Photonic Band Gap Engineering of Solar Cells

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ABSTRACT: The scope of this work is to investigate the influence of photonic structures (i.e. angle or spectral selective filters) on the effective band gaps of semiconductors. This especially is interesting to influence the working points of solar cells. The concepts investigated within this work will only be pronounced for direct band gap semiconductors (high fraction of radiative recombination). Thus, predestined systems to evaluate such effects are light emitting diodes (LED). In this work the understanding of occurring processes in a realistic system shall be deepened with the help of fundamental experiments.
Keywords: III-V Semiconductors, High-Efficiency, Optical Losses

1 INTRODUCTION

The thermodynamic working point of solar cells can be changed by photonic filters. In principle, there are two different possibilities to influence the operation conditions: The first way is to decrease the angle of emission in order to decrease radiative losses, which leads to an increase in the open-circuit voltage of the solar cell [1]. The second way is to inhibit emission into all angles for certain wavelengths. To this end, a band-edge filter can be placed on top of the solar cell. This (ideal) filter transmits light up to a cutoff wavelength for all angles. If the wavelength of this cutoff is below the band gap wavelength of the solar cell, the solar cell will behave like one with a band gap corresponding to the cutoff wavelength (Figure 1, [2]).

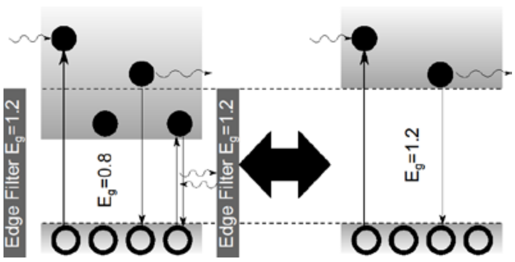

Figure 1: Principle of the combination of an ideal spectrally selective filter and a solar cell [2]. On the one hand the ideal edge filter prevents photons with lower energy than the edge energy from being emitted. On the other hand photons with energy lower than the band edge impinging upon the system are reflected by the filter and can therefore not be absorbed by the cell. This means that this ideal system will behave like a system with a higher band gap.

The interesting question now is: What happens when applying real filters to the system? Here, new problems arise from the imperfect filter function. On the one hand, the filters do not reflect all light back into the solar cell; on the other hand, the angular behavior will not be perfect. The aim of this work is to deepen the understanding of occurring processes in such a realistic system.

The implementation of real angle selective filters into ideal solar cell simulation is already known [3]. In this paper the simulation is expanded to solar cell systems with a certain amount of non-radiative losses. The implementation of perfect band edge filters into simulation is already realized. Here fundamental simulations with realistic edge filters are shown and compared to experiments using light emitting diodes (LED) as analogue system to solar cells [4]. A dielectric broadband mirror is placed on top of an LED (to keep all radiation within the system) and the IV-curve is measured and compared to the curve without a filter.

2 THEORETICAL CONSIDERATIONS

In the following section at first detailed balance calculation is introduced. Afterwards, it is shortly shown how non-radiative losses can be considered. In the last part it is finally pointed out how wavelength selective edge filters can be implemented into detailed balance theory.

2.1 Detailed balance calculation

The current-voltage dependence of a solar cell can be calculated using terms of detailed balance. Assuming no non-radiative losses, the resulting current of a solar cell can be written as a difference of incoming light and emitted radiation [5][6]:

$$J(V) = J_{rec}(V) - J_{gen} \qquad (1)$$

J_{gen} describes the current density resulting from the incident light. It is assumed that each absorbed photon creates exactly one electron-whole pair. The generated current therefor depends, except of irradiance, mainly on the band gap wavelength (λ_g) of the used semiconductor as this defines the energy up to which photons can be absorbed. Equation (1) describes the IV-characteristic of a solar cell respectively LED. In the case of a LED J_{gen} of course is zero.

The recombination current density $J_{rec}(V)$ can be derived from the generalized Planck's law.

$$J_{\mathrm{rec}} = \int_0^{\lambda_g} (e_0 \cdot dj_{\mathrm{cell}}(\lambda, V) - e_0 \cdot dj_{\mathrm{cell}}(\lambda, V = 0)) \qquad (2)$$

The constant e_0 is the elementary charge, λ the wavelength and V the voltage of the solar cell. The term $dj_{\mathrm{cell}}(\lambda, V)$ describes the black body radiation:

$$dj_{\mathrm{cell}}(\lambda, V) = \frac{\Omega_{ext}}{4\pi\hbar^3 c^2} \cdot \frac{\hbar^3 (2\pi c/\lambda)^2 d(2\pi c/\lambda)}{exp\left(\frac{\hbar 2\pi c/\lambda - e_0 V}{kT_0}\right) - 1} \qquad (3)$$

The angle Ω_{ext} is the solid angle of extraction, c the vacuum speed of light, h the Planck's constant and k the

Boltzmann constant. The driving voltage V of the cell in open circuit conditions depends on the quasi-Fermi-level splitting and with this on the band gap of the solar cell.

The overall efficiency η of the solar cell depends on both current and voltage [6]:

$$\eta = \frac{V_{oc} \cdot J_{sc} \cdot FF}{P_{sun}} = \frac{V_{mpp} \cdot J_{mpp}}{P_{sun}}, \qquad (4)$$

where FF is the filling factor of the IV-characteristic at the maximum power point (V_{mpp}, J_{mpp}). The power P_{sun} is the integrated irradiance of the sun. A large band gap leads to a high open circuit voltage, a small band gap to a high short circuit current density J_{sc}. This leads to the behavior of the solar cell's efficiency shown in Figure 2. In this and the following calculations the generation current density J_{gen} is calculated by integrating the AM1.5g-spectrum [7] up to the band gap energy. Absorption is assumed to be unity, what is an acceptable assumption for direct semiconductors if a good antireflection coating is implemented and the cell is thick enough.

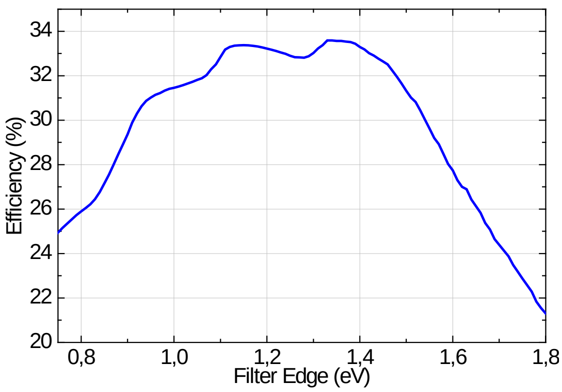

Figure 2: Effect of the electrical band gap to the efficiency of the solar cell. At low band gap energies the efficiency is limited due to the low voltage of the device, at high energies due to the loss in absorption and therefore in current.

2.2 Non-radiative Recombination

In principle non-radiative recombination can be considered in detailed balance as an additional current $J_{rec,nonrad}(V)$:

$$J(V) = J_{rec}(V) + J_{rec,nonrad}(V) - J_{gen} \qquad (5)$$

It is assumed that in solar cells made of direct semiconductors with a good material quality the major non-radiative loss mechanisms is Auger recombination. Therefore only this loss is additionally taken into account.

When assuming that the semiconductor is intrinsic or so lightly doped, that n=p is valid under illumination, $J_{Auger}(V)$ can for all voltages V be written as [8]

$$J_{Auger}(V) = e_0 \cdot L \cdot {n_i}^3 \cdot C_{Aug} \cdot \exp(\frac{3e_0V}{kt}). \qquad (6)$$

Here L is the thickness of the cell, n/p the electron/hole carrier density and n_i the intrinsic carrier density. C_{Aug} is the high injection Auger coefficient.

The detailed balance calculation can now be performed by:

$$J(V) = J_{rec}(V) + J_{Auger}(V) - J_{gen}. \qquad (7)$$

2.3 Effect of edge filters to the band gap

Optical respectively photonic filters do only affect the radiative parts of recombination as well as the absorption of the incident light. As long as the filter is only wavelength but not angle dependent, the transmission function $T(\lambda)$ of the filter can easily be implemented into the integration of the loss/generation current $J_{rec/gen}$:

$$J_{rec}(V) = \int_0^{\lambda_g} e_0 \cdot (1 - T(\lambda)) \cdot dj_{rec}(V,\lambda) - \int_0^{\lambda_g} e_0 \cdot (1 - T(\lambda)) \cdot dj_{rec}(V = 0,\lambda) \qquad (8)$$

$$J_{gen} = \int_0^{\lambda_g} e_0 \cdot (1 - T(\lambda)) \cdot dj_{gen}(\lambda) \qquad (9)$$

The function $dj_{gen}(\lambda)$ describes the wavelength dependent irradiance expressed in terms of photon number. This formula is a special case of the implantation of angular and wavelength dependent filters shown in [3]. With (8) and (9) perfect edge filters as well as edge filters with imperfect reflection can be considered. In the case of perfect filters T is a heavy-side function, which in fact results in a reduction of the upper integration bound to the wavelength of filter edge (as long as this wavelength is smaller than λ_g). In this case the result shown in [2] is reproduced.

In combination with equation (7) the effect of realistic edge filters and the effect of non-radiative losses can both be considered.

3 RESULTS

At first the potential of this approach assuming realistic filters and non-radiative recombination in terms of Auger recombination is investigated. As cell material gallium antimonide (GaSb), as also described in [2], is used. After these general considerations the measurement results of a gallium nitride (GaN)-LED's IV characteristic are shown. Here the LED was measured with a broadband dielectric mirror placed on top of the LED and compared to the measurement without the mirror.

3.1 Simulation

As cell material GaSb is used, since GaSb is a direct semiconductor with a small band gap of $E_g = 0.73$ eV. A solar cell made out of gallium arsenide (GaAs) ($E_g \approx 1.42$ eV) would not show any improvement in efficiency when applying an edge filter, as this semiconductor already lies in the optimal band gap range (Figure 2).

As long as the filter is perfect and the only loss mechanism is radiative recombination, a band edge filter shows the same effect as a change in the electric band gap (Figure 3, [2]). As soon as the filter is not perfect anymore only an efficiency increase up to a certain band edge energy of the filter can be seen. This happens even with "almost perfect" filters, meaning the reflection at the edge is as large as R=99.9%. As in a realistic system the filter will always have R<100%, the possible shift of the band gap is limited due to the filter and even without assuming non-radiative losses

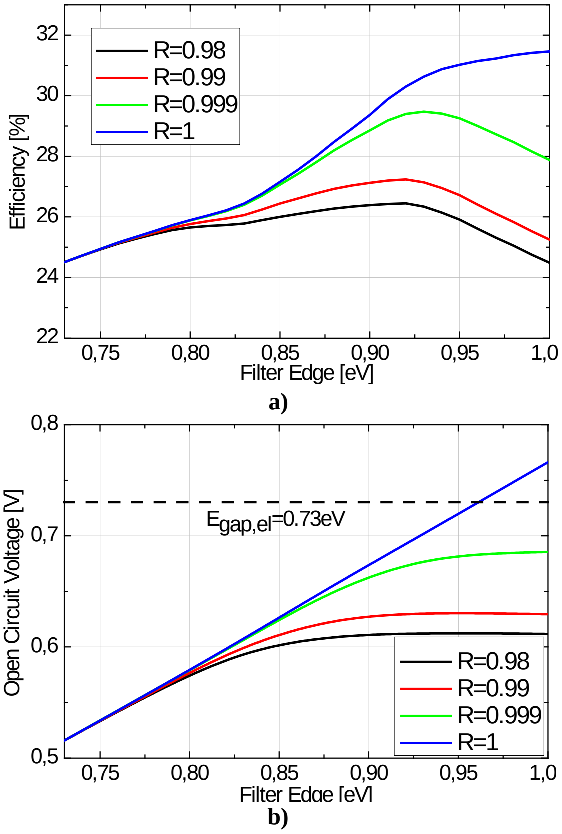

Figure 3: The different graphs belong to filters with different reflections R of the filter at energies lower than the filter edges. Non-radiative losses are neglected.
a) Efficiency gain due to an optical band edge filter.
b) Gain in open circuit voltage V_{oc} due to an optical edge filter. When assuming non-ideal filters, the win in voltage is restricted by the electrical band gap. An ideal edge filter is essential when trying to overcome the restrictions due to the electrical band gap.

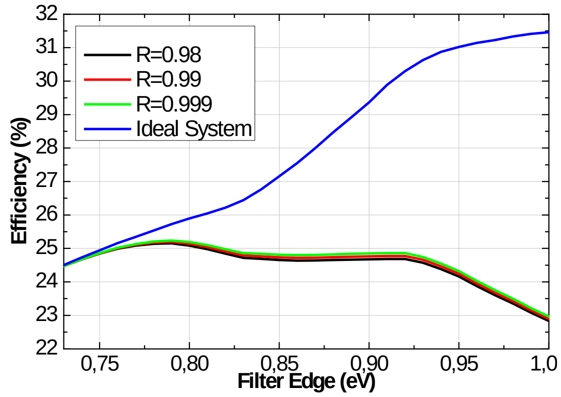

Figure 4: Efficiency gain due to an optical band edge filter. The different lines belong to filters with different reflections R of the filter at energies higher than the filter edges. Auger recombination is assumed. The Auger coefficient is set to $C_{Aug} = 5 \cdot 10^{-30}\text{cm}^{-3}$ [2] and intrinsic carrier density is set to $n_i = 1.5 \cdot 10^{12}\text{cm}^{-3}$ [2]. The cell thickness is assumed to be 2µm.

To understand what happens, when also non-radiative losses have to be taken into account the same simulations are repeated, enabling Auger recombination (Figure 4). Now the overall efficiency drops because of the presence of a non-radiative loss. The possible shift of the effective band gap now becomes even smaller. The losses due to an imperfect filter are now much less important than the losses due to Auger recombination.

When non-radiative losses get stronger this possible gain in efficiency disappears. From these considerations valuable insights can be extracted, when trying to measure the effects:

Firstly, the efficiency gain results from an increase in voltage that overcompensates the loss due to the decrease in current (Sec 2.1). This allows for a proof of the concept to measure only the IV-characteristic in the dark ($J_{\text{gen}} = 0$) with a filter and without a filter. In the case with a suitable filter the voltage at the same current should increase. Secondly, the filter does not have to be perfect, as the gain in efficiency respectively voltage is limited due to non-radiative recombination. A filter with a reflection of $\text{R} \approx 98\%$ is suitable in this case (Figure 4).

3.2 Comparison of measurement and simulation

Having in mind the insights of the last section, a system that is optimized to emit light has to be chosen. In such a system non-radiative losses are minimized. As LEDs and solar cells in principle are equivalent systems [4], the use of an LED for first experiment seems natural, as LEDs are optimized to emit light. The measurement of an increase in voltage in the IV-characteristic in the dark is sufficient as proof of concept, as stated above. Therefore a dielectric broadband mirror instead of an edge filter can be used in these first measurements (Figure 5), as incident light does not play a role in this case.

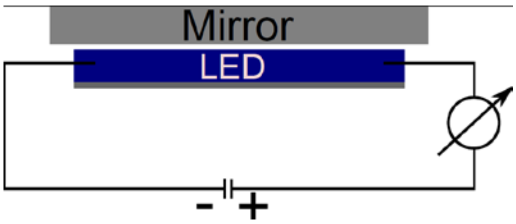

Figure 5: Sketch of the measurement setup.

The difference in voltage of the IV-characteristics with and without this mirror is shown in Figure 6. For these measurements a GaN-LED with an emission around 440nm was used. One can see that up to a certain current the predicted gain in voltage can be detected (positive values in Figure 6).

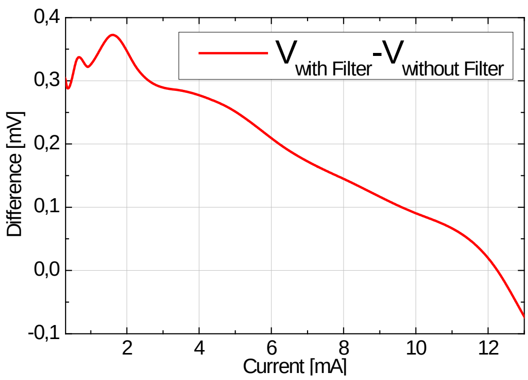

Figure 6: Difference of the VI-characteristic of the LED with filter and without filter. At low currents, where the radiative efficiency is high, the expected increase in voltage can be seen. This drops to higher currents occurs

probably due to a droop effect [9] and heating of the cell. This gain drops when reaching higher currents. This could be an effect of a reduction of the internal quantum efficiency at high currents in the LED, called droop, as described in [9, 10]. This effect also could be increased by a heating of the LED, as the LED was not cooled during the measurement and the mirror insulates thermally as well. Nevertheless, the measured increase in voltage is a proof of the idea that radiative losses can be influenced by an external filter.

4 CONCLUSION AND OUTLOOK

It was shown that radiative recombination can be influenced by optical filters. The manipulation of this recombination rate can only be measured as long as other recombination types do not play a significant role. As long as non-radiative recombination rates that also depend on the voltage of the system exist, the gain due to optical filters always will be restricted to a certain gain in voltage. At some point non-radiative losses will then get dominant.

With these results in mind, one should have a closer look at the effects of angularly selective filters on solar cells [1, 3], as this concept does not try to inhibit radiative recombination completely to shift the effective band gap, but to decrease the losses due to radiative recombination by a restriction of the angle of emission. Here, a gain in efficiency should be achievable much easier, as the gain in voltage is not necessarily combined with a loss in current.

5 ACKNOWLEDGEMENT

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6 REFERENCES

[1] M. Peters, J.C. Goldschmidt, B. Blaesi, Angular confinement and concentration in photovoltaic converters, Solar Energy Materials and Solar Cells, 94 (2010) 1393-1398.
[2] A. Niv, Z.R. Abrams, M. Gharghi, C. Gladden, X. Zhang, Overcoming the bandgap limitation on solar cell materials, Appl. Phys. Lett., 100 (2012).
[3] O. Hoehn, M. Peters, M. Zilk, C. Ulbrich, A. Hoffmann, U.T. Schwarz, B. Blaesi, Combination Of Angular Selective Photonic Structure and Concentrating Solar Cell System, Proceedings of the 27th EUPVSEC, (2012).
[4] T. Kirchartz, U. Rau, Detailed balance and reciprocity in solar cells, physica status solidi (a), 205 (2008) 2737-2751.
[5] W. Shockley, H.J. Queisser, Detailed balance limit of efficiency of p-n junction solar cells, Journal of Applied Physics, 32 (1961) 510-519.
[6] Würfel, P., Physics of Solar Cells, WILEY-VCH Verlag, Weinheim, 2009.
[7] IEC, Photovoltaic devices - part 3: measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data. , 2nd ed. International Standard, IEC 60904–3, ed. International Electrotechnical Commission (2008).
[8] T. Tiedje, E. Yablonovitch, G.D. Cody, B.G. Brooks, Limiting efficiency of silicon solar cells, Electron Devices, IEEE Transactions on, 31 (1984) 711-716.
[9] J. Piprek, Efficiency droop in nitride-based light-emitting diodes, physica status solidi (a), 207 (2010) 2217-2225.
[10] Y.C. Shen, G.O. Mueller, S. Watanabe, N.F. Gardner, A. Munkholm, M.R. Krames, Auger recombination in InGaN measured by photoluminescence, Applied Physics Letters, 91 (2007) 141101.