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Maximal power output by solar cells with angular confinement

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Abstract: Angularly selective filters can increase the efficiency of radiatively limited solar cells. A restriction of the acceptance angle is linked to the kind of utilizable solar spectrum (global or direct radiation). This has to be considered when calculating the potential enhancement of both the efficiency and the power output. In this paper, different concepts to realize angularly selective filters are compared regarding their limits for efficiency and power output per unit area. First experimental results of a promising system based on a thin-film filter as the angularly selective element are given to demonstrate the practical relevance of such systems.

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References and links
1. W. Shockley and H. J. Queisser, “Detailed balance limit of efficiency of p-n junction solar cells,” J. Appl. Phys. 32(3), 510–519 (1961).
2. T. Tiedje, E. Yablonovitch, G. D. Cody, and B. G. Brooks, “Limiting efficiency of silicon solar cells,” IEEE Electron. Dev. 31(5), 711–716 (1984).
3. T. Kirchartz and U. Rau, “Detailed balance and reciprocity in solar cells,” Phys. Status Solidi A 205(12), 2737–2751 (2008).
4. J. E. Parrott, “Radiative recombination and photon recycling in photovoltaic solar cells,” Sol. Energy Mater. Sol. Cells 30(3), 221–231 (1993).
5. M. A. Green, “Radiative efficiency of state-of-the-art photovoltaic cells,” Prog. Photovolt. Res. Appl. 20(4), 472–476 (2012).
6. O. D. Miller, E. Yablonovitch, and S. R. Kurtz, “Strong internal and external luminescence as solar cells approach the Shockley-Queisser limit,” IEEE J. Photovolt. 2(3), 303–311 (2012).
7. M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, “Solar cell efficiency tables (version 42),” Prog. Photovolt. Res. Appl. 21(1), 827–837 (2013).
8. E. Yablonovitch, O. D. Miller, and S. R. Kurtz, “The opto-electronic physics that broke the efficiency limit in solar cells,” in IEEE Phot. Spec. Conf. (2012), pp. 1556–1559.
9. T. Markvart, “Solar cell as a heat engine: energy-entropy analysis of photovoltaic conversion,” Phys. Status Solidi A 205(12), 2752–2756 (2008).
10. M. Peters, J. C. Goldschmidt, and B. Bläsi, “Angular confinement and concentration in photovoltaic converters,” Sol. Energy Mater. Sol. Cells 94(8), 1393–1398 (2010).
11. A. W. Bett, C. Baur, F. Dimroth, G. Lange, M. Meusel, S. Van Riesen, G. Siefer, V. M. Andreev, V. Rumyantsev, and N. Sadchikov, “FLATCON modules: technology and characterisation,” in Proc. of 3rd World Conference on Photovoltaic Energy Conversion (2003), pp. 634–637.
12. G. L. Araujo and A. Marti, “Absolutely limiting efficiencies for photovoltaic energy conversion,” Sol. Energy Mater. Sol. Cells 33(2), 213–240 (1994).
13. A. Marti, J. L. Balenzategui, and R. F. Reyna, “Photon recycling and Shockley's diode equation,” J. Appl. Phys. 82(8), 4067–4075 (1997).
14. V. Badescu, “Spectrally and angularly selective photothermal and photovoltaic converters under one-sun illumination,” J. Phys. D Appl. Phys. 38(13), 2166–2172 (2005).
15. T. Markvart, “Thermodynamics of losses in photovoltaic conversion,” Appl. Phys. Lett. 91, 064102 (2007).
16. S. Fahr, C. Ulbrich, T. Kirchartz, U. Rau, C. Rockstuhl, and F. Lederer, “Rugate filter for light-trapping in solar cells,” Opt. Express 16(13), 9332–9343 (2008).
17. C. Ulbrich, S. Fahr, J. Üpping, M. Peters, T. Kirchartz, C. Rockstuhl, R. B. Wehrspohn, A. Gombert, F. Lederer, and U. Rau, “Directional selectivity and ultra-light-trapping in solar cells,” Phys Status Solidi A 205(12), 2831–2843 (2008).
18. M. Peters, J. C. Goldschmidt, T. Kirchartz, and B. Bläsi, “The photonic light trap—Improved light trapping in solar cells by angularly selective filters,” Sol. Energy Mater. Sol. Cells 93(10), 1721–1727 (2009).
19. E. D. Kosten and H. A. Atwater, “Limiting acceptance angle to maximize efficiency in solar cells,” Proc. SPIE 8124, 812404 (2011).
20. E. D. Kosten, J. H. Atwater, J. Parsons, A. Polman, and H. A. Atwater, “Highly efficient GaAs solar cells by limiting light emission angle,” Light Sci. Appl. 2(1), e45 (2013).
21. National Renewable Energy Laboratory, “Reference Solar Spectral Irradiance: Air Mass 1.5, ASTM G-173-3,” available at http://rredc.nrel.gov/solar/spectra/am1.5/ (2012).
22. E. Yablonovitch, “Statistical ray optics,” J. Opt. Soc. Am. 72(7), 899–907 (1982).
23. O. Höhn, M. Peters, M. Zilk, C. Ulbrich, A. Hoffmann, U. T. Schwarz, and B. Bläsi, “Combination of angular selective photonic structure and concentrating solar cell system,” in Proc. of the 27th EUPVSEC (2012).
24. O. Höhn, M. Peters, C. Ulbrich, A. Hoffmann, U. T. Schwarz, and B. Bläsi, “Optimization of angularly selective photonic filters for concentrator photovoltaic,” Proc. SPIE 8438, 84380A (2012).
25. A. Braun, E. A. Katz, D. Feuermann, B. M. Kayes, and J. M. Gordon, “Photovoltaic performance enhancement by external recycling of photon emission,” Energy Environ. Sci. 6(5), 1499–1503 (2013).
26. G. J. Bauhuis, P. Mulder, E. J. Haverkamp, J. C. C. M. Huijben, and J. J. Schermer, “26.1% thin-film GaAs solar cell using epitaxial lift-off,” Sol. Energy Mater. Sol. Cells 93(9), 1488–1491 (2009).

1. Introduction

In order to approach the Shockley-Queisser limit [1], or, more precisely, the detailed balance limit under consideration of Auger recombination [2], solar cells have to become strongly radiatively limited (meaning they have to become ideal LEDs) [3]. The Shockley-Queisser limit of approximately 33% (some per cent less when assuming Auger-Recombination [2]) in single junction GaAs devices, can only be reached if efficient photon recycling is present [4]. For a long time, the efficiency record of single junction GaAs solar cells has remained at 26.4% because radiatively emitted light was not reabsorbed in the active region, but in the “dead” bulk at the back of the cell [5, 6]. Thereby, the cell did not recycle the emitted photons. Recently, GaAs solar cells have been reported with efficiencies of 28.8% [7]. This has been achieved by efficient photon recycling, which leads to a higher injection regime and thus to a higher quasi-Fermi level splitting [4, 6, 8], and ultimately increases the open circuit voltage significantly. The external radiative efficiency of these cells was larger than 22% [5]. The Shockley-Queisser limit can be overcome if a solar cell’s efficiency is limited by radiative recombination [9]. This occurs if the generation of optical entropy (ratio of etendüs) is decreased by matching the angles under which light impinges from the sun and into which light is emitted from the solar cell [9]. This entropy expansion $\sigma_{\text{ext}}$ is given by

$$\sigma_{\text{ext}} = k_B \ln \left( \frac{E_{\text{out}}}{E_{\text{in}}} \right),$$

with $k_B$ the Boltzmann constant and $E_{\text{out}}$ and $E_{\text{in}}$ the etendüs of emitted and incident light, respectively. This generation of entropy is always larger than or equal to zero and thus the ratio of the etendüs is always larger or equal to one, because the angle of emission cannot become smaller than the angle of incidence.

In a standard solar cell system without concentration or angular confinement, this ratio is as large as 46,200, which is the ratio of the solid angles of emission and incidence. There are two options to decrease this ratio [10]: One can increase the angle of incidence in order to decrease the ratio of etendüs by applying a concentrator to the system, or one can decrease the angle of emission by applying angularly selective filters. Both ways are thermodynamically equivalent. The first way - applying concentrator optics - is already realized in industry [11]. The concept of angular confinement has been proposed several times. First formulations of this idea can be found in [12–14]. What’s more, a combination of
the two concepts was proposed in [10]. A formalism for calculating the maximal possible voltage gain due to this decrease is published in [15].

Angle selective filters in solar cells serve two functions. The first is the restriction of the étendue of escape, as described above. The second is to increase the short circuit current by absorbing more photons close to the bandgap energy, which would otherwise be weakly absorbed. This is achieved by combining the angularly selective filter with a light scattering mechanism, such as a textured surface. Suitable thin-film filters for angular confinement were presented in [16–18]. These mainly aimed at serving the second function; however, since the radiative emission happens at photon energies close to the band-gap energy, such filters are also suitable for decreasing radiative losses. Thus, thin film filters that only show an angularly selective behavior in a very narrow spectral range are sufficient.

Nevertheless, in the case of very thin cells, where even absorption of photons with energies far above the band gap energy is not ideal, light-trapping concepts are required to achieve acceptable absorption. To this end, a broadband light trapping structure at the back will be needed. To achieve high efficiencies in the thinnest cells, a broadband angularly selective filter, for which the angle of emission is restricted exactly to the angle of incidence for all wavelengths, will also become necessary on the front side. With such a system, it is possible to reach the highest efficiencies [19]. A high quality broadband angularly selective filter is described in [20], which employs micro-concentrators at the front side to act as angle confining elements. A good light-trapping structure is a Lambertian Diffuser, which is considered in the following.

When assuming broadband angularly selective filters, there is a price to pay: The angular acceptance range is decreased to the maximum allowed angle of emission, so the systems have to be tracked and cannot access the whole global spectrum (AM1.5G, 1000W/m²) but only its direct part (AM1.5D, 900W/m²) [21]. Furthermore, what counts in the end is not the efficiency, which is normalized to the assumed spectrum; but the output power per unit area. In order to decide which concept can deliver highest power output, one has to consider the appropriate spectrum, as will be shown in the following.

2. Theoretical background

To estimate the limits of efficiency and power output for single-junction solar cells, detailed balance calculations [1] considering Auger recombination [2] were performed. The current density - voltage dependence (JV-curve) is defined by

\[ J(V) = J_{\text{rad}}(V) + J_{\text{Aug}}(V) - J_{\text{gen}}. \]  

(2)

where \( V \) is the voltage of the system. \( J_{\text{rad}}(V) \) describes current density losses due to radiative recombination, \( J_{\text{Aug}}(V) \) losses due to Auger recombination and \( J_{\text{gen}} \) the generation of charge carriers due to incident light. The generation current density per unit area \( J_{\text{gen}} \) is given by

\[ J_{\text{gen}} = q \cdot \int_0^\infty a(\lambda, W) \cdot AM1.5(\lambda) d\lambda. \]  

(3)

where AM1.5 is either the global AM1.5G spectrum or the direct AM1.5D spectrum, \( \lambda \) is the wavelength and \( q \) the elementary charge.

The absorptivity \( a(\lambda, W) \) can have different forms. In the case of an ideal mirror at the back of the cell,

\[ a_{\text{LB}}(\lambda, W) = 1 - \exp(-2\alpha(\lambda)W). \]  

(4)

describes the absorptivity in terms of the absorption coefficient, \( \alpha(\lambda) \), and the cell width, \( W \). In the case of an ideal diffusor at the backside, \( a \) will become [22]
\[ a_{\text{diffuse}}(\theta_{\text{ext}}, \lambda, W) = \frac{\alpha(\lambda)}{\alpha(\lambda) + \frac{\sin^2 \theta_{\text{ext}}(\lambda)}{4n(\lambda)^2 W}}. \]  

where \( n \) is the refractive index and \( \theta_{\text{ext}}(\lambda) \) the wavelength dependent maximum angle of emission (with respect to the normal of the cell surface). The modal structure of light in thin cells is considered according to [20].

The Auger recombination is, in the case of intrinsic or very lightly doped material, given by [2]:

\[ J_{\text{Auger}} = qC W n^3 \exp\left(\frac{3qV}{2k_B T}\right). \]

where \( C \) is the high injection Auger coefficient, \( n \) the intrinsic charge carrier density, and \( T \) the temperature of the cell. For the simulations, \( C = 7 \times 10^{-30} \text{cm}^6/\text{s} \) [20] was chosen and the temperature was set to \( T = 300 \text{K} \). The radiative recombination current density is

\[ J_{\text{rad}} = \int_a^{\infty} a(\lambda, W) [q \cdot d_j_{\text{cell}}(\lambda, V) - q \cdot d_j(\lambda, V = 0)]. \]

With

\[ d_j_{\text{cell}}(\lambda, V) = \frac{(2c \cdot \sin^2 \theta_{\text{ext}}(\lambda))}{\lambda^4} \frac{d\lambda}{\exp((hc / \lambda - qV) / (k_B T)) - 1}. \]

where \( h \) is the Planck constant and \( c \) the speed of light. Since thermal emission occurs even without illumination or applied voltage, these photons have to be subtracted from the radiative losses; this is the second term in Eq. (7). The efficiency \( \eta \) of a solar cell can be calculated by maximizing the power \( P(V) = V J(V) \) and dividing by the power of the incident spectrum. The \( V_{oc} \) is defined as the voltage at the open circuit condition \( (J(V_{oc}) = 0) \) and \( J_{sc} \) is the short circuit current density \( (V = 0) \). An ideal binary angularly selective filter can be simulated by a decrease in the angles of incidence and emission at certain wavelengths \( \lambda \) (for a thin-film filter, this behavior is wavelength dependent [Fig. 6(a)]). It is shown in [23] how realistic filters can be implemented, and the optimization of realistic thin-film filters for use in such a system is described in [24].

3. Simulation of different systems

3.1. System specification

Three different systems are compared in this work [Fig. 1]:

(i) The “Lambert-Beer system”: A GaAs solar cell with an ideal mirror at the backside and a narrowband angularly selective filter on the front side. The angularly selective filter only reflects light under high emission angles at wavelengths close to the band gap.

(ii) The “Diffuse, Narrowband” system: A system with the same filter at the front side as the previous case, but with an ideal diffuser at the back.

(iii) The “Diffuse, Broadband” system: A system with a diffuser at the back and a broadband angularly selective filter on the front, which reflects light under high angles for every wavelength.
In the simulations, the cell width and the maximum angle of emission $\theta_{\text{ext}}$ will be varied. For the two systems with the narrowband filter ((i) and (ii)), the global spectrum AM1.5G can be addressed, whereas for the system with the highest expected efficiencies (iii), only the direct AM1.5D-spectrum may be considered in calculations. Of course, the system with the narrowband filter will also cut a part of the diffuse light. Assuming that all diffuse light between 830 and 870nm is lost, this is as little as 2W/m², which is less than 0.2% of the incident global spectrum. In a real system, the loss compared to a cell without a filter will be even less, since absorption and angular restriction in this wavelength range are not perfect for such a cell.

### 3.2. Simulation results

In Fig. 2, the short-circuit current densities of the three systems are shown. It can be seen that in the case of the “Diffuse, broadband” system, the maximum current is reached even for very thin cells. However, the maximum current that can be reached is lower because of the different utilized spectrum.

When looking at the limits for the open circuit voltage [Fig. 3], one can see a very similar behavior for all systems. For thinner cells, the $V_{\text{oc}}$ increases since Auger recombination becomes less important. The dependence on the maximum angle of emission is also similar in all systems. This is because, since luminescent emission occurs near the bandgap, it is equally influenced by a narrowband and a broadband filter. However, it should be observed that, for thinner cells, the maximum voltage in both diffuse systems is slightly higher than in the Lambert-Beer system. This is because the diffuse systems have a higher $a(\lambda)$, leading to higher $J_{\text{sc}}$ and a corresponding logarithmic increase in the $V_{\text{oc}}$.

The open circuit voltage at point of maximum power in the systems (i) and (ii) is clearly smaller than this maximal open circuit voltage. This can be seen in Fig. 4, as the point of maximal efficiency in the systems with the narrowband filter is neither the point of maximal voltage nor the one of maximal current, but a compromise of both.
Figure 4 shows the efficiency limit of all three systems. The “Diffuse, Broadband” system allows for the highest efficiencies, which are achieved with very thin cells (thickness below 100 nm).

As mentioned in the introduction, the most important measure is the power output of the cell, which is shown in [Fig. 5]. It is apparent that the best system is the “Diffuse, Narrowband” system. Firstly, compared to the “Diffuse, Broadband” system, it enables the best use to be made of the AM1.5g spectrum. Secondly, compared to the “Lambert-Beer-system”, it allows thinner cells to be employed whilst maintaining high absorption, thereby reducing Auger recombination losses. Since the “Lambert-Beer-system” is not considerably worse, it might also be very interesting from the point of view of realization as it is less demanding.

In the systems with narrowband filters, the maximum power is reached even without a perfect restriction of the angle. The system will be limited by Auger recombination below a certain angular restriction anyway. E.g., for the “Lambert-Beer-System”, a restriction to $\theta_{\text{ext}} =$
25° is sufficient to still reach 95% of the maximal power output. Due to this ability of applying a filter which allows a wide acceptance range of more than 25°, a system with a narrowband filter is very tolerant to the tracking accuracy. This can be as bad as 25° without losing a reasonable amount in power output compared to a system without the filter. Additionally, since the filter is only a narrowband filter, the system will still work without any tracking, since, in the worst case (when the angle of incidence is more than 25°), only the light very close to the band gap is lost. This is in contrast to the system with the broadband filter, which will not work at all without extremely accurate tracking.

4. Experimental results

To show the practical relevance of such systems, very first measurements of a realized solar cell system with an applied angularly selective filter were made. In [25], Braun et al. show that the performance of a high efficiency GaAs solar cell can be increased by an angularly selective element. In these experiments, an oblate hemi-ellipsoidal gold-coated dome is applied to redirect emitted radiation back into the cell, where it can be reabsorbed. Indeed, such a system is suited nicely to demonstrate the positive effect; however, as also stated in their publication, it is not intended as an industrially feasible cell design [25]. In contrast to this system, angularly selective elements based on thin-film interference effects might be an industrially feasible approach. Here, very first measurements of the realized “Lambert-Beer-System” are shown using such a filter and a thin-film GaAs solar cell with a Au back side mirror [26]. The filter was coated on glass as a separate element produced by Optics Balzers Jena (filter characteristics shown in Fig. 6(a); filter layout not known).

Fig. 6. Left (a): Angular dependent Fourier spectrometer measurement of the filter reflectance. Right (b): Measurement of the difference in voltage of the system with and without filter.

The solar cell was simulated as described in Sec. 3, but considering the measured filter characteristics and applying the formalism described in [23]. The simulation predicted a gain in voltage of approx. 20mV and a consequent gain of 0.7% absolute in efficiency. As the filter shows quite ideal transmittance, no loss in current is expected. As this model does not account for bulk or surface recombination, the real gain will be – depending on these losses – much less.

In first measurements, the IV-characteristics of a 1cm² cell were captured in the dark. The results of such a measurement can generally indicate how the system can benefit from the filter. They are clearly just a first step, but they show that a promising realization of a cell filter system exists. The measurement was repeated on the same solar cell with and without the filter. In Fig. 6(b), the difference in voltage of cell with and without the angularly selective filter is plotted as a function of the current. The experiment shows that, when the filter is in place, a higher voltage is needed to reach the same current. As the filter only affects radiative losses, the increase in voltage indicates a reduction of this loss mechanism. Or, the other way around, injecting an identical current leads to a higher injection regime and thus a higher splitting of the quasi-Fermi levels. This can be interpreted as a proof-of-concept of this idea. Of course the measurement in the dark provides preliminary results, and a further
evaluation of the system is needed. Nonetheless, the physical relevance of the comparison in the last section has been shown.

5. Conclusion and outlook

It was shown that a system with a narrowband angularly selective filter allows for a higher power output than a system with a broadband filter even if two-axis tracking is not employed. This becomes very important when considering that at most places on earth the amount of diffuse light is even higher than in the norm of the AM1.5 spectrum. Dark measurements of a GaAs solar cell with a narrowband angularly selective filter show promising results. In the next steps, measurements under illumination will be made to demonstrate a positive effect on the efficiency.

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