High Efficiency Integrated Solar Energy Converter

Research findings on photon enhanced thermionic emission

SES2050 seminar 21.10. – 22.10.2015, Oslo, Norway

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Project participants

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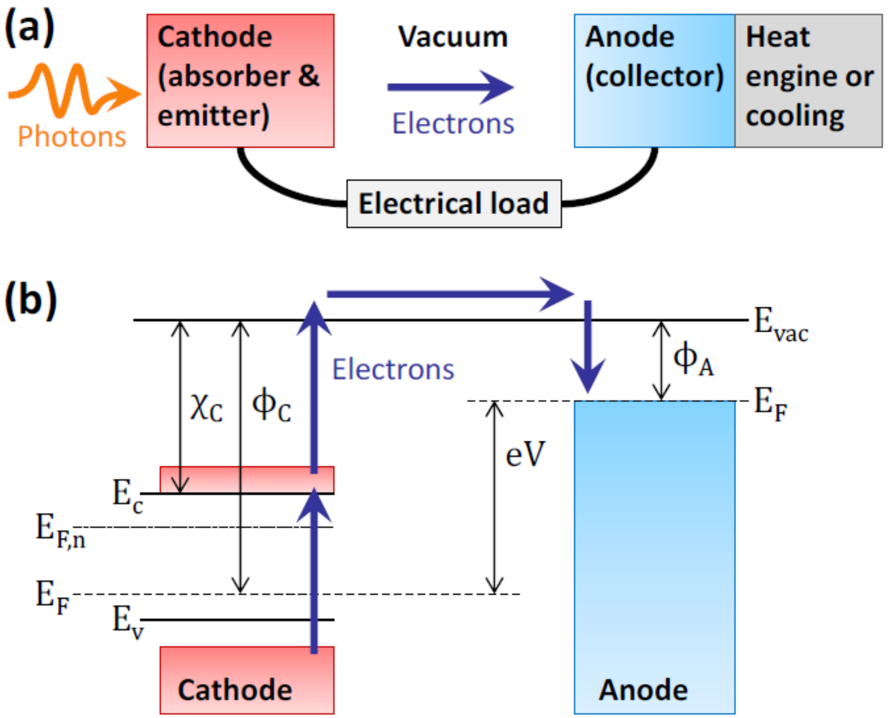
Outline

- Introduction
- Modelling work and results
- Experimental work
- Design of PETE demonstrator
- SWOT analysis of PETE
- Publications
- Conclusions

Inroduction

- In 2010 Schwede et al. [Schwede2010] proposed the photon-enhanced thermionic emission (PETE) device which is a photovoltaic device operating at high temperatures.
- This technology can be combined with the existing thermal solar energy systems, thereby allowing the solar-energy-to-electricity conversion efficiencies above 50% to be potentially reached.
- Its main characteristics include high temperature operation, use of high illumination intensity (i.e., the intensity is 100 W/cm^2 at 1000 suns) and promise of efficiencies much higher than conventional solar cells.



Goals of the work

- To develop theoretical PETE solar cell model
- To develop specific PETE solar cell designs
- To evaluate materials and structures for PETE solar cells.
- To evaluate the efficiency and commercial potential of PETE solar cells.

Modelling work

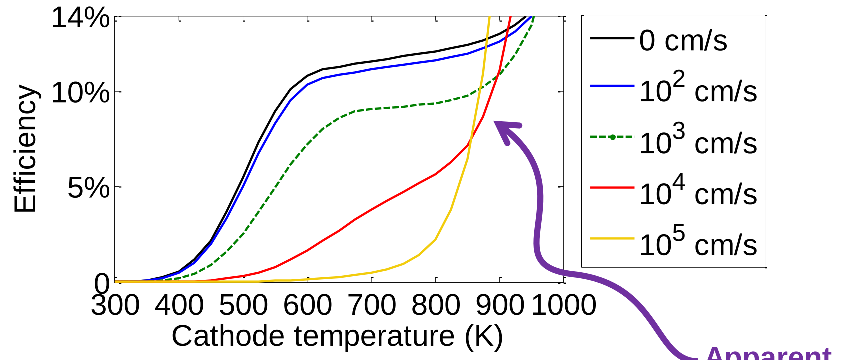
- The first detailed model of PETE devices developed
  - Takes the relevant effects in semiconductors into account
  - Both numerical model for all calculations and analytical formulas for special cases and approximate calculations
  - Model published in Journal of Applied Physics in 2012 [1]
  - Modelled cathode material: Silicon
- Analysis of space charge effects in emission current measurements
- Equivalent circuit model of PETE devices developed
- Extension of the model
  - New materials
    - Czochralski and magnetic Czochralski silicon [2]
    - GaAs and InP [3,4]
  - Electron density dependence of the electron diffusion constant (a minor effect) [4]

[1] A. Varpula, M. Prunnila, Journal of Applied Physics 112, 044506 (2012).
[2] A. Varpula, K. Reck, M. Prunnila, O. Hansen, PETE-2014, Tel Aviv, 23-24 June 2014.
[3] A. Varpula and M. Prunnila, EU PVSEC Proceedings, p. 331, EU PVSEC 2014, Amsterdam, 22-26 Sep. 2014.
[4] A. Varpula, K. Tappura, M. Prunnila, "Si, GaAs, and InP as cathode materials for photon-enhanced thermionic emission solar cells", Solar Energy Materials & Solar Cells, revised manuscript submitted.

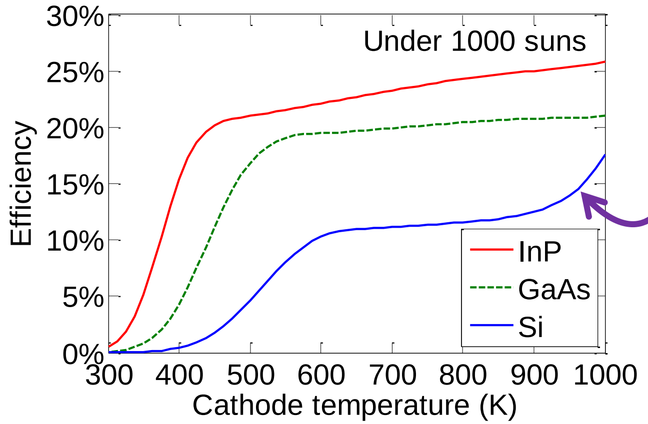
Modelling results

- Surface recombination and (effective) electron affinity on cathode surfaces must be controlled in order to reach high efficiencies [1–4]
- Silicon is feasible cathode material for PETE devices [1,2]
- Bulk recombination seems to have lower effect on the efficiency of PETE devices → Standard Czochralski silicon should be adequate [2]
- GaAs and especially InP seem to be very promising for PETE because of their strong photon absorption characteristics → High efficiency [3,4]

Effect of recombination on emitting surface [2]



Comparison of cathode materials [4]



[1] A. Varpula, M. Prunnila, Journal of Applied Physics 112, 044506 (2012).
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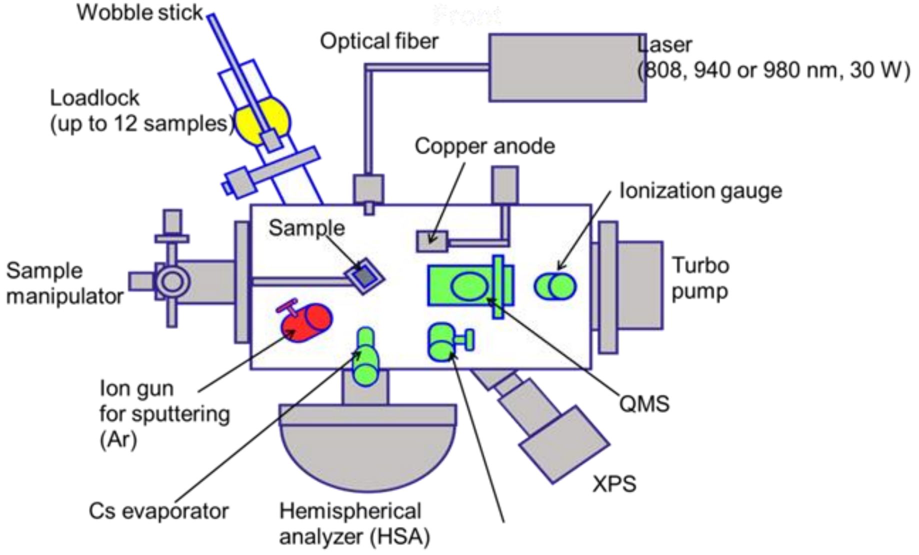
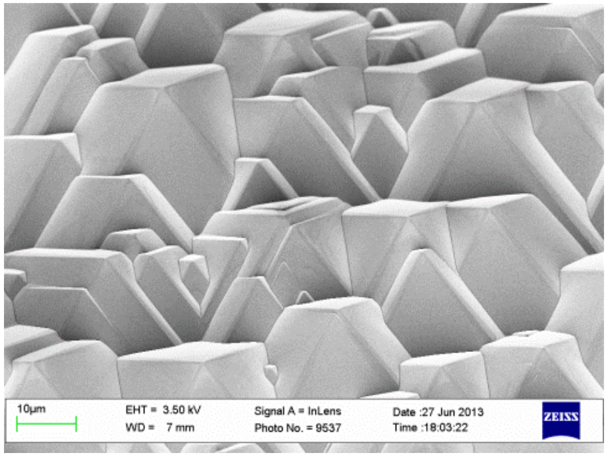
Experimental

- Materials testing and PETE measurements were carried out in an ultra-high vacuum (UHV) chamber at DTU.
- The chamber was fitted with a 4-axis sample manipulator, loadlock, Ion gun for sputter cleaning, caesium evaporator, a copper anode, a 30 W laser source for sample illumination, an X-ray source and a hemispherical energy analyser for XPS and work function measurements.
- Other measurements: HR-XRD, AFM, Raman spectroscopy, STS/STM, LITG

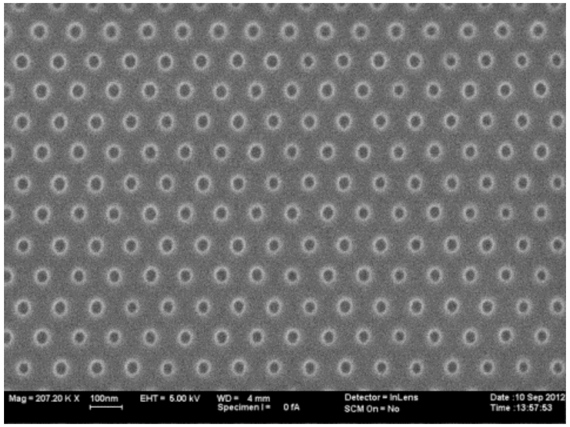


Studied materials

- highly doped p-type and n-type silicon
- surface structured silicon
- caesiated silicon
- cesiated and oxidized silicon
- GaAs
- GaAs with InP nanodots
- C12A7
- Graphene
- cesiated graphene
- InAs/GaAs
- $In_xGa_{1-x}N$



Distance between pyramid tips 3–20 µm

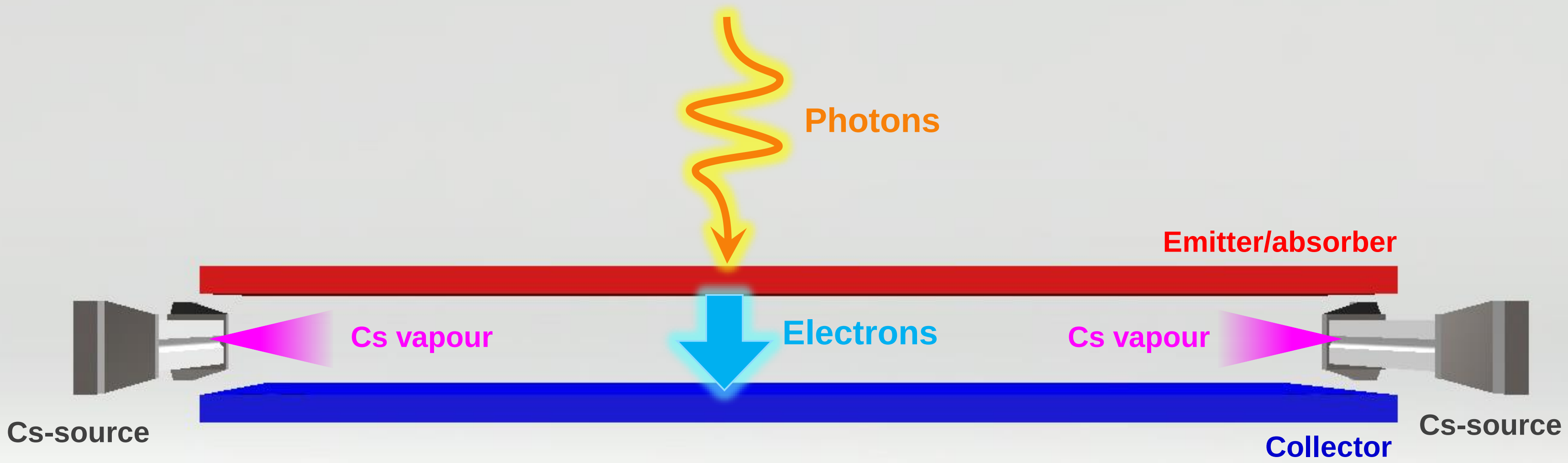


Distance between 50 nm dots: ~50 nm

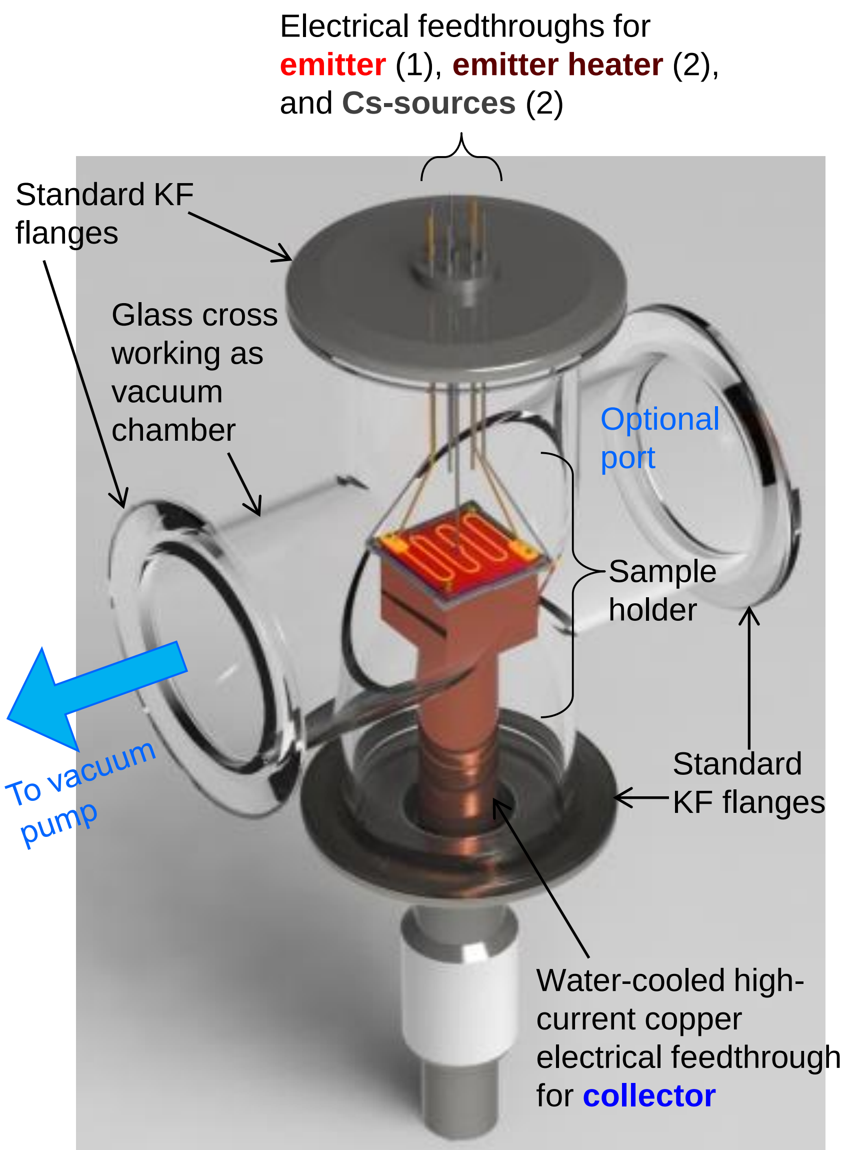
Demonstrator design

- Experimental setup designed for demonstration of operation of PETE devices
- Features
  - Illumination through transparent vacuum chamber or via an optical feedthrough (no restrictions on the type of external photon source)
  - Vacuum with standard vacuum pumps
  - Replaceable emitter and collector sample chips
  - Additional heater for temperature control of emitter
  - Cs-sources for work-function and space charge reduction
- Mostly commercial components used
  - Present design with KF flanges
  - Chamber can be replaced by CF-flange version for higher vacuum ($\leq 10^{-9}$ mbar)
  - Spacers for accurate control of the gap between emitter and collector

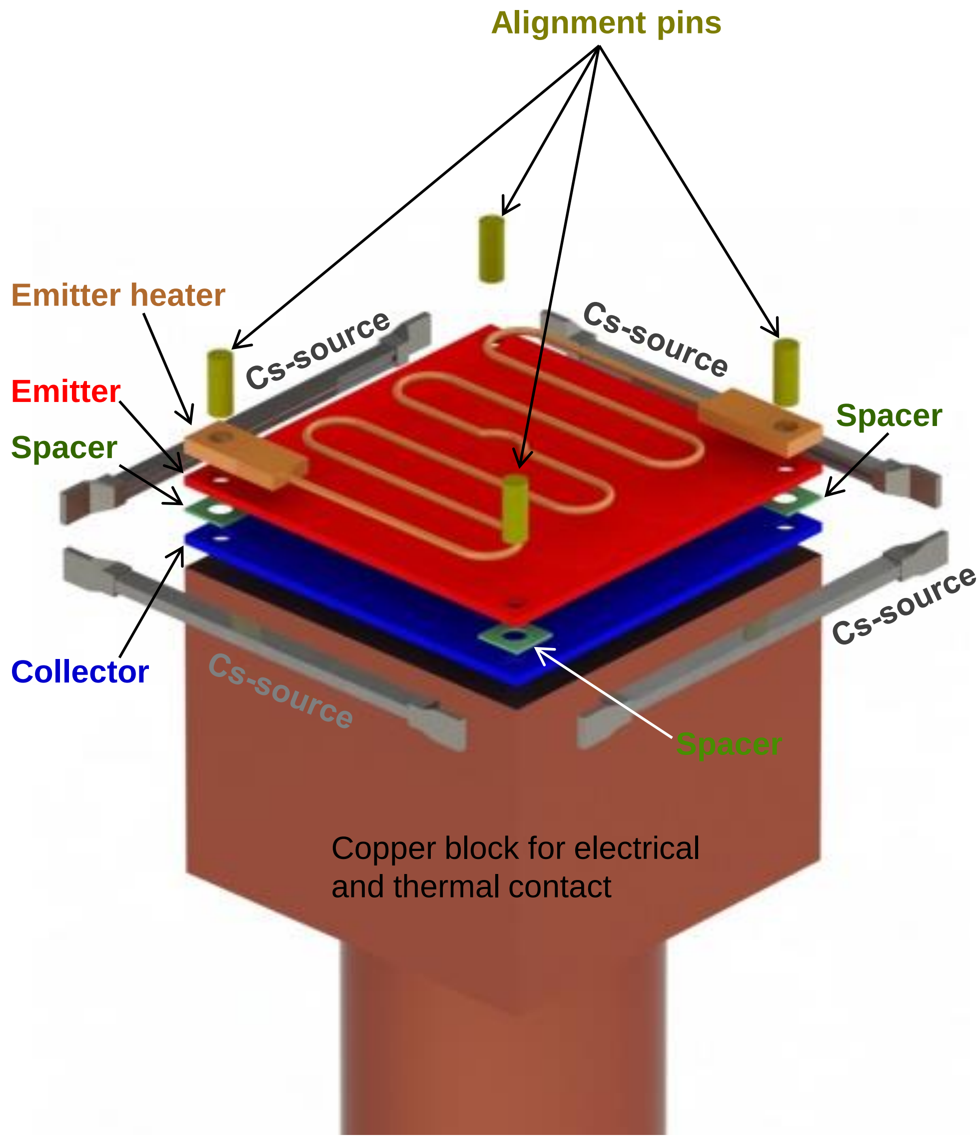
Operating principle



Exploded view

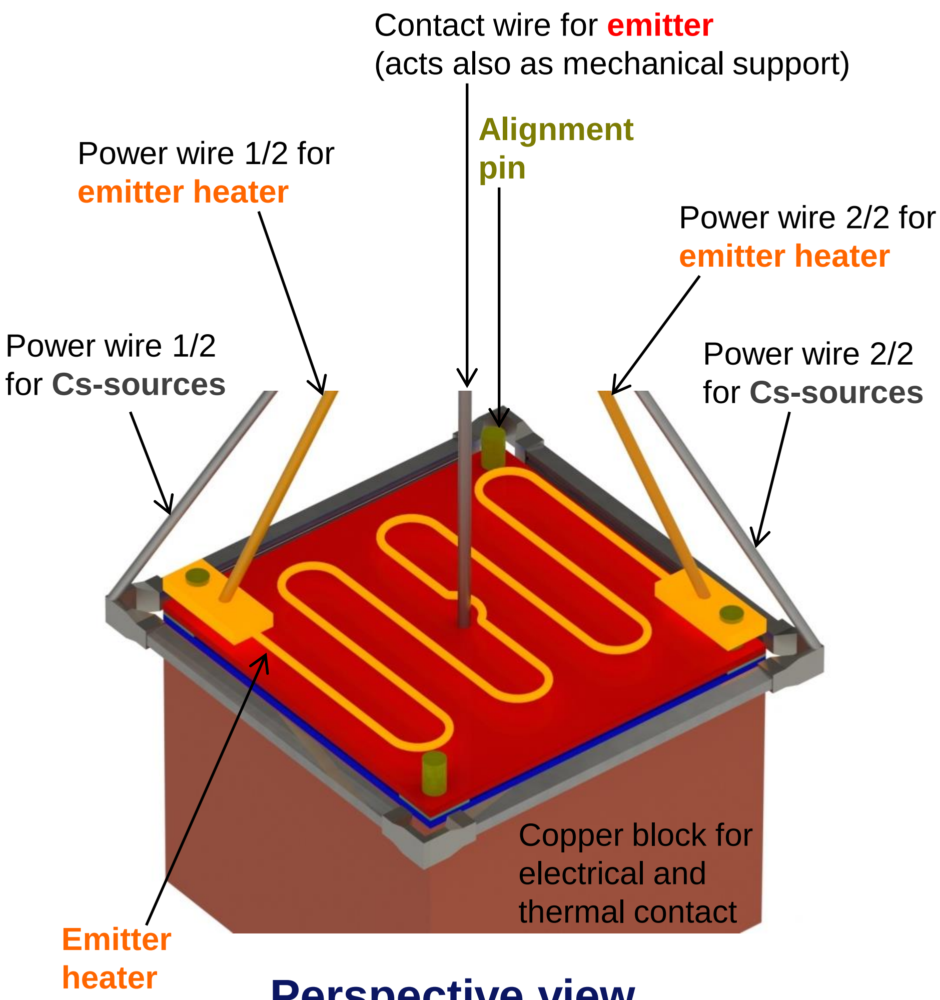


Overview

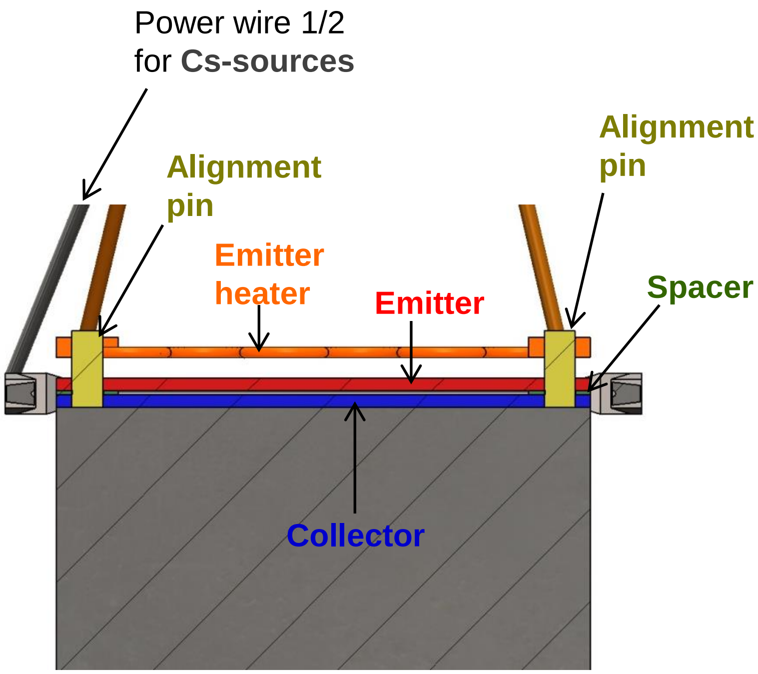


Sample holder

Assembled sample holder

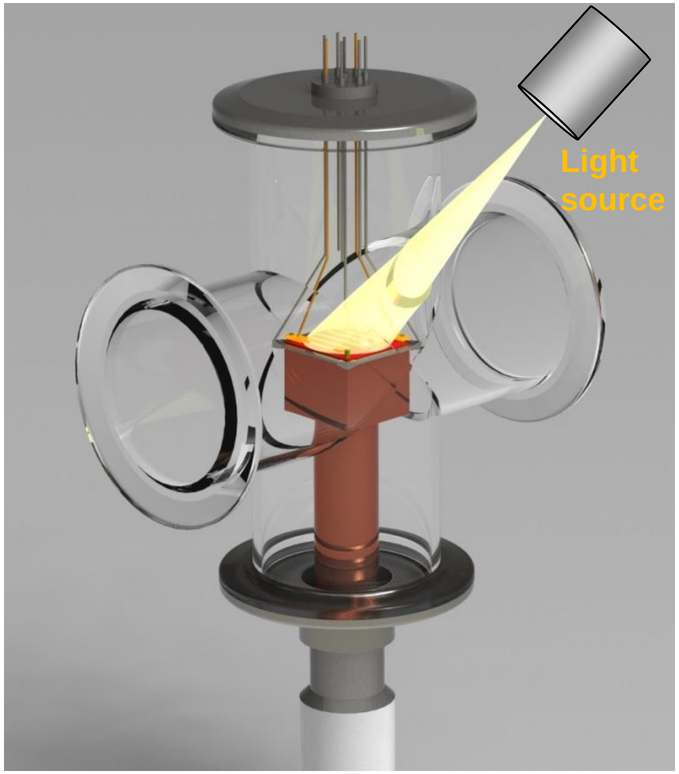


Perspective view

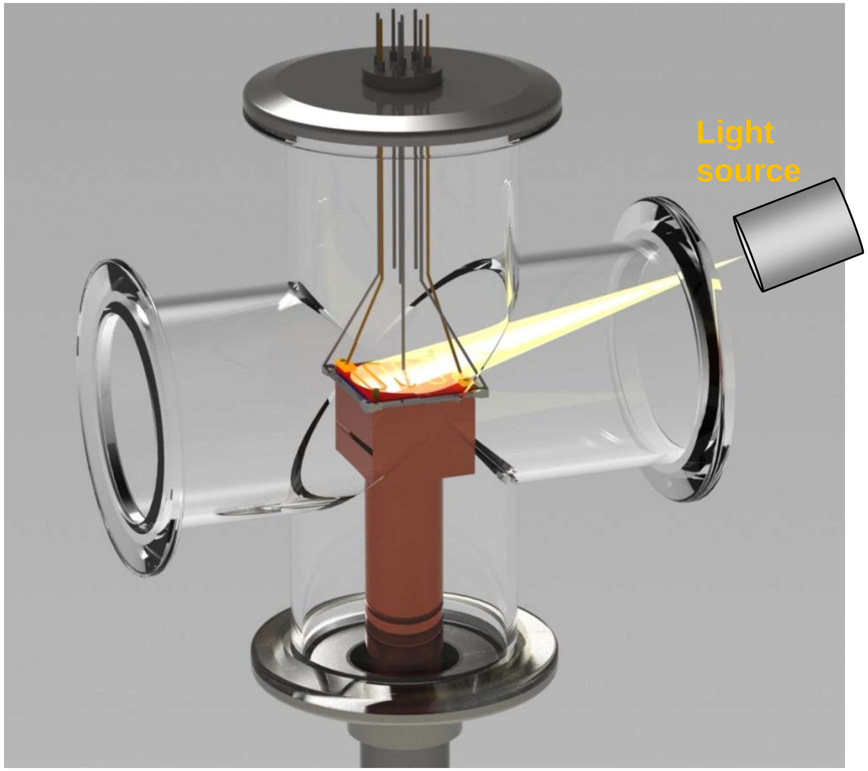


Side view (cross section)

Illumination possibilities



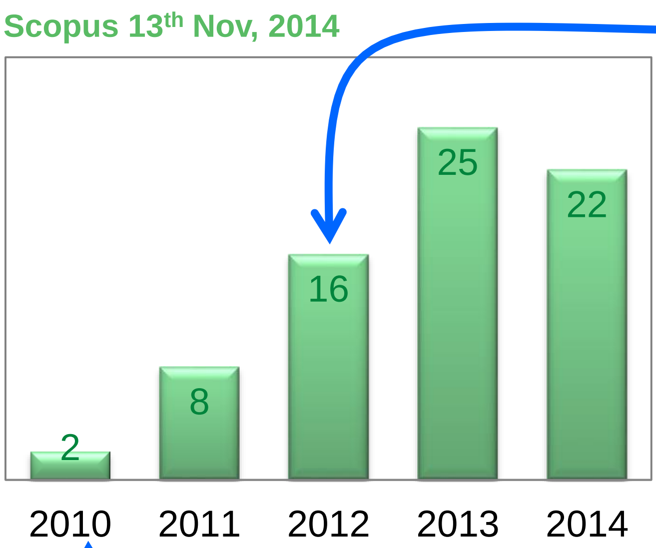
Through transparent chamber wall



Through port with optical feedthrough

PETE publications

Number of articles citing the original PETE paper [5]



Our scientific article (1st detailed model) published in August 2012

Original paper published in September

HEISEC begins

Our publications:
2 conference presentations
1 conference paper
1 scientific article

[5] J.W. Schwede *et al*., “Photon-enhanced thermionic emission for solar concentrator systems”, Nature Materials 9, 762 (2010).

SWOT analysis of PETE

Strengths

- Potential for high efficiency
- No moving parts
- No emissions (greenhouse effect and pollution)
- Allows cogeneration of solar electric power and heat
- Can be incorporated into existing solar concentrator systems
    - Low amount of materials needed → Use of exotic materials possible
    - Device cost not issue

Weaknesses

- Based on non-existing materials (problems with work function, heat emissivity, charge-carrier recombination)
- Vacuum and high temperature differences required
    - Complex system
    - Illumination more difficult
    - Tight material requirements
- Maximum efficiency requires
    - Light concentration
    - Secondary heat engine
- Direct measurement of phenomenon difficult
- Solution of space charge problems requires small gap, neutralizing plasma or other means

Opportunities

- New IPR (materials and structures)
- Markets available
    - Device manufacturing
    - Material deposition tools
    - Power generation

Threats

- Realization difficulties
- No stable low work function materials can be found
- Competition