FULLSPECTRUM: A new PV wave of more efficient use of solar spectrum

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The purpose of this paper is to present to the Russian scientific community a research programme that with the cooperation of one of its institutional members — the Ioffe Physicotechnical Institute — has been presented and sponsored by the European Commission (EC) in order to provide a long term basis for the development of the photovoltaic conversion of the solar energy. This programme constitutes what in the EC is called an integrated project, named like this paper's title — for short FULLSPECTRUM — and involves 19 research centres of eight different countries with a grant of 8.4 million euros for five years.

Photovoltaic (PV) electricity is today a fast growing business. In Fig. 1 the explosive growth of the PV module market is presented [1]. However, the cost of the PV electricity is several times higher than that of the prevalent electricity. The future of the PV electricity has been forecasted by several authors [2–4]. It is concluded that, most probably, the present technology, based on silicon, will support an important growth but will not be albe to lead to the low prices necessary for a mass utilisation of the Sun as electricity source.

The reason for it is that in spite that the Sun provides every year a tremendous amount of energy, much more than the energy used by the man, however its flux is relatively weak. This is the ultimate reason why its exploitation is today expensive. Mass utilisation of the solar energy will require the best exploitation of this disperse resource.

Present PV technology is based in the following principle. A solar cell is formed of a semiconductor and contacts that are preferential to the conduction band and the valence band. Usually they are n and p doped semiconductors respectively. That is why a solar cell is usually formed of a semiconductor with a $p-n$ junction.

Photons pump electrons from the valence band to the conduction band. The electrons are collected by the selective contact to the conduction band (the contact to the n-region) at high energy and are returned at low energy, after having realised a useful work, to the valence band through the other selective contact (the contact to the p-region).

Only photons of energy not much higher than the band gap of the semiconductor are effectively converted; the energy of the photons of higher energy is recovered at less than the band-gap energy; the energy of the photons with less energy is lost. This is the motivation of FULLSPECTRUM, that aims at this better exploitation of the resource by a good utilisation of the whole solar spectrum.

The specific objectives of FULLSPECTRUM are the development of:

a) III–V multijunction cells (MJC),

b) Solar thermo-photovoltaic (TPV) converters,

c) Intermediate band (IB) materials and cells (IBC),

d) Molecular based concepts (MBC) for full spectrum utilisation and

e) Manufacturing technologies (MFT) for novel concepts including assembling.

Nineteen centres are involved in FULLSPECTRUM. They are listed in Table.

The MJC technology is based in depositing a stack of solar cells of different band gaps so that the photons that are not absorbed by the top semiconductors are absorbed by the successive ones lying underneath. The different solar cells may be interconnected by several means of which the most used today is a tunnel junction through which the conduction and the valence bands of successive semiconductors are interconnected. In Fig. 2 such a stack is schematically drawn. The voltage developed in the stack is the sum of the voltages in each individual cell. Besides the monolithic stack just depicted some researchers are developing mechanically stuck stacks, where the different cells can be connected to independent circuits.

Shockley and Queisser presented in 1961 a detailed balance analysis [5] that led to the highest efficiency a solar cell can theoretically have. A single solar cell may have under full concentration (that is, illuminated by an isotropic

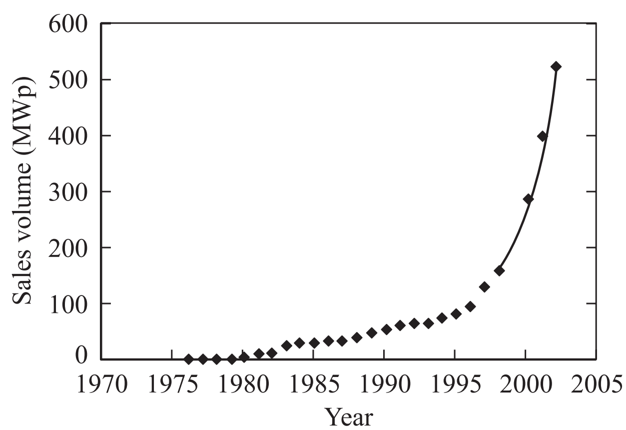

Figure 1. Evolution of the annual sales of PV modules according to P. Maycock (several publications). The line is the result of the model by A. Luque [2].

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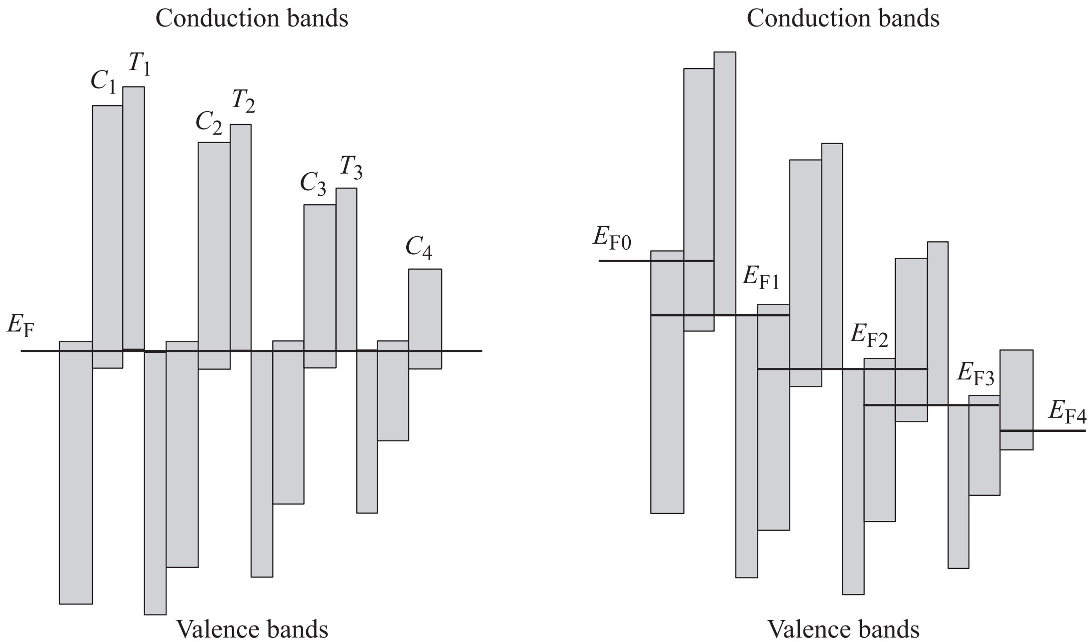

Figure 2. Band diagram of a monolithic stack of four solar cells (C_1-C_4) interconnected with three tunnel junctions (T_1-T_3). Left: thermal equilibrium; right: under illumination. The Fermi level E_{F0} splits into four quasi Fermi levels $E_{F1}-E_{F4}$.

radiation at 6000 K, approximately the Sun's photosphere temperature) efficiency of 40% and 86% for a MJC stack of infinite number of cells [6]. It is clear the enhancing-efficiency potential of this approach.

The challenge for a monolithic MJC stack is to select the proper band gaps that produce similar current in all the series connected cells because the total stack current will be limited by the cell generating less current. But for this purpose the band gap as well as the layer thickness are parameters to adjust. Ternary alloys allow for band gap adjustment. But in general lattice mismatch is to be avoided in the whole stack so removing one degree of freedom and suggesting the need of searching solutions among the quaternary alloys (possibly of lower mobility). However good results have been also obtained with mismatched stacks.

Participant research centers in the FULLSPECTRUM Integrated Project

Participant number	Participant name	Participant short name	Country
1	Instituto de Energía Solar — Universidad Politécnica de Madrid	IES–UPM	Spain
2	Projektgesellschaft Solare Energiesysteme mbH	PSE	Germany
3	Fraunhofer Institute for Solar Energy Systems(1)	FhG–ISE	Germany
4	Ioffe Physicotechnical Institute	IOFFE	Russia
5	CEA–Départment pour les Technologies des Energies Nouvelles	CEA–DTEN	France
6	RWE–SSP	RWE–SSP	Germany
7	Philipps University of Marburg	PUM	Germany
8	Paul Scherrer Institute	PSI	Switzerland
9	University of Glasgow	UG	United Kingdom
10	Instituto de Catálisis y Petroleoquímica. Consejo Superior de Investigaciones Científicas	CSIC	Spain
11	Energy Research Centre of the Netherlands	ECN	The Netherlands
12	University of Utrecht	UU–Sch	The Netherlands
13	Imperial College of Science, Medicine and Technology	ICSTM	United Kingdom
14	Fraunhofer–Institut fuer Angewandte Polymerforschung(1)	FhG–IAP	Germany
15	Solaronix	Solaronix	Switzerland
16	ISOFOTON S.A	ISOFOTON	Spain
17	INSPIRA	INSPIRA	Spain
18	Joint Researh Centre — Institute for Enviorment and Sustainability	EC–DG JRC	Italy
19	University of Cyprus	UCY	Cyprus

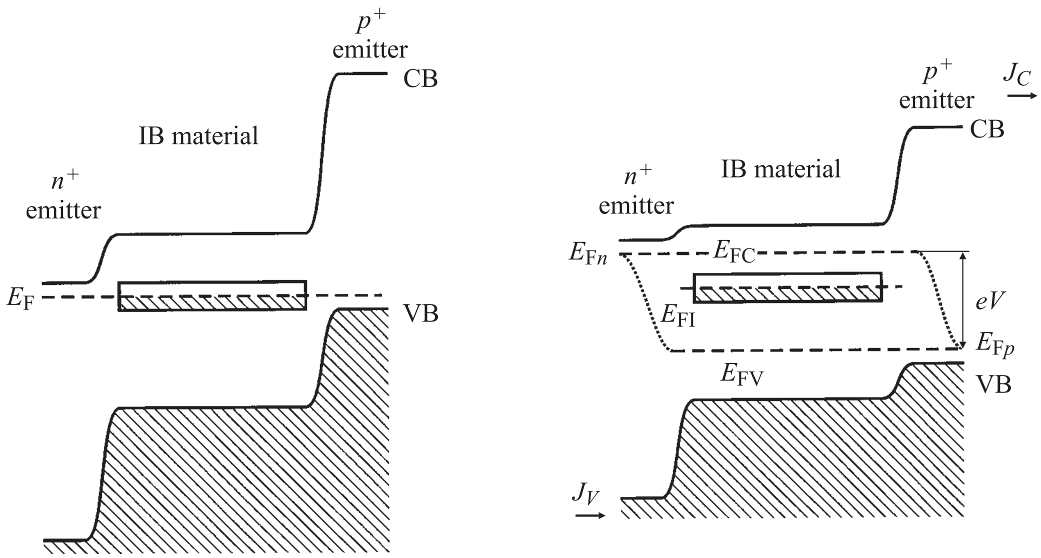

Figure 3. Band diagram of an intermediate band solar cell (IBC). There is a mid region of intermediate band material sandwiched between two p and n ordinary semiconductors. Left — thermal equilibrium; right — under illumination. The Fermi level E_F splits into three quasi Fermi levels E_{FC}, E_{FI} and E_{FV}.

So far the best results, 36.5% at 100 suns (i. e., at an irradiance of $10\,W/cm^2$) has been obtained with an InGaP/InGaAs/Ge 3-junction solar cell by Sharp, NASDA, and the Toyota Technological Institute in Japan [7], but this consortium is closely followed by American and European ones and there is a frantic search for a proper 1 eV band-gap cell that would use better the Ge cells (today illuminated with too many photons) and would open the way the to the 40% efficiency figure.

In the TPV conversion [8] a radiator is heated to high temperature by the sun or by a fuel and this radiation is converted into electricity by a solar cells. The efficiency potential of this device is high because it can recycle the photons not well converted by the solar cell. This means that the photons not absorbed by the cell or even those of energy well above the cell band gap are returned to the radiator, keeping it hot, by reflection in a filter letting only the pass of the desired photons. An alternative way is the use of selective emission radiators that emit photons mainly in the desired range of energies.

The theoretical potential of this concept is 85% [6], almost as high of the one in the MJC. However most of the technological effort in TPV has been devoted to fuel heated converters and the attention to solar heated converters has been much less. One of the challenges here today is probably the achievement of a good photon-recycling scheme, with low losses or alternatively a good selective radiator, but much work is still necessary in this concept.

In the IBC approach subband-gap photons are exploited by means of an intermediate band (IB). Subband-gap photons pump electrons from the valence band to the IB and then, from this band, to the conduction band. In this way, two low energy photons pump to the conduction band one electron, as represented in Fig. 3. For proper operation the Fermi level must split into three quasi Fermi levels as represented in the same figure. The potential efficiency of this concept is 63.2% [9].

The formation of a material exhibiting an intermediate band can be achieved by means of quantum dots [10]. They present a level in the band gap of the barrier material that can become the origin of the intermediate band. Solar cells based on quantum dots have been initially fabricated by a consortium formed by the Instituto de Energía Solar, the University of Glasgow and Compound Semiconductor Technologies and, although the cells does not reach the efficiency of the same structure without quantum dots, there is evidence of subband-gap absorption [11]. In this moment we are involved in measuring the possible separation of quasi Fermi levels in our quantum dot IB solar cells. IB materials based on alloys have been sought by theoretical band calculation [12] and recently found experimentally [13].

In the case of molecular based concepts the research aims, on one side, to the search of mechanisms where molecules adsorbed to a wide band gap semiconductor (TiO_2) pump electrons form an electrolyte to the conduction band of the semiconductor by using two photons instead of only one as it is the case in the dye solar cells existing today [14].

On the other hand a new type of purely static concentrator will be investigated (Fig. 4). Concentrators are of interest to reduce the area of the expensive solar converter separating in this way the functions of energy collector, left to the concentrator and energy converter, left to the solar cell. But high concentration concentrators need today mobile elements to focus the sunlight into the solar cells.

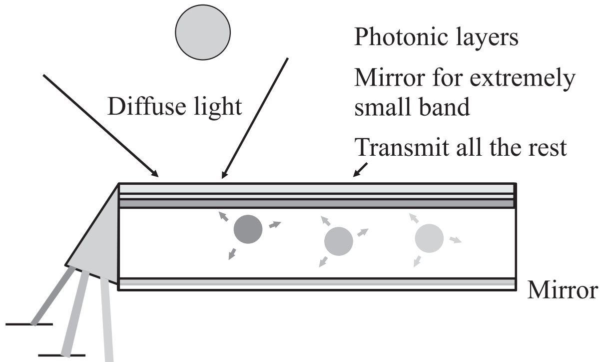

Figure 4. Schematic of a stationary luminescent concentrator.

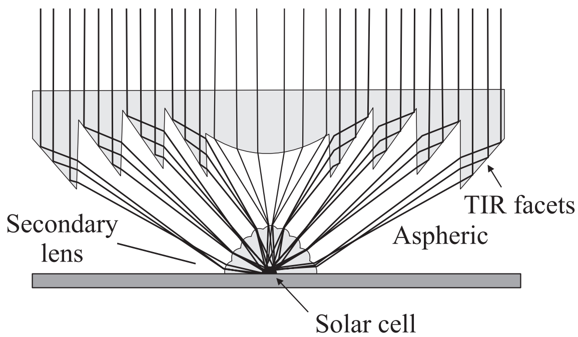

Figure 5. Schematic of the Hamlet concentrator formed of an aspheric total internal reflection primary lens and a combined secondary. It exhibits high acceptance angle and high light homogeneity on the solar cell. Joint development of ISOFOTON and the Instituto de Energía Solar.

The static concentrators are made of a transparent matrix in which some luminescent molecules are diluted. These molecules absorb the light incident on the plate and emit luminescent quasi-monochromatic radiation at some lower energy. This radiation is partly transmitted to the edge of the plate due to the total internal radiation experienced by the light when trying to leave the optically dense transparent plate [15].

In the planed work further investigation will be devoted to the described process and to the utilisation of photonic crystals [16] to prevent the escape of the luminescent monochromatic light at any incidence direction. This would greatly increase the efficiency of the light transter to the plate edge [17].

Most of the concepts indicated above involve long or very long-term research but in the case of MJC the concept is already ripe for industrialization. Therefore FULLSPECTRUM involves also manufacturing concepts. In particular concentrators are very important because MJC cells are very expensive. Concentration levels of 1000 suns, that is to irradiance fluxes of $100\,\mathrm{W/cm^2}$ are contemplated in this project. One important requirement to reduce prices is the use of wide angular acceptance. This means that the sunrays must stay focused into the cell even if the structure swings a little due to the wind or is somewhat misaligned due to manufacturing errors. The principles of design are in reference [18]. Multitude of devices has been designed in our Institute in the last years based on the principles there. Furthermore, at the high concentration envisaged the illumination must be as homogeneous as possible and this is difficult to conjugate with the angle acceptance requirement. Fig. 5 shows an optical system designed for this purpose.

In addition to the optical design, manufacturing the lenses at low cost and assembling the whole system taking into account cost heat removal requirements is also a challenge that is undertaken by the consortium in FULLSPECTRUM.

In summary, the mass exploitaion of the solar electricity is highly desirable for several reasons. Only mass production of the present PV technology will probably not be enough as to reduce PV electricity costs to reach the levels of prevalent electricity. A better exploitation of the solar spectrum is necessary.

Today there are scientific bases, for instance the MJC or TPV, for this better utilisation but they are not yet developed for a practical utilisation. Our fist goal is to develop them. It is necessary that a product with better potential than present technology be developed as soon as possible. Otherwise it will be forced to compete with products that are cheaper due to extensive market-associated development.

Besides, there are other technologies based on novel concepts and that deserve to be developed, although this will take more time. They may have the key for cheaper and more modular exploitation of the solar energy than the solutions envisaged today, much less modular than present PV. It is not to be ignored that modularity has been that key of the present success of the PV market.

FULLSPECTRUM aims to make substantial contributions on all these issues.

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