Nx-TEC: Next-Generation Thermionic Solar Energy Conversion

SLAC National Accelerator Laboratory

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Solar Power Conversion

A lot of high-quality energy is available from the sun… how can we harvest it?

Solar Thermal (CSP)

- Converts sunlight into heat
- Concentrated solar thermal
- Uses well-known thermal conversion systems
- Efficiencies of 20-25%

Photovoltaics (PV)

- Collects fraction of incident energy
- "High grade" photon energy
- Direct photon to electricity
- Efficiencies 17-24% (single junction Si)

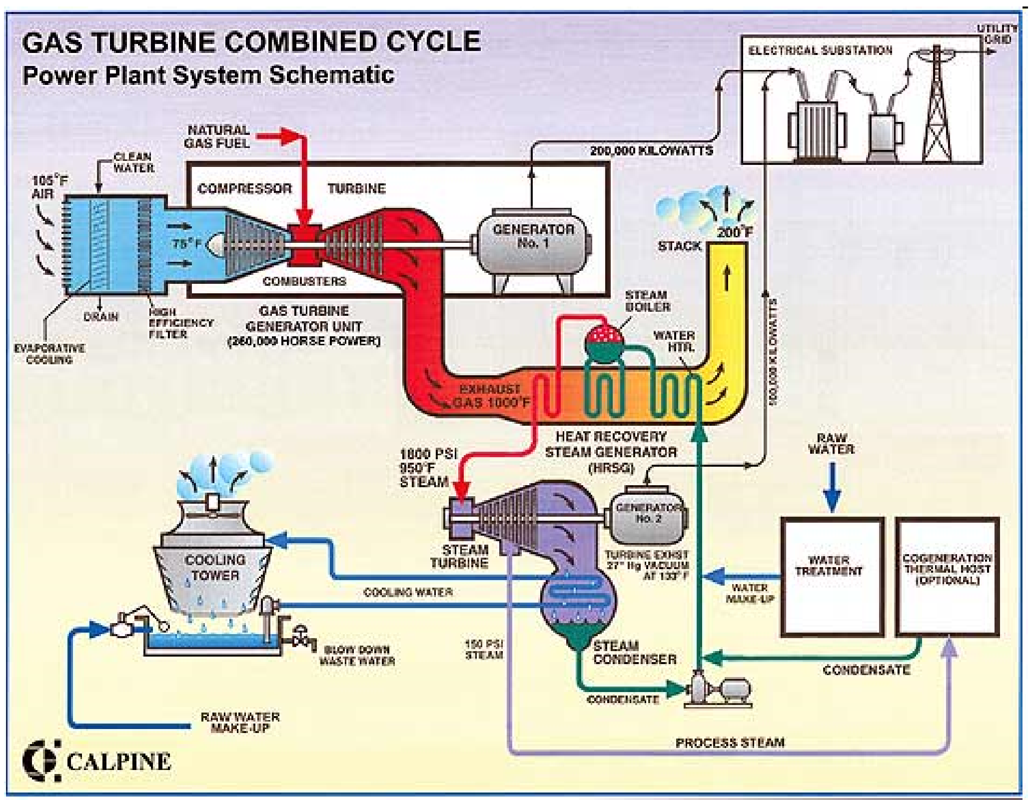
How *Efficient* are fossil fuels?

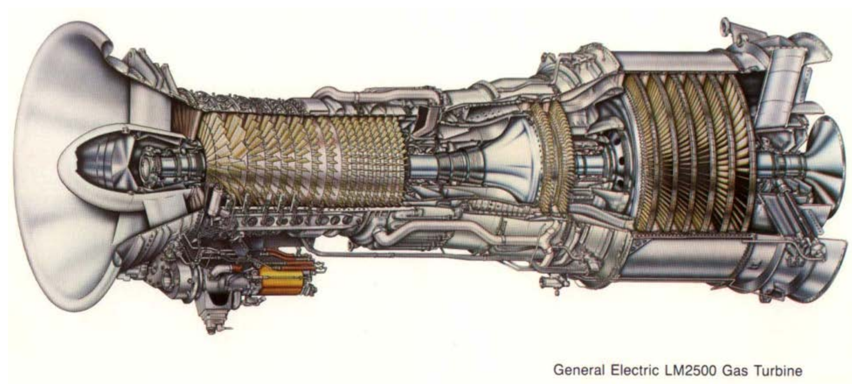
Coal Plants are ~30% efficient.

Natural Gas Plants are > 50% efficient!

How come?

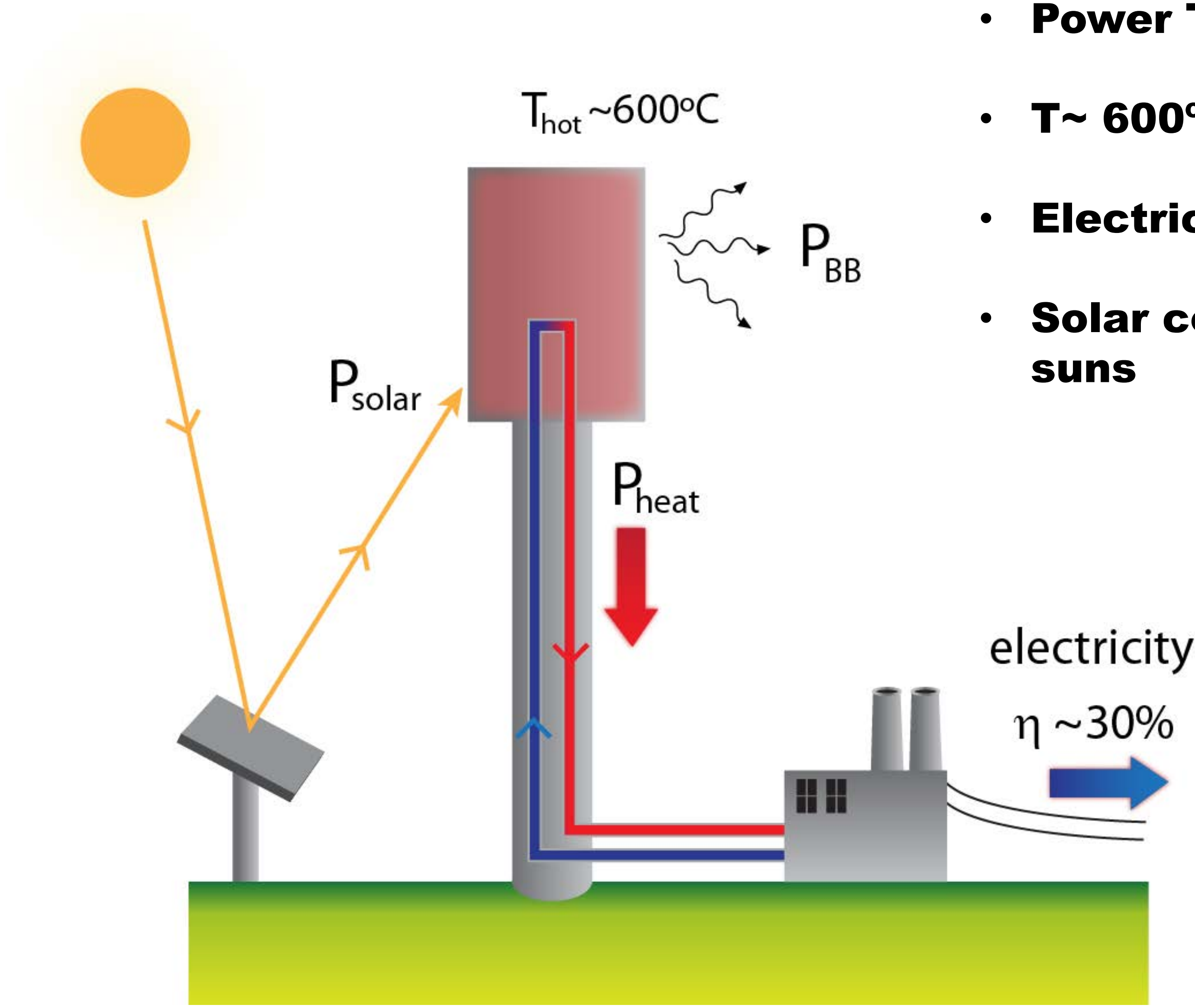
Tandem Cycles.





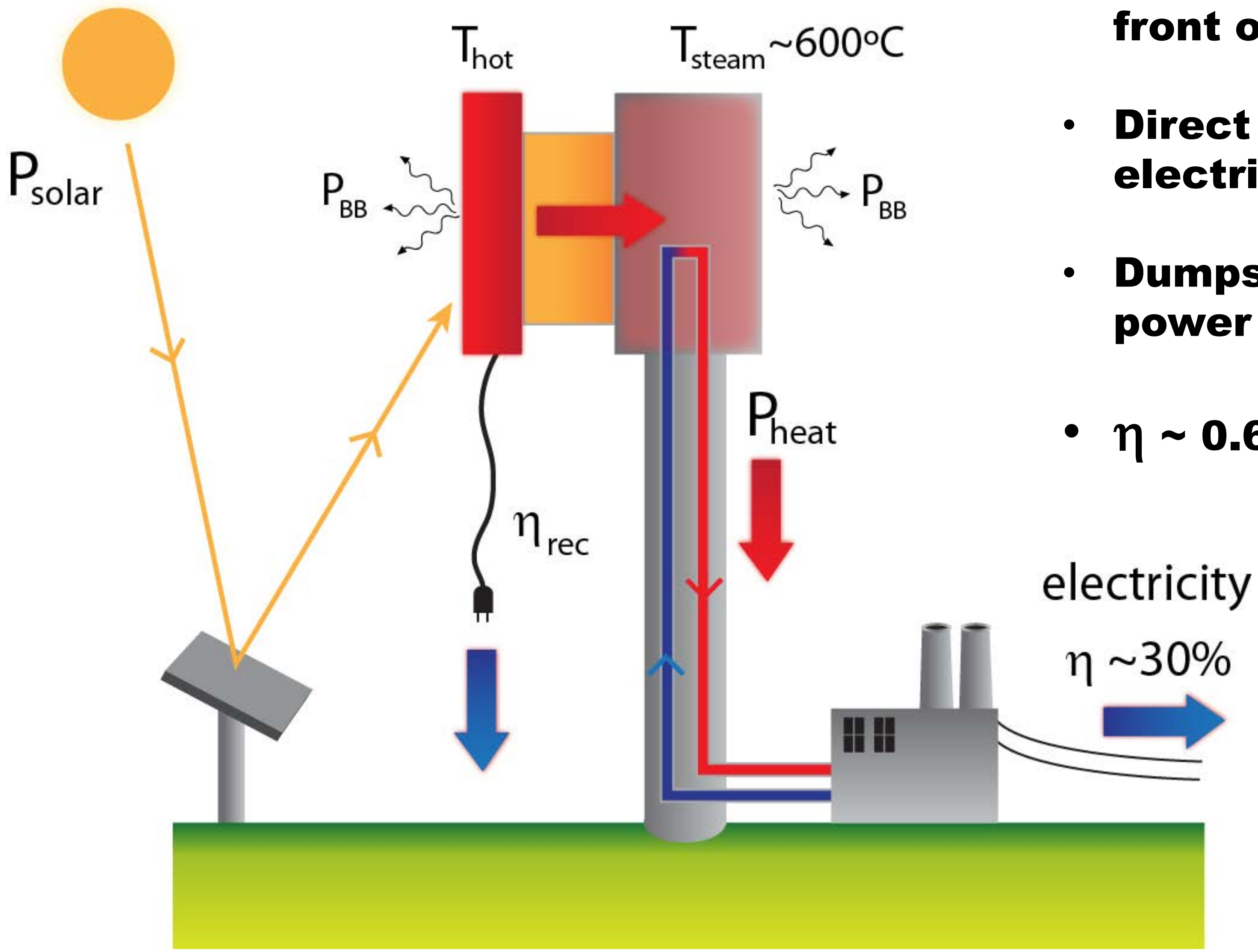
A GE gas turbine

Do 'topping' cycles on solar thermal make sense?



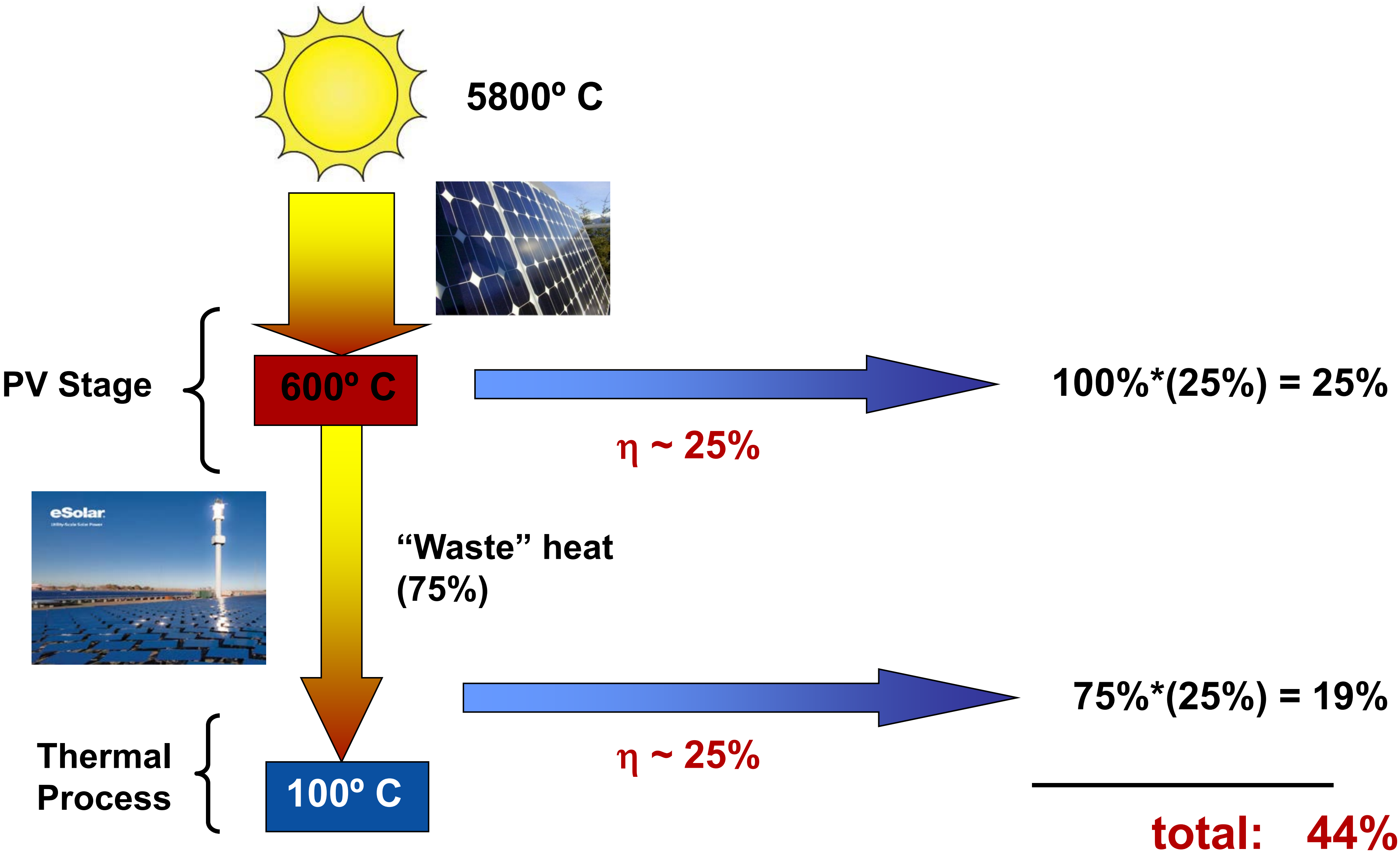
- **Power Tower receiver alone**
- **T~ 600° C**
- **Electrical efficiency ~ 30%**
- **Solar concentration ~500 suns**

Add a High-Temperature Converter



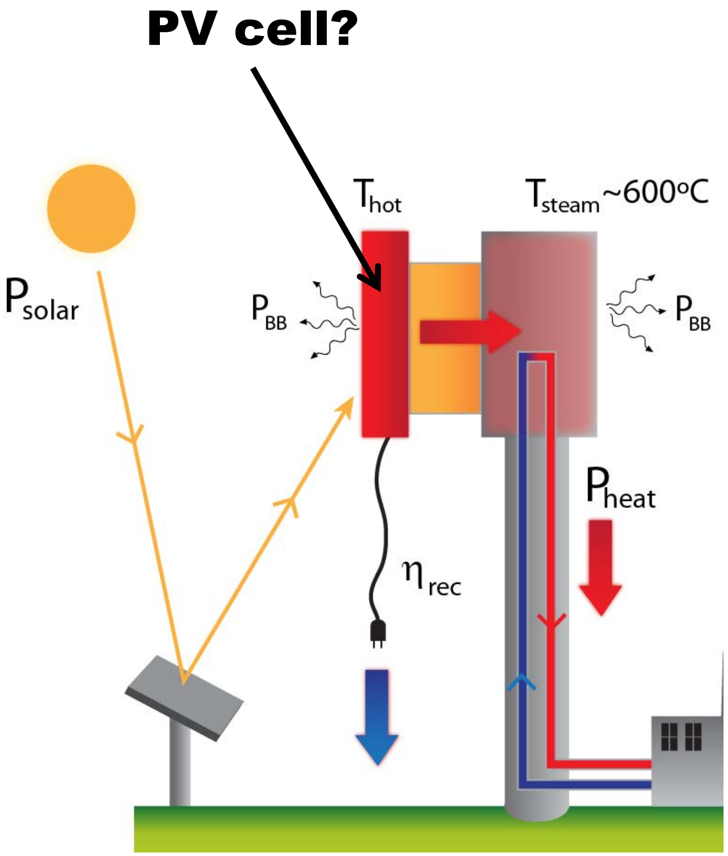
- **Add high-T receiver in front of tower**
- **Direct thermal/solar to electrical conversion**
- **Dumps waste heat to power tower**
- $\eta \sim 0.60(1 - T_{steam}/T_{hot})$

Ideal: Combined HT-PV/ Thermo Cycle



Combined cycles can take two modest performance devices to form a very high efficiency device.

High-Temperature PV?



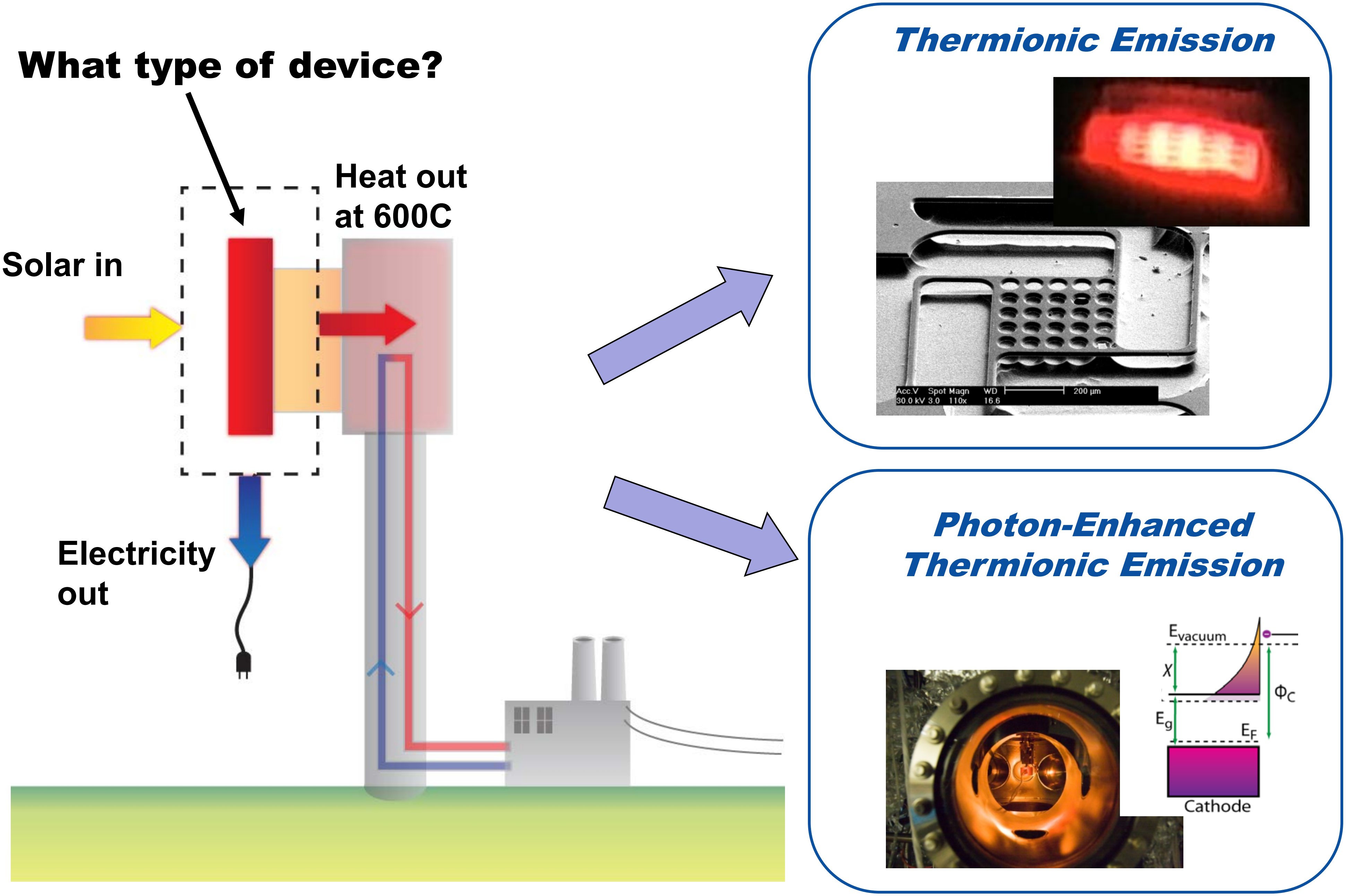
The key is a PV cell that can operate at high temperatures (~600+ ºC)

- **Adding 25% efficient High Temperature-PV (HT-PV) increases a 25% thermal system to 44%**
- **Possibly add on to existing designs**
- **PV must operate at higher temperature than the thermal cycle (~600ºC)**

Can we make a High-Temperature Photovoltaic?

No.

High Temperature Thermal Conversion

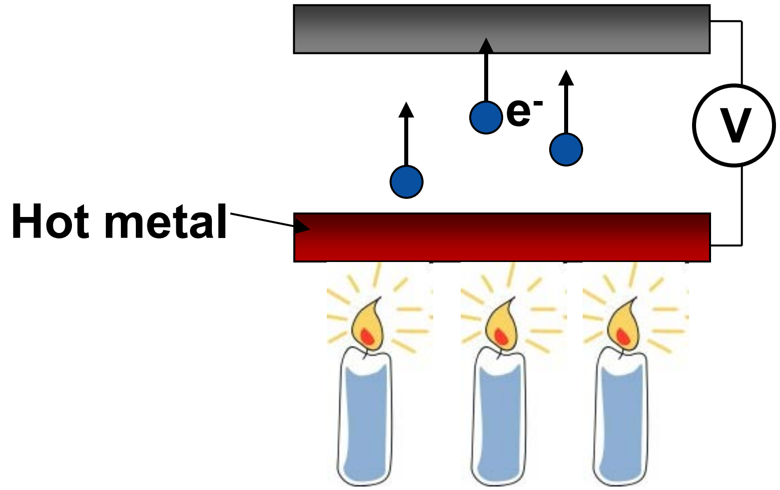


Thermionic Emission

Boiling water:

- **Input heat energy to overcome energy barrier to change liquid into gas**

Boiling electrons from a metal:

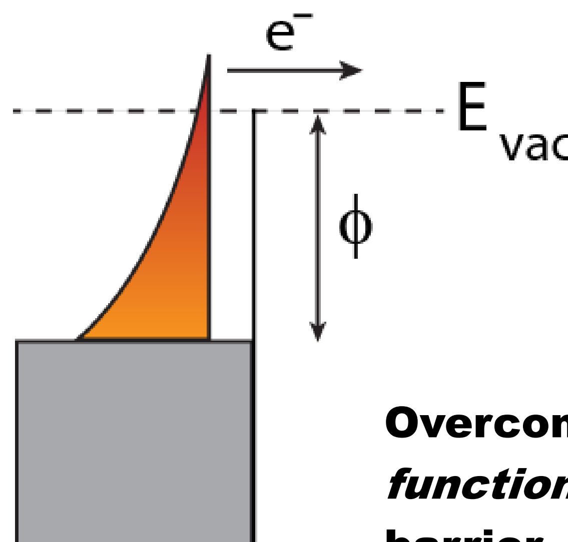


- **Operates at very high temperatures; generally >800ºC**
- **Robust**

$$J = AT^2 e^{-\Phi_E / kT}$$

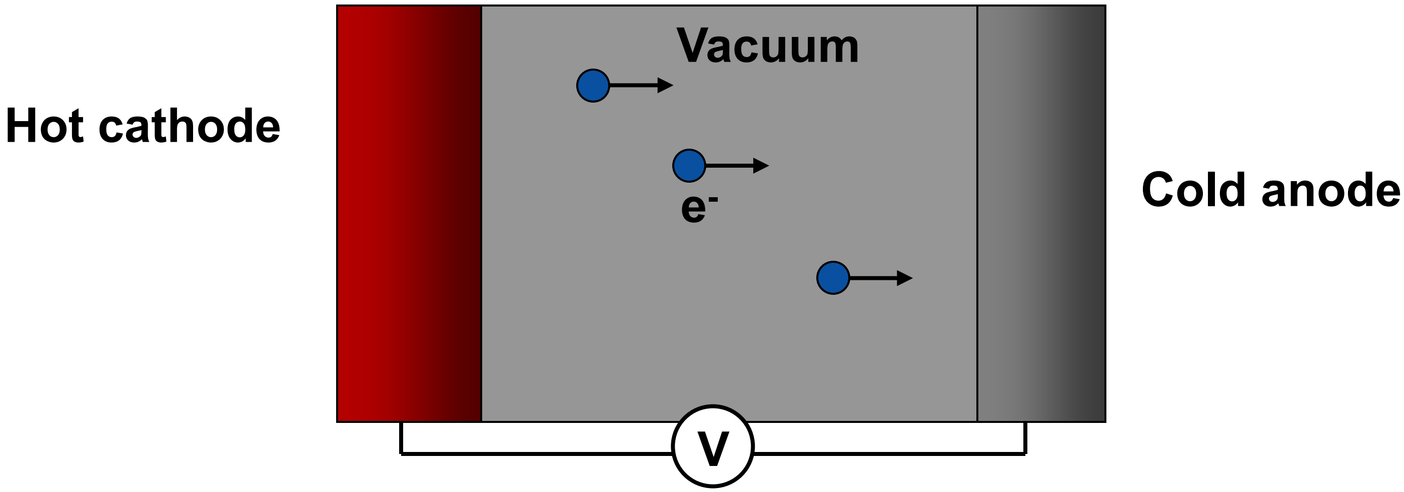
(Richardson-Dushman law)

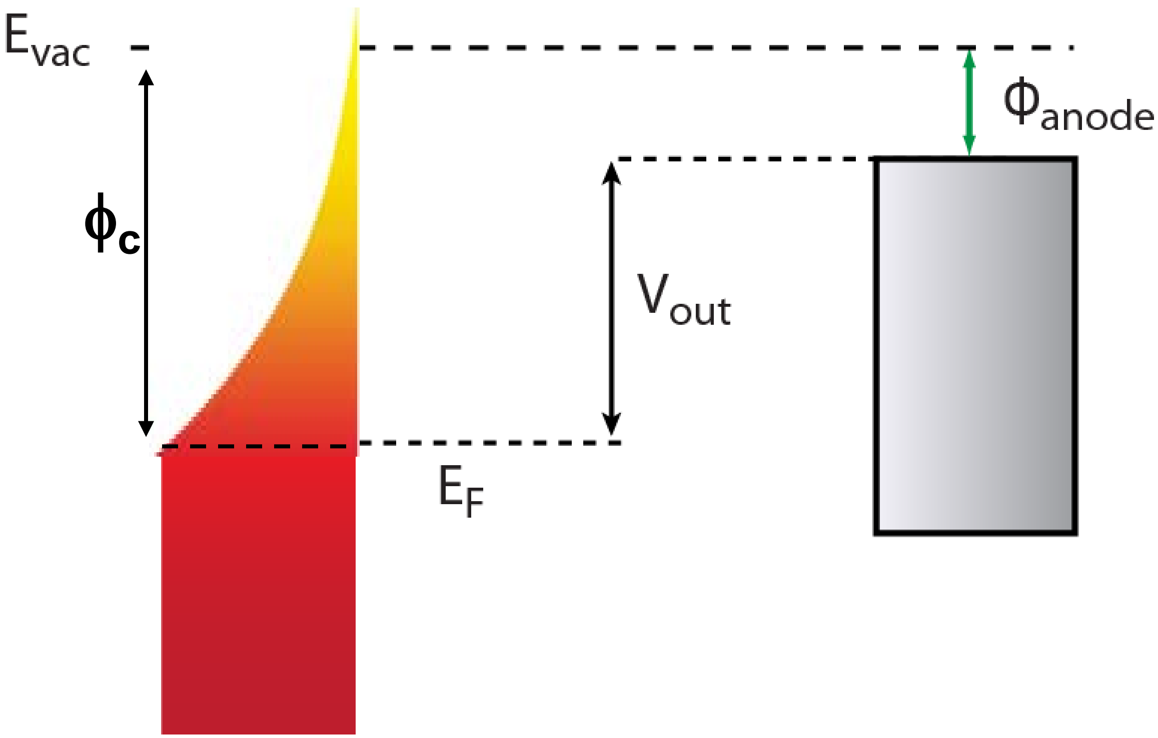
J = current density (Acm^{-2}),
Φ_E = emitter work function (eV)



Overcome *work-function* energy barrier

Thermionic Emission Converter (TEC)

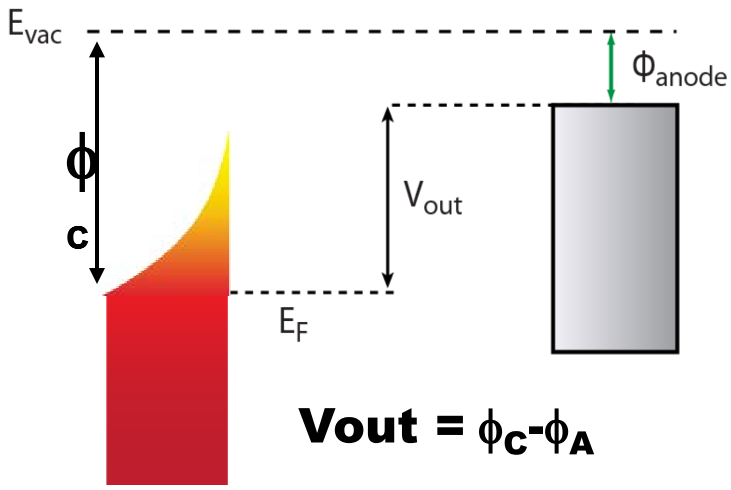




- Heating the cathode boils off electrons into vacuum
- Collected by low-workfunction anode
- Want large cathode ϕ_c for larger V_{out}, requires high T

Two Key problems with TEC:

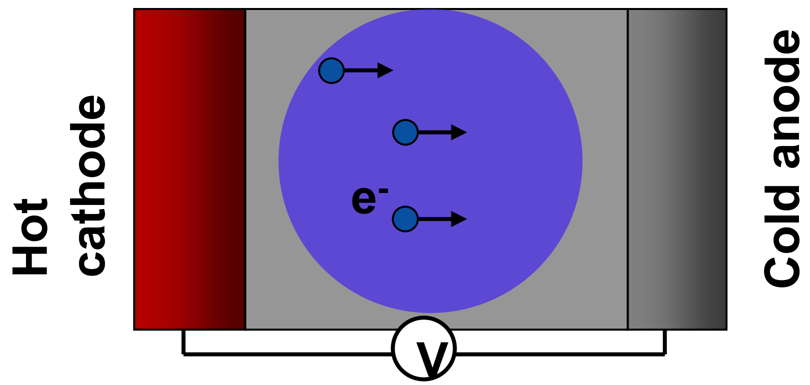
Low Voltage



Vout = ϕ_C-ϕ_A

- need small cathode ϕ_c to keep temperature reasonable
- need smaller anode ϕ_A
- V_{out} ~ 0.1- 0.2 eV
- Result: poor efficiency

Space Charge



- Electrons take time to cross vacuum gap
- Electric field builds up, decreasing electron emission
- Current saturation given by Child-Langmuir equation

Why Revisit Thermionics Now?

New Fabrication Techniques:

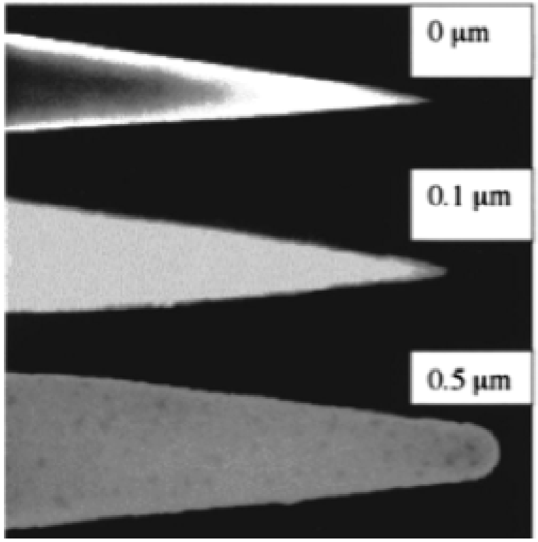
- MEMS devices
- Wafer-bonded vacuum encapsulation
- Refractory semiconductor processing (SiC)

New Materials:

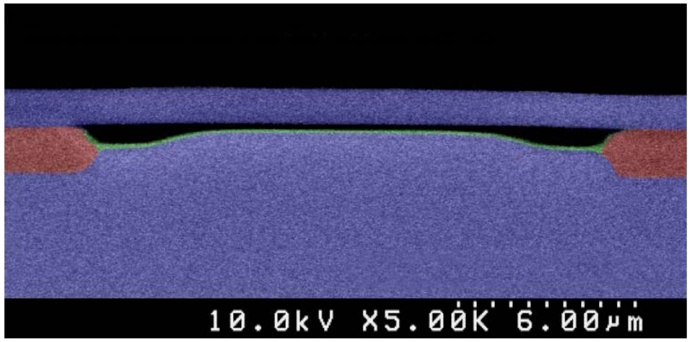
- Nanowires, nanoparticles
- High-quality III-V's available
- Nano-texured surfaces

New Urgency:

- Energy harvesting critical
- Can add onto existing solar-thermal infrastructure?

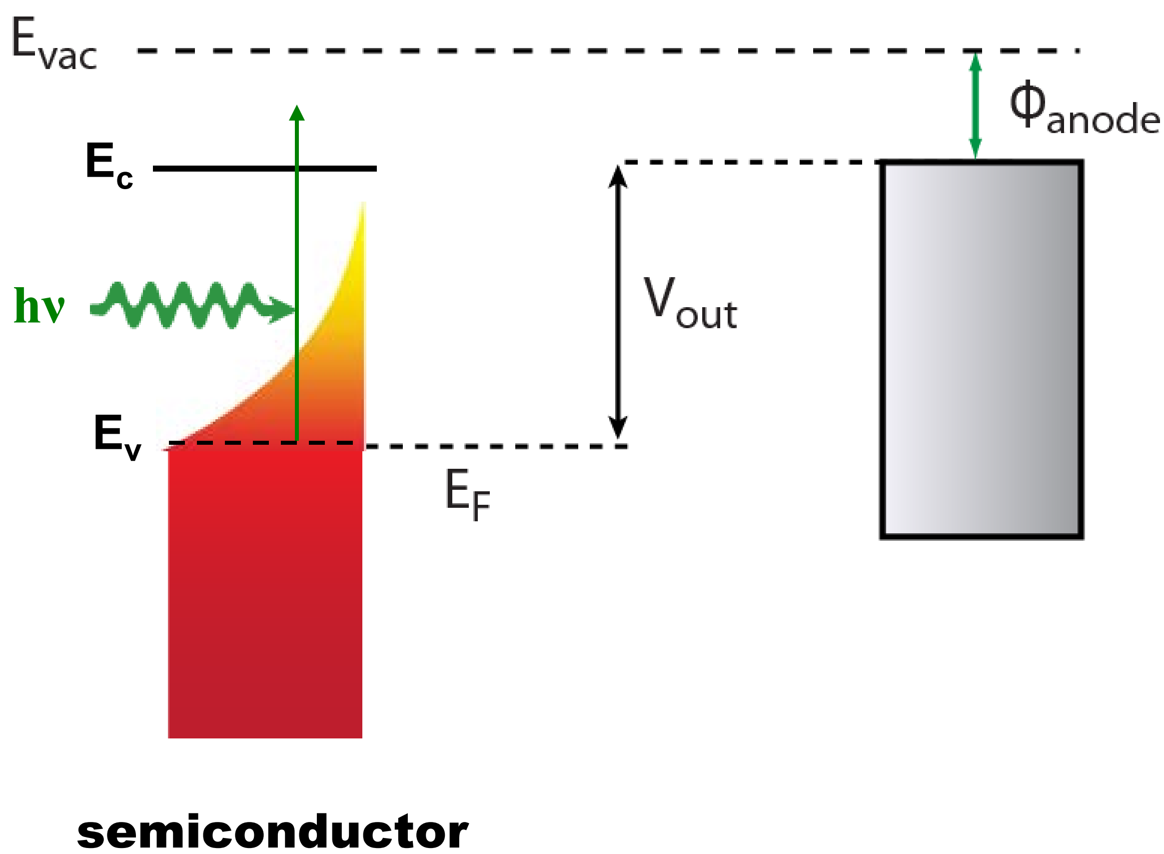


Diamond deposition onto Si tips [Krauss et al., J. Appl. Phys. 2001]



CMUT/ Kuri-Yakub, Stanford

Photon Enhanced Thermionic Emission



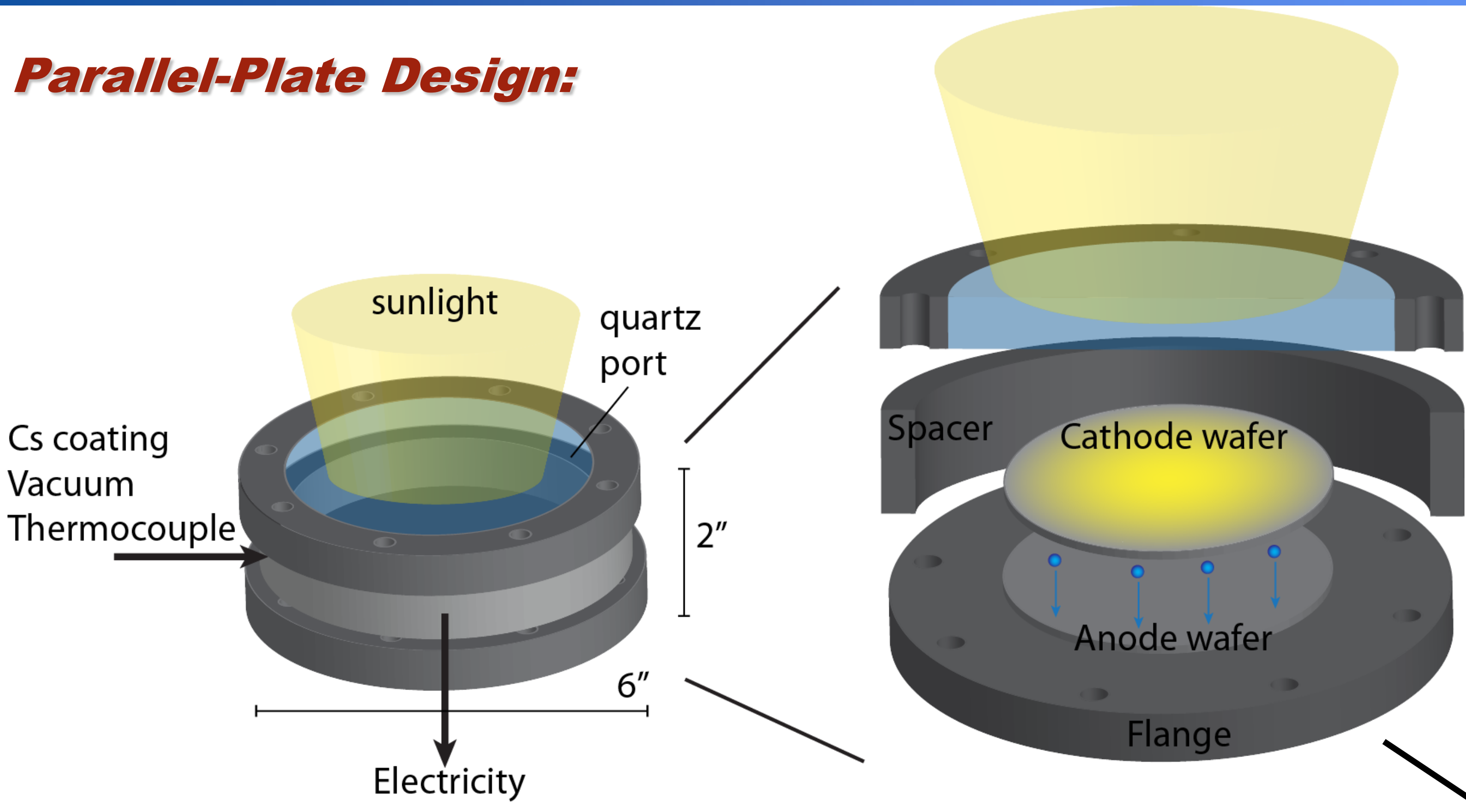
Photon-enhanced Thermionic Emission (PETE)

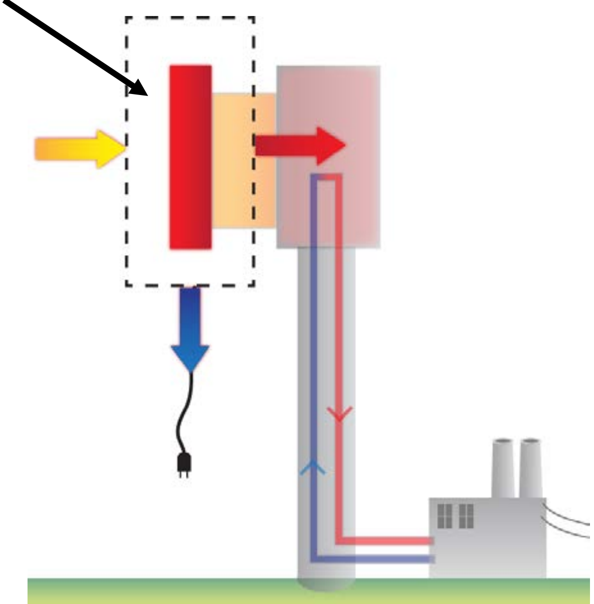
- **Acts like a high-T PV cell: direct solar to electrical generation at high-T**

Schwede et al, Nature Materials, 9 ,762–767, 2010

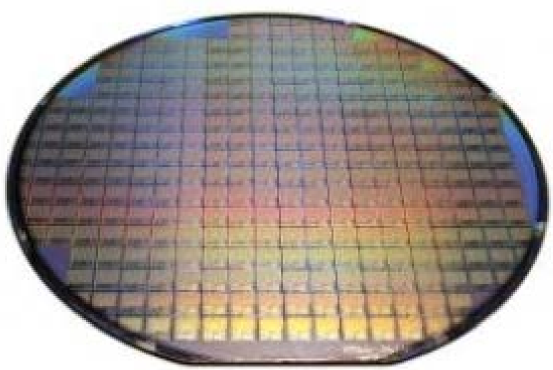
What would PETE look like?

Parallel-Plate Design:

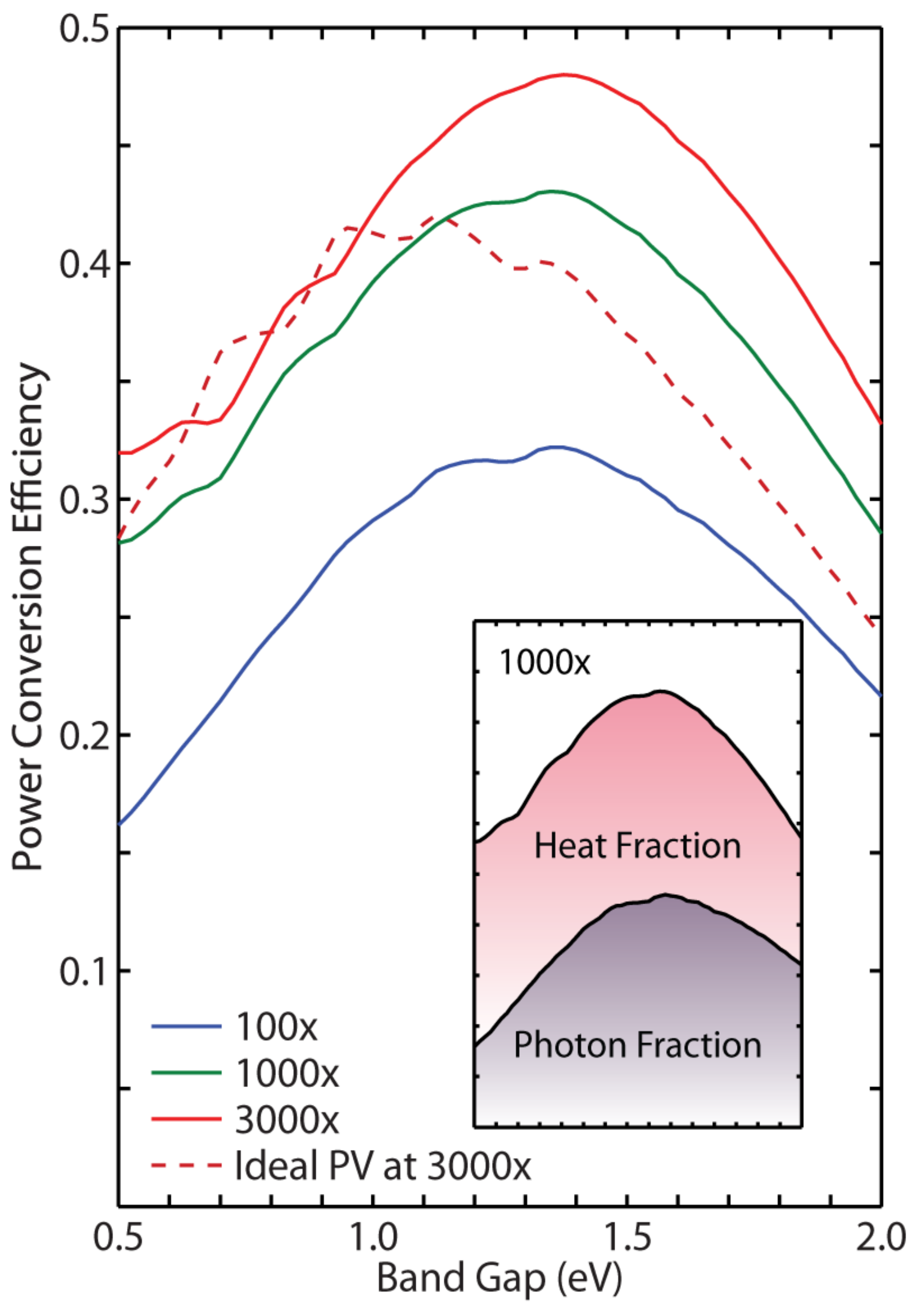


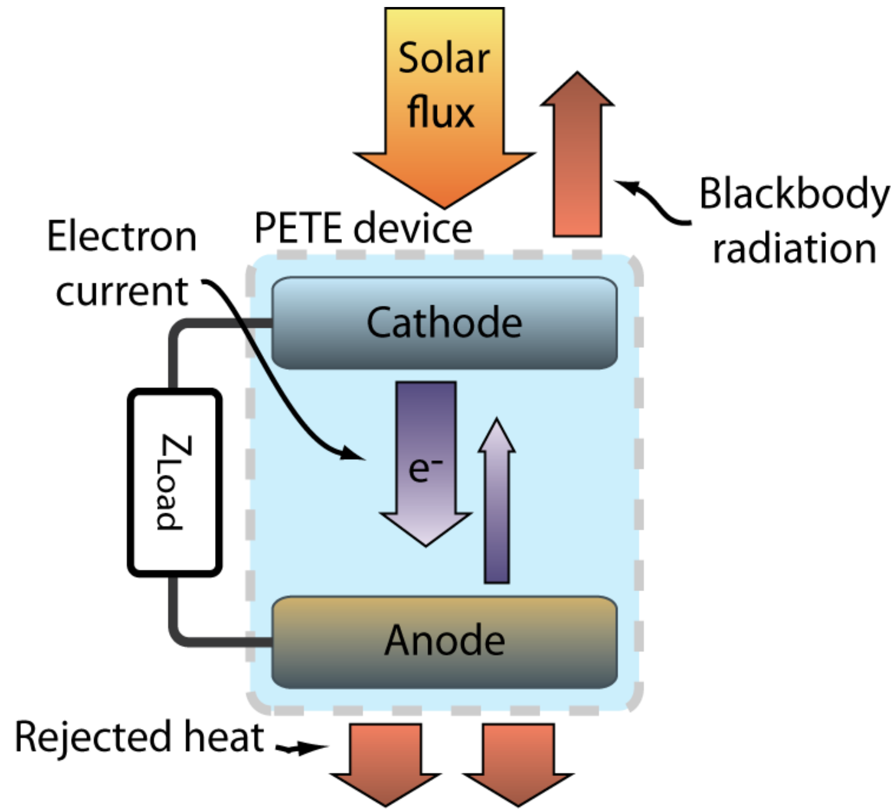


Standard materials:
Si, GaAs



Theoretical Efficiency





- To adjust: E_g, χ , T_C
- φ_A = 0.9 eV
  - [Koeck, Nemanich, Lazea, & Haenen 2009]
- $T_A \leq 300°C$
- Other parameters similar to Si
  - 1e19 Boron doped

Schwede et al, Nature Materials, 9 ,762–767, 2010

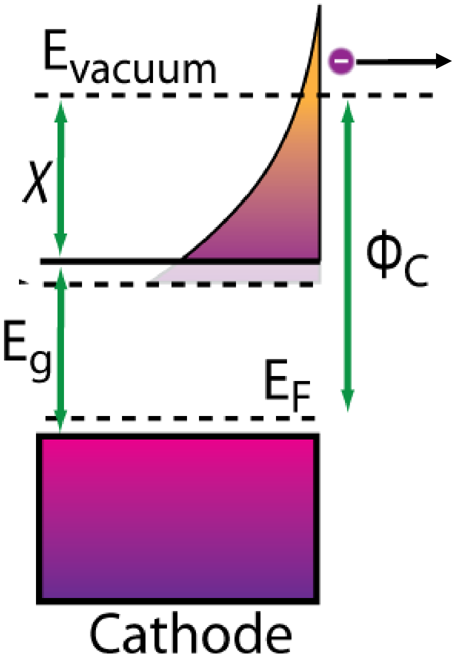
Experimental Demonstration

- GaN with Cs coating
- Thermally Stable
  - E_g = 3.3 eV
  - 0.1 μm Mg doped
  - $5x10^{18}$ cm^{-3}

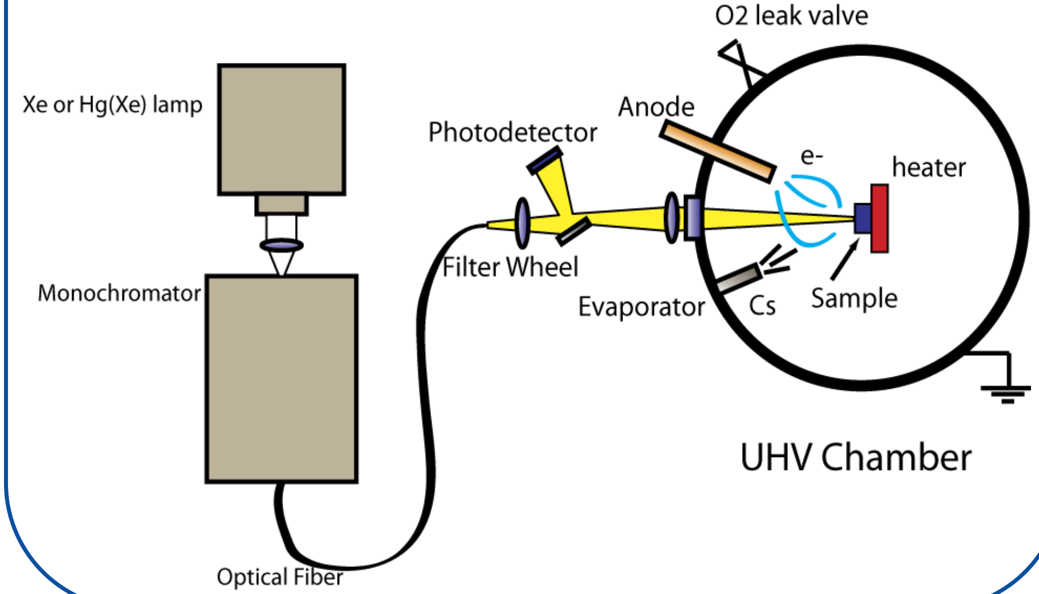
Gallium Nitride

~0 to 0.5 eV

3.3 eV

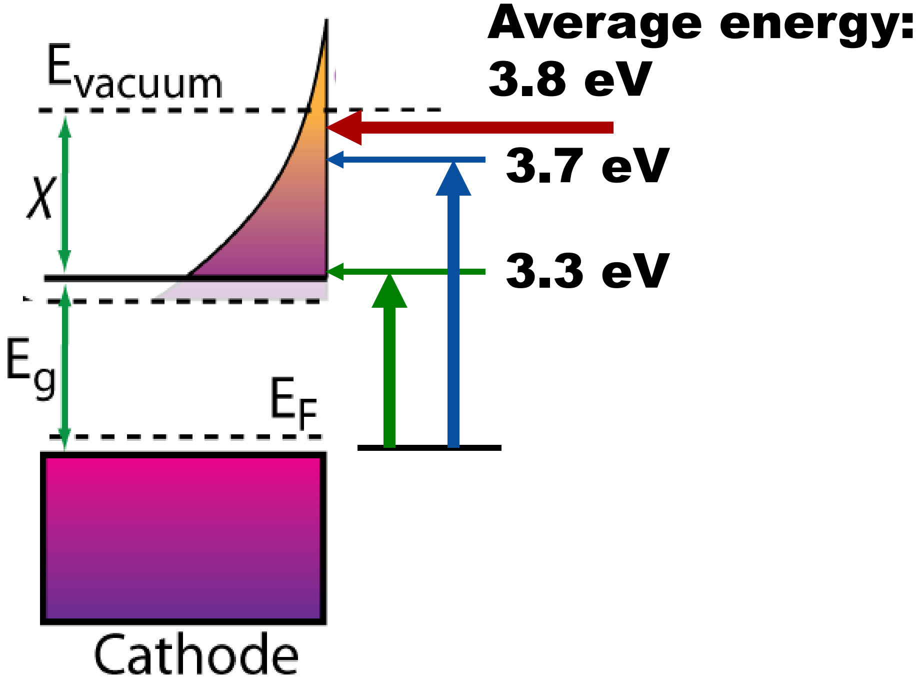


Experimental Apparatus:

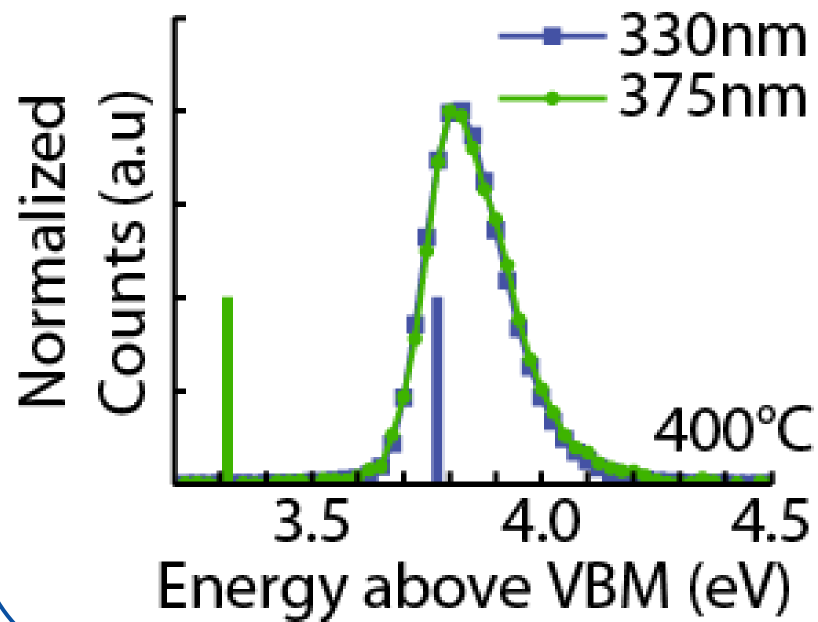


Photon-independent Emission Energy

- **Photon energy should not matter above band gap**
- **Very different from photoemission**
- **Green = just above gap**
- **Blue = well above gap, not above E_{vac}**



Energy distribution for different excitation energy

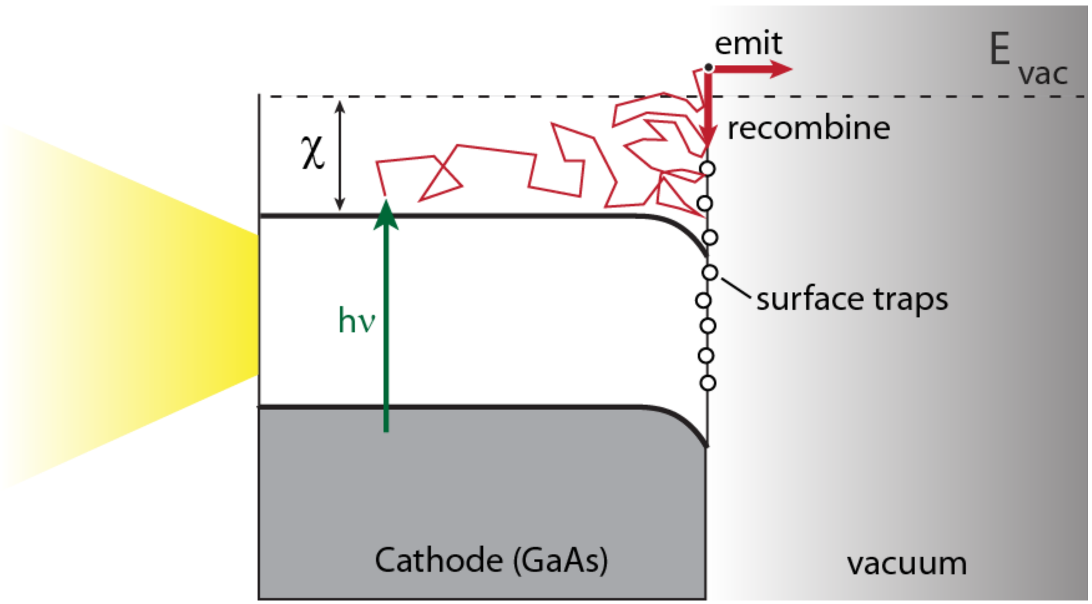


- **0.5 eV thermal voltage boost**
- **Efficiency ~10^{-4}**

Schwede et al, Nature Materials, 9 ,762–767, 2010

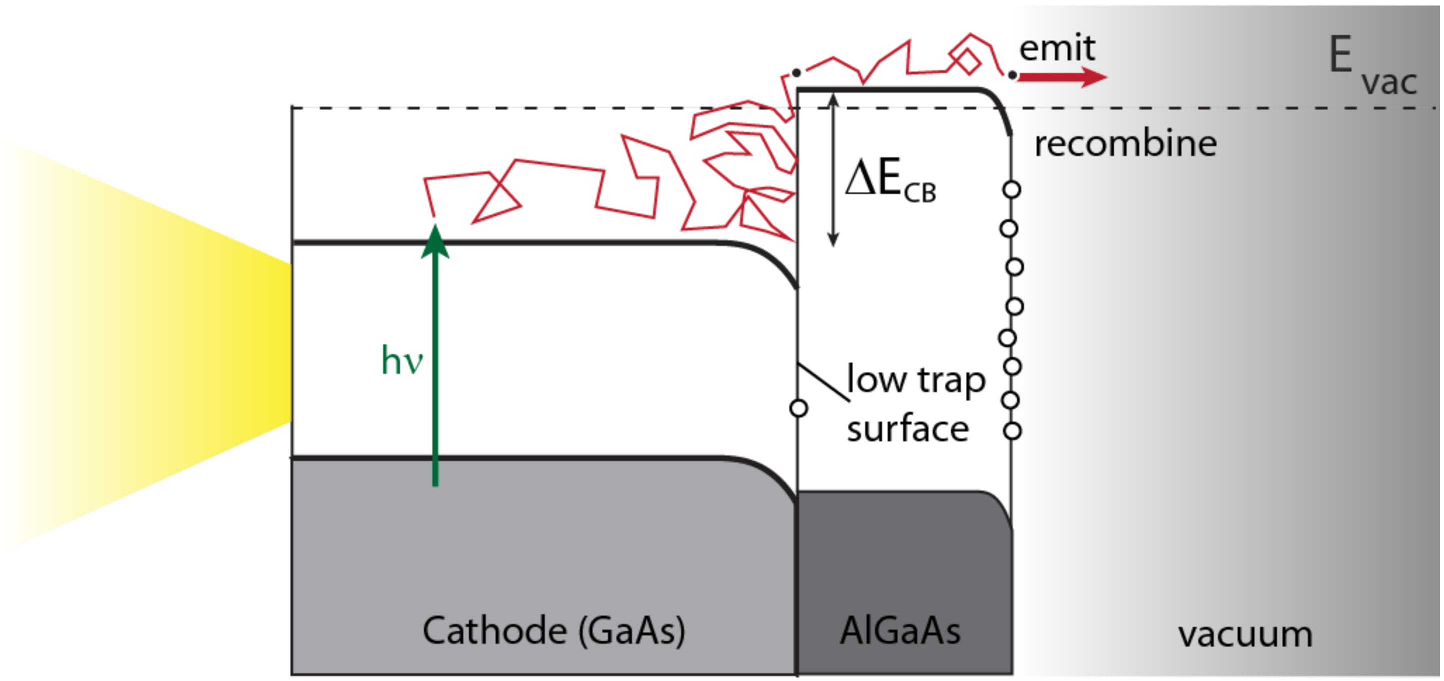
Sunshot Goal: Increasing Performance

Problem: Surface Recombination



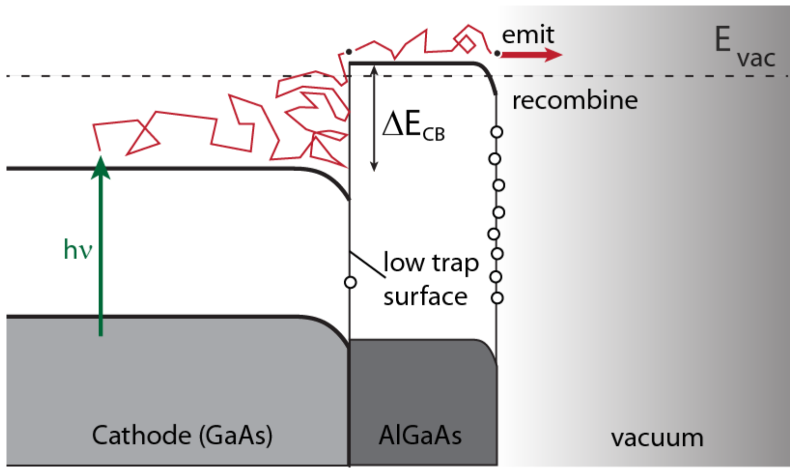
- Front-surface recombination directly competes with emission
- High surface recombination in most cathode materials
  - **10^6 cm/s in GaAs**
  - **Yield < 20% for T < 300°C, χ = 200 meV**

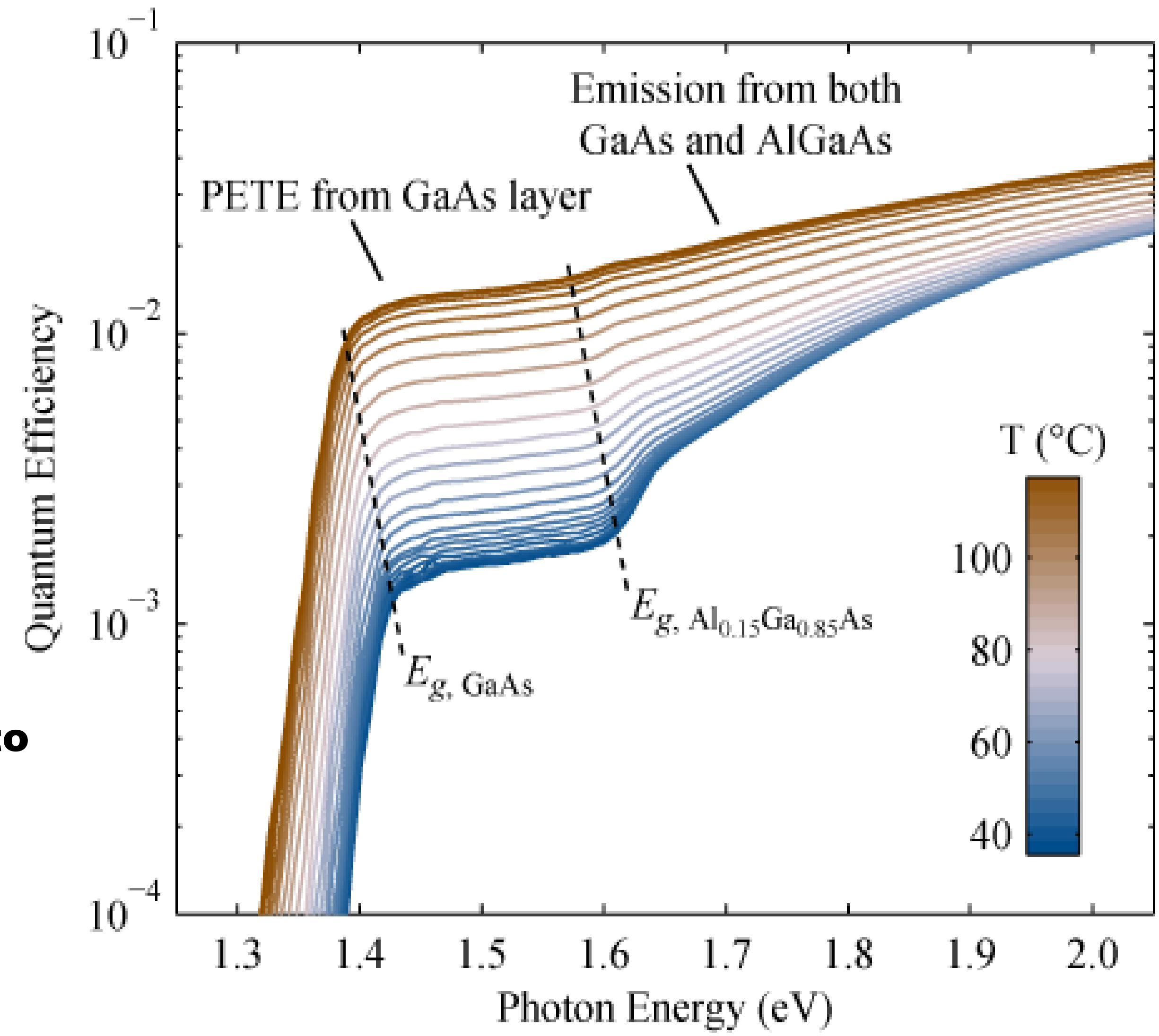
Heterostructure cathode for PETE



- Reduce recombination at surface by adding $Al_{0.15}Ga_{0.85}As$ layer
  - Very low recombination
  - Excellent control over barrier height
    - ΔE_{CB} ~= 190 meV, largely independent of temperature
- Coat front surface to be negative electron affinity
  - little sensitivity to surface recombination

Heterostructured cathode performance



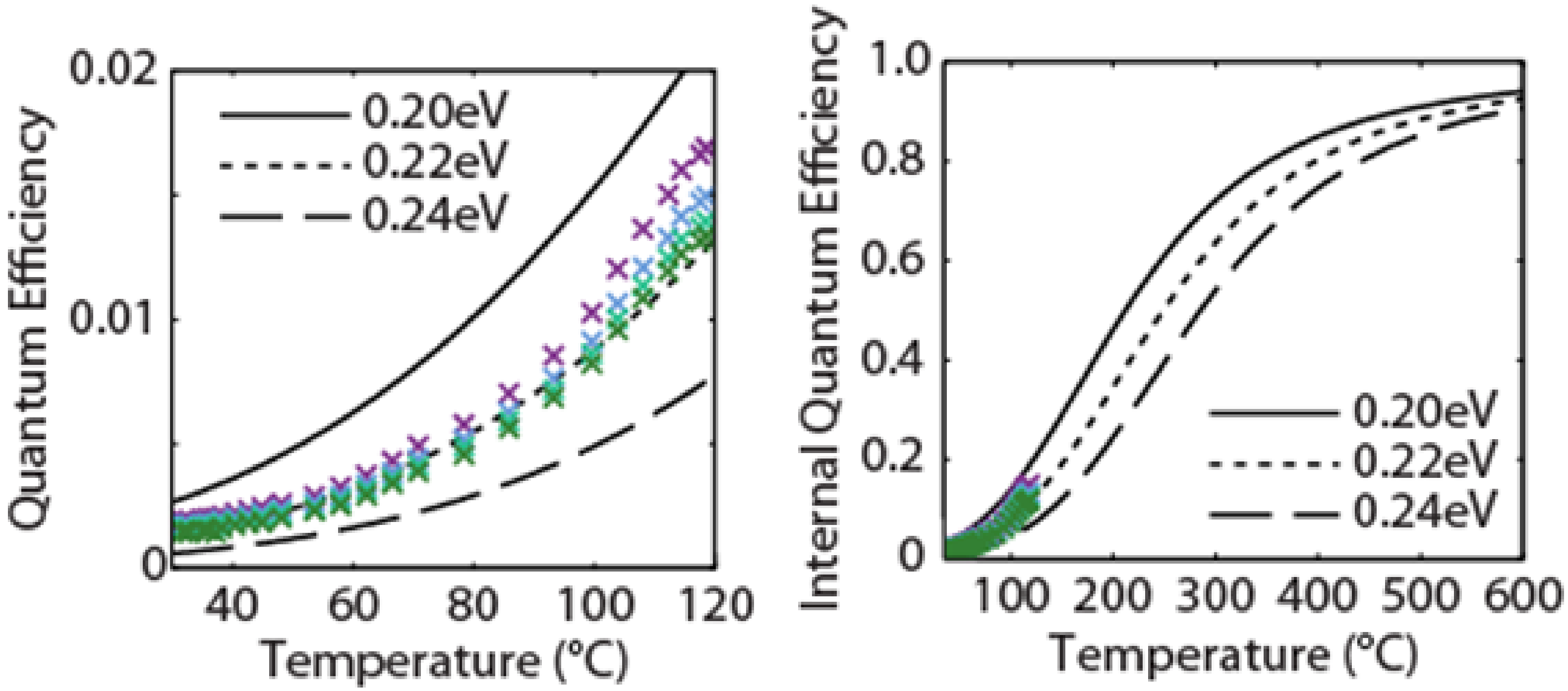


- **Very strong temperature dependence**
- **Yield increases 10x from 40ºC to 120ºC**
- **PETE current dominates photoemission**
- **Limited by thermal stability of CsO coating**

Improved quantum yield from 10^{-4} to 2.5%

Schwede et al, *Nature Materials,* 2013

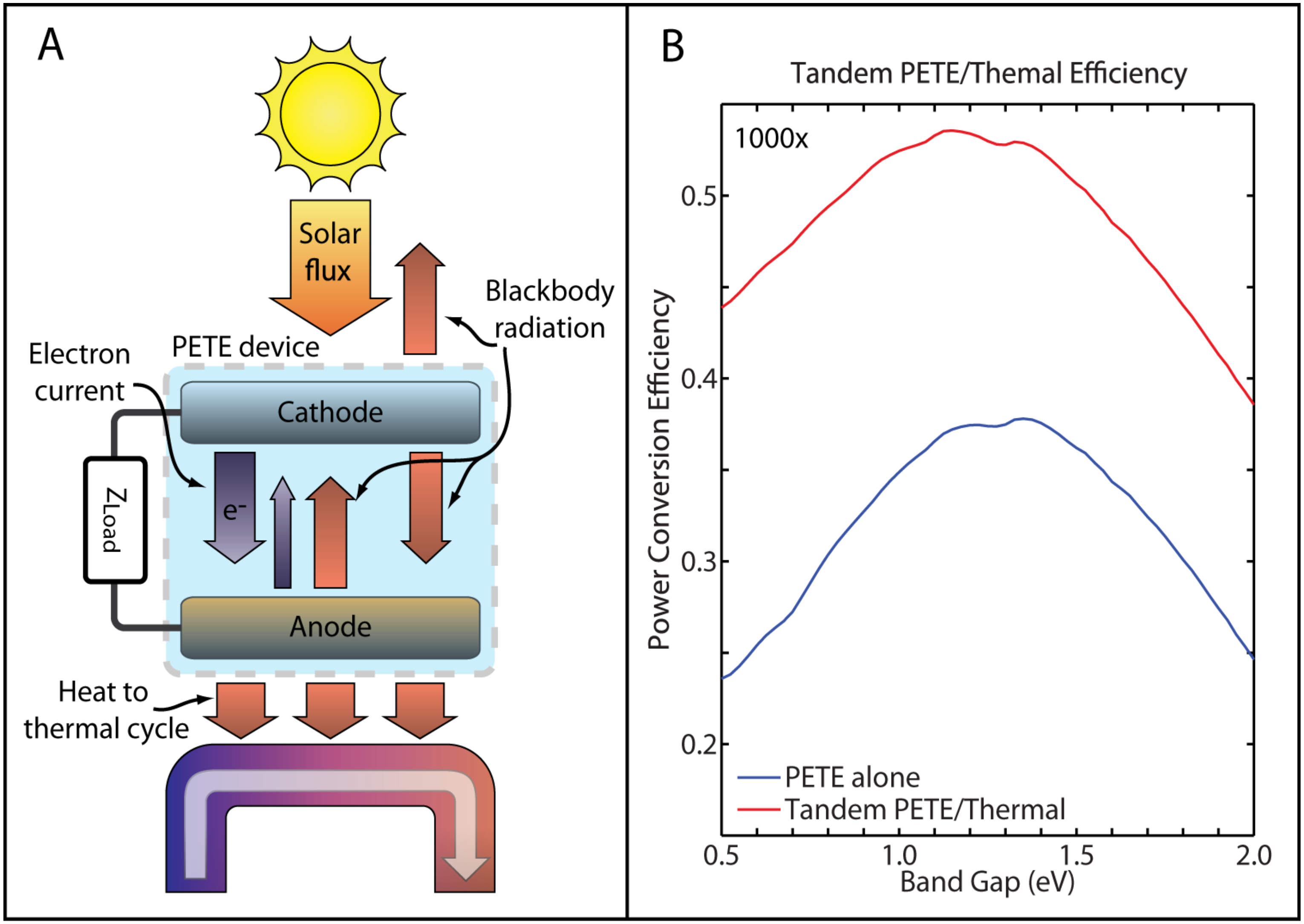
Tantalizing performance with Temperature



- **QY increases as calculated from RT to 120 C**
- **Something happens to sample above 150C**
- **If we could get just to 400C with exactly these properties, would have >80% QY.**

Schwede et al, *Nature Materials,* 2013

Theoretical Tandem Efficiency



31.5% Thermal to electricity conversion [Mills, Morrison & Le Lieve 2004]

285°C Anode temperature [Mills, Le Lievre, & Morrison 2004]

Take Home Messages

- ***Combined Cycles* may be practical means to greatly increase renewables energy conversion efficiency**
- **Thermionic systems are worth revisiting with modern tools**
- **PETE is a new way to combine thermal and photon energy**
- **Moderate PETE efficiency could make economic impact**