Efficient up-conversion of non-concentrated solar radiation for solar cells

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T. Trupke et al. (this workshop) show that low energy photons can be up-converted into high energy photons in a 3-level system, in which the upper level is reached from the ground level by the successive absorption of 2 low energy photons, the first exciting an electron to the intermediate level, from where it is excited to the upper level by a second photon. High energy photons are then emitted by radiative recombination from the upper level to the ground level and can be utilized in solar cells. If the up-converter is placed behind a solar cell, solar photons with energy above the band-gap are directly absorbed by the solar cell, while the low energy photons are transmitted to the up-converter, from where high energy photons are emitted back into the solar cell. Since these photons come in addition to the high energy photons from the solar spectrum, an improvement of the solar cell efficiency is expected. Trupke et al. (this workshop) show that efficiencies over 60% are achievable for full concentration (46200-fold) of the solar radiation (see Fig.2). For non-concentrated sunlight, however, almost no improvement is found, because the transition from the upper level in the up-converter to the ground level is more probable via the intermediate level leading to the emission of 2 low-energy photons instead of 1 high energy photon for the direct transition to the ground level.

Each of the 3 levels may actually be a group of levels spread over an energy interval.

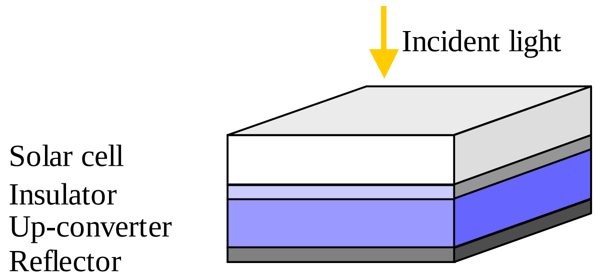

Fig. 1 Incident solar radiation is either absorbed in the solar cell (high energy photons) or transmitted to a 3-level system in an up-converter (low energy photons), in which it is transformed to high energy photons which, with the help of a rear reflector, are emitted back into the solar cell.

Energy relaxation

The probability for a transition from the upper level to the ground level may be reduced, if the electrons in the upper level would be allowed to relax into a lower lying level from where selection rules prohibit a transition to the intermediate level, but allow a transition to the ground level.

The calculation is done using detailed balance arguments, predicting the emission of photons by a generalised Planck's law. The transition rate between two states depends on the matrix element for the transition and on the occupation of the states involved. Each of the 3 groups of states, the ground states, the intermediate states and the upper states is occupied according to Fermi functions with different Fermi energies for each group of states. The relaxed state is treated as being in chemical equilibrium with the upper state. The occupation of both states is then governed by the same Fermi function with the same Fermi energy.

A similar energy relaxation can also be applied to the group of intermediate states, which might reduce the transition rate from the intermediate states to the ground states. It turns out that relaxation in the upper states is most important. If the system is optimised with respect to the energy loss by relaxation from the upper states, an additional relaxation from the intermediate states does not improve the efficiency.

In all these calculations, non-radiative transitions, except for the relaxation, are not taken into account. The results obtained are, therefore, upper limits for the efficiencies.

Fig.3 shows the results. Compared to an up-converter without relaxation in non-concentrated light, represented by the lowest of the black dot curves, a substantial improvement is achieved by energy relaxation in the upper states as demonstrated by the triangles. A maximal conversion efficiency is found for the following parameters: The solar cell has a band gap of 2.0 eV. In the up-converter the intermediate level is 0.83 eV above the highest ground state level, the lowest unrelaxed upper level is at 2.33 eV above the ground state levels, an energy loss of 0.33 eV by relaxation from the upper levels leaves 2 eV for the minimum energy of the emitted photons in transitions to the ground states.

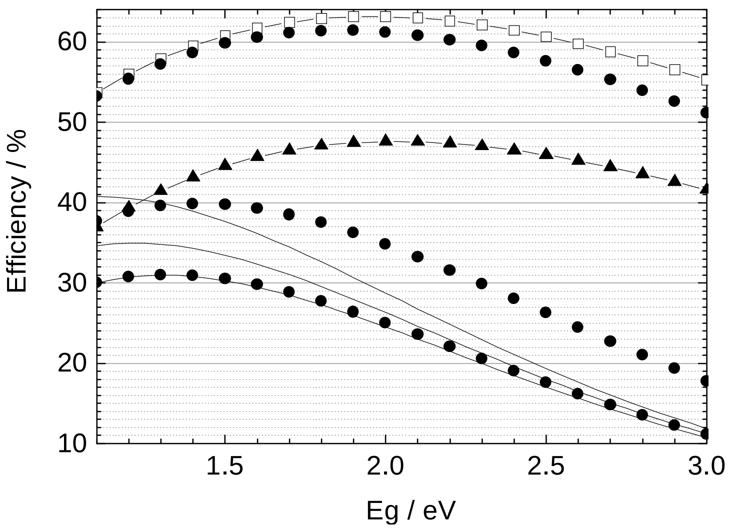

Fig.2 Efficiencies of combinations of solar cells with band gap E_g and an up-converter with optimised position of the intermediate level. Without energy relaxation the 2 upper curves are found for full concentration. The lowest curve marked by circles is obtained for non-concentrated radiation. It is almost identical to the lowest line, which is the Shockley-Queisser limit for a solar cell without an up-converter. A significant improvement for non-concentrated light is seen in the curve marked by the triangles, for which an optimised relaxation is considered.

The improved efficiency found for the combination of a single-junction solar cell and an up-converter is almost identical to what was found earlier for a 3-band solar cell. In contrast to the 3-band cell, the up-converter has the advantage that the electrical transport properties can be very bad, since no transport is necessary in the up-converter. It is, therefore, much easier to optimise its optical properties and it is expected that some organic dyes may have the desired quality.