NanoMatCell

PROJECT FINAL REPORT

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Project acronym: **NANOMATCELL**

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[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm ; logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

3.1 Final publishable summary report

EXECUTIVE SUMMARY

NANOMATCELL is a FET Energy European project that aims to innovate in new materials and technologies for high efficiency solution processed solar cells. To achieve this we have summoned experts in the fields of material science, chemistry, surface passivation and physics to tackle this interdisciplinary challenge.
The vision of Nanomatcell is to invent new materials that yield high power conversion efficiency solar cells and explore novel panchromatic semiconductors that are based on environmentally friendly compounds and processes to efficiently harness the solar spectrum. We aim to do so utilizing high-vacuum-free processes, based on deposition from solution for cost minimization. The project has been structured in the following Research Work Packages (WPs) and the following progress has been made accordingly:

WP2: Development of novel light harnessing electron acceptors

Within this WP we have developed novel strategies for the synthesis on environmentally friendly, Earth abundant colloidal semiconductor nanocrystals with bandgap tuned in the range from 1 -1.3 eV and very high absorption coefficients in excess of 104 cm-1 from 800nm – 400 nm. We have also developed novel growth strategies in solution for Bi2S3 nanowire arrays for their employment in solar cells. Last but not least we have devised novel active doping strategies based on heterovalent cation substitution to tune the electronic doping in colloidal nanocrystals and the development of robust homojunctions.

WP3: Ultra thin passivation and barrier interlayers

We have developed atomic layer deposition (ALD) processes to conformally coat metal chalcogenide nanostructured semiconductor layers with ultra-thin oxide layers for passivation and protection. We have shown in conjunction with WP6 and WP7 the added benefits of ultra-thin layers in device performance.

WP4: NIR and black dyes for panchromatic harnessing

New dyes have been developed based on D-A- π –A architecture for the short wavelengths as well as pthalocyanine dyes for extended absorption range in the NIR.

WP5: Electrolytes (ionic liquids) and solid state hole transport layers

We have identified and synthesized new solid-state hole transport layers whose energetic levels and electronic properties can be molecularly engineered to match the needs for hole extraction and minimum light filtering. In particular benzothieno[2,3-b][1]benzothiophene (BTTB) small molecules have been successfully synthesized as well as arylamine based polymers and oligomers.

WP6: Physics and carrier dynamics

Carrier development and kinetics of inorganic-hybrid materials and geometries have been analyzed by microsecond to millisecond transient absorption spectroscopy (TAS). These studies have been complimented by steady state optical spectroscopy. The studies carried out here have culminated in insights into active component physics and thus device fabrication using these materials. Improved understanding of carrier physics has been continuously fed back into the other work packages for device optimization.

WP7: Development, optimization of solar cell structure & evaluation of potential exploitation

We have developed a series of solar cells based on panchromatic inorganic and hybrid absorbers with compelling performances. We have achieved power conversion efficiencies in excess of 3% in solution processed solar cells, based on Sb_2S_3 and $AgBiS_2$ nanocrystals pointing to significant performance to be within reach after optimization. We have also achieved ground breaking performance in the new class of organo-metal-halide perovskite solar cells in excess of 15% by developing novel facile deposition methods and architectures.

WP8: Dissemination & evaluation of potential exploitation

The work during NANOMATCELL has been published in 52 scientific journal articles of very high impact and the results have been disseminated with in international and European level conferences.

SUMMARY DESCRIPTION OF THE PROJECT CONTEXT AND OBJECTIVES

NANOMATCELL´s vision was to develop and progress the field of solution processed solar cells with compelling power conversion efficiencies and expand the available technologies that can address the TW challenge. To achieve this NANOMATCELL focussed on solution processed inorganic nanocrystals and hybrid organic-inorganic materials (perovskites). To achieve the intended goals the project identified and successfully addressed specific objectives, scientific as well as technological:

Scientific Objectives:

- Development of novel electron acceptor materials (n-type semiconductors) with optimal optical and electronic properties to act as (co)sensitizers and enable panchromatic solar harnessing. Those nanocrystalline materials are expected to replace traditional n-type electrodes used in Dye-sensitized type of structures, such as TiO_2 with the potential to expand the spectral solar harnessing of these architectures. Those materials needed to be designed and optimized to serve both as efficient electron transport and acceptor media as well as efficient photocarrier generation media.
- Development of new interlayer materials and processes thereof at the interfaces of the electron (n-type) and hole (p-type) acceptor materials to retard interface recombination and facilitate efficient charge separation. At the same time the development of such ultra-thin passivating layers may act as protective barriers against degradation. The advances made within this project were based on the use of industrially accepted and large-area manufacturing based on atomic-layer deposition (ALD).
- Gain new understanding of the interfacial recombination processes in the novel type of architectures developed in this project by interrogation of the charge transfer processes that take place via transient absorption spectroscopy. Both carrier lifetimes and quantum yield of charge separated carriers can be monitored as a function of the employed materials and architectures to provide guidelines for the overall cell optimization.
- Design of novel types of Dye sensitizers targeting to extended spectral coverage as well as optimized molecular structures that offer increase charge separation and suppressed recombination when in contact with electron acceptor matrices. Some of the intended target features of the sensitizer include: Improved light absorption at near IR regions and increased molar extinction coefficient by extending the chromophore bridging unit in the D-π-A structure, increased separation between the injected electrons and the oxidized dye, by introducing a supramolecular control of charge-transfer dynamics, thus minimizing recombination.
- Design, development and optimization of novel solid-state hole transport layers with optoelectronic properties suitable for efficient charge separation and hole extraction. Molecularly engineered solids needed to be developed to match the HOMO-LUMO

requirements for efficient hole extraction and minimized interface recombination, offering at the same time sufficient electronic conductivity. The final goal was to identify low-cost substitutes of the standard and costly SpiroOMeTaD that has been traditionally used in solid-state DSSC type of solar cells.

By achieving the afore-mentioned scientific objectives NANOMATCELL has set a challenging yet realistic set of technological objectives that aimed to meet.

Technological Objectives:

- Development of record performance solid-state, solution processed solar cells manufacturable using low-temperature, high throughput processes. The aim of Nanomatcell was to present at hand a multitude of novel solar energy materials architectural platforms for photovoltaics that could meet concomitantly some very important features: low-temperature, solution processing; panchromatic solar harnessing; solid-state operation; potential for high robustness; based on Earth abundant elements to address the TW challenge; ideally consisting of environmentally friendly materials. The specific targets that were set to reach was PCE > 10% for solid state devices and 15% for standard DSSC architectures.
- Development of solar cell architectures of different size areas towards large area demonstrations and close to realistic platforms.
- Development of novel passivation techniques via chemical surface passivation or employment of material barriers to facilitate prolonged device lifetime showcasing the potential towards successful product development.

DESCRIPTION OF THE MAIN S&T RESULTS OF THE PROJECT

NANOMATCELL has made significant contributions in the field of nanomaterials and photovoltaics. This project was structured in 8 Workpackages each one of them addressing a specific challenge, as shown in Fig. 1 below.

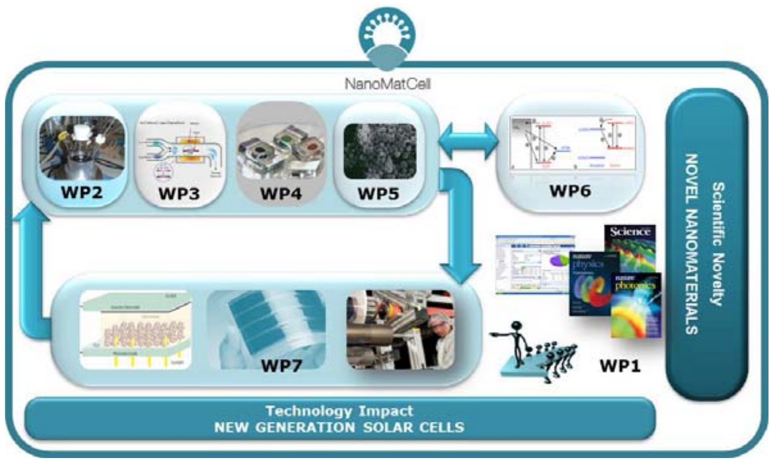


Fig. 1 Workpackage Structure of NANOMATCELL

WP1 was dedicated to project management and coordination. WP2 was devoted with the development, synthesis and optimization of inorganic nanocrystals that cater for panchromatic solar harnessing and at the same time would serve as electron acceptors in hybrid solar cells. WP3 developed novel interfacial barrier layers to engineer the interfaces of the photoactive layers and cater for suppressed recombination, interface passivation and also act as effective encapsulants. WP4 dealt with designing and optimizing sensitizer molecules, initially metallo-organic and organic dyes and then also Organo-lead halide perovksites. WP5 addressed the issue of efficient hole extraction layers designed and engineered at the molecular level to optimize hole scavenging with minimal over-potential losses and recombination at the interface. WP6 functioned as an interrogation tool, using advanced spectroscopic techniques to elucidate the charge transfer and carrier dynamics at the interfaces of the solar cells developed in this project. Finally WP7 assembled the findings and progress of the previous WPs into high efficiency solar cell devices and was responsible for the thorough characterization of their performance in terms of efficiency and stability. In this WP, significant efforts and progress was also made in solar modules under the industrial partner which cannot be further disclosed in this summary report. Last but not least, WP8 was the medium to disseminate and render the knowledge and results of this project known to the public via publications in high impact journals and oral talks in national and international conferences.

In what follows we present a succinct summary of some of the key results that can be publicly disclosed at this point, with minimum technical terminology to access also the general public.

WP2: Development of novel light harvesting electron acceptors

WP2 was responsible for the development of novel semiconducting nanocrystalline materials that can serve both as electron acceptors and sensitizer layers in hybrid solar cell structures. Within this

WP several such materials were developed and tested in devices, followed by extensive analytical and optoelectronic characterization. Amongst them we hereby focus and report in a few successful demonstrations. One of the first and most studied semiconductor compounds were those based on bismuth, emphasizing on its environmentally friendly character. Some first attempts implemented and reported in this project comprised Bi2S3 colloidal nanocrystals forming the electron acceptor in polymer-nanocrystal hybrid solar cells. In those studies both the effect of size of nanocrystals and the electronic coupling with the electron donor polymeric matrices were studied and optimized to achieve preliminary power conversion efficiencies on the order of 1%. One of the major roadblocks towards higher efficiencies based on Bi2S3 nanocrystals was their poor carrier mobilities and fast recombination that prevented their use in optically thick devices. To circumvent this we devised a new growth process of Bi2S3 Nanowires that yielded highly crystalline NW arrays employing a low-cost solution-based growth technique. The NW structures developed are schematically shown in Fig. 1. We also tested these NW arrays by forming a novel heterojunction between Bi2S3 and Ag2S as the n-type and p-type semiconductors respectively achieving power conversion efficiencies up to 2.5%.

In addition to Bi-based semiconductors we also investigated Sb-based electron acceptors. Antimony sulfide (Sb_2S_3) has been investigated as an absorber and transport material in hybrid solar cells and the key outcomes of these studies are:

- Fabrication of efficient bilayer and mesoporous Sb_2S_3 based devices
- Demonstration that Sb_2S_3 can function as a sensitizer and electron and hole transport material

Antimony Sulphide can be produced from thermal or chemical decomposition of antimony xanthate. Crystallinity and composition are confirmed by XRD and TEM methods and are comparable to crystals produced by other methods. Devices of both thin-film bilayer (Sb_2S_3|P3HT) and mesoporous (mesoTiO_2:Sb_2S_3|P3HT) geometry have been produced from antimony xanthate precursors. With these methods, photovoltaic devices have been reported with power conversion efficiencies (PCE) exceeding 3.25 % under 1 sun illumination, rising to almost 4% PCE at 0.1suns.

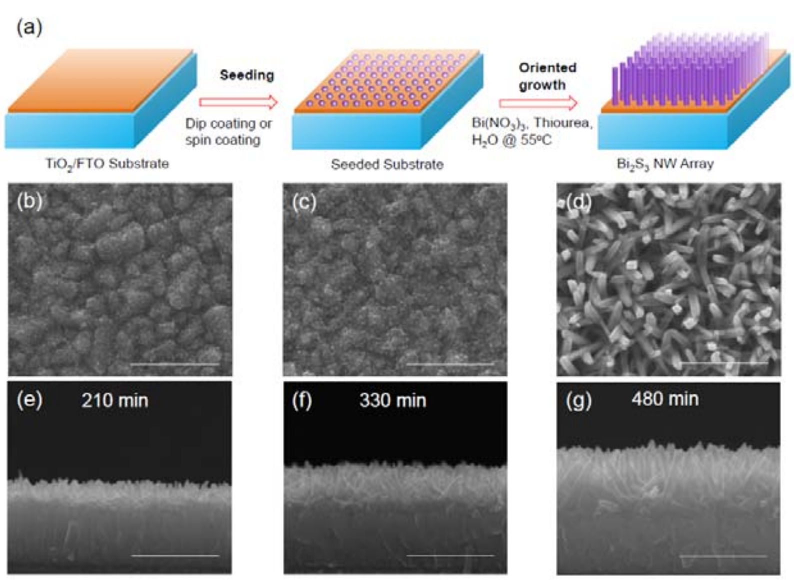


Figure 1 Scheme (a) shows the growth of bismuth sulfide nanowire from a seeded substrate via mild aqueous chemistry Figure (b), (c), and (d) display the SEM of the TiO_2-coated substrate, seeded substrate, and resulted bismuth sulfide nanowire arrays. As increasing the growth time, we can obtain bismuth sulfide films with longer, bigger, and more oriented nanowires, as shown in Figure (e), (f), and (g). Scale bar: 500 nm.

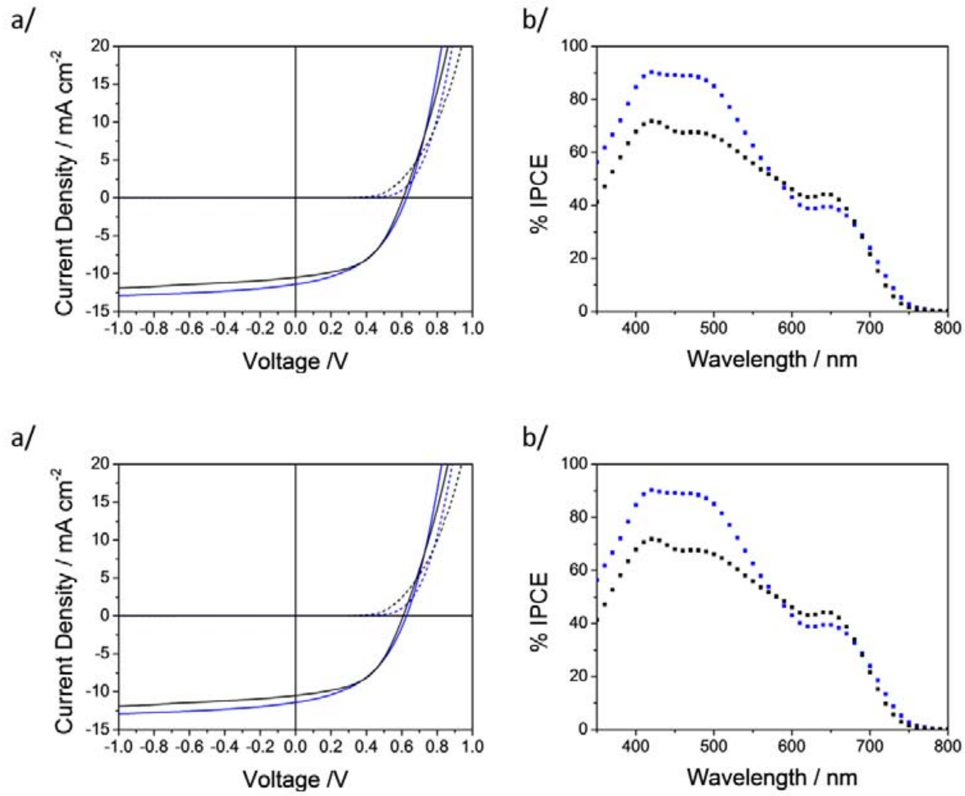


Figure 2 Current-voltage response in the dark (dashed lines) and under 100 mW cm-2 AM1.5 illumination. Mesostructured devices are illustrated in black while bilayer devices are shown in blue.

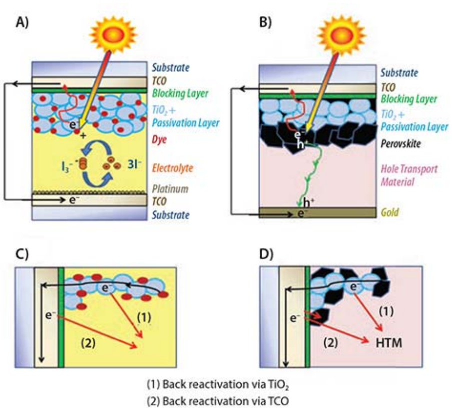
In view of the challenges met in the case of Bi2S3 nanocrystals we invested efforts in this project for the synthesis and study of AgBiS2 nanocrystals as a novel colloidal nanocrystal solar cell. This material was found to possess a favourable bandgap of 1.3 eV and extremely high absorption coefficient. We performed an extensive study of the effect of size, stoichiometry and ligand surface passivation on solar cell device performance and we have reported power conversion efficiencies of 6.3%. These results are further reported under WP7.

Last but not least within this project we developed novel doping schemes of colloidal quantum dots to tailor their doping character through heterovalent substitution. We used PbS QDs as a baseline material system for it is known to possess initially p-type behaviour. We then showed that by appropriate selection of tri-valent cations we can robustly convert this material into n-type semiconductor and we convincingly demonstrated a robust p-n homojunction based entirely on PbS QDs. That was the first report of an air-robust PbS QD homojuntion solar cell, published in Nature Communications.

WP3: Ultra-thin Passivation and Barrier Interlayers

In this project we performed extensive studies on applying atomic layer deposition techniques as a means to grow ultra-thin barrier layers in nanoporous metal-chalcogenide and metal oxide nanocrystal solids (Fig. 3 Left). Significant efforts were made and new ALD process methodologies were developed to enable atomic layer deposition in 600 nm thick nanoporous layers with porosity on the order of 1-3 nm. Extensive characterization via TEM and EDS was employed to monitor the growth and ensure that uncontrolled chemical vapour deposition was avoided. The development of such a powerful tool was then employed in this project to facilitate the deposition of ultra-thin (< 1nm) barrier layers consisted of Alumina in Bi2S3 Nanowire and nanocrystal solar cells. The results showed that the use of such layers indeed led to enhanced surface passivation and suppressed recombination. In addition to this, the know-how developed in this project was also directly applied to perovskite solar cells. In this case the use of a 0.1 nm thick Alumina interlayer has led to an overall 30% increase in solar cell performance, proving the potential of this technique as an invaluable tool for nanostructured solar cells.

ALD was also extended to use it as a low-temperature alternative to developing efficient electrodes for perovskite solar cells that no longer necessitate the use of calcination temperatures and open the way towards plastic flexible perovskite solar cells. This has been successfully demonstrated not only at cell but also at module level (Fig. 3 Right).



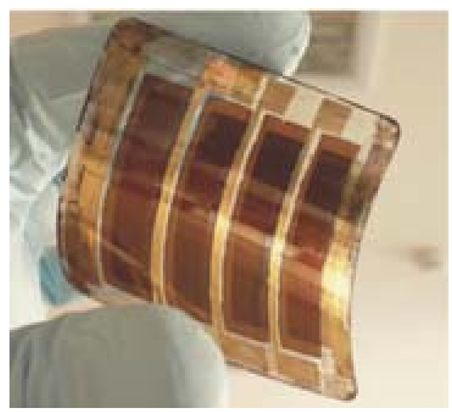


Figure. 3 (Left) Configuration of hybrid mesoscopic solar cells in which ALD has been employed : A) dye-sensitized and B) perovskite solar cells. The application of passivation and blocking layers has the purpose of limiting the primary interfacial back reactions in C) dye-sensitized and D) perovskite solar cells (Right) A perovskite flexible photovoltaic module developed for the first time with an active area of 8 cm^2 [*Advanced Energy Materials* **2015**, 5].

WP4: Novel Organic (and hybrid) sensitizers

In this WP NANOMATCELL made significant contributions in the field of molecularly engineered sensitizers for DSSC architectures. Efforts undertaken by EPFL with contributions and testing also taking place by the industrial partner GCell we have progressed significantly on multiple fronts. Novel donor-acceptor-pi-acceptor dyes have been developed and optimized to serve as efficient, low-cost blue and green organic sensitizers (Fig.4). Moreover both squaraine sensitizers and cosensitization schemes have been developed that have yielded power conversion efficiencies of up to 7.9%. The next thrust on DSSC optimization through novel sensitizers was the development of symmetric and assymetric phthalocyanine (PC) dyes as narrowband NIR sensitizers. Amongst the most successful strategies was the report of a molecularly engineered D-pi-A porphyrin dye family that was optimized for both solar harnessing and electrolyte compatibility resulting in power conversion efficiencies of 13% (Fig. 5).

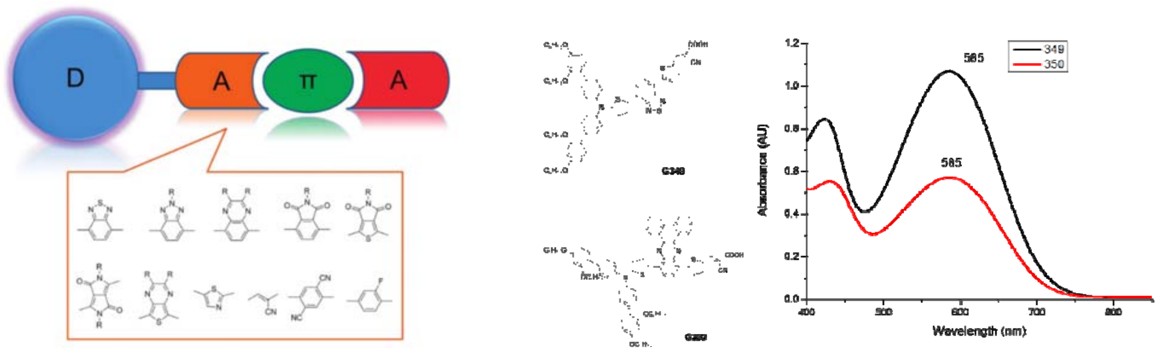


Figure. 4 (Left) Concept and schematic illustration of D-A- π -A structure. (Right) UV-VIS spectrum of two proto-typical blue colored D-A- π -A sensitizers.

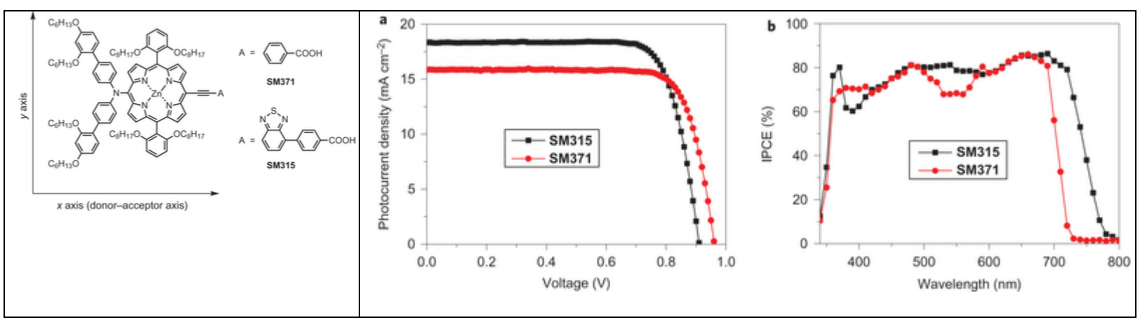


Figure. 5 (Left) Molecular structure of the porphyrin dye of D-pi-A developed. (Right) a J-V characteristics and (b) IPCE spectra of the resultant solar cells based on these Dye molecules (Nature Chemistry 2014).

The second part of this WP was devoted to the employment of a new type of sensitizer, based on hybrid methyl-ammonium lead halide perovskites. A sequential deposition method of the perovskite sensitizer within the nanoporous metal-oxide electrode was disclosed that have led to record (at that time) power conversion efficiencies of 15%. The device structure of this new class of DSSC architecture is shown in Fig. 6.

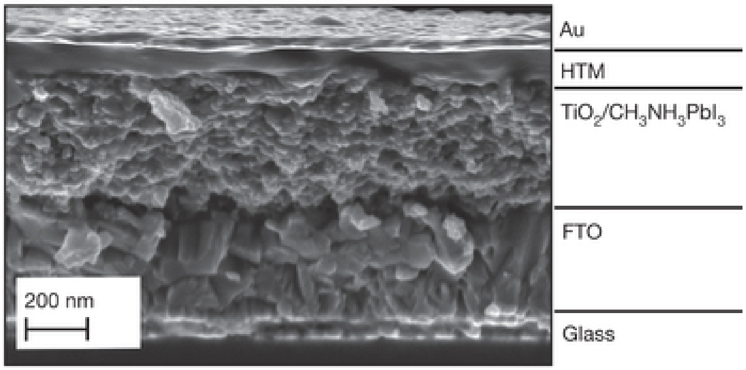


Figure.6 A perovskite-based DSSC device architecture that was achieved in this project with PCE of 15% (Nature 2013).

WP5: Electrolytes and Solid State Hole Transport Layers

The main objective of this WP was the development of optimized hole-transport layers for thin film solution processed solar cells investigated in this project. One of the main issues addressed was the development of low-cost HTLs compared to the standard ones used hitherto based on SpiroOMeTad. To this end a plethora of hole transport layers were employed and tested in solar cell architectures comprising small molecules and conductive polymers. Amongst the small molecules tested emphasis was placed on benzothiobenzothiophene (BTTB)-based small molecules as well as DPP-based polymers. Those materials were tested and evaluate by the partners within this project, showing in some cases promising results. Two particularly successful examples of the materials developed in this project were demonstrated in perovskite-based solar cells. First, the use of a small-molecule hole conductor (V886) that yields very high current density (>21 mA cm^{-2}) and overall efficiency close to 17% in $CH_3CH_2NH_3PbI_3$-based solar cells was demonstrated. V886 (Fig. 7a) is less expensive than the spiro hole conductors: it can be synthesized in two steps from commercially available materials, and is thus useful for large-scale production of perovskite solar cells. The good solubility and film-forming properties allows the formation of thicker films of high quality. We strongly believe that V886 can be also an ideal candidate for other optoelectronic applications such as OLEDs and solid-state dye- sensitized solar cells. Second, a molecularly engineered hole transport molecule was developed that has a simple dissymmetric fluorene–dithiophene (FDT) core substituted by *N,N*-di-p-methoxyphenylamine donor groups, which can be easily modified, providing the blueprint for a family of potentially low-cost hole-transport materials. The production cost of this material is estimated to be at 60$/g at a lab scale, i.e. five times cheaper than Spiro, and with the potential for further decrease by applying economies of scale (i.e. large scale production). Perovskite solar cells using FDT as a HTM compare favourably with spiro-OMeTAD, with effciencies exceeding 20% (Fig. 7).

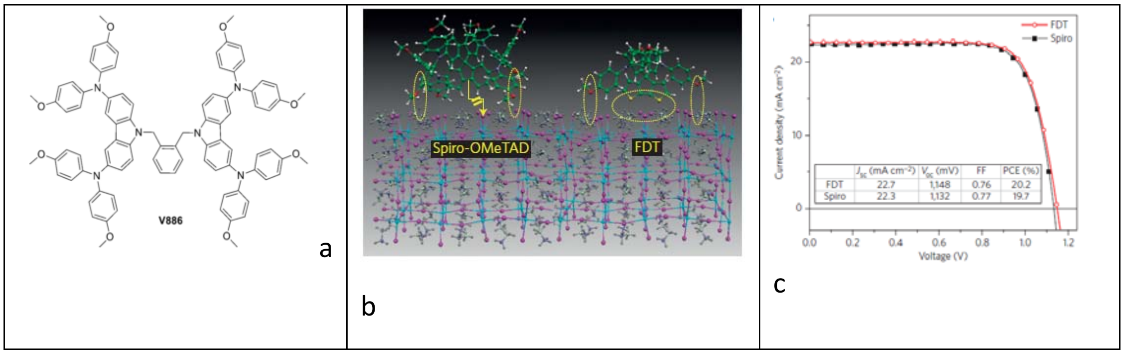


Figure. 7 (a) molecular structure of V866, (b) molecular structure of FDT molecule and its orientation on a perovskite layer, (c) I-V characteristics of a perovskite structure comparing Spiro and FDT molecules as HTL, reaching PCE of 20% (Nature Energy 2016).

WP6: Physics and Carrier Dynamics

In this WP we have used advanced transient absorption spectroscopy (TAS) to monitor charge transfer dynamics and recombination kinetics in the solar cell architectures investigated in this project to gain insights on the underlying mechanisms at play, so that we gain understanding on the limiting factors of their performance. We have therefore used this as an interrogation tool in a feedback process to optimize the efficiency of our solar cells. Some of the cases that TAS has provided valuable input was on the optimization and understanding of the Bi2S3-polymer hybrid solar cells as well as the Bi2S3-Ag2S NW core-shell architectures and the effect of the interlayers, developed at WP3, on the interface recombination mechanisms of those devices. The particular importance of this research can be reflected upon the achievement of photovoltaic devices with a range of new materials that have not been reported before in this context. The investigation of various environmentally friendly nanocrystal compounds has been augmented by the use of this approach, including Bi2S3, SnS, Sb2S3 and CuSbS2. A successful example of this methodology is illustrated in Fig. 8 wherein TAS spectra and charge transfer kinetic studies have led to the demonstration of a SnS-based solar cell with promising performance (PCE of 1.2%).

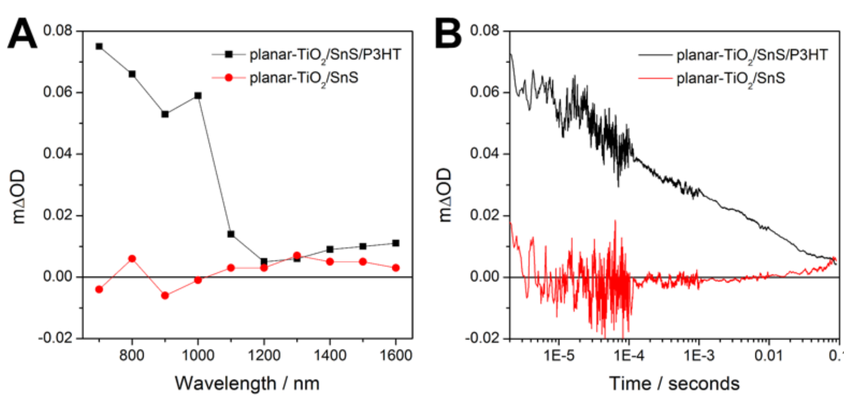
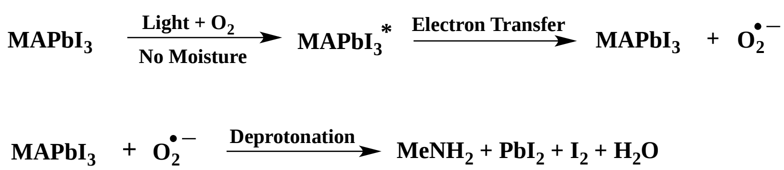


Figure. 8 (A) Transient absorption spectra of a SnS as well as a SnS/P3HT layer on planar-TiO_2 10 µs after pulsed excitation at 510 nm and (B) transient absorption kinetics of the same samples recorded at 1000 nm following excitation at 510 nm. The resultant solar cells yielded PCE of 1.2%.

A second yet also impactful research result of this WP was the use of TAS as a monitoring tool of the degradation mechanisms of perovskite solar cells. We have determined a key degradation pathway for the solar cell material: methyl ammonium lead triioide perovskite (ref: Angew. Chemie, Int. Ed. 2015 DOI: 10.1002/anie.201503153). In particular, we have shown that when exposed to both light and oxygen (at same time) the $CH_3NH_3PbI_3$ material decomposes yielding methylamine, PbI_2 and I_2 as products. Scheme 1 below shows the mechanism of the degradation. A combination of x-ray diffraction, Raman, NMR and EDX was employed to identify the reaction side products.



Scheme 1. Reaction scheme indicating a potential route for degradation caused by superoxide. Optical excitation of $MAPbI_3$ results in the formation of $MAPbI_3$*. Superoxide is generated via electron transfer from $MAPbI_3$* to O_2. The resulting superoxide attacks the $MAPbI_3$ perovskite leading to degradation.

We have shown that ageing $CH_3NH_3PbI_3$ based photoactive layers in light and oxygen can affect the yield of photo-induced charge separation. We have also shown that the use of a mesoporous TiO_2 electron acceptor electrode can reduce the effect of light and oxygen induced degradation of the charge separation yield (Fig. 9), paving the way to more robust perovskite solar cells.

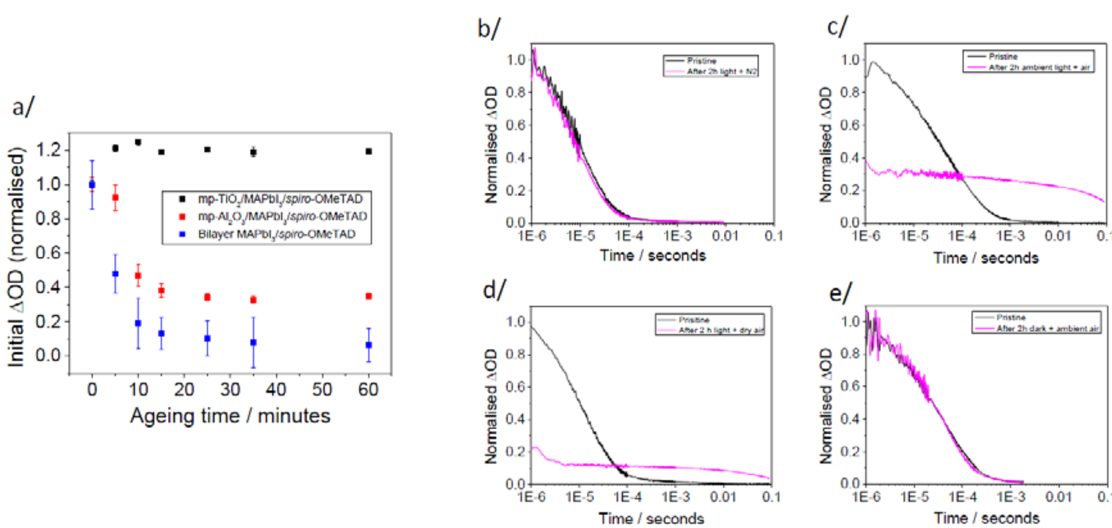


Figure 9. Left Panel: (a) Initial amplitude of ΔOD at 1600 nm as a function of ageing time in atmospheric conditions under ambient light for glass/mp-TiO2/MAPbI3/spiro-OMeTAD (black), glass/mp-Al2O3/MAPbI3/spiro-OMeTAD (red) and glass/MAPbI3/spiro-OMeTAD (blue). Data points determined from the mean value of ΔOD between 2 and 5 µs for each measurement. Films excited at 567 nm with a 25 µJ cm^{-2} laser pulse. Right Panel: (b - e) Effect of exposure to varying environmental conditions for two hours on the transient absorption signal at 1600 nm for a mesoporous Al2O3/MAPbI3/spiro-OMeTAD film: b/ ambient light, sealed under flowing N2, c/ ambient light, non-sealed, d/ ambient light, sealed under flowing dry air (H_2O < 2 vpm), e/ dark, non-sealed. Laser excitation energy density = 25 µJ cm^{-2} at 567 nm.

WP7: Development and Optimization of Solar Cell Structures

Under this WP NANOMATCELL fabricated, optimized and tested the solar cell devices developed in this project. Although several significant results on high performance solar cell devices reported in this project have already been summarized under the other WPs whose findings were instrumental in reaching those compelling efficiencies, in the present section we illustrate a concise summary of results that have contributed to the success of this project and that have not been mentioned until now. Some key results that merit particular mention in this summary report are pertinent to three classes of PV technologies addressed herein.

PbS QD solar cells. One of the key findings in this project was an architectural platform for colloidal QD solar cells that enables the transformation of a QD solar cell from trap-assisted recombination regime to band-to-band recombination. That was achieved with the use of a bulk heterojunction formed with PbS QDs and ZnO nanocrystals. It was found that the presence of ZnO, through the donation of electrons, acted as a remote passivation element that passivated electron traps in the PbS QD solid. This resulted in achieving open circuit voltages that cannot be reached in standard bilayer devices and most important that the open circuit voltage can be maintained at high values even at dim illumination conditions (Fig.10). This work also yields the highest reported Voc of 0.7 V for a PbS QD solar cell of a given bandgap 1 eV. The resultant power conversion efficiency of the bulk heterojunction solar cells was measured 5.2% at 1 Sun conditions and reached up to 7.1% at 0.1 Suns.

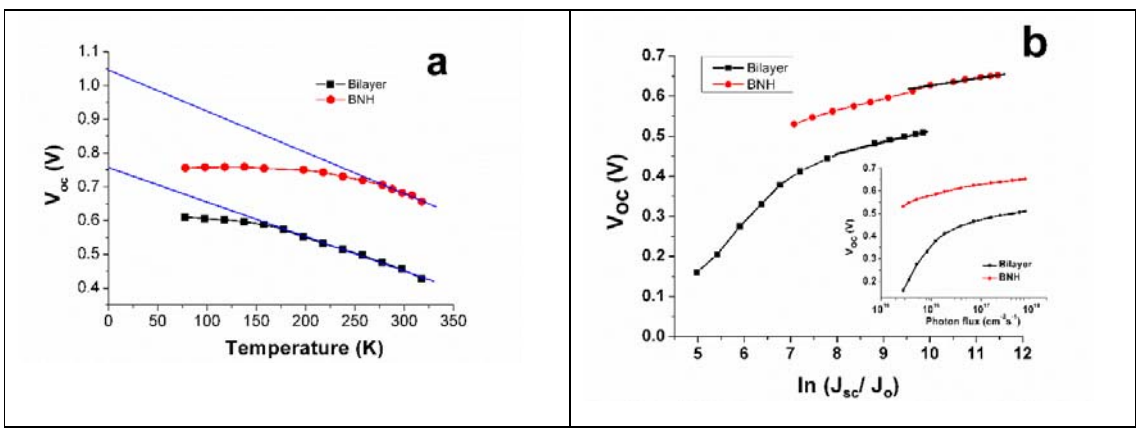


Figure. 10 Optoelectronic characterization of the bilayer and BNH solar cells. a) Temperature dependence of V_{oc} for the bilayer and BNH structures under AM1.5 solar simulated conditions. The BNH structure shows a band-to-band recombination-limited behavior whereas the bilayer device suffers from trap-assisted interface recombination. b) Left: Plot of V_{oc} as a function of ln(J_{sc}/J_o) for the bilayer and BNH devices under monochromatic excitation at 635 nm. The linear fit in the high injection regime for the bilayer case yields an ideality factor of 1.41, indicative of trap-assisted recombination, whereas the ideality factor for the BNH devices fits to 1.04, pointing to band-to-band recombination. Right: Dependence of V_{oc} on intensity, demonstrating that BNH devices outperform bilayer ones at low intensity conditions (Adv. Mat 2014).

Optimization of QD solar cells also took place at the QD surface level to improve not only performance but also the photostability of this class of devices. By thorough investigation of the surface of QDs via X-ray photoelectron spectroscopy, we shed new light on what governs the performance and stability of high efficiency QD solar cells and the critical role of ligand binding. We identified the presence of OH ions as detrimental for both efficiency and stability and we devised new ligand binding schemes that have led to power conversion efficiencies in excess of 9.5 % (certified values up to 8.8%) for solar cells that can operated under continuous illumination for periods of 1200h with less than 20% loss in their efficiency. Although such stability reports are still far from commercial-grade solar cells this work demonstrated that further stability enhancement is within reach in QD-based solar cell technologies. Fig 11 illustrates a full optoelectronic and material characterization example of a PbS QD solar cell device that was tested in this project using a new halide-ligand proposed that serves as a more efficient replacement of oleic acid and inhibitor of OH formation than previously reported ligand molecules.

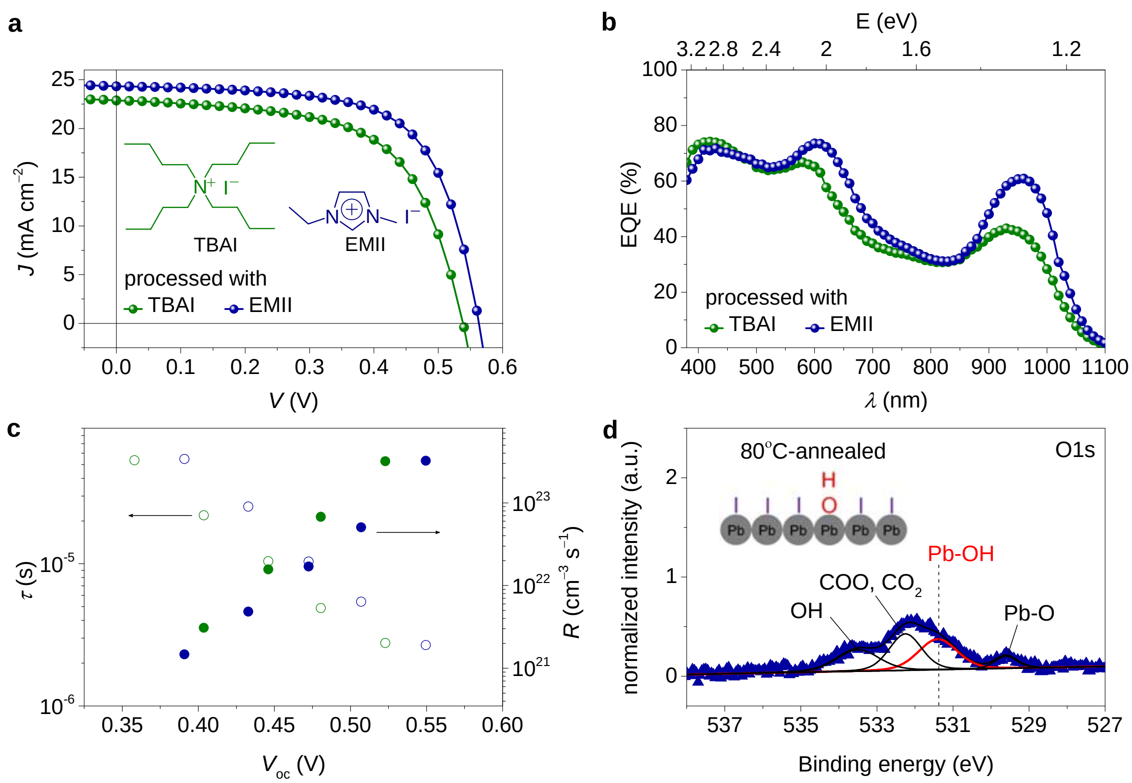


Figure. 11 *J-V* characteristics of TBAI-and EMII-processed QD solar cells (Au anode) with 80°C annealing under simulated AM1.5G 100 mW cm^{-2} illumination. The inset shows the molecular structures of TBAI and EMII. **b,** EQE spectra of TBAI-and EMII-processed QD solar cells with 80°C annealing. **c,** V_{oc}-dependent carrier lifetime (τ, open circle) and recombination rates (*R*, solid circle) of TBAI- (green colour) and EMII-processed (royal colour) QD solar cells with 80°C annealing. **d,** The relative intensity of O1s of EMII-processed QD layer with 80°C annealing normalized to that of TBAI-treated QDs. (Nature Energy 2016)

AgBiS2 Nanocrystal Solar cells. One of the key targets of this project was the development of environmentally friendly solution processed inorganic and hybrid solar cells. To this end we have synthesized, optimized and developed solar cells based on a newly synthesized and reported compound. We have demonstrated $AgBi_2$ solar cells with promising efficiencies. In the best performing devices, the $AgBiS_2$ is sandwiched between a ZnO electron-transport layer and a thin (~10 nm) hole-transport layer comprised of poly[(4,8-bis-(2-ethylhexyloxy)-benzo(1,2-b:4,5-b')dithiophene)-2,6-diyl-alt-(4-(2-ethylhexyl)-3-fluorothieno[3,4-b]thiophene-)-2-carboxylate-2-6-

diyl)] (PTB7). A ligand exchange process with tetramethylammonium iodide (TMAI) is used to remove and replace the oleic acid ligands on the surface of the $AgBiS_2$ nanocrystals. These solar cells have exhibited efficiencies as high as 6.3% (Figure 12), also certified by Newport. The material presents a favourable bandgap of 1.3 eV and very high absorption coefficient. It is noteworthy that although the $AgBiS_2$ layer is only 35-nm thick, a J_{SC} of 22 mA/cm^2 has been achieved. This highlights the promise of $AgBiS_2$ as a high-efficiency solar-cell material. This solar cell technology is based on ambient and low-temperature solution-processed methodologies and is thus directly compatible with roll-to-roll manufacturing on even flexible substrates.

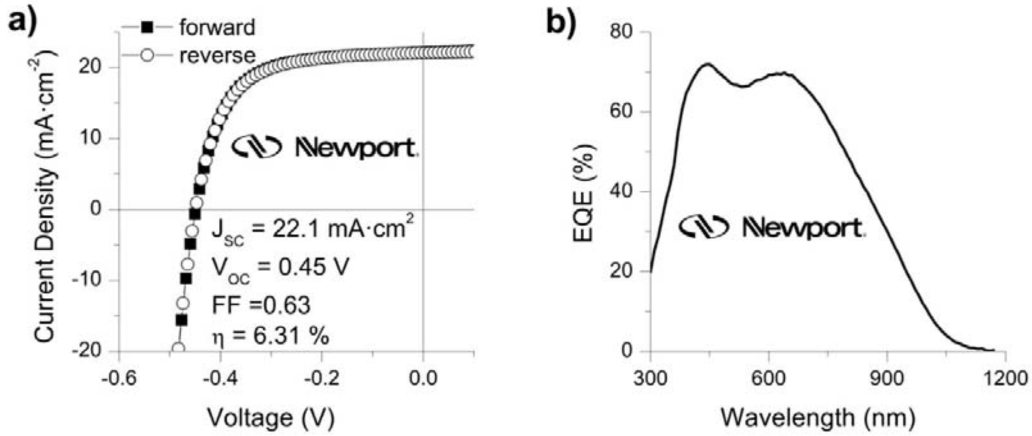


Figure 12 Newport-certified (a) J-V and (b) light-biased EQE spectrum.

Perovskite Solar cells. In view of the eminent emergence and progress of organo-metal halide perovskite solar cells we (as a consortium) decided not to overlook this new technology and therefore incorporated it in the project. This was also supported by the industrial partner of the project. We have therefore significant efforts (involving EPFL and ICL) on the exploration of perovskite solar cells and some very significant results have been achieved:

i. **Sequential deposition as a route to high-performance perovskite-sensitized solar cells:** Solution-processable organic–inorganic hybrid perovskites—such as $CH_3NH_3PbX_3$ (X = Cl, Br, I)—have attracted attention as light-harvesting materials for mesoscopic solar cells. So far, the perovskite pigment has been deposited in a single step onto mesoporous metal oxide films using a mixture of PbX_2 and CH_3NH_3X in a common solvent. However, the uncontrolled precipitation of the perovskite produces large morphological variations, resulting in a wide spread of photovoltaic performance in the resulting devices, which hampers the prospects for practical applications. A sequential deposition method has been developed for the formation of the perovskite pigment within the porous metal oxide film. PbI_2 is first introduced from solution into a nanoporous titanium dioxide film and subsequently transformed into the perovskite by exposing it to a solution of CH_3NH_3I. Using this technique for the fabrication of solid-state mesoscopic solar cells greatly increases the reproducibility of their performance and allows us to achieve a power conversion efficiency of approximately 15 per cent [Nature, DOI:10.1038/nature12340].

ii. **Perovskite solar cells employing organic charge-transport layers:** To date, all high-efficiency perovskite solar cells reported make use of a (mesoscopic) metal oxide, such as Al_2O_3, TiO_2 or ZrO_2, which requires a high-temperature sintering process. We have shown in this work [Nature Photonics 8, 128-132, 2014] that methylammonium lead iodide perovskite layers, when sandwiched between two thin organic charge-transporting layers, also lead to solar cells with high power-conversion efficiencies (12%). To ensure a high purity, the perovskite layers were prepared by sublimation in a high-vacuum chamber. This simple planar device structure and the room-temperature deposition processes are suitable for many conducting substrates, including plastic and textiles.

iii. **Mixed-Organic-Cation Perovskite Photovoltaics for Enhanced Solar-Light Harvesting:** An important target for the further improvement of the performance of perovskite-based photovoltaics is to extend their optical-absorption onset further into the red to enhance solar-light harvesting. Herein, we show that this goal can be reached by using a mixture of formamidinium ($HN{=}CHNH_3^+$, FA) and methylammonium ($CH_3NH_3^+$, MA) cations in the A position of the $APbI_3$ perovskite structure. This combination leads to an enhanced short-circuit current and thus superior devices to those based on only $CH_3NH_3^+$. This concept shows great potential as a versatile tool to tune the structural, electrical, and optoelectronic properties of the light-harvesting materials [Angewandte Chemie 53, 3151–3157, 2014]. Employing mesoporous TiO_2 and spiro-MeOTAD as electron and hole specific contacts, respectively, we fabricate perovskite solar cells that achieve a maximum power conversion efficiency of 20.8 % for a molar ratio of PbI_2/FAI of 1.05 in the precursor solution a record for perovskite photovoltaics approaching that of the best silicon solar cells. Correspondingly, the open circuit photovoltage reaches 1.18 V under AM 1.5 sunlight (Fig. 13).

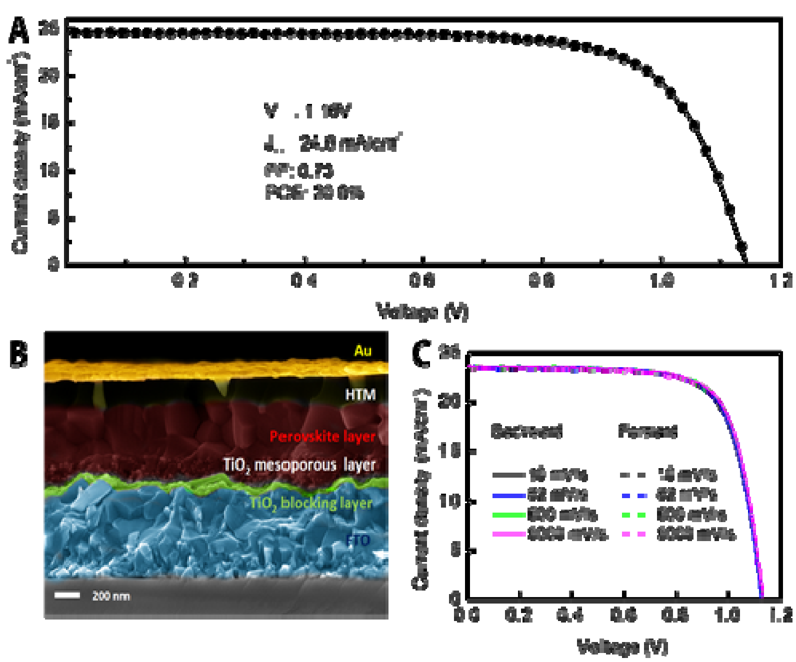


Figure. 13. (A) J-V curves of the champion solar cell under AM 1.5 G illumination, measured from VOC to JSC. (B) Cross section SEM image of the champion cell. (C) Hysteresis measurements of one PSC using different scanning speed under AM 1.5 G illumination.

THE POTENTIAL IMPACT, DISSEMINATION AND EXPLOITATION OF THE RESULTS

Scientific Impact and Dissemination of Results

NANOMATCELL has been instrumental in bringing European Research at the forefront of solution processed thin film solar cells. Within the NANOMATCELL project the involved partners succeeded in developing record performance solar cell devices in their corresponding classes:

i. A record performance colloidal quantum dot solar cell have been developed at ICFO with exceptional photostability. This brings ICFO second in the world in developing high PCE PbS QD solar cells also certified by accredited laboratories. In a work that has been accepted for publication in ***Nature Energy*** we demonstrated the first high efficiency (9.6%) and highly photostable PbS QD solar cell. After this result Europe no longer lags behind the compelling performance results demonstrated in the U.S and Canada and expertise in this class of solar cells is now available in Europe for future potential commercial uptake.

ii. We demonstrated the first ever solid-state solution-processed at low temperature and ambient conditions inorganic solar cell based entirely on non-toxic RoHS compliant materials. This brings about a huge impact for it demonstrates for the first time that compelling performance can be achieved using environmentally friendly nanomaterials paving the way for immediate commercial uptake and introduction on a broader scale (including wearable platforms, building integrated-PVs and distributed power grid networks) without regulatory concerns on closed-cycle recycling processes. This new material developed within NANOMATCELL, comprising $AgBiS_2$ Nanocrystals has achieved PCE´s of 6.3%, also certified by independent accredited labs (Newport), and the result is expected to be published.

iii. NANOMATCELL contributed in achieving record efficiency in DSSC´s via the use of molecularly engineered porphyrin dyes that consist of donor–p-bridge–acceptor moieties and that both maximize electrolyte compatibility and improve light-harvesting properties by the extending the spectral harnessing into the near infrared. This result was published in ***Nature Chemistry***.

iv. Within NANOMATCELL a novel sensitizer was developed and optimized that consisted of the recently discovered methyl-ammonium lead-halide perovskite materials. The first grand achievement of NANOMATCELL that was published in ***Nature*** demonstrated the first high performance perovskite-DSSC with efficiencies of 15%. Subsequently and with further optimization and designs of molecularly engineered hole transport layers, power conversion efficiencies exceeding 20% have been achieved. One of the world records in perovksites developed and demonstrated in Europe. This result was recently published in ***Nature Energy***.

The aforementioned landmark achievements that took place within NANOMATCELL indicate the high quality level research performed in this project and the dramatic impact this has in the European Research Landscape. Those are just a few of the significant scientific results that were reported in NANOMATCELL as indicated by the large number of peer-reviewed scientific publications (51 journal publications).

The scientific results of NANOMATCELL have been widely disseminated in high impact journals and international conferences. Just to name a few examples of the high level of dissemination, more than 7 publications have appeared in top-notch journals (Nature family and Science) and more than 30 publications have been accepted in Journals with impact factor > 9.

Several news releases have appeared following the publication of those significant results in Nature-family and Science magazines attracting the attention of public media:

http://actu.epfl.ch/news/dye-sensitized-solar-cells-rival-conventional-ce-2/

https://actu.epfl.ch/news/cheaper-solar-cells-with-202-efficiency/

http://actu.epfl.ch/news/cheap-hydrogen-fuel-from-the-sun-without-rare-meta/

https://www.icfo.eu/newsroom/news/article/2173

Socio-Economic Impact

With NANOMATCELL´s achievements European Research comes at the forefront of developing novel disruptive solar cell technologies that have now reached performance equal to that of standard and widely accepted Si-PV. The latter is widely dominated by production and development outside Europe, thus an opportunity arises for industrial development and SME creation that will take over the commercialization of technologies developed within Europe. For this to take place skilled and experienced personnel is required and NANOMATCELL has played a major role in training new scientists. Within NANOMATCELL at least 6 PhD students as well as several postdoctoral fellows have been trained and educated in the technologies developed. Moreover the intellectual property on the materials and devices that has been generated within NANOMATCELL as well as the proprietary know-how on several of the processes developed will form a strong basis for subsequent potential commercialization of these technologies.

The developments that took place in this project have led to the demonstration of disruptive solar cell technologies with commercially competing features in various levels:

- ✓ PbS QD solar cells with efficiencies in excess of 10% and operational lifetime under operating conditions have been achieved. This is a major milestone towards potential commercialization of this technology, for which a predicted PCE of 15% is considered the threshold for commercial deployment. Although this material platform contains Pb, PbS is considered one of the most stable phases as it is not water soluble and therefore similar encapsulation and closed recycling process schemes to those adopted for CdTe technologies can be adopted.
- ✓ $AgBiS_2$ nanocrystal based solar cells with efficiencies in excess of 6% have been realized. This major finding paves the way towards direct commercialization of this green technology free of RoHS and toxic compounds. At present the efficiencies achieved are not considered compelling enough for immediate commercialization, however with the recent findings developed of alternative QD materials, ICFO will proceed in further boosting the efficiency record of this material targeting for a potential commercialization plan.
- ✓ Perovskite solar cells with impressive efficiencies of over 20% have been recorded in NANOMATCELL. The present achievement renders this technology ready for commercial uptake as it yield efficiency comparable to that of Si PV, yet with manufacturing and production costs only at a fraction of it. What remains to be further explored is the stabilization (robustness) of those cells as well as the identification of appropriate sealing and recycling processes in view of the presence of Pb in a water-soluble form. Alternatively the findings reported in this project ignite new interest in the community in search for

alternative Pb-free perovskite compounds that may reach the efficiencies reported with Pb-based perovskites.

Once such technologies reach the market, EU will benefit from the truly renewable supply of energy provided by the Sun and will eventually lead towards a carbon-free economy and society. It is particularly noteworthy that the PV technologies reported herein enabling high-performance, low-cost solar cells with low-weight and flexible form factor may enable their use in applications well beyond power-grid, including self-powered sensor systems, communication networks/beacons, and wearable/portable electronics for IoT applications. Of particular importance to this is the non-toxic nature of the compounds that have been developed in this project that can be directly integrated in consumer electronic devices.

Exploitation of Results

Within NANOMATCELL two patents have been generated. One is from the industrial partner GCell, for which no further public disclosure can be made at this point. The other is from ICFO on the newly developed photovoltaic material that is Pb-free.

Within the project we conceived and synthesized this new material compound in colloidal nanocrystal phase, developed the proof-of-principle in working solar cell devices at the lab and then made significant optimization studies to report certified efficiencies in excess of 6%. The technology was taken from TRL1 to TRL3. Despite the end of this project ICFO is committed to progress the TRL of this technology by having secured additional funding (national (National funding scheme by the ministry of competitiveness and economy) and European (Marie Curie actions)) as a result of the successful demonstration within the current project. Our focus now is on further improving the performance of these solar cells towards a first milestone at 10%.

The address of the project website

www.nanomatcell.eu

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NanoMatCell

3.2 Use and dissemination of foreground

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES

NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages
1	Sequential deposition as a route to high-performance perovskite-sensitized solar cells	Burschka, Julian	Nature	Volume: 499 Issue: 745 8	Nature Publishing Group	United Kingdom	2013	316-+
2	Solution Processed Solar Cells based on Environmentally Friendly AgBiS2 Nanocrystals with Efficiencies over 5%,	M. Bernechea	Nature Photonics	Submitted	Nature Publishing Group	United Kingdom	TBD	
3	A molecularly engineered hole-transporting material for efficient perovskite solar cells	Saliba	Nature Energy	1, Article number: 15017	Nature Publishing Group	United Kingdom	2016	
4	The Role of surface passivation for efficient and photostable quantum dot Solar cells	Y. Cao	Nature Energy		Nature Publishing Group	United Kingdom	2016	
5	Perovskite solar cells employing organic charge-transport layers	Malinkiewicz, Olga	Nature Photonics	Volume: 8 Issue: 2	Nature Publishing Group	United Kingdom	2014	128-132
6	Water photolysis at 12.3% efficiency	Luo,	Science	Volume: 345 Issue: 620	Amercian	United	2014	1593-

	via perovskite photovoltaics and Earth-abundant catalysts.	Jingshan		4	Association for the Advancement of Science	States		1596
7	Heterovalent cation substitutional doping for quantum dot homojunction solar cells	A. Stavrinadis ,	Nature Commun.	4	Nature Publishing Group	United Kingdom	2013	2981
8	Remote trap passivation in colloidal quantum dot bulk nano-heterojunctions and its effect in solution-processed solar cells.	A. K. Rath	Adv. Mater.		Wiley-VCH	Germany	2014	
9	Role of oxygen in the degradation of methylammonium lead trihalide perovskite photoactive layers.	Aristidou	Angewandte Chemie International Edition	54	Wiley-VCH	Germany		8208
10	Dye-sensitized solar cells with 13% efficiency achieved through the molecular engineering of porphyrin sensitizers, S.	S. Mathew	Nature Chem.	6	Nature Publishing Group	United Kingdom	2014	242–7.
11	Flexible Perovskite Photovoltaic Modules and Solar Cells Based on Atomic Layer Deposited Compact Layers and UV-Irradiated TiO2 Scaffolds on Plastic Substrates.	F. Di Giacomo	Advanced Energy Materials	5	Wiley-VCH	Germany	2015	
12	Formation of porous SnS nanoplate networks from solution and their application in hybrid solar cells.	Thomas Rath	Chem. Commun	51	Royal Society of Chemistry	United Kingdom	2015	10198-10201
13	Mixed-Organic-Cation Perovskite Photovoltaics for Enhanced Solar-Light Harvesting.	Pellet, Norman	Angewandte Chemie-International Edition	Volume: 53 Issue: 12	Wiley-VCH	Germany	2014	3151-3157
14	Stable and Efficient Perovskite Solar	Qin, Peng	Small	Volume: 11 Issue: 41,	Wiley-VCH	Germany	2015	5533-

	Cells Based on Titania Nanotube Arrays			Nov 4, 2015				5539
15	Improved environmental stability of organic lead trihalide perovskite-based photoactive-layers in the presence of mesoporous TiO2	Flannan O'Mahony	Mater. Chem. A	3, 14, 7219-7223	Royal Society of Chemistry	United Kingdom	2015	
16	Solution processed bismuth sulfide nanowire array core/silver sulfide shell solar cells	Yiming Cao	Chemistry of Materials	27	American Chemical Society	United States	2015	3700-3706
17	Unraveling the Reasons for Efficiency Loss in Perovskite Solar Cells.	Lee, Yong Hui	Advanced Functional Materials.	Volume: 25 Issue: 25	Wiley-VCH	Germany		3925-3933
18	Understanding the Impact of Bromide on the Photovoltaic Performance of CH3NH3PbI3 Solar Cells.	Dar, M. Ibrahim	Advanced Materials.	Volume: 27 Issue: 44	Wiley-VCH	Germany		7221
19	Hybrid solution-processed bulk heterojunction solar cells based on bismuth sulfide nanocrystals.	L. Martinez	Phys. Chem. Chem. Phys		Wiley-VCH	Germany	2013	
20	High efficiency methylammonium lead triiodide perovskite solar cells: the relevance of non-stoichiometric precursors.	Roldan-Carmona, C	Energy & Environmental Science.	Volume: 8 Issue: 12	Royal Society of Chemistry	United Kingdom		3550-3556
21	Imprinted electrodes for enhanced light trapping in solution processed solar cells	A. Mihi	Adv. Mater	26	Wiley-VCH	Germany	2014	443-448
22	Indolizine-Based Donors as Organic Sensitizer Components for Dye-Sensitized Solar Cells.	Huckaba, Aron J	Advanced Energy Materials.	Volume: 5 Issue: 7	Wiley-VCH	Germany	2015	
23	Low-Temperature Solution Processing of Mesoporous Metal-Sulfide Semiconductors as Light-	Flannan O'Mahony	Angew. Chemie. Int.	52,46	Wiley-VCH	Germany	2013	12047-12051

	Harvesting Photoanodes.							
24	Investigation Regarding the Role of Chloride in Organic-Inorganic Halide Perovskites Obtained from Chloride Containing Precursors.	Dar, M. Ibrahim	Nano Letters	Volume: 14 Issue: 12	American Chemical Society	United States	2014	6991-6996
25	Nanowire Perovskite Solar Cell	Im, Jeong-Hyeok	Nano Letters	Volume: 15 Issue: 3	American Chemical Society	United States	2015	2120-2126
26	Nanocrystalline Rutile Electron Extraction Layer Enables Low-Temperature Solution Processed Perovskite Photovoltaics with 13.7% Efficiency.	Yella, Aswani	Nano Letters.	Volume: 14 Issue: 5	American Chemical Society	United States	2014	2591-2596
27	Molecular Engineering of Functional Materials for Energy and Opto-Electronic Applications	Gao, Peng	Chimia	Volume: 69 Issue: 5			2015	253-263
28	Silolothiophene-linked triphenylamines as stable hole transporting materials for high efficiency perovskite solar cells.	Abate, Antonio	Energy & Environmental Science.	Volume: 8 Issue: 10	Royal Society of Chemistry	United Kingdom	2015	2946-2953
29	Thermal Behavior of Methylammonium Lead-Trihalide Perovskite Photovoltaic Light Harvesters.	Dualeh, Amalie	Chemistry of Materials	Volume: 26 Issue: 21	American Chemical Society	United States	2014	6160-6164
30	Triazatruxene-Based Hole Transporting Materials for Highly Efficient Perovskite Solar Cells.	Rakstys, Kasparas	Journal of the American Chemical Society	Volume: 137 Issue: 51	Amerciam Chemical Society	United States		16172-16178
31	Solution-Processed mesoscopic Bi_2S_3:polymer photoactive layers	Andrew Maclachlan	Chem. Phys. Chem.	16	Wiley-VCH	Germany	2014	1019-1023
31	Unravel the Impact of Anchoring	Ganesan,	ACS	Volume: 3 Issue: 10, Oct	American	United	2015	11409-

	Groups on the Photovoltaic Performances of Diketopyrrolopyrrole Sensitizers for Dye-Sensitized Solar Cells.	Paramagur u	Sustainable chemistry & Engineering.	2015	Chemical Society	States		11413
32	Size and bandgap tunability in Bi_2S_3 colloidal nanocrystals and its effect in solution processed solar cells	M. Bernechea	J.Mater. Chem	3	Royal Society of Chemistry	United Kingdom	2015	20642-20648
33	Opportunities of Atomic Layer Deposition for Perovskite Solar Cells	V. Zardetto,	ECS Transactions	69	Electrochemical Society	United States	2015	15-22
34	Organohalide lead perovskites for photovoltaic applications	Gao, Peng	Energy & Environmental Science	Volume: 7 Issue: 8	Royal Society of Chemistry	United States	2014	2448-2463
35	A Novel Oligomer as a Hole Transporting Material for Efficient Perovskite Solar Cells.	Qin, Peng	Advanced Energy Materials	Volume: 5 Issue: 2	Wiley-VCH	Germany	2015	
36	Perovskite as Light Harvester: A Game Changer in Photovoltaics.	Kazim, Samrana	Angwandte Chemie-International Edition.	Volume: 53 Issue: 11	Wiley-VCH	Germany	2014	2812-2824
37	Photoanode Based on (001)-Oriented Anatase Nanoplatelets for Organic-Inorganic Lead Iodide Perovskite Solar Cell	Dar, M. Ibrahim	Chemistry of Materials.	Volume: 26 Issue: 16	American Chemical Society	United States	2014	4675-4678
38	Prospects of nanoscience with nanocrystals	M. V. Kovalenko	ACS Nano	9	American Chemical Society	United States	2015	1012-1057
39	Strategies for controlled electronic doping of colloidal quantum dot solids	A. Stavrinadis	ChemPhysChem	online DOI: 10.1002/cphc.201500834	Wiley-VCH	Germany	2015	
40	The influence of doping on the optoelectronic properties of PbS colloidal quantum dot solids	P. Papagiorgis	Sci. Rep.	5,	Nature Publishing Group	United Kingdom	2016	18735

41	Strong Photocurrent Amplification in Perovskite Solar Cells with a Porous TiO2 Blocking Layer under Reverse Bias	Moehl, Thomas	Journal of Physical Chemistry Letters	Volume: 5 Issue: 21	ACS Publications	United States	2014	3931-3936
42	Thiol-free synthesized copper indium sulfide nanocrystals as optoelectronic quantum dot solids	D. So	Chemistry of Materials	27	American Chemical Society	United States	2015	8424-8432
44	A Methoxydiphenylamine-Substituted Carbazole Twin Derivative: An Efficient Hole-Transporting Material for Perovskite Solar Cells.	Gratia, Paul	Angewandte Chemie-International Edition.	Volume: 54 Issue: 39 Special Issue:SI	Wiley-VCH	Germany	2015	11409-11413
45	Energy level alignment in TiO2 /metal sulfide/polymer interfaces for solar cell applications	Rebecka Lindblad	Phys. Chem. Chem. Phys	16	Wiley-VCH	Germany	2014	17099
45	Perovskite Solar Cells: Influence of Hole Transporting Materials on Power Conversion Efficiency.	Ameen, Sadia;	Chemsuschem	Volume: 9 Issue: 1	Wiley-VCH	Germany	2016	10-27
46	Double D-pi-A Dye Linked by 2,2'-Bipyridine Dicarboxylic Acid: Influence of para- and meta-Substituted Carboxyl Anchoring Group	Ganesan, Paramaguru	Chemphyschem	Volume: 16 Issue: 5	Wiley-VCH	Germany	2015	1035-1041
47	Charge Transfer Dynamics from Organometal Halide Perovskite to Polymeric Hole Transport Materials in Hybrid Solar Cells.	Brauer, Jan C.	Journal of Physical Chemistry Letters.	Volume: 6 Issue: 18	ACS Publications	United States	2015	3675-3681
48	Atomic Layer Deposition of Highly Transparent Platinum Counter Electrodes for Metal/Polymer Flexible Dye-Sensitized Solar Cells.		Advanced Energy Materials	Volume 4, Issue 4, March 11 (2014)	Wiley-VCH	Germany	2014	
49	A simple spiro-type hole	Ganesan,	Energy &	Volume: 8 Issue: 7	Royal Society	United	2015	1986-

	transporting material for efficient perovskite solar cells.	Paramagur u	Environment al Science		of Chemistry	Kingdom		1991
50	Improved electronic coupling in hybrid organic-inorganic nanocomposites employing thiol-functionalized P3HT and bismuth sulfide nanocrystals.	L. Martinez	Nanoscale	6	Royal Society of Chemistry	United Kingdom	2014	10018
51	Determination of carrier lifetime and mobility in colloidal quantum dot films via impedance spectroscopy	A. K. Rath	Appl. Phys. Lett.	104	American Institute of Physics	United Stated	2014	63504

Template A2: list of dissemination activities							
NO.	*Type of activities[1]*	*Main leader*	*Title*	*Date /Period*	*Place*	*Type of audience[2]*	*Countries addressed*
1	*Conference*	*G.Konstantatos*	*Solution processed QD solar cells*	*2013*	*3rd international conference on semiconductor sensitized and quantum dot solar cells, Granada*	*Scientific*	*International*
2	*Conference*	*G.Konstantatos*	*Solution processed QD optoelectronics and solar cells*	*2013*	*4th International Conf. from nanomaterials to nanosystems and devices, IC4N, Corfu Greece,*	*Scientific*	*International*
3	*Conference*	*Alexandros Stavrinadis*	*Electronic doping of quantum dots for air stable homojunction*	*2013*	*5th International Conference on Hybrid and Organic Photovoltaics*	*Scientific*	*International*

			photovoltaics		*(HOPV2013), Seville, Spain*		
4	*Conference*	*G.Konstantatos*	*Solution processed nanocrystal solar cells¨ Bayern-Innovative, Next generation of Solar Cells*	*2013*	*Bayern-Innovative, Next generation of Solar Cells, Erlangen, Germany*	*Scientific*	*International*
5	*Conference*	*G. Konstantatos*	*NANOMATCELL a FET Energy EU project for new materials for solar cells" in Progress in Photovoltaics and Nanotechnology: From FP7 to Horizon 2020*	*2013*	*EU PV Clusters workshop*	*Scientific*	*EU*
6	*Conference*	*Alexandros Stavrinadis*	*Cation doping of PbS quantum dots with a range of elements and the exceptional case of bismuth as a dopant for achieving air-stable homojunction solar cells"*	*2014*	*30 years of colloidal quantum dots. Paris, France*	*Scientific*	*International*
7	*Conference*	*V. Zardetto*	*Low Temperature Atomic Layer Deposition for Flexible Dye Sensitized Solar Cells*	*2014*	*ALD4PV Workshop, Eindhoven, The Netherlands,*	*Scientific*	*International*

8	*Conference*	*V. Zardetto*	*Low Temperature Plasma Assisted Atomic Layer Deposition of TiO2 Blocking Layers for Flexible Hybrid Mesoscopic Solar Cells*	*2014*	*AVS, Baltimore, USA*	*Scientific*	*International*
9	*Conference*	*V. Zardetto*	*ALD processes for photovoltaic applications*	*2014*	*Baltic ALD conference, Helsinki, Finland*	*Scientific*	*International*
10	*Conference*	*V. Zardetto*	*Counter-Electrode and Compact Layers for Flexible Dye-Sensitized Solar Cells by means of Low Temperature Atomic Layer Deposition*	*2014*	*Baltic Atomic Layer Deposition, Helsinki,Finland*	*Scientific*	*International*
11	*Conference*	*A. Stavrinadis*	*Doping in Colloidal quantum dot solids and development of QD homojunctions*	*2014*	*ESPCI, Paris, France*	*Scientific*	*International*
12	*Poster*	*V. Zardetto*	*Synthesis of Platinum Nanoparticles by means of Low Temperature Atomic Layer Deposition Processes for Flexible Dye-Sensitized Solar Cells*	*2014*	*FOM, Veldhoven, The Netherlands*	*Scientific*	*International*
13	*Conference*	*S. Haque*	*Antimony sulfide solar cells*	*2014*	*HOPV 14, EPFL, Lausanne*	*Scientific*	*International*

14	*Conference*	*A. Stavrinadis*	*Hybrid Bi2S3 – polymer solar cells*	*2014*	*HOPV Sevilla, Spain*	*Scientific*	*International*
15	*Conference*	*G.Konstantatos*	*Solution processed nanocrystal solar cells*	*2014*	*MRS Fall Mtg, Boston, USA*	*Scientific*	*International*
16	*Conference*	*Yong Hui Lee*	*Influence of Porosity and Pore Size on Perovskite Solar Cell Efficiency*	*2014*	*MRS Spring Meeting , San Francisco, California*	*Scientific*	*International*
17	*Poster*	*V. Zardetto*	*Low Temperature Plasma Assisted Atomic Layer Deposition of TiO2 Blocking Layers for flexible Hybrid Mesoscopic Perovskite Solar Cells*	*2014*	*MRS, Boston, USA*	*Scientific*	*International*
18	*Conference*	*G.Konstantatos*	*Solution processed QD optoelectronics and solar cells¨Nanoscience with Nanocrystals*	*2014*	*NANAX6, Bad Hofgastein, Austria*	*Scientific*	*International*
19	*Conference*	*Gerasimos Konstantatos*	*Colloidal Quantum dot Optoelectronics and solar cells*	*2014*	*NANAX6, Bad Hofgestein, Austria*	*Scientific*	*International*
20	*Conference*	*M. Bernechea*	*Colloidal* $AgBiS_2$ *Nanocrystals. New Non-Toxic Material for Solution Processed Solar Cells*	*2014*	*Solution processed Semiconductor Solar Cells (SSSC14). Oxford, UK*	*Scientific*	*International*
21	*Conference*	*M. Bernechea*	*AgBiS2 Nanocrystals as a novel panchromatic*	*2014*	*SSSC Oxford, Unite Kingdom*	*Scientific*	*International*

			solution processed inorganic semiconductor for environmentally friendly solar cells				
22	*Poster*	*Y. Cao*	*Solution processed solar cells based on Bismuth Sulfide Nanowire Array Core/Silver Sulfide Shell Structure*	*2014*	*SSSC Oxford, Unite Kingdom*	*Scientific*	*International*
23	*Conference*	*G.Konstantatos*	*Solution processed nanocrystal solar cells¨International Conference Solution processed Semiconductor Solar Cells*	*2014*	*SSSC14, Oxford, UK*	*Scientific*	*International*
24	*Conference*	*G.Konstantatos*	*"Engineering the Electron Properties of CQDs from the Atomic to Supra-nanocrystalline Level for Solar Cell Applications*	*2014*	*The International Conference Solution processed Semiconductor Solar Cells (SSC14). Oxford, United Kingdom*	*Scientific*	*International*
25	*Conference*	*V. Zardetto*	*Low thermal ALD Al2O3 on mesoporous layer for photovoltaic applications*	*2015*	*ALD FUNdamental Workshop, Eindhoven, The Netherlands*	*Scientific*	*International*
26	*Conference*	*V. Zardetto*	*Low Temperature Plasma-Assisted Atomic Layer Deposition of TiO2*	*2015*	*AVS,San Jose,USA*	*Scientific*	*International*

			Blocking Layers for Organo-Metal Halide Perovskite Solar Cells				
27	Conference	V. Zardetto	Opportunities of Atomic Layer Deposition for Perovskite Solar Cells	2015	ECS, Phoenix, USA	Scientific	International
28	Conference	V. Zardetto	Atomic Layer Deposition of TiO2 Compact Layers for Flexible Mesostructured Perovskite Cells and Modules on Plastics	2015	EU PVSEC, Hamburg,Germany	Scientific	EU
29	Conference	G.Konstantatos	Solution processed nanocrystal solar cells	2015	KAUST conference on Functional Nanomaterials and Devices, KAUST, Saudi Arabia.	Scientific	International
30	Conference	G.Konstantatos	Colloidal Quantum dot Photovotaics	2015	NANOTEXNOLOGY 2015, Thessaloniki, Greece	Scientific	International
31	Conference	V. Zardetto	Atomic Layer Deposition of TiO_2 Compact Layers for Flexible Perovskite Cells on Plastics	2015	NGOPV, Groningen, The Netherlands,	Scientific	International
32	Conference	V. Zardetto	Atomic Layer Deposition of TiO2 Blocking Layers for Flexible Perovskite Cells and Modules on Plastics",	2015	Perovskite Workshop, Delft, The Netherlands	Scientific	International

33	*Conference*	*V. Zardetto*	*Low temperature Atomic Layer Deposition of TiO2 Compact Layers for Flexible Perovskite Cells on Plastics*	*2015*	*SPIN15, Santiago de Compostela, Spain*	*Scientific*	*International*
34	*Conference*	*V. Zardetto*	*Atomic layer deposition for interface engineering in dye-sensitized and perovskite solar cells*	*2015*	*SVC Techcon, Santa Clara, USA*	*Scientific*	*International*
35	*Conference*	*Gerasimos Konstantatos*	*Colloidal Quantum dot solar cells tailoring their properties from the atomic to suprananocrystalline level*		*HOPV, Lausanne, Swiss*	*Scientific*	*International*

Section B (Confidential[3] or public: confidential information to be marked clearly)
Part B1

The applications for patents, trademarks, registered designs, etc. shall be listed according to the template B1 provided hereafter.

The list should, specify at least one unique identifier e.g. European Patent application reference. For patent applications, only if applicable, contributions to standards should be specified. This table is cumulative, which means that it should always show all applications from the beginning until after the end of the project.

TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.					
Type of IP Rights[4]:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)
	Yes	10/07/2015	EP15176300	CONFIDENTIAL	G. Konstantatos, M. Bernechea, N.C. Miller;
	Yes	08/04/2015	GB2518837 (A)	CONFIDENTIAL	V-L. Silvia and K. G. Chittibabu

[3] Note to be confused with the "EU CONFIDENTIAL" classification for some security research projects.

[4] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

NanoMatCell

Part B2

Please complete the table hereafter:

Type of Exploitable Foreground[5]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[6]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
-	-	-	-	-	-	-	-	-

In addition to the table, please provide a text to explain the exploitable foreground, in particular:

- Its purpose
- How the foreground might be exploited, when and by whom
- IPR exploitable measures taken or intended
- Further research necessary, if any
- Potential/expected impact (quantify where possible)

[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[6] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

3.3 Report on societal implications

Replies to the following questions will assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information *(completed automatically when **Grant Agreement number** is entered.*	
Grant Agreement Number:	308997
Title of Project:	NANOMATCELL
Name and Title of Coordinator:	Dr. Gerasimos Konstantatos

B Ethics	
1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***No***
2. Please indicate whether your project involved any of the following issues (tick box) :	***NO***
RESEARCH ON HUMANS	
• Did the project involve children?	
• Did the project involve patients?	
• Did the project involve persons not able to give consent?	
• Did the project involve adult healthy volunteers?	
• Did the project involve Human genetic material?	
• Did the project involve Human biological samples?	
• Did the project involve Human data collection?	
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	
• Did the project involve Human Foetal Tissue / Cells?	
• Did the project involve Human Embryonic Stem Cells (hESCs)?	
• Did the project on human Embryonic Stem Cells involve cells in culture?	
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	
• Did the project involve tracking the location or observation of people?	
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	
• Were those animals transgenic small laboratory animals?	

• Were those animals transgenic farm animals?	
• Were those animals cloned farm animals?	
• Were those animals non-human primates?	
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	
DUAL USE	**NO**
• Research having direct military use	
• Research having the potential for terrorist abuse	

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	**Number of Women**	**Number of Men**
Scientific Coordinator	0	1
Work package leaders	2	4
Experienced researchers (i.e. PhD holders)	6	16
PhD Students	0	5
Other	2	11

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	**5**
Of which, indicate the number of men:	3

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project?	○ ●	Yes No

6. Which of the following actions did you carry out and how effective were they?

	Not at all effective				Very effective
☐ Design and implement an equal opportunity policy	○	○	○	○	○
☐ Set targets to achieve a gender balance in the workforce	○	○	○	○	○
☐ Organise conferences and workshops on gender	○	○	○	○	○
☐ Actions to improve work-life balance	○	○	○	○	○

○ Other:

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

- ○ Yes- please specify
- ● No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

- ● Yes- please specify: Support was provided to Soapbox Science Newcastle, The Royal Society "Colourful Chemistry" Summer school at Newcastle and a IUPAC International Year of Light exhibit "Light for Life" at The Great North Museum: Hancock, Newcastle.University
- ○ No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

- ● Yes- please specify: Http://www.nanomatcell.eu G24 has developed a basic DSSC assembly kit using flexible electrodes and sealing materials.
- ○ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

- ● Main discipline[7]: 2.3, 1.3
- ● Associated discipline[7]: 1.2, 1.3
- ○ Associated discipline[7]:

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*	○ ●	Yes No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

- ● No
- ○ Yes- in determining what research should be performed

[7] Insert number from list below (Frascati Manual).

○ Yes - in implementing the research
○ Yes, in communicating /disseminating / using the results of the project

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

○ No
○ Yes- in framing the research agenda
○ Yes - in implementing the research agenda
○ Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
○ No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid		Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport	

13c If Yes, at which level?

- ○ Local / regional levels
- ○ National level
- ○ European level
- ○ International level

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**51**
To how many of these is open access[8] provided?	**10**
How many of these are published in open access journals?	**17**
How many of these are published in open repositories?	**6**
To how many of these is open access not provided?	**34**
Please check all applicable reasons for not providing open access:	
☒ publisher's licensing agreement would not permit publishing in a repository ☐ no suitable repository available ☒ no suitable open access journal available ☐ no funds available to publish in an open access journal ☐ lack of time and resources ☐ lack of information on open access ☐ other[9]: ……………	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	**2**

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	**0**
	Registered design	**0**
	Other	**0**

17. How many spin-off companies were created / are planned as a direct result of the project?	**0**
Indicate the approximate number of additional jobs in these companies:	

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

☐ Increase in employment, or	☐ In small & medium-sized enterprises
☐ Safeguard employment, or	☐ In large companies
☐ Decrease in employment,	☐ None of the above / not relevant to the project
☐ Difficult to estimate / not possible to quantify	

[8] Open Access is defined as free of charge access for anyone via Internet.
[9] For instance: classification for security project.

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*
Difficult to estimate / not possible to quantify	❑

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

○ Yes ○ No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes ○ No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

- ❑ Press Release
- ❑ Media briefing
- ❑ TV coverage / report
- ❑ Radio coverage / report
- ❑ Brochures /posters / flyers
- ❑ DVD /Film /Multimedia
- ❑ Coverage in specialist press
- ❑ Coverage in general (non-specialist) press
- ❑ Coverage in national press
- ❑ Coverage in international press
- ❑ Website for the general public / internet
- ❑ Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

- ❑ Language of the coordinator
- ❑ Other language(s)
- ❑ English

Question F-10: Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)
2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]
2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES
3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)
3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)
3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES
4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)
4.2 Veterinary medicine

5. SOCIAL SCIENCES
5.1 Psychology
5.2 Economics
5.3 Educational sciences (education and training and other allied subjects)
5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES
6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)
6.2 Languages and literature (ancient and modern)
6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]