Improving solar cell efficiencies by the up-conversion of sub-band-gap light

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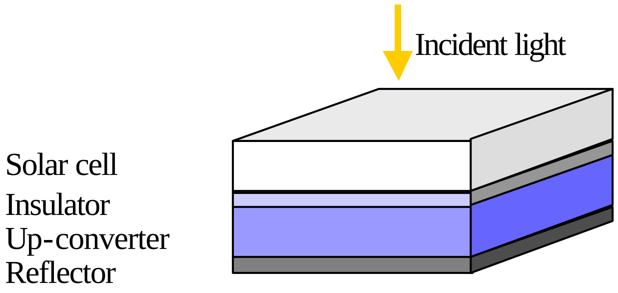
The concept of improving the infrared absorption of wide band-gap-materials by the insertion of impurities with energies located in the band-gap, the so-called impurity photovoltaic effect (IPV), is an interesting option to increase the efficiency of solar cells. However, the introduction of impurities into a solar cell material has also a major disadvantage. From detailed balance follows that the additional generation channel for electron hole pairs also represents an additional recombination channel. A problem inherent in an IPV-system is that not only the additional electron hole pairs, which are gained by the insertion of impurities, are affected by the additional recombination channel, but all electron hole pairs.

We present calculations on the theoretical efficiency limit of an alternative approach to improve the utilisation of infrared photons by a photovoltaic system, which involves the up-conversion of sub-band-gap light.

The up-conversion solar cell system is schematically represented in Fig.1. It is based on a conventional bifacial single junction solar cell. The second main element of the system is the *up-converter*, which partially transforms the sub-band-gap photons transmitted by the solar cell into high-energy photons. The up-converter is electronically isolated from the solar cell and located behind it. A perfect reflector is located at the rear surface of the up-converter.

Fig.1

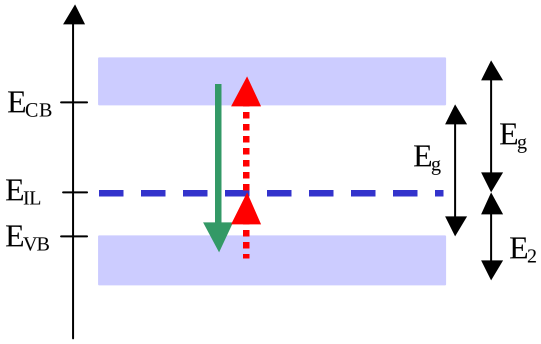


Contrary to second harmonic generation or simultaneous two-photon absorption, up-conversion involves a sequential excitation of electrons into an excited state via a real, lower-lying metastable excited state. A schematic energy-level diagram of such an up-converter is shown in Fig.2.

It consists of a material with a band-gap equal to or larger than the band-gap of the solar cell and contains intermediate levels (IL) with energy E_1 above the valence band edge. Similar to the processes in an IPV-solar cell the absorption of sub-band-gap photons in the up-converter leads to the generation of electron hole-pairs via transitions from the valence band into the IL and from the IL into the conduction band.

A fraction of the excess electron hole pairs generated inside the up-converter recombines via radiative band to band-transitions (solid arrow in Fig.2), which is accompanied by the emission of photons with energies above the band-gap. The absorption of these photons leads to an additional generation rate of electron hole pairs in the solar cell.

Fig.2



One advantage of this system is that no additional recombination channel is introduced into the active solar cell material in contrast to an IPV-solar-cell. Radiative (and in a non-ideal system also non-radiative) recombination of electrons and holes via the intermediate level is possible only inside the up-converter. Another advantage is that in our system the materials of the up-converter and of the solar cell can be optimised independently. An optimised up-converter might be stacked behind any existing bifacial solar cell, potentially increasing its efficiency.

Furthermore photon selectivity can be achieved in our proposed system by limiting the width of the bands in the up-converter as shown in Fig.2. Contrary to an IPV solar cell this restriction of the bands does not result in a reduced photocurrent as the high energy-photons can still be absorbed in the solar cell in which the widths of the bands are not limited.

The maximum efficiency of the up-conversion system is evaluated for different illumination conditions using detailed balance calculations. Maximum concentration of sunlight can be realised either by restricting the effective external solid angle into which luminescence can be emitted (minimum emission case) or by focussing the sunlight onto the surface of the solar cell with an infinitely extended lens (maximum concentration case). Interestingly these two situations yield different limiting values for the efficiency of our system.

The highest efficiency is obtained in the minimum emission case. For a band-gap of 1.955 eV and an energy of the IL at E_1=0.713eV the maximum efficiency achievable with equal band-gaps of the solar cell and of the up-converter is 63.17%. The maximum-efficiency for the maximum concentration case is slightly lower. For Eg=1.86 eV and an IL at E_1=0.667 eV a maximum efficiency of 61.40 % is calculated.