FULLSPECTRUM: A NEW PV WAVE MAKING MORE EFFICIENT USE OF THE SOLAR SPECTRUM

A.Luque[1], A. Martí[1], L. Cuadra[1], C. Algora[1], P. Wahnon[1], G. Sala[1], P. Benítez[1], A.W. Bett[2] , A. Gombert[2], V.M. Andreev[3],
C. Jassaud[4], J.A.M. Van Roosmalen[5], J. Alonso[6], A. Räuber[7,] G. Strobel[8], W. Stolz[9], B. Bitnar[10], C. Stanley[11], J.C. Conesa[12],
W. Van Sark[13], K. Barnham[14], R. Danz[15], T. Meyer[16], I. Luque-Heredia[17], R. Kenny[18], C. Christofides[19]

[1]Universidad Politécnica de Madrid (IES-UPM), *Coordinator e-mail: luque@ies-def.upm.es, Tel: +34 91 544 10 60*;
[2]Fraunhofer ISE, Freiburg Germany; [3]Ioffe Physico-Technical Institute, St. Petersburg, Russia; [4]CEA, Grenoble, France;
[5]ECN, Petten, The Netherlands; [6]Isofoton, Málaga, Spain; [7]Projektgesellschaft Solare Energiesysteme (PSE), Freiburg,
Germany; [8]RWE Solar Space Power, Heilbronn, Germany; [9]Philipps University of Marburg, Germany; [10]PSI, Villigen,
Switzerland; [11]University of Glasgow (UG), United Kingdom; [12]CSIC, Madrid, Spain; [13]University of Utrecht, The
Netherlands; [14]Imperial College, London, United Kingdom; [15]FHG, Golm, Germany; [16]Solaronix, Aubonne, Switzerland;
[17]Inspira, Las Rozas, Spain; [18]European Commission, DG JRC, Ispra, Italy; [19]University of Cyprus, Nicosia, Cyprus

ABSTRACT: This work introduces the five lines of research that the FULLSPECTRUM project is pursuing. Sponsored by the European Commission under the Sixth Framework Programme, FULLSPECTRUM aims to make better use of the solar spectrum than conventional single-gap cells currently do. The aforementioned lines of research are: 1) multi-junction solar cells, 2) solar thermophotovoltaic converters, 3) intermediate band materials and cells, 4) molecular-based concepts, and 5) novel, non-imaging optic techniques for sunlight concentration and assembling procedures, as well as normative related work. Some of the photovoltaic concepts involved are completely novel requiring a profound, basic scientific research and innovative technological approach. Others, such as multi-junction cells, have already been proven scientifically and probably just need further technological development. This work summarises the efforts that FULLSPECTRUM will be making during the next five years towards a more efficient generation of electricity and at a lower and competitive cost.

Keywords: Fundamentals, High Efficiency, Low Cost.

1 INTRODUCTION

The conventional single-gap solar cell makes poor use of the solar spectrum. On the one hand, sub-bandgap photons cannot be absorbed and exploited for the photovoltaic (PV) conversion. On the other hand, the absorption of high energy photons generates electron-hole pairs whose energy excess over the gap is wasted quickly through phonon emission. The most idealised single-gap solar cell would exhibit, under fully concentrated sunlight, a limiting efficiency of 40,7% [1, 2]. This inefficient exploitation of the solar spectrum is one of the reasons why the PV-generated electricity is not cheap enough to compete with fuel-based, hydroelectric and nuclear energies. There are, however, a variety of economical, political, social and ecological reasons [3] that compel us to look for a new generation of PV converters which, thanks to a better use of the FULL solar SPECTRUM, are capable of enhancing their efficiency and reducing the cost of PV-generated electricity. This is the general goal of FULLSPECTRUM, an Integrated Project (IP) supported by the European Commission. It is made up of the nineteen research institutions and companies listed in the heading of this paper. The research and development activities have been classified into the following five groups: 1) Multi-junction cells (MJC) based on III-V compound semiconductors, 2) Solar thermo-photovoltaic (TPV) converters, 3) Intermediate band (IB) materials and cells (IBC), 4) Molecular-based concepts (MBC) for full PV use of the solar spectrum, and 5) Manufacturing Technologies (MFG) (which includes novel, compact, non-imaging optics and assembling procedures) as well as normative work for the novel PV systems under development.

Each of the sections below briefly centres on summarising these research activities.

2. MULTI-JUNCTION SOLAR CELLS (MJC)

Simply put, a multi-junction solar cell consists of a stack of single-gap solar cells as illustrated in Figure 1. The cell on top exhibits the broadest of the gaps, while the rest of the cells are ordered by decreasing gaps. Each cell absorbs those photons whose energy ranges its own gap and that of the cell on top of it. The limiting efficiency of a stack containing an infinite number of cells is 86.6% [4], much greater than that of the single-gap cell (40.7%) [1, 2].

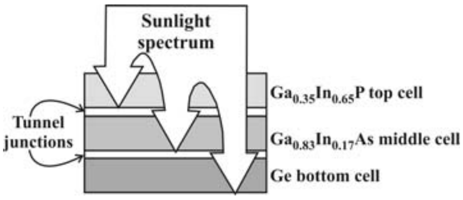

Figure 1. Simplified sketch of a three-junction solar cell.

Currently, high-concentration MJCs seems to be the most realistic path to a better use of the solar spectrum, increasing the efficiency and decreasing the cost of PV-generated energy. Non-imaging optics, that maximise the transfer of light power on the cell rather than forming an image, plays an important role in cost reduction and will be developed within the MFG activity. Some estimates predict costs of about 0.1 € kWh^{-1} if the MJC operates at efficiencies of 30 % under a sunlight concentration of over 500 suns. The Fraunhofer Institute for Solar Energy Systems (FhG-ISE) has already developed monolithic two-junction cells ($Ga_{0.35}In_{0.65}P$ and $Ga_{0.83}In_{0.17}As$ cells), which have reached efficiencies over 30 % under 1000 suns. In this respect, the target of the MJC activity is the development of a high concentration (~1000 suns), MJCs with efficiencies ranging from 35% to 40%, and susceptible to commercialization for terrestrial use since MJC are currently only commercialised for space.

MJCs can be manufactured by using two approaches: mechanically stacked, or monolithically (internally series connected) stacked cells. The advantage of monolithic series connected cells in comparison to mechanically stacked cells is the use of only one substrate, which reduces its cost at the expenses of increasing its complexity. Just as with the goal of reducing the cost, the monolithic approach has been the one chosen here. These more complex device structures can be grown using industrial-size MOVPE (Metal-Organic Vapour Phase Epitaxy) technology.

Figure 1 shows the structure of one of the monolithic, triple-junction cells that will be produced. Similarly, sophisticated and advanced multi-layer structures will be developed within this activity. As mentioned, FhG-ISE, the co-ordinator of this activity, is already able to manufacture dual-, triple- and even quadruple-junction solar cells. Novel materials consisting of ternary and/or quaternary III-V compound semiconductors will be researched further in reaching the 40% goal. FhG-ISE, the Instituto de Energía Solar–Universidad Politécnica de Madrid (IES-UPM), the Philipps University of Marburg (PUM), the IOFFE Institute, RWE-SSP and ISOFOTON will be collaborating in the manufacture of high efficiency monolithic MJCs.

3. SOLAR THERMOPHOTOVOLTAIC (TPV) CONVERTERS

In a TPV converter, sunlight is used to heat a material that emits a spectrum for which the cell gap is better matched [5, 6]. Figure 2 will assist us in explaining its basic operation. Thanks to the concentrator, a special material called "emitter" (or "radiator") absorbs the concentrated solar energy and re-emits it with a spectrum close to that of a blackbody at a given temperature. Part of this radiation reaches the TPV cell after passing through a filter, which allows only the transmission of those photons whose energy is above and close to its gap. Note that, although high energy photons could be absorbed by the cell by generating high-energy carriers, nevertheless its full energy cannot be exploited for PV conversion because of their extremely fast thermalisation. Therefore, these photons are better used if they are reflected in the filter and sent back to the emitter where they can be absorbed and contribute to heating it. The limiting efficiency of this concept is 85.4% [7].

Although known since the 60's, the TPV concept has still not been manufactured nor commercialized. To accomplish these objectives, FULLSPECTRUM relies on a variety of research and development activities.

The first cluster of works is related to the design and manufacture of the concentrator system used to heat the emitter. The IOFFE Institute will be researching into a composite, low cost, high efficiency "silicone-glass" Fresnel lenses to obtain a high power (up to 100 W) solar source capable of efficiently heating the emitters.

The second group of tasks will be the development of the solar-powered emitters (including vacuum tungsten emitters), mirrors and selective filters.

The final area of work involves the development of the TPV cells themselves. High-efficient, GaSb-based, single-junction as well as tandem TPV cells (consisting of InGaAsSb/GaSb or AlGaAsSb/GaSb heterostructures) will be developed and manufactured. Their open circuit voltage is expected to be increased by more than twice while their efficiency by 1.15-1.25 times when compared to GaSb cells.

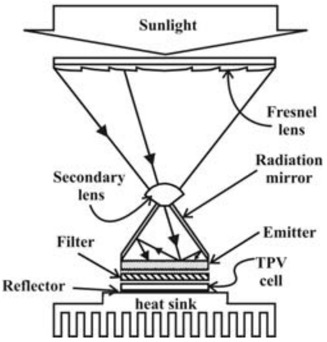

Figure 2. Illustration of the TPV concept

The distribution of the activities is as follows. IOFFE and CEA-DTEN will be involved in the crystalline growth of GaSb and GaInSb and in the wafer manufacture. The TPV cells will be grown by IOFFE, FhG-ISE, IES-UPM, and CEA–DTEN, while the selective emitters and solar-powered emitters will be researched by FhG-ISE, PSI, and IOFFE. Finally, the complete solar TPV converter and its industrialisation will be carried out by IOFFE, PSI, IES-UPM, and ISOFOTON.

4. INTERMEDIATE BAND MATERIALS AND CELLS

The intermediate band cell (IBC) [8] aims to exploit the two-step absorption of sub-bandgap photons via a half-filled "intermediate band" (IB) within the gap between the conduction band (CB) and the valence band (VB). Modelled by means of three different quasi-Fermi levels for electrons in each of these bands, its basic structure, shown in Figure 3, consists of an IB material sandwiched between two conventional *n*- and *p*-type emitter layers [9]. The absorption of sub-bandgap photons such as those labelled "1" excites electrons from the VB to the IB, while the absorption of sub-bandgap photons "2" pumps electrons from the IB to the conduction band. Thanks to this two-step absorption of sub-bandgap photons, wasted in single-gap cells, the IBC increases its current. The emitters are necessary for extracting the current without reducing the voltage and for preventing the IB from becoming short-circuited with the metallic contacts. The limiting efficiency of the IBC is 63.2% [8], much greater than that of the single-gap cell and even that of the 2-junction cell.

A second approach that is closely related to the IB concept is the "up-conversion of sub-bandgap photons"

[10]. The up-conversion mechanism also involves the absorption of two sub-bandgap photons causing the two-step generation of electrons via an intermediate level. The radiative band-to-band recombination produces the emission of an up-converted photon (i.e. with a higher energy than that of any of the two individual absorbed photons). The complete device would thus consist of an up-converter behind a conventional bifacial solar cell. The up-converter is electronically isolated from the cell and is capable of absorbing the sub-bandgap photons transmitted by the cell. The up-converted photons emitted by the up-converter can therefore be absorbed by the cell, which leads to an extra generation of carriers. This approach eases the constrains required when the IB is implemented within the bulk of the solar cell (mainly because of the danger of introducing devastating non-radiative recombination), and has the advantage that it can be used with current conventional solar cell technology, and that the up-converter and the cell can be optimised independently. The last approach, known as "down-conversion of high-energy photons" [11], photons with energies larger than twice the bandgap of the solar cell are absorbed by a luminescence converter, which transforms them into two lower-energy photons, which can be absorbed by the cell.

The main objectives of IBC activity are: 1) The improvement of the physics and technology for the IB concept (IES-UPM, University of Glasgow (UG), and CSIC). 2) The manufacture and characterisation of quantum-dot (QD) intermediate band cells [12, 13] (UG, IES-UPM, University of Cyprus). 3) Search for IB materials through quantum mechanical calculations (IES-UPM, CSIC). 4) Chemical guidance for identification and synthesis of those stable IB materials capable of putting the aforementioned concepts into practise (CSIC, IES-UPM).

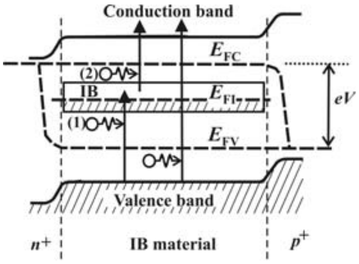

Figure 3. Basic band structure of an IBC. E_{FC}, E_{FI}, E_{FV} label respectively the quasi-Fermi levels for electrons in the conduction, intermediate and valence bands.

5. MOLECULAR BASED CONCEPTS (MBC)

"Molecular-based" refers here to those concepts that aim to take advantage of certain especific material properties which are mainly determined by the "small" size (nanometre scale) of their individual constituents (for instance, molecular dyes and quantum dots) rather than by the matrix itself where they are imbedded. In particular, two concepts for better photovoltaic conversion will be addressed here: the mesoporous metaloxide structure (e.g. the dye solar cell) and the flat plate (luminescent) concentrator shown in Figure 4. Five partners will collaborate in developing these concepts: ECN, the University of Utrecht (UU-Sch), Imperial College of London (ICSTM), the Fraunhofer-Institut fuer Angewandte Polymerforschung (FhG-IAP), and Solaronix.

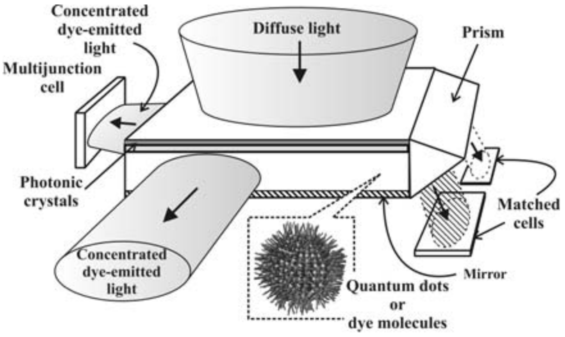

Figure 4. Illustration of a flat concentrator.

The dye solar cell [14] is characterised by a mesoporous titanium dioxide lattice which is sensitised by a monomolecular dye layer. Absorption of light and charge separation is arranged within the dye layer while the further carrier transport to the electrodes is carried out by majority carriers only. By introducing two (or more) photon processes in the dye, the spectral sensitivity can be enhanced towards full spectrum use. The search for these dyes is one of the targets aimed at.

This flat concentrator is a very interesting concept proposed by Goetzberger *et al*. [15] in the 70's. In recent years a number of achievements and proposals [16] have renewed the interest of using these concepts to put a low cost, flat, static concentrator into practise. First, the ability to get full spectrum use by using various colour centres [17]. Second, the development of quantum dots as stable, high efficiency luminescent absorbers in combination with several developments in organic/ molecular materials [18, 19]. Three, the advances in photonic crystals, which have a forbidden energy gap for photons and can assist in light confinement [20]. Figure 4 will assist us in explaining how the flat concentrator makes a better use of diffuse sunlight. Sunlight enters the concentrator with full angular aperture. Within the concentrator, molecular-based materials are capable of absorbing it causing some of its constituents to reach an excited energy state. When these elements de-excite, they emit radiation within a narrow bandwidth. This is the case in luminescent dyes of different colors or in quantum dots. Sunlight is thus absorbed by these molecules that radiate it as luminescent radiation at the corresponding wavelength. By an appropriate combination of photonic crystals (placed at the illuminated surface) and a rear mirror, the dye-emitted radiation is concentrated and laterally transported up to the edges of the concentrator, through which it escapes and illuminates the MJCs. These are designed to exploit the PV conversion optimally for the aforementioned set of different colors emitted by the molecules. Alternatively, a prism can separate the colors spatially and project each one onto individual, single-gap cells matched to any of the colors.

6. MANUFACTURING TECHNOLOGIES (MFG) AND NORMATIVE WORK

The double goal of this activity is, on the one hand, the development of optical, assembling and tracking techniques for manufacturing IBCs and MJCs and, on the other hand, the development of pre-normative work for the novel PV systems developed.

Non-imaging optics, which aim to transfer the radiant energy maximally rather than the image formation, plays a crucial role in cost reduction. This is because these optical elements collect light through a longer surface than that of the cell, but they are manufactured with a much cheaper material than the cell. These novel and flat concentrators, like the one in Figure 5, will be developed by IES-UPM and ISOFOTON. Since these concentrators are rather flat, it is feasible to integrate them into modules with a thickness comparable to that of a flat module. A great advantage of this approach is that it could be manufactured by using the LED-assembling techniques, which will probably be extensively used and help in reducing the cost. The tracking system for these modules will be carried out by INSPIRA and IES-UPM.

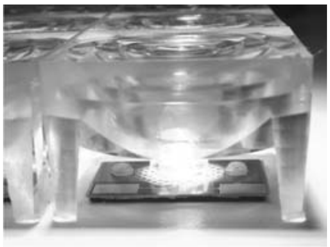

Figure 5. Photograph of a flat, non-imaging optics concentrating light energy onto a cell.

Finally, the Joint Researh Centre - Institute for Enviorment and Sustainability (JRC-IES) will prepare a pre-normative definition of a standard rating for MJC systems and, if possible, also for systems with general better use of the solar spectrum.

7 SUMMARY

This work has summarised the five lines of research included in FULLSPECTRUM project. 1) Multi-junction cells based on III-V compound semiconductors and non-imaging optics aim to reach efficiencies ranging from 35% to 40% under 1000 suns. 2) The research into solar thermophotovoltaic converters pursues the achievement of a prototype capable of commercialisation. 3) The research into the IBC concept centres, on one hand, on searching for stable IB materials and, on the other hand, the manufacture of a QD-IBC. 4) The progress in molecular-based concepts for full PV utilisation of the solar spectrum will be focusing on dye-cells and flat concentrators. 5) The project will be completed with the development of a set of manufacturing technologies (compact, non-imaging optics and assembling procedures) as well as normative work for the novel aforementioned PV approaches.

ACKNOWLEDGEMENTS

This work has been supported by the European Commission through the funding of the project FULLSPECTRUM (Ref. N: SES6-CT-2003-502620).

REFERENCES

[1] Shockley W, Queisser H, *J. Appl. Phys.* **32**, 510-519 (1961).

[2] Araújo G.L. and Martí A., *Solar Energy Materials and Solar Cells* **31**, 213-240 (1994).

[3] A. Luque and A. Martí, in A. Martí and A. Luque (Edt.) “NEXT GENERATION PHOTOVOLTAICS. High efficiency through full spectrum utilization”, IOP Publishing, ISBN 0 7503 0905 9, (2004), pp. 1–18.

[4] De Vos A, Pauwels H, *Appl. Phys.* **25**, 119–125 (1981).

[5] V. M. Andreev, *Proc. of the Workshop “The Path to Ultra High Efficiency Solar Cells”*, JRC, Italy (2001), pp. 51-65.

[6] P.A. Davies, A. Luque, Solar Energy Materials and Solar Cells, **33**, 11-22, (1994).

[7] A Luque, and A. Martí, in A Luque and S Hegedus, (eds.), *Handbook of Photovoltaic Science and Technology,* Chapter 4, Wiley, Chichester, 2003.

[8] A. Luque and A. Martí, *Physical Review Letters,* vol. 78, no. 26, pp. 5014–5017, 1997.

[9] A. Luque and A. Martí, *Progress in Photovoltaics: Research and Applications*, vol. 9. no. 2, pp. 73–86, 2001.

[10] T. Trupke, M.A. Green and P. Wurfel, *Journal of Applied Physics*, vol. 92, no.7, pp 4117–4122, 2002.

[11] T.Trupke, M.A.Green and P.Wurfel, *Journal of Applied Physics*, vol. 92, no. 3, pp. 1668–1674, 2002.

[12] A. Martí, L. Cuadra and A. Luque, *IEEE Transactions on Electron Devices*, vol. 48, no. 10, pp. 2394–2399, 2001.

[13] A. Martí, L. Cuadra and A. Luque, *IEEE Transactions on Electron Devices*, Vol. 49, No. 9, pp. 1632–1639, 2002.

[14] M. Späth, J.M. Kroon, P.M. Sommeling, J. Wienke, J.A.M. van Roosmalen. 26th IEEE Photovoltaic Specialists Conference, 29 Sep - 3 Oct 1997, Anaheim, USA.

[15] A.Goetzberger, W.Greubel, *Appl. Phys.* **14** (1977), 123.

[16] K.Barnham, J.L.Marques, J.Hassard, P.O’Brien, Appl.Phys.Lett. **76, (**2000**)** 1197.

[17] A.P.Alivisatos *MRS Bulletin*, February 1998, 18.

[18]W.G.J.H.M. van Sark, P.L.T.M. Frederix, A.A. Bol, H.C. Gerritsen, A. Meijerink, *Chem.Phys.Chem.* **3** (2002) 871-879.

[19] T.Trindade, P.O’Brien and X.Zhang, *Chemistry of Materials* **9 (**1997**)** 523.

[20] K. P. Velikov, C. G. Christova, R. P. A. Dullens, and A. van Blaaderen, *Science* **296**, 106-109 (2002).