Approaches for Ultra-High Efficiency Solar Cells

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ABSTRACT

A critical goal for photovoltaic energy conversion is the development of high efficiency, low cost photovoltaic structures which can reach the thermodynamic limit of solar energy conversion. Recently, many approaches have been suggested on how to reach these efficiency limits. This paper shows that the suggested approaches can be grouped into five broad classes and that the practical efficiencies of these approaches are substantially different, despite similar thermodynamic efficiencies.

1. Objectives

Mature energy conversion technologies typically operate closer to their optimum thermodynamic efficiency. For solar cells, this efficiency is between 68% and 87%, depending on the level of concentration and the spectrum. Using conventional detailed balance calculations, it was previously shown that the only way to reach these efficiencies was to use multiple junction tandems under concentration. However, more recent calculations [1,2,3] demonstrate that there are a large range of approaches that may be used to reach the efficiency limit of solar energy conversion. The objective of the present work is to compare the practical efficiency limits of these approaches and to identify the critical physical phenomena important for solar energy conversion.

2. Technical Approach

The largest loss mechanism in photovoltaic energy conversion arises from the mismatch between the wavelengths in the solar spectrum and those that can efficiency be used by a solar cell. Photons below the band gap of a semiconductor are not absorbed and do not contribute to energy conversion, while the portion of energy above the band gap is also lost. These losses are quantified by efficiency limit approaches, usually detailed balance analyses. Conventional detailed balance calculations contain several assumptions, including; (1) the input is the solar spectrum at a given concentration level; (2) one photon generates one electron-hole pair; (3) one quasi-Fermi level separation exists in the solar cell; and (4) a constant temperature exists across the device. “3rd Generation” photovoltaic solar cells [4] refer to any approach that exceeds the efficiency of a single junction solar cell, which includes not only the well-known tandem solar cells but also any approach which circumvents one of the four previous assumptions, giving the basic approaches to high efficiency as:

(1) Multiple junction solar cells (tandems);
(2) Multiple spectrum solar cells, where the solar spectrum is changed into a different spectrum with the same energy;
(3) Multiple absorption path solar cells, in which the absorption process is altered such that either two photons are absorbed to create a single electron-hole pair or alternately one photon creates multiple electron-hole pairs;
(4) Multiple energy level solar cells, which have more than a single quasi-Fermi level separation;
(5) Multiple temperature solar cells, which involve the extraction of energy from variations in either carrier or lattice temperature.

3. Results and Accomplishments

Detailed balance calculations show that the efficiency limit of the suggested approaches are essentially identical for a given set of initial assumptions. However, the physical mechanisms and their practical efficiencies differ markedly. The following section summarizes the key physical mechanisms, practical efficiency limits, trade-offs and advantages of each approach.

Multiple junction solar cells

Multiple junction solar cells, or tandem solar cells, consist of a multiple, single junction solar cells stacked on one another, with each solar cell absorbing part of the part of the solar spectrum closest to its band gap. Existing tandem devices have achieved efficiencies over 37% [5], and further efficiency increases can be achieved by increasing the number of junctions. Despite the high efficiency potential, tandem devices have an inherent drawback: the efficiency of a tandem is tied to the material quality and the existance of materials with a specified band gap, often using less common or understood material systems. Consequently, the key promise of the new approaches to solar cells that achieve their thermodynamic limit involves decoupling the need for a large number of ideal materials from solar cell efficiency.

Multiple spectrum solar cells

Multiple spectrum solar cells involve the transformation of the solar spectrum from one with a broad range of energies to one with the same power density but a narrow range of photon energies. The central feature of these approaches, which include up and down-conversion [6] and thermophotonics, is that the transformation of the solar spectrum is done separately from the solar cell itself, thus increasing the efficiency of an existing solar cell structure via additional coatings. This technology could be applied to any solar cell provided that power gained through spectral alternation offsets the cost of the additional optical coating. As many of the suggested approaches can potentially be implemented in a low cost fashion, multiple spectrum solar cells primarily offer a mechanism for relatively moderate efficiency increases using existing solar cell technology.

Multiple absorption path solar cells

A central limitation of existing solar cell approaches is the one-to-one relationship between an absorbed photon and a generated electron-hole pair. This relation can be circumvented via either two photon absorption (TPA), in which two photons are absorbed to generate a single electron-hole pair, or via impact ionization (also called Auger generation), in which a single high energy photon generates multiple electron-hole pairs. Although such absorption processes have been measured in bulk materials [7], nano-structured materials are required in order to measure a large effect. For example, nano-structured materials have demonstrated high two-photon absorption and impact ionization processes, with close to 100% impact ionization reported [8]. While high impact ionization or TPA rates are an important first step, such high rates alone do not insure high solar cell efficiency, and the critical measurement for such devices are to demonstrate quantum efficiencies substantially exceeding unity.

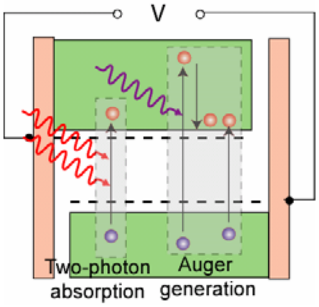
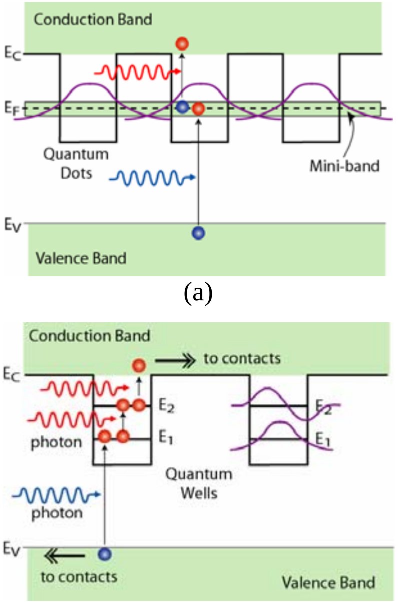


Fig 1: Absorption in multiple absorption path solar cells.

. *Multiple energy level solar cells*

In multiple energy level solar cells, the mismatch between the incident energy of the solar spectrum and a single band gap is accommodated by introducing additional energy levels such that photons of different energies can be efficiently absorbed. Multiple energy level solar cells can be implemented either as localized energy levels (first suggested as a quantum well solar cell) or as continuous mini-bands (also called intermediate band for the first solar cell to suggest this approach). Both cases, which are shown in Figure 2, have a fundamental similarity in that the key issue is the generation of multiple light-generated quasi-Fermi levels.



(b)

Fig 2: Implementation of multiple energy level solar cells.

The transport of the carriers between the two approaches, however, is substantially different. In the mini-band case, the transport must occur along the mini-bands and hence the carriers must not be able to thermalize from one band to another. This means that the density of states must be zero between the bands, and hence that such approaches must use either quantum dots or a material which inherently has multiple bands. In localized energy level approaches, transport is accomplished by having the carriers at each localized energy level escape by light absorption. To maintain high collection efficiency, the escape time should be faster than the recombination time. The feasibility of the escape process is well demonstrated by quantum-well infrared photodetectors, which have high collection from intra-sub band processes. Localized band approaches have a further advantage in that successive localized energy levels can have different energies, thus allowing the a large number of effective band gaps and high efficiencies.

Multiple temperature solar cells

A solar cell which contains multiple temperatures in a single device can use these temperature differentials to generate power. The multiple temperatures may be due to variations in the physical temperature of the lattice, but it is easier to maintain a temperature differential between hot carriers and thermalized carriers. The multiple temperature approach has the advantage that a thermal converter allows higher efficiencies given identical high concentration structures. A thermal converter can be implemented by a structure in which the band edges in the converter vary, allowing interactions between hot carriers and carriers at the band edge. While this approach allows efficiencies 66% with three energy levels, the physical effect of thermal interactions have not been demonstrated.

4. Conclusions

Detailed balance calculations demonstrate that the thermodynamic efficiency potential of new approaches to solar energy conversion are essentially identical. However, each of the five approaches have substantially different practical limits and advantages. Key advantages include the ability to use effects in self-assembling nanostructures and the ability achieve high efficiency in a greater range of materials.

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