Project 08: Third Generation Spectral Engineering for Increased Solar Cell Efficiencies

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Introduction

The primary technological challenge associated with the efficient capture of energy from the solar spectrum is the broad distribution of energy, with 99% of its energy falling between 340 and 3500 nm (0.35 to 3.7 eV). For a single junction device, the conversion efficiency is limited to ~32% for a semiconductor bandgap E_g ~ 1.35 eV, based on a simple model for the optical absorption and thermodynamic considerations, referred to as the Shockley-Queisser limit[1]. So-called third generation technologies[2] seek to move beyond the Shockley-Queisser limit to achieve significant increases in efficiency, while doing so using low cost manufacturing methods, such as thin film technologies. The only proven and implemented strategy to move beyond the Shockley-Queisser limit is the use of multi-junction technology as described in other projects in this research proposal.

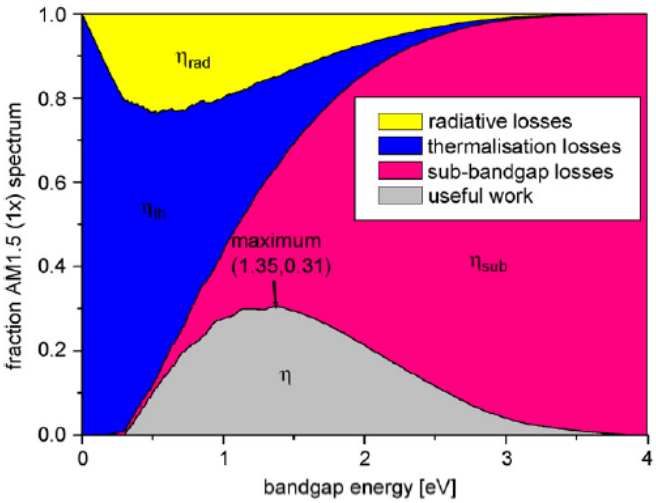


Fig. 17

The fundamental energy losses for a single junction device are illustrated in Fig. 17 (Fig. 3 of Ref. 3). For Silicon, with E_g ~ 1.1 eV we see that a maximum theoretical efficiency of 30% can be achieved, with ~20% being lost to photons below the bandgap that are not absorbed, 31% to the thermalization of photons above the bandgap down to the bandgap energy and the remaining 19% lost due to emission of radiation. In principle, the sub-bandgap and above-bandgap thermalization losses can be mitigated by approaches which effectively serve to narrow the solar spectrum. These approaches fall into 2 broad categories (with other third generation approaches, such as hot carrier cells, omitted); a) purely optical conversion of incoming photons to an energy closer to and above the semiconductor bandgap and b) optical excitation of multiple electron-hole pairs (i.e. Multiple Exciton Generation (MEG)) and creation of electron-hole pairs via multiple sub-bandgap photons.

While there has been important recent progress in MEG [4,5] and the creation of electron-hole pairs via multiple sub-bandgap photons[6] this approach also faces additional challenges in the diffusion of the electron hole pairs to a place in the device where they can dissociate and be converted into useful work. In the purely optical approach, above-bandgap photons are converted to typically two lower energy photons via *down conversion* and typically two sub-bandgap photons are converted to one higher energy photon via *up conversion*. The purely optical approach, which we will focus on exclusively in this project, has the distinct advantage that the up and down conversion processes can be studied and optimized separately from a specific solar cell design and in fact the results can be applied to achieve efficiency increases in any single junction solar cell. From a technological point of view this greatly simplifies the integration of the up and down conversion layers with the solar cell. Ideally, these can take the form of thin films, made from inexpensive precursors and integrated using low cost processing techniques. Conceptually the solar cell formed in this manner can be formally considered as a multi-junction cell, which is coupled optically and not electrically. This insight[7] clarifies the connection to multi-junction technology and the potential simplification of the purely optical approach by obviating the need for the design of complex lattice-matched tunnel junctions in the typical triple junction high

efficiency cells.

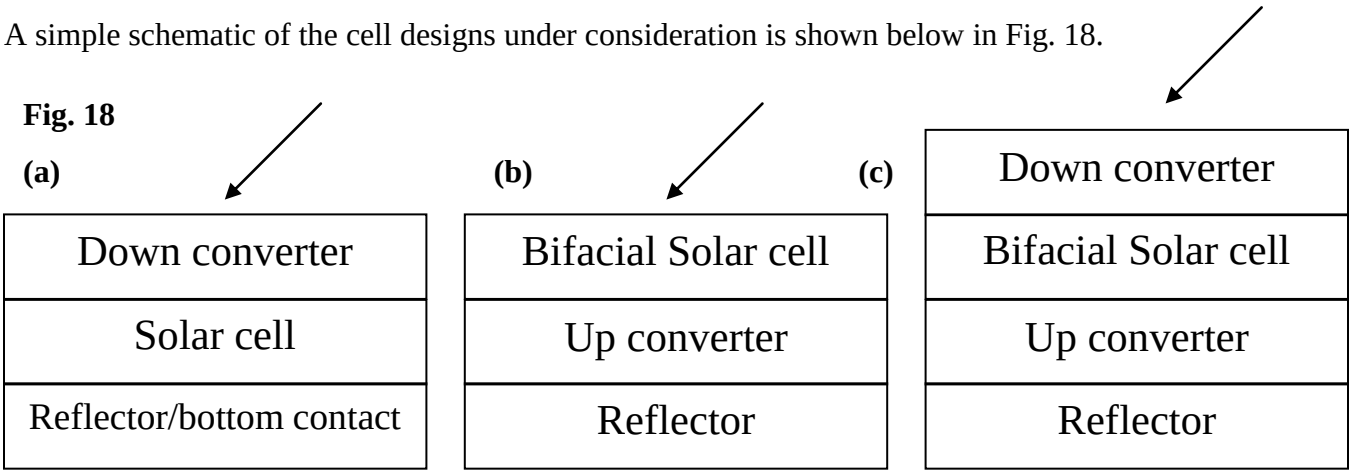
Background

Optical conversion has been used for many years in a wide variety of applications, yet only considered quite recently for its potential benefits to solar cell applications. In general, these occur most simply in 3 level systems (E_1, E_2, E_3) where $\Delta E = E_3 - E_1$ is the incident (outgoing) photon energy in the case of down (up) conversion. E_2 is an intermediate state that is typically established by the introduction of a suitable dopant. Trupke, *et al* have considered down conversion[8] and up conversion[9] in their application to solar cells, finding potential increases of efficiency to 37% for down conversion at 1 sun and 37% for up conversion at 100 suns for Silicon with $E_g \sim 1.1$ eV. Shpaisman, *et al* found[10] an increase to 39% for MEG at 1 sun, 38% for up conversion at 1 sun, with a combined increase to 48% for Silicon with $E_g \sim$ 1.1 eV. Not surprisingly, the up conversion mechanisms favour a higher bandgap (~1.8 eV), the down conversion mechanisms a lower bandgap (~0.9 eV), while together they have an optimal efficiency at ~1.4 eV. For use in conjunction with Silicon solar cells it is clearly advantageous to utilize both processes if possible. While down conversion mechanisms are typically linear processes, up conversion mechanisms are highly non-linear and are expected to increase rapidly with solar concentration (as compared to the more modest logarithmic increase predicted and observed in single junction devices). These efficiency increases are commercially very significant and offer an attractive route to increased solar cell efficiencies leveraging the installed base of conventional devices, while imposing a minimal risk to companies in the adoption of a new technology. While Silicon solar cells would be the primary beneficiary, the same approach could be applied to other single junction technologies, including CdTe, CIGS, a-Si and other thin film devices.

Strümpel, *et al* have reviewed[11] the main material systems used to date for modifying the solar spectrum via up conversion, down conversion and photoluminescence.

A simple schematic of the cell designs under consideration is shown below in Fig. 18.

Fig. 18



In Fig. 18a the down conversion layer is placed on the front face of a conventional solar cell, whereas Fig. 18b shows the up conversion layer on the rear face of the solar cell. In the latter case, the solar cell must be substantially accessible optically on both sides, while electrical contact must also be made to both faces. This can be accomplished by a bifacial device, such as the Passivated Emitter Rear Locally diffused (PERL) solar cell design from the U. of New South Wales (Australia). We have assumed that the down- and up-converting layers have an insulating dielectric matrix and that electrical contacts are made to the top surfaces with minimal areal coverage and on the bottom surface of the bifacial device with minimal areal coverage. In Fig.18c, both down and up conversion layers are utilized for maximum efficiency gains.

Down conversion

As Fig. 18 indicates, the down conversion layer is placed above the conventional solar cell and ideally

must absorb above bandgap photons and transmit the near and below bandgap photons. This immediately suggests a layer of nanoparticles in a dielectric matrix and recent research has shown some promising results. In general, quantum confinement effects in Silicon nanocrystals provide the opportunity to create discrete states in the energy spectrum and tune the energy gap higher as the particle size is reduced to nanoscale dimensions. Quite recently Timmerman, *et al* have used[12] Space-Separated Quantum Cutting (SSQC) in closely packed 3.1 nm diameter Silicon nanocrystals, in the presence of Er^{3+} to demonstrate down conversion of photons with $\lambda < 768$ nm to two or more 1535 nm photons. While this particular wavelength is not optimal for photovoltaic applications, this process shows a promising route to relatively simple down conversion by bandgap engineering methods. More striking is their demonstration, via detection of photoluminescence at 914 nm, of SSQC in the absence of Er^{3+}, using only the confinement enhanced bandgap of the spatially separated Silicon nanocrystal to capture the excess photon energy.

We propose to study the optical properties (over the entire solar spectrum) of Silicon nanocrystals in an SiO_2 or Silicon oxynitride matrix as a function of particle size, packing density and rare earth doping. These will be made in thin film form using both ion implantation and PECVD growth in the Centre for Emerging Device Technologies at McMaster. Recently, A.P. Knights (and our UK collaborators listed above) have developed a new technique for the formation of rare earth doped Silicon nanocrystals in a dielectric host which results in a virtually defect free film with high quantum efficiency for photoluminescence. Furthermore, the implanted dopant is distributed throughout the dielectric thin film and is not restricted to the original implantation profile. P. Mascher has developed the capacity to fabricate complex superlattice structures that have excellent control over the size and distribution of Silicon nanoclusters along with the capability of rare earth doping. Structural characterization using high resolution TEM will be done at McMaster, while optical measurements will be performed at the SUNLab at the U. of Ottawa.

Up conversion

Gibart, *et al* were the first to report up conversion in a solar cell by placing a 100 μm thick vitroceramic doped with Er^{3+} and Yb^{3+} on the backside of a GaAs solar cell whose substrate had been removed[13]. There are many possible up conversion processes, as detailed in a review by Auzel[14]. Most approaches utilize a rare earth or transition metal atom in a suitable host to provide the appropriate intermediate level in the 3 level system. While most host materials are themselves quite complex materials, Er^{3+} has been used in SiO_2 fibres and waveguides for many years in the development of Erbium Doped Fiber Amplifiers (EDFA). For that purpose, significant up conversion is a deleterious side effect and in fact high up conversion rates are strongly correlated with lower gain in EDFA's[15]. Consequently, Er^{3+} in SiO_2 has historically been optimized to minimize up conversion rates, while conversely we propose to maximize up conversion rates. Early reports showed substantial up conversion rates depending on anneal temperature and in the presence of other dopants[16].

We will use rare earth doped $Si_xTi_{1-x}O_2$ in thin film form[17] produced by ion implantation and/or PECVD. These films will be characterized optically over a broad range of wavelengths and intensities at the U. of Ottawa and McMaster to optimize their up conversion rates. Of particular interest for the up conversion layers is the strong expected intensity dependence. For this purpose we will take advantage of the unique Class A solar simulator at the SUNLab at the U. of Ottawa which can achieve solar concentrations of up to of 2000 suns.

As the up and down conversion layers show promising performance for photovoltaic devices, they will be integrated into conventional solar cells as illustrated in Fig. 18 for further device evaluation by the Ottawa group as described in more detail in the activity schedule. We note that the increased efficiencies in this project will be achieved using materials that are inherently low cost and non-toxic. The rare earth elements are not actually geologically rare and are only used in dopant level concentrations.

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