Exciting silicon: from Planck to nanoscale

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Efficient capture of sunlight remains one of the great challenges to photovoltaics today. This is particularly so for the dominant photovoltaic material – crystalline silicon – which, as an indirect gap semiconductor, needs several hundred micrometers thickness for efficient operation. This paper will give an overview of the principal concepts that are currently being considered to enhance light capture by the solar cell. We shall, in particular, try to compare and contrast two main ideas of thought that underpin the current status of the field. The first, based on thermodynamics, makes use of light trapping where photon path within a structure is extended by virtue of a stochastic photons distribution inside a dielectric / weakly absorbing semiconductor. The second approach rests on the use of sub-wavelength or nano-scale structures which allow the possibility of electromagnetic energy injection into very thin semiconductor layers, by direct interaction with the trapped modes or via the near field of an intermediate dipole absorber or scatterer.

The use of light trapping to enhance current generation in silicon solar cells can be traced to the COMSAT "black cell" in the 1970's, with a surface texture in the form of etched pyramids [1]. A theoretical explanation which gives the limit to light trapping in thermodynamic terms soon followed [2] but we shall show that the origins of the fundamental ideas are much older, and date back to Planck's celebrated papers that marked the beginning of the quantum theory [3]. This approach has more recently been revisited and combined with the frequency management of light, more usually encountered in the so-called fluorescent concentrators / collectors [4,5]. If supplemented with simple photonics one can show that this thermodynamic "squeezing" of light can produce devices which can concentrate diffuse light and operate with photon collection efficiency in excess of 90%. A similar structure (the "photonic bandgap solar cell") can be optimised for light trapping, and the resulting energy conversion efficiency can match (or even slightly exceed) the efficiency of an ideal (thick) crystalline silicon solar cell.

We shall also take a look at photon management at the "nanoscale", by distinguishing two principal mechanisms for the generation of electron-hole pairs in a very thin layer of weakly - absorbing semiconductor such as silicon, via the excitation of molecules near the surface:

(i) Photon tunnelling between an excited molecular state and the trapped modes inside the semiconductor layer, mediated by the evanescent field;

(ii) Interaction between the near field of the molecular dipole and the transition dipole moment of the electron transition between the valence and conduction band of the semiconductor. This mechanism, similar to Förster's resonance dipole interaction between molecules, parallels the energy collection by light harvesting in the photosynthetic unit (Fig. 1) [6, 7, 8]. Most interestingly, there are indications that this interaction can be used to break the symmetry laws that prevent silicon from direct gap absorption, effectively turning silicon into a direct gap material.

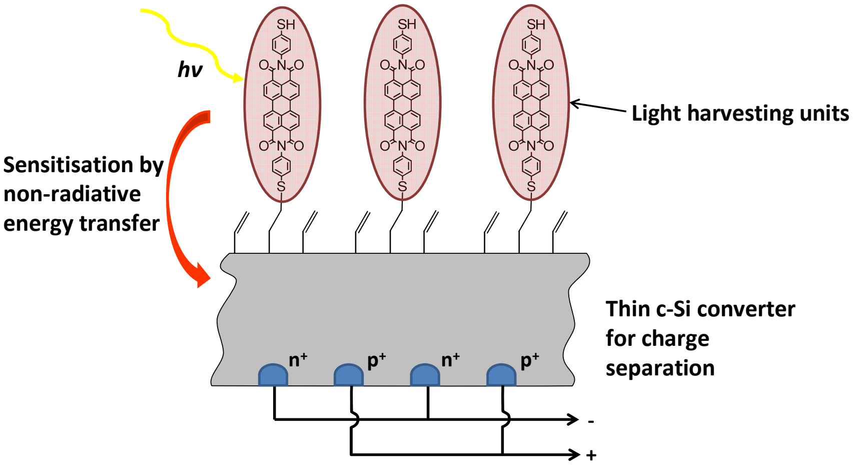

Fig. 1. A schematic diagram of a crystalline silicon solar cell sensitised by a light-harvesting structure on the surface.

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