Thermodynamics of Light Management in Near-Field Thermophotovoltaics

Nanolight, Benasque, 07/03/2022

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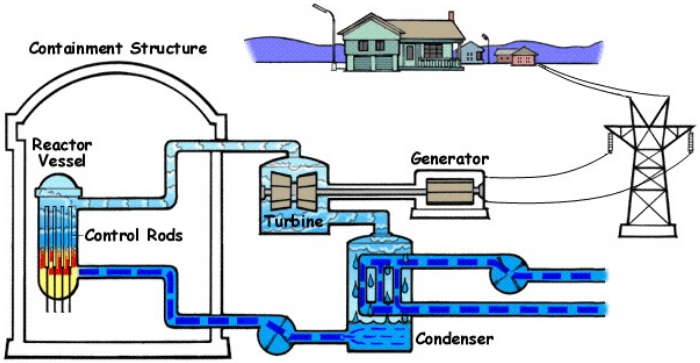
Waste heat

electratherm.com

Standard approaches

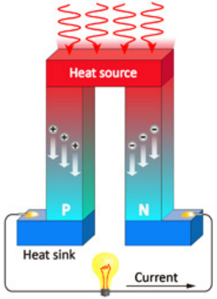
Fluid-based heat engines



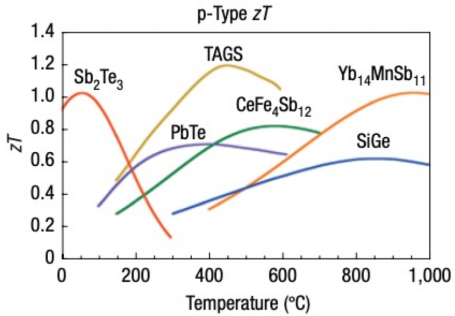
commons.wikimedia.org

- ➔Fluid-based
- ➔Bulky components

Thermoelectric materials



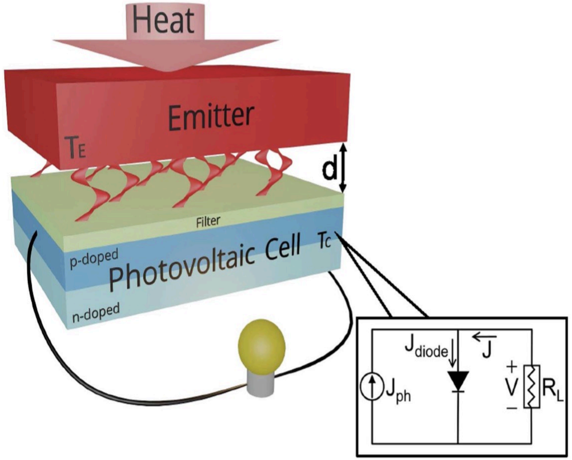
chem.au.dk



G. J. Snyder, E. S. Toberer, Nature Mat. 7, 105-114 (2008)

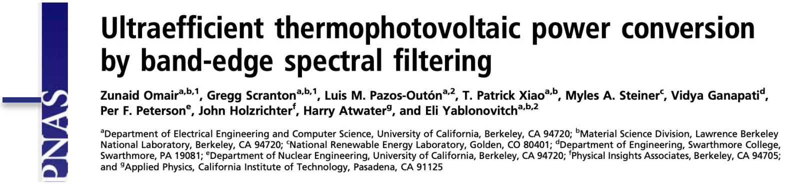
- ➔Low efficiency (<10%)
- ➔Low power density (~ 1Watt/cm^2)
- ➔Low melting point (<750 K)

Thermophotovoltaic energy conversion



M. S. Mirmoosa *et al.*, Journal of Optics 18, 115104 (2016)

2019



PNAS

Ultraefficient thermophotovoltaic power conversion by band-edge spectral filtering

Zunaid Omair[a,b,1], Gregg Scranton[a,b,1], Luis M. Pazos-Outón[a,2], T. Patrick Xiao[a,b], Myles A. Steiner[c], Vidya Ganapati[d], Per F. Peterson[e], John Holzrichter[f], Harry Atwater[g], and Eli Yablonovitch[a,b,2]

[a]Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA 94720; [b]Material Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720; [c]National Renewable Energy Laboratory, Golden, CO 80401; [d]Department of Engineering, Swarthmore College, Swarthmore, PA 19081; [e]Department of Nuclear Engineering, University of California, Berkeley, CA 94720; [f]Physical Insights Associates, Berkeley, CA 94705; and [g]Applied Physics, California Institute of Technology, Pasadena, CA 91125

2020

Article

Near-perfect photon utilization in an air-bridge thermophotovoltaic cell

LETTERS

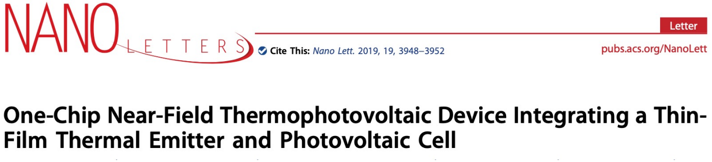
https://doi.org/10.1038/s41565-018-0172-5

nature nanotechnology

2018

Nanogap near-field thermophotovoltaics

2019



NANO LETTERS

Letter

Cite This: *Nano Lett.* 2019, 19, 3948–3952

pubs.acs.org/NanoLett

One-Chip Near-Field Thermophotovoltaic Device Integrating a Thin-Film Thermal Emitter and Photovoltaic Cell

2020

ARTICLE

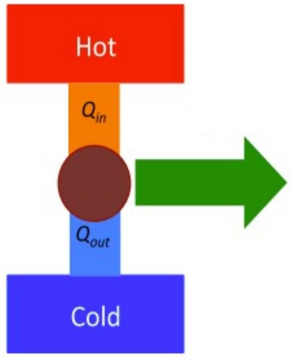
https://doi.org/10.1038/s41467-020-16197-6

OPEN

Integrated near-field thermo-photovoltaics for heat recycling

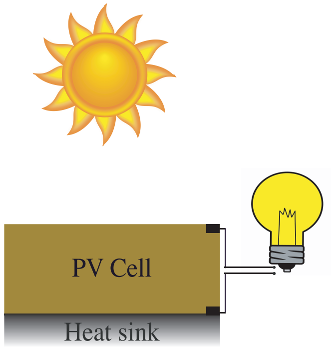
Comparing solar PVs and TPVs

Carnot engine



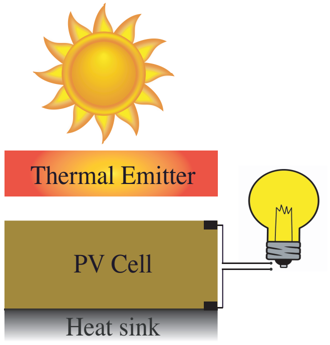
$$\eta_{\mathrm{Carnot}} = 1 - \frac{T_{\mathrm{C}}}{T_{\mathrm{H}}}$$

Solar PVs, *ΔT*=5700K



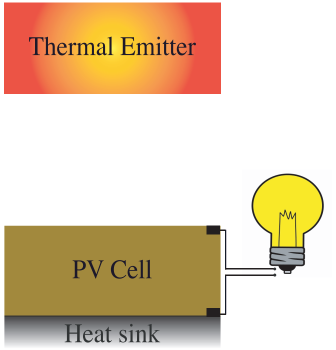
$$\eta_{\mathrm{SQ}} = 30\% \;\; [1]$$

Solar TPVs, *ΔT*=5700K



$$\eta_{\mathrm{solar\ TPV}} = 54\% \;\; [2]$$

TPVs, *ΔT*<<2000K

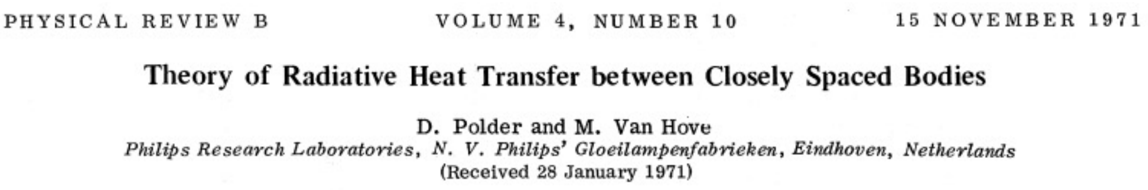


$$\eta_{\mathrm{theory}} > 50\% \;\; [3]$$

$$\eta_{\mathrm{exp}} \geq 29.1\% \;\; [4,5]$$

[1] W. Shockley, H. J. Queisser, J. Appl. Phys. 32, 510 (1961)
[2] N.-P. Harder, P. Wurfel, Semicond. Sci. Technol. 18, S151 (2003)
[3] G. T. Papadakis *et al*., Nano Lett. 20, 3 (2020)
[4] Z. Omair *et al.,* PNAS 116, 31 (2019)
[5] D. Fan *et al.,* Nature 583 (2020)

The thermal near-field

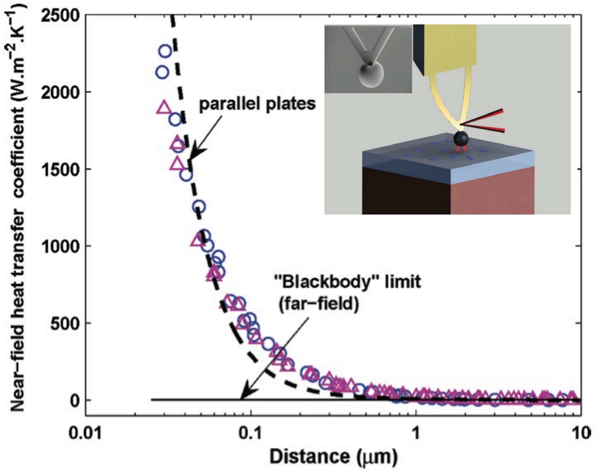


PHYSICAL REVIEW B VOLUME 4, NUMBER 10 15 NOVEMBER 1971

Theory of Radiative Heat Transfer between Closely Spaced Bodies

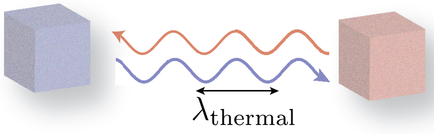
D. Polder and M. Van Hove
Philips Research Laboratories, N. V. Philips' Gloeilampenfabrieken, Eindhoven, Netherlands

(Received 28 January 1971)

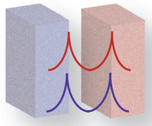


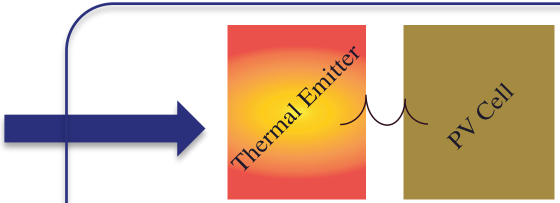
Narayanaswamy, Chen *et al.*, Phys. Rev. B 78, 115303 (2008)

Far-field



Near-field





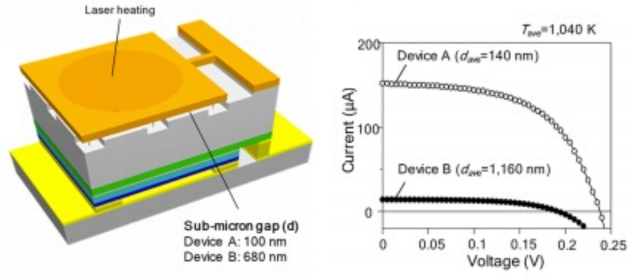
$$P_{\text{el}} = J \times V$$

$$\eta = \frac{P_{\text{el}}}{P_{\text{phot}}}$$

Mainly P_{el} enhancement via near-field coupling

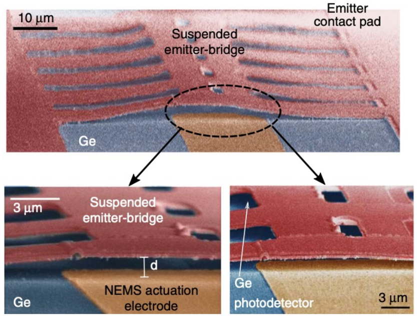
Recent experimental demonstrations of near-field TPVs

$d<150$ nm, T_H=427 deg. C



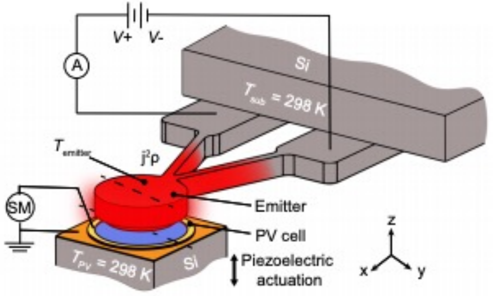
I. Inoue *et al.*,
ACS Nano Lett. 19, 1948 (2019)

$d\sim100$ nm, T_H=607 deg. C



G. R. Bhatt *et al.*,
Nature Comm. 11, 2545 (2020)

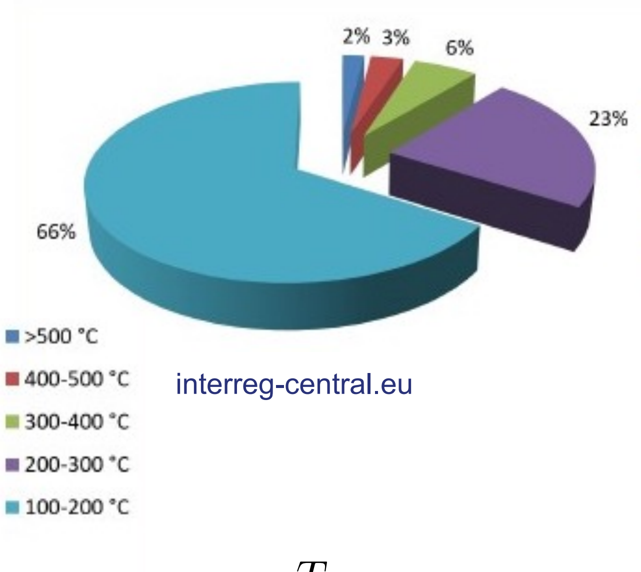
$d<100$ nm, T_H=1000 deg. C



R. Mittpally *et al.*,
Nature Comm. 12, 4364 (2021)

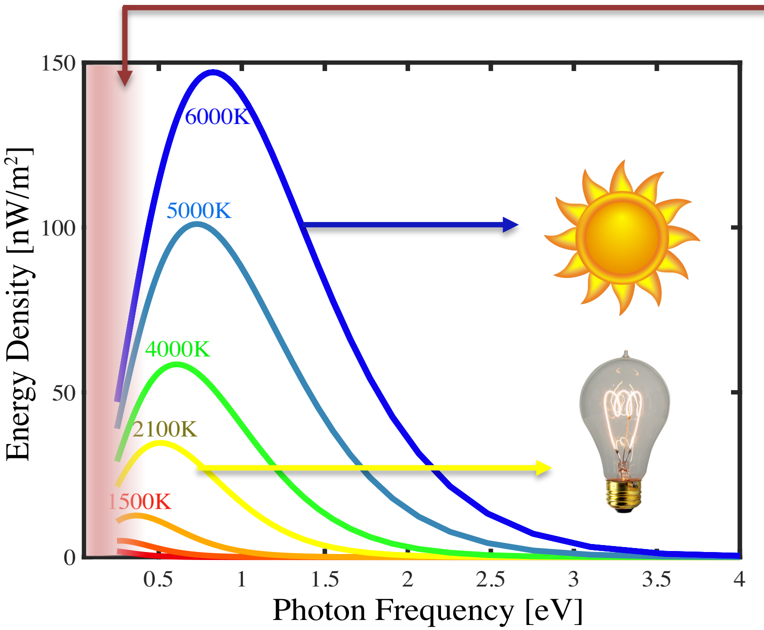
Waste heat temperatures, band gap and efficiency

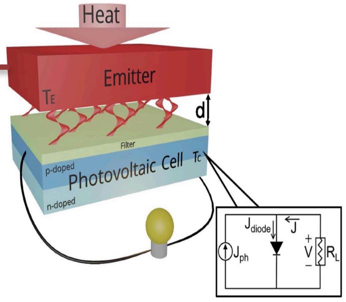
Waste heat temperatures



interreg-central.eu

Low-T_H requires low-band gap

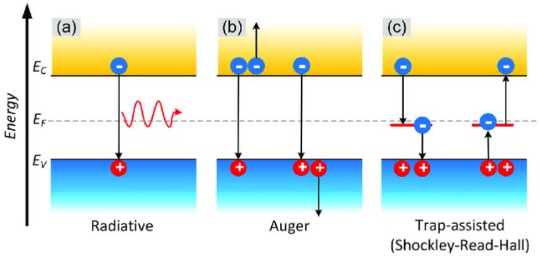




M. S. Mirmoosa *et al.* (2016)

$$\eta_{\text{Carnot}} = 1 - \frac{T_{\mathrm{C}}}{T_{\mathrm{H}}}$$ ➔ Low T_H restricts maximum efficiency

Low-band gap yields non-radiative losses



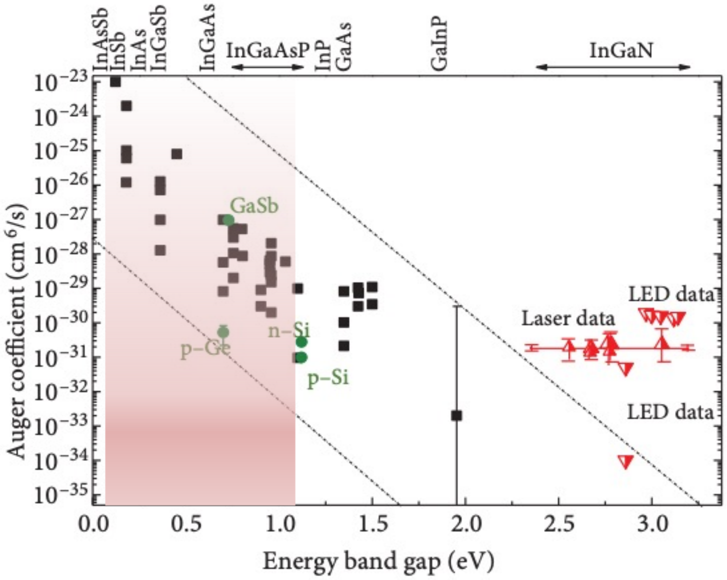
M. Plakhotnyuk, PhD Thesis, dtu.dk (2018)

$$Q_{\mathrm{e}} = \frac{J_{\mathrm{o}}}{J_{\mathrm{o}}+R_{\mathrm{o}}}$$

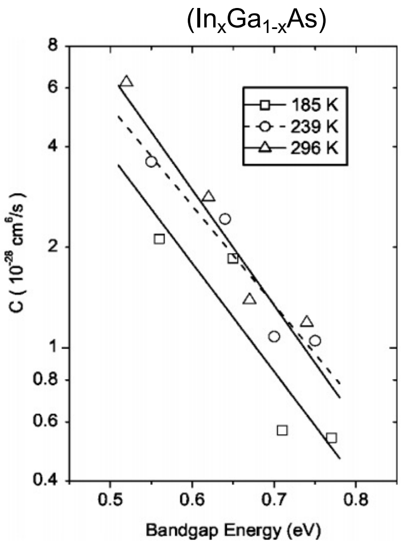
$$J_{\mathrm{o}} \ll R_{\mathrm{o}}$$

Non-radiative limit

➔ Auger recombination is severe for low-band gap materials



V. Avrutin *et al.*,
Turk. J. Phys 38, 269 (2014)



T. H. Gfoerer *et al.*,
Journal of Applied Physics 94, 3 (2003)

Here: thermodynamic analysis of V_{oc}

Near-field spectrum

Light-trapping in the near-field

Photon recycling

How to mitigate nonradiative losses in near-field TPV operation?

Analytical TPV model

PHYSICAL REVIEW APPLIED

Photovoltaic Energy Conversion

PHYSICAL REVIEW APPLIED **16,** 064063 (2021)

Thermodynamics of Light Management in Near-Field Thermophotovoltaics

Georgia T. Papadakis,[1,2] Meir Orenstein,[3] Eli Yablonovitch,[4] and Shanhui Fan[2,*]

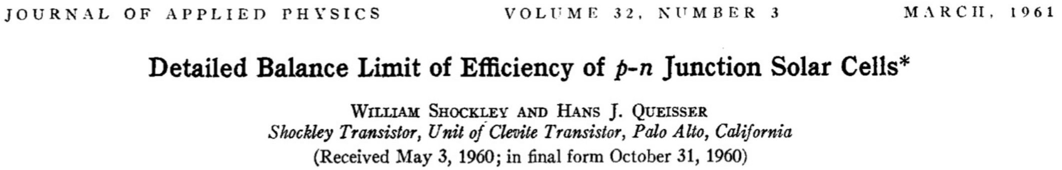
[1] *ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Castelldefels (Barcelona) 08860, Spain*

[2] *Department of Electrical Engineering, Ginzton Laboratory, Stanford University, California 94305, USA*

[3] *Department of Electrical Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel*

[4] *Department of Electrical Engineering & Computer Sciences, University of California, Berkeley, California 94720, USA*

Principles of detailed balance

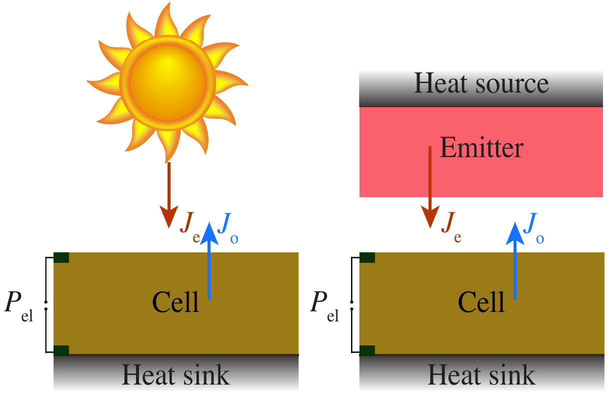


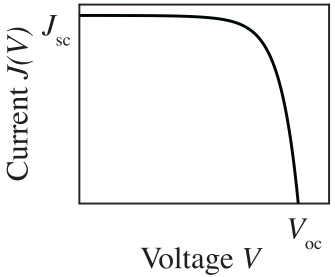
JOURNAL OF APPLIED PHYSICS VOLUME 32, NUMBER 3 MARCH, 1961

Detailed Balance Limit of Efficiency of *p-n* Junction Solar Cells*

William Shockley and Hans J. Queisser
Shockley Transistor, Unit of Clevite Transistor, Palo Alto, California

(Received May 3, 1960; in final form October 31, 1960)





$$J(V) = J_{\mathrm{e}} + R_{\mathrm{o}} - J_{\mathrm{o}} e^{qV/kT_{\mathrm{C}}} - R(V)$$

$$qV_{\mathrm{oc}} = kT_{\mathrm{C}} \log \frac{J_{\mathrm{e}}}{J_{\mathrm{o}}} + kT_{\mathrm{C}} \log \frac{J_{\mathrm{o}}}{J_{\mathrm{o}} + R_{\mathrm{o}}}$$

The open-circuit voltage

$$qV_{\mathrm{oc}} = kT_{\mathrm{C}}\log\frac{J_{\mathrm{e}}}{J_{\mathrm{o}}} + kT_{\mathrm{C}}\log\frac{J_{\mathrm{o}}}{J_{\mathrm{o}} + R_{\mathrm{o}}}$$

Radiative V_{oc}

Non-radiative V_{oc}

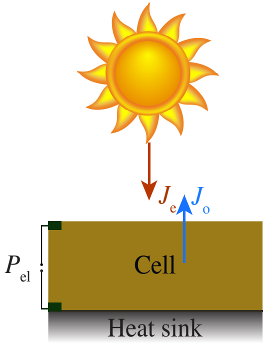
➡ Emission spectrum

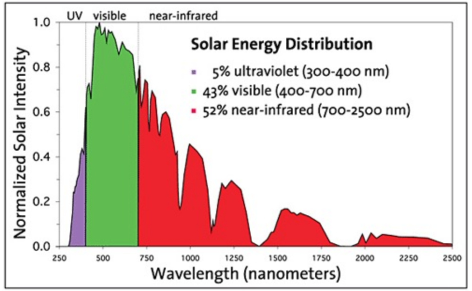
Light-trapping

Luminescence enhancement

Emission spectrum

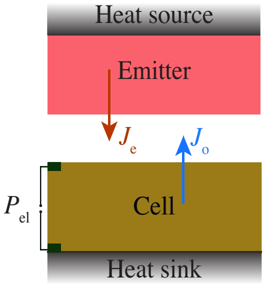
Solar PVs





AlternativeEnergySolutions.info

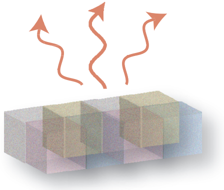
TPVs



Nanophotonic design ➔ optimization of thermal emission spectrum

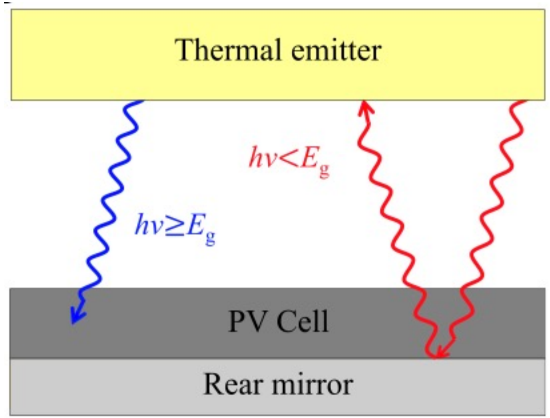
Below-band gap

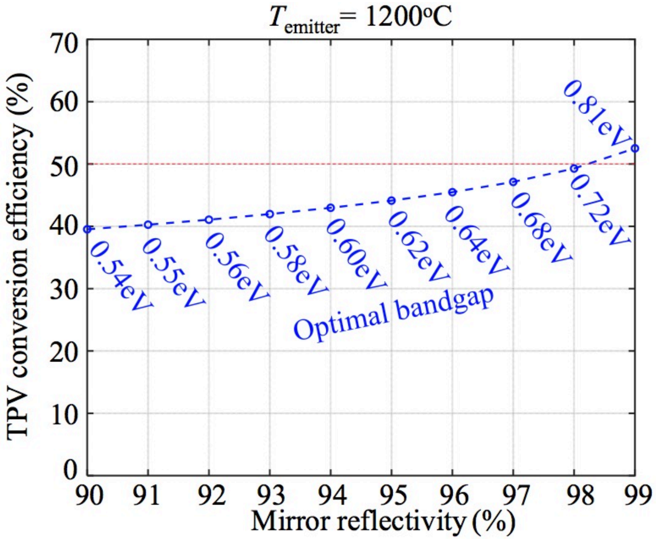
Above-band gap



G. T. Papadakis, M. Orenstein, E. Yablonovitch, S. Fan, arxiv.org/3845173

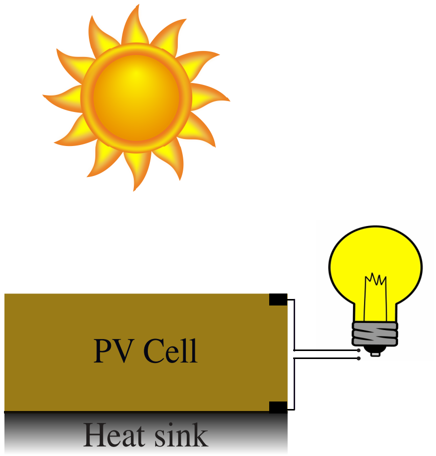
Spectrum control below-band gap

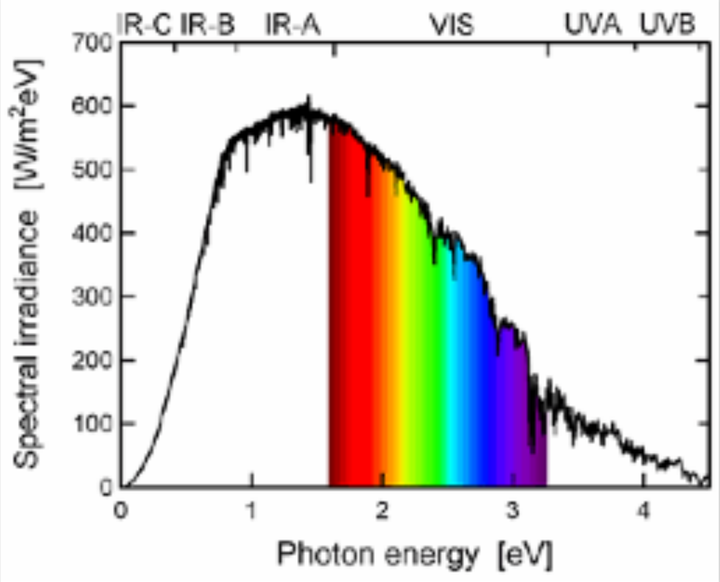




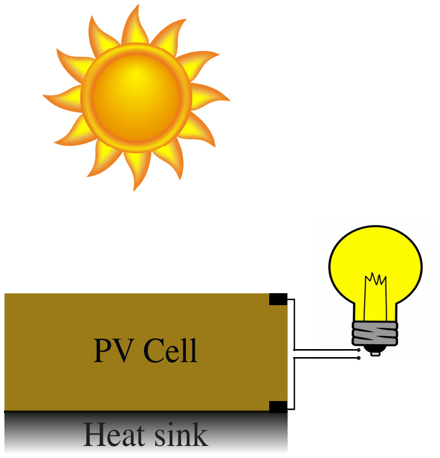
Z. Omair,G. Scranton, L. M. Pazos-Outon, T. P. Xiao, M. A. Steiner, V. Ganapati, P. F. Peterson, J. Holzrichter, H. A. Atwater, E. Yablonovich, PNAS 116, 31 (2019)

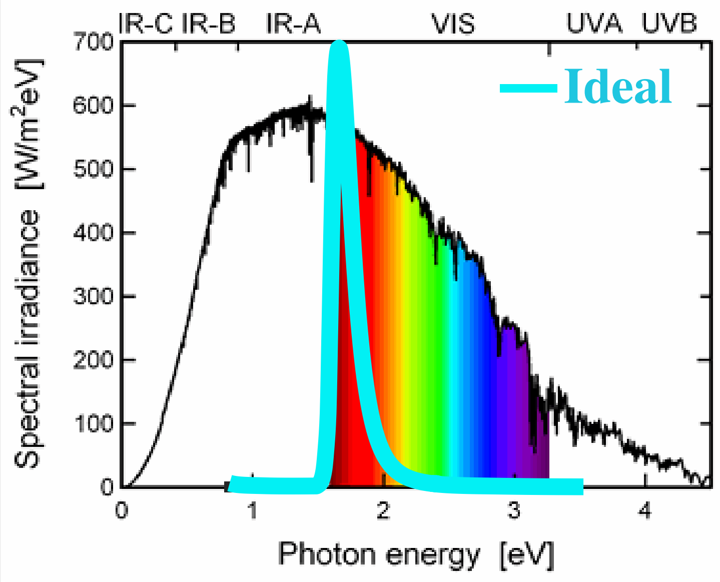
Spectrum above-band gap



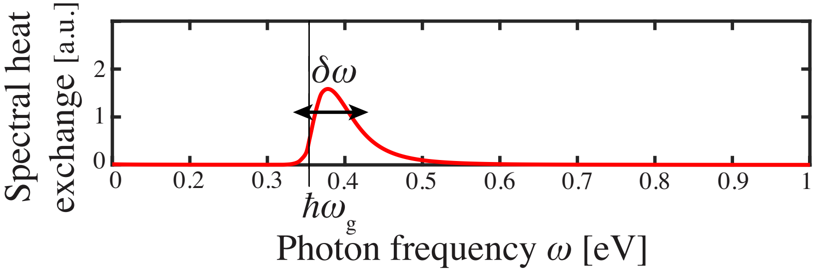


Spectrum above-band gap





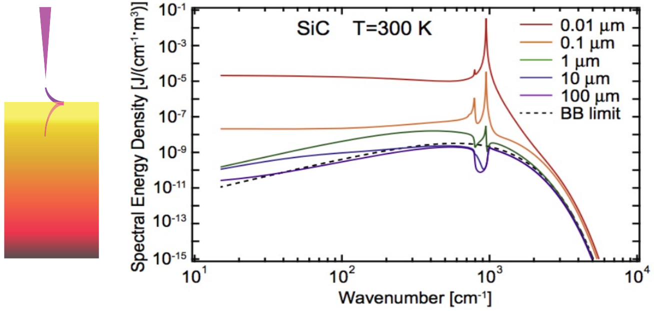
General rule for maximum efficiency



As $\delta\omega \to 0$ the efficiency $\eta \to \eta_{\mathrm{Carnot}}$

and $V_{\mathrm{oc}} > \hbar\omega_{\mathrm{g}}\eta_{\mathrm{Carnot}}$

Near-field thermal radiation is narrow-banded:



A. C. Jones *et al.*, Progress in Surface Science 88 (2013)

➔ In the near-field, polaritonic modes of the thermal emitter have narrow bandwidth, thus allowing to approach the thermodynamic limit.

G. T. Papadakis *et al.*, Nano Lett. 20, 3 (2020)

The open-circuit voltage

$$qV_{\mathrm{oc}} = kT_{\mathrm{C}}\log\frac{J_{\mathrm{e}}}{J_{\mathrm{o}}} + kT_{\mathrm{C}}\log\frac{J_{\mathrm{o}}}{J_{\mathrm{o}} + R_{\mathrm{o}}}$$

Radiative V_{oc}

Non-radiative V_{oc}

✓ Emission spectrum

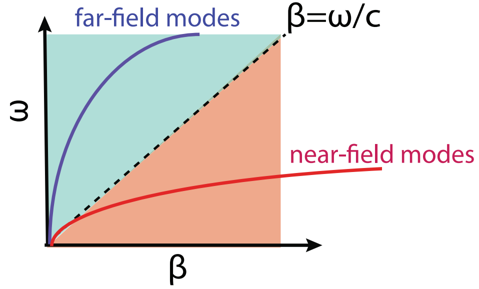
➡ Light-trapping

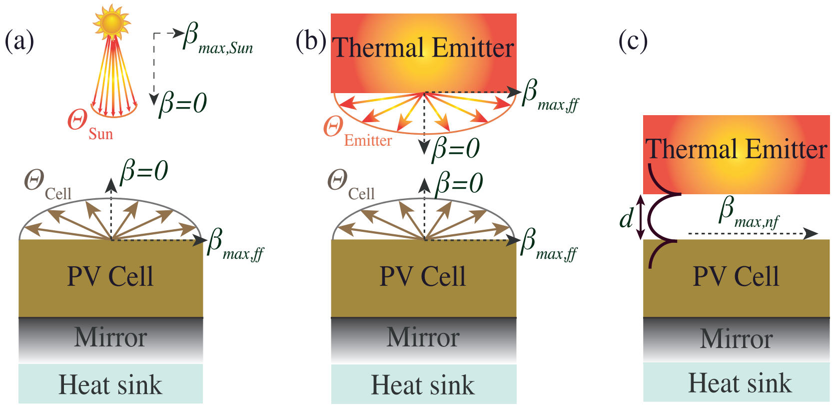
Luminescence enhancement

G. T. Papadakis, M. Orenstein, E. Yablonovitch, S. Fan, Phys. Rev. Applied 16, 064063 (2021)

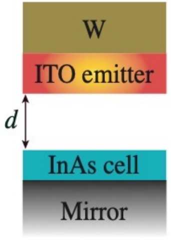
Formalism

$$J_{\mathrm{o/e}} = \frac{q}{4\pi^2}\int_0^\infty \Phi(\omega)\, n(\omega, T_{\mathrm{C/H}})\, d\omega \quad \text{where} \quad \Phi(\omega) = \int_0^{\beta_{\max}} \xi(\omega,\beta)\,\beta\, d\beta$$



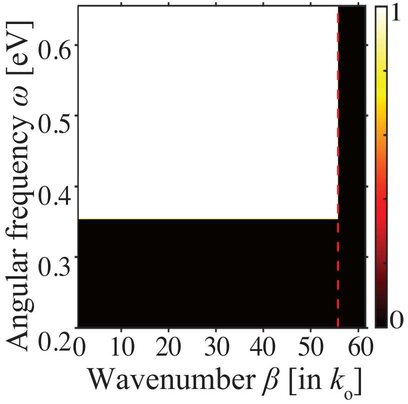


The near-field and $\beta_{\max}$



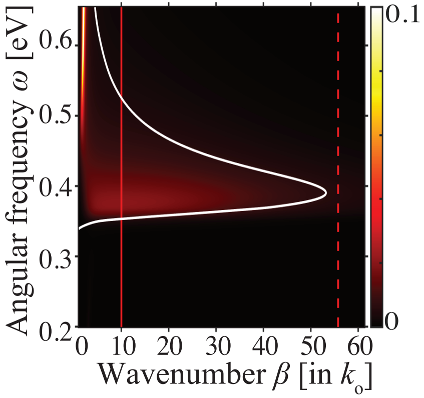
Blackbody model [1-5]

$$\beta_{\max} = \frac{1}{d}$$



Fluctuational electrodynamics [6,7]

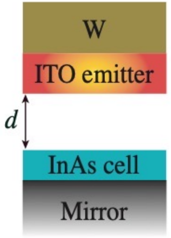
$$\beta_{\max} = \infty$$



[1] J. B. Pendry, J. Phys.: Condens. Matter 11 6621 (1999)
[2] S.-A. Beihs *et al.*, Phys. Rev. Lett. 105, 234301 (2010
[3] M. Francoeur *et al.,* Phys. Rev. B 84, 075436 (2011)
[4] J. DeSutter *et al.,* Phys. Rev. Applied 8, 014030 (2017)
[5] H. Iizuka, S. Fan, Phys. Rev. Lett. 120, 063901 (2018)

[6] D. Polder, M. Van Hove, Phys. Rev. B 4, 3303 (1971)
[7] K. Chen *et al.*, Comp. Phys. Comm. 231, 163 (2018)

The near-field and $\beta_{\max}$



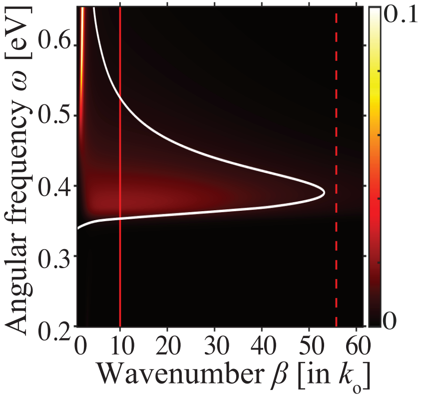
Blackbody model [1-5]

$$\beta_{\max} = \frac{1}{d}$$

Need a narrowband model

Fluctuational electrodynamics [6,7]

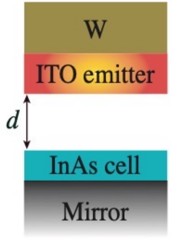
$$\beta_{\max} = \infty$$



[1] J. B. Pendry, J. Phys.: Condens. Matter 11 6621 (1999)
[2] S.-A. Beihs *et al.*, Phys. Rev. Lett. 105, 234301 (2010
[3] M. Francoeur *et al.,* Phys. Rev. B 84, 075436 (2011)
[4] J. DeSutter *et al.,* Phys. Rev. Applied 8, 014030 (2017)
[5] H. Iizuka, S. Fan, Phys. Rev. Lett. 120, 063901 (2018)

[6] D. Polder, M. Van Hove, Phys. Rev. B 4, 3303 (1971)
[7] K. Chen *et al.*, Comp. Phys. Comm. 231, 163 (2018)

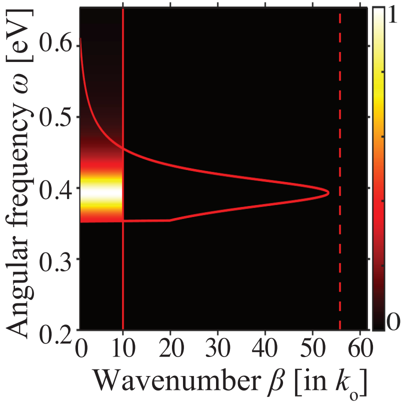
The near-field and $\beta_{\max}$



Narrowband model

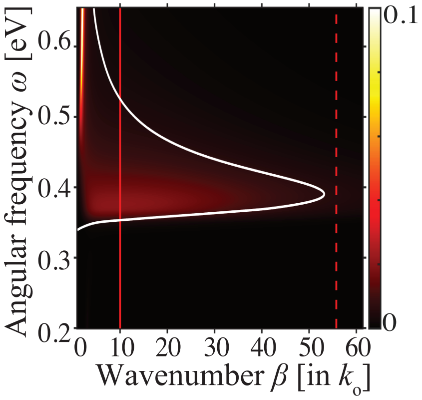
$$\xi_{\mathrm{NR}}(\omega,\beta)=\begin{cases}0 & \text{for } \omega<\omega_{\mathrm{g}}, \text{ all } \beta\text{'s}\\ \frac{\Gamma^2}{\Gamma^2+(\omega-\omega_{\mathrm{o}})^2} & \text{for } \omega\geq\omega_{\mathrm{g}} \text{ and } \beta\leq\rho/d\\ 0 & \text{for } \omega\geq\omega_{\mathrm{g}} \text{ and } \beta>\rho/d,\end{cases}$$

$$\rho \ll 1$$



Fluctuational electrodynamics

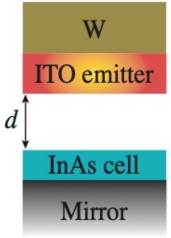
$$\beta_{\max} = \infty$$

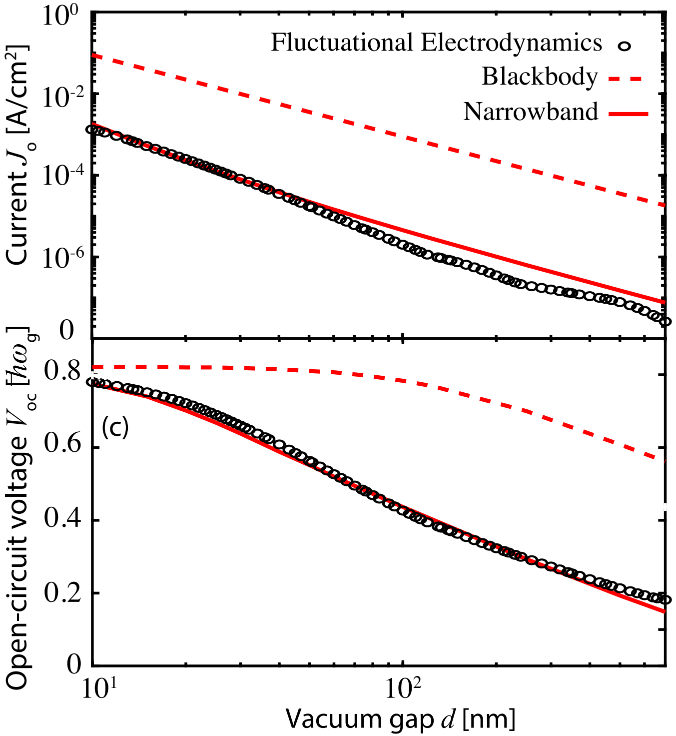


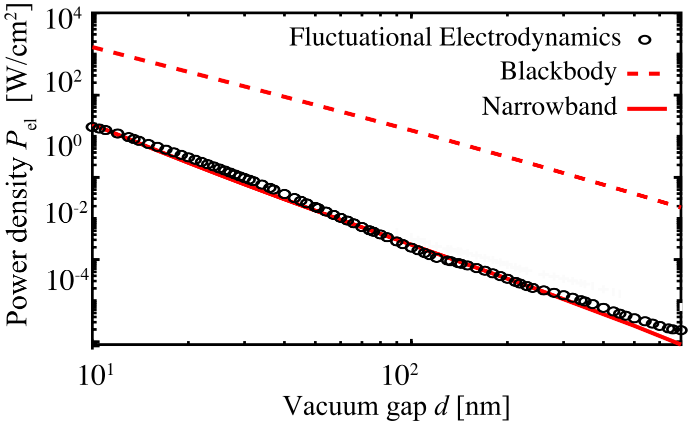
➔ Three parameters suffice for accurately modeling TPV performance.

G. T. Papadakis, M. Orenstein, E. Yablonovitch, S. Fan, Phys. Rev. Applied 16, 064063 (2021)

Comparison of blackbody and narrowband model





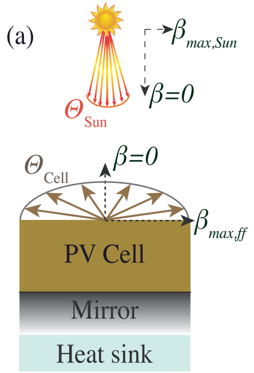


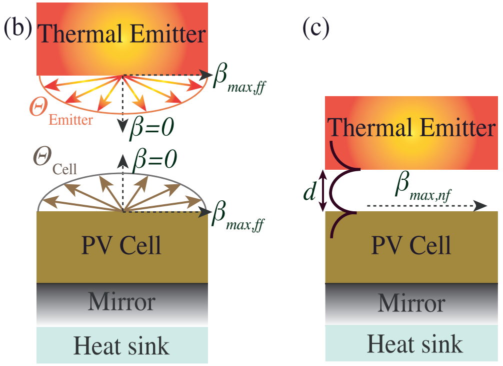
➔ Three parameters suffice for accurately modeling TPV performance.

G. T. Papadakis, M. Orenstein, E. Yablonovitch, S. Fan, Phys. Rev. Applied 16, 064063 (2021)

Radiative V_{oc} and light-trapping

$$qV_{\mathrm{oc,rad}} = kT_{\mathrm{C}}\log\frac{J_{\mathrm{e}}}{J_{\mathrm{o}}}$$





$$V_{\mathrm{oc,rad}} = \hbar\omega_{\mathrm{g}}\left(1-\frac{T_{\mathrm{C}}}{T_{\mathrm{Sun}}}\right)$$
$$+2kT_{\mathrm{C}}\ln\left(\sin\frac{\Theta_{\mathrm{Sun}}}{2}\right)$$
$$+kT_{\mathrm{C}}\ln\left(\frac{T_{\mathrm{Sun}}}{T_{\mathrm{C}}}\right)$$

$$V_{\mathrm{oc,rad}} \approx \hbar\omega_{\mathrm{g}}\left(1-\frac{T_{\mathrm{C}}}{T_{\mathrm{H}}}\right)$$
$$+0$$
$$+kT_{\mathrm{C}}\ln\left(\frac{T_{\mathrm{H}}}{T_{\mathrm{C}}}\right)$$

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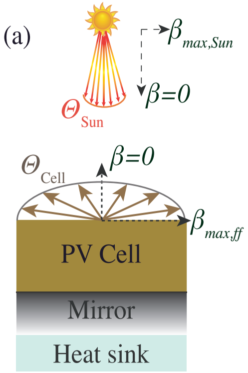
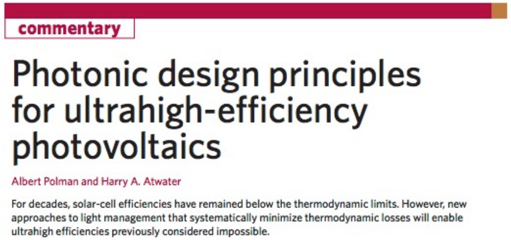
Radiative V_{oc} and light-trapping

$$qV_{\mathrm{oc,rad}} = kT_{\mathrm{C}}\log\frac{J_{\mathrm{e}}}{J_{\mathrm{o}}}$$



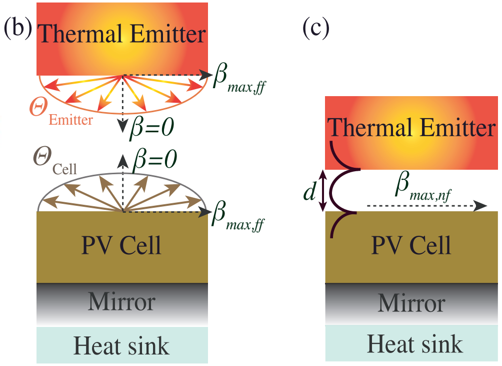


commentary

Photonic design principles for ultrahigh-efficiency photovoltaics

Albert Polman and Harry A. Atwater

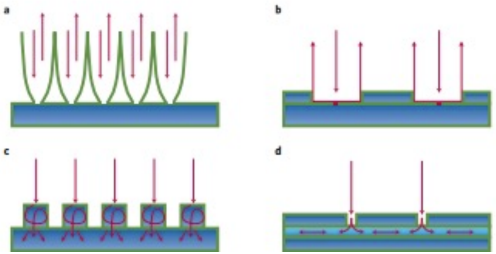
For decades, solar-cell efficiencies have remained below the thermodynamic limits. However, new approaches to light management that systematically minimize thermodynamic losses will enable ultrahigh efficiencies previously considered impossible.



$$V_{\mathrm{oc,rad}} = \hbar\omega_{\mathrm{g}}\left(1-\frac{T_{\mathrm{C}}}{T_{\mathrm{Sun}}}\right)$$
$$+2kT_{\mathrm{C}}\ln\left(\sin\frac{\Theta_{\mathrm{Sun}}}{2}\right)$$
$$+kT_{\mathrm{C}}\ln\left(\frac{T_{\mathrm{Sun}}}{T_{\mathrm{C}}}\right)$$

$$\approx 25\%\hbar\omega_{\mathrm{g}}$$

$$V_{\mathrm{oc,rad}} \approx \hbar\omega_{\mathrm{g}}\left(1-\frac{T_{\mathrm{C}}}{T_{\mathrm{H}}}\right)$$
$$+0$$
$$+kT_{\mathrm{C}}\ln\left(\frac{T_{\mathrm{H}}}{T_{\mathrm{C}}}\right)$$



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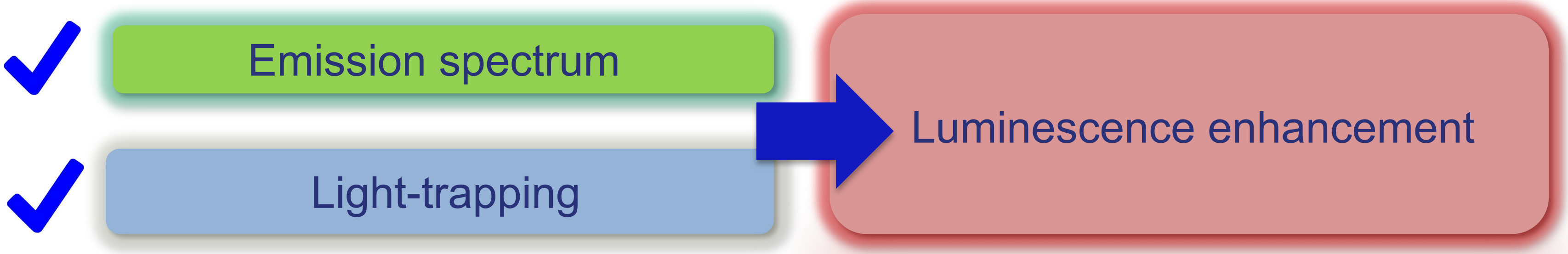
The open-circuit voltage

$$qV_{\mathrm{oc}} = \boxed{kT_{\mathrm{C}} \log \frac{J_{\mathrm{e}}}{J_{\mathrm{o}}}} + \boxed{kT_{\mathrm{C}} \log \frac{J_{\mathrm{o}}}{J_{\mathrm{o}} + R_{\mathrm{o}}}}$$

Radiative V_{oc}

Non-radiative V_{oc}



✓ Emission spectrum

✓ Light-trapping

Luminescence enhancement

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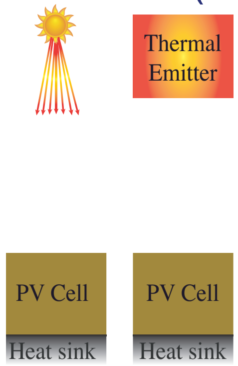
Non-radiative V_{oc} and luminescence enhancement

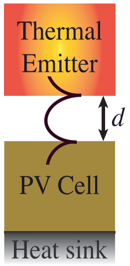
$$qV_{\mathrm{oc,nrad}} = kT_{\mathrm{C}} \log \frac{J_{\mathrm{o}}}{J_{\mathrm{o}} + R_{\mathrm{o}}}$$

Isolated PV cell (far-field)



Typically $Q_{\mathrm{e,ff}} < 0.15$

Near-field TPVs



$$J_{\mathrm{o,nf}} = \alpha^2 J_{\mathrm{o,ff}}$$

$$\boxed{Q_{\mathrm{e,nf}} = \frac{J_{\mathrm{o,ff}}}{J_{\mathrm{o,ff}} + R_{\mathrm{o}}/\alpha^2} \gg Q_{\mathrm{e,ff}}}$$

$$\alpha_{\mathrm{BB}} = \frac{1}{2\pi} \frac{\lambda_{\mathrm{g}}}{d} \sim [10 - 100]$$

$$\alpha_{\mathrm{NB}} = \rho \sqrt{\frac{\hbar\Gamma}{kT_{\mathrm{C}}}} \alpha_{\mathrm{BB}} \sim [1 - 10]$$

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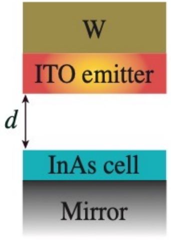
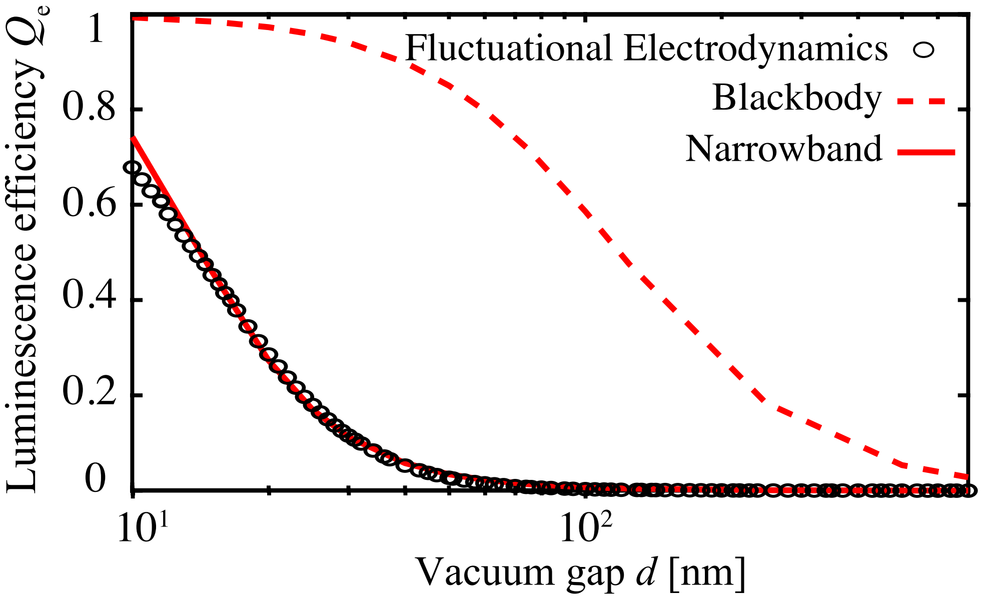
Near-field luminescence enhancement





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The open-circuit voltage

$$qV_{\text{oc}} = kT_{\text{C}}\log\frac{J_{\text{e}}}{J_{\text{o}}} + kT_{\text{C}}\log\frac{J_{\text{o}}}{J_{\text{o}} + R_{\text{o}}}$$

Radiative V_{oc}

Non-radiative V_{oc}

✓ Spectrum engineering

✓ Light-trapping

Luminescence enhancement ✓

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Thickness considerations

➔ In isolated PV cells (far-field), large thickness maximizes absorption.

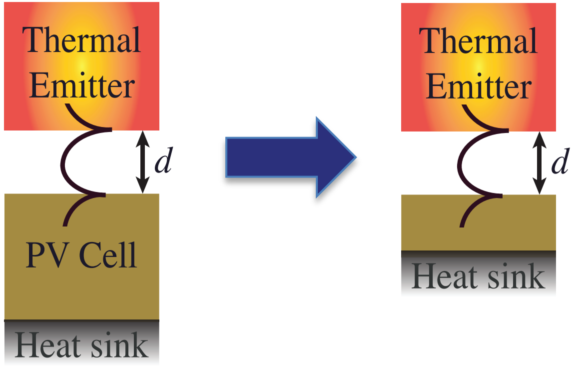
➔ In the near-field, most photon emission/absorption occurs near the surface.

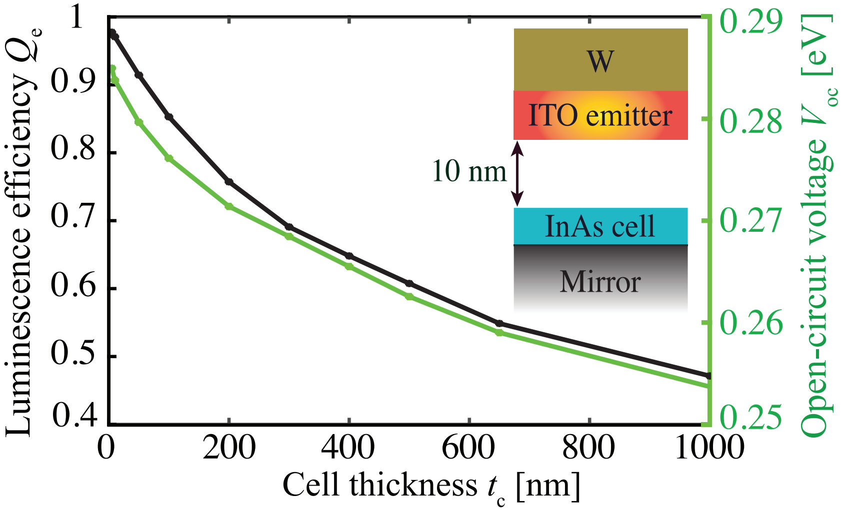
➔ Non-radiative recombination is volumetric.

$$R_{\mathrm{Auger}}(V) = [C_{\mathrm{p}}p + C_{\mathrm{n}}n](np - n_{\mathrm{i}}^2)t_{\mathrm{c}}$$

➔ A thin cell improves luminescence efficiency.

Thick vs thin near-field TPVs





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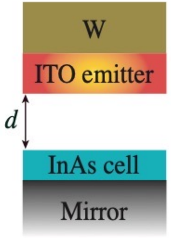
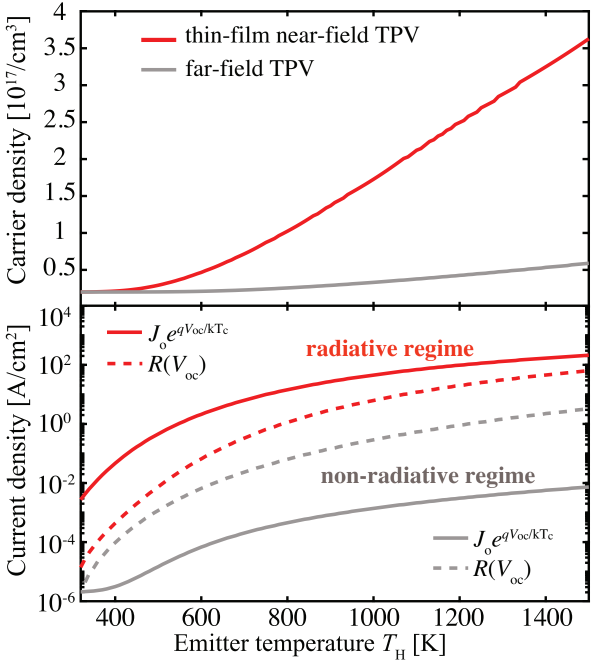
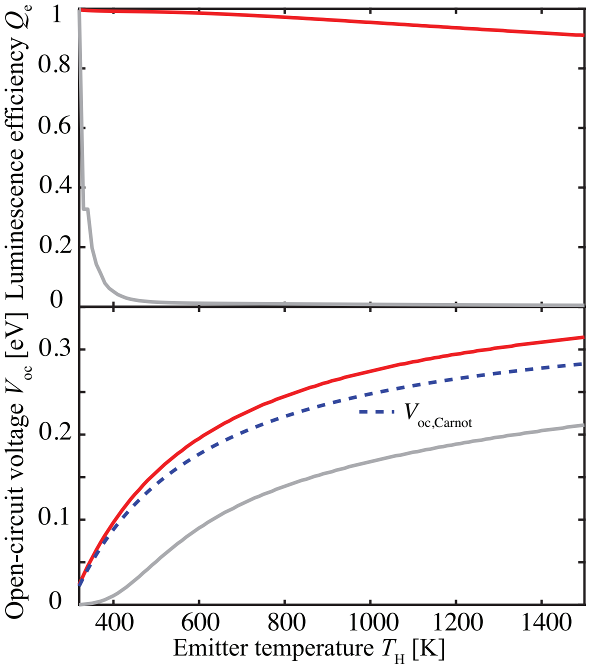
Understanding luminescence in the far-field and near-field







$$qV_{\mathrm{oc,Carnot}} = \hbar\omega_{\mathrm{g}}\left(1 - \frac{T_{\mathrm{C}}}{T_{\mathrm{H}}}\right)$$

thin film near-field TPV: 20 nm
thick far-field TPV: 400 nm

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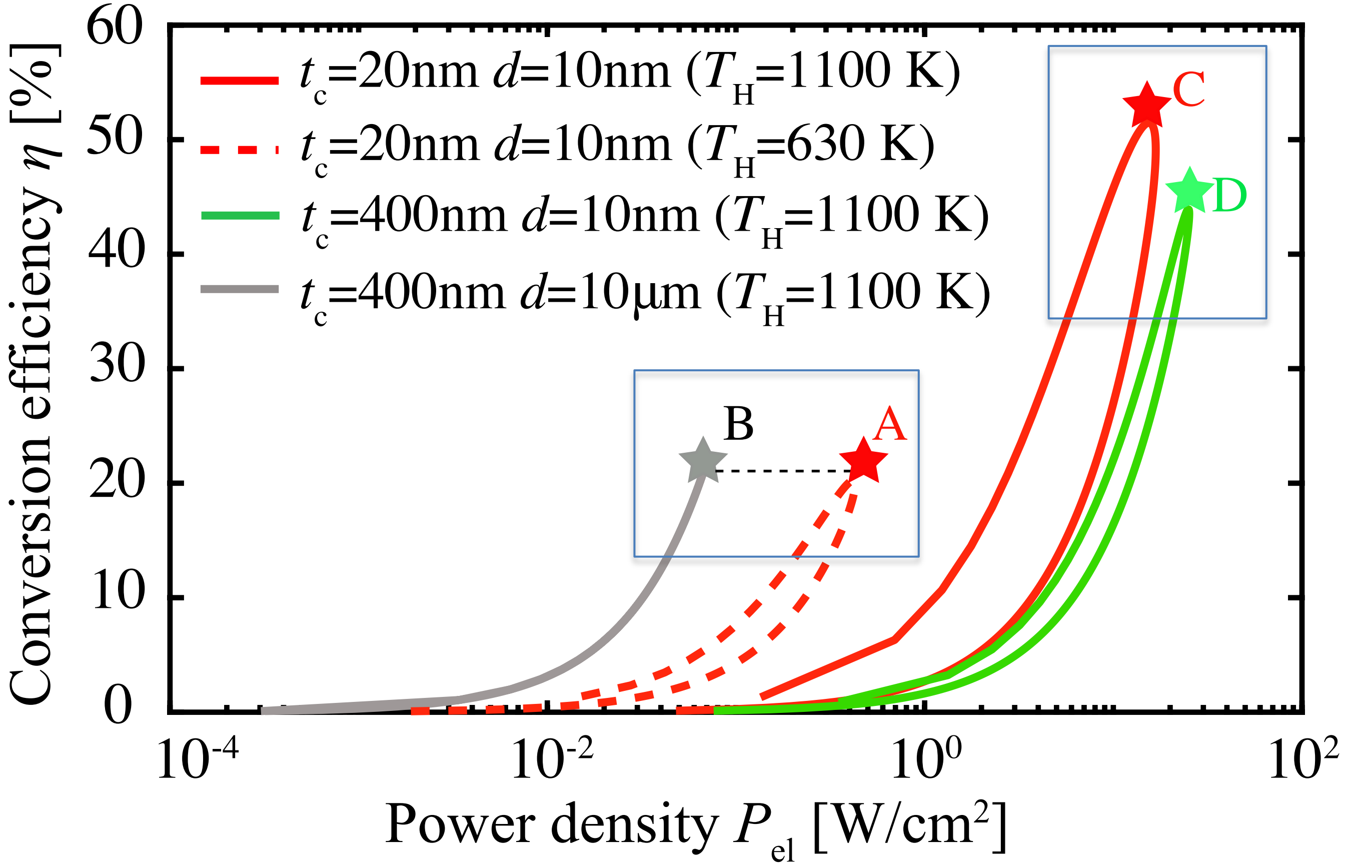
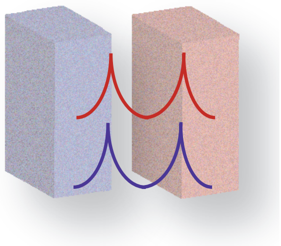
Performance in terms of efficiency and electrical power density

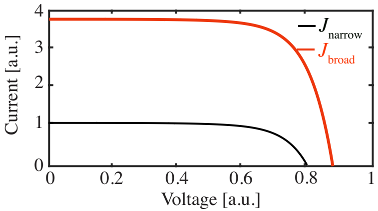


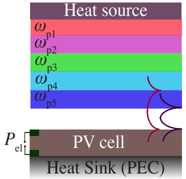
Take-home messages

The thermal near-field



Improving TPV performance





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Letter

Broadening Near-Field Emission for Performance Enhancement in Thermophotovoltaics

Georgia T. Papadakis, Siddharth Buddhiraju, Zhexin Zhao, Bo Zhao, and Shanhui Fan*

Cite This: https://dx.doi.org/10.1021/acs.nanolett.9b04762

Read Online

Emission spectrum

Light-trapping

Luminescence enhancement

Thin-film near-field TPVs

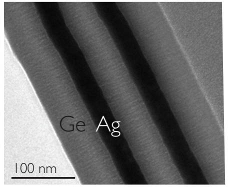
Thank you for your attention!


M. Enders

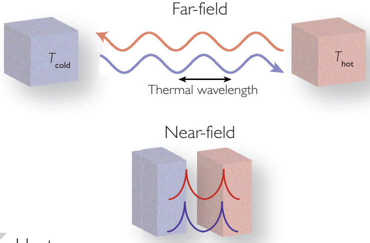

Dr. M. Giteau

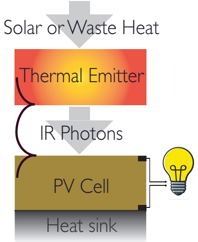

Dr. M. Sarkar

IR spectroscopy + characterization



Novel concepts in thermal photonics



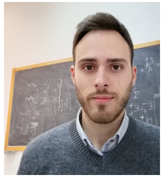


Renewable energy


H. Raghavan


Dr. L. Wang


Dr. M. Picardi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