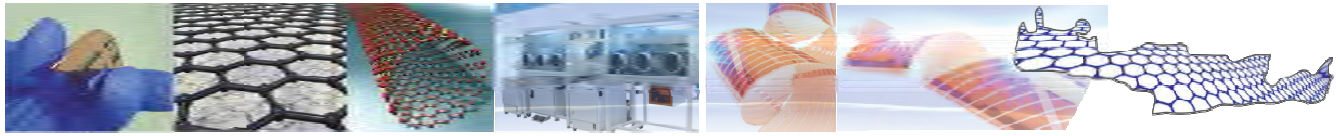
The advantages of laser assisted vs. chemical synthesis

- Generation of NPs over a controlled size range with a high degree of reproducibility
- Highly soluble in organic solvents
- Accurate determination of wt concentration by gravimetric measurements of the target before and after the ablation process
- ***Free of surfactants & passivation layers – no capping layers***



→ Exciton quenching in the photoactive layer is minimized

E. Stratakis et al, **Optics Express** (2009), 17, 12650-12659



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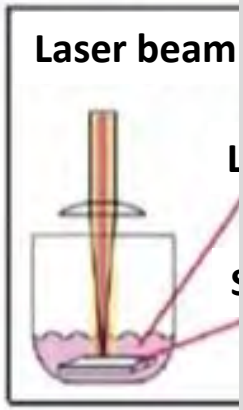
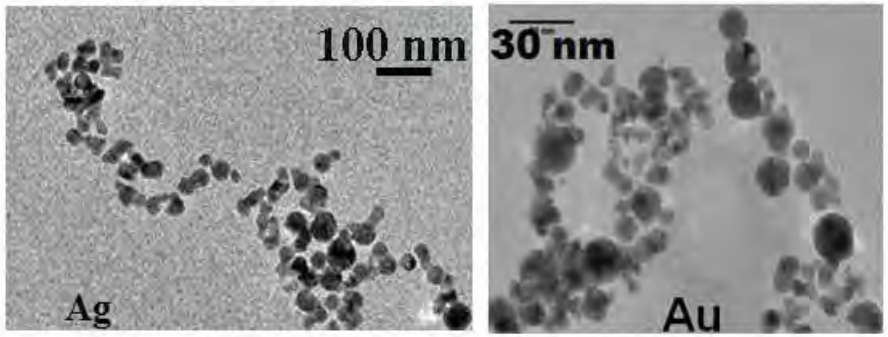
Production on nanoparticles with laser-ablation

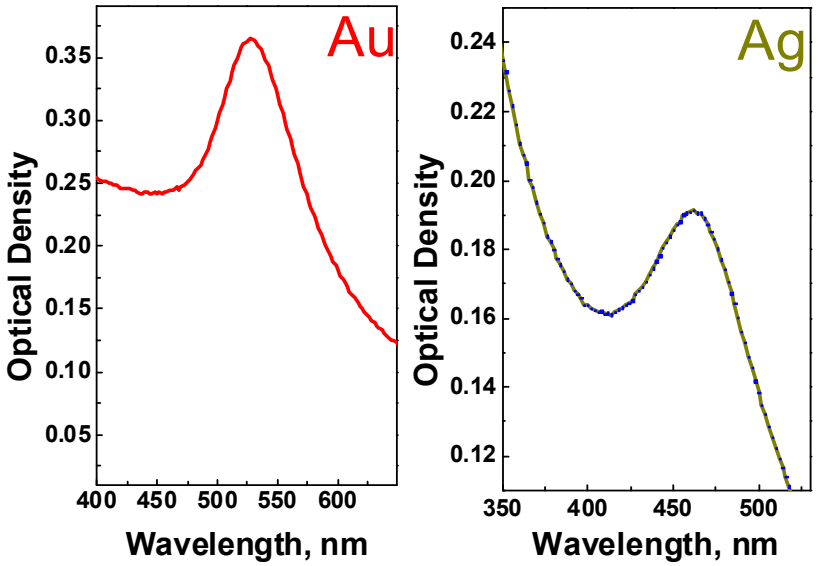


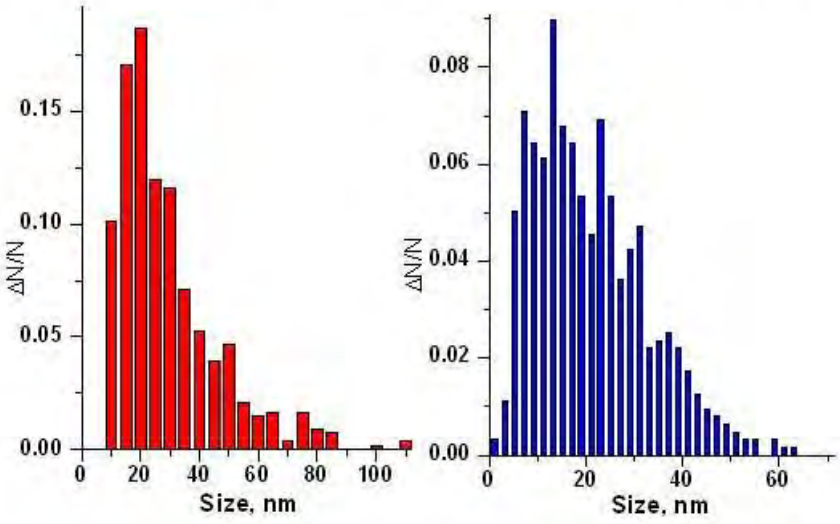
A pulsed la orption of
the laser p densed in
the solvent

Surfactant free metallic NPs

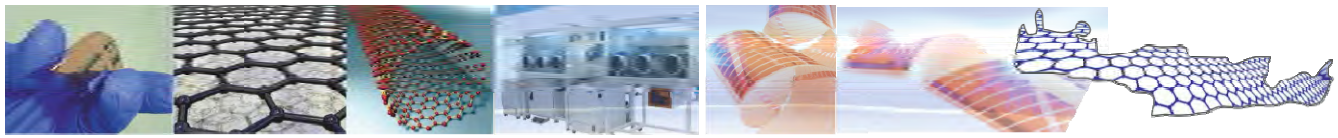
Ag Au







Size distribution histogram of NPs calculated from the respective TEM images



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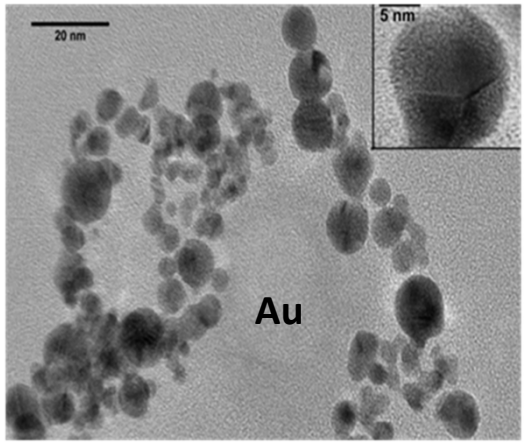
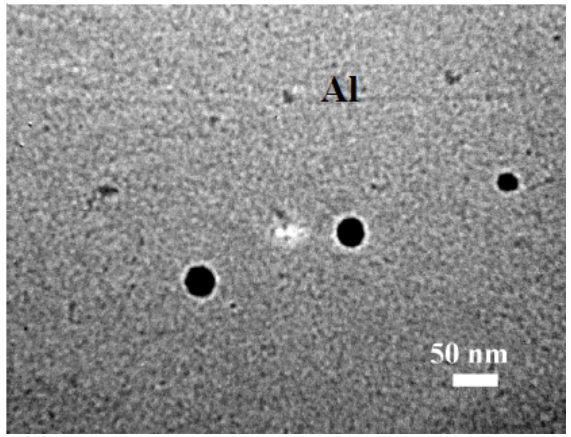
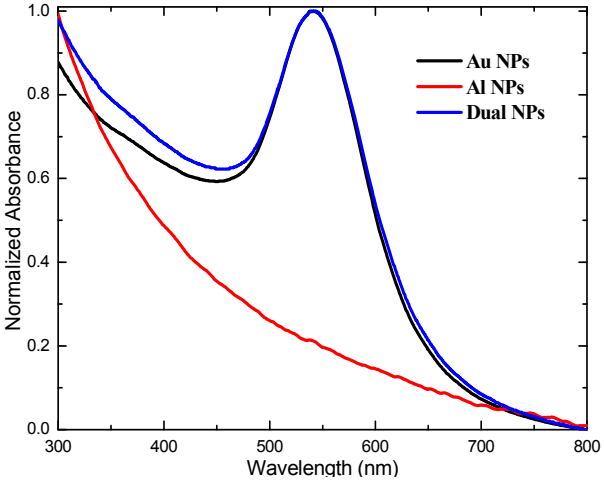
Surfactant free metallic NPs

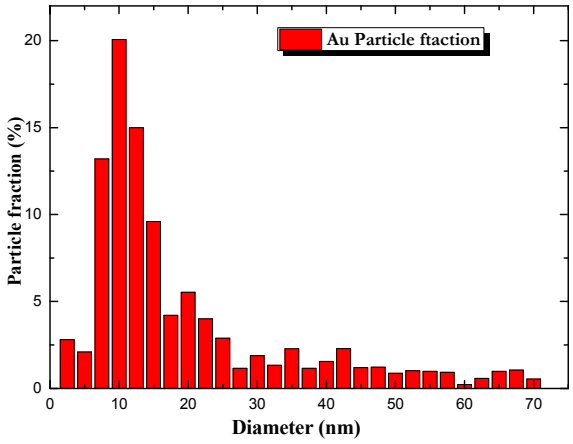
Al NPs Au NPs

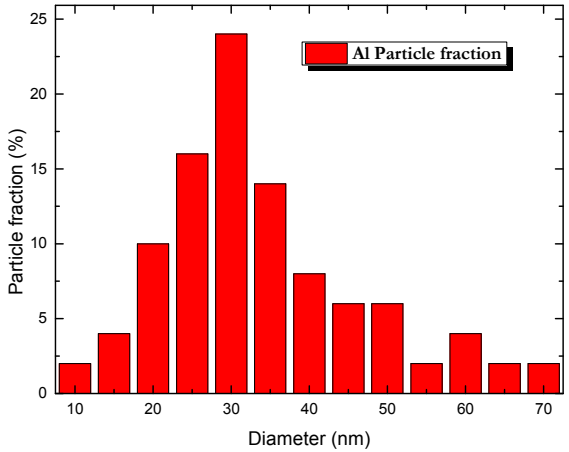
E. Stratakis et al, **Optics Express** (2009), 17, 12650-12659



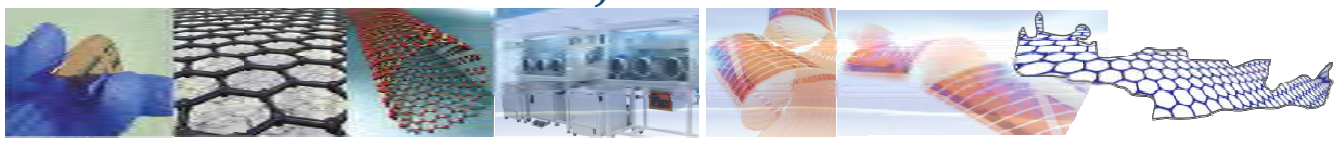








The coloration is assigned to the plasmon oscillation of electrons in the Au, Al nanostructures formed on the target.



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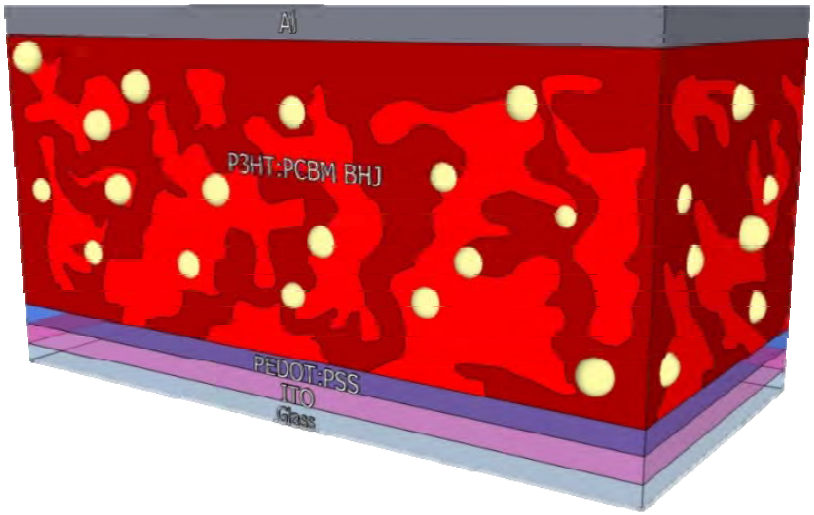
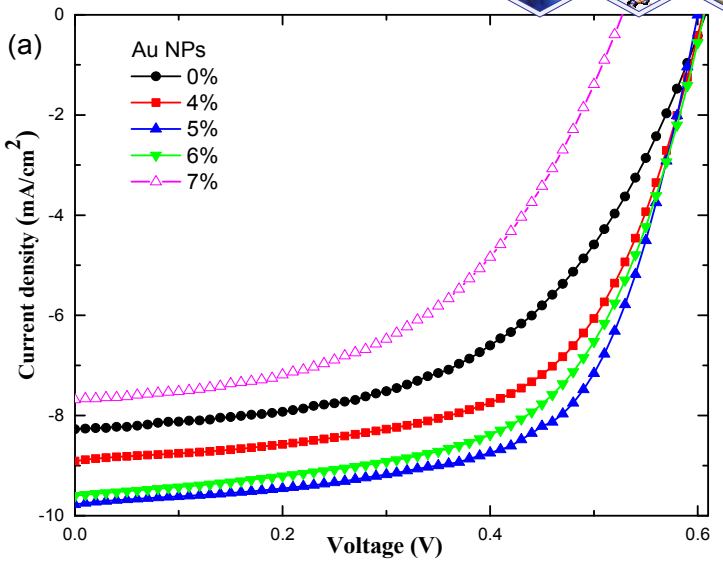
Au NPs are placed into the photoactive P3HT:PCBM layer





Device	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	η (%)
Pristine	8.27 ± 0.12	0.6	53.22 ± 0.30	2.64 ± 0.05
4 % Au	9.60 ± 0.15	0.6	61.32 ± 0.48	3.53 ± 0.08
5 % Au	**9.77 ± 0.24**	**0.6**	**63.38 ± 0.54**	**3.71 ± 0.12**
6 % Au	8.90 ± 0.20	0.6	61.03 ± 0.40	3.26 ± 0.09

Incorporation of surfactant free Au NPs in the active layer →

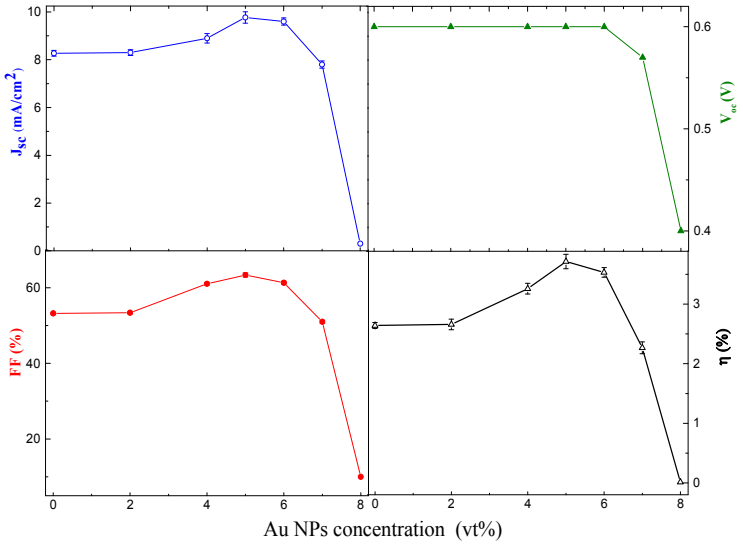
↑ J_{SC} by 18 %

↑ FF by 19 %

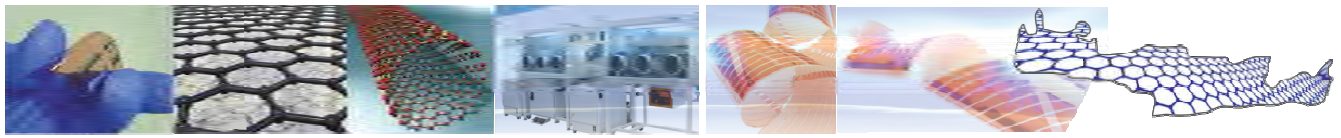
↑ η by **40.5 %**

η ~ 2.64→ 3.71 %

(b)



Applied Physics Letters (2012), 100, 213904



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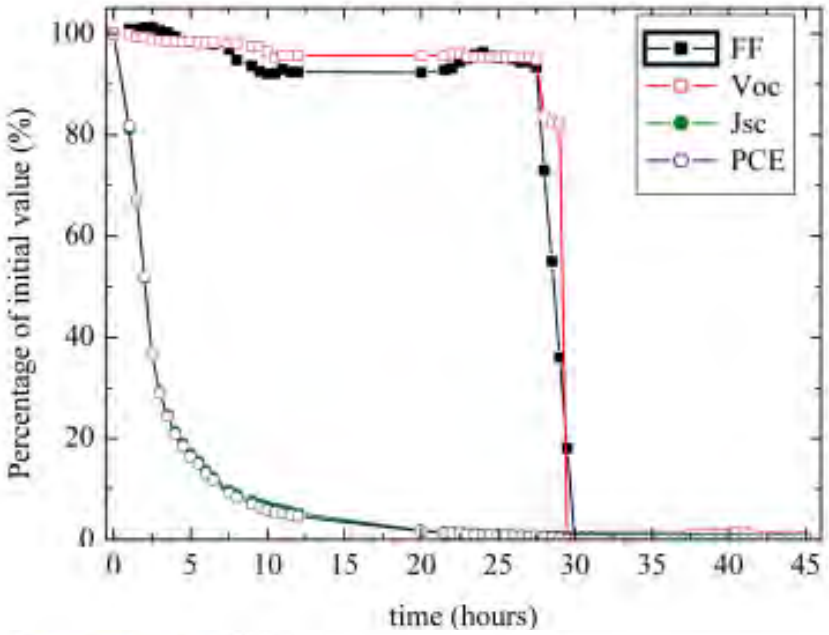
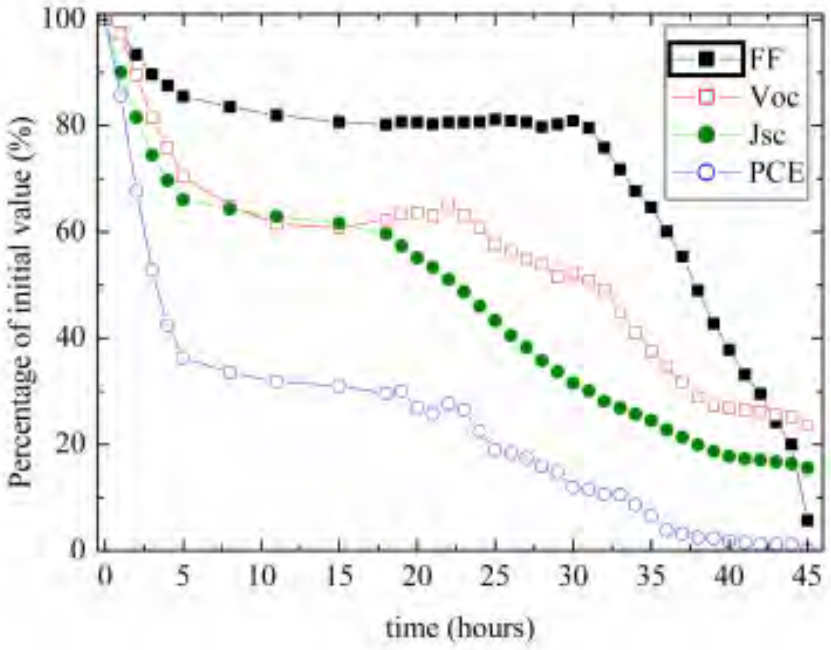
Morphological effects

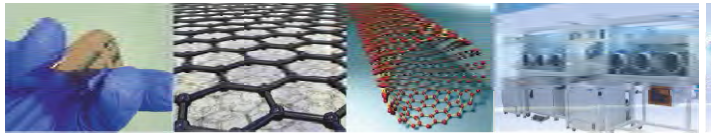


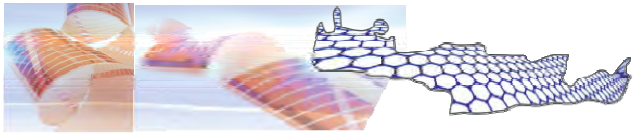
Reference cell without NPs



NPs-based cell

Incorporation of NPs leads to reduced device degradation rate during prolonged illumination !!!





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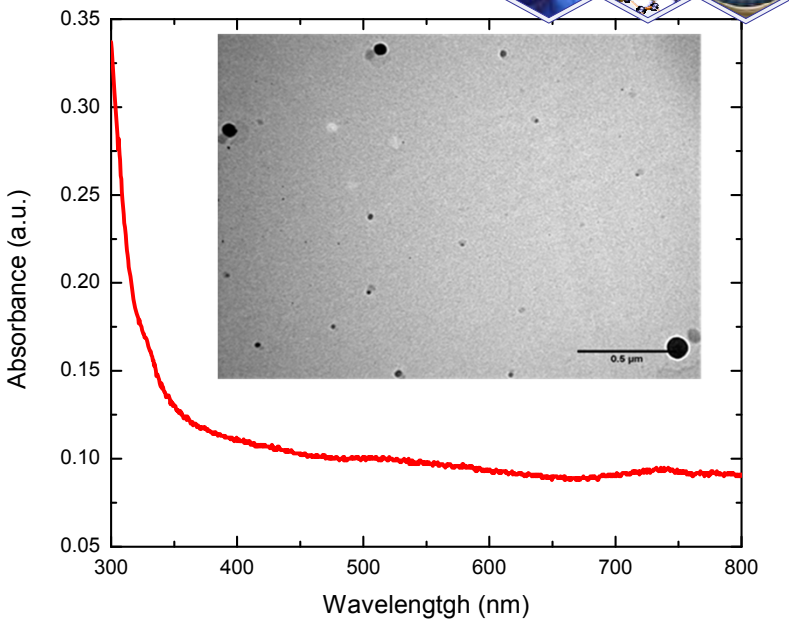
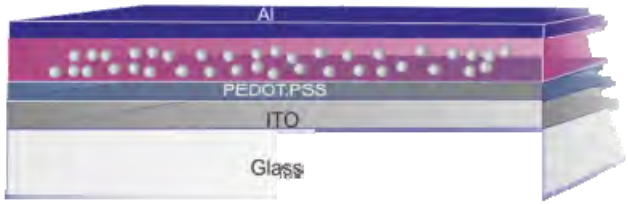
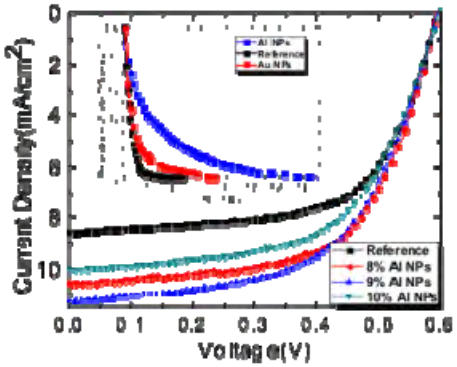
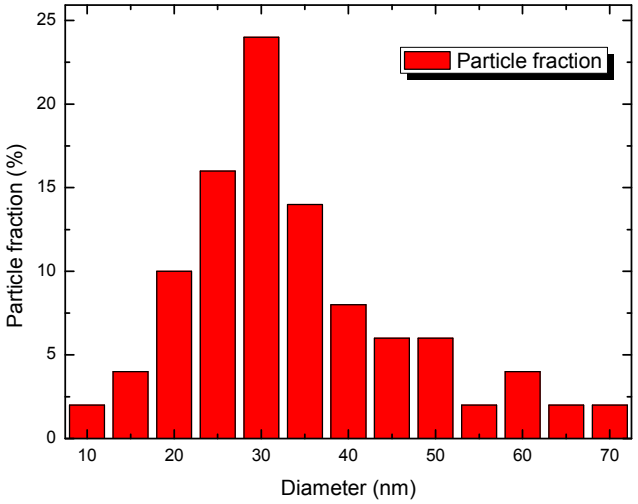
Al NPs are placed into the photoactive P3HT:PCBM layer

- Al NPs have the potential to yield significantly greater enhancement than Ag or Au, due to the much higher plasma frequency of Al
- Al NPs used exhibit sizes ranged from 10 to 70 nm with an average of ~30 nm

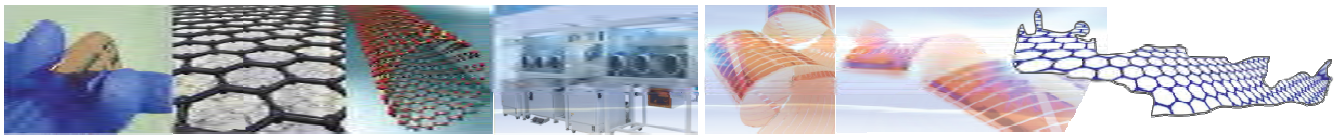








RSC Advances (2013), 3, 16288-16291



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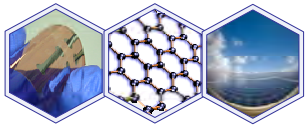
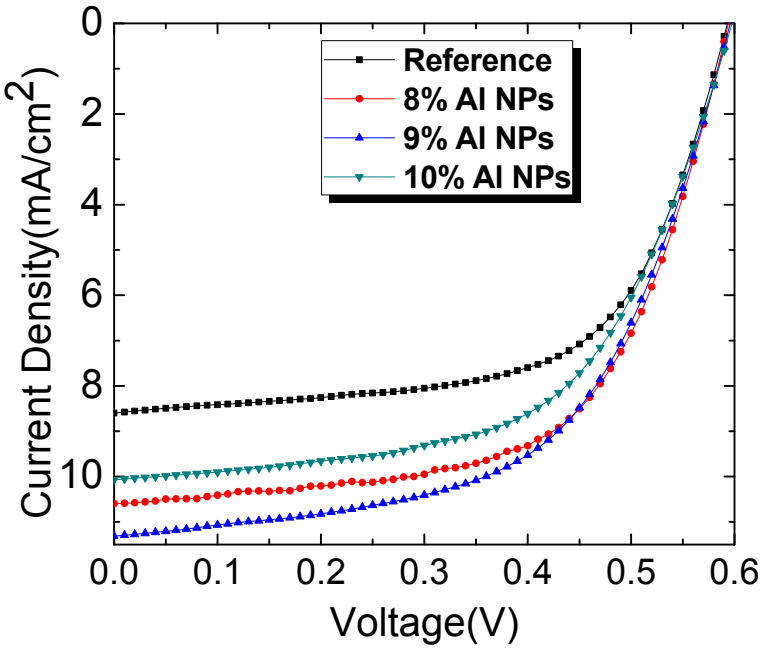
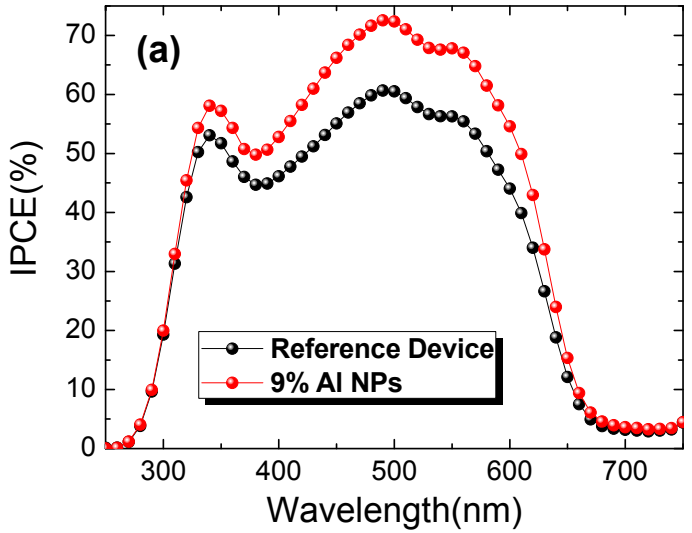
Al NPs are placed into the photoactive P3HT:PCBM layer

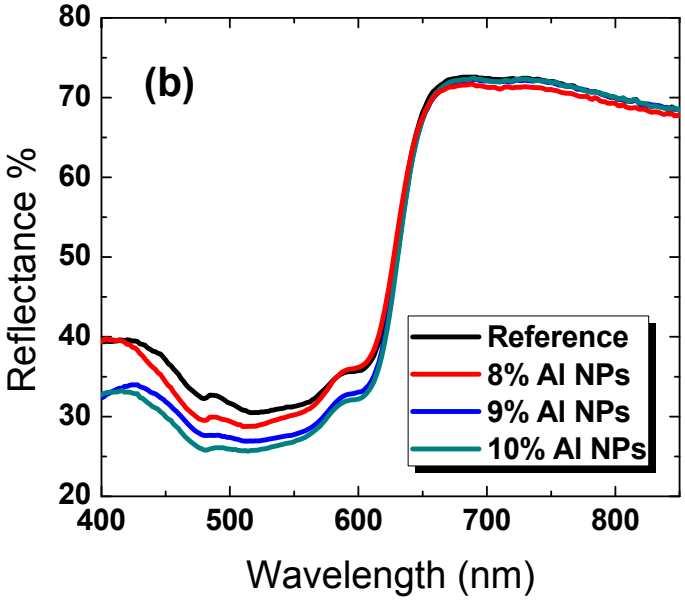


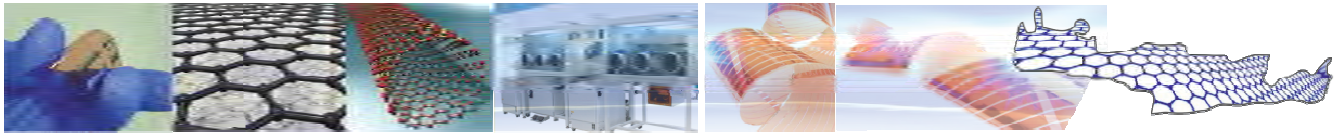




An efficiency enhancement by 30% is demonstrated, which can be attributed to multiple scattering effects and enhanced structural stability of the photoactive blend.

	J_{SC} (mA/cm^2)	V_{OC} (V)	FF (%)	PCE (%)
Pristine	8.59	0.6	61	3.14
8 % Al NPs	10.60	0.6	60	3.82
9 % Al NPs	**11.31**	**0.6**	**59**	**4.00**
10 % Al NPs	10.06	0.6	58	3.50





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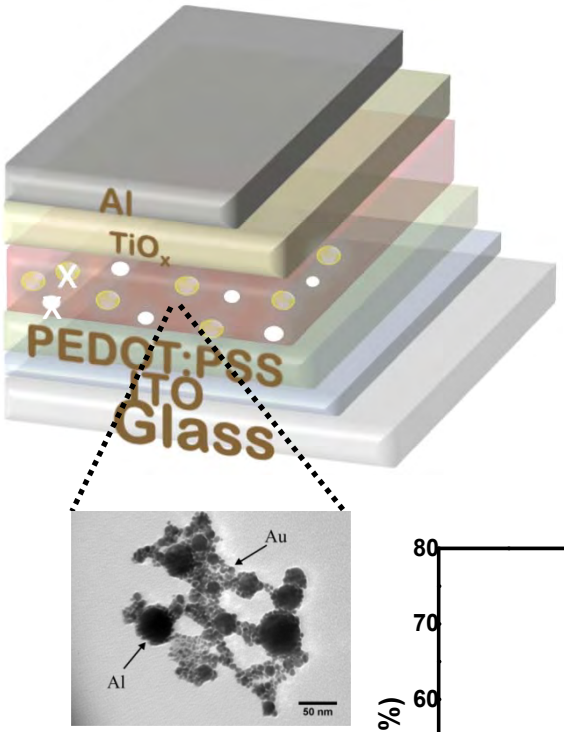
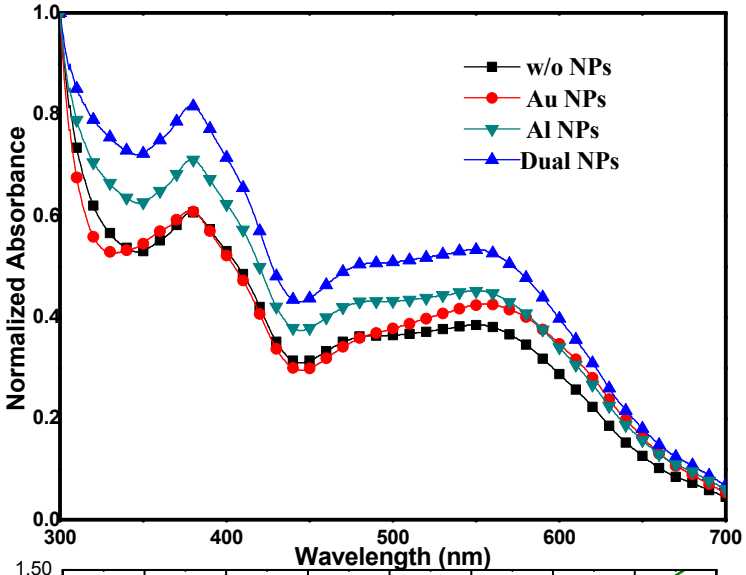
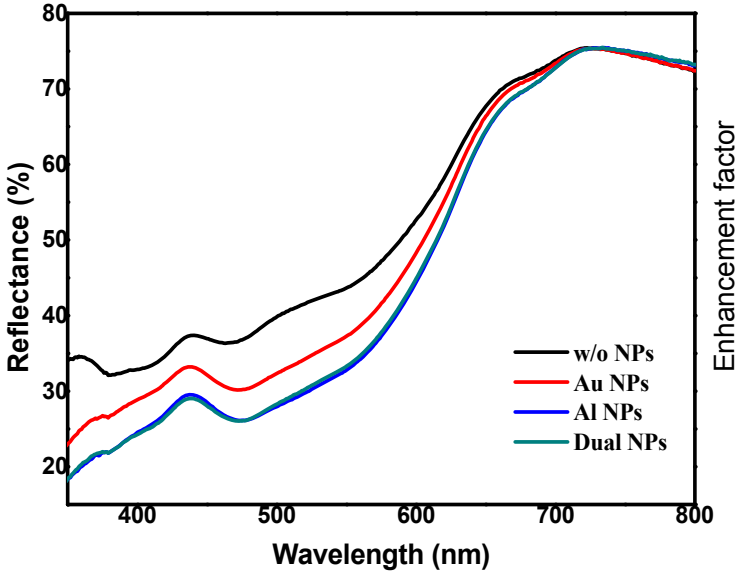
Au & Al NPs inside the PCDTBT:$PC_{71}BM$ photoactive layer

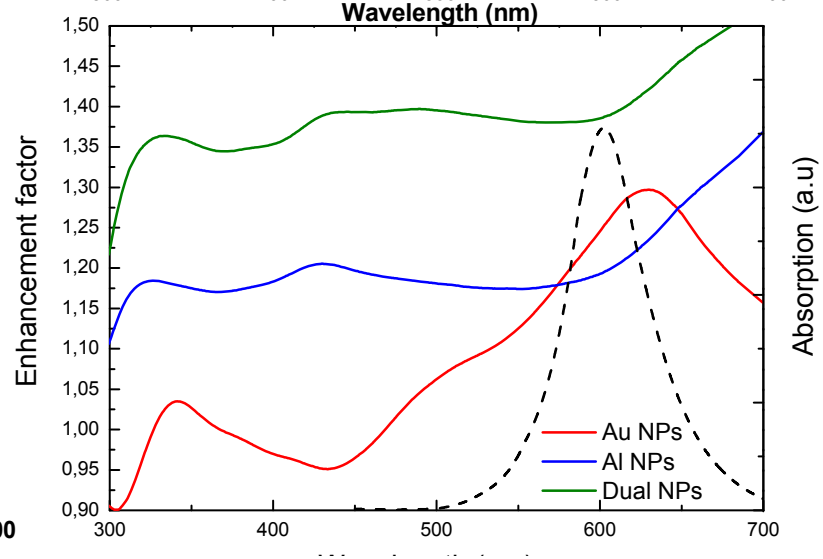


Light trapping inside the photoactive layer

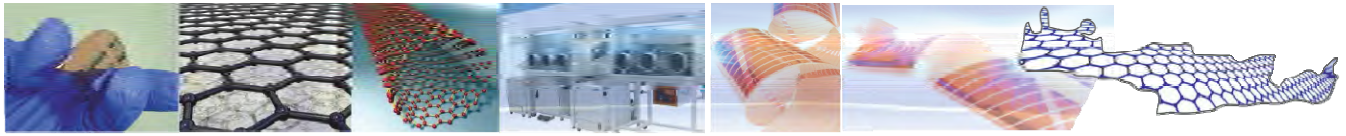
- ✓ Au NPs -> LSPR
- ✓ Al NPs-> Light scattering







Chem. Commun. (2014), 50, 5285-5287



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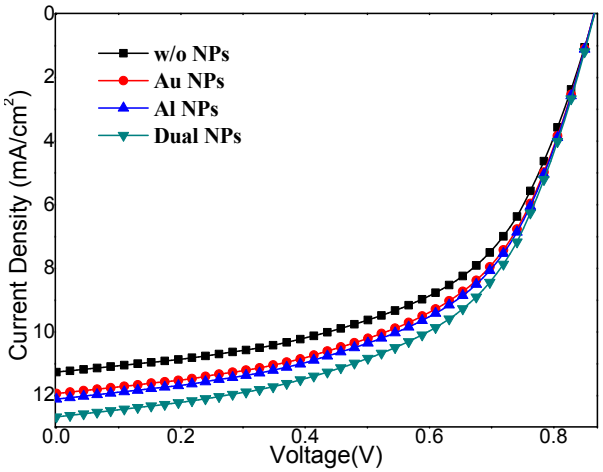
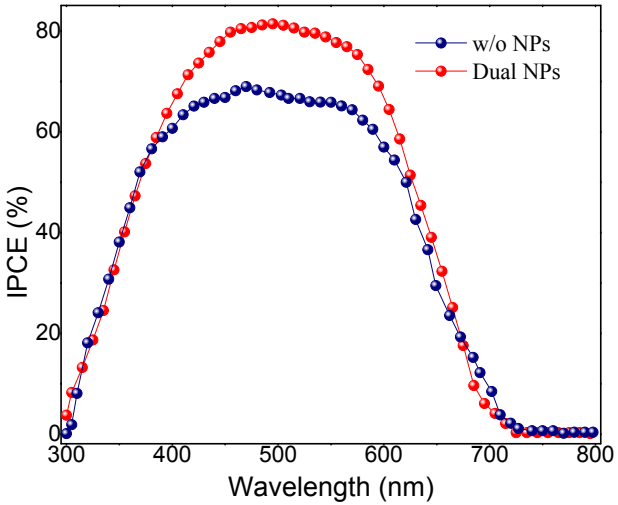
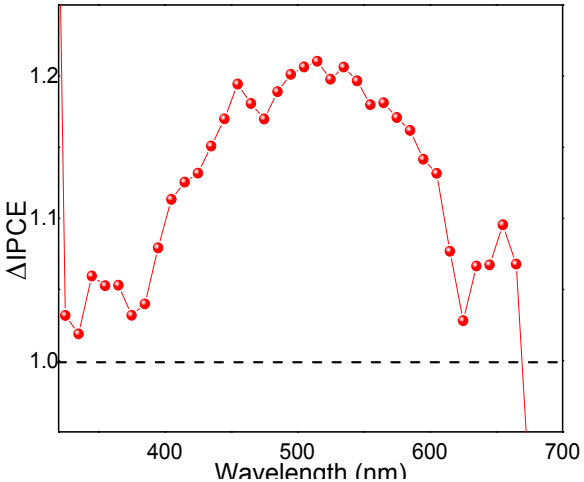
Au & Al inside the photoactive layer

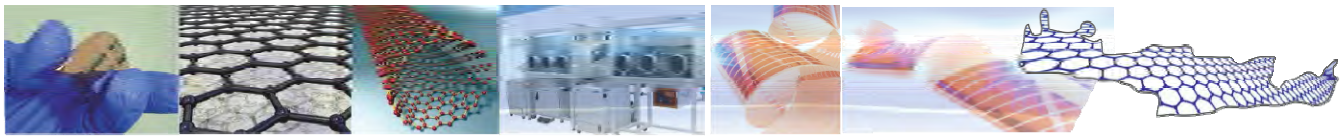






NPs	J_{sc} (mA/cm²)	V_{oc}(V)	FF (%)	PCE (%)	
No	11.27 ± 0.12	0.86	55.00±0.30	5.33±0.05	
Au	11.95 ±0.20	0.86	56.00±0.40	5.76±0.09	↑ ***8%***
Al	12.12±0.24	0.86	56.00±0.54	5.84±0.12	↑ ***9.6%***
Au-Al	12.71±0.15	0.86	56.00±0.48	6.12±0.08	↑ ***14.8%***

Chem. Commun. (2014), 50, 5285-5287



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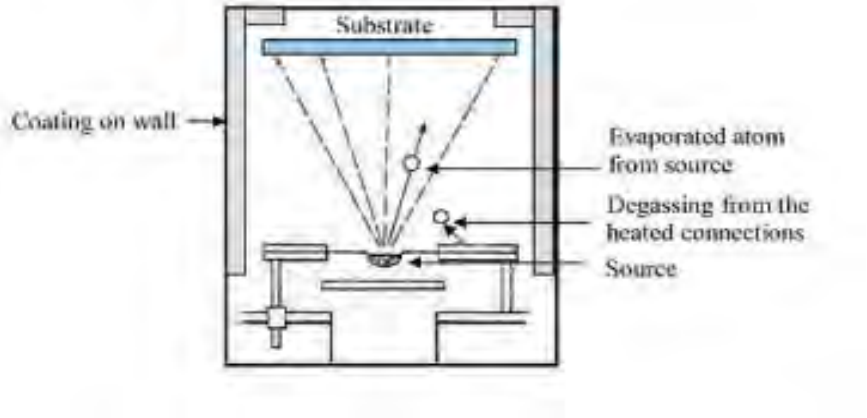
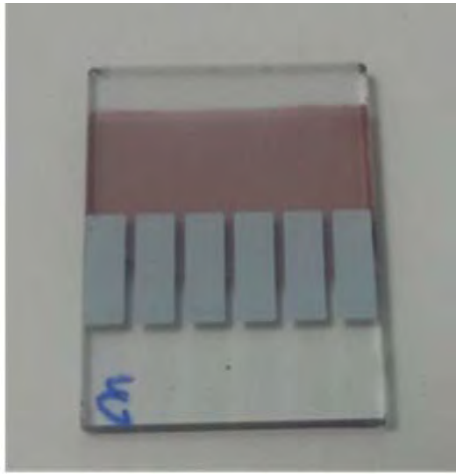
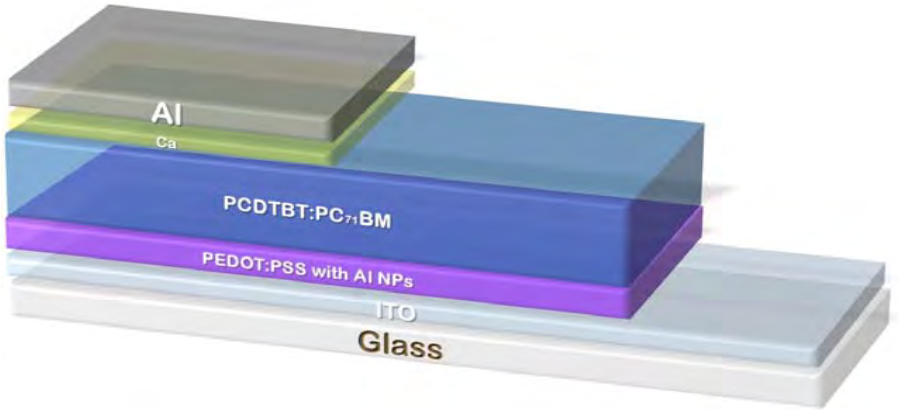
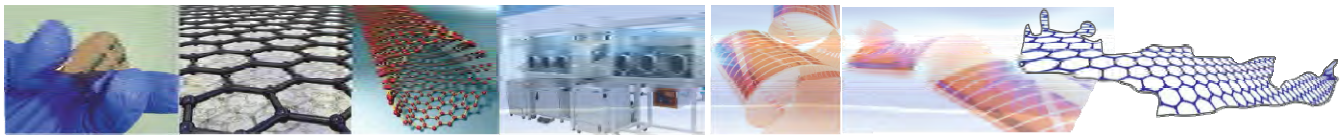
Al NPs into PEDOT:PSS buffer layer







Krassas et al., RSC Advances, 5, 71704 – 71708, 2015



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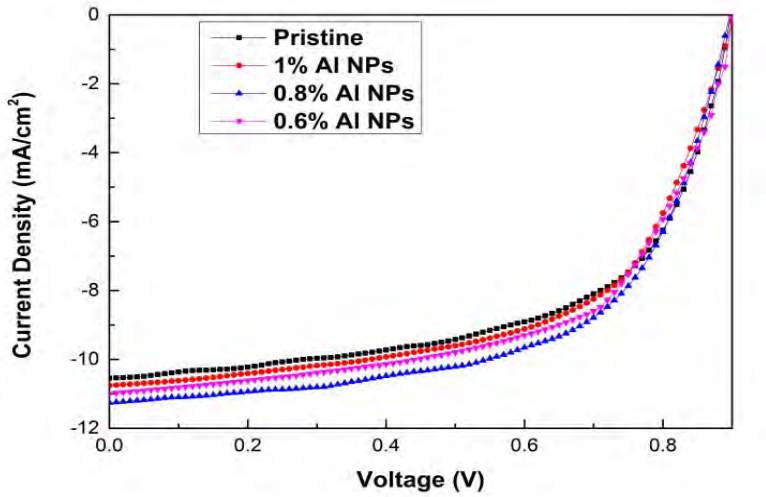
Al NPs into PEDOT:PSS buffer layer

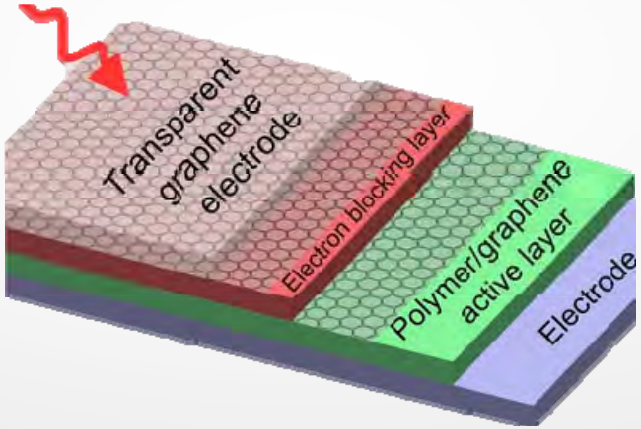
	J_{SC} (mA/cm^2)	V_{OC} (V)	FF (%)	PCE (%)
PEDOT:PSS	10.92 ± 0.12	0.883 ± 0.010	60.0 ± 0.5	5.78 ± 0.12
PEDOT:PSS with 0.6 % Al NPs	11.33 ± 0.10	0.884 ± 0.020	60.0 ± 0.4	6.00 ± 0.12
PEDOT:PSS with 0.8 % Al NPs	11.47 ± 0.15	0.883 ± 0.020	62.0 ± 0.6	6.28 ± 0.16
PEDOT:PSS with 1 % Al NPs	11.13 ± 0.09	0.885 ± 0.010	59.6 ± 0.4	5.87 ± 0.09

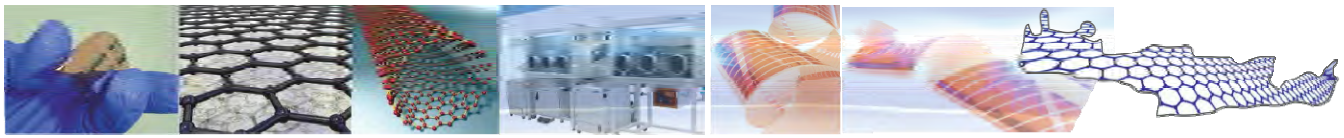


Krassas et al., RSC Advances, 5, 71704 – 71708, 2015

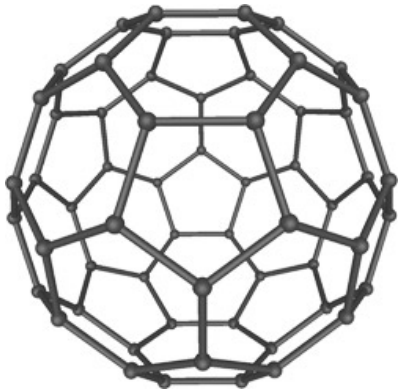
Solution processable graphene and 2D-based materials

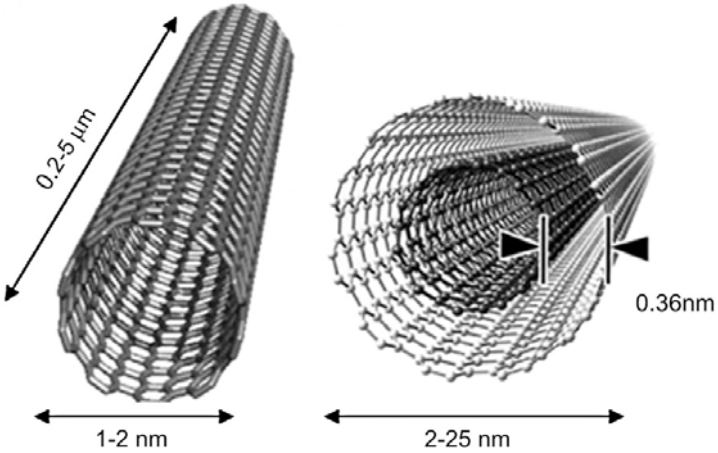
As electrode, interfacial layer, electron acceptors, and additive materials, compatible with r2r





Carbon Nanomaterials



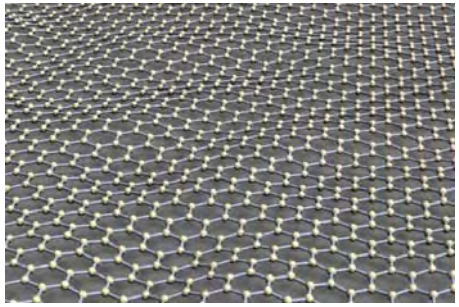


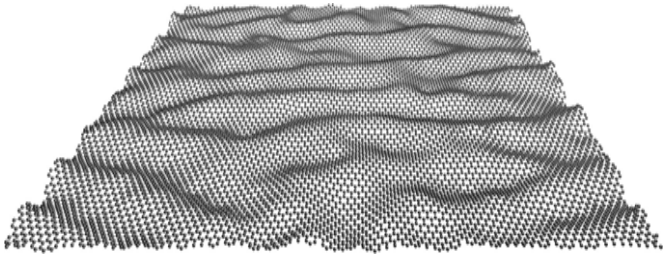
Fullerenes – 0D

- Discovered in 1985 (C60)
- C60, C70, C84
- Films – n-type semiconducting

Carbon Nanotubes (CNTs) – 1D

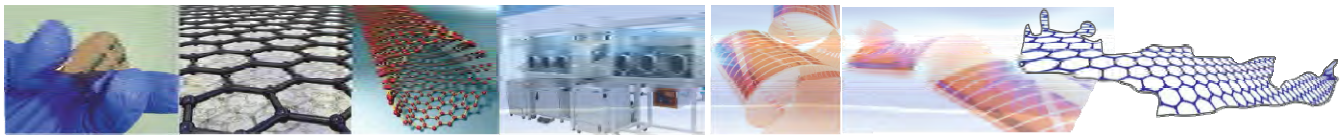
- Discovered in 1991
- Single and multi-walled
- Semiconducting or Metallic





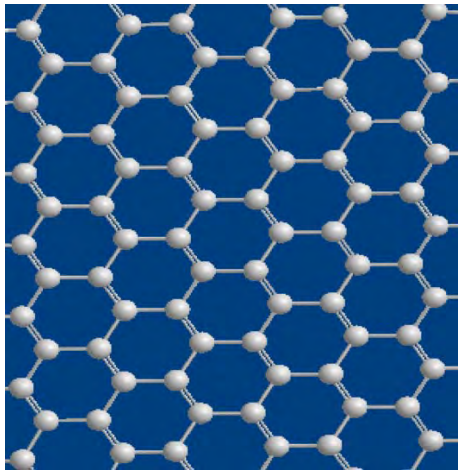
Graphene – 2D

- Discovered in 2004
- 2010 Nobel Prize
- Metallic/transparent

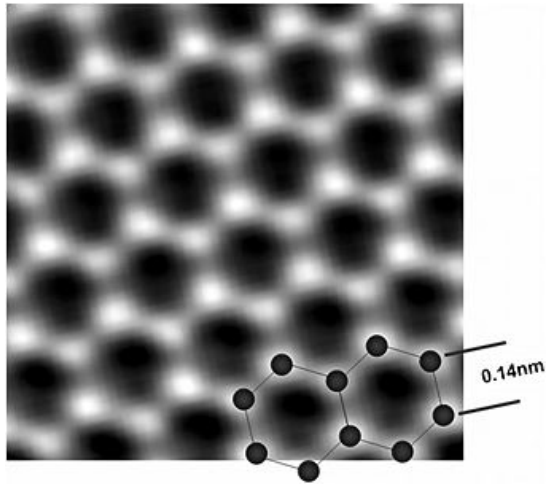


2010 Nobel Physics Prize !!!

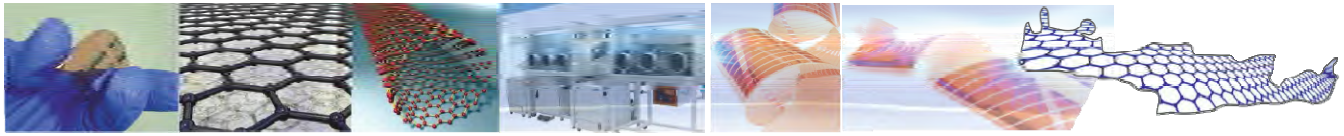
"for groundbreaking experiments regarding the two-dimensional material graphene"



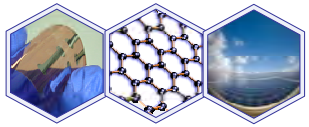
Molecular structure of graphene



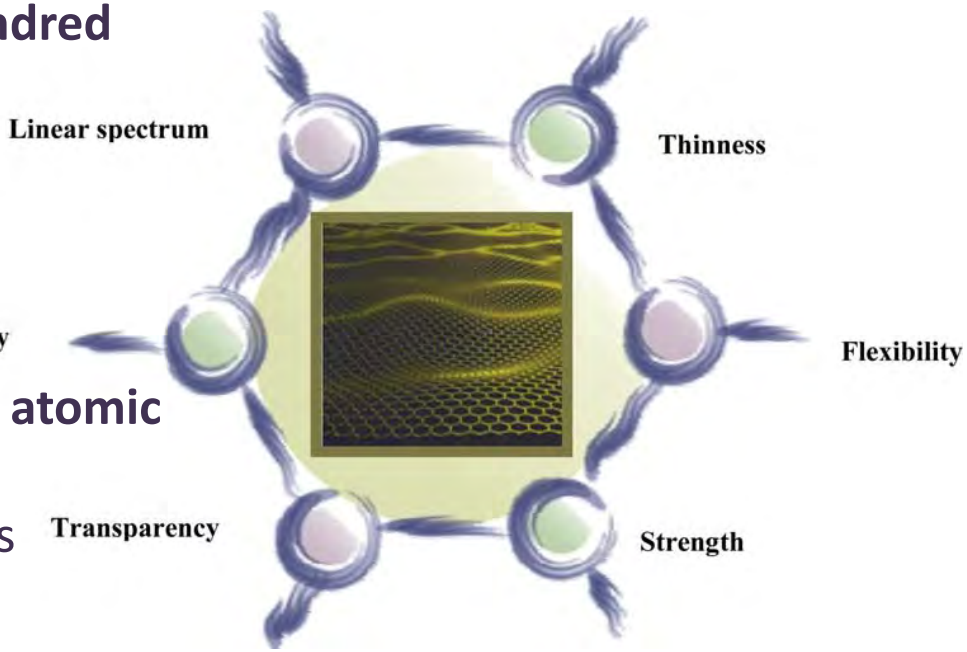
High resolution transmission electron microscope images (TEM) of graphene

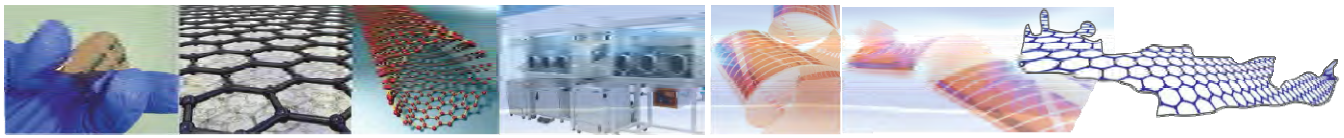


What is so special about Graphene?



- ✓ **Atomically thin sheet of carbon**
  → flexible, light, abundant material
- ✓ **Electrical mobility that is several hundred times that of Si**
  → potential for fast electronics
- ✓ **Transparent conductor**
  → can combine electrical and optical functionalities
- ✓ **Long spin coherence time due to low atomic weight**
  → potential for spintronic applications
- ✓ **The strongest material we know**
  → lightweight composites
- ✓ **New material with unique properties**
  → ”graphene is probably the only system where ideas from quantum field theory can lead to patentable innovations”





Electronic structure of graphene

Effective mass (related with 2nd derivative of E(k)) ➔ Massless Graphene charged particle is massless Dirac fermion.

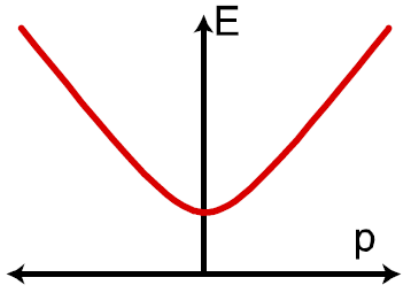
➔ **Zero gap semiconductor or Semi-metal**

Massive Particle (e.g. electron)

$$E = \sqrt{(mc^2)^2 + (cp)^2}$$

Nonrelativistic limit (v<<c)

$$E \approx mc^2 + \frac{p^2}{2m} + \ldots$$

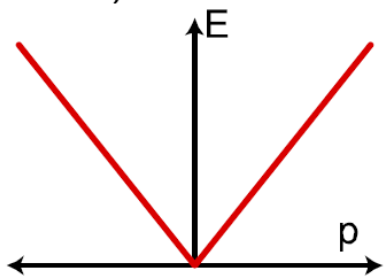


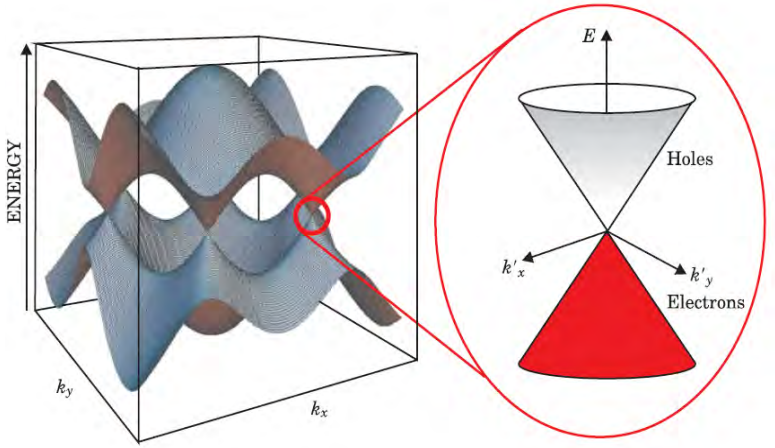
Massless Particle (e.g. photon)

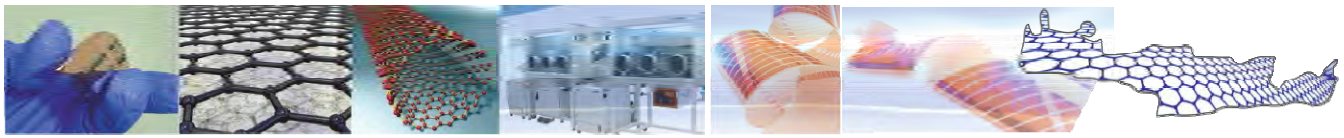
$$m = 0$$

$$E = c\,|\,p\,|$$

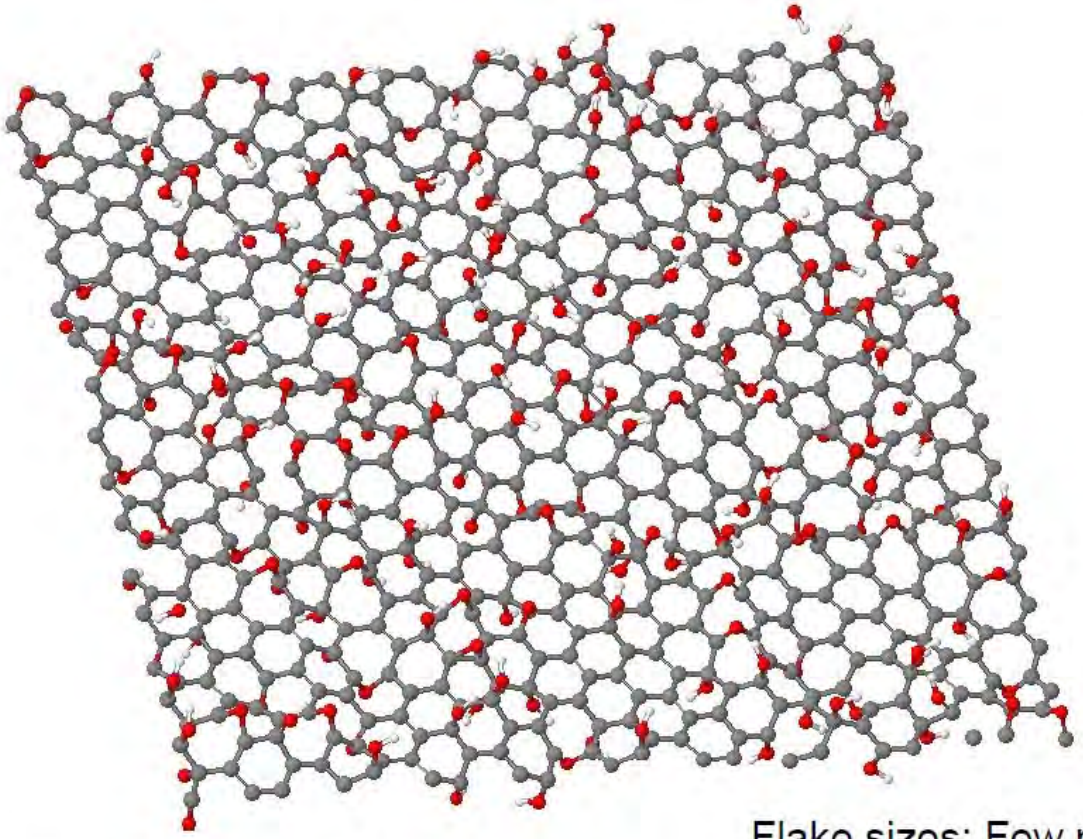
$$v = c$$

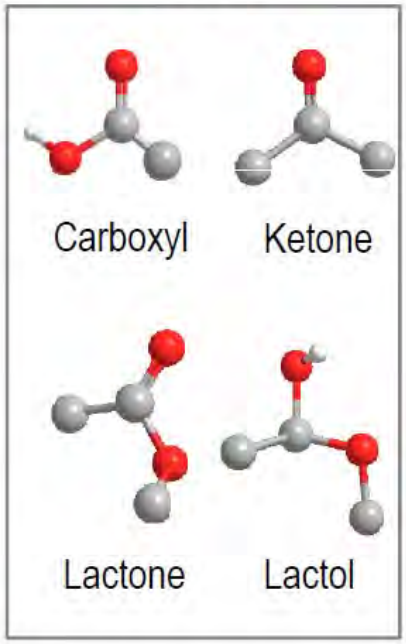






Graphene Oxide structure

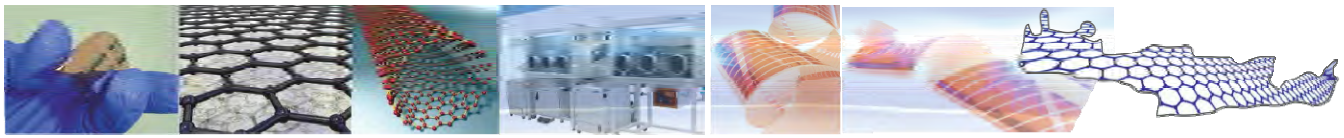




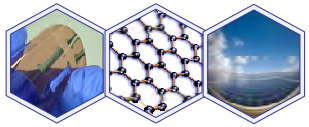
Flake sizes: Few microns up to 100μm.

1. As- Synthesized GO: sp^3 = 60%
2. Solution Processable
3. Can be produced in ton quantities

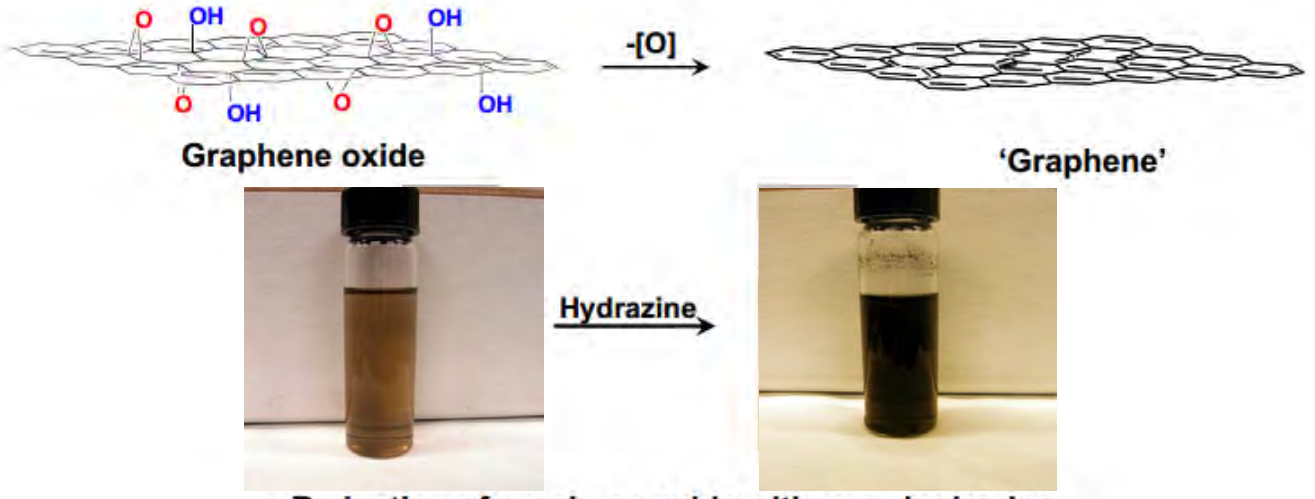
Nature Chemistry 2, 581 (2010)

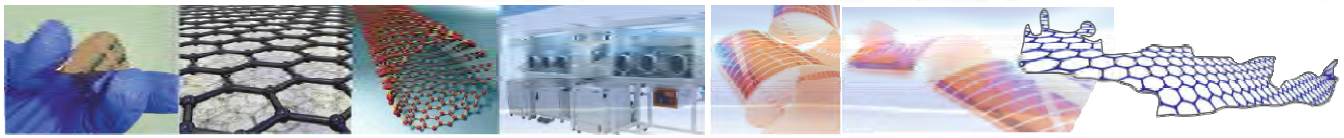


Reduction Approach

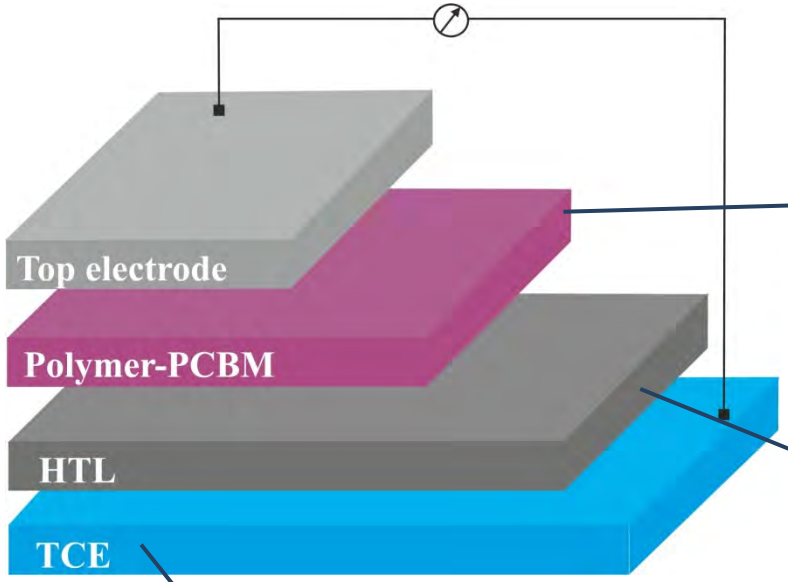


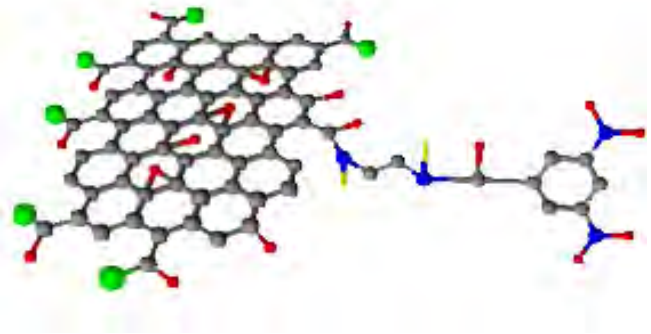
- Graphene oxide sheets are not electrically conductive
- Reduction (de-oxygenation) can be employed to partially restore the graphene network



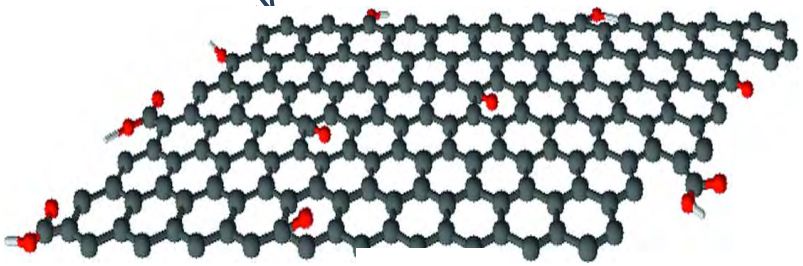


Graphene in OPVs

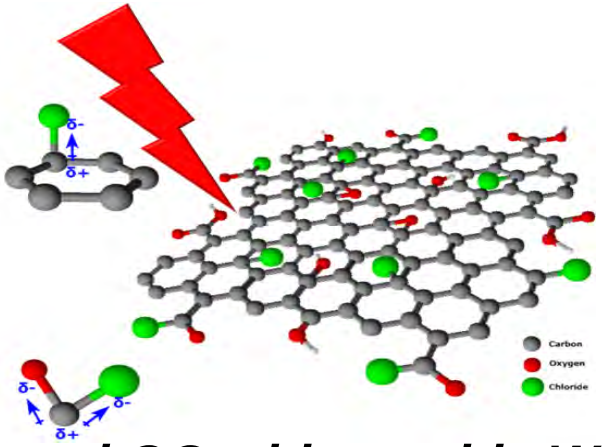




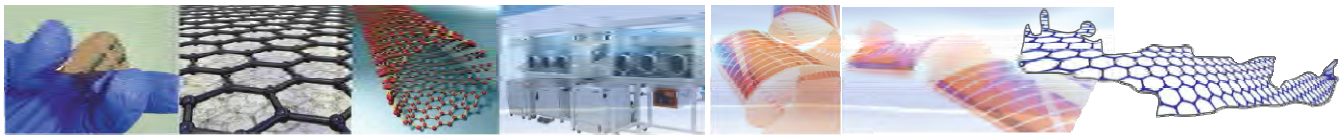
Functionalized GO



rGO



Doped GO with tunable WF



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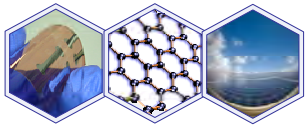
Graphene in OPVs



Disadvantages of ITO

- Expensive

The cost of indium due to its scarcity and the low throughput deposition process

- Brittleness (not flexible)

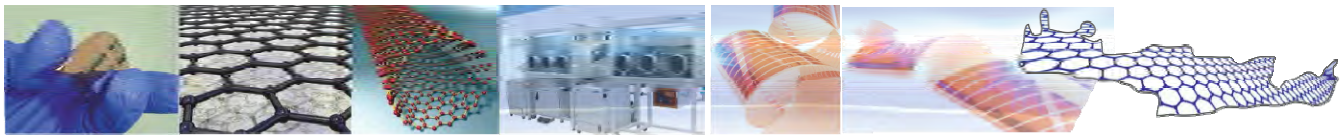
Metal oxides such as ITO (about 150 nm thick to ensure electrical performance) are brittle and therefore of limited use on flexible substrates

- Metal Diffusion

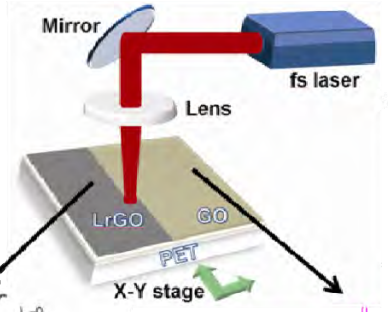
Indium is known to diffuse into the active layers of OLEDs, which leads to a degradation of performance over time

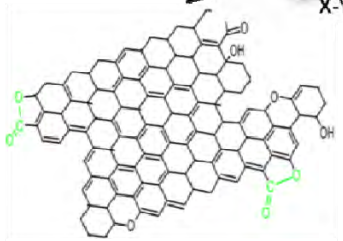
Looking for other transparent electrodes….

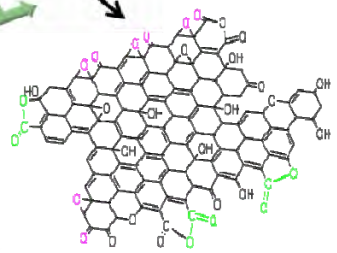
C.Petridis et.al. Nanoscale Horizons,1, 375 – 382, 2016

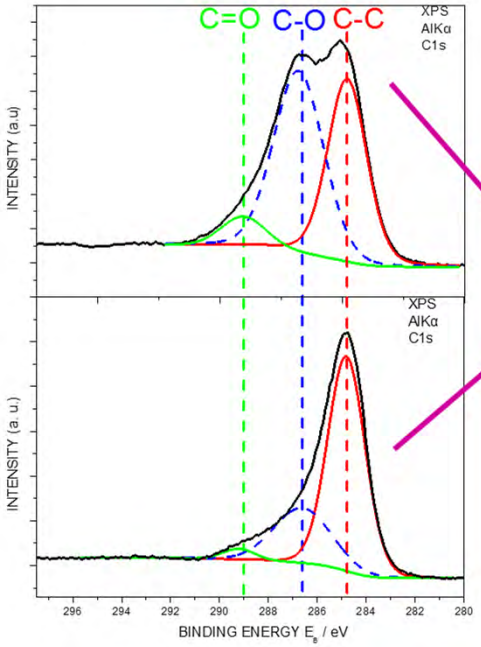


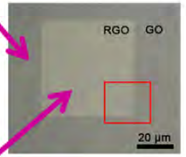
Pulsed laser in-situ GO reduction

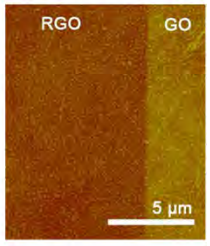


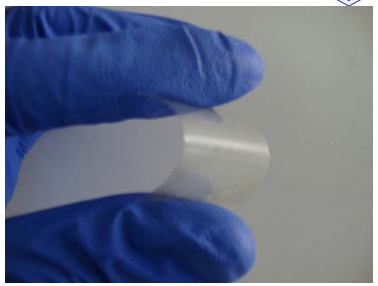


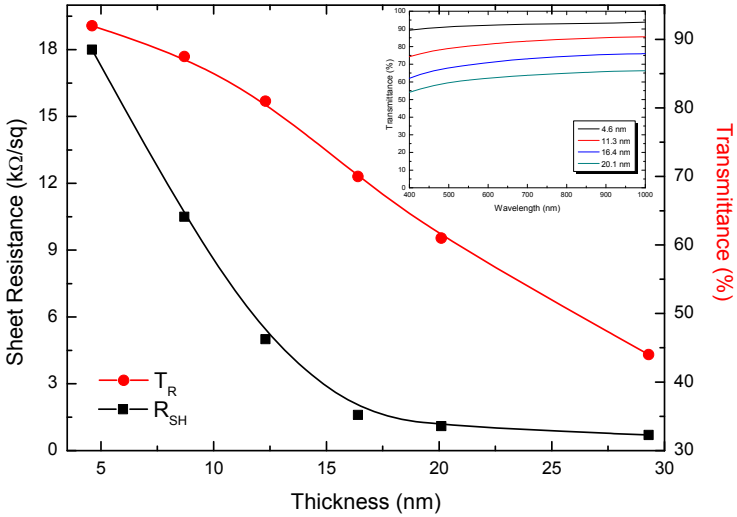






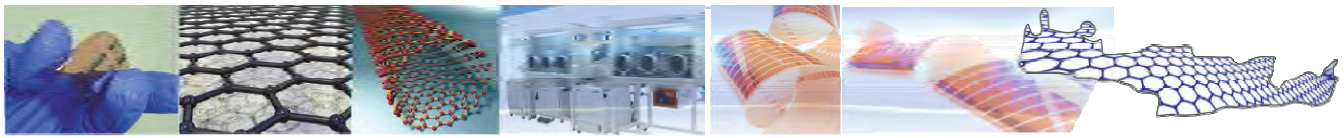






- ✓ Chemically exfoliated graphite can be solution processed into graphene-like thin films
- ✓ Graphene oxide (GO) can be effectively in-situ reduced by ultrafast UV fs laser irradiation
- ✓ Flexible OPVs were successfully demonstrated on spin coated transparent conductive rGO with a comparable performance

Advanced Functional Materials (2013) 23, 2742-2749



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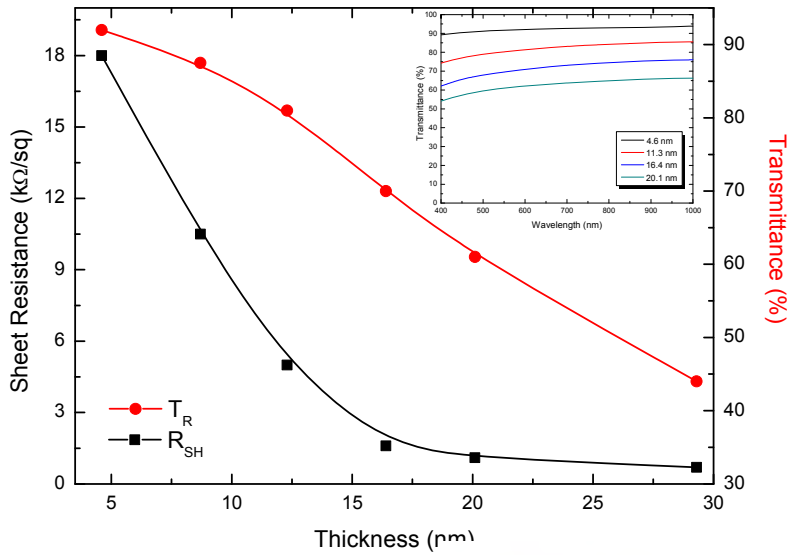
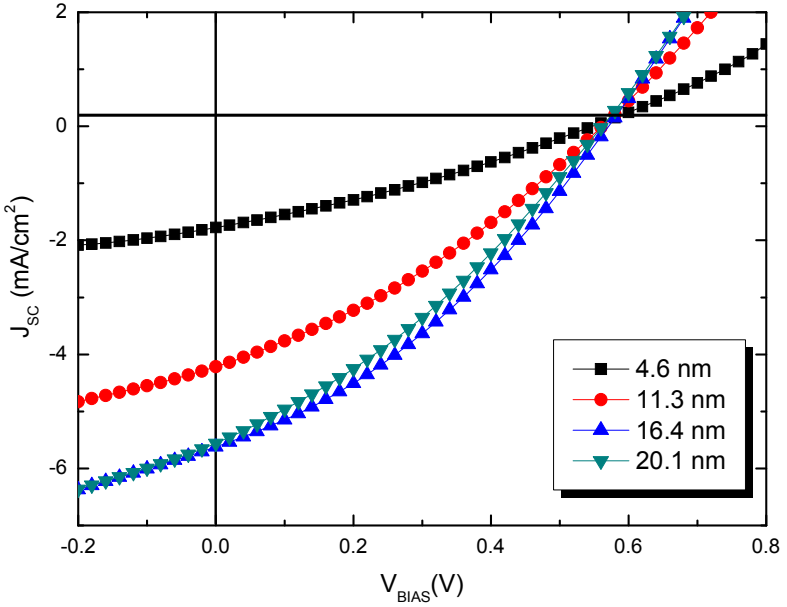
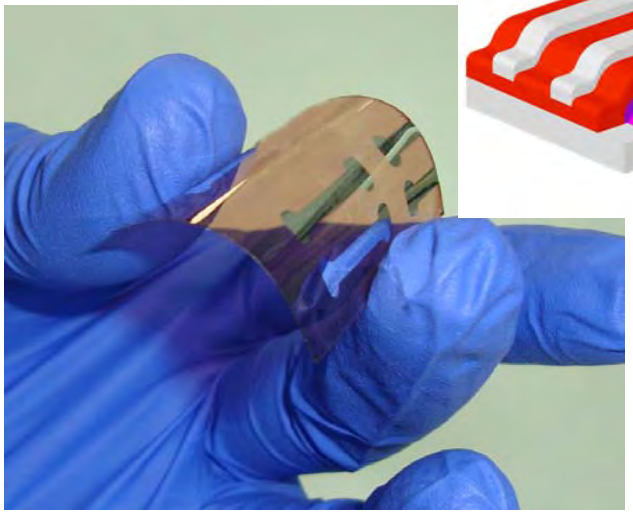
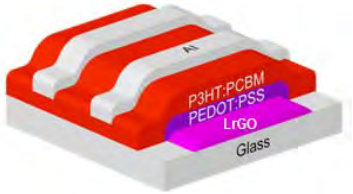
Flexible OPVs with Spin Coated Transparent Graphene Electrodes Reduced by Laser Irradiation



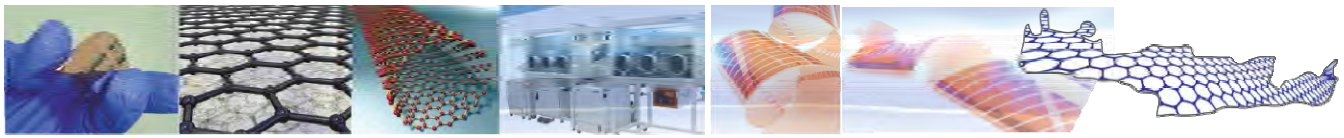






GO thickness (nm)	J_{SC} (mA/cm^2)	V_{OC} (V)	FF	η (%)
4.6	1.77	0.55	0.30	0.29
11.3	4.22	0.57	0.32	0.76
16.4	***5.62***	***0.57***	***0.34***	***1.1***
20.1	5.56	0.57	0.32	1.01

Advanced Functional Materials (2013) 23, 2742-2749



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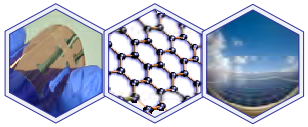
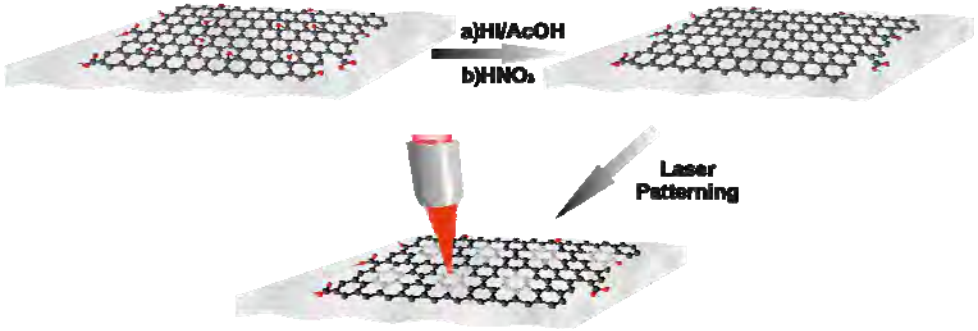
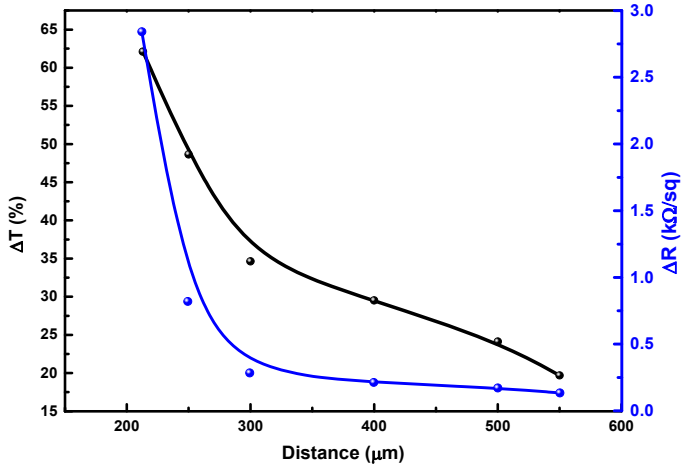
Laser induced rGOMMs as TCE in OPVs

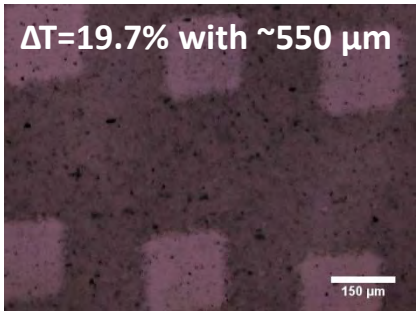


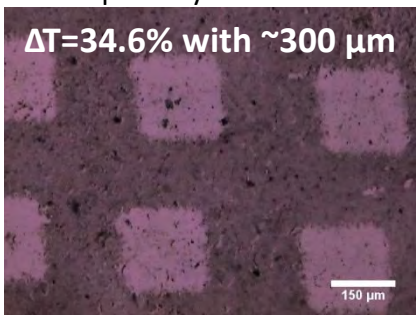
✓ A laser-based patterning technique, compatible with flexible substrates, for the production of reduced graphene oxide micromesh (rGOMM) electrodes

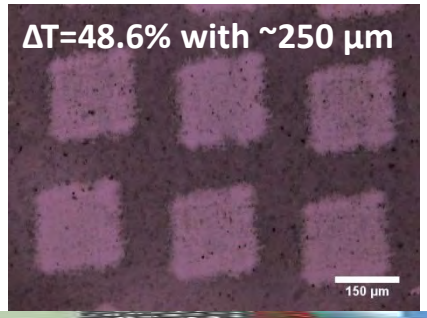


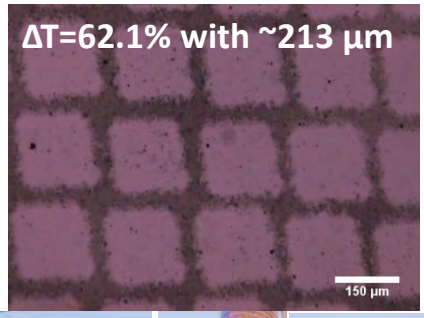


➔By controlling the periodicity, the transparency can be tuned

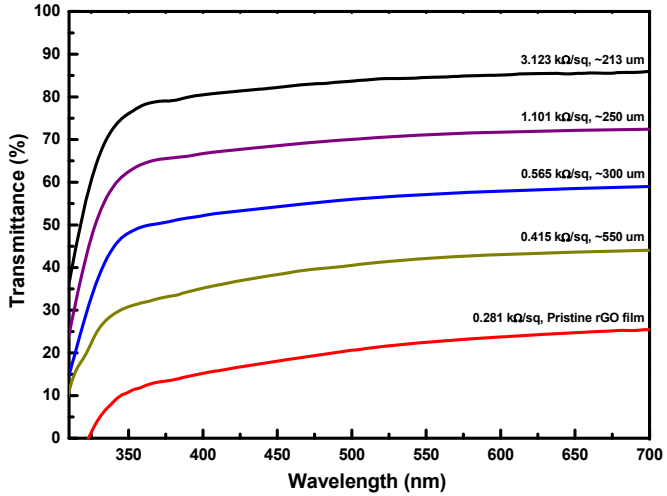


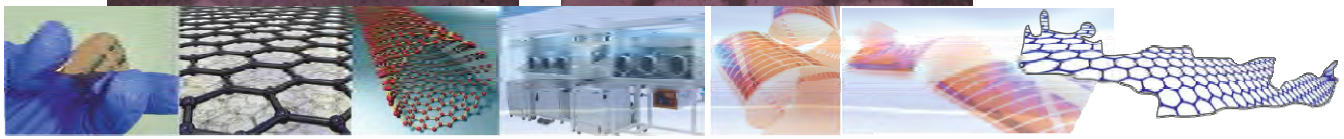






➔Starting with ~20% T, subsequent T increases were achieved, reaching the highest value of ~85%.





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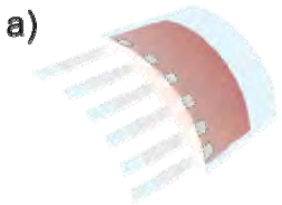
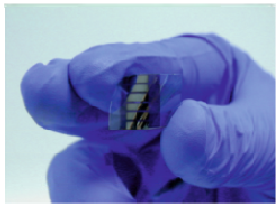
Laser indu

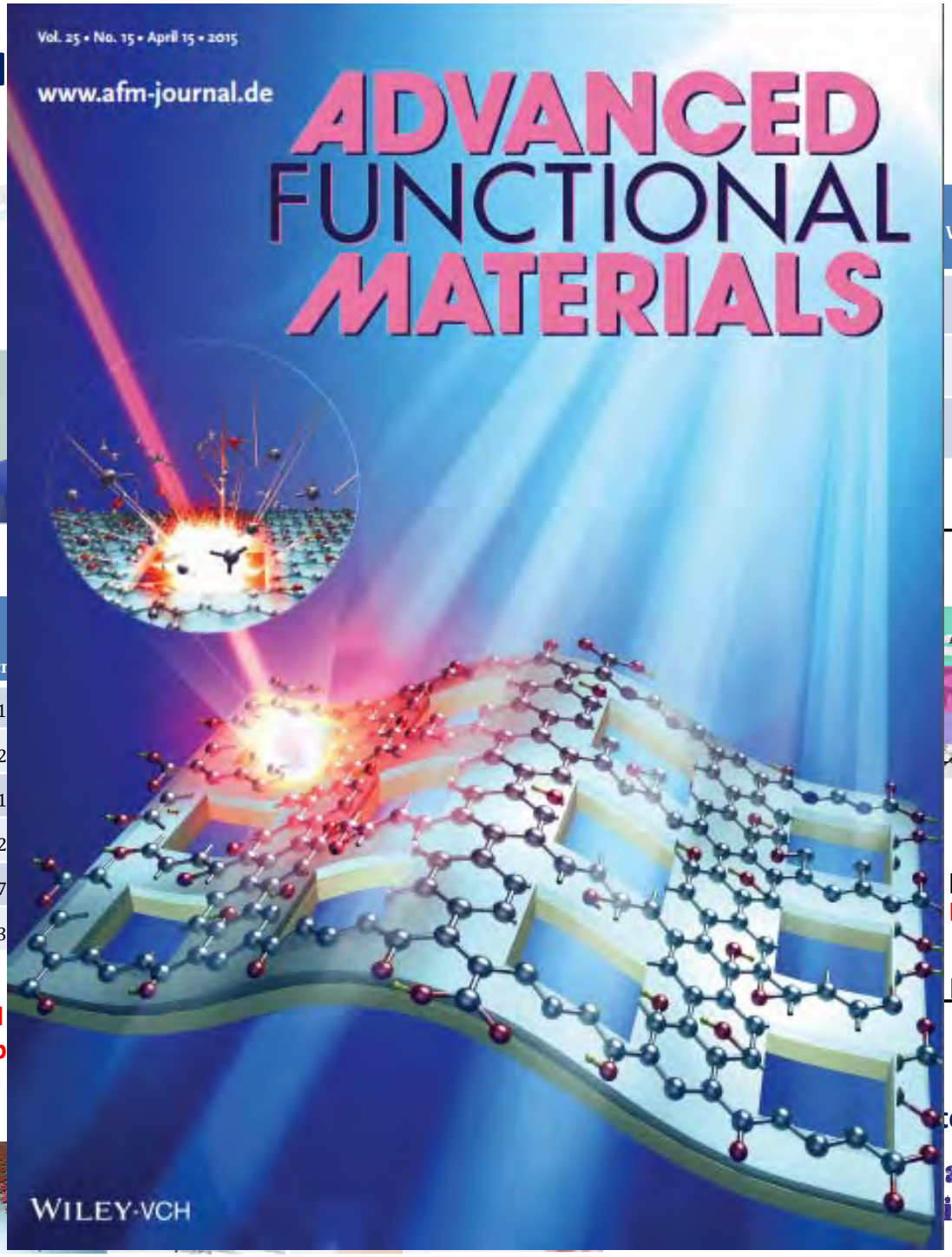


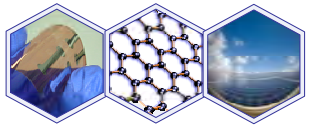


PET/rGOMM (T, R_s)	J_{sc} (mA/cr
22.5%, 0.281 kΩ/sq	4.51
42.2%, 0.415 kΩ/sq	6.52
57.1%, 0.565 kΩ/sq	7.81
71.1%, 1.101 kΩ/sq	3.72
84.6%, 3.123 kΩ/sq	2.37
PET/ITO	8.93

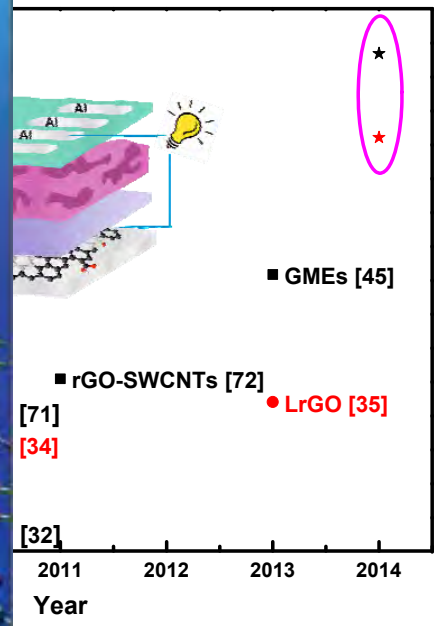
PCE of 3.05 %

✓ **Highest ever reported processed graphene-b**





V_{oc} (mV)	FF (%)	PCE (%)
848	45.9	3.05
846	38.9	1.79
831	33.2	1.07



erials (2015), 25, 2213-2221

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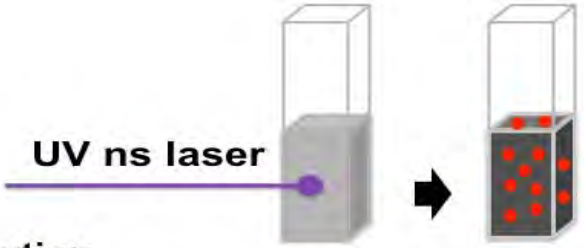
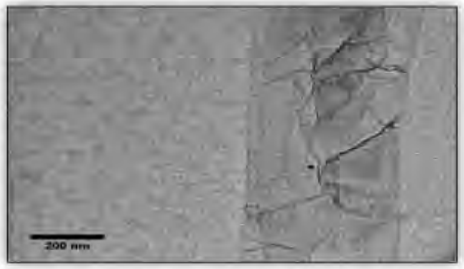
Laser induced Plasmonic rGOMMs as TCE in OPVs

KrF Excimer laser, 248 nm
Pulse duration ~ 20 ns
Single laser pulses



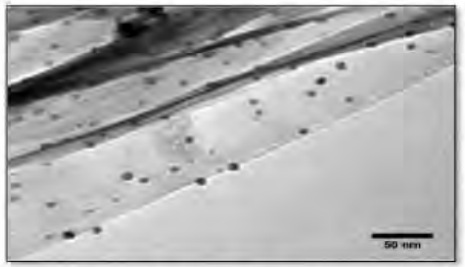
GO flakes + $AgNO_3$ or $HAuCl_4$ solution

➔ This method involves the irradiation of 2D pristine materials solutions with chloroauric acid ($HAuCl_4$) or silver nitrate ($AgNO_3$) with short duration UV laser pulses. UV photons absorption activates the surface of the nanosheets and Au/Ag ions are reduced only on the surface of the nanosheet.

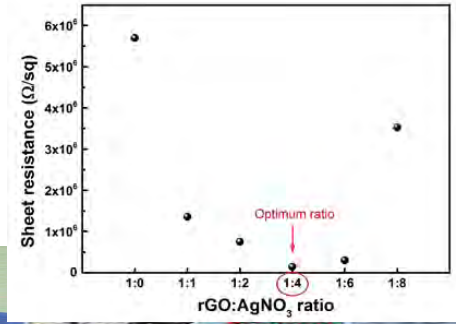


GO flakes-pristine solution

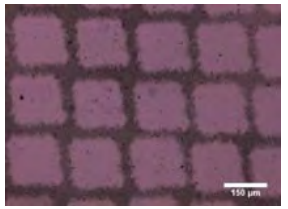
GO flakes-Au NPs, laser fluence: 100 mJ/cm²

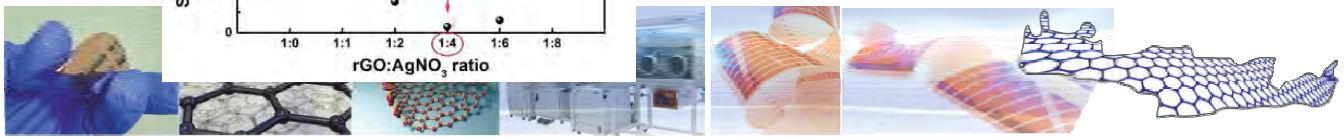


GO flakes-Ag NPs, laser fluence: 100 mJ/cm²



➔ Loading graphene flakes with Ag NPs reduces the sheet resistance over an order of magnitude.





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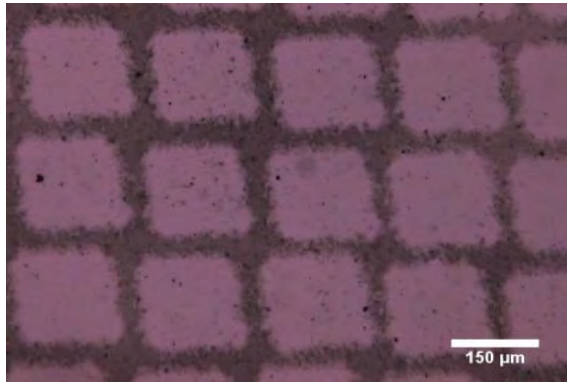
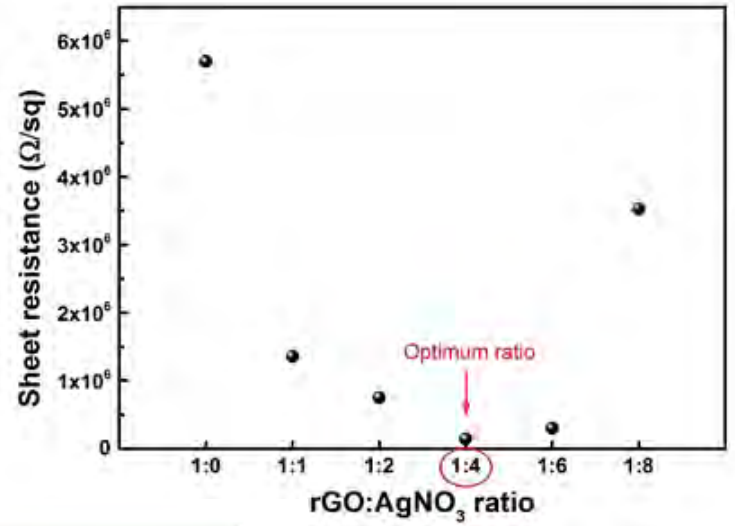
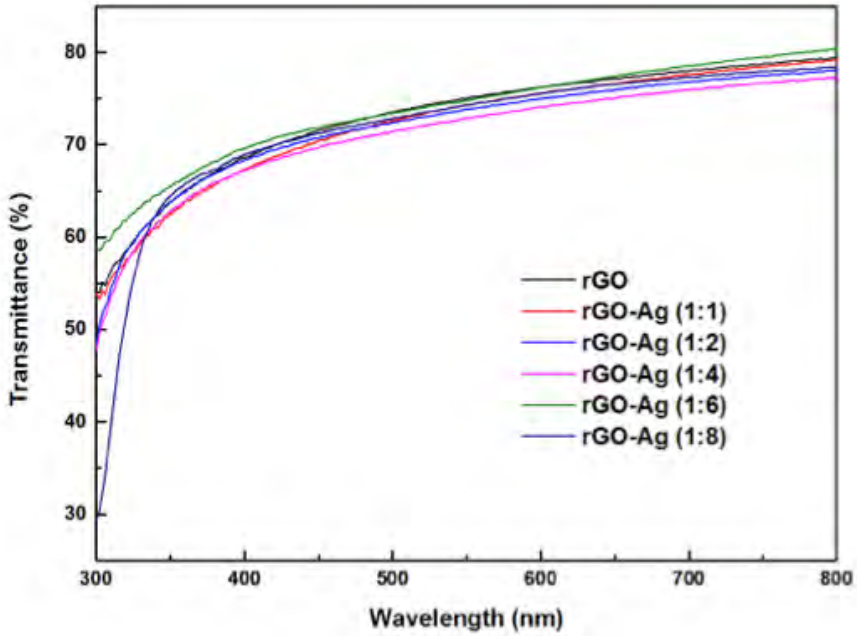
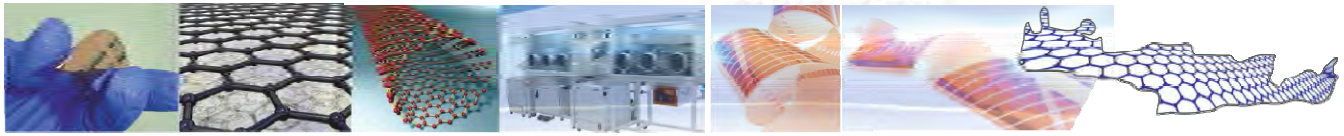
Laser induced Plasmonic rGOMMs as TCE in OPVs









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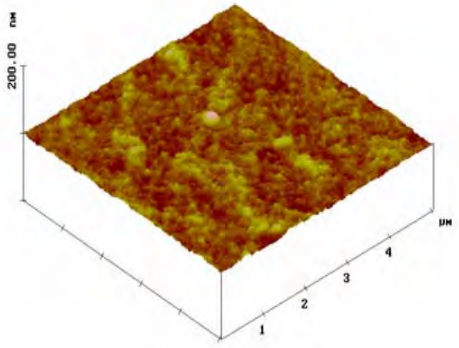
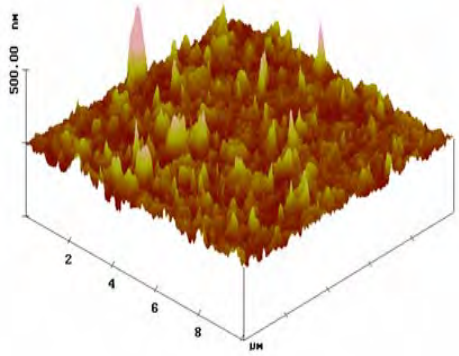
Laser induced Plasmonic rGOMMs as TCE in OPVs

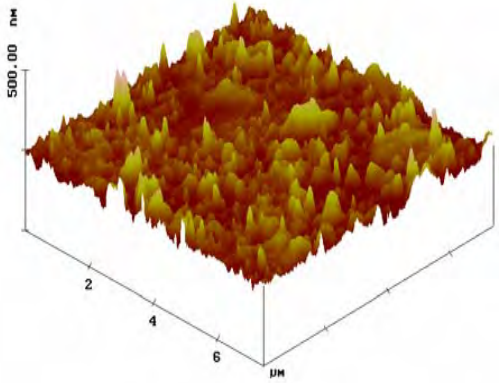
rGO rms = 1.587nr



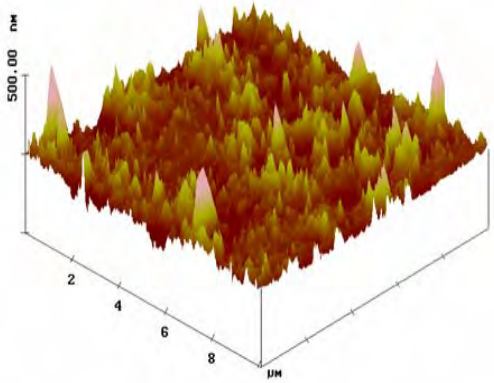
rGO-Ag (1:1) rms = 17.39



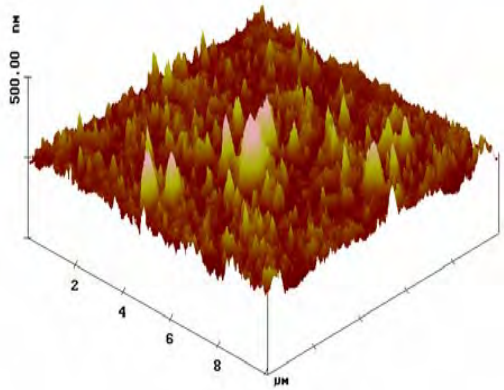
rGO-Ag (1:2) rms = 18.613nm



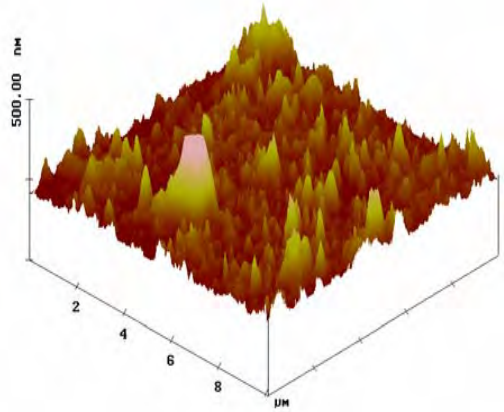
rGO-Ag (1:4) rms = 21.447nm



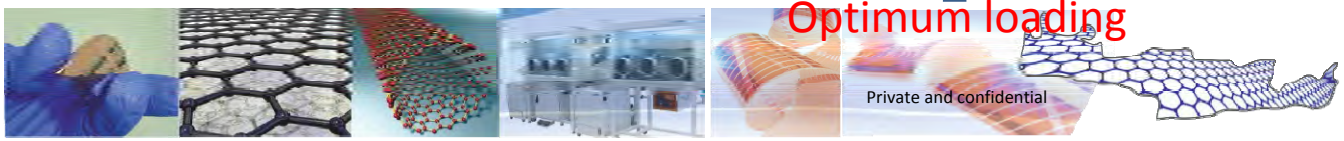
rGO-Ag (1:6) rms = 23.142



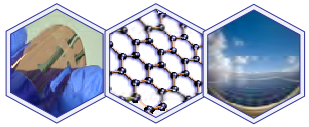
rGO-Ag (1:8) rms = 29.133nm



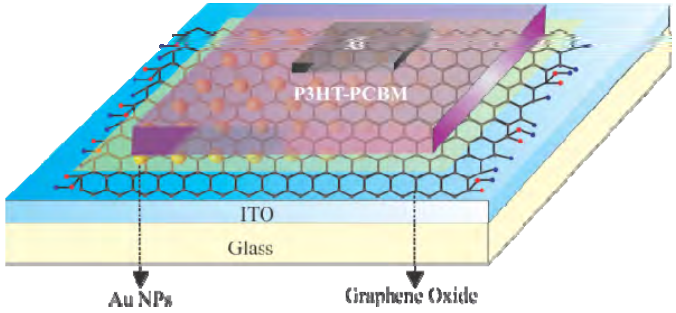
Optimum loading



Graphene based HTL

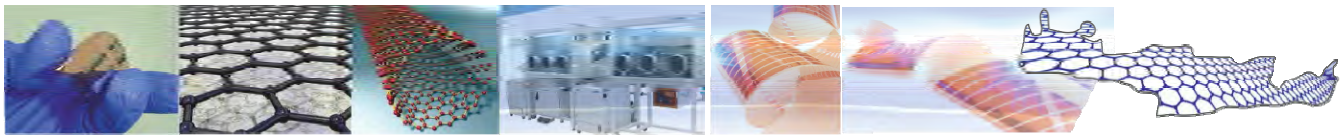


Material	Device Structure	PCE	Used as	Ref.
GO	ITO/GO/P3HT:PCBM	3.6%	HTL	ACS Nano (2010), 4, 3169
pr-GO	ITO/pr-GO/P3HT:PCBM/Ca/Al	3.63	HTL	Adv. Mater. (2011), 23, 4923
GO-SWCNTs(1:0.2)	ITO/GO:SWCNTs/P3HT:PCBM/Ca/Al	4.10	HTL	Adv. Energy Mater. (2011), 1, 1052
GO & CO-Cs	ITO/GO/P3HT:PCBM/GO-Cs/Al	3.67	HTL & ETL	Adv. Mater. (2012), 24, 2228
GO & Au NPs	**ITO/GO/Au_NPs/P3HT:PCBM/Al**	**2.9**	**HTL**	**Nanoscale (2013), 5, 4144**
GO-Cl	**ITO/GO-Cl/PCDTBT:PCBM/TiOx/Al**	**6.56**	**HTL**	**Nanoscale (2014), 6, 6925**

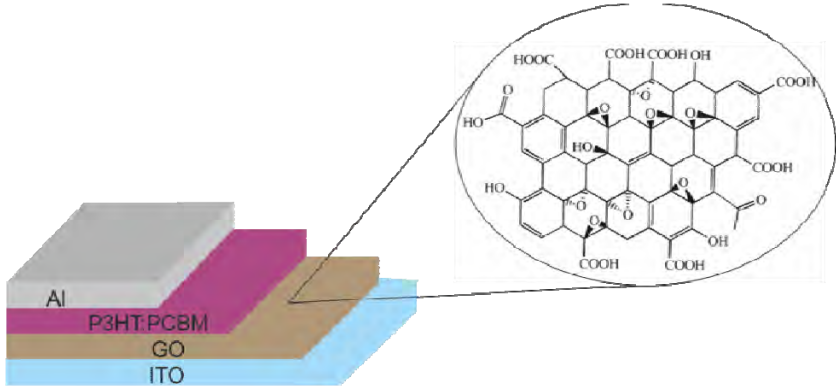


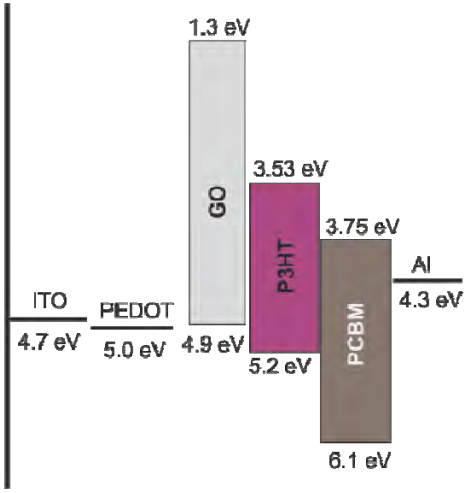
- The plasmonic GO-based devices exhibited a performance enhancement by 30% compared to the devices using the traditional PEDOT:PSS layer.
- They preserved 50% of their initial PCE after ***45 hrs of continuous illumination, contrary to the PEDOT:PSS-based ones that die after 20 hrs***

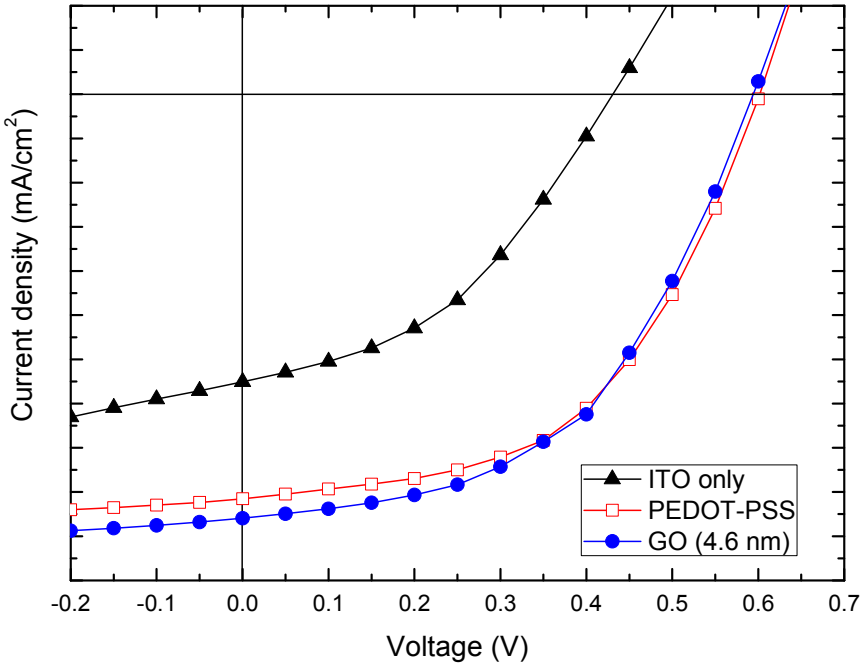
- ***Main reason ➔ Stability improvement***



Photovoltaic Devices - GO replacing PEDOT







HTL	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF (%)	PCE (%)
ITO only	0.42	6.51	42.5	1.16
PEDOT:PSS	0.60	9.15	51.7	2.86
GO (2.0 nm)	0.43	6.65	36.2	1.04
GO (2.6 nm)	0.54	9.04	43.8	2.09
GO (4.3 nm)	0.60	9.59	50.7	2.90
GO (5.2 nm)	0.60	8.02	44.1	2.12

Nanoscale (2013), 5, 4144-4150

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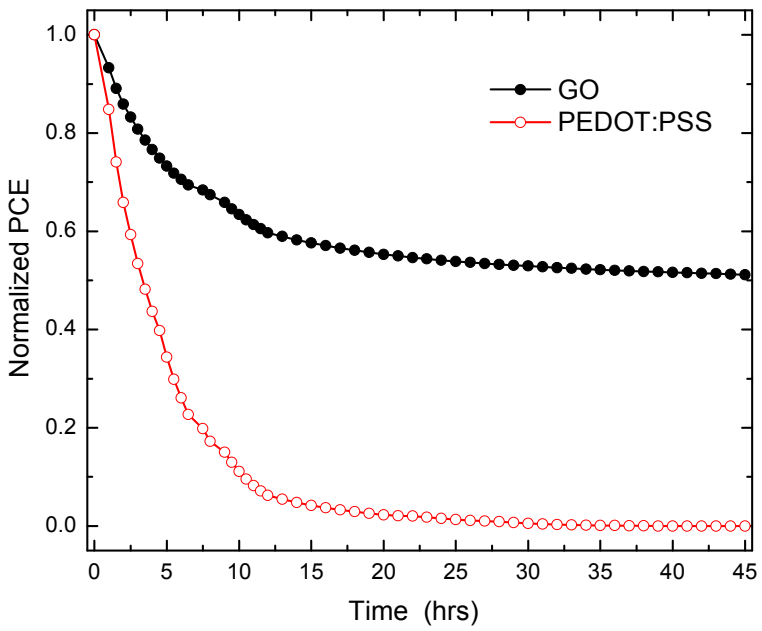
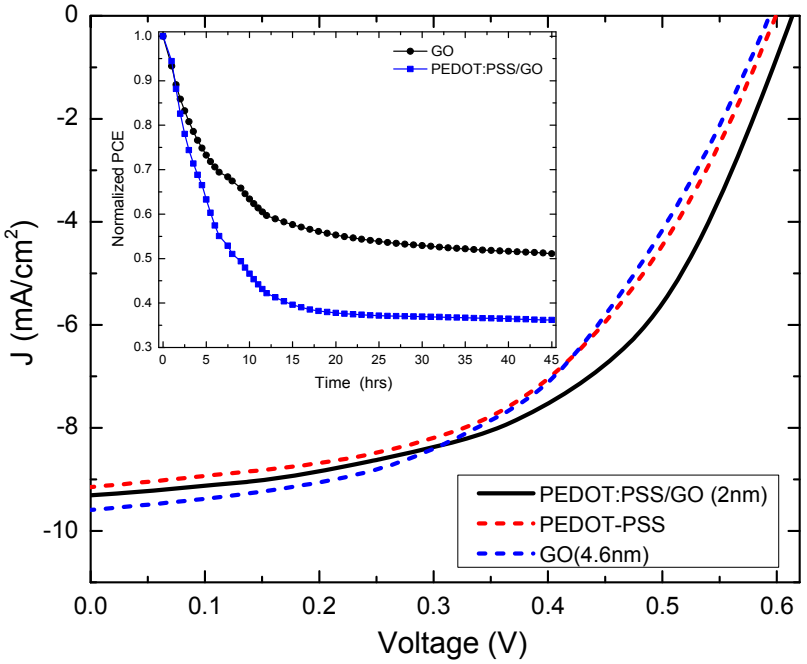
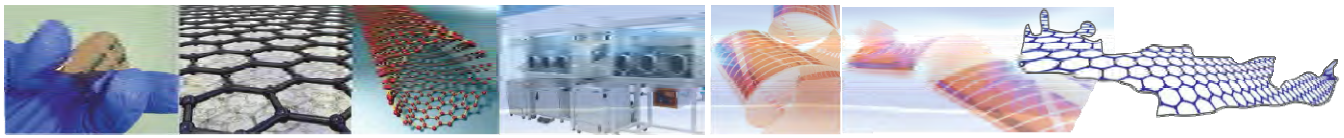
GO replacing PEDOT – Stability enhancement





- The devices with GO as the HTL preserve more than 50% of their initial efficiency after 45 hrs of continuous illumination
- The PEDOT:PSS based devices die after 20 hrs

Nanoscale (2013), 5, 4144-4150



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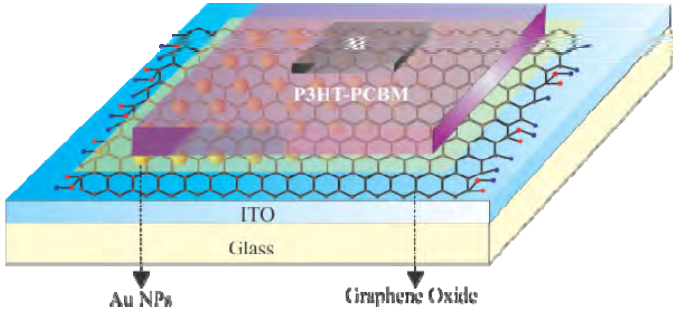
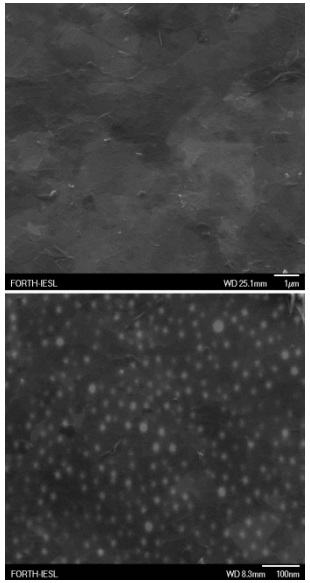
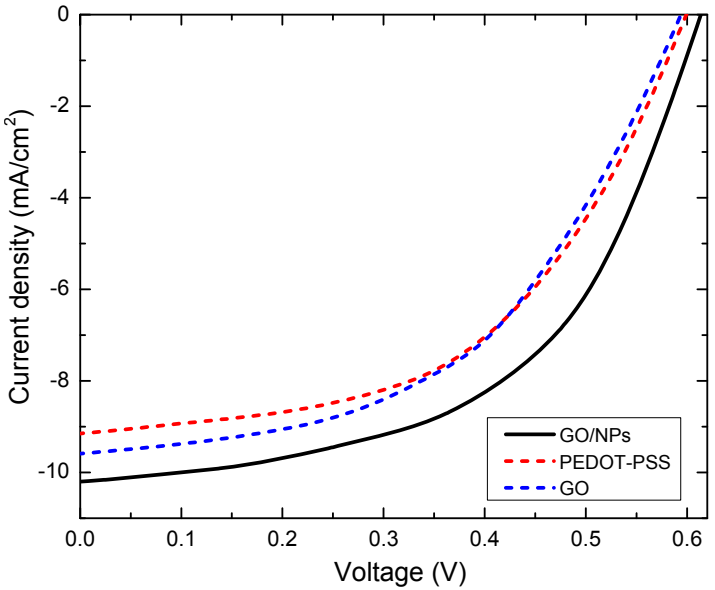
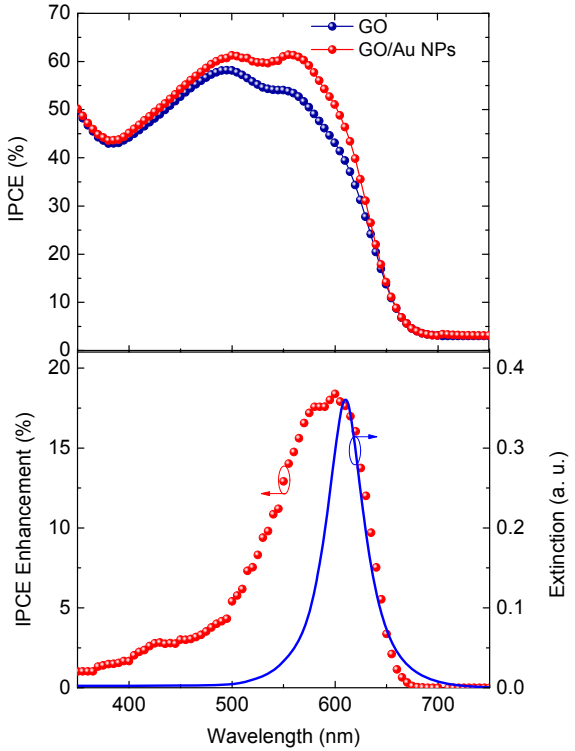
Combining Plasmonics with Graphene



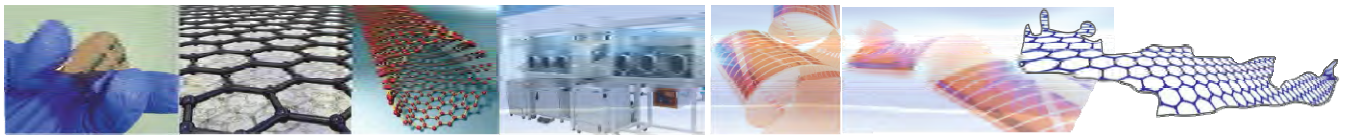






- The plasmonic GO-based devices exhibited a performance enhancement by 30% compared to the devices using the traditional PEDOT:PSS layer.
- They preserved 50% of their initial PCE after 45 hrs of continuous illumination, contrary to the PEDOT:PSS-based ones that die after 20 hrs

Nanoscale (2013), 5, 4144-4150



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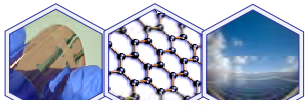
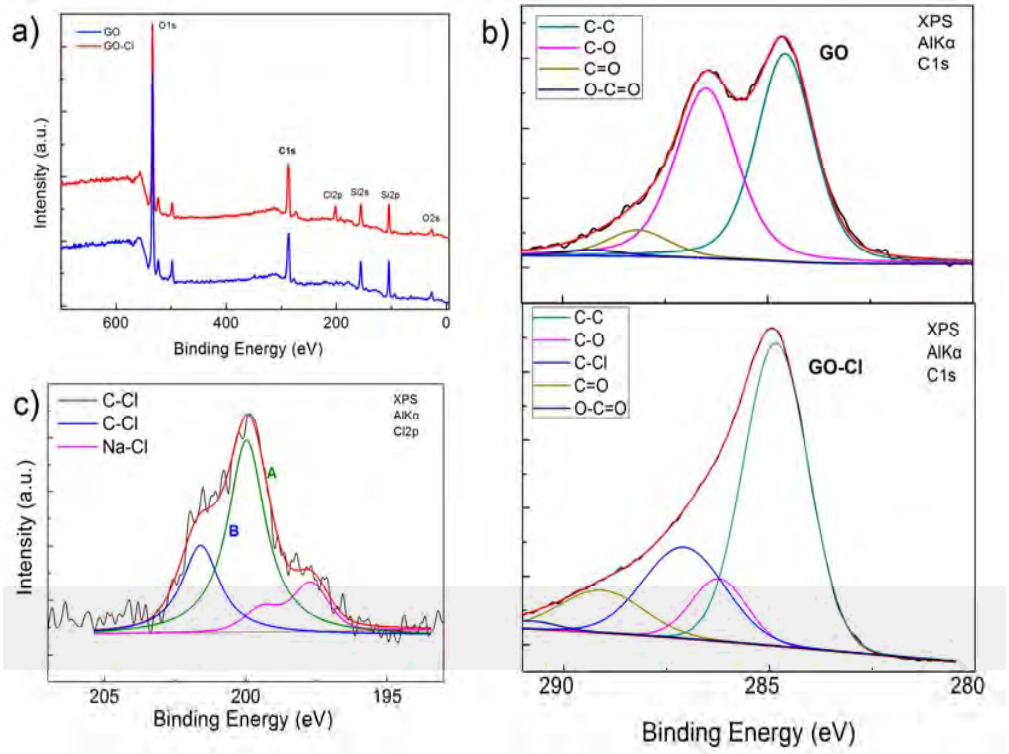
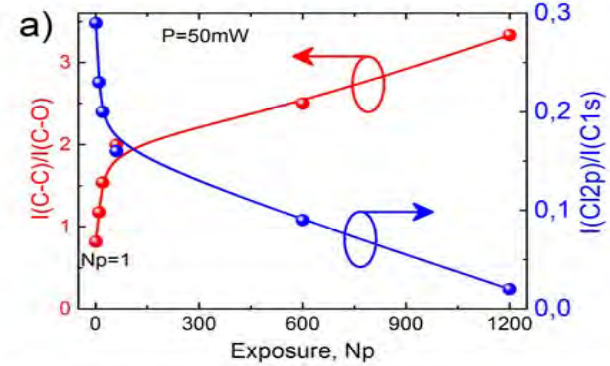
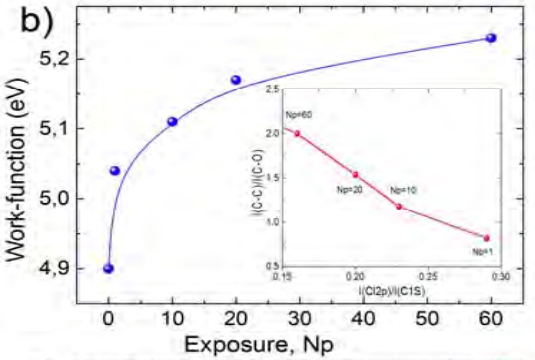
Doped GO replacing PEDOT

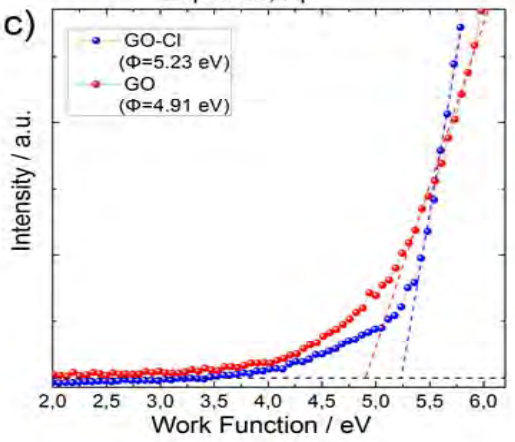


- R2r compatible photochemical method for the simultaneously partial reduction and doping of GO films through ultraviolet laser irradiation in the presence of Cl_2 precursor gas
- Photochlorination → grafting of chloride to the edges and the basal plane of GO
- Tailoring of the GO work-function from 4.9 eV to a maximum value of 5.23 eV.

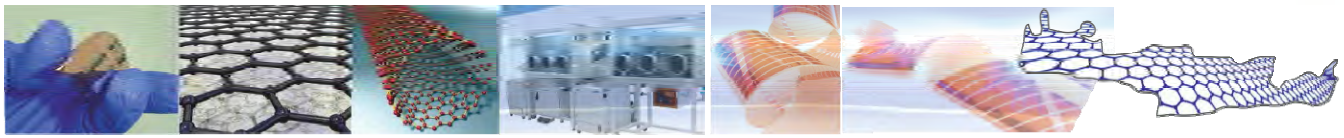








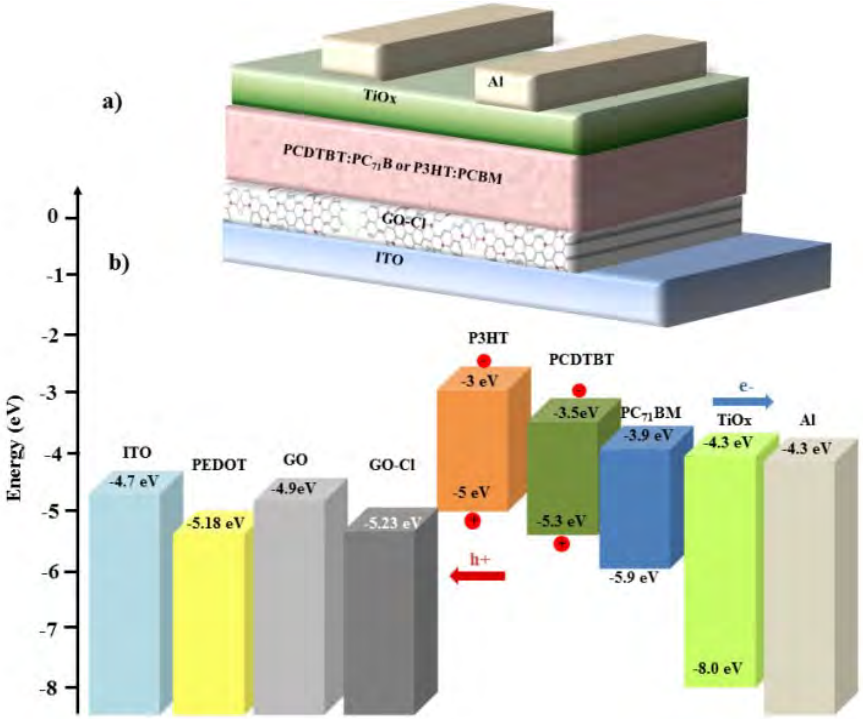
Nanoscale (2014), 6, 6925-6931

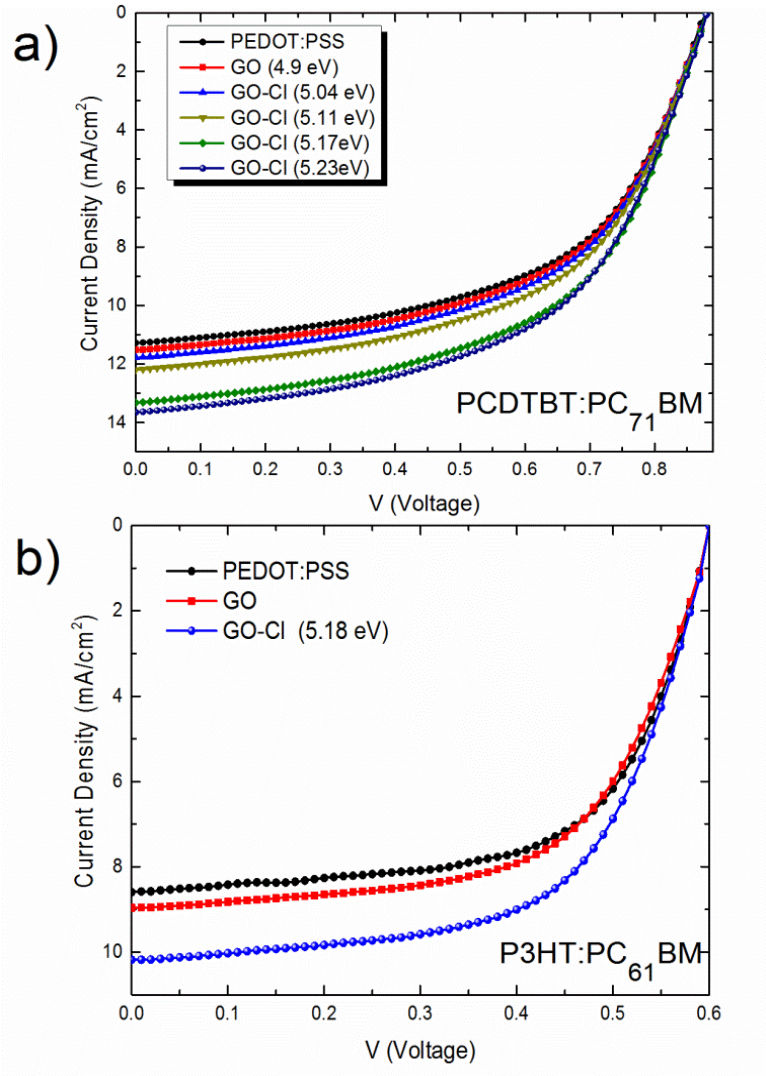


Nanomaterials & Organic Electronics Group

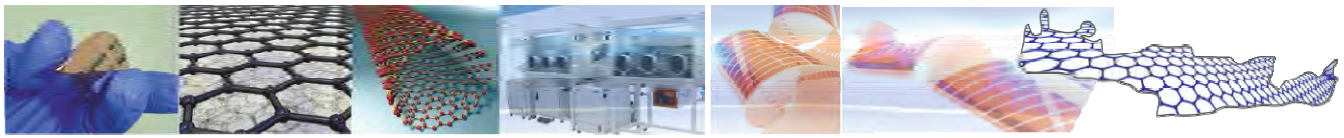
Doped GO replacing PEDOT

- OPVs with GO-Cl as the hole transporting layer (HTL) were demonstrated with power conversion efficiency (PCE) of 6.56 %
  - ✓ >14.1 than GO based OPVs
  - ✓ > 15.7 % than PEDOT:PSS based OPVs
- The performance enhancement was attributed to more efficient ***hole transportation*** due to the energy levels matching between the GO-Cl and the polymer donor.





Nanoscale (2014), 6, 6925-6931



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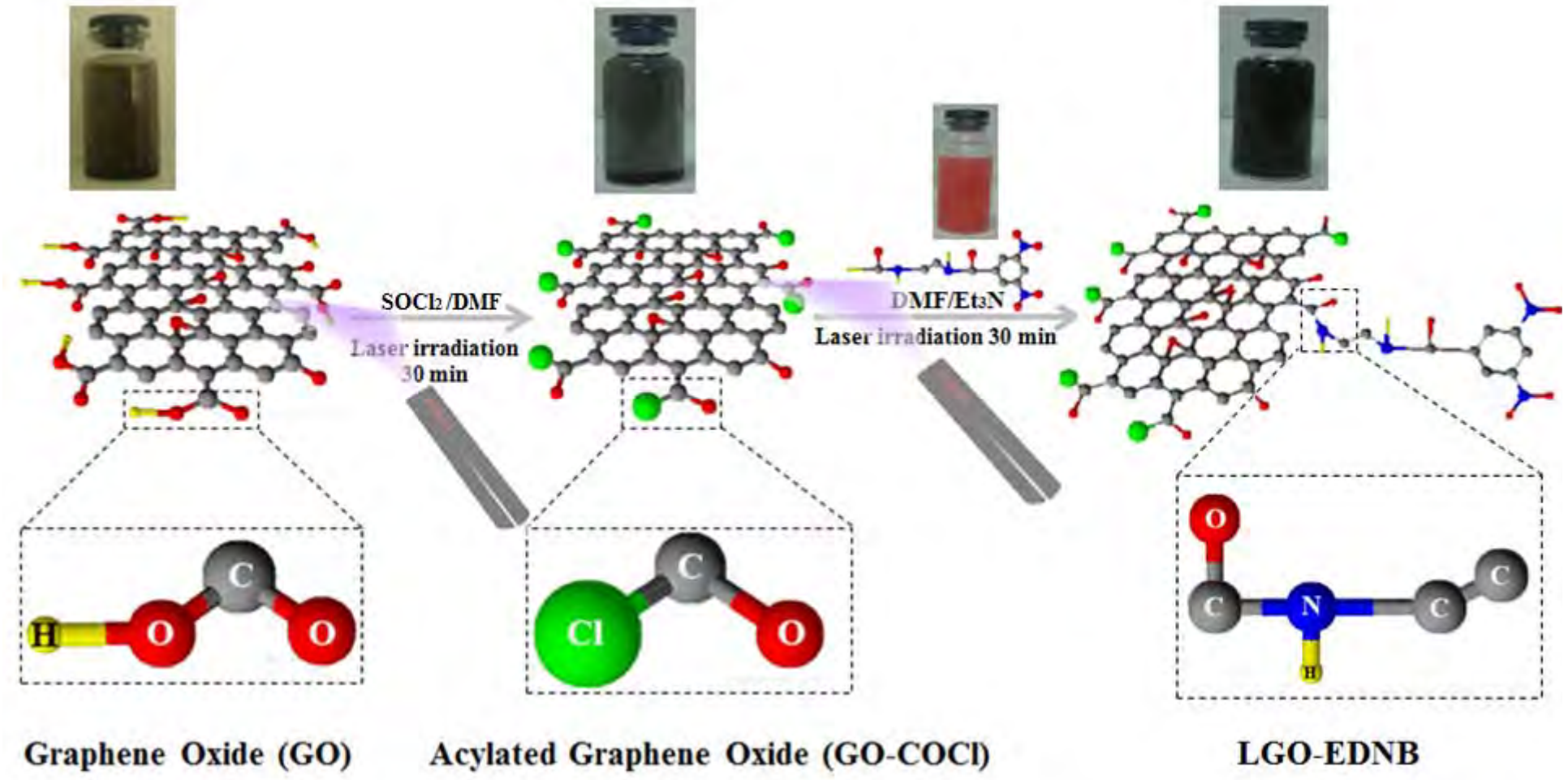
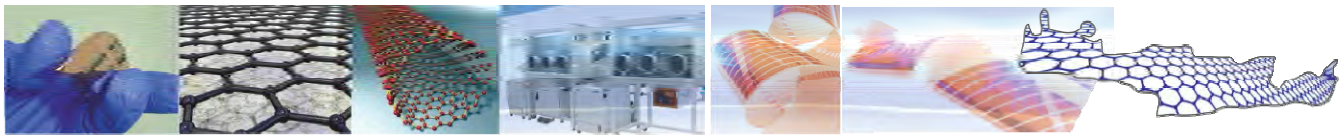
The Photochemical Synthesis

(Laser assisted)



Total time for functionalization: ~ 2 hours !!!!

Advanced Optical Materials 2015, 5, 658-666



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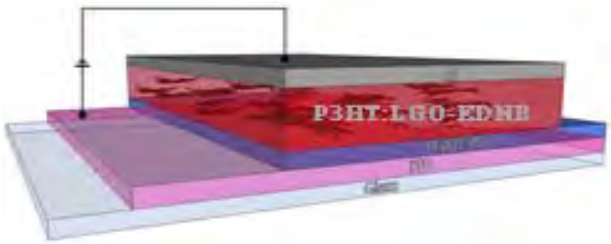
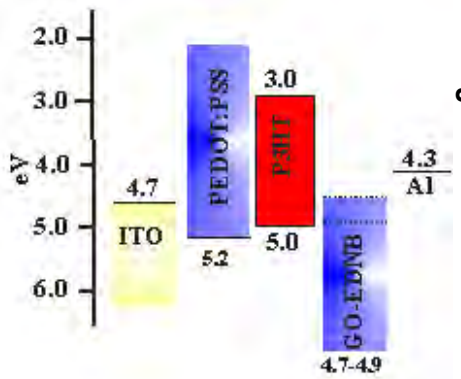
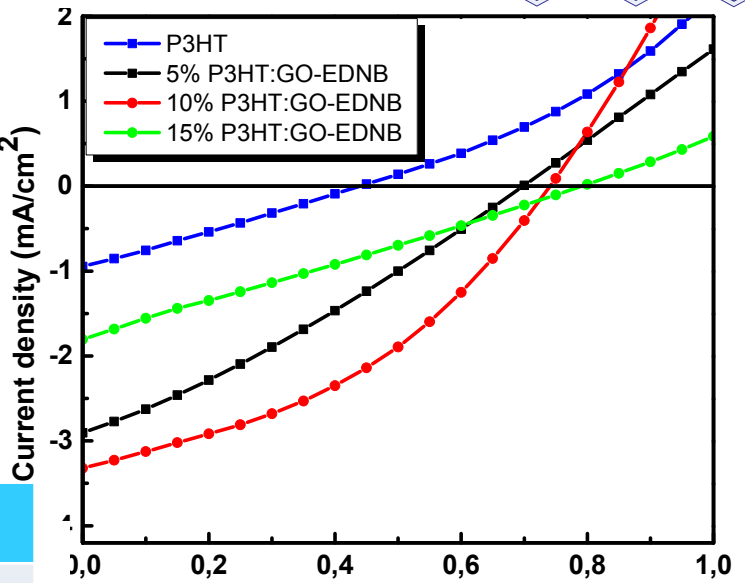
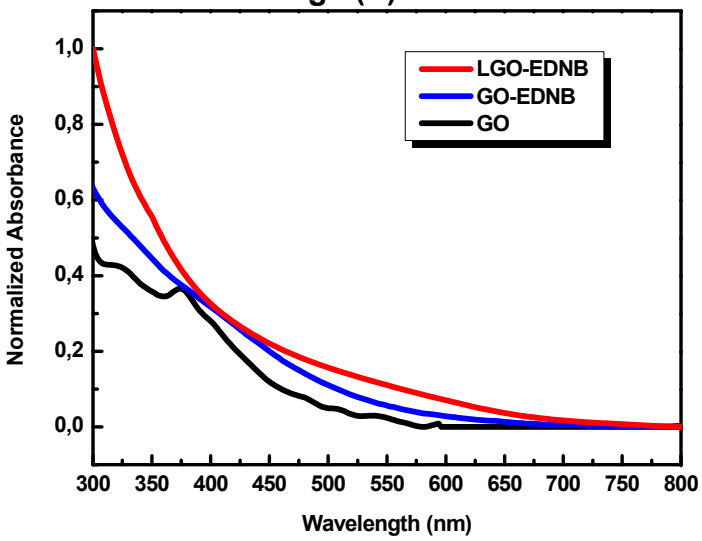
Chemical functionalization





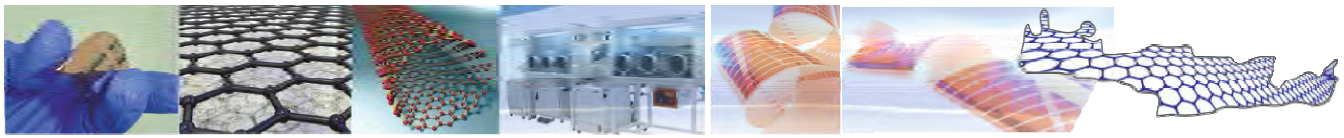


Chemically functionalized GO-EDNB	J_{sc} (mA/cm²)	V_{oc} (V)	FF (%)	PCE (%)
ITO/PEDOT:PSS/P3HT/Al	0.04	0.40	28	0.004
ITO/PEDOT:PSS/P3HT:GO-EDNB (5%)/Al	2.90	0.67	32	0.62
ITO/PEDOT:PSS/P3HT:GO-EDNB(10%)/Al	**3.32**	**0.72**	**40**	**0.96**
ITO/PEDOT:PSS/P3HT:GO-EDNB(15%)/Al	1.78	0.76	28	0.38
Photochemically functionalized LGO-EDNB				
ITO/PEDOT:PSS/PCDTBT:GO-EDNB(5%)/Al	1.99	1.1	25	0.55
ITO/PEDOT:PSS/PCDTBT:GO-EDNB(10%)/Al	3.98	1.09	31	1.34
ITO/PEDOT:PSS/PCDTBT:GO-EDNB(20%)/Al	**5.29**	**1.17**	**39**	**2.41**
ITO/PEDOT:PSS/PCDTBT:GO-EDNB(30%)/Al	2.91	1.12	29	0.95



Voltage (V)

Photochemical functionalization



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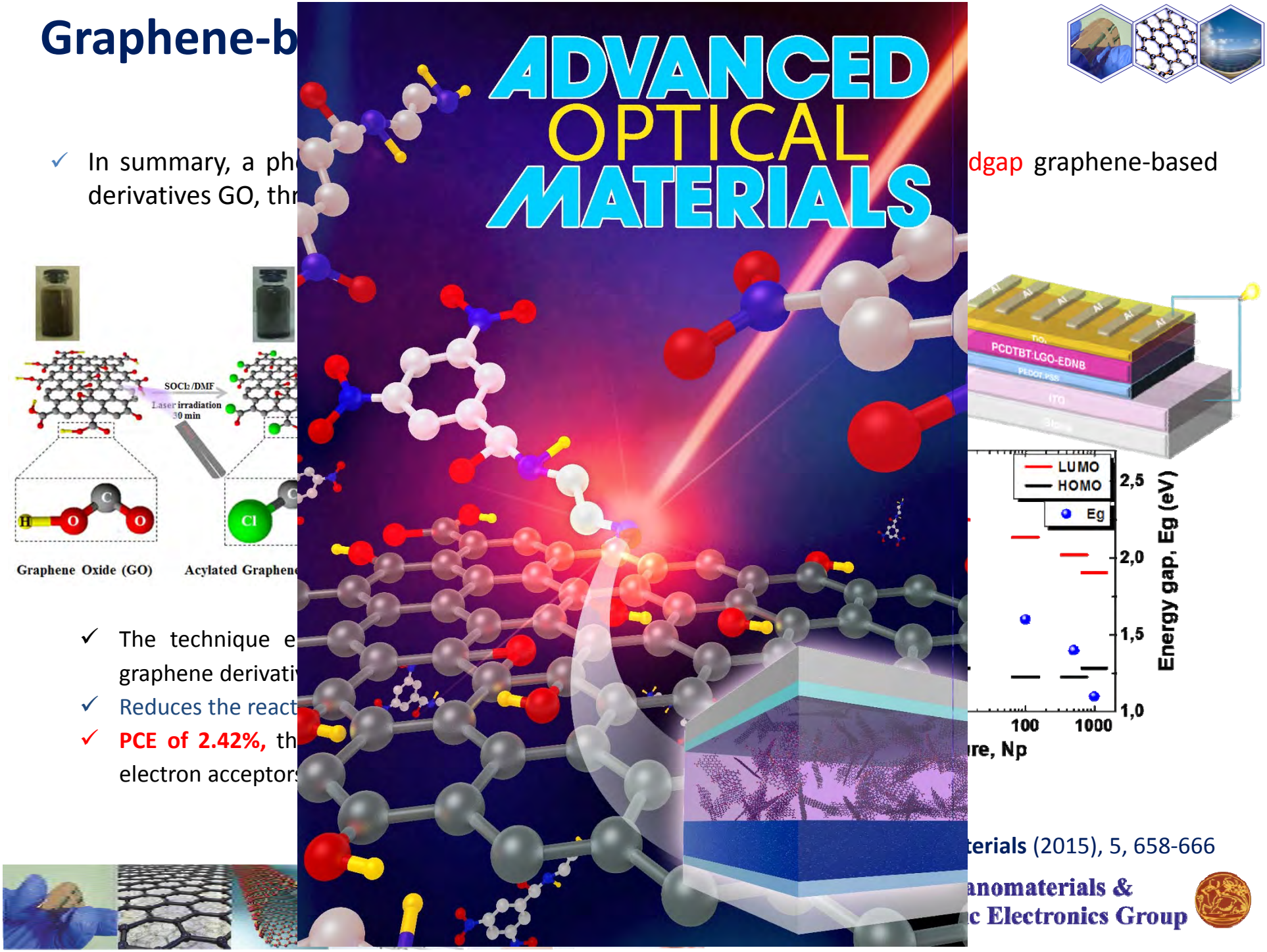
Graphene-b



- ✓ In summary, a ph dgap graphene-based derivatives GO, thr

- ✓ The technique e graphene derivati
- ✓ Reduces the react
- ✓ **PCE of 2.42%,** th electron acceptor

terials (2015), 5, 658-666

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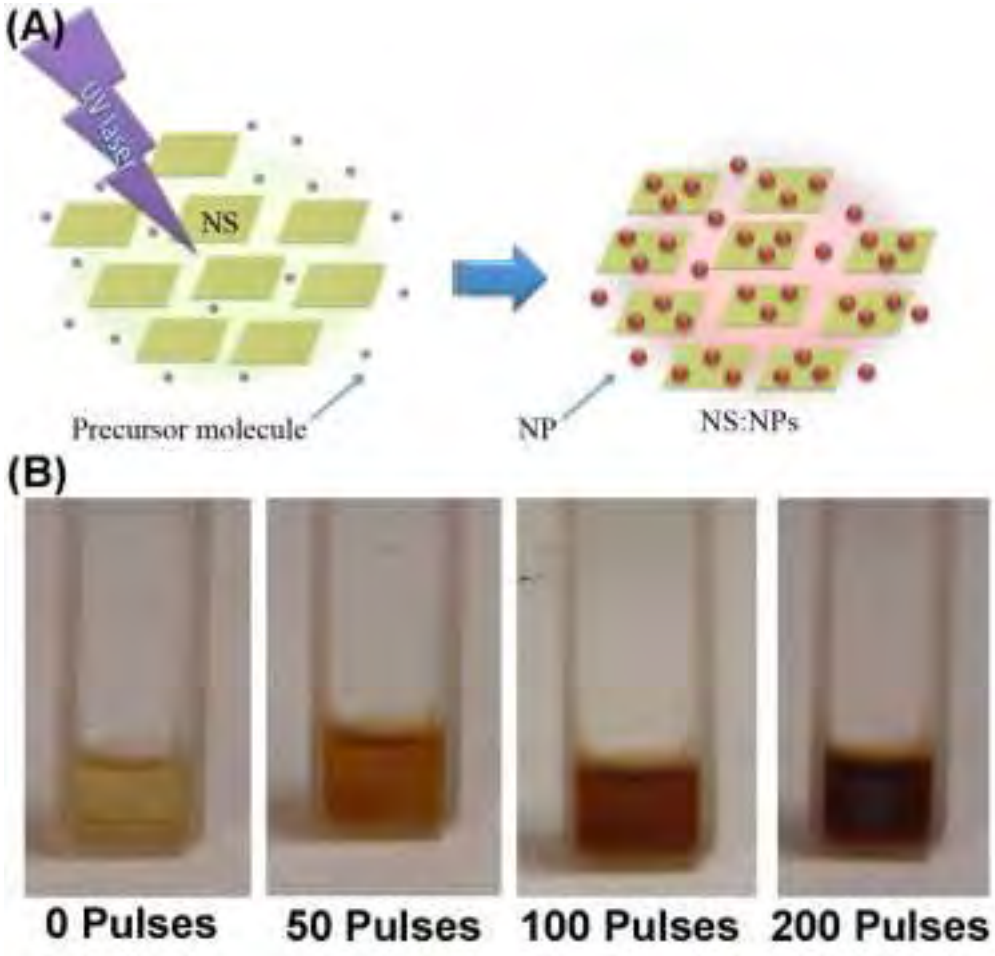
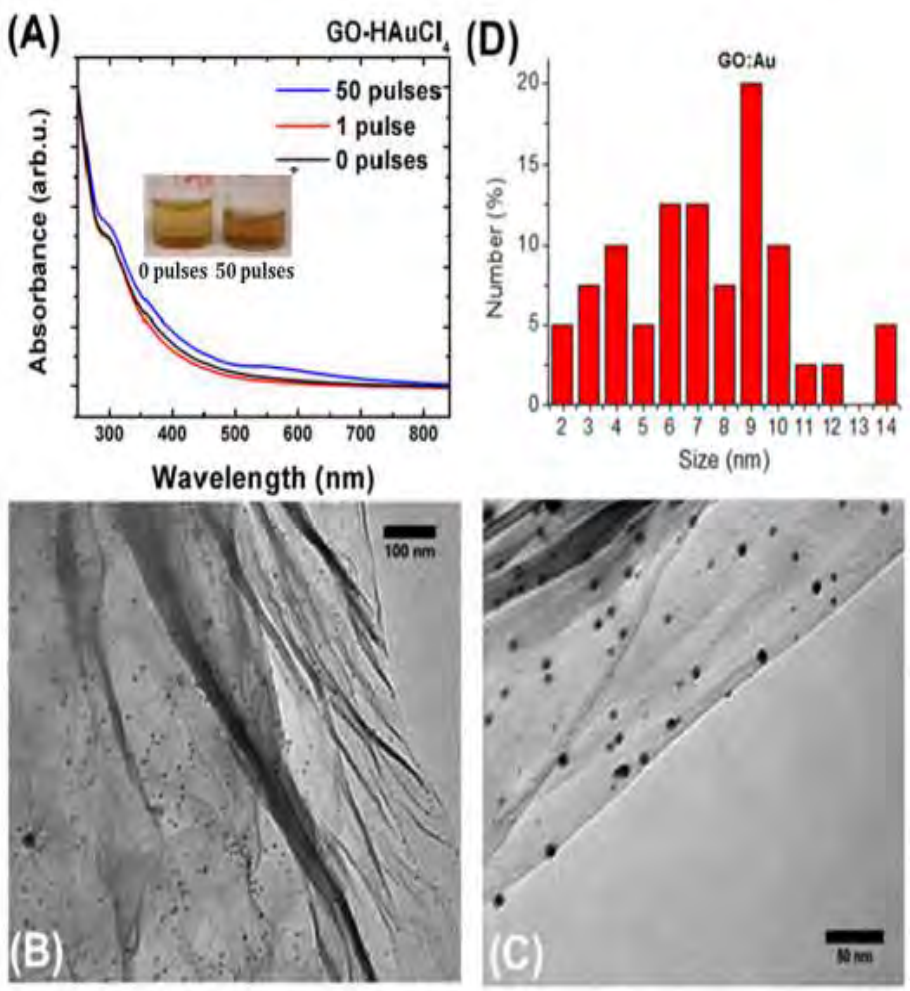
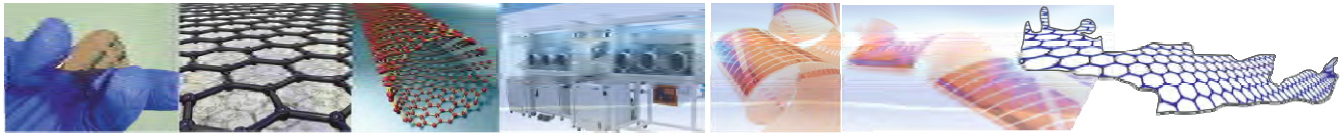
2D Materials-based additives in ternary OPVs







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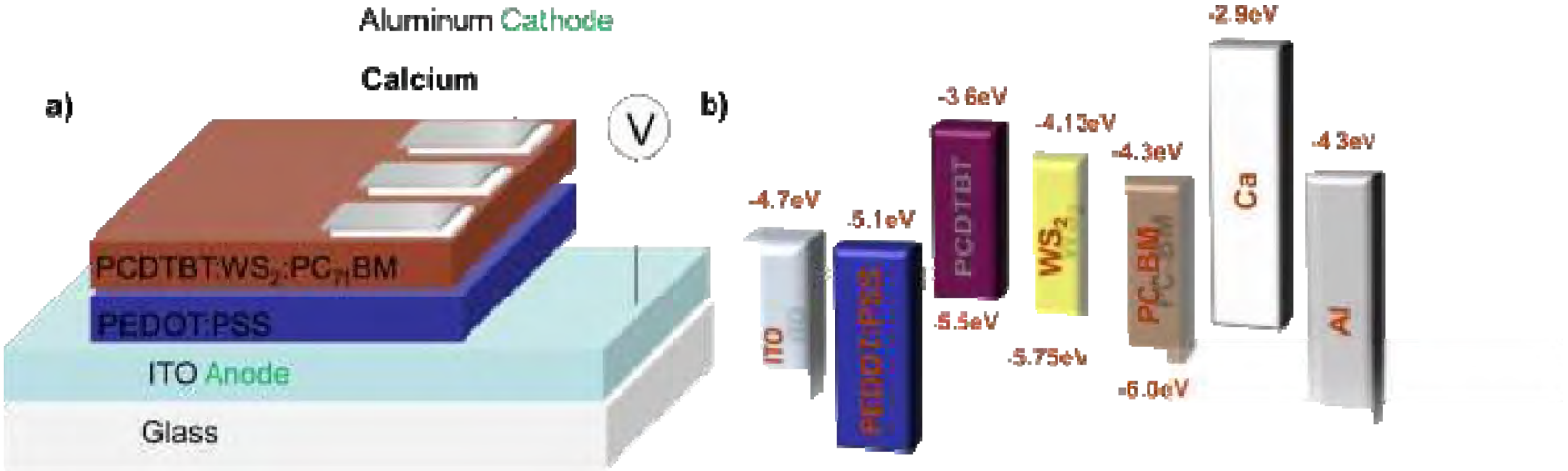
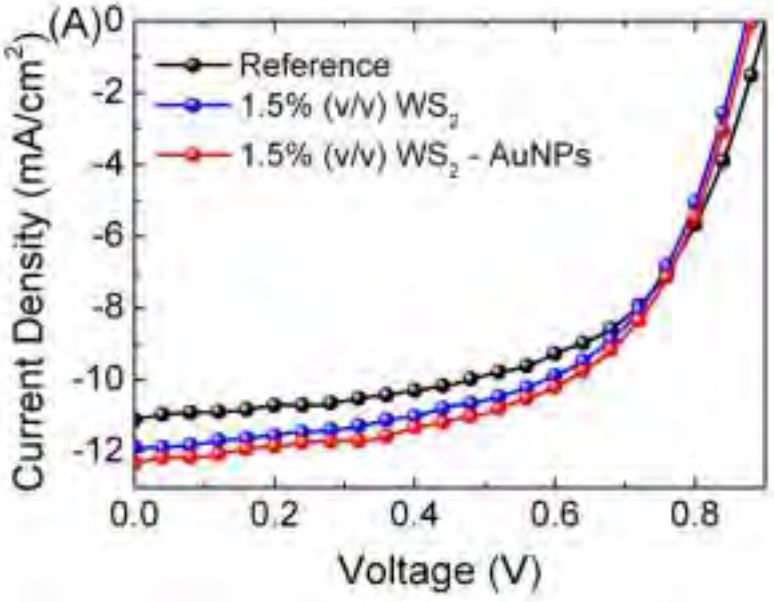
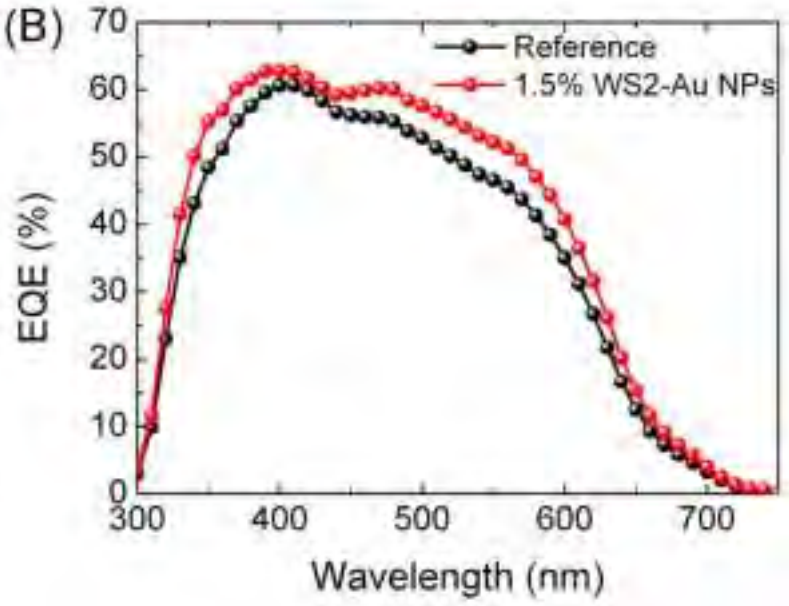
2D Materials-based additives in ternary OPVs







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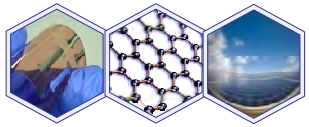
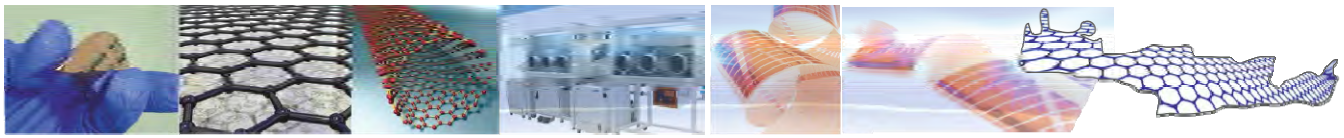
2D Materials-based additives in ternary OPVs

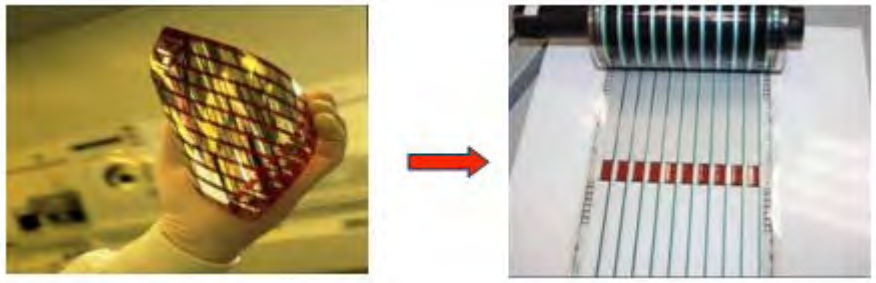


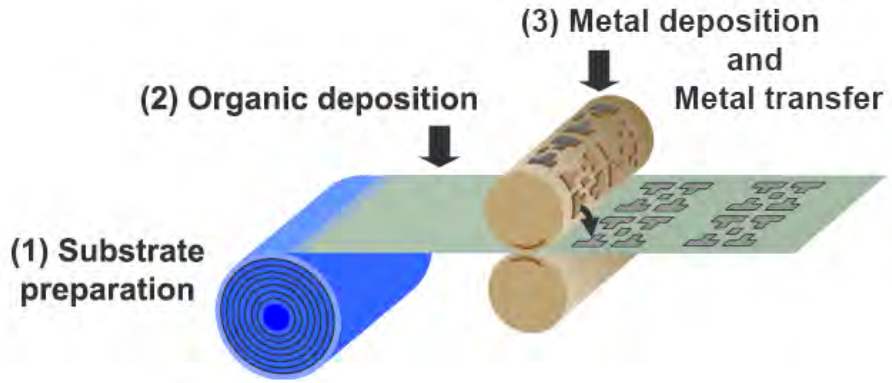
Device structure	J_{SC} (mA cm^{-2})	V_{OC} (V)	FF (%)	PCE (%)
PCDTBT:$PC_{71}BM$	10.6±0.13	0.89±0.1	60.2±0.3	5.6±0.1
1.5% (v/v) WS_2	11.9±0.21	0.87±0.1	59.1±0.2	6.1±0.1
1.0% (v/v) WS_2-Au	11.1±0.18	0.86±0.1	57.3±0.3	5.4±0.2
1.5% (v/v) WS_2-Au	12.3±0.22	0.89±0.1	58.4±0.2	6.3±0.1
2.5% (v/v) WS_2-Au	10.8±0.14	0.86±0.1	57.0±0.4	5.2±0.2

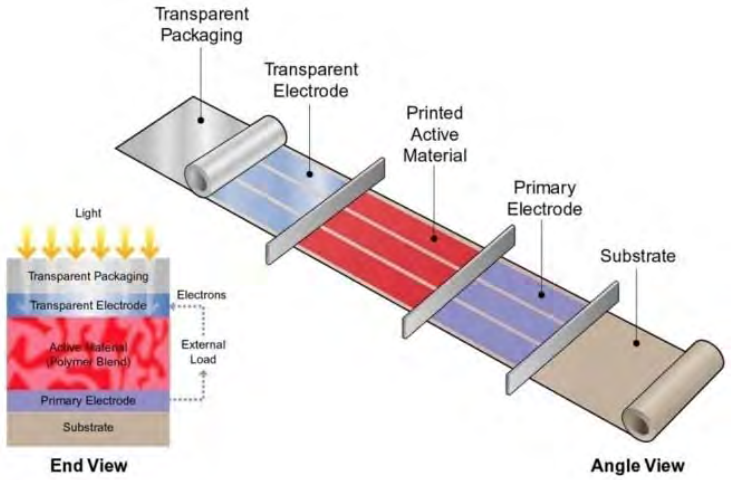


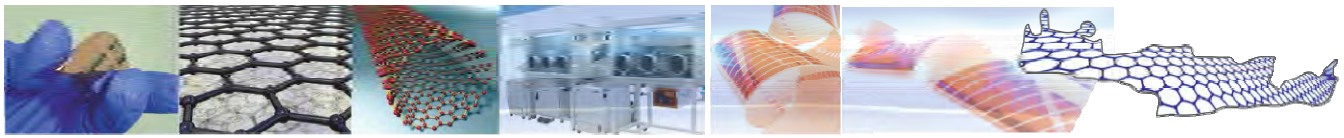
From lab-cells to mass production

- A proposed means to lower the cost of producing flexible displays in a high-volume manufacturing environment by taking advantage of a unique attribute of flexible substrates relative to the traditional glass substrate









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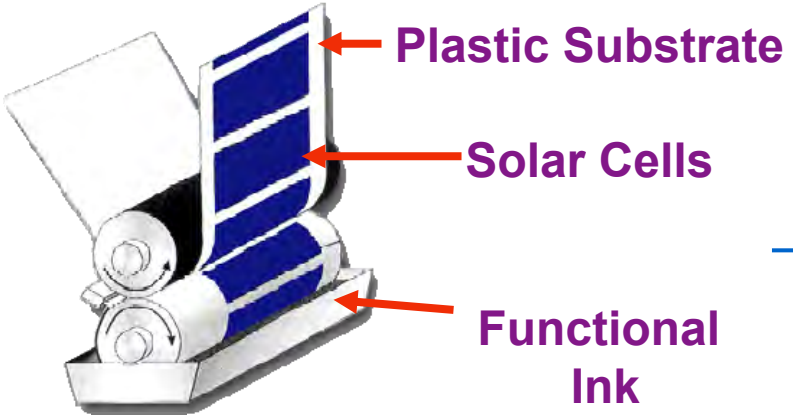
Printing solar cells

"inks" ---- with electronic functionality!

The Dream →



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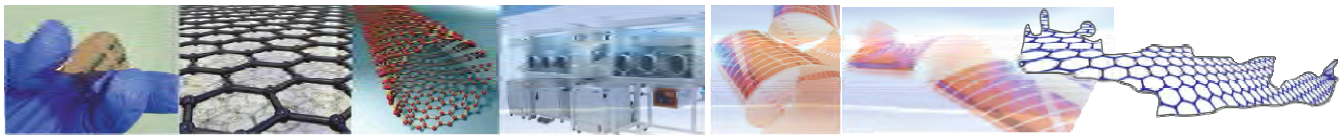

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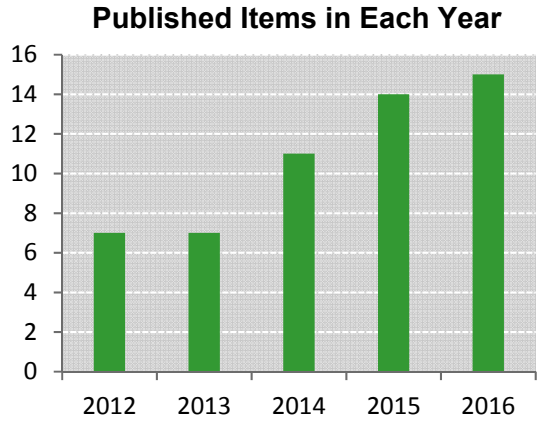
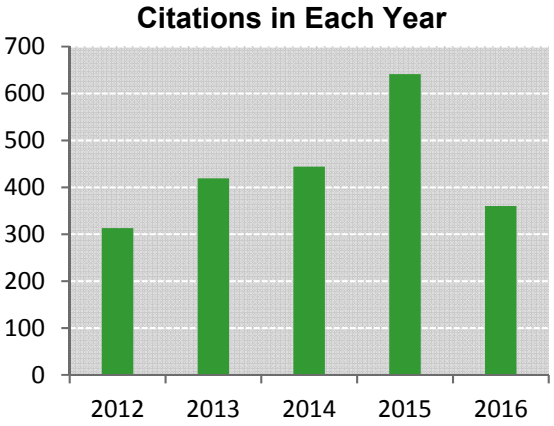
Recent research output

- In situ laser photochemical reduction of graphene oxide for use as the transparent electrode in flexible OPVs
- Chemical functionalization of graphene oxide for use as the electron acceptor or as additives in OPVs
- Combination of graphene oxide with metal nanoparticles for use as the buffer layer in OPVs
- Field emission cathodes based on polymer-graphene and polymer-WS_2 nanotubes electrodes
- Post fabrication laser assisted reduction of GO based FETs



83 publications
4.100 citations
475,18 Impact points



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http://nano.teicrete.gr

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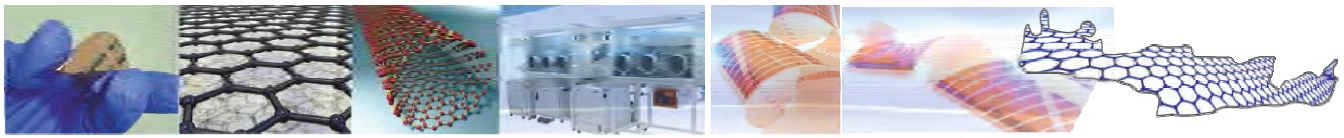
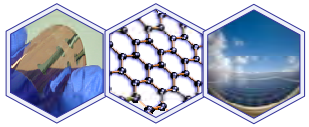


Erasmus LLP Organic Electronics & Applications



- **Design and Construction** of the curriculum of a two year MSc joined degree in the modern field of organic semiconductors

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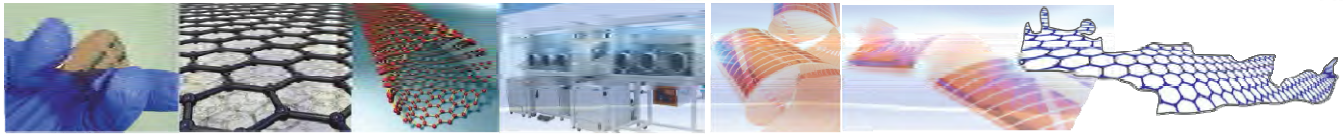

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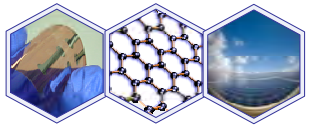
Erasmus LLP Organic Electronics & Applications



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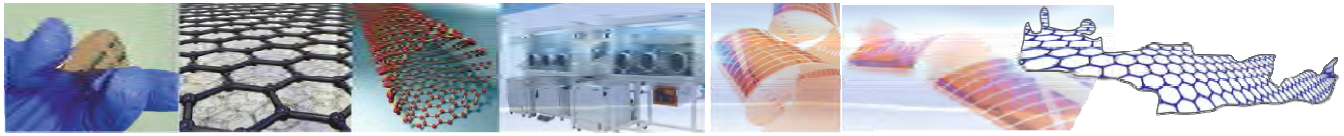
TECHNOLOGICAL EDUCATION INSTITUTION OF CRETE

UNIVERSITY OF CRETE

FORTH Institute of Electronic Structure and Laser

Αριθμ. 3833/Φ120 (3)

Έγκριση λειτουργίας του Δι-Ιδρυματικού Μεταπτυχιακού Προγράμματος Σπουδών (Δ.Π.Μ.Σ.), το οποίο συνδιοργανώνεται μεταξύ των Τμημάτων (1) Ηλεκτρολόγων Μηχανικών Τ.Ε. και (2) Ηλεκτρονικών Μηχανικών Τ.Ε. του Τεχνολογικού Εκπαιδευτικού Ιδρύματος Κρήτης, και των Τμημάτων (3) Χημείας και (4) Επιστήμης και Τεχνολογίας Υλικών με του Πανεπιστημίου Κρήτης, με τίτλο "Organic Electronics and Applications" («Οργανικά Ηλεκτρονικά και Εφαρμογές»).



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ELBYSIER

Electronics Beyond Silicon Era

The objectives of this Erasmus Plus KA2 Strategic Partnerships for Higher Education entitled **El**ectronics **Bey**ond **Si**licon **Er**a are the followings:

- Introduce to students & academics the modern trends of electronics
- Strengthen the collaboration and interaction of students and academics in Europe
- Inspire the first year postgraduate student's research
- Trigger the introduction of modern educational curricula in the field of Electronic Engineering

Partners

- **University of Crete – GR**
- **New University of Lisbon – PT**
- **University of Bucharest – RO**
- **University of Warsaw – PL**
- **École des Mines St Etienne – FR**
- **TEI of Crete – GR**

Forthcoming Event

Intensive Course in Transparent & Flexible Electronics

Chania, Crete, GR, 9-14 October 2016

Info: *https://elbysier.chania.teicrete.gr*/

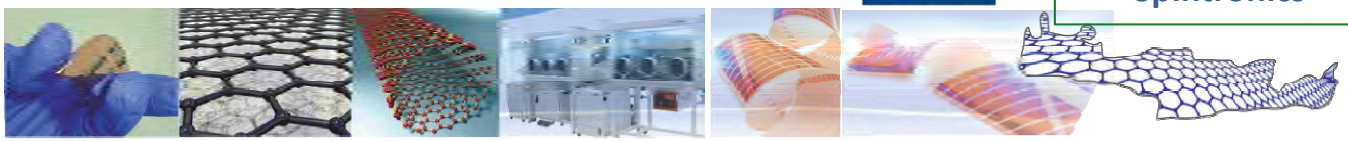
Erasmus+

ΙΚΥ

Intellectual Outputs

Educational Programs for final year undergraduate & first year postgraduate students in

- **Organic Electronics**
- **Transparent & Flexible Electronics**
- **Bioelectronics**
- **Nanoelectronics**
- **Spintronics**



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Special achievements

- Graphene Flagship funding and deputy leader in the work package of energy in the **EU's biggest research initiative ever.**

- Other national and international funds

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StableNextSol COST MP1307

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Ευρωπαϊκό Κοινωνικό Ταμείο

ΕΠΙΧΕΙΡΗΣΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
ΕΚΠΑΙΔΕΥΣΗ ΚΑΙ ΔΙΑ ΒΙΟΥ ΜΑΘΗΣΗ
επένδυση στην κοινωνία της γνώσης
ΥΠΟΥΡΓΕΙΟ ΠΑΙΔΕΙΑΣ ΚΑΙ ΘΡΗΣΚΕΥΜΑΤΩΝ
ΕΙΔΙΚΗ ΥΠΗΡΕΣΙΑ ΔΙΑΧΕΙΡΙΣΗΣ
Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

ΕΣΠΑ 2007-2013
ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ

- **Design and Construction** of the curriculum of a two year MSc joined degree in the modern field of organic semiconductors

Imperial College London

UNIVERSITY OF OXFORD

FORTH Foundation for Research & Technology - Hellas

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Asst. Prof. Konstantinos Petridis

Dr. Minas Stylianakis

Dr. Dimitrios Konios

George Viskadouros, PhD Candidate

George Kakavelakis, PhD Candidate

Myron Krassas, PhD Candidate

Pavlos Tzourmpakis, Postgraduate Student

Valina Foustanaki, Postgraduate Student

Gina Kalafataki, Postgraduate student

Temur Maksudov, Undergraduate student

Michael Papahatzakis, Undergraduate student

Michalis Christofi, Undergraduate student

Anna Orfanoudaki, PA to Prof. Kymakis

Collaborators

Dr. Emmanuel Stratakis, Ultrafast Laser Micro- and Nano- processing group of IESL of FORTH

Dr. Vittorio Pellegrini and Dr. Francesco Bonaccorso, Istituto Italiano di tecnologia, Graphene Labs

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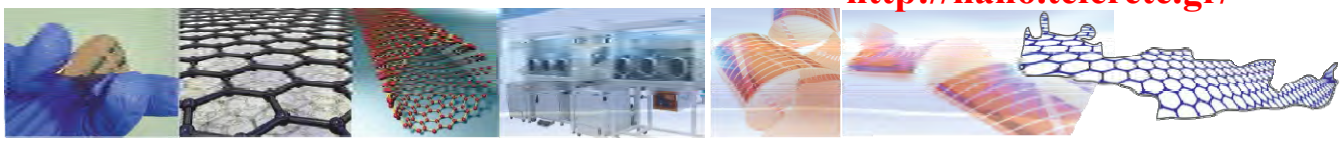

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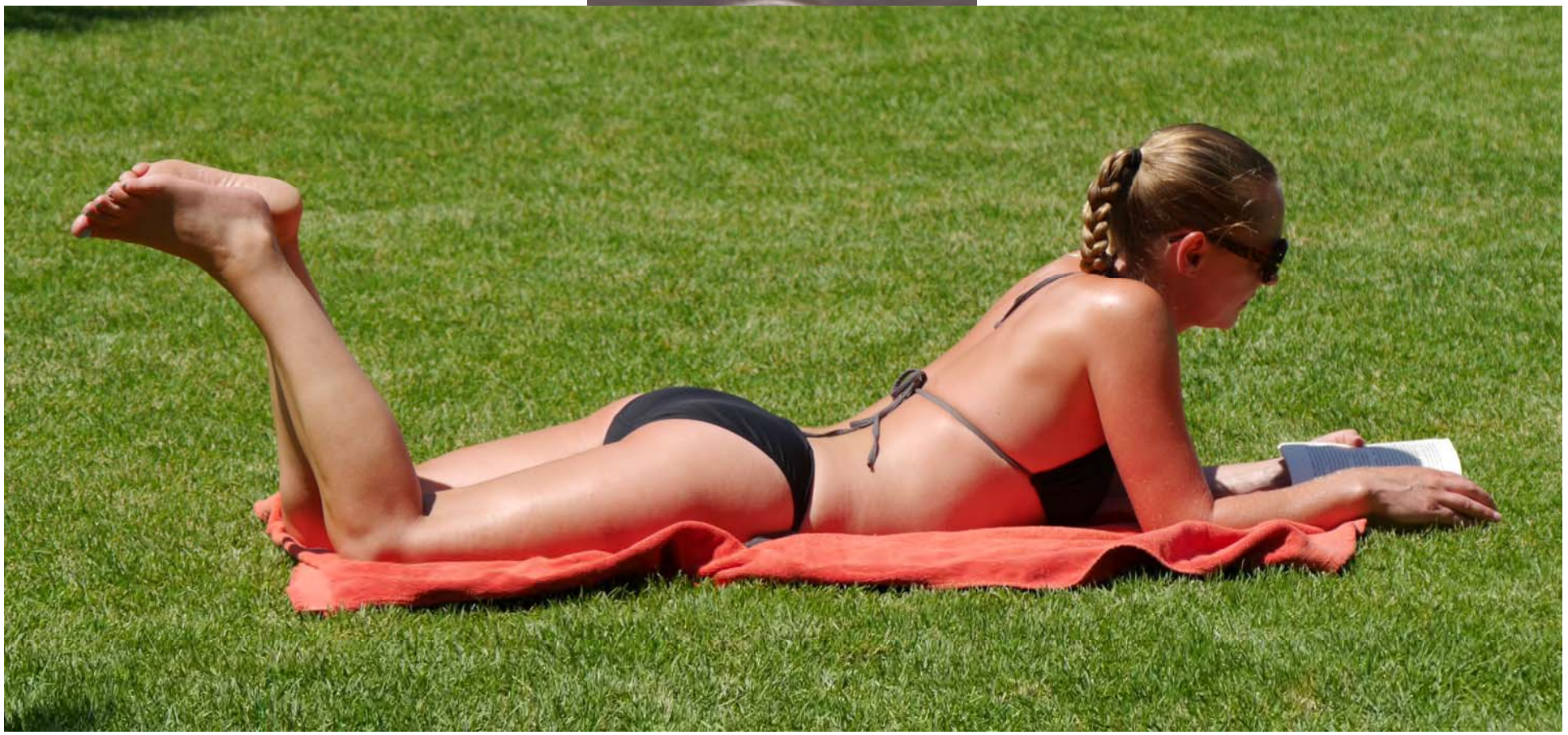
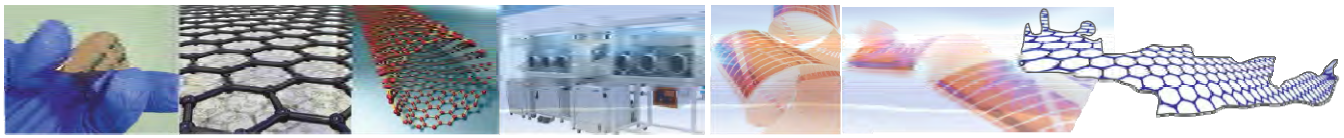
Special Thanks





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Thank you for you attention!!!