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

(*Opt. Express, v21, 2013*)

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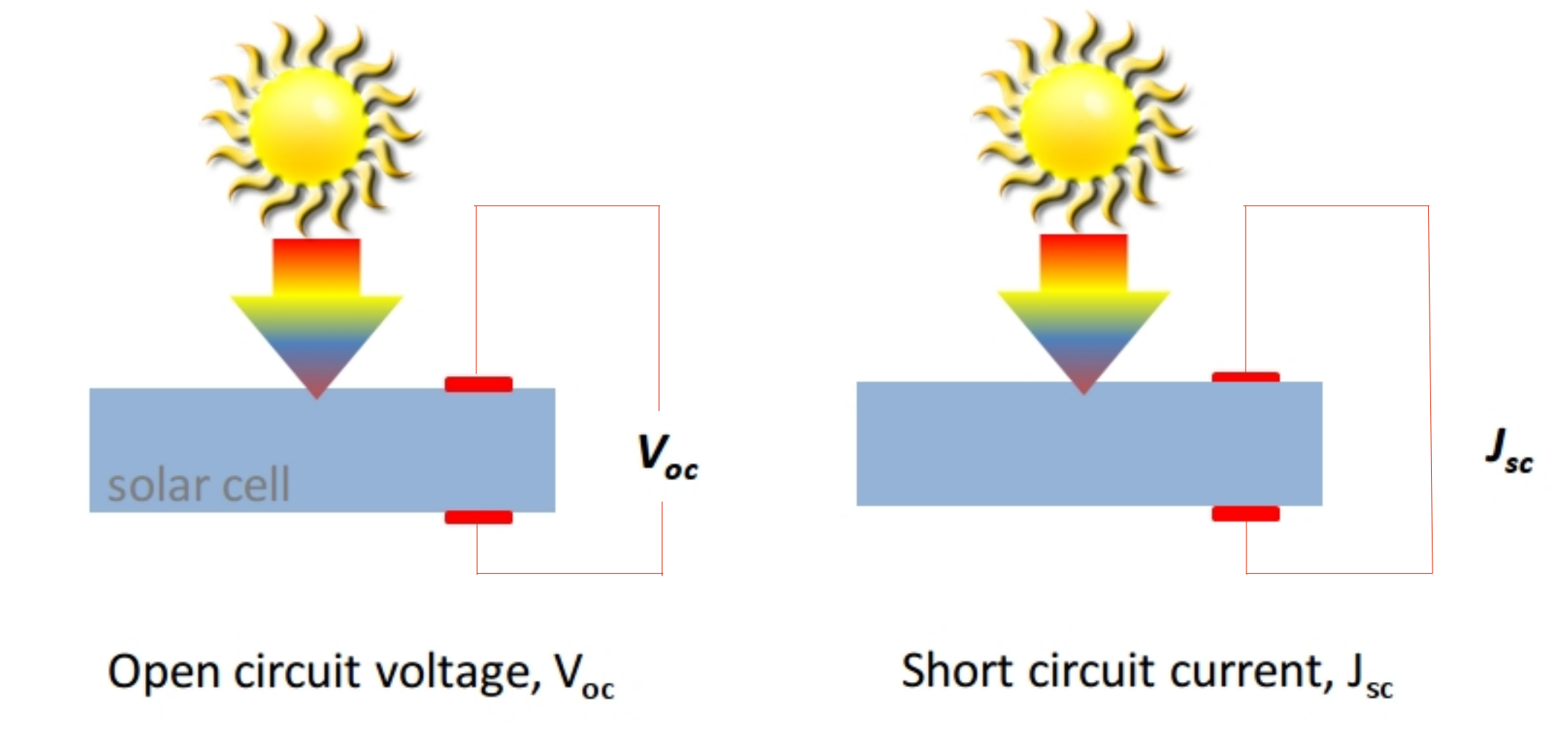
Abstract

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.

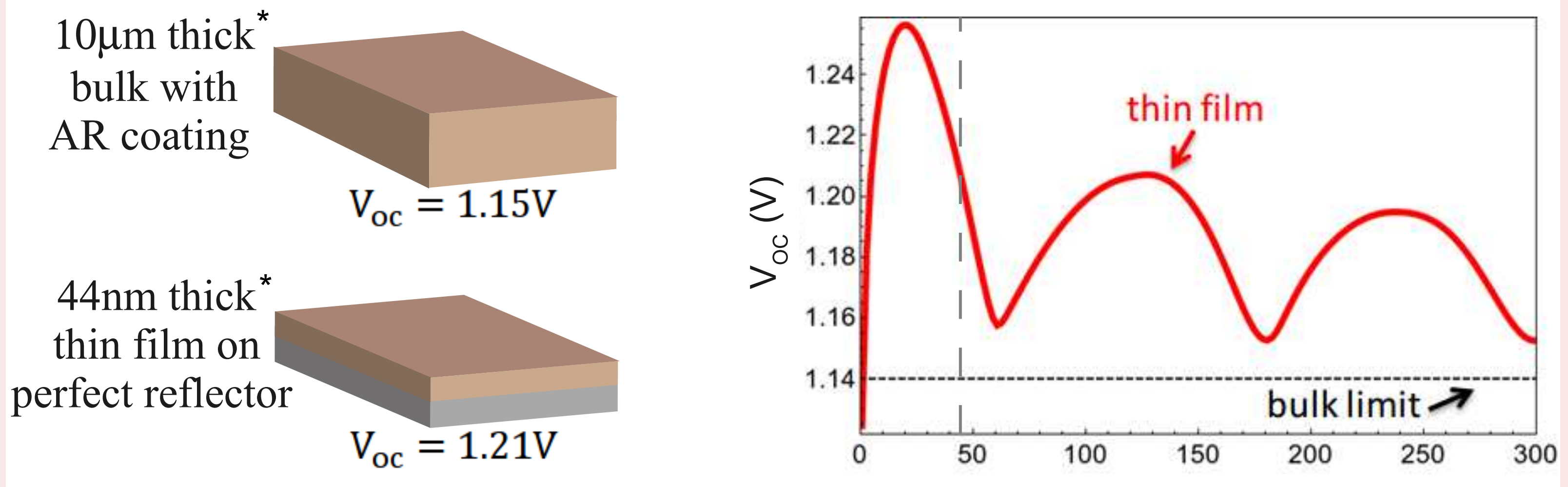
Understanding Nanophotonic Solar Cells

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



V_{oc} Enhancement of a Nanoscale GaAs Thin Film (*A. Niv et. al., PRL, v109, 2012; S. Sandhu et. al., Opt. Exp., v21, 2013*)

- 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.



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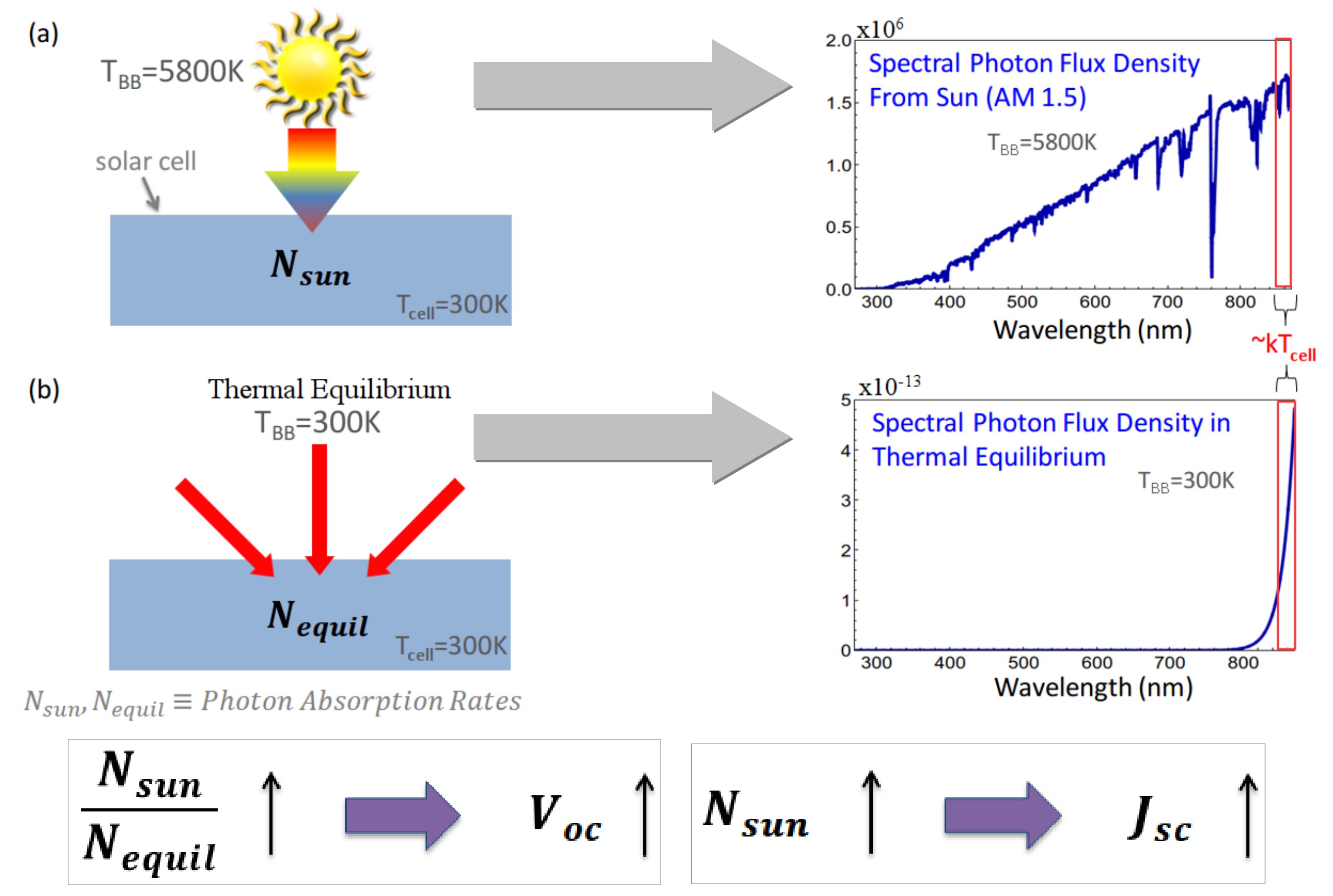
Physics of Voltage Enhancement (Detailed Balance Analysis)

The V_{oc} is mainly dependent on two different photon absorption rates:

(a) the photon absorption rate (N_{sun}) when the cell is under direct sunlight

(b) the photon absorption rate (N_{equil}) when the cell is in thermal equilibrium with incoming blackbody radiation at all angles of incidence.



$N_{sun}, N_{equil} \equiv$ *Photon Absorption Rates*

$$\frac{N_{sun}}{N_{equil}} \uparrow \Rightarrow V_{oc} \uparrow \qquad N_{sun} \uparrow \Rightarrow J_{sc} \uparrow$$

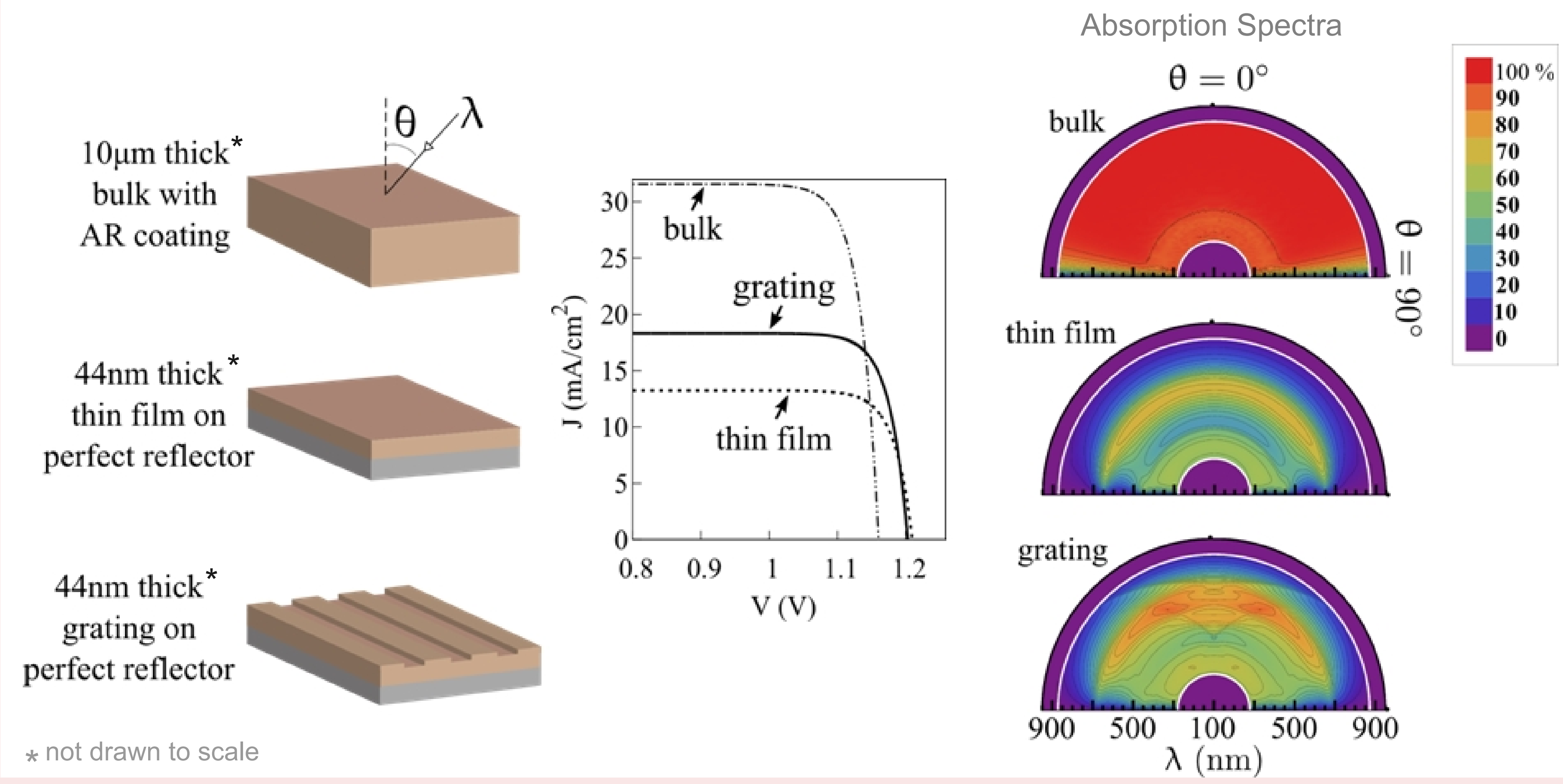
The narrowband thermal equilibrium spectral photon flux density has a width of $\sim kT_{\mathrm{cell}}$ near the bandgap ($E_{\mathrm{g}} \approx 870\mathrm{nm}$). We can enhance the cell's $N_{\mathrm{sun}}/N_{\mathrm{equil}}$ ratio and, thus, its V_{oc} by:

- suppressing absorption within this kT_{cell} window i.e. $N_{\mathrm{equil}} \downarrow$
- maintaining a large absorption outside this kT_{cell} window i.e. $N_{\mathrm{sun}} \uparrow$.

Explaining V_{oc} Enhancement of a Nanoscale GaAs Thin Film

- Comparing the absorption spectra of the thin film with that of the bulk cell, we find:
  - the bulk structure has $\sim$ 100% absorption for all wavelengths λ and angles of incidence θ
  - the thin film has (1) profound absorption suppresion within the kT_{cell} window near the GaAs bandgap for all angles of incidence, and (2) relatively larger abosorption outside this kT_{cell} window.

  This results in the thin film having a larger $N_{\mathrm{sun}}/N_{\mathrm{equil}}$ ratio and consequently, a significantly larger V_{oc} over that of the bulk structure.
- An optimized GaAs grating structure on a nanoscale thin film can enhance the thin film's J_{sc}, while preserving its V_{oc} enhancement over a bulk cell.



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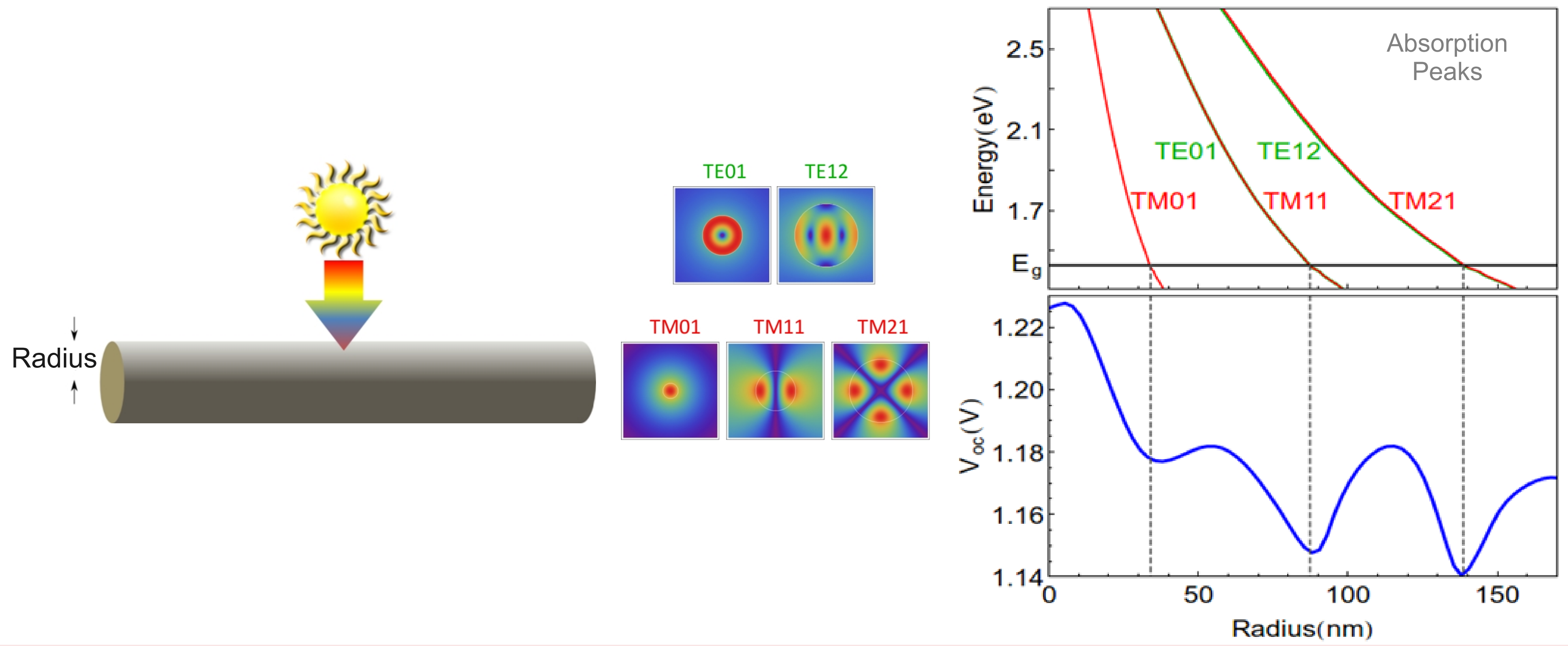
V_{oc} Enhancement of a GaAs Nanowire

The above voltage enhancement recipe can be applied to other nanostructure geometries. For example, a nanowire geometry supports a variety of absorption resonances whose spectral positions can be tailored by varying the nanowire's radius:

- By appropriately selecting the nanowire's radius, we can get a significantly larger V_{oc} over that of a bulk structure.
- In addition, we find that the dips in the nanowire'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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