Detailed Balance Analysis and Enhancement of Open Circuit Voltage in Nanophotonic Solar Cells

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Abstract
We present a detailed balance based approach for performing current density-voltage characteristic modeling of nanophotonic solar cells. This approach takes into account the intrinsic material non-idealities, and is useful for determining the theoretical limit of solar cell efficiency for a given structure. Our approach only requires the cells absorption spectra over all angles, which can be readily calculated using available simulation tools. Using this approach, we elucidate the physics of open-circuit voltage enhancement over bulk cells in nanoscale thin film and single wire structures, by showing that the enhancement is related to the absorption suppression in the immediate spectral region above the bandgap.

Understanding Nanophotonic Solar Cells
To completely understand the limiting performance of a nanophotonic solar cell, we need to characterize its:
- open circuit voltage ($V_{sc}$) behavior
- short circuit current ($J_{sc}$) behavior
- Most of the previous works on nanophotonic cells have focussed on $J_{sc}$ enhancement.

A nanoscale thin film solar cell can achieve a $V_{oc}$ that is significantly larger over that of a bulk cell.
A detailed balance analysis can help us understand the physics of this voltage enhancement.

Physics of Voltage Enhancement (Detailed Balance Analysis)
The $V_{oc}$ is mainly dependent on two different photon absorption rates:
(a) the photon absorption rate ($N_{N_{eq}}$) when the cell is under direct sunlight
(b) the photon absorption rate ($N_{N_{eq}}$) when the cell is in thermal equilibrium with incoming blackbody radiation at all angles of incidence.

10μm thick* bulk with AR coating $V_{oc} = 1.15V$
44μm thick* thin film on perfect reflector $V_{oc} = 1.21V$
Bulk limit

The narrowband thermal equilibrium spectral photon flux density has a width of ∼$\Delta f_{sc}$ near the bandgap ($E_g ≈ 870 μeV$).
We can enhance the cell's $N_{N_{eq}}/N_{N_{eq}}$ ratio and, thus, its $V_{oc}$ by:
- suppressing absorption within this $\Delta f_{sc}$ window i.e. $N_{N_{eq}}$
- maintaining a large absorption outside this $\Delta f_{sc}$ window i.e. $N_{N_{eq}}$.

In addition, we find that the dips in the nanoscale's $V_{oc}$ vs $Radius$ plot coincides with the cases where an absorption resonance is in the immediate vicinity of the material bandgap i.e. $E_g$.

Conclusion
- Nanoscale solar cells allow us to achieve higher $V_{oc}$ than a bulk cell, while at the same time providing the flexibility to absorb a particular part of the solar spectrum by, for example, tuning the radius of a nanowire
- Such a capability for voltage engineering can open new avenues for achieving high efficiency nanoscale solar cells

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