Faculty of Engineering
School of Photovoltaic and Renewable Energy Engineering

Demonstrating the Thermoradiative Diode: Generating Electrical Power Through Radiative Emission

2022 Space Power Workshop

N.J.Ekins-Daukes, A.Pusch, M.Nielsen, Md.Sazzad, P Pearce, P.Reece

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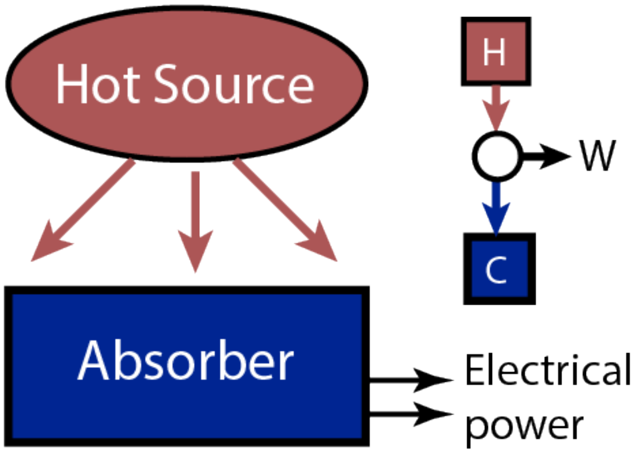
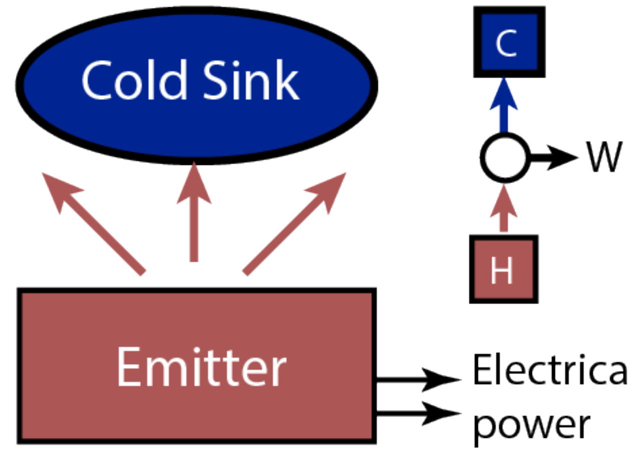
EkinsNed

Electrical Power from Radiative Processes



Photovoltaic Solar Cell

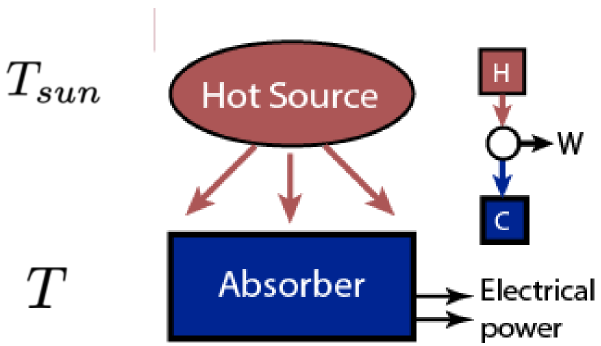


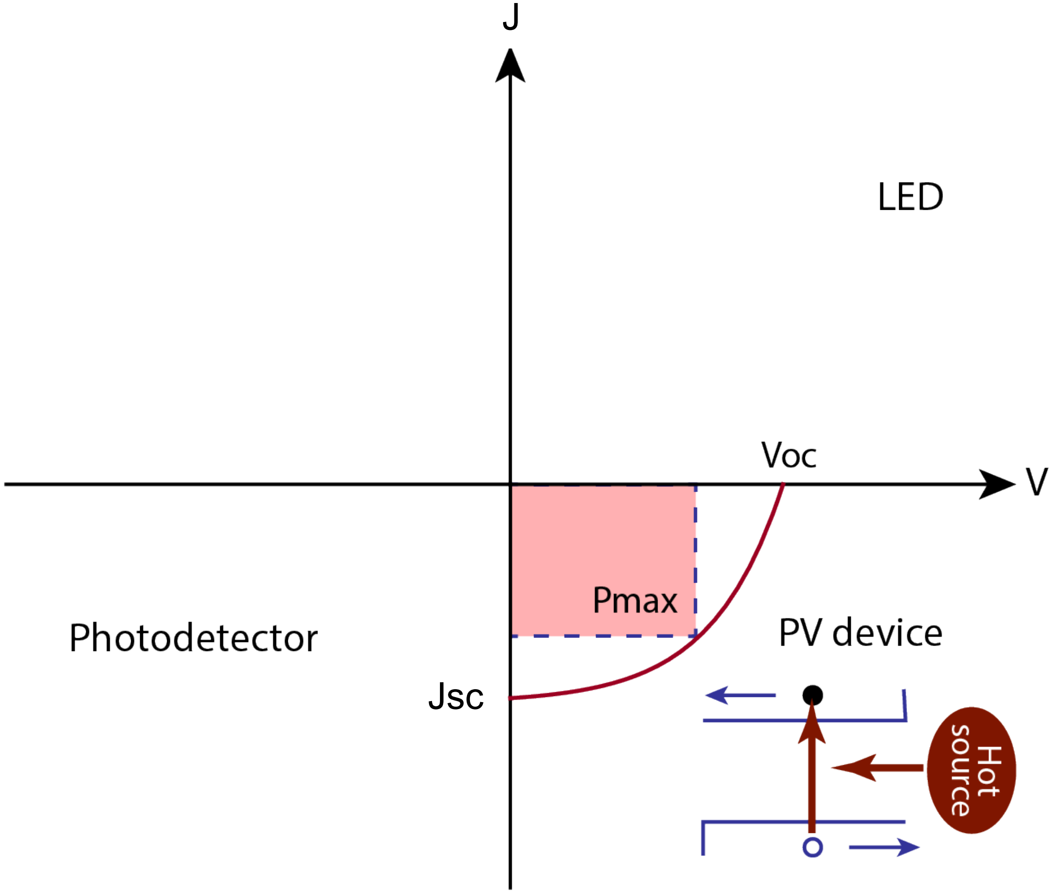
Thermoradiative Device

?

S.J.Byrnes, R.Blanchard, & F.Capasso, *Proc. National Academy of Sciences* **111**, 3927 (2014)
R.Strandberg, *Journal of Applied Physics* **117**, 055105 (2015)
S.Buddhiraju, P.Santhanam, & S.Fan, *Proc. National Academy of Sciences* **115**, E3609 (2018)

PV Solar Cell IV Curve





Ideal diode equation:

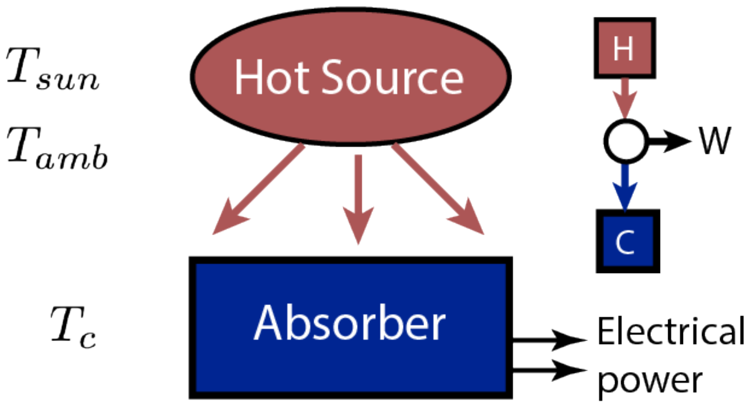
$$J(V) = J_0(e^{\frac{qV}{kT}} - 1) - J_{sun}$$

$$J_{sc} = J(0) = J_{sun}$$

Assuming: radiative limit, Boltzmann approx., abrupt absorption edge:

$$J_0 = q\frac{2\pi}{h^3c^2}kT(E_g^2 + 2kTE_g + 2k^2T^2)e^{\frac{-E_g}{kT}}$$

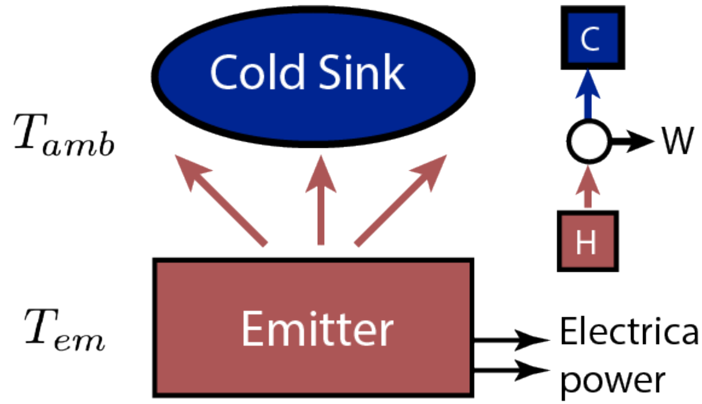
PV Device



$$J(V) = J_0(e^{\frac{qV}{kT_c}} - 1) - J_{sun}$$

PV device is exposed to the sun T_{sun} or a radiative environment at the ambient temperature $T_{amb.}$

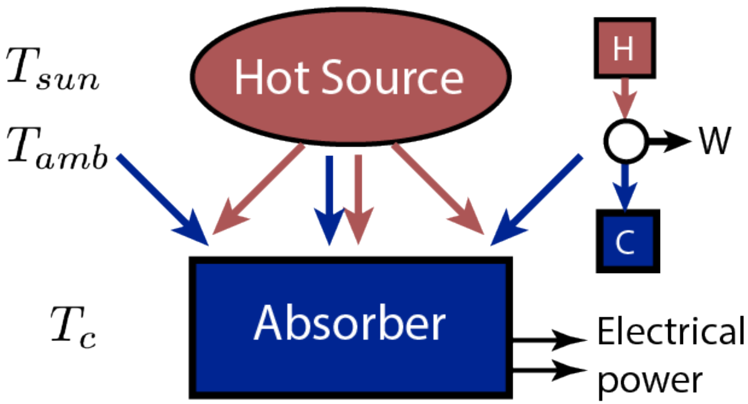
Thermoradiative device



No sun! So $J_{sun} = 0$

TR device at temperature T_{em} is exposed to the cold ambient sink at temperature T_{amb}

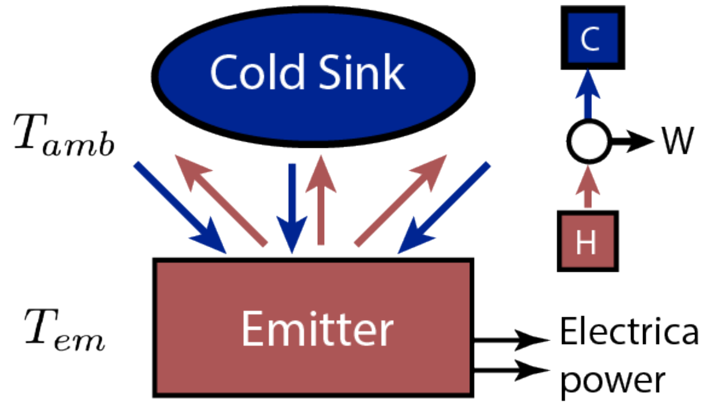
PV Device



$$J(V) = J_0(e^{\frac{qV}{kT_c}} - 1) - J_{sun}$$

PV device is exposed to the sun T_{sun} or a radiative environment at the ambient temperature $T_{amb.}$

Thermoradiative device



No sun! So $J_{sun} = 0$

TR device at temperature T_{em} is exposed to the cold ambient sink at temperature T_{amb}

In general:

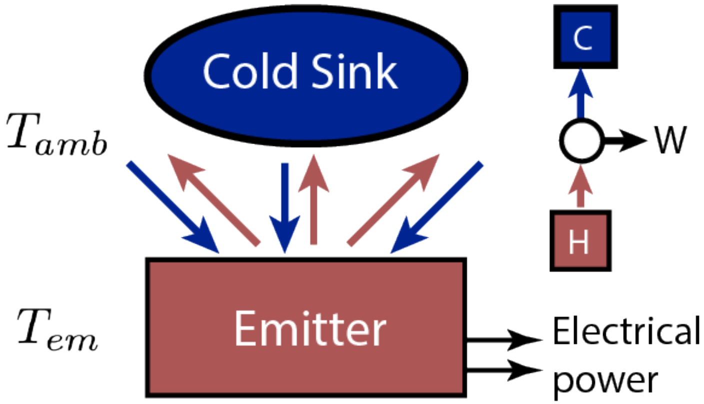
$$J(V) = J_{em} e^{\frac{qV}{kT_{em}}} - J_{amb} - J_{sun}$$

$$T_c = T_{amb} = T_{em}$$
$$J_{em} = J_{amb} = J_0$$

$$J_{em} = q\frac{2\pi}{h^3c^2}kT_{em}(E_g^2 + 2kT_{em}E_g + 2k^2T_{em}^2)e^{\frac{-E_g}{kT_{em}}}$$
$$J_{amb} = q\frac{2\pi}{h^3c^2}kT_{amb}(E_g^2 + 2kT_{amb}E_g + 2k^2T_{amb}^2)e^{\frac{-E_g}{kT_{amb}}}$$

Ekins-Daukes, N. J., Sazzad, M. H., Al Kiyumi, L., Nielsen, M. P., Reece, P., Mellor, A., Green, M. A., & Pusch, A. 47th IEEE Photovoltaic Specialists Conference (PVSC) (2020) pp. 2214-2218

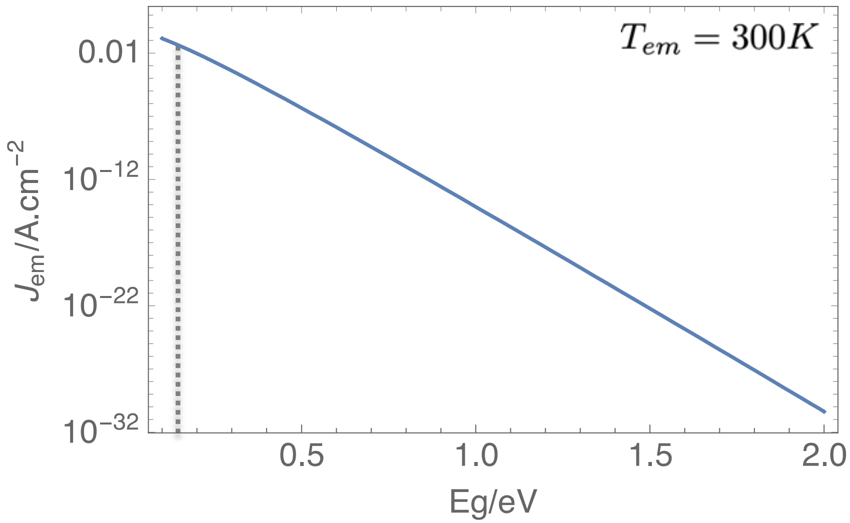
Thermoradiative device : Jsc



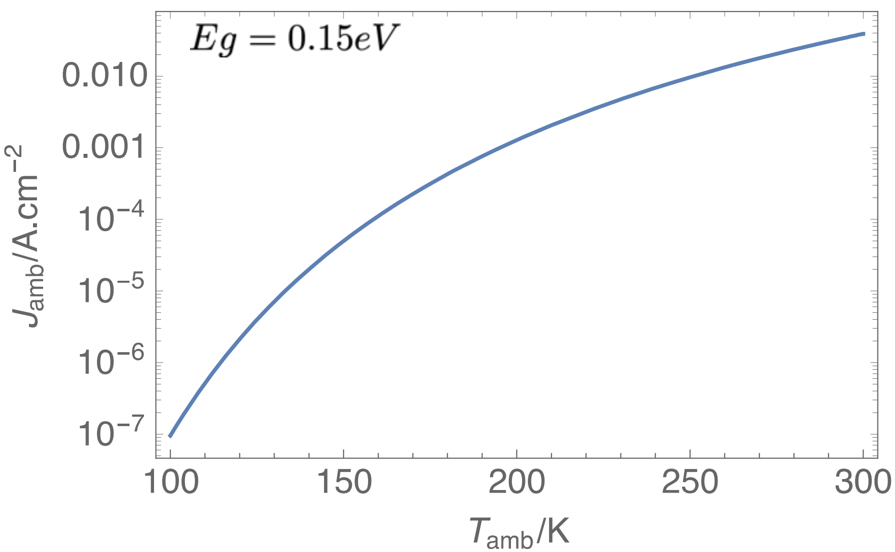
$$J(V) = J_{em} e^{\frac{qV}{kT_{em}}} - J_{amb}$$

$$J_{sc} = J(0) = J_{em} - J_{amb}$$

$$J_{em} = q\frac{2\pi}{h^3c^2}kT_{em}(E_g^2 + 2kT_{em}E_g + 2k^2T_{em}^2)e^{\frac{-E_g}{kT_{em}}}$$



$$J_{amb} = q\frac{2\pi}{h^3c^2}kT_{amb}(E_g^2 + 2kT_{amb}E_g + 2k^2T_{amb}^2)e^{\frac{-E_g}{kT_{amb}}}$$

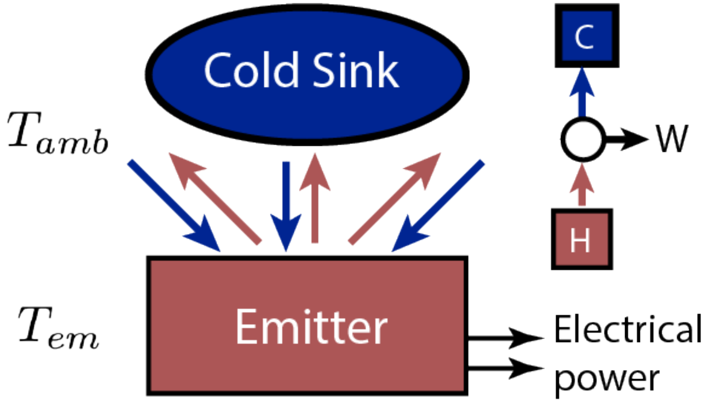


- Thermoradiative device favours low-band gap semiconductors : 39mA.cm^{-2} for E_g=0.15eV
- Jsc saturates with relatively small temperature differences

$$J_{sc} \rightarrow J_{em} \text{ for } \Delta T > 50K$$

Ekins-Daukes, N. J., Sazzad, M. H., Al Kiyumi, L., Nielsen, M. P., Reece, P., Mellor, A., Green, M. A., & Pusch, A. 47th IEEE Photovoltaic Specialists Conference (PVSC) (2020) pp. 2214-2218

Thermoradiative device : Voc



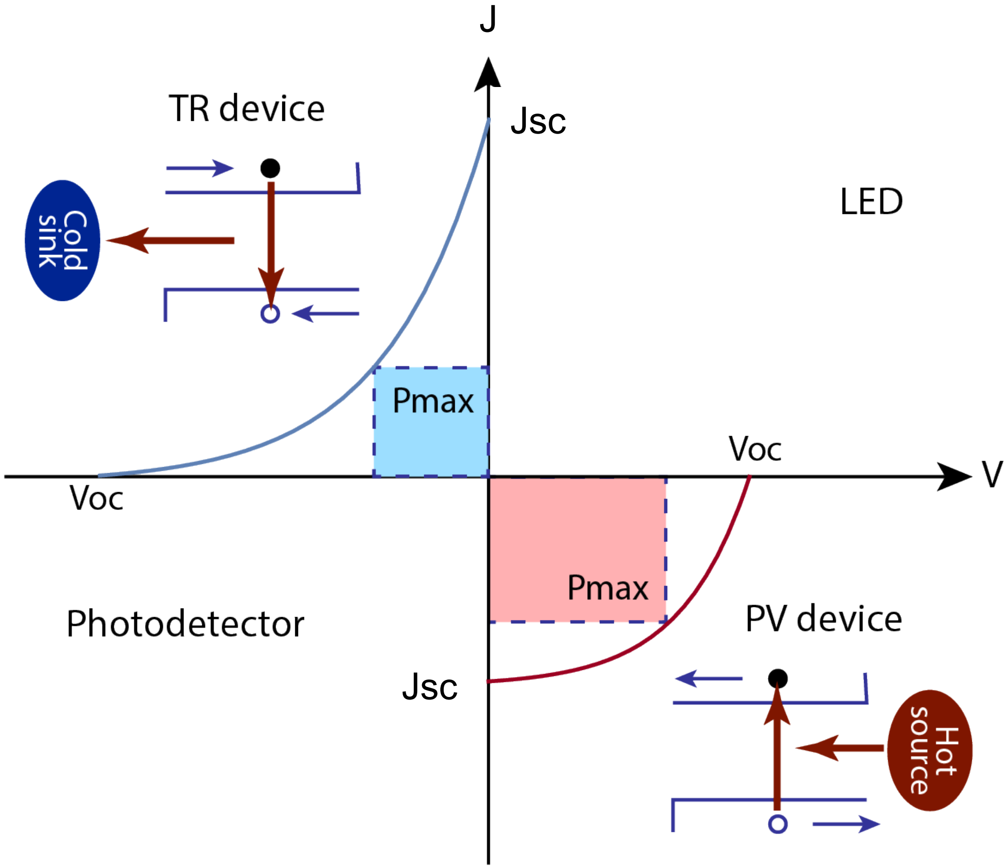
$$J(V) = J_{em} e^{\frac{qV}{kT_{em}}} - J_{amb}$$

Voc: $J(V_{oc}) = 0$

$$J_{em} e^{\frac{qV}{kT_{em}}} = J_{amb}$$

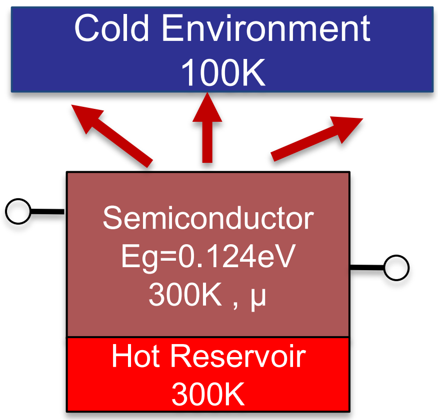
$$V_{oc} = \frac{kT}{q} \ln\left(\frac{J_{amb}}{J_{em}}\right)$$

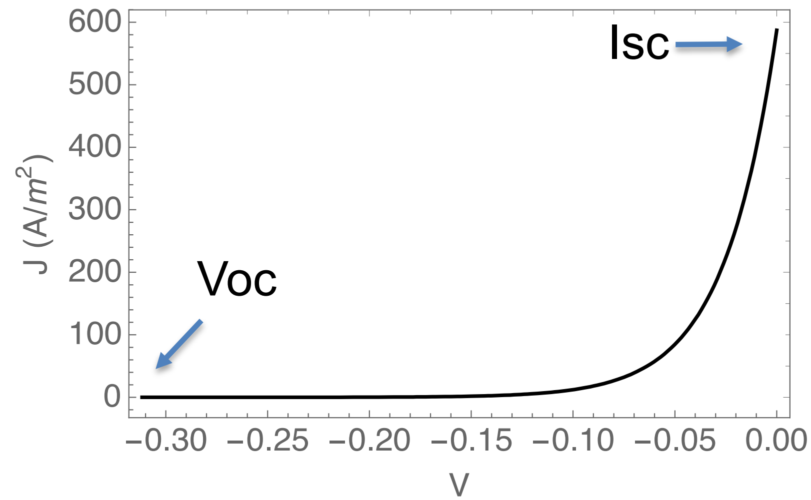
$J_{amb} << J_{em}$ Voc is negative!

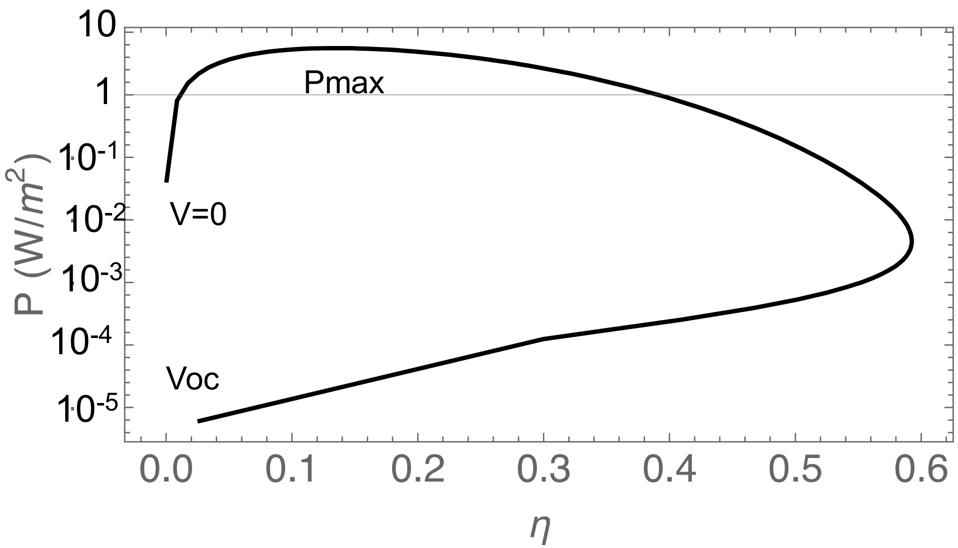


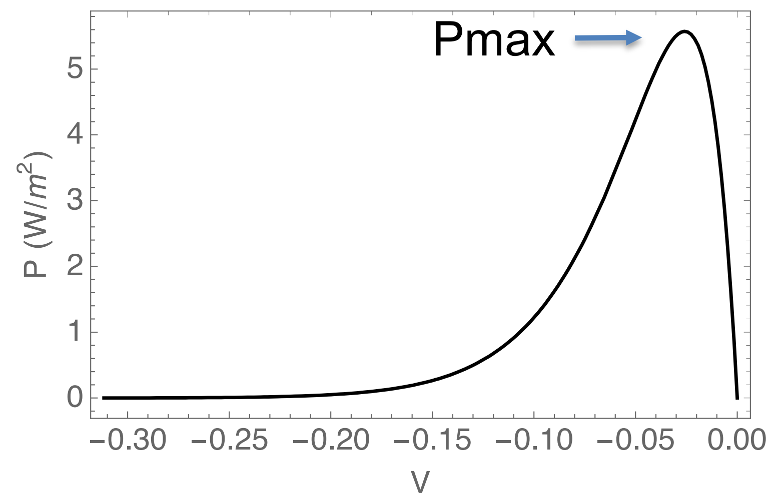
Ekins-Daukes, N. J., Sazzad, M. H., Al Kiyumi, L., Nielsen, M. P., Reece, P., Mellor, A., Green, M. A., & Pusch, A. 47th IEEE Photovoltaic Specialists Conference (PVSC) (2020) pp. 2214-2218

Thermoradiative diode, IV, Power & Efficiency



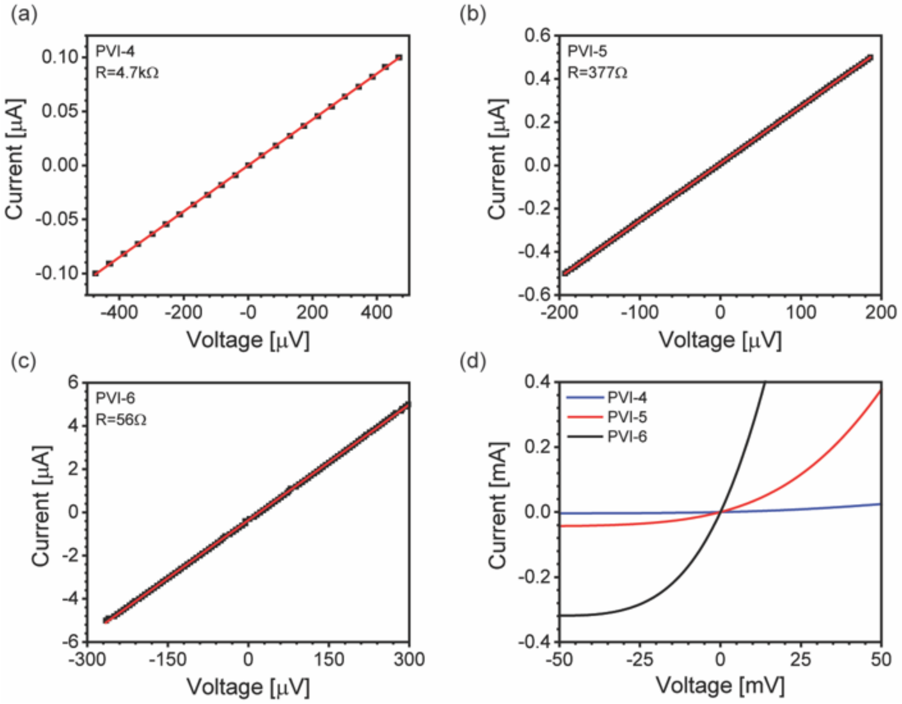


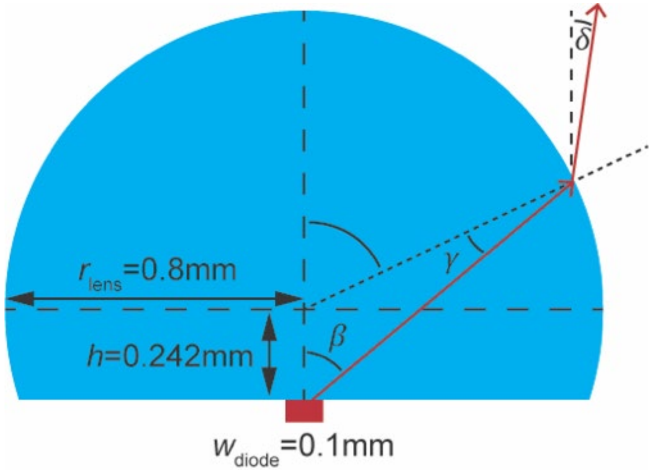




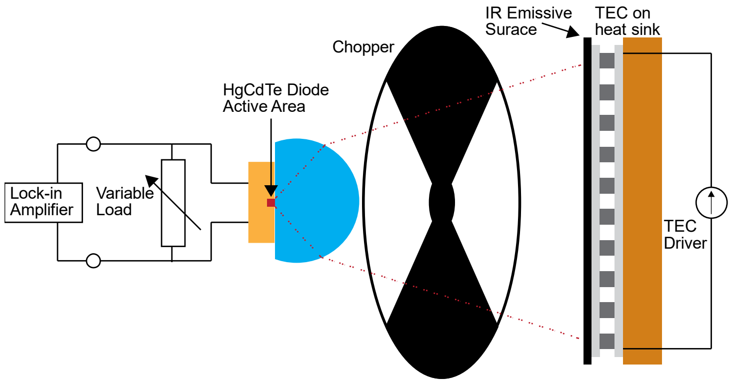
HgCdTe Photodiodes

- Commercial HgCdTe photodetectors from VIGO Systems with nominal bandgaps at 4, 5 and 6 µm (PVI-4, PVI-5, PVI-6) and hyperhemispherical GaAs immersion lenses

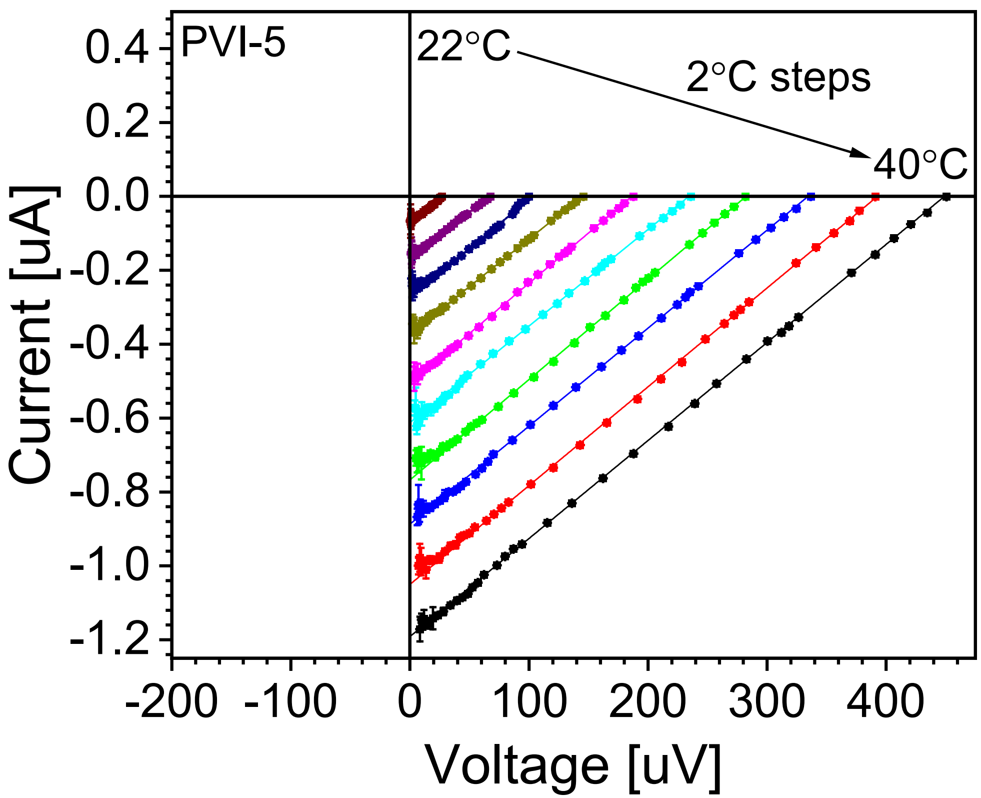


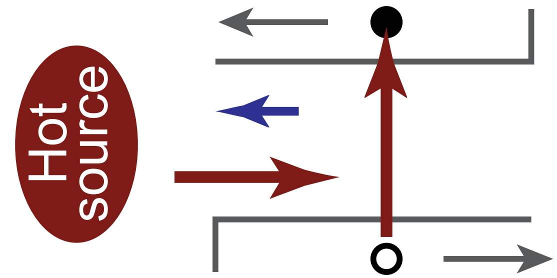


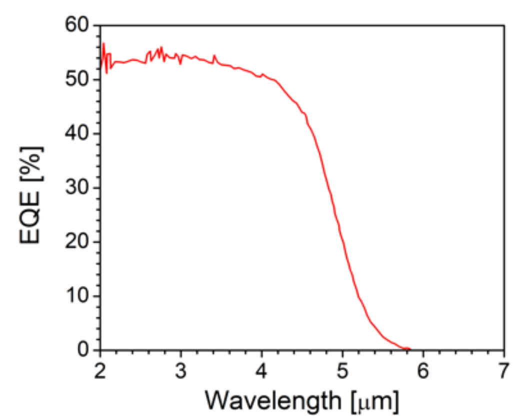
Photovoltaic Operation



Photodiode @ 20.5°C

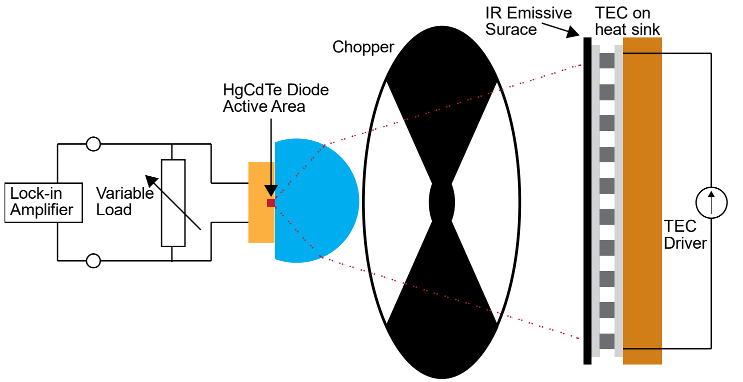


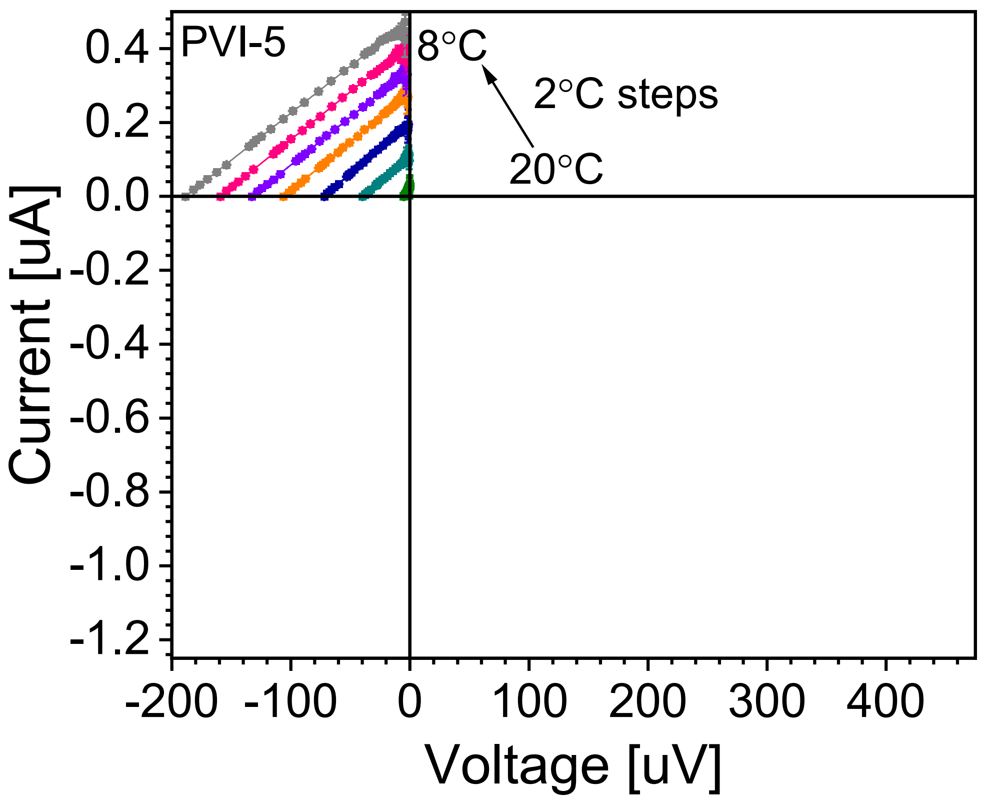




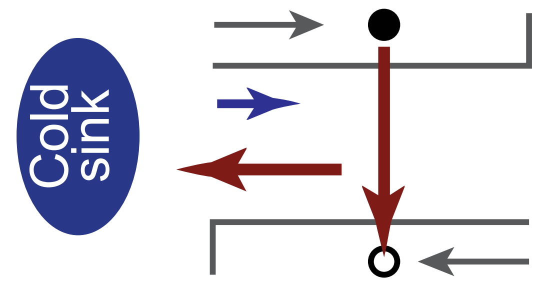
M.Nielsen, A.Pusch, M.H.Sazzad, P.Pearce, P.J.Reece, N.J.Ekins-Daukes, “Thermoradiative Power Conversion from HgCdtTe Photodiodes and Their Current-Voltage Characteristics”, ACS Photonics, under review (2022)

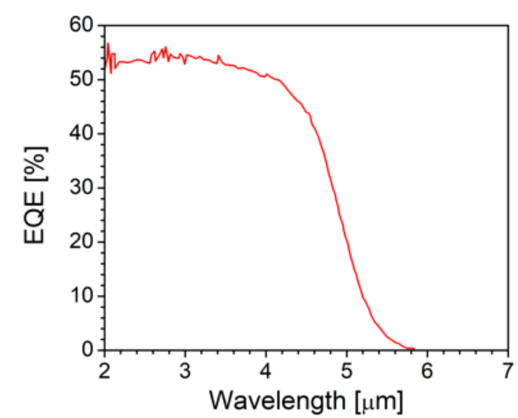
Thermoradiative Operation





Photodiode @ 20.5°C





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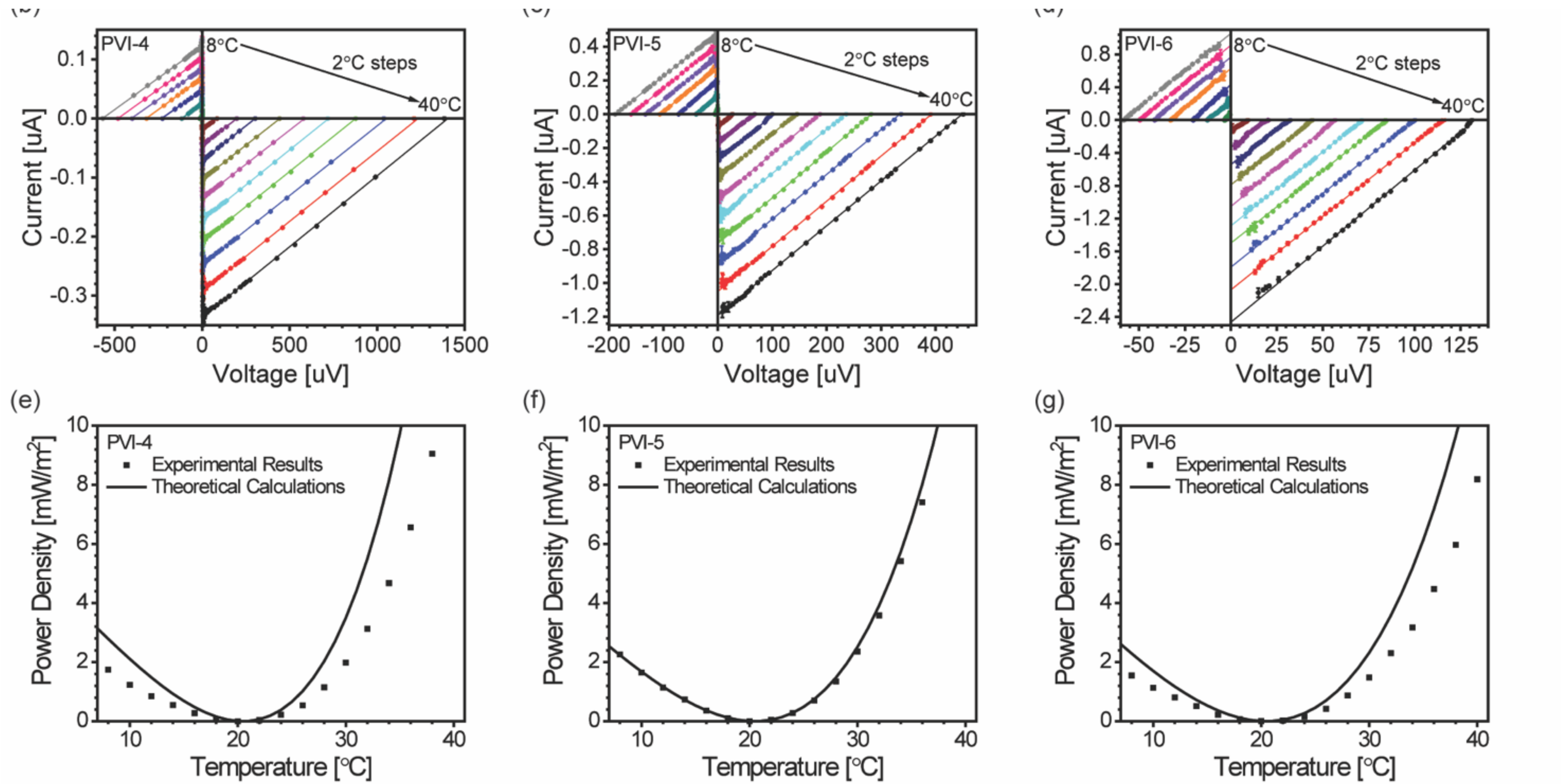
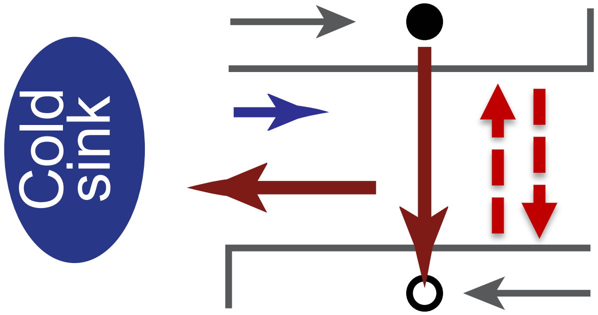
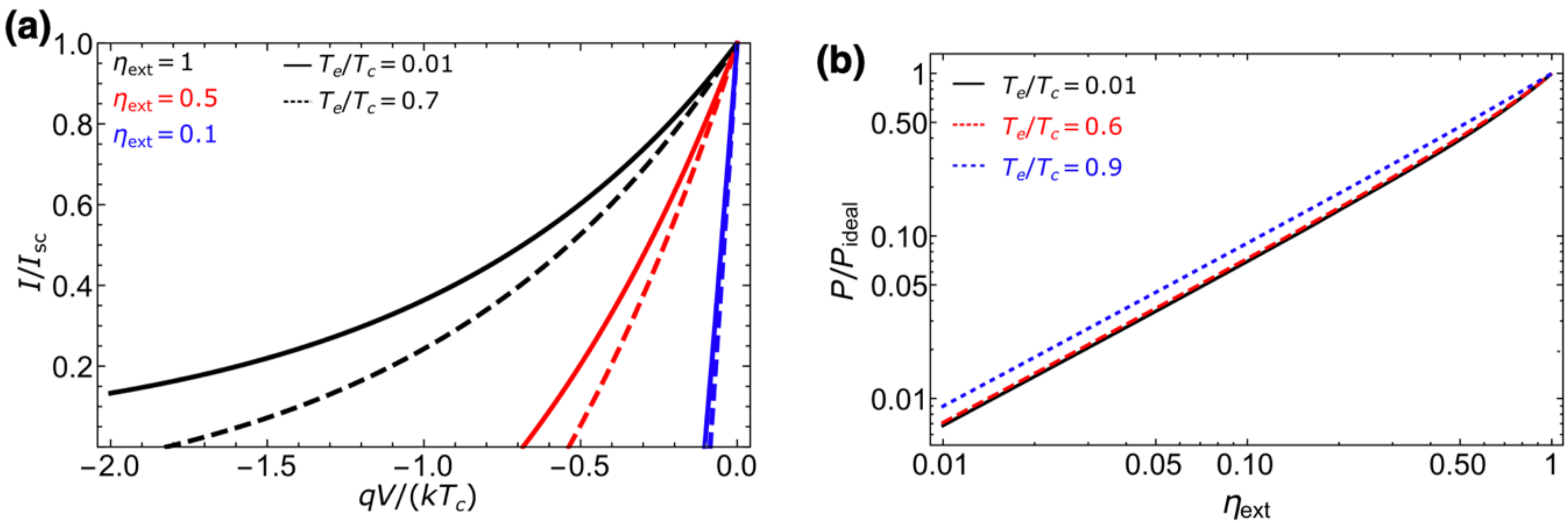
IV & Power characteristics for 4μm, 5μm & 6μm diodes



M.Nielsen, A.Pusch, M.H.Sazzad, P.Pearce, P.J.Reece, N.J.Ekins-Daukes, “Thermoradiative Power Conversion from HgCdtTe Photodiodes and Their Current-Voltage Characteristics”, ACS Photonics, under review (2022)

Why such low voltages?

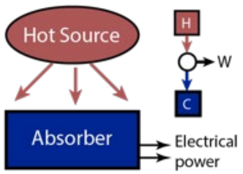




$$\eta_{ext} = \frac{\dot{N}(qV, E_g, T_c)}{\dot{N}(qV, E_g, T_c) + R_{nr}(qV)}$$

A.Pusch, J.M.Gordon, A.Mellor, J.J.Krich, & N.J.Ekins-Daukes, *Physical Review Applied* **12**, 064018 (2019).

Conclusions

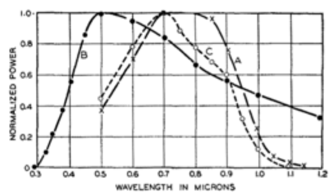


A New Silicon *p-n* Junction Photocell for Converting Solar Radiation into Electrical Power

D. M. Chapin, C. S. Fuller, and G. L. Pearson
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey
(Received January 11, 1954)

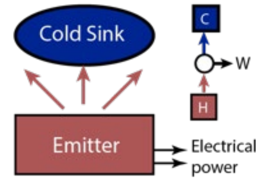
THE direct conversion of solar radiation into electrical power by means of a photocell appears more promising as a result of recent work on silicon *p-n* junctions. Because the radiant energy is used without first being converted to heat, the theoretical efficiency is high.

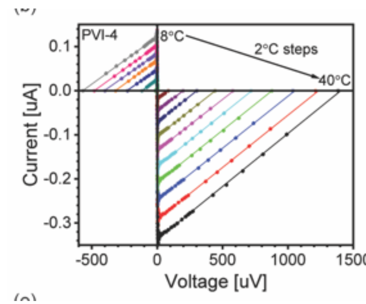
Photons of 1.02 electron volts (λ=1.2 microns) are able to produce electron-hole pairs in silicon. In the presence of a *p-n* barrier, these electron-hole pairs are separated and made to do work in an external circuit. All of the light of wavelength shorter than 1.2 microns is potentially useful for generating electron-hole pairs but the efficiency of energy conversion decreases for short wavelengths because the energy above the necessary 1.02 electron

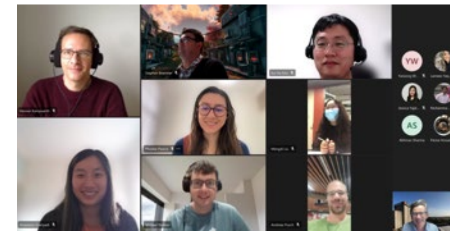


Silicon solar cell: G.Pearson, D.Chapin, C. Fuller, Bell Labs, 1952

- Traditional photovoltaic R&D can be traced back to Becquerel in 1839.
- First silicon solar cell demonstrated in 1952
- Photovoltaic power quickly became ubiquitous in space.



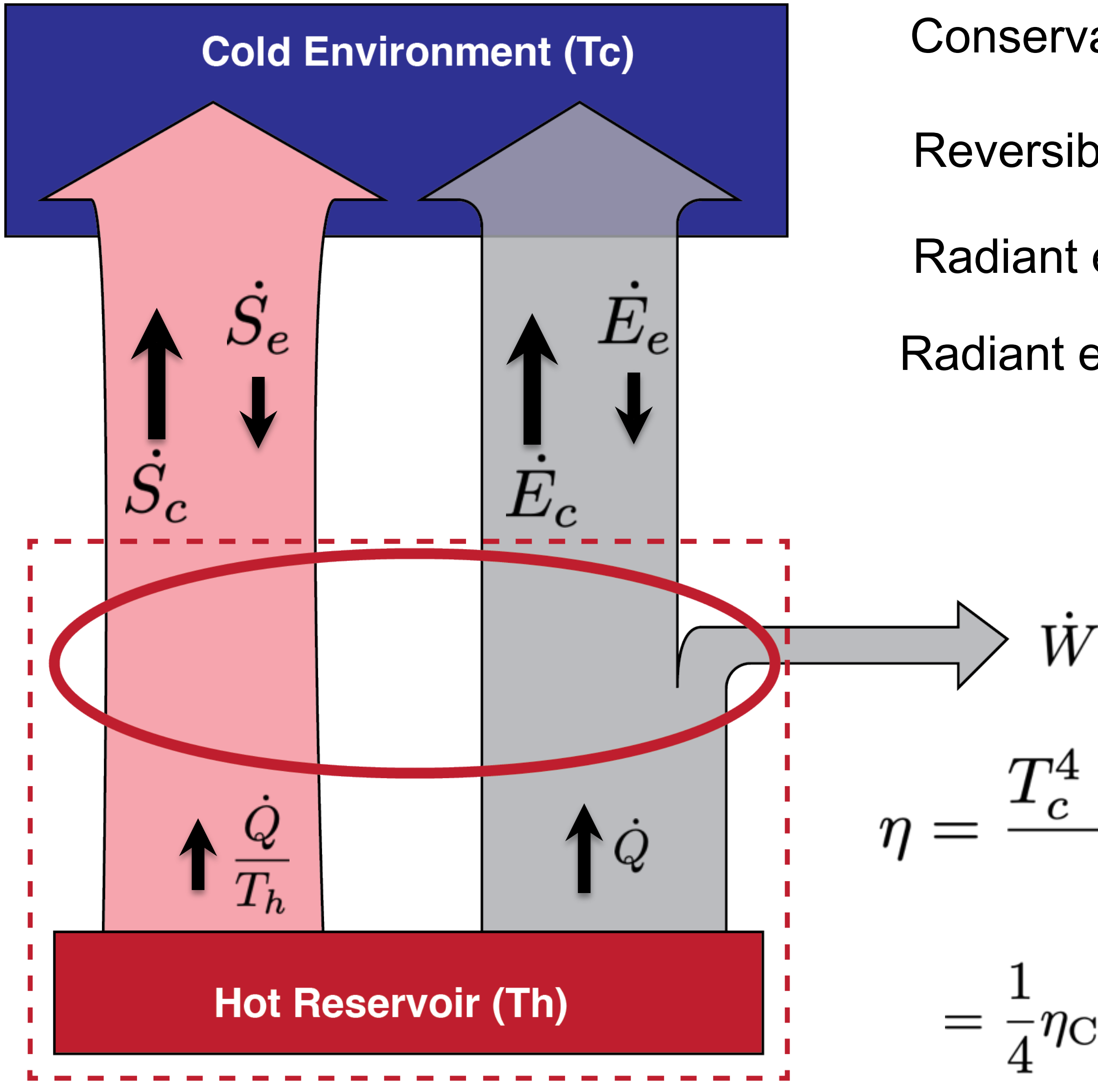




Thermoradiative diode: Nielsen, Pusch, Sazzad, Pearce, Reece, Ekins-Daukes, 2021 UNSW

- Thermoradiative power conversion recognized theoretically in 2014.
- Thermoradiative power can, in principle, be generated at levels of tens $W.m^{-2}$ in the radiative limit.
- Thermoradiative power generation has been demonstrated, in practice, with $mW.m^{-2}$ electrical power density.
- Practical thermoradiative devices delivering $W.m^{-2}$ demand very high radiative efficiency.

Electrical Power from Radiative Processes : Thermoradiative Conversion



Conservation of Energy: $\dot{Q} + \dot{E}_e = \dot{W} + \dot{E}_c$

Reversible operation: $\dot{S}_c = \dot{S}_e + \dfrac{\dot{Q}}{T_h}$

Radiant energy flux density: $\dot{E} = \sigma T^4$

Radiant entropy flux density: $\dot{S} = \dfrac{4}{3}\sigma T^3$

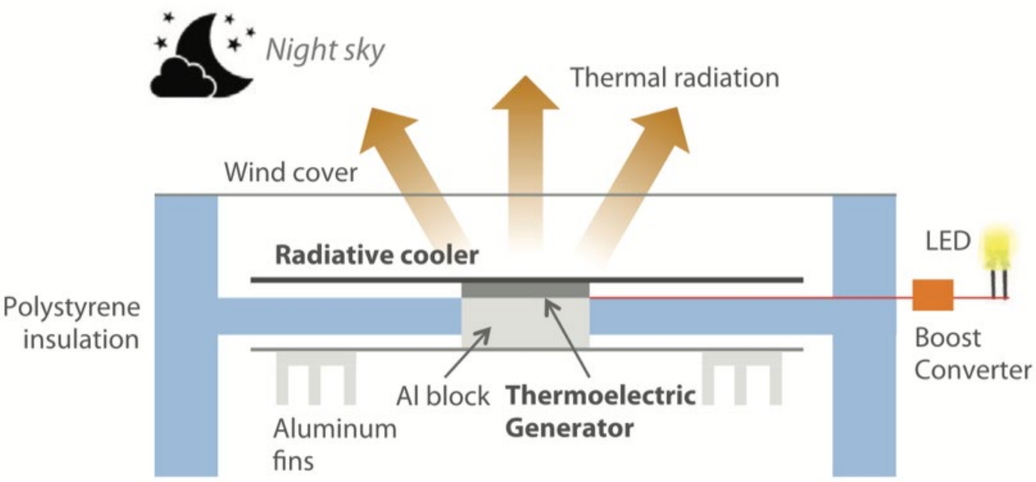
$$\eta = \frac{\dot{W}}{\dot{Q}}$$

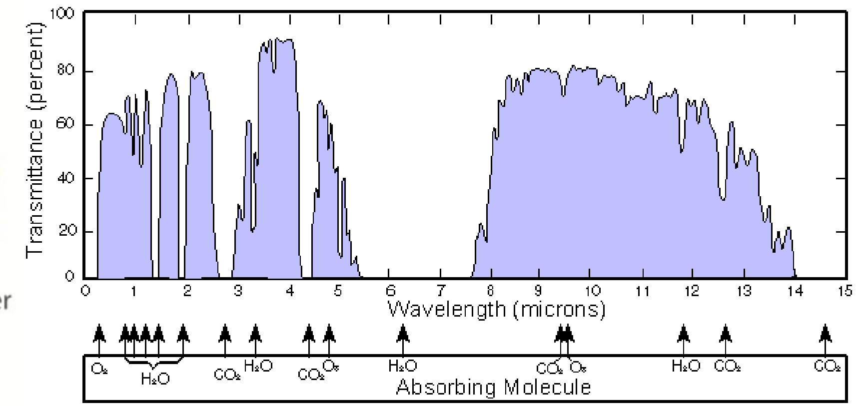
$$\eta = \frac{T_c^4 + (1/3)T_h^4 - (4/3)T_h T_c^3}{(4/3)\left(T_h^4 - T_h T_c^3\right)}$$

$$= \frac{1}{4}\eta_{\text{Carnot}} \frac{1 + 2\,(T_c/T_h) + 3\,(T_c/T_h)^2}{1 + T_c/T_h + (T_c/T_h)^2}$$

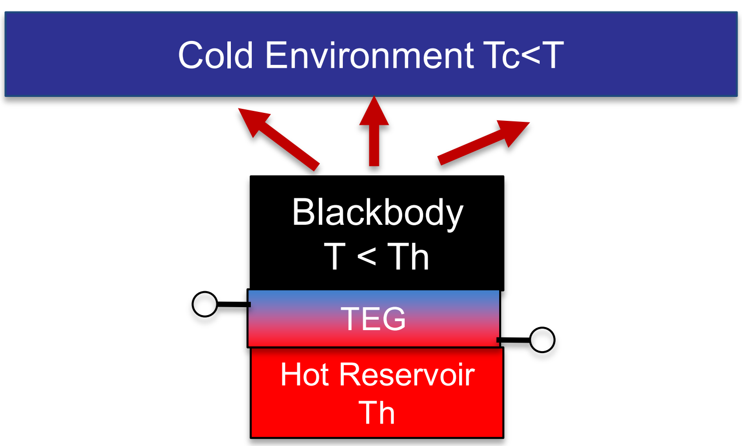
A.Pusch, J.M.Gordon, A.Mellor, J.J.Krich, & N.J.Ekins-Daukes, *Physical Review Applied* **12**, 064018 (2019).

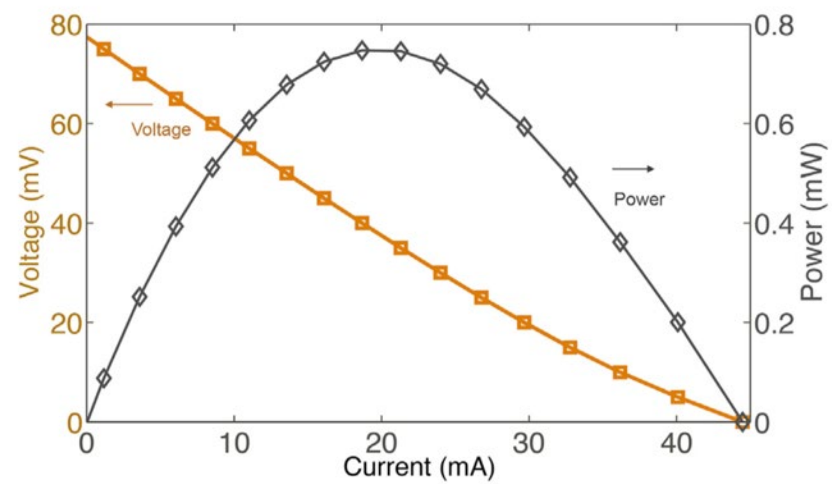
Thermoradiative generation at night:



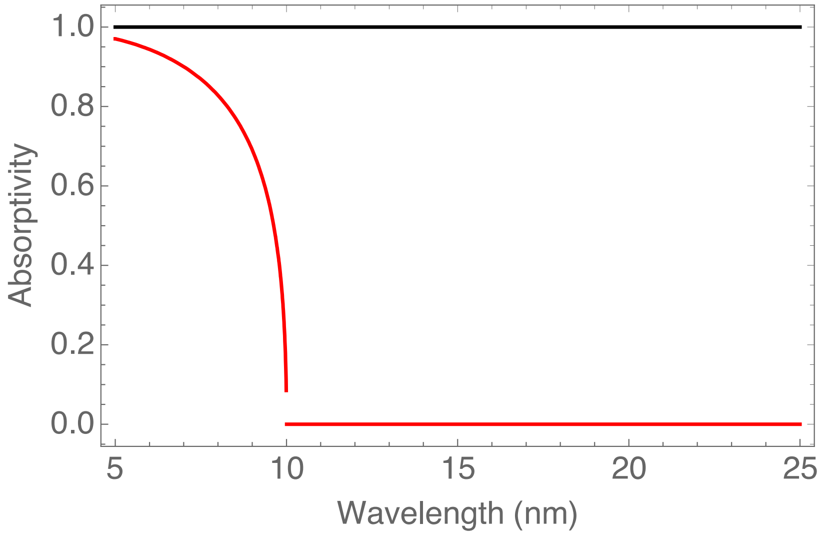


https://en.wikipedia.org/wiki/Infrared_window





Blackbody vs Semiconductor

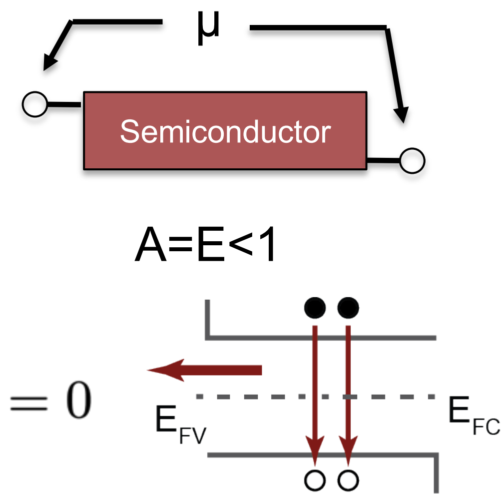


Blackbody

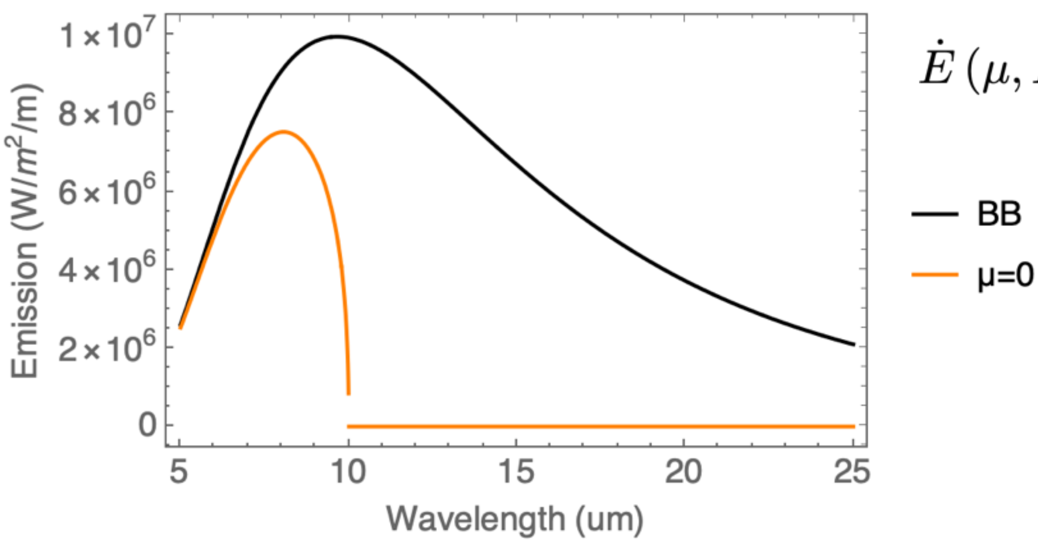
A=E=1

μ=0

$$\dot{E}(T) = \sigma T^4$$



$$\mu = 0$$



$$\dot{E}\left(\mu, E_g, T\right) = \frac{2\pi}{c^2 h^3} \int_0^{\infty} \frac{a(E) E_{\mathrm{ph}}^3}{e^{(E_{\mathrm{ph}}-\mu)/kT} - 1} dE_{\mathrm{ph}}$$

Wurfel, P. (1982). The Chemical Potential of Radiation Journal Of Physics C-Solid State Physics, 15(18), 3967-3985

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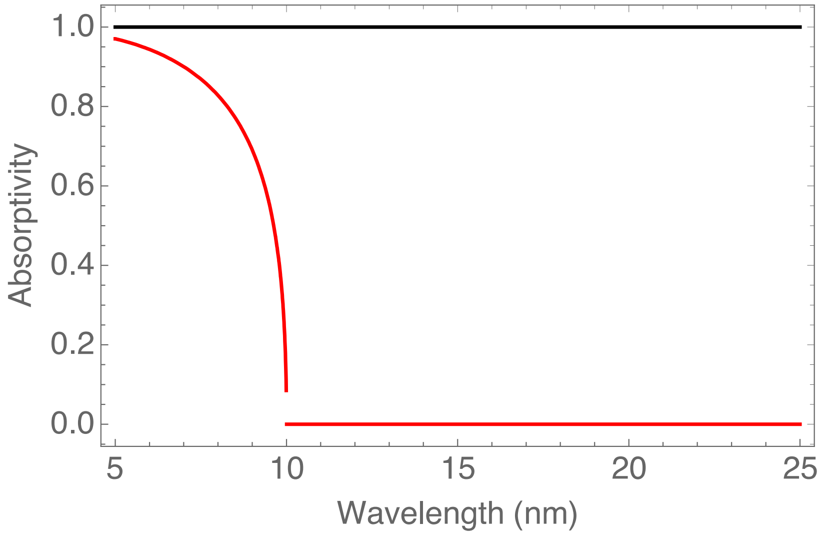
Blackbody vs Semiconductor



Blackbody

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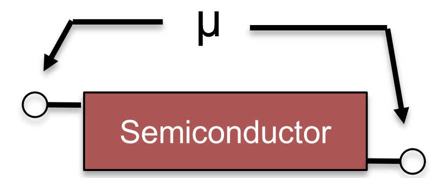
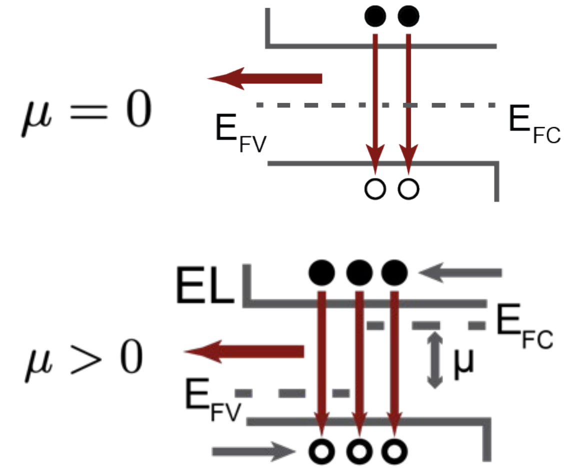
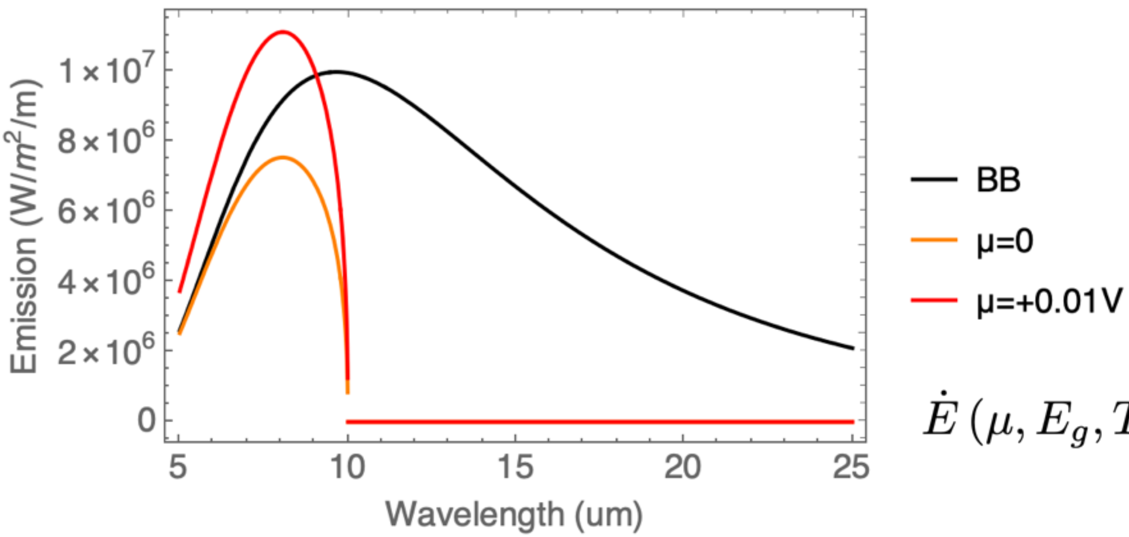


A=E<1

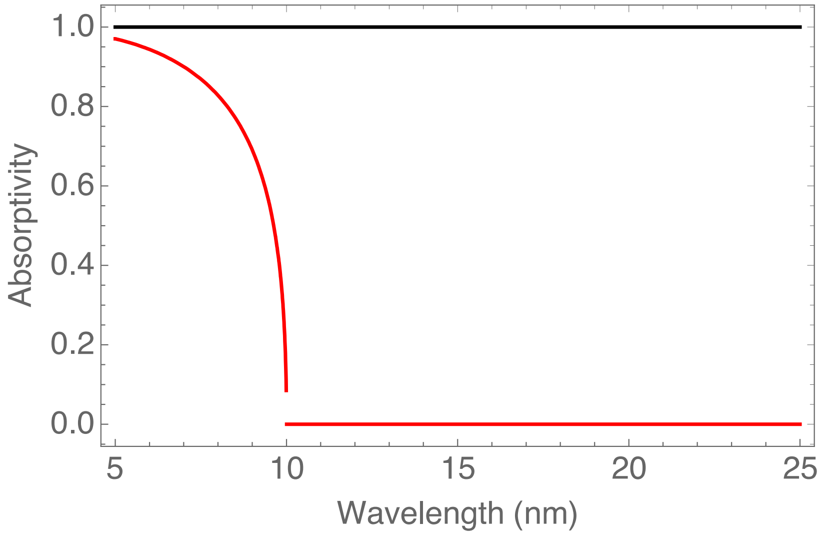




$$\dot{E}\left(\mu, E_g, T\right) = \frac{2\pi}{c^2 h^3} \int_0^{\infty} \frac{a(E) E_{\text{ph}}^3}{e^{(E_{\text{ph}} - \mu)/kT} - 1} dE_{\text{ph}}$$

Feuerbacher, B., & Wurfel, P. (1990). Verification of a generalized Planck law by investigation of emission from GaAs luminescent diodes Journal Of Physics-Condensed Matter, 2(16), 3803-3810

Blackbody vs Semiconductor

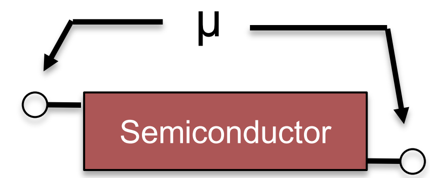


Blackbody

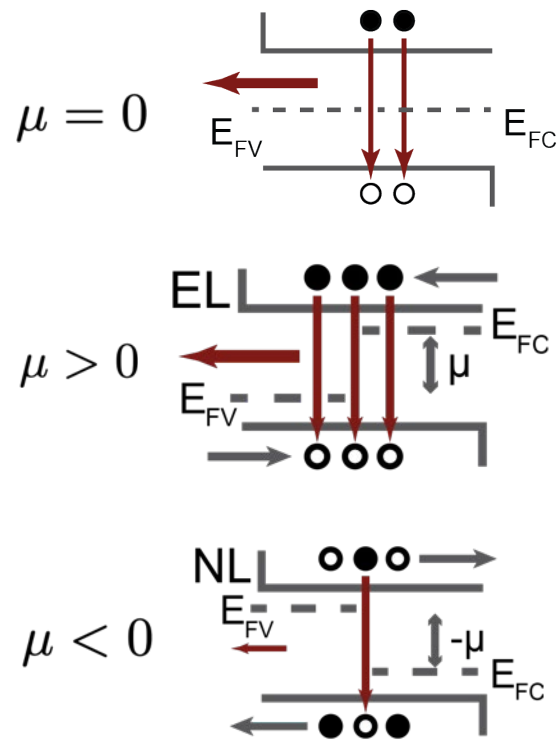
A=E=1

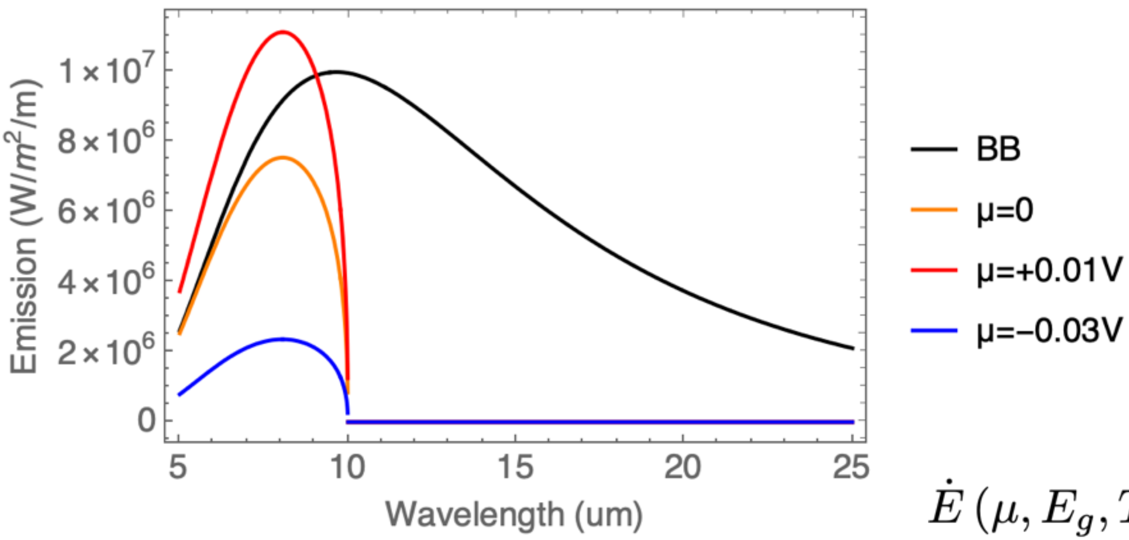
μ=0

$$\dot{E}(T) = \sigma T^4$$



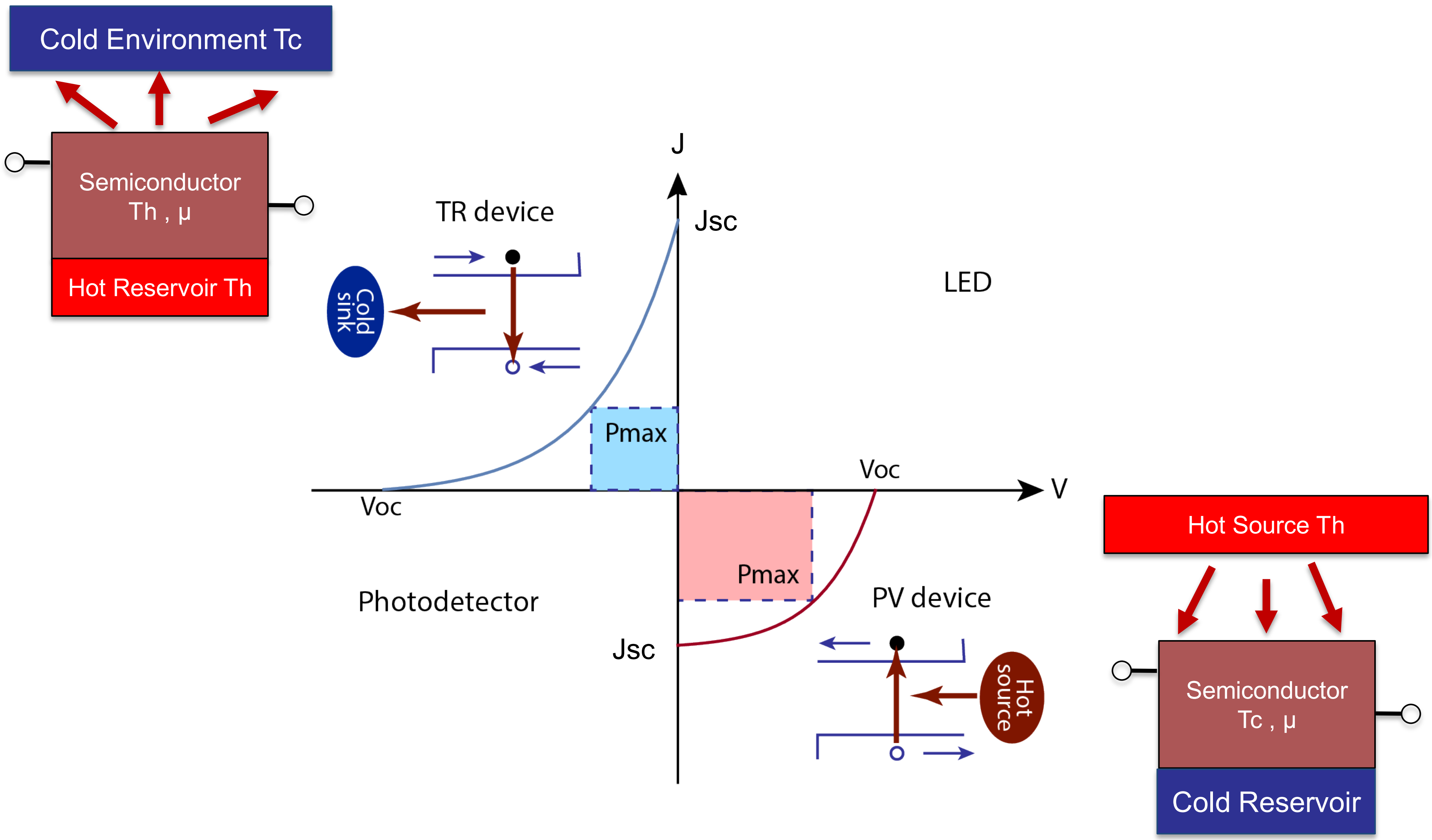
A=E<1



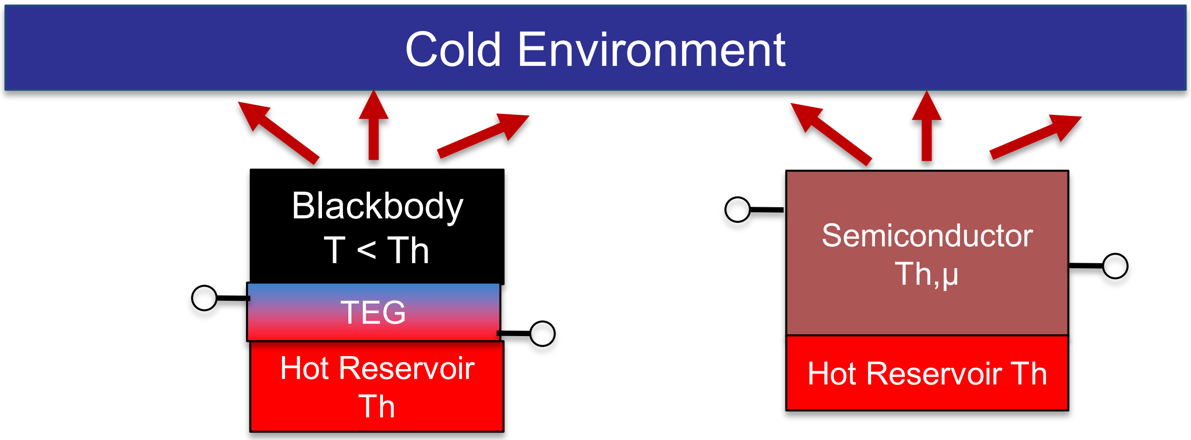


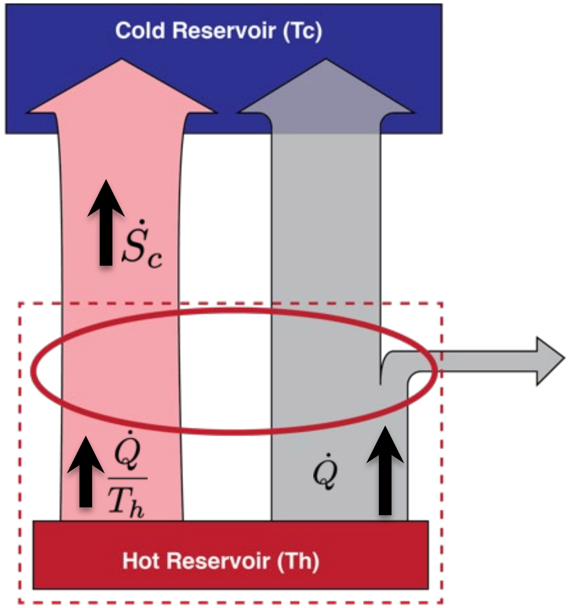
$$\dot{E}\left(\mu, E_g, T\right) = \frac{2\pi}{c^2 h^3} \int_0^\infty \frac{a(E) E_{\mathrm{ph}}^3}{e^{(E_{\mathrm{ph}} - \mu)/kT} - 1} dE_{\mathrm{ph}}$$

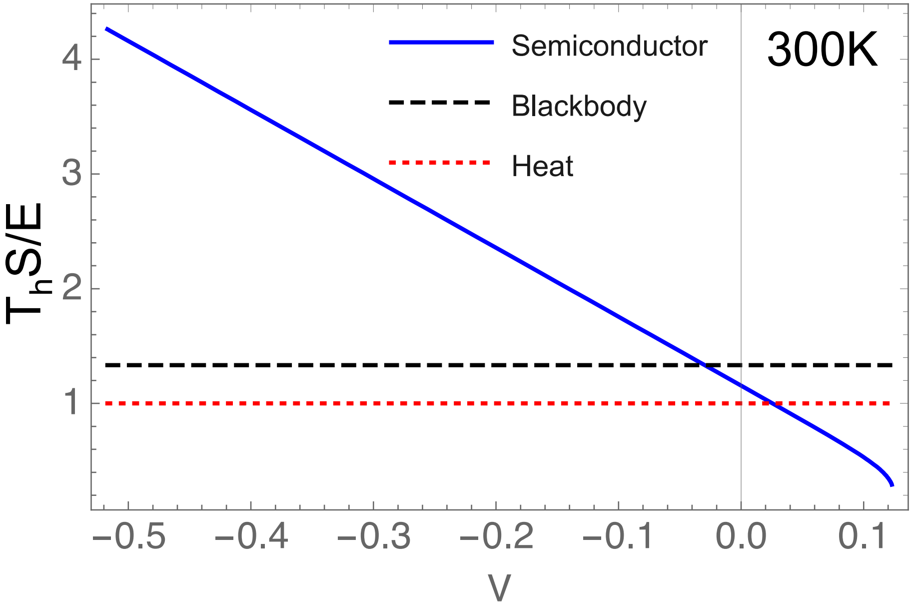
Power vs Efficiency relations for Thermoradiative Diode Generators



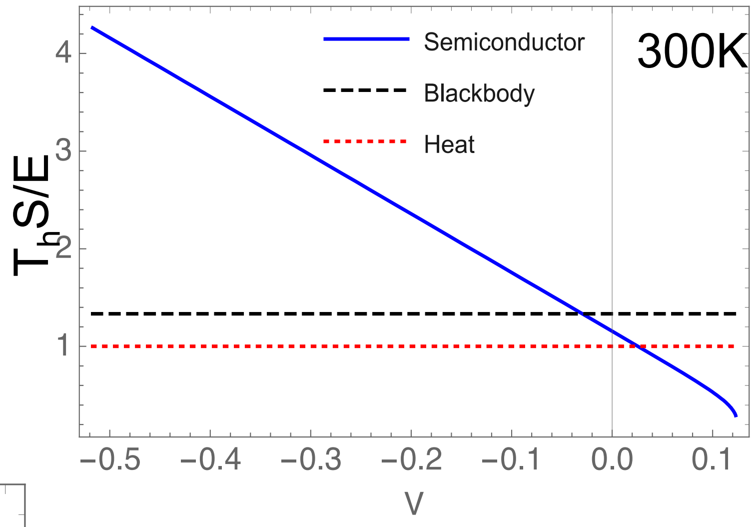
Energy to Entropy Ratio for a Blackbody and Semiconductor Emitter

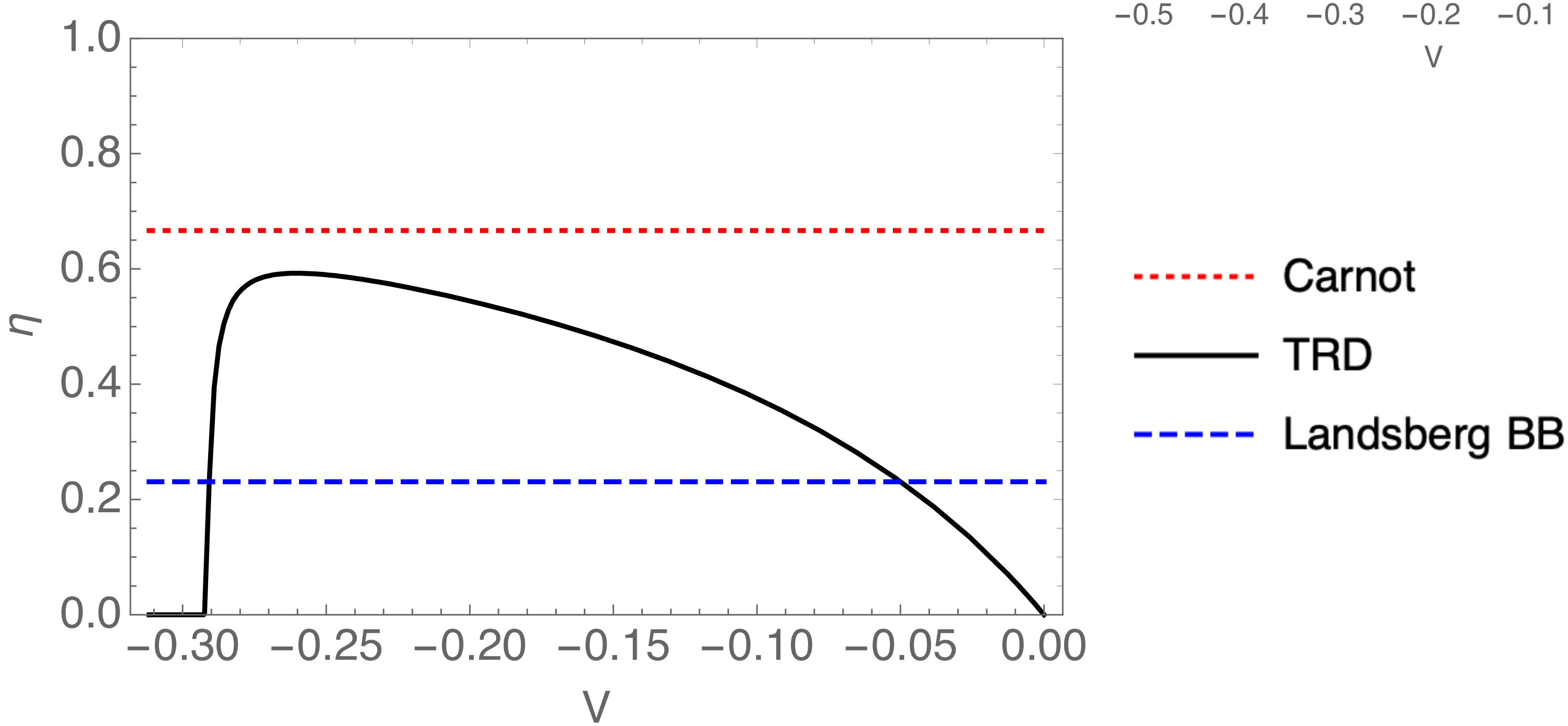






Thermoradiative diode efficiency is higher than the Landsberg BB thermoradiative generation limit.





A.Pusch, J.M.Gordon, A.Mellor, J.J.Krich, & N.J.Ekins-Daukes, *Physical Review Applied* **12**, 064018 (2019).