Of dipoles, films and interfaces : enhancing the capture of sunlight

Tom Markvart,[a] Nick Alderman,[b] Lefteris Danos,[c] Liping Fang[a] and Thomas Parel[a]

[a]Solar Energy Laboratory, University of Southampton, UK
[b]Department of Chemistry, University of Ottawa, Canada
[c]Department of Chemistry, University of Lancaster, UK

Efficient light capture remains one of the great challenges to photovoltaics. This talk will take a look at how light capture can be enhanced by the presence of a dipole (molecule, metal particle, …) in close proximity to the surface of a dielectric or weakly absorbing semiconductor. Following a brief overview of the statistical approach which underpins light trapping (with a history going back to Planck) we shall explore more modern avenues taking advantage of the photon-matter interaction at the nanoscale. We will consider two key phenomena in more detail: photon tunnelling through the evanescent field, and light harvesting in terms of the near-field dipole-dipole interaction. The various strands will be brought together in an analysis of the limit to light trapping in an ultrathin waveguide with discrete guided modes.

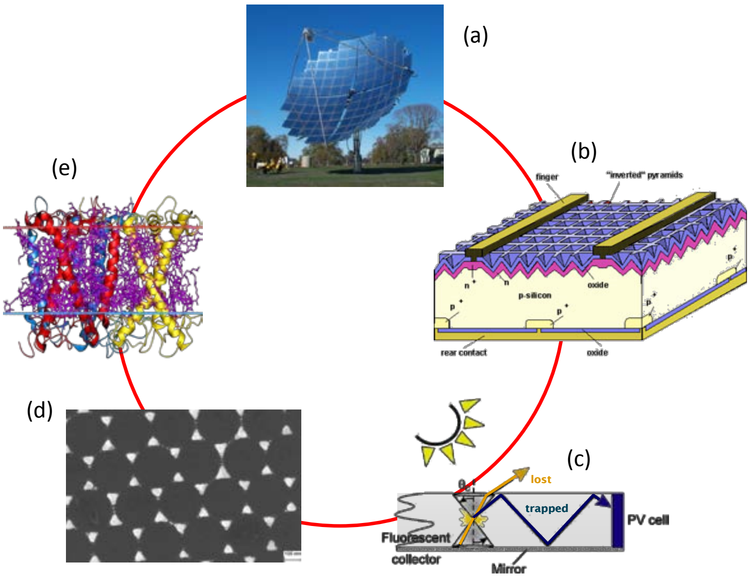

Fig. 1. Various strategies to enhance the capture of sunlight (Image sources: Solar Systems Pty Ltd; Martin Green, UNSW; Fang Xie, Imperial College; Wikipedia).

Examples that depict different approaches are shown in Fig. 1. Concentration of light by mirrors or lenses is probably the most widespread example of light management (Fig. 1a). These systems can only concentrate the direct beam; hence, most of the diffuse radiation is unused and a mechanism is needed to move the array and track the sun. A different way to reduce the amount of photovoltaic material is to trap the incident light inside the solar cell. This is now a standard technique in many commercial silicon solar cells (Fig. 1b) for reducing reflection but also for light trapping: to increase the path length of light inside the cell. The key aspect here is that light trapping is a stochastic process – in this instance, scattering - which re-distributes ray directions to fill the available volume in the phase space. A device which provides a more general example of a similar process is a fluorescent concentrator (Fig. 1c) which adds the dimension of frequency. Instead of scattering, the frequency of emitted light rays is changed by the Stokes shift of fluorescent beam. One can say that the fluorescent concentrators employ this energy to reduce the entropy (and hence the étendue) of the emitted beam, and therefore represent a “perfect” concentrator which can collect even diffuse radiation.[1]

Fluorescent concentrators share one principal attribute with the main topic of this talk: how dipoles (at molecules, plasmonics, …, Fig. 1d) can be used to enhance the light capture at the nanoscale. Photon tunnelling[2] can be used to inject directly photons into the trapped modes of a silicon film. When viewed at the statistical level photon tunnelling from molecules or metal particles on the surface is similar to light trapping but, in the case of layers with subwavelength thickness *d*, the fundamental features come from waveguide characteristics of the layer rather than of the dipole. We shall focus discussion on the fundamental limit to light trapping in an ultrathin single-mode waveguide. We shall show that the probability of absorption (expressed in terms of the mean photon path length) is governed principally by the confinement factor for the waveguide mode which is proportional to $(d/\lambda)^2$ and therefore significantly shorter than the Yablonovitch path length (Fig. 2).

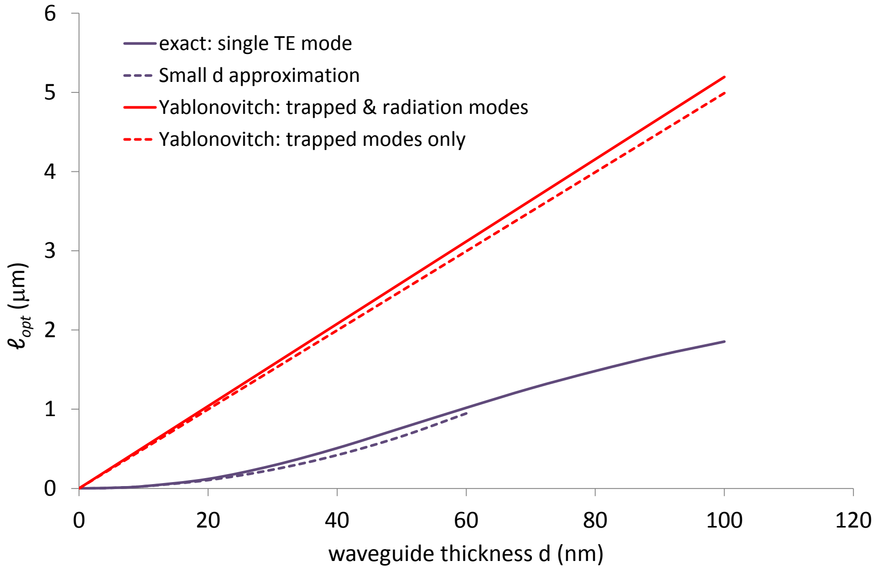

Fig. 2. The effective absorption length in a single-mode planar silicon waveguide, compared with the Yablonovitch limit $\ell_{opt} = 4n^2d$

We shall conclude with a brief look at the perhaps most exciting facet of the dipole interaction mechanism at nanometre distances when the near-field interaction of the exciting dipole interact with the transition dipole moment of the electron-hole pair in silicon. The resulting energy transfer, which resembles the Förster resonance energy transfer, is familiar from the light-harvesting processes in photosynthesis (Fig. 1e). Our results[3] provide a strong evidence of very fast energy transfer which, in principle, would make it possible to manufacture crystalline silicon with thickness at the sub-micrometer level.

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[1] T. Markvart, Thermodynamics of optical étendue, J. Opt. A 10, 015008 (2008); T. Markvart, Solar cell as a heat engine: energy-entropy analysis of photovoltaic conversion, phys stat sol. (a) 205, 2752 (2008).

[2] L. Fang, K. S. Kiang, N. P. Alderman, L. Danos, and T. Markvart, Photon tunneling into a single-mode planar silicon waveguide, Optics Express, vol. 23, no. 24, pp. A1528-A1532, 2015.

[3] Nick Alderman et al, to be published.