NGCPV: A NEW GENERATION OF CONCENTRATOR PHOTOVOLTAIC CELLS, MODULES AND SYSTEMS

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ABSTRACT: Starting on June 2011, NGCPV is the first project funded jointly between the European Commission (EC) and the New Energy and Industrial Technology Development Organization (NEDO) of Japan to research on new generation concentration photovoltaics (CPV). The Project, through a collaborative research between seven European and nine Japanese leading research centers in the field of CPV, aims at lowering the cost of the CPV-produced photovoltaic kWh down to 5 €cents. The main objective of the project is to improve the present concentrator cell, module and system efficiency, as well as developing advanced characterization tools for CPV components and systems. As particular targets, the project aims at achieving a cell efficiency of at least 45% and a CPV module with an efficiency greater than 35%. This paper describes the R&D activities that are being carried out within the NGCPV project and summarizes some of the most relevant results that have already been attained, for instance: the manufacturing of a 44.4% world record efficiency triple junction solar cell (by Sharp Corp.) and the installation of a 50 kWp experimental CPV plant in Spain, which will be used to obtain accurate forecasts of the energy produced at system level.

Keywords: Concentration Photovoltaics (CPV), Dome Fresnel Köhler (DFK), Multijunction, Intermediate band, Quantum wells, Quantum dots, Dilute nitrides, III-V on Silicon.

1 INTRODUCTION

In March 2007, the EU heads of state and Government set a series of demanding climate and energy targets to be met by 2020, known as the "20-20-20". Among these targets is that 20% of EU energy to come from renewable energy. Concurrently, in June 2008, the Japanese prime minister announced a plan to reduce the CO_2 emissions 50% by 2050 in the so-called "Cool Earth in 2050". A specific objective of this plan was to attain a cumulative PV capacity of 14 GW and 53 GW until 2020 and 2030, respectively.

In this scenario, the Directorate-General Research, with the support of the several services of the EC including the Joint Research Center (JCR) and in particular, the Institute of Energy together with the New Energy and Industrial Technology Development Organization (NEDO) of Japan, devised a cooperative strategy that was materialized by the issue, on July 20th 2010 of a call FP7-ENERGY-2011-JAPAN: Ultrahigh Efficiency Concentration Photovoltaics (CPV) Cells, Modules and Systems / EU-Japan Coordinated call.

The NGCPV project responds to this call and, with its impact, is expected to contribute to the achievement of both the "20-20-20" and "Cool Earth in 2050" targets. The project started in June 2010 and will end on November 2014.

The NGCPV project integrates a total of 16 scientific partners (Fig. 1): 9 Japanese (Toyota Technical Institute, AIST, The University of Tokyo, Daido Steel, Sharp, Kobe University, Asahi Kasei, Takano, and Miyazaki University) and 7 Europeans (UPM, Fraunhofer-ISE, Imperial College, ENEA, CEA-INES, BSQ and PSE). 10 of these partners are Universities and 6 are companies (Daido, Asahi Kasei, Sharp, Takano, BSQ and PSE).

The main objective of the NGCPV project is to reduce the cost of the CPV-generated kWh. The potential of CPV lies on that it enables the use of extremely high efficient and expensive solar cells which wouldn't be affordable in flat-plate approaches [1], [2]. The continuous increase in the efficiency of multijunction solar cells has made this technology to be taken seriously. More than 20 MW of CPV systems were installed in 2011 and the market is expecting to reach GW level in the next 5 years.

Although considerable progress has already been done, there are still huge possibilities to further increase their efficiency and reduce the cost. In this regard, there are three main targets that are being pursued by the NGCPV project: (1) understand what are the actual costs involved in the installation of a CPV plant (2) to forecast the energy production of a CPV plant as a function of the site radiation and technology used, and (3) to progress in the state-of-the-art of the technology involved in a CPV system itself, namely: high efficiency cells, modules and trackers.

In what follows we describe the different R&D activities that are being carried out in this project. Also, the most relevant results that have been already attained will be pointed out as they emerge.

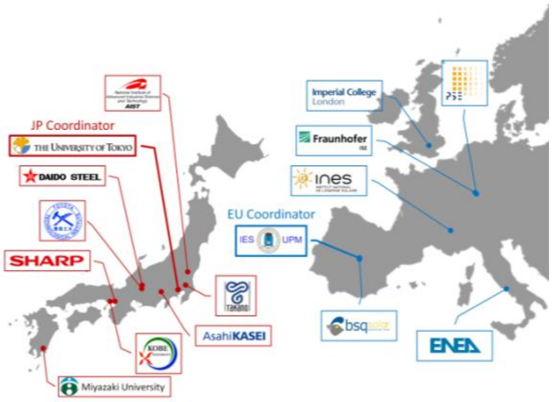

Fig. 1: NGCPV partners: 9 Japanese and 7 Europeans, 10 Universities and 6 Companies. EU Coordinator: UPM, JP Coordinator: The University of Tokyo.

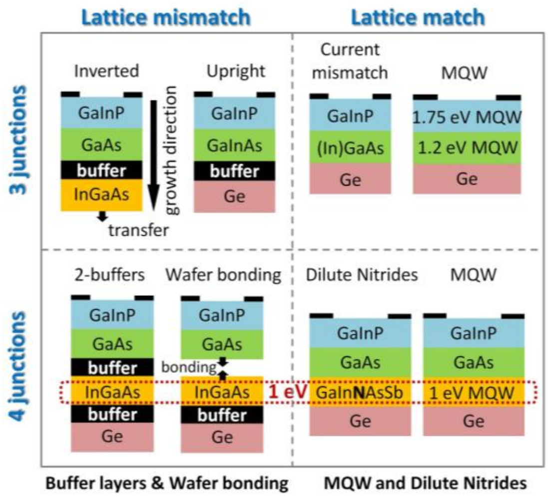

Fig. 2: Summary of the multijunction CPV solar cells investigated in the NGCPV project.

2 CPV CELL

Several strategies are being followed within the Project in order to approach 50 % efficient [2] CPV cells. Most of these strategies focus on improving the efficiency of multijunction solar cells (MJSC) but we also investigate novel approaches such as the intermediate band solar cell (IBSC), that pursues the development of new materials which enable the absorption of two below bandgap photons without bringing voltage degradation, or the growth of III-V materials on silicon, that aims at reducing the cost of high efficient solar cells. Triple junction solar cells were already commercially available at the beginning of the project and had demonstrated efficiencies at laboratory scale slightly above 40%.

2.1 Multijunction solar cells

Several kinds of multijunction solar cells (MJSC) are investigated (Fig.2): we can classify them according to the number of sub-cells (3JSC or 4JSC) and to the material growth strategy: lattice matched (LM) or lattice mismatched (LMM). The LMM approach allows for an optimal bandgap combination (current matching between subcells) to the expense of a potential degradation on material quality due to the difference in lattice constant. On the contrary, LM approach avoids material degradation to the expense of constraining the kind of materials that need to be grown to that ones with the same lattice constant than the substrate (usually Germanium). This key difference determines the kind of investigations that are being carried out for each strategy: For the LMM approach, the main research focuses on investigating the proper intermediate buffer layers for accommodating the difference in the lattice constant. On the contrary, for the LM approach the main research focuses on finding new materials lattice matched to the Ge substrate and with the desired bandgap energy. In this regard, this project focuses on two kinds of materials: Multi-Quantum Wells (MQW) or Superlattices (SL) and Dilute Nitrides (GaInNAsSb). In what follows we describe each of these three tasks in detail.

The use of buffer layers in the LMM approaches has lead to remarkably good results. Before the starting of the project, Fraunhofer-ISE had already obtained a world record efficiency of 41.1% [3] with a LMM-3JSC upright grown on Ge substrate (Fig. 2). Recently, Sharp Corp. has announced a new world record efficiency of 44.4% using the inverted approach of a LMM-3JSC. A particular exhaustive research on buffer layers is carried out by TTI at the synchrotron radiation facility, SPring-8 beamline 11XU, by using an MBE-XRD system. A method to measure the strain relaxation and the dislocations in InGaAs for each individual buffer layer is being investigated by using in-situ X-ray reciprocal space mapping (or 3D-RSM) (see section 5). As an alternative to buffer layers, Fraunhofer-ISE is also investigating the wafer bonding technique to implement the LMM-4JSC.

MQW and SL consist of periodic nanostructures with alternating layers of at least two semiconductors (named QW and barrier material) and can be engineered to obtain a tunable effective bandgap. The difference between MQW and SL lies in that SL has a particularly thin barrier material (typically < 5nm) enabling tunneling effects between adjacent layers. By using a strain-balanced (SB) structure, a variety of materials can be grown dislocation-free on Ge and GaAs substrates, so they are being investigated as subcells in the LM approach for both triple and quadruple junction solar cells (Fig.2). In particular, the following subcells are being investigated: (1) lattice-matched (not SB) GaInAsP/GaInP MQW for the 1.75 eV top cell in the LM-3JSC, (2) strain-balanced InGaAs/GaAsP for the 1.20 eV middle cell in the LM-3JSC and (3) strain-balanced InGaAsN/InGaAs or GaAsN/InGaAs for the 1 eV middle-bottom cell in the LM-4JSC.

From simulation of MQW-SC, it has been predicted that MQW not only allows tuning the bandgap but also provides a strong radiative coupling between subcells, resulting in a multijunction cell that is tolerant to daily and seasonal changes to the solar spectrum [4]. Preliminary results on the manufacturing of solar cells incorporating MQWs have demonstrated an efficiency of 28% [5]. This cell consisted of a 2J-MQW with a top cell comprising 40 repeats of lattice-matched GaInAsP/GaInP (fundamental transition at 1.67 eV) and a bottom cell with 50 repeats of strain-balanced InGaAs/GaAsP (fundamental transition at 1.21 eV). Further research will follow to optimize this device as well as to incorporate the Ge bottom junction. Another interesting result came from the I-V characterization of SL solar cells under

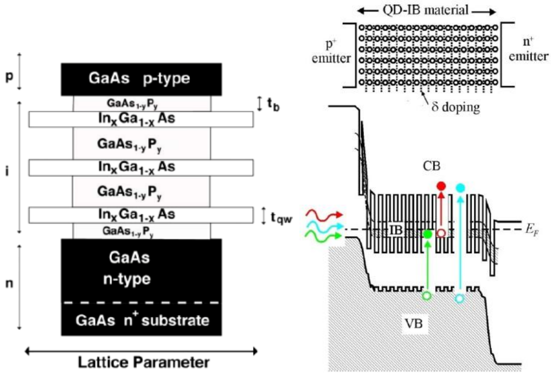

Fig. 3: Schematic of strain balanced InGaAs/GaAsP MQW (left, ICSTM) and QD (right, UPM) solar cells investigated in the NGCPV project to implement multijunction and intermediate band solar cells, respectively.

concentrated light: it has been measured that the open-circuit voltage of a SL solar cell under concentrated light can be as high as their counterpart without QWs [6].

Dilute nitrides are a kind of highly mismatched alloy in which a small fraction of Nitrogen (typically less than 5%) is diluted in the semiconductor. Due to interaction between localized states of N and the extended states of the GaAs lattice, the conduction band of GaAs is splitted in two bands, one of them with a lower energy than that of GaAs, which enables reducing the GaAs bandgap down to 1 eV (band anticrossing). However, the addition of N to GaAs not only reduces the bandgap but also decreases the lattice constant. To compensate this lattice diminution, the simultaneous incorporation of In to fabricate 1eV-band gap materials latticed matched to GaAs is required. Finally, it is also necessary to add Sb as surfactant to improve the material quality [7]. This brings us to the final GaInNAsSb material as a promising material to manufacture the 1.0 eV middle-bottom subcell in the LM-4JSC (Fig. 2).

Unfortunately, the growth of dilute nitrides is very challenging due to the appearance of N-related defects that drastically can deteriorate the material quality. Along this project, a strong effort has been devoted to the exhaustive characterization of those defects in GaAsN and GaInAsN materials [8–13]. For that, several advanced techniques, such as DLTS, PPT, TR-PL, etc., have been used (see section 5). From the examination of single junction GaAsN solar cell grown by Chemical Beam Epitaxy (CBE) it has been recently observed that the main recombination in the cell happens in the space charge region and is dominated by a non-radiative recombination center at 0.31 eV below the bottom edge of the conduction band [10]. This center has been tentatively suggested to be related with a split interstitial of a N and As atoms in a single V-site $(N\text{-}As)_{As}$ and has been found to be very stable, behaving as an atom in its ideal site, so that its elimination is very challenging. Recent works carried out within this project have shown that both thermal annealing [12] and Hydrogen irradiation [13] are effective removing this center. As a result of this exhaustive research, it was recently reported the highest electron mobility of 2000 cm^2/Vs in Ga(In)NAs material grown by MBE [9], which opens the door to develop high efficient LM-4JSC. This will be done with the strong collaboration among the project partners.

2.2 Intermediate band solar cells

The IBSC concept can be implemented by embedding quantum dots (QDs) within a high bandgap semiconductor material matrix (Fig.3). The confined states that each QD introduces within the matrix bandgap represent a path for sub-bandgap photocurrent generation without voltage degradation, according to the IBSC concept. Two-photon experiments at cryogenic temperatures have already demonstrated the IB behavior of QDSC [14]; however there are still fundamental issues that must be addressed forwarded to enhance the absorption of the QDs and minimize the non-radiative recombination. With these objectives as target, several aspects are being investigated: increasing the QDs density without degrading the material quality, the effect of QD doping, different barrier materials, etc. For that, several techniques are being developed for ad-hoc characterization of QDSC, such as two-photon QE at low temperatures, I-V characterization at low temperature and high concentration, transient PL, two-color photo-excitation spectroscopy, etc. From I-V characterization under concentrated light it has been demonstrated an open-circuit voltage convergence between a strain-balanced InAs/GaAsN QDSC and their counterpart without QDs [15], which suggest that the voltage preservation principle has been attained under concentrated light. More recently, it has been reported [16] the photocurrent generation by two-step photon absorption in InAs/AlGaAs QDSC at room temperature, which has been attributed to the suppression of thermal escape of electrons out of the QD layers due to the high bandgap offset between the InAs QDs and the AlGaAs barrier.

2.3 III-V on Silicon

The growth of high quality III-V semiconductors on silicon substrate is a promising structure for high-efficiency, low-cost multijunction solar cells. Particularly, in this project we are investigating the growth of GaAs on silicon which involves the investigation on the formation of rotational twin domains that degrade the material quality. Recently, it has been reported that those stacking faults can be reduced by using indium pre-evaporation during the epitaxial growth [17]. Research will continue by using in-situ X-ray reciprocal space mapping (or 3D-RSM) (see section 5) to understand the physical mechanisms of the growth process.

3 CPV MODULE

In order to have a cost-effective CPV system, three key aspects must be ensured: high concentration factor, efficiency and tolerance. A new type of CPV module is being investigated aiming to achieve an efficiency of 35%. This module is designated “Intrepid” HCPV module. The key distinctive feature is the use of a novel optical design: the Dome-shaped Fresnel Köhler (DFK) concentrator [18], [19] which provides with extended tracking error and alignment tolerances as well as allows operating under higher concentration factors with a very high optical efficiency. This design is based in two previous successful designs: the dome-shaped Fresnel lens system developed by Daido Steel and the FK concentrator designed by UPM. Additionally, the

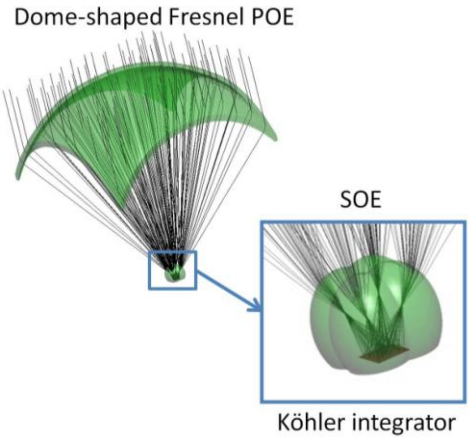

Fig. 4: Dome-Fresnel Köhler (DFK) concentrator (UPM)

“Intrepid” CPV module will incorporate the best performing multijunction cells manufactured by the other partners (see section 2).

The free-form DFK concentrator (Fig.4) comprises two parts: a dome-shaped Fresnel lens as Primary optical Element (POE) and a refractive secondary optical element (SOE) performing Köhler integration. Both parts are designed with free-form surfaces following a 4-fold scheme in which both POE and SOE are divided into 4 identical and symmetrical sectors. Each quarter of POE works together with its corresponding quarter of SOE performing concentration and Köhler integration. The key features of this design are: high optical efficiency (~85%), a very high concentration-acceptance product (CAP) of 0.72 [19], high spatial and spectral irradiance uniformity in the cell (due to the Köhler integration), no light leakage losses [20], [21] and a very compact design, due to the low *f* number. The very high CAP value is particularly important since it enables the possibility of increasing the concentration without degrading the acceptance angle (Fig.5). Besides, the SOE allows the encapsulation to provide an excellent cell protection, and the 4-fold scheme mitigates the aging issues (due to solarization) in the SOE. These characteristics make this concentrator a robust and reliable design that enables the development of cost-effective CPV systems.

The manufacturing of the DFK concentrator involves a key issue regarding the POE molding process. The dome-shaped Fresnel lens cannot be designed with positive draft angles for the inactive facets (leading to a simple demolding process) so that a novel manufacturing process is required. Daido Steel has developed a demolding technique in which 9-part molding dies are separated from the piece in a sequence where each independent part can be demolded independently from the others. This technique has been already successfully proved in other concentrators manufactured by Daido Steel in mass-production.

Further research is conducted by Daido and Miyazaki University to enhance the heat dissipation from the cells by using advanced radiative coatings.

4 CPV SYSTEMS

The evaluation of full CPV systems will serve to provide first hand experience in order to forecast the energy produced by a CPV system installed in a particular location, knowing the typical meteorological

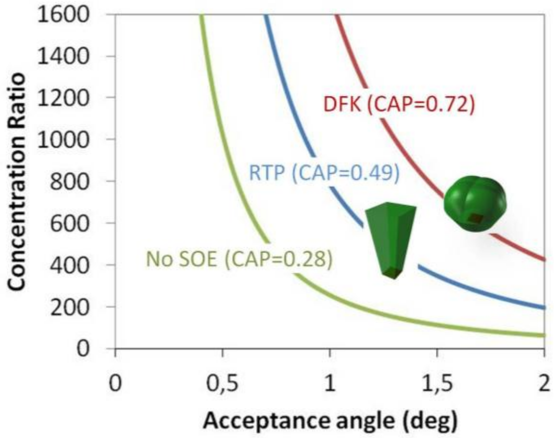

Fig. 5: Comparison among different concentrator optical designs using a dome-shaped Fresnel lens as POE.

Fig. 6: CPV plant installed by BSQ with Daido modules in Villa de Don Fadrique (Toledo, Spain). Picture courtesy of BSQ.

data in that place and the rated performance of the plant (under some standard operating conditions). This knowledge is important to work out the power definition for CPV plants, something that is currently under discussion in the WG7– TC 82 of the IEC (International Electrotechnical Commission).

An experimental 50 kWp CPV plant was built by BSQ in Villa de Don Fadrique (Toledo, Spain) and is operative since mid-2012 (Fig.6). BSQ also developed the tracking systems and is responsible of the operation and maintenance tasks. The plant consists of 5 arrays, each one comprising 48 Daido CPV modules with different configurations (back pan thickness, anti-soiling system, radiative paints, etc.). The nominal concentration of each module is 820X and uses commercial LM-3JSC.

The plant is being continuously monitored since October 2012. Based on an exhaustive meteorological characterization (total irradiance, spectral irradiance, ambient temperature, module temperature, wind velocity and direction, relative humidity, etc.) the main objective is the obtainment of the translating equations from standard to real operating conditions. For that, UPM and ENEA have developed advanced software tools for analyzing the many parameters acquired. Preliminary results [22] have suggested that the northern wind produces a much better cooling of the cells (35% more effective) in the Northern hemisphere. Other aspects such as the better location for anemometers for wind characterization are being investigated.

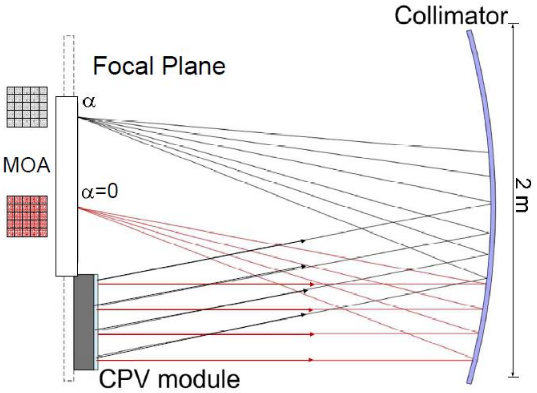

Fig. 7: Overview of the operation principle of the Module Optical Analyzer (MOA) developed to characterize CPV modules in a production line (taken from [23])

5 ADVANCE CHARACTERIZATION TOOLS

5.1 Characterization of novel materials and devices

In this section we summarize several techniques that are being developed in this project to characterize materials and devices for CPV applications. These include more or less conventional techniques, but also advanced techniques. Among the conventional ones we count, for example, with transmission electron microscopy (TEM), photoluminescence (PL), photoreflectance (PR), deep level transient spectroscopy (DLTS), surface photo-voltage (SPV) and time resolved photoluminescence (TR-PL). Among the advanced techniques, we count with two newly developed techniques: the three dimensional real-time reciprocal space mapping (3D-RTSM) and the piezoelectric photoconductivity (PPT). 3D-RSTM is an MBE in-situ X-ray diffraction (XRD) measurement used to characterize in real-time the lattice relaxation during the growth of lattice mismatched semiconductor layers (for instance, InGaAs on GaAs or GaAs on silicon). This equipment uses the X-ray radiation coming from the Spring-8 synchrotron facility, where the MBE is also located. PPT technique has been developed by U. Miyazaji and consists on the detection of the vibrational modes induced in a piezoelectric when the sample is illuminated; thus, it allows studying non-radiative recombination processes, for instance in GaAsN [8].

5.2 Characterization of CPV cells and modules

There are two complementary techniques for characterizing CPV cells and modules: out-door and in-door measurements. In-door characterization provides a controllable environment (spectrum, cell temperature, irradiance, etc.) so that it is well suited for standardization purposes and importantly, for a fast in-door rating in the industrialization of CPV components. On the contrary, out-door measurements unveil the possible problems related with the structure, as well as it allows presenting the thermal effects on the cell (or module) performance. The combination of in-door and out-door measurements provides the most complete information and both kinds of measurements are being carried out in this project following a round-robin methodology. According to this methodology, we compare and evaluate the results obtained by different laboratories in order to define accurate measurement techniques.

For the in-door measurements of CPV modules, the Helios 3198 solar simulator (conceived and developed by UPM and licensed to Soldaduras Avanzadas in 2008) is being used at several laboratories. This simulator produces a uniformly distributed light pulse on the CPV module with very similar characteristics to the sun’s light and records the I-V curve. In order to extend the functionality of this simulator, UPM has developed a new system to unveil the possible defects during the manufacturing of CPV modules. This system is denominated Module Optical Analyzer (MOA) (Fig.7) and is based on the luminescence inverse (LI) method [23]. It provides by one shot in few seconds, not only the angular transmittance function but also the misalignments between units caused by defects in the CPV module. Therefore, it is suitable for characterizing CPV modules in the production line. One unit has been recently installed at Daido Steel factory and will be used as an extension to the Helios 3198 simulator that was already available at the manufacturing line of Daido Steel.

Several out-door platforms are being used for testing CPV modules at different partner sites, following a round-robin scheme. In particular, CEA has developed an out-door test facility called OSFAM (One Size Fits All Module) for testing cells under out-door conditions. Besides, ENEA is characterizing a 6.3 kWp CPV plant installed at their site in order to develop tools for the characterization of CPV plants that can be applied to the characterization of the 50 kWp CPV plant in Spain (see Section 4).

6 SUMMARY

NGCPV project is the first joint project between Japan and Europe to develop a new generation of concentrator photovoltaic cells, modules and system. This paper has described the research activities carried out within the project, including CPV cell, module and the whole system, and pointed out the main results attained for the moment: the installation of an 50 kWp CPV plant that is being used to forecast the energy production in whole CPV systems, the achievement of a new world record efficiency for a multijunction cell of 44.4% (Sharp Corp.) and the development of novel characterization tools for CPV modules, such as the MOA.

7 AKNOWLEDGEMENTS

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