INFOTEH-JAHORINA Vol. 11, March 2012.

Technology, Light Source and Topography as a Challenge for proper Modeling of PV Cells

Duško Lukač
Rheinische Fachhochschule Köln gGmbH
University of Applied Sciences
Vogelsanger Strasse 295, 50825 Köln, Deutschland ,
E-mail: lukac@rfh-koeln.de

Srdjan Vukomirović
University of Novi Sad,
Faculty of Technical Sciences,
Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia
E-mail: srdjanvu@uns.ac.rs

Abstract— **With the development of the energy-optimized sensor technology with a middle electric power demand of some microwatt and with the progress of more alternatively photovoltaic technologies as for example of the organic photovoltaic cells, the photovoltaic use of radiation (insolation) is to be revalued especially for the application in the daily life, like for instance for the installations of photovoltaic cells in the buildings or carports. In this paper the operational modes of the photovoltaic cells, efficiency yield dependence on the band gap of the solar cell, kind of light source and topology as impact factors on efficiency, are as consideration factors for modeling of the PV cells presented.**

Keywords – Photovoltaic, Insolation Topology, Efficiency Yield, Band Gap

I. INTRODUCTION

The increased efficiencies of the established PV technologies leave no more leeway and space for bigger surprises. In its tables, Green et al. [1,2,3] deliver a good documentation of the advanced development and state of the art of the different PV cells. According to [1, p.86] form the Year 2009 "of the revised results…most notable as a result of the recalibration has been the increase in confirmed silicon cell efficiency to 25%, that of GaAs to beyond 26%, that of InP to beyond 22% and the increase in CIGS cells to 19.4%, reducing the gap to the 20% milestone for a 1 cm2 cell based on this technology". According to [2, p.347] from the Year 2010 "The first new result in Table I is a new record for a single-junction cell of any type under non-concentrated sunlight. An efficiency of 26.4% is reported for a 1 cm2 GaAs cell fabricated and measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE)". According to [3] from the Year 2011 "fourteen new results are reported in the present version. The first new result … is an outright record for solar conversion by any single-junction photovoltaic device. An efficiency of 27.6% has been measured at the National Renewable Energy Laboratory (NREL) for a 1 cm2 thin-film GaAs device fabricated by Alta Devices, Inc.. Alta Devices is a Santa Clara based ''start-up'' seeking to develop low-cost, 30% efficient solar modules". Consequently the record efficiency of 25% (Test center Sandia (3/99)) is unbroken with mono-crystalline silicon solar cells since 1998. Also the amorphous silicon cells reached the last record in 2011 with 10.1%. Above all, the new organic solar cells showed with an increase of 3,4% of efficiency in 2006 at 8.3% in 2011 (compared with 7,9% in 2009) comparative wise a bigger steps of development. Besides, as stated in [4] the PV research limits itself particularly to use of the terrestrial solar radiation in the outside area. Researches to applications in the astronautics or building technology are less spread. According to [5, p.5] "the building designer already has a number of sustainable technologies to choose from: premium thermal insulation, advanced heating, ventilation and air conditioning etc. which have significantly reduced especially the thermal energy requirements of buildings. But now a new technology, photovoltaic, has emerged as a viable option". The photovoltaic technology in the buildings is shaped by the energy supply of electronic small devices by means of amorphous silicon modules or high-efficient crystalline silicon. Probably also by the possibility to align when required the device to the optimum light source and to compensate thus failures of dimensioning, primarily the pocket computers, solar garden lamps etc. have found a wide market.

II. DEPENDENCE OF THE DEGREE OF THE EFFICIENCY ON SOLAR CELL TECHNOLOGY, LIGHT SOURCE AND TOPOGRAPHY

Generally, degree of the efficiency of the photovoltaic cells depends on many factors, like used technology for manufacturing of the cell like Double-Junction- Silicon cells (a-Si), CdTe-thin layer cells and conventional mono-crystalline silicon cells (sc-Si) etc., on source of the light depending on the wavelength and topography. According to [6, p.1] three different operating points can be observed with the function of the PV cells: "no-load operation (idle state), short-circuit state and normal operating state.

A. Characteristics of the no-load operation (idle state)

The electric voltage reaches in the idle state their maximum value, which is almost as high with a low illumination as with the strong illumination. The output power is zero because no electrical current flows.

B. Short-circuit state

The electrical current reaches its maximum value which depends on the intensity of the illumination as well as on the size and the efficiency of the respective solar cell. The electrical tension measured on the short-circuit cell is likewise as the output power zero valued.

C. Normal operating state

The working (operating) point is adjusted in that way, that a maximum output power by the solar cell is delivered. In addition electrical tension and current by the power inverter are, according to the lighting situation, adapted constantly to the optimum values." Operating points are presented in the Figure 1.

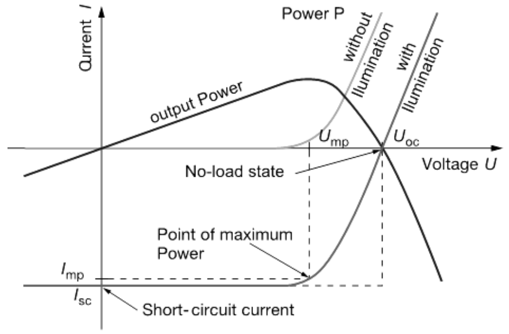

Fig. 1. Operating points of the PV cell

Basic construction of the sc-Si photovoltaic cell is presented in the following figure.

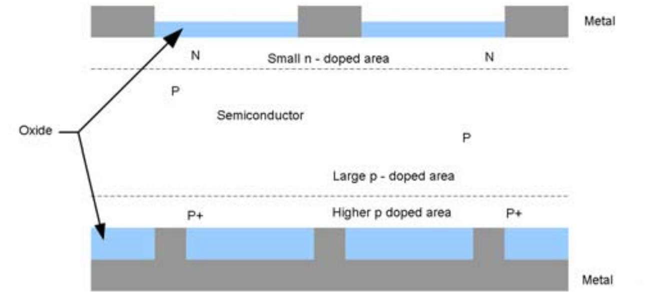

Fig. 2. Construction of the sc-Si photovoltaic cell

If we notice that electrons own slightest effectual masses than the holes and therefore a higher mobility, it is meaningfully to choose the N-endowed (doped) area small and the P-endowed area big, so that most photons pass the N area and are absorbed in the P area. To hinder that too much of the electrons resulted diffuse to the metal contact instead of in the so called space-charge region, one attaches to the p-endowed semiconductor crystal still a higher P-endowed semiconductor (P+) to arrange a additional potential degree in the way of the electrons to the contact in order to be pulled in the interior P-area. The metal contacts must be satisfactory low resistive and be small in order not to guard surface too much. The surface between the contacts is covered with an oxide layer. This should protect, above all, the solar cell. Nevertheless, much more importantly it is that it prevents surface recombination, which can have a main impact both on the short-circuit current and on the open-circuit voltage, and decreases the reflection of the light. Also the lower contact is not connected completely with the silicon by which the number of the electrons which reach the contact and get lost is further reduced [7]. Further, the efficiency of the solar cells depends strongly on the topography. As argued in [6,8] "for the attitude under 170 ms MSL, looking on the A-Si modules and Cd-Te modules oriented to the south, however, the I_{SC} (short – circuit current) value measured in the morning decreases in comparison to evening value less strongly than with the SC-Si modules. Looking at to the east oriented A-Si-and Cd-Te modules, it can observed that I_{SC} (6h p.m.) / I_{SC} (8h a.m.) show even an increase. By contrast I_{SC} decreases with the A-Si aimed to the west and Cd-Te modules in the day course. The changes directly arise from the different spectral components p (λ) and the orientations" and therefore are depending on the topography. We reefer for further reading to [6,8]. In the ideal solar cell every striking photon with satisfactory big light frequency contributes to the electric electricity. How the efficiency of the solar cells can be calculated is described in [1,2,3]. The maximum efficiencies of ideal solar cells for different emitters becomes calculated at first. Then the efficiencies as a function of the band gap specific for material and the striking photon electricity of the light source becomes calculated. In the following figure according to [4] the calculated theoretical maxima for a white LED, a fluorescent lamp with daylight spectrum (the spectrum of an energy savings lamp is comparable with of a fluorescent lamp), a halogen lamp and terrestrial sunlight with in 1.5 Air Mass is presented.

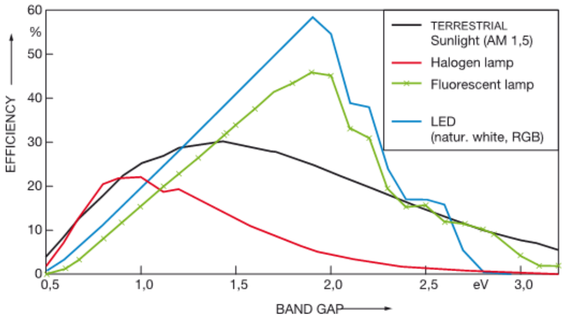

Fig. 3. Efficiency vs. Band gap for different light sources

"Air Mass (AM) explains that the solar radiation (insolation) is decreased on their way through the terrestrial atmosphere by reflection, absorption (by aerial molecules and aerial particles) and dispersion. The decrease of the insolation grows, the longer the way of the radiation through the terrestrial atmosphere is. The factor Air Mass declares how long is the way of the solar radiation thought the terrestrial atmosphere and it is given in proportion to atmosphere-thick" [6, p.2]. While cold "black body" emitter like electric light bulbs or halogen lamps nearly always reduce the attainable efficiency of photovoltaic converters - the efficiency of photovoltaic converters for electric light bulb lies under the result for halogen lamps. Electric light bulbs with a temperature of the glow spiral from about 2700 to 2800 K, like the classical electric light bulb or like the halogen lamps with the range from 3100 to 3200 K lie with the radiation maximum in the close infrared area. The spectral part in the visible area gives a yellowish impression. The color impression of the radiation of a thermal emitter as well as a black emitter can be used for its temperature regulation. Cold black emitter is nothing else than one idealized system which should absorb all occurring radiation. For light sources with a narrow wavelength area (narrow band) like LED are efficiencies of 40% to nearly 60% theoretically attainable. This at first astonishing result gets understandable, if looking at the next figure.

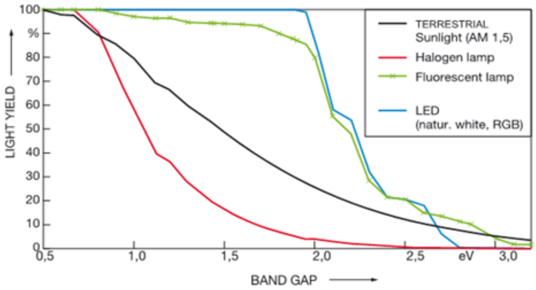

Fig. 4. Light yield vs. Band gap for different light sources

Light sources like LED or fluorescent lamps are optimized for the narrow optical window of the responsivity of the human eye of about 380 nm to 780 nm. Thus the radiation of the investigated fluorescent lamps lies only to about 4% beyond the visible area [4]. The light of the white LED can be already almost completely photovoltaically used for the a band gap by about up 1.9 eV, this corresponds to a border wavelength of 653 nm. For the spectrum of the solar radiation (sun light) only about 29% of the radiation contribute with this band gap to the photovoltaically energy conversion. Just with the development of narrow-band light sources a new, thrilling field of the photovoltaic becomes developed. In the ideal case the materials of the light source and the photovoltaic converter show the identical band gap. In the following figure, measured and with a diode factor n calculated efficiencies of photovoltaic converters for the spectrum of a fluorescent lamp to daylight spectrum are compared.

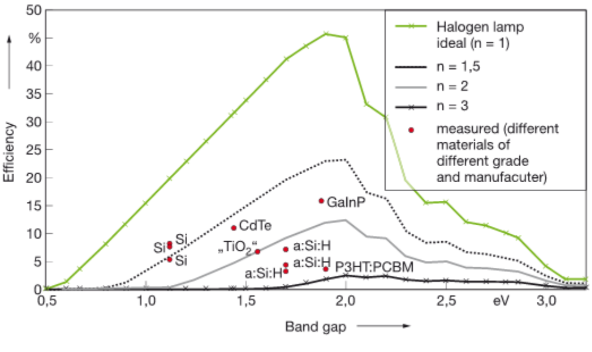

Fig. 5. Efficiency vs. Band gap in dependence of diode factor

The diode factor takes into consideration deviation of the ideality of real solar cells. Solar cells are modeled mostly as diodes. Besides, the factor of deviated ideality of the diode "n" describes loss processes by non-radiant recombination. Typically, this factor confirms values in the area from 1 to 2 [4,9]. Especially in the cases in which the recombination are to be modeled more complicated, higher values are also used. As stated in [9, p.1] "the diode factor is found to be strongly increased, sometimes to values that are too large to be explained by recombination theory". For some comparatively new technologies, like the organic PV or coloring solar cells, still exist no basic models and the set up models which are based on a classical PN junction, are only limited expressively. One understands by recombination the union of positive and negative charge carriers (ions, electrons) to an electrically neutral particle (atom, molecule). Recombination expresses the return process to the ionization, that is to say for the case of the "giving up" of a photons or phonons (grid oscillation) and "falling back" in the valence gape. Photons or phonons whose energy ($E = h*\nu$) is bigger than the energy gap Eg in the semiconductor , can deposit their energy in the valence electrons that can participate in the formation of chemical bonds with other atoms, and can generate electrons-hole-pairs in the semiconductor. These charge carriers (electrons and holes) go by radiation and/or grid oscillations (phonons) again in the direction of the band edge, because their energy is minimized. This effect delimits decisively the efficiency of solar cells which is effectively minimized with multi-junction solar cell. A recombination of these electrons and holes can be either irradiant or non-irradiant. If irradiant recombined, so is this effect called luminescence. It is vital that for a observing irradiant recombination, a direct semiconductor is necessary, with which there is no pulse difference of the gap minimum. In the classical calculation method $n \leq 2$ is used. Nevertheless, by some researchers $n > 2$ for certain applications has been used. The measured efficiencies lie thus as expected still far under the theoretical borders, even if the efficiency of single cells rose clearly according to the prediction in comparison to solar spectrum. For the case of the organic cells mentioned in [4] a maximum efficiency of 4.6% (average value: 3.5%) with the insolation with a fluorescent lamp with 9.1 W/m2 irradiance in comparison with an efficiency of about 2.7% for the solar spectrum and 1000 W/m2 irradiance. Also the CdTe cells improved their efficiency form about 5,7% to 16,7 % [3]. All measured samples were optimized in their absorption properties still for the solar spectrum, meaning they have been maladjusted. Also here lies a big optimization potential. The really attainable efficiencies in the buildings are by far not definitely exhausted , in any case, in the practice they open, possibly in the building automation, quite new application fields of the photovoltaic.

D. Discussion

By measurements, according to [4] it could be confirmed that, on the one hand, the efficiency of solar cells is bigger while irradiating with the spectrum of fluorescent lamps, than while irradiating with a spectrum of solar light with AM 1.5. On the other hand, materials with band gaps from about 1.44 eV likewise, have a higher efficiency for the case that they are irradiated with the spectrum of a fluorescent lamp. Nevertheless, the measured efficiencies lay clearly under their ideal maximum in each case. The upward gradient of the efficiency of the measured samples as a function of the band gap was lower than in the theoretical model predicted. The different measuring results also within material-homogeneous sample groups allow to suppose that by specific optimization for the application with irradiation less than 10 W/m2 as well as an improvement of the quality of small modules in the square centimeter area still offers the possibility of the essential increases of the efficiency. This counts in particular to the theoretically optimal materials as GaInP. In the cases in which miniaturization and voltage stability have priority, to the present state of development GaInP is to be recommended. Organic and coloring modules are under circumstances superior over the amorphous silicon modules by potentially low manufacturing costs with the identical efficiency in the voltage level and expense factor. Here the enclosure and housing of the modules for the protection of performance-diminishing reactions of the polymers, above all, with oxygen and ultraviolet light are further research subject. Calendar life's tests of the Fraunhofer ISE which tested about 1.5 years of exposition under sunlight achieved after 1500 test hours an efficiency of 90% compared with the initial efficiency. Further all investigated samples were optimized in their reflecting properties for solar spectrum, so that also here still optimization potential for the application in interiors exists. For a standardization of the measurement of photovoltaic converters for interior applications should also evaluated points like the definition of a radiation source of specific radiation also cell size and cell temperature be standardized. A possibility is the orientation towards the IEC 60904-3, 2nd edition (2008) as stated in the [3], which prescribes a cell size of 1 cm2 and a module temperature of 25 °C. “There are also certain minimum values of the area sought for the different device types (above 0.05 cm2 for a concentrator cell, 1 cm2 for a one-sun cell and 800 cm2 for a module)” [3, p.84].

CONCLUSION

In this work basic operating points and construction of the PV cells is presented. Furthermore it becomes evident that the efficiency of the PV cells strongly depends on the technology used for production of the cell, source of the light which is closely linked with the wave length of the light used for insolation as well as form the topography. Those information are valuable for development of the proper model of PV cell of made by using of different technology.

LITERATURE

[1] Martin A. Green, Keith Emery, Yoshihiro Hishikawa and Wilhelm Warta (2009),"Solar cell efficiency tables (version 33)" PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, Prog. Photovolt: Res. Appl. 2009; 17:85–94, Published online in Wiley InterScience (www.interscience.wiley.com) DOI: 10.1002/pip.880

[2] Martin A. Green, Keith Emery, Yoshihiro Hishikawa and Wilhelm Warta (2010), "Solar cell efficiency tables (version 36)", PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, Prog. Photovolt: Res. Appl. 2010; 18:346–352, Published online 18 June 2010 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/pip.1021

[3] Martin A. Green, Keith Emery, Yoshihiro Hishikawa and Wilhelm Warta (2011), "Solar cell efficiency tables (version 37)", PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, Prog. Photovolt: Res. Appl. 2011; 19:84–92, Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.1088

[4] Müller, M (2010) "Hocheffizient per Definition – Photovoltaik im Gebäude", ep Photovoltaik, pp.62-64

[5] Sick, F and Erg, T (2010) "PHOTOVOLTAICS IN BUILDINGS - A Design Handbook for Architects and Engineers, Fraunhofer Institute for Solar Energy Systems (FhG-ISE), pp.1-69

[6] Duško Lukač, Miona Andrejević Stošović, Vančo Litovski (2001), "Operating Points and Topographic Dependence of the Thin Layer-Photovoltaic Cells as Relevant Characteristics for Modeling of the PV Cells", SSSS Conferece, Univesrity of Nis, Serbia, pp.1-4

[7] Stober,F and Will, M (2005), "Solarzelle", Working Paper, pp.1-17

[8] Rennhofen, M.. (2010) "Topographischer Einfluss auf Dünnschicht-Photovoltaik", ep Photovoltaik, pp.60-62

[9] Van der Heide, ASH, Schönecker,A, Bultman,JH and Sinke, WC (2004), "Explanation of high solar cell diode factors by non-uniform contact resistance", Energy research Centre of the Netherlands, pp.1-16