UPCONVERSION FOR SILICON SOLAR CELLS

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1 INTRODUCTION

Silicon solar cells lose about 20% of the energy incident from the sun because photons with energy below the band-gap are transmitted straight through the device. Upconversion of these photons is a promising approach to reduce the losses [1]. An upconverter generates one high-energy photon out of at least two low-energy photons, which then creates a free charge carrier in the solar cell. Up to now, the application of upconverters has been hindered by low efficiency of the upconversion process itself and the fact that only a small fraction of the solar spectrum was upconverted.

In the past, the investigation of upconversion has been limited mostly to experiments with monochromatic laser excitation. Often, the solar cell itself was used as detector for the determination of upconversion efficiency to which the upconverter was attached e.g. [2], which resulted in uncertainties because of effects of the optical and electrical properties of the solar cells. In this study, the upconverting efficiencies are determined directly with calibrated photoluminescence measurements. Because silicon solar cells are not operated under monochromatic irradiation, but under the broad solar spectrum, we investigate as well the upconversion behavior under concentrated sunlight. Furthermore, a rate-equation model is presented, that enables the assessment of different strategies of how to increase upconversion efficiency.

2 PHOTOLUMINESCENCE MEASUREMENTS

Our setup features laser excitation, tuneable both in excitation wavelength and intensity. For the calibration, the photon flux of the excitation per area and the efficiency of the detection unit were determined. The presented upconversion efficiency is defined as the number of upconverted high energy photons emitted divided by the number of the incoming low energy photons of the excitation. We used the setup to characterize the upconverter material NaYF4 : 20 % Er^{3+}, which is the most efficient upconverter material up to now. The results can be seen in figure 1a and b.

3 MEASUREMENTS ON UPCONVERTER/SOLAR CELL SYSTEMS

We performed measurements on systems with the upconverter attached to silicon solar cells. For laser excitation at 1522 nm with 1090 Wm^{-2} an EQE of 0.34 % was reached. These results are in agreement with the optical measurements, when several aspects such as the transmission of the silicon solar cell are taken into account.

Because silicon solar cells are operated under the broad solar spectrum it is interesting to investigated as well the upconversion behavior under concentrated sunlight (See figure 2). To our knowledge, this is the first time that such an investigation has been performed on a material system relevant for silicon photovoltaics. As can be seen in figure 3, for a concentration of 129x an extra current of 0.69 ±0.14 mA due to upconversion effects could be achieved for an active cell area of 0.2025 cm^2. These values exceed the values that could be expected from the optical measurements. Therefore we conclude that broad spectrum illumination increases upconversion efficiency and in consequence relatively high efficiencies could be achieved under realistic operating conditions. A possible explanation is that under white light illumination for every possible transition photons are available that have an optimum energy.

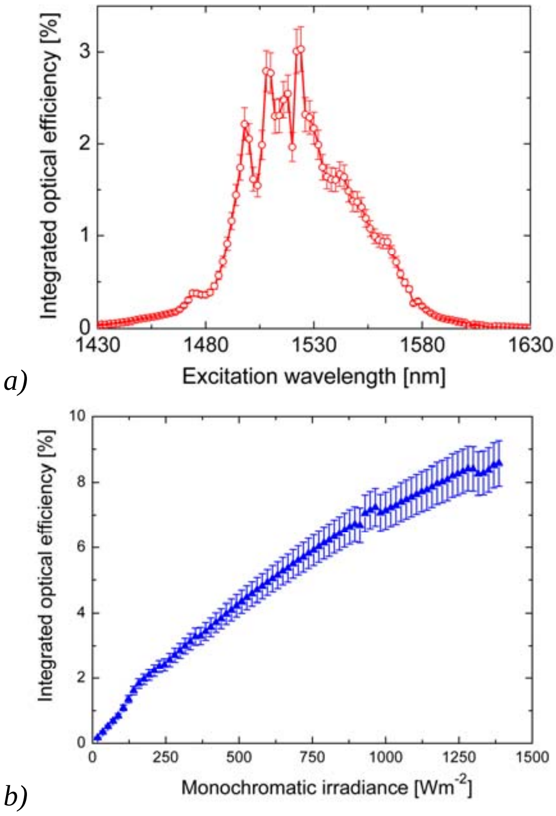

Figure 1: *By integration over the luminescence from all transitions that generate photons with energies high enough to generate free charge carriers in a silicon solar cell, the integrated optical upconversion efficiency is calculated. Figure 1a) shows the dependence on the excitation wavelength for an irradiance of 900 Wm^{-2}. Photons with a wavelength of 1523 nm are most efficiently upconverted. The shape of the excitation spectrum is formed by the sub-energy levels of Er^{3+}.*

Due to the non-linearity of the upconversion the integrated optical upconversion efficiency increases with the irradiance. This can be seen in figure 1b), where the efficiency is shown for different irradiances at a wavelength of 1523 nm.

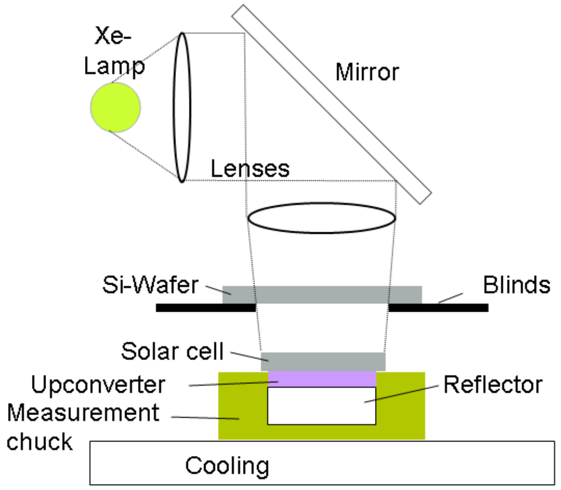

Figure 2: *Set-up used for the measurements under concentrated white light.*

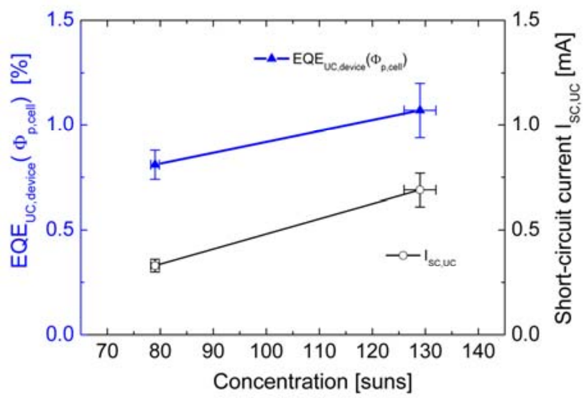

Figure 3: *The extra short-circuit current due to the upconverter $I_{SC,UC}$ and the spectrally integrated external quantum efficiency of the silicon solar cell upconverter device $EQE_{UC,device}$ at two different concentration levels are shown. This is the first time a significant effect of an upconverter on the short-circuit current of a silicon solar cell was measured under white light illumination. Both extra current and $EQE_{UC,device}$ show a trend of increasing with higher concentration. This fact supports the conclusion that the observed effect is due to upconverted photons as this is the kind of non-linear behavior which is expected from upconverting material.*

3 SIMULATION OF UPCONVERSION DYNAMICS

We developed a rate-equation model based on material parameters obtained from optical characterization. The rate equation model considers ground state absorption, excited state absorption, spontaneous and stimulated emission, multi-phonon relaxation and energy-transfer processes. The model reproduces qualitatively the dependence of the upconversion luminescence from the irradiance as can be seen in figure 4. The model was also used successfully to investigate the effect of multi-phonon relaxation and the possible increase of upconversion efficiency with the help of plasmon resonance.

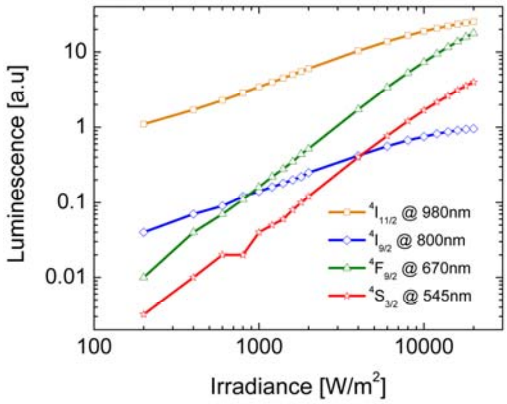

Figure 4: *The photoluminescence from the different excited levels to the ground state is shown as simulated with a rate equation model. The experimental observations agree very well with theoretical expectations. This includes the steeper slope for luminescence from levels populated by three photon processes and the intersection of curves from different levels that was observed experimentally as well.*

2 SUMMARY

We have shown that with calibrated photoluminescence measurements, a relatively high upconversion efficiency of $NaYF4 : 20\,\%\,Er^{3+}$ could be determined. The upconversion efficiency increases with the irradiance of the excitation. This behaviour can be modelled with the help of a rate equation model. For the first time a positive effect of an upconverter on the short-circuit current of a silicon solar cell under white light illumination was determined.

3 ACKNOWLEDGEMENTS

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