Executive Summary:

Our Proposal has been investigating the practical implementation of the intermediate band solar cell (IBSCs) pursuing strategies of high efficiency and low cost. An intermediate band solar cell consists of an 'intermediate band material' sandwiched between two conventional semiconductors of p and n type. The 'intermediate band material', that gives the name to the solar cell, is characterised by the existence of a collection of energy levels (intermediate band, IB) located between the conduction and valence bands (CB and VB). This IB divides the semiconductor bandgap, EG, into two bandgaps EL and EH. The potential of this cell is equivalent to a 3-junction solar cell but without the requirement for tunnel junctions. Its practical implementation requires:

1. An intermediate band material, to which it is possible to manufacture appropriate contacts.
2. The absorption of two sub-bandgap photons in the sense of one photon pumping an electron from the valence band (VB) to the intermediate band (IB) and a second photon pumping an electron from intermediate band (IB) to the conduction band (CB). It is this two photon absorption process (which it is not a simultaneous three particle collision process) that allows the extraction of a higher current when compared to the operation of single gap solar cells.
3. Carrier relaxation between bands has to occur at a much lower rate than carrier relaxation within bands. This is normal in conventional semiconductors and in the IBSC allows for the existence of three distinguishable quasi-Fermi levels associated with each of the bands (EFC, EFI and EFV for the CB, IB and VB respectively). Since the output voltage of the cell is related to the difference between electron and hole quasi-Fermi levels and this difference is set by the emitters, the output voltage of the cell is still limited by the largest of the bandgaps EG. This allows for the extraction of the higher current arising from the additional two photon generation process without voltage degradation.

Project Context and Objectives:

Using energy levels inside the bandgap to increase the efficiency of solar cells was first analysed by Wolf [M. Wolf, Proc. IRE ; Vol/Issue: 48:7, Pages: 1247 (1960)] in 1960, before Shockley and Queisser published [W. Shockley, and H. J. Queisser, J. Appl. Phys. 32, 510 (1961)] their detailed balance analysis of the efficiency of solar cells. After his analysis, the possibility of using these levels to increase the efficiency of solar cells was rejected. It is perhaps worthwhile pointing out that the possibility of using tandem solar cells (proposed by Jackson [E. D. Jackson, Trans. Conf. on the Use of Solar Energy, Tucson, 1955, University of Arizona Press, Tucson 5, 122 (1958)]) was also rejected at that time since the use of tunnel junctions for connecting the cells was not yet realised. In 1997 [A. Luque, and A. Martí, Physical Review Letters 78, 5014 (1997)] researchers now in the IBPOWER consortium, used detailed balance arguments to recalculate the efficiency limit of a system with energy levels inside the bandgap assuming recombination to and from this intermediate level was radiative. They concluded that the efficiency limit of the concept was 63.2 % at maximum light concentration. This maximum was achieved for bandgaps EG=1.95 eV, EL=0.71 eV and EH=1.24 eV. They also pointed out the need for an intermediate 'band' rather than a collection of intermediate 'levels' to suppress the non-radiative recombination generally introduced by energy levels located inside the gap, and the need of emitters to isolate the IB ir order to make possible the split of quasi-Fermi levels and hence the production of an output voltage [A. Luque, and A. Martí, Progress in Photovoltaics: Res. Appl. 9, 73 (2001)] not limited by EL nor EH. In order to enable the IB to accommodate electrons from the VB as well as supply electrons to the CB, the IB should be partially filled with electrons.

Nevertheless, something had to be done about this intermediate level or levels to approach the radiative limit since these traditionally behave as non-radiative recombination centres that degrade the cell efficiency and must be avoided. In this respect, it was hypothesized that in order to have potential to perform radiatively, the collection of energy levels inside the bandgap, when implemented in bulk material, should constitute a 'band' [A. Luque, and A. Martí, Progress in Photovoltaics: Res. Appl. 9, 73 (2001)] and therefore the name, 'intermediate band'. Forming a 'band' vs. a 'level' means that the electronic properties of the electrons in this intermediate band should be similar to the ones they have in the conduction or valence band. If recombination radiatively limited is possible between conduction and valence band why should it not be possible between the conduction band and the valence band if in the latest the electrons have the same properties than in a conventional valence band, for example? In this respect, it was postulated that the path for inhibiting non-radiative recombination through deep centres was through the achievement of the delocalization of the electron wavefunction when at the intermediate levels. It was postulated that this could be achieved by increasing the impurity concentration to the point where impurities became to 'see' each other [A. Luque et al., Physica B 382, 320 (2006)].

Implementing the intermediate band from deep levels acting as precursors was not the only approach proposed to take the intermediate band approache to practice. In 2000 [A. Martí, L. Cuadra, and A. Luque, Conference Record of the Twenty-Eighth IEEE Photovoltaic Specialists Conference, 2000, 940] it was proposed that the intermediate band could be implemented in practice using quantum dots. When using quantum dots the intermediate band would arise for the energy levels corresponding to the electrons confined in the dots. Quantum 'dots' and not 'wells' were preferred to implement the IBSC because, on the one hand, quantum wells do not provide a true null density of states between the intermediate band and the conduction band but it is actually a continuum [C. Weisbuch, and B. Vinter, Quantum Semiconductor Structures (Academic Press, San Diego, 1991]. On the other hand, what it would be the absorption of light from the IB to the CB is forbidden in a quantum well for front illumination [J. P. Loehr, and M. O. Manasreh, Semiconductor quantum wells and superlattices for long-wavelength infrared detectors (Artech House, Boston, 1993)].

Building on these ideas IBPOWER proposed the development of intermediate band solar cells following four approaches:

I. Quantum dots. Quantum dots were actually the first experimental systems where the IB was implemented that lead to an actual solar cell [A. Luque et al., J. Appl. Phys. 96, 903 (2004)]. These quantum dot systems (based on InAs/GaAs) allowed also the demonstration of some of the principles of operation of the IB concept, as for example, the absorption of two below bandgap energy photons to produce one electron-hole pair [A. Martí et al., Physical Review Letters 97, 247701 (2006)]. University of Glasgow has been leading this approach.

II. Thin films. It was postulated [A. Martí, D. F. Marrón, and A. Luque, J. Appl. Phys. 103, 073706 (2008)] that the insertion of Fe or Ti into CuIn1-xGaxS2 could lead to the formation of an intermediate band at an appropriate position inside the bandgap with the potential to produce a high efficiency solar cell. IBPOWER proposed to investigate this possibility in practice. This approach, therefore, pursues the implementation of the IBSC as a low cost PV solution. Helmholtz Zentrum Berlin leaded this approach.

III. Indium Gallium Nitride with Mn. The bandgap of In1-xGaxN can potentially be tailored from <=0.77 eV (x=0) to 3.42 eV (x=1) by changing the In composition. Manganese (Mn) introduces a deep centre in InGaN. Because Mn can be incorporated at high dilution factors into InGaN, it was proposed [A. Martí et al., Sol. Energy Mater. Sol. Cells 93, 641 (2009)] that this deep centre could evolve into an (intermediate) band when the Mn concentration would exceed the Mott transition (6×1019 cm-3). IBPOWER proposed to elaborate on this idea by studing this approach experimentally. Unversity of Nottingham leaded this approach.

IV. Transition metals in III-V compounds. Transition metals introduce deep centres in III-V semiconductors and, therefore, could lead to the formation of an IB if inserted at sufficiently high densities. IBPOWER proposed to study, in particular the insertion of Ti in GaAs and attempt the manufacturing of cells based on this material. Riber SA leaded this approach.

The Instituto de Energia Solar of the Universidad Politécnica de Madrid has coordinated the Project.

Project Results:

During its development our proposal has deployed a large effort in disseminate its results through international journals where the reader can find discussed in more detail the results we will summarise in the next paragraphs. Some of these publications will be quoted as our description of the main S& T results/foregrounds progresses.

The operation of an intermediate band solar cell relies on two main physical principles. The first is the absorption of below bandgap energy photons; the second is that the open circuit voltage of the cell is not limited by the intermediate band.

The absorption of below bandgap energy photons in quantum dot intermediate band solar cells (QD-IBSCs) was already demonstrated before this project started [A. Martí, E. Antolin, C. R. Stanley, C. D. Farmer, N. Lopez, P. Diaz, E. Canovas, P. G. Linares, and A. Luque, "Production of Photocurrent due to Intermediate-to-Conduction-Band Transitions: A Demonstration of a Key Operating Principle of the Intermediate-Band Solar Cell," Physical Review Letters, vol. 97, pp. 247701-4, 2006.] Once the below bandgap photon absorption was demonstrated, during this proposal we have been able to demonstrate that voltage preservation also takes place in quantum dot intermediate band solar cells. First it was demonstrated using a laser source to illuminate the cells [E. Antolín, A. Martí, P. G. Linares, I. Ramiro, E. Hernández, C. D. Farmer, C. R. Stanley, and A. Luque, "Advances in quantum dot intermediate band solar cells," in Photovoltaic Specialists Conference (PVSC), 2010 35th IEEE, 2010, pp. 000065-000070] and a few months later using concentrated white light [P. G. Linares, A. Martí, E. Antolín, I. Ramiro, and A. Luque, "Voltage recovery in intermediate band solar cells operated under concentration," Solar Energy Materials and Solar cells, vol. in press, 2011].

At room temperature, the open circuit voltage (VOC) of the IBSCs is lower than that of the reference cell without QDs. However, as the temperature decreases, the VOC of both cells becomes approximately the same (the VOC of the QD cell being actually higher). Then, in this way, it is shown that the open-circuit voltage of the cell is not limited by the intermediate band created in the cell from the electron confinement in the quantum dots.

The fact we have to lower the temperature to achieve this result is well explained by the IBSC theory since it is when the temperature is lowered that the thermal escape from the IB to the CB is inhibited and voltage can be recovered. When thermal escape is dominant [A. Luque, A. Marti, E. Antolin, P. G. Linares, I. Tobias, and I. Ramiro, "Radiative thermal escape in intermediate band solar cells," AIP Advances, vol. 1, pp. 022125-6, 2011], the quantum dots only serve to the purpose of tailoring the bandgap (which can be useful for other solar cell approaches but it is not our goal here).

Voltage recovery does not occur in all QD-IBSC. QD-IBSCs fabricated to date from InGaAs/GaAs quantum dot arrays exhibit a quantum efficiency that extends to below bandgap energies. However, the production of sub-bandgap photocurrent relies often on the thermal and/or tunneling escape of carriers from the QDs, that is, without a second external photon has had necessarly to be absorbed . In [E. Antolín, A. Martí, C. D. Farmer, P. G. Linares, E. Hernández, A. M. Sánchez, T. Ben, S. I. Molina, C. R. Stanley, and A. Luque, "Reducing carrier escape in the InAs/GaAs quantum dot intermediate band solar cell," Journal of Applied Physics, vol. 108, p. 064513, 2010] we tested the effectiveness of introducing a thick GaAs spacer in addition to an InAlGaAs strain relief layer over the QDs to reduce carrier escape. From an analysis of the QE at different temperatures, it was concluded that escape via tunneling can be completely blocked under short-circuit conditions, and that carriers confined in QDs with an InAlGaAs strain relief layers exhibited a thermal escape activation energy over 100 meV larger than in the case of InAs QDs capped only with GaAs.

Within the context of the QD-IBSC, it is of interest to investigate the maximum value that can be achieved for the smaller of the transitions EL, since values larger than 0.3 eV are required for improved performance. In [P. G. Linares, A. Martí, E. Antolín, A.Luque, C.D.Farmer, S.Chakrabarti, C.R.Stanley, A.M.Sánchez, T.Ben, and S.I.Molina, Energy Procedia 2, 133-141 (2010).] we provided both theoretical and experimental arguments to verify the shift of the IB position to deeper energies by using an Inx(GayAl1-y)1-xAs capping layer, fulfilling the double function of increasing the QD size and eliminating the discontinuity in the conduction band between the quaternary cap and the GaAs barrier.

The presence of multiple energy levels in the intermediate band solar cell was studied in [A. Luque, P. G. Linares, E. Antolín, E. Cánovas, C. D. Farmer, C. R. Stanley, and A. Martí, Applied Physics Letters 96, 013501-3 (2010).] by detailed balance calculations under ideal conditions. Since multiple levels are often found experimentally in IB cells made with quantum dots, these act to reduce the limiting efficiency determined from detailed balance calculations.

Based on a generalized model of the Shockley   Read   Hall (SRH) statistics published in [A. Luque, A. Martí, N. López, E. Antolín, E. Cánovas, C. R. Stanley, C. Farmer, and P. Díaz, Journal of Applied Physics 99, 094503 (2006).], the effect of the partial filling of the intermediate band in IB solar cells and the ways of producing it were analyzed in [A. Luque and A. Marti, Electron Devices, IEEE Transactions on 57, 1201-1207 (2010).] as is its influence on the electron   hole pair generation by subband-gap photons. The differences between cells with the conduction band and the IB thermally coupled and uncoupled were stressed.

The sub bandgap photon absorption of light provided by the quantum dots is insufficient to boost the cell efficiency. To solve this problem, we have proposed several strategies during the course of the Project, including the investigation of growth methods that yield to increased quantum dot densities and the investigation of the impact of the shape of the quantum dots on the absorption in order to improve our understanding of the absorption processes in QDs. In [A. Luque, A. Martí, E. Antolín, P. G. Linares, I. Tobías, I. Ramiro, and E. Hernandez, "New Hamiltonian for a better understanding of the quantum dot intermediate band solar cells," Solar Energy Materials and Solar cells, vol. 95, pp. 2095-2101, 2011.] for example, we proposed a new mathematical method to calculate the wave-functions of the electrons in the quantum dots. This knowledge is necessary to attempt the calculation of the absorption coefficients involved in the operation of the intermediate band solar cell as we did, for example in [A. Luque, A. Martí, E. Antolin, and P. Garcia-Linares, "Intraband absorption for normal illumination in quantum dot intermediate band solar cells," Solar Energy Materials and Solar cells, vol. 94, pp. 2032-2035, 2010].

In [I.Tobias, A. Luque, and A.Martí, Semic. Sci. Tech 26, 014031 (2011).] we reported on the development of a numerical model for the IB solar cell in one dimension and studied with this model the influence doping the IB layer has on the device performance. At this stage, the IB model was simplified and included neither transport nor multiple energy levels. Two solar cell structures were simulated. Both featured a similar short circuit current increment at low concentration due to the IB; however, the open-circuit voltage and behavior under concentration were very different. In the first structure, the sub-bandgap current was large and achieved with an empty IB because the generation was completed via a strong thermal coupling of the intermediate and conduction bands; however, this implied large recombination under forward bias. Consequently the voltage was low and the current responsivity decreased steeply with concentration. In the second structure, both sub-bandgap transitions were light-induced. This lead to much better performance, although the IB must be thicker to achieve the same current as in the previous case.

During the Project we have also researched on technologies to assist the absorption of light by the QDs such as the use of diffraction grids and metal nanoparticles. For example:

1. In [A. Mellor, I. Tobías, A. Martí, M. J. Mendes, and A. Luque, "Upper limits to absorption enhancement in thick solar cells using diffraction gratings," Progress in Photovoltaics: Research and Applications, vol. 19, pp. 676-687, 2011] we studied the application of diffraction gratings to solar cells to supersede the light trapping limits of conventional Lambertian structures. In this paper a mathematical formalism was derived for calculating the absorption that could be expected in a solar cell equipped with a diffraction grating, which could be applied to any lattice geometry and grating profile. Furthermore, the formalism was used to calculate the upper limit of total absorption that can theoretically be achieved using a diffraction grating. The derived formalism and limits were valid when the solar cell thickness is greater than the coherence length of the illuminating solar spectrum. Comparison was made to the upper limit achievable using an angularly selective Rugate filter, which was also calculated. Both limits were found to be considerably higher than the Lambertian limit within the range of sunlight concentration factors practically employed in photovoltaic systems (1   1000 X). The upper limit of absorption using the diffraction grating was shown to be equal to the thermodynamic limit for all absorbances and concentration factors. The limit for the Rugate filter is generally lower, but tends to the thermodynamic limit for lower cell absorbances.

2. In [M. J. Mendes, A. Luque, I. Tobias, and A. Marti, "Plasmonic light enhancement in the near-field of metallic nanospheroids for application in intermediate band solar cells," Applied Physics Letters, vol. 95, pp. 071105-3, 2009], in order to enhance infrared light absorption in sub-bandgap transitions in an intermediate band solar cell, we studied the scattered near-field potential from uncoated and coated metallic nanoparticles with a spheroidal shape using an electrostatic model. We found that the absorption enhancement produced at the surface plasmon frequency of the nanoparticles could be of several orders of magnitude in some cases.

The gap of the GaAs is not the optimum for an IBSC. Higher bandgap materials should be investigated. The fundamental theory states that this bandgap should be in the range of 2 eV while the gap of GaAs is 1.42 eV. In this respect, in [P. G. Linares, A. Marti, E. Antolin, and A. Luque, "III-V compound semiconductor screening for implementing quantum dot intermediate band solar cells," Journal of Applied Physics, vol. 109, pp. 014313-8, 2011.] we searched for optimum material QD systems to implement the IBSC in the As/AlxGa1xAs, InAs1yNy /AlAsxSb1x, and InAs1zNz /AlxGayIn1y1xP families. For the search we presented an analytical method consisting of the following steps: 1) calculation of the heterojunction band alignment taking material strain into account; 2) calculation of the QD confined energy levels constituting the IB, and 3) calculation of the efficiency limits in the detailed balance realm and optimization of the QD systems in terms of QD size and material composition. The optimum QD sizes were also calculated.

We have also proposed new kind of quantum dot materials for the implementation of the intermediate band solar cell [E. Antolín, A. Martí, and A. Luque, "The Lead Salt Quantum Dot Intermediate Band Solar Cell," Proc. 37th IEEE PVSC, 2011]. One set of new materials is formed by lead salt QDs of the family IV-VI (PbTe, PbSe or PbS) embedded in a semiconductor of the family II-VI (Cd1-xMgxTe, CdxZn1-xTe, and CdS1-xSex or ZnSe1-xTex, respectively). These QDs are not nucleated due to lattice mismatch, as it is the case of the InAs/GaAs QD material system grown by the Stranski-Krastanov (S-K) mode. In these materials, the QDs precipitate due to the difference in lattice type: the QD lead salt material crystallizes in the rocksalt structure, while the II-VI host material has the zincblende structure. Therefore, it is possible to use lattice-matched QD/host combinations, avoiding all the strain-related problems found in previous QD-IBSC developments. We have studied the properties of the lead salt QD materials and proposed that they are appropriate to overcome the fundamental drawbacks of present III-V based QD-IBSC prototypes. We have also calculated the band diagram for some examples of IV-VI/II-VI QD materials.

Another class of quantum dots we have explored are colloidal QDs with metal nanoparticles inserted [M. Mendes, A. Martí, I. Tobías, and A. Luque, "Intermediate band solar cell having solution processed colloidal quantum dots," US patent request no. 61/547,312, 2011]. The quantum dots are provided with a shell which enables the absorption of photons with energies within an extended range as 10 compared to conventional solar cells, thus increasing the efficiency of the solar cell. The metal nanoparticles are efficient optical antennas at their surface plasmon resonance, attracting the light from their surroundings and focusing it in their near-field, thereby forming a light trapping structure in the cell that increases the absorption of light in the intermediate band and, thus, further improves the conversion efficiency of the solar cell.

Regarding the thin film approach, titanium has been incorporated in CuInS2 thin films and devices by diffusion of Ti from the substrate during the CuInS2 co-evaporation growth process. The CuInS2 crystal structure resulted un affected but the grain size was reduced compared to Ti-free reference samples [B. Marsen, L. Steinkopf, I. Lauermann, M. Gorgoi, H. Wilhelm, T. Unold, R. Scheer, and H. W. Schock, Solar Energy Materials and solar Cells, 1730-1733 (2010)] X-ray photoelectron spectroscopy showed the presence of TiO2 at the front of the absorber layer, which appeared at the heterojunction interface of the completed CuInS2/TiO2/CdS/ZnO solar cells. Low temperature photoluminescence spectra showed no additional transitions that could be assigned to Ti-based impurity defect levels. Ti-containing cells showed conversion efficiencies higher than the Ti-free reference cells due to higher open-circuit voltage (efficiency 11%, VOC 731 mV). No reduction in short circuit current was detected indicating that the titanium did not introduced additional bulk recombination. Temperature-dependent current-voltage measurements indicated a reduced interface recombination for cells containing Ti, which is attributed to the TiO2 interlayer detected by X-ray photoelectron spectroscopy. About 0.04 at% titanium was incorporated in CuInS2 thin films by means of a Ti-precursor layer deposited on the molybdenum back contact. The titanium did not affect the chalcopyrite crystal structure as detected by XRD, but it did result in slightly smaller grains compared to Ti-free devices. The titanium content increased toward the front surface of the films, indicating significant diffusion of titanium within the CuInS2 lattice during the film growth. XPS measurements showed that the titanium is bonded to oxygen, establishing the presence of TiO2 in the region close to the front surface. Solar cells made from Ti-containing material showed an increase in open-circuit voltage and an increase in efficiency compared to the Ti-free devices. No significant increase in non-radiative recombination due to defects was detected. From temperature-dependent I V measurements it was concluded that the increased open-circuit voltages resulted from a change in interface recombination due to an increased interface bandgap. In conjunction with the XPS results we concluded that the TiO2 surface layer, which in the device becomes a TiO2 interlayer between CuInS2 and CdS, was responsible for the reduced interface recombination. With the present methods of investigation, no evidence for Ti entering the chalcopyrite lattice, or for the emergence of new electronic states within the fundamental CuInS2 bandgap was found. Improvements in device performance were not due to intermediate band action but reduction of interface recombination. The current findings suggested that the efficiency of (non-IB) Cu(In,Ga)S2-based heterojunction solar cells could be improved by the use of suitable functional layers at the heterojunction interface. Other synthesis methods (co-evaporation of impurity species) and material systems (CuGaS2) were suggested as avenues toward bulk intermediate band materials.

In order to progress towards thin film semiconductor hosts with larger bandgaps, the incorporation of metal impurities M (M=Ti, Fe, or Sn) into CuGaS2 films was investigated experimentally as a function of impurity concentration [B. Marsen, S. Klemz, G. Landi, L. Steinkopf, R. Scheer, S. Schorr, and H. W. Schock, Thin Solid Films (2011).]. Films were synthesized by thermal co-evaporation of the elements onto glass/Mo substrates heated to 400 °C   570 °C. The compositions of the resulting films were measured by energy-dispersive X-ray spectroscopy and the structures of the present phases are studied by X-ray diffraction. The formation of Cu   M   S ternary phases was observed in a wide range of conditions. Films of Cu   Ga   Ti   S, synthesized at 500 °C, showed the presence of a cubic modification of CuGaS2 and Cu4TiS4. Alloying of CuGaS2 and tetragonal Cu2SnS3 was observed for substrate temperatures of 450 °C. A miscibility gap opens at 500 °C and above with separate Sn-rich and Ga-rich phases. Similarly, alloys of CuFeS2 and CuGaS2 were only found in Cu   Ga   Fe   S films synthesized at lower substrate temperature (400 °C), whereas at 500 °C a miscibility gap opened leading to separate Fe-rich and Ga-rich phases. Photovoltaic devices were fabricated from CuGa1-xFexS2 thin films concurrently deposited on Mo-coated glass substrates using the standard chalcopyrite glass/Mo/absorber/CdS/ZnO device structure. The device characteristics of these solar cells were evaluated by current   voltage and quantum efficiency measurements. For Fe-containing CuGaS2 films, distinct sub-gap absorption bands at 1.2 eV and 1.9 eV were detected, which increased in prominence with increasing Fe content. On the other hand, the solar cell parameters were found to deteriorate with increasing iron content, indicating an increase in non-radiative recombination when high levels of iron are incorporated. However, for the lowest iron content (x=0.003), an increase in the sub-gap photoresponse at about 1.9 eV was observed, which is attributed to a combination of sufficient intermediate band absorption and carrier collection at this dilution level [B. Marsen, S. Klemz, T. Unold, and H.W. Schock, Progress in Photovoltaics: Research and Applications, n/a-n/a (2012)].

The electronic structure of modified CuGaS2 was also analyzed from first principles within the density functional theory. The chalcopyrite matrix was modified by introducing a high concentration of atomic impurities that included transition metals and elements of group IVa at substitutional sites of the lattice host. For selected cases, an intermediate band was theoretically predicted that potentially fulfills the requirements as stated for intermediate-band solar cell materials. Preliminary thermochemical estimations of the stability of the compounds proposed against eventual secondary phases in the form of binary chalcogenides greatly simplified the general screening. Elements of groups VIIIb and IVa were identified as interesting impurity candidates to obtain intermediate bands within the main gap of the modified ternary host. Additionally, modified chalcopyrite compounds with potential applications as magnetic semiconductors or spintronic materials were identified. The transformation of chalcopyrite compounds as used for thin-film solar cells into intermediate-band materials could have a particular impact on the design of thin-film intermediate-band solar cells, with improved figures of energy conversion efficiency expected [C. Tablero and D. Fuertes Marrón, The Journal of Physical Chemistry C 114, 2756-2763 (2010)].

In progress towards a next generation of photovoltaics, devices based on InGaN may play a significant role, due to the unique properties of the nitride-based materials. In particular, because the band gap covers the entire range from 0.64 eV for InN to 3.4 eV for GaN, devices based on InGaN are now being extensively studied for various applications. InGaN-based opto-electronic devices already form the basis for industrial applications including, blue light emitting diodes (LEDs) and blue/violet laser diodes and for electronic devices including high-power RF transistors. The same material system will form the basis for future solid state lighting, by combining efficient nitride based LEDs with appropriate phosphors to obtain the correct colour balance. In many cases, a key issue is the quality and availability of suitable substrates, since unlike other III V compounds, no bulk substrates are available for group III-Nitride semiconductors. For photovoltaic applications, the ability to cover the whole of the spectral range in a single materials system could have significant implications for cost savings; however, there is a considerable mis-match in lattice parameter between InN and GaN, which would make conventional multi-junction solar cells difficult to produce without introducing a high defect density. In our Project we have investigated an alternative approach to high-efficiency solar cells as it is the Intermediate Band Solar Cell (IBSC). In [C. T. Foxon, S. V. Novikov, and R. P. Campion, in Next Generation of Photovoltaics: New Concepts edited by A.B.Cristóbal, A.Martí, and A.Luque (Springer Verlag, Berlin, 2012).] we discussed the growth method needed to produce suitable InGaN-based structures, in particular the use of Mn in InGaN to form the intermediate band within an InGaN p i n heterojunction. It is also well known, however, that there are significant difficulties associated with p-doping for In-rich InGaN, which were also discussed. In our Project we have collaborated also with University of Cadiz [F. M. Morales, D. Carvalho, T. Ben, R. García, S. I. Molina, A. Martí, A. Luque, C. R. Staddon, R. P. Campion, and C. T. Foxon, Scripta Materialia 66, 351-354 (2011)] to study the morphology of our InGaN grown by MBE [J. L. Hall, A. J. Kent, C. T. Foxon, and R. P. Campion, Journal of Crystal Growth 312, 2083-2088 (2010)] in which special attention was devoted to the control of the temperature during growth. In this respect, temperature rises during growth of nxGa1-xN on non-mounted GaAs substrates were observed. The magnitude of the rise was found to increase with increasing In content. A semi-quantitative model has been presented, which despite its limitations we believe explains the origin of the rises observed during the growth of GaN and InN on GaAs. The small rise in GaN is a result of a phonon frequency difference between GaAs and GaN, while the large rise in InN is due to large numbers of free carriers present in the InN layer. The lack of a heat loss mechanism in the model currently means that it cannot yet be used for other growth scenarios. Model results were only presented for GaN and InN, as too many unknowns exist for InxGa1-xN.The rises in temperature largely occur as only a small percentage of the heater radiation is coupled into the substrate prior to growth. Different system configurations are therefore expected to yield different results, for example, substrates mounted on PBN plates should lead to much smaller temperature rises.

Concerning the implementation of the IBSC on GaAs using transition metals, it is expected that the main results appear published in some journal in the next months. However, at the moment of writing these lines and given that this document is public domain, we cannot unclose yet the results.

Potential Impact:

The research this Project has undertaken is of fundamental type and therefore, its real socio-economic impact is foreseen in the long term. Related to long term targets, the intermediate band concept pursues, by producing high efficiency solar cells at low cost, to impact in the achievement of the goals identified by the European Photovoltaic Technology Platform for 2020 (0.1   /kWh for the typical electricity generation costs in Southern Europe; 1.5   /Wp for the typical turn-key price for a 100 kW; 0.5 years for the typical system energy payback time in Southern Europe) in their roadmap to achieve the SET Plan objectives (to reduce carbon dioxide emissions by 20 percent by 2020, increase to 20 percent by 2020 the renewable energy share of the energy mix, and improve energy efficiency by 20 percent by 2020).

At scientific level, the scheme followed in the Project to research on intermediate band solar cells is expected to impact the research with which other Groups could develop the idea. Our scheme encourages accelerating the research at device level as the approach to achieve the general picture about whether a particular intermediate band solar cell implementation is going to work as well as to early identify its weaknesses. For example, it might happen that very efficient intermediate band materials are identified in the future but, although without doubt interesting from a fundamental point of view, they might become will be useless to produce efficient solar cells if we do not develop in parallel the technology for properly contacting them without losses. If these materials are too exotic, it might be that the technology for contacting them also requires substantial research effort. This is why we encourage research at complete device level.

It has been motivating that other Groups worldwide have independently developed proof of concept intermediate band solar cell devices based on different materials. Some examples worldwide are ZnTe:O solar cells [W. Wang, A. S. Lin, and J. D. Phillips, Applied Physics Letters 95, 011103, 2009] and GaNxAs1-x alloys [N. Lopez, L. A. Reichertz, K. M. Yu, K. Campman, and W. Walukiewicz, Physical Review Letters, vol. 106, p. 028701, 2010]. The number of intermediate band material candidates increases yearly. Not all of them will work, but this fact emphasises our idea of attempting their practical implementation as early as possible in order to learn if this is the case.

The Project has done a large dissemination effort mainly through international peer-reviewed journals. We hope this effort is useful to other researchers, not only to learn from the things we might have done right but, most importantly, from our mistakes. The following is a selected list of publications that reflect IBPOWER's work.

1. E. Antolín, A. Martí, C. Farmer, P. G. García- Linares, E. Hernández, A. M. Sánchez, T. ben, S. I. Molina, C. Stanley, and A. Luque, "Reducing carrier scape in the InAs/GaAs quantum dot intermediate band solar cell," Journal Applied Physics, vol. 108, p. 064513 2010.

2. E. Cánovas, D. F. Marron, A. Martí, A. Luque, A. Bett, F. Dimroth, and S. Phillips, "Photoreflectance analysis of a GaInP/GaInAs/Ge multijunction solar cell," Appl. Phys. Lett., vol. 97, p. 203504, 2010.

3. E. Canovas, A. Marti, A. Luque, and W. Walukiewicz, "Optimum nitride concentration in multiband III-N-V alloys for high efficiency ideal solar cells," Applied Physics Letters, vol. 93, p. 174109, Oct 27 2008.

4. P. G. García- Linares and e. al., "Inx(GayAl1-y)1-xAs quaternary alloys for quantum dot intermediate band solar cells," Energy Procedia, vol. 2, pp. 133-141, 2010.

5. J. L. Hall, A. J. Kent, C. T. Foxon, and R. P. Campion, "Temperature effects during the growth of InxGa1-xN films through the whole compositional range by plasma-assisted molecular beam epitaxy," Journal of Crystal Growth, vol. 312, pp. 2083-2088, Jul 2010.

6. P. G. Linares, A. Martí, E. Antolin, and A. Luque, "III-V compound semiconductor screening for implementing quantum dot intermediate band solar cells," Journal Applied Physics, vol. 109, p. 014313, 2011.

7. F. LLopis, I. Tobias, and M. Jakas, "Light intensity enhancement inside the grooves of metallic gratings," J. Opt. Soc. Am. B, vol. 27, p. 129233, 2010.

8. A. Luque, P. García-Linares, E. Antolin, E. Cánovas, C. Farmer, C. Stanley, and A. Martí, "Multiple levels in intermediate band solar cells," Appl. Phys. Lett., vol. 96, pp. 013501-3, 2010.

9. A. Luque and A. Marti, "Can impurities be beneficial to photovoltaics?," Solid State Phenomena, vol. 156-158, pp. 107-114, 2010.

10. A. Luque and A. Martí, "On the Partial Filling of the Intermediate Band in IB Solar Cells," IEEE Transactions on Electron Devices, vol. 57, pp. 1201-1207, 2010.

11. A. Luque and A. Martí, "Photovoltaics: Towards the intermediate band," Nature Photonics, vol. 5, pp. 137-138, 2011.

12. A. Luque, A. Martí, E. Antolín, and P. G. García- Linares, "Intraband Absorption for Normal Illumination in Quantum Dot Intermediate Band Solar Cells," Solar Energy Materials and Solar Cells, vol., 2010.

13. A. Luque, A. Marti, E. Antolín, P. García-Linares, I. Tobías, and I. Ramiro, "Radiative thermal escape in intermediate band solar cells," AIP Advances, vol. 1, pp. 022125-6, 2011.

14. A. Luque, A. Martí, E. Antolín, P. García-Linares, I. Tobías, I. Ramiro, and E. Hernandez, "New Hamiltonian for a better understanding of the quantum dot intermediate band solar cells," Solar Energy Materials and Solar Cells, vol. 95, pp. 2095-2101, 2011.

15. B. Marsen, S. Klemz, G. Landi, L. Steinkopf, R. Scheer, S. Schorr, and H. W. Schock, "Evaluation of Impurity- Modified CuGaS2 as Thin Film Intermediate Band Absorber Materisl," Thin Solid Films, vol. 2010.

16. B. Marsen, S. Klemz, G. Landi, L. Steinkopf, R. Scheer, S. Schorr, and H. W. Schock, "Phases in Copper-Gallium-Metal-Sulfide Films (Metal=Titanium, Iron, or Tin)," Thin Solid Films, vol. 519, pp. 7284-7287, 2011.

17. B. Marsen, S. Klemz, T. Unold, and H. W. Schock, "Investigation of the Sub-Bandgap Photoresponse in CuGaS2:Fe for Intermediate Band Solar Cells," Progress in Photovoltaics: Research and Applications, 2011.

18. B. Marsen, L. Steinkopf, A. Singh, H. Wilhelm, I. Lauermann, T. Unold, R. Scheer, and H. W. Schock, "Effects of Ti- incorporation in CuInS2," Solar Energy Materials and Solar Cells, vol. 94, pp. 1730-1733, 2010.

19. B. Marsen, H. Wilhelm, L. Steinkopf, S. Klemz, T. Unold, R. Scheer, and H. W. Schock, "Effect of copper-deficiency on multi-stage co-evaporated Cu(In,Ga)S2 absorber layers and solar cells," Thin Solid Films, vol. 519, pp. 7224-7227 2011.

20. A. Martí, C. Tablero, E. Antolín, R. P. Campion, S. V. Novikov, and C. T. Foxon, "Potential of Mn doped In1-xGaxN for implementing intermediate band solar cells," Solar Energy Materials and Solar Cells, vol. 93, pp. 641-644, 2009.

21. A. Mellor, I. Tobias, A. Marti, and A. Luque, "A numerical study of Bi- periodic binary difraccion granting for solar cells," Solar Energy Materials and Solar Cells, vol. 95, pp. 3527-3535, 2011.

22. A. Mellor, I. Tobías, A. Martí, M. J. Mendes, and A. Luque, "Upper limits to absorption enhancement in thick solar cells using diffraction gratings," Progress in Photovoltaics, vol. 18, pp. 1-12, 2011.

23. M. J. Mendes, A. Luque, I. Tobias, and A. Marti, "Plasmonic light enhancement in the near-field of metallic nanospheroids for application in intermediate band solar cells," Applied Physics Letters, vol. 95, p. 3, Aug 2009.

24. M. J. Mendes, I. Tobias, A. Marti, and A. Luque, "Light concentration in the near-field of dielectric speroidal particles with mesoscopic sizes," Optics Express, vol. 19, pp. 16207-16222, 2011.

25. M. J. Mendes, I. Tobias, A. Martí, and A. Luque, "Near-field scattering by dielectric spheroidal particles with sizes on the order of the illuminating wavelength," Journal of the Optical Society of America B-Optical Physics, vol. 27, pp. 1221-1231, 2010.

26. I. Ramiro, E. Antolin, P. G. Linares, E. Hernández, A. Martí, A. Luque, C. D. Farmer, and C. Stanley, "Application of photoluminescence and electroluminescence techniques to the characterization of intermediate band solar cells," Energy Procedia, vol. 10, pp. 117-121, 2011.

27. C. Tablero, "Representations of the occupation number matrix on the LDA/GGA+U method," Journal of Physics: Condensed Matter, vol. 20, p. 325205, 2008.

28. C. Tablero, "Effects of the orbital self-interaction in both strongly and weakly correlated systems " Journal of chemical Physics, vol. 130, p. 054903, 2009.

29. C. Tablero, "Effects of the impurity-impurity and impurity-host interactions on the charge density and the related processes," Physica B-Condensed Matter, pp. 4023-4028, 2009.

30. C. Tablero, "Quantum dot energy levels and spectrum for different geometries," Journal Applied Physics, p. 074306, 2009.

31. C. Tablero, "Ionization levels of doped sulfur and selenium chalcopyrites," Journal Applied Physics, p. 073718, 2009.

32. C. Tablero, "Static and dynamic ionization levels of transition metal-doped zinc chalogenides," Theoretical Chemistry Accounts pp. 23-24, 2010.

33. C. Tablero, "Acceptor and donor ionization energy levels in O-doped ZnTe," Computational Materials Science, vol. 49, pp. 368-371, 2010.

34. C. Tablero, "Electronic and magnetic properties of the Fe doped CuInS2," Chem. Phys. Lett, vol. 499, pp. 75-78, 2010.

35. C. Tablero, "Effects of the impurity-host interactions on the non-radiative processes in ZnS:Cr," Journal Applied Physics, vol. 108, p. 093114, 2010.

36. C. Tablero, "Electronic and optical properties of the group IV doped copper gallium chalcopyrites," Thin Solid Films, vol. 19, pp. 1435-1440, 2010.

37. C. Tablero and D. F. Marron, "Analysis of the electronic structure of modified CuGaS2 with selected substitutional impurities: prospects for intermediate band thin film solar cells based on Cu-containing chalcopyrites," Journal of Physical Chemistry C, vol. 114, pp. 2756-2763, 2010.

38. C. Tablero, A. Martí, and A. Luque, "Ionization Energy levels in Mn-doped InxGa(1-x) alloys," Journal of Applied Physics, vol. 105, pp. 033704-4, 2009.

39. C. Tablero, A. Martí, and A. Luque, "Analyses of the intermediate energy levels in ZnTe:O alloys," Applied Physics Letters, vol. 96, p. 3, 2010.

40. I. Tobias, A. Luque, and A. Marti, "Numerical modeling of intermediate band solar cells," Semic. Sci. Tech., vol. 26, p. 014031, 2011.

In addition to the publication in journals referred to in the previous section, the Project has disseminated its results in several international conferences:

First results were communicated in 2008 at the 23rd European Photovoltaic Solar Energy Conference, Valencia (Spain) where we presented the optical characterization of the first quantum dot Intermediate Band Solar Cells grown within the Project [E. Cánovas, A. Martí, D. Fuertes-Marrón, E. Antolín, P. G. Linares, A. Luque, C. D. Farmer, and C. R. Stanley, "Optical Characterization of Quantum Dot Intermediate Band Solar Cells," in 23rd European Photovoltaic Solar Energy Conference, Valencia (Spain), 2008, pp. 298-301]. The cells were developed by growing a stack of ten InAs/GaAs QDs layers between p and n doped GaAs conventional emitters. Electroluminescence, EL, photoreflectance, PR, and transmission electron microscopy, TEM, were applied to the samples in order to test and characterize them optically. The results, derived from the application of the different techniques, showed a good correlation. TEM images revealed a very good structural quality of the QDs, which seemed to evolve in shape-strain from the bottom to the top of the stack. Corresponding to the quality observed by TEM, strong signals from EL and PR resolved unambiguously the energy band diagram of the QDIBSCs. By fitting PR data we were able to identify the coexistence of bands and discrete energy levels coming from the IB material. The PR data evidenced also a strong electric field over the dots, attributed to the space charge region created between the p-n emitters sandwiching the IB material. From EL results, we identified the predominantly radiative nature of the IB material related energy transitions.

We also published the first studies on the theoretical analysis of thin Film intermediate band chalcopyrite solar cells performance and prospects for their realisation that we exhibited during the 23rd European Photovoltaic Solar Energy Conference held in Valencia (Spain) [D. Fuertes-Marrón, A. Martí, C. Tablero, E. Antolín, E. Cánovas, P. García-Linares, and A. Luque, "Thin Film intermediate band chalcopyrite solar cells: Theoretical Analysis of device performance and prospects for their realisation," in 23rd European Photovoltaic Solar Energy Conference, Valencia (Spain), 2008, pp. 33-35.]. Compounds belonging to the group of I-III-VI2 chalcopyrites, used as absorbers in the leading thin-film technology, appeared as promising candidates for the realization of IB-devices. In this work we first analyzed the expected performance of such a thin-film intermediate band solar cell (TF-IBSC) by considering different levels of idealization, and secondly we discussed some issues relevant for the practical realization of IBs in chalcopyrites and identified impurities acting as potential IB-precursors in the chalcopyrite sulphide host.

In the same conference, a study of recombination properties of intermediate band solar cells -expected to be different from those traditionally attributed to deep levels- was shown by exploiting computational models based on ab-initio calculations [C. Tablero, A. Martí, D. Fuertes-Marrón, E. Antolín, and A. Luque, "Intermediate band and non radiative recombination," in 23rd European Photovoltaic Solar Energy Conference, Valencia (Spain), 2008].

We also disseminated our results at the European Material Research Conference, one of the largest conferences on materials worldwide [D. Fuertes-Marrón, A. Martí, and A. Luque, "Thin-Film intermediate band chalcopyrite solar cells," in Symposium on Thin Film Chalcogenide Photovoltaic Materials held at the EMRS 2008 Spring Conference, Strasbourg (FRANCE) 2008, pp. 2452-2454]; , and in the 3rd International Workshop on Modulation Spectroscopy of Semiconductor Structures presenting studies about thin film intermediate band solar cells [D. Fuertes-Marrón, A. Martí, and A. Luque, "Thin film intermediate band photovoltaics: advanced concepts for chalcopyrite solar cells," in 3rd International Workshop on Modulation Spectroscopy of Semiconductor Structures, Poland, 2008, pp. 1021-1025.].

In 2009 we attended the IEEE Photovoltaic Specialists Conference. The IEEE PVSEC Conference registers around 1000 contributions in each conference. Here and with an oral contribution we disseminated the objectives of the project and the work that we have been done within this European research proposal [A. Marti, E. Antolin, P. García-Linares, E. Cánovas, M. J. Mendes, I. Tobias, M. Levy, A. Luque, C. D. Farmer, C. R. Stanley, R. P. Campion, S. V. Novikov, C. T. Foxon, R. Scheer, B. Marsen, H. W. Schock, and M. Picault, "IBPOWER: Intermediate band materials and solar cells photovoltaics with high efficiency and reduced cost," in 34th IEEE Photovoltaic Specialist Conference, Philadelphia, USA, 2009, pp. 2486-2491]. A similar work describing the impact of our research consortium was presented at the European Photovoltaic Conference (24th Edition) [A. Luque, A. Marti, E. Antolin, E. Cánovas, P. G. Linares, C. Tablero, D. Fuertes Marron, I. Tobias, M. J. Mendes, A. Mellor, M. Levy, E. Hernández, C. R. Stanley, C. D. Farmer, R. P. Campion, S. V. Novikov, C. T. Foxon, R. Scheer, B. Marsen, H. W. Schock, G. Gonzalez, I. Martil, J. Olea, and D. Pastor, "New approaches to the intermediate band solar cell concept," in 24th European Photovoltaic Solar Energy Conference and Exhibition, Hamburgo, Alemania, 2009, pp. 7-14.]

In 2010 we presented our results on the advances in quantum dot intermediate band solar cells during the 35th IEEE Photovoltaic Specialists Conference, Honolulu, Hawaii (EEUU). In that work, we discussed the contribution of thermal and tunneling mechanisms to IB-CB carrier escape in current QD-IBSCs. It is experimentally demonstrated that in QDIBSC prototypes where tunnel escape has been eliminated, the sub-bandgap QE is suppressed at sufficiently low temperatures, and when this occurs, the only limit for the open-circuit voltage (VOC) is the fundamental semiconductor bandgap, as stated by the IBSC theoretical model. [E. Antolín, A. Martí, P. García Linares, I. Ramiro, E. Hernández, C. D. Farmer, C. R. Stanley, and A. Luque, "Advances in quantum dot intermediate band solar cells," in 35th IEEE Photovoltaic Specialists Conference, Honolulu, Hawaii (EEUU), 2010, pp. 000065-000070.]

That year we also discussed how we could raise the efficiency limit of the GaAs-based intermediate band solar cell through the implementation of a monolithic tandem with an AlGaAs top cell at the 5th World Conference on Photovoltaic Energy Conversion, Valencia, Spain. We proposed the implementation of a multi-junction device consisting of an IBSC combined with a single gap cell. We calculate the efficiency limits using the detailed balance model and conclude that they are very high (> 60% under maximum concentration) for any fundamental bandgap from 0.7 to 3.6 eV in the IBSC inserted in the tandem. In particular, the two-terminal tandem of a GaAs-based IBSC current matched to an optimized AlGaAs top cell has an efficiency limit as high as 64%. [E. Antolín, A. Martí, P. García-Linares, I. Ramiro, E. Hernández, and A. Luque, "Raising the efficiency limit of the GaAs-based intermediate band solar cell through the implementation of a monolithic tandem with an AlGaAs top cell," in 25th European Photovoltaic Solar Energy Conference and Exhibition - 5th World Conference on Photovoltaic Energy Conversion, Valencia, Spain, 2010, pp. 65-68.]

We also presented the modelling and characterization of multiple level intermediate band solar cell. In the framework of the project we had manufactured InAs/GaAs QD-IBSCs in order to test the validity of the intermediate band solar cell concept, although their real size and shape were far from the optimum and this caused extra electron levels to appear within the nanostructure confining potential, degrading the performance of the device. The effect of these extra levels were studied through a multiple level IBSC model based on the detailed balance, but modified so a term accounting for the non-radiative recombination (NRR) is also included. The model was completed with constant fitting parameters so the concentration JL-VOC curves (which do not incorporate series resistance effects) can be fitted. Several QD-IBSCs were manufactured, measured and fitted with this model, rendering relevant information about the recombination nature of the QD-IBSCs. [P. García-Linares, A. Martí, E. Antolín, E. Hernández, I. Ramiro, and A. Luque, "Modeling and characterization of multiple level intermediate band solar cell," in 25th European Photovoltaic Solar Energy Conference and Exhibition - 5th World Conference on Photovoltaic Energy Conversion, Valencia, Spain, 2010, pp. 468-471.]

In the field of characterization and at the same conference the results of the optoelectronic characterisation of intermediate band solar cells by photoreflectance comparison to other advanced architectures were introduced. We knew that the fabrication and design of novel materials and devices for advanced photovoltaics, like the intermediate-band solar cell (IBSC), required the use of specific characterization tools providing information about their optoelectronic properties. So we tested the suitability of photoreflectance for the characterization of IBSC prototypes based on quantum dots and compared the results obtained with those predicted by the theory. Non idealities in operative devices were identified and detailed information obtained about the electronic structure of the materials. We demonstrated the potential of the technique. [E. Cánovas, D. Fuertes Marron, A. Martí, A. Luque, C. R. Stanley, C. D. Farmer, and A. Bett, "Optoelectronic characterisation of intermediate band solar cells by photoreflectance comparison to other advanced architectures," in 25th European Photovoltaic Solar Energy Conference and Exhibition - 5th World Conference on Photovoltaic Energy Conversion, Valencia, Spain, 2010, pp. 428-431.]

Within the strategy of increasing the absorption of quantum dots, as mentioned, the Project has also considered the option of light trapping in the near and far field. Works regarding both options were exhibited at this conference. We explored an experimental procedure to embed MNPs in gallium arsenide (GaAs) and silicon (Si), which can be applied to other semiconductor host materials. The approach consisted in spin-coating colloidal MNPs dispersed in solution onto the substrate surface. Then a capping layer of the same material as the substrate is deposited on top to embed the MNPs in the semiconductor. The extinction spectra of silver (Ag) and gold (Au) MNPs embedded in GaAs and Si is modeled with Mie theory for comparison with optical measurements. This contribution constituted the initial step towards the realization of quantum-dot intermediate band solar cells (QD-IBSC) with MNPs [M. J. Mendes, E. Hernández, I. Tobías, A. Martí, and A. Luque, "Embedment of metal nanoparticles in GaAs and Si for plasmonic absorption enhancement in intermediate band solar cells," in 25th European Photovoltaic Solar Energy Conference and Exhibition - 5th World Conference on Photovoltaic Energy Conversion, Valencia, Spain, 2010, pp. 218-222.]. On the other hand computational calculations of light trapping properties of cylindrical well diffraction gratings in solar cells (far field) were also presented conclusing that a field intensity enhancement of the order of 100 is achievable [A. Mellor, I. Tobías, A. Martí, and A. Luque, "Light trapping properties of cylindrical well diffraction gratings in solar cells: Computational calculations," in 25th European Photovoltaic Solar Energy Conference and Exhibition - 5th World Conference on Photovoltaic Energy Conversion Valencia, Spain, 2010, pp. 647-649.].

Finally, in a plenary talk at the European PV Conference, the experimental advances in the next generation of solar cells were exposed comparing the experimental results obtained for three most reliable concepts for exceeding 50% efficiency: the multiple exciton generation (or impact ionization or multiple carrier generation) solar cell, the intermediate band solar cell and the hot carrier solar cell. These concepts were proposed theoretically more than ten years ago. In the last years, the number of experiments supporting the theories behind and paving the way towards their practical implementation has leaped forward. We reviewed these experimental advances.[A. Martí and A. Luque, "Experimental advances in the next generation of solar cells," in 25th European Photovoltaic Solar Energy Conference and Exhibition - 5th World Conference on Photovoltaic Energy Conversion, Valencia, Spain, 2010, pp. 4-9.]

It is worth highlighting that the impact of all results presented in this exhibition and congress were extremely high as that year the conference joined the 25th European Photovoltaic Solar Energy Conference and Exhibition, the 36th US IEEE Photovoltaic Specialists Conference and the 20th Asia/Pacific PV Science and Engineering Conference.

On the other hand at that time prototypes based on InAs/GaAs QDs had been also manufactured in order to realize the theoretically predicted high efficiency intermediate band solar cells (IBSCs). We analyzed the absorption coefficient of the IB material by developing a sample in an optical wave-guided configuration. This configuration allowed us to illuminate the QDs laterally, increasing the path length for photon absorption. Using a multi-section metal contact device design, we were able to measure an absorption coefficient of similar to 100cm(-1) around the band edge (similar to 1eV) defined by the VB -> IB transition in InAs/GaAs QD-IB materials. These results were shown at the European Material Research Society Conference a 5 days conference with 25 sessions running in parallel. [E. Canovas, A. Marti, A. Luque, C. D. Farmer, C. R. Stanley, A. M. Sanchez, T. Ben, and S. I. Molina, "Lateral absorption measurements of InAs/GaAs quantum dots stacks: potential as intermediate band material for high efficiency solar cells," in Proceedings of Inorganic and Nanostructured Photovoltaics, Amsterdam, 2010, pp. 27-34.]

At the same conference the potential of In-x(GayAl1-y)(1-x)As quaternary alloys for quantum dot intermediate band solar cells was proposed. Within the context of quantum dot Intermediate Band Solar Cells (QD-IBSC), it is of interest to investigate the maximum value that can be achieved for the smaller of the transitions (E-L), since values larger than 0.3 eV are required for improved performance. Our work provided both theoretical and experimental arguments to verify the shift of the IB position to deeper energies by using an In-x(GayAl1-y)(1-x)As capping layer, fulfilling the double function of increasing the QD size and eliminating the discontinuity in the conduction band between the quaternary cap and the GaAs barrier. [P. García Linares, C. D. Farmer, E. Antolin, S. Chakrabarti, A. M. Sanchez, T. Ben, S. I. Molina, C. R. Stanley, A. Marti, and A. Luque, "In-x(GayAl1-y)(1-x)As quaternary alloys for quantum dot intermediate band solar cells," in Proceedings of Inorganic and Nanostructured Photovoltaics, Amsterdam, 2010, pp. 133-141.]

In 2011 we participated again at the IEEE Photovoltaic Specialists Conference (37Th Edition) due to the relevance and impact of this conference. We proposed a new kind of quantum dot (QD) materials for the implementation of the intermediate band solar cell (IBSC). The materials were formed by lead salt QDs of the family IV-VI (PbTe, PbSe or PbS) embedded in a semiconductor of the family II-VI (Cd1-xMgxTe, CdxZn1-xTe, and CdS1-xSex or ZnSe1-xTex, respectively). These QDs are not nucleated due to lattice mismatch, as it is the case of the InAs/GaAs QD material system grown by the Stranski-Krastanov (S-K) mode. In these materials, the QDs precipitate due to the difference in lattice type: the QD lead salt material crystallizes in the rocksalt structure, while the II-VI host material has the zincblende structure. Therefore, it is possible to use lattice-matched QD/host combinations, avoiding all the strain-related problems found in previous QD-IBSC developments. We discussed the properties of the lead salt QD materials and proposed that they are appropriate to overcome the fundamental drawbacks of present III-Vbased QD-IBSC prototypes. We also calculated the band diagram for some examples of IV-VI/II-VI QD materials.[E. Antolín, A. Marti, and A. Luque, "The Lead Salt Quantum Dot Intermediate Band Solar Cell " in 37th IEEE Photovoltaic Specialists Conference. 2011.]

Our advances on light trapping strategies were introduced in the Optical Society American meeting on Photovoltaic, in the Electromagnetics Research Symposium held in Marrakesh and in the 8th Spanish Conference on Electron Devices. In the first one we explored the near-field concentration properties of dielectric spheroidal scatterers with sizes close to the wavelength, using an analytical separation-of-variables method [Mendes, M. J., I. Tobías, et al. (2011). Near-field light focusing by wavelength-sized dielectric spheroids for photovoltaic applications. OSA meeting on Photovoltaics. Austin, TX, Nov-2-4]. In the second one we explaining the possibility of using the rectangular-shaped grooves of a perfectly conducting diffraction grating as a light-trapping structure for producing light-confinnement in photovoltaic and optoelectronic devices [Jakas, M. M., F. Llopies, et al. (2011). Light Trapping within the Grooves of Diffraction Gratings. Progress In Electromagnetics Research Symposium Proceedings, Marrakesh, Morocco]. And in the last one we evaluated the potential improvements derived from the absorption increase employing a simplified model to analyze the low-injection behaviour of a solar cell with a metallic grating backreflector [Llopis, F., M. M. Jakas, et al. (2011). Low-injection behaviour of a solar cell with a metallic grating back-reflector. 8th Spanish Conference on Electron Devices, CDE'2011, Palma de Mallorca, Spain].

Finally we participated in the 2011 edition of the European Material Research Society Congress, where we explained that luminescence spectra render valuable information for the analysis of IBSCs, as they reveal the dynamics of carrier relaxation between the different bands. In that work the temperature dependence of the PL and EL spectra of two InAs/GaAs QD-IBSCs was studied. The EL spectra at room temperature was not in agreement with the IBSC model and they can be explained by a too fast carrier relaxation between CB and IB. However, at low temperatures that relaxation was slowed down and the results were consistent with a QFL split between those two bands as predicted by the IBSC model. PL spectra appeared to be less useful for this kind of analysis than EL spectra since the luminescence of the emitter of the cell cannot be distinguished from that of the IB material. [Ramiro, I., E. Antolín, et al. (2011). Application of photoluminiscence and electroluminiscence techniques to the characterization of intermediate band solar cells. European Materials Research Society Conference, (EMRS). Symp. Advanced Inorganic Materials and concepts for photovoltaics. Nice.]

An important effort has also been done to disseminate our knowledge in a more comprehensive and detailed way through the following chapters of books:

1. C. T. Foxon, S. V. Novikov, and R. P. Campion, in Next Generation of Photovoltaics: New Concepts, edited by A. B. Cristobal, A. Marti, and A. Luque (Springer Verlag., 2012), pp. 277.

2. P. G. Linares, in Advanced Solar Cell Materials, Technology, Modeling, and Simulation, edited by R. a. M. Y. T. T. I. Laurentiu Fara (Polytechnic University of Bucharest, Japan) (IGI Global Dissemination of Knowledge, 2012).

3. A. Martí, and A. Luque, in Next Generation of Photovoltaics: New Concepts, edited by A. B. Cristobal, A. Marti, and A. Luque (Springer Verlag., 2012), pp. 209.

4. Stanley et al., in Next Generation of Photovoltaics: New Concepts, edited by A. B. Cristobal, A. Marti, and A. Luque (Springer Verlag., 2012), pp. 251.

5. E. Antolín, A. Martí, A. Luque, 'The intermediate band solar cell' in Comprehensive Renewable Energies, Eds. Ali Sayigh, Elsevier.

We also would like to mention that the project have been also working for increasing the awareness of researchers of cross-cutting areas, policy makers and general public by giving explanatory talks on renewable energies, photovoltaics and novel concepts. For example:

1. Display stand at University of Glasgow Industry Days (2010).

2. Invited talk From Semiconductor to New Energy - the PV Value added Chain. 'European - American Energy Conference 2011, Nice.

3. Invited talk: Photovoltaics: Large Scale Power-Providing Semiconductor Industry, 2011.

4. Invited talk: Nanostructured and bulk materials in intermediate band solar cells. MRS Spring Meeting.

5. Invited talk: Progress in intermediate band solar cells. Bayer innovative. Schloss Erlangen, Alemania, 2011

6. Invited talk: Intermediate Band Solar Cells. OECC 2009. Hong-Kong, 2009

7. Invited presentation at 1st Annual SU2P Symposium, University of Strathclyde. 2010.

8. Presentation to Sasol Technology (UK), St Andrews, Scotland. 2010.

9. Invited talk 'Examples of partcipation in FP7, IBPOWER' at CDTI, Spain, 2009.

10. Invited presentation at 'Third Generation Photovoltaics' Workshop, Heriot-Watt University, Edinburgh. 2010.

11. Talk 'The intermediate band solar cell: theory and praxis'at the workshop NANOfutures: A cross-ETP Coordination Initiative on nanotechnology, 2011.

12. Invited talk in PV Trends 2008 Bucharest, 2008.

13. Invited talk 'Empirical methods in quantum dot intermediate band solar cell research' at the Workshop on Empiral methods on Solid StatePhysics, Manchester, 2010.

14. Invited talk 'On the temperature rise model for InGaN on GaAs' at ETSI Telecomunicación, Universidad Politécnica de Madrid, 2009.

15. Invited talk 'On the temperature rise model for InGaN on GaAs' at UK Nitride Consortium Conference at Sheffield University, 2009.

16. Talk 'Chalcopyrite-based nanostructures: new prospects for highly efficient photovoltaic devices' in Trends in NanoApplications Energy. Imaginenano 2011, Bilbao, 2011.

17. Invited Seminar at the University of Cambridge (Department of Physics, 2010.

18. Talk 'The AME technique' at the UK Nitride consortium meeting at the University of Bath, UK., 2011.

19. Presentation 'Growth of III nitrides using the AME process' at the International Nitrides (ICNS9) conference, Glasgow, UK., 2011.

20. Talk 'The AME technique' at the UK MBE Workshop Sheffield (UK), 2011.

21. Invited talk 'Advances in Intermediate Band Cell Research' at the Nature Photonics Technology ConferenceTokio, Japan, 2010.

22. Invited talk 'Nanotechnology for more efficient photovoltaics: the quantum dot intermediate band solar cell' at CASP 2011 Annual Meeting Los Alamos National Laboratory, Nuevo Mejico, EEUU, 2011.

23. Invited talk 'Intermediate band Solar cell' at Rusnano Forum: IV Nanotechnology International ForumRussia, 2011).

24. Classes at the School on Nanotechnology and New Materials for Environmental Challenges (First Bilateral Japan-Spain Meeting on Nanotechnology and New Materials for Environmental Challenges) Toledo, Spain, 2011.

25. Invited talk ImagineNano 2011 'Nanotechnology for more efficient photovoltaics: the quantum dot intermediate band solar cell' Bringing together Nanoscience and Nanotechnology, Bilbao, 2011.

26. Invited talk 'Novel Photovoltaic Devices: the intermediate band solar cell' at NANOMAT 2008, Ankara, Turkey, 2008.

27. Invited talk 'Intermediate band solar cells' to 17th International Conference on Photochemical Conversion and Storage of Solar Energy Conference Sydney, Australia, 2008.

28. Invited talk 'Energía Solar Fotovoltica' by Telefónica S.A. Madrid, Spain, 2008.

29. Invited talk by Workshop "Progress Towards a Next Generation in Photovoltaics, Cercedilla, 2008.

30. Invited talk 'Células de 3ª generación. Novel Concepts in Photovoltaics' at 2 Cumbre de Concentración Fotovoltaica Toledo, España, 2009.

31. Invited talk 'A quick guide to intermediate band solar cell research' at the heriot Watt University 2010.

32. Invited Talk 'Intermediate band solar cells"at CIMTEC 2010, 2010.

33. Invited talk 'Intermediate-band gap solar cells' at the 24th Nordic Semiconductor MeetingFuglsøcentret, Denmark, 2011.

and some other activities as tours, news and press-releases related to the intermediate band solar cell have been also generated:

1. Photon Internacional 'Intermediate band cells are on their way' February 2012.

2. NCPV Hotline 'Intermediate-band solar cells' February 2012.

3. La Vanguardia. 'Reseracher of the UPM invents the intermediate band solar cell' February 2012.

4. Energías Renovables 'The intermediate Band solar cell conquists Nature Photonics' February 2012.

5. GENERA Renoweble Energy Fair. B2B meetings 2010.

6. Madrid Week of Science 'Photovoltaics', 2009, 2010 and 2012. Guided visits to IBLAB, the Intermediate Band Solar Cell Laboratory.

List of Websites:

The website of the Project is located at http://www.ies.upm.es/ibpower.

The partners in IBPOWER , with their corresponding contact details are:

1. The Instituto de Energía Solar of the Universidad Politécnica de Madrid, that coordinates the Project (http://www.ies.upm.es). Contact persons are Profs. Antonio Martí (amarti@etsit.upm.es) and Antonio Luque (a.luque@upm.es).

2. The University of Glasgow, that implements the technology based on quantum dots (http://www.gla.ac.uk/departments/electronicsandelectricalengineering/). Contact person is Prof. C.R.Stanley (C.Stanley@elec.gla.ac.uk).

3. The Helmholtz Zentrum Berlin (http://www.helmholtz-berlin.de) that implements the technology based on the thin film approach. Contact persons are Prof. H. W. Schock (hans-werner.schock@helmholtz-berlin.de) and Dr. Thomas Unold (unold@helmholtz-berlin.de)

4. The University of Nottingham (http://www.nottingham.ac.uk) that implements the technology based on InGaN. Contact persons are Profs. C.T.Foxon (C.Thomas.Foxon@nottingham.ac.uk) and R. Campion (Richard.Campion@nottingham.ac.uk).

5. Riber S.A. (http://www.riber.com) that implements the technology dealing with the implementation of transition elements on III-V compounds. Contact person is Dr. C. Chaix (cchaix@riber.fr)