Workshop on

Thermal radiation to electrical energy conversion

ESIEE Paris

November 14th – November 16th

Sponsored by CNRS – INSIS

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November 14th

13h30 [30 min]	**Reception at ESIEE**	
14h00 [20 min]: Rodolphe Vaillon	IES, Univ Montpellier – CNRS, France	**Introduction to the workshop**
Session 1	**Thermophotovoltaics and thermal energy storage**	
14h20 [60 min]: Alejandro Datas	IES, UPM, Spain	**Thermophotovoltaic batteries**
15h20 [30 min]: Thomas Fasquelle	IUSTI, Aix-Marseille Université – CNRS, France	**Can proposed energy storage technologies be deployed on a large scale? A comparison of three promising candidates**
15h50 [40 min]	**Coffee break**	
16h30 [60 min]: Xavier Py	LTEN, Univ Nantes – CNRS, France	**High-temperature thermal energy storages (sensible or latent heat): from related materials to industrial applications**
17h30 [20 min]: Alexis Vossier	PROMES, CNRS, France	**On the dispatchability of solar electricity with thermal and electrochemical storage**

November 15th

Session 2	**Photovoltaic conversion: fundamentals and advanced concepts**	
9h00 [60 min]: Jean-François Guillemoles	IPVF, CNRS – Ecole Polytechnique – ENSCP, France	**What is the temperature of a solar cell and why it is important**
10h00 [40 min]: Maxime Giteau	ICFO, Spain	**Opportunities for high-performance thermophotovoltaics – a fundamental analysis**
10h40 [40 min]	**Coffee break**	
11h20 [40 min]: Basile Roux	IES, Univ Montpellier – CNRS, France	**InAs/InAsSb superlattice thermophotovoltaic cells**
12h00 [40 min]: Julien Legendre	CETHIL, INSA Lyon – CNRS – UCBL, France	**Near-field thermophotonics: extending near-field thermophotovoltaics with LEDs as emitters**
12h40 [1h20]	**Lunch break**	

Session 3 (1)	**Materials and their properties**	
14h00 [40 min]: Mounir Zahir	Institut Pprime, CNRS – Univ Poitiers, France	**Improved thermophotovoltaic performance with a novel metamaterial thermal emitter and the radiative cooling approach**
14h40 [40 min]: Tarik Bourouina	ESYCOM, Univ Gustave Eiffel – CNRS, France	**Ultra-broadband black-silicon: radiative properties and applications**
Session 4	**Posters**	
15h20 [1h20]		**Contributed posters* on all topics**
16h00	**Coffee served**	
Session 3 (2)	**Materials and their properties**	
16h40 [40 min]: Simon Hurand	Institut Pprime, CNRS – Univ Poitiers, France	**Measuring temperature dependent optical indexes by spectroscopic ellipsometry**
17h20 [20 min]: Léa Penazzi	LEMTA, Univ Lorraine – CNRS, France	**Thermal and optical characterization of materials at high temperature**
17h40 [40 min]	**Visit of ESYCOM's cleanroom installations**	Limited to a small group (more details soon)

November 16th

Session 5	**Light harvesting and trapping**	
9h00 [60 min]: Andrea Cattoni	C2N, CNRS – Univ Paris-Saclay, France	**Light trapping in ultra-thin solar cells: progress and prospects**
10h00 [40 min]: Mathieu Thomas	CETHIL, INSA Lyon – CNRS – UCBL, France	**Harvesting near-field thermal radiation**
10h40 [30 min]	**Coffee break**	
11h10 [40 min]: Kevin Austry	L2C, Univ Montpellier – CNRS, France	**Effect of top metallic contacts on radiation transfer and conversion efficiency for near-field thermophotovoltaics**
11h50 [40 min max]	**Conclusions, closing discussions: new coordinated actions**	

* Contributed posters

- Kartika Nimje et al., ICFO, Spain, **Leveraging hot-carriers for high performance thermophotovoltaics – an analytical approach**
- João Carlos De Aquino Carvalho et al. (presented by Daniel Bloch), LPL & CEMHTI, France, **Near-field Thermal emission of sapphire at high-T: precisely locating the T dependent polariton resonances in view of energy conversion**
- Thomas Châtelet et al., CETHIL, France, **Photonic heat pumps instead of heat engines: the near-field thermophotonic refrigerator**
- Olivier Farges et al., LEMTA, France, **Research and expertise activities of the LEMTA «Heat Management» team**
- Aloyse Degiron, LMPQ, France, **The crucial role played by hot carriers in colloidal quantum dot optoelectronics**
- Olivier Rozenbaum et al., CEMHTI, France, **Determination of the optical properties of materials up to very high temperatures by measuring the spectral emittance**

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Thermophotovoltaics and thermal energy storage

Thermophotovoltaic batteries

Alejandro Datas *† [1]

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The availability of cost-effective energy storage technologies with durations from 10 h to several days is key for variable renewable energy sources to become major contributors to electricity generation. In upcoming years, battery prices are expected to remain too high, with energy storage as heat emerging as a cheaper and more promising solution. Even if there is an efficiency penalty in converting heat back to electricity, the low cost of heat storage is a big advantage, especially because this conversion is not always necessary, since heat accounts for about 50% of global energy demand.
Thermophotovoltaic (TPV) "batteries" allow for much lower cost than state-of-the-art electrochemical batteries and can provide both heat and electricity on demand, which make them attractive for grid-scale, long duration energy storage, and distributed dispatchable cogeneration. TPV batteries store energy in the form of heat at very high temperatures (> 1000ºC) and convert this heat back to electricity on demand using TPV. A key advantage is the flexibility of the energy input, which makes possible to design systems that store concentrated sunlight (solar-to-heat-to-power) or surplus generation of renewable electricity (power-to-heat-to-power).

The urgent need to find a cost-effective energy storage solution has speeded up the development of TPV batteries in the recent years. Projects in the US are focusing on the development of "sensible heat" storage systems that operate at extreme temperatures near or above 2000ºC, whereas projects in the EU focus on "latent heat" storage designs operating at lower temperatures of 1400ºC or less. Very recently, two collaborative projects have been granted in the EU to develop latent heat TPV batteries for power-to-heat-to-power (THERMOBAT) and solar-to-heat-to-power (SUNSON) applications.
In this talk I will describe TPV batteries, covering from technology fundamentals to techno-economic analysis. I will also review the current state of the art of these systems, with an especial focus on the EU projects that develop latent heat TPV systems.

Keywords: thermophotovoltaic, energy storage, power, to, heat, to, power

*Speaker

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Can proposed energy storage technologies be deployed on a large scale? A comparison of three promising candidates.

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The ability to provide large-scale energy storage for high grid penetration of intermittent renewables is estimated using order-of-magnitude calculations for three promising candidates: i) power-to-heat-to-power using commercially available two-tank molten salt storage combined with high-efficiency steam turbines; ii) large-scale deployment of lithium-battery electric cars and smart grids; iii) thermophotovoltaic energy storage. The goal is to be able to provide at least 12 hours of electricity at the global average consumption value, with minimal increase in electricity price, and without depletion of materials due to large-scale deployment of the chosen solution. Other criteria are also discussed, such as the maturity of the technology, its recyclability and its social acceptance. The results show that all three technologies are capable of meeting the defined needs, but that thermophotovoltaics is not ready, that li-ion batteries would pose problems regarding battery life and material availability, and that molten salt electricity storage could compete with agriculture and suffer from political constraints such as Seveso regulations.

Keywords: Power to Heat to Power, Electric cars, Thermophotovoltaic, Large scale deployment

*Speaker

High temperature thermal energy storages (sensible or latent heat), from related materials to industrial applications.

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In the context of the energy transition, innovative and efficient Power-to-X approaches are highly needed to address major related issues such as: industry decarbonation through electrification and massive integration of intermittent renewable energies in the grid.
Among Power-to-X and especially Power-to-Power emerging technologies, thermophotovoltaic systems associated to upstream electrothermal converter and thermal energy storage (TES) systems are highlighted today as very promising. Such thermophotovoltaic batteries benefit from researches and related industrial achievements in high temperature thermal energy storage materials (HT-TESM) and systems previously and currently developed for other applications. The aim of the present communication is to review some of TES related research studies developed during the two last decades for concentrating solar power (CSP) applications and currently for industrial waste heat valorization (IWHV) or power-to-heat (P2H) applications.

In the particular case of CSP, recycled ceramics made of industrial wastes (asbestos containing waste, fly ash, slags,...) have been elaborated, characterized and tested up to 1000◦C and even cycled (between 500 and 1000◦C under air) under direct concentrating solar flux. They present similar thermal storage capacities than those of molten salts and very high resistance to thermal cycling even thermal shocks. Compared to more conventional CSP TESM, those high temperature ceramics are available at low cost and better LCA indicators. They have been tested at pilot scale in the two shapes of granular packing and structured packing of static mixers allowing enhanced heat transfer at low pressure drop.

Still for CSP TES systems, composites of phase change materials (PCM) and graphite have been developed and tested, offering enhanced thermal conductivities to reach high and controlled charging/discharging powers and operating PCM temperature stability. Compared to usual PCM properties (roughly in the range of 0.2 to 2 W/(m K)), the obtained composite thermal conductivities can reach up to 70 W/(m K). Their specific anisotropic character offers additionally to the TES system not only an enhanced radial heat transfer but also the advantage of axial thermal stratification.

During an ongoing PEPS-CNRS research program, those TESM are applied to the emerging case of power-to-heat systems in which the electro converter is integrated in-situ to the TES unit by using the TESM as electromagnetic charge. Then, thanks to the graphite fraction,

*Speaker

graphite/PCM composites offer simultaneously the needed electric conductivity for the induction or microwaves heating and the needed thermal conductivity to heat uniformly the TESM (and also for the discharge step). The composite TESM composition (in terms of selected PCM, graphite amount and graphite distribution) allows high flexibility to offer optimized properties for both charging and discharging steps.
Such latent heat electro-thermal energy storage (LH-ETES) could offer new perspectives for thermophotovoltaic systems.

Keywords: high temperature thermal energy storage, sensible heat, latent heat, composite materials, CSP, P2H

On the dispatchability of solar electricity with thermal and electrochemical storage

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Further deploying Variable Renewable Energy (VRE) in the electricity mix will require the development of efficient storage solutions for smoothing renewable electricity production and better matching the electrical demand. A number of storage technologies are currently available or under development, covering a wide range of time response, power, and energy characteristics. Because of the cost structure, the efficiency, or the operating conditions, the techno-economic performances of each storage technology may vary significantly depending on the intrinsic storage characteristics (i.e. energy, power) as well as the dispatch strategy of the electrical energy stored (i.e. baseload or tracking load).

In this work, we provide a benchmark study aiming at evaluating how the integration of storage into conventional PhotoVoltaic (PV), Concentrating Solar Power (CSP) and hybrid PV/CSP plants will affect both their dispatchability and the cost of the electricity produced, considering BESS, TES and finally TPV as a mean of storage. We use an in-house model to evaluate the annual electricity generation, the ability of the different plants under investigation to satisfy the electrical demand, and the cost of the electricity produced.

We provide a physical description of each solar technology under investigation and formulate the underlying assumptions. Then, the selected storage technologies and their integration in the different solar plants are portrayed. The ability of the different systems to provide dispatchable electricity at an acceptable cost is finally discussed.

Keywords: storage PV CSP battery thermal TPV

*Speaker

Photovoltaic conversion: fundamentals and advanced concepts

Opportunities for high-performance thermophotovoltaics – a fundamental analysis

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Thermophotovoltaics (TPV) generalizes the concept of solar photovoltaic (SPV) cells to the energy conversion of thermal radiation from any hot source into electric power. The field has attracted a lot of interest recently, with an impressive 40% conversion efficiency experimentally reported this year. The concept can directly be integrated into solar energy converters, with other promising applications in waste heat recovery and thermal storage.
TPV differs from SPV in one fundamental way: the spectral shape of the radiation incident on the cell can be engineered. The efficiency of an ideal TPV cell is maximal when the source only emits photons at the bandgap energy. However, in this narrowband limit, the power density tends to zero. Therefore, the objective cannot simply be to maximize efficiency. Some broadening of the incident radiation is always desirable. The key question is how much broadening leads to the optimal combination of high power and high efficiency.
I will first introduce the detailed balance framework which is central to this work and apply it to determine the analogue of the Shockley-Queisser single-junction limit for TPV. I will then move on to analyze different ways this limit can be overcome. I will show in particular how advanced PV concepts, such as multi-junction and hot carriers, can help improve TPV performance significantly. I will also emphasize the crucial advantages provided by operating in the near field, in terms of power density and radiative efficiency.

Keywords: Power density, efficiency, hot carrier, multi, junction, near, field

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Near-field thermophotonics: extending near-field thermophotovoltaics with LEDs as emitters

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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. Interestingly, an LED is physically similar to a TPV cell, but used in the opposite fashion, i.e. to emit light from electrical power. 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 photovoltaic 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 tunneling.
In order to model accurately the device and deduce the electrical power output, we couple a radiative transfer solver based on fluctuational electrodynamics - a framework allowing to deal with electromagnetic emission within the medium - with a drift-diffusion equations (DDE) solver used for both junctions (4,5). This reveals that a power density as high as 2.2 W/cm^2 (˜7 mW/cm^{2}K) can be reached by using realistic AlGaAs PIN homojunctions. Through a thorough analysis of such device, we point out the significant impact of non-radiative processes (Auger, Shockley-Read-Hall) on the performance and their coupling with near-field effects, which are much more critical for TPX than for usual TPV (5). A thermal study of TPX devices also shows the necessity to eliminate sub-bandgap energy photon transfer, especially in the near field, and how efficient the thermal management system should be for both components to maintain good performance.

(1) N.P. Harder and M.A. Green, Semicond. Sci. Technol. **18**, S270 (2003).

(2) T. Sadi et al., Nat. Photonics 14(4), 205 (2020).

(3) C. Lucchesi et al., Nano Lett. 21(11), 4524 (2021).

*Speaker

(4) J. Legendre and P.-O. Chapuis, Sol. Energy Mater. Sol. Cells **238**, 111594 (2022).
(5) J. Legendre and P.-O. Chapuis, arXiv:2208.03984 (2022), Appl. Phys. Lett., to be published.

Keywords: Thermophotonics, Near field radiative heat transfer, Energy harvesting.

InAs/InAsSb superlattice thermophotovoltaic cells

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Unlike solar cells, thermophotovoltaic (TPV) cells convert photons from a relatively close emitter. This proximity, extreme in the near-field configuration (1), brings a new constraint limiting the efficiency of such converters: thermal heating of the TPV cell by the hot emitter. Usually, the hotter the cell, the less efficient it becomes which implies cooling needs and thus power consumption in a system meant to be a generator. In order to avoid that, we consider here a TPV system designed for the conversion of radiations from medium-grade heat-source (700-1000◦C) (2), with a focus on the TPV converter (in far-field conditions for the time being). With such emitter temperatures, a very-low bandgap is required for the TPV cell to convert a sufficient share of the incident spectrum. Detailed balance calculations indicate that the theoretical optimum bandgap ranges approximatively from 150 to 300 meV. Few materials possess such small bandgaps, however InAs (3) and InSb (1) seem to be good candidate. We decided to base our TPV cell structure on infrared photodetectors developed in our lab, made of an InAs/InAsSb superlattice (SL) absorber (_˜250 meV bandgap) and an AlAsSb electron-barrier (4). This kind of photodetector was made in order to increase the operational temperature from 80K for conventional devices (e.g. InSb or Mercury Cadmium Telluride) to 150K by reducing the SRH recombination current and getting rid of Ga-native defects specific to Ga-containing superlattices (5). Electrical characterization of existing photodetectors fabricated using Molecular Beam Epitaxy and clean-room processes indicate that a small photovoltaic effect takes place. Hence, modifications are required to adapt the photodetector structure for TPV applications.

A specificity of the superlattice absorber is the relative tunability of some parameters, especially its bandgap, carrier mobility and lifetime, which depend among other things on the superlattice period and Sb-concentration controlled during epitaxy. Simulations of the device are done using an in-house TCAD code, to explore the best design choices, coupled with clean-room process and electrical characterization for experimental results.

(1) C. Lucchesi & al., "Near-Field Thermophotovoltaic Conversion with High Electrical Power Density and Cell Efficiency above 14%," Nano Lett. 21, 4524-29, 2021.

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(2) Datas, A., & Vaillon, R. "Thermophotovoltaic energy conversion" In *Ultra-High Temperature Thermal Energy Storage, Transfer and Conversion*, Woodhead Publishing, 285-308, 2021.

(3) A. Krier et al., "Low bandgap InAs-based thermophotovoltaic cells for heat-electricity conversion," J. Electron. Materials 45, 2826-30, 2016.

(4) U. Zavala-Moran & al., "Structural, optical and electrical characterizations of midwave infrared Ga-free type-II InAs/InAsSb superlattice barrier photodetector," Photonics 7, 76, 2020.

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Keywords: Thermophotovoltaic, narrow, bandgap, Ga, free superlattice, infrared

Materials and their properties

Ultra-Broadband Black-Silicon: Radiative Properties and Applications

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Metasurfaces based on silicon micro-structuration take the advantage of precise definition of two-dimensional geometrical features from micrometers to millimeters, addressing different spectral ranges including the infra-red. Most often than not, these metasurfaces involve bi-periodic patterns.

On the other hand, Black Silicon involves random micro- nano-structuration of the silicon surface and it can be produced easily from bare silicon. According to its name, Black Silicon appears black to the naked eye, suggesting that it has nearly-zero reflectivity (and high absorptivity) in the visible spectral range.

In this talk, we will first introduce recent advances on black silicon, which was tailored to extend its absorptivity from the UV-visible range till the Mid-Infra-red range (25 μm) making it a good candidate for highly emissive surfaces. The experimental results are supported by theoretical foundation and related modeling and simulation.

Among the application of such Ultra-Broadband Black, we will introduce three examples where it was effective for (i) solar-driven enhanced steam generation, for the purpose of water desalination, (ii) black-body light sources.

Finally, we will introduce preliminary results on harvesting water from air, using black silicon as a dual-functionality surface involving both radiative cooling capabilities and exceptional wetting properties.

Keywords: Metasurfaces, Mid, Infra, Red: Black silicon

*Speaker

Measuring temperature dependent optical indexes by spectroscopic ellipsometry

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Spectroscopic Ellipsometry is a powerful tool to unravel the optical properties of materials (bulk or thin films), allowing to extract their optical indexes. It is non destructive, fast, and can be performed in ambient environment or as an in-situ measurement. While reference optical indexes of materials are often available in the litterature for the UV-visible-NIR range, it is often hard to find similar references in the infrared range. Morever, optical indexes available from a reference "ideal" material are often not transposable to a given preparation method (e.g. Physical Vapor Deposition) because it can induce for example porosity, non-stoechiometry, partly amorphisation or multi-grain microstructure, among others. This can induce significant discrepancy in the simulation of the radiation behavior of materials or nanoscale heterostructures. When it comes to temperature dependent optical indexes, the avalaible data base of optical indexes becomes even more sparse. Therefore, there is a need for the measurement of optical indexes of specific materials, in order to correctly represent radiation properties of materials, including spectral variation (up to the infrared range) and temperature dependence. In this presentation, I will introduce the principle of Spectroscopic Ellipsometry, with a focus on the limitations of the measurement and the analysis method to extract the optical indexes, and present some examples of temperature-dependent optical indexes from the UV to the FIR range.

Keywords: Spectroscopic Ellipsometry, optical indexes, temperature dependence

*Speaker

Thermal and optical characterization of materials at high temperature

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[3] Saint-Gobain Research Paris – Saint Gobain Recherche – France

The characterisation of the thermal properties (thermal conductivity, thermal diffusivity) of complex heterogeneous solid materials at high temperature is not trivial and has been the subject of developments for many years at the Lemta laboratory. Over the years, measurement techniques have been developed and implemented using inverse methods adapted to increasingly complex materials and/or extreme thermal conditions where the heat transfer modes are strongly coupled.
The Lemta's experimental plateform is equipped with several spectrometers, microscopes, laser sources, infrared cameras, a fast multispectral camera, black bodies, a DSC calorimeter, furnaces and many other characterization benches. This plateform is in continuous development to extend the laboratory know-how in order to move from high temperatures (above 1000◦C) to very or ultra-high temperatures (beyond 1500-2000◦C).

More specifically, in Lemta there is a bench for high temperature thermal characterization using the flash method and a bench dedicated to the measurement of insulating material thermal conductivity using the three-layer method in a vacuum chamber.

At the heart of the current research works, in the context of the running joint CNRS laboratory Canopée, a new measurement bench was recently developed to measure the thermal properties of insulating materials with the hot wire method up to 1600◦C. Furthermore, there a measurement bench under development dedicated to temperature and emissivity estimation by multi and hyper-spectral methods on opaque and semi-transparent materials up to 2000◦C.
In direct link with these measurement benches, analytical and numerical models are developed associated to inverse methods to elaborate diagnostic tools (fault detection, non-destructive testing etc.). The current and further development on this measurement field in Lemta aims to constantly improve the estimation of heterogeneous materials and complex energy systems thermal properties. They also aims to meet the challenges of measurmement on high or ultra-high temperatures. Direct and inverse coupled models are developed to take into account the interactions between the tree heat transfer modes.

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Keywords: thermal properties, high temperature, coupled heat transfer, conduction, radiation

Improved thermophotovoltaic performance with a novel metamaterial thermal emitter and the radiative cooling approach

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Thermophotovoltaic (TPV) energy conversion systems have gained great interest in recent years as they can directly convert thermal energy into electricity using photovoltaic (PV) cells. The increase of the radiative power and the efficiency in TPV systems is mainly due to two keys factors. The first one deals with the nature of the selective emitter. A new high temperature selective emitter should be designed to have a high emissivity (absorptivity) below the bandgap energy (Eg) and a low emissivity above the Eg of the PV cells. The second key factor is related to the cooling mechanism of the PV cell as the conversion efficiency of the latter degrades with increasing temperature. In this work, we firstly propose and investigate a new efficient metamaterial thermal emitter, to reach a desired emissivity in the wavelength range. Secondly, in order to minimize the operating temperature of the TPV system, a passive radiative cooling approach is suggested in which an efficient double layer coating deposited on the substrate of PV cells is elaborated. It has a high emissivity in the atmospheric transparency windows and low absorptivity in the solar spectrum. We show that the high temperature metamaterial design can achieve high emissivity, over in the wavelength range, while reducing the sub-band loss from the PV cells. At 1400K, we demonstrate that adding the proposed cooling design on the substrate of a GaSb PV cells panel with an area ratio between the radiative cooler (RC) and the PV cells panel γ=10 , can improve the efficiency of the latter by and drop its operating temperature by 90K.

Keywords: Thermophotovoltaic, Energy conversion systems, High temperature emitter, Radiative cooling

*Speaker

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Poster session

Near-field Thermal emission of sapphire at high-T: precisely locating the T dependent polariton resonances in view of energy conversion

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In the near-field of a hot (T £ 1100 K) window, we use atom spectroscopy as an ultra-narrow spectral filter to probe the T-dependent surface polariton resonance of sapphire (_˜12.2μm). The results agree only partly with predictions derived from broadband far-field emissivity. Sapphire birefringence makes predictions difficult, but adds to versatility. Near-field thermal emission could be converted into a molecular excitation, opening a path to electrical conversion.

*Speaker

Photonic heat pumps instead of heat engines: the near-field thermophotonic refrigerator

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Heat-to-electricity converters such as thermophotovoltaic (TPV) (1) or thermophotonic (TPX) (2) devices are based on the efficient conversion of energy radiated from a hot source into work, but conversely external work can be used to generate radiative fluxes in TPX heat pumps and refrigerators (3). Such conceptual devices could compete with fluid-based devices, which are known to be noisy, involve polluting refrigerants and cannot be miniaturized easily, or Peltier thermoelectric coolers, which are smaller solid-state, vibration-free heat pumps that suffer however from low efficiency at room temperature and are difficult to miniaturize further without reducing the temperature difference between the hot and cold sides. In the considered design, the TPX converter consists of a cold light-emitting diode (LED) and a warmer photovoltaic (PV) cell separated by a vacuum gap. The LED illuminates the PV cell, which converts the radiative power into electricity sent back to the LED reducing its need for external supply. The LED extracts heat from the environment through electroluminescent cooling (3). The expected improved efficiency of such a device comes from the ability to match the LED's emission spectrum with the PV cell's absorption spectrum. In addition, the vacuum gap limits the thermal exchange between the two sides, which allows maintaining the temperature difference.
The aim of the present work is to improve the cooling efficiency by exploiting near-field radiative heat transfer, i.e. the increase of the radiative exchange between the LED and the PV cell due to evanescent-wave tunneling. Such effects have been applied experimentally for TPV devices (4) and numerically for TPX (5) to increase performances. By means of detailed balance analysis, we investigate the effect of internal quantum efficiency and temperature on the potential performances of near-field TPX refrigerators made of GaAs-based materials.

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Keywords: Electroluminescent cooling, Thermophotonics, Near, Field, LED, Photovoltaic cell, GaAs, Gallium Arsenide

The crucial role played by hot carriers in colloidal quantum dot optoelectronics

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Colloidal quantum dots offer attractive opportunities for light sources, photodectectors and solar cells. They can self-assemble into solid compact layers and their optoelectronic properties can be adjusted with great flexibility to address frequency windows that are otherwise difficult and/or expensive to cover with standard semiconductors.
In this contribution, we will see that hot carriers play a central role in such systems. Using near-infrared PbS quantum dots as an example, we will quantify the type and temperature of hot carriers based on rigorous comparisons between steady-state luminescence and absorption spectra (1). We will then show how these hot carriers govern all the optoelectronic properties of the samples, such as the precise Stokes shift between absorption and emission, the shape of the spectra and wavevector distribution (1,2). Finally, we will use this insight to demonstrate unconventional optoelectronic devices in which ensembles of PbS nanocrystals are coupled to tailored photonic environments, such as incoherent sources emitting light with broadband phase and/or polarization singularities (2,3).

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Keywords: Hot carriers, colloidal quantum dots, optolectronics, Kirchhoff law for non, thermal emitters

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Research and expertise activities of the Lemta "Heat Management" team

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The actions of Lemta's "Heat Management" research team aim to improve the performance of energy systems, to optimise their integration within more global multi-physical systems, and to study systemic architectures in order to recover and valorise waste heat. Its experimental and modelling activities are based more particularly on specific thermal studies:
- Thermal characterisation of materials, increasingly complex (anisotropic, porous, semi-transparent, ...) and under extreme thermal conditions, where the heat transfer modes are strongly coupled. The recognised skills in thermal metrology of materials and systems and the associated experimental resources are grouped together in the thermal metrology Métro'NRJ platform. These low and high temperature (1500◦C) thermal metrology resources have been labelled via the Carnot Institute ICEEL at the national level, and then extended to measurements at Very High Temperatures (VHT: above 2000◦C).

- The development of analytical or numerical modelling of the objects studied, directly or by inverse methods, associated with experimental work, in order to develop, among other things, diagnostic tools (fault detection, non-destructive testing, etc.). These methods and tools developed within this framework cover a wide range of spatial and temporal scales, as well as a variety of application fields, with the common basis of problems relating to the conversion, storage and transport of heat. A strong expertise in numerical simulation supports these models, in particular through the development and continuous enrichment of several calculation tools specific to the team (inverse method codes, virtual sensors, stochastic approach for coulped heat transfer, etc.).

- The scientific and/or technico-economic analysis of innovative energy recovery systems (ORC, Stirling, etc.), heat storage/unstorage (thermocline, flooded mines, etc.), and thermal control (exchangers, heat pipes, etc) have been the subject of continuous attention for several years with a strong development around thermal storage.
All of the team's research work is thus part of a global approach to developing experimental tools (thermal characterisation platform, state-of-the-art thermal measurement equipment, etc.) and digital tools (virtual sensors, coupled heat transfer, etc), in order to understand the study of tomorrow's energy systems within more complex multi-physical systems. Because of the strong applicative potential of the work carried out, the team relies of course on numerous industrial collaborations, but also academic, at the regional, national and international levels. This was recently reflected in the creation on 23 October 2020 of the CANOPEE joint laboratory with

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Saint-Gobain Recherche (Paris and Provence centres) and the CEMHTI (Orléans). It associates two CNRS institutes: INSIS for the LEMTA and INC for the CEMHTI. CANOPÉE (enjeu CArbone: matériaux inNOvants pour des Procédés Économes en Énergie) is the extension and programming of a long collaboration between LEMTA and Saint-Gobain Recherche (Paris).

Keywords: thermal characterisation, heat storage, coupled heat transfer, Monte Carlo method

Leveraging hot-carriers for high performance thermophotovoltaics - an analytical approach

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Theoretically, the efficiency of a heat engine converting the radiation coming from the Sun into electrical energy can be as high as 93% (Landsberg limit). However, the efficiency of single-junction solar cells is bounded by 34% due to the spectral mismatch between the bandgap of the cell and the solar spectrum: the sub-bandgap photons are not absorbed by the cell while the extra energy gained by the carriers after absorbing high-energy photons is quickly dissipated to the lattice as heat in a process called thermalisation.
There are several ways to surpass the single-junction limit. For instance, multi-junction solar cells absorb different parts of the spectrum in sub-cells with varying bandgap energies. Alternatively, in hot-carrier solar cells, the power typically lost in thermalisation can be recovered by extracting high-energy carriers, promising efficiencies up to 85%.

In thermophotovoltaics (TPV), the Sun is replaced by a thermal emitter with controllable spectral emissivity. For solar cells, the conversion efficiency is simply defined as the ratio of power density to the power received from the Sun. For TPV however, photons radiated by the cell can be reabsorbed by the emitter, not counting as an efficiency loss. As such, optimizing the conversion efficiency is different from optimizing the power output.

In principle, a narrowband TPV emitting photons with energy equal to the bandgap of the PV cell can achieve a conversion efficiency close to the Carnot limit, but with zero power density. Broadening the emitter spectrum, on the other hand, boosts power density, but at the expense of efficiency. This trade-off between conversion efficiency and power density in a TPV can be overcome by using advanced PV concepts such as multi-junctions and hot carriers. Indeed, the record conversion efficiency of 40% is obtained in a TPV device employing two junctions.
In this work, we analyse how hot-carriers can benefit TPV devices, considering a broadband thermal emitter. We then derive analytical expressions for the optimal efficiency and power density using detailed-balance principle for both the conventional and the hot-carrier TPV up to second-order approximation. We find that, contrary to conventional TPV systems, hot-carrier TPV can always reach the Carnot limit even with broadband illumination. Finally, we show that TPV benefits significantly from hot-carrier effects, by enabling a higher power density for a given conversion efficiency.

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Keywords: Hot, carriers, Thermophotovoltaics, Detailed, balance, Thermalisation

Determination of the optical properties of materials up to very high temperatures by measuring the spectral emittance

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A spectroscopic method to measure the directional spectral emittance of semi-transparent materials such as single crystals, ceramics or glasses is described. The experimental setup is equipped with two Fourier transform spectrometers (FT-IR) which allow to compare the thermal radiation emitted by a sample with that emitted by a black body over a wide spectral range (30-17000 cm-1). The samples are heated with a CO2 laser (500 W), allowing to reach temperatures well above the melting temperature of most materials. The performances of the device are illustrated here through the example of alumina. The analysis of the thermo-radiative properties then allows the optical properties of the materials to be determined by fitting the experimentally obtained data to dielectric function models. This method of emission spectroscopy allows to study materials up to very high temperatures (_˜ 2700 K).

Keywords: spectral emittance, dielectric function models, FTIR

*Speaker

Light harvesting and trapping

Effect of top metallic contacts on radiation transfer and conversion efficiency for near-field thermophotovoltaics

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Experiments performed so far to increase the efficiency of near-field thermophotovolatic cells take into account the periodic metallic contact resistance at the front of the cell only in an approximate way. Our study, based on a rigorous approach, investigates the influence of the front metal contact and predicts an effect wich is very different from the existing approximated predictions.

Keywords: Thermophotovoltaic cell, Near field radiation transfer, Conversion efficiency

*Speaker

Light trapping in ultra-thin solar cells: progress and prospects

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Efficiency of state-of-the-art single-junction solar cells is approaching the Shockley-Queisser limit (c-Si, GaAs). In contrast, the thickness of state-of-the-art solar cells is far from its theoretical limits and could be reduced by more than one order of magnitude with efficient light-trapping. Ultrathin solar cells, with thicknesses at least 10 times lower than conventional solar cells, could have the unique potential to efficiently convert solar energy into electricity while enabling, depending on the specific technology considered, significant material savings, higher industrial throughput, improved carrier collection in defective/degraded absorber materials and improved power production and lifetime.
In this talk, I first present a benchmark of recent experimental and modelling advances of single-junction ultra-thin solar cells based on three well established technologies (c-Si,Cu(In,Ga)(S,Se)2, GaAs) and compare their optical performances against theoretical light-trapping models (1). I will focus on some specific architectures (2) highlighting best designs to reduce optical losses, I will briefly address the challenges in the fabrication of ultrathin absorber layers and in nanoscale patterning of light-trapping structures and I will conclude by offering some perspective to go beyond light trapping sin single-junction solar cells.

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Keywords: Light trapping, Si, GaAs, CIGS

*Speaker

Harvesting near-field thermal radiation

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Thermophotovoltaics (TPV) allows converting thermal energy from infrared photons, therefore harvesting energy from thermal emitters in a range of temperatures closer to ambient than conventional photovoltaics. While the efficiency of TPV devices can reach 40% for single junctions, the power output is limited by the blackbody limit imposed by Planck's law in far field and stays moderate in comparison to other types of harvesting devices such as thermoelectrics. It is therefore key to increase the output power density of low or medium-grade TPV devices. This can be done by various means, which could ideally be combined. One option is to place a light–emitting diode (LED) on the heated emitter side, which allows controlling the emission spectrum; such device is termed thermophotonic (TPX). Another way is to exploit the increase of the radiative transfer when the distance between emitter and cell decreases below the characteristic wavelength of thermal radiation (few micrometers in the 300-1000 K range), i.e. when they are in near field. Explained by the additional contribution of evanescent waves to the radiative transfer, this phenomenon is used to increase the power generation.
Following first steps (1) and the demonstration that Stefan-Boltzmann's law is modified in near field (2), we analyse the near-field radiative heat transfer between a heated emitter and different types of samples. We report on the experiments, which consist in executing several approaches of a heated micrometric spherical emitter close to the flat studied sample in order to obtain the near-field radiative conductance as a function of distance. III-V semiconductors typically used for TPV and TPX devices, such as InSb and GaAs, are the targeted samples. Since the increase of the radiative flux depends dramatically on distance, we also report on our recent efforts to determine it more accurately in the last 50 nm before contact by means of combined analysis of laser deflection, fiber interferometry and resistive thermometry. (1) Near-field thermophotovoltaic conversion with high electrical power density and efficiency above 14%, C. Lucchesi, D. Cakiroglu, J.-P. Perez, T. Taliercio, E. Tournié, P.-O. Chapuis, R. Vaillon, Nano Letters 21, 4524 (2021)
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Keywords: Near, field, Near, field radiative heat transfer, Thermophotovoltaics