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CRITICAL ASSESSMENT OF HIGH EFFICIENCY PHOTOVOLTAIC CONCEPTS

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Abstract
Solar cells efficiency forecasts have been carried out from the very beginning of photovoltaic (PV) converters in order to guide research activities. Revising the topics of efficiency limits is pertinent because there are more than one attempts in developing new concepts for solar cells towards obtaining a higher efficiency. The paper reports a comparative survey of theoretical limits of new proposed nanoscale converters – known as third generation- multi quantum well tandem, intermediate bands cells and up/down converters. In our studies we use numerical simulations.
Keywords: nanostructure solar cells, efficiency, numerical simulation.

1. Introduction

A major limitation in spreading the use of solar energy is the expense of the PV converters. More, as Fig 1 suggest, only by decreasing fabrication costs of actual solar cells without increasing the conversion efficiency, we cannot hope in the solar electricity to become competitive on the energy market.

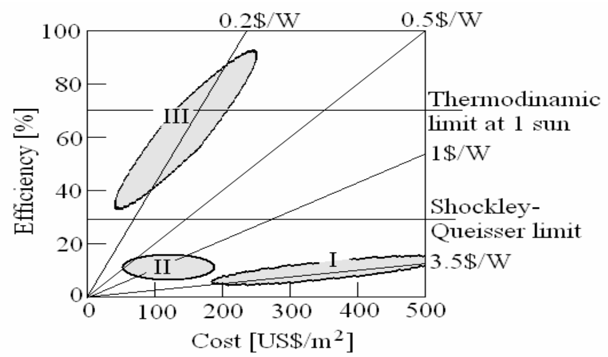

Fig 1 Solar cell efficiency and costs for different types: I. Silicon single junction; II. Cells using thin layers (amorphous Si, CIGS, CdTe); III – Third generation cells (after M A Green, [1])

The paper surveys new concepts of PV converters that are subject of nanoscale science and tehnology: multi-quantum-wells (MQW), intermediate bands (IB) up/down conversion (UDC). We are focusing on the respective theoretical conversion limits.

2. High efficiency PV concepts

Fig 1 shows the three PV cell generations efficiencies as a function of their costs [1]. Since the 60'th, in Sockley-Queisser (SQ) Detailed Balance Theory (DBT) the maximum efficiency limit for a single junction cell have been evaluated at 33% [2]. The Carnot thermodynamic limit of photovoltaic efficiency is 94% and the theoretical limit for a two terminal infinite tandem has been estimated to 86.8% [3]. Laboratory multijunction solar cells reach conversion efficiency [4] but having a sophisticated design and a prohibitive cost mass production.

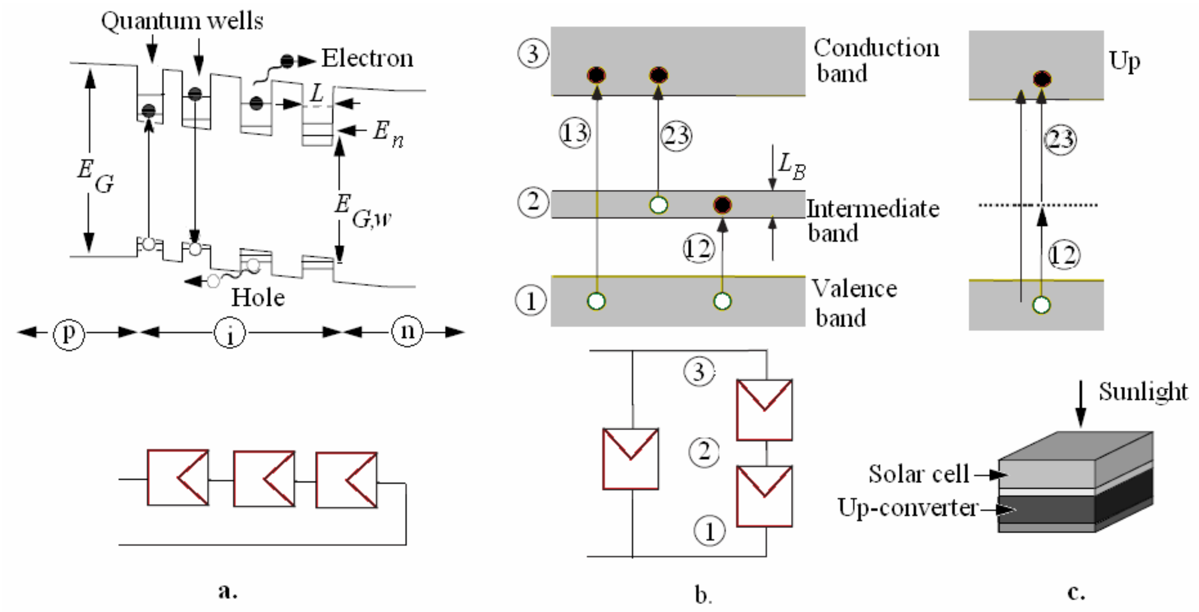

Figure 2 a. p-i-n structure of a MQW cell and the equivalent circuit for a stack with three cells; b. The IB cell concept and equivalent circuit; c. Up-converter from UDC concept and cell schematic.

The MQW concept is the closest possible to multijunction structure of solar cells. The quantum potential well forms the basis of this method: by varying the width of the wells (fig 2a), one can create synthetic semiconductors with desired effective band-gaps [5]:

$$E_n = \left(\pi^2 \hbar^2 n^2\right) / \left(2 m_e^* L^2\right) \quad (1)$$

Practically, with different energy levels created by the wells, we are able to absorb photons with energy less than the band-gaps of bulk materials. By incorporating a MQW structure into a single p-i-n junction, we gain the advantage to have *a single-cell* instead of a multijunction-stack for appropriate multiple band-gap structure (fig 2a).

IB concept is an extension of impurity photovoltaics approach, but in nanoscale technology apart from traditionally doping, the mini-bands inside bulk band-gap (fig 2b) are induced by regular spatially distributed quantum dots or superrlatices [6].

UDC concept is quite different because the solar cell (with E_G bandgap) is coupled with an optical device which transform unusable ($\hbar\omega < E_G$) and/or inefficiently utilized ($\hbar\omega > E_G$) portion of the solar spectrum into narrower spectral range close to optimal. During the up-conversion multiple photons are "summing" to create a single photon with energy equal to E_G. In opposite, a down-converter "splits" a single photon with energy greater than the band gap in multiple photons with energy also close to E_G. An up-converter is coupled to a typical solar cell as shown in figure 2c. Photons with energy less than E_G pass through the converter, where it is up-converted and radiated outward. A back reflector ensures that all photons are kept inside the cell.

In fact, all three solutions are basically equivalent with tandem concept (fig 2). The SQ conversion limit has been computed to be around 63% within a model with one intermediary band [7], a little too optimistic as we will see in the following.

2. A simplified Detailed Balance Theory

A simplified variant of SQ of DBT have been developed for computation of the above cells efficiency. Under AM1.5 solar spectrum [8] the rate of electron-hole pair generation is:

$$g_s = \int_{\nu_{\min}} q(\nu)N(\nu)d\nu \tag{2}$$

where $q(\nu)$ is the quantum efficiency and $N(\nu)$ is the number of incident photons on the cell surface per unit of area and bandwidth in each second. If we assume an ideal situation where all the generated carriers are collected, the photocurrent will be:

$$J_L = eg \tag{3}$$

The DBT principle establishes that the total current that flows in the cell is determined by the rate of electron-hole pair generation minus the total recombination rate (out of equilibrium). If f_r is the radiative recombination fraction, the total current could be read:

$$J = e\left[g_s - (r(V) - r(0))/f_r\right] \tag{4}$$

where the radiative recombination rate is from $r(V) = r_{0T} \exp(V / V_T)$ with $r_{0T} = \int_{\nu_{\min}} 8\pi \left(\frac{\nu}{c}\right)^2 \exp\left(-\frac{h\nu}{kT}\right) d\nu$ at thermal equilibrium [9]; c is the speed of light.

In the radiative limit $f_r = 1$ and from the condition $J = 0$, the open circuit voltage is:

$$V_{0C} = V_T \ln\left(1 + \frac{g_s}{r_{0T}}\right) \tag{5}$$

Writing the total incident radiation power as: $P_0 = \int_{\nu_{\min}} h\nu g_s(\nu) d\nu$, then the solar cell efficiency as function of fill factor F_f is:

$$\eta = \frac{J V_{0C}}{P} F_f \tag{6}$$

Now we can do the computations and assess the efficiencies of solar cells based on new PV concepts.

3. Numerical results

Based on the above theory we proceed to a simulation of efficiency on the case of solar cells with novel structure. Assuming AM1.5G spectrum and in the hypothesis of all conditions being ideal: unitary quantum efficiency, only radiative recombination and 100% collection of photo-generated carriers, the results for 3 cell stack and 1 intermediary band are presented in fig 3a,b respectively. The cell parameters when the maximum efficiency is achieved are listed in table 1.

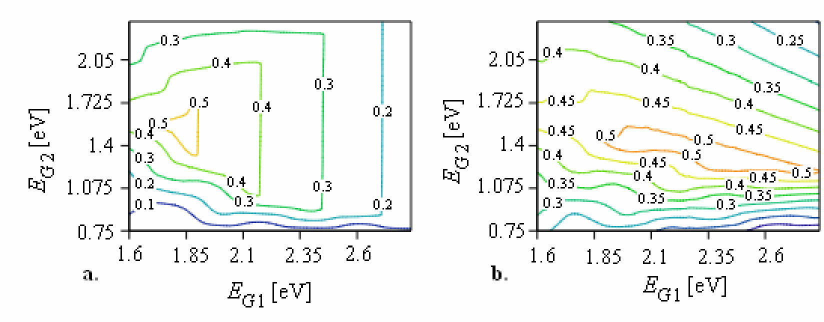

Fig 3. Solar cells efficiency as function of band-gap for: a three cell tandem (a) and one intermediary band (b). E_{G1} and E_{G2} are middle cells bandgap. Down cell badgap are E_{G1} - E_{G2}.

Table 1. The optimal band gap E_G for which the solar cells efficiency reach the highest value. The photocurrent density J_L and the open circuit voltage V_{0C} are also listed.

	E_{G1}[eV]	E_{G2}[eV]	L_L[mA]	V_{0C} [V]	η
Three cells serial	1.82	1.21	19.53	2.72	0.537
One intermediary band	2.41	1.48	29.81	1.81	0.54

4. Conclusions

The results points out that the cell efficiency can be significantly increased by using nanotechnology concepts. But our prediction is not as optimistic as reported by others, our estimated values being ≈10% lower.

Acknowledgements

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