Heterostructure Materials for Photon Enhanced Thermionic Emission and Micro-Thermionics

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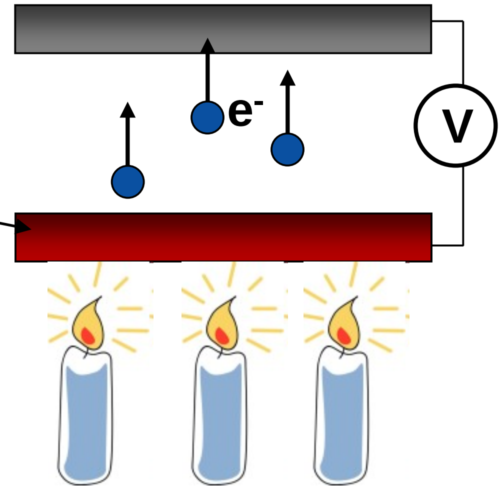
Thermionic Emission

Boiling water:

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

Boiling electrons from a metal:

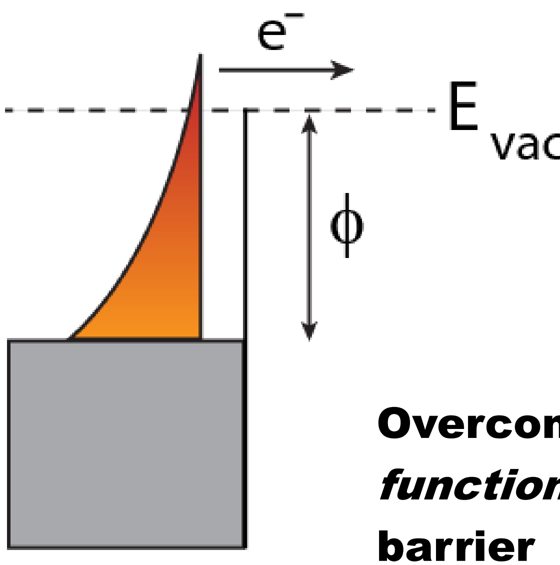


- **Operates at very high temperatures; generally >800ºC**
- **Robust**

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

(Richardson-Dushman law)

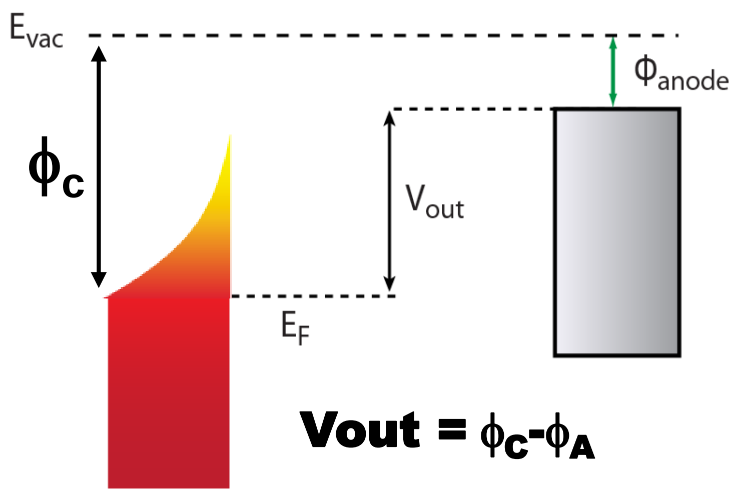
J = current density (Acm^{-2}),
Φ_E = emitter work function (eV)



Overcome *work-function* energy barrier

Two Key problems with TEC:

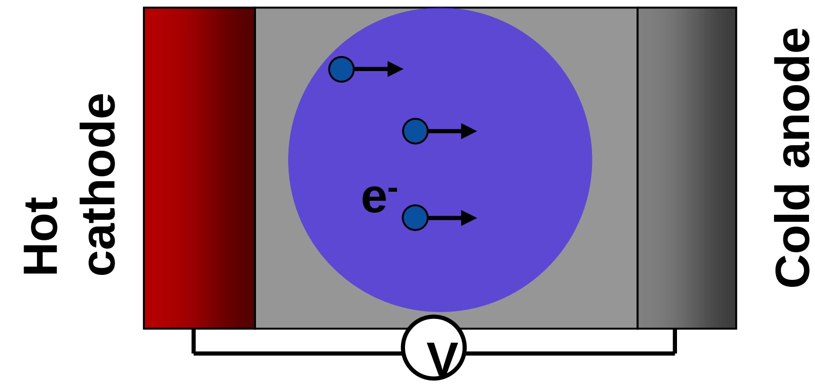
High-T / Low V_{out}



$V_{out} = \phi_C - \phi_A$

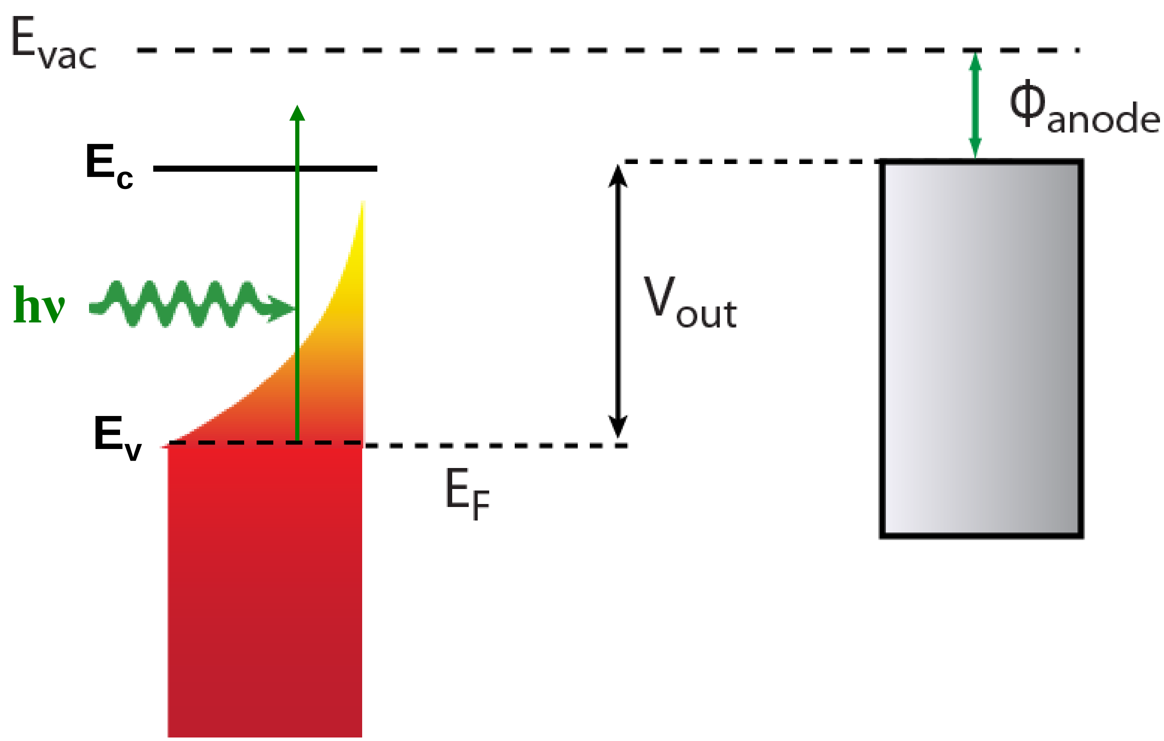
- need reasonable cathode ϕ_c to have decent voltage
- Need high temperature (>1200C) to overcome workfunction
- Still need small anode ϕ_A

Space Charge



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

The PETE Process



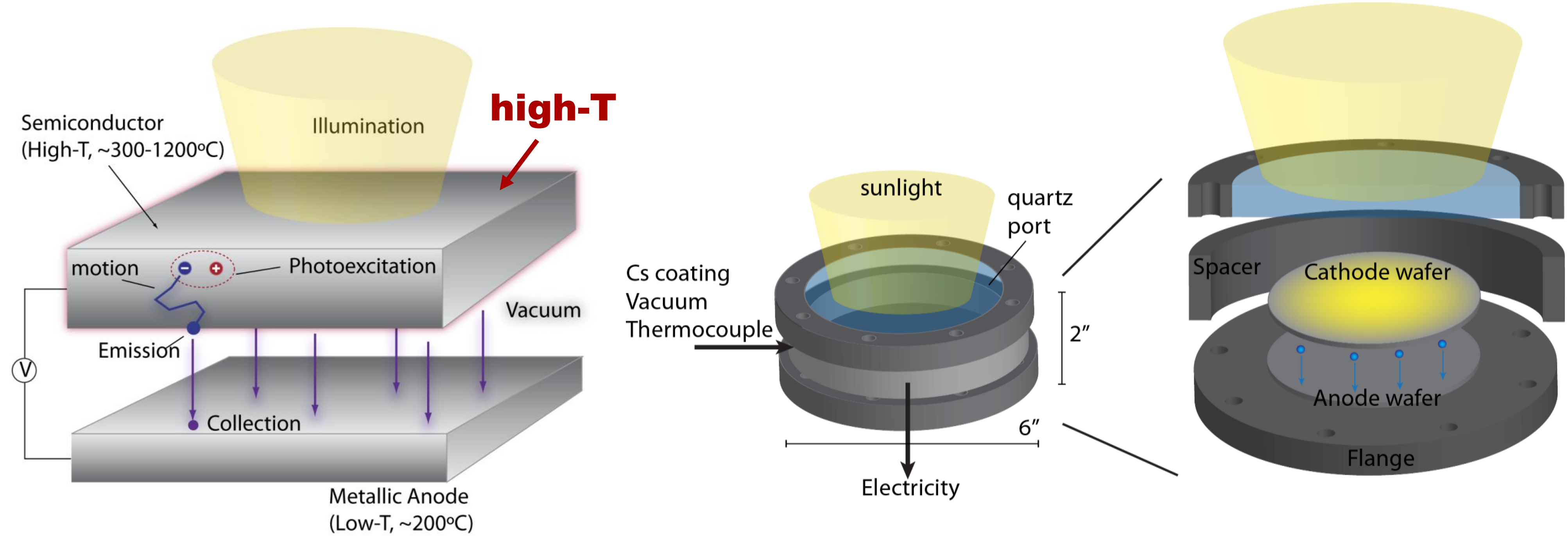
semiconductor

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

Photon Enhanced Thermionic Emission (PETE)

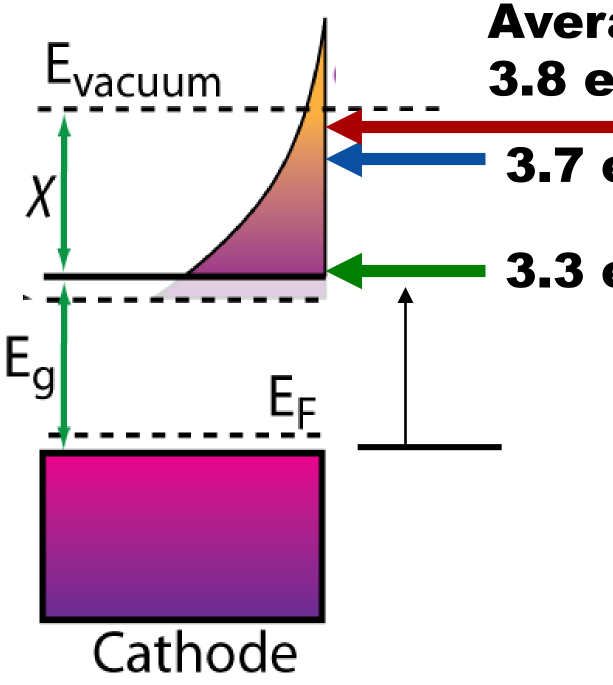


- **Photo-excite carriers into conduction band**
- **Thermionically emit these excited carriers**
- **Overcome electron affinity barrier (not full work-function)**
- **Collected at low work-function anode**

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

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}**



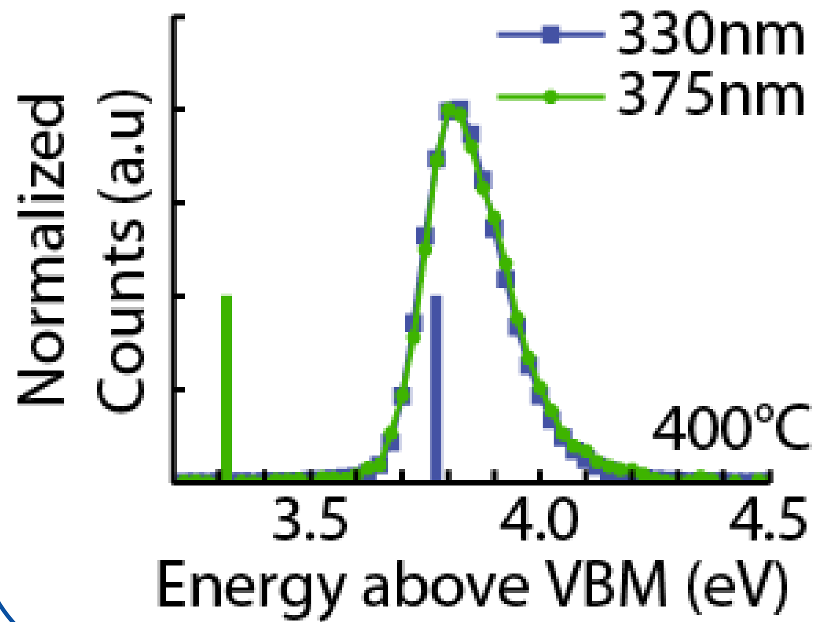
Average energy: 3.8 eV

3.7 eV

3.3 eV

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

Energy distribution for different excitation energy

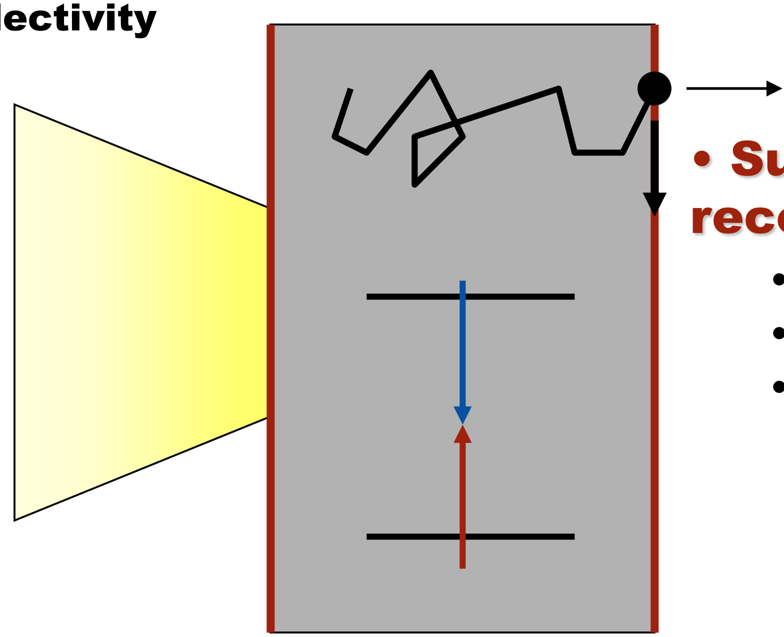


- **Identical energy distributions**
- **0.5 eV thermal voltage boost significant**
- **400C = 0.056 eV**
- **efficiency ~10^{-4}-10^{-5}**

Making PETE more efficient

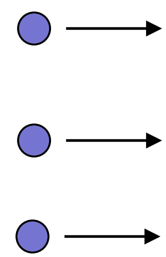
Mechanisms that determine PETE efficiency:

- **Incomplete absorption**
  - thin films
  - reflectivity



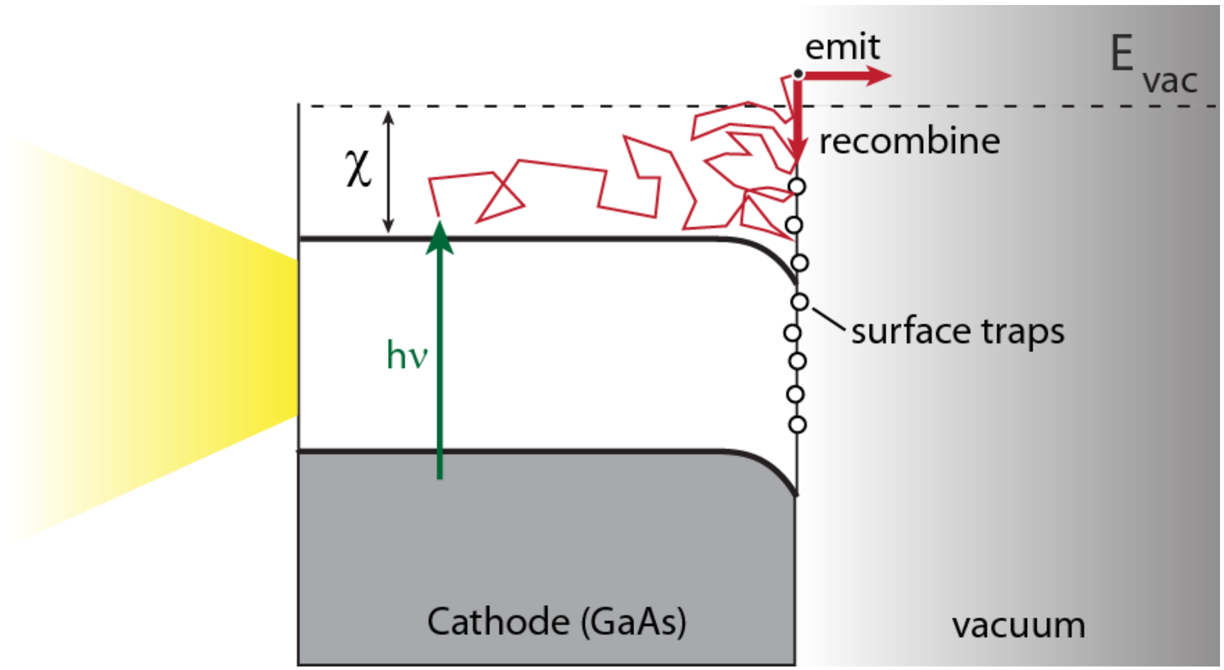
- **Surface recombination**
  - defects
  - coatings
  - intrinsic surface

- **Space Charge**



- **Bulk recombination**
  - black body
  - auger
  - defects

Reducing Surface Recombination



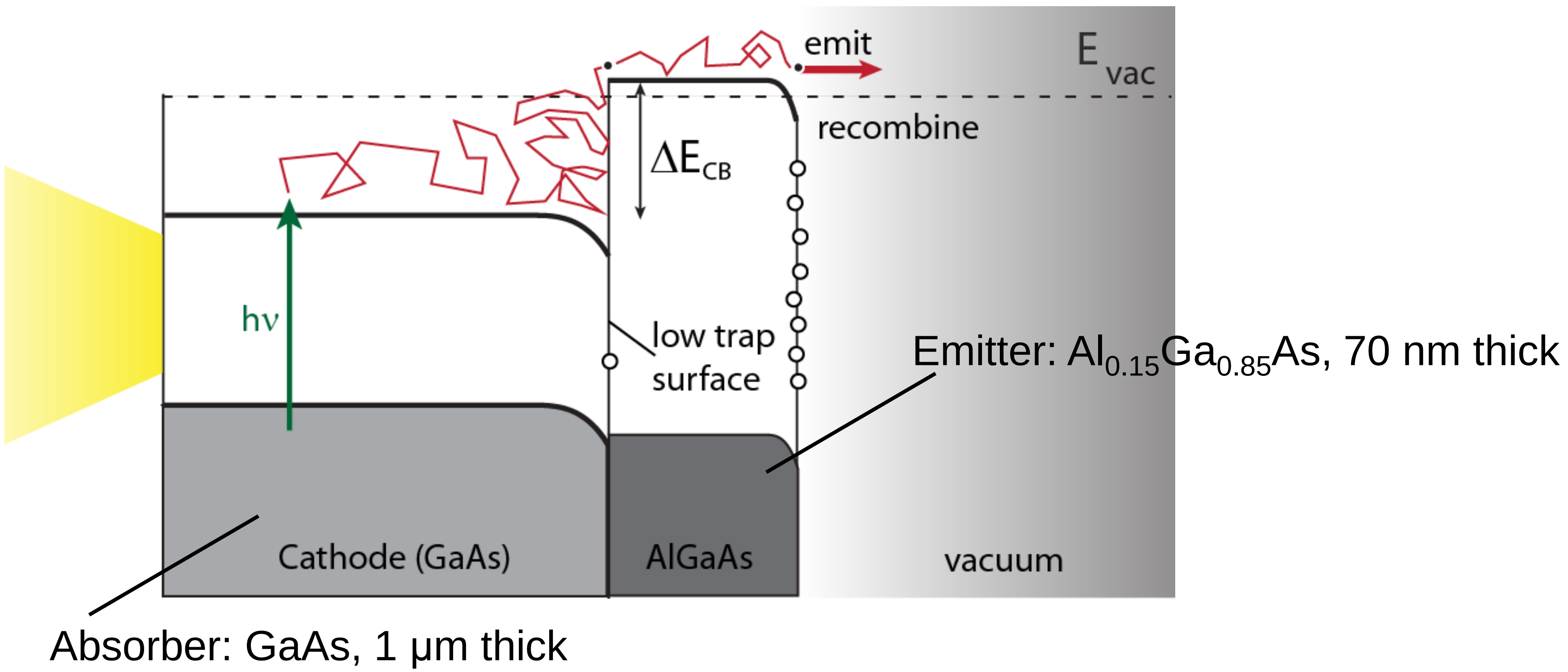
S_{surf} ~ 10^1-10^6 cm/s

$S_{emit} = \langle v_x \rangle e^{-\chi/kT}$

~ 10^1-10^5 cm/s

- Front-surface recombination directly competes with emission
- Surface coatings (Cs, etc) increase recombination
- Can lower χ, but lose voltage
- High surface recombination in most cathode materials:
  - **10^6 cm/s in GaAs**
  - **Yield < 20% for T < 300°C, χ = 200 meV**

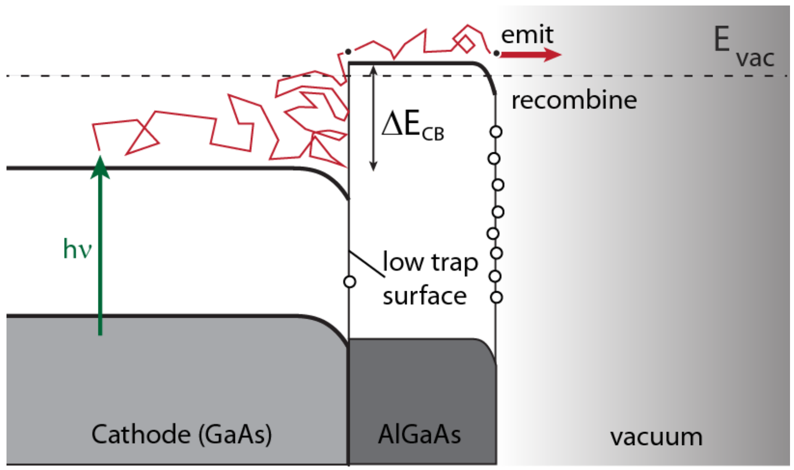
Heterostructure cathode for PETE

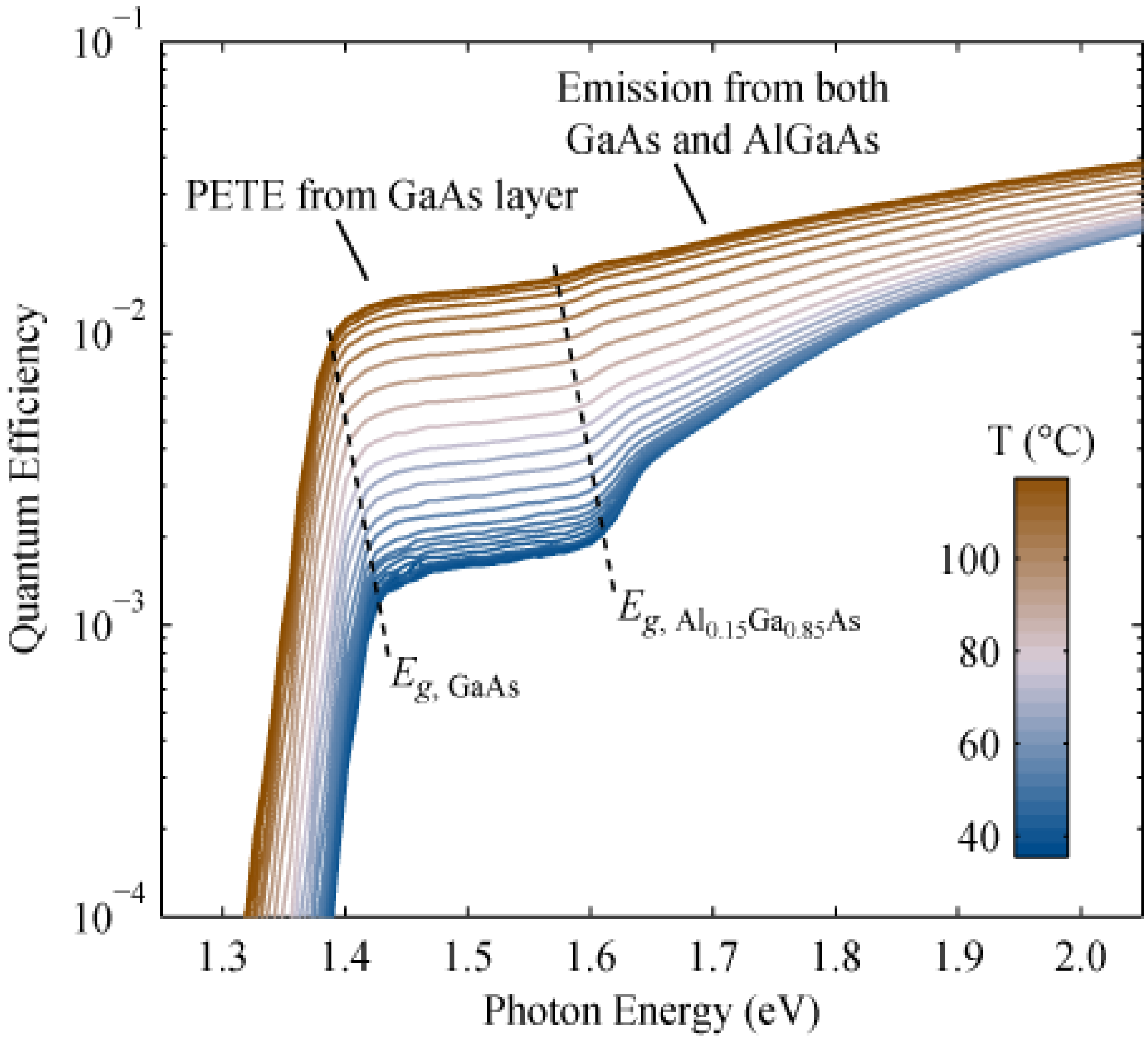


- Reduce recombination at surface by adding $Al_{0.15}Ga_{0.85}As$ layer
  - Very low recombination
  - Excellent control over barrier height
    - ΔE_{CB} ~= 220 meV, largely independent of temperature
- Coat front surface to be negative electron affinity
  - little sensitivity to surface recombination

Heterostructures grown by Tomas Sarmiento, Prof. James Harris

Heterostructured cathode performance



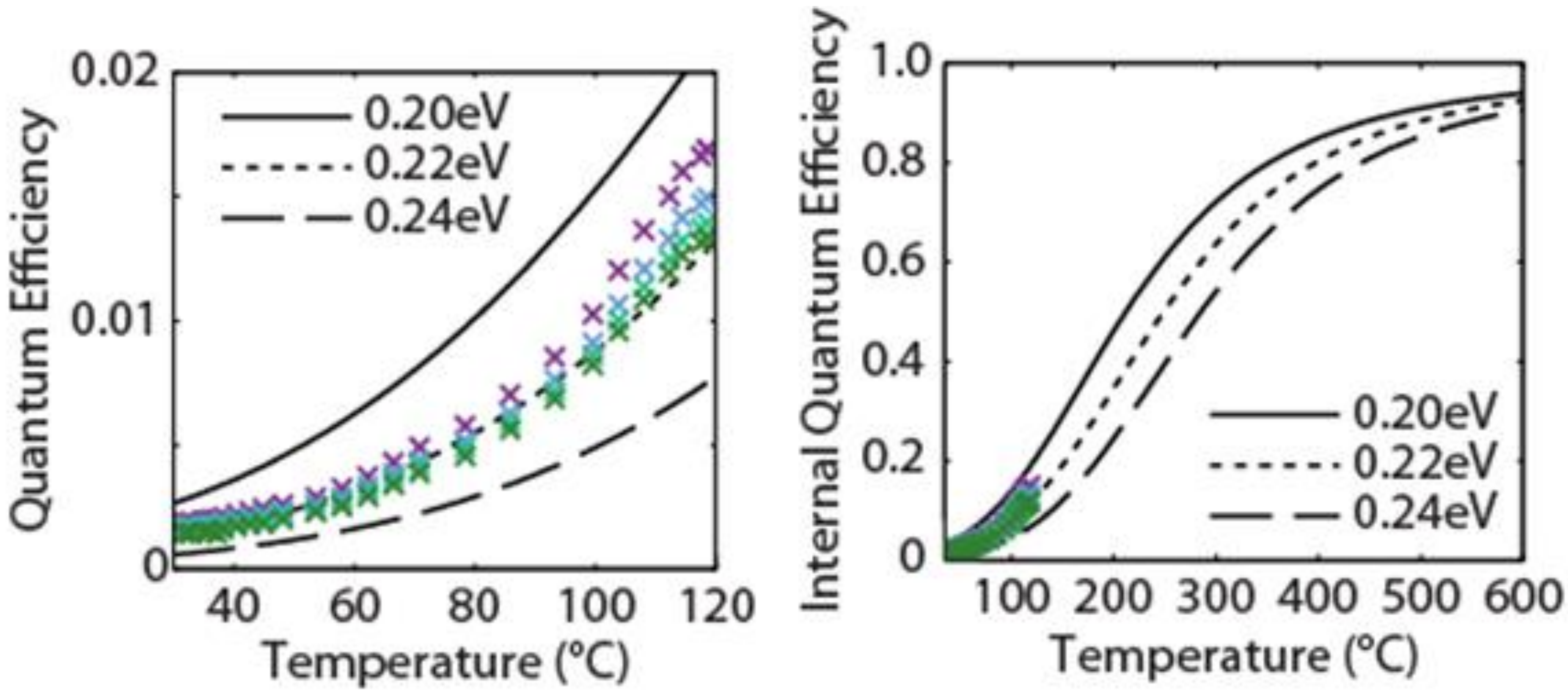


- **Very strong temperature dependence**
- **Yield increases 10x from 313 K to 393**
- **PETE current dominates photoemission from GaAs layer**
- **Limited by thermal stability of CsO coating**

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

Schwede et al, Nature Communications, 2013

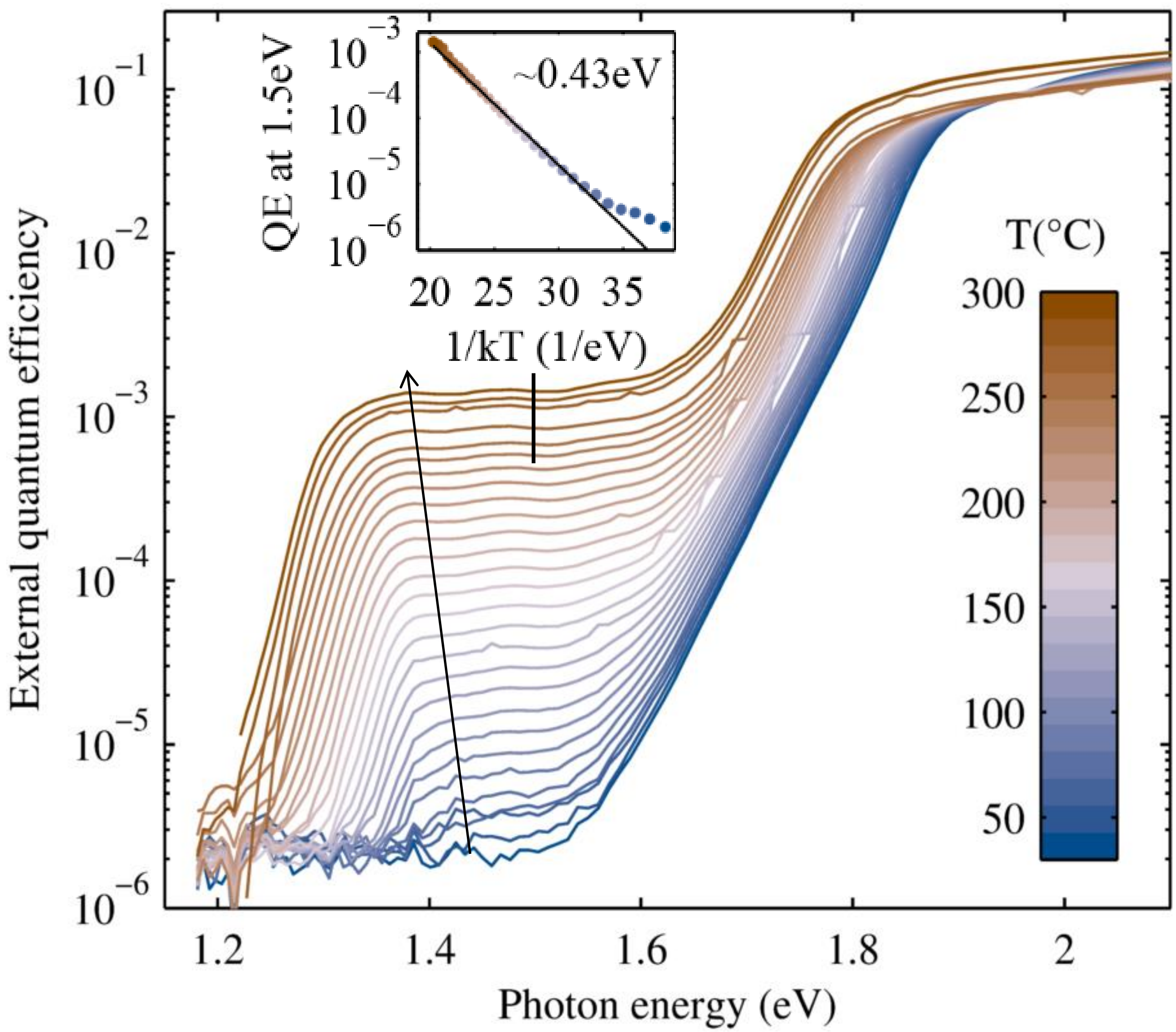
Tantalizing performance with Temperature



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

Schwede et al, Nature Communications, 2013

“Solid-state” GaInP PETE device



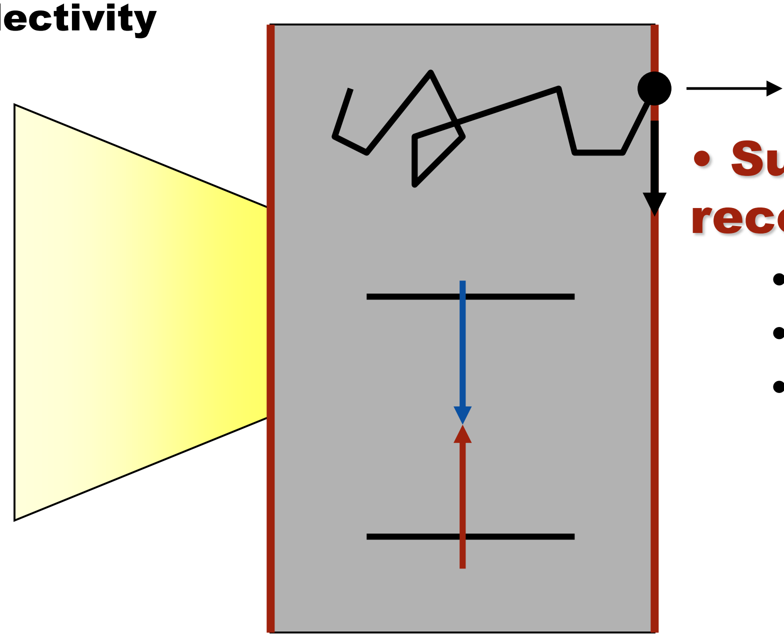
- Much larger temperature range is possible
- 1000x improvement in current

Making PETE more efficient

Mechanisms that determine PETE efficiency:

•Incomplete absorption

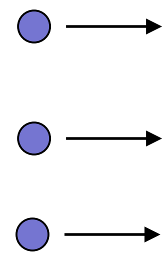
- thin films
- reflectivity



• Surface recombination

- defects
- coatings
- intrinsic surface

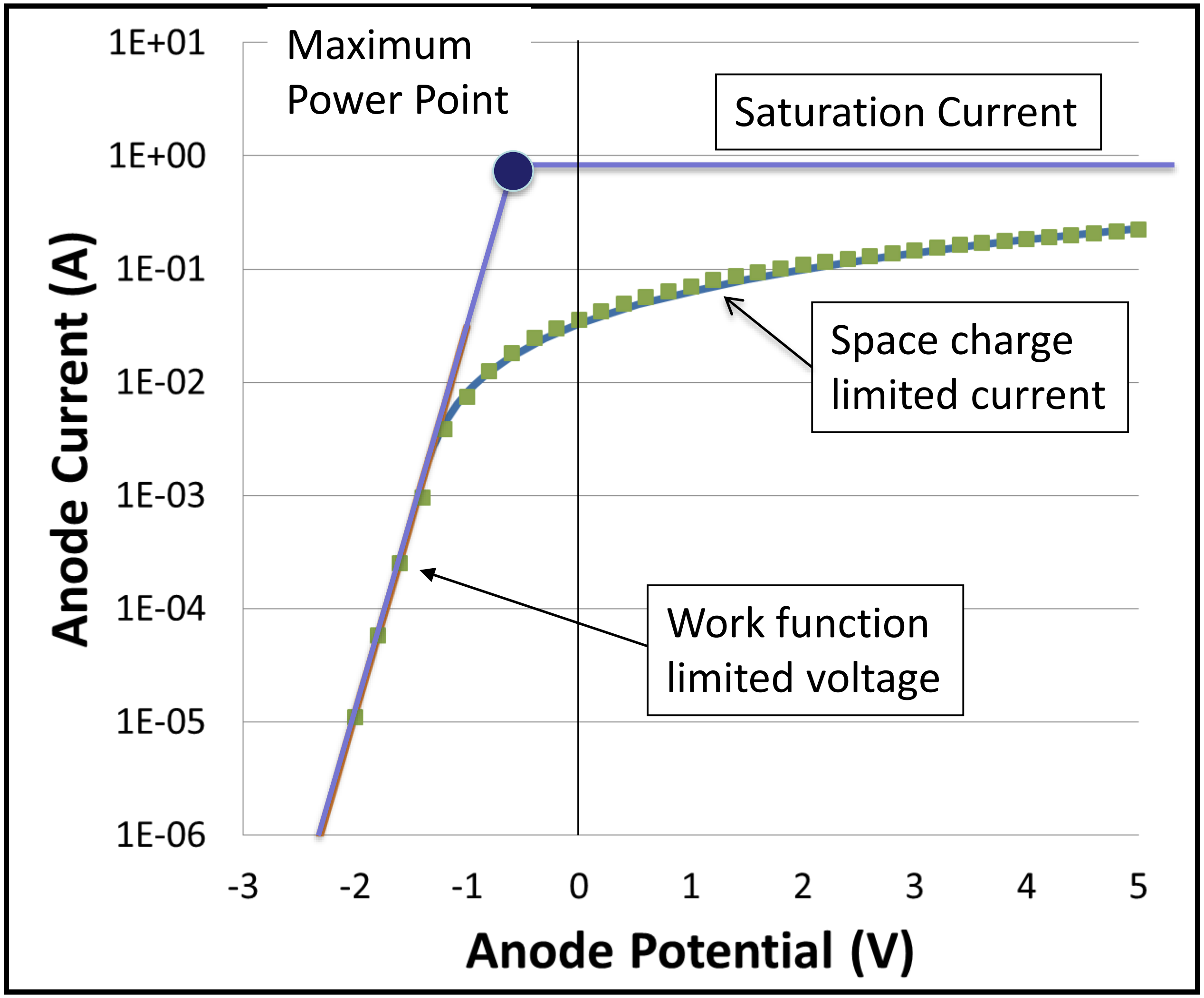
• Space Charge



• Bulk recombination

- black body
- auger
- defects

The Space Charge Limit



- **At a given T, current saturates due to space charge:**

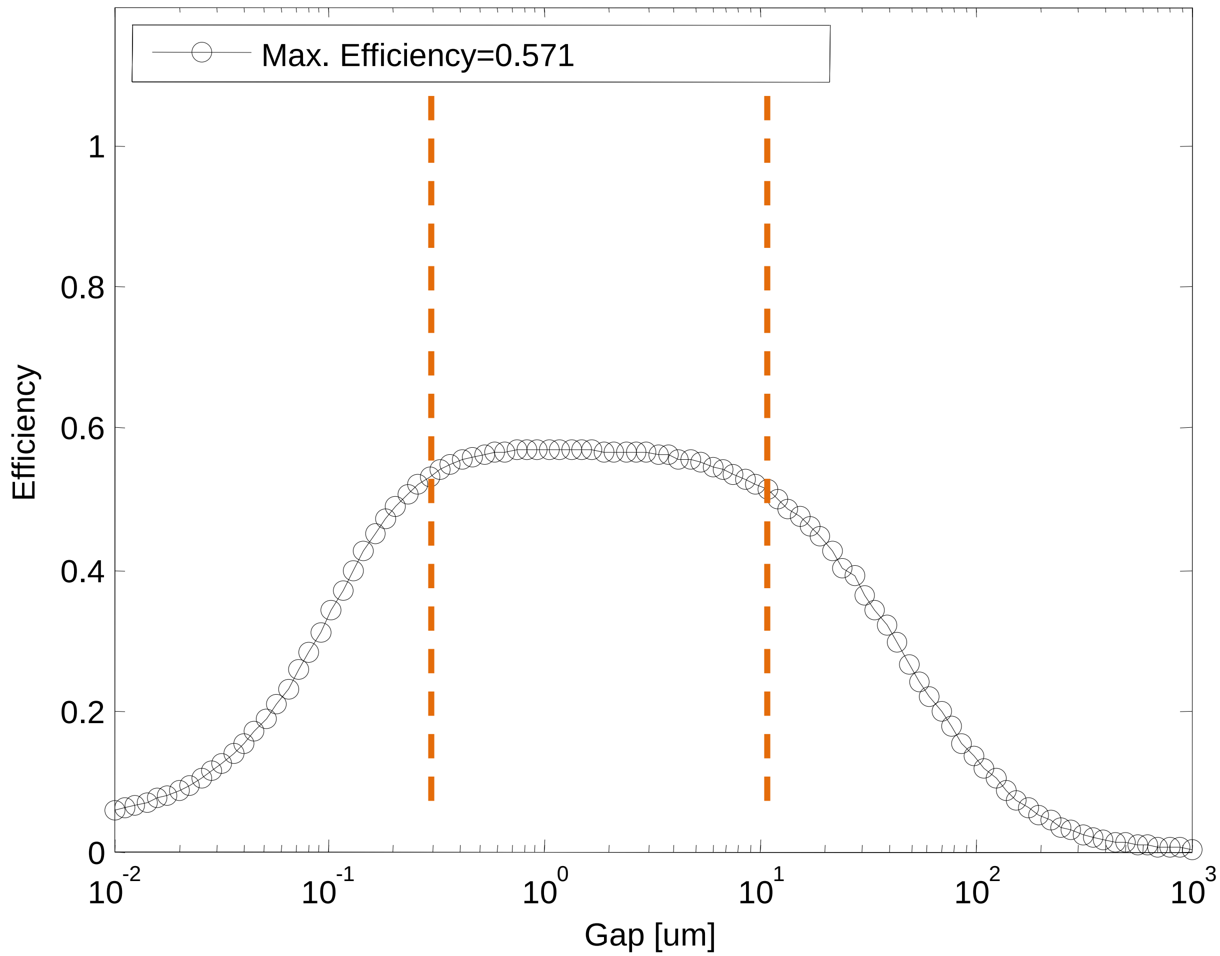
$$J = \frac{4\sqrt{2}}{9}\varepsilon_o\left(\frac{e}{m_e}\right)^{1/2}\frac{|V|^{3/2}}{d^2}$$

Child-Langmuir Law

- **Depends on output voltage, electrode separation distance**

- **Power generation occurs at negative anode potentials**

Optimal Gap Size



Photon tunneling

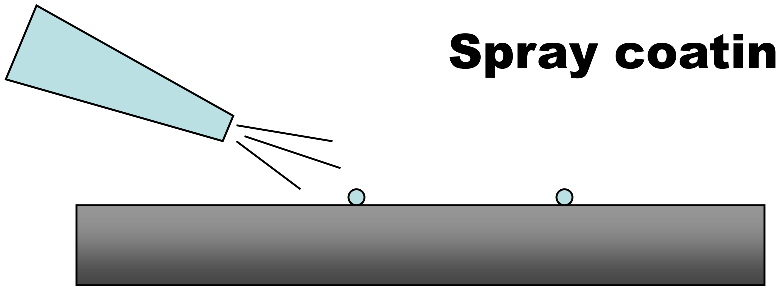
Optimal Gap: > 90% of Max. Eff.

Space charge limit

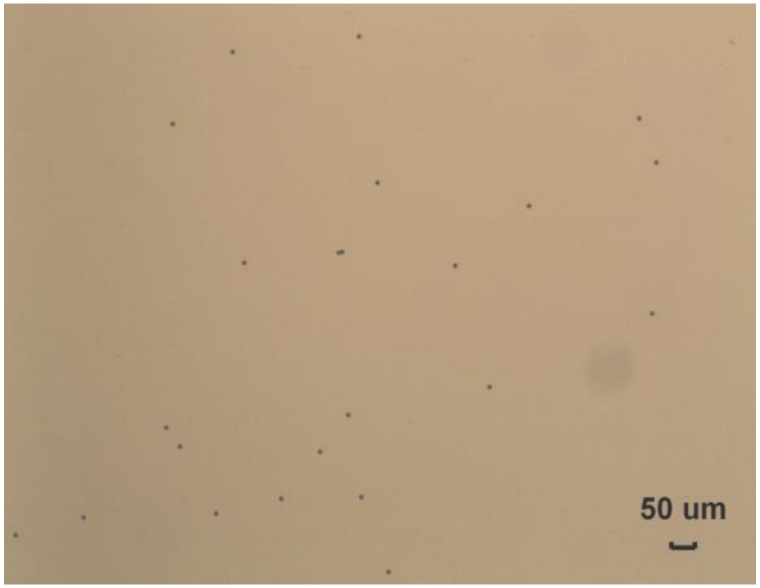
TE=2000[K],TC=300[K], φ_E =3[eV], φ_C =0.7[eV],

J. Lee et al (Howe group), APS, 2012

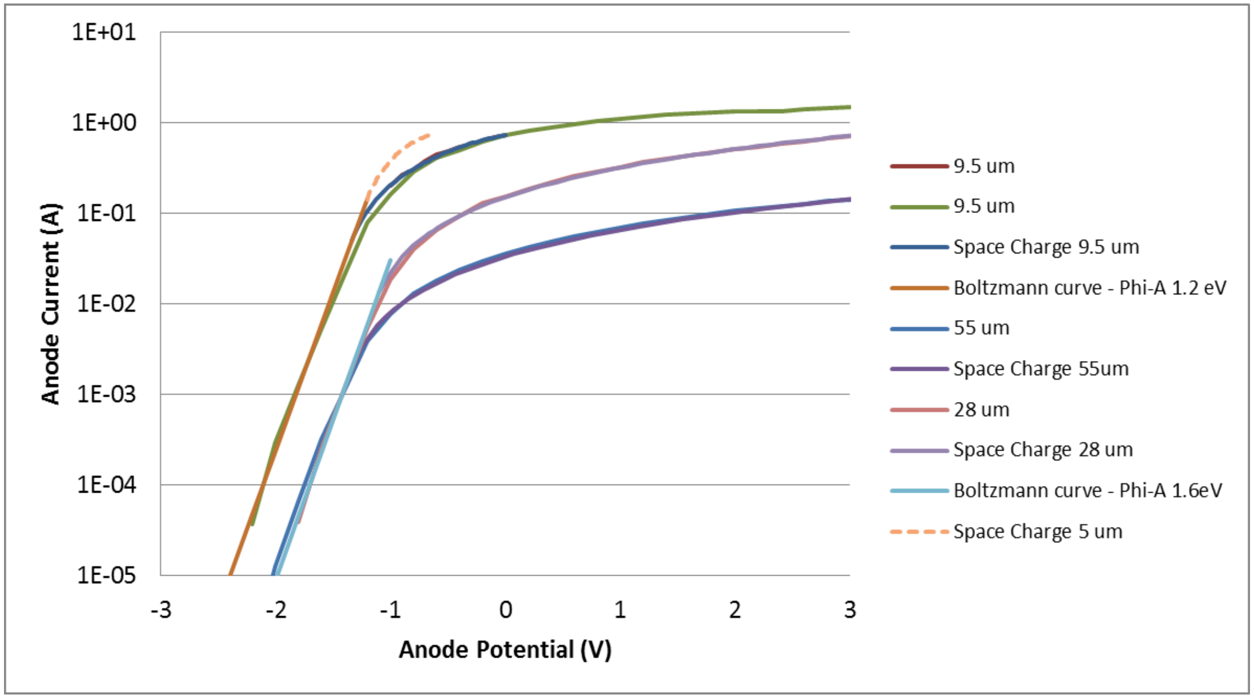
MicroSphere Spacers



Spray coating



Low density 5 um Microspheres

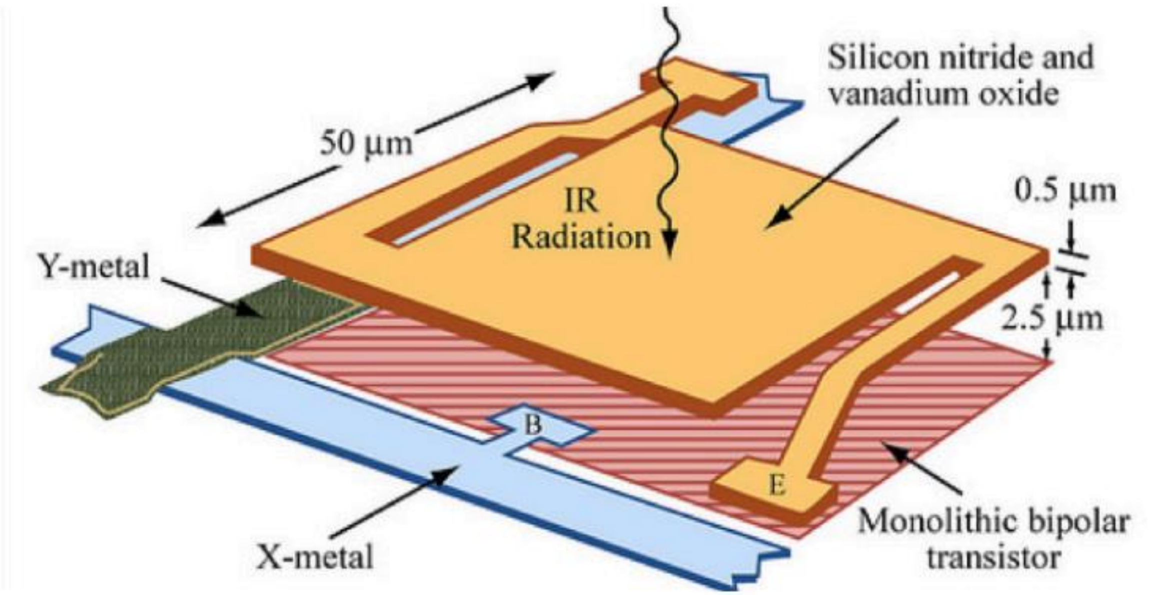


- Current is severely space charge limited at 55 um gap
- At 9.5 um gap, conversion efficiency of 1.8% at mpp
  - Does not account for heating losses, which are significant.
- Richardson constant 60-90 A/cm^{2}K^2, I_{mpp} > 1.5 A/cm^2
- 5 um gap model predicts x2 increase in current and efficiency

Sahasrabuddhe et al ,EES, 2013

Micro-fabrication Approach

- Micro-bolometer arrays for uncooled IR imaging (Honeywell Research, 1980s – 1990s)



IR radiation, Φ

↓

Temperature change, T

↓

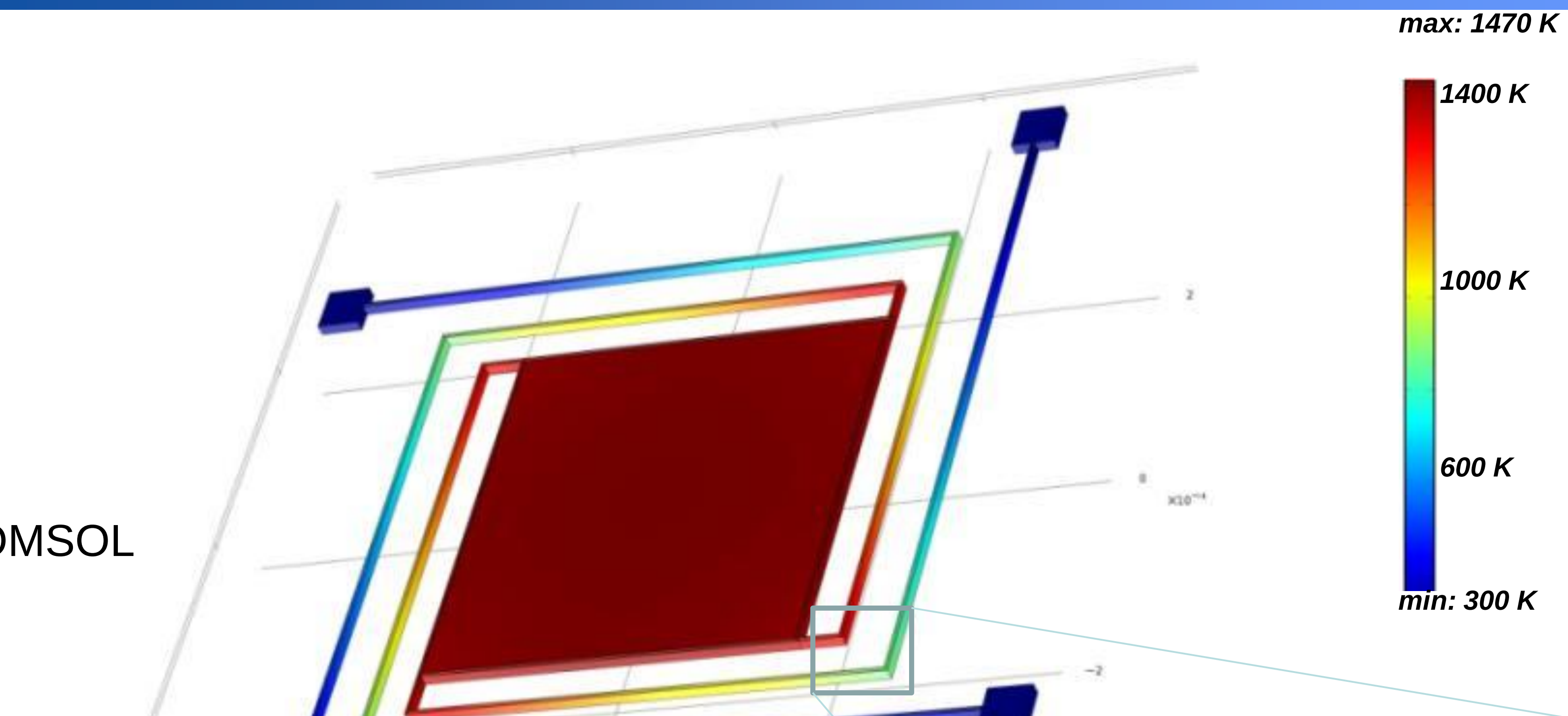
Resistance change, R

> Temperature changes on the order of milli-K can be detected

> Renewed interest for heads-up night vision for automobiles

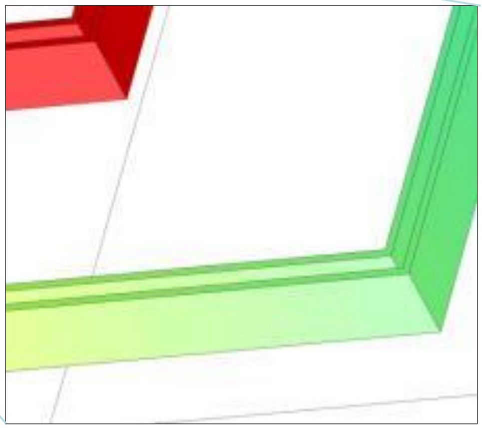
P. W. Kruse, *et al*., *SPIE Proc*., **3436**, 572-577 (1998).

Thermal Expansion and Isolation



COMSOL

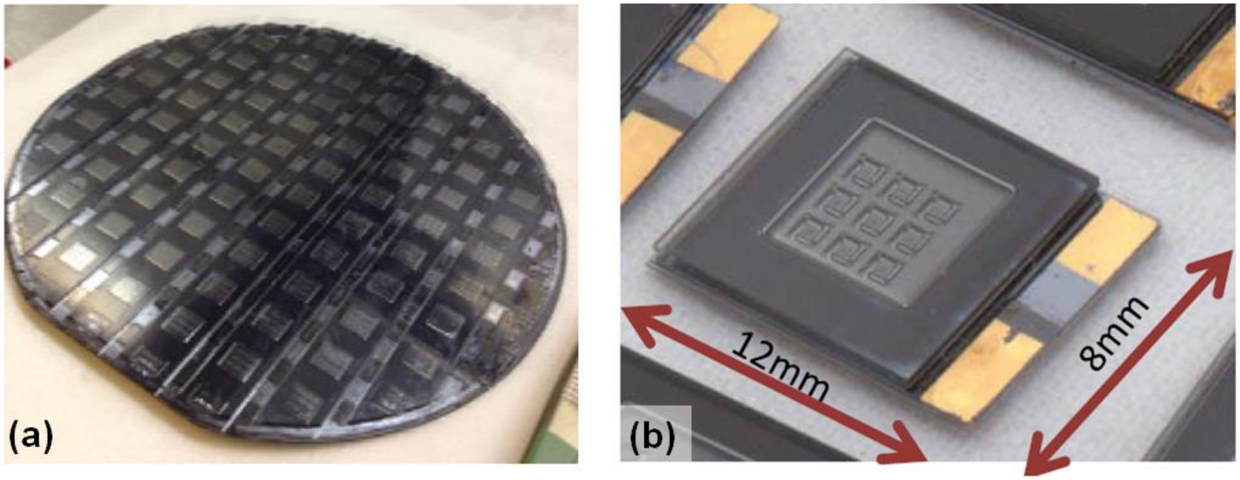
Pixel side 350 μm,
U-trough wall height 10 μm,
film thickness 1μm

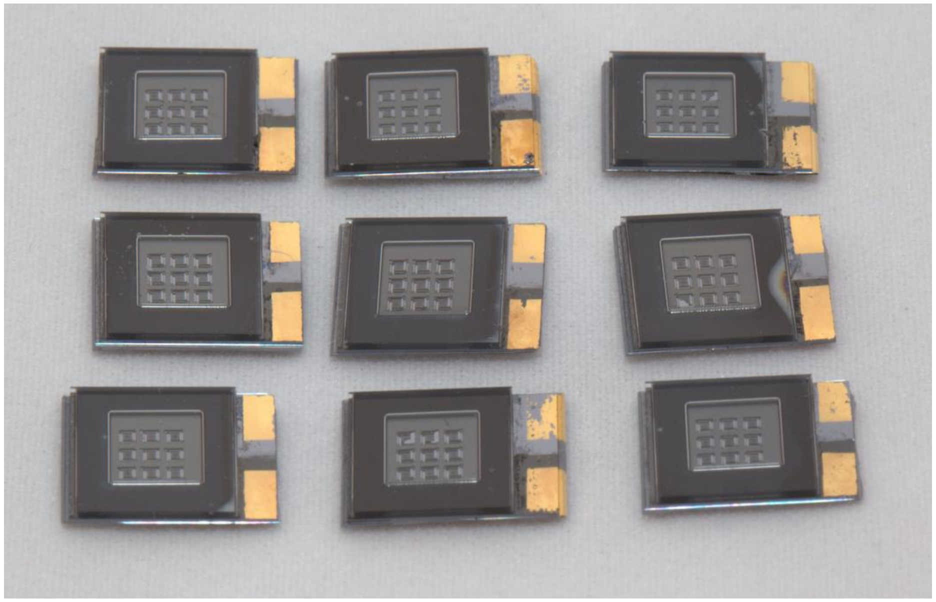


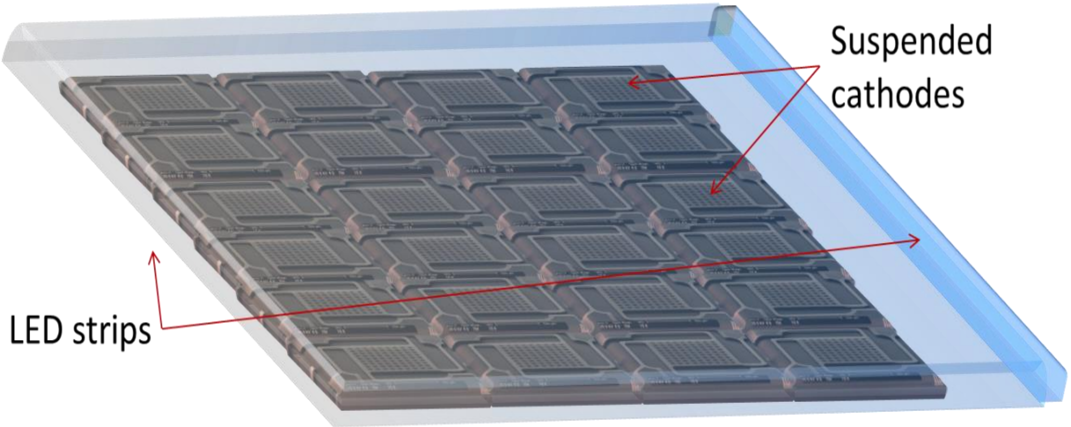
U-trough suspension

With I. Bargatin and R. T. Howe, unpublished

Vacuum-Encapsulated Micro-TECs

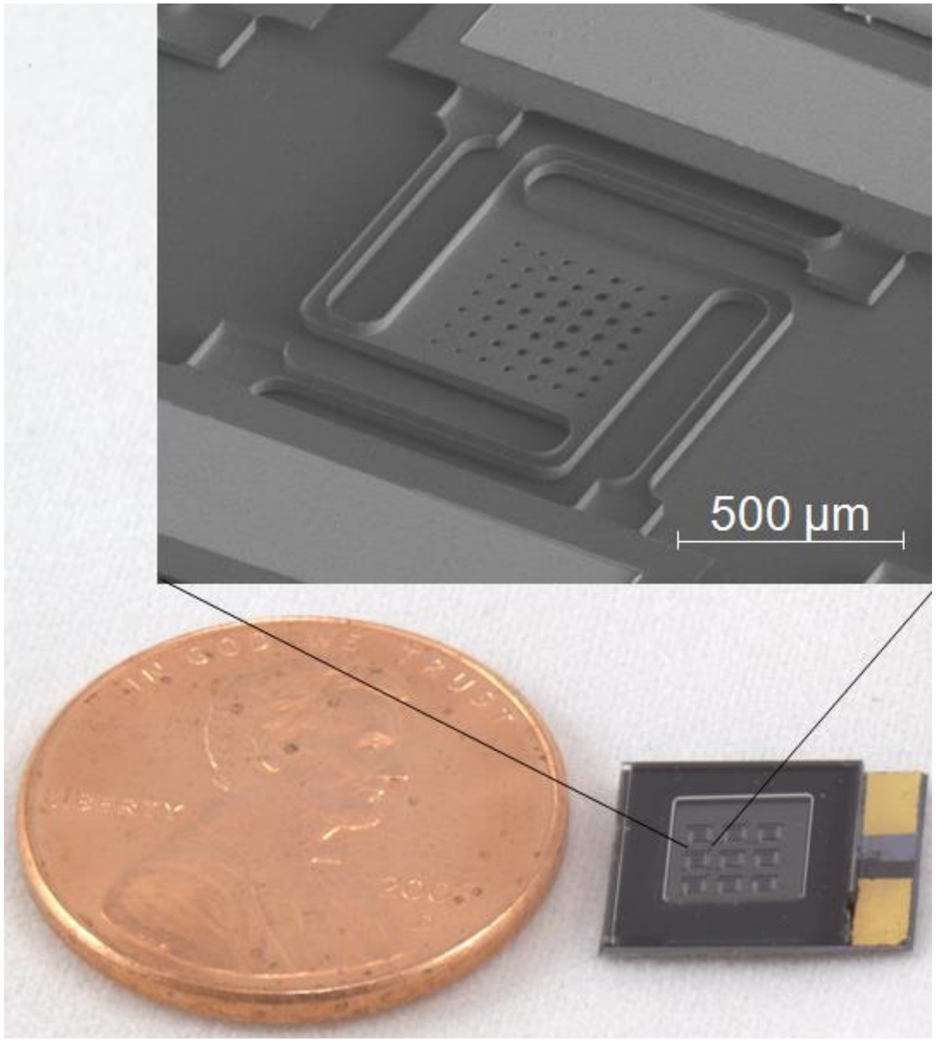


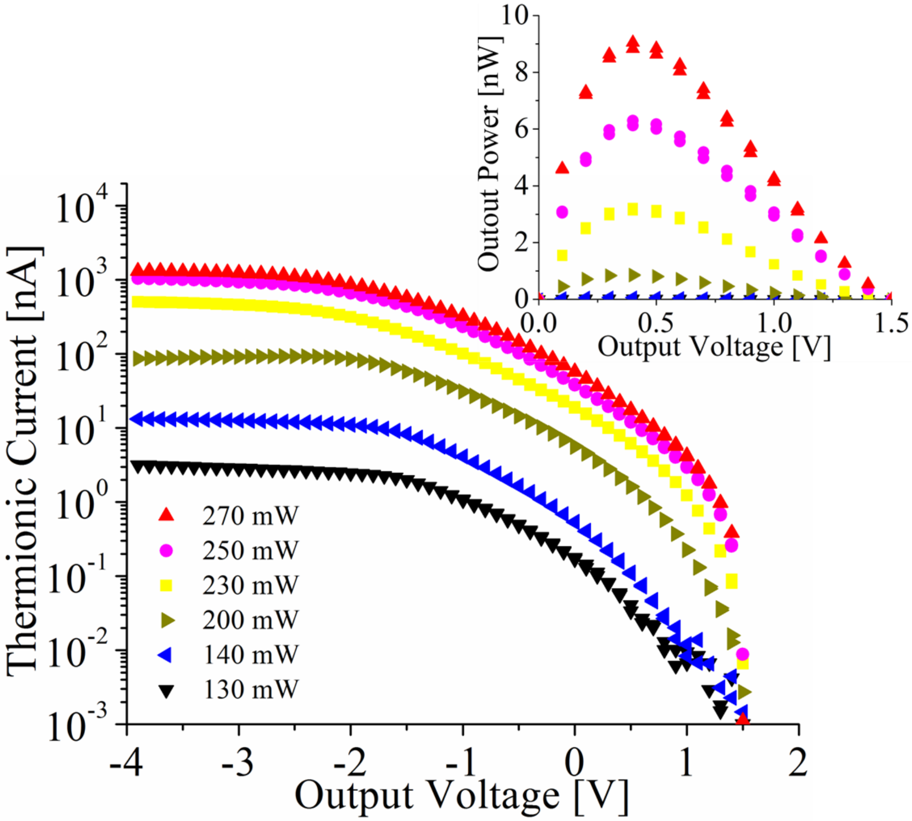




J. H. Lee, *et al*, Hilton Head 2012

U-shape TEC

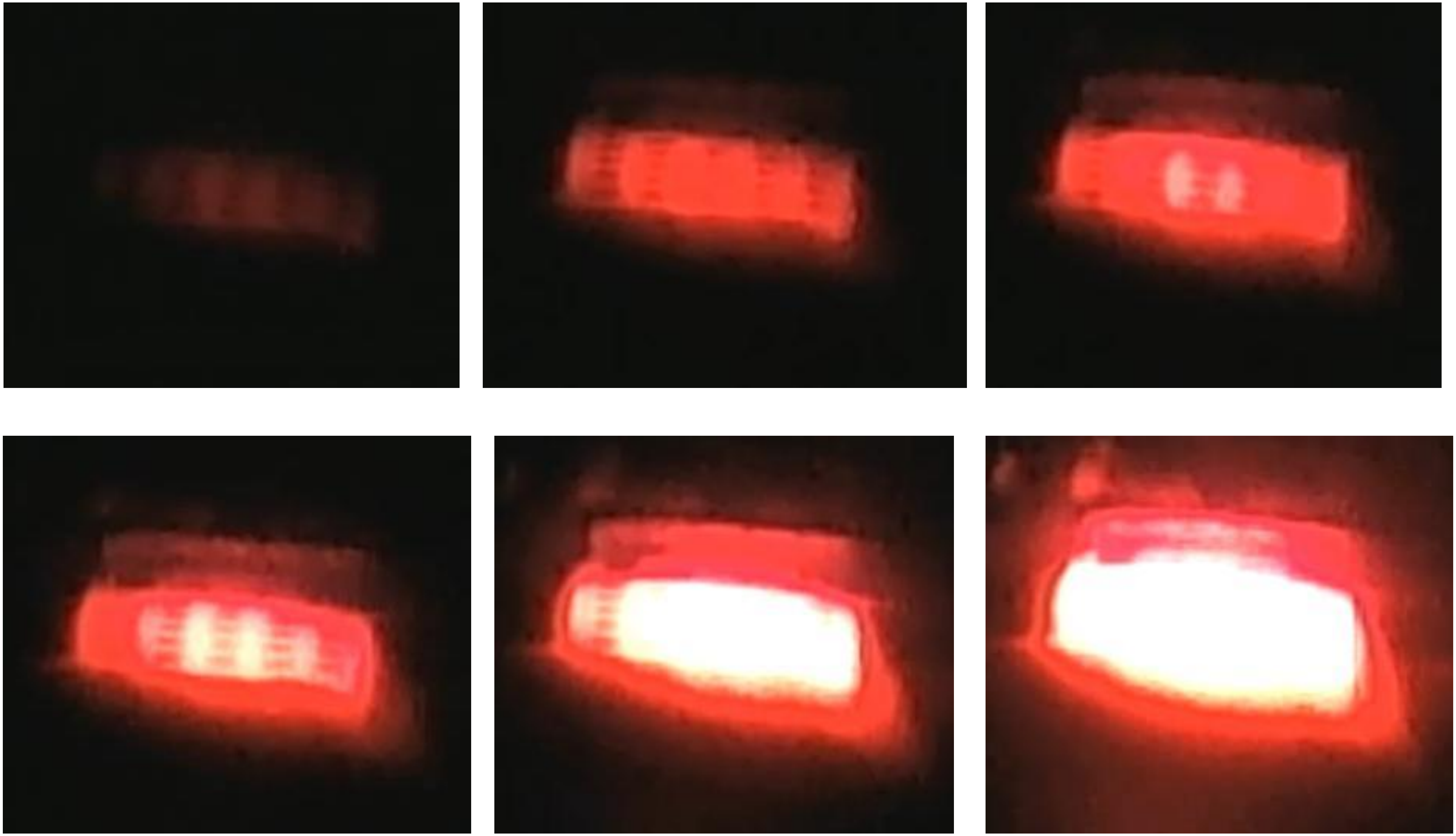




- **U-shaped devices on chip**
- **Anodically bonded encapsulation**
- **Prevents warping, shorting**
- **Current density up to 4 A/cm²**

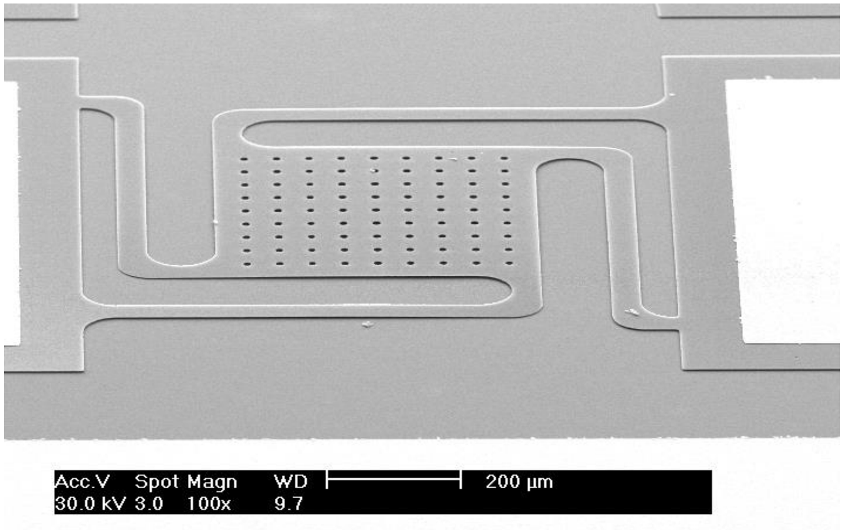
"ENCAPSULATED THERMIONIC ENERGY CONVERTER WITH STIFFENED SUSPENSION"
Jae Hyung Lee[1], Igor Bargatin[1], Kentaro Iwami[1,2], Karl A. Littau[1], Maxime Vincent[3],
Roya Maboudian[3], Z.-X. Shen[1], Nicholas A. Melosh[1], and Roger T. Howe[1]
Hilton Head MEMS Workshop, 2012

Optical Heating of Poly-SiC Microcathode

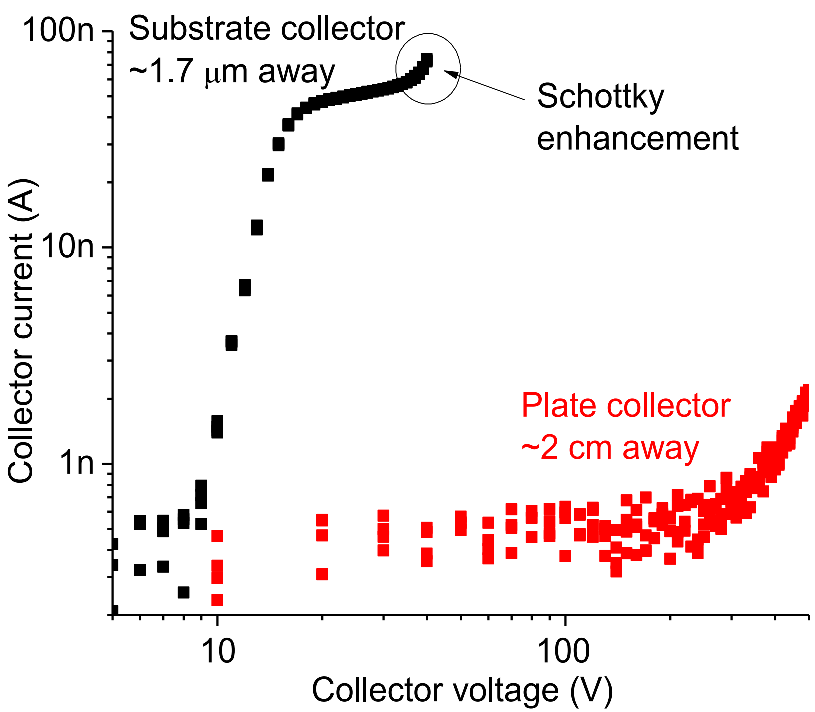


J.-H. Lee, *et al*, *IEEE MEMS 2012*, Paris, France.

Microfabricated SiC TEC device



1.6 µm gap

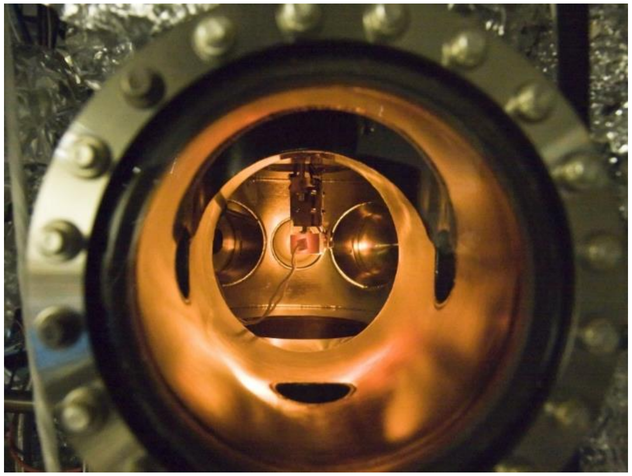


- **100x higher current**
- **Non-shorting**
- **Stable at high temperatures**

Micro-scale spacing can largely mitigate space-charge issues

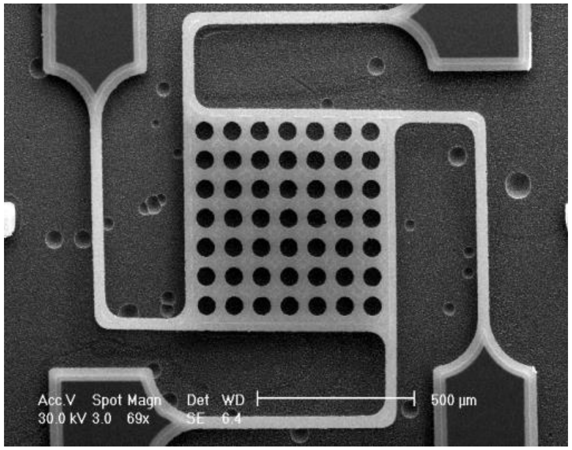
J. Lee, I. Bargatin, Roger Howe

PETE Opportunities and Challenges

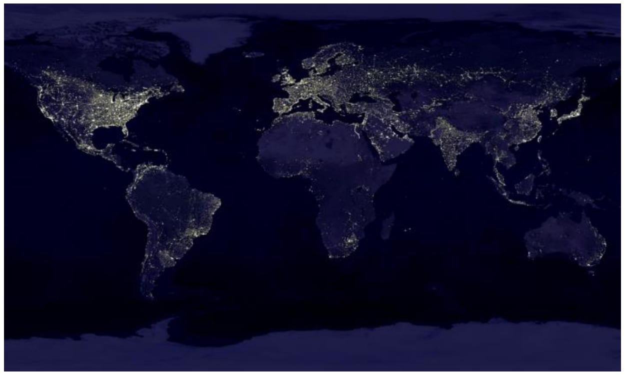


- Surface recombination is an issue, but can be overcome

- Heterostructure design looks very promising



- Best results will be achieved by balancing thickness, electron affinity to recombination and emission rates



- Space charge can be lessened using beads for large devices, or microfabrication

STANFORD MATERIALS SCIENCE AND ENGINEERING

Acknowledgements

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Dr. Trevor Willey (LLNL)

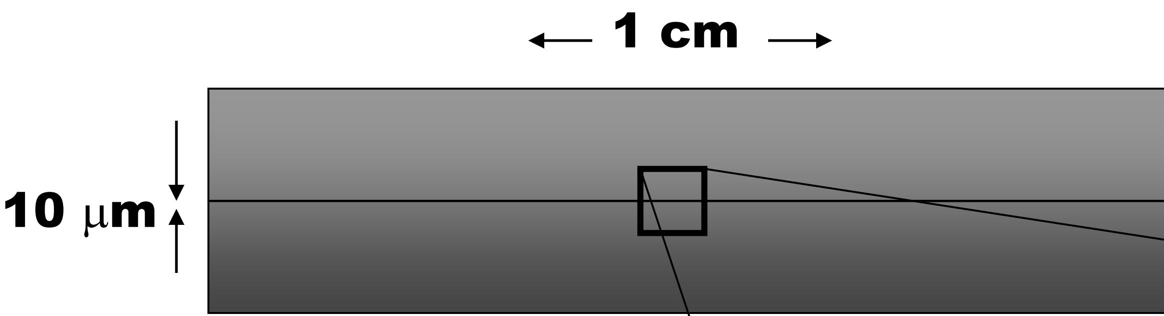
Jeremy Dahl, Bob Carlson

SunShot U.S. Department of Energy

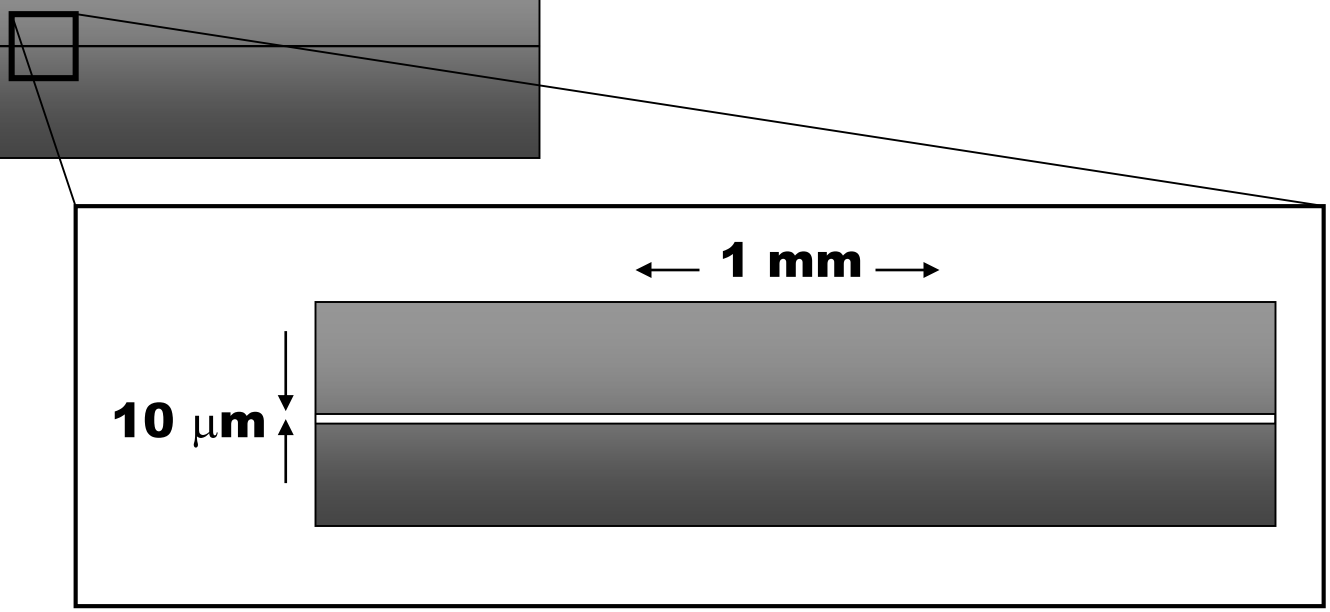
GCEP

GORDON AND BETTY MOORE FOUNDATION

Taking Thermionics below 100um



Two tungsten plates



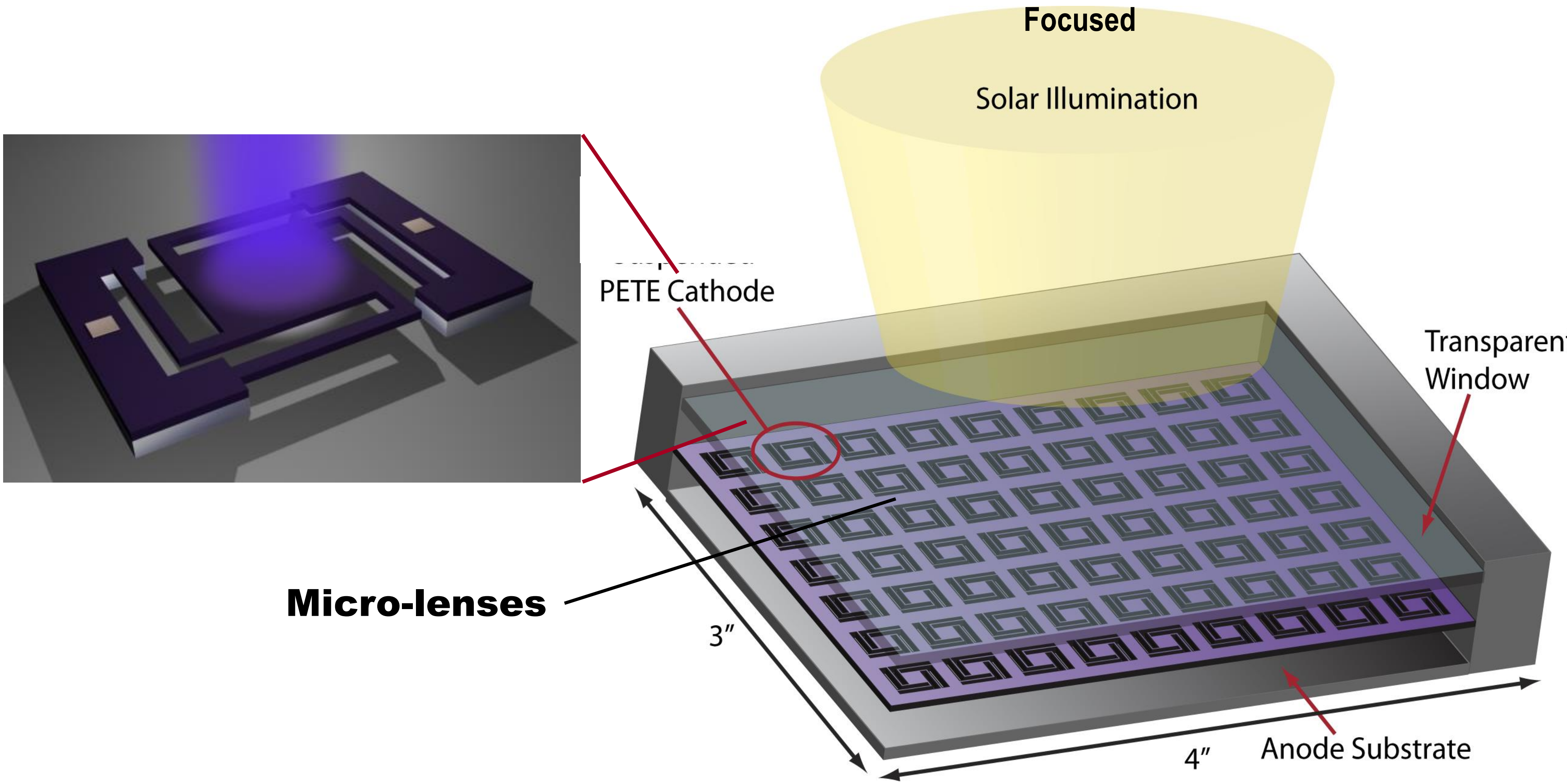
- **large area**
- **no shorting**
- **perfect planarity**
- **no thermal expansion issues**

Simple Approach: Microbead Spacers

- **simple, cheap**
- **low density by spraying**
- **poor thermal contact**
- **allows expansion**

Sahasrabuddhe et al ,EES, 2013

Small Scale Device Concept



- Substrate functions as anode
- Vacuum encapsulation with a transparent lid
- Work-function lowering vapors in the cavity

Solar Power Conversion

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

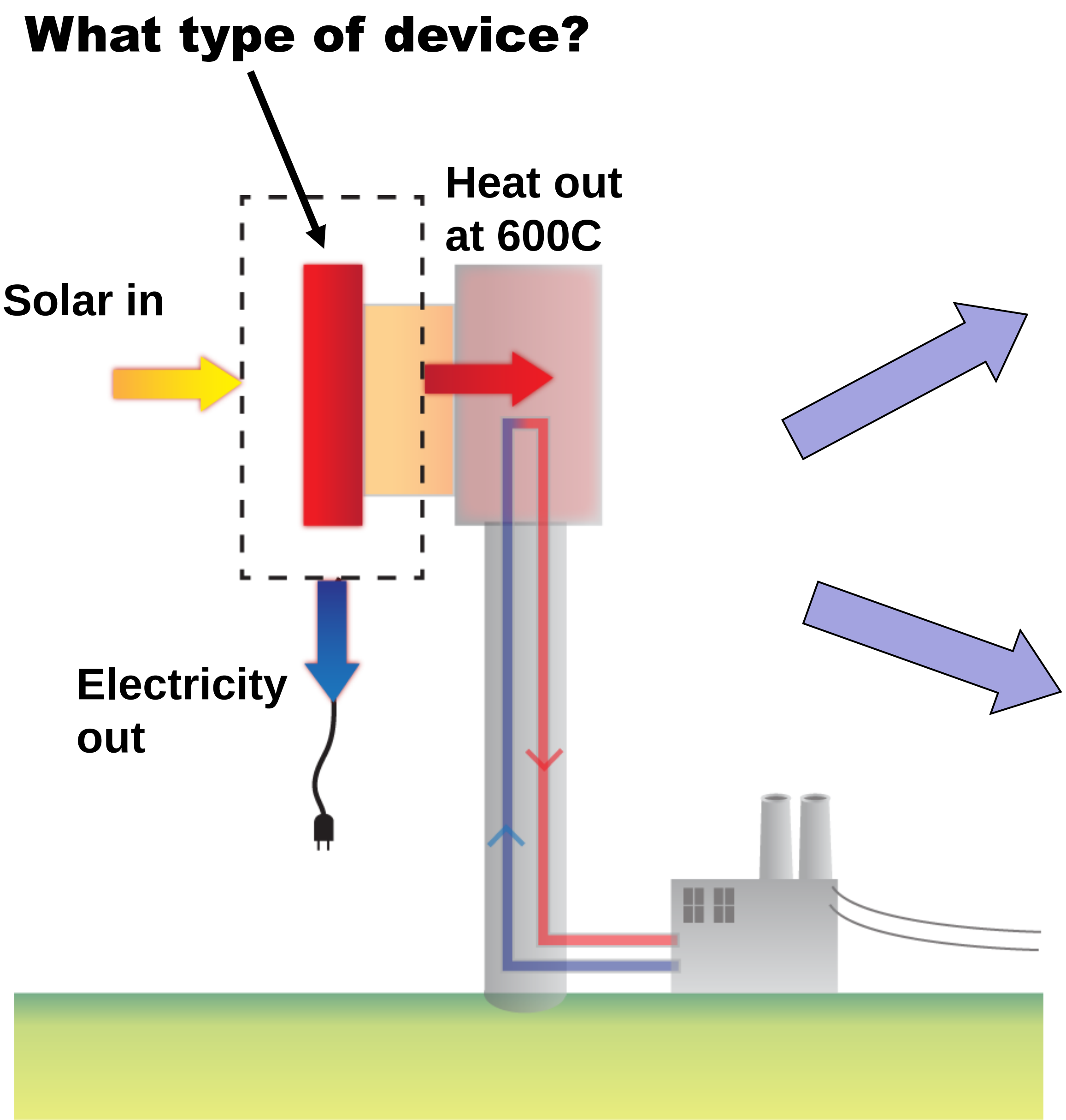
Solar Thermal (CSP)

- **Converts sunlight into heat**
- **Concentrated solar thermal**
- **Uses well-known thermal conversion systems**
- **Efficiencies of 20-30%**

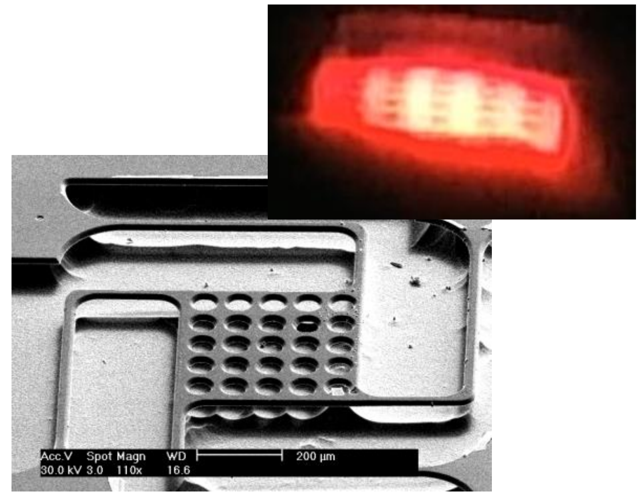
Photovoltaics (PV)

- **collects fraction of incident energy**
- **"high grade" photon energy**
- **direct photon to electricity**
- **efficiencies 19-24% (single junction Si)**

High Temperature Thermal Topping Cycles



Thermionic Emission



Photon-Enhanced Thermionic Emission