Second Workshop on

Thermal radiation to electrical energy conversion

LTeN

Nantes

October 9th – 11th

Sponsored by CNRS – INSIS

Scientific organization by members of the project-team TREE
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Coordination
Rodolphe Vaillon

Program

October 9th

13h30 [30 min]	Reception at LTEN	
14h00 [30 min]: Steven Le Corre, Xavier Py and Rodolphe Vaillon	Introduction to the workshop	**Welcome address and program**
Session 1	**Thermal energy storage**	
14h30 [60 min]: Yasmine Lalau	RAPSODEE, IMT Mines d'Albi, France	**Life Cycle Assessment (LCA): methodology and application to solar energy & thermal energy storage**
15h30 [45 min]	Coffee break	
16h15 [60 min]: Nicolas Tessier-Doyen	IRCER, France	**Chracterization of refractory ceramics: thermomecanical properties related to microstructure**
17h15 [20 min]: Xavier Py	LTEN, France	**ST4TPV, a CNRS national research project devoted to high temperature thermal storage for TPV**
Session 2	**Thermal radiation emitters**	
17h35 [30 min]: Maha Ben Rhouma	ESYCOM, France	**Fourier modal methods as applied to periodic micro/ nanostructures for thermophotovoltaics applications**

October 10th

Session 3	**Photovoltaic conversion (1)**	
9h00 [60 min]: Amaury Delamarre	C2N, France	**Low-cost III-V solar cells**
10h00 [30 min]: Maxime Giteau	ICFO, Spain	**Fundamental power-efficiency trade-off for thermophotovoltaic and thermoradiative cells**
10h30 [45 min]	Coffee break + posters	
11h15 [60 min]: Ignacio Rey-Stolle	IES, UPM, Spain	**Germanium TPV cells: interest, efficiency potential and key technical challenges**
12h15	Lunch break	
Session 4	**Characterization**	
14h00 [60 min]: Esther Lopez	IES, Spain	**Challenges in the characterization of thermophotovoltaic devices**
Session 5	**Near-field effects**	
15h00 [30 min]: Julien Legendre	CETHIL, France	**Thermophotonic energy harvesters: thermodynamic analysis and near-field performances of 1D architectures**
15h30 [30 min]	Coffee break + posters	
16h00 [30 min]: Minggang Luo	L2C, France	**Effect of the graphene grating coating on near-field radiative heat transfer**
16h30 [30 min]: Thomas Châtelet	CETHIL, France	**Electroluminescence overcoming thermal radiation in near field: conditions for a nanothermophotonic refrigerator**
17h00 [60 min]	**Visit of LTEN installations**	

October 11th

Session 6	**Photovoltaic conversion (2)**	
9h00 [30 min]: Rodolphe Vaillon	IES, France	**Thermophotovoltaic conversion with a silicon vertical multijunction cell**
9h30 [30 min]: Thomas Villemin	LEMTA, France	**Multiphysics and multiscale modeling of a photovoltaic panel using Monte Carlo methods**
10h00 [30 min]	Coffee break	
10h30 [30 min]: Basile Roux	IES, France	**InAs/InAsSb superlattice thermophotovoltaic cell: how to adapt an infrared photodetector for TPV conversion**
Session 7	**Work in progress**	
11h00 [15 min]: Wissal Sghaier	CETHIL, France	**Design of a near-field thermophotonic device in the planar configuration for energy harvesting and refrigeration**
11h15 [15 min]: Mathieu Thomas	CETHIL, France	**Near-field radiative heat transfer between a sphere and a flat surface in the sub-200 nm regime and prospects for energy harvesting**
11h30 [30 min]	**Concluding remarks and discussion**	

End of the workshop at 12h00

Table of contents

Thermal energy storage

Life Cycle Assessment (LCA): methodology and application to solar energy & thermal energy storage

Yasmine Lalau * [1,2], Xavier Py , Thomas Fasquelle , Alexis Vossier , Antoine Meffre , Guilhem Dejean , Al Asmi Ibrahim , Diane Le Roux

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Life Cycle Assessment (LCA) is a method of quantifying environmental impacts that has been developed since the early 1990s in its standard approach. Prior to the work of SETAC (Society of Environmental Toxicology and Chemistry) and ISO (International Standard Oranization) in 1993 and 1994 respectively, the first studies carried out over the previous two decades (1970-1990) were highly disparate in terms of defining boundaries, indicators and methodology. Extended work on data reliability and methodology framework has strengthened subsequent work to date. Studies on solar energy, and mainly photovoltaic (PV) energy, appeared in the mid-2000s, and harmonisation work began around ten years later. The disparity of functional units (kW, kWh, m^2, kg, number of cells) made comparison difficult, and the rapid efficiency improvements required constant updating. Thus, the quality of LCA in a given field appears to lies in the joint development of the technology and its environmental assessment. Moreover, one should be improved by the other. The relevance of LCA methodology in the context of an emerging technology such as thermo-photovoltaic (TPV) can therefore be analysed through the following questions: What are the main stages and requirements of an LCA? How has it been applied to assessing the impact of solar energy, and what are the current issues? And what are the methodological specifications and work in progress with a view to using energy storage systems to valorise waste energy with TPV? This presentation attempts to answer these questions with a brief presentation of the principles of the methodology, followed by a review of the literature and a case study.

Keywords: Life Cyce Assessment (LCA), Solar energy, Thermal energy storage

*Speaker

ST4TPV, a CNRS national research project devoted to high temperature thermal storage for TPV

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The ST4TPV national research project focuses on the upstream "Power-to-Heat" conversion brick including thermal energy storage (TES) at the interface between variable and intermittent electrical renewable resources and thermophotovoltaic (TPV) conversion. With regard to the international state-of-the-art in the development of TPV batteries (decarbonized "Power-to-Heat-to-Power" conversion solution with storage), the high-temperature thermal storage material pair (metallic liquid-solid phase-change materials (PCMs) between 1000-2500◦C) and its envelope, adapted to the upstream constraints of renewable energies and the downstream constraints of TPV conversion, constitute a potentially differentiating key lock. The project is devoted to this key PCM/shell pairing, as well as on the load of high-temperature thermal storage by in situ electrothermal conversion.
Selected inorganic salts and metal alloys considered as PCM candidates will be presented with the corresponding available properties and preliminary related characterizations. First designs considered at the Power-to-heat/TES level will be also presented and discussed according to their respective estimated performances in terms of temperature and discharge power stabilities.
ST4TPV is a one-year emerging low TRL level project funded through the PEPS CNRS 2023 call, it gathers three TREE laboratories members, namely the LTeN (coordinator) the IES and the CEMHTI.

Keywords: Thermal energy storage, TPV, PCM

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Characterization of refractory ceramics: thermomechanical properties related to microstructure

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Fine-grained ceramics are widely used in high-temperature systems thanks to their strong thermal and chemical inertia, and to their mechanical performances up to 1500◦C. However, their susceptibility to withstand severe thermal shock constitutes a challenge of interest, particularly for companies developing materials for such applications. Indeed, if ceramics are submitted to quick heating / cooling cycles, internal stresses resulting from thermal gradient can cause a catastrophic failure of refractory parts. To improve thermal shock resistance, an approach based on Kingery theory consists in increasing both intrinsic thermal conductivity and mechanical strength. However, this strategy is usually limited when materials face to intensive/repeated thermal shock. For multiphase materials composed of coarse aggregates, an alternate solution based on Hasselman theory is usually implemented: in this case, the design of microstructure can be judiciously tailored so that a network of microcracks can be promoted by the large variety of phases chosen in the chemical formations. Indeed, various compositions of refractory materials can be tuned by introducing suitable inclusions in terms of chemical nature, volume proportion, particle size distribution and shape. For example, considering carbon/alumina, magnesia containing spinel inclusions or materials based on andalusite or aluminium titanate aggregates, the approach consists to vary either the mismatch in the coefficient of thermal expansion (CTE) between matrix and inclusions or the intrinsic CTE anisotropy of coarse grains assumed to be single crystals (case of andalusite and aluminium titanate). In this presentation, we propose to present several results coming from different works devoted to tune microstructural design in order to improve thermomechanical properties of damaged industrial and model refractory materials. Contrary to what can be expected at first sight, these pre-existing microcracks can be fully beneficial (and not at all detrimental) to the integrity of the materials when submitted to severe temperature variations. The effect of this microstructural tailoring is accurately evaluated using

*Speaker

various highly sensitive experimental techniques of materials inspection. In this way, strategies involving combined specific characterization methods (ultrasonic pulse echography and acoustic emission in temperature, traction/compression testing in temperature, thermodilatometry and a recent equipment devoted to deeply characterize thermal shock resistance of materials) are presented.

Keywords: Thermomechanical properties, refractory materials, microstructure

Thermal radiation emitters

Fourier Modal Methods as applied to Periodic micro/ nanostructures for Thermophotovoltaics Applications

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Thermophotovoltaics (TPV) is a promising technology that converts directly thermal energy to electricity by using the so-called photovoltaic effect. It consists of a thermal emitter working at high temperatures and a photovoltaic (PV) cell that can generate a photocurrent by creating electron-hole pairs. Thermophotovoltaic devices have been considered as clean energy conversion systems, that allow recycling of the waste heat and harvesting solar energy. However, the principle drawback of TPV devices is their low and poor conversion efficiency due to the mismatch between emission spectrum of emitter and absorption spectrum of PV cell. The conversion efficiency of TPV cells can be enhanced by using selective emitters which are characterized by strong emission at certain wavelengths. The so-called selective emitters were achieved using optical/electromagnetic micro/nanostructures including 1D and 2D gratings, photonic crystals, metamarials ans metasurfaces. As a result, the numerical modeling and the simulation of their electromagnetic response play an important role in the development of TPV systems and can be successfully studied thanks to the so-called modal methods. Here, we present an overview of Fourier Modal methods used for modelling the electromagnetic properties of periodic micro/nanostructures. We will start by describing the standard Fourier modal modal (FMM) which is considered as one of the most popular methods used for modeling diffraction from gratings as well as the Fourier modal method equipped with the concept of adaptive spatial resolution (FMM-ASR) employed to improve and accelerate the convergence of the FMM. After that, we will descibe the C-method. Finally, we will introduce the concept of perfectly matched layers (PML) and combine it with the FMM Method to solve the problem of aperiodic structures

Keywords: Fourier Modal Method, Nanostructures, TPV

*Speaker

Photovoltaic conversion (1)

Low-cost III-V solar cells

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Solar cells made of III-V materials are the most efficient available, with a record at 39.2% under one sun illumination. In the current research and industrial trend towards tandem devices to overcome the silicon devices physical limitation, III-V are unfortunately not an alternative today due to their high costs, limiting them to specific markets such as space applications. Different technological strategies are currently explored to make those solar cells more affordable and will be reviewed in this communication.
The largest share of the III-V cells cost lies in the monocrystalline substrates, up to 80%. Growth on low cost substrates, or substrate recycling are the first options to be explored. For the first alternative, a preferred substrate would be silicon wafers, with various intermediate buffers to limit or manage the generation of dislocations. Other methods relatively independent on the substrate will also be mentioned (planar VLS, nanowire growth in the vapour phase). Regarding substrate recycling, one can note that several companies have proposed commercial products based on such processes. Nevertheless, some progress is desirable to further reduce the cost, by enabling more recycle loops or simplifying the process, e.g. by reducing the time required to peel off the thin films from their substrates, or simplifying the surface processing steps before now growths.

Although avoiding the cost of III-V substrates is the first challenge to tackle, it would not be sufficient to reach the two orders of magnitude cost reduction required to be competitive with mainstream silicon modules. Increasing the growth rates, by CVD methods, is investigated by several institutes as a mean to reduce the remaining costs. Keeping in mind that next generation devices will be tandems, low-cost and defect-tolerant bonding of III-V cells on silicon are also required.

One technique developed in our team towards substrate recycling will be presented with more details. III-V substrates, covered by graphene, have been shown to allow the deposition of monocrystalline films in epitaxial relation with the substrate beneath the graphene, while providing a mechanically weak plane allowing exfoliation. This promising method still rises technological and scientific questions on the mechanisms in play that will be highlighted. Two other strategies currently investigated at the institute will be mentioned: germanium template deposition by low temperature CVD on silicon followed by III-V epitaxy, and bonding methods of III-V on silicon.
Finally, III-V solar cells would be cheaper thanks to scale effects generated by larger markets. The technological solutions mentioned above must be developed in parallel with the identification of potential applications that would tolerate prices intermediate between classical modules

*Speaker

and those used in satellites. This could be mobile systems, modules on vehicles or for personal mobile devices.

Keywords: III, V, epitaxy, solar cells, cost

Fundamental power-efficiency trade-off for thermophotovoltaic and thermoradiative cells

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Thermophotovoltaic (TPV) cells belong to the broad class of radiative heat engines that exchange heat as radiation with a hot thermal emitter. As such, their performance is characterized by two metrics: power output and efficiency (i.e., the power output divided by the net heat drawn from the emitter). It is well known that the efficiency of TPV devices is bounded by the Carnot limit, in the limit of zero power output (1). At the same time, the maximum power output (regardless of efficiency) can be directly calculated from the thermodynamic limits of solar energy conversion (2) by replacing the temperature of the sun (6000 K) with that of the emitter. However, while TPV systems should combine high power output and high efficiency, the exact nature of the trade-off between the two metrics has not been identified previously. In this presentation, we show the thermodynamic performance bounds for radiative heat engines in terms of the maximum power output achievable for any given efficiency (3). We also briefly discuss the performance bounds of single- and multi-junction TPV cells, showing that current devices operate very far from their ideal limits.
Subsequently, we evaluate these bounds for thermoradiative (TR) cells (the counterpart of TPV cells). While TPV cells receive heat radiatively from a hot emitter and exchange it conductively with a cold bath, TR cells are connected to a hot source and generate power by radiating heat (and entropy) away towards a cold sink. We will demonstrate that for all configurations, the performance bounds of radiative heat engines are always superior to those of TR heat engines.

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Keywords: thermodynamics, thermophotovoltaics, thermoradiative, trade, off, bounds

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Germanium TPV cells: interest, efficiency potential and key technical challenges

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Latent heat thermal batteries constitute a novel electricity storage technology that, in combination with thermophotovoltaic cells, can offer drastic cost reductions at elevated energy densities. In these devices, incoming electricity is used to melt a material with a high fusion point, which stores energy in the form of latent heat. When needed, the stored heat is turned back to electricity by a TPV converter. InGaAs TPV cells have produced the highest efficiencies so far, but their cost is so high that hampers the volume development of these batteries. In this talk, we will discuss the possibilities of Ge as a cost-effective Ge TPV cell material by discussing 1) the existing infrastructure around Ge semiconductor device manufacturing; 2) the limitations of Ge as a TPV material; 3) the calculation of realistic TPV efficiency potential; and 4) discussion of current experimental results and technological routes and challenges to materialize the calculated potential. The bottom line of these analyses is that _˜30% TPV efficiencies using cost-effective Ge cells seem within reach.

Keywords: Ge TPV cells

*Speaker

Characterization

Challenges in the characterization of thermophotovoltaic devices

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Thermophotovoltaic (TPV) cells are solid-state devices capable of converting the heat radiated by incandescent bodies (named emitters) into electricity using low bandgap semiconductor materials. One of the advantages of the TPV technology is the capability to reach high conversion efficiencies in a wide range of power outputs, from applications that require few W's to several hundreds of MWs. This is why this technology is very appealing in different applications such as waste heat recovery, energy storage, combined heat and power, etc. The key of high conversion efficiencies is the fact that the emitter and the cells can see each other with high view factors, so it is possible to reflect back to the emitter the low energy photons that do not contribute to photogeneration in the cell. Then, the energy associated to those photons is not considered an energy loss since it can be recycled in the heat source. This recycling process establishes a net radiative heat flux from the emitter to the cells that need to be quantified to determine the TPV conversion efficiency. The net radiative heat flux is influenced by all the characteristics of the optical cavity formed between the emitter and the cells, such as the elements included (mirrors, filters, etc.), the materials used, the geometry (size and location), the temperature, etc. Therefore, to measure the TPV efficiency can be quite complex because it requires a characterization setup that reproduces exactly the same conditions that the ones of the final application, and there are so many different applications that operate at different temperatures, with different geometries, etc., that achieving this flexibility is very difficult in practice. For this reason, the results reported to date have focused on characterizing the TPV efficiency at different emitter temperatures using, in general, random geometrical factors. This is not ideal because it is already known that these factors affect the TPV efficiency obtained, and especially the electrical power density generated which is the main parameter for some TPV applications. Therefore, the TPV community is currently seeking standardized characterization methods that allow to compare different experimental results in rigor and thus of facilitating the technology development. One of these methods will be presented at the workshop. In addition, there is a recent interest to define new merit functions to determine optimal system designs. Because of the TPV efficiency and power density generated can be maximized independently, a priori it is not clear how to proceed to maximize the overall efficiency of a system (which is not the same that the TPV efficiency that can be characterized more easily at laboratory level). For example, in order to boost the TPV efficiency, the bandgap of the cells could be increased (this reduces the thermalization losses) if high-quality mirrors are incorporated (this reduces the sub-bandgap absorption losses), but this would reduce the power density generated because less portion of the radiated spectrum will be usable. A very small power density might lead to very low overall conversion efficiency in open TPV systems like the ones used in solar-TPV applica-

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tions. In this case, maximizing the overall system efficiency typically results in TPV devices that maximize power density rather than the TPV efficiency. Besides, in practice high-power density will be also necessary to reduce power cost and compensate both cavity and thermal insulation losses. This trade-off between the TPV efficiency and power density will be also discussed at the workshop.

Keywords: thermophotovoltaic, conversion efficiency, power density

Near-field effects

Electroluminescence overcoming thermal radiation in near field: conditions for a nanothermophotonic refrigerator

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Thermophotovoltaic (TPV) and thermophotonic (TPX) (1-6) devices are used to convert the radiated energy from a hot source into electric power through a photovoltaic converter. TPX devices extend the concept of TPV by replacing the hot body by a light-emitting diode (LED). Under particular conditions, LEDs are expected to emit larger radiative power than the supplied electrical power, by extracting heat from their crystalline lattice, resulting in cooling of the LED and its surroundings. This effect is called electroluminescent cooling (2) and can be used either to increase power harvesting from a hot body or to build a radiation-based cooling device. In this second configuration, the LED is kept at a lower temperature than the PV cell. In this work we focus on such cooling applications of TPX (5-6) and analyze the impact of near-field radiative effects on the device performances.
Single LEDs experience unfortunately low cooling power and a low coefficient of performance (COP), which is the efficiency metrics of heat pumps. TPX devices allow in theory to improve the COP, because the PV cell recycles part of heat losses in order to decrease the external electrical power required. In near field, the power extraction is expected to be larger and a higher cooling power should be obtained.

A key issue in such device, however, is that the warmer PV cell radiates thermally towards the LED, counteracting the cooling power of the LED. The issue is particularly significant when the two components are in near field. By means of accurate nanoscale radiative computation (fluctuational electrodynamics) and detailed balance, we investigate the effect of quantum efficiency (device quality), temperature and vacuum gap distance on the potential performances of near-field TPX refrigerators made of GaAs-based materials. We analyse the impact of surface polaritons in the near-contact distance range and compare the performances to more-usual thermoelectric materials. We include some nonidealities such as surface roughness or grid shadowing in a second step.

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(2) P. Santhanam et al., Physical Review Letters, **108**, 097403 (2012)

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(3) N.-P. Harder and M.A Green, Semiconductor Science and Technolology **18**, S270 (2003)

(4) J. Legendre and P.-O. Chapuis, Solar Energy Materials and Solar Cells **238,** 111594 (2021)

(5) F. Yang et al, Applied Physics Letters **120**, 053902 (2022)

(6) J. Song et al., ASME Journal of Heat Transfer **142**, 072101 (2020)
This work has received funding from project EU H2020 FETOpen-2018-2019-01/GA964698 (OPTAGON).

Keywords: Cooling, Near, field, Radiative heat transfer, Thermophotonics

Effect of the graphene grating coating on near-field radiative heat transfer

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In this work, the near-field radiative heat transfer (NFRHT) between finite-thickness planar fused silica slabs coated with graphene gratings is analyzed beyond the effective medium approximation by using an exact Fourier modal method incorporated with the local basic functions (FMM-LBF), which is needed for realistic experimental analysis. In general, coating substrate with a full graphene sheet has been shown to decrease the NFRHT at short separations (typically for d< 100 nm). We show that by pattering graphene sheet into grating, the topology of the plasmon mode induced by graphene nanostructure changes from circular to hyperbolic, allowing for more channels for energy transfer between the substrates. We show that at short separations the NFRHT between coated graphene gratings is higher than the one between full-graphene-sheet coated substrates and also than that between uncoated substrates. A significant dependence of the radiative heat transfer on the chemical potential is found, which can be applied to in situ modulate the scattering details of the graphene grating without any geometric alternations, and thus fine-tune non-additivity in radiative heat transfer. This work has the potential to unveil new avenues for harnessing non-additive heat transfer effects in graphene nanomechanical system devices.

Keywords: Near, field radiative heat transfer, graphene grating, substrate effect, scattering matrix, FMM, LBF

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Thermophotonic energy harvesters: thermodynamic analysis and near-field performances of 1D architectures

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Thermophotonics (TPX) (1) is a technology close to thermophotovoltaics (TPV), where a heated light-emitting diode (LED) is used as the active emitter. With such a device, the emission profile can be tuned: initially in the infrared range, it can be shifted by means of electroluminescence to a spectral range matching better the gap of efficient TPV cells. With the development of LEDs and the increase of their achievable quantum efficiency, TPX has come out as an attractive concept for both energy harvesting and refrigeration (2). One advantage is that the emitter temperature can stay moderate, close to few hundreds of degrees Celsius, in contrast to usual TPV emitters. The many studies on near-field (NF) thermal radiation and their application into efficient NF-TPV devices (3) highlight the possibility to extend the concept to near-field thermophotonics (NF-TPX), where enhanced energy conversion is due to both electrical control and wave tunnelling.
We start by analysing the thermodynamics of TPX devices. As photovoltaic, thermophotovoltaic or thermoradiative devices, they can be understood as photonic (or radiative) heat engines. However, the fact that both the emitter and the absorber are active gives TPX devices interesting properties. Considering only above-bandgap radiation for instance, it is the only one able to operate at Carnot efficiency for any bandgap energy in the reversible limit, and to have non-zero power output at this efficiency. This opens a path for the development of thermodynamic limits specific to TPX devices.

In a second step, we study the performance of devices based on III-V heterostructures. These are simulated with an internal solver coupling near-field radiative heat transfer and charge transport in 1D (4,5), and capable of handling both thermionic emission and tunnelling effects at the heterointerfaces (6). In the initial simulations performed with AlGaAs or GaAs active layers and InGaP confinement layers, an electrical power output of 1.7 W.cm-2 could be reached when the LED is heated at 300∘C. These calculations were carried out assuming constant AlGaAs non-radiative recombination lifetimes equal to that of GaAs at 25∘C due to the lack of data related to temperature and composition dependency. However, using simple models to account for such dependencies reveals that the performances of the device are deteriorated, making it sometimes inoperable. To limit the performance reduction, we propose a second structure in which additional low-doped InGaP layers are added on the LED side to prevent excessive Auger recombination rate. Furthermore, the use of a GaAs active layer in the LED – instead of AlGaAs

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in the initial structure – allows maximising its quantum efficiency and therefore the overall performance, an InGaAs active layer being used in the PV cell to ensure bandgap matching. With these two modifications, the power output is only reduced by a factor 4 when considering both dependencies, the device still being able to generate around 0.4 W.cm-2 of electrical power density.

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We acknowledge the support of EU project H2020 FET-PROACT-2019 951976 TPX-Power.

Keywords: Thermophotonics, Near field radiation, Photonic heat engines

Photovoltaic conversion (2)

Thermophotovoltaic conversion with a silicon vertical multijunction cell

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When the emitter of a thermophotovoltaic converter is at high temperature (> 1800 ◦C), the photovoltaic cell is subjected to high illumination conditions. Typically, a cell illuminated by a blackbody emitter at 2100 ◦C with a unit view factor receives 179.8 W/cm2. As in concentrated solar photovoltaics, under these conditions, series resistance losses are critical, due to the squared dependence of the electrical current. One solution is to use (standard) horizontally-stacked multijunction cells in order to reduce the current. This pathway is currently successfully pursued in thermophotovoltaics (1-3), with limitations of performances caused by series resistance losses. Another solution is to use vertical multijunction (VMJ) cells, proposed in the seventies as a new type of solar cell (4), and envisaged for TPV conversion in the nineties (5) but without experimental testing. Our work consists in the experimental assessment of the performances of a ˜1 cm2 silicon VMJ solar cell in solar and thermophotovoltaic conditions (6). As expected, when the emitter is at 2100 ◦C, operation at low short-circuit current density (< 6 mA) and high open-circuit voltage (> 25 V) and a low series resistance (˜2.5 m ohms) lead to negligible series resistance losses. Because of substantial out-of-band absorption, a pairwise efficiency of 10.4% is found. This value could be increased to 52.9% by designing a perfect reflector of the out-of-band photons. These preliminary results obtained with a cell designed for solar photovoltaics suggest that it is worth reopening the research path to develop thermophotovoltaic devices based on VMJ cells.

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Acknowledgements
D. Chemisana thanks the Institució Catalana de Recerca i Estudis Avançats (ICREA) for the ICREA Acadèmia award.

Keywords: Series resistance losses, Silicon, Vertical multijunction cell

Multiphysics and multiscale modeling of a photovoltaic panel using Monte Carlo methods

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The optical, electrical and thermal performance of a photovoltaic panel under real conditions is the result of a complex interaction between the panel and its environment: intermittent solar radiation, airflow fluctuations, and possible shading (1). However, the design and performance assessment of PV cells performed under the Standard Test Conditions (STC) corresponding to a situation where the incident solar radiation power density is 1000 W.m-2 (AM-1.5 solar spectrum) and the cell temperature is equal to 25 ◦C. However, it was observed that photovoltaic panels are almost always operating far from the STC conditions in a realistic environment (2). Therefore, it seems necessary to rethink the modeling chain of a photovoltaic panel in real operating conditions. This modeling chain requires the development of electrical, optical and thermal models involving multiphysics and multi-scale coupling issues (from the cell to the solar plant). First, a macroscopic model of the heat balance of a 310 W photovoltaic panel was developed in a probabilistic way by the Monte Carlo (MC) method (3). An estimation of the temperature at the backside of the panel was obtained and validated against experimental data. This method also allowed to evaluate the electrical production over a large period of time by considering the varying meteorological parameters.

Second, in order to develop a unified framework for the Multiphysics multiscale model of the

*Speaker

panel, it was decided to start the building of a probabilistic opto-electrical model for the photovoltaic cell. As a first stage, this model was developed by assuming that minority carriers can be separated in a simple crystalline silicon PN junction and by solving for their diffusion. The total current is expressed as the sum of the photocurrent and the diode current. The total current was calculated by implementing two different algorithms describing random walks either on a reverse (back to the source of electron-hole pairs) or a direct (start from source) path space, exhibiting two viewpoints for the analysis of the physics involved.

Benefits are expected from this path space formulation: renewed physical images, insensitivity of computation times to the dimension of the integration domain (here to the number of coupled phenomena) and to the geometrical complexity at all scales, sensitivity calculation, symbolic Monte Carlo. This work is part of a strong dynamic of the EDStar group (4), both at the level of the initial application question, and at the methodological level.

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Keywords: photovoltaics, Monte Carlo method, heat transfers

InAs/InAsSb superlattice thermophotovoltaic cell: how to adapt an infrared photodetector for TPV conversion

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Similar to solar photovoltaics (PV) on the principle but different regarding its applications, thermophotovoltaics (TPV) is recently regaining interest (1, 2), especially thanks to low cost energy storage perspectives (i.e. thermal battery (3)). Looking at this increasing research topic, especially concerning the TPV cell side, it is noticeable that most of the structures focus on gallium-containing absorbers with bandgaps ranging between 0.5 to 0.8 eV. These bandgaps are still far from the optimum ones (around 0.3 eV) predicted by the detailed balance limit (no photon recycling) for emitter temperatures lower than 1300 ◦C.
Thus, we propose in our work to design and investigate the performances of a very-low bandgap (0.25 eV) TPV cell made of an InAs/InAsSb superlattice (SL) absorber. This choice was motivated by the possibility to increase the part of the emitter spectrum used for conversion, while decreasing the cooling power flux (usually more than a few W/cmˆ2) needed to prevent a rise in cell temperature. The counterpart of this very-low bandgap choice is the low (cryogenic) temperature requirement for the cell. Overcoming this limitation is somewhat similar to what researches in the infrared photodetectors community are trying to address (4). Thus, we decided to apply the same strategy proposed in this closely related field and use a barrier structure for suppressing the generation-recombination current and increasing the operational temperature.

TCAD simulations (5) were performed to optimize the structure and better match it to TPV figures of merits. GaSb was chosen in place of the SL for the front contact layer in order to improve spectral and electrical performances. The metallic contacts were modified to better match the high currents expected in TPV. These theoretical studies were followed by molecular beam epitaxy growth of the samples on GaSb substrates, and clean room processing. A strong anisotropic (wet) etching was observed, leading to adjustments in the process. The different aspects of these steps will be presented and discussed more thoroughly in this communication.

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Financial supports by the French National Research Agency (ANR) under grants No. ANR-18-CE24-0019 and ANR-21-CE50-0018, and by CNRS-INSIS (project-team TREE) are acknowledged.

Keywords: thermophotovoltaic cell, very, low, bandgap, superlattice, photodetector, simulation, clean, room, process

Work in progress

Design of a near-field thermophotonic device in the planar configuration for energy harvesting and refrigeration

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There is a growing demand for efficient and sustainable solutions for both cooling and thermal-energy harvesting in a world facing respectively climate change challenges and increasing energy needs. One of the potential solid-state technologies of interest in this context is thermophotonics (1). Well-known thermophotovoltaic (TPV) systems convert radiative thermal energy emitted in the infrared by a passive thermal surface into electrical energy using a photovoltaic (PV) cell. By using a light-emitting diode (LED) as the emitter one can improve energy conversion efficiency due to the spectral matching between the emitter and the PV cell. This increases the power converted in the PV cell, and part of it can be fed back to the LED to decrease its electrical consumption, therefore leading to potentially efficient thermal-energy harvesters called thermophotonic (TPX) ones. Similarly, the performances of passive radiative cooling (PRC) relying on surfaces that emit thermal radiation in the mid-infrared range can be surpassed by those of active radiative cooling, which involves an LED controlled with an external bias. Further, recycling the radiative power extracted from the LED in a PV cell allows to feed partly the LED, therefore minimizing the electrical-power input. This configuration is a TPX refrigerator (2). Both applications are expected to perform well in near field (NF), where the radiative exchange is enhanced due to evanescent waves. This regime takes place when distance between emitter and receiver decreases below the characteristic wavelengths of the involved radiation: around 10 μm for thermal one and below 1 μm for electroluminescent one in the case of the considered GaAs devices. This NF approach has already demonstrated its success for thermal radiation in TPV, resulting in a notable increase in converted power (3), and it has also been subject to theoretical examination for planar TPX devices (4).

Here, we introduce an experimental setup aiming at carefully analyzing the NF exchange in a TPX planar geometry. It shares some similarities with our spherical-emitter based experiment (5), but the adaptation for planar surfaces requires to tackle in particular parallelism, bowing and roughness issues (6-7). Since the two applications (cooling and energy harvesting) are targeted, the LED side should be able to withstand temperatures from 77 K to 1000 K. The study requires also characterizing the different elements, especially the pin junctions being used as LED or PV cells, as a function of temperature. This is done independently by performing

*Speaker

I-V characteristics either in cryostat environment or in a microscope-based Fourier transform infrared and visible spectrometer, which allows to characterize the emission spectrum including the Urbach tail. Challenges linked to the electrical control of the complex devices are also discussed.

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We acknowledge the support of EU H2020 projects FET-PROACT-2019 951976 TPX-Power and FETOpen-2018 964698 OPTAGON.

Keywords: thermophotonic, Near, field thermal radiation, energy conversion

Near-Field Radiative Heat Transfer Between a Sphere and a Flat Surface in the Sub-200 nm Regime and Prospects for Energy Harvesting

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When the distance between objects decreases below the characteristic wavelength of thermal radiation (few micrometres in the 300-1000 K range), the radiative heat exchanged between these objects is increased beyond the blackbody limit imposed by Planck's law in far field. This increase of thermal radiation, which takes place in the near field and is due to the additional contribution of evanescent waves, can reach several orders of magnitude. This phenomenon can be of interest for thermal-energy harvesting. For instance, thermophotovoltaics (TPV) can take advantage of this enhancement of the radiative heat flux in order to increase the electrical output power density when the emitter is brought closer to the cell (1). A further improvement of such a device is thermophotonics (TPX) which consists in placing a light-emitting diode (LED) on the heated emitter side, thus controlling emission spectrum via electroluminescence. This would theoretically allow reaching power output densities that could exceed near-field TPV performances (2).
As the radiative flux between objects depends dramatically on distance, it is critical to determine it with extreme precision. We report on our recent efforts to evaluate the stability of our experiment. It involves a heated micrometric sphere as the emitter, which is glued on a Scanning Thermal Microscopy probe cantilever. Using a piezoelectric actuator, the emitter is moved either towards the cold sample (thermal-radiation measurements) or towards a pn junction (TPV cell or LED, for energy-conversion measurements). Radiative transfer is monitored throughout the approach by means of resistive thermometry, which requires delicate calibration prior to the experiments (1,3). We analyze the vibrations of our cantilever-based system during the approach with combined means of interferometry, optical deflection and resistive thermometry in order to provide accurate data in the sub-200 nm distance regime, both in terms of mechanical stability and snap-in at contact. We discuss the TPV results and prospects for TPX.

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Keywords: near, field, energy harvesting, SThM, Thermophotovoltaics