Thermophotovoltaic devices for solar and thermal energy conversion

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Outline

- Introduction
  Thermophotovoltaics (TPV)

Solar thermophotovoltaic devices
Concept: using an intermediate solar absorber – thermal emitter
Key challenges – Ongoing research and sample results

Thermionic-thermophotovoltaic devices
Concept: high-temperature energy storage and hybrid conversion
Key challenges – Ongoing research and sample results

Near-field thermophotovoltaic devices
Concept: electrical power enhancement using evanescent waves
Key challenges – Ongoing research and sample results

Conclusions
Solar/Thermo-photovoltaics

Introduction

STPV
TIPV
NF-TPV

Solar photovoltaics

STPV
TIPV
NF-TPV

Solar photovoltaics

SUN 5800 K

\( \Omega = 6.85 \times 10^{-5} \text{ sr} \)

C = 46.200 (max)

PV cell

concentration

\( q_{\text{Sun}}(\text{AM1.5}) = 1 \text{ kW m}^{-2} \)

Irradiation spectrum

[0.3-2.5] microns not tunable

Best (research) conversion efficiencies

Si, CIGS, CdTe, AsGa,…, perovskites

bandgap \( E_g \sim [1-1.5] \text{ eV} \)

\( \text{Max: 33\% (no conc.), 41\% (max conc.)} \)

R. Vaillon et al. – JNES 2018, 06/28/2018
Introduction

Solar/Thermo-photovoltaics

Thermophotovoltaics

WASTE HEAT

\[ q_{bb}(T_e=1000-2000 \text{ K})=57-907 \text{ kW m}^{-2} \]

Irradiation spectrum

[0.3-15] microns tunable

emission where the cell is the most efficient

PV cell materials

mostly compounds from the III-V group (In, As, Ga, Sb,…) bandgap \( E_g \sim [0.17-0.8] \text{ eV} \)

Best (research) conversion efficiencies

20 – 25 % [limited data!]
Max: Carnot efficiency \( (T_e=2000 \text{ K} & T_c=300\text{K}: 85\%) \)

Dupré et al., Springer, 2017

1000-2000 K

emitter

\( \Omega \sim \pi \text{ Sr} \)

PV cell

cooling system
Thermophotovoltaics

Journal articles over the years

Web of Science
(topic or title contains “thermophotovoltaic*”)

811 (“Niche”)

30
(at least one co-author with a French affiliation)

110


1999 2001 2003 2005 2007 2009 2011 2013 2015 2017

growth factor=6.9 (all=1.66)

“Ups” and “downs”. Clear “up” since 2006

R. Vaillon et al. – JNES 2018, 06/28/2018
Solar thermophotovoltaics

**Concept**

**Introduction**

- **STPV**
- **TIPV**
- **NF-TPV**

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**Max. theoretical efficiency**

Complex device, \( C=46.200, T_e=2500 \text{ K} & T_c=300\text{K} \): **85.4%**

Harder & Würfel, SST, 2003

Planar device, \( C=4.4, T_e=1060 \text{ K} & T_c=300\text{K} \): **45.3%**

Datas & Algora, PIP, 2013

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**Best (research) efficiency**

**6.8%**


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**Advantage:**

Spectral tuning of radiation emitted toward the cell to maximize efficiency

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**Practical implementation in the lab**

MIT STPV device

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**Promising but many challenges to overcome**
Solar thermophotovoltaics

Key challenges

Research & technological needs

- photonics
- high-temperature material science
- thermal radiation transfer
- low-bandgap semiconductor material science
- electrical engineering
- thermal insulation / cooling

Many challenges: multi- and interdisciplinary solutions

Lenert et al., Nature Energy, 2014
Solar thermophotovoltaics

Sample results  Univ. Tohoku STPV device

Absorber-emitter design

Collaboration: Univ. Tohoku - CETHIL

Measurement  Simulation

Efficiency = 5.1%

Material science and thermal radiation design


Blandre et al., Optics Express, 2018
Solar thermophotovoltaics

Sample results

B.S. senior design project at the University of Utah

5 students x 8 h x 32 weeks

Collaboration: Univ. Utah - CETHIL

Nice educational design project requiring multidisciplinary skills
Thermionic-thermophotovoltaic devices

Concept


Enhanced output voltage and grid-less front contact
Introduction

STPV

TIPV

NF-TPV

Key challenges

small distance & vacuum

low workfunction


Challenges: low workfunction coatings, small-gaps to reduce the space-charge
Introduction

STPV

TIPV

NF-TPV

Ongoing research

Sample results

Collaboration: IES Madrid - CETHIL

Radiation – electrical simulations

Materials to be found to optimize both thermionic and thermophotovoltaic conversions

LaB$_6$ (lanthanum hexaboride)

thermionic device

vacuum

PV cell

receiver

BaF$_2$ (barium fluoride)

back reflector ($t_{brl}$)

collector ($t_{col}$)

emitter ($t_{emi}$)

p-ln$_{0.53}$Ga$_{0.47}$As ($N_{p}$, $t_p$)

n-ln$_{0.53}$Ga$_{0.47}$As ($N_{d}$, $t_n$)

n-InP substrate ($N_{d,sub}$, $t_{sub}$)

TPV efficiency = 21.6%

spectral radiation flux absorbed by the

receiver

PV cell

substrate

angular frequency ($10^{15}$ rad/s)

bandgap of the PV cell

useless for TPV

R. Vaillon et al. – JNES 2018, 06/28/2018
Near-field thermophotovoltaic devices

**Introduction**

STPV

TIPV

NF-TPV

**Concept**

Near-field thermophotovoltaic devices

- **NF-TPV**
- **STPV**
- **TIPV**

Theoretically predicted huge near-field enhancements of electrical power

**Advantage:** additional contribution of the evanescent waves

\[d < \lambda_{\text{Wien}}\]

\((10 \, \mu\text{m} \, \text{at} \, 300 \, \text{K})\)

**Near-field radiation effects experimentally observed multiple times**

**Thermal conductance (nW K\(^{-1}\))**

- **Experimental data**
- **Ideal parallel planes**
- **Modeled plates**
- **Blackbody conductance for 48 \, \mu\text{m} \times 48 \, \mu\text{m}**

Contact: Snap-in

Approach: Receiver

Particle

Mesa

\(~ \times 100-1000\)

See also [Bernardi et al., Nature Communications, 2016](#)

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Pan et al., IEEE TED, 2000

Whale & Cravhalo, IEEE TEC, 2002

Song et al., Nature Nanotechnology, 2016

R. Vaillon et al. – JNES 2018, 06/28/2018
Introduction

STPV
TIPV
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Key challenges

- Large emitter temperature
- Building a sub-micron gap
- Efficient low band-gap PV cell in near-field illumination conditions

Experiments

First (inconclusive attempt)

DiMatteo et al., PRL, 2001

Very recent breakthrough

Fiorino et al., Nature Nanotechnology, 2018

Huge challenges, recent breakthrough, lot of room for improvement

Diagram showing
- TPV power output, $P_{MPP}$, vs. voltage (mV)
- Current ($\mu$A) vs. gap size, $d$ (nm)
- Inset showing current vs. voltage for different gap sizes: 60 nm, 65 nm, 85 nm, 145 nm, 330 nm, 1.1 µm, 4 µm, 12 µm

$\sim x40$
Near-field thermophotovoltaic devices

Sample results

Radiative-electrical design

CETHIL

High-injection effects?

p-on-n GaSb cell

Collaboration: Univ. Utah - CETHIL

External luminescence in NF-TPV devices

Optimum doping of the p-doped layer ($N_a$) is function of emitter-cell distance ($d$) and cell top surface passivation

Radiative recombination/total recombination (performances of the PV cell) increases in the near-field

Specific design of the PV cell according to near-field radiation conditions

Blandre et al., Sci. Reports, 2017

DeSutter et al., PR Applied, 2017

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Near-field thermophotovoltaic devices

Ongoing research

Collaboration: CETHIL – IES Montpellier

Micro-scale lab experiment with a spherical emitter and a very low bandgap cell at around 77 K

Lucchesi et al., Poster JNES, 2018
Near-field thermophotovoltaic devices

Ongoing research

Technological issues with front contacts because of high currents and lateral series resistance ($R_{ls}$)

\[ A = 1 \times 1 \text{ mm}^2 \]

\[ A = 100 \times 100 \, \mu \text{m}^2 \]

\[ d = 100 \text{ nm} \]

\[ V (V) \]

\[ I (A) \]

\[ \text{with} \quad R_{ls} \]

\[ \text{without} \quad R_{ls} \]

\[ d, \text{down to} \quad 100 \text{ nm}!! \]

Collaboration:
Univ. Utah - CETHIL - IES Madrid

$p$-on-$n$ InAs cell

\[ V (V) \]

\[ A = 1 \times 1 \text{ mm}^2 \]

\[ I (A) \]

\[ V (V) \]

\[ I (A) \]
A chart for TPV devices?

Best Research-Cell Efficiencies

- **Multijunction Cells (2-terminal, monolithic)**
  - LM = lattice matched
  - MM = metamorphic
  - IMM = inverted, metamorphic
  - Three-junction (concentrator)
  - Three-junction (non-concentrator)
  - Two-junction (concentrator)
  - Two-junction (non-concentrator)
  - Four-junction or more (concentrator)
  - Four-junction or more (non-concentrator)

- **Single-Junction GaAs**
  - Single crystal
  - Concentrator
  - Thin-film crystal

- **Crystalline Si Cells**
  - Single crystal (concentrator)
  - Single crystal (non-concentrator)
  - Multicrystalline
  - Silicon heterostructures (HT)
  - Thin-film crystal

- **Thin-Film Technologies**
  - CIGS (concentrator)
  - CIGS
  - CdTe
  - Amorphous Si:H (stabilized)

- **Emerging PV**
  - Dye-sensitized cells
  - Perovskite cells (not stabilized)
  - Organic cells (various types)
  - Organic tandem cells
  - Inorganic cells (CZTSSe)
  - Quantum dot cells (various types)

- **Solar Thermophotovoltaics**
  - STPV
  - TIPV
  - NF-TPV

- **Conclusions**

Best research TPV device power outputs?
Conclusions

Key challenges require expertise in

- thermal radiation / photonics
- semiconductor material science
- low-bandgap PV cell design, fabrication & characterization
- thermal insulation
- nanoscale device fabrication (NF-TPV)

“A picture speaks a thousand words”

Multi- & interdisciplinary research is required with international collaborations
Further readings and acknowledgments

Further details on our recent results

STPV
TIPV
NF-TPV

Blandre et al., Optics Express, 2018
Datas, APL, 2016
Blandre, Chapuis, Vaillon, Sci. Reports, 2017

Lucchesi et al., poster, JNES 2018

Acknowledgements

DEMO-NFR-TPV (CETHIL – IES Montpellier)

AMADEUS (IES Madrid)

Career Award (Univ. Utah)

Merci pour votre attention