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EFFICIENCY LIMITS IN PHOTOVOLTAICS – CASE OF SINGLE JUNCTION SOLAR CELLS

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Abstract. *The conversion efficiency of solar energy into electrical energy is the most important parameter when discussing solar cells, photovoltaic (PV) modules or PV power plants. So far many papers have been written to address the limiting efficiency of solar cells, the theoretical maximum conversion efficiency an ideal solar cell could achieve. However, most of the researches modelled sun's spectrum as a blackbody which does not represent a realistic case. In this paper we have calculated the limiting efficiency as a function of absorbers band gap at standard test conditions using the solar spectrum AM1.5. In addition, the other key solar cells performance parameters (open-circuit voltage, short-circuit current density and fill factor) are evaluated while the intrinsic losses in the solar cells are also explained and presented in light of a cell temperature.*

Key words: *efficiency limit, single junction solar cell, loss mechanisms, AM1.5 spectrum.*

1. INTRODUCTION

The conversion efficiency is one of the most important parameters when discussing photovoltaic or any other energy conversion devices, telling us the ratio between output and input energy. Besides the actual state of the art average or record efficiencies, theoretical limiting efficiency is also very important since it declares how much progress is still left to achieve. In photovoltaics, the first limiting efficiency for solar cells was calculated by Shockley and Queisser in 1961 [1]. In their work they assumed the detailed balance principle based on the second law of thermodynamics. They calculated limiting efficiency to be 30% for single junction solar cells modelling sun as a blackbody with T = 6000 K. Later, other attempts in this field were also reported [2]–[4].

Different techniques were examined in an attempt to achieve or even exceed the limiting efficiency. Most popular are light management through optical light scattering [7], tandem solar cells and concentrator solar cells. Other approaches, such as multiple exciton generation[8] and up-[9] and down-[10]conversion, are also researched. Here we will focus on single-junction solar cells under terrestrial conditions.

In the existing studies most of the researchers used sun's blackbody radiation spectrum. This, however, does not represent realistic situation for terrestrial conditions as part of

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sun's spectrum is absorbed in the atmosphere. In this paper we will use standard solar spectrum AM1.5[11]. The two spectra are shown in Fig. **1**. The difference is clear, thus an analysis has to be done separately. We will determine the maximum efficiency under AM1.5 one sun illumination for single junction solar cell at standard testing conditions together with the key performance parameters of the solar cells. In the second part of this paper intrinsic losses will be explained and calculated. Also, a comparison between results underAM1.5 or blackbody radiation spectrum will be shown.

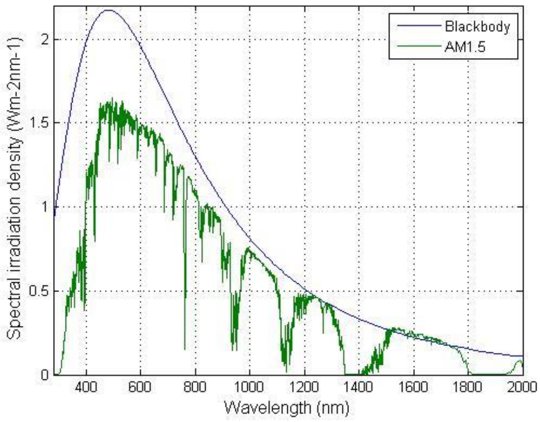

Fig. 1 Comparison between blackbody radiation spectrum at T_S = 6000 K (G=1550Wm^{-2}) and solar spectrum AM1.5 (G=1000 Wm^{-2}). Same energy span for both spectra was considered here.

2. Efficiency Limit

According to the detailed balance principle[1], in equilibrium everything that is absorbed has to be emitted. Radiative recombinations are therefore the only recombination mechanism present in the solar cell and as such necessary and unavoidable. All other recombinations diminish the efficiency significantly. The emission from the solar cell in equilibrium follows the Planck equation where the emission spectrum is described by the solar cell temperature T_C:

$$B(E) = \frac{2}{h^3c^2}\frac{E^2}{\exp\left(\frac{E}{k*T_C}\right)-1} * \varepsilon \qquad (1)$$

E is the energy of the emitted photon, h is Planck's constant, c speed of light and k Boltzmann's constant. Emissivity ε = 1 was used in the following calculations as black body was assumed.

Under the illumination the system is no longer in equilibrium. Due to chemical potential between quasi-Fermi levels the photon emission increases by $\exp(\mu/kT_C)$ following the normalised np product, where $\mu = q*V_{OC}$ is a chemical potential, q is elementary charge. Absorbed incident photons create electron-hole pairs. At the open-circuit voltage V_{OC} generated electrons cannot be extracted as no load is connected to the solar cell. In the ideal solar cell they are all radiatively recombined and emitted. Open-circuit voltage can therefore be derived by equalling recombinations R_{ext} (Equation 2) and generations P_{pump} (Equation 3):

$$R_{ext} = \exp\left(\frac{\mu}{k*T_C}\right) * \int_0^{2\pi} \int_{E_G}^{\infty} B(E)dE \cos\theta \, d\Omega \tag{2}$$

$$P_{pump} = \int_0^{2\pi} \int_{E_G}^{\infty} S(E)dE \cos\theta \, d\Omega \tag{3}$$

$$R_{ext} = P_{pump} * \eta_{ext} \tag{4}$$

$$\eta_{ext} = \frac{R_{ext}}{R_{ext}+R_{nr}} \;\; => R_{ext} + R_{nr} = \frac{R_{ext}}{\eta_{ext}} \tag{5}$$

E_G denotes band gap, $S(E)$ is spectrum of the solar radiation while Ω and Θ stand for solid and polar angle, respectively. If non-radiative recombinations R_{nr} do occur, they can be described with external fluorescence efficiency: η_{ext}<1. V_{OC} is then:

$$V_{OC} = \frac{k*T_C}{q} \ln \frac{\iint S(E)dE \cos\theta \, d\Omega}{\iint B(E)dE \cos\theta \, d\Omega} - \frac{k*T_C}{q} * |\ln \eta_{ext}| \tag{6}$$

The current in the solar cell is the difference between the generated electrons from solar radiation and the recombined electrons, radiatively or non-radiatively, and is voltage V dependent. This gives us:

$$J = q\left(P_{pump} - R_{ext} - R_{nr}\right) = q * \left(P_{pump} - \frac{R_{ext}}{\eta_{ext}}\right) =$$

$$q \iint S(E)dE \cos\theta \, d\Omega - \frac{q*\pi}{\eta_{ext}} * \exp\left(\frac{q*V}{k*T_C}\right) * \int_{E_G}^{\infty} B(E)dE \tag{7}$$

Here, we consider only radiative recombinations since we assumed an ideal solar cell, where only loss in the solar cell is emission loss due to radiative recombination. Therefore η_{ext} = 1. The short circuit current J_{SC} can easily be calculated from Equation 7 by inserting V=0.

Maximum power can be obtained as a product of J_{mpp} and V_{mpp}, current and voltage in maximum power point, while efficiency, the most important factor when discussing solar cells, is the ratio between generated electrical power P_{el} and incoming power from the sun P_{in}.

$$\eta = \frac{P_{el}}{P_{in}} = \frac{V_{mpp}*J_{mpp}}{P_{in}} = \frac{V_{OC}*J_{SC}*FF}{P_{in}} \tag{8}$$

where FF is the fill factor and calculated by the following equation:

$$FF = \frac{V_{mpp}*J_{mpp}}{V_{OC}*J_{SC}} \tag{9}$$

The discussed parameters are presented in Fig. **2** in band gap dependency. The first graph shows the famous SQ limit for the two spectra. The peak is 33.8% at 1.34 eV for AM1.5 and 31.4% at 1.29 eV for blackbody radiation. V_{OC} increases linearly with band gap while J_{SC} decreases due to less photons absorbed at higher band gap energies. The discussed parameters of c-Si and GaAs record solar cells are also inserted in the graphs.

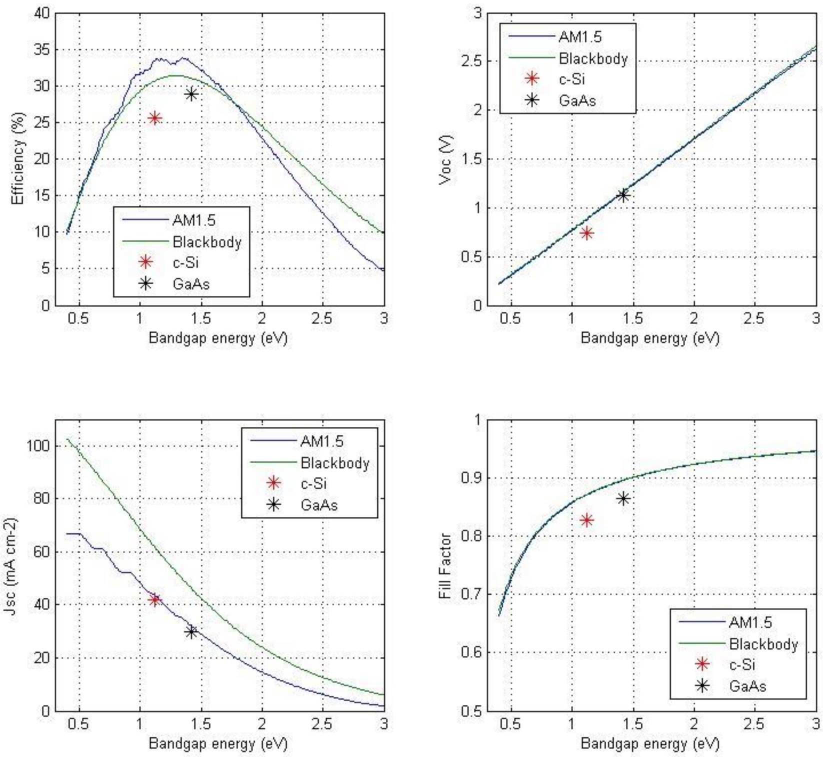

Fig. 2 Graphical presentation of solar cell parameters for AM1.5 (blue line) and blackbody radiation (green line) at T_C = 25°C with inserted points for record c-Si [12] and GaAs [13] solar cells

Since most of the papers are based on blackbody radiation we decided to show the comparison between blackbody radiation at T_S = 6000 K and AM1.5 spectrum for all the basic parameters of the solar cell. To calculate parameters with blackbody radiation only AM1.5 spectrum data has to be replaced with blackbody formula. While there is not much difference at V_{OC} and *FF*, clear difference between generated currents can be observed. This is a result of a higher number of photons if we consider the blackbody radiation. The efficiency of the solar cell is higher at AM1.5 despite less current due to lower incident power density.

In Table 1 we present the comparison between theoretical efficiency limits and the achieved record efficiencies for crystalline Silicon (c-Si) and crystalline Gallium arsenide (GaAs) solar cells. The columns 3 and 4 show that the material properties are very important at determining the limiting efficiency of solar cells while record solar cells are still some way below theoretical limits. The *J-V* characteristics for the record and the ideal solar cell for both c-Si and GaAs are presented in Fig. **3**. Since there is no *J-V* data about 28.8% GaAs solar cell, the one of the 27.6%solar cell [14] is used instead. The record c-Si cell exhibits better utilization of incident photons (higher J_{sc} compared to J_{sc_ideal}), while the record GaAs cell exhibits better utilization of photovoltage (higher V_{oc} compared to V_{oc_ideal}). In both cases and in particular in thin-film solar cells there is room for further improvements [11]

Table 1 Comparison between efficiencies for Si and GaAs solar cells, solar spectrum AM1.5

Material	EG	Limit at EG	Limit for the material	Record cell[13]
c-Si	1.12 eV	33.2%	29.8%	25.6%
GaAs	1.42 eV	33.4%	33.4%	28.8%

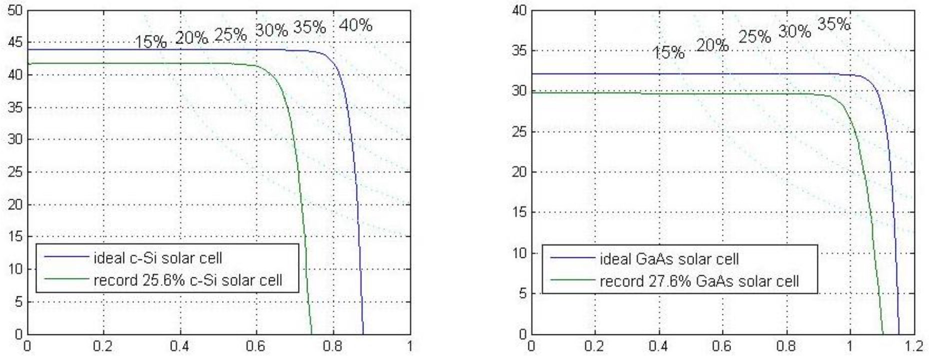

Fig. 3 I-U characteristics for the ideal and record c-Si (a) and GaAs (b) solar cell at STC (AM1.5, T_C=25°C)

3. Loss Mechanisms

As shown in the previous section the efficiency limit is 33.8%. Where is the rest of the power lost? In this section we will explain intrinsic losses in a solar cell. Since the amount of absorbed incident photons is strongly related with band gap, the biggest losses are spectral losses. Other losses, such as emission, Carnot and Boltzmann losses, also contribute to the lower efficiency of the solar cells.

3.1. Spectral losses

The band gap is the most important parameter when determining efficiency. The photons with energy below the band gap do not have enough energy to generate an electron-hole pair and are therefore transmitted and not absorbed. Such losses are named below band gap losses. They can be calculated by the following equation where we integrate the AM1.5 spectrum for all the energies below the band gap.

$$pLoss_{BelowEg} = \int_0^{E_g} S(E)dE = \int_{\lambda_G}^{\infty} S(\lambda)d\lambda \qquad (10)$$

The photons with energy above the band gap are absorbed in the active layer, creating free electron-hole pairs. The excessive energy, difference between photon's energy and the band gap, however, is lost in a thermalization process where the generated electron thermalizes from the conductive band to its edge. Such losses are named above band gap losses or thermalization losses.

$$pLoss_{AboveEg} = \int_{E_g}^{\infty} \frac{E-E_g}{E} * S(E)dE = \int_0^{\lambda_G} \frac{\lambda_g-\lambda}{\lambda} * S(\lambda)d\lambda \qquad (11)$$

3.2. Emission loss

The free electrons generated by the incoming photons are not stable and eventually drop back to the valence band where they recombine. Recombination results in a phonon if the recombination is non-radiative or in photon if it is radiative. Here we assumed only radiative recombinations occur in the solar cell as they are unavoidable due to detailed balance principle where everything absorbed has to be emitted. The emission loss can be calculated as a radiation from a blackbody at the maximum power point.

$$pLoss_{Emission} = q * \pi * \exp\left(\frac{q*V_{mpp}}{k*T_C}\right) * E_g * \int_{E_g}^{\infty} B(E)\, dE \qquad (12)$$

3.3. Energy less than band gap

Ideally the open circuit voltage would be equal to the band gap. However, in application open circuit voltage is lower and corresponds to the potential difference between quasi- Fermi levels while voltage in the maximum power point is even lower. This is a result of Carnot and Boltzmann factor. Carnot factor appears as the conversion from thermal to electrical work needs some energy [15], while Boltzmann factor is a consequence of unequal solid angles of absorption and emission.

$$pLoss_{Carnot} = E_g * \frac{T_C}{T_S} * J_{mpp} \qquad (13)$$

$$pLoss_{Boltzmann} = \frac{k*T_C}{q} * \ln\frac{\Omega_E}{\Omega_A} * J_{mpp} \qquad (14)$$

The symbol Ω_E denotes solid angle of emission and Ω_A is solid angle of absorption. Their values are π and 6.8221e-5, respectively.

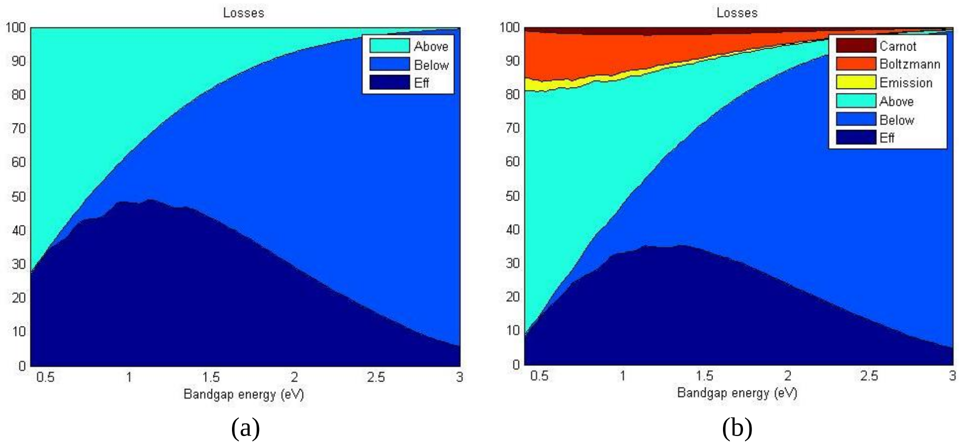

Fig. 4 Losses in solar cell for AM1.5 at T_C=0 K (a) and T_C = 298.15 K = 25°C (b)

The structures of the losses are presented in Fig. **4**. First we assumed the temperature of the solar cell to be 0 K. By observing Equations 1, 12, 13 and 14, we see that at T_C = 0 K the emission, Carnot and Boltzmann losses all equal to 0. The only loss mechanism present are spectral losses that are not temperature dependant, therefore the efficiency increases. Maximum efficiency is now 49.1% at 1.14 eV. Such a state is shown in Fig. **4** a.

Second, we calculated the losses for STC conditions which demand solar cell temperature to be 25°C (298.15 K). The result is shown in Fig. **4** b. The spectral losses present most of the losses. Thermalization losses decrease with the band gap while below band gap losses increase due to less photons absorbed. The emission loss presents only a small fraction while Carnot and Boltzmann losses are not insignificant. The maximum efficiency at T_C = 25°C is 33.8% at 1.34 eV.

CONCLUSIONS

We have calculated efficiency limit of single junction solar cells for standard solar spectrum AM1.5 under STC conditions. The peak efficiency is 33.8% at 1.34 eV. The basic solar cell parameters – efficiency, J_{SC}, V_{OC} and *FF*- were derived and shown in band gap dependency. The blackbody radiation and solar spectrum AM1.5 comparison was also shown to emphasize the difference between the two spectra.

In addition, intrinsic losses in solar cells were explained and discussed. Spectral losses, due to unabsorbed photons with energy below band gap or thermalization process of absorbed photons, contribute to over 50% drop of efficiency. Attention was also paid to losses that are present in the solar cell at T_C = 0 K, where only spectrum losses would have been present and increasing the efficiency limit under AM1.5 spectrum to 49.1%.

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REFERENCES

[1] W. Shockley and H. J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells," *J. Appl. Phys.*, vol. 32, no. 3, pp. 510–519, Mar. 1961.

[2] G. Araujo and A. Marti, "Absolute Limiting Efficiencies for Photovoltaic Energy-Conversion," *Sol. Energy Mater. Sol. Cells*, vol. 33, no. 2, pp. 213–240, Jun. 1994.

[3] T. Tiedje, E. Yablonovitch, G. D. Cody, and B. G. Brooks, "Limiting efficiency of silicon solar cells," *IEEE Trans. Electron Devices*, vol. 31, no. 5, pp. 711–716, May 1984.

[4] L. C. Hirst and N. J. Ekins-Daukes, "Fundamental losses in solar cells," *Prog. Photovolt. Res. Appl.*, vol. 19, no. 3, pp. 286–293, May 2011.

[5] C. H. Henry, "Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells," *J. Appl. Phys.*, vol. 51, no. 8, pp. 4494–4500, Aug. 1980.

[6] O. D. Miller, E. Yablonovitch, and S. R. Kurtz, "Intense Internal and External Fluorescence as Solar Cells Approach the Shockley-Queisser Efficiency Limit," *IEEE J. Photovolt.*, vol. 2, no. 3, pp. 303–311, Jul. 2012.

[7] E. Yablonovitch and G. D. Cody, "Intensity enhancement in textured optical sheets for solar cells," *IEEE Trans. Electron Devices*, vol. 29, no. 2, pp. 300–305, Feb. 1982.

[8] A. J. Nozik, M. C. Beard, J. M. Luther, M. Law, R. J. Ellingson, and J. C. Johnson, "Semiconductor Quantum Dots and Quantum Dot Arrays and Applications of Multiple Exciton Generation to Third-Generation Photovoltaic Solar Cells," *Chem. Rev.*, vol. 110, no. 11, pp. 6873–6890, Nov. 2010.

[9] T. Trupke, M. A. Green, and P. Würfel, "Improving solar cell efficiencies by up-conversion of sub-band-gap light," *J. Appl. Phys.*, vol. 92, no. 7, pp. 4117–4122, Oct. 2002.

[10] T. Trupke, M. A. Green, and P. Würfel, "Improving solar cell efficiencies by down-conversion of high-energy photons," *J. Appl. Phys.*, vol. 92, no. 3, pp. 1668–1674, Aug. 2002.

[11] "Solar Spectral Irradiance: Air Mass 1.5." [Online]. Available: http://rredc.nrel.gov/solar/spectra/am1.5/. [Accessed: 19-Mar-2014].

[12] "Panasonic HIT(R) Solar Cell Achieves World's Highest Energy Conversion Efficiency of 25.6% at Research Level | Headquarters News | Panasonic Global." [Online]. Available: http://panasonic.co.jp/corp/news/official.data/data.dir/2014/04/en140410-4/en140410-4.html. [Accessed: 08-Jul-2014].

[13] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, “Solar cell efficiency tables (version 44),” *Prog. Photovolt. Res. Appl.*, vol. 22, no. 7, pp. 701–710, Jul. 2014.

[14] B. M. Kayes, H. Nie, R. Twist, S. G. Spruytte, F. Reinhardt, I. C. Kizilyalli, and G. S. Higashi, “27.6% Conversion efficiency, a new record for single-junction solar cells under 1 sun illumination,” in *2011 37th IEEE Photovoltaic Specialists Conference (PVSC)*, 2011, pp. 000004–000008.

[15] E. Fermi, *Thermodynamics*. Courier Dover Publications, 1956.